Probing dark forces with LSS

Based on work with

M. Archidiacono, E. Castorina, E.Salvioni *arXiv:2204.08484*

S. Bottaro, E. Castorina, M. Costa, E.Salvioni *appeared today!*
arXiv:2309.11496

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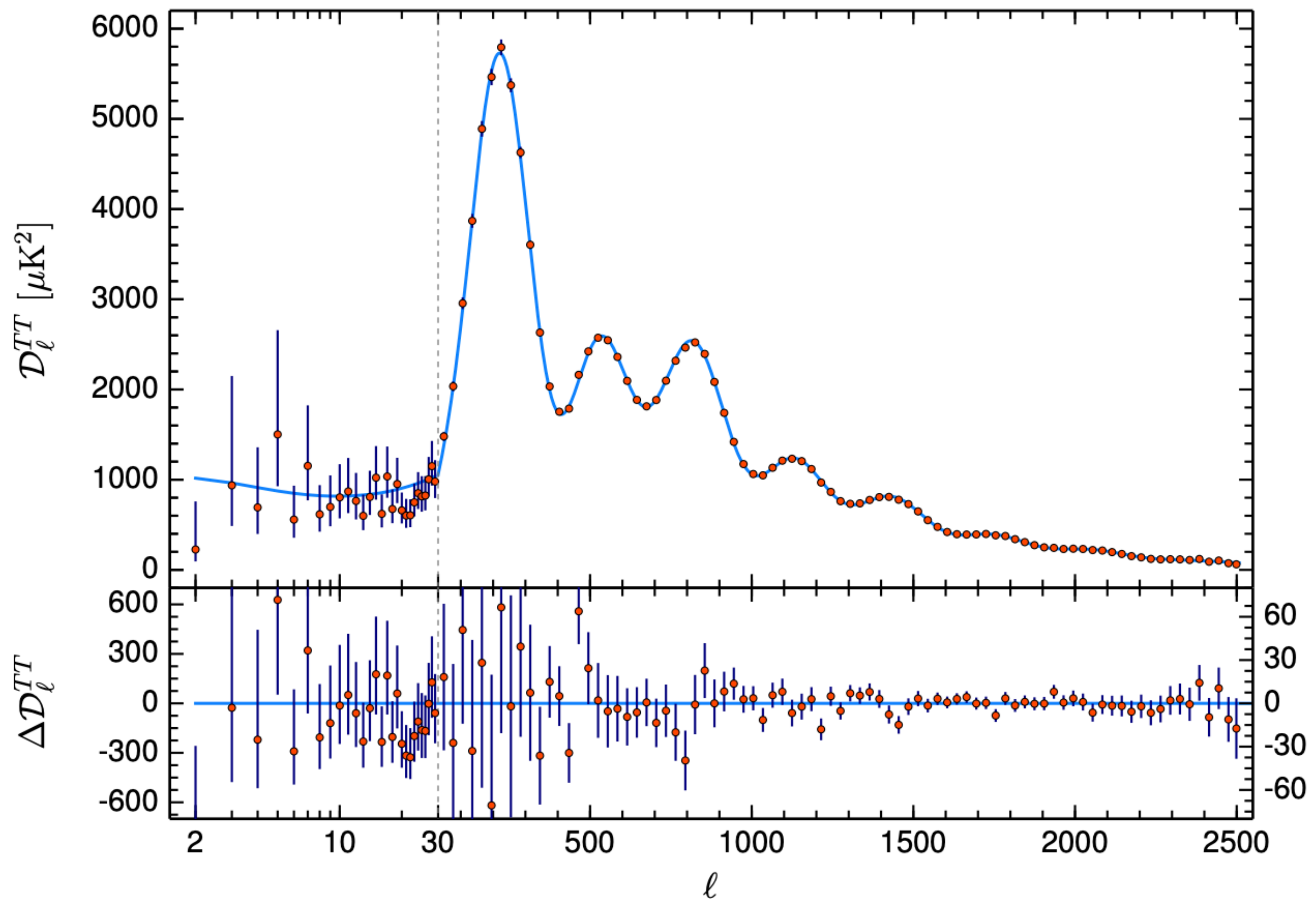
What do we know about the Universe?

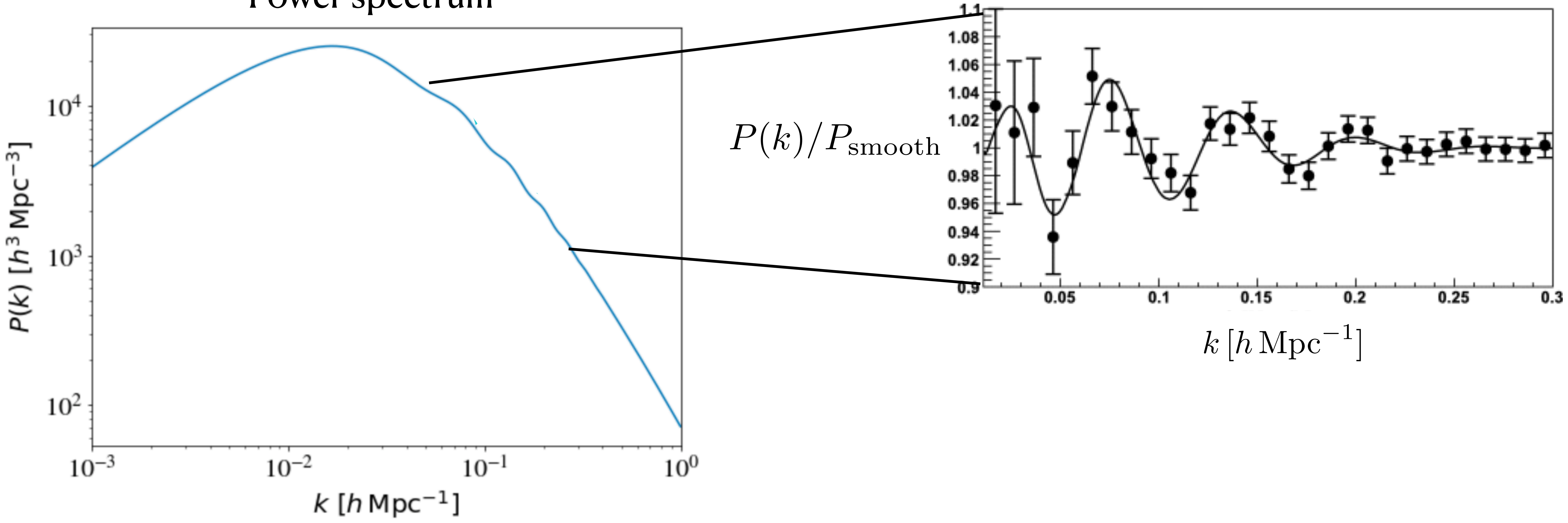
Most of the information comes from precision cosmology

CMB anisotropies



Power spectrum

BAO



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Standard cosmological model

cosmological parameters

primordial parameters

6 independent parameters: $\Omega_b h^2,\ \Omega_c h^2,\ \theta_{\rm MC},\ \tau,\ n_s,\ A_s$

Fixed parameters: $\Omega_k = 0,\ w = -1,\ \sum m_\nu = 0.06,\ N_{\rm eff} = 3.046,\ Y_{\rm He} = 0.2453,\ r = 0,\ \frac{dn_s}{d\log k} = 0$

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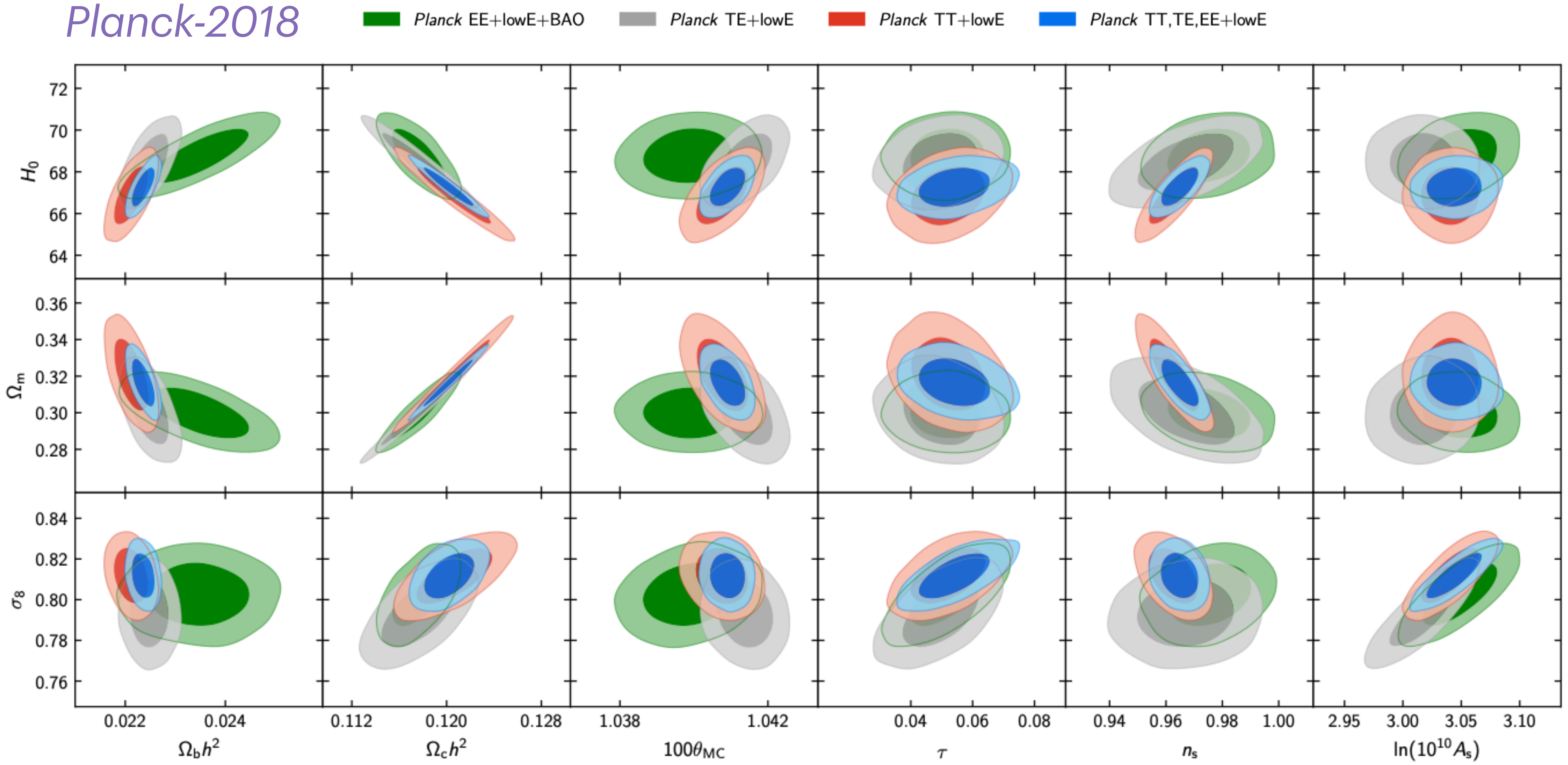
cosmological parameters

primordial parameters

Planck-2018

derived parameters



Input parameters

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42

Parameters measured with sub-percent precision with Planck CMB data

Matter power spectrum info needed to nail Ω_m

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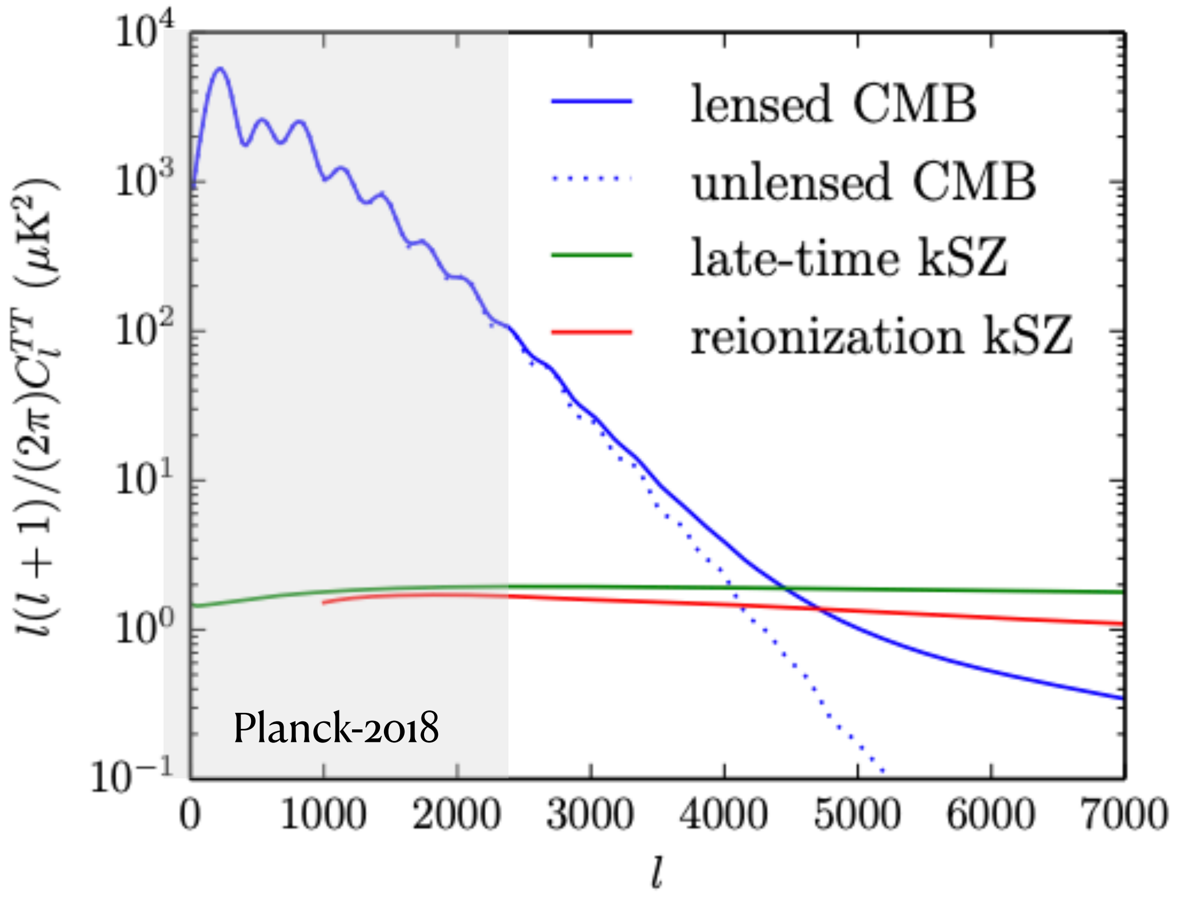
What's for the future?

Ferraro et al. 2016



$$(S/N)^2|_{\rm CMB} \sim N_{\rm modes}|_{\rm CMB} \sim \ell_{\rm max}^2$$

Increasing $\ell_{\rm max}$ CMB 2D map is limited by small scale fluctuations affecting the map

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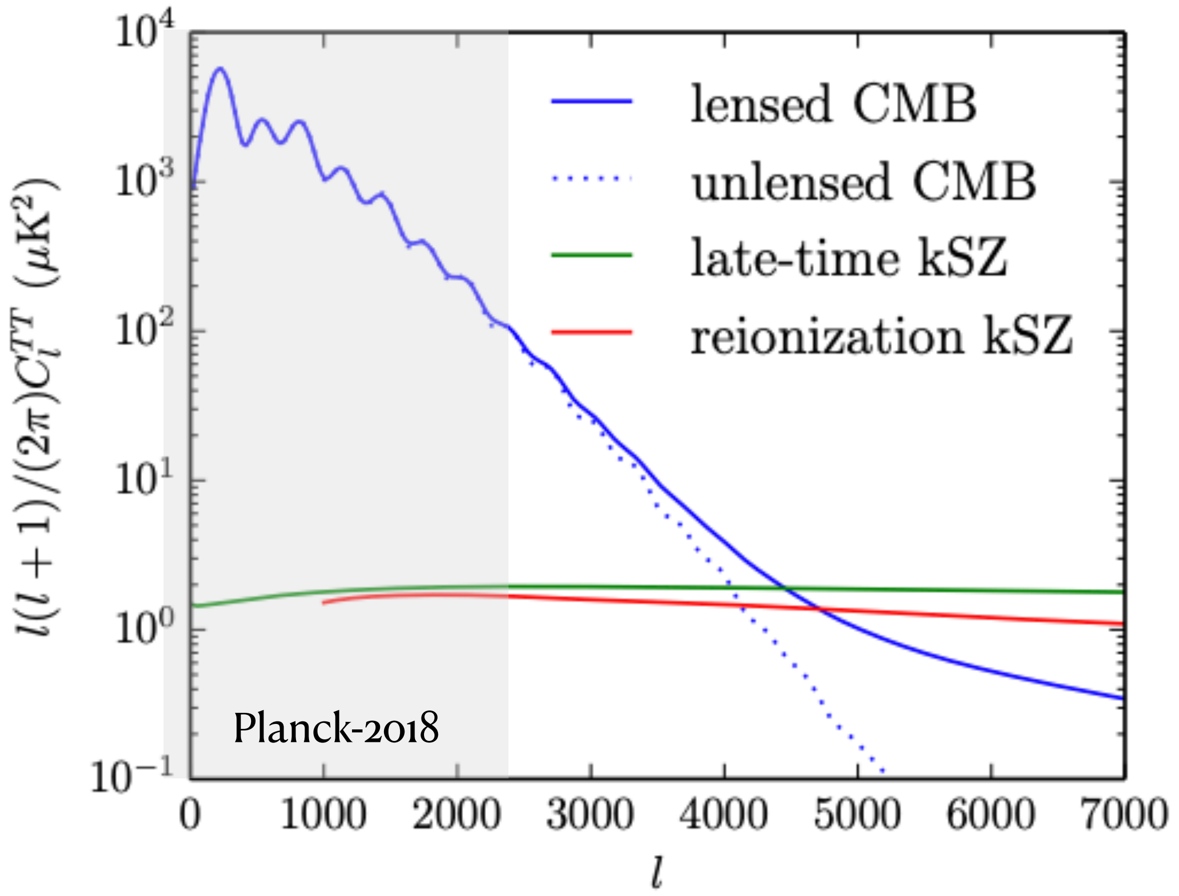

$$(S/N)^2|_{\rm CMB} \sim N_{\rm modes}|_{\rm CMB} \sim \ell^2_{\rm max}$$

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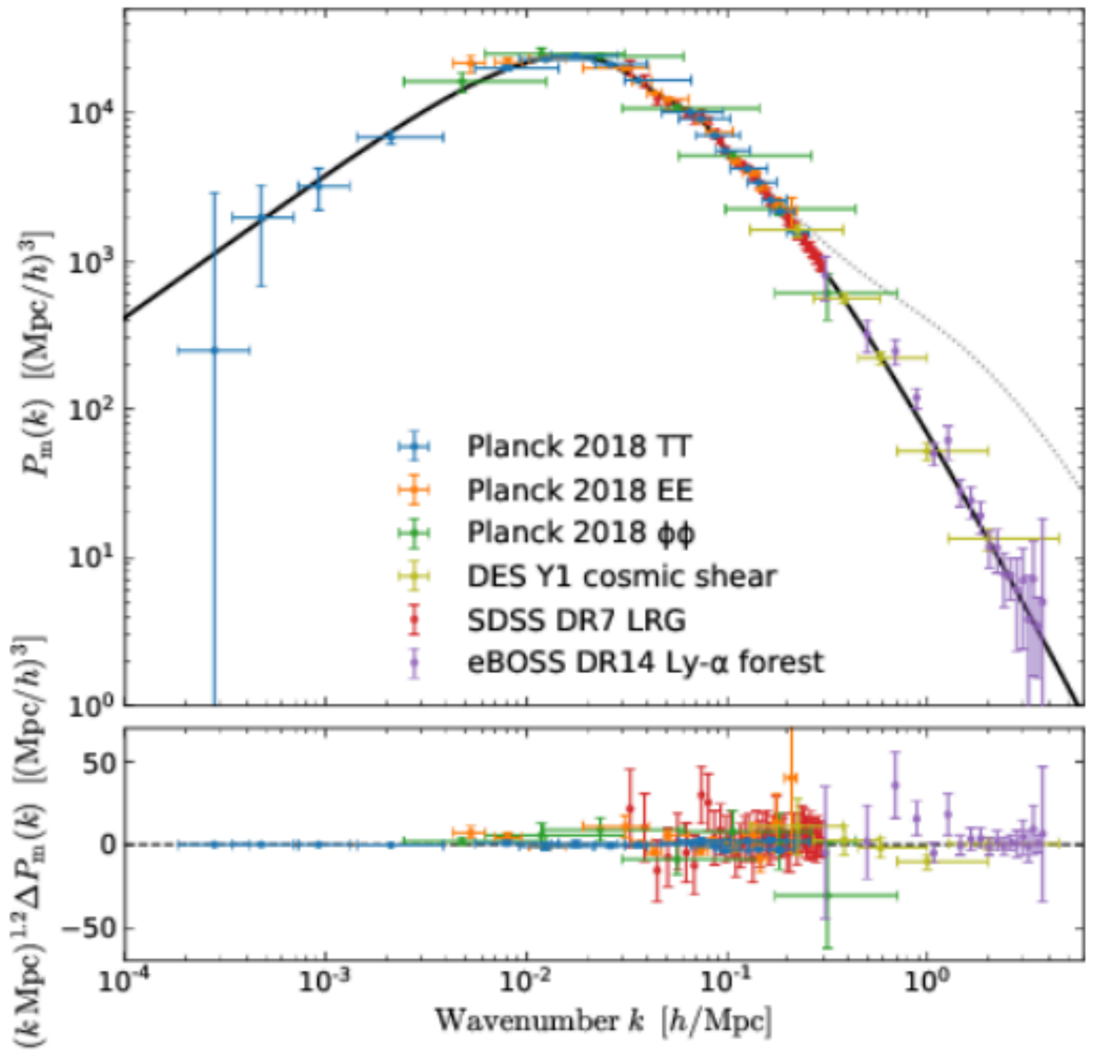
Chabanier et al. 2016



$$(S/N)^2|_{\rm LSS} \sim N_{\rm modes}|_{\rm LSS} \sim k^3_{\rm max}\text{Volume} \qquad \bar{n}_{\rm noise}P(k) \gg 1$$

Increasing $k_{\rm max}$ depends on our ability of making predictions on mildly non-linear scales

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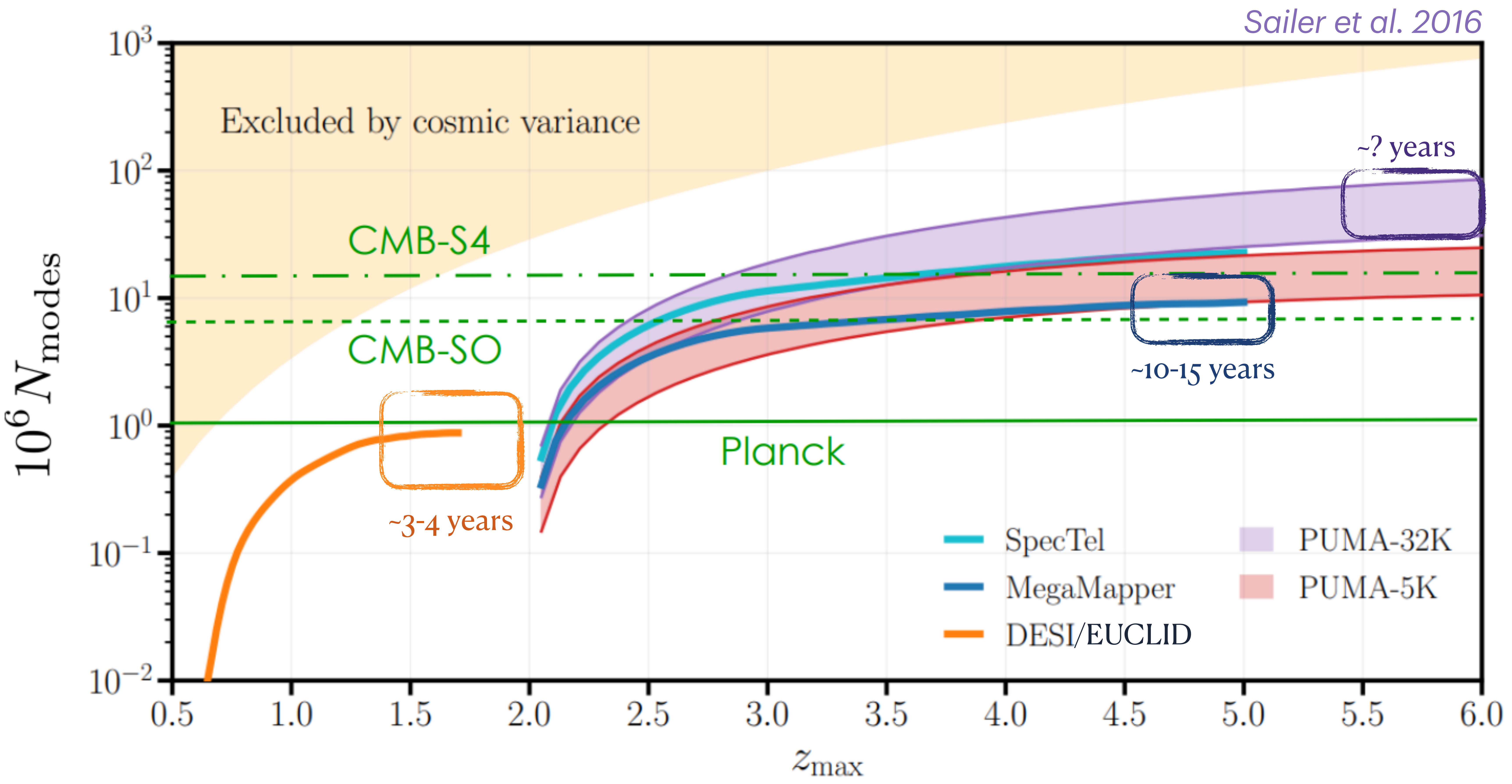
Figure of merit

Galaxy Clustering data will soon reach Planck sensitivities



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The EFT of LSS-I

We want to make predictions about the galaxy distribution in the Universe

This can be encoded in correlators of the galaxy fluctuations: $\langle \delta_g(p)\delta_g(k)\rangle = (2\pi)^3\delta^{(3)}(p+k)P_g(k)$

$$\delta_g \equiv n_g/\bar{n}_g - 1$$

$$\langle \delta_g(p)\delta_g(k)\delta_g(q)\rangle = (2\pi)^3\delta^{(3)}(p+k+q)B_g(p,k,q)$$

...

Looking at scales: $kR_{\text{halo}} << 1$ we can map the galaxy fluctuations to matter fluctuations order by order

$$\delta_g = b_1\delta_m + \frac{b_2}{2}\delta_m^2 + b_K K_{ij}K^{ij} + \dots$$

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$$\delta_g = b_1\delta_m + \frac{b_2}{2}\delta_m^2 + b_K K_{ij}K^{ij} + \ldots$$

Assumption: no sources of relative density or velocities!
(See later)

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The EFT of LSS-II

Now we need a model for the matter fluctuations: $\delta_m \ll 1$ as long as $k/k_{\rm NL} < 1$

Carrasco et al 2012, Baumann et al 2012

$$\delta'_m + \theta_m = -\nabla_i(\delta_m v^i_m)$$

$$\theta'_m + \mathcal{H}\theta_m + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_m = -\nabla_i(v^j_m \nabla_j v^i_m) - \frac{k^2}{\rho_\Lambda}\tau_{\rm eff}$$

Matter domination + sub-horizon the time dependence factorizes:

$$\delta_m(k,\tau) = D(\tau)\delta^{(1)}_m(k) + D^2(\tau)\delta^{(2)}_m(k) + \dots$$

In $\Lambda\mathrm{CDM}: D(\tau) = \frac{\Omega_m}{4} H_0^2 \tau^2$

Order by order we can solve: *Bernardeu et al 2002 and many others*

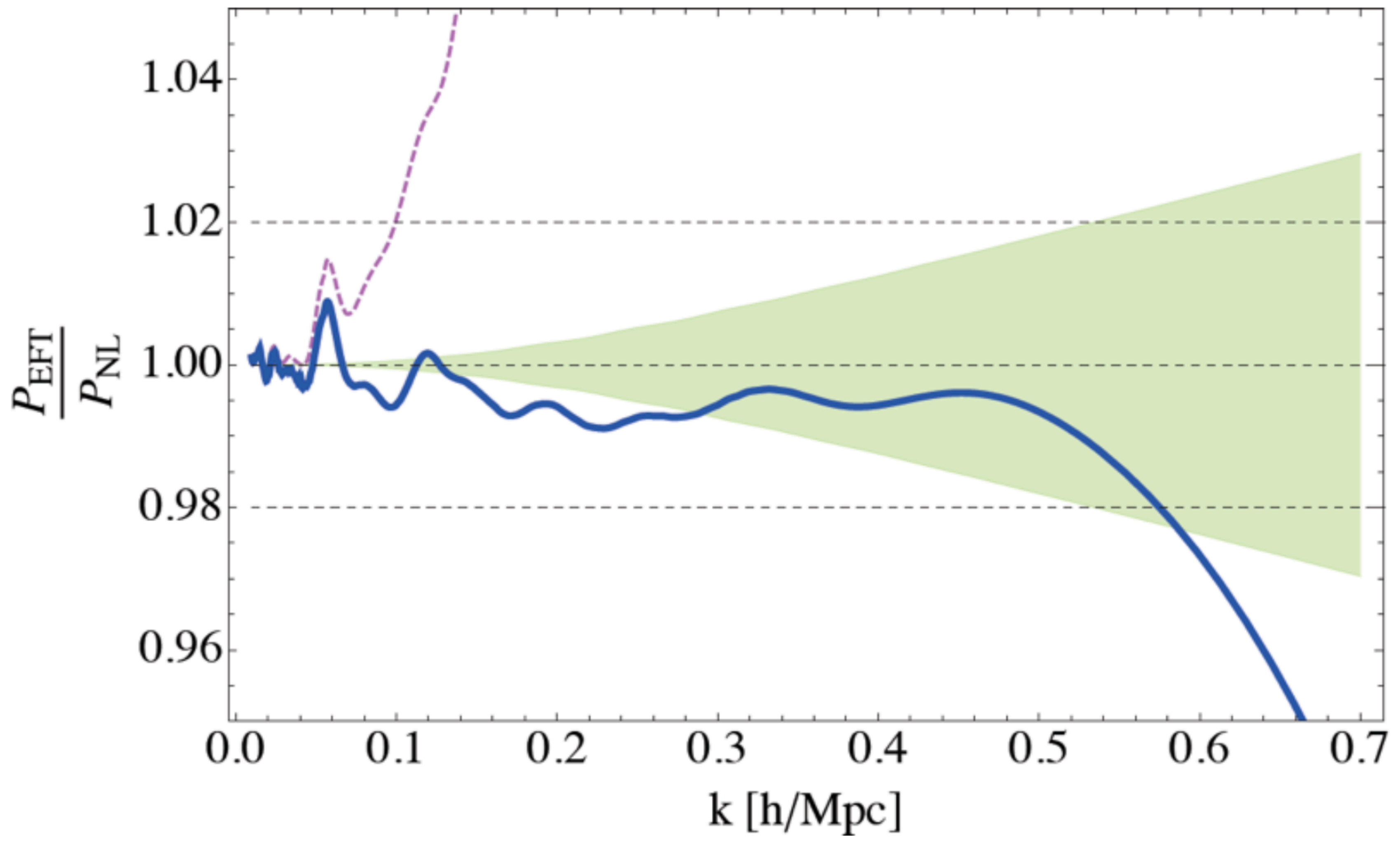
$$\delta^{(2)}_m(k) = \int \frac{{}^3q}{(2\pi)^3} F_2(q, k-q)\delta^{(1)}_m(q)\delta^{(1)}_m(k-q)$$

These kernels controls the corrections to the cosmological correlators

Plus counter-terms encoding the contribution from UV physics $\tau_{\rm eff} \simeq -3c_s^2 \rho_\lambda$

The EFT of LSS-III

Modelling of the power spectrum up to $k_{\rm NL} \simeq 0.2\ {\rm h/Mpc}$



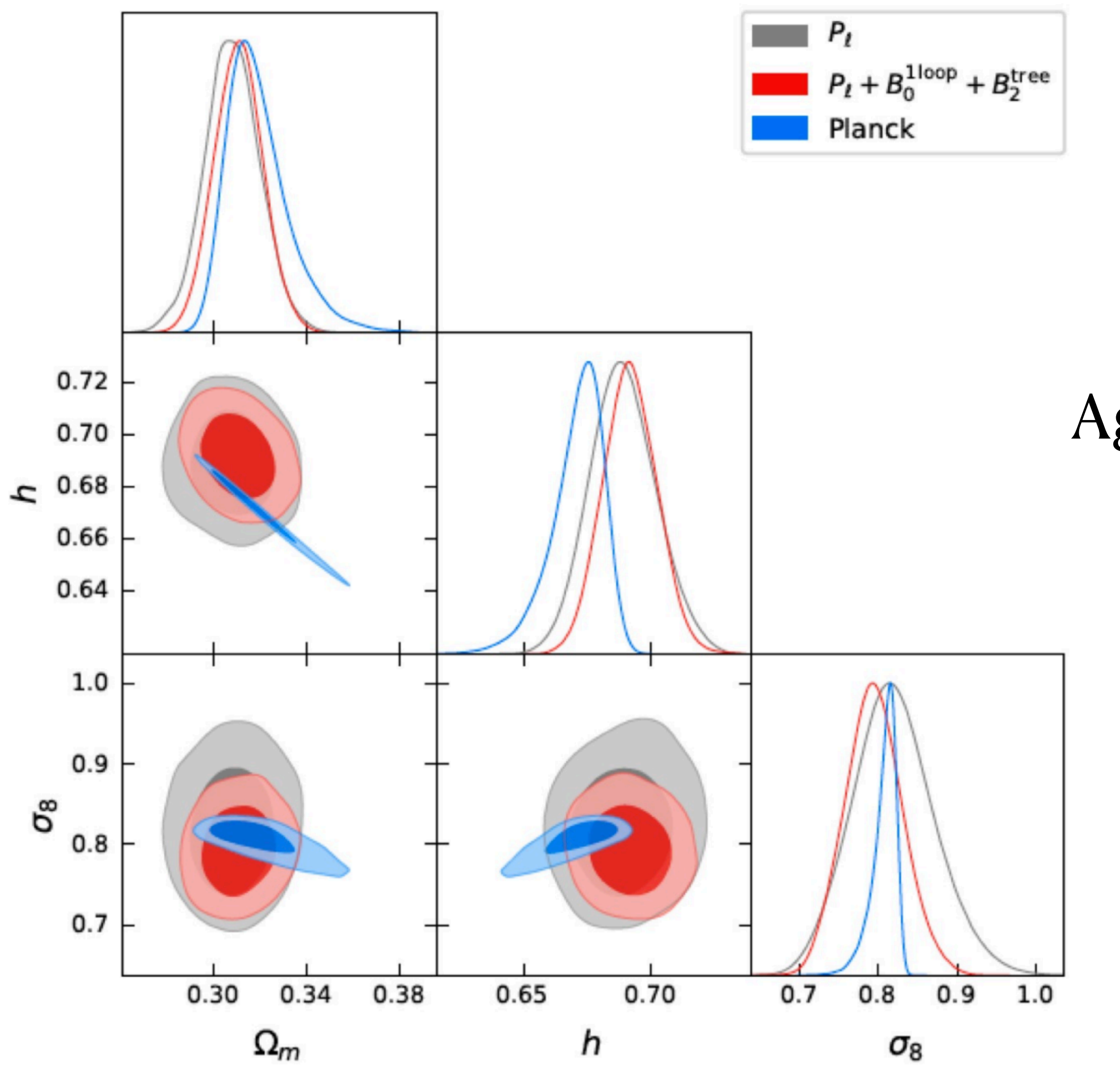
+Bispectrum up to $k_{\rm NL} \simeq 0.15\ {\rm h/Mpc}$ @ 1-loop

$k_{\rm NL} \simeq 0.08$ @ tree-level

Great amount of information extracted from BOSS data

D'Amico, Lewandowski, Senatore, Zhang + other

Ivanov, Philcox, Simonovic, Zaldarriaga+ others



Agreement with Planck for H_0

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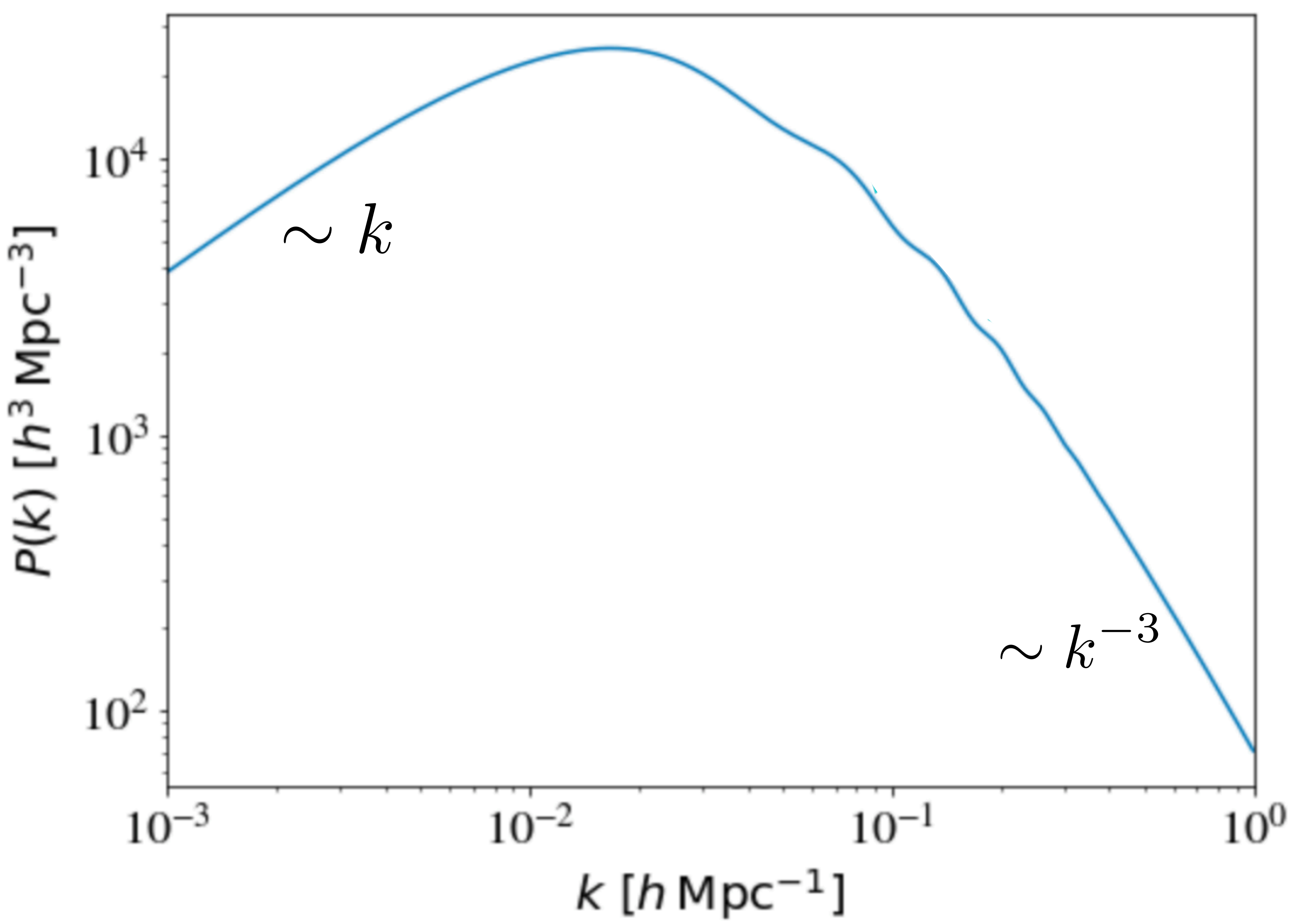
What can we test/discover beyond the standard cosmological model with LSS?

The matter power spectrum



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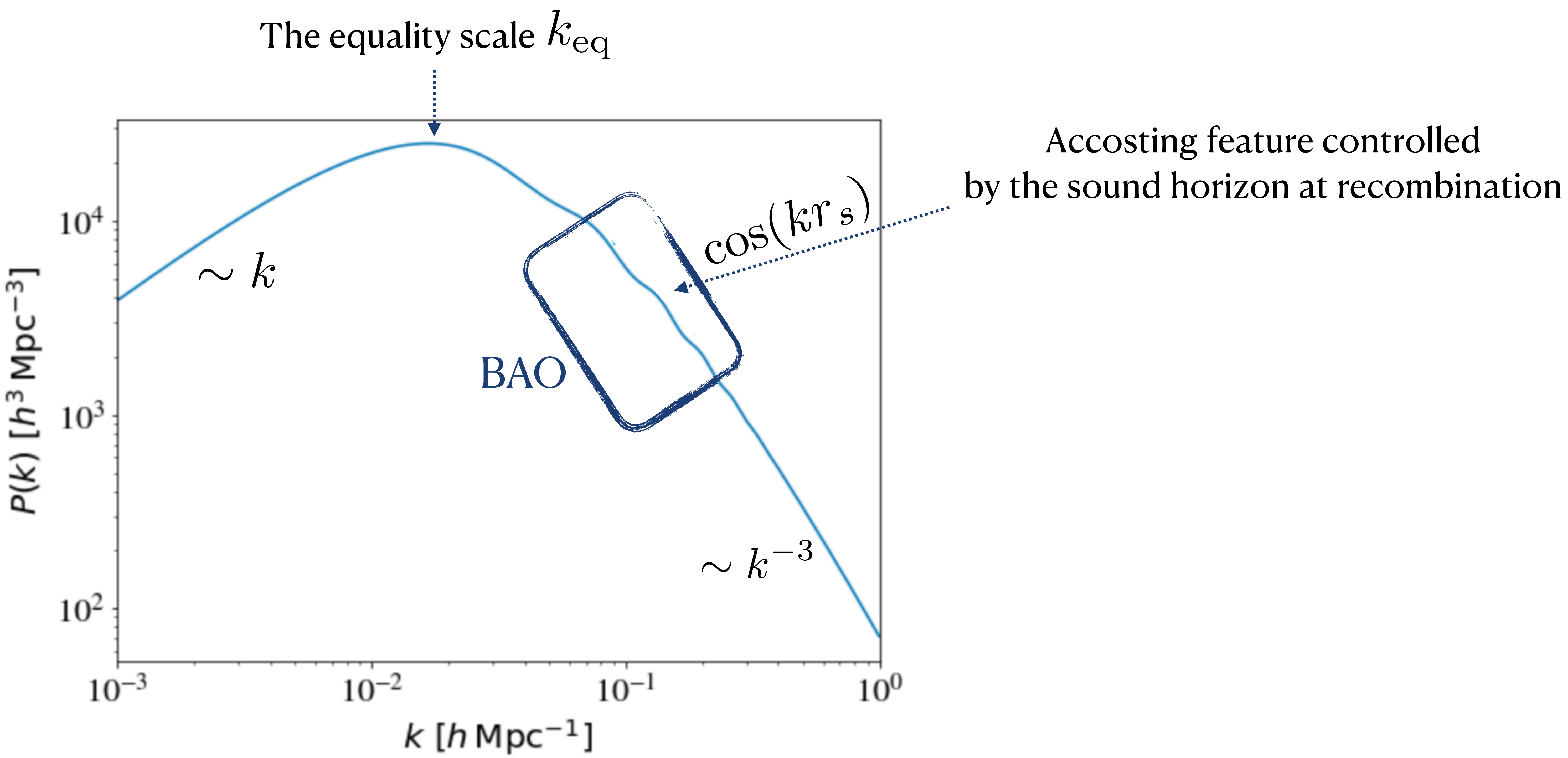

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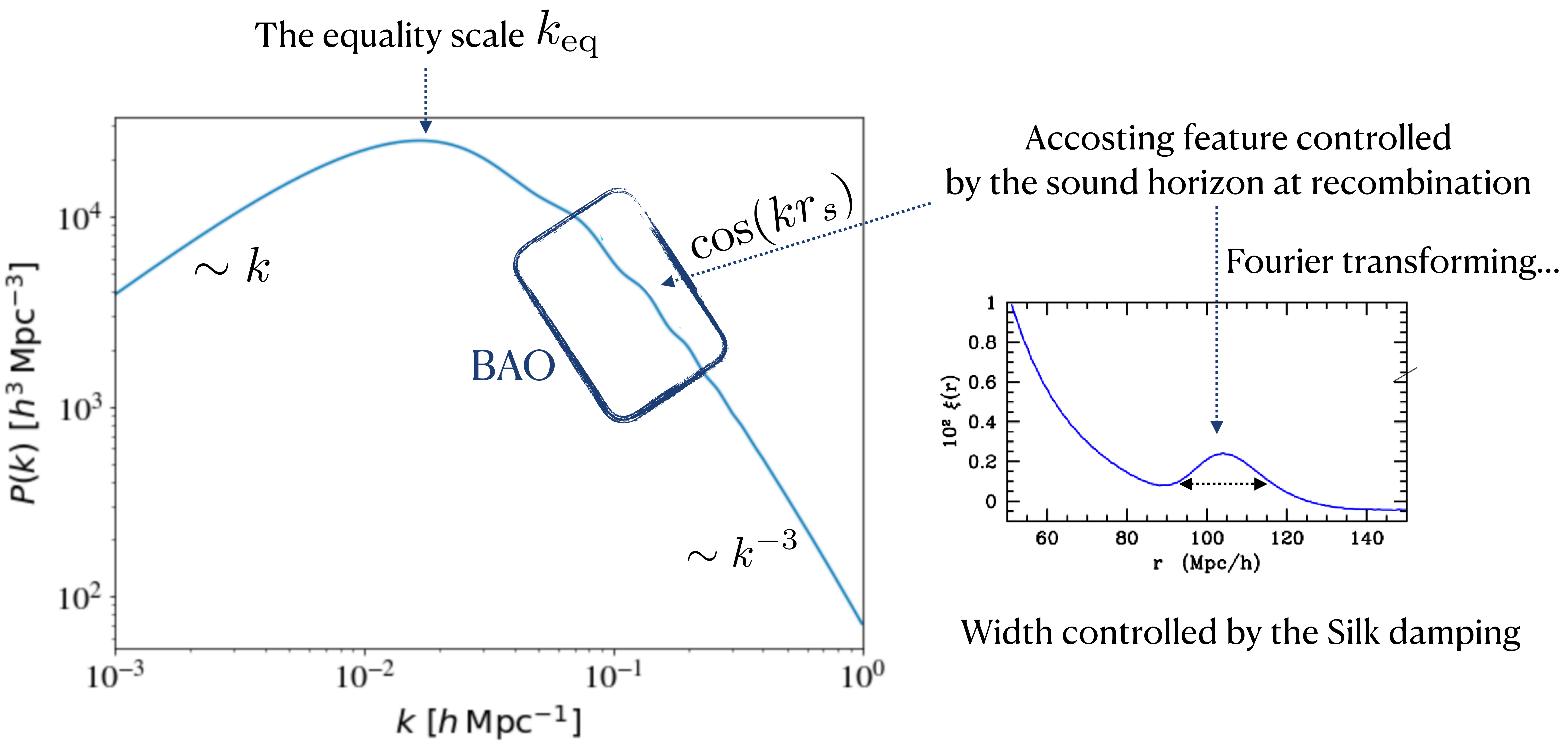
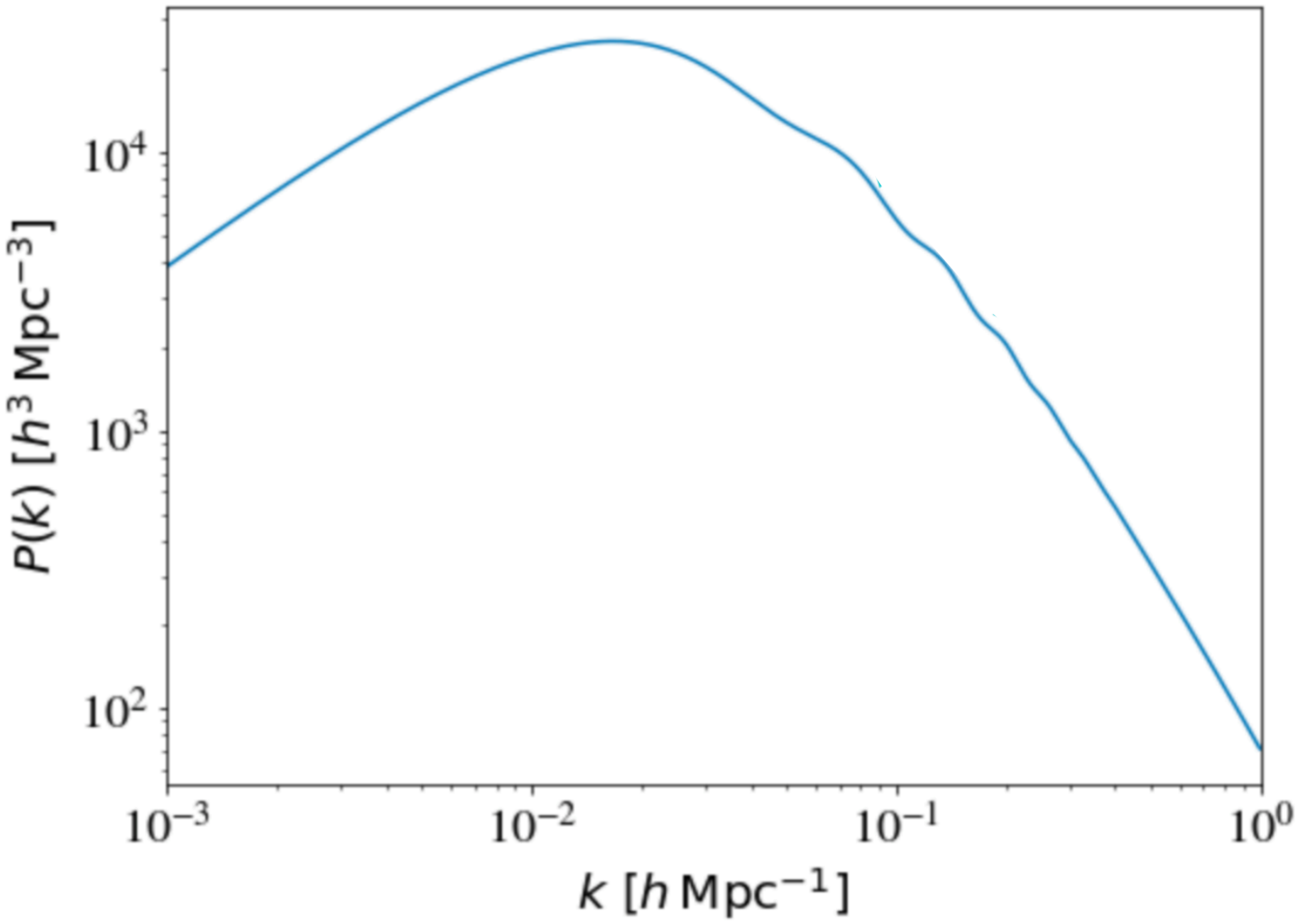


New features?



New physics in the tail

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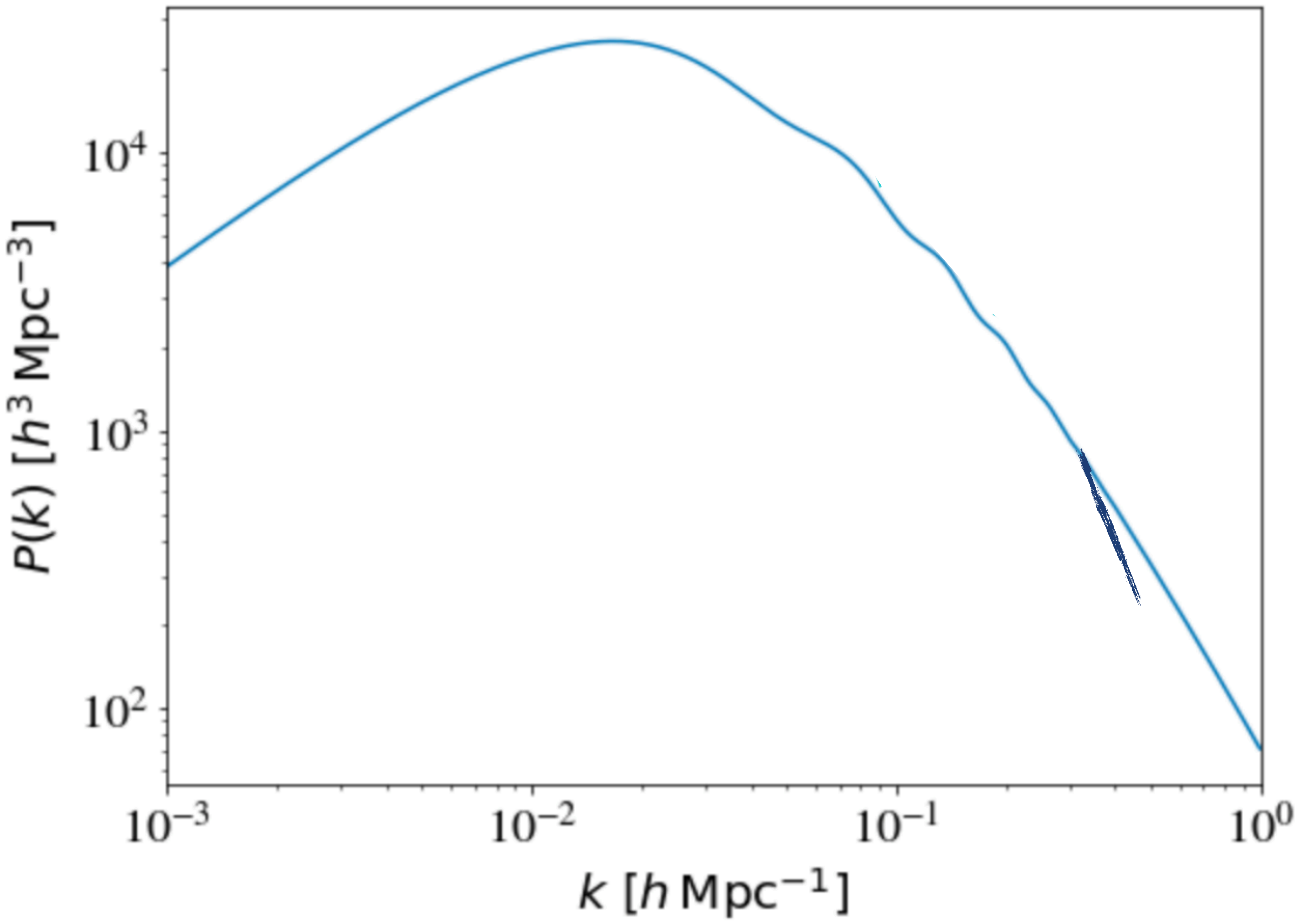

New physics in the tail

Drop: new relativistic species, … *Xu et al 2021*

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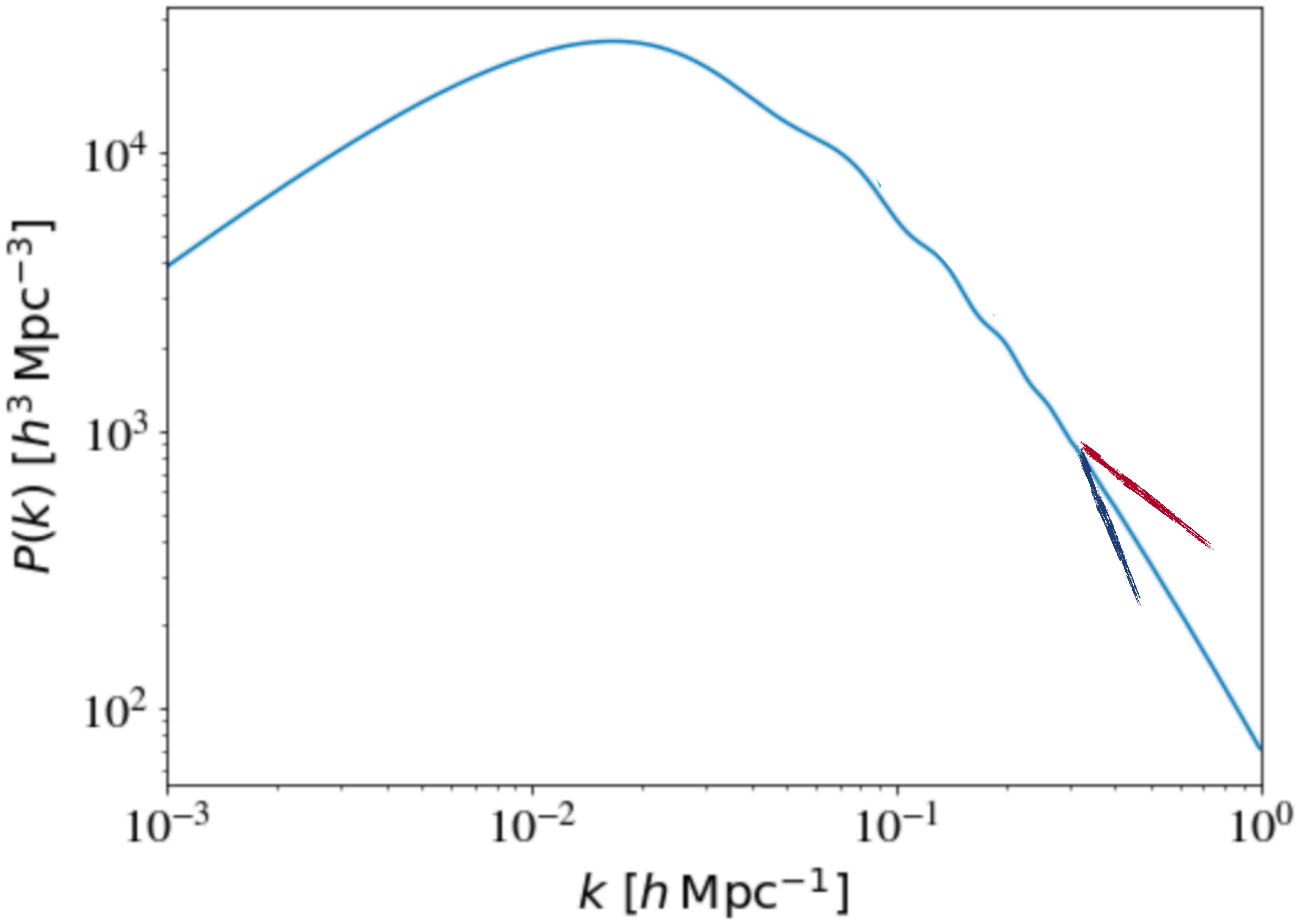

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Raise: Isocurvatures, etc…

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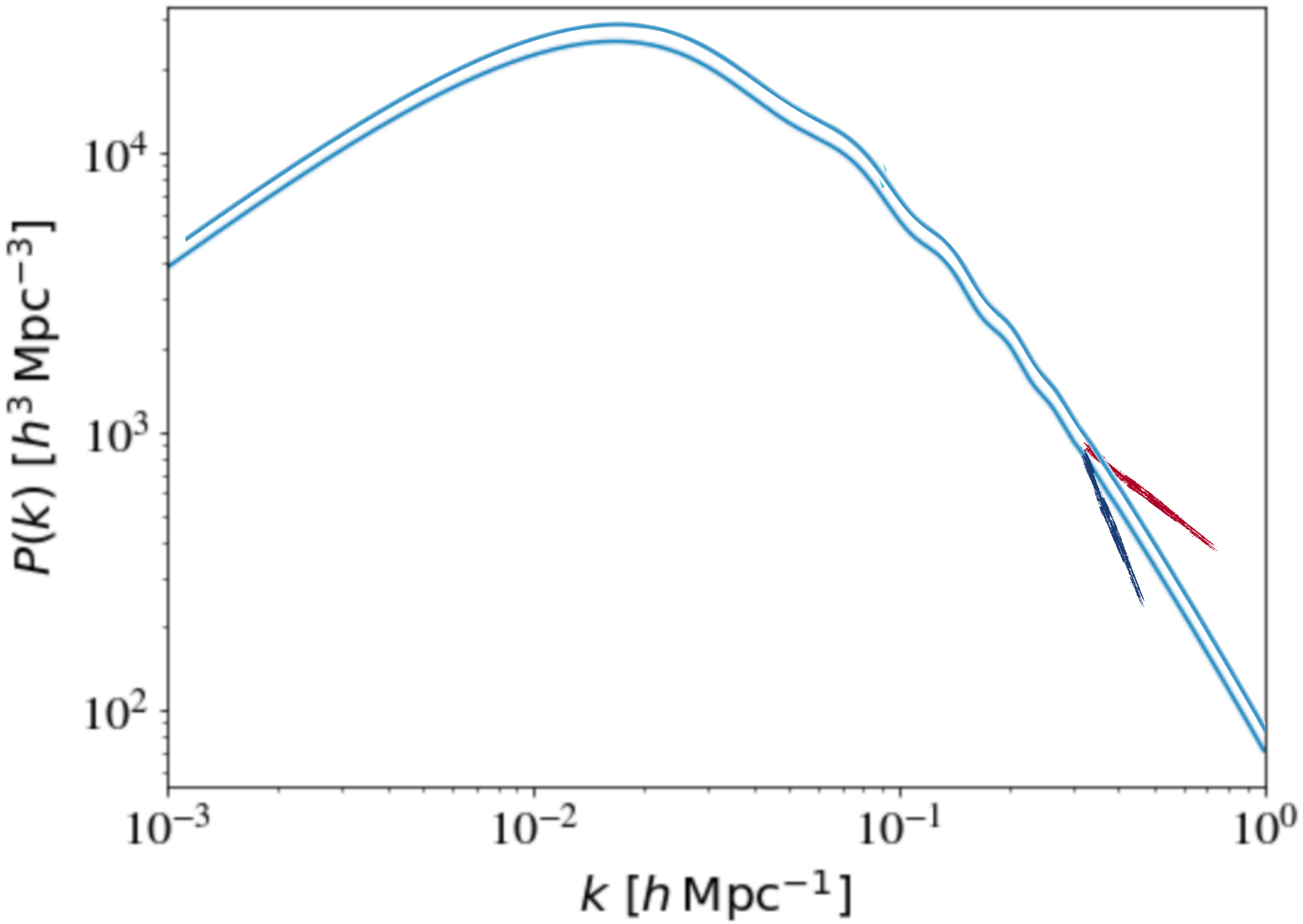

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Today

Increase of power at all scales!

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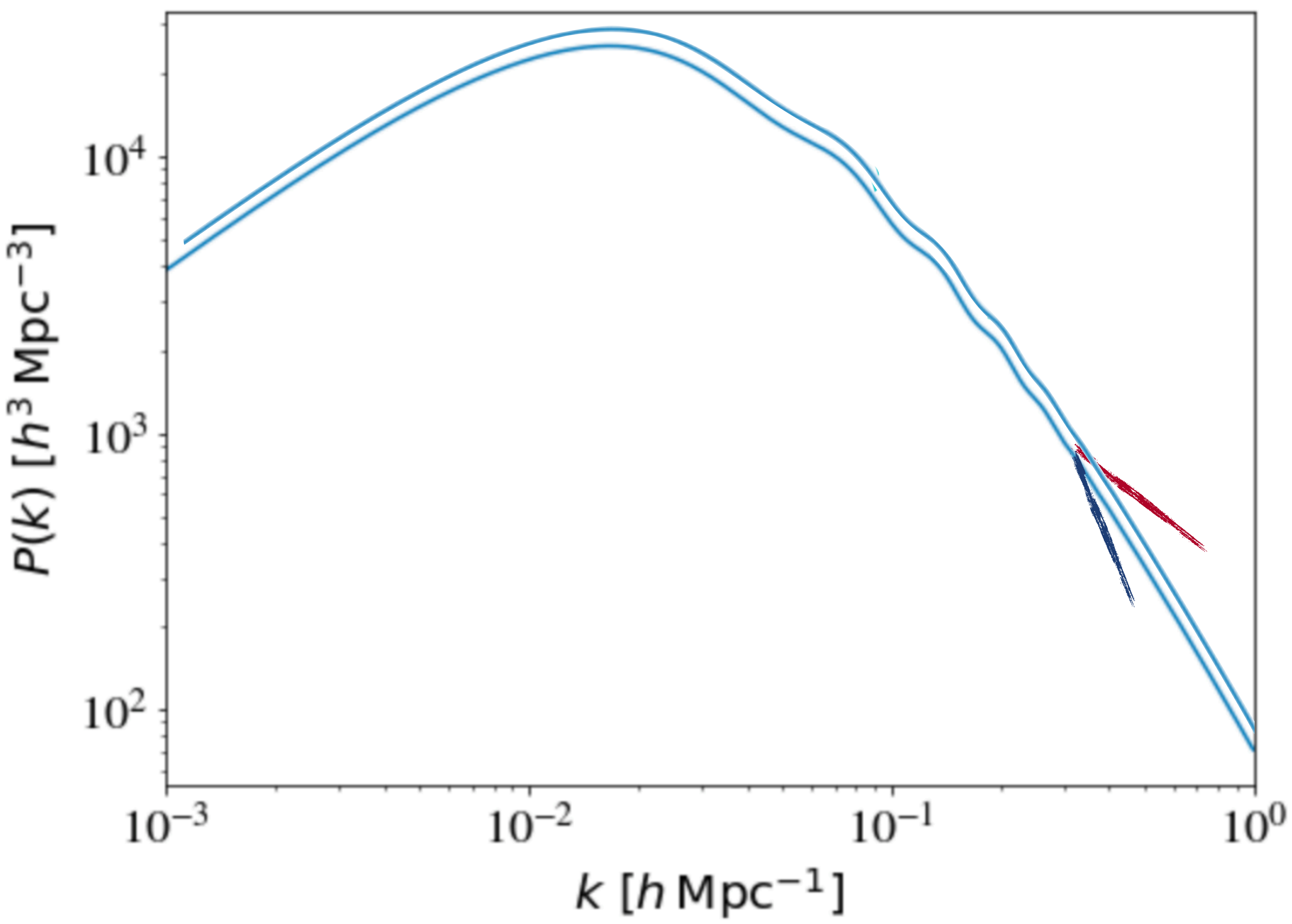

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Today

Increase of power at all scales!

Important comment full of optimism

The EFT of LSS gives a calculable model,
modifying it *consistently* in the presence of new physics
gives to cosmology the possibility to *discover* new physics in precision data

The Dark Sector

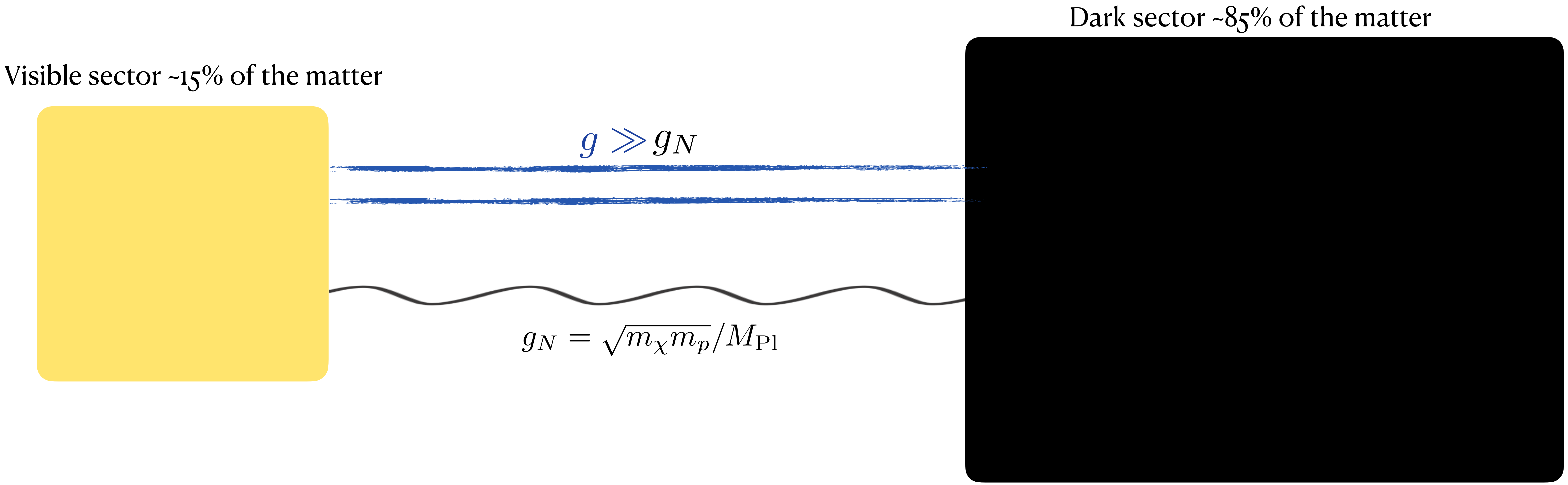
Looking for guiding principles to explore this huge parameter space...

Visible sector ~15% of the matter

Dark sector ~85% of the matter

Example 1: Minimal optimism

1) Visible and dark sector interact via a portal
2) Dark Matter is produced thermally
3) We can test it combining terrestrial, cosmological and astrophysical probes



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Is the DM the lightest neutral component of an EW multiplet?

Cirelli, Strumia, Fornengo 2005

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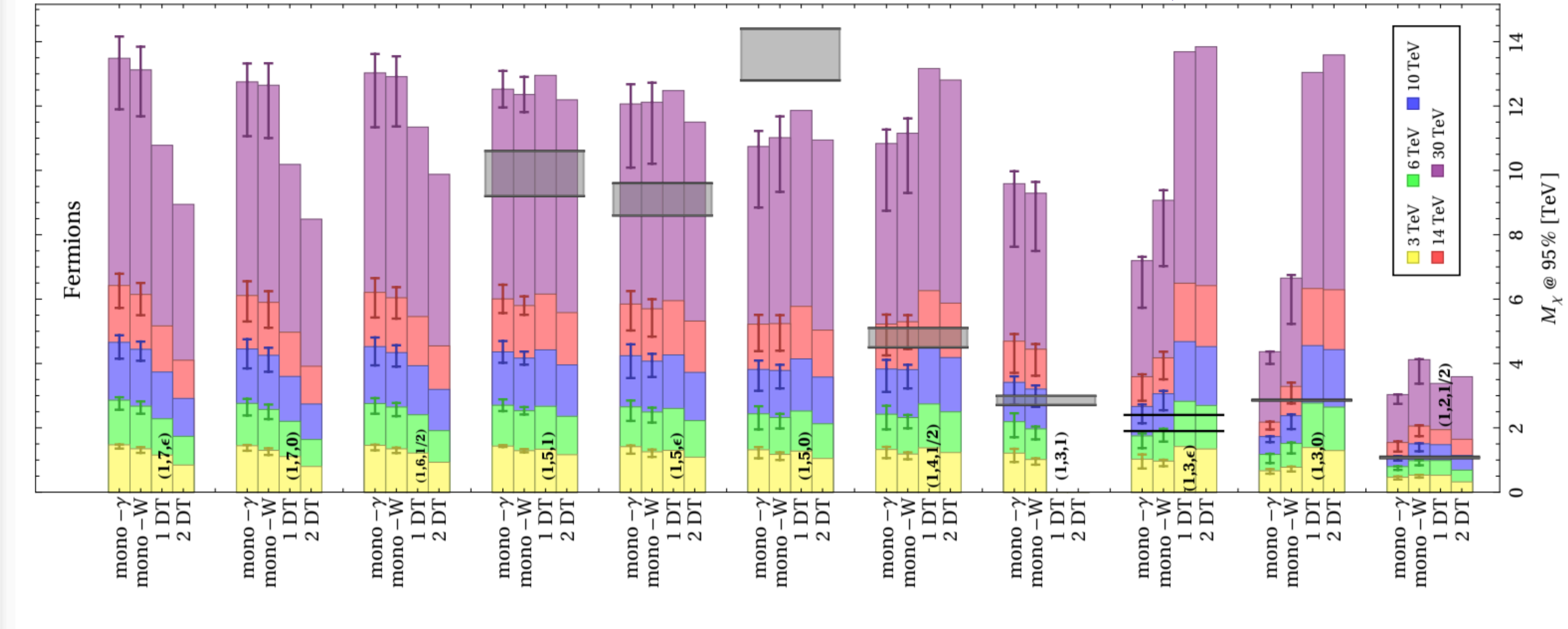
This question can be potentially be closed by a combination of multiton Xenon experiments + future muon collider,

Bottaro, Costa et al. 2023



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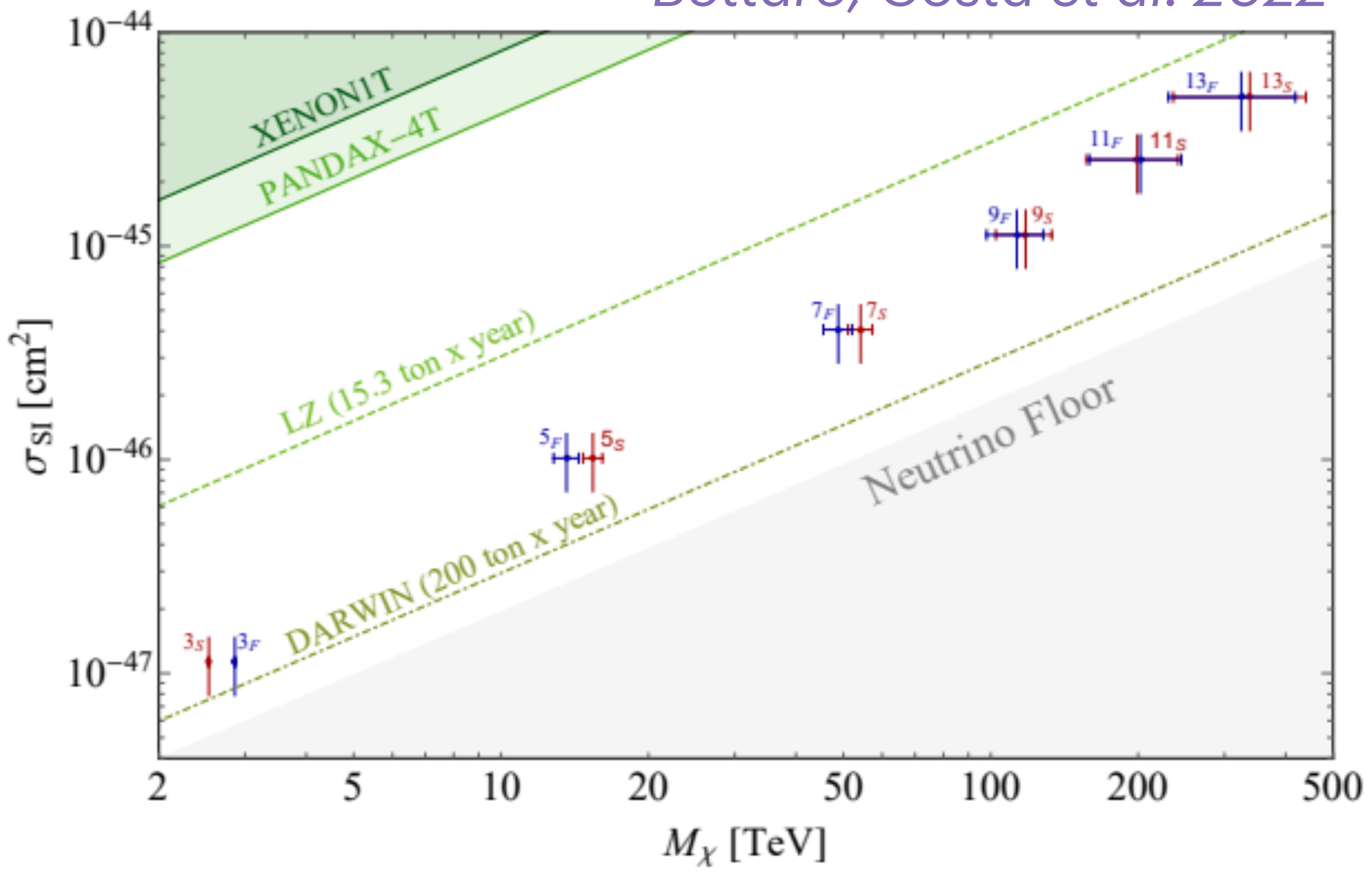

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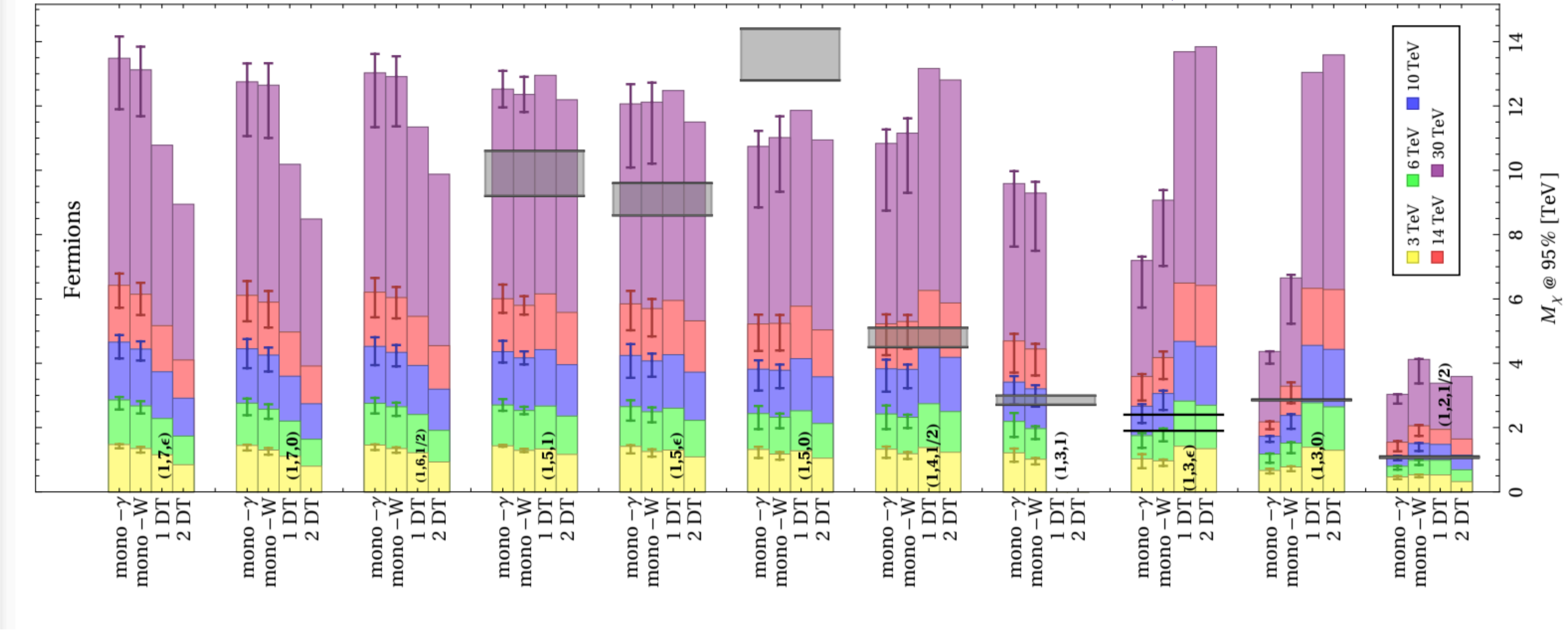
Is the DM the lightest neutral component of an EW multiplet?

Cirelli, Strumia, Fornengo 2005

This question can be potentially be closed by a combination of multiton Xenon experiments + future muon collider, +indirect detection searches (a lot of work to be done!)

Bottaro, Costa et al. 2023



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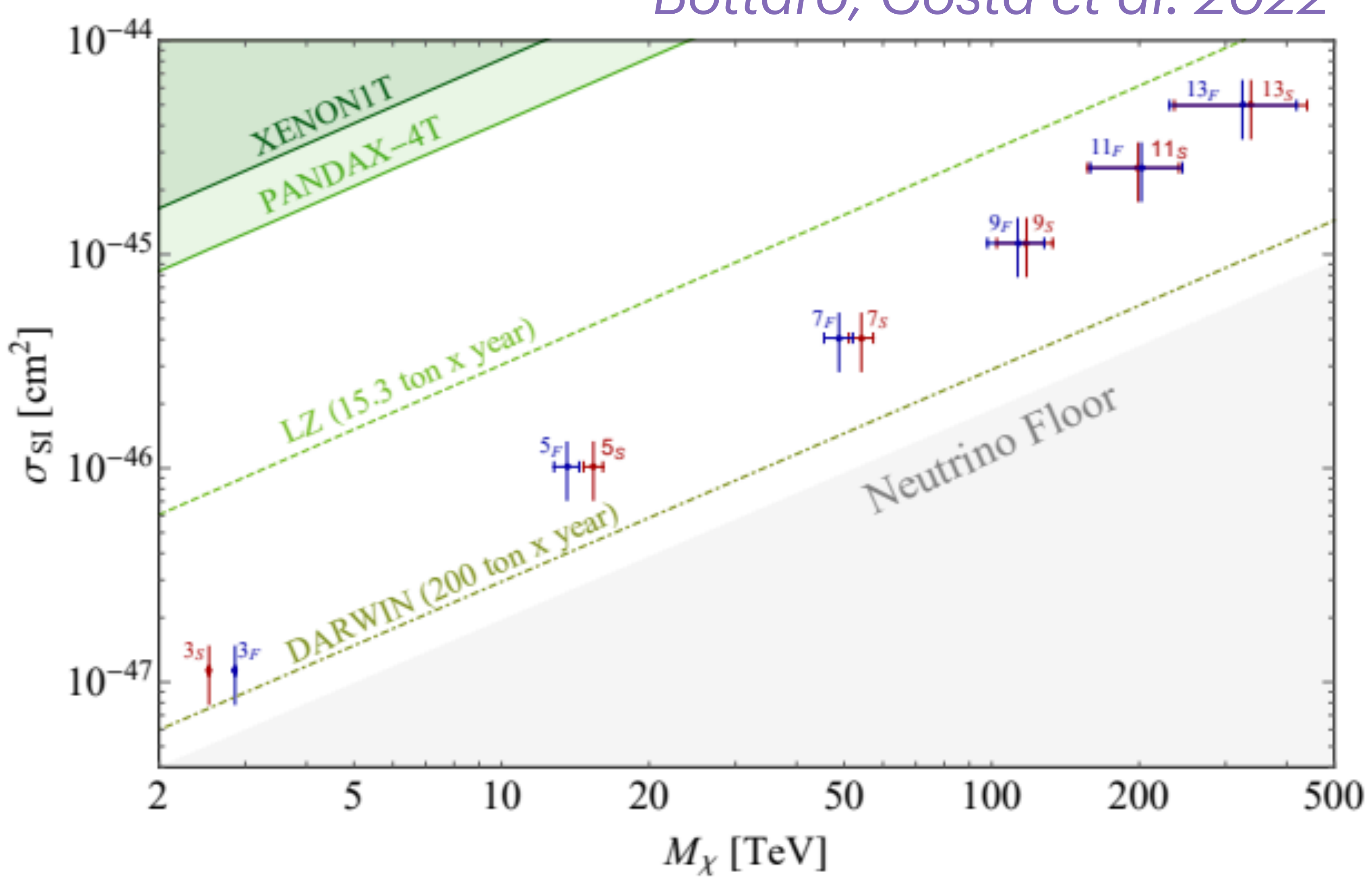

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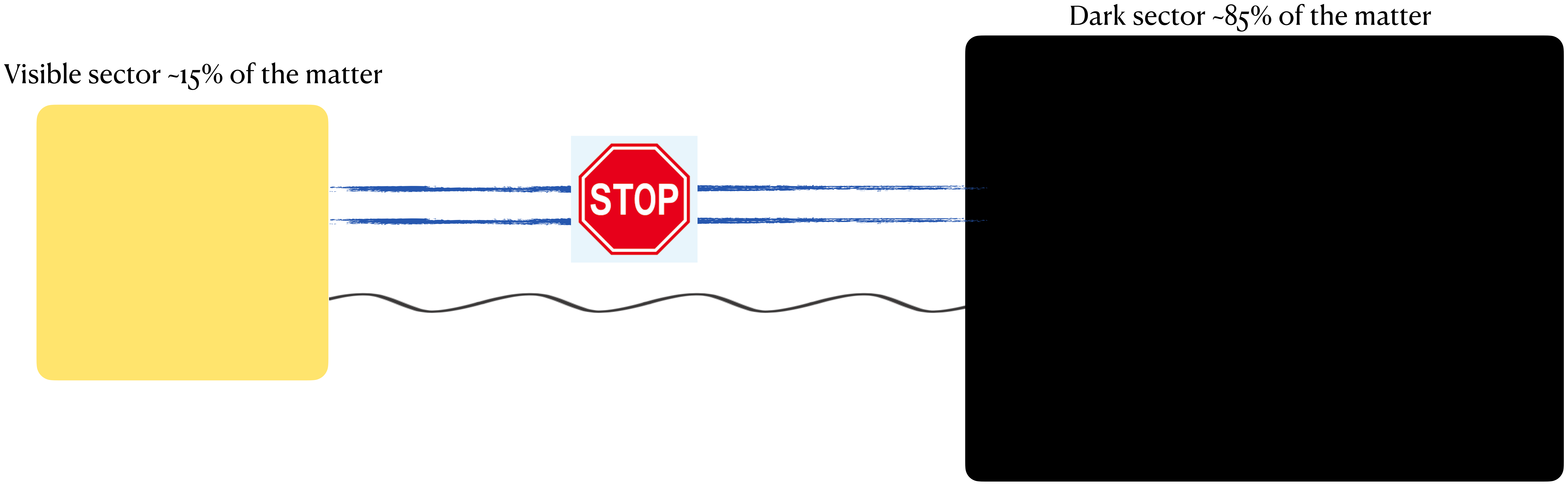
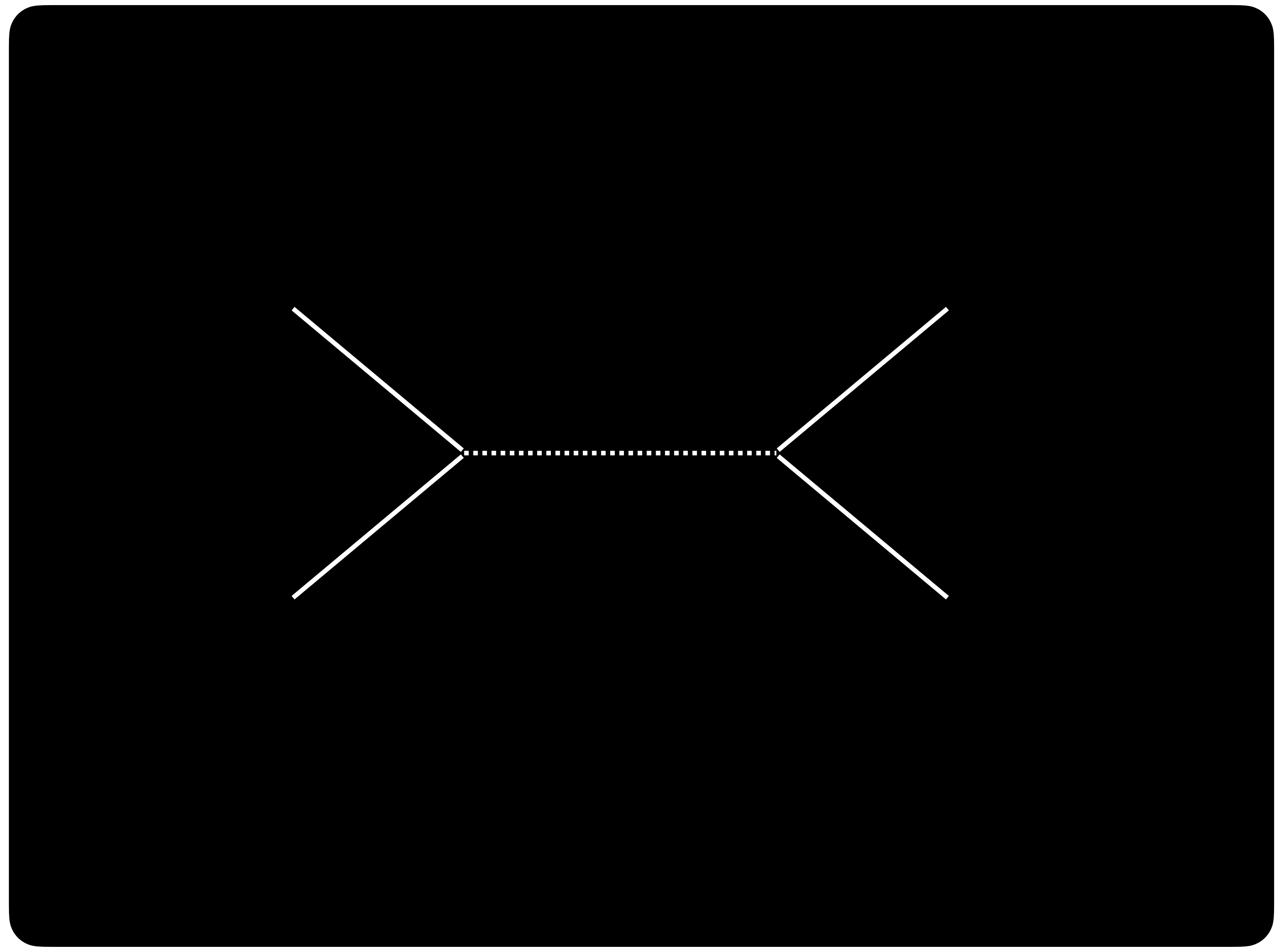
Example 2: Minimal pessimism

1) Visible and dark sector interact only gravitationally
2) Dark Matter is produced non-thermally
3) Cosmology & astrophysics are the only probes of the dark sector dynamics



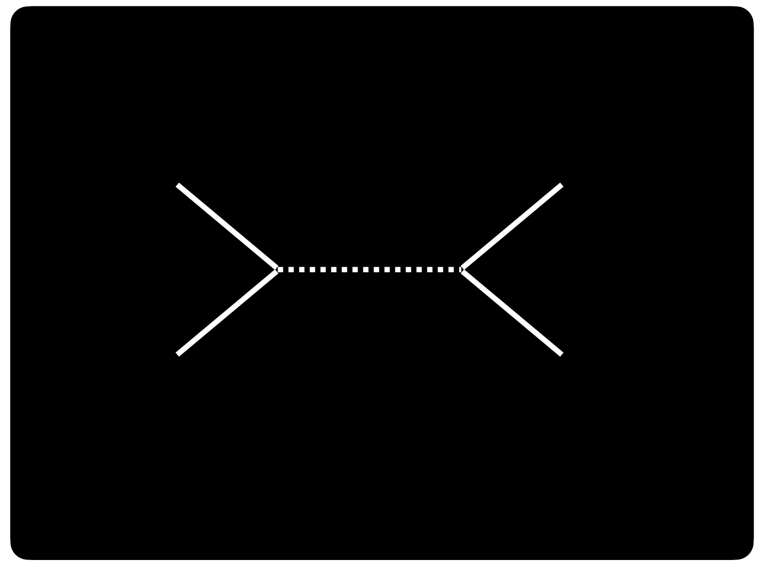
Probing dark forces with LSS



New physics Parameters:

1) the range of the force
2) the strength of the force
3) the fraction of DM interacting

A concrete model



$$\mathcal{L}_{\text{int}} = \kappa \varphi \chi^2$$

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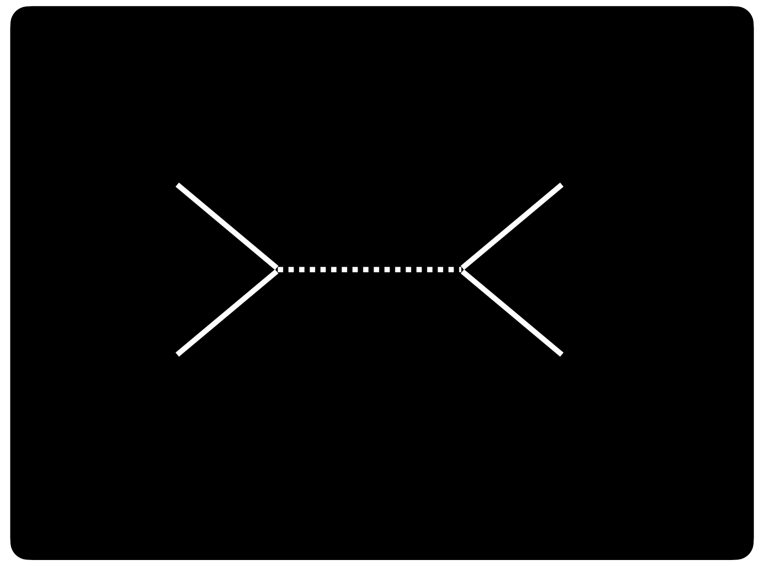

$$\mathcal{L}_{\rm int} = \kappa \varphi \chi^2 \xrightarrow[G_s \equiv \kappa^2/m_\chi^4]{\varphi = G_s^{-1/2} s} \mathcal{L}_{\rm int} = m_\chi^2(s)\chi^2 \qquad m_\chi^2(s) = m_\chi^2(1+2s)$$

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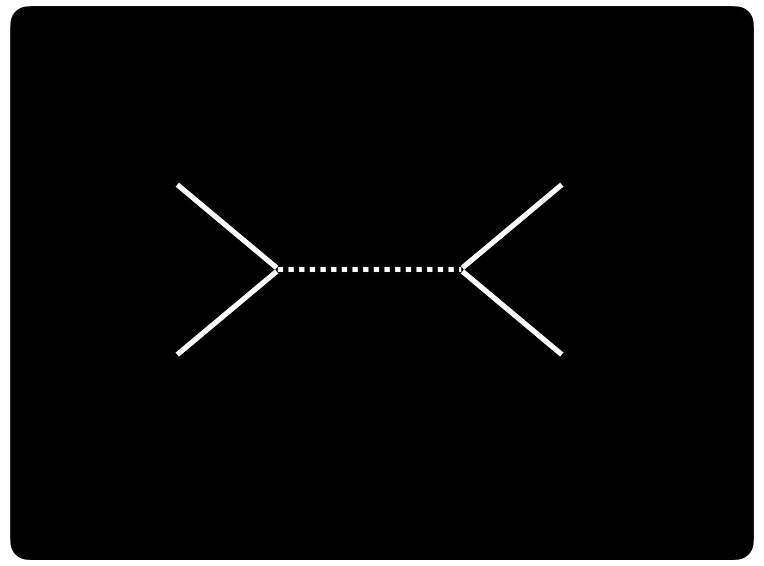

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The effect of the new dark force
can be thought as a field dependent DM mass

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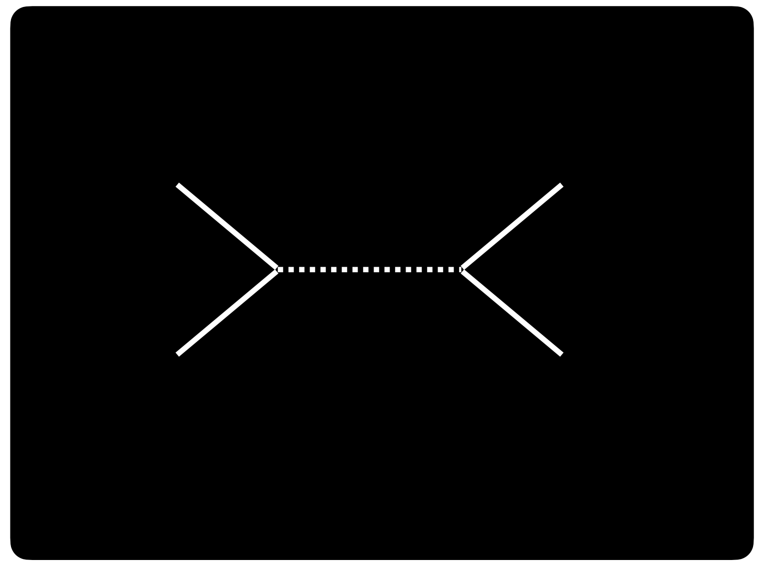

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$$2G_s\mathcal{L}_s = (\partial s)^2 + m_s^2 s^2 + \dots$$

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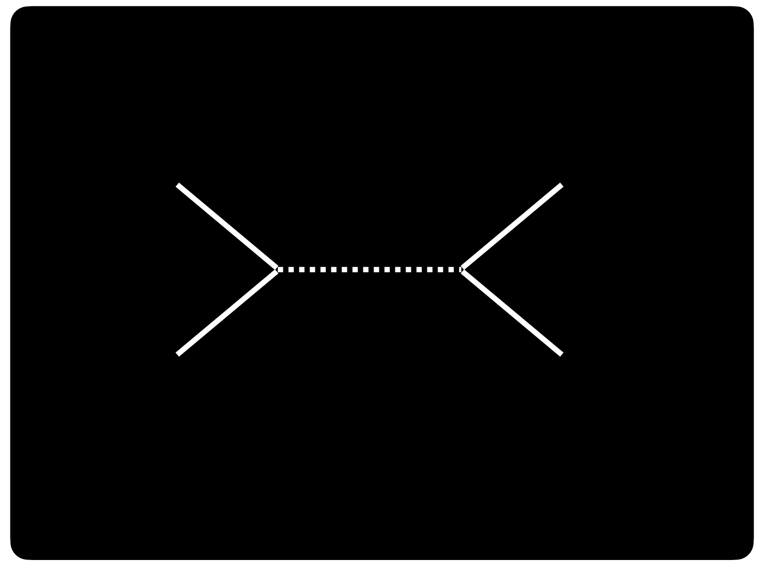

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$G_N \sim G_s \to \infty$

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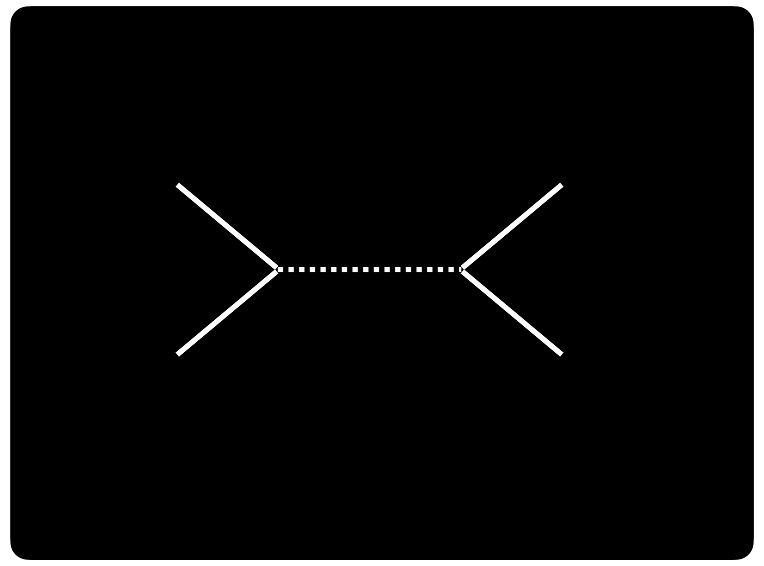

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WORKING ASSUMPTIONS: $m_s \lesssim H_0 \simeq 10^{-33}$ eV

$f_\chi = \rho_\chi / \rho_m \simeq 1$

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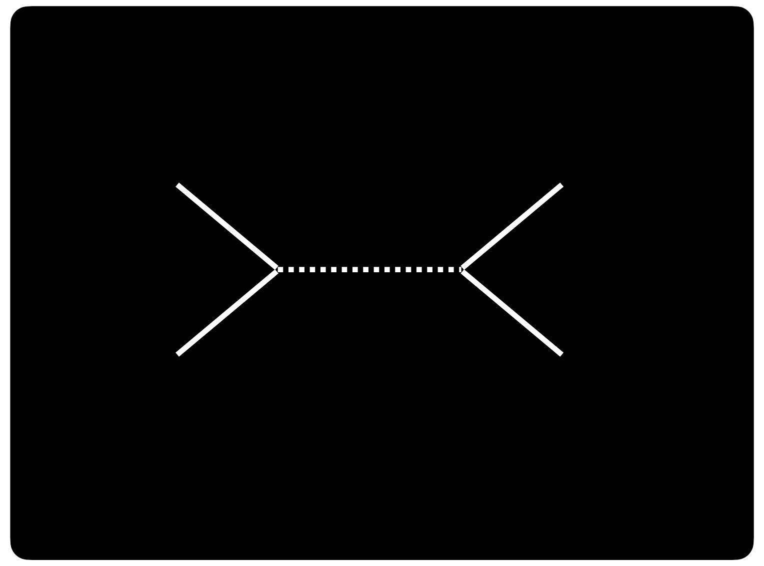
A concrete model



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$$2G_s \mathcal{L}_s = (\partial s)^2 + m_s^2 s^2 \boxed{+ \dots}$$

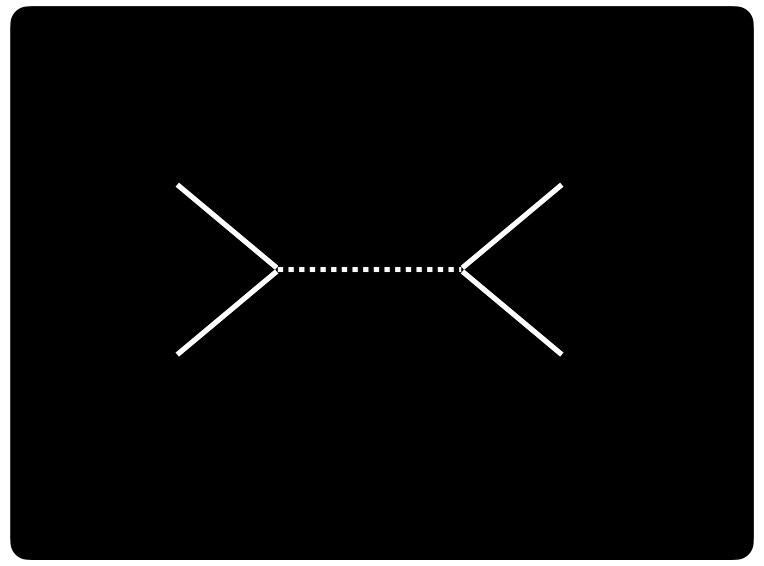
← we can neglect scalar self interactions

$$G_N \sim G_s \to \infty$$

WORKING ASSUMPTIONS: $\boxed{m_s \lesssim H_0 \simeq 10^{-33}\ \text{eV}}$ ← The force is long range throughout the whole history of the Universe!

$$f_\chi = \rho_\chi/\rho_m \simeq 1$$

A concrete model



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we can neglect scalar self interactions

$$G_N \sim G_s \to \infty$$

WORKING ASSUMPTIONS:

$m_s \lesssim H_0 \simeq 10^{-33}$ eV — The force is long range throughout the whole history of the Universe!

$f_\chi = \rho_\chi/\rho_m \simeq 1$ — 100% of the DM interacts with the new force

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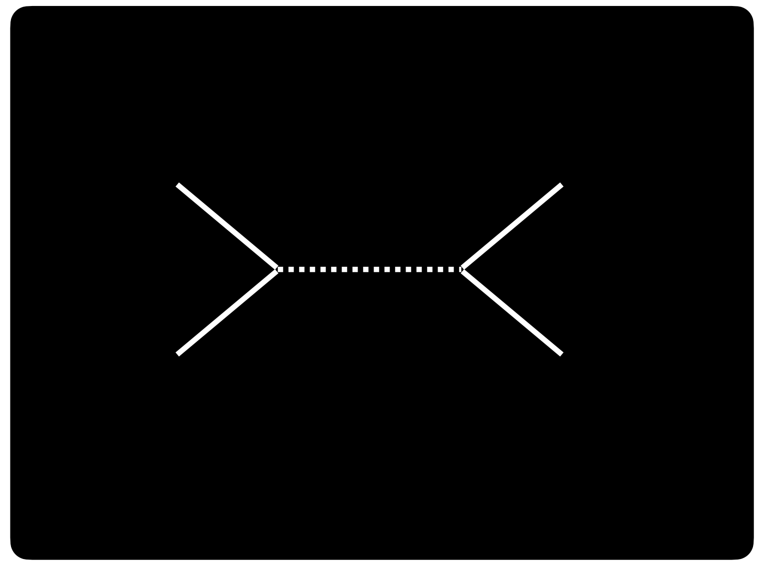
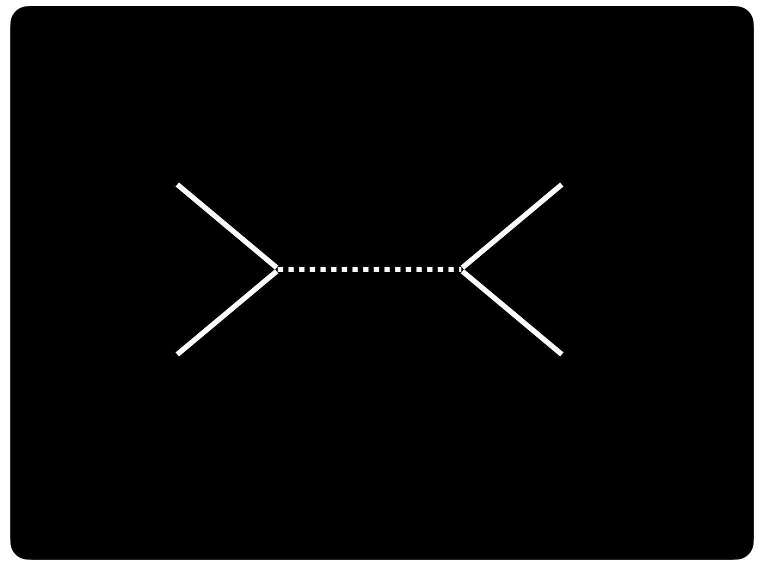
Modification of distances



The DM follows new geodesics accounting for the background evolution of the light scalar

$$d(z) \propto H^{-1} = (H_{\Lambda\text{CDM}} + \Delta H)^{-1}$$

Modification of distances



The DM follows new geodesics accounting for the background evolution of the light scalar

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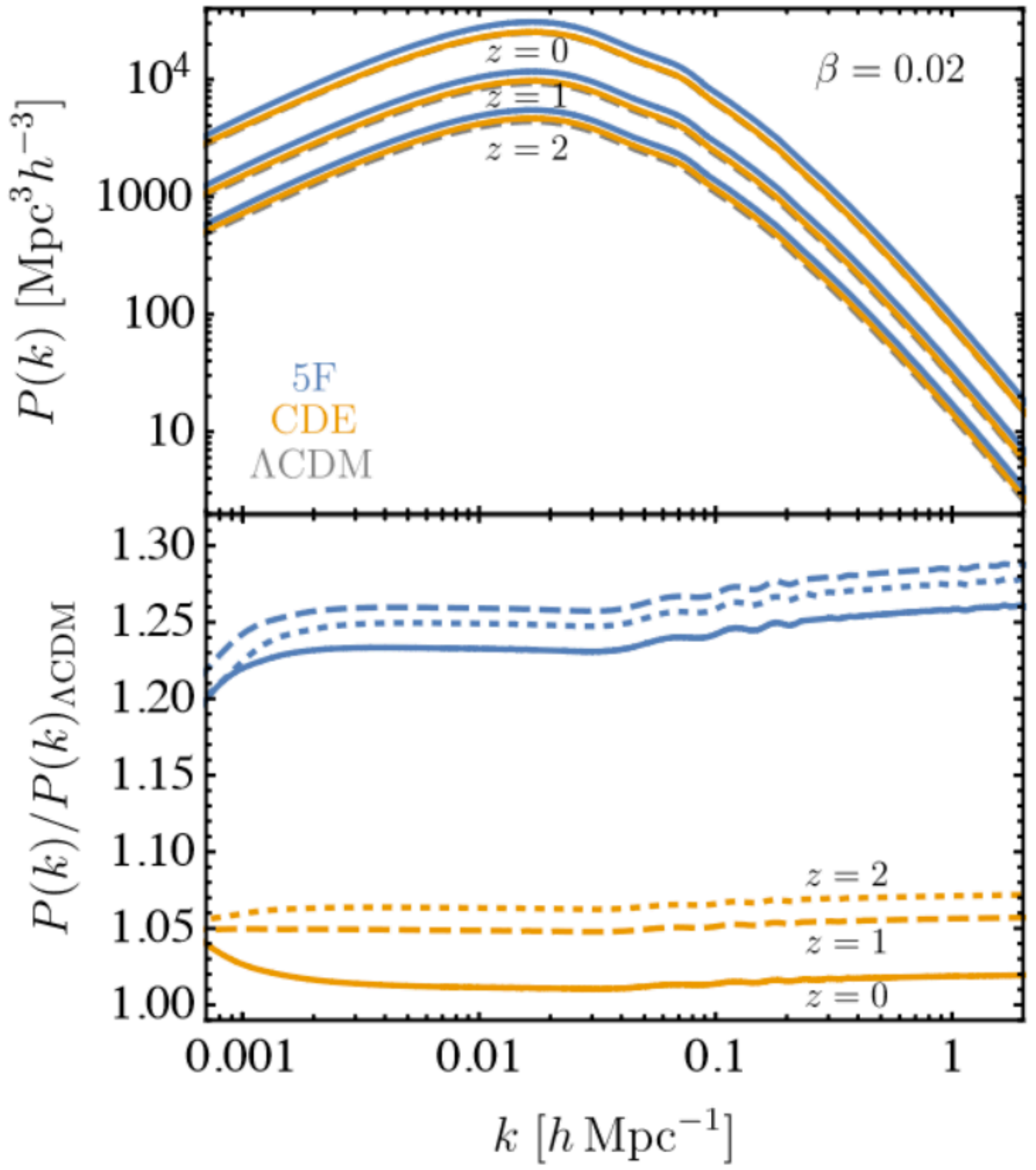
Enhanced growth of matter fluctuations

$$\delta_m(a) \simeq D_{\Lambda\mathrm{CDM}} \left(1 + \frac{6}{5}\beta \log \frac{a}{a_{\mathrm{eq}}}\right) \delta_m(a_{\mathrm{eq}})$$

$$\beta \equiv \frac{G_s}{4\pi G_N}$$



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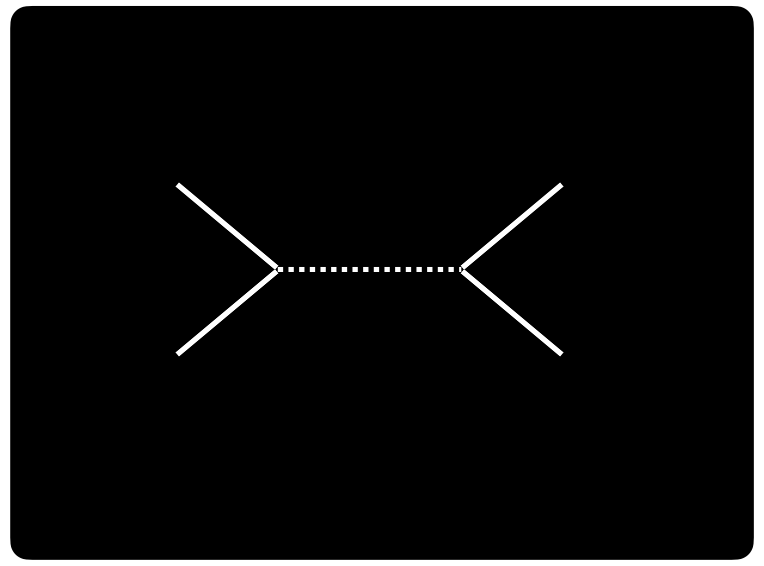
Modification of distances



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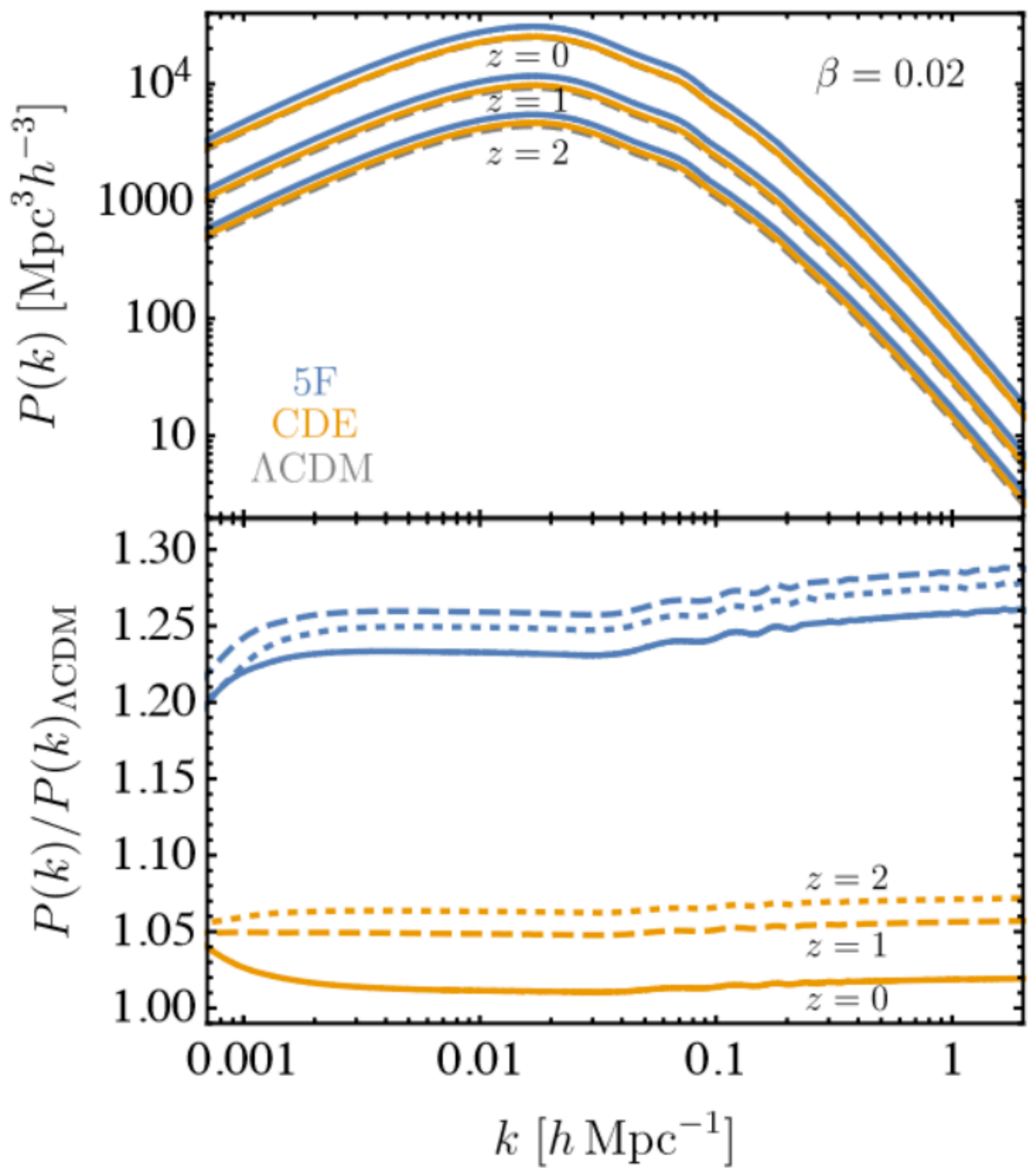

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the large-log (~8) is due to the long range nature of the force

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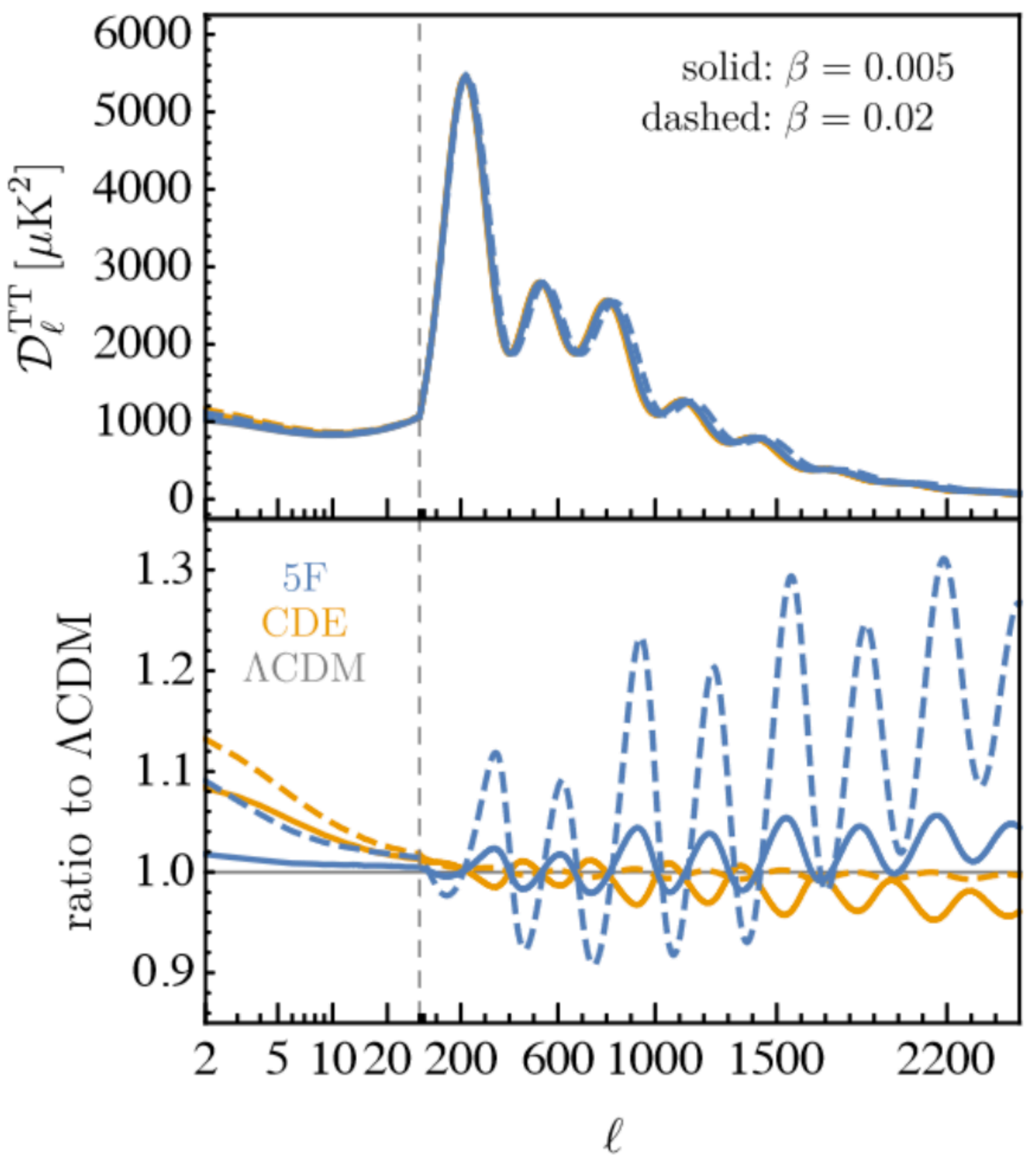
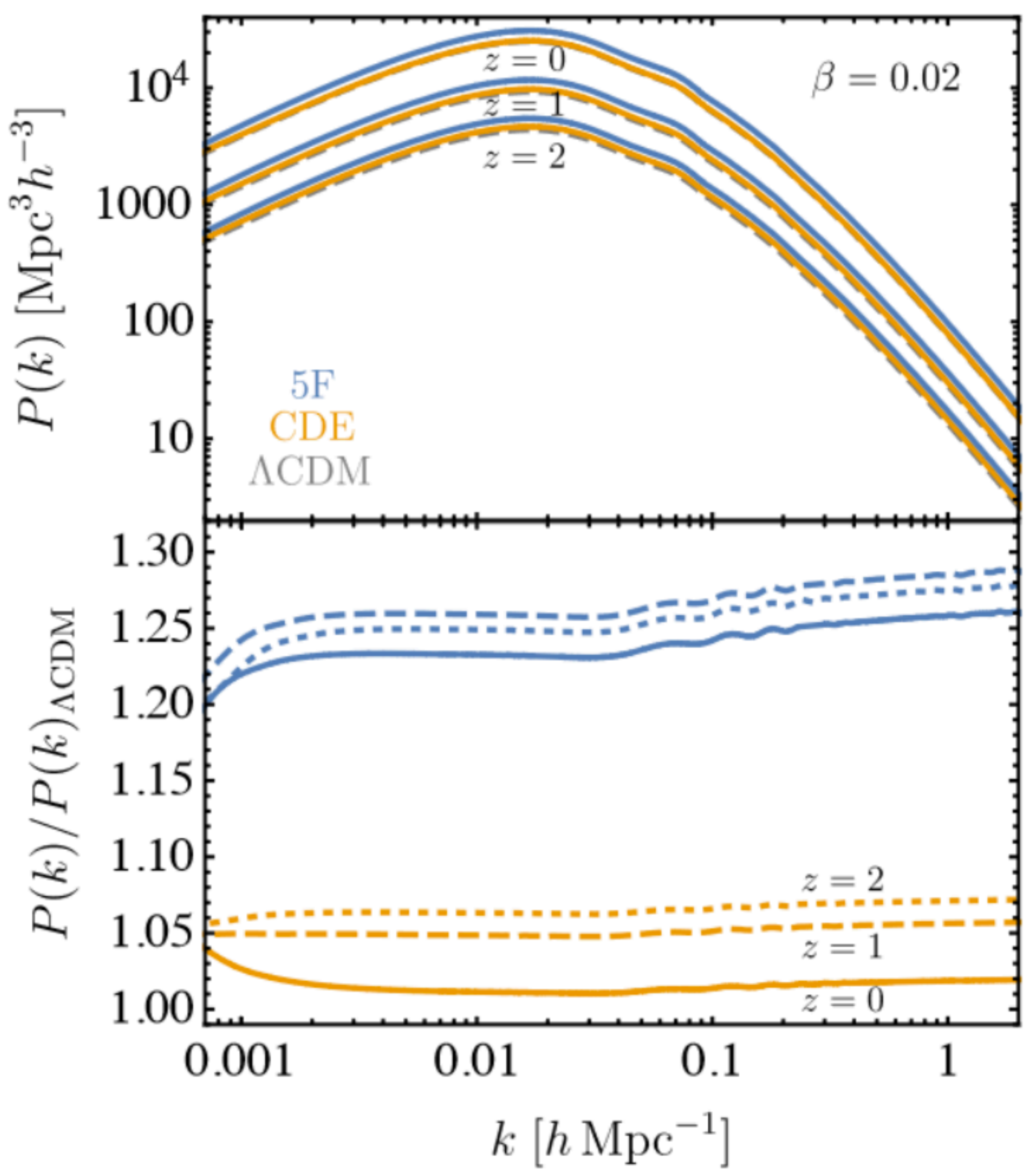
How we test this in cosmology?





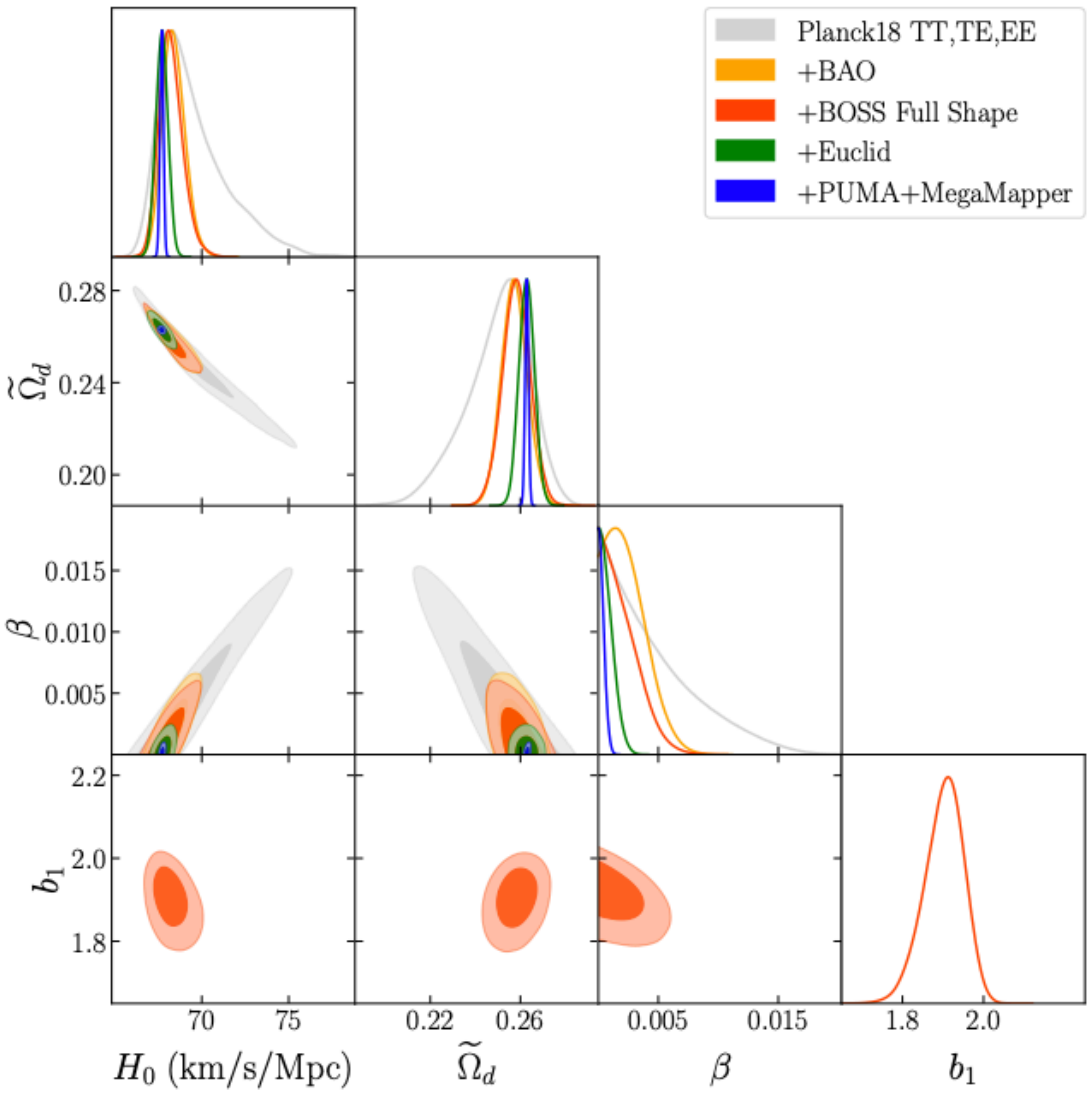
1) All CMB peaks shift

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

2) The power spectrum is rescaled up

Results

arXiv:2309.11496



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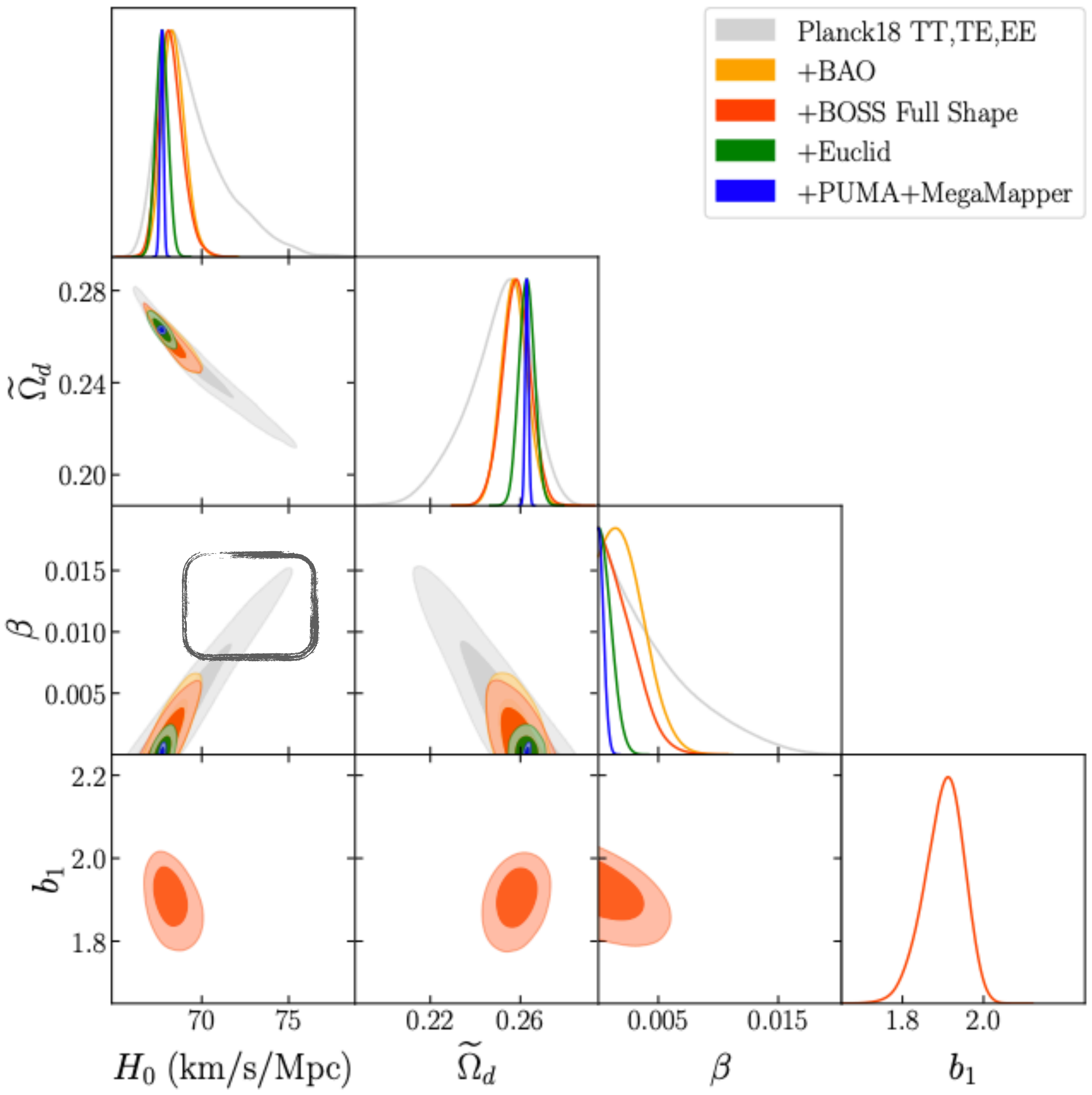

CMB alone suffers from the usual matter-Hubble degeneracy which limits the sensitivity to the dark force strength

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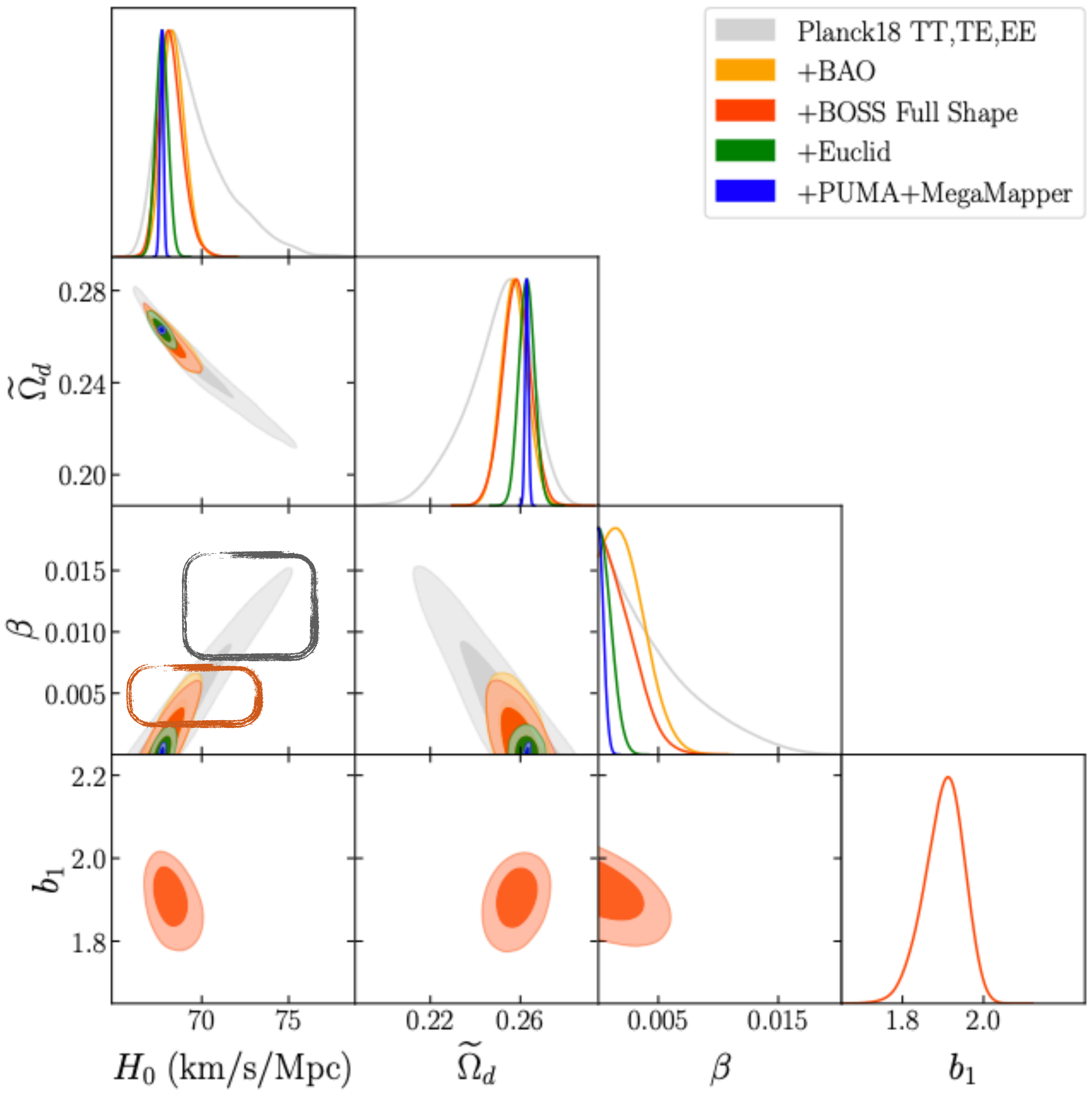

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The full shape of the PS breaks this degeneracy

With BOSS full shape = BAO

Credit to Pierre Zhang for guidance In the use of the PyBird code!

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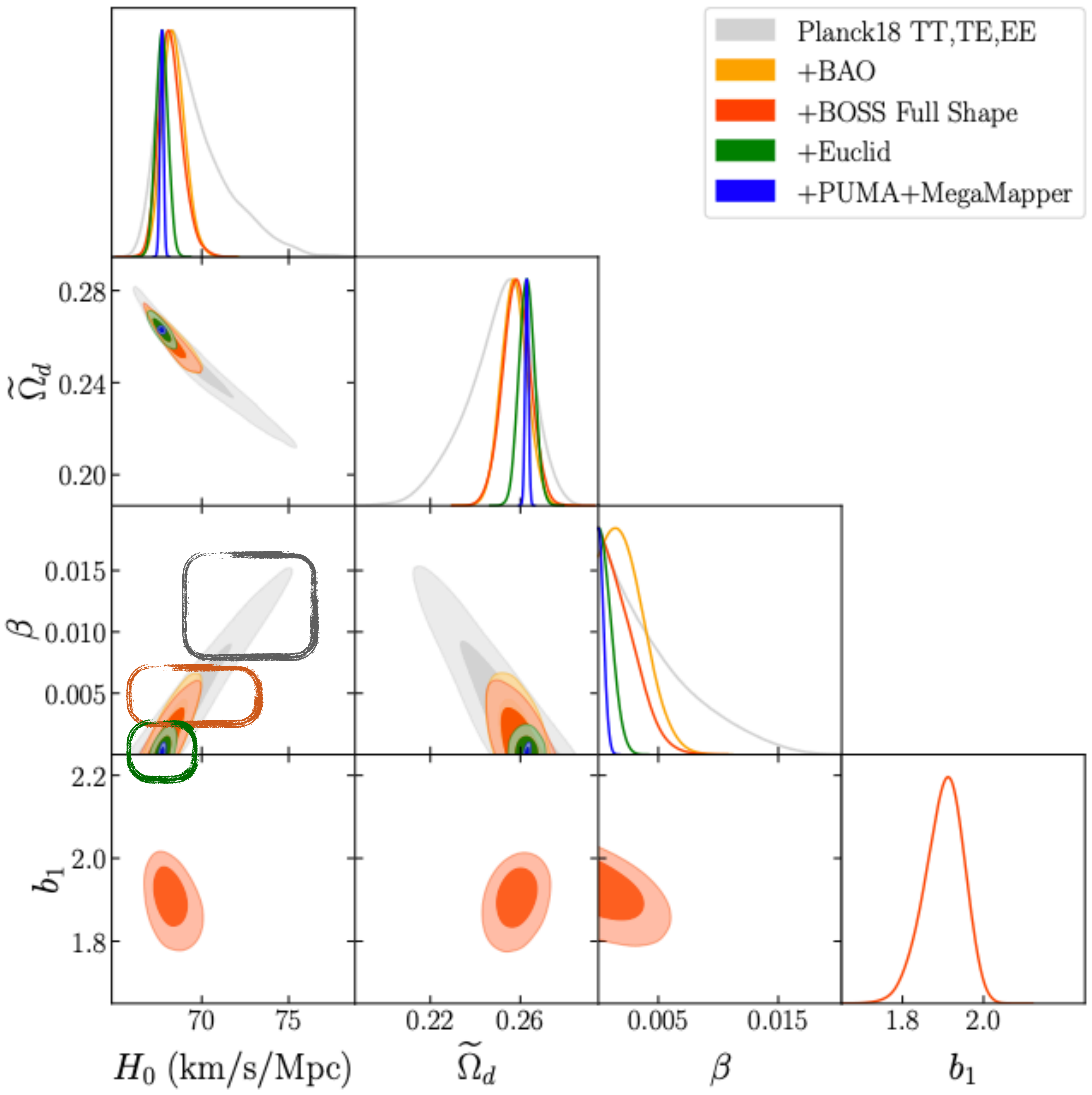

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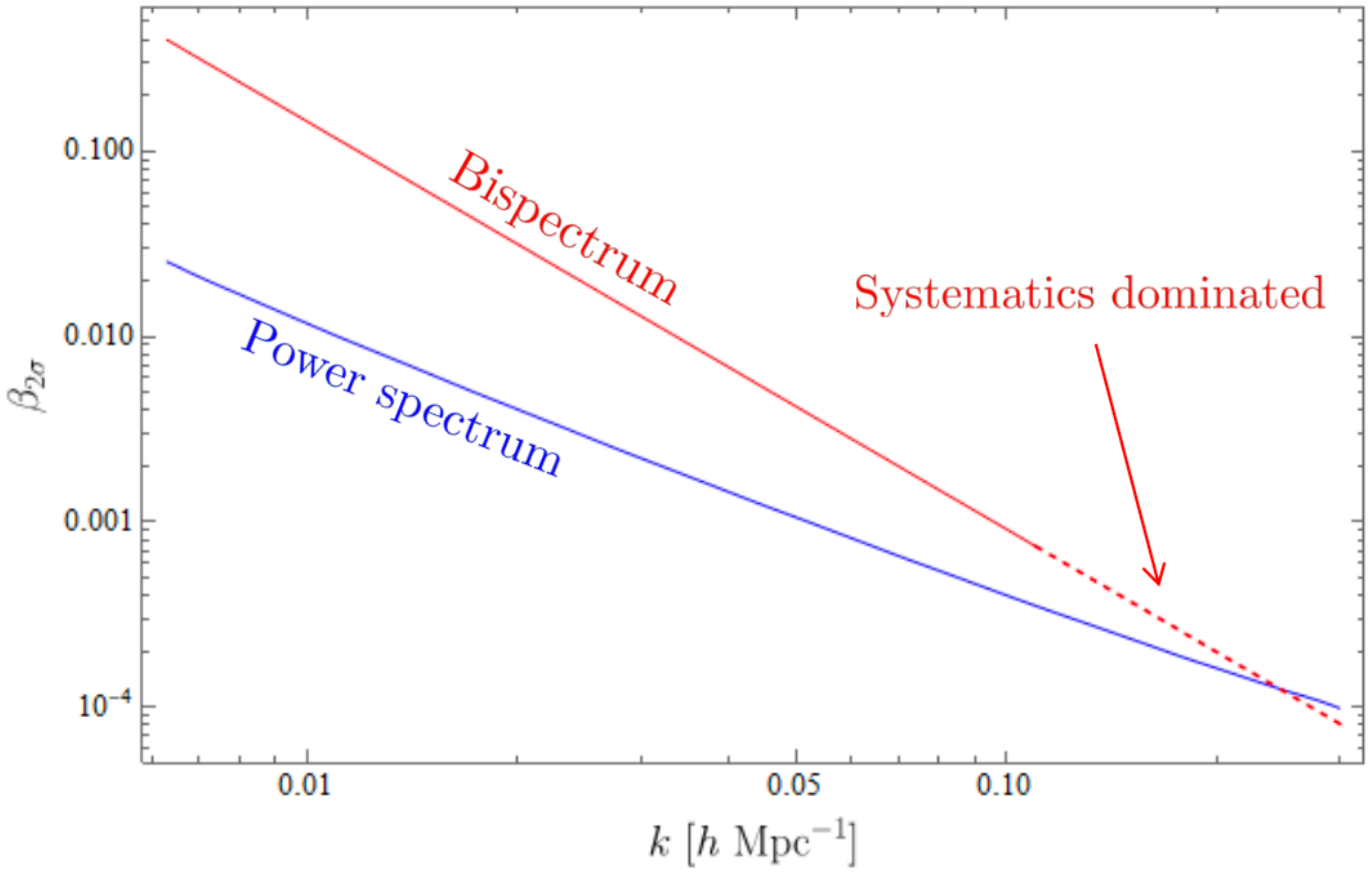
Euclid will push further thanks to a better determination of the linear bias

Forecast with FishLSS- Sailer et al 2021

Can we improve further?

$$\langle \delta_g(p)\delta_g(k)\delta_g(q)\rangle = (2\pi)^3\delta^{(3)}(p+k+q)B_g(p,k,q)$$ Looking at the bispectrum



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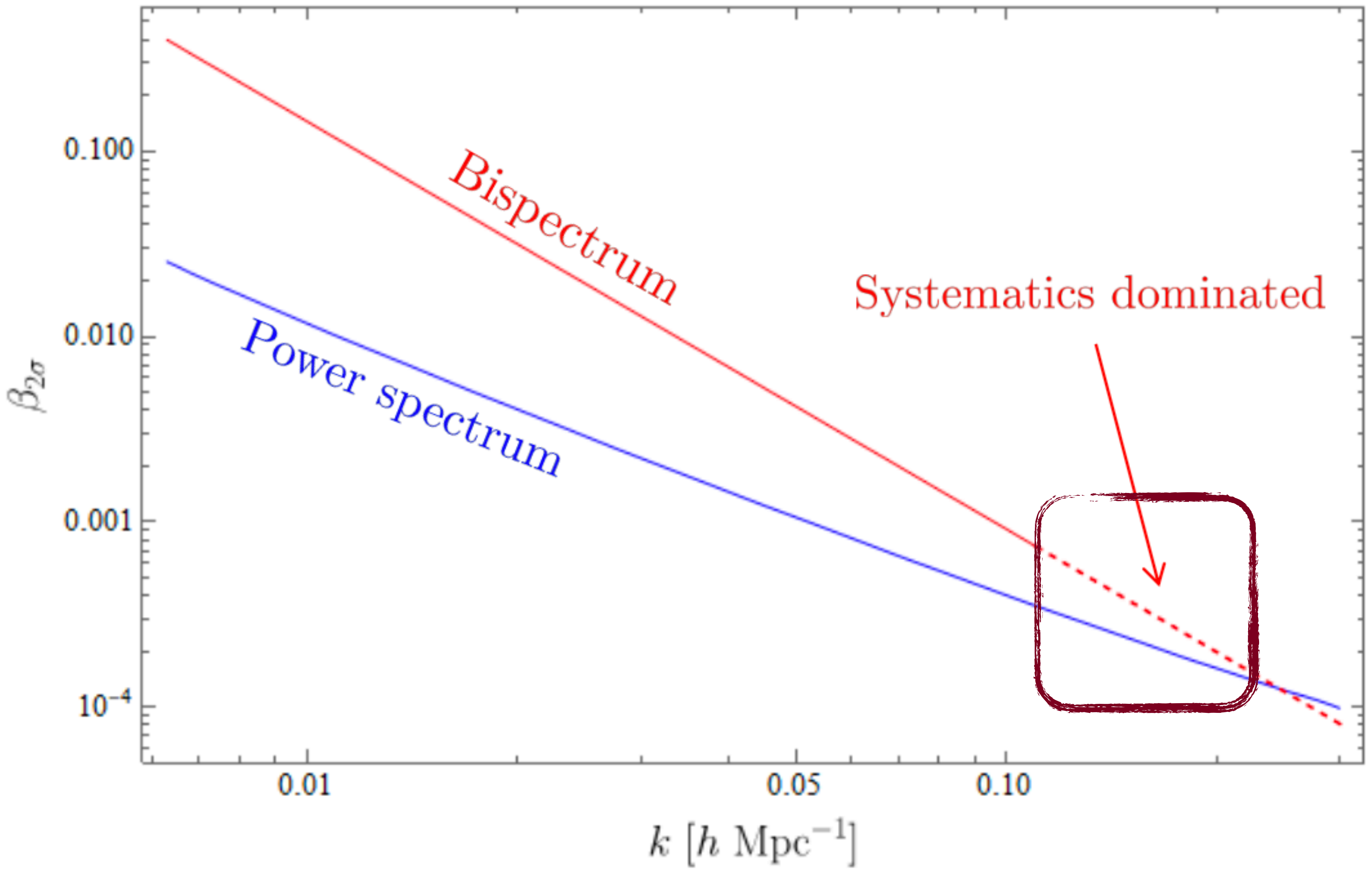

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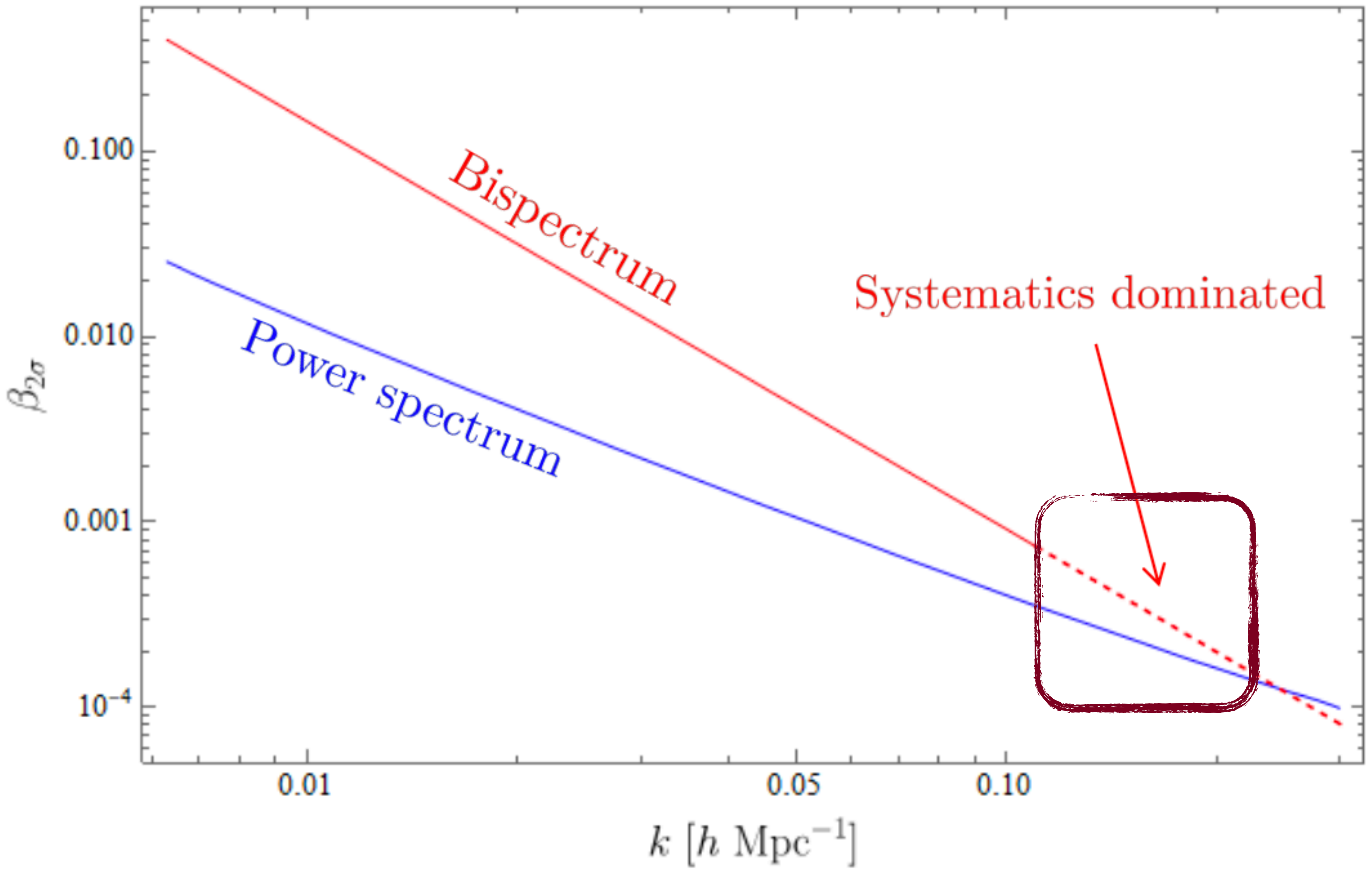

Our modelling of the bispectrum at tree-level does not allow to get further information

The 1-loop power spectrum modelling should ameliorate the sensitivity further!

D'Amico et al 2023

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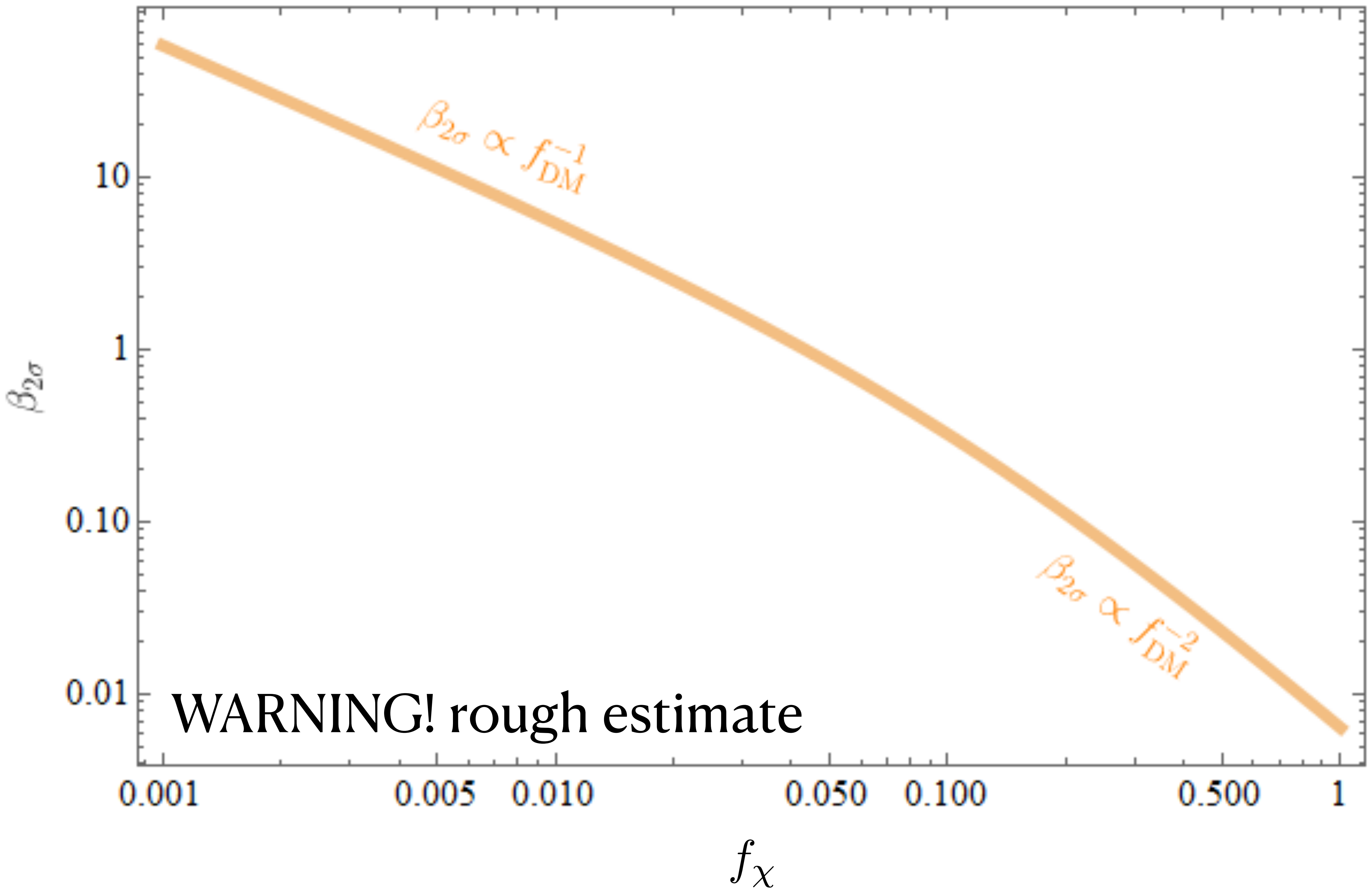
Relative densities and velocities



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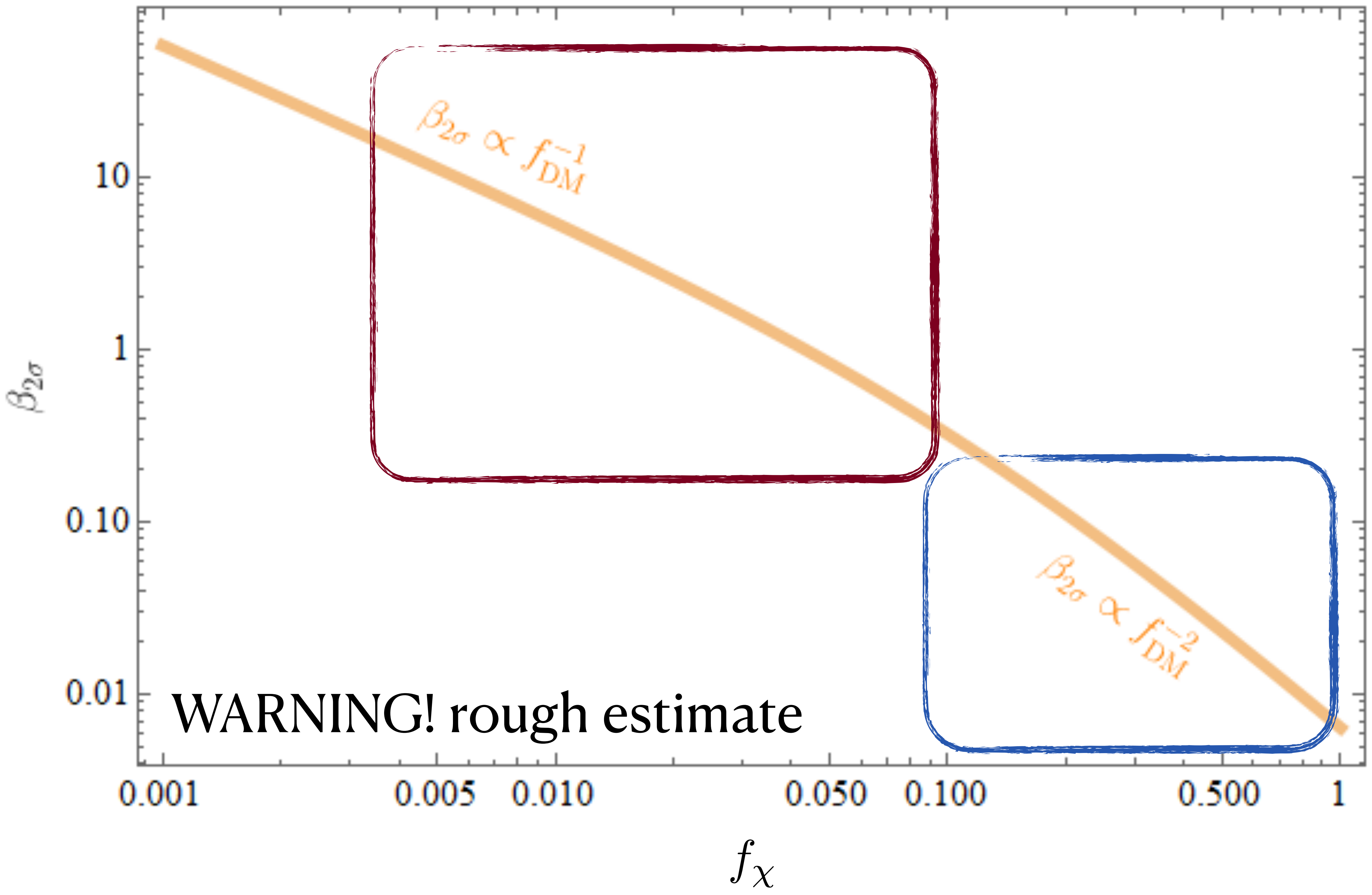

$$\delta_r = \frac{5}{3}\beta f_\chi \delta_m$$

$f_\chi \lesssim 10\%$ relative densities dominate the signal

$$\delta_m(a) \simeq D_{\Lambda\rm CDM}\left(1 + \frac{6}{5}\beta f_\chi^2 \log a/a_{\rm eq}\right)\delta_0$$

Extending the EFT of LSS

Looking at scales: $kR_{\rm halo} << 1$ the galaxy fluctuations should be mapped accounting for relative densities and velocities

$$\delta_g = b_1\delta_m + \frac{b_2}{2}\delta_m^2 + b_K K_{ij}K^{ij} + \dots$$

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$$\delta_g = \underbrace{b_1\delta_m}_{b_r\delta_r + b_\theta\theta_r} + \frac{b_2}{2}\delta_m^2 + \underbrace{b_K K_{ij}K^{ij} + \dots}_{b_{mr}\delta_m\delta_r + b_{\delta\theta}\delta_m\theta_r + b_{\nabla\delta}\nabla_i\delta_m v_r^i + b_K K^{ij}\nabla_i v_r^j + b_{Kr}K_{ij}\frac{\nabla^i\nabla^j}{\nabla^2}\delta_r}$$

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New structures enter in the matter correlators: $\delta_r^{(2)}(\mathbf{k},a) = \varepsilon\,(D_{1m}^{\rm CDM})^2\int_{\mathbf{k}} \mathrm{d}k_{12}F_{2r}(\mathbf{k}_1,\mathbf{k}_2)$

Leading BSM correction to the EFT!

New Smoking guns

$$\Delta P(k) \sim \beta f_\chi^2 \log a_{\rm eq} P_{\Lambda\rm CDM}(k) + f_\chi \beta \Delta P(k)$$

$$\Delta B(q,k,k') \sim \beta f_\chi^2 \log a_{\rm eq} B_{\Lambda\rm CDM}(q,k,k') + f_\chi \beta \Delta B(q,k,k')$$

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Relative densities and velocities induce NEW SPATIAL FEATURES

+ VIOLATION OF CONSISTENCY RELATIONS

(violation of the EP)

Peloso et al 2013, Creminelli et al. 2013

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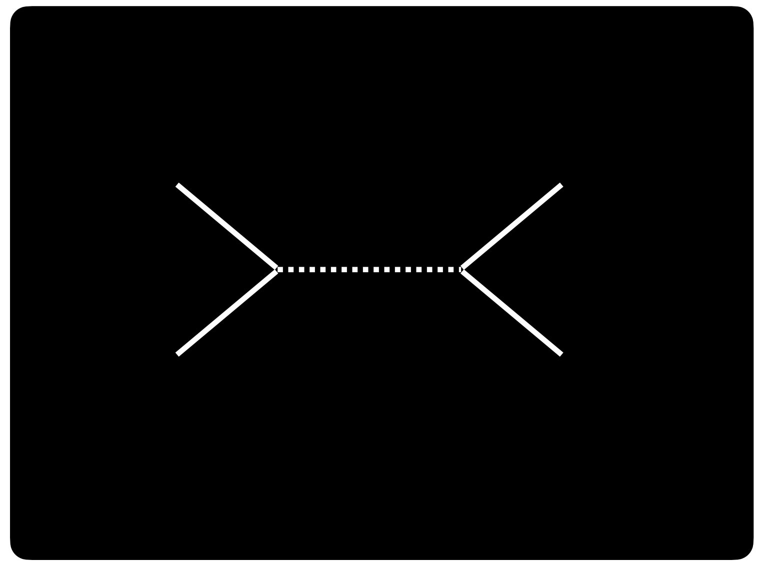
Looking forward

Maybe the Dark Sector is dark but its dynamics complex



The exploration of the potential of future LSS surveys to unveil dark sector dynamics just started

A lot of theory work is needed to understand how new dynamics modify the structure of cosmological observables

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Backup

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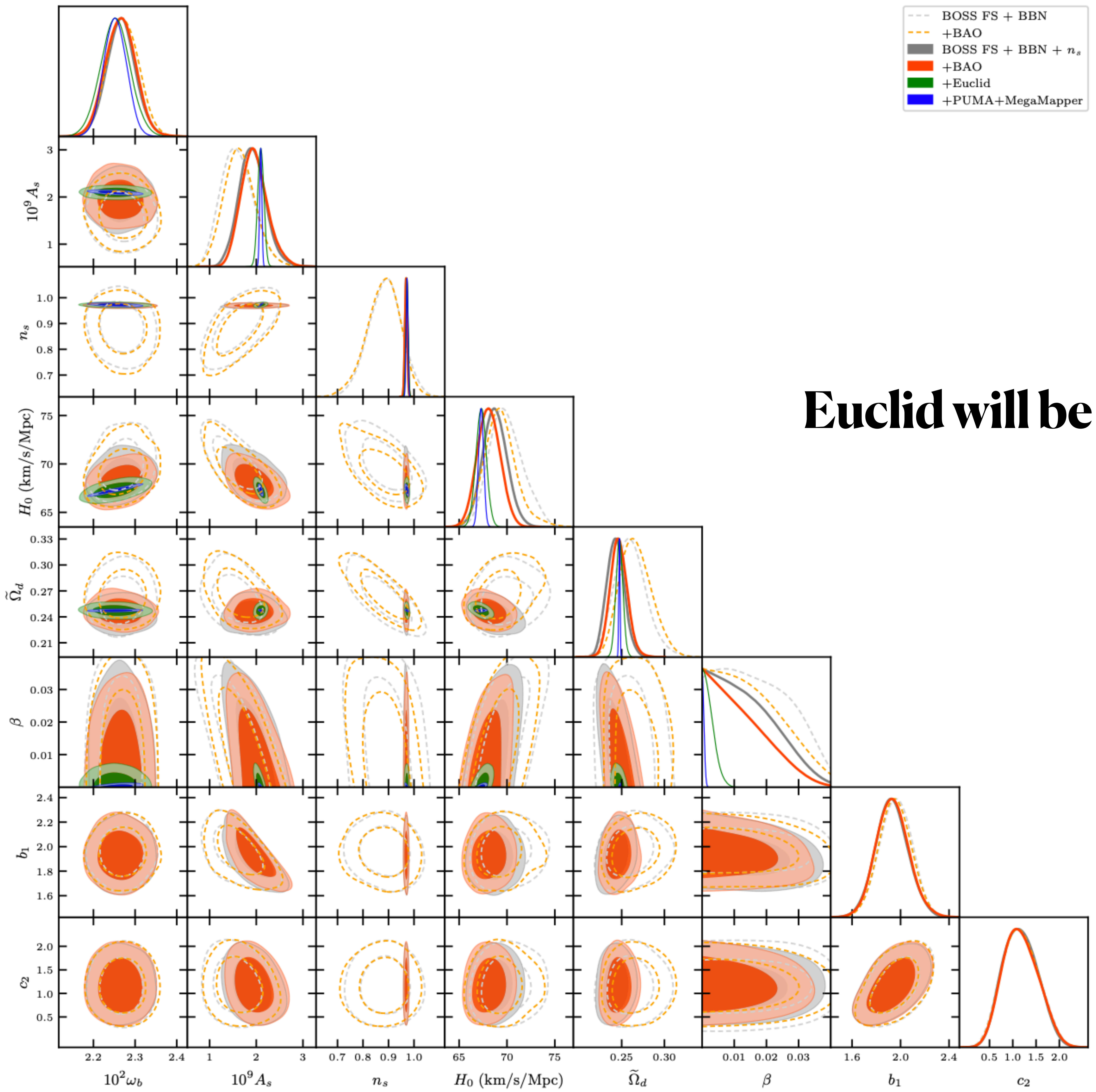
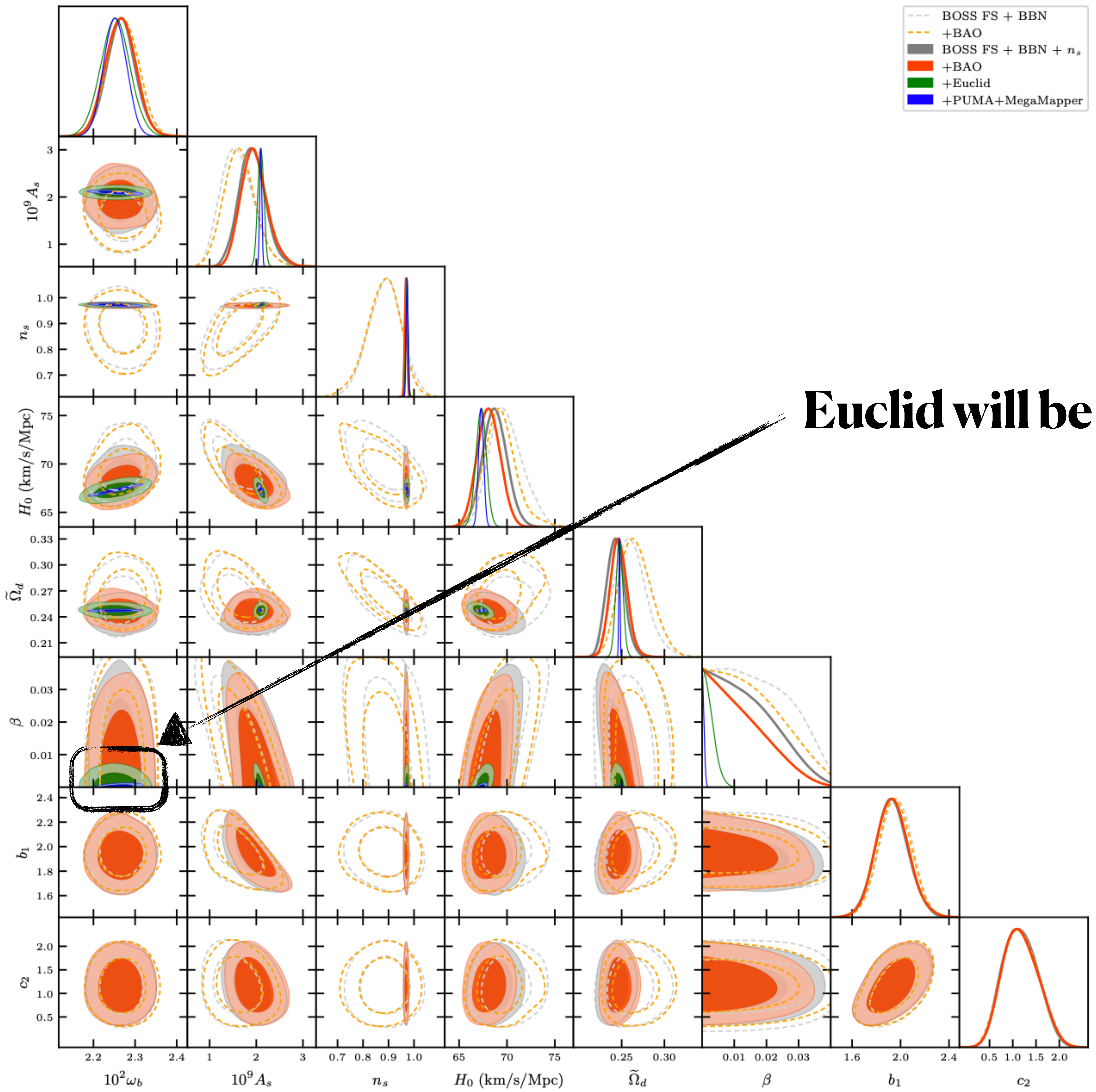


Euclid will be competitive even without CMB!

Diego Redigolo, Light Dark World 2023



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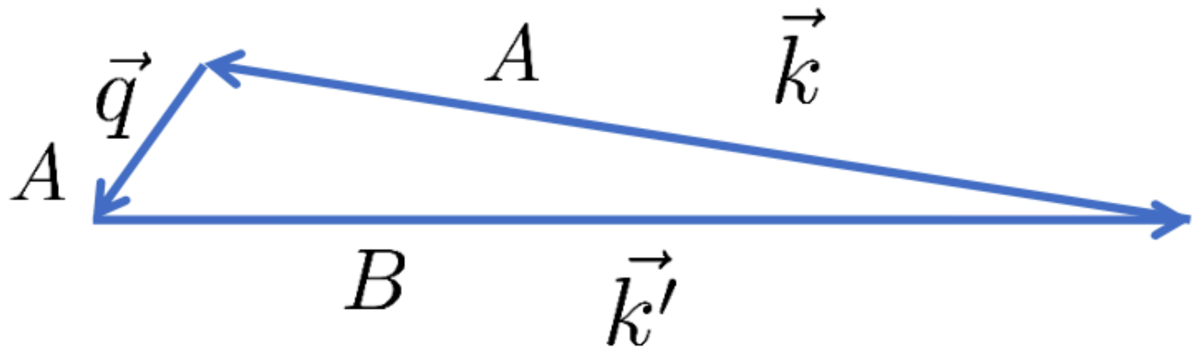
The double tracer bispectrum



$$\lim_{q\to 0} \Delta\mathcal{B}_{AAB}(q,k,k') \propto \underbrace{\frac{\vec{q}\cdot\vec{k}}{q^2}}_{\frac{7}{6}b_1^A \Delta b^{AB}} P_{\rm lin}(q) P_{\rm lin}(k)$$

The bispectrum has a pole which is zero in ΛCDM

Two different tracers are required $\Delta b^{AB} \equiv b_1^A \bar{b}_r^B - b_1^B \bar{b}_r^A \quad = 0 \text{ if } A = B$

This is a test of EP: We see two different objects falling differently in the rest frame of the long-mode