LSS Probes of Cosmic Acceleration

a phenomenological implementation of screening

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based on a series of works with Zvonimir Vlah

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Motivations

c.c. problem

Old: “understand why the vacuum energy is so small”

Weinberg

New: “why it is comparable to the present mass density”

Accept Λ

“..wait for a better solution, go anthropic etc...”

Dark Energy/Modified Gravity

Uniqueness of GR

Lorentz-invariant
massless
spin-2

L-breaking theories

massive gravity

directly add e.g.
scalars, DE

Beyond ΛCDM

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

* not necessarily, e.g. Lorentz-violating massive gravity

Dark Energy/Modified Gravity

Extra d.o.f.

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

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

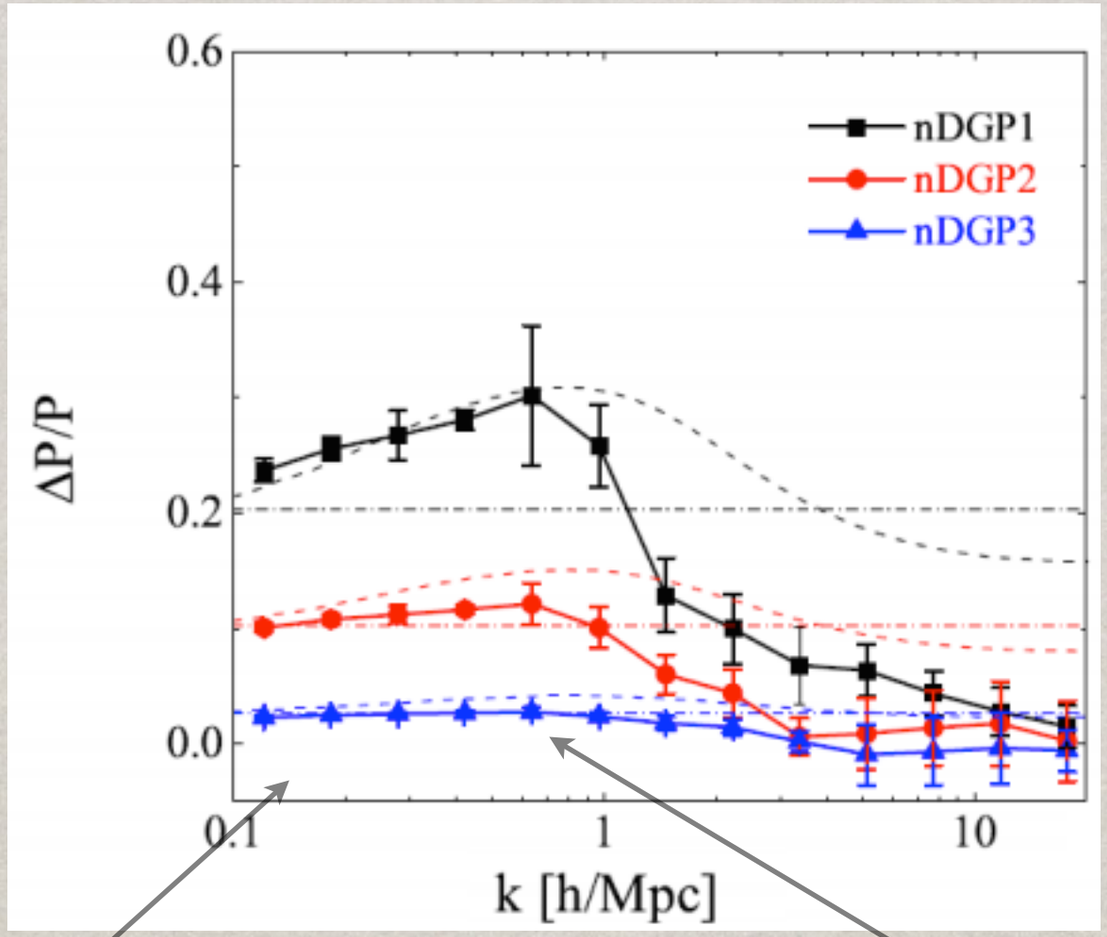
$$V(r) \sim -\frac{g^2(\phi)}{Z(\phi)} \frac{e^{-\frac{m(\phi)}{\sqrt{Z(\phi)}}r}}{4\pi r}\mathcal{M}$$

Symmetron

Vainshtein

Chameleon

N-body

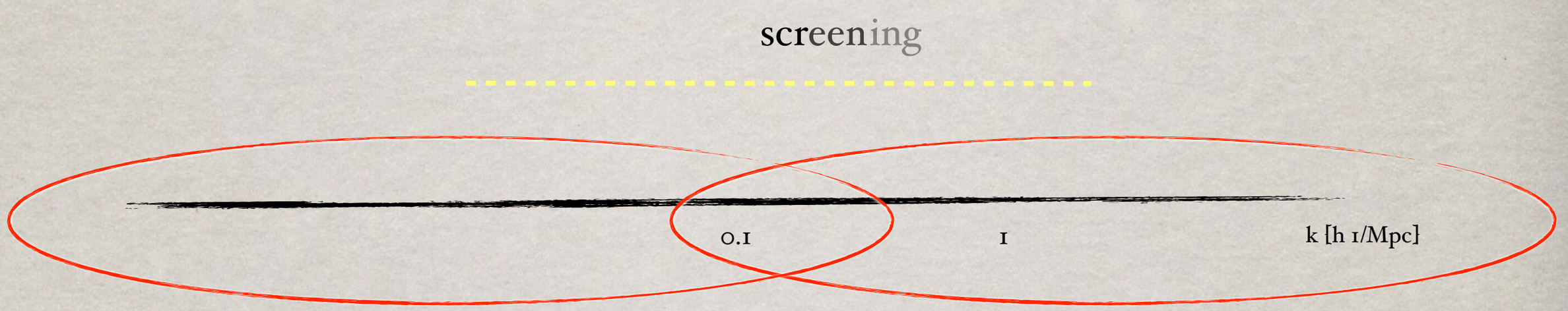


Falck, Koyama, Zhao (2015)

Linear scales

Onset Vainshtein Screening

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)
TSPT(Blas, Garny, Ivanov, Sibiryakov)
....
Lagrangian approach
(Matsubara; Porto et al; Vlah et al)
...

EFT of LSS

Why also Perturbation Theory?

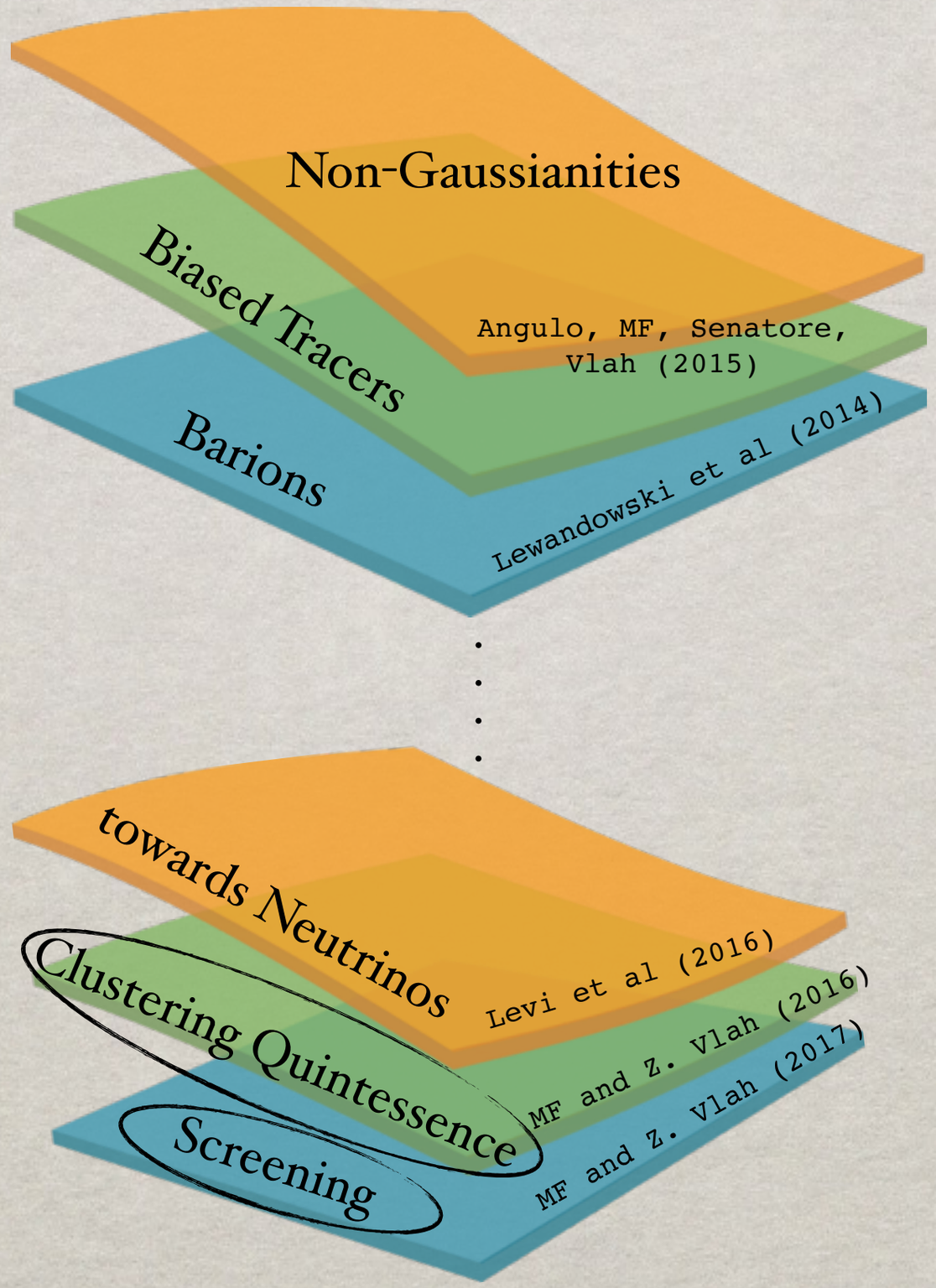
Underlying physical principles

clear cut map with DE/MG model space

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

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

Layers of physics



Clustering Quintessence

Creminelli et al (2009);
Sefusatti, Vernizzi (2011);
Anselmi et al (2011);
D'Amico, Sefusatti (2011);
Lewandowski et al (2016)

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

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 up to quadratic order

new variables $\delta = \delta_T \;;\; \Theta = -\dfrac{C}{\mathcal{H} f_+}\theta$

Sefusatti, Vernizzi (2011)

$$\begin{cases} \dfrac{\partial \delta_{\mathbf{k}}}{\partial \eta} - \Theta_{\mathbf{k}} = \dfrac{\alpha(\mathbf{q_1}, \mathbf{q_2})}{C} \Theta_{\mathbf{q_1}} \delta_{\mathbf{q_2}} \;, \\ \dfrac{\partial \Theta_{\mathbf{k}}}{\partial \eta} - \Theta_{\mathbf{k}} - \dfrac{f_-}{f_+^2}(\Theta_{\mathbf{k}} - \delta_{\mathbf{k}}) = \dfrac{\beta(\mathbf{q_1}, \mathbf{q_2})}{C} \Theta_{\mathbf{q_1}} \Theta_{\mathbf{q_2}} \;, \end{cases}$$

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

reduced to familiar system,
C features in the non-linear

All orders, integral & differential solutions

MF, Vlah (2016)

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

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

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

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

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

iteratively derived, first recursion are usual

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

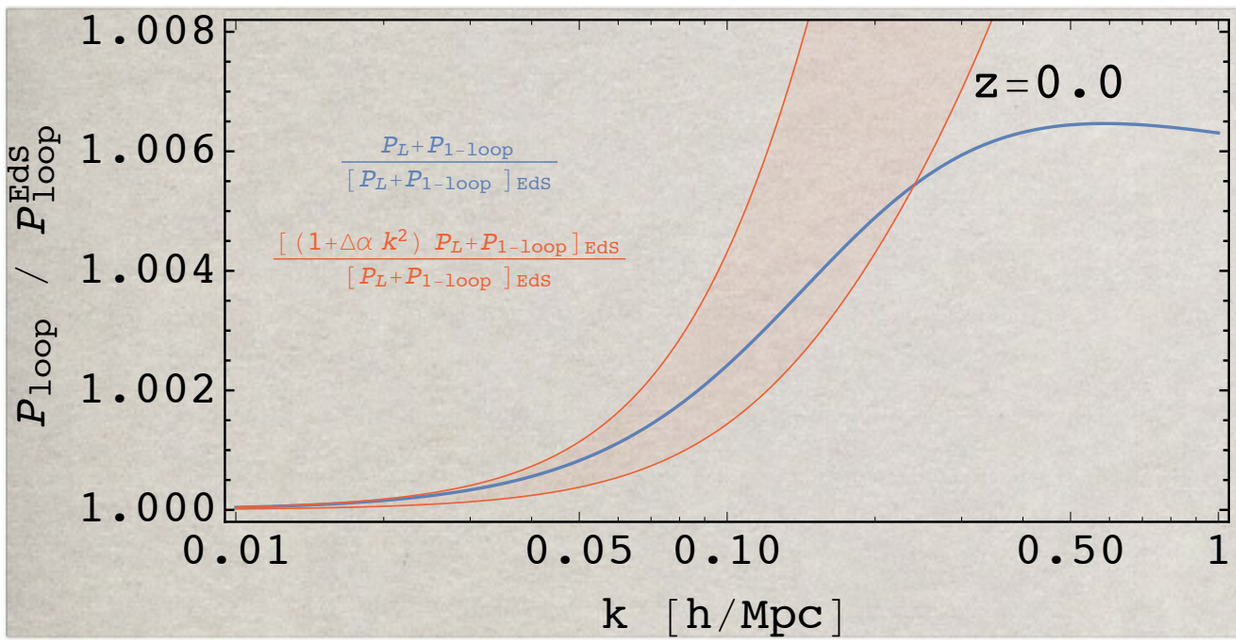
related to

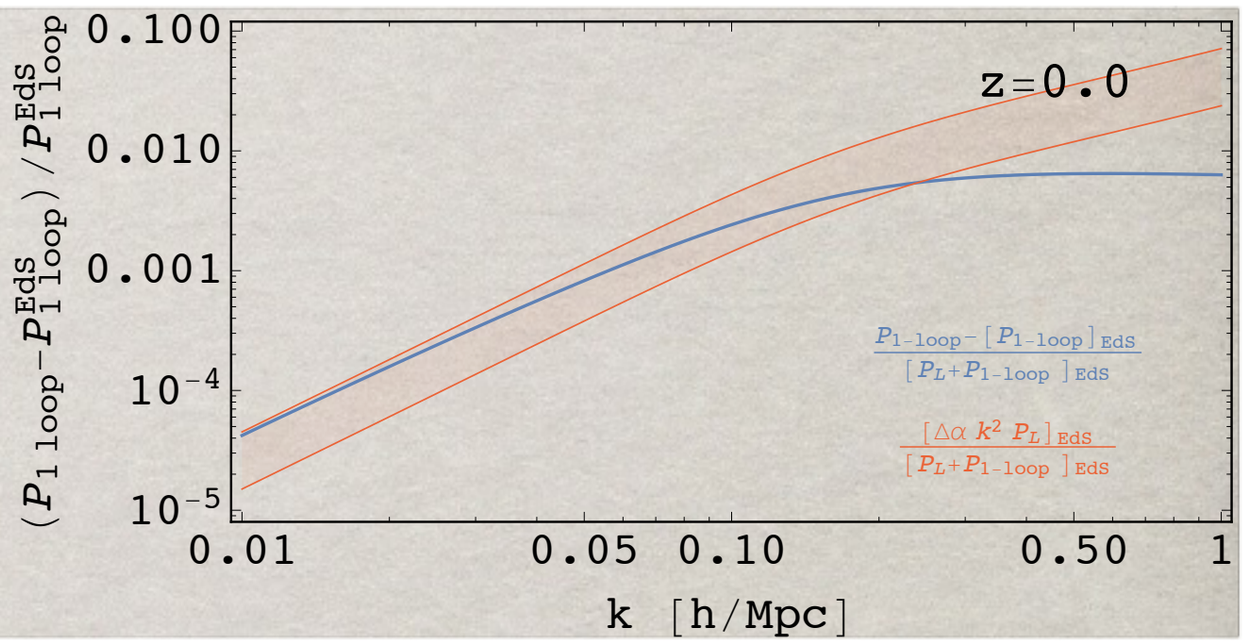
$\propto$ linear growth rate

Observables

MF, Vlah (2016)

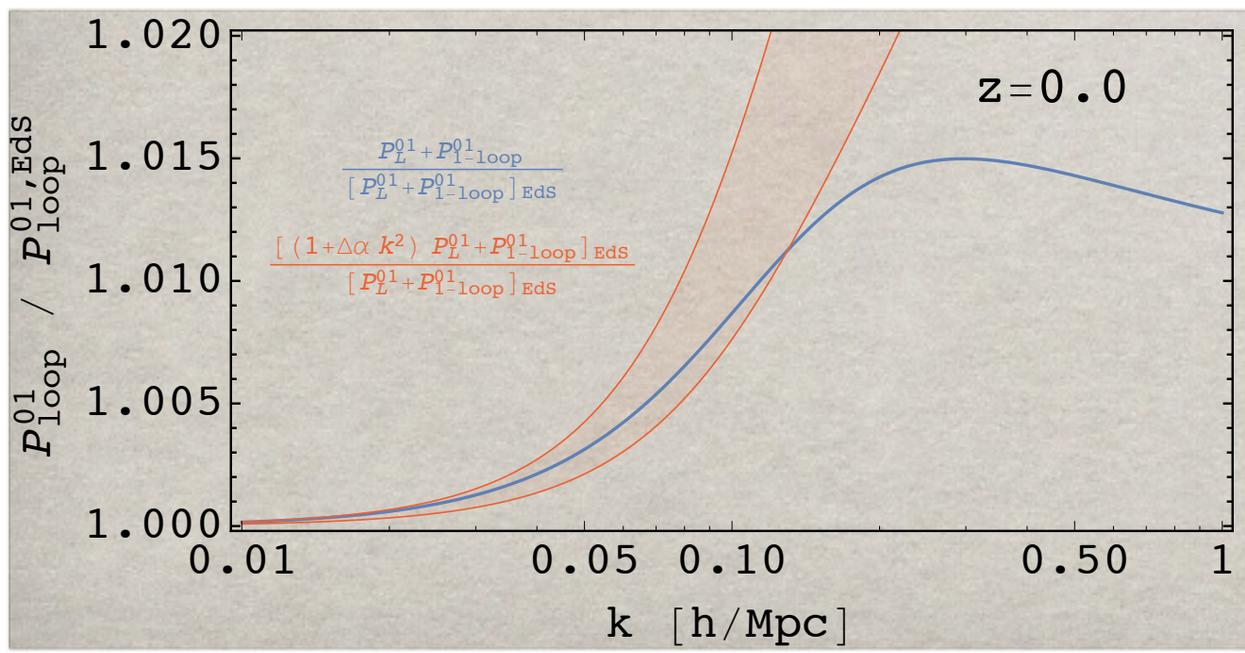
$$P_{1-\mathrm{loop}}(k,a) = P_{\mathrm{L}}(k,a) + P_{22}(k,a) + 2P_{13}(k,a) + P_{\mathrm{c.t.}}(k,a)$$

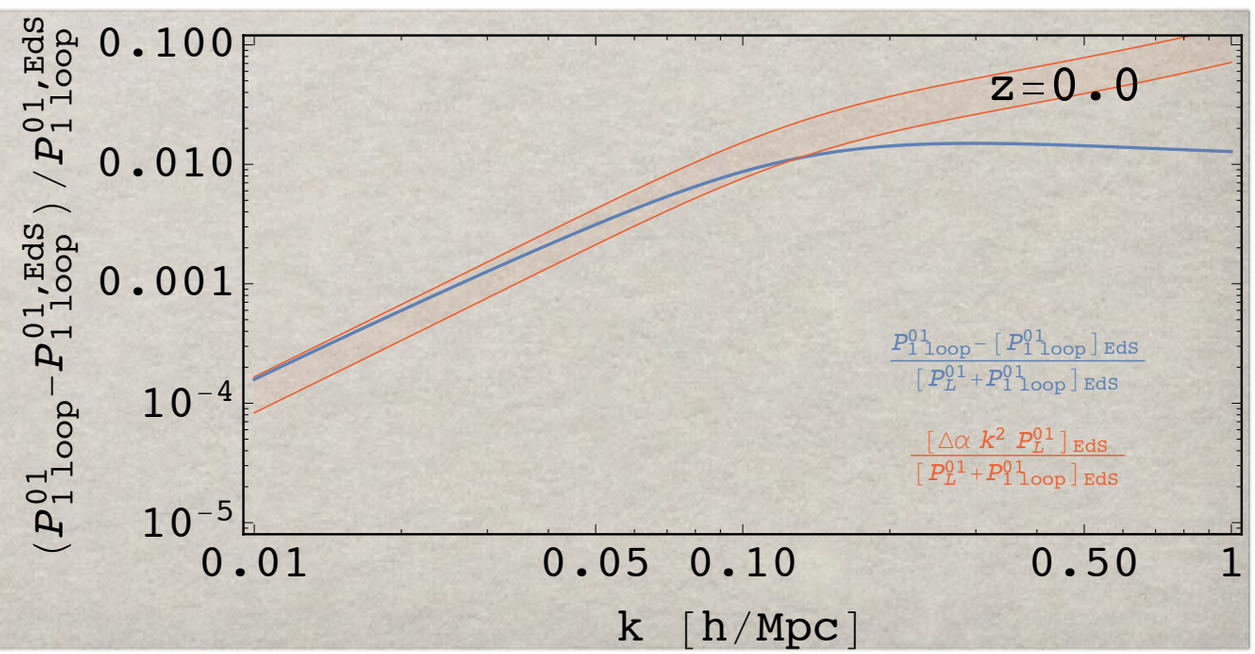




$C(\eta) = 1$

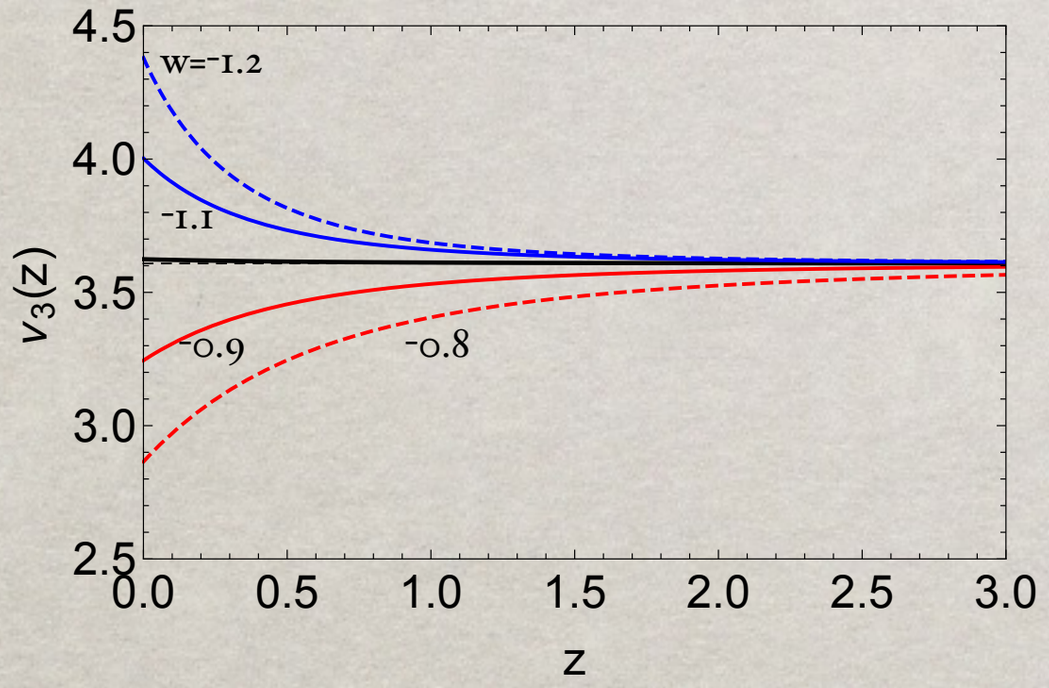
test with ΛCDM

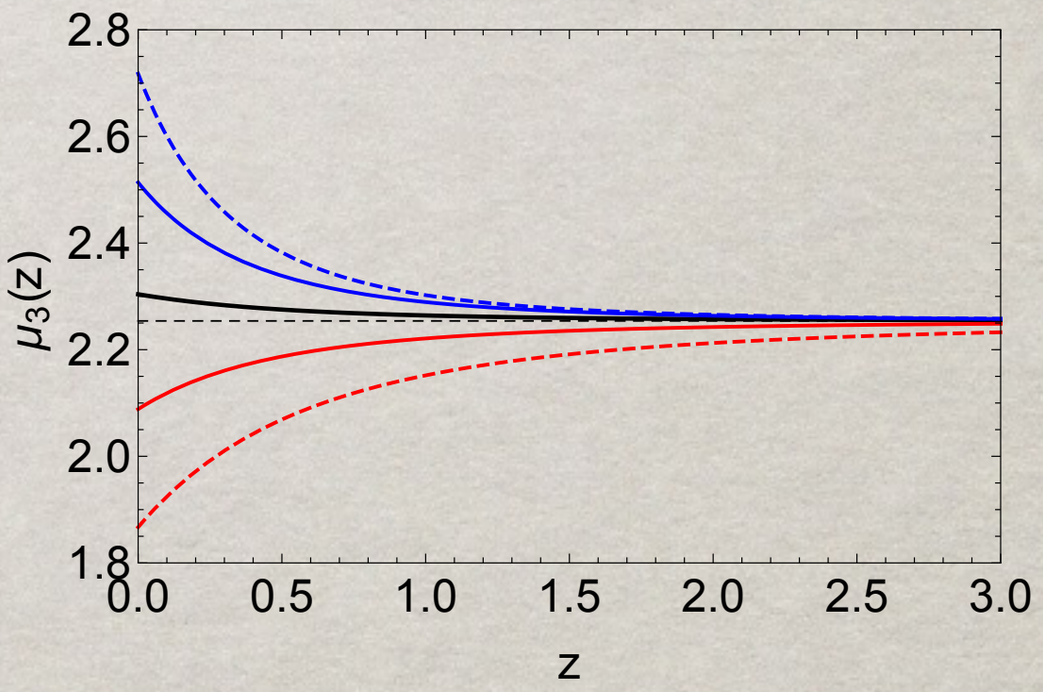




$$F_3 = (1-\epsilon^{(2)})\mathcal{F}_3^{\epsilon} + \nu_3\mathcal{F}_3^{\nu_3} + (1-\epsilon^{(1)})\nu_2\mathcal{F}_3^{\nu_2} + \lambda_1\mathcal{F}_3^{\lambda_1} + \lambda_2\mathcal{F}_3^{\lambda_2}$$

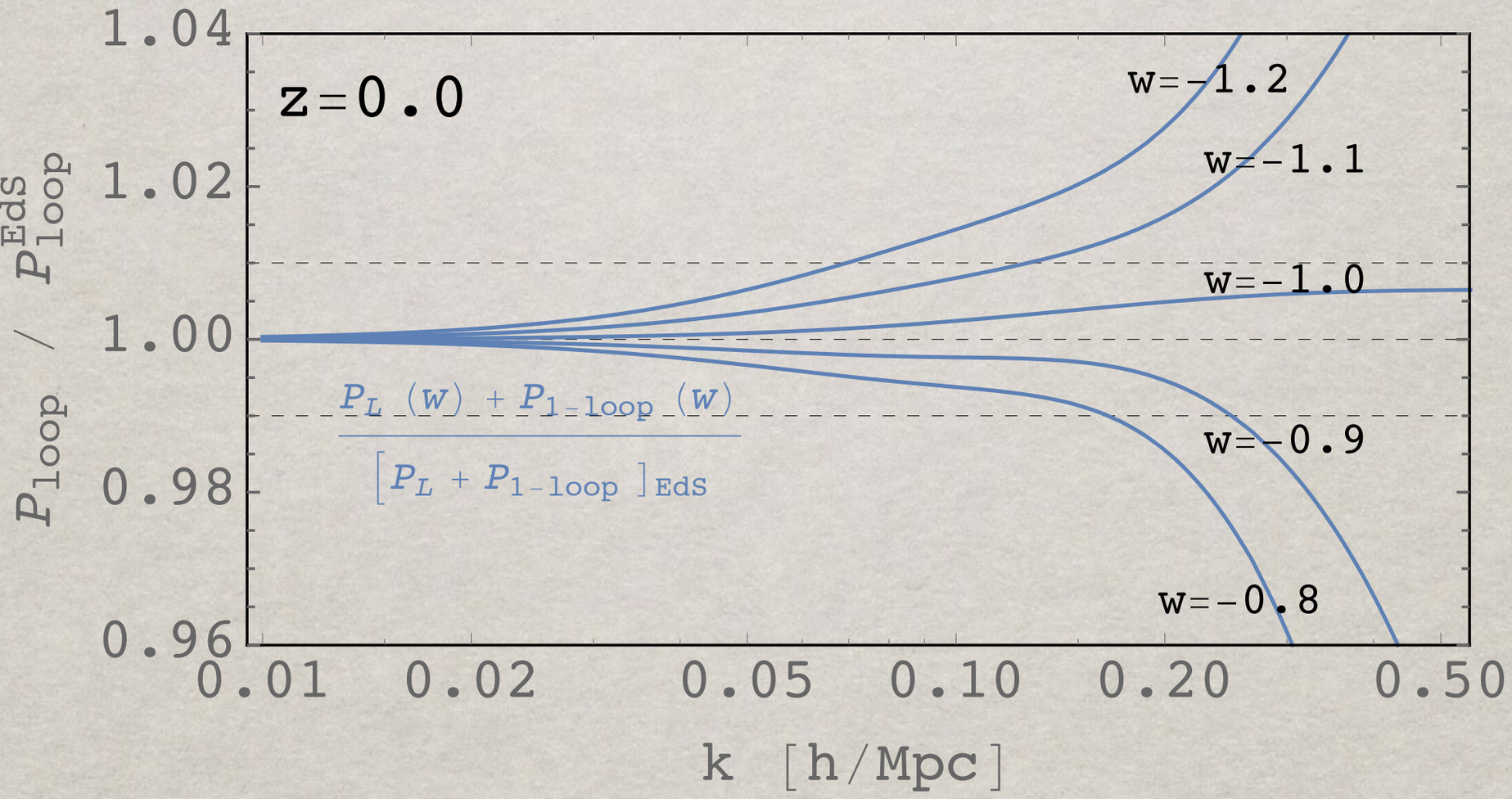
$$G_3 = (1-\epsilon^{(2)})\mathcal{G}_3^{\epsilon} + \mu_3\mathcal{G}_3^{\mu_3} + (1-\epsilon^{(1)})\mu_2\mathcal{G}_3^{\mu_2} + \kappa_1\mathcal{G}_3^{\kappa_1} + \kappa_2\mathcal{G}_3^{\kappa_2}$$



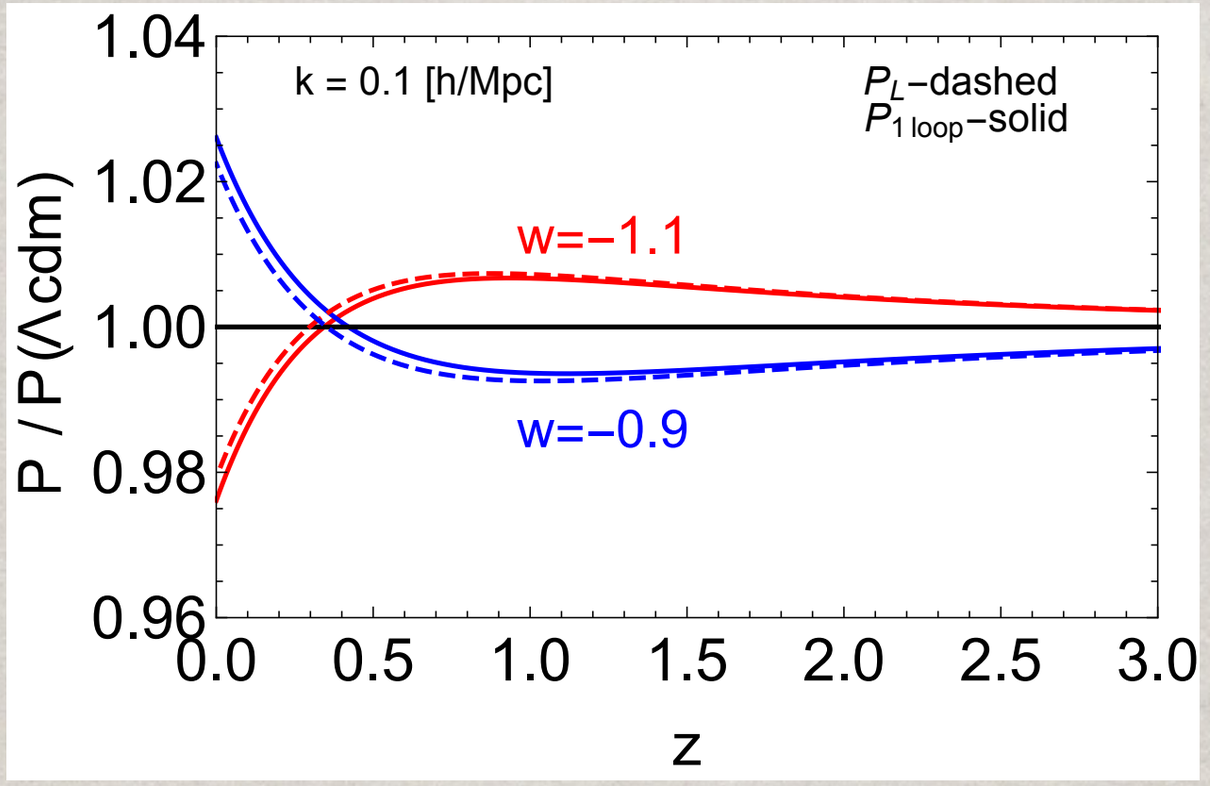


similarly for $\lambda_1, \lambda_2, \kappa_1, \kappa_2(z)$ while $\mathcal{F}_3 = \mathcal{F}_3(\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3)$

MF, Vlah


z=0.0
w=-1.2
w=-1.1
w=-1.0
w=-0.9
w=-0.8
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]
$P_{\rm loop} / P_{\rm loop}^{\rm EdS}$
$\frac{P_L(w) + P_{1\text{-loop}}(w)}{[P_L + P_{1\text{-loop}}]_{\rm EdS}}$

MF, Vlah



All the way to Biased tracers

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

Screened system: dark matter + Galileon-like dof

Lue et al (2004);
Koyama and Silva (2007);
de Rham et al (2012);
Barreira et al (2013);
……

$$
\begin{cases}
\dfrac{\partial \delta_m}{\partial \tau} + \partial_i[(1+\delta_m)v_m^i] = 0 \,, \\
\dfrac{\partial v_m^i}{\partial \tau} + \mathcal{H} v_m^i + v_m^j \partial_j v_m^i = -\nabla^i \Phi \,, \\
\nabla^2 \Phi = \dfrac{3}{2}\mathcal{H}^2 \Omega_m \delta_m + F(\bar{\phi}) \nabla^2 \delta\phi \\
\nabla^2 \delta\phi + \text{non linearities} = \dfrac{\beta}{M_{\rm Pl}}\, \delta_m \,,
\end{cases}
$$

Two different scales ==> 2 expansions parameters

k/k_{NL} vs k/k_V

The existence of a k_{NL} - k_V hierarchy can be useful

$$
\begin{cases}
k_{\rm V} \sim H_0 & \Lambda\text{CDM} \\
H_0 \ll k_{\rm V} < k_{\rm NL} & \text{==> screening can happen on quasi-linear (for DM) scales} \\
k_{\rm V} \gg k_{\rm NL} & \text{very weak screening, if any}
\end{cases}
$$

Origin of k_V

$$\nabla^2\phi + \frac{1}{\Lambda^3}\left[(\nabla^2\phi)^2 - (\nabla_i\nabla_j\phi)^2\right] = \beta\frac{\rho}{M_{\rm Pl}} \ .$$

Ex: solution for top-hat distribution of radius R, spherical symmetry

Barreira et al, JCAP (2013)

$$\varphi_{,r} = \frac{4M_{\rm Pl}a^2r^3}{3\beta r_{\rm V}^3}\left[\sqrt{\left(\frac{r_{\rm V}}{r}\right)^3+1}-1\right]\frac{GM(R)}{r^2}$$

$$r_{\rm V}^3 = \frac{8M_{\rm Pl}r_S}{9\Lambda^3\beta_1\beta_2}$$

$$\partial^2\Phi = 4\pi G a^2\delta\rho_m - \frac{\kappa c_3}{\Lambda^3}\frac{\beta}{\beta_2}\dot{\bar{\phi}}^2\partial^2\varphi$$

$$F_{\rm 5th} = -\frac{\kappa c_3}{\Lambda^3}\frac{\beta}{\beta_2}\dot{\bar{\phi}}^2\varphi_{,r}$$

$r \gg r_{\rm V}$

$$F_{\rm 5th} = -\frac{2c_3a^2\dot{\bar{\phi}}^2}{3\Lambda^3M_{\rm Pl}\beta_2}\frac{GM(R)}{r^2}$$

$r \ll r_{\rm V}$

$$F_{\rm 5th} \sim -\frac{2c_3a^2\dot{\bar{\phi}}^2}{3\Lambda^3M_{\rm Pl}\beta_2}\frac{GM(R)}{r^2}\times\left(\frac{r}{r_{\rm V}}\right)^{3/2}$$

suppression!

$$r_{\rm V} \leftrightarrow k_{\rm V}$$

As k nears k_V, non-linearities in the ϕ sector become very important,
perturbation theory not enough ==> <u>need to resum</u>

Solve each model exactly

Phenomenological approach: screening "filter"

$$P_{\rm res}\big|_N(k,\tau) = \sum_{n=0}^{N} P_{\rm res}^{(n)}(k,\tau) = \sum_{n=0}^{N} \int \frac{d^3k'}{(2\pi)^3}\, \mathcal{K}_n^N(k',k,\tau) P^{(n)}(k,\tau),$$

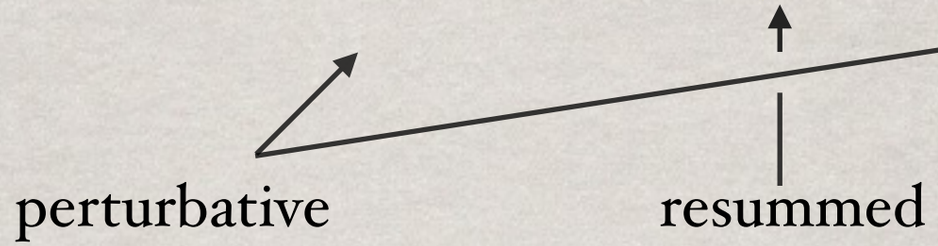
formally similar to recent BAO resummation scheme

Senatore et al; Vlah et al; Blas et al;

Quest for the right kernels $\mathcal{K}_n^N$

Guiding principles:
- Asymptotic behaviour
- Symmetries
- no double-counting

$$P_{\rm res}\big|_N(k,\tau) \quad = \sum_{n=0}^{N} \Big[P^{(n)}_{\Lambda\rm CDM}(k,\tau) + K^N_n(k,\tau)\Delta P^{(n)}(k,\tau) \Big]$$



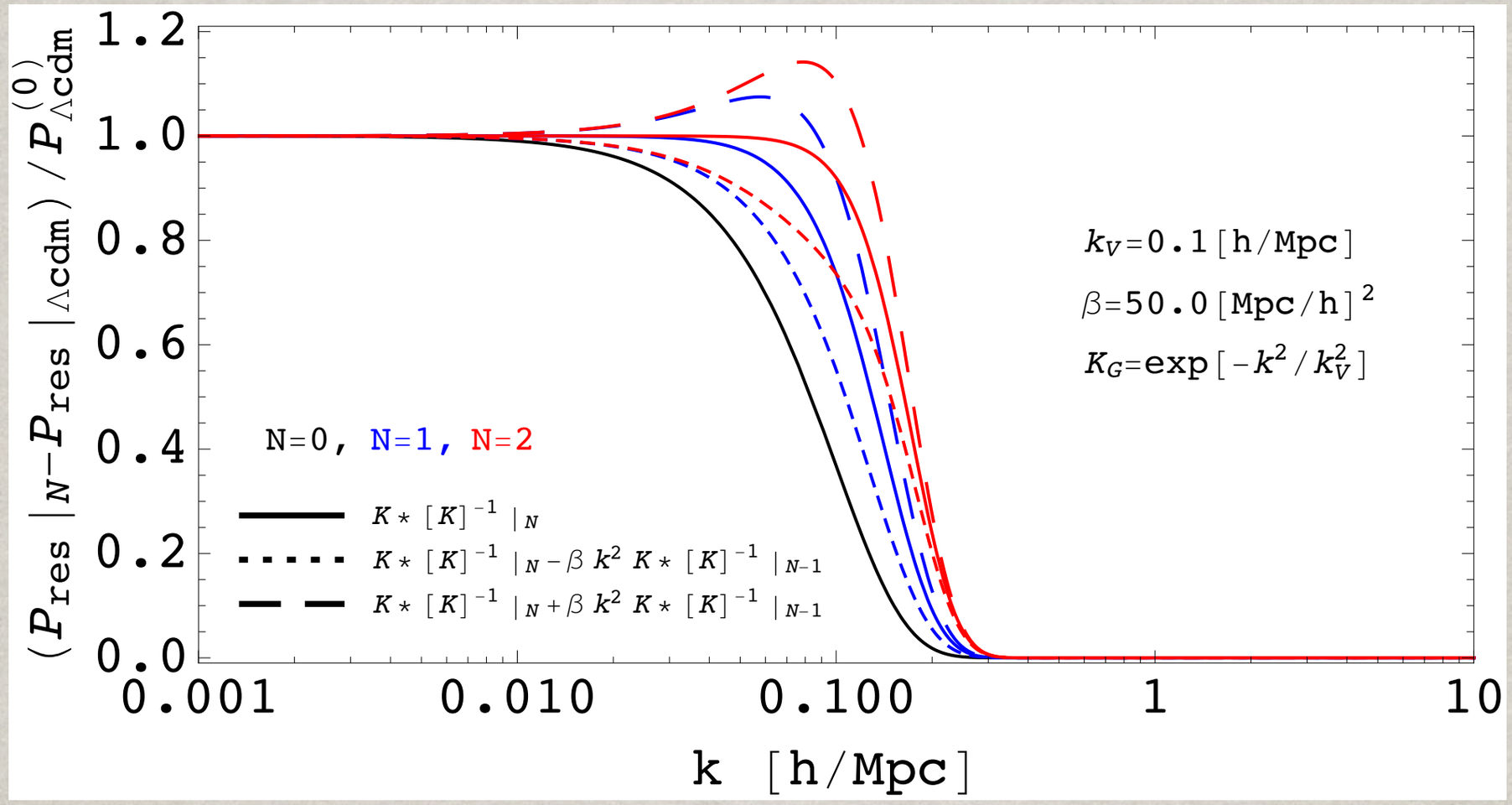
Two Candidates

$$K_{\rm G}(k,\tau) \quad = \exp\left(-\textstyle\sum_m \alpha_m (k/k_{\rm V})^{2m}\right) \qquad , \qquad K_{\rm L}(k,\tau) \quad = 1/\left(1+\textstyle\sum_m \alpha_m (k/k_{\rm V})^{2m}\right)$$

- Asymptotic behaviour ✓
- Symmetries ✓
- no double-counting ?

Perturbative + Resummed contributions balance

$$K^N_n(k,\tau) = K(k,\tau)\big[K\big]^{-1}\Big|_{N-n}(k,\tau)$$



$$
\begin{aligned}
P_{\rm res}\big|_N(k,\tau) \;\; = \;\; & P_{\Lambda{\rm CDM}}\big|_N(k,\tau) + K(k,\tau)\big[K\big]^{-1}\Big|_N(k,\tau)\Delta P^{(0)}(k,\tau) \\
& + K(k,\tau)\left[K\right]^{-1}\Big|_{N-1}(k,\tau)\,\Delta P^{(1)}(k,\tau) + k^2\Delta P^{(0)}(k,\tau)K(k,\tau)\sum_{n=2}^{N}\beta_n^0\big[\tilde{K}\big]^{-1}\Big|_{N-n}(k,\tau)
\end{aligned}
$$

What's next?

test framework against

exactly-solvable model

simulations

Thank you!