The future of the primordial features down to non-linear scales

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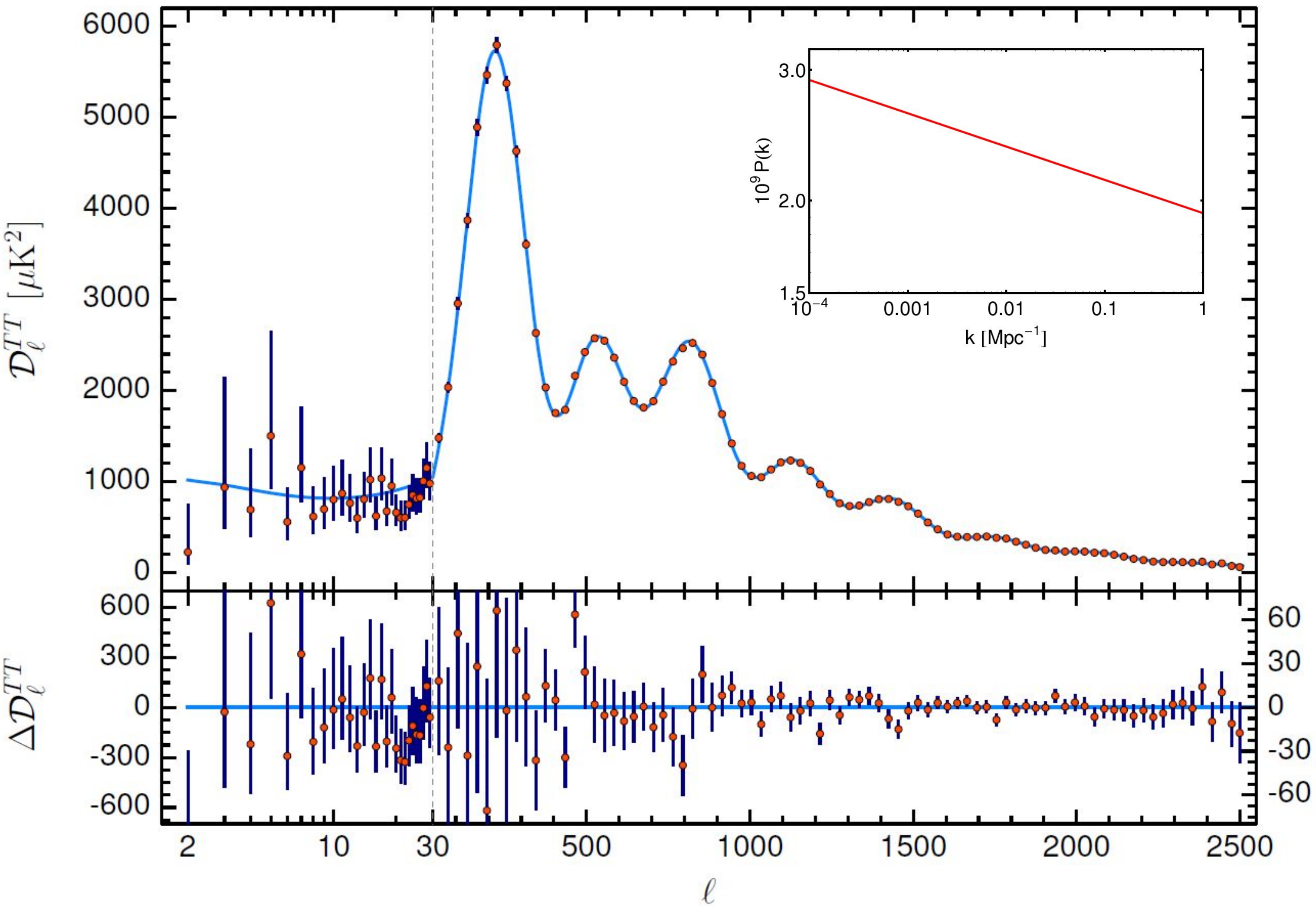
FEATURES IN THE CMB TEMPERATURE APS

Planck 2018 results. VI. Cosmological parameters



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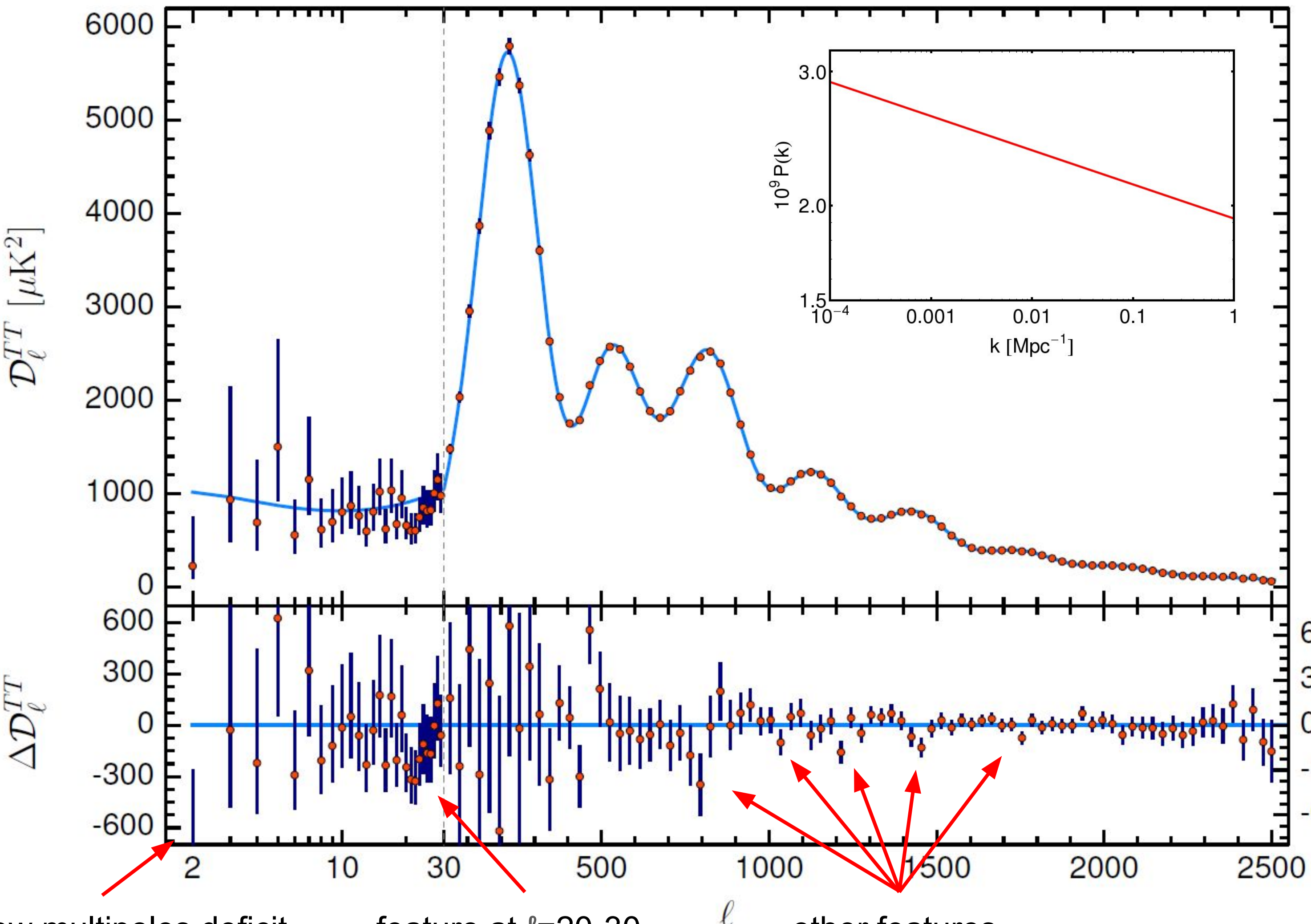


low multipoles deficit

feature at ℓ=20-30

other features

SUPERIMPOSED OSCILLATIONS - CMB

Superimposed linear and logarithmic wiggles all over the spectra:

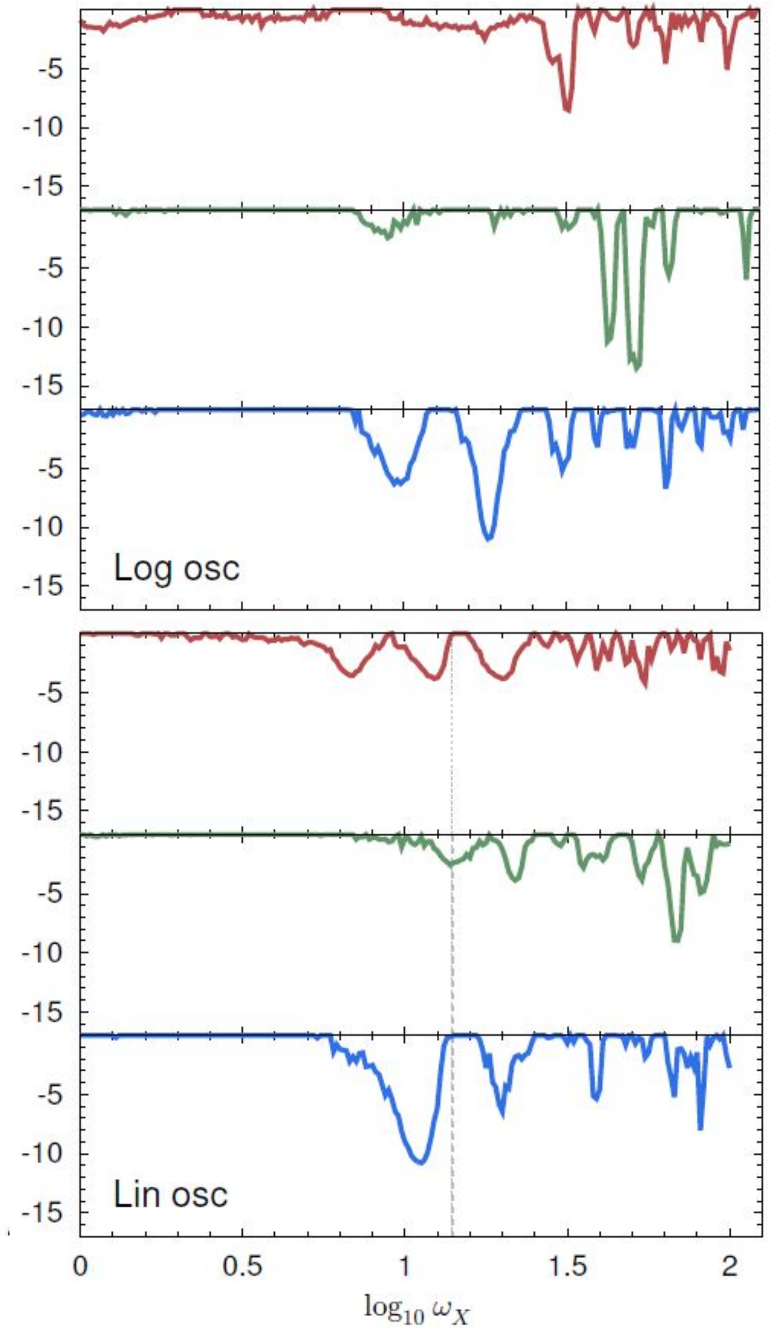
$$P_\zeta(k) = P_{\zeta,0}(k)\left[1 + \mathcal{A}_{\rm lin}\cos\left(\omega_{\rm lin}\frac{k}{k_*} + \phi\right)\right]$$

$$P_\zeta(k) = P_{\zeta,0}(k)\left[1 + \mathcal{A}_{\rm log}\cos\left(\omega_{\rm log}\log\frac{k}{k_*} + \phi\right)\right]$$

Chen, Easther, Lim & Xu, JCAP 2008

	Log osc			Lin osc		
	TT	EE	TT,TE,EE	TT	EE	TT,TE,EE
$\Delta\chi^2_{\rm eff}$	−8.5	−13.5	−11.0	−4.2	−9.0	−10.8
$\ln B$	−1.5	−0.2	−0.9	−1.8	−1.3	−0.8
$\mathcal{A}_X$	0.024	0.073	0.014	0.024	0.046	0.015
$\log_{10}\omega_X$	1.51	1.72	1.26	1.74	1.84	1.05
$\varphi_X/(2\pi)$	0.60	0.07	0.07	0.34	0.81	0.56
$\alpha_{\rm rf}$	...	...	...	...	...	...

Planck 2018 results. X. Constraints on inflation



WHAT’S NEXT ?

SUPERIMPOSED OSCILLATIONS - GC

- Superimposed linear and logarithmic oscillations all over the spectra:

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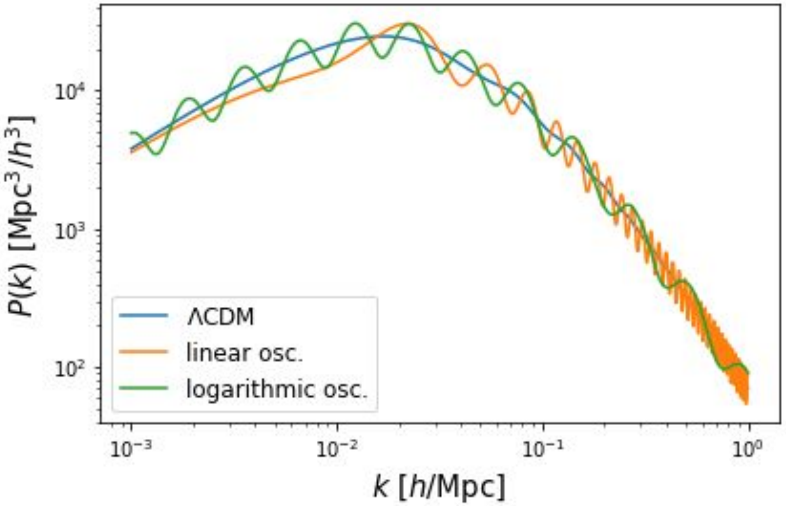
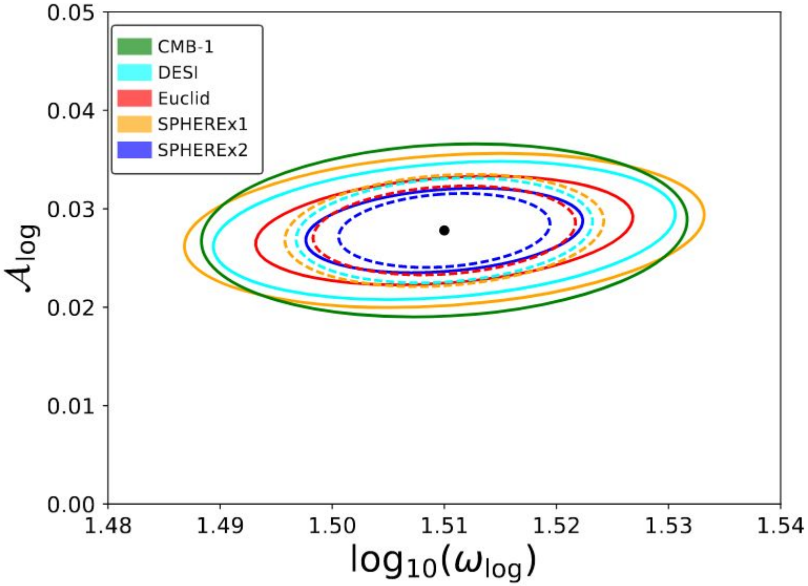


- Thanks to galaxy clustering information it's possible to detect the current best-fit from CMB (*Planck* 2018) data at more than 3σ just by adding quasi-linear scales k < 0.1 h/Mpc.
Huang, Verde, Vernizzi, 1201.5955, JCAP (2012)
Chen et al., 1605.09365, JCAP (2016)
Ballardini et al., 1606.03747, JCAP (2016)



- In order to exploit higher k it is necessary to study the non-linear evolution in these cosmologies.

COSMOLOGICAL SIMULATIONS

- N-body simulations with 1024^3 DM particles in a comoving box with side length of 1024 Mpc/h produced with GADGET-3 (plus some at higher resolution with 2048^3 particles and 2048 Mpc/h).
- The initial conditions have been produced by displacing the DM particles from a cubic Cartesian grid according to second-order Lagrangian Perturbation Theory at z=99.
- We extract also DM halos with a Friends-of-Friends algorithm with standard linking length of b = 0.2.

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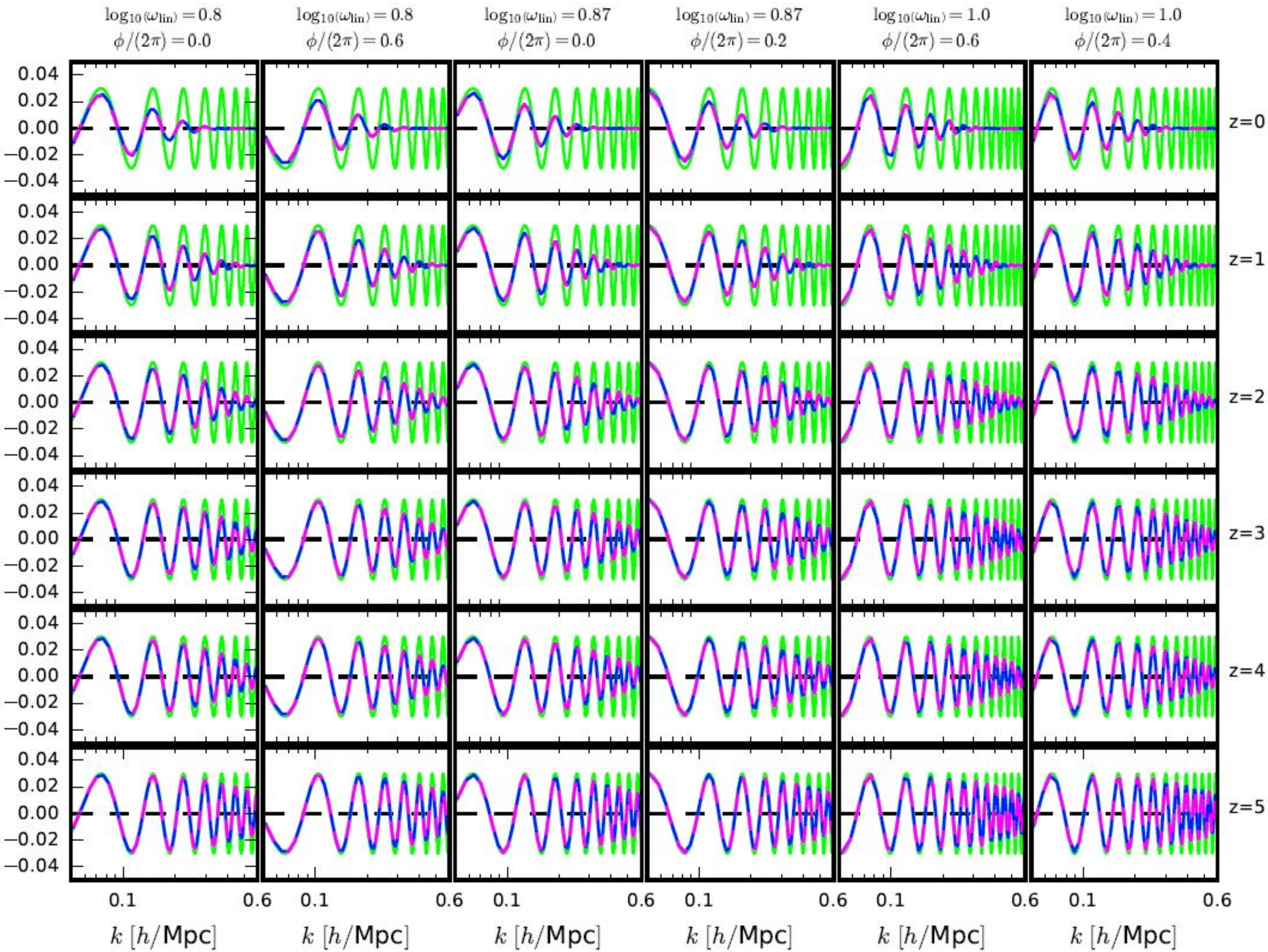
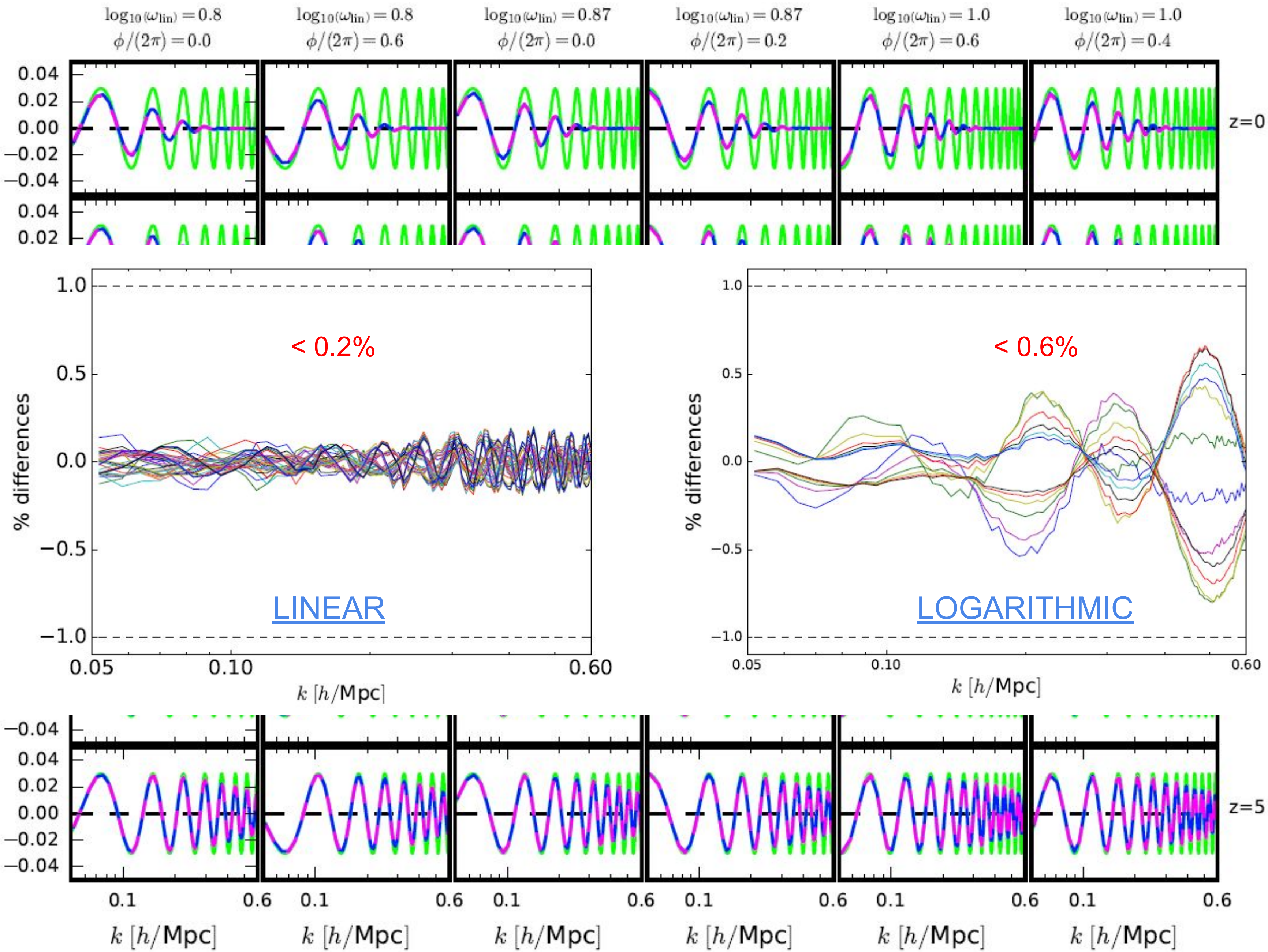
- We extract also DM halos with a Friends-of-Friends algorithm with standard linking length of b = 0.2.

- Semi-analytical template to model the non-linear effects on the range 0.05 h/Mpc < k < 0.6 h/Mpc with a Gaussian damping analogously to the one used for BAO (Seo & Eisenstein 2007):

$$\boxed{\begin{aligned} &P_{\mathrm{i,fit}}(k,z,\Sigma) = P(k,z)\left[1 + \mathcal{A}_i \cos\left(\omega_i \kappa_X + \phi_i\right) \mathcal{D}(k,z,\Sigma)\right] \\ &\mathcal{D}(k,z,\Sigma) = e^{-k^2\Sigma^2(z)/2} \end{aligned}}$$



$\log_{10}(\omega_{\rm lin}) = 0.8$ $\phi/(2\pi) = 0.0$
$\log_{10}(\omega_{\rm lin}) = 0.8$ $\phi/(2\pi) = 0.6$
$\log_{10}(\omega_{\rm lin}) = 0.87$ $\phi/(2\pi) = 0.0$
$\log_{10}(\omega_{\rm lin}) = 0.87$ $\phi/(2\pi) = 0.2$
$\log_{10}(\omega_{\rm lin}) = 1.0$ $\phi/(2\pi) = 0.6$
$\log_{10}(\omega_{\rm lin}) = 1.0$ $\phi/(2\pi) = 0.4$
0.04
0.02
0.00
−0.02
−0.04
z=0
z=1
z=2
z=3
z=4
z=5
0.1
0.6
k [h/Mpc]



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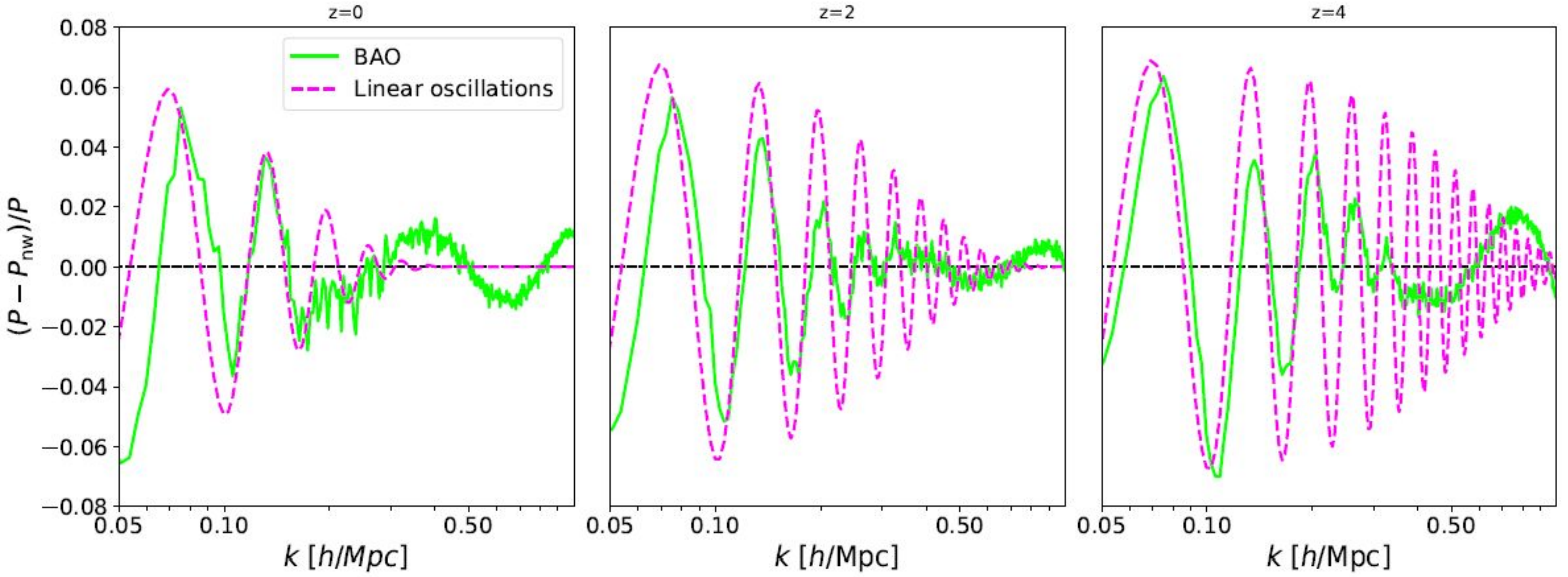
$\log_{10}(\omega_{\rm lin}) = 1.0$ $\phi/(2\pi) = 0.4$
z=0
z=5
< 0.2%
< 0.6%
% differences
LINEAR
LOGARITHMIC
k [h/Mpc]

COMPARISON WITH BAO DAMPING

The linear oscillation introduces a signal on the matter power spectrum similar to the one imprinted by BAO (for a frequency $\log_{10} \omega_{\rm lin} = 0.87$)

$$P(k,z) \approx P_{\rm nw}(k,z)\left[1 + A_{\rm BAO}(k)\sin\left(kr_s(z) + \phi\right)\right]$$



THEORETICAL PREDICTIONS

We compare the damping parameter to the one predicted at leading order from perturbation theory:

$$\Sigma^2_{\rm th}(k,z) = \frac{1}{3\pi^2}\int_0^\Lambda \mathrm{d}q\,[1 - j_0(q\omega) + 2j_2(q\omega)P_{\rm lin}(q,z)]$$

$$\omega \to \omega_{\rm lin}/0.05$$

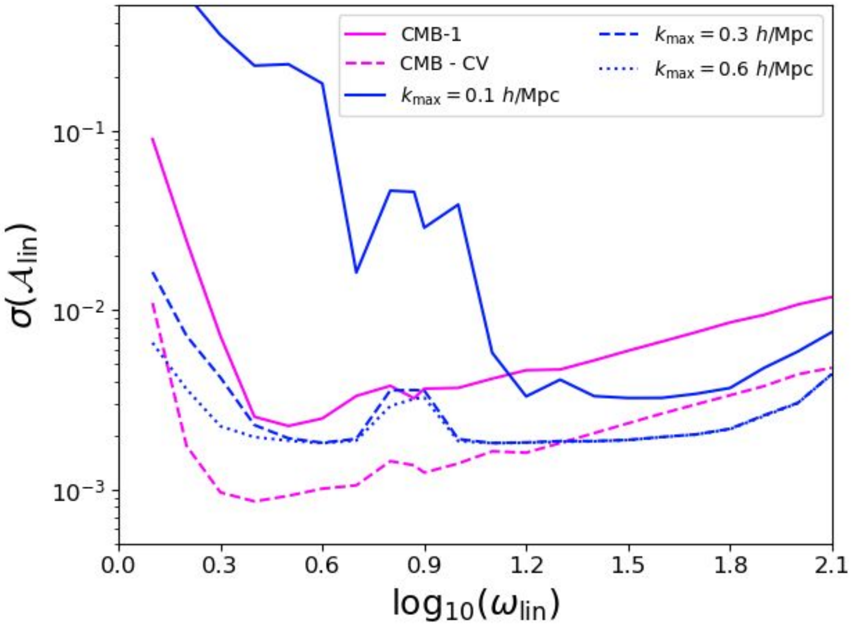
$$\omega \to \omega_{\rm log}/k$$

Vlah et al., 1509.02120, PRD (2016)
Vasudevan et al., 1906.08697, JCAP (2019)
Beutler et al., 1906.08758 (2019)

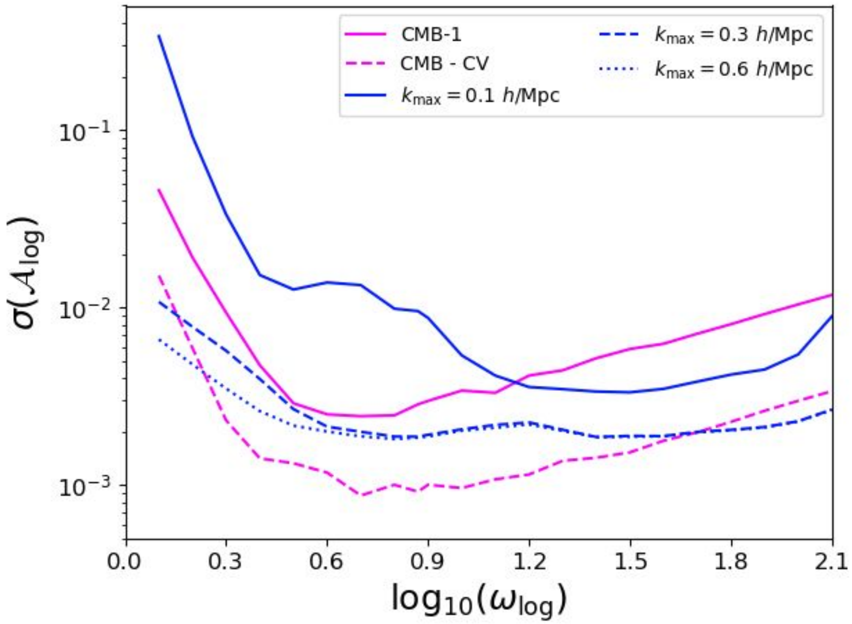
where the separation scale is $\Lambda = \epsilon$ k with ϵ << 1.

FISHER FORECASTS FOR CMB AND GC

Marginalized 68% uncertainties on the amplitude for CMB and galaxy clustering (Euclid-like spectroscopic experiment)



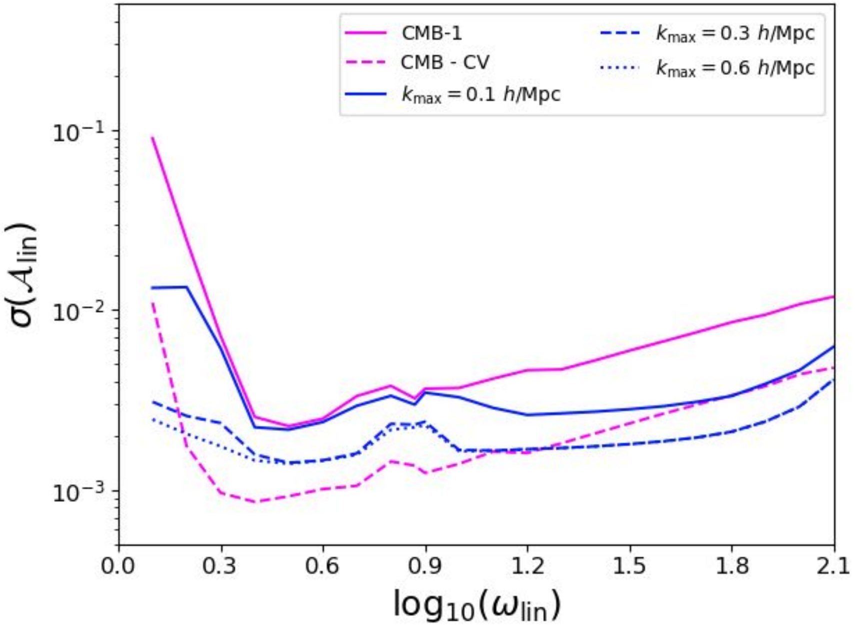
LINEAR



LOGARITHMIC

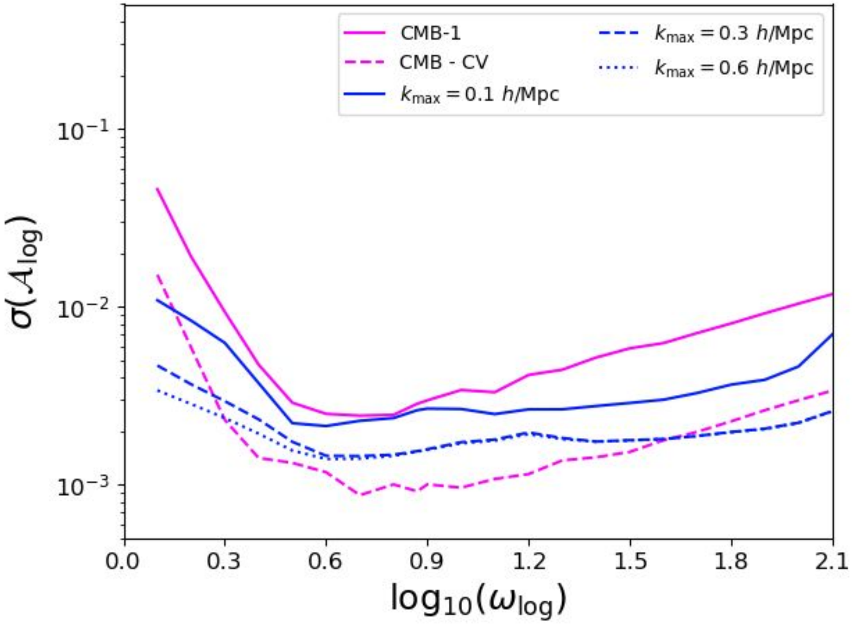
FISHER FORECASTS COMBINED

Marginalized 68% uncertainties on the amplitude for CMB and galaxy clustering (Euclid-like spectroscopic experiment)



LINEAR

A ~ 0.03 ± 0.002



LOGARITHMIC

SUMMARY

- Primordial features provide a variety of valuable information on the physics of the early Universe ranging from detecting new heaviest particles, the presence of a fast-roll stage, to ne details in the inflationary dynamics. They can also be used to discriminate between in ation and alternative scenarios in presence of signals oscillatory in time.

- LSS experiments give the opportunity to further investigate the presence of any salient features in the matter power spectrum, complementing the findings based on CMB (Planck) observations to smaller scales, i.e. $k > 0.1$ h/Mpc.

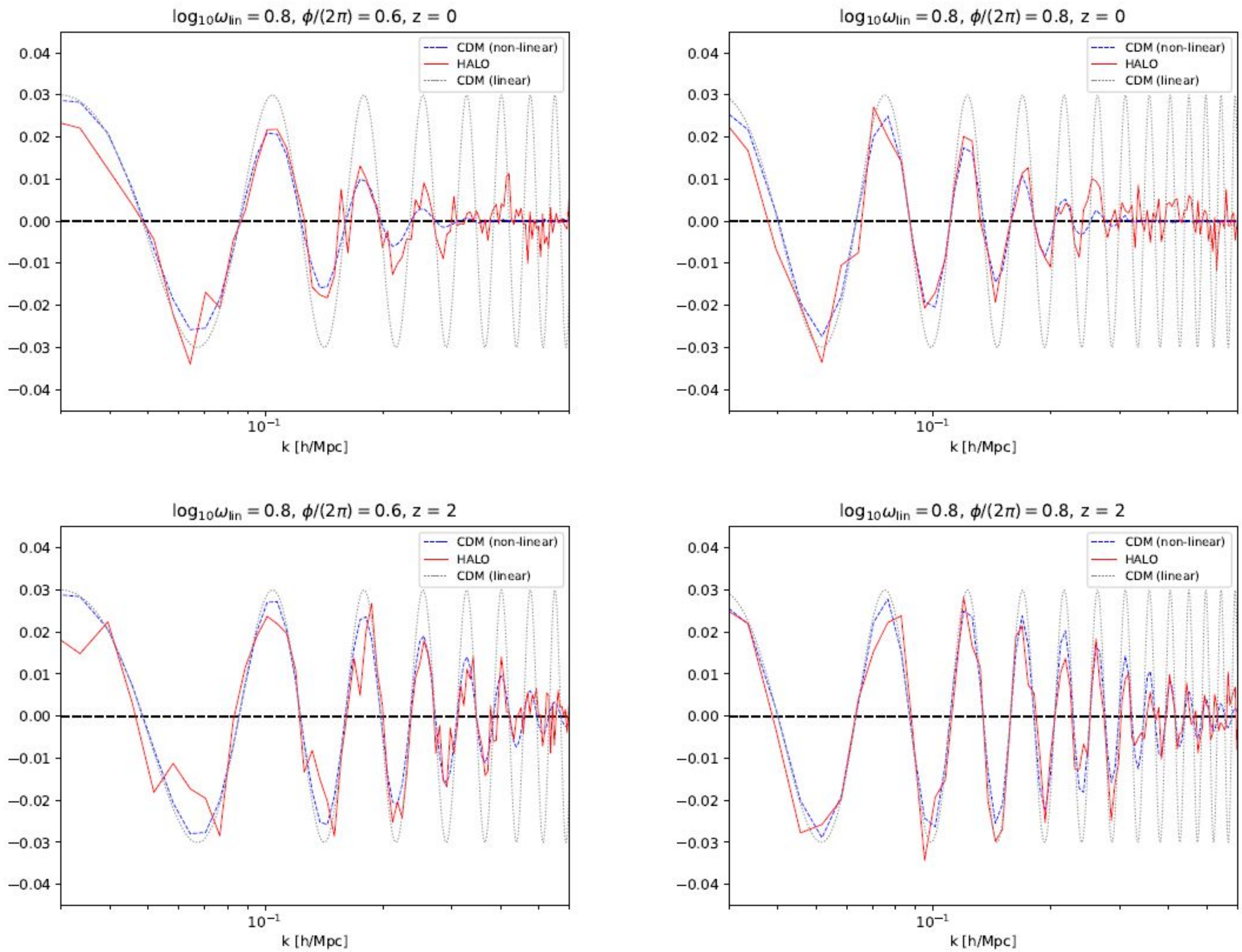
- We run a set of high-resolution simulations to study how the features evolve in the fully non-linear regime and to complement analytic approximation for these models based on a perturbative treatment.

- After calibrating the damping of the primordial oscillations against the matter power spectrum extracted from the N-body simulations at different redshift, we have studied the forecasted uncertainties for a (wide) Euclid experiment covering the redshift range $0.9 < z < 1.8$ over a sky patch of 15000 deg^2.
  For $A = 0.03$ (Planck best-fit):
  $\sigma(A) \sim 0.0025$ (0.0034) for $\log_{10} \omega_{lin} = 0.1$,
  $\sigma(A) \sim 0.0017$ (0.0018) for $\log_{10} \omega_{lin} = 1.1$,
  $\sigma(A) \sim 0.0041$ (0.0026) for $\log_{10} \omega_{lin} = 2.1$
  for Euclid (galaxy clustering) in combination with CMB (Planck-like).

- We also study an experiment like PSF-Subaru deeper in redshift $0.8 < z < 2.4$ over a smaller patch of sky of 1464 deg^2 (~10%) finding uncertainties only two times larger.

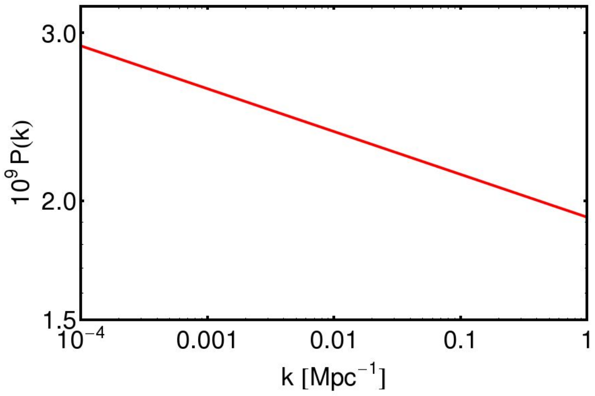
THANKS !

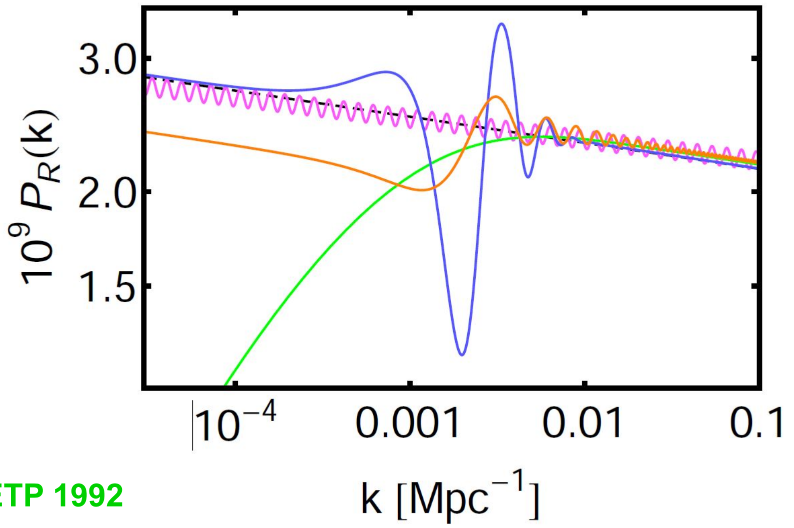
HALOS POWER SPECTRA



SEARCH FOR PARAMETERIZED FEATURES

There are several theoretical motivations beyond violation of the slow-roll conditions: slow-roll parameters are not necessary small or slowly varying. The theoretical interest in models beyond the slow-roll approximation is corroborated by observations.





Starobinsky, JETP 1992

Adams, Cresswell & Easther, PRD 2001

Contaldi, Peloso, Kofman & Linde, JCAP 2003

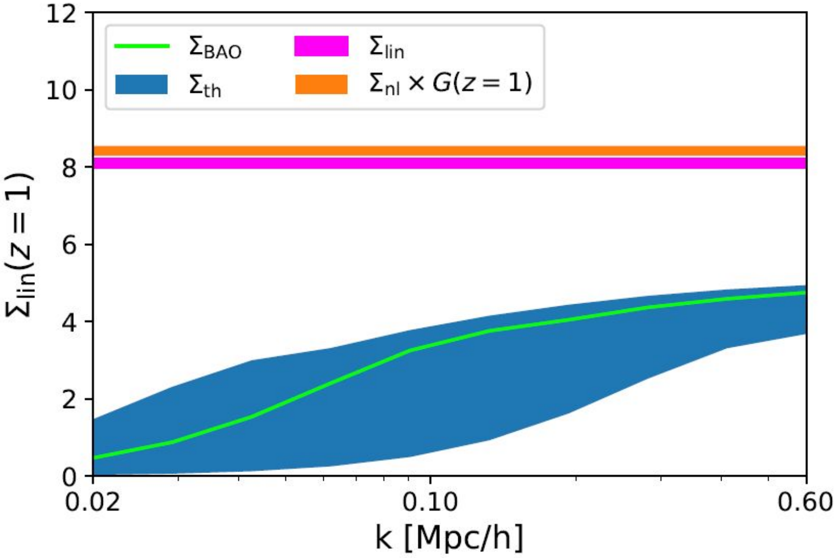
Chen, Easther, Lim & Xu, JCAP 2008

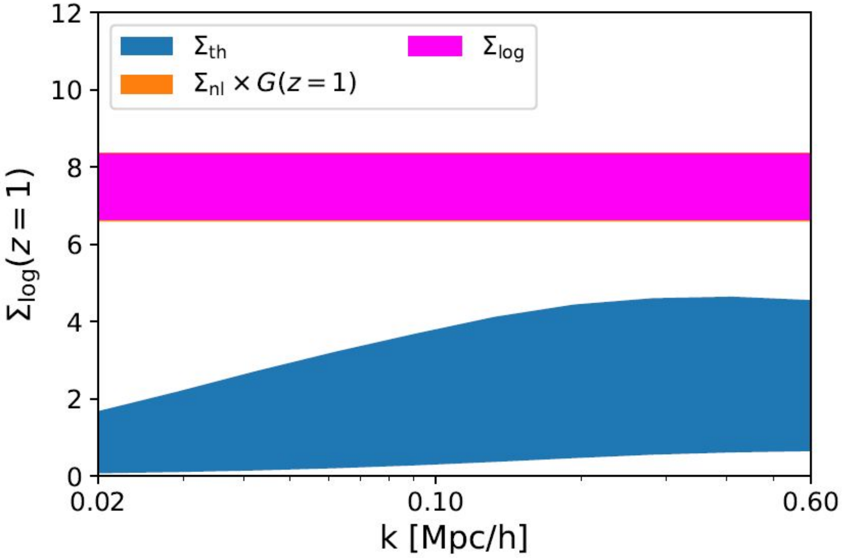
THEORETICAL PREDICTIONS

$$\boxed{\Sigma(z)}$$

$$\boxed{\Sigma_{\rm nl}\, G(z)}$$

$$\boxed{\Sigma^2_{\rm th}(k,z) = \frac{1}{3\pi^2}\int_0^{\Lambda} {\rm d}q\,[1 - j_0(q\omega) + 2j_2(q\omega)P_{\rm lin}(q,z)]}$$





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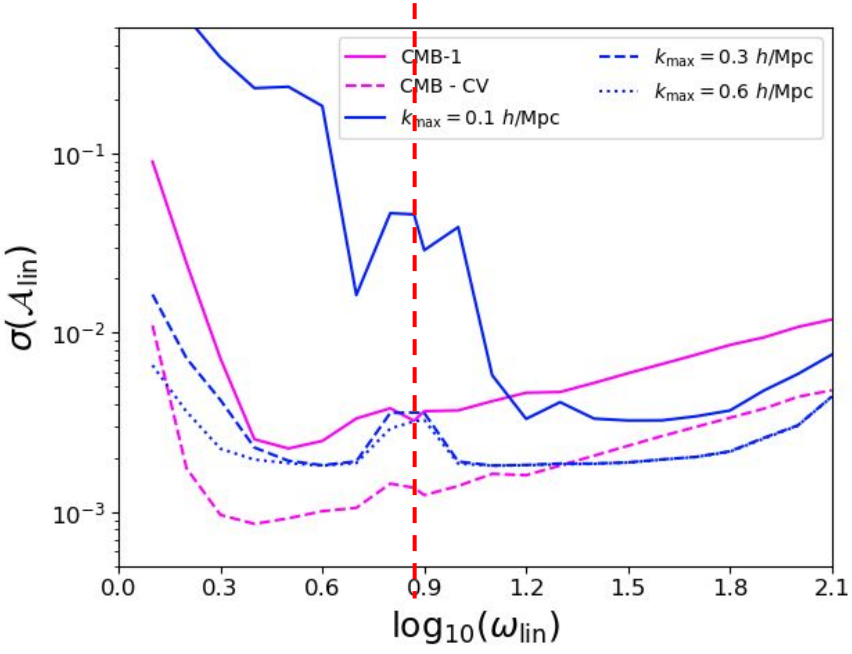
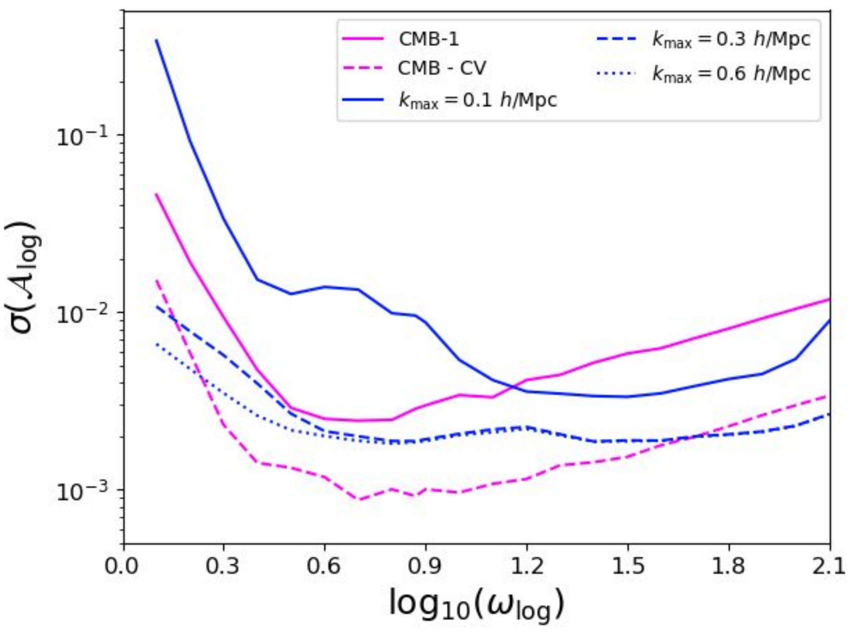
Marginalized 68% uncertainties on the amplitude for CMB and galaxy clustering (Euclid-like spectroscopic experiment)



LINEAR



LOGARITHMIC

FISHER FORECAS

$$\hat{P}(k_i, z) = \frac{1}{\Delta k} \int_{k_i - \Delta k}^{k_i + \Delta k} \mathrm{d}k' P(k', z)$$

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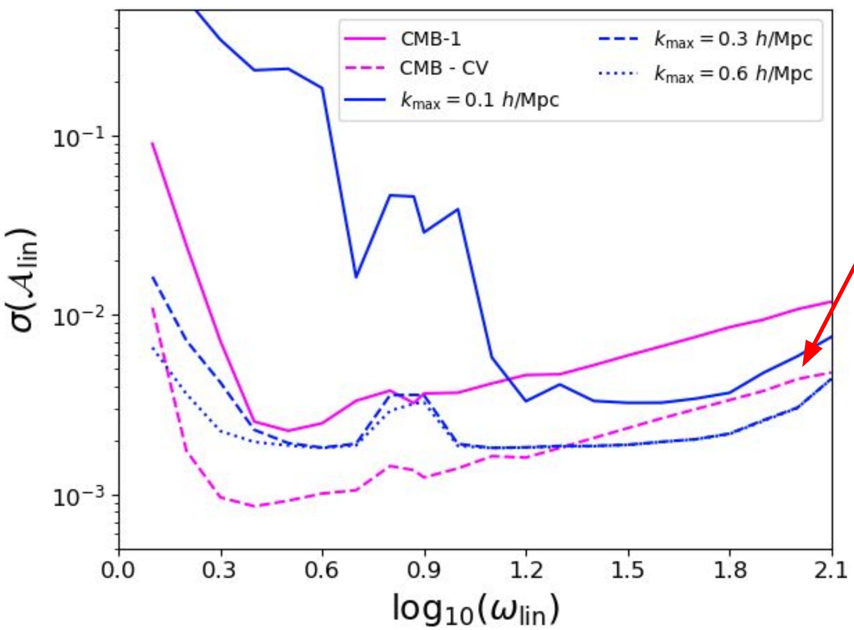

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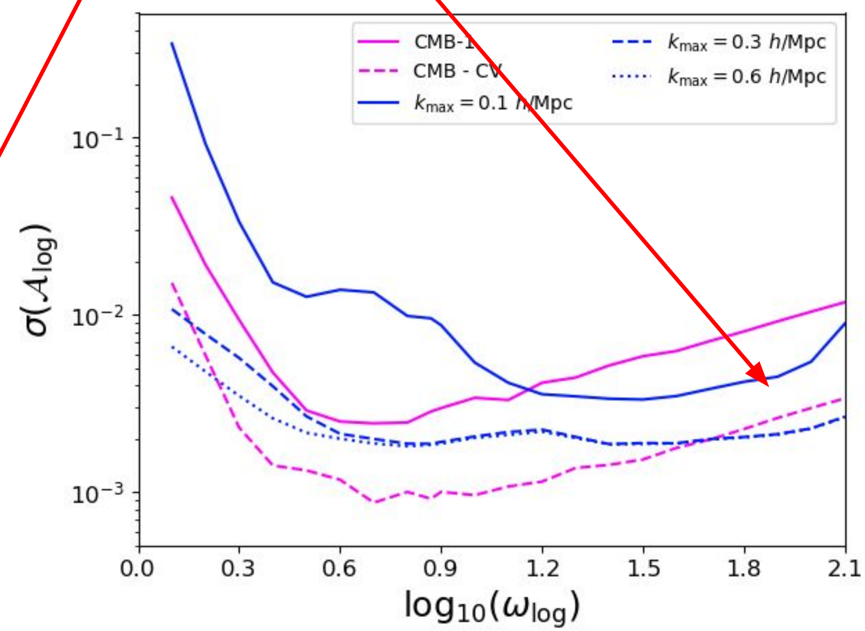

LOGARITHMIC

Δk = 0.05 BOSS, Δk = 0.025 Euclid-sp

THEORETICAL PREDICTIONS

We compare the redshift evolution of the damping match with the standard growth of perturbations with the growth factor:

$$\Sigma_{\rm nl}\, G(z)$$

We compare the damping parameter to the one predicted at leading order from perturbation theory:

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