LSS Probes of Cosmic Acceleration

a phenomenological implementation of screening

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based on works with Zvonimir Vlah

Phys.Rev. D94 (2016) no.6, 063516

Phys.Lett. B773 (2017) 236-241

Yukawa Institute, Kyoto University, Feb. 22nd 2018

Motivations

c.c. problem

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

Weinberg

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

Dark Energy/Modified Gravity

Accept Λ

within string theory landscape program

Your

favorite idea!

Etc

Self-tuning

Nitti + Kiritsis’ talks

Dark Energy/Modified Gravity

Uniqueness of GR

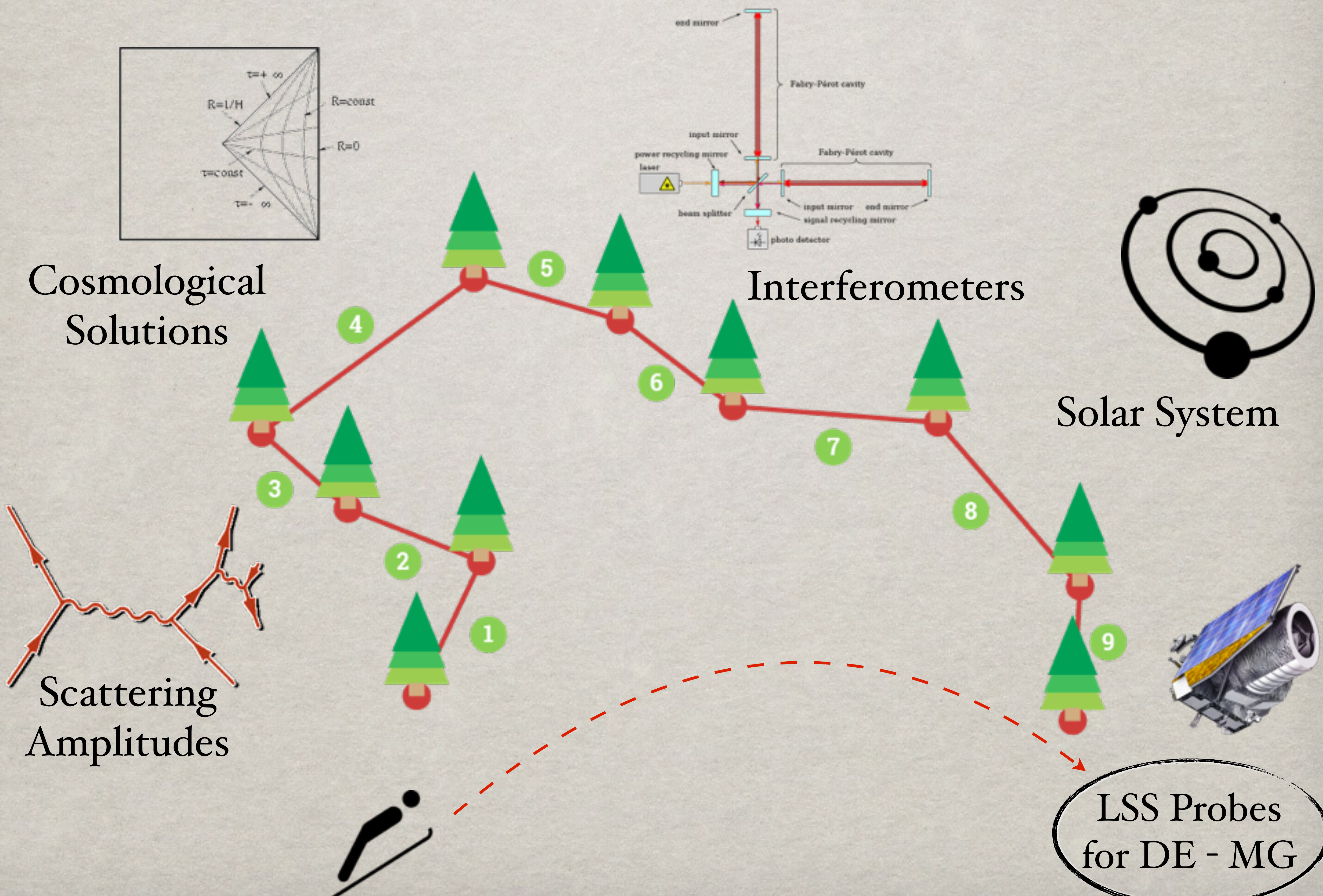
Lorentz-invariant
massless
spin-2

L-breaking theories

Add degrees of freedom
e.g. scalars, DE

Massive Gravity

Tests of dark energy & modified gravity



Beyond ΛCDM

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

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

Screening Mechanisms

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

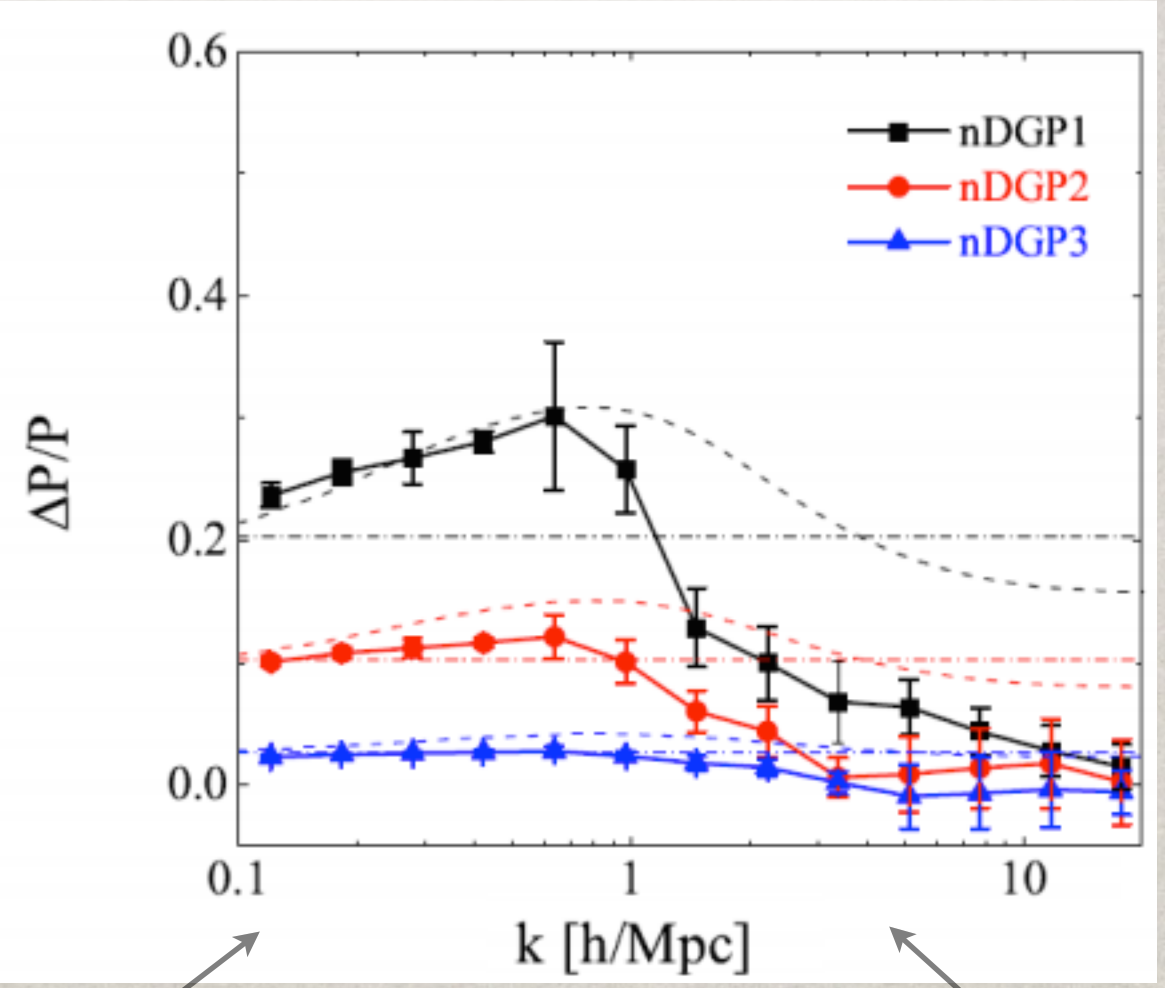
$$V(r) \sim -\frac{g^2(\phi)}{Z(\phi)} \frac{e^{-\frac{m(\phi)}{\sqrt{Z(\phi)}}r}}{4\pi r}\mathcal{M}$$

Chameleon

Vainshtein

Symmetron

N-body

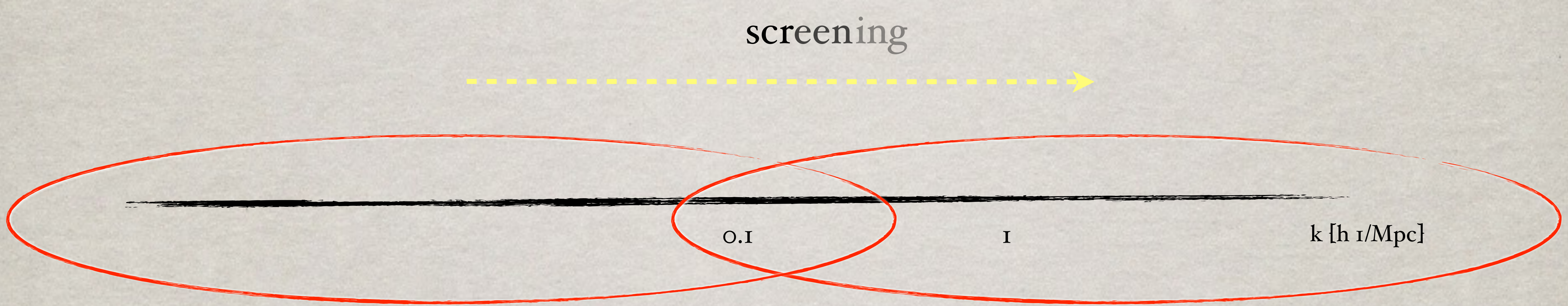


Falck, Koyama, Zhao (2015)

Linear scales

Onset Vainshtein Screening

Perturbation Theory



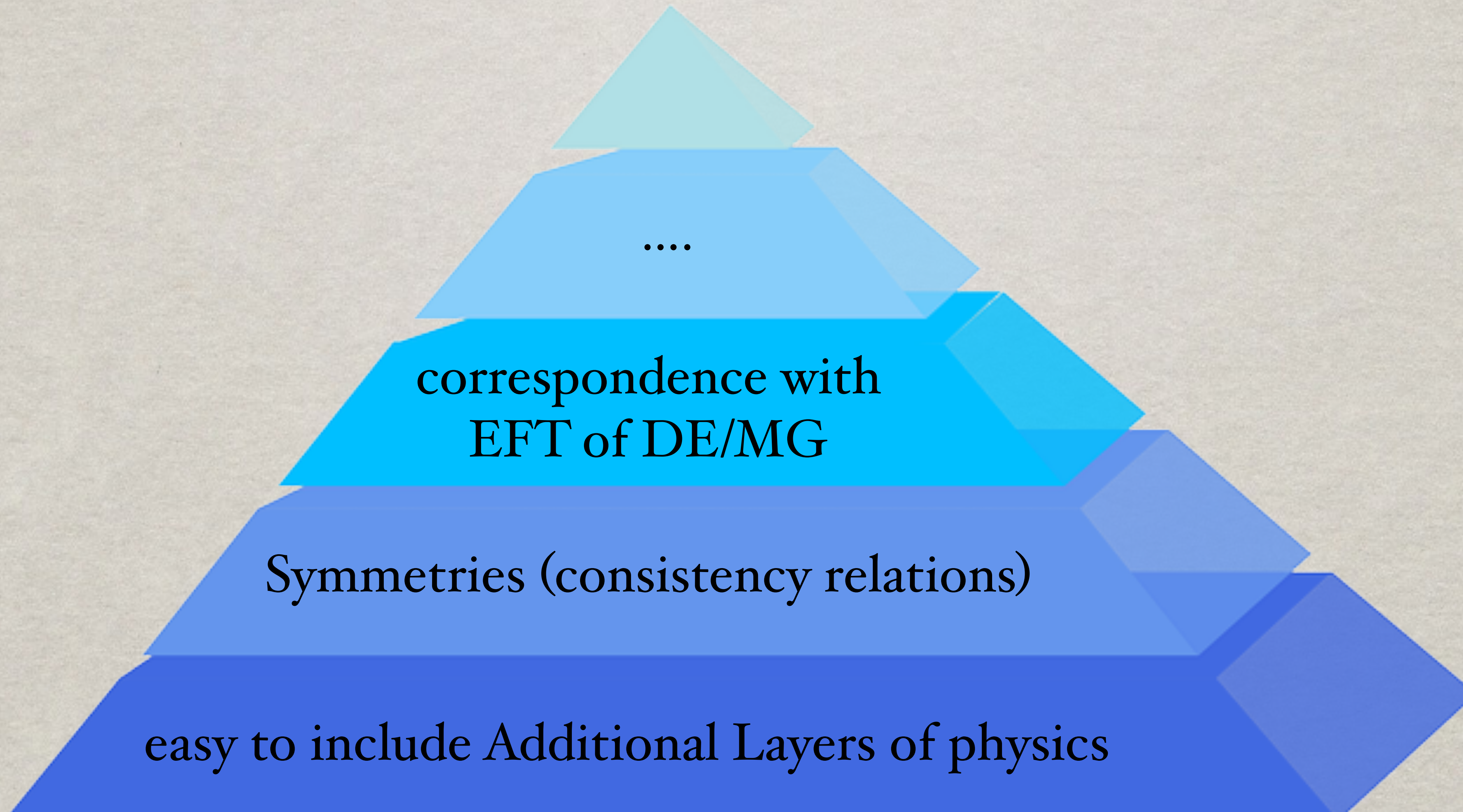
full perturbative control

bulk of the information on growth

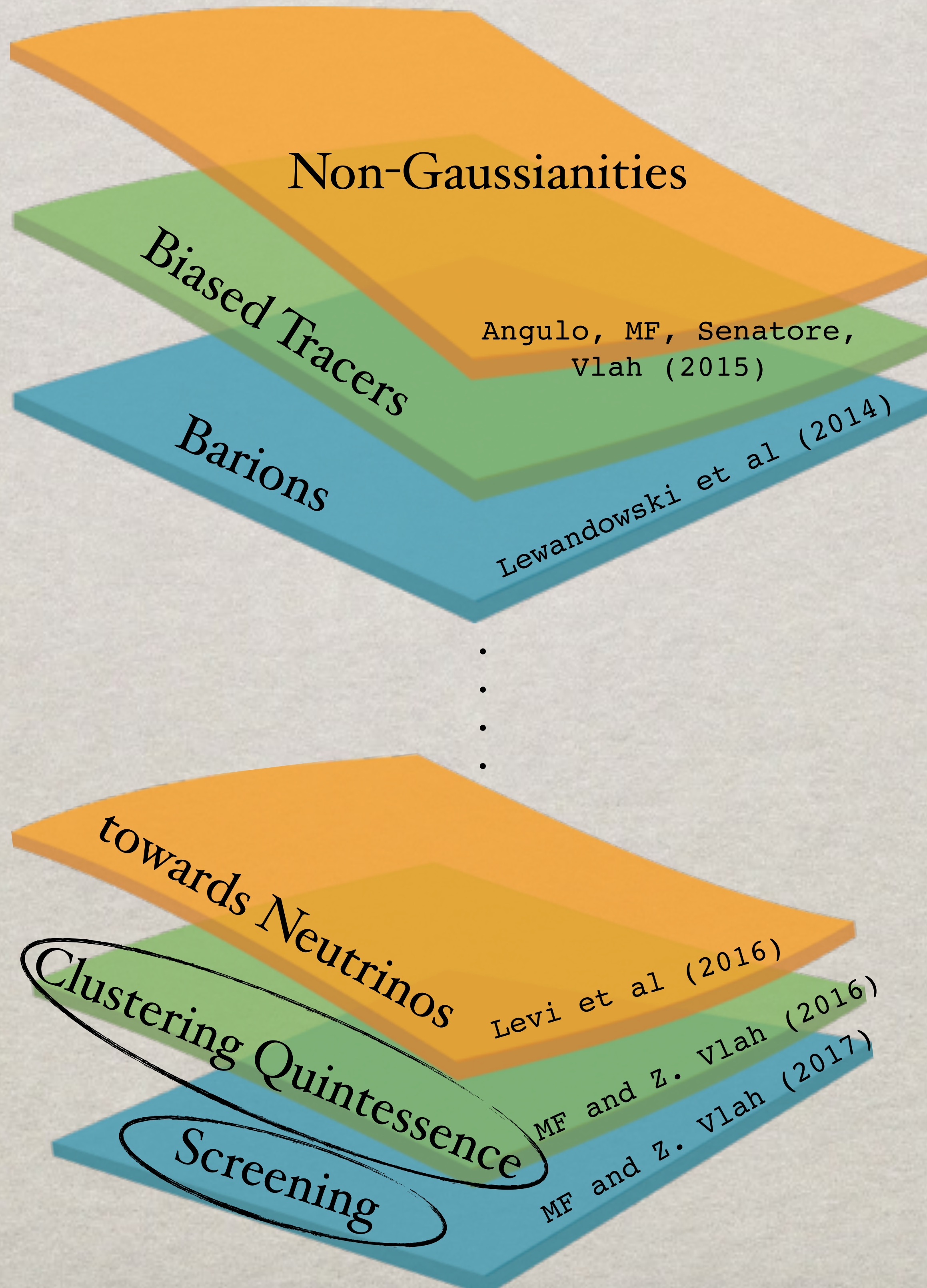
A lot going on to conquer the quasi-linear scales

RPT (Crocce, Scoccimarro)
TRG (Matarrese, Pietroni)
TSPT(Blas, Garny, Ivanov, Sibiryakov)
Closure (Taruya Hiramatsu)
....
Lagrangian approach
(Matsubara; Porto et al; Vlah et al)
...
EFT of LSS

Why also Perturbation theory ?



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

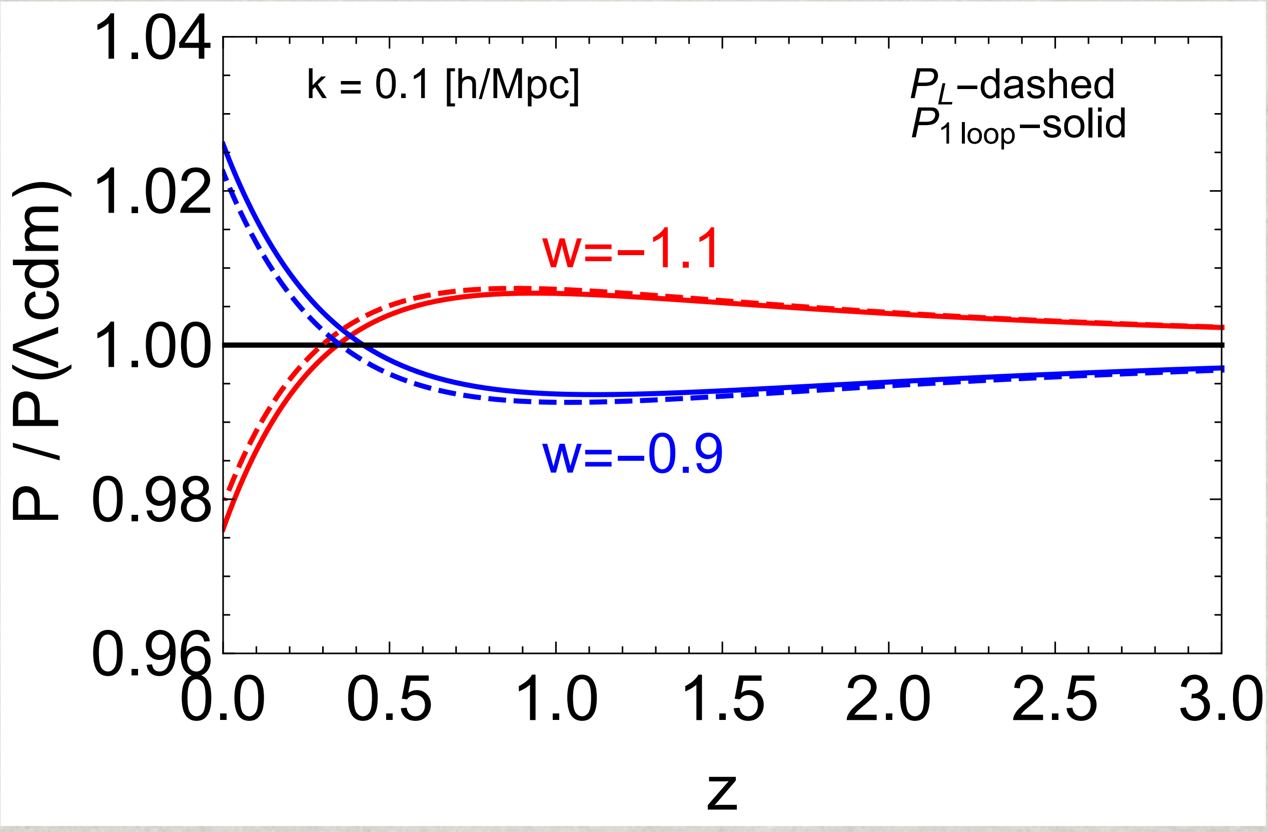
$$\nabla^2 \Phi = \frac{3}{2}\mathcal{H}^2 \Omega_m \underbrace{\left(\delta_m + \delta_Q \frac{\Omega_Q}{\Omega_m}\right)}_{\delta_T}$$

known exactly up to quadratic order

MF, Vlah (2016)

All orders Solution

MF, Vlah, 2016



All the way to Biased tracers

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

Screened system: DM + Galileon-like dof

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

Lue et al (2004);
Koyama and Silva (2007);
de Rham et al (2012);
Barreira et al (2013);
……
à la EFT:
Cusin et al (2017)
Bose et al (2018)

Two scales ==> 2 expansions parameters

$k/k_{\rm NL}$ vs $k/k_{\rm V}$

Hierarchy

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

Origin of kV

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

kV very reminiscent of

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

$r \gg r_{\rm V}$

$r \ll r_{\rm V}$

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

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

suppression!

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

As k nears kv, 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; Pietroni&Peloso +…

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

Guiding principles:

- Asymptotic behaviour
- Symmetries
- no double-counting

$$P_{\text{pert}} = P_{\Lambda\text{CDM}} + \underbrace{(P_{\text{pert}} - P_{\Lambda\text{CDM}})}_{\equiv \Delta P}$$

$$P_{\text{res}}\big|_N(k,\tau) \quad = \sum_{n=0}^{N}\left[P^{(n)}_{\Lambda\text{CDM}}(k,\tau) + K_n^N(k,\tau)\Delta P^{(n)}(k,\tau)\right]$$

perturbative resummed

Two Candidates

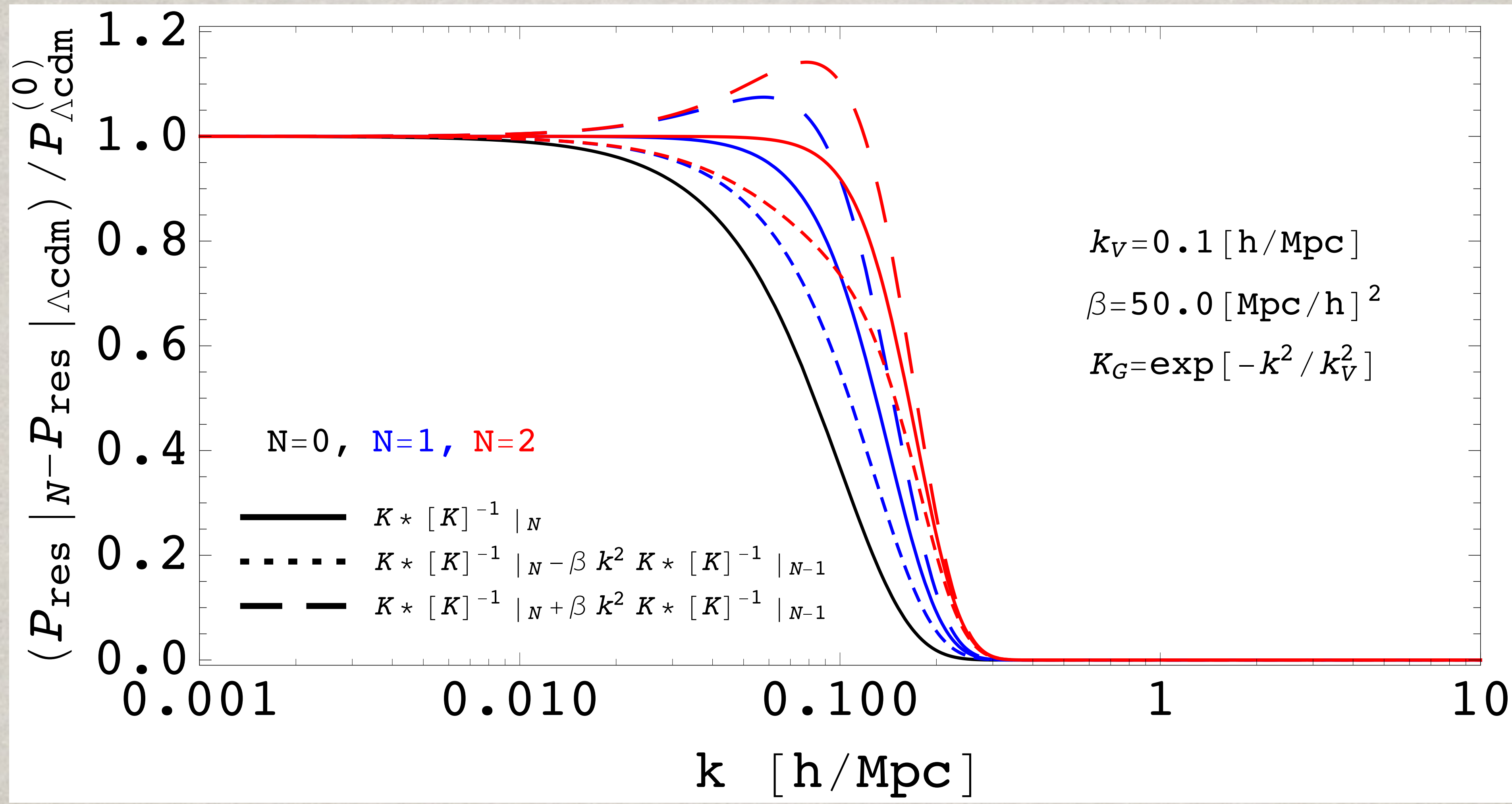
$$K_{\text{G}}(k,\tau) \quad = \exp\left(-\sum_m \alpha_m (k/k_{\text{V}})^{2m}\right) \qquad , \qquad K_{\text{L}}(k,\tau) \quad = 1/\left(1 + \sum_m \alpha_m (k/k_{\text{V}})^{2m}\right)$$

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

MF, Vlah, 2017

Perturbative + Resummed contributions balance

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



MF, Vlah, 2017

$$P_{\rm res}\big|_N(k,\tau) \quad = \quad P_{\Lambda\rm CDM}\big|_N(k,\tau) + K(k,\tau)\big[K\big]^{-1}\Big|_N(k,\tau)\Delta P^{(0)}(k,\tau)$$

$$+K(k,\tau)\,\big[K\big]^{-1}\Big|_{N-1}(k,\tau)\,\Delta P^{(1)}(k,\tau) + k^2\Delta P^{(0)}(k,\tau)K(k,\tau)\sum_{n=2}^{N}\beta_n^0\big[\tilde{K}\big]^{-1}\Big|_{N-n}(k,\tau)$$

What's next?

test framework against

exactly-solvable model

simulations

Thank you!

All orders, integral & differential solutions

MF, Vlah (2016)

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

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

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

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

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

iteratively derived, first recursion are usual

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

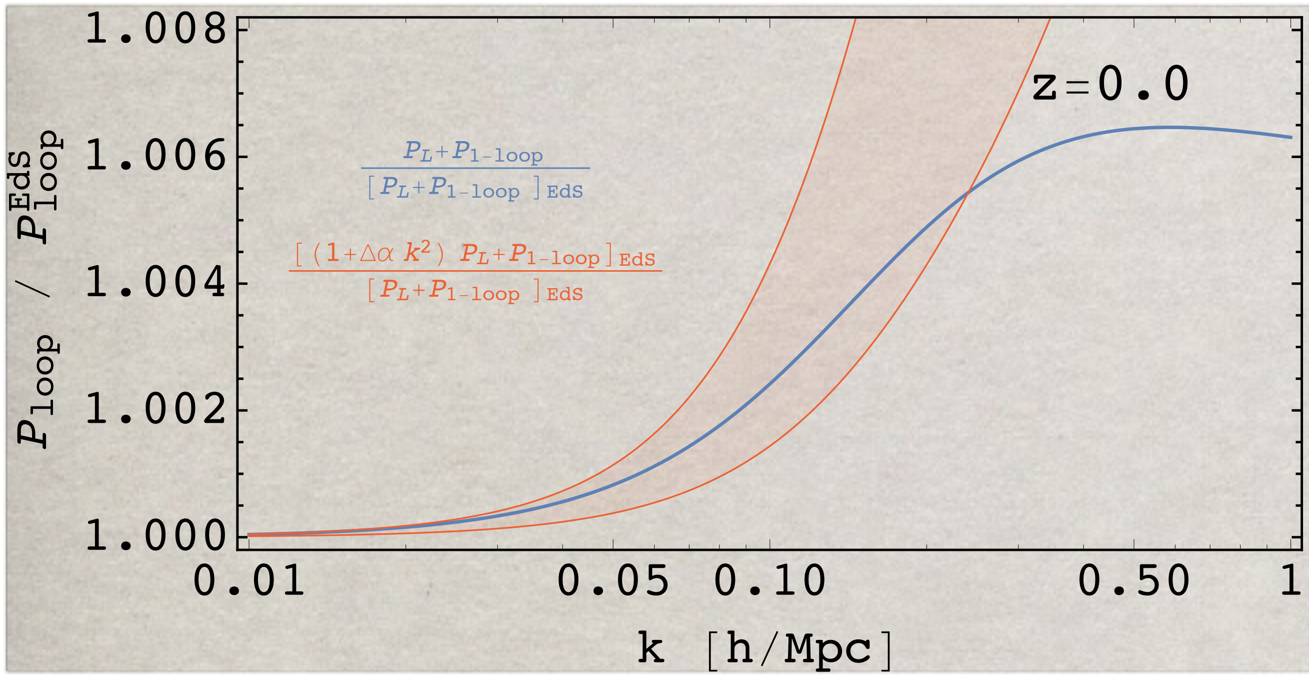
related to

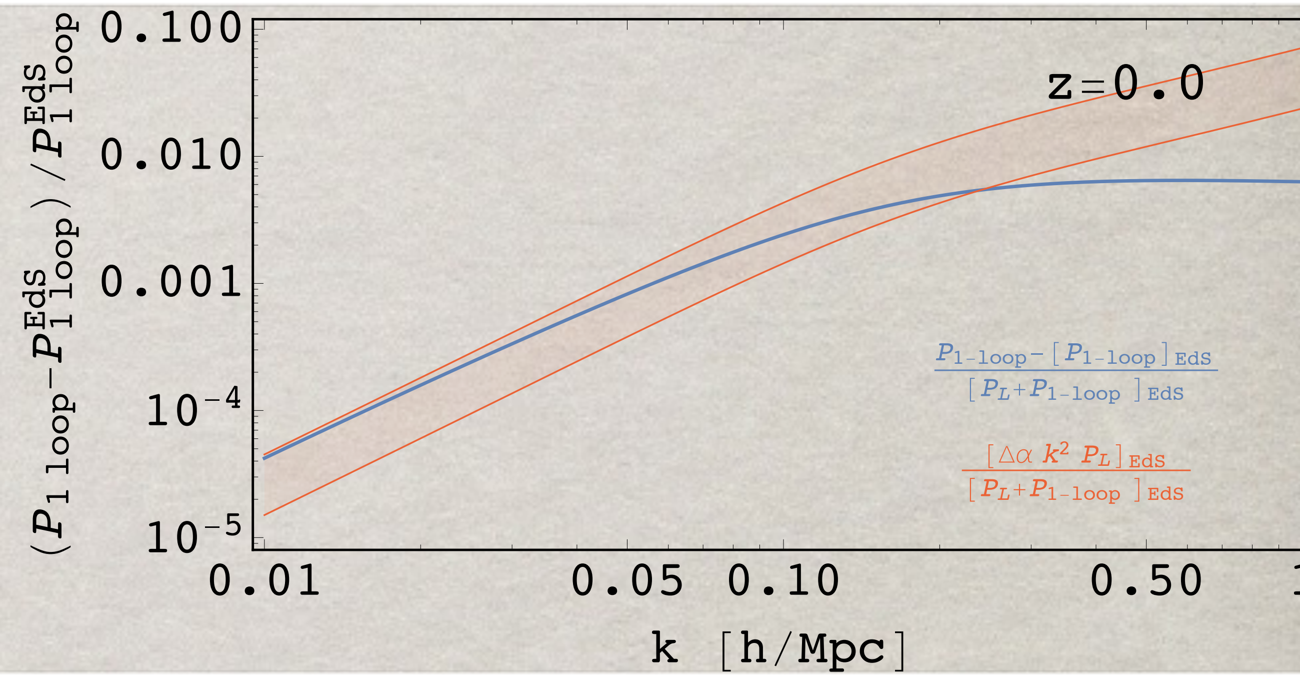
$\propto$ linear growth rate

Observables

MF, Vlah (2016)

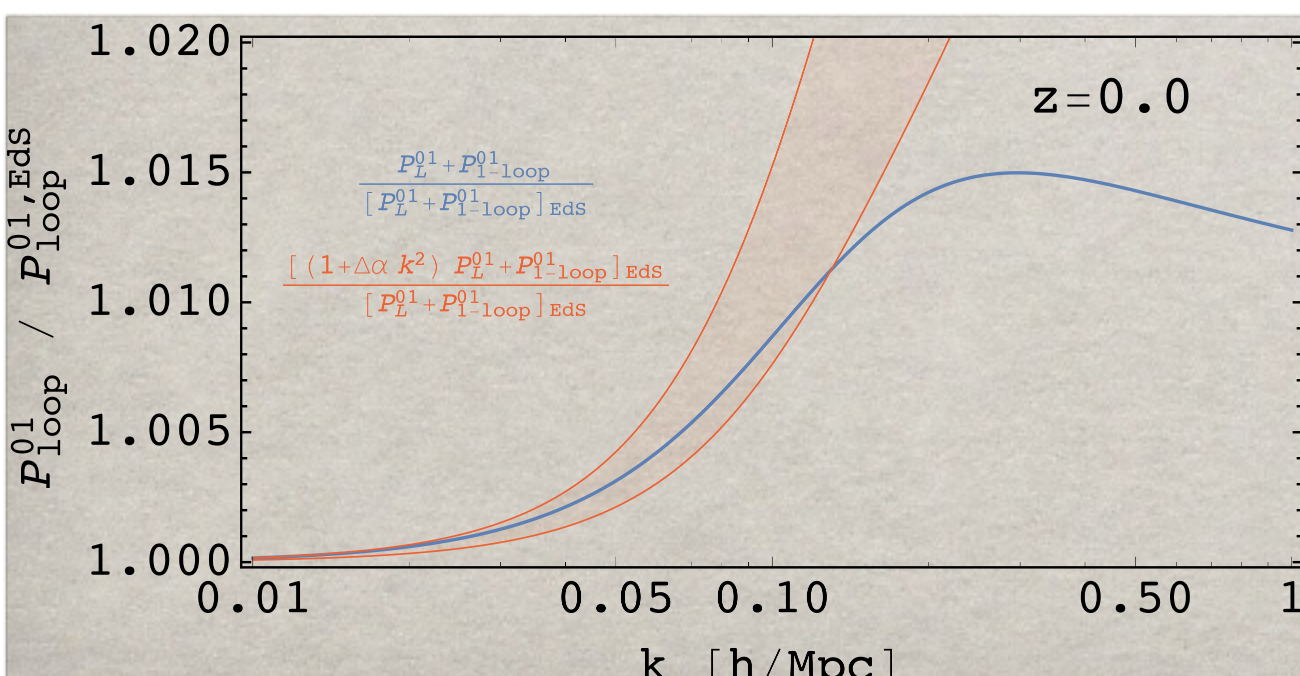
$$P_{1-\mathrm{loop}}(k,a) = P_{\mathrm{L}}(k,a) + P_{22}(k,a) + 2P_{13}(k,a) + P_{\mathrm{c.t.}}(k,a)$$

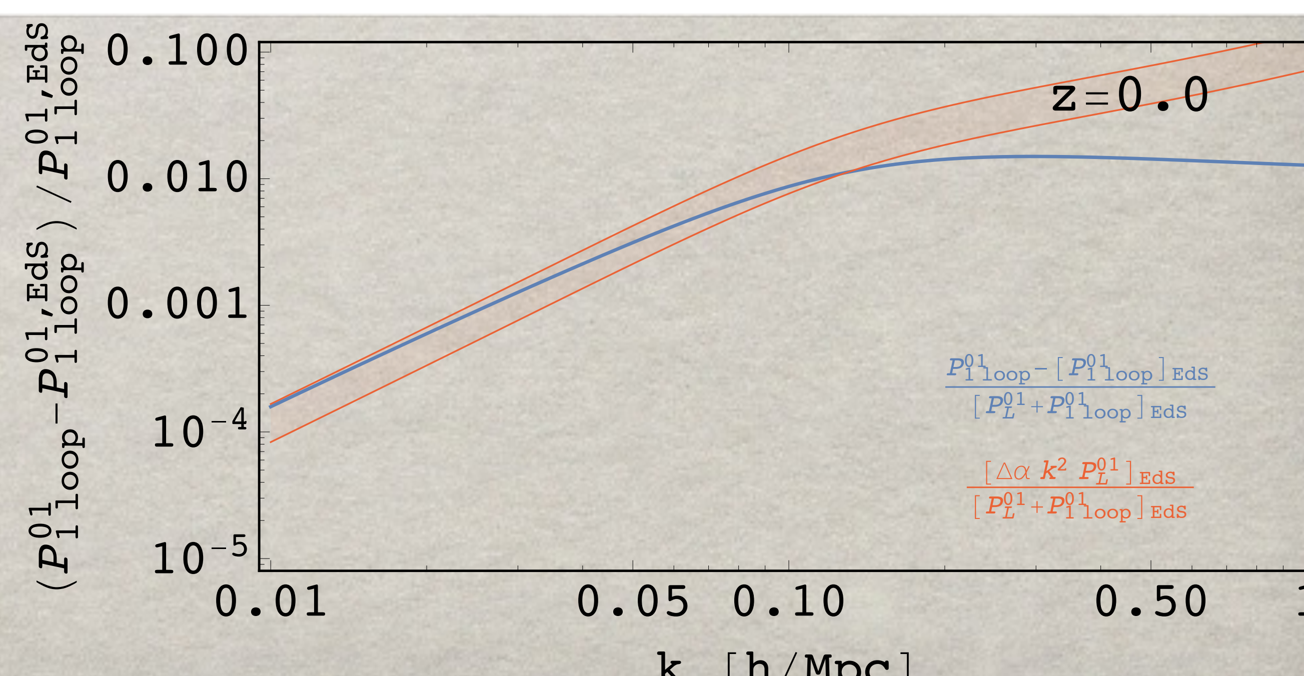




$C(\eta) = 1$

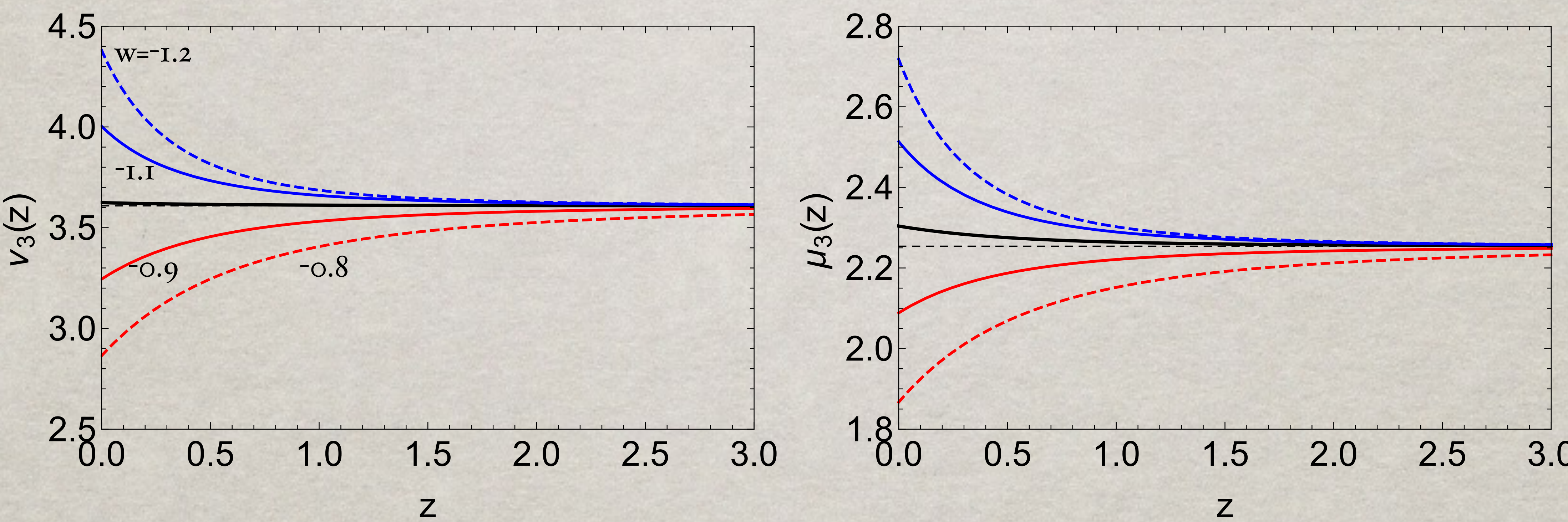
test with ΛCDM





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

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



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