Unveiling dark fifth forces with Linear Cosmology and the LSS

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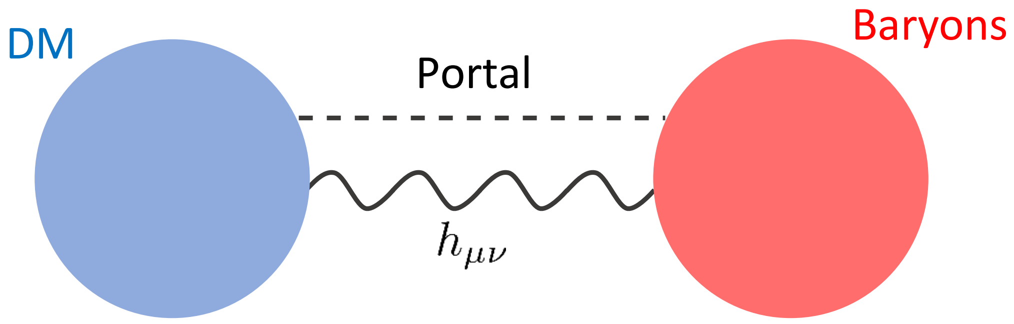
New Frontiers in Theoretical Physics – XVIII Convegno Nazionale di Fisica Teorica

Exploring the Dark Sector

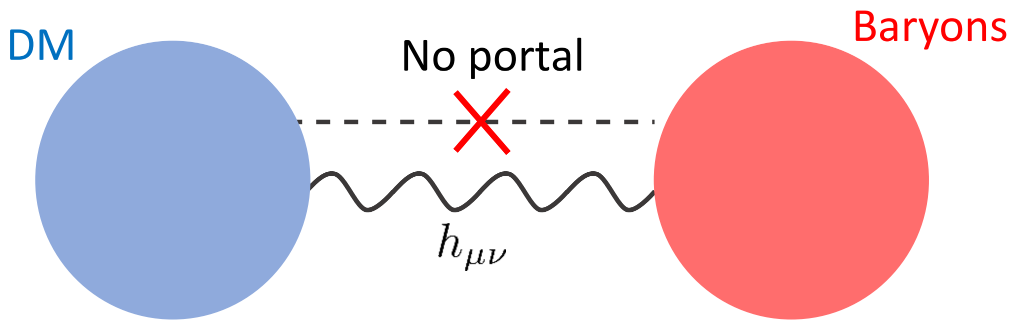
Most of DM models and searches assume the existence of a portal between visible and dark sector



Terrestrial (direct detection, colliders), astrophysical (indirect detection) and cosmological probes

Exploring the Dark Sector

No portal, only gravitational interactions between DM and visible matter. Known examples: PBHs, Fuzzy DM…



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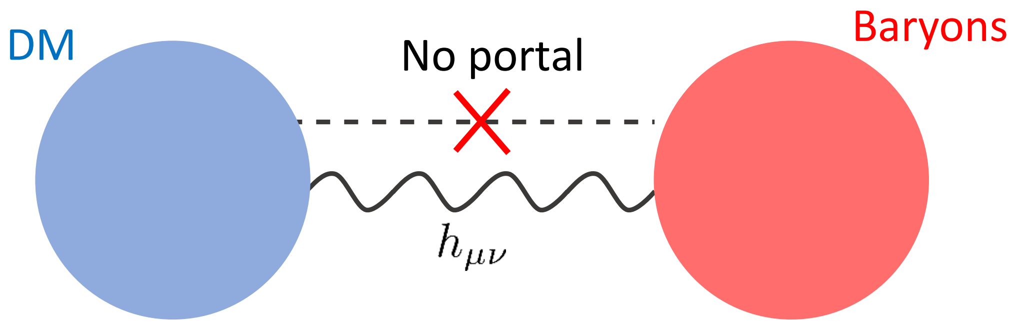
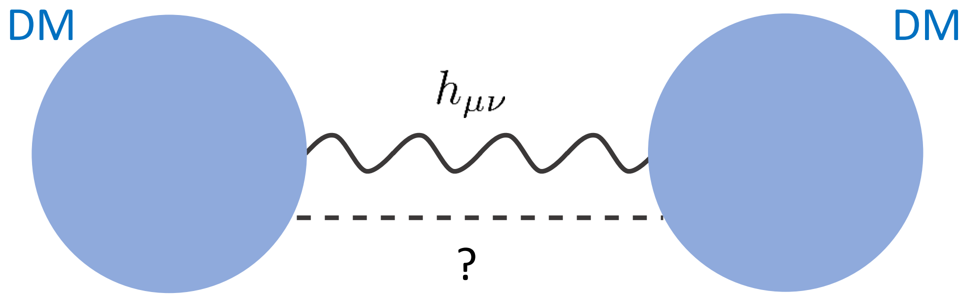


Internal dynamics in the dark sector?

- Dark phase transitions?
- Long range interactions?



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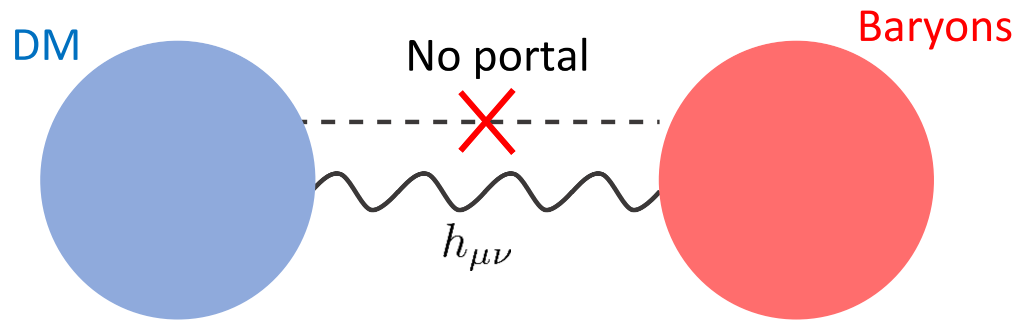

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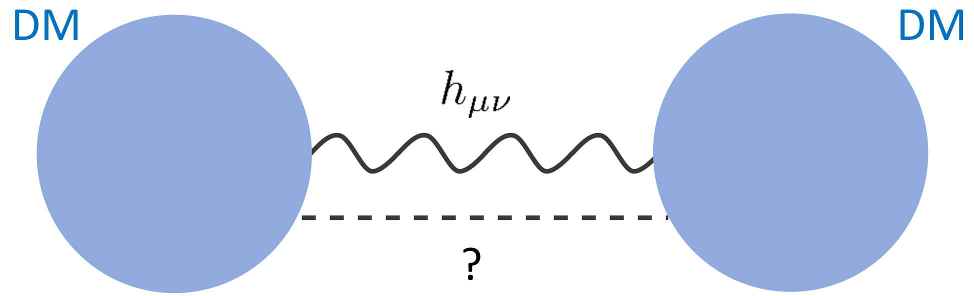
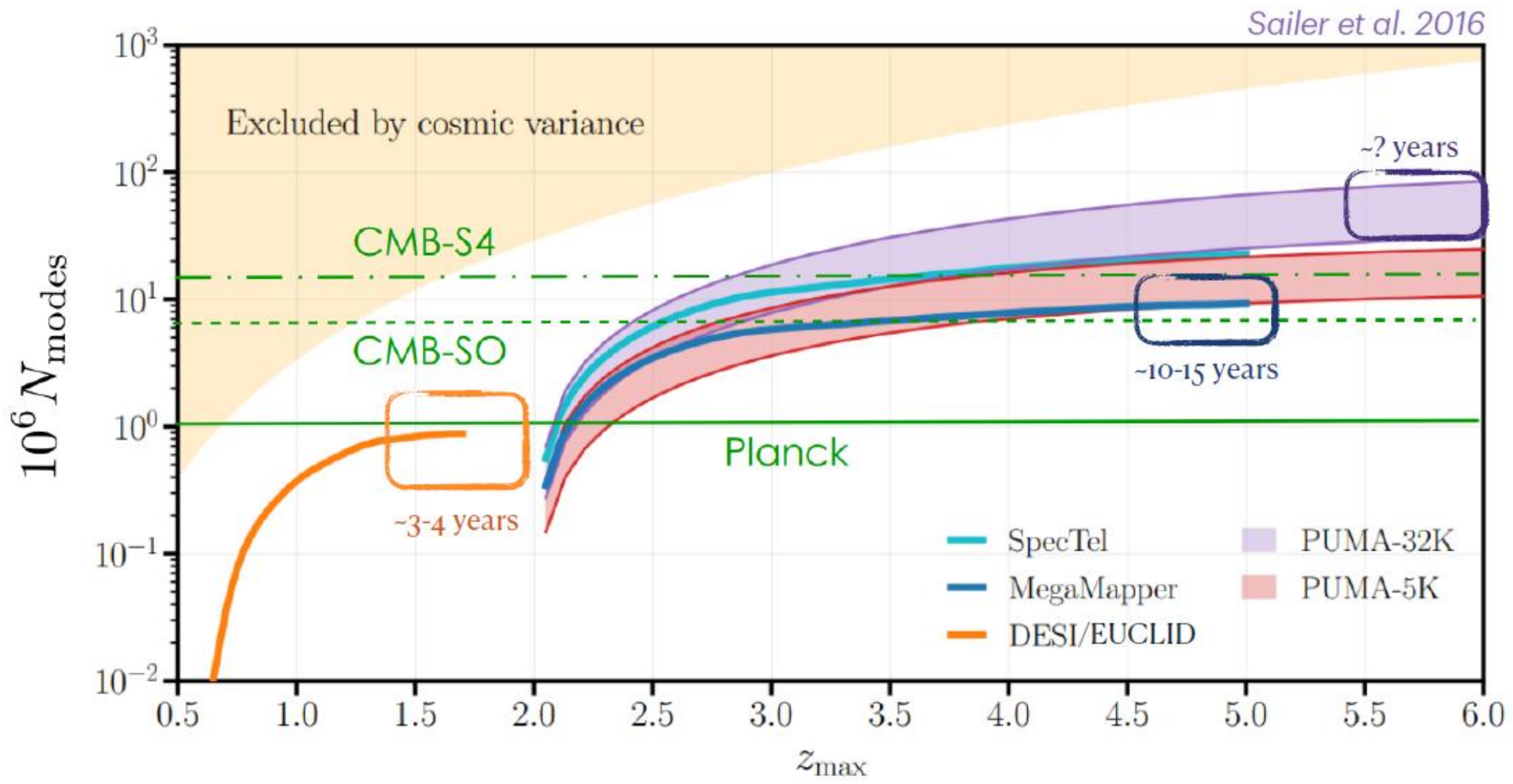
Testable with precision cosmology
Future experiments will significantly improve the sensitivity

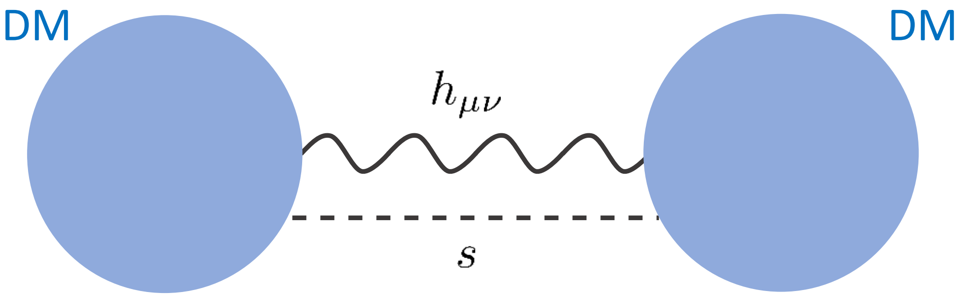


Exploring the Dark Sector

Current and future galaxy survey will make LSS competitive if not more precise probe than CMB



Fifth forces in the Dark Sector



Scalar mediator

$$\mathcal{L} \propto s\chi^2$$

$$V_s(r) = -4\pi\beta G_N \frac{m_\chi m'_\chi}{r} e^{-m_s r}$$

$$m_\chi^2 \to m_\chi^2(s) = (1+2s)m_\chi^2$$

Space-time dependent DM mass!

Working assumptions

- Effectively massless mediator $m_s \lesssim H_0 \simeq 10^{-33}$ eV
- All DM feels the fifth force $f_\chi = \rho_\chi/\rho_{\rm m} = f_{\rm DM} \approx 0.85$

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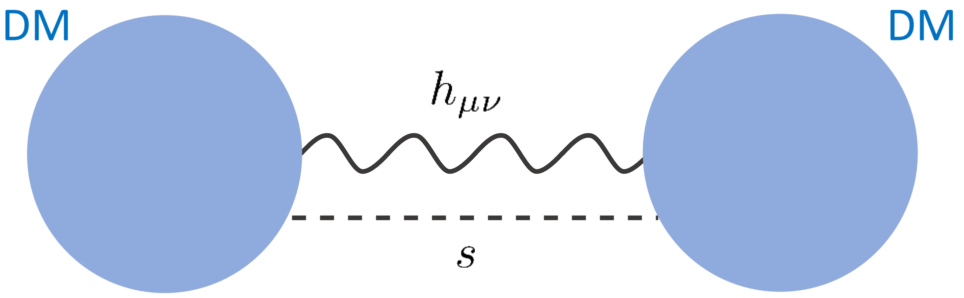

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Naturalness

$$m_\chi \leq 0.02 \text{ eV} \left(\frac{0.01}{\beta}\right)^{\frac{1}{4}} \left(\frac{m_s}{H_0}\right)^{\frac{1}{2}}$$

Scalar DM produced via misalignment is favored

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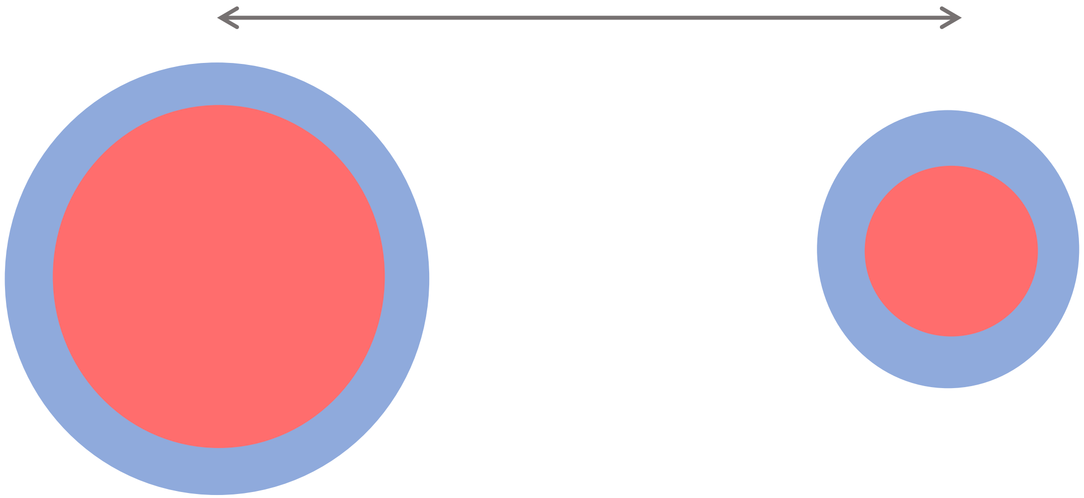
Fifth forces in the Dark Sector

Different bkg evolution: modified distances $d(z) \propto H^{-1} = (H_{\Lambda\mathrm{CDM}} + \Delta H)^{-1}$



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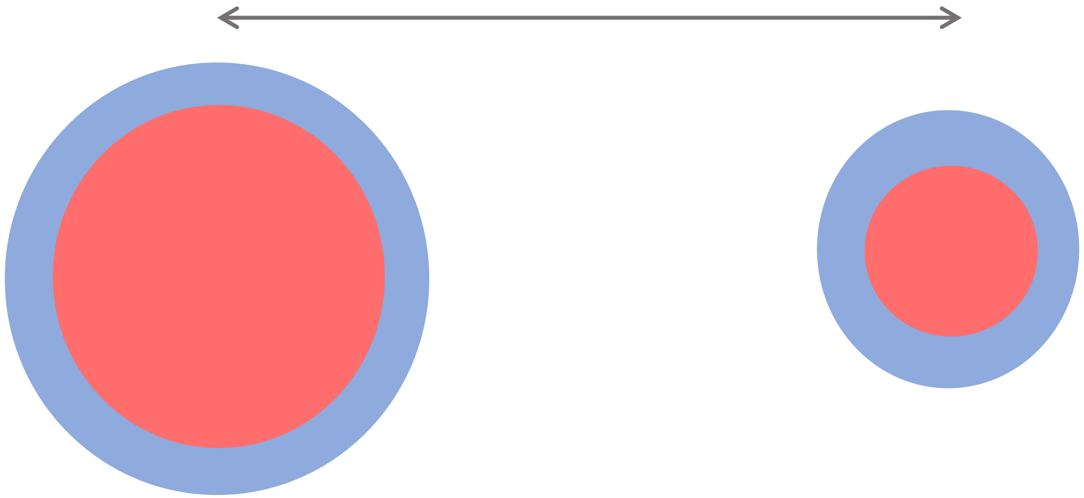

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Faster growth of matter fluctuations

$$\delta_m(a) = D_{m,\Lambda\text{CDM}}(a)\left(1 + \frac{6}{5} f_\chi^2 \beta \log \frac{a}{a_{\text{eq}}}\right) \delta_m(a_{\text{eq}})$$

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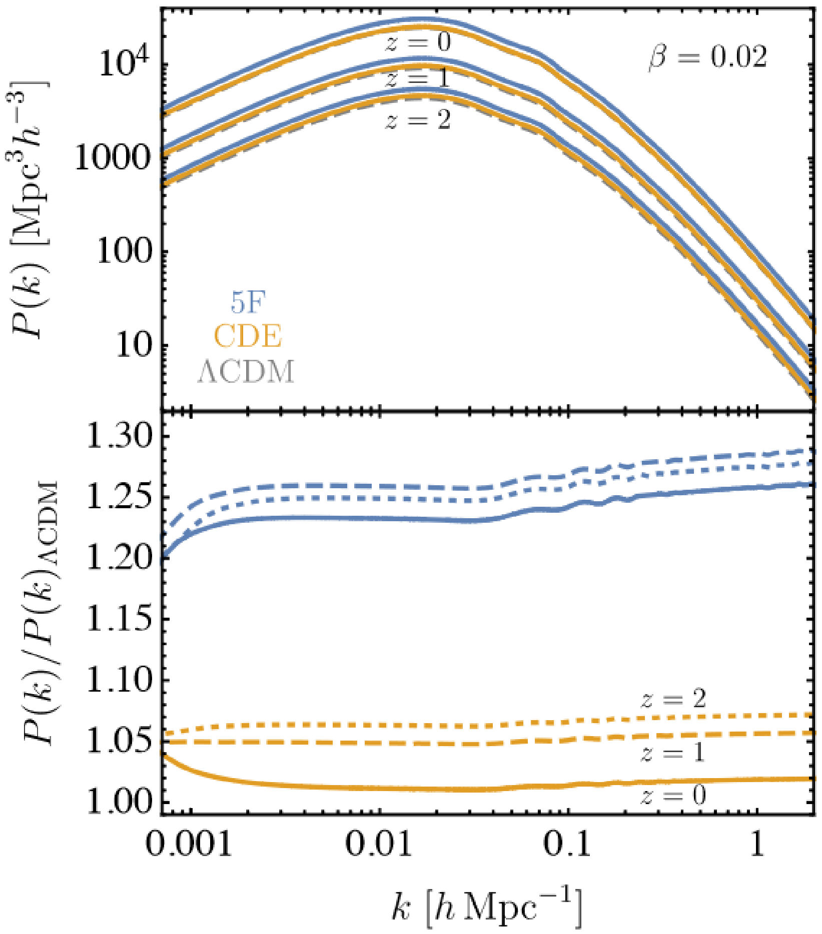

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Log-enhanced growth!

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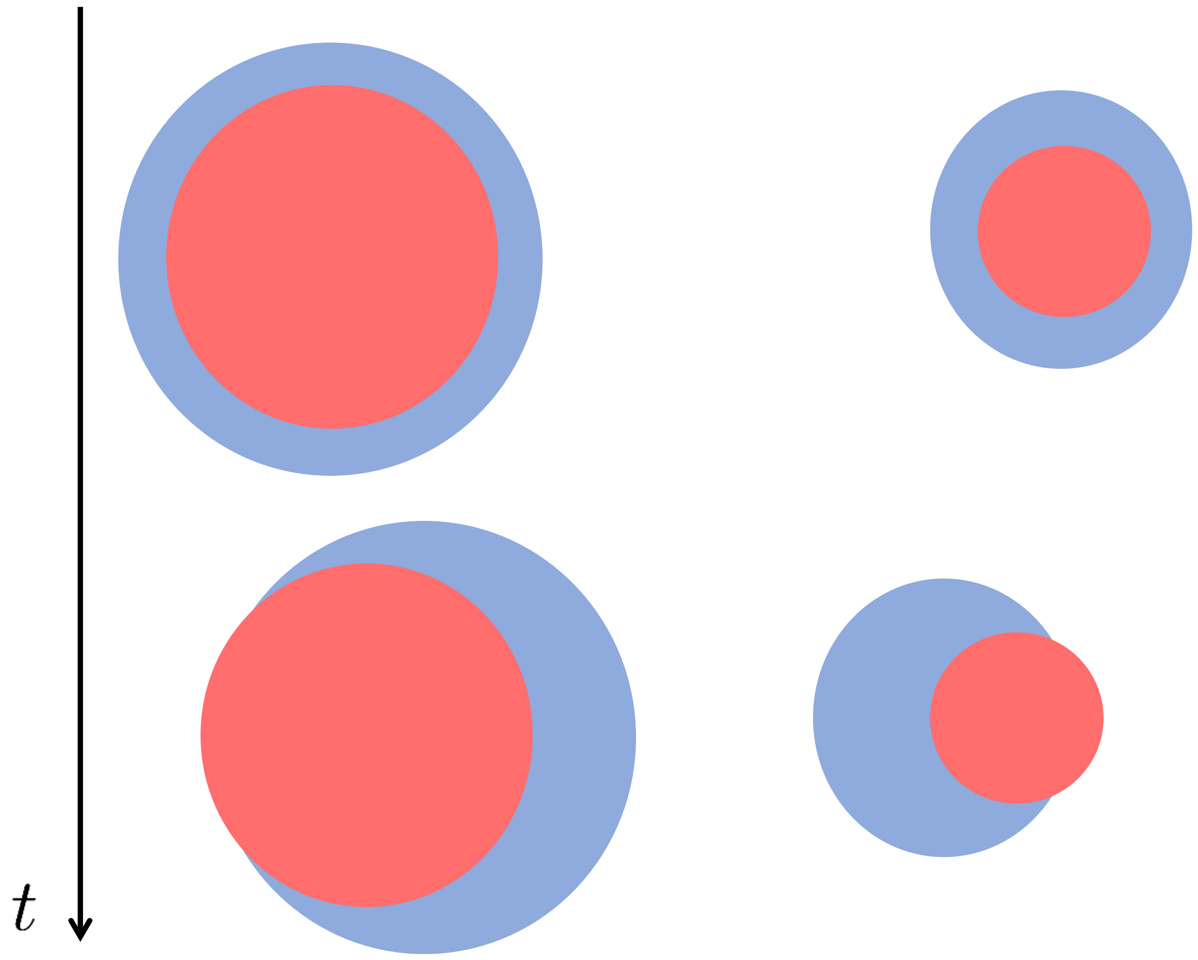

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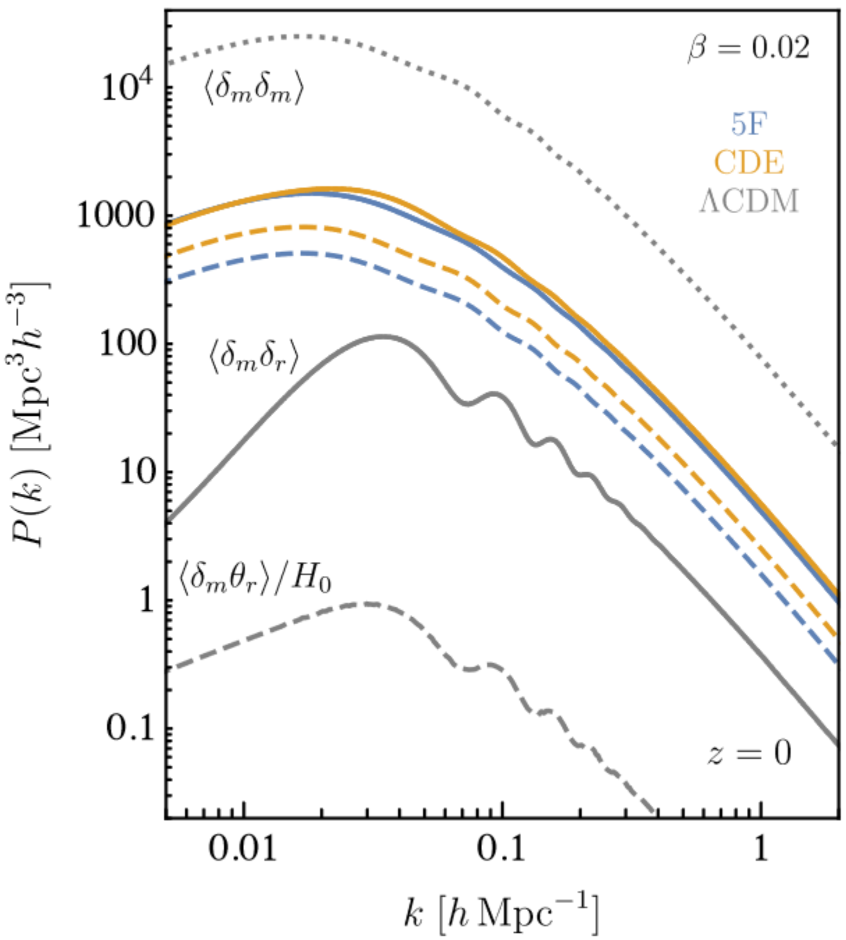

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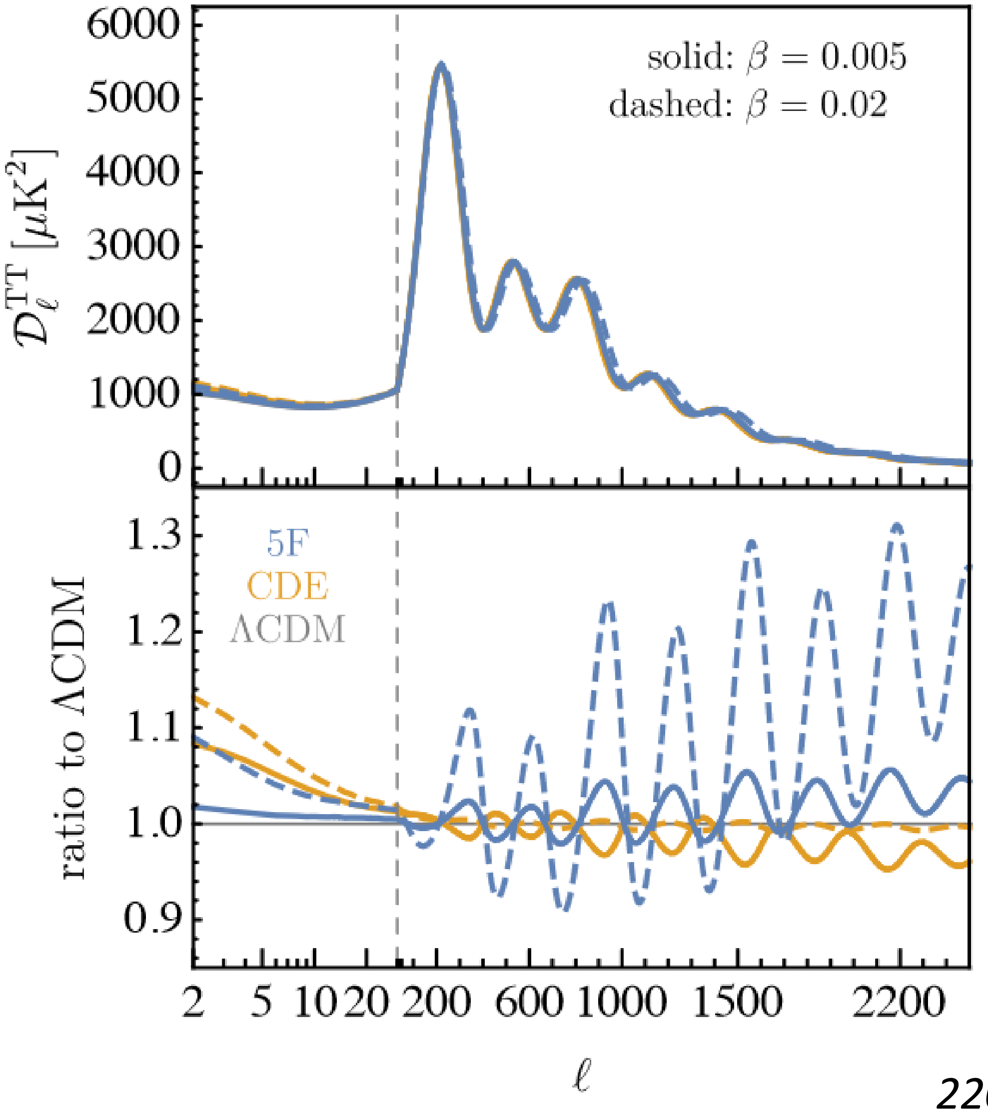
Effects on linear cosmology

CMB power spectrum mostly affected by bkg

$$\beta f_\chi^2 \log \frac{a_{\rm rec}}{a_{\rm eq}} \approx \beta \ll 1$$

Shift in the peaks from modified angular diameter distance

$$l_n \approx \frac{n\pi}{c_s t_{\rm rec}} D_A(z_{\rm rec}) \propto \int_0^{z_{\rm rec}} \frac{{\rm d}z}{H_{\Lambda{\rm CDM}}(z) + \Delta H(z)}$$



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Effects on LSS

Problem: we observe galaxies, which track dark matter fluctuations ⟶ *Bias expansion*

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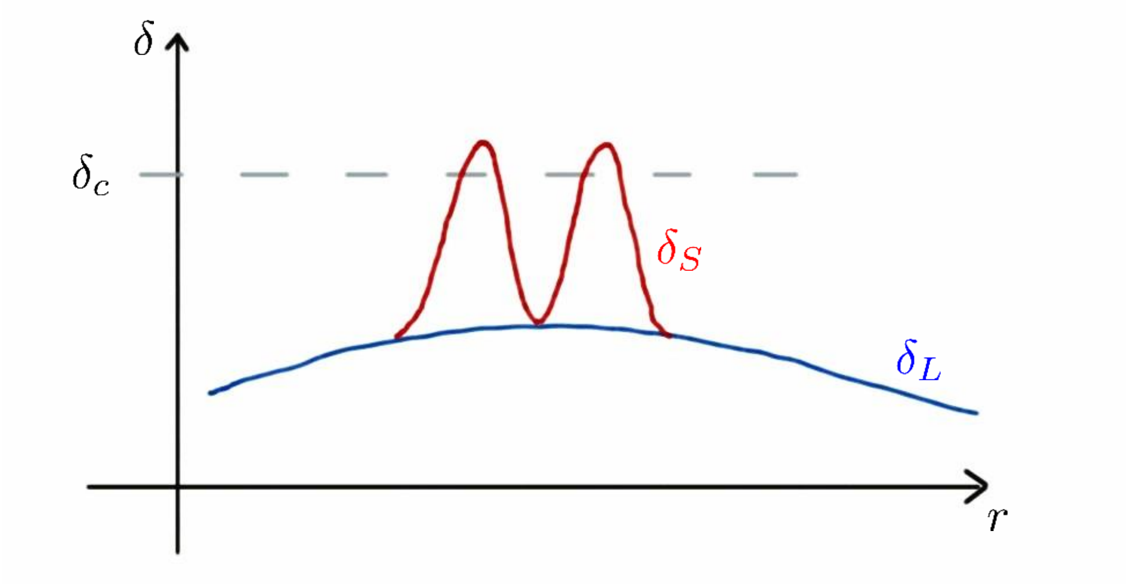
$$\delta_g(\vec{k}) = b_1\delta_m(\vec{k}) + b_r\delta_r(\vec{k}) + \cdots$$

Fluctuation of the galaxy number density

Bias parameters $b_i = \frac{1}{\bar{n}_g}\frac{\mathrm{d}\bar{n}_g}{\mathrm{d}\delta_i}$



Effects on LSS

Power spectrum $\langle \delta_g(\vec{k}) \delta_g(\vec{k}') \rangle = (2\pi)^3 \delta^{(3)}(\vec{k} + \vec{k}') P(k)$

$$P(k) = \left(1 + \frac{6}{5} f_\chi^2 \beta \log \frac{1}{a_{\rm eq}}\right)^2 P^{\rm lin}_{\Lambda{\rm CDM}}(k) + \left(1 + \frac{6}{5} f_\chi^2 \beta \log \frac{1}{a_{\rm eq}}\right)^4 P^{\rm 1-loop}_{\Lambda{\rm CDM}}(k) + f_\chi \beta \Delta P(k)$$

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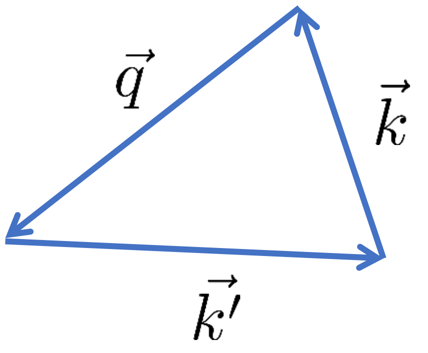
Bispectrum $\langle \delta_g^A(\vec{q})\delta_g^A(\vec{k})\delta_g^B(\vec{k}')\rangle = (2\pi)^3\delta^{(3)}(\vec{q}+\vec{k}+\vec{k}')\mathcal{B}(q,k,k')$



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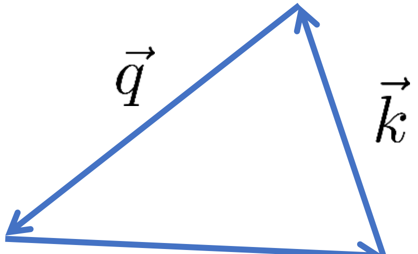

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- From $\delta_m \subset \delta_g$
- Log-enhancement
- Globally rescaled ΛCDM structures

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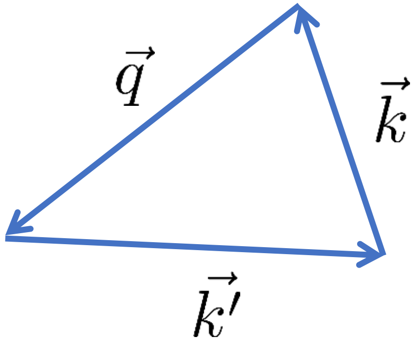

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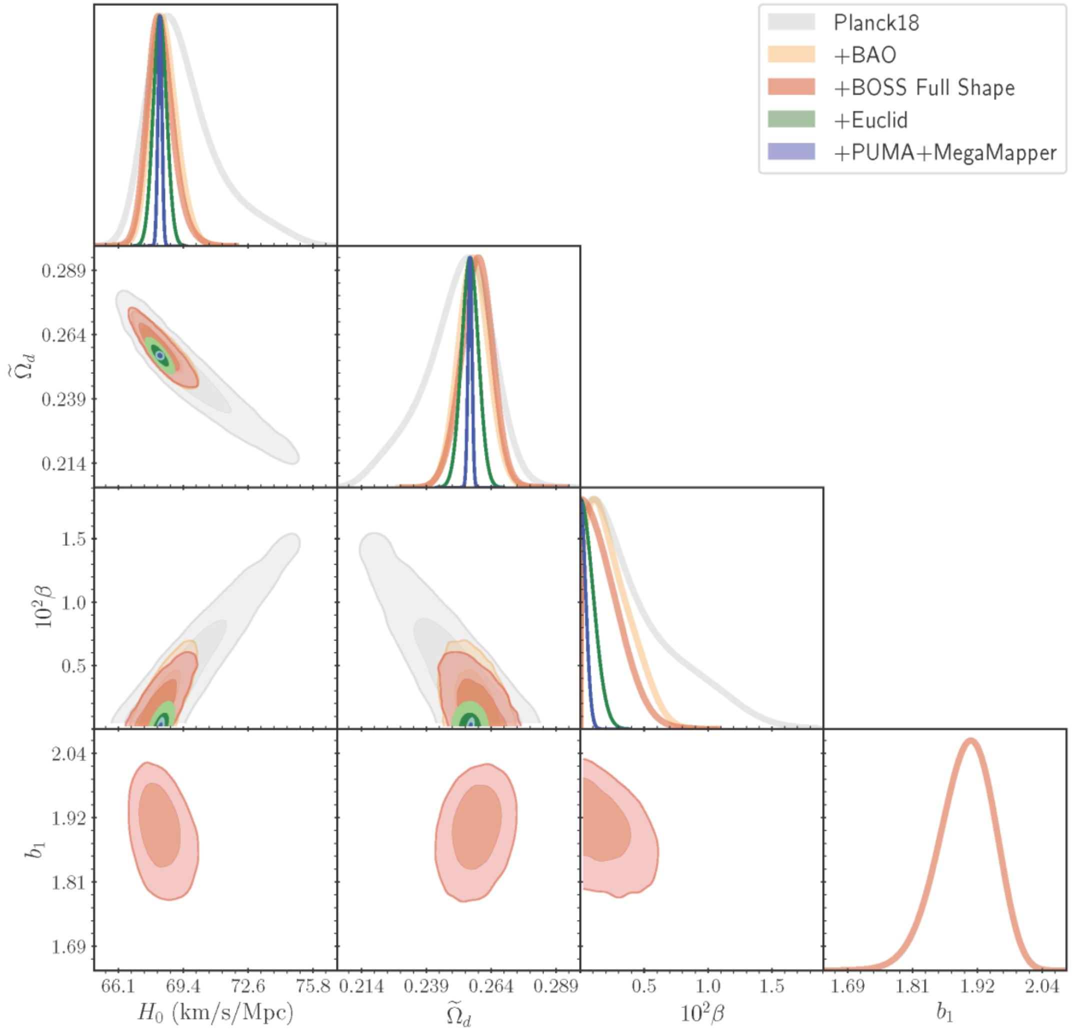
- From $\delta_m \subset \delta_g$
- Log-enhancement
- Globally rescaled ΛCDM structures

- From $\delta_r \subset \delta_g$
- Different spatial structure
- Not log-enhanced
- Possible poles in the squeezed bispectrum

Effects on LSS

SB, M. Costa, E .Castorina, D. Redigolo, E. Salvioni - 2309.11496



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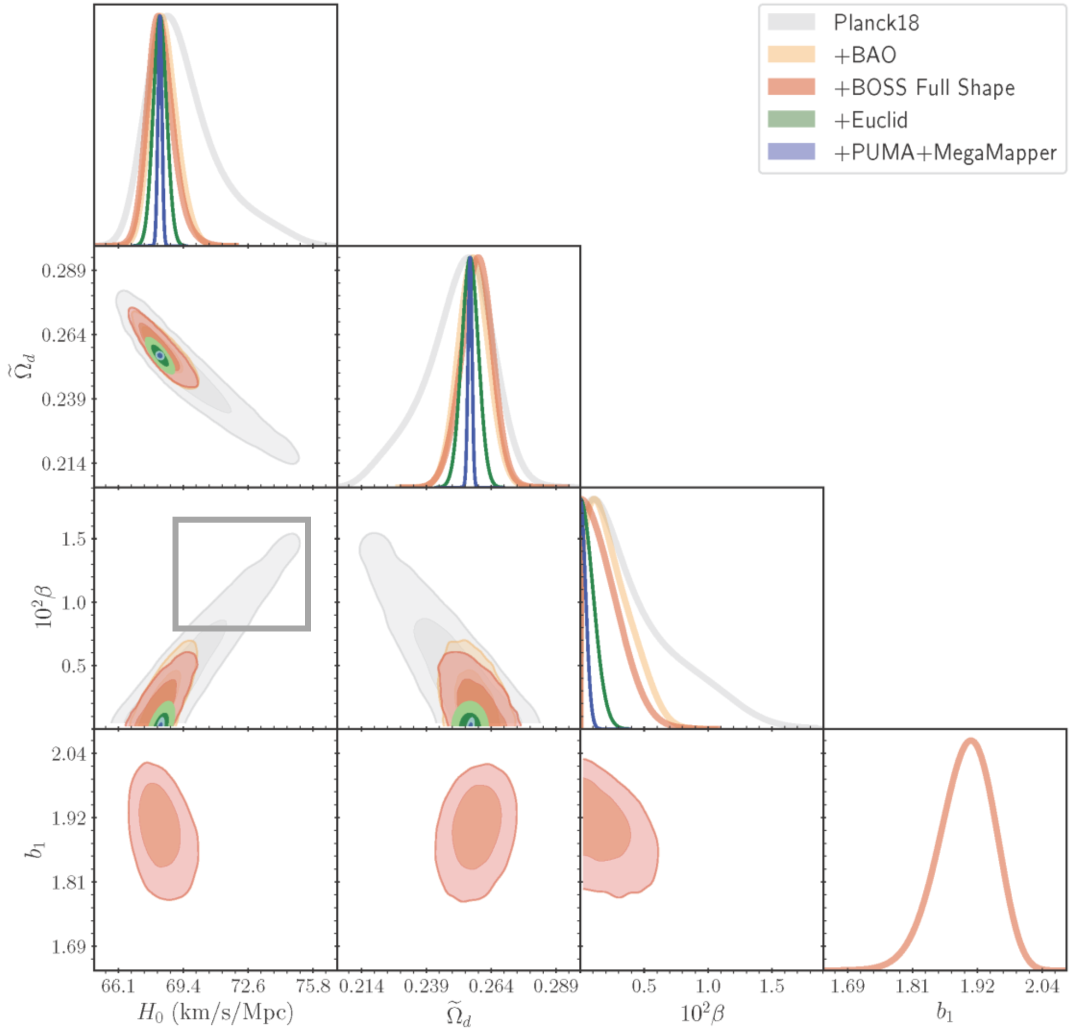

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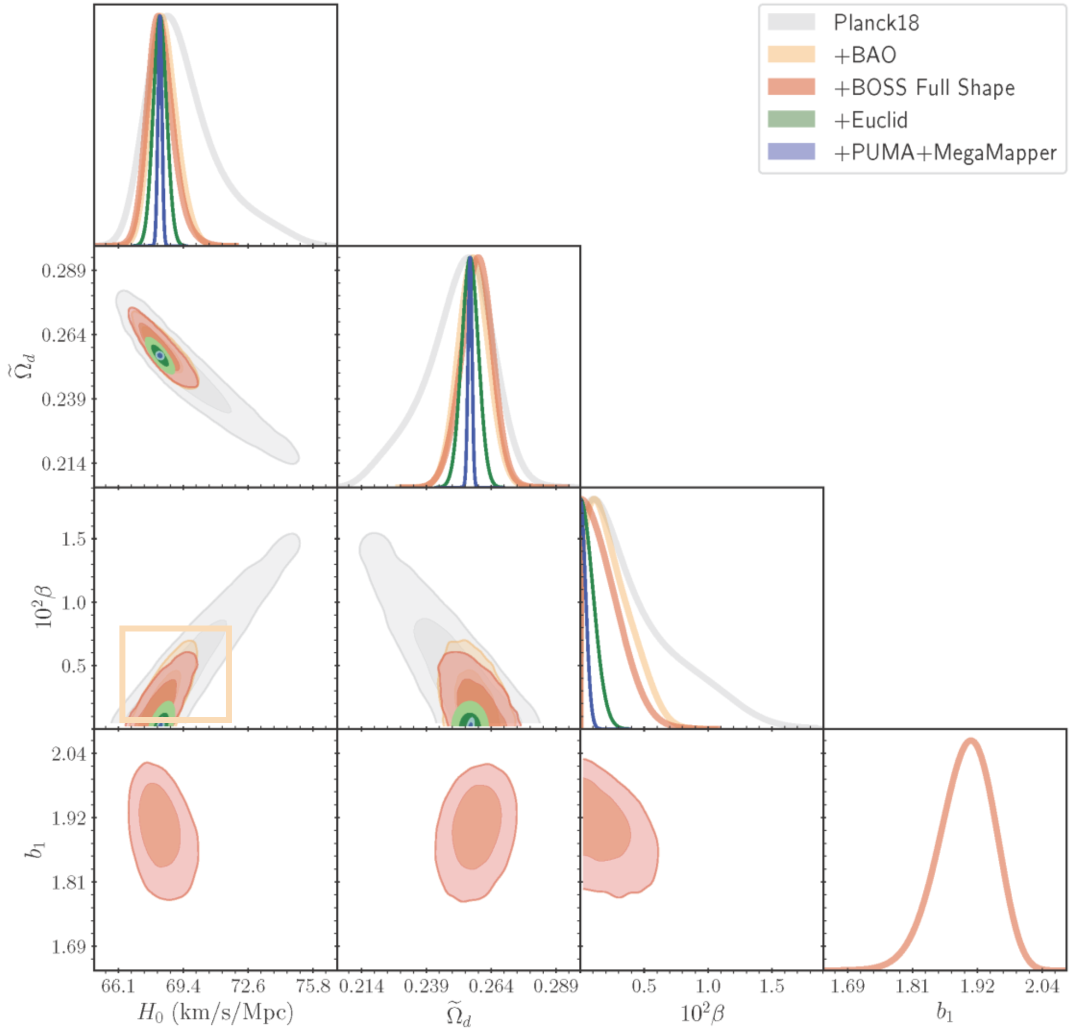

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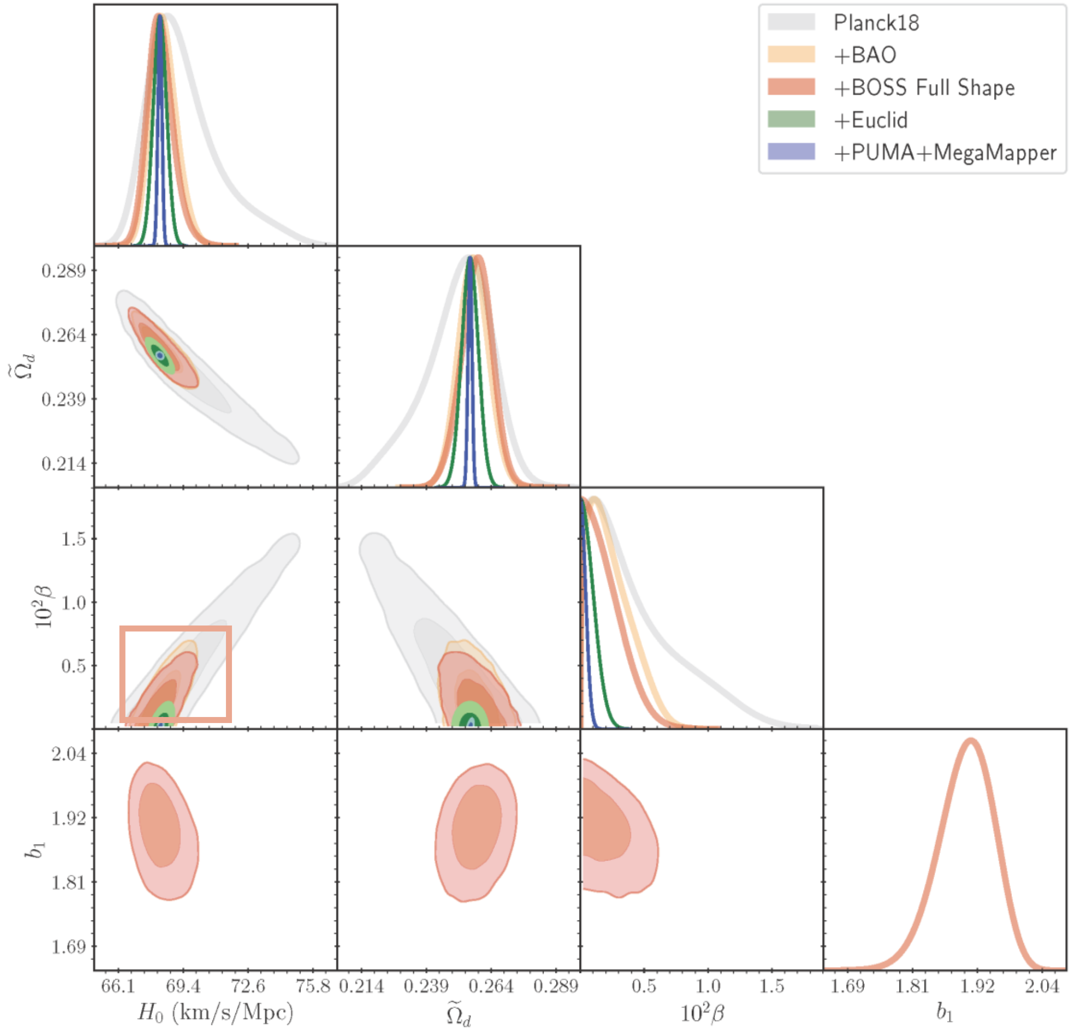

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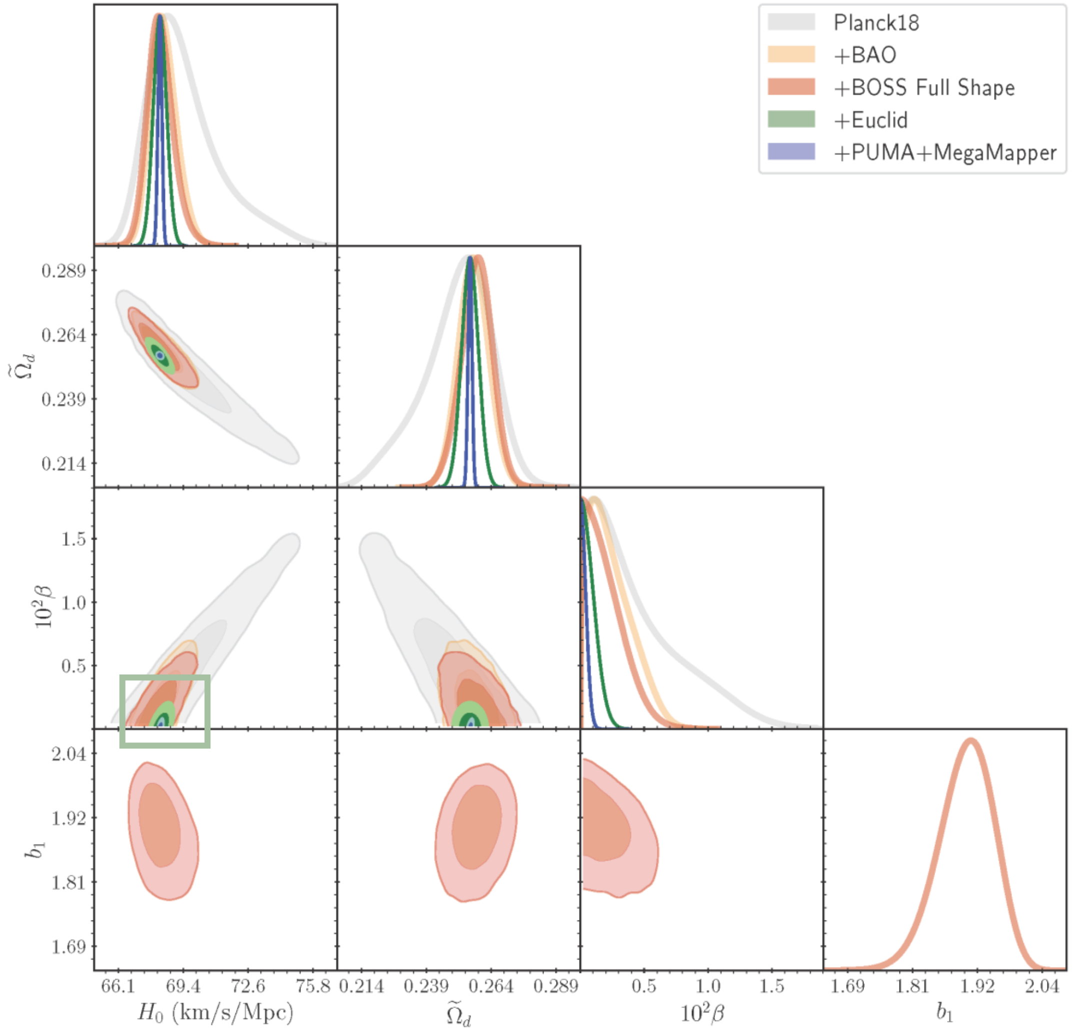

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- BAO break the degeneracy
- BOSS data not enough precise to improve the bound
- Euclid will further improve the bound by a factor 3, thanks to a better determination of b_1

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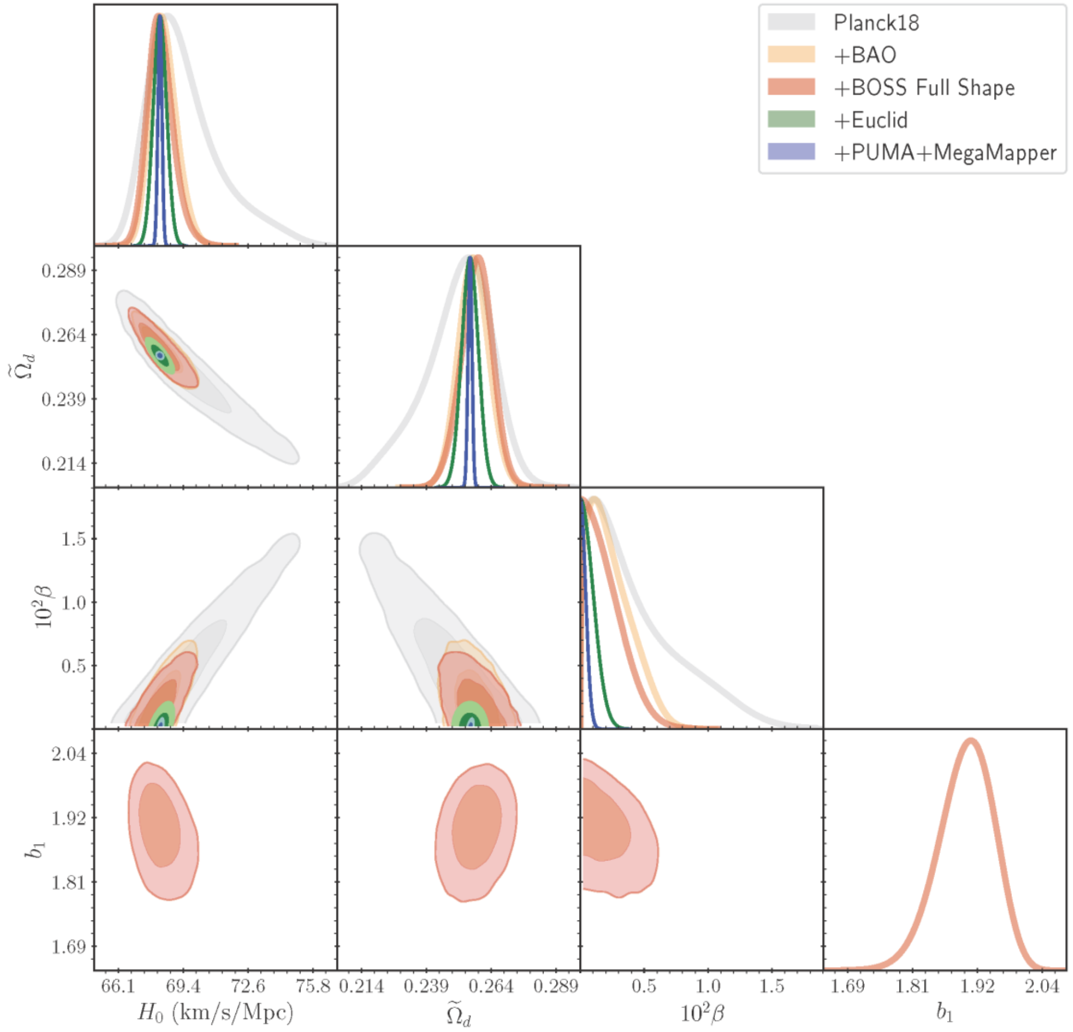

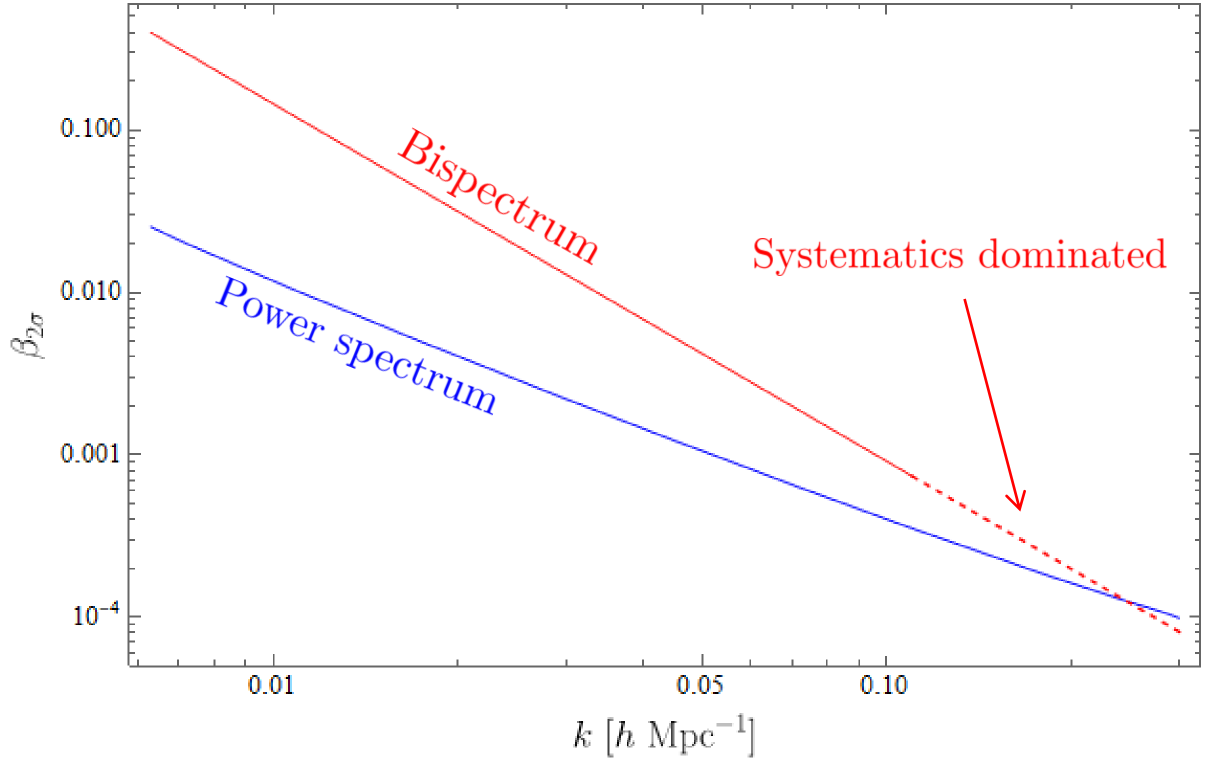

- Bound driven by the power spectrum
- Bispectrum dominated by systematics

Effects on LSS

$$\mathcal{B}(q,k,k') = \left(1 + \frac{6}{5} f_\chi^2 \beta \log \frac{1}{a_{\rm eq}}\right)^4 \mathcal{B}_{\Lambda{\rm CDM}}(q,k,k') + f_\chi \beta \Delta\mathcal{B}(q,k,k')$$

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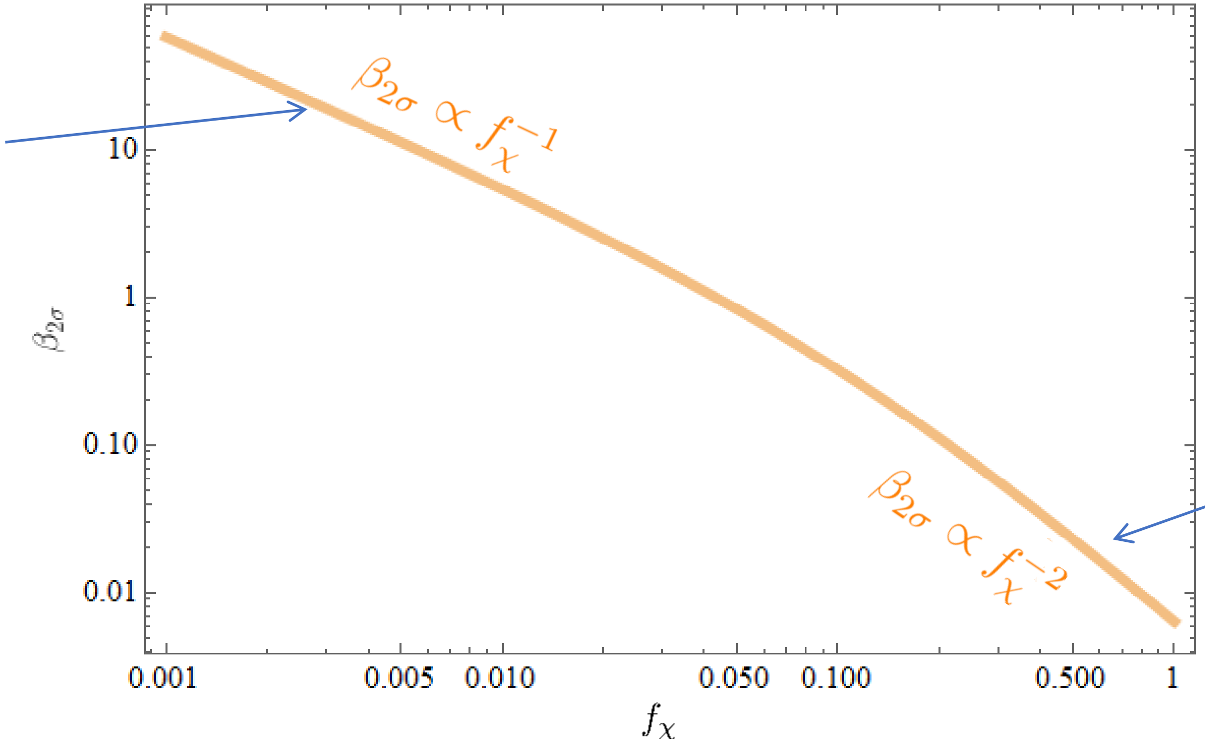
Different scaling with the DM fraction

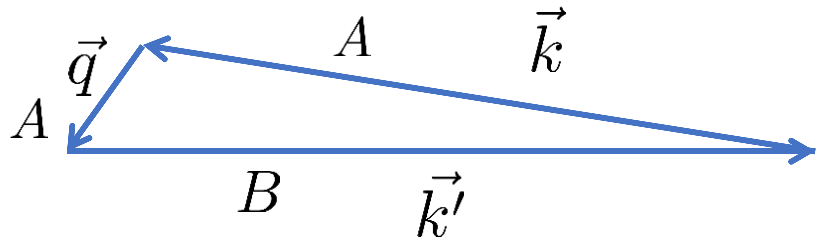
Signal dominated by new spatial features



Signal dominated by log-enhanced corrections

Effects on LSS - Pole of the Bispectrum

In the squeezed limit with two *different* tracers, the bispectrum has a pole



$$\lim_{q\to 0} \Delta\mathcal{B}_{AAB}(q,k,k') \propto \frac{\vec{q}\cdot\vec{k}}{q^2} P_{\rm lin}(q) P_{\rm lin}(k)$$

Creminelli et al. - 1309.3557, 1311.0290, 1312.6074

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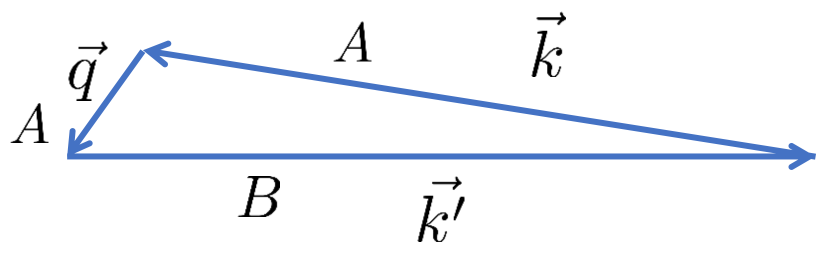

EP violation!

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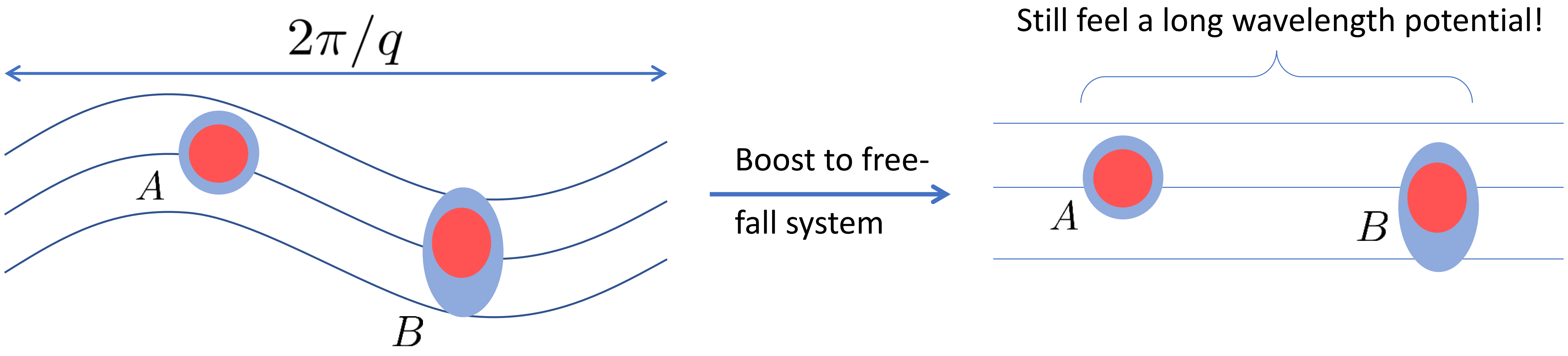

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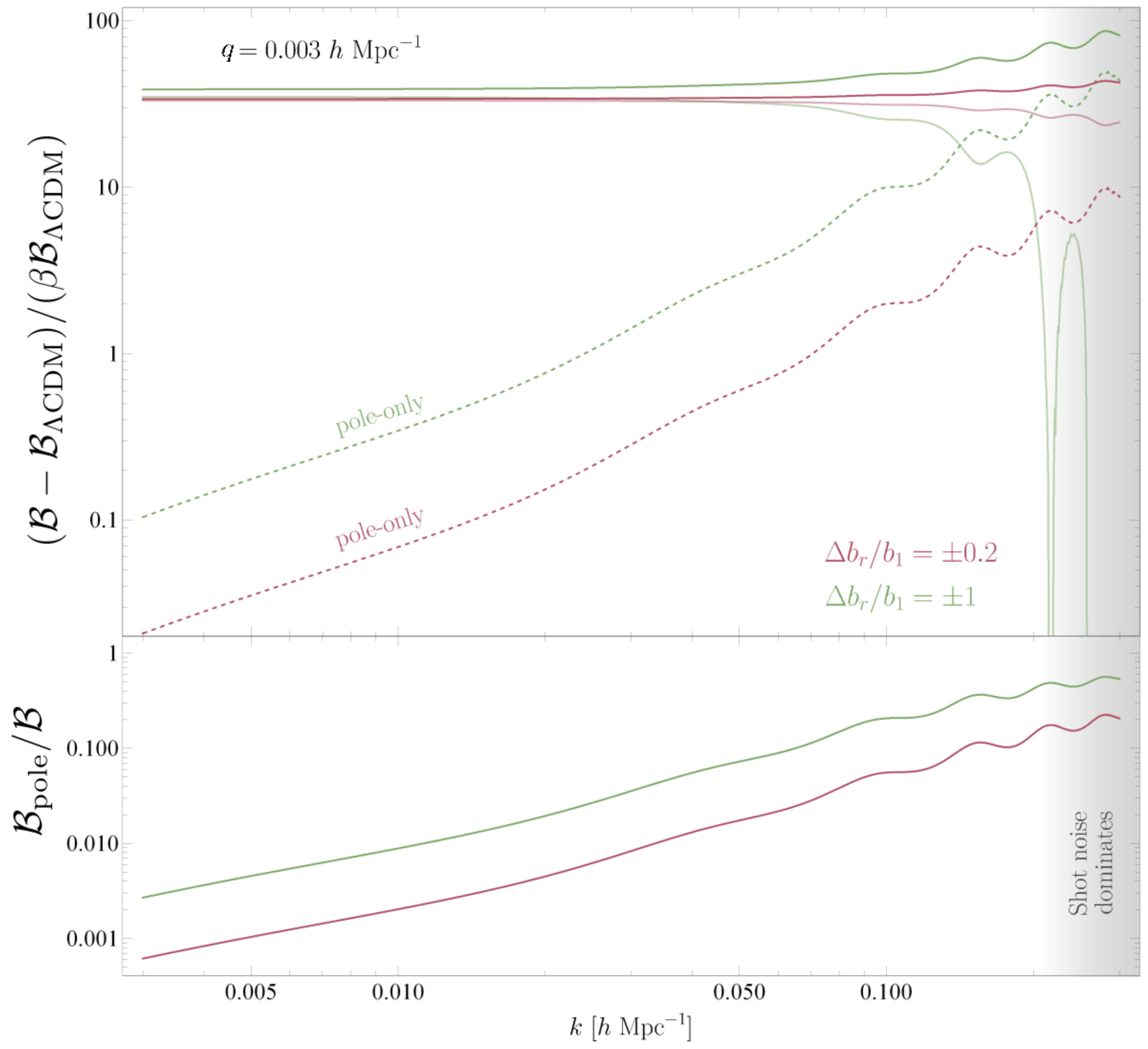

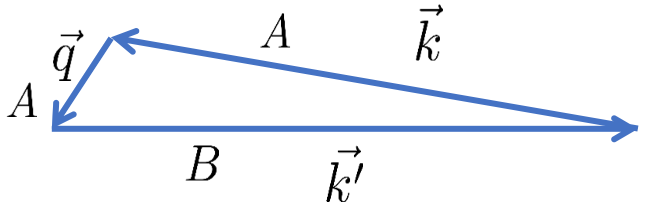

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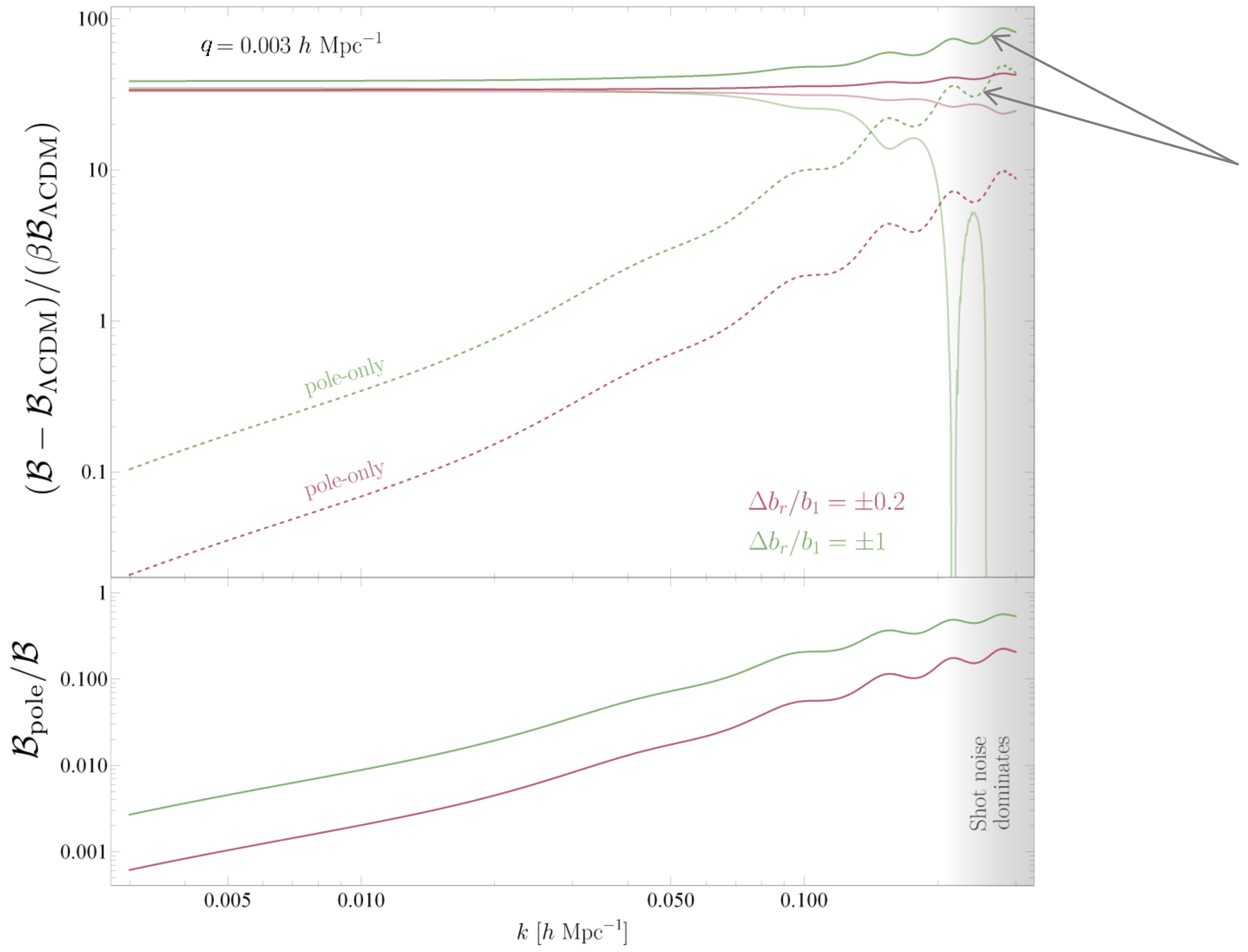

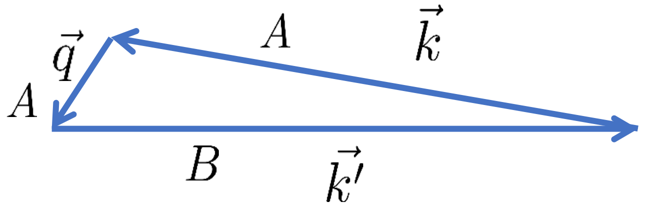

- The log enhanced growth factor ''covers'' the pole

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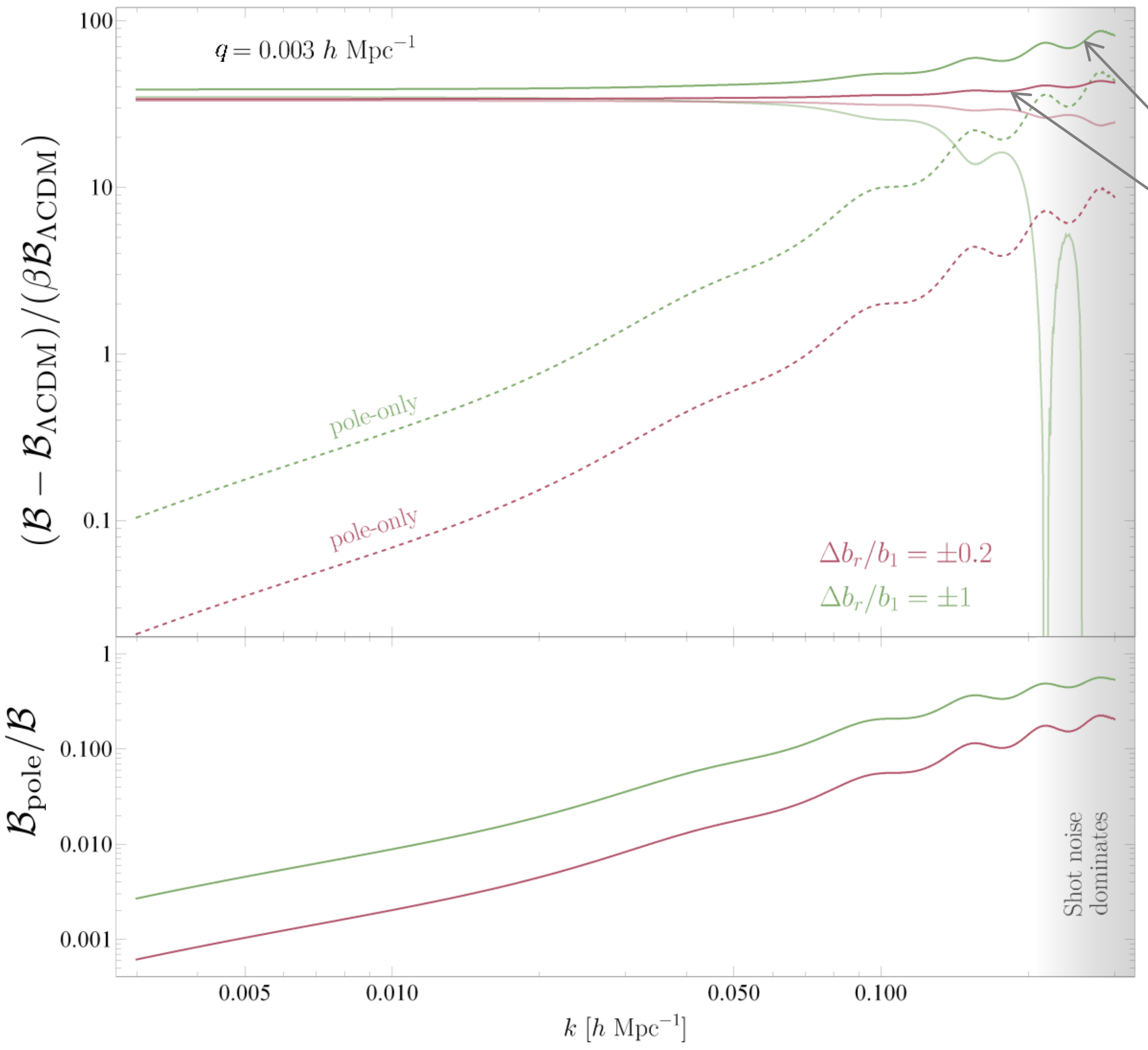

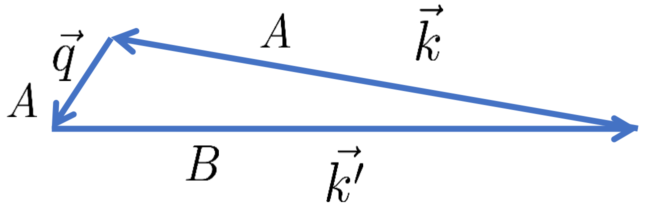

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- The prominence of the pole depends on the difference of relative bias

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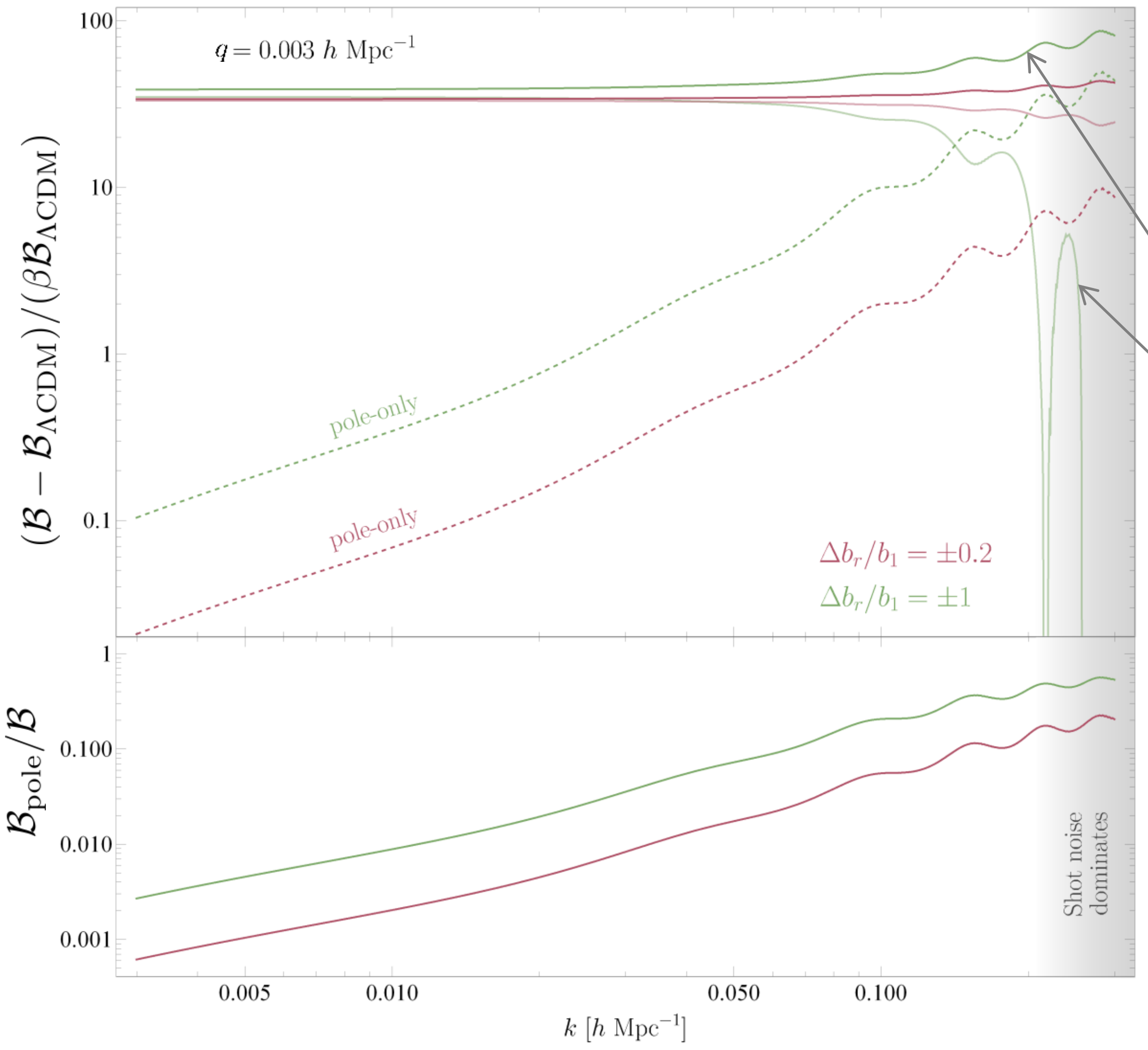

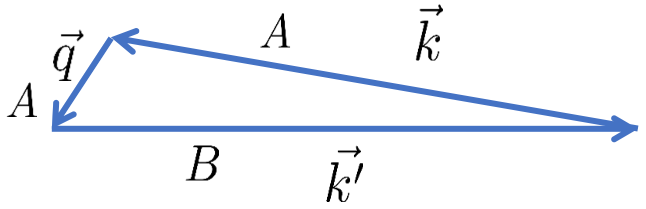

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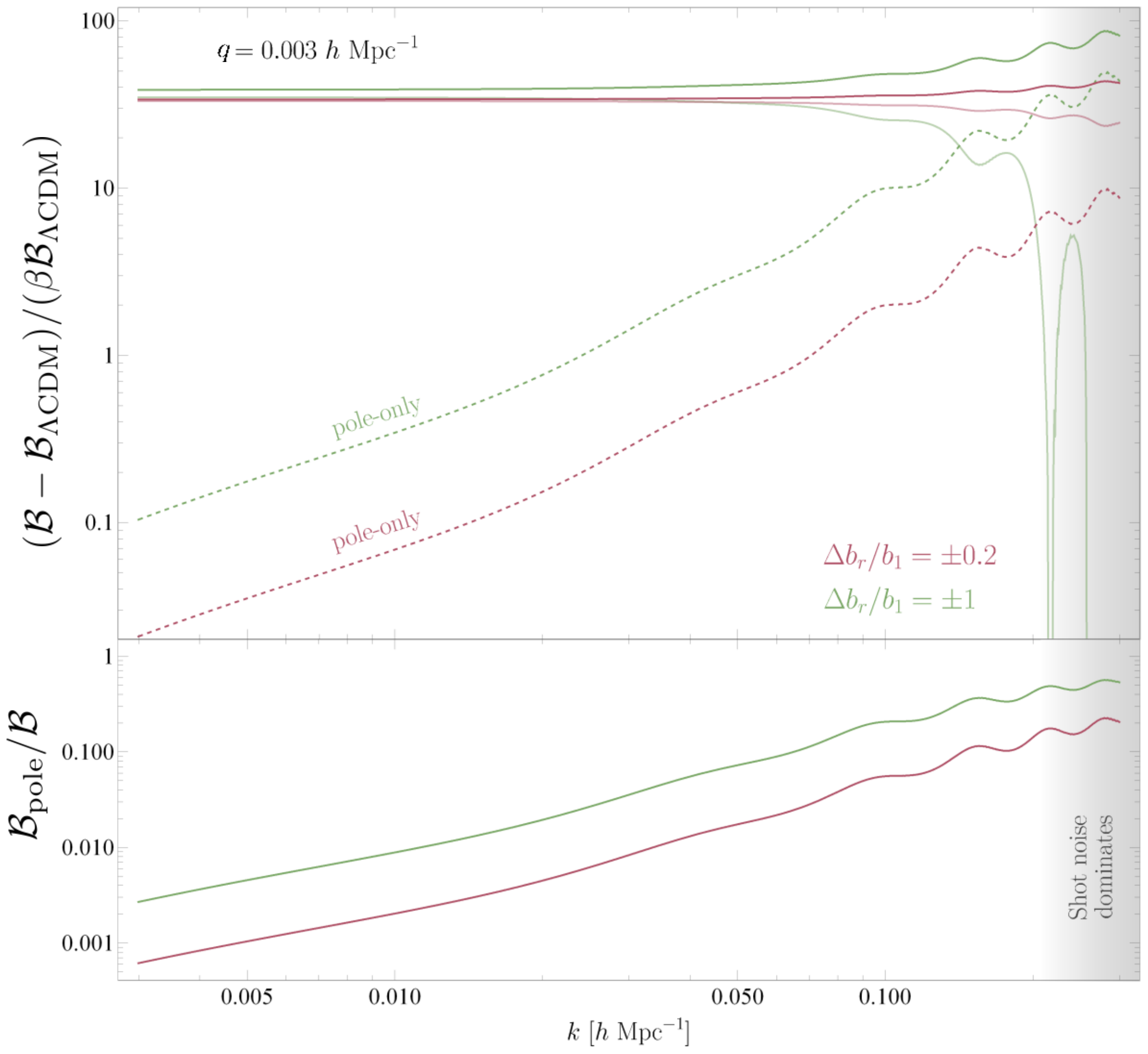
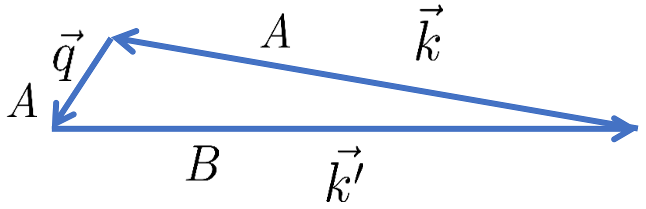
- The prominence of the pole depends on the difference of relative bias
- Depending on the sign of there can be an enhancement or a cancellation in the signal

Effects on LSS - Pole of the Bispectrum





- The log enhanced growth factor ''covers'' the pole
- The prominence of the pole depends on the difference of relative bias
- Depending on the sign of there can be an enhancement or a cancellation in the signal
- Pole observables

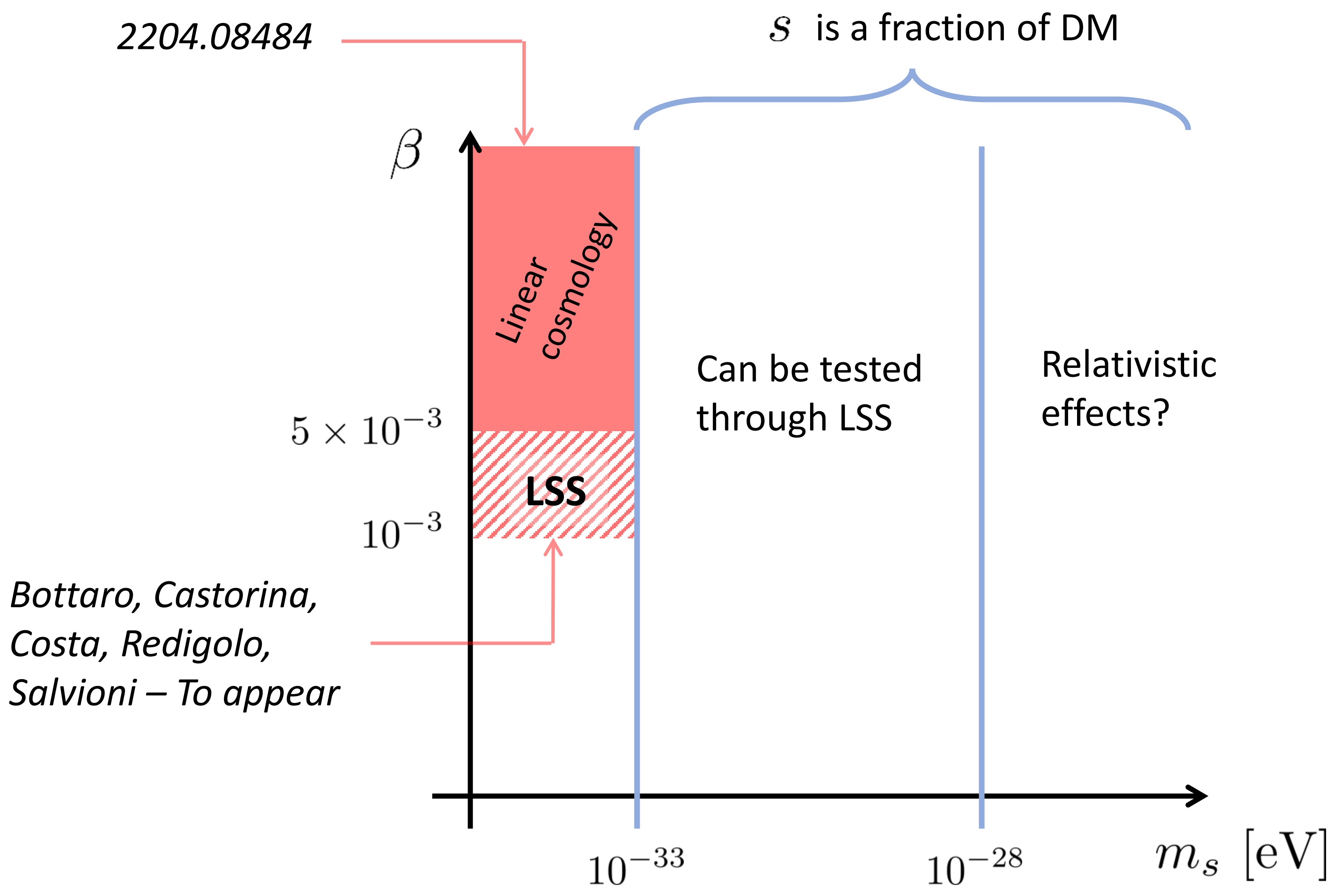
$$\mathcal{B}_{\mathrm{pole}}(k_1, k_2, k_3) \equiv \frac{\mathcal{B}_{AAB}(k_1, k_2, k_3) - \mathcal{B}_{ABA}(k_1, k_2, k_3)}{P(k)^2}$$

Conclusions

Dark fifth forces affect cosmology in three ways

- Background evolution
  - Early time observables like CMB constrain dark fifth forces at percent level w.r.t. gravity
- (Log-)enhanced growth of matter fluctuations
  - LSS (Euclid) will constrain dark fifth forces at the permille level w.r.t. gravity
  - Power spectrum determines the bound while the bispectrum is systematics dominated
- Large relative fluctuations
  - New spatial features and violation of EP and consistency relations
  - Relevant for small DM fractions

Outlook



2204.08484
s is a fraction of DM
β
Linear cosmology
LSS
5×10^{-3}
10^{-3}
Can be tested through LSS
Relativistic effects?
Bottaro, Castorina, Costa, Redigolo, Salvioni – To appear
10^{-33}
10^{-28}
m_s [eV]

Back-up

Naturalness of the model

Assuming scalar DM:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{1}{2} m_\chi^2 \chi^2 + \frac{1}{2}\partial_\mu s \partial^\mu s - V_s(s) - g_D m_\chi s \chi^2$$

$$\beta = \frac{g_D^2}{4\pi G_N m_\chi^2}$$

Simplest case: quadratic potential

$$V_s(s) = \frac{1}{2} m_s^2 s^2$$

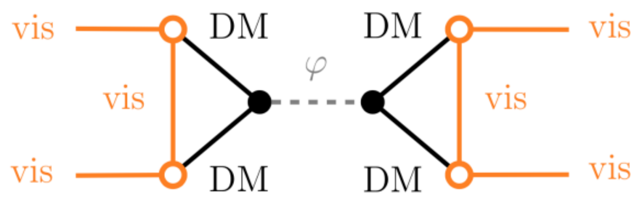
Estimate of the one-loop correction to the scalar mass gives:

$$m_s^2 \geq \frac{\beta}{(4\pi)^2} \frac{m_\chi^4}{M_P^2} \longrightarrow m_\chi \leq 0.02 \text{ eV} \left(\frac{0.01}{\beta}\right)^{\frac{1}{4}} \left(\frac{m_s}{H_0}\right)^{\frac{1}{2}}$$

Relation with other fifth force experiments

The scalar mediator can couple to the SM if DM does, e.g. the axion

$$\mathcal{L} = \frac{\alpha}{8\pi}\frac{E}{N}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_3}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu\ a} - g_D m_a s a^2$$



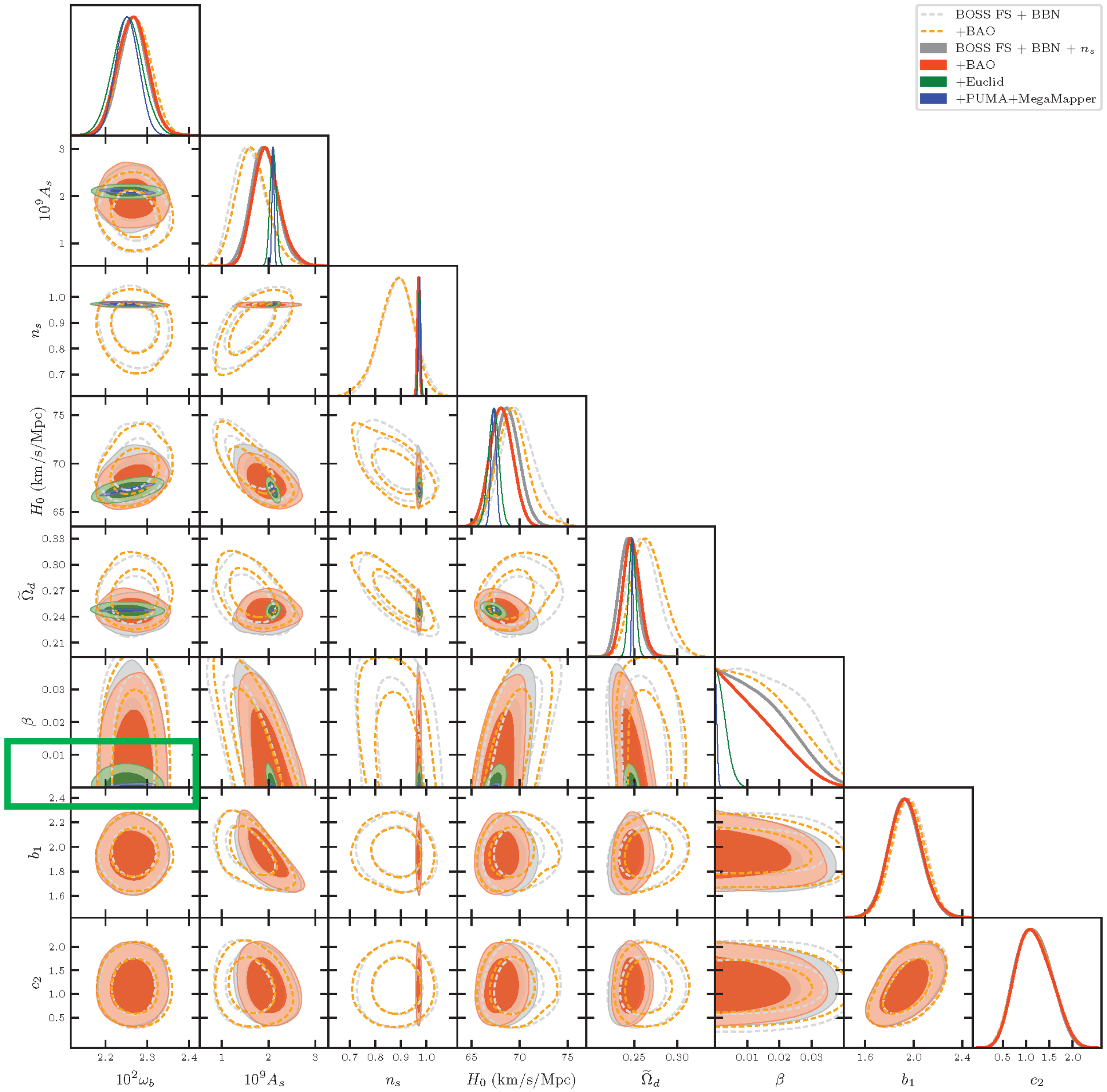
$$\mathcal{L} = \sqrt{4\pi G_N}\, s\left(\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} + \frac{d_g b_3 \alpha_3}{8\pi}G^a_{\mu\nu}G^{\mu\nu\ a} + \cdots\right)$$

$$d_e \simeq \sqrt{\beta}\left(\frac{m_a}{4\pi f_a}\right)^2 \frac{\alpha^2}{16\pi^2} \simeq 2\times 10^{-10}\sqrt{\frac{\beta}{0.01}}\left(\frac{m_a}{f_a}\right)^2 \leq 2.1\times 10^{-4}$$

$$d_g \simeq \sqrt{\beta}\left(\frac{m_a}{4\pi f_a}\right)^2 \frac{\alpha_3}{8\pi b_3} \simeq 3\times 10^{-6}\sqrt{\frac{\beta}{0.01}}\left(\frac{m_a}{f_a}\right)^2 \leq 2.9\times 10^{-6}$$

MICROSCOPE (1712.01176)

Euclide alone will be competitive with Planck

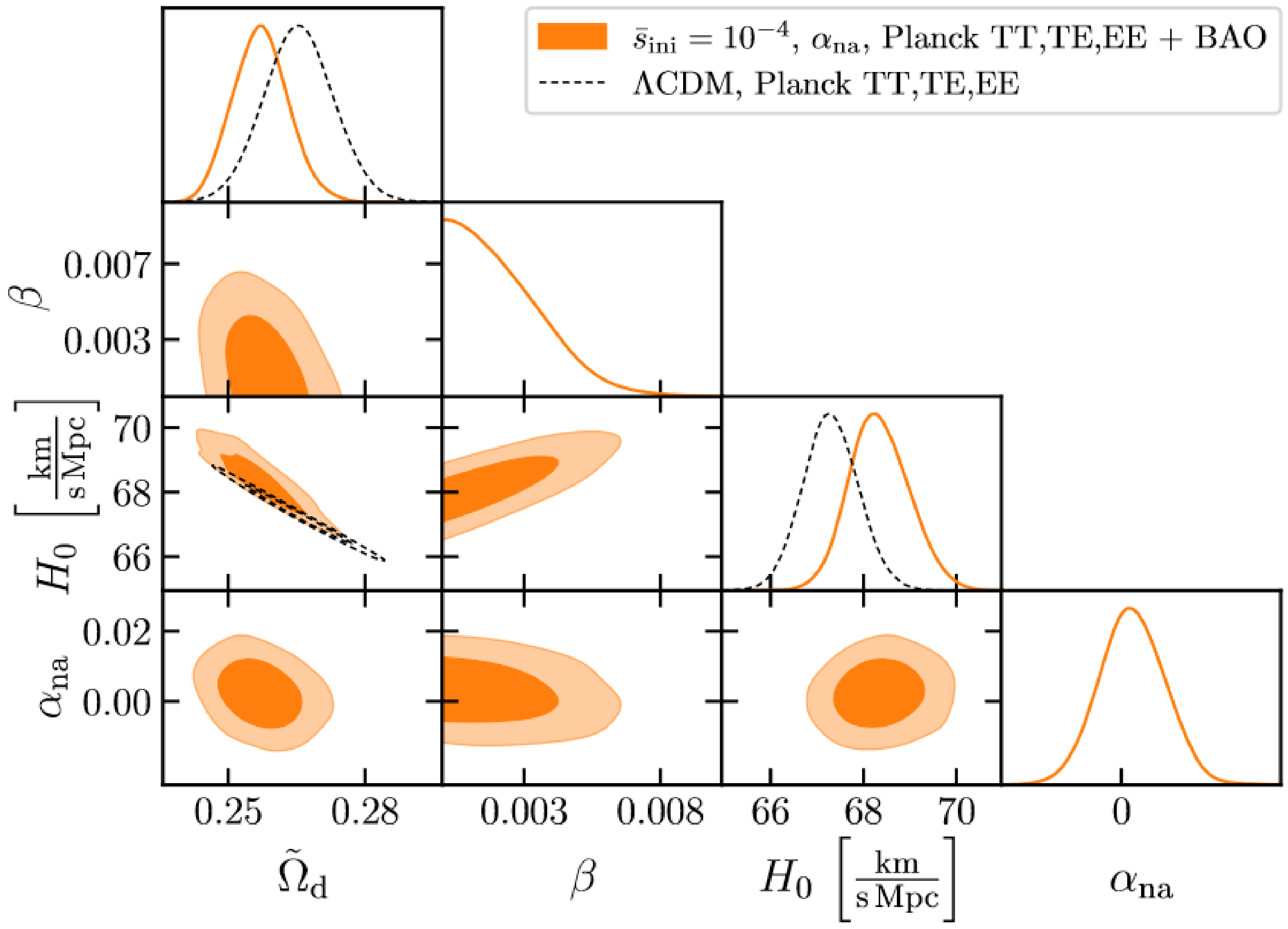


Non-adiabaticities

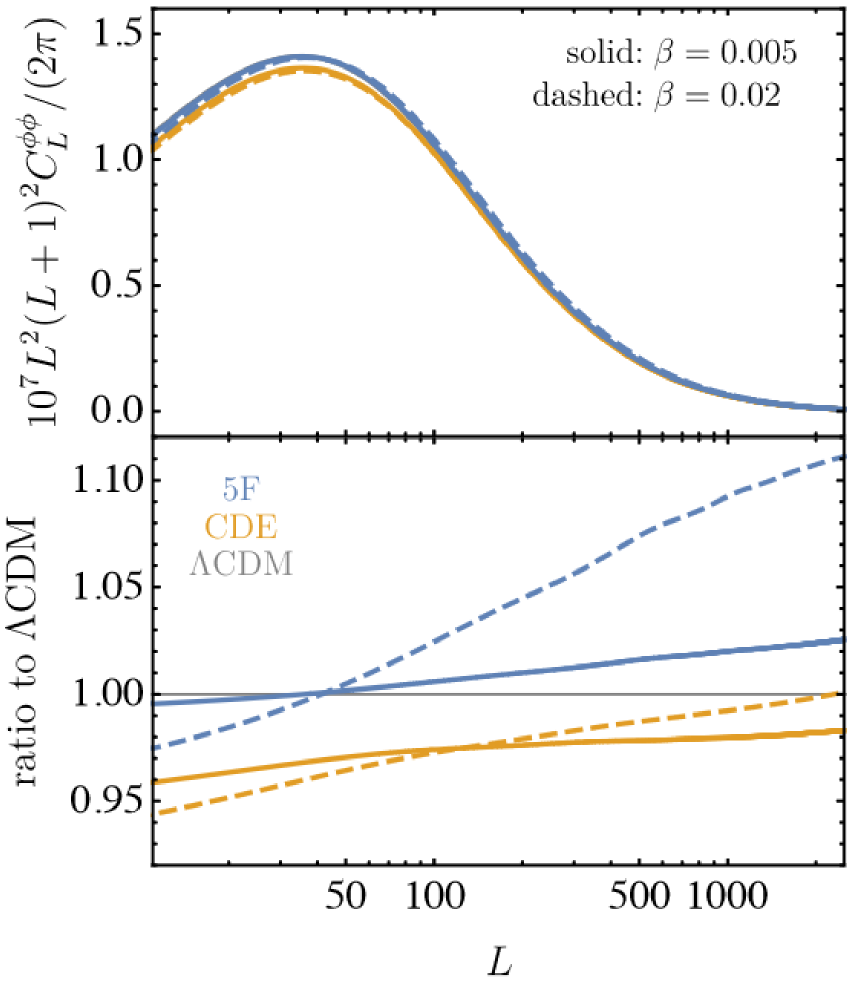
$$\delta_s = (\delta_s)_{\rm ad} + 2\alpha_{\rm na}$$

↓

$$\theta_\chi = (\theta_\chi)_{\rm ad} + \frac{\alpha_{\rm na}}{2} k^2 \tau$$



CMB lensing



$10^7 L^2(L+1)^2 C_L^{\phi\phi}/(2\pi)$
1.5
1.0
0.5
0.0
solid: $\beta = 0.005$
dashed: $\beta = 0.02$
ratio to ΛCDM
1.10
1.05
1.00
0.95
5F
CDE
ΛCDM
50
100
500
1000
L