Unveiling dark fifth forces with Large Scale Structures

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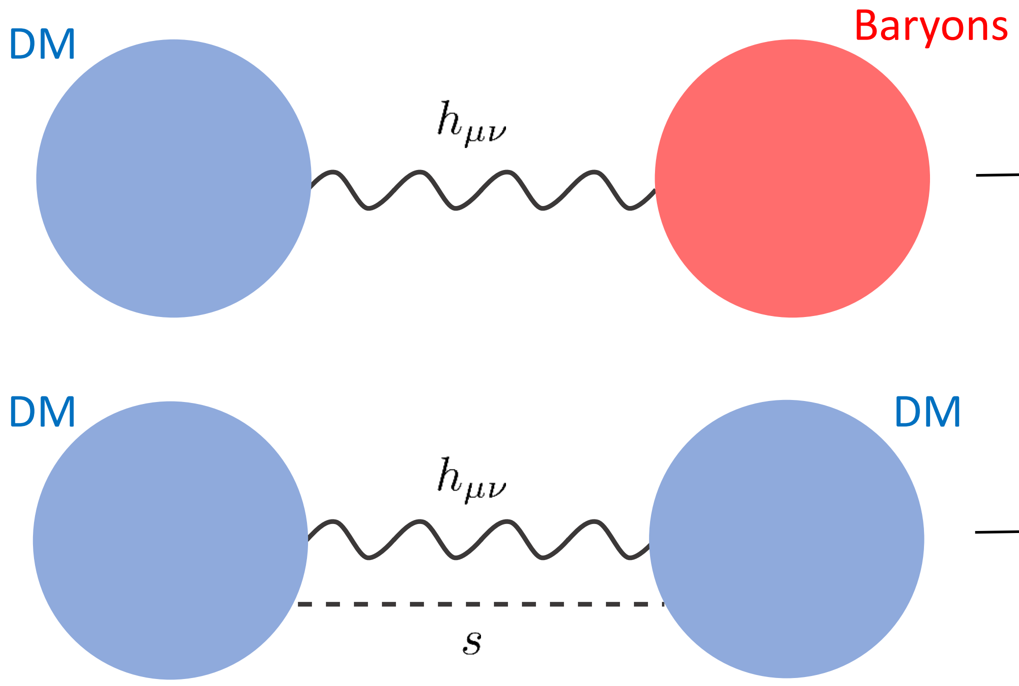
Cosmology in Miramare - August 31, 2023

Fifth forces in the Dark Sector

- Long-range forces in the dark sector can be constrained by present cosmological observations
- Sensibly more precision will be reached with present and future galaxy surveys (DESI, EUCLID…)

Simplest scenario



$$V_G(r) = -G_N \frac{mm'}{r}$$

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

Archidiacono, Castorina, Redigolo, Salvioni - 2204.08484

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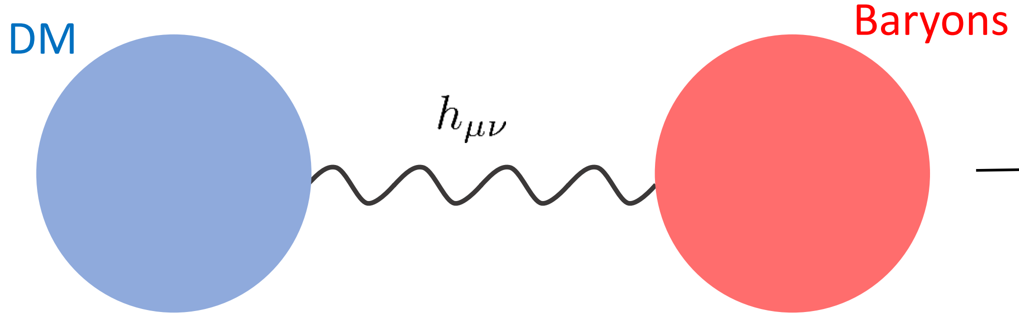

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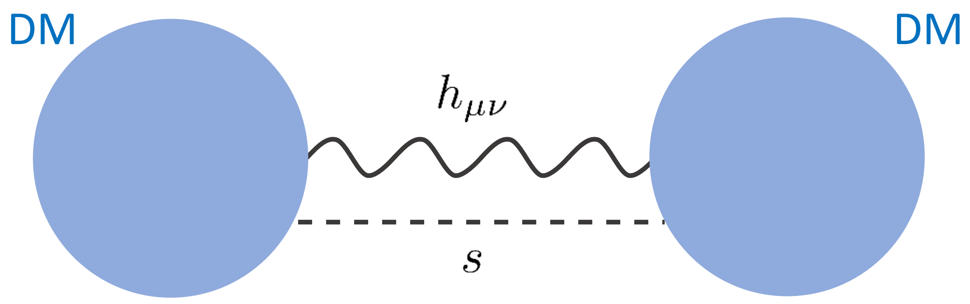
Example

$\mathcal{L}_{\text{int}} \propto s\chi^2$

Space-time dependent DM mass!



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≈ 1

$m_s \leq H_0$

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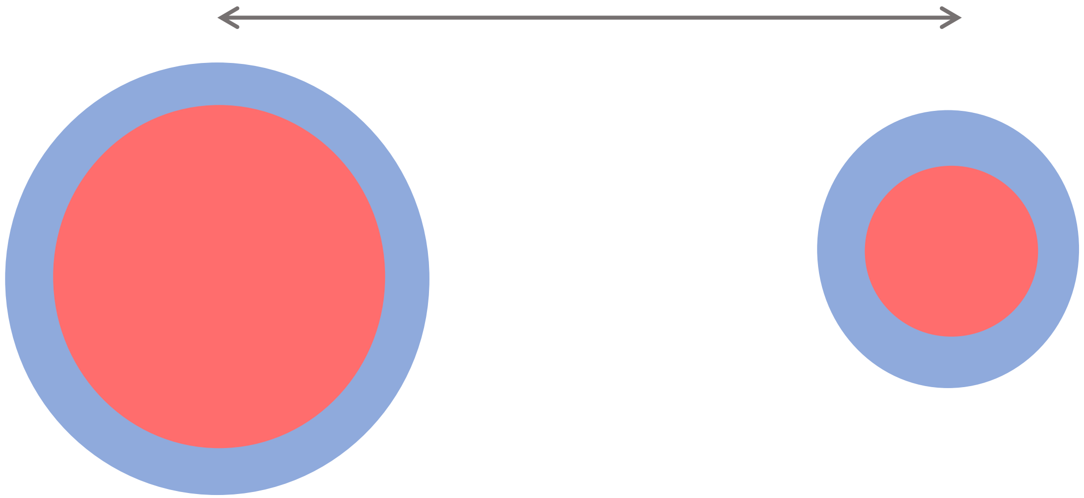
Fifth forces in the Dark Sector

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



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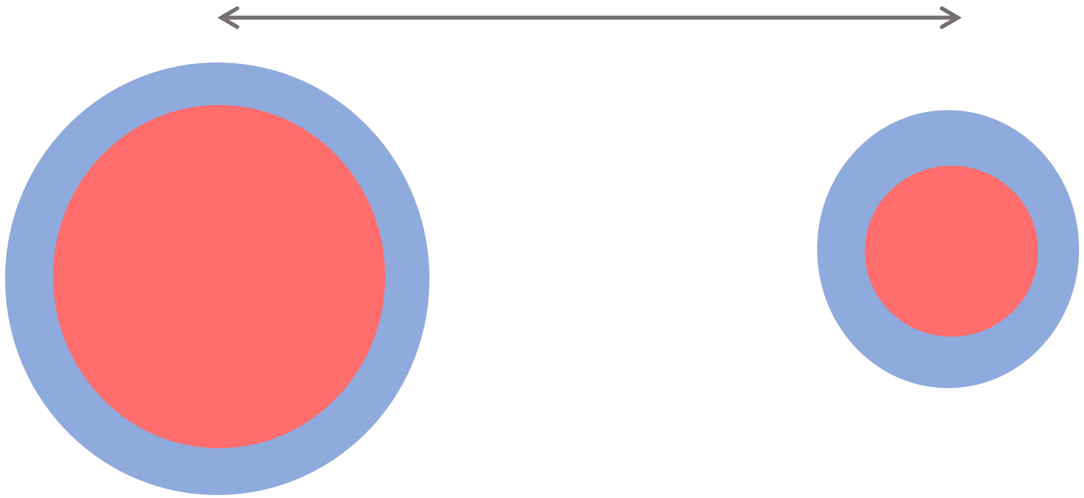

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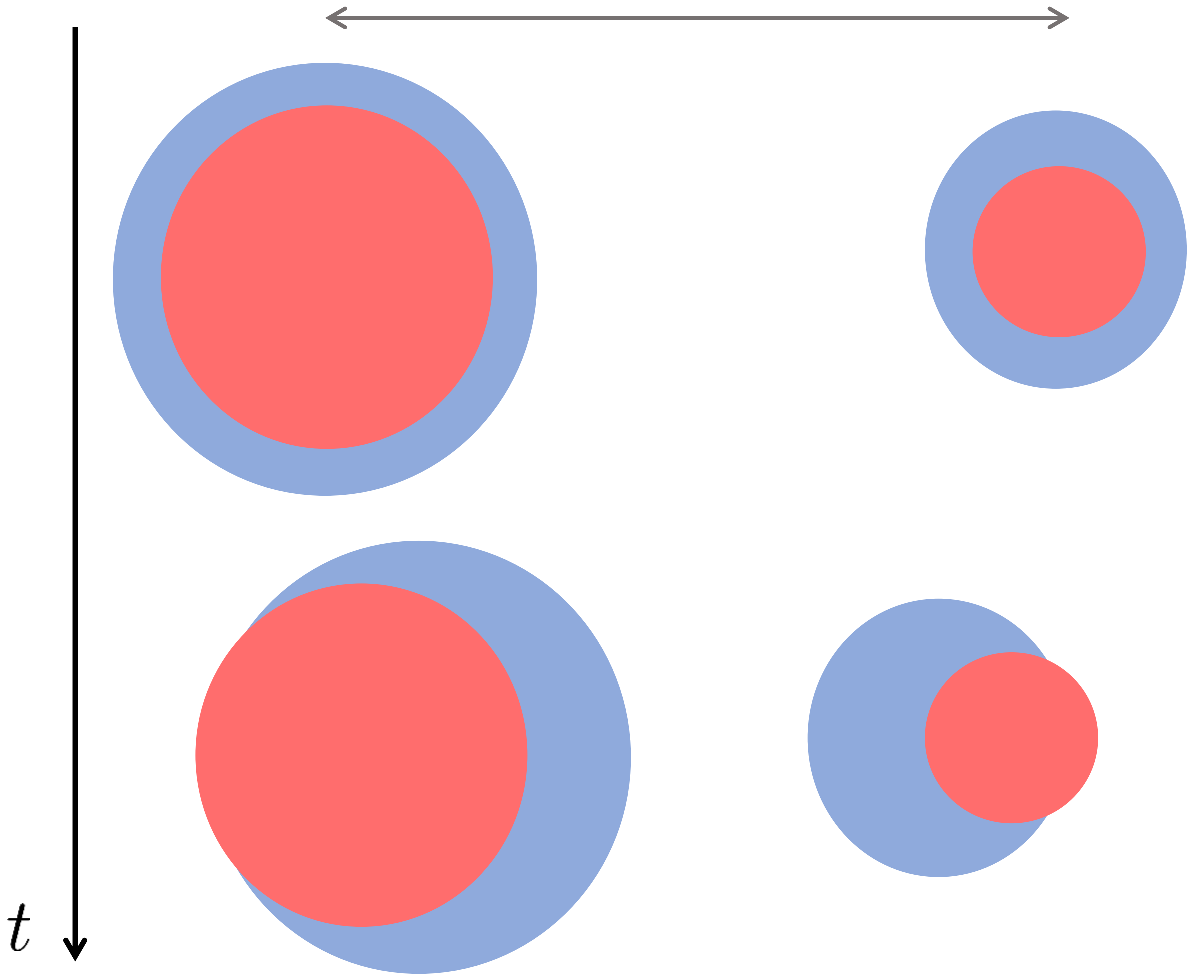

Faster growth of matter fluctuations

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

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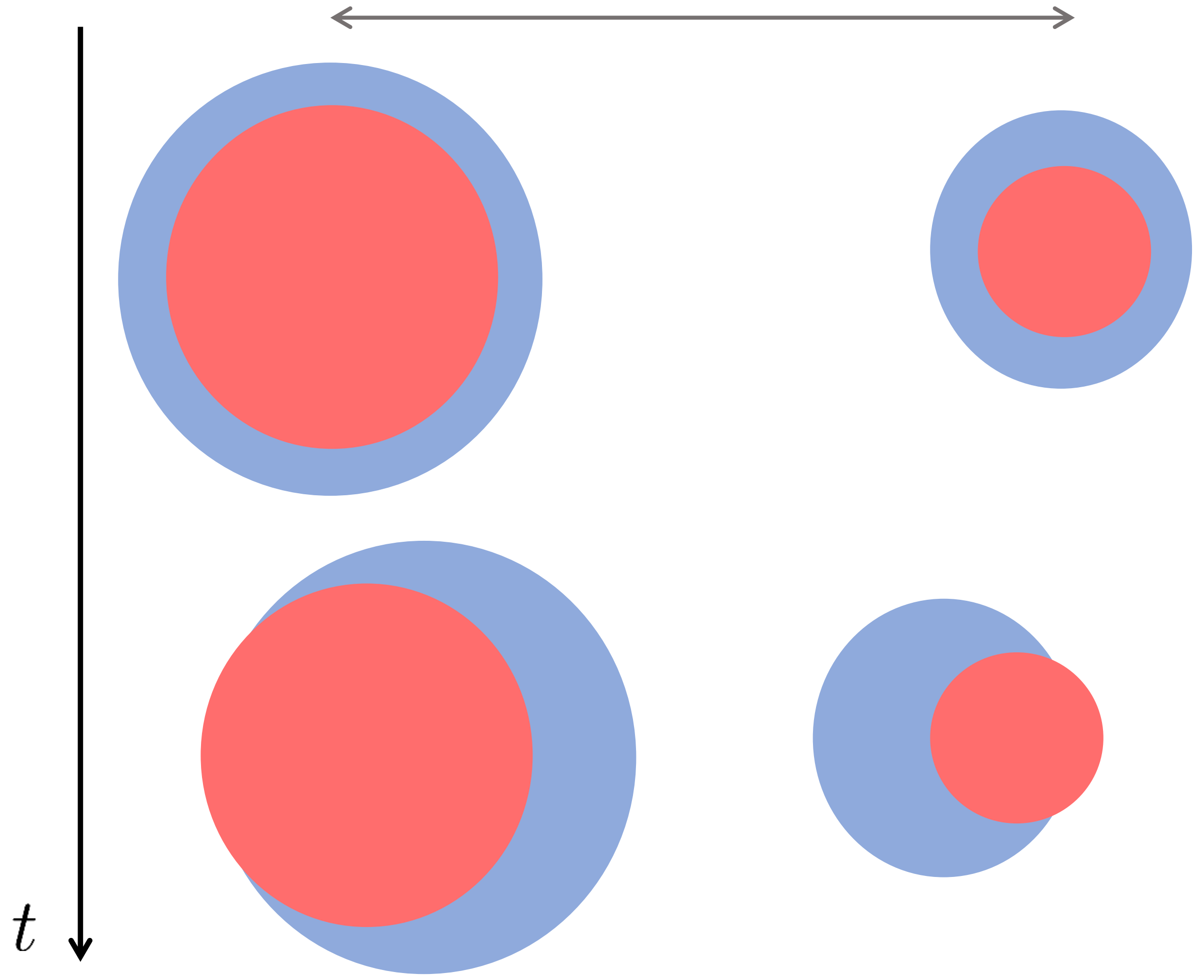

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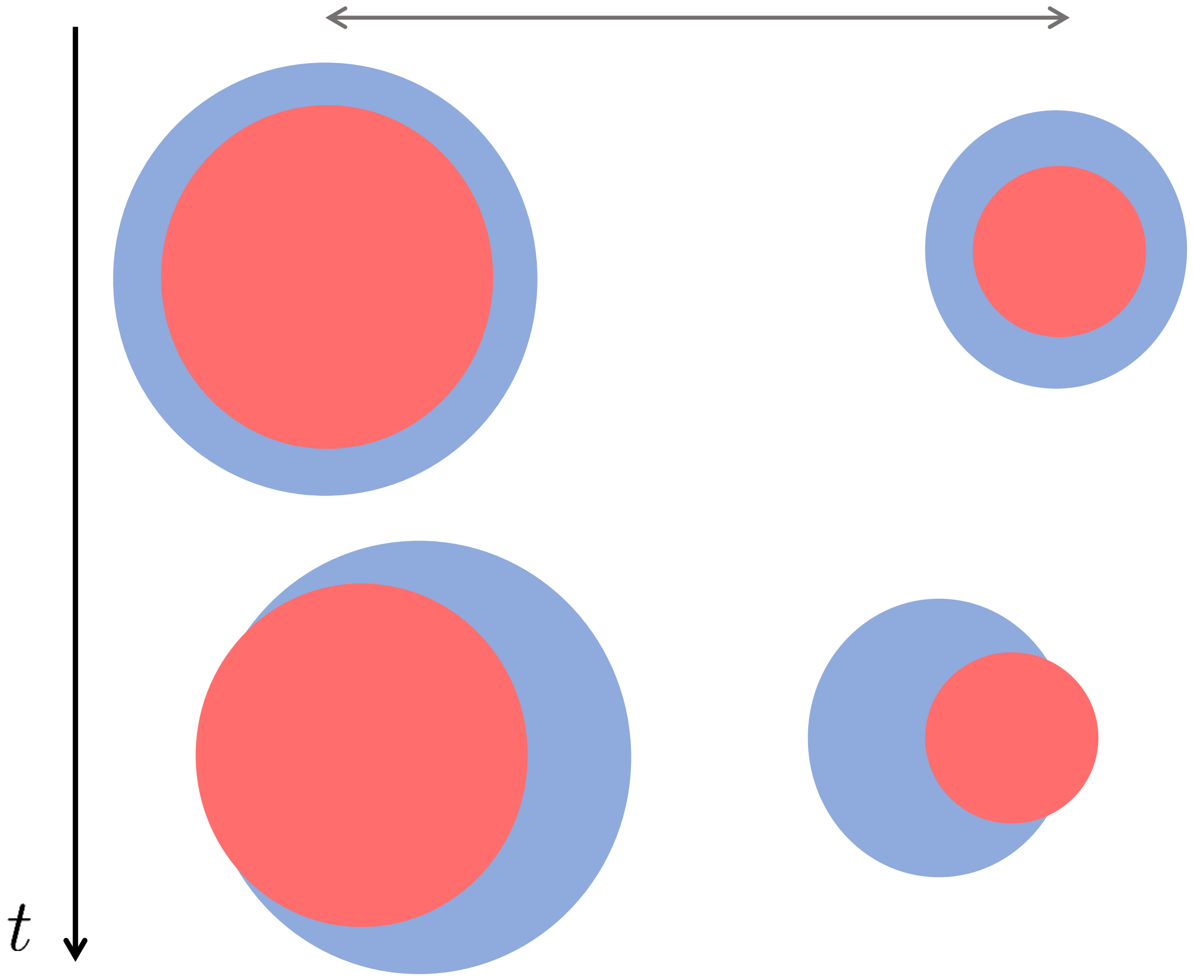

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Log-enhanced growth

EP violation: non-trivial evolution of relative fluctuations

$$\delta_r(a) = \frac{5}{3}\beta\tilde{m}^2 f_{\mathrm{DM}}\delta_{m,\Lambda\mathrm{CDM}}(a)$$

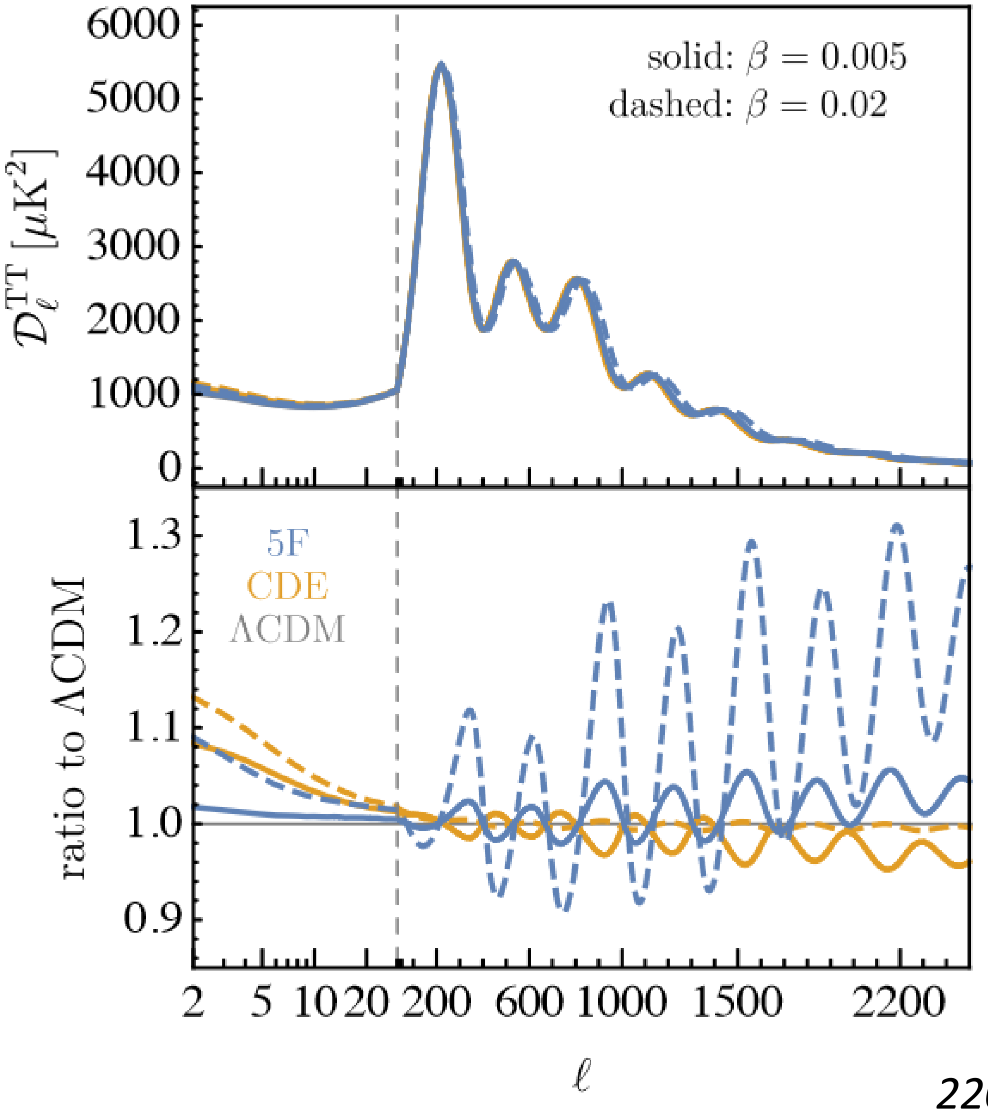
Effects on linear cosmology

CMB power spectrum mostly affected by bkg

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

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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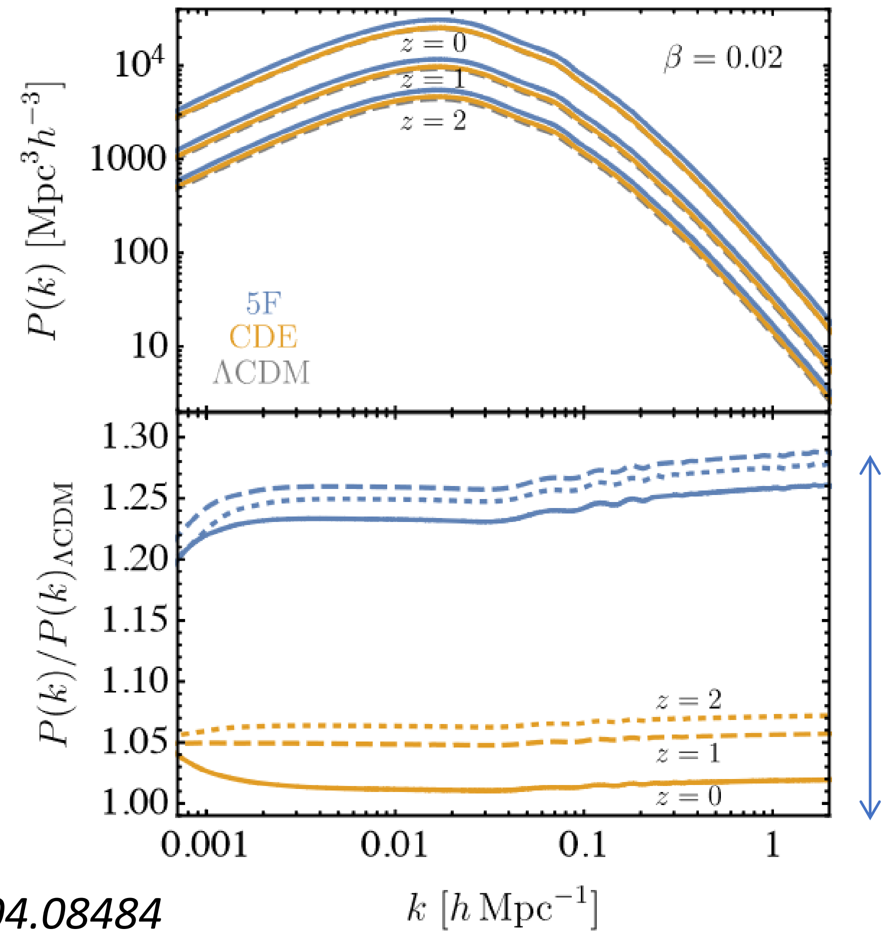
Effects on LSS



$$\approx 2\frac{\Delta D_m}{D_m} = \frac{12}{5} f_{\mathrm{DM}}^2 \tilde{m}^2 \beta \log \frac{1}{a_{\mathrm{eq}}}$$

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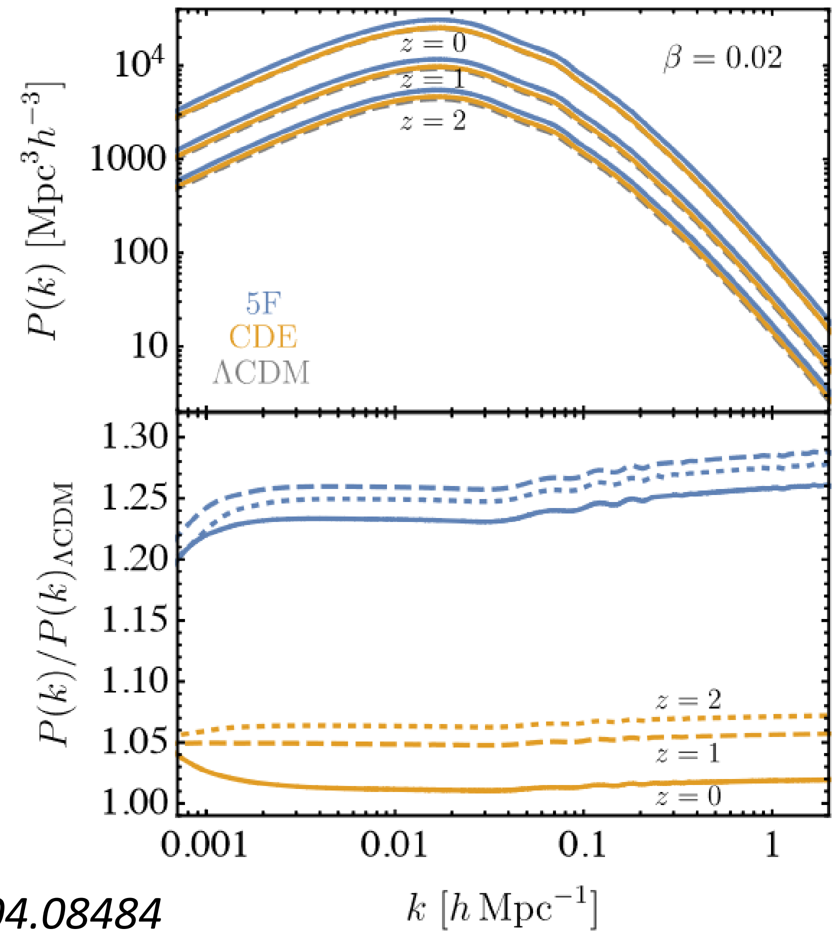
Effects on LSS



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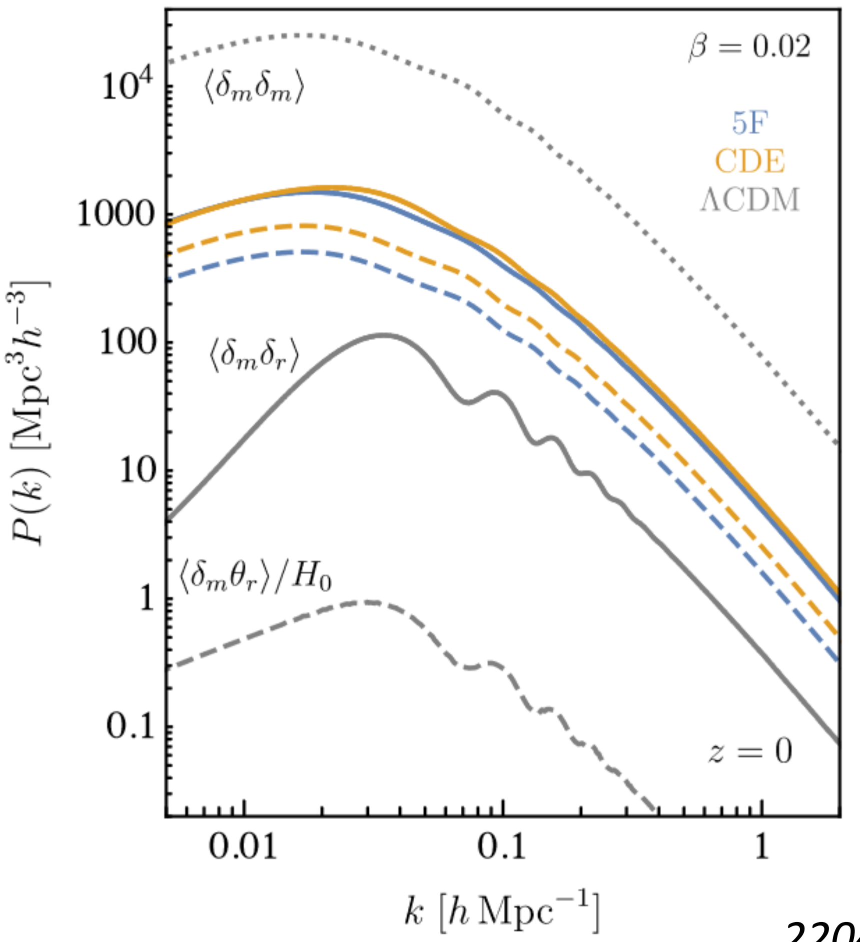

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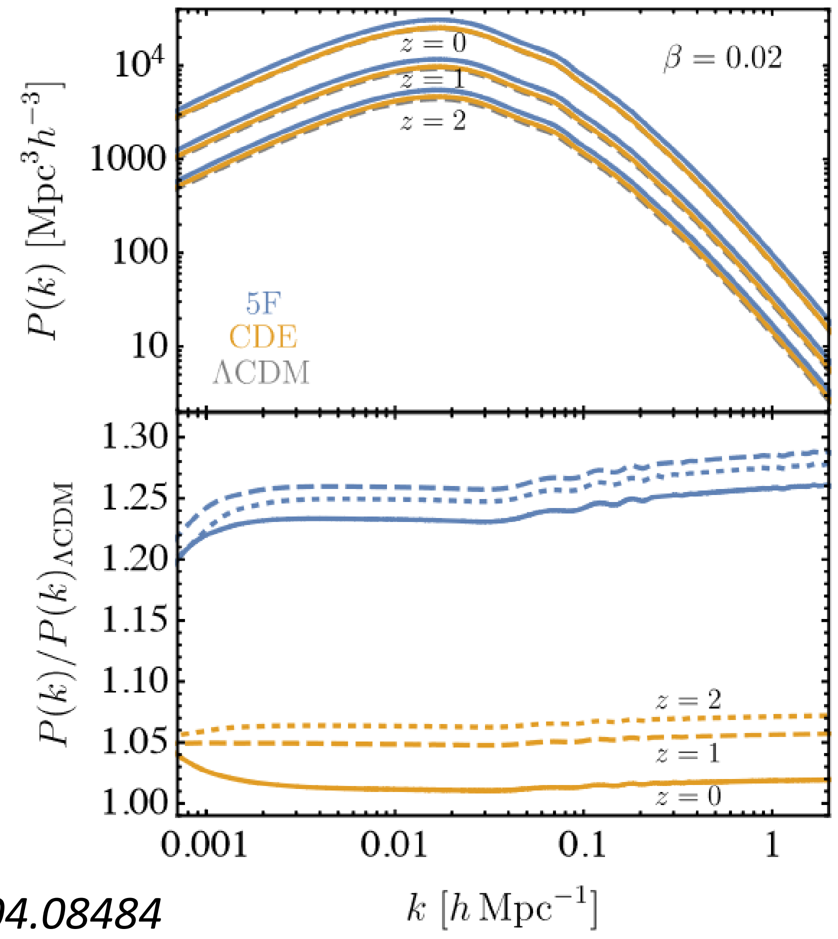

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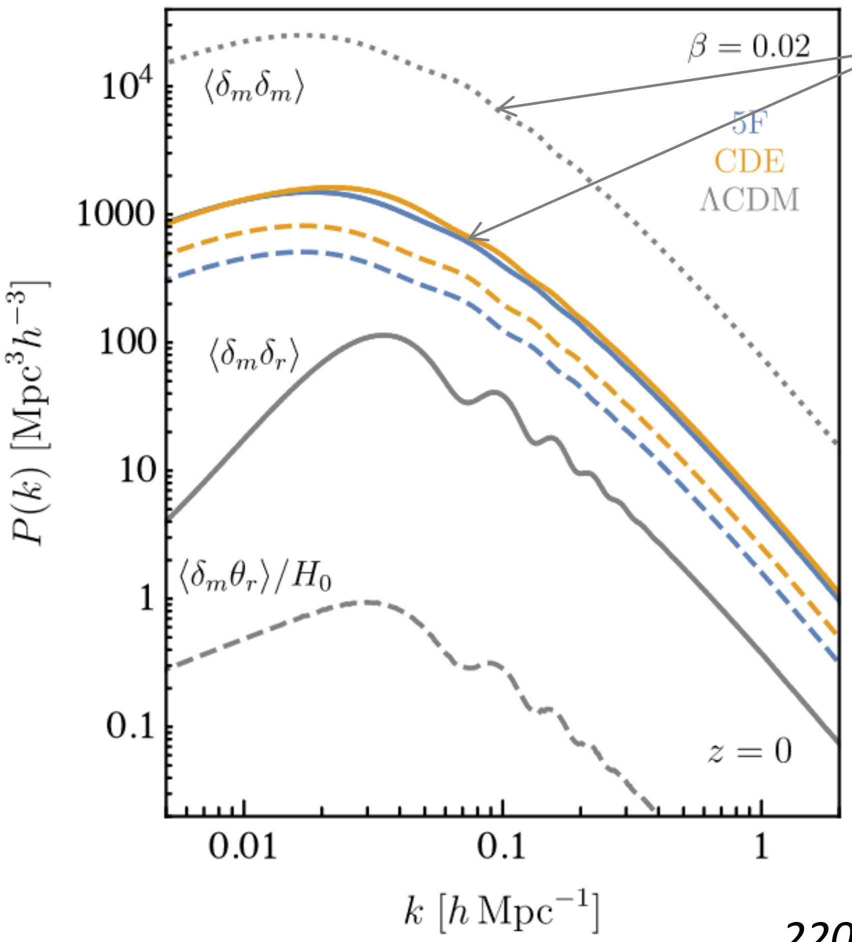

Relative fluctations are large and have a similar shape to that of total matter

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Effects on LSS

Problem: we observe galaxies, which track dark matter fluctuations $\longrightarrow$ *Bias expansion*

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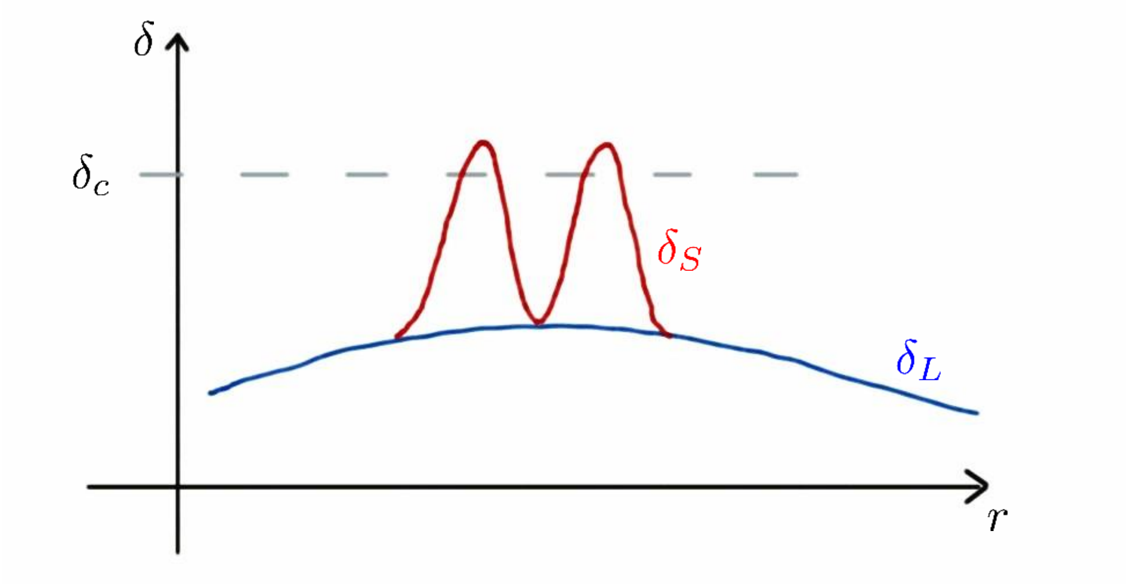
$$\delta_g(\vec{k}) = b_1 \delta_m(\vec{k}) + b_r \delta_r(\vec{k}) + \cdots$$

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

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

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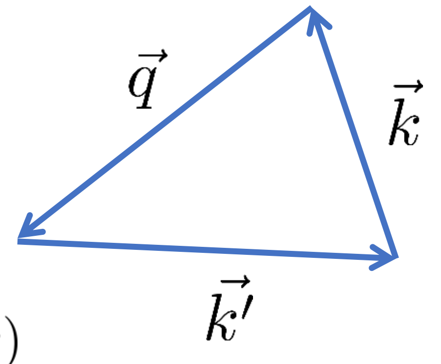
Bispectrum $\langle \delta_g^A(\vec{q})\delta_g^A(\vec{k})\delta_g^B(\vec{k}')\rangle = (2\pi)^3\delta^{(3)}(\vec{q}+\vec{k}+\vec{k}')\mathcal{B}(q,k,k')$



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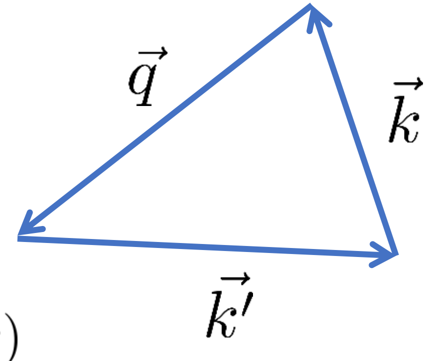

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- From $\delta_m \subset \delta_g$
- Log-enhancement from bkg effects
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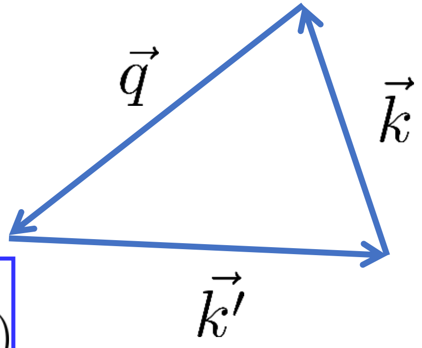

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- From $\delta_m \subset \delta_g$
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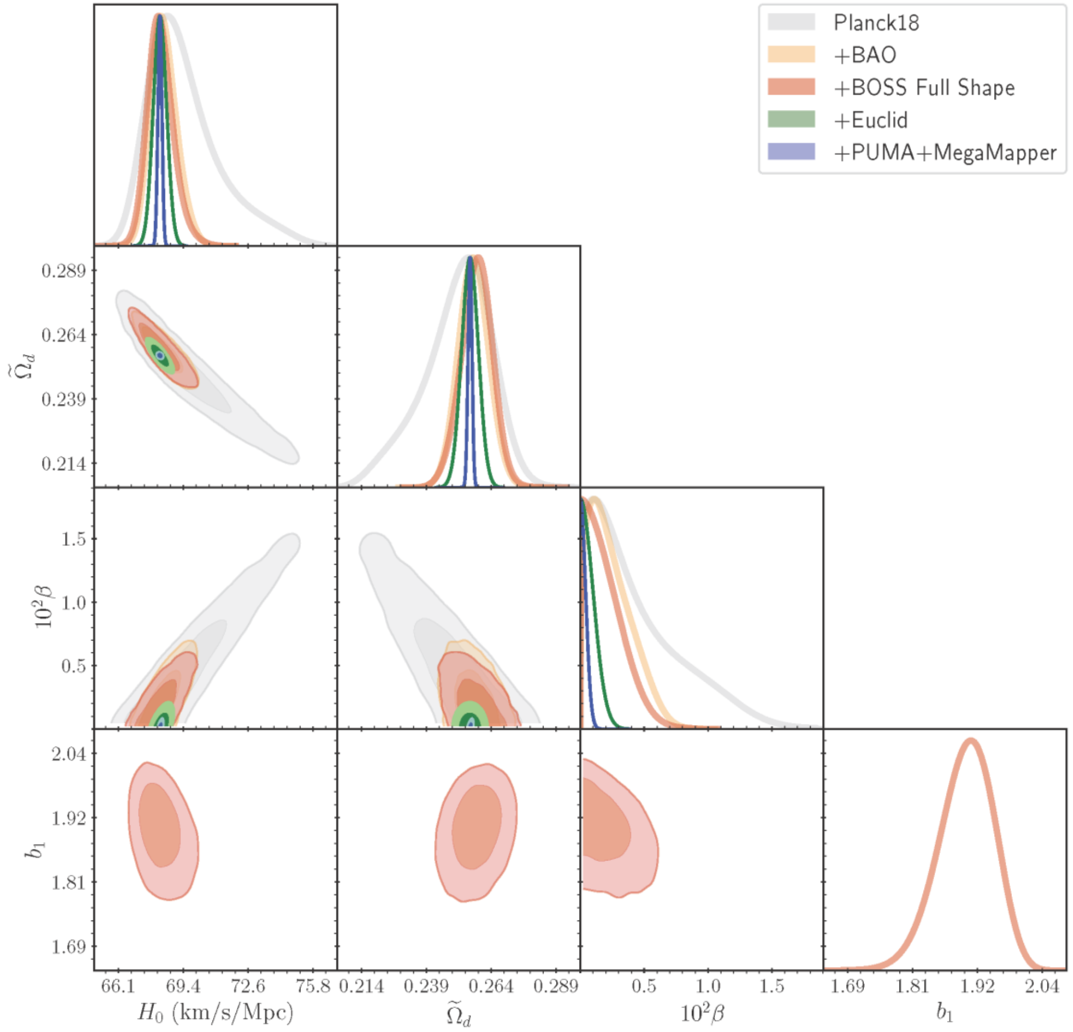
- From $\delta_r \subset \delta_g$
- Different spatial structure
- Not log-enhanced
- Possible poles in the squeezed bispectrum

Effects on LSS



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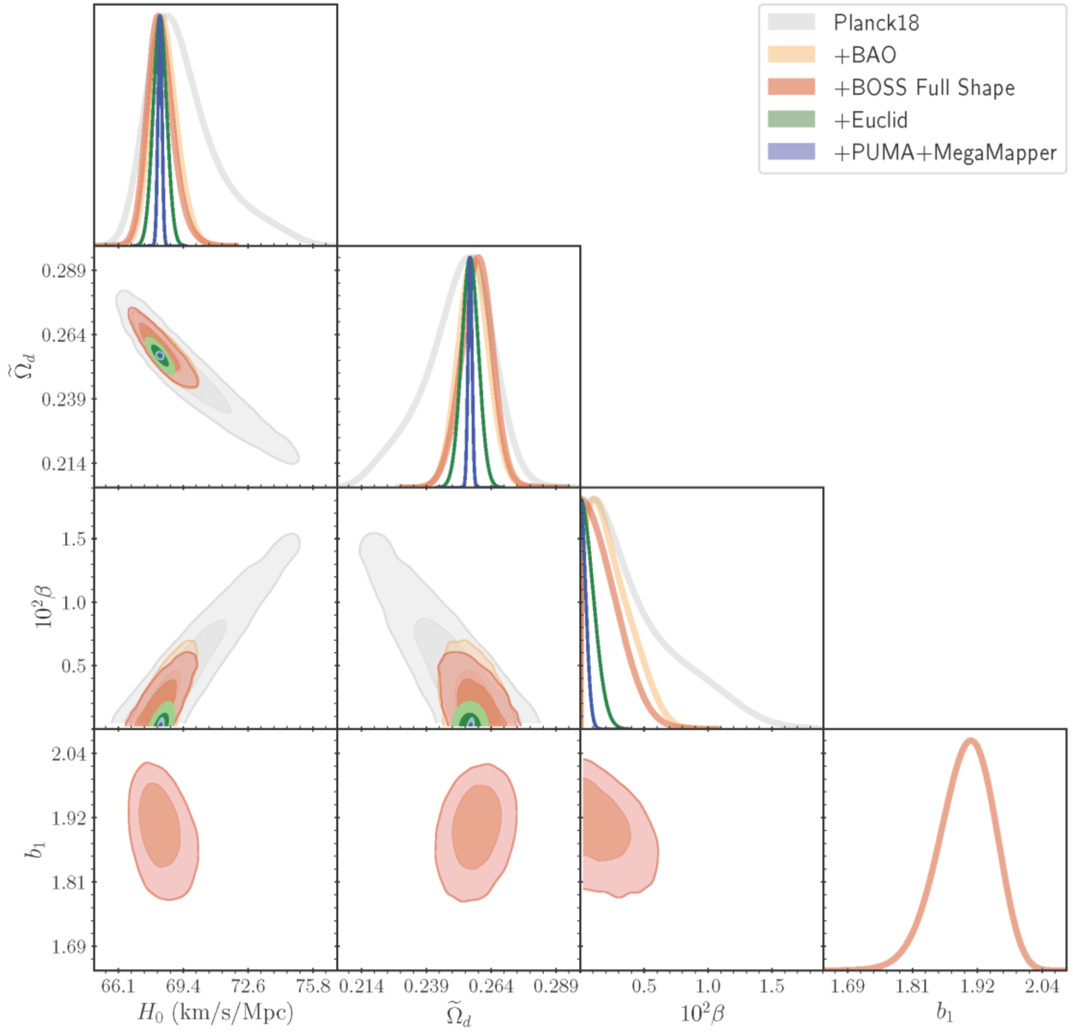

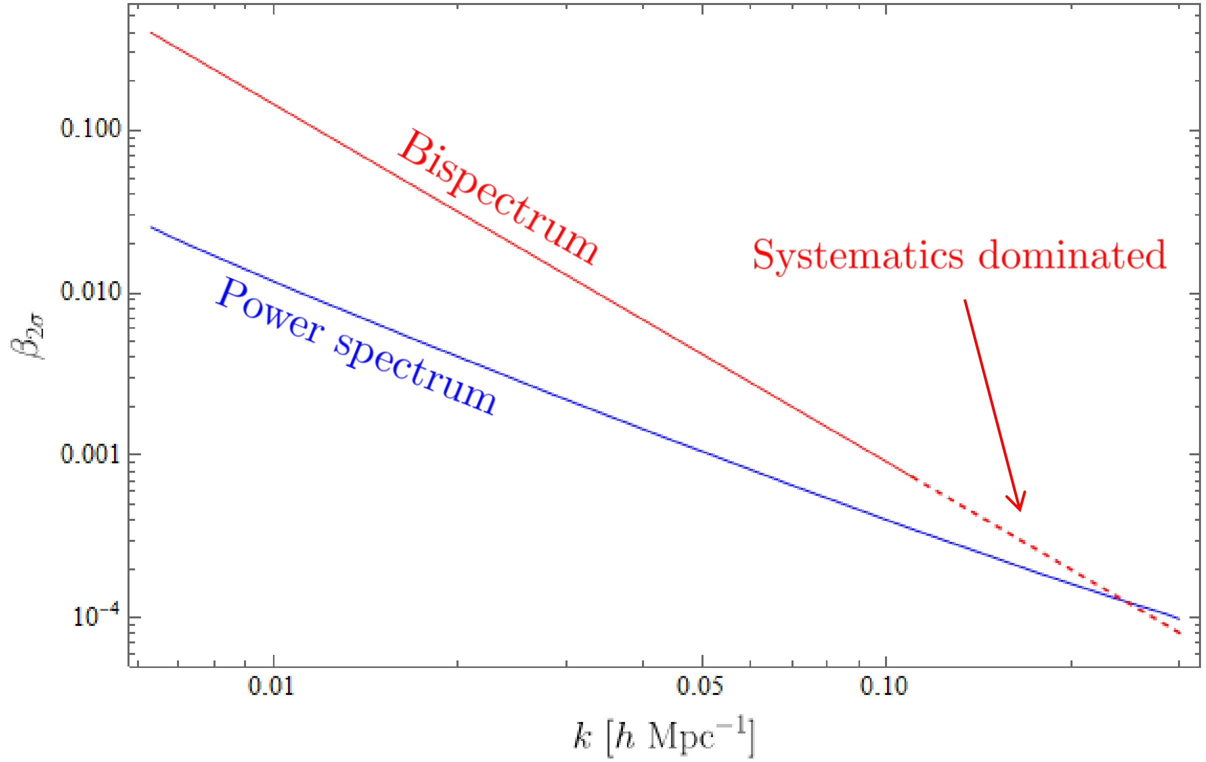

Effects on LSS

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

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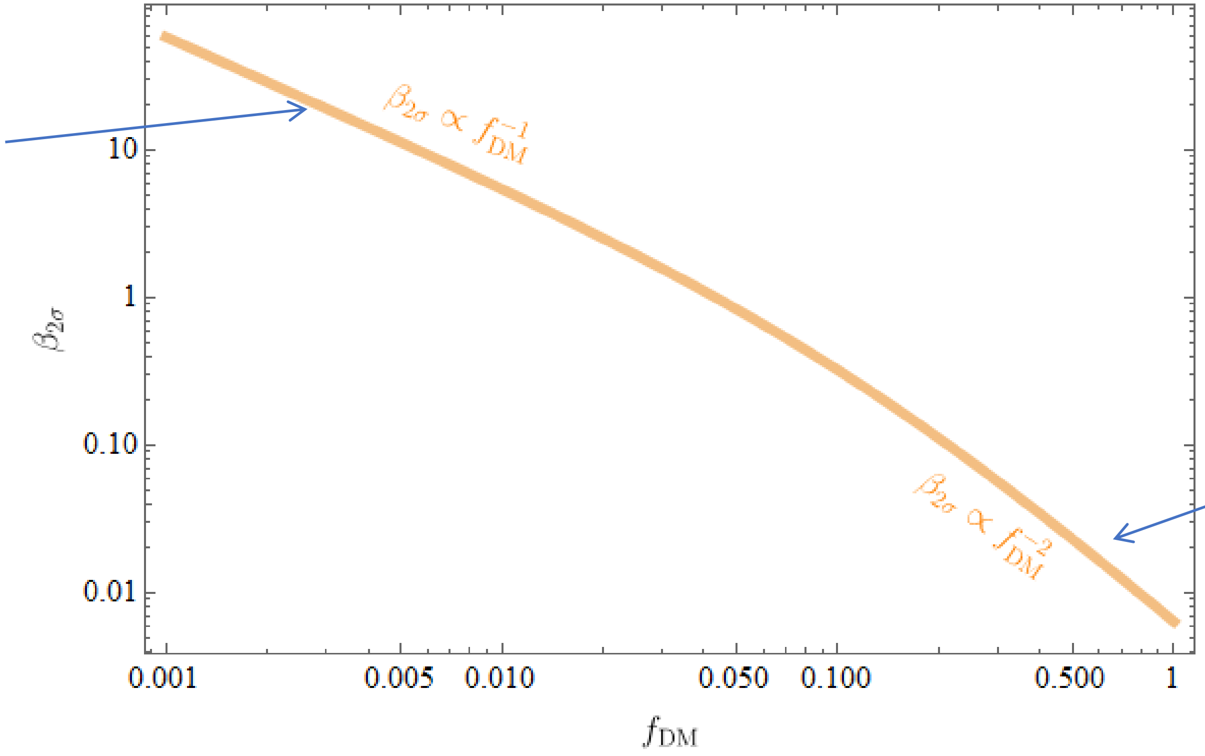
Different scaling with the DM fraction

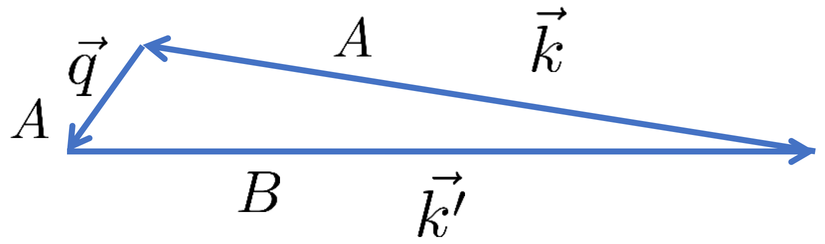
Signal dominated by new spatial features



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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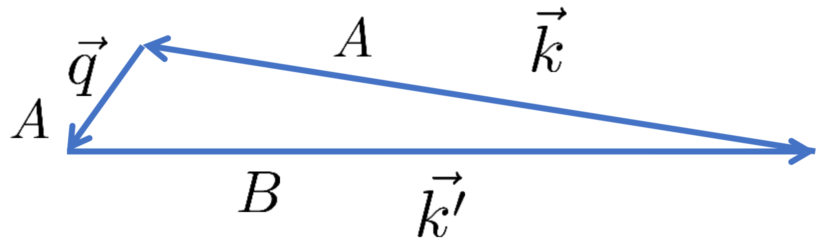

EP violation!

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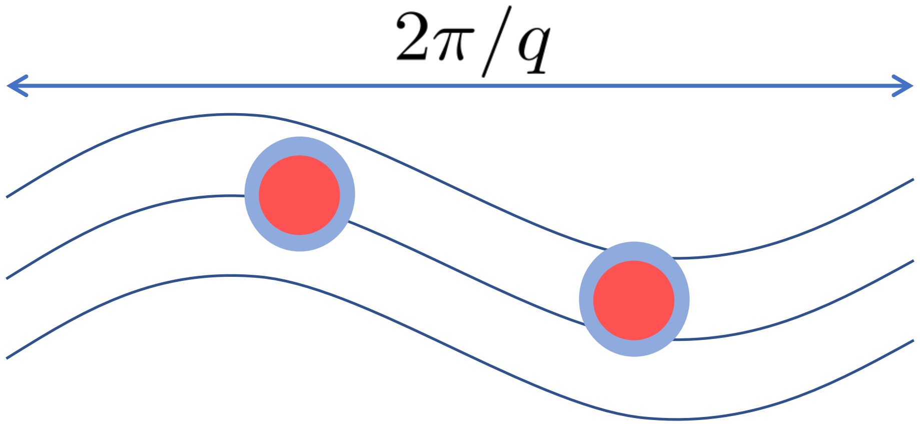
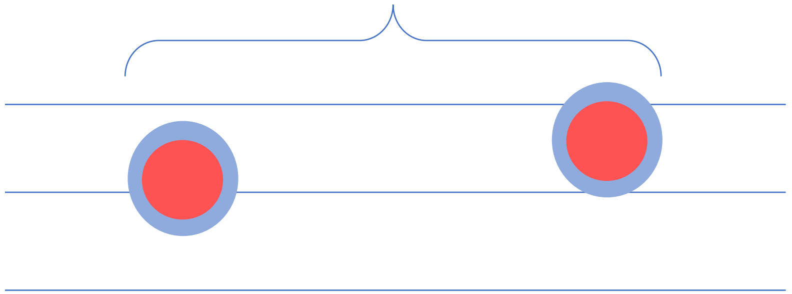


Boost to free-fall system

Still feel a long wavelength potential!



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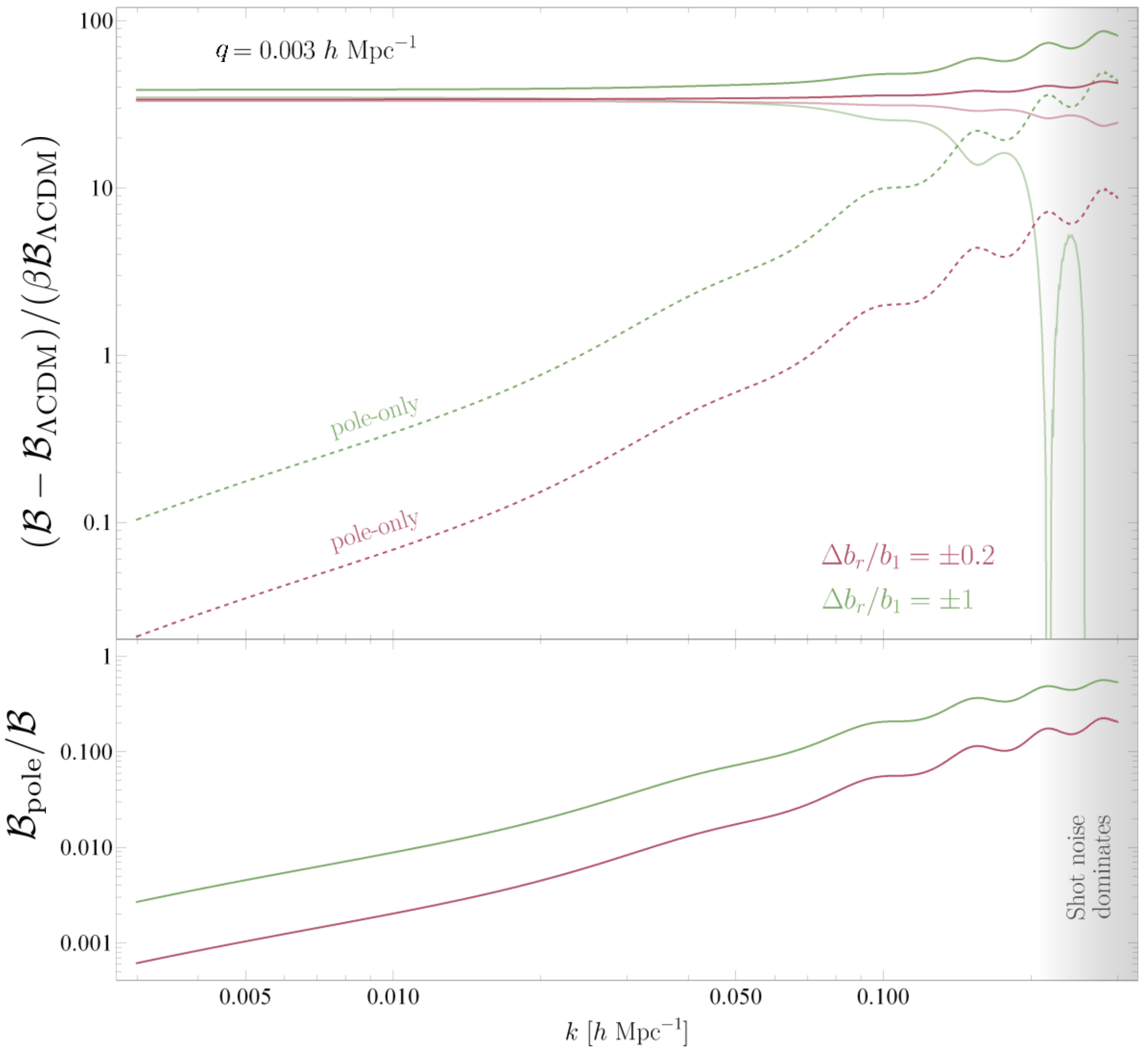

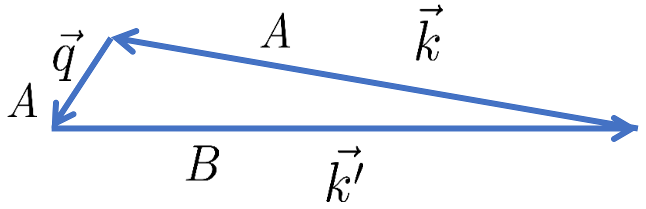

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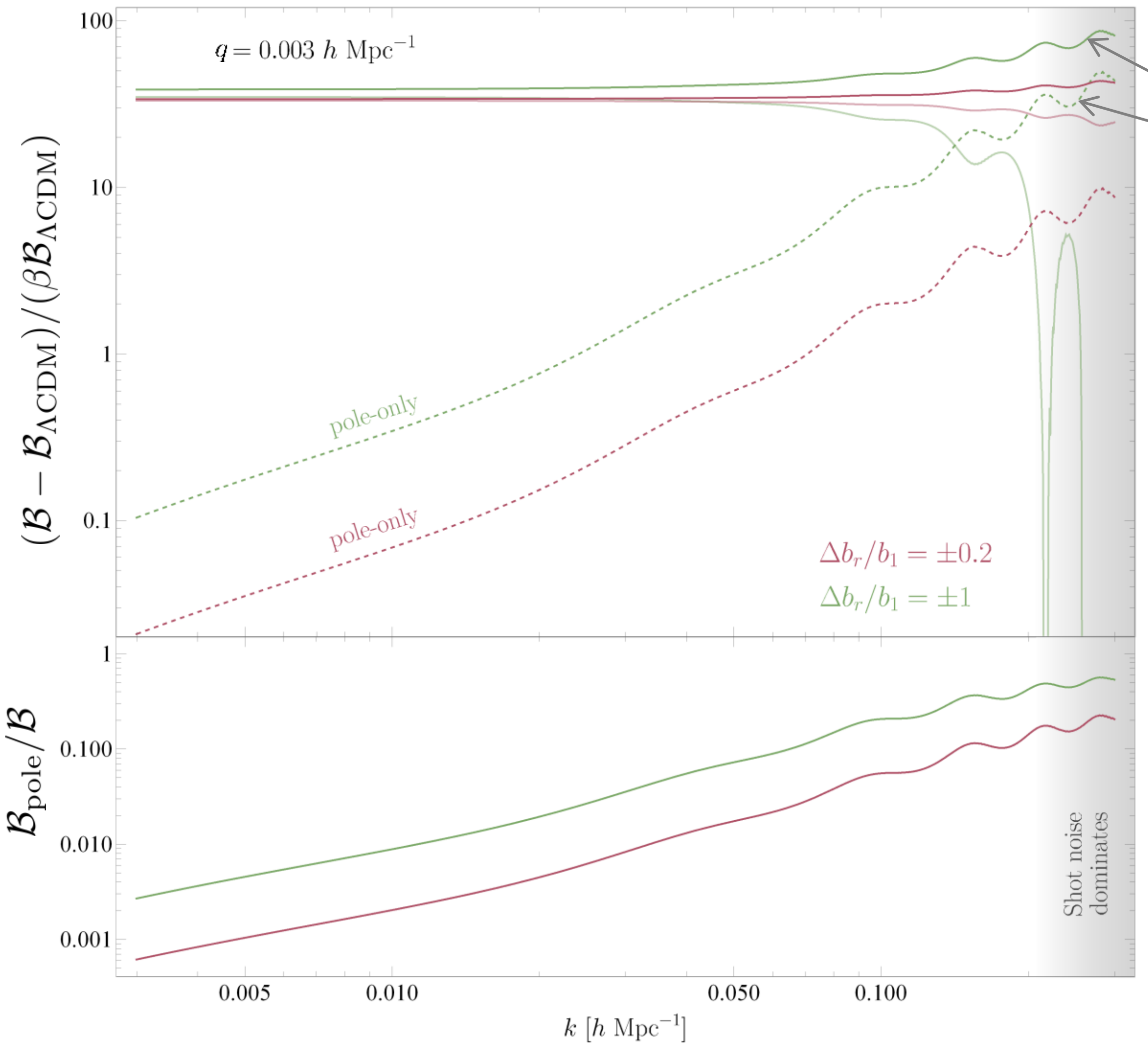

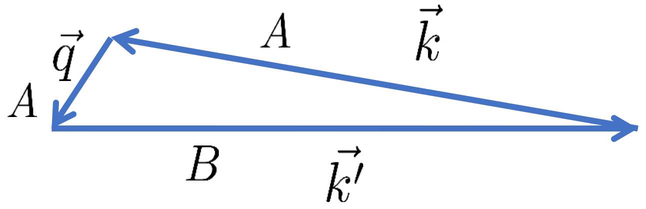

- The log enhanced growth factor ''covers'' the pole

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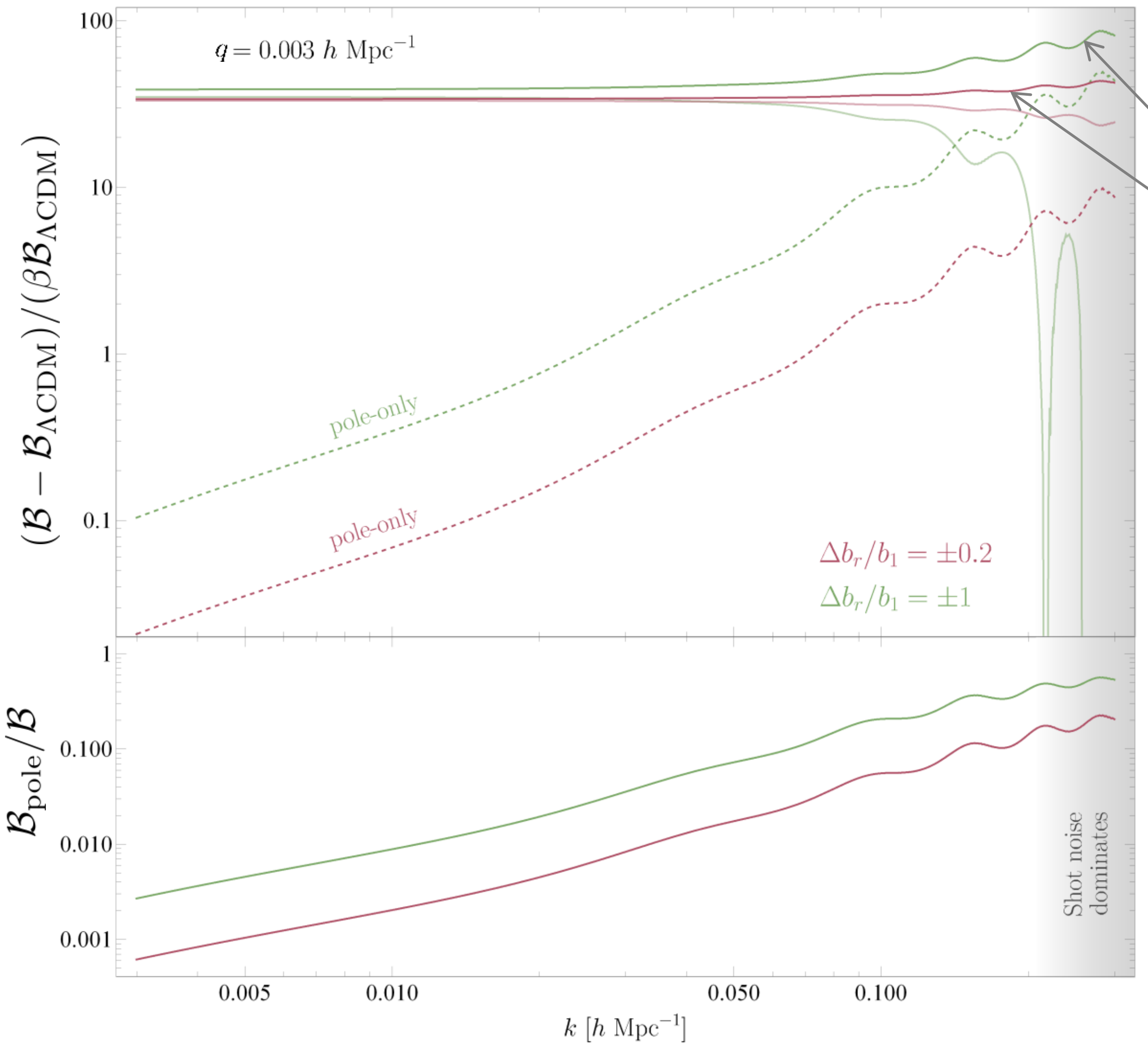

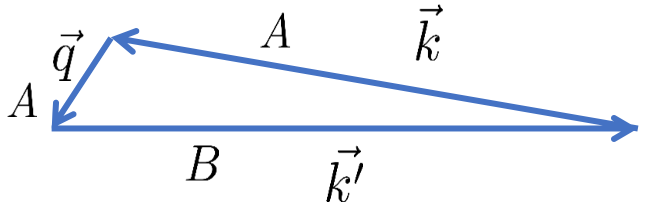

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- The prominence of the pole depends on the difference of relative bias

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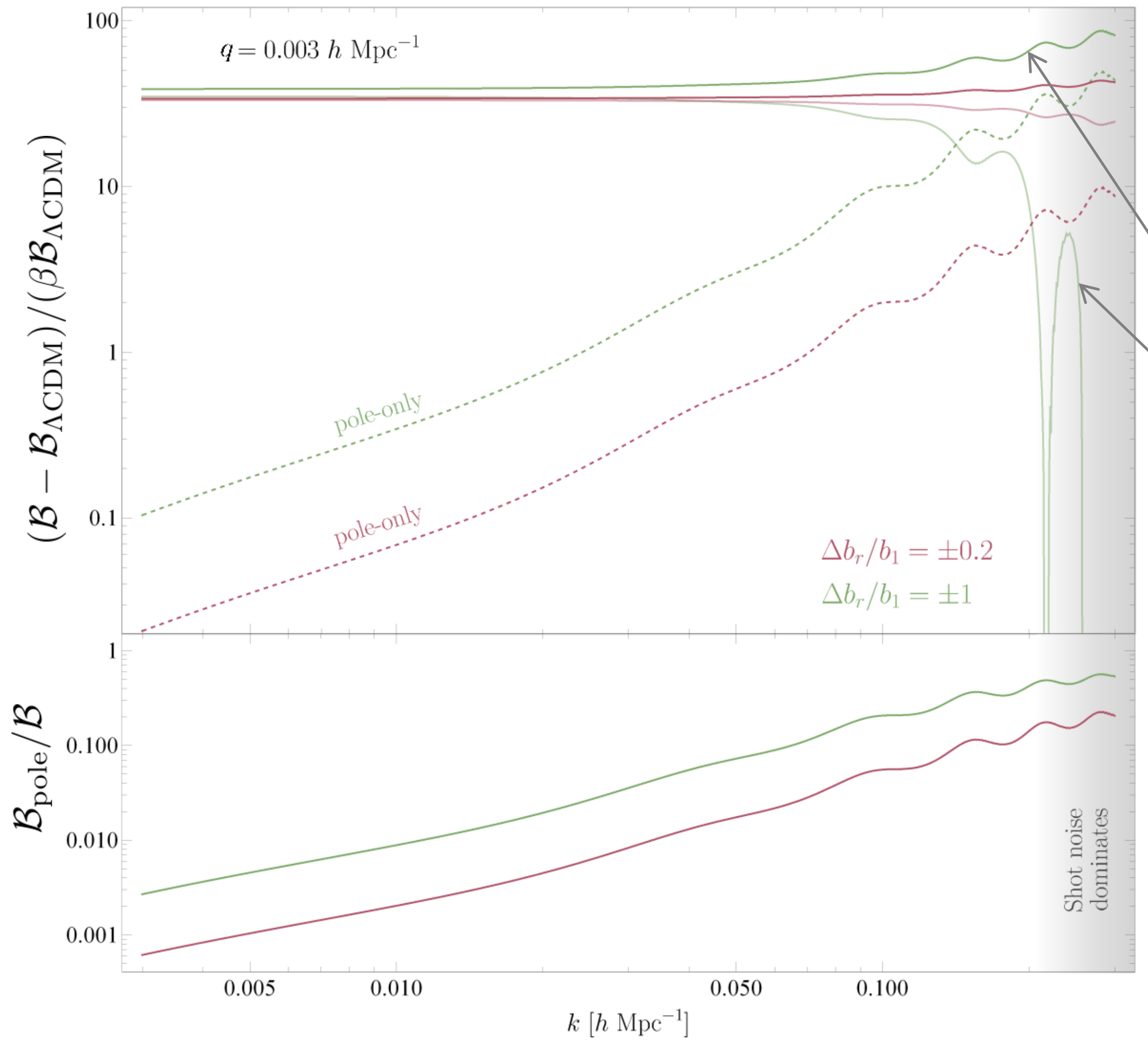

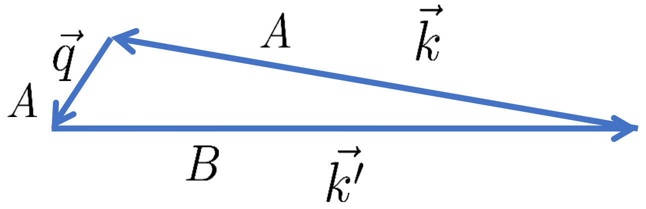

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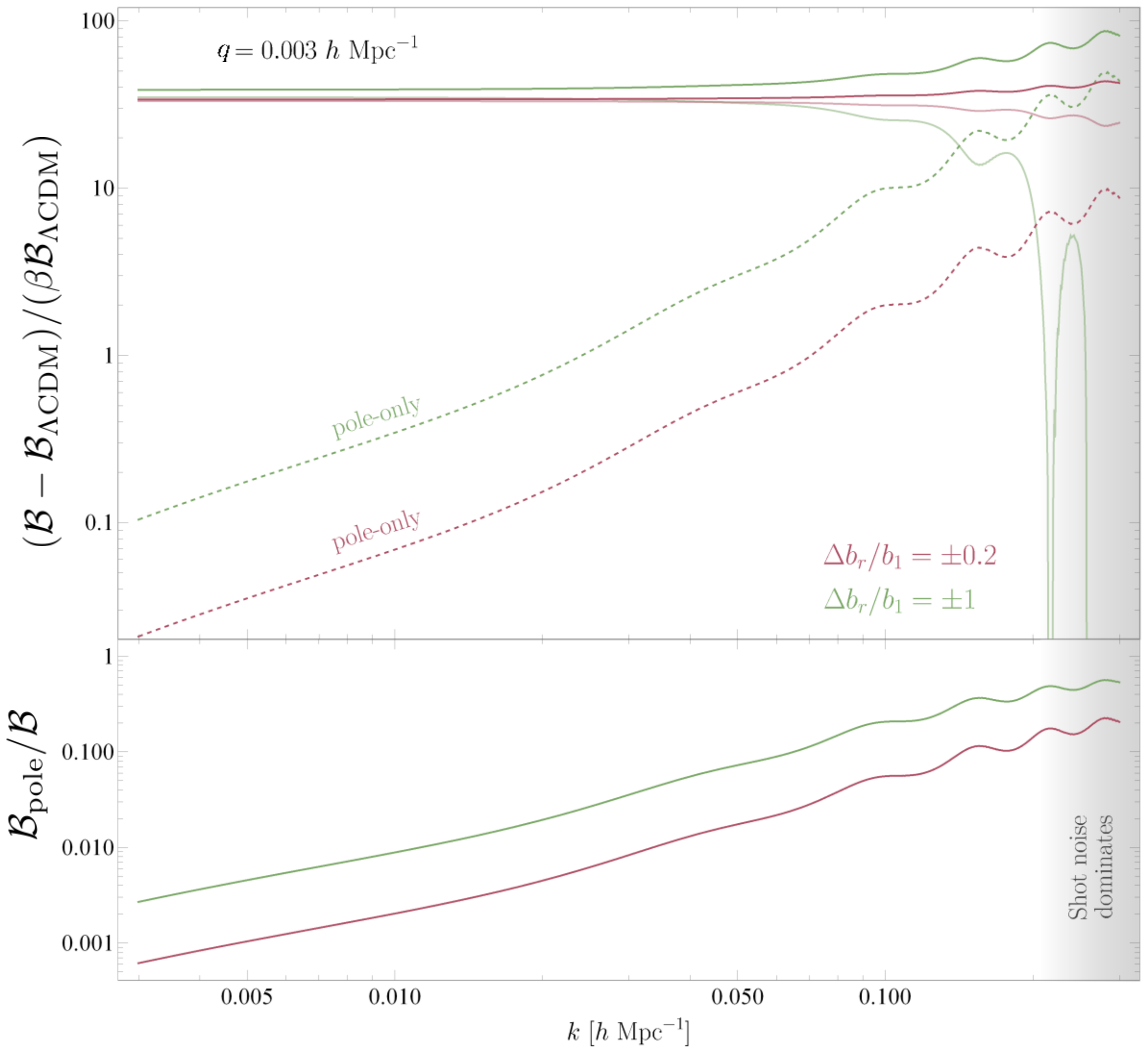

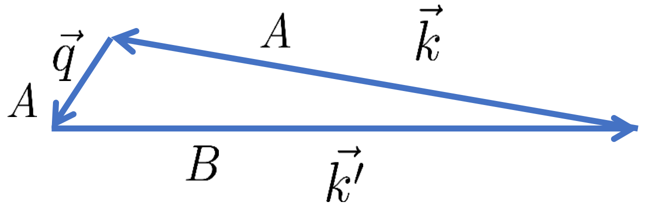

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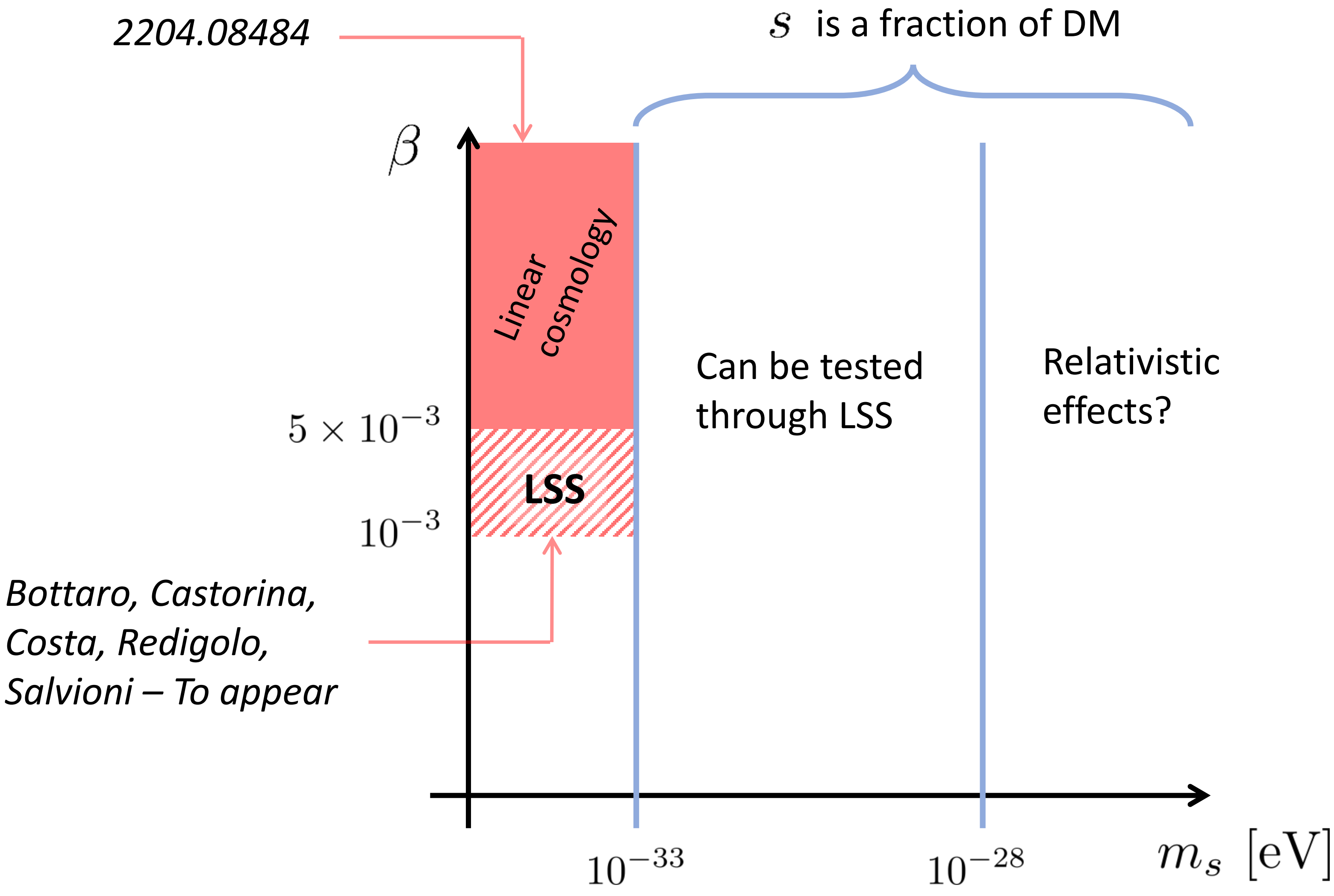
- The prominence of the pole depends on the difference of relative bias
- Depending on the sign of there can be an enhancement or a cancellation in the signal
- Pole observables

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

Conclusions

- Fifth forces in the dark sector modify both the evolution of the background and of the perturbations
- LSS expected to improve bounds from linear theory by a factor 2-5
- Signal dominated by background effects, relative density and velocity effects dominate only for small DM fractions
- Bispectrum limited by systematics, need to improve the theoretical predictions
- Pole observables can make equivalence principle violation manifest in the squeezed limit of the bispectrum

Outlook


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

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

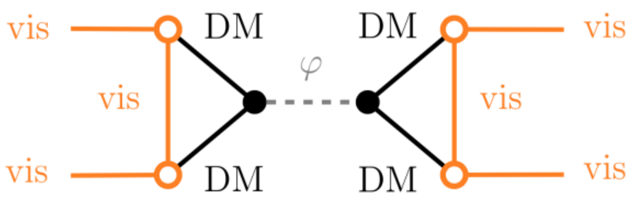
Estimate of the one-loop correction to the scalar mass gives:

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

Relation with other fifth force experiments

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

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



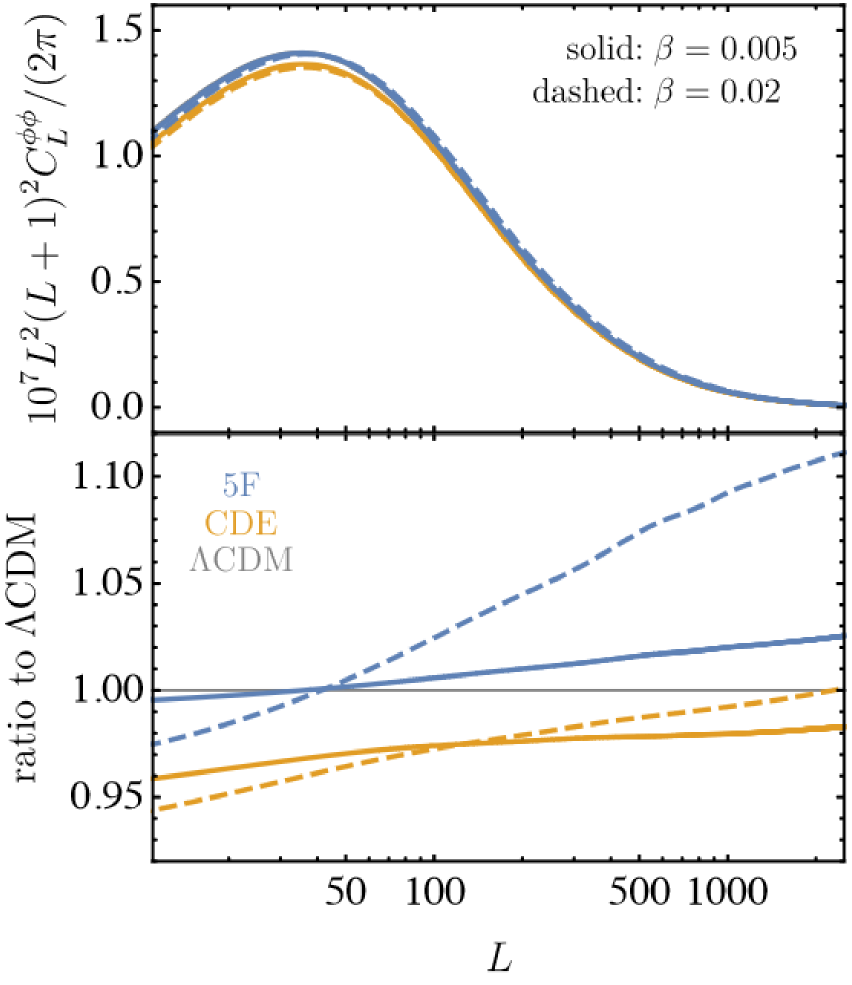
$$\mathcal{L} = \sqrt{4\pi G_N}s\left(\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} + \frac{d_g b_3 \alpha_3}{8\pi}G^a_{\mu\nu}G^{\mu\nu\ a} + \cdots\right)$$

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

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

MICROSCOPE (1712.01176)

CMB lensing



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