The Dark Sector
&
The Large Scale Structure of the Universe

Diego Redigolo @ ALPS2024

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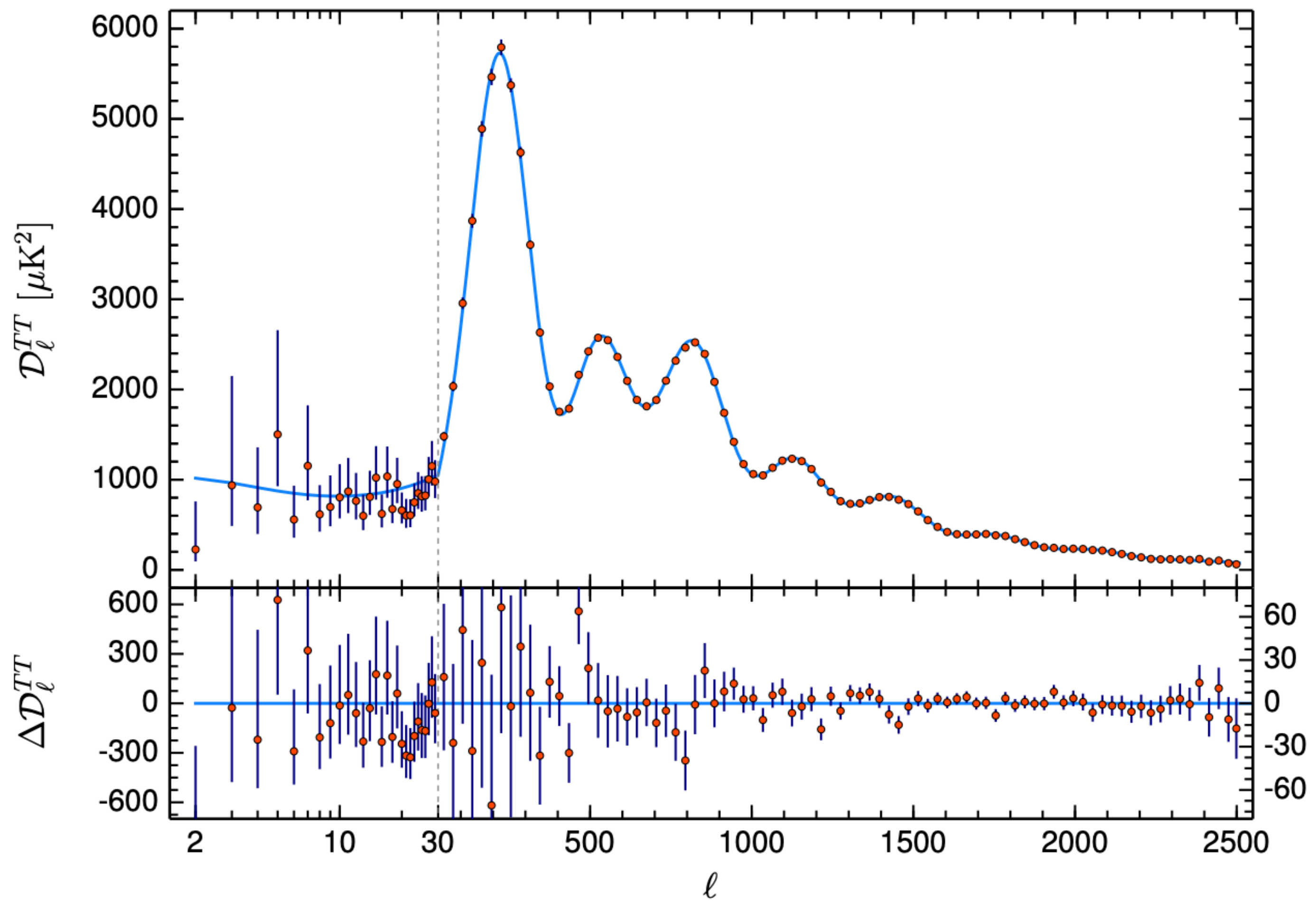
Sezione di Firenze

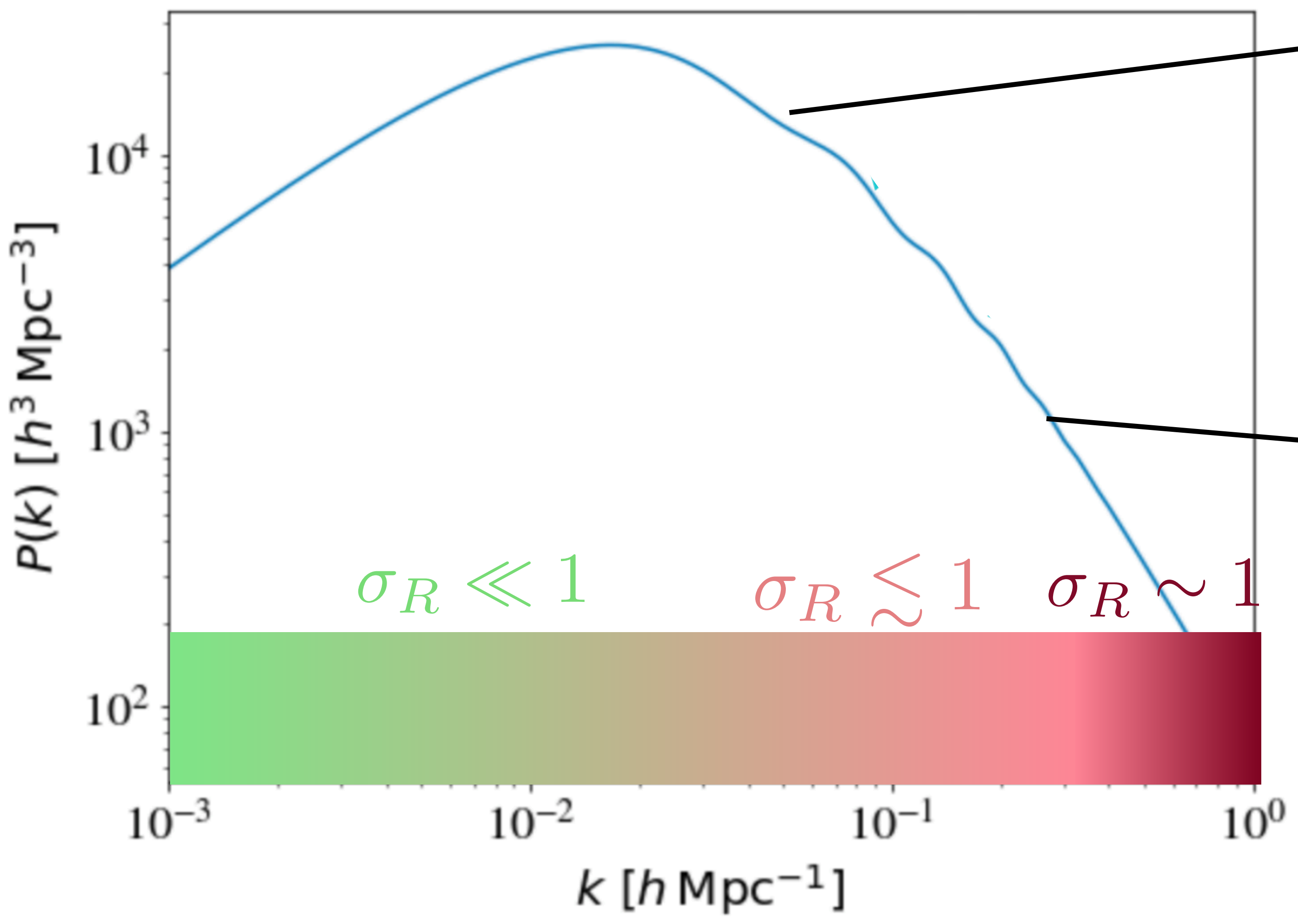
What do we know about the Universe?

Most of the information comes from precision cosmology

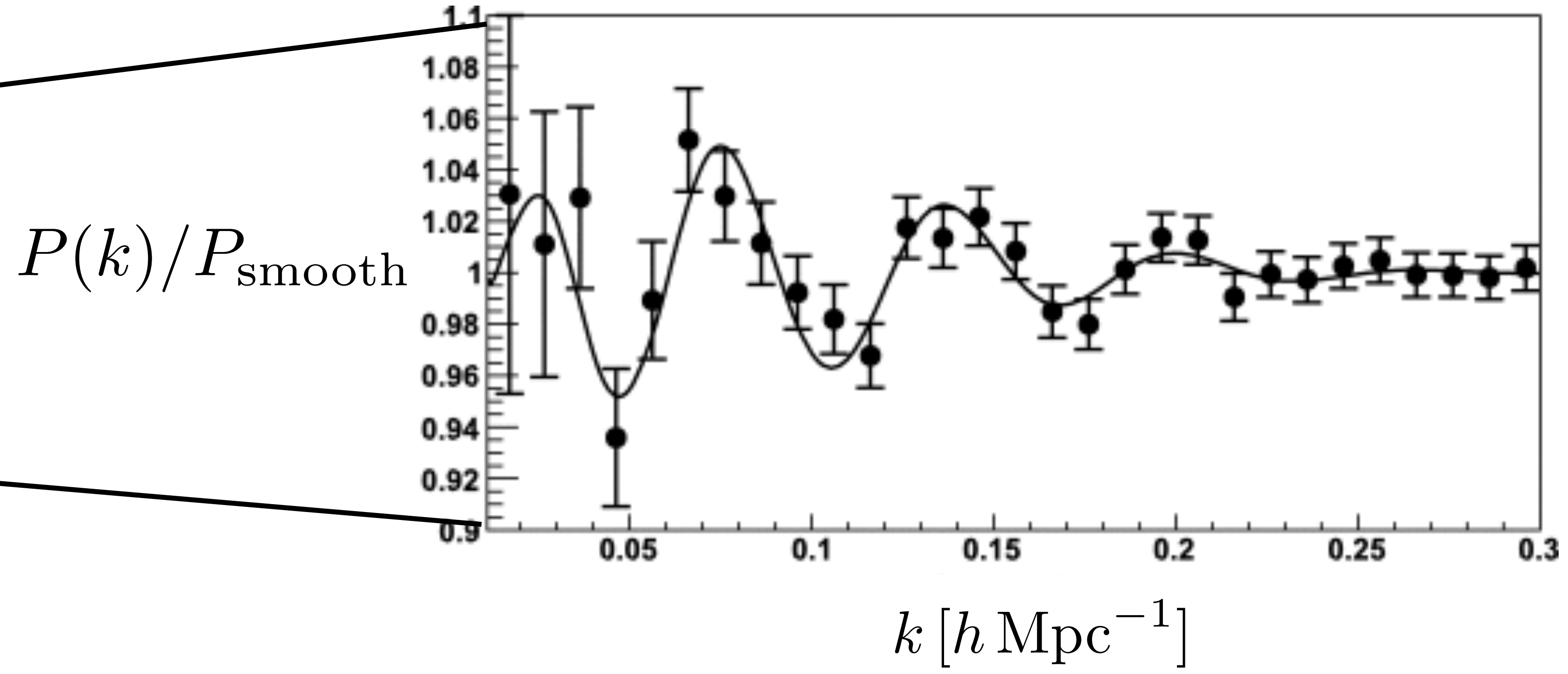
CMB anisotropies around the peak



Power spectrum @ low redshifts



baryonic-acoustic oscillations



$$\sigma_R^2 = \frac{1}{2\pi^2}\int_0^{1/R} k^2 dk P_{\mathrm{lin}}(k)$$

Standard cosmological model

cosmological parameters

primordial parameters

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

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

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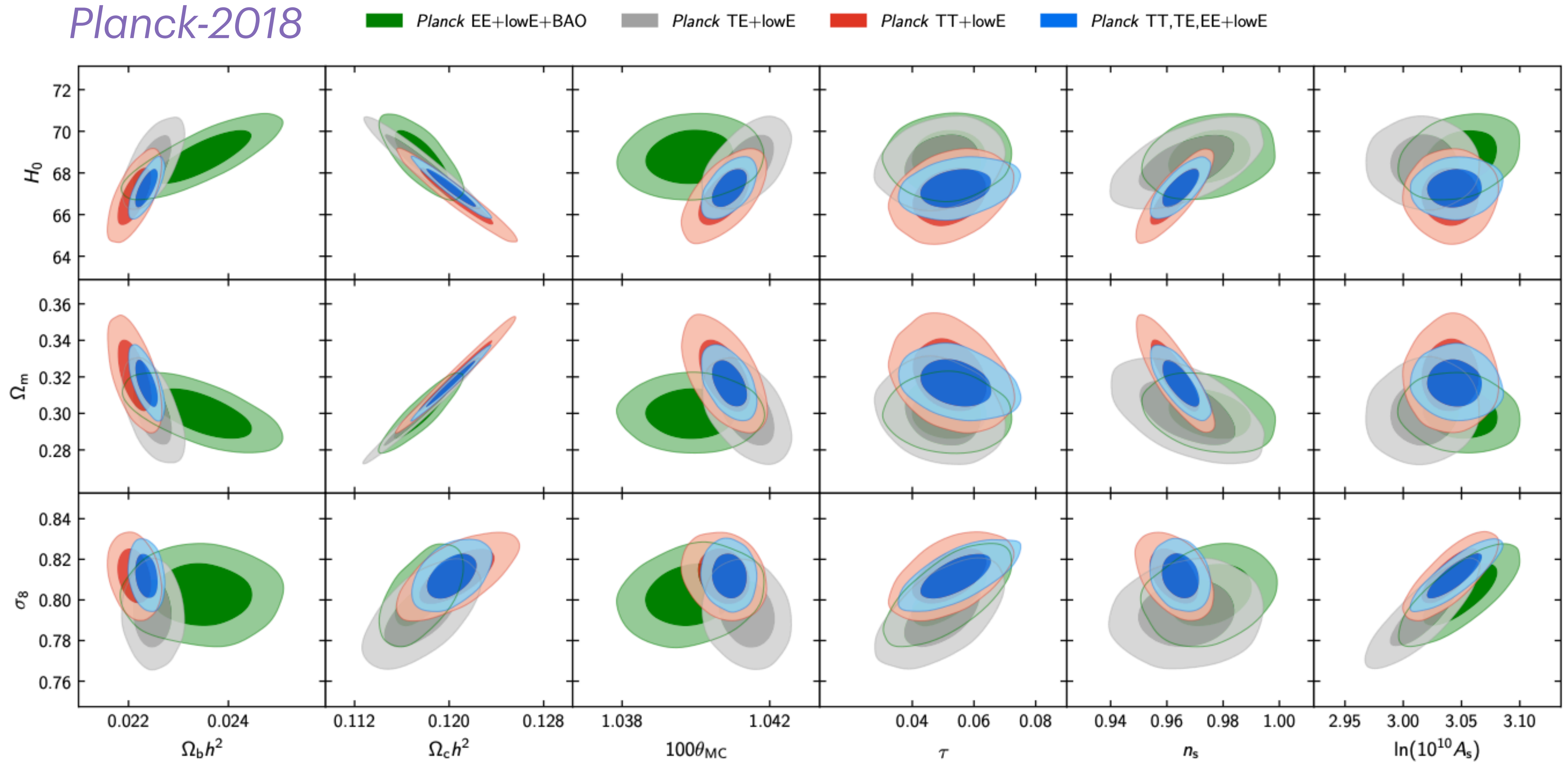
Planck-2018

derived parameters



Input parameters

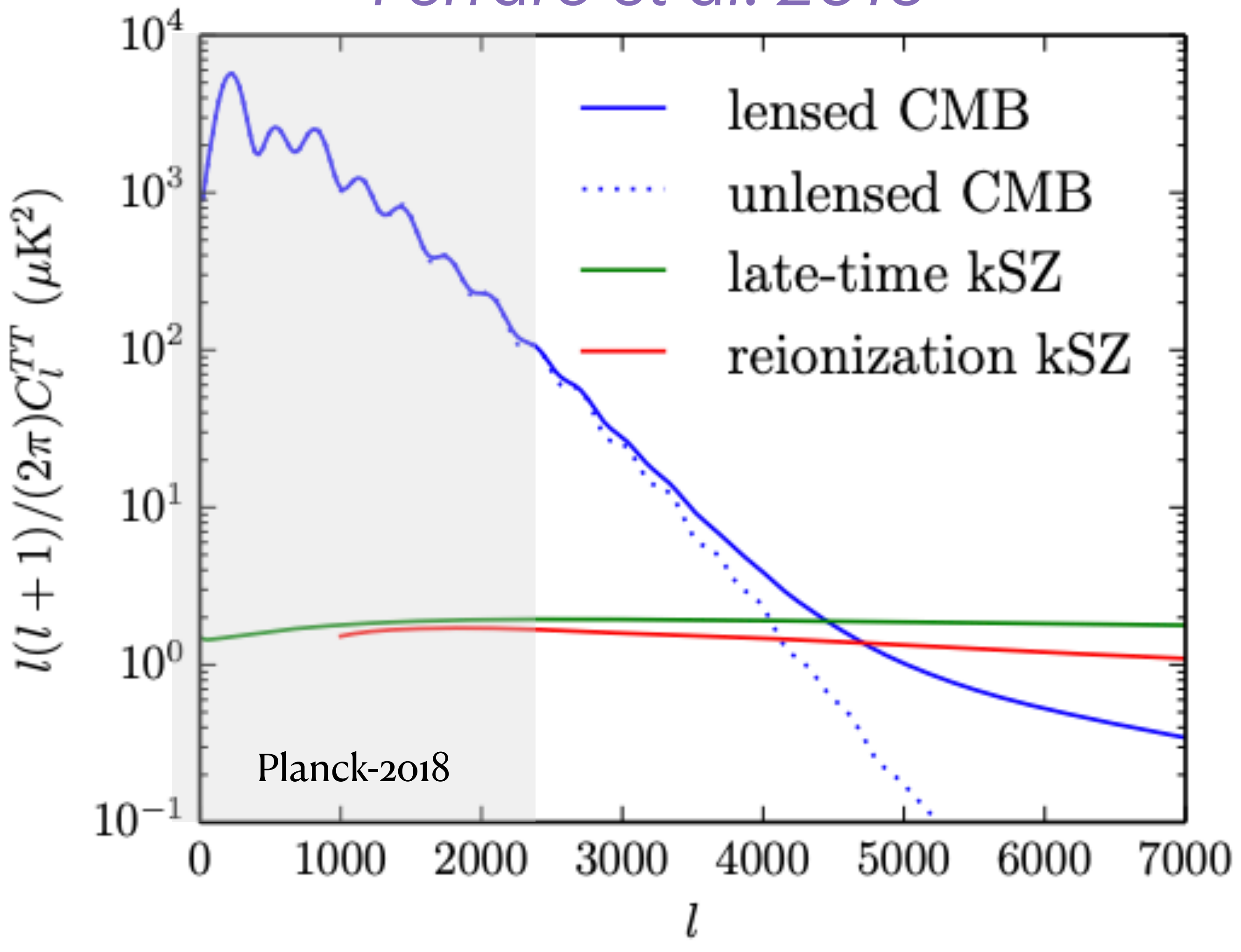
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{\rm MC}$	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 reduce the CMB degeneracy Ω_m vs H_0

What's for the future?

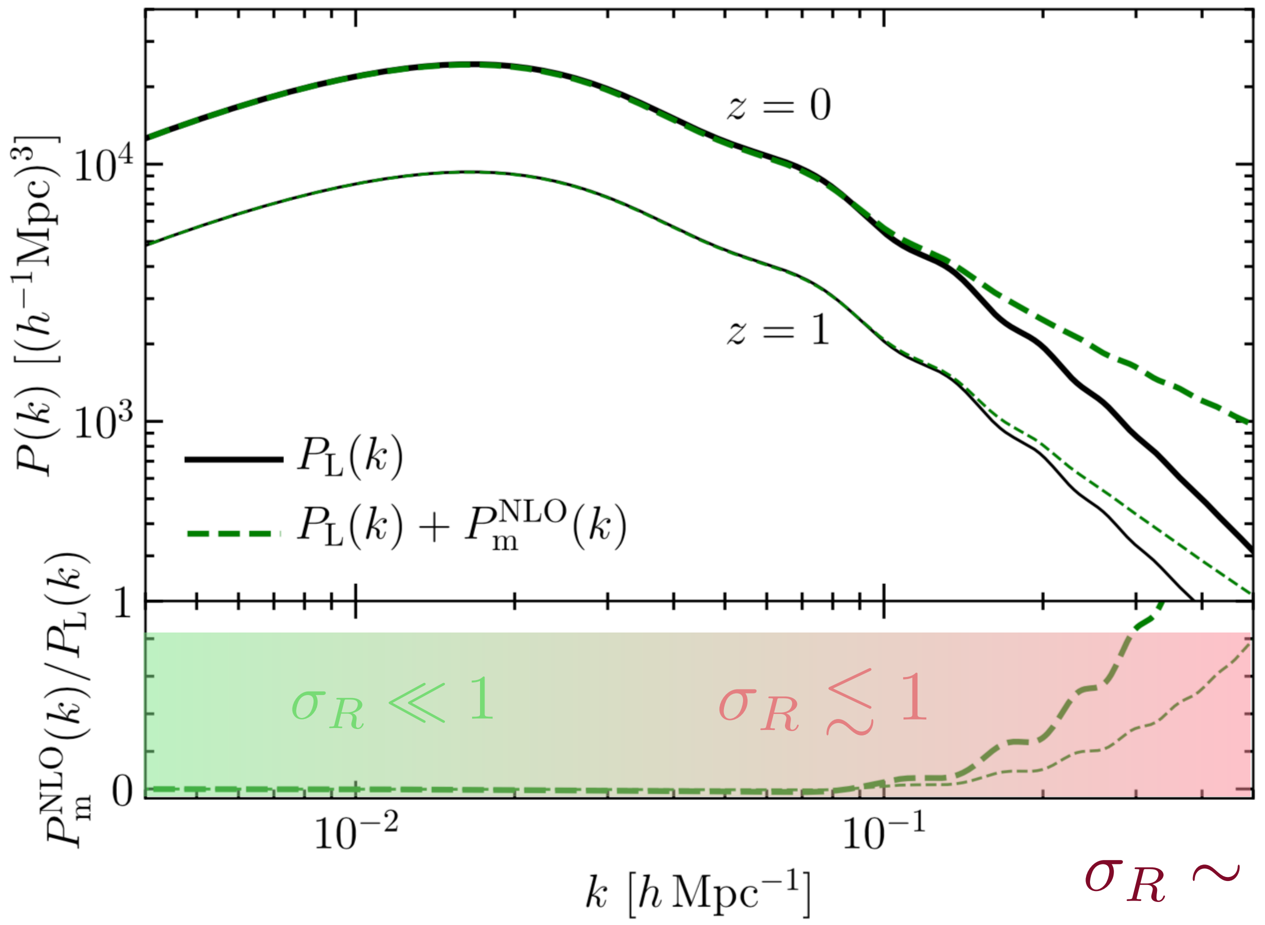
Ferraro et al. 2016



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

Increasing $\ell_{\rm max}$ in the temperature map is limited by small scale fluctuations

Most of the progresses are expected for CMB polarisation



$\sigma_R \sim 1$

$$(S/N)^2|_{\rm LSS} \sim N_{\rm modes}|_{\rm LSS} \sim k^3_{\rm max}{\rm Volume}$$

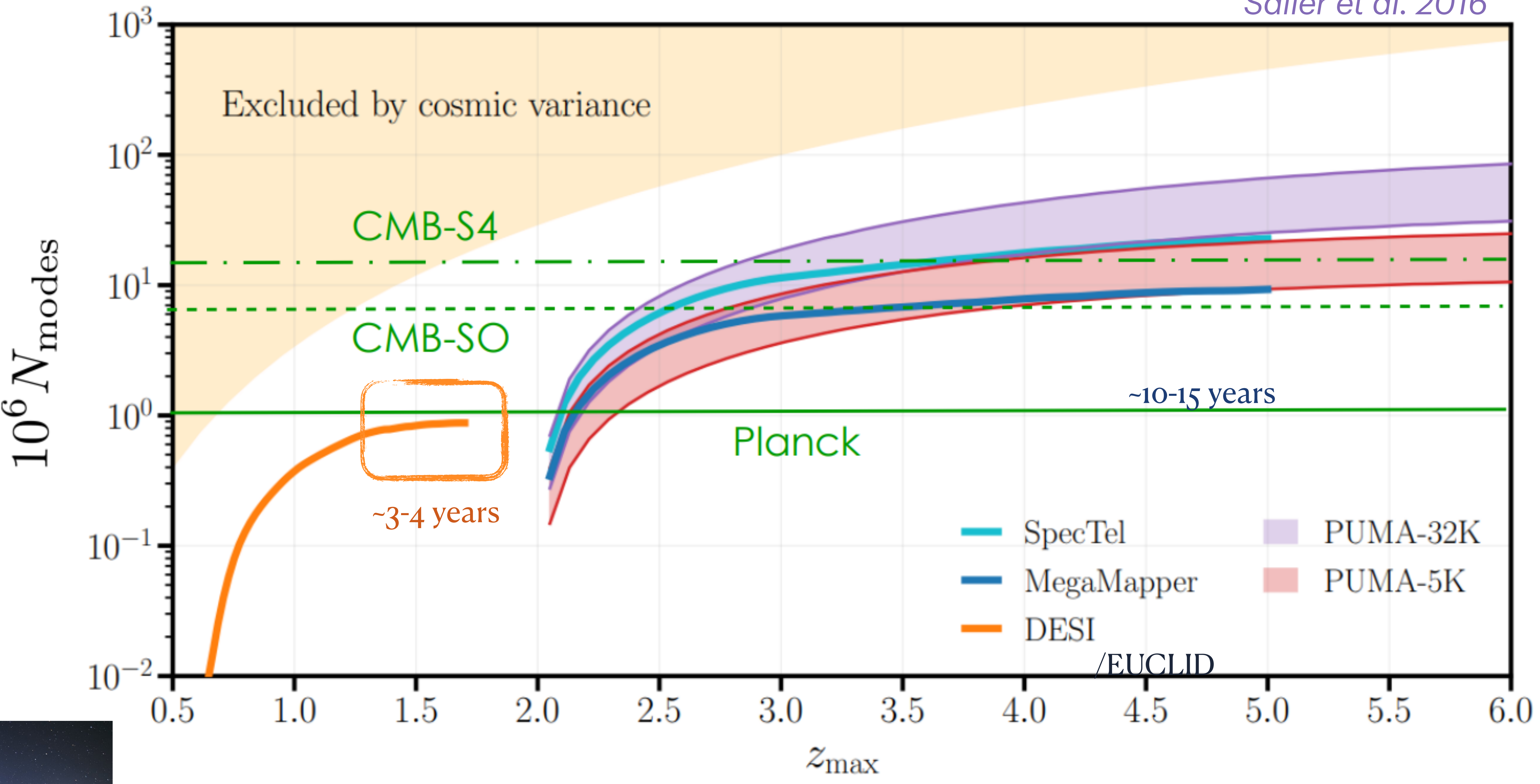
$$\bar{n}_{\rm noise}P(k) \gg 1$$

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

Going to higher redshift allows higher $k_{\rm max}$

Figure of merit

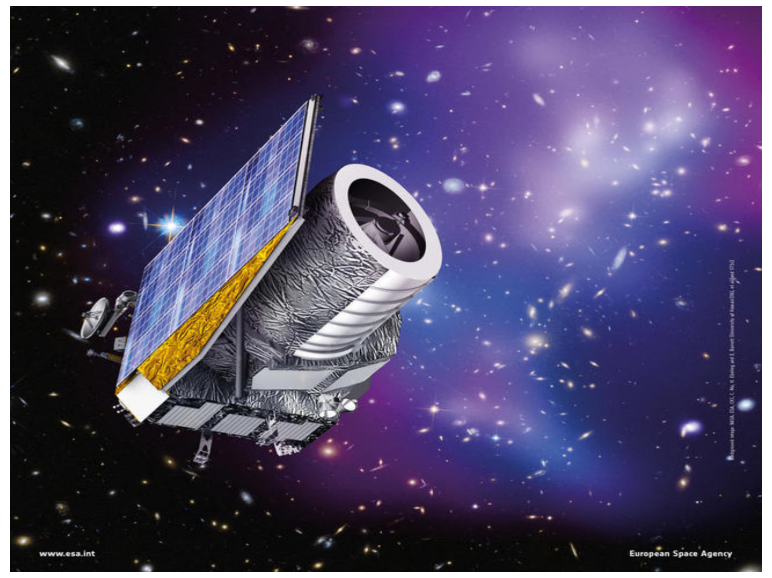
Sailer et al. 2016



Very soon, LSS will become competitive with CMB

DESI: first data
expected in 2024 (BAO today!)

EUCLID: first data
expected in 2025



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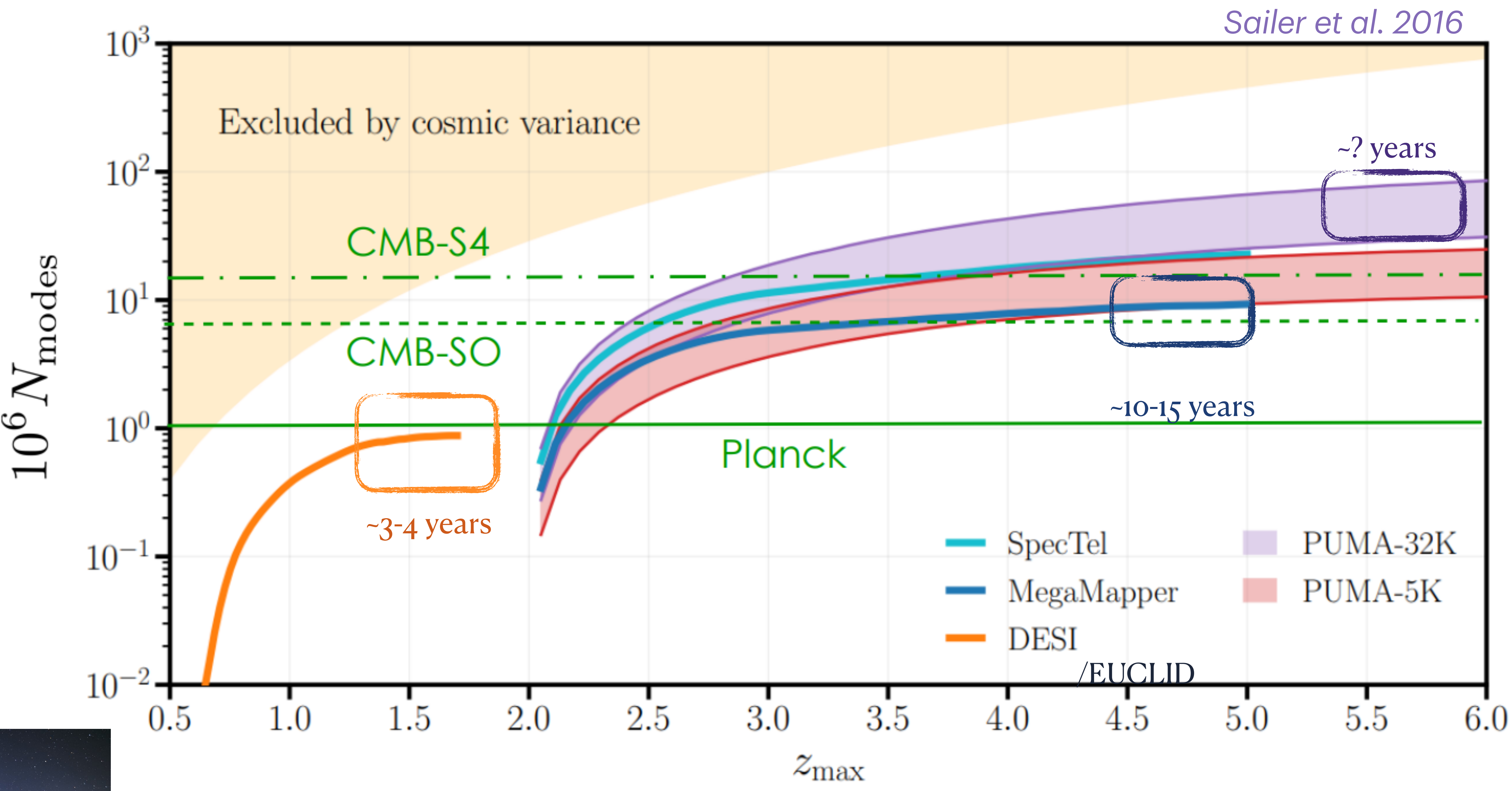

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MegaMapper is likely to happen

21cm ?

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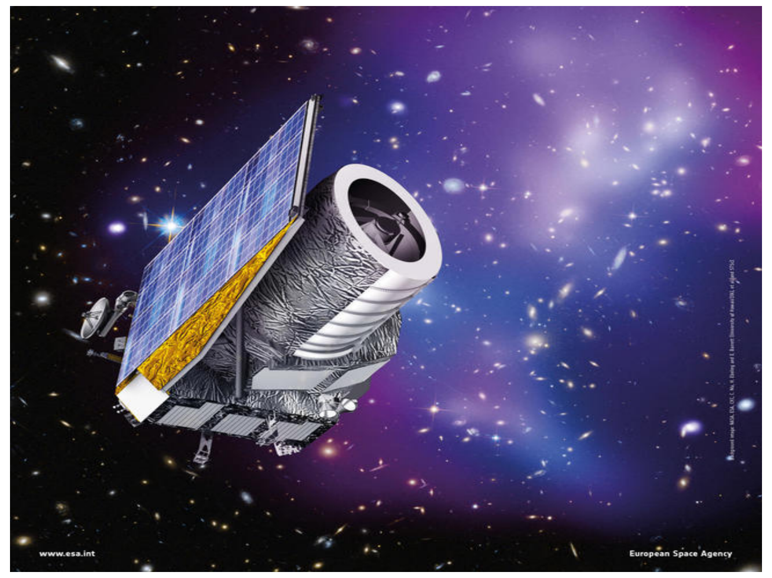
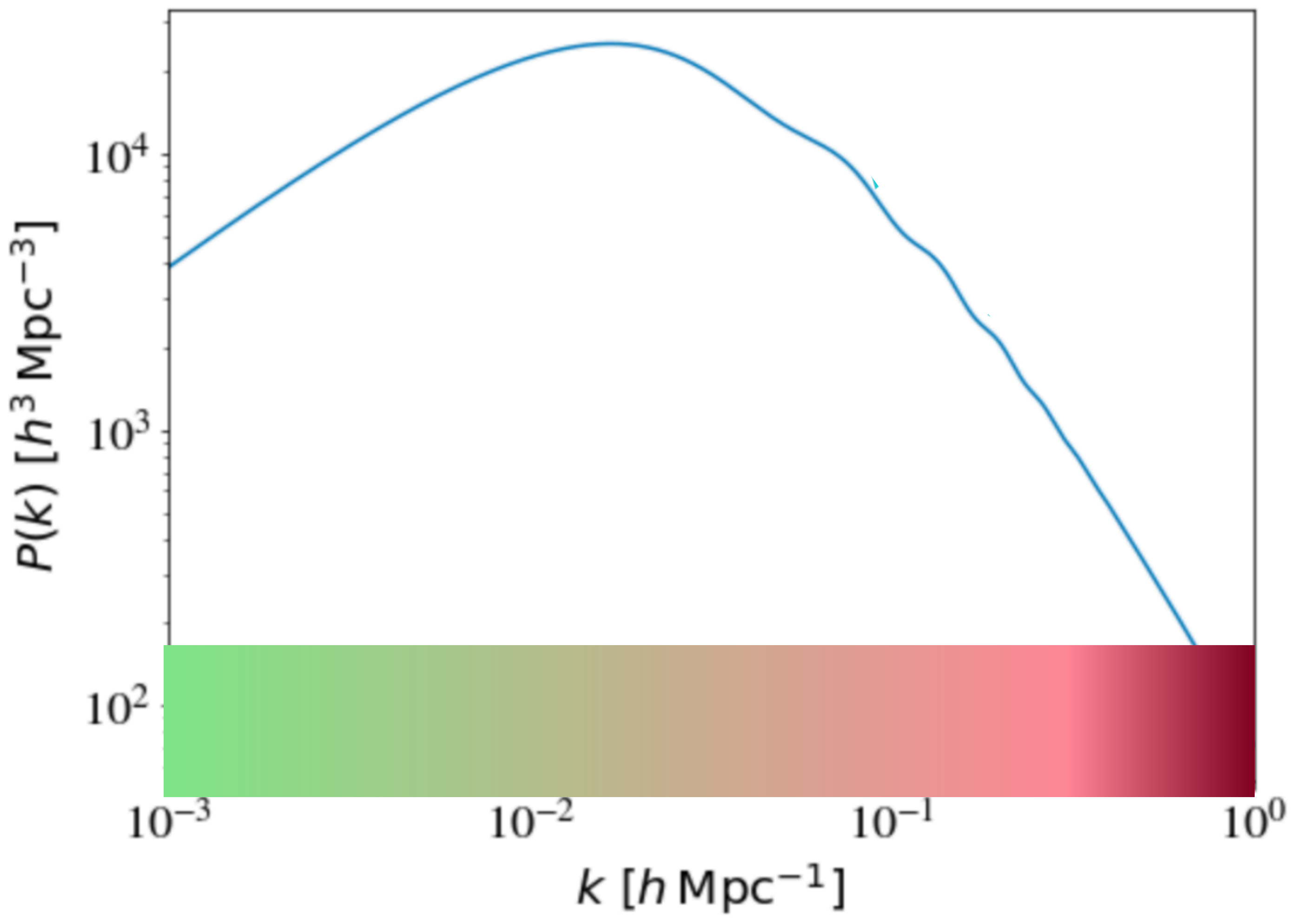


Theory of matter density fluctuations



$\sigma_R \ll 1$ Linear theory of matter perturbations

$\sigma_R \lesssim 1$ Effective field theory of Large Scale Structure (EFT of LSS)

$\sigma_R \sim 1$ N-body simulations *(see Julien's talk)*

$k_{\mathrm{max}} \lesssim 30\ \mathrm{Mpc}$

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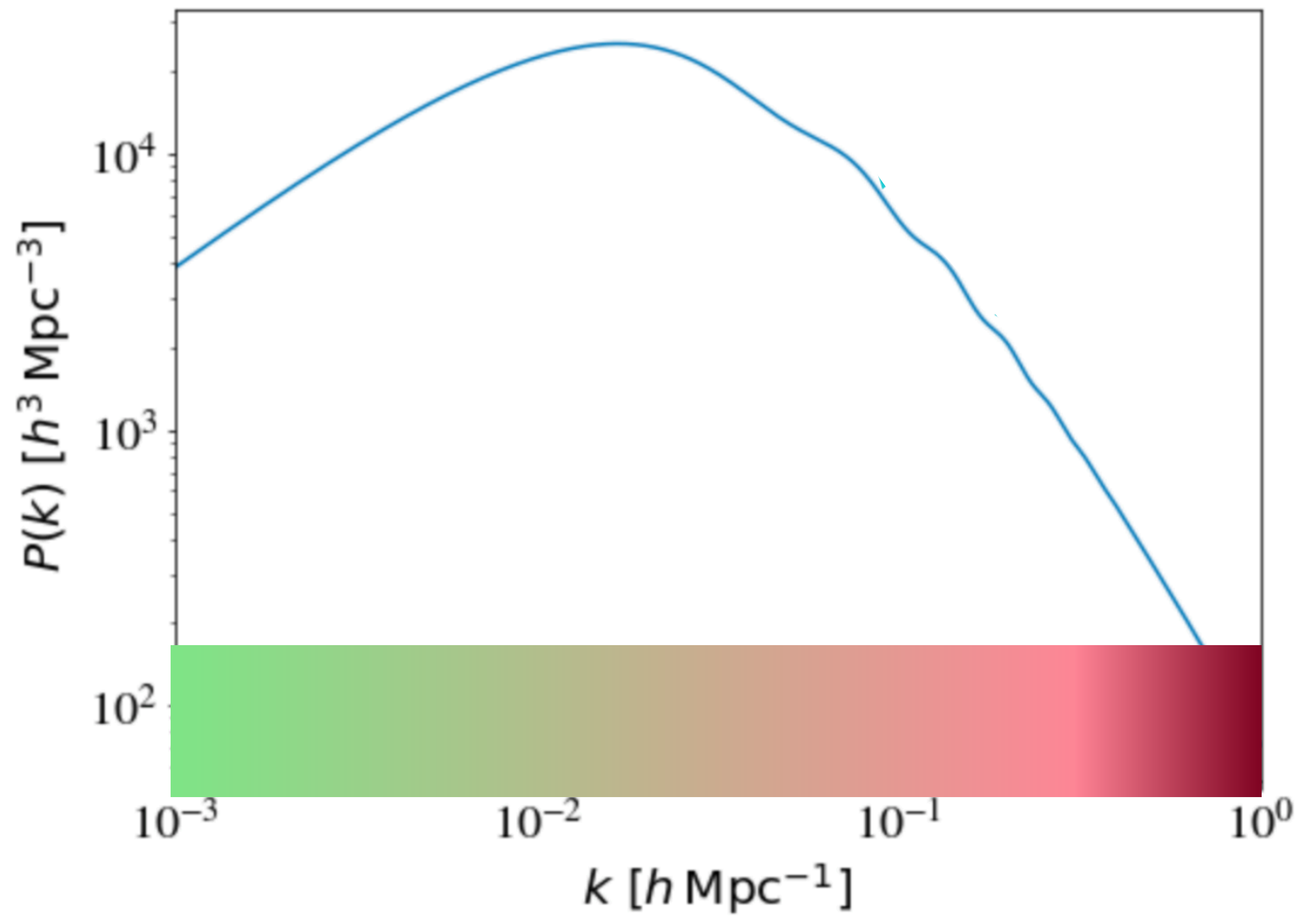

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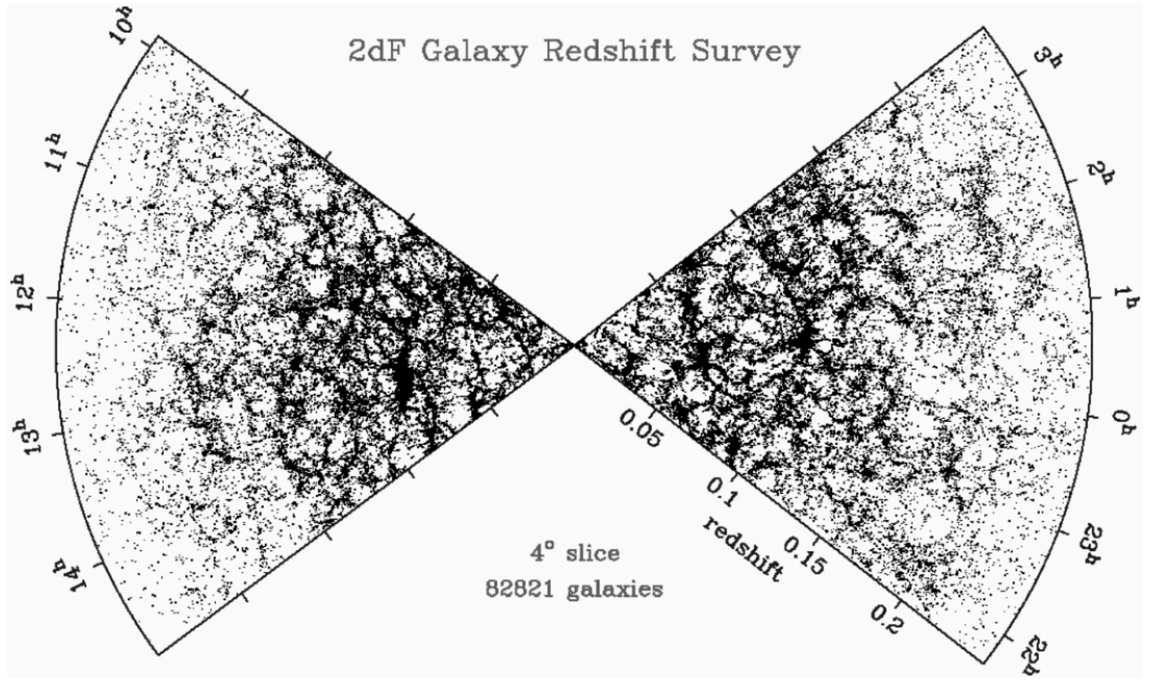
EFT of LSS:

- Large scale d.o.f. is the galaxy number density
- The description is fluid-like (including gravity)
- Small parameters are δ_g , $k/k_{\max}$
- Short distance physics is encoded in a handful of coefficients

Calculating observables

Fundamental physics makes predictions for the matter fluctuations $\delta_m(\vec{k}, z) \equiv \dfrac{\delta \rho_m}{\bar{\rho}_m}$

We observe the distribution of galaxies (angles + redshift) $\delta_g(\vec{k}, z) \equiv \dfrac{\delta n_g}{\bar{n}_g}$



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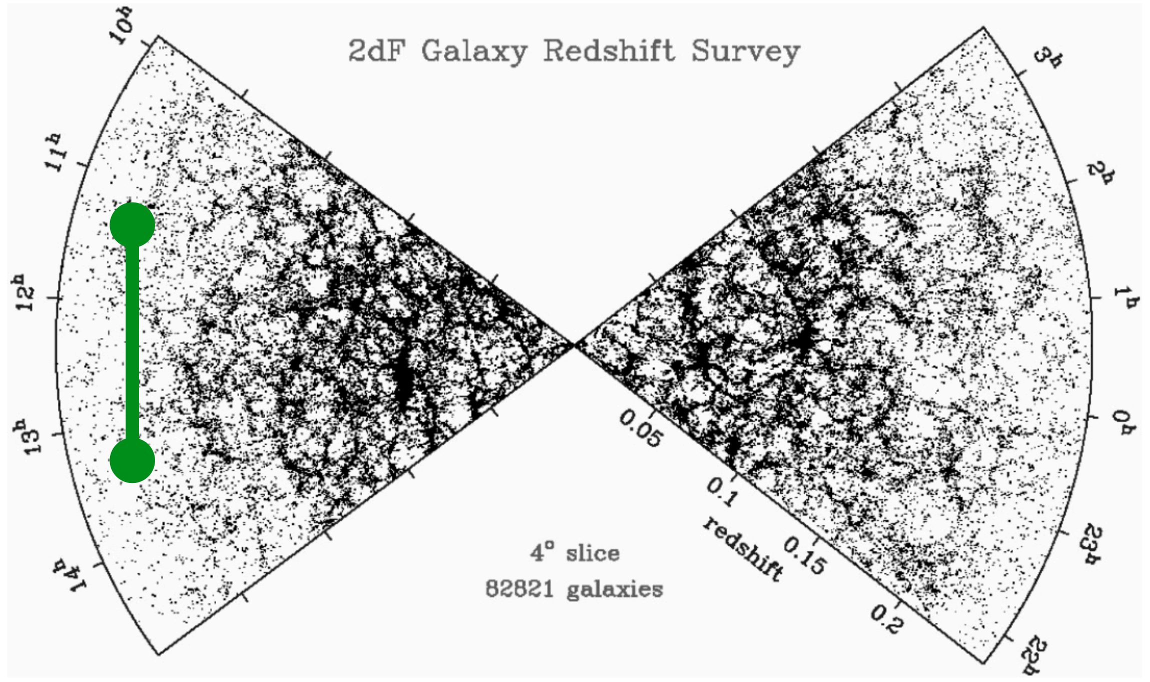

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$\langle \delta_g(p) \delta_g(k) \rangle = (2\pi)^3 \delta^{(3)}(p+k) P_g(k)$ POWER SPECTRUM (linear + non-linear)

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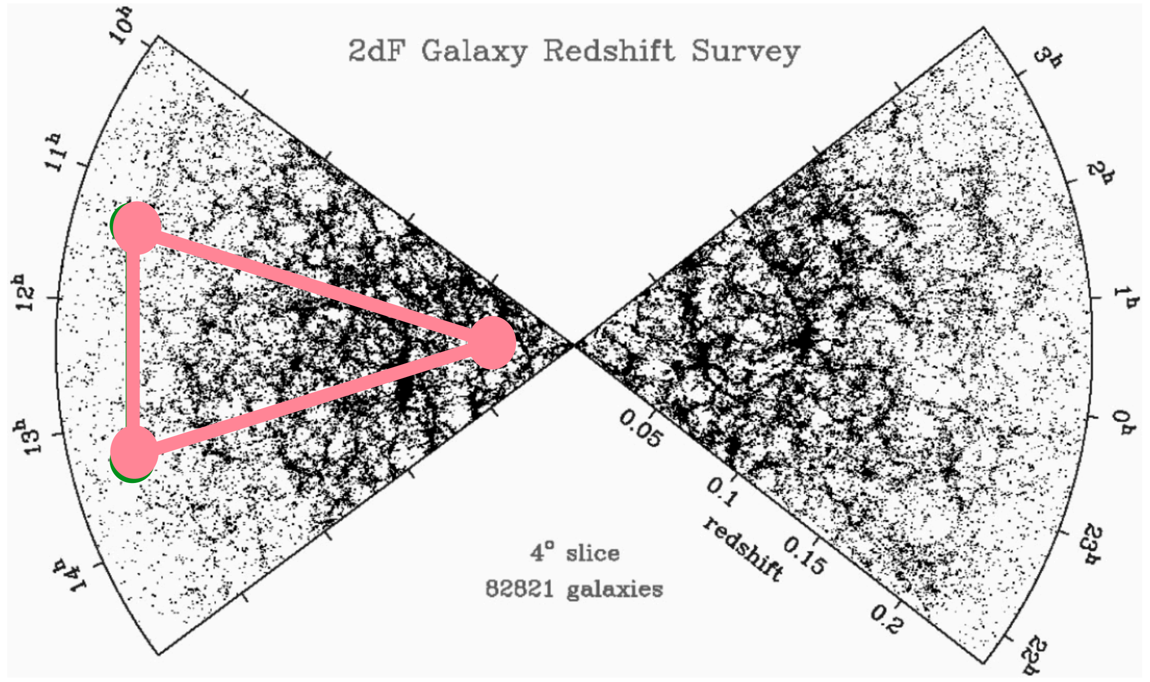

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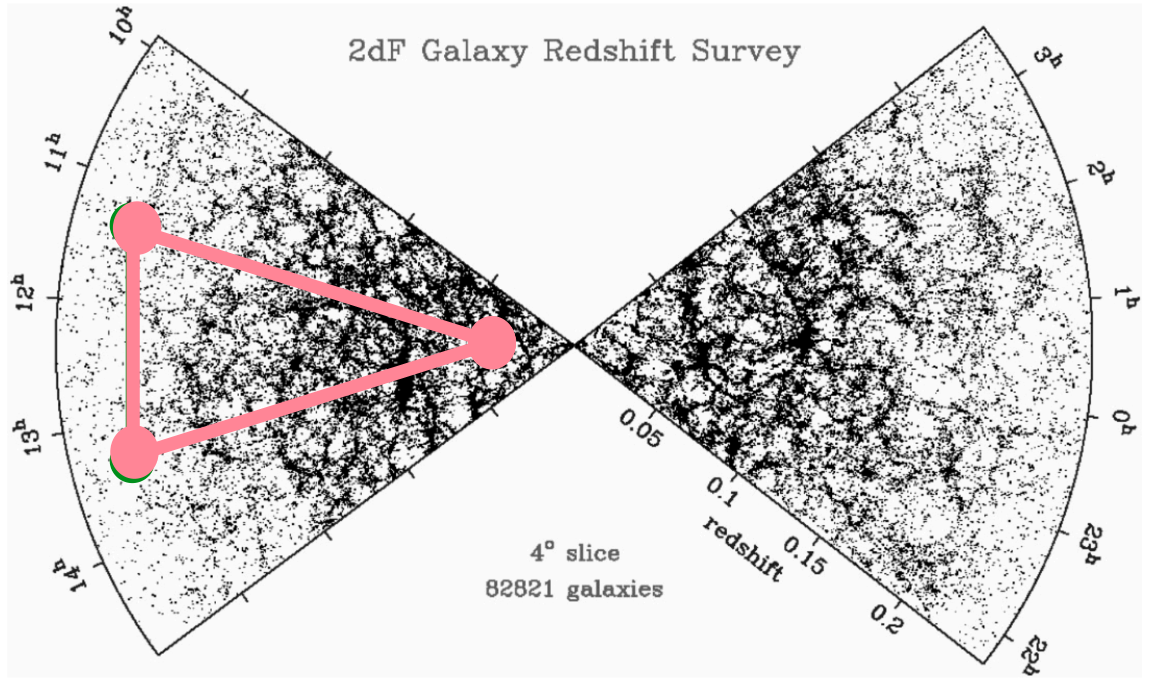

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Galaxy overdensities tracks matter overdensities $\delta_g = b_1 \delta_m + \frac{b_2}{2}\delta_m^2 + b_{K^2} K_{ij}K^{ij} + \dots$

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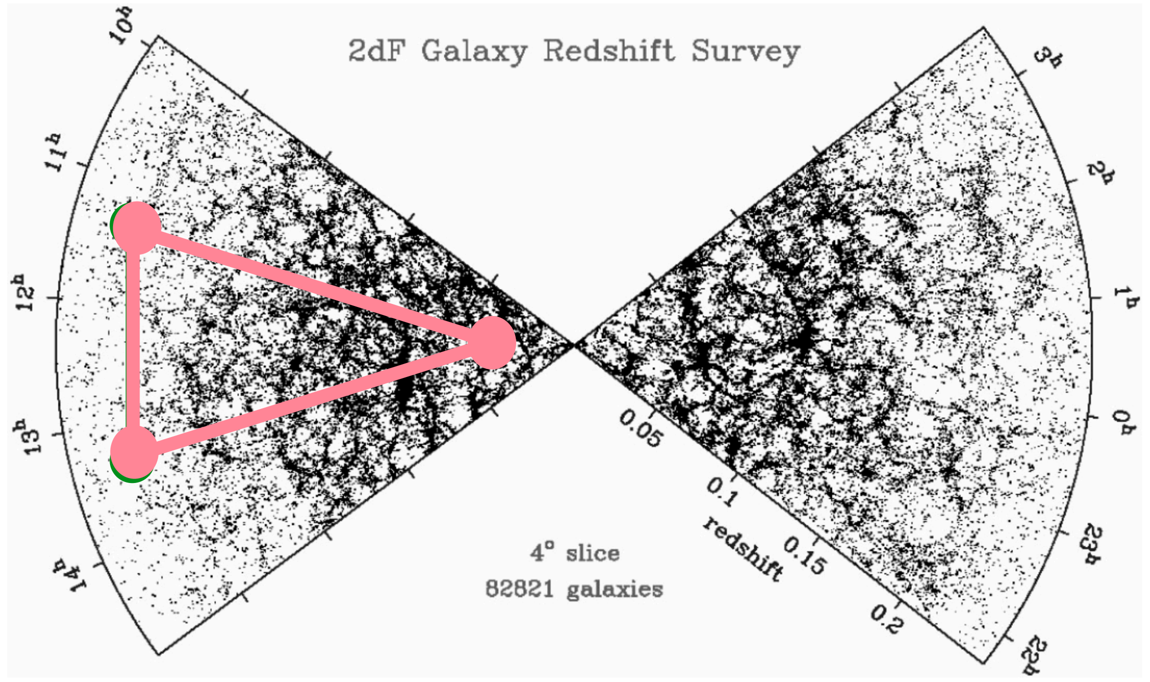

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(time-dependent) bias parameters
encoding physics on halo scales

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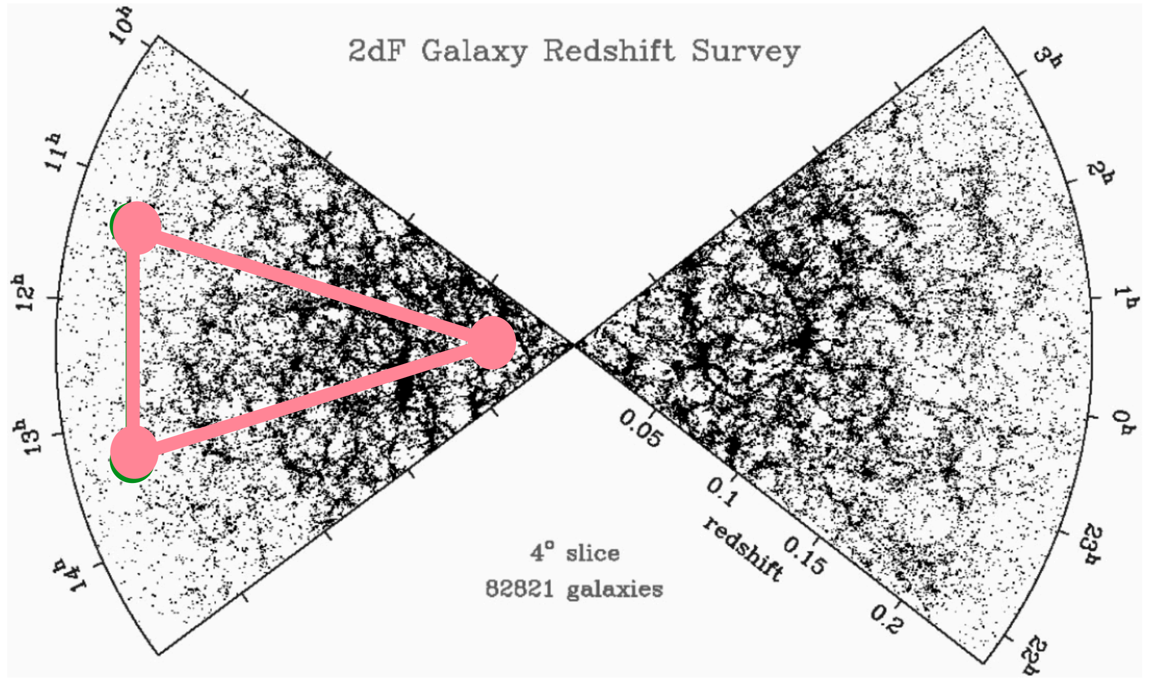

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Galaxy correlators can be expressed in terms of correlators of underlying fields

Our analysis is in redshift space, here real space for simplicity

Calculating observables in LCDM

Starting from the Boltzmann equation of a collisionless fluid, in matter domination for sub-horizon scales

$$\delta'_m + \theta_m + \nabla_i(\delta_m v^i_m) = 0 \ ,$$

Carrasco et al 2012, Baumann et al 2012

$$\theta'_m + \mathcal{H}\theta_m + \frac{3}{2}\mathcal{H}^2\delta_m + \nabla_i(v^j_m \nabla_j v^i_m) = \frac{1}{\bar{\rho}_m}\nabla_i\nabla_j\tau^{ij}_{\rm eff}$$

effective stress-energy tensor,
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Matter density and velocity fluctuations

$(\theta_m \equiv \nabla_i v^i_m)$

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Non-linear kernels in LCDM
(gravity induces mode coupling)

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For example

$$F_2(\vec k_1, \vec k_2) = \frac{5}{7} + \frac{\vec k_1\cdot\vec k_2}{2}\left(\frac{1}{k_1^2}+\frac{1}{k_2^2}\right) + \frac{2}{7}\frac{(\vec k_1\cdot\vec k_2)^2}{k_1^2 k_2^2}$$

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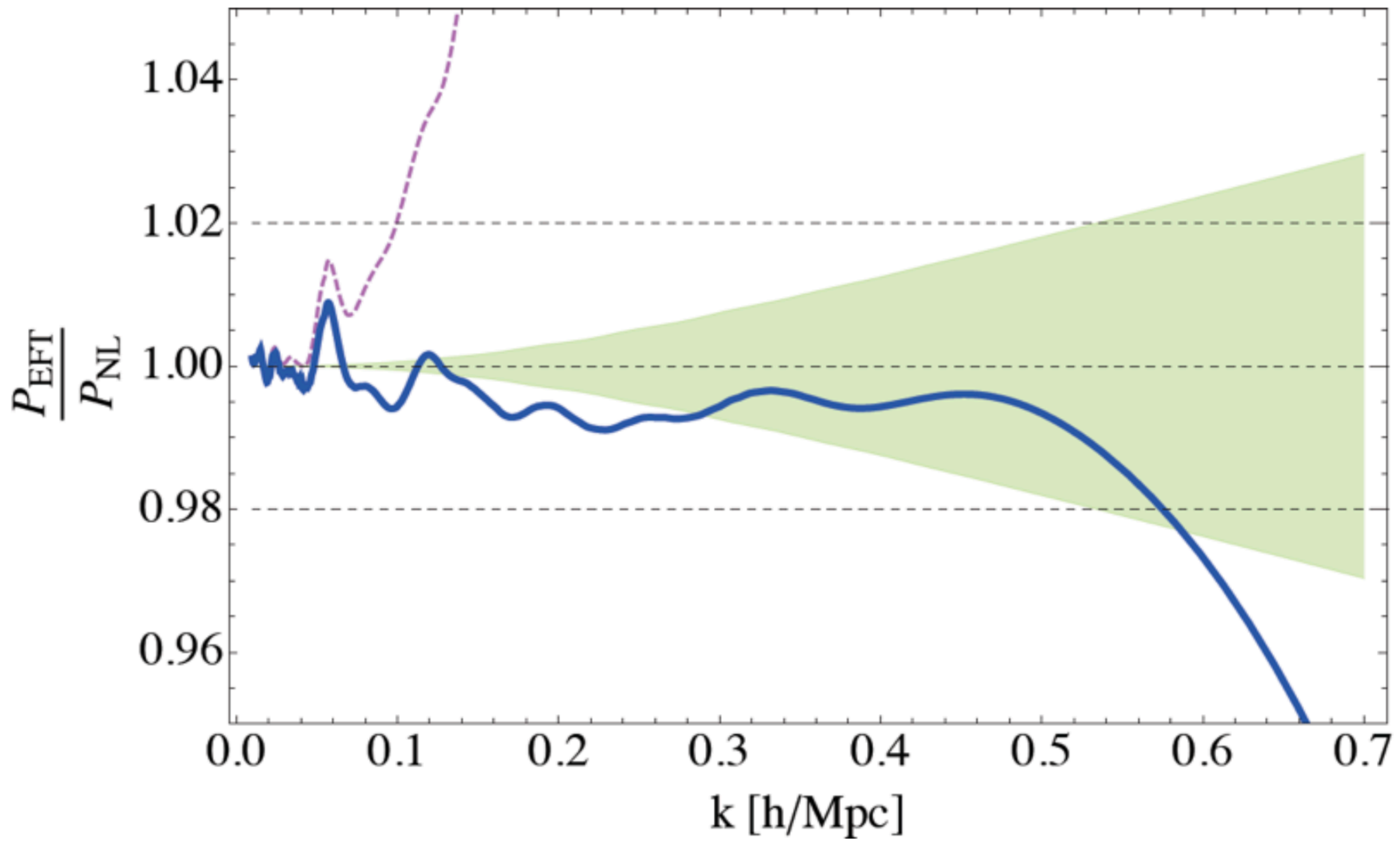
Successes of the LSS program

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



+Bispectrum up to $k_{\rm NL} \simeq 0.15 \text{ h/Mpc}$

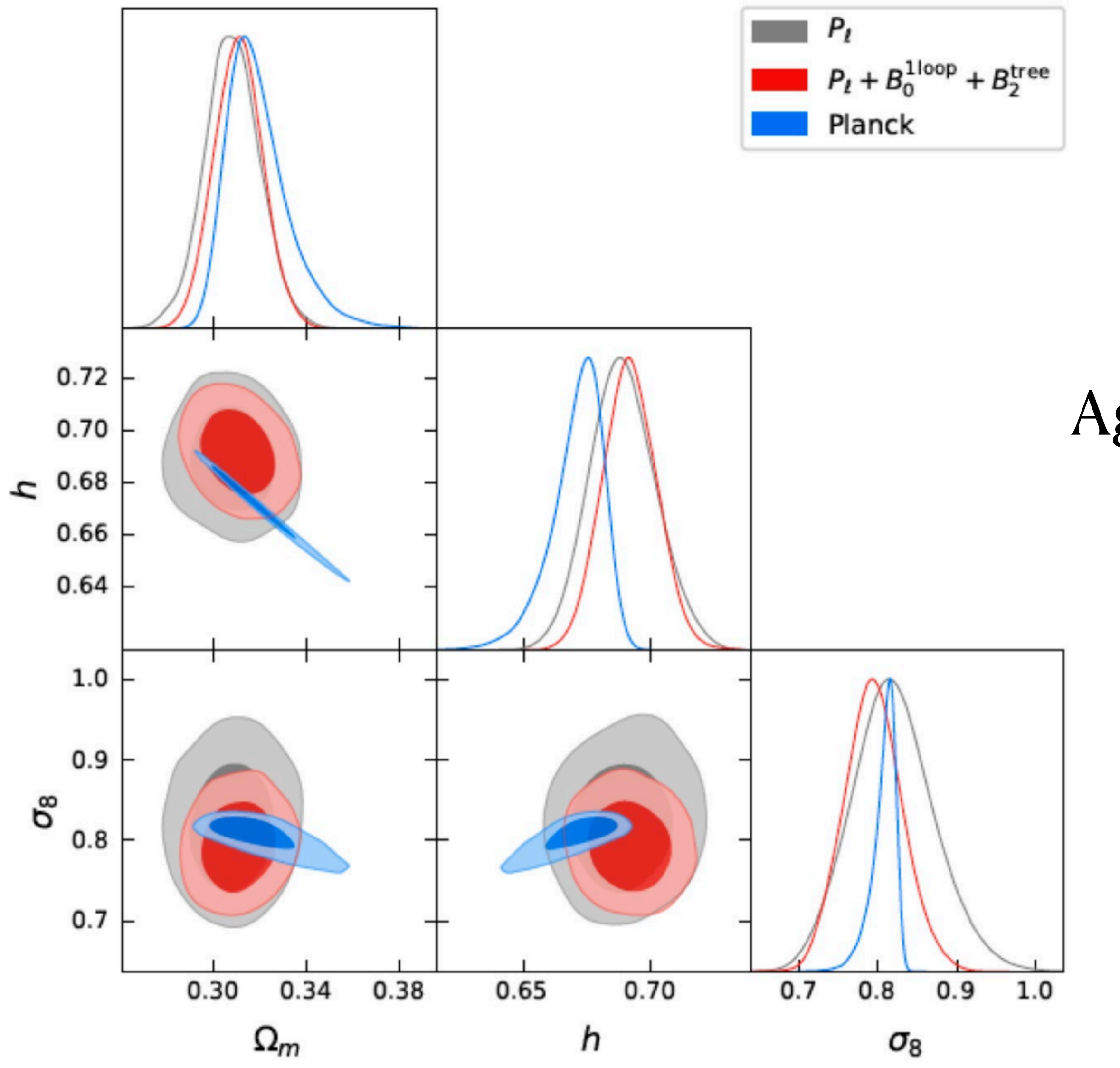
$$k_{\rm NL} \simeq 0.08$$

Great amount of information extracted from BOSS data

D'Amico, Lewandowski, Senatore, Zhang + others

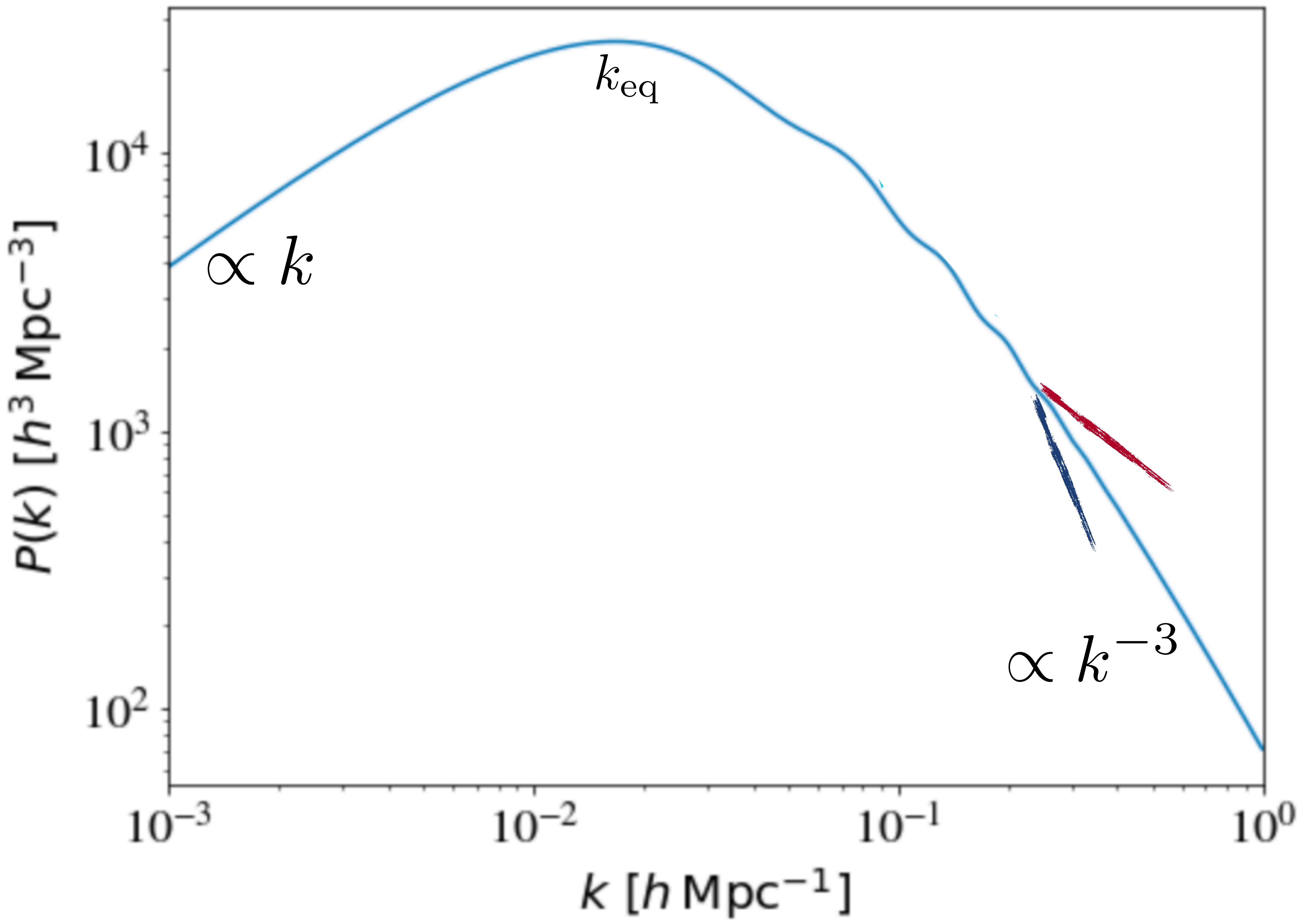
Ivanov, Philcox, Simonovic, Zaldarriaga+ others

Full shape analysis of BOSS data with BBN prior



Agreement with Planck for H_0

New features in the Power Spectrum



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Raise: Isocurvatures, Long range forces,...

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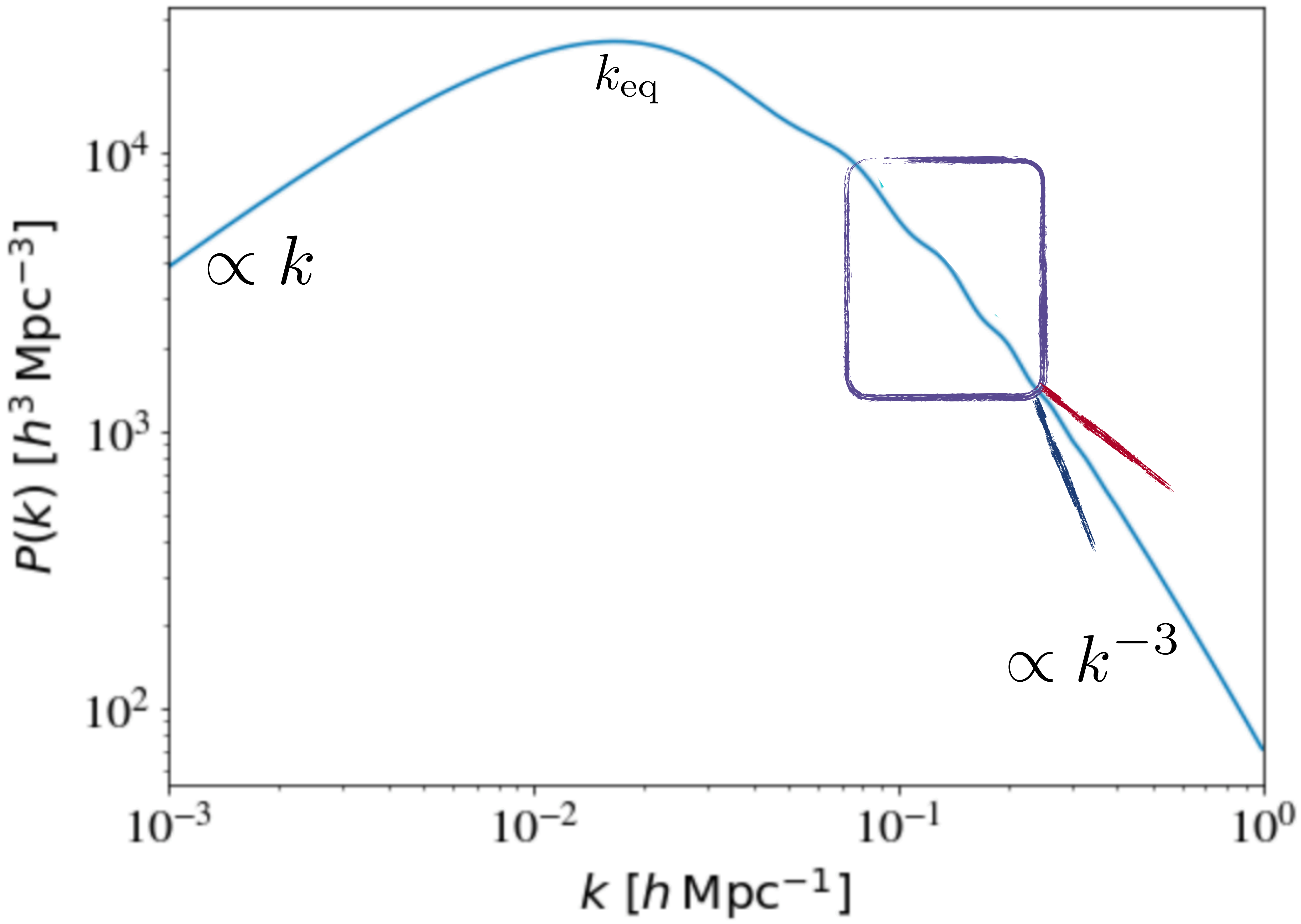

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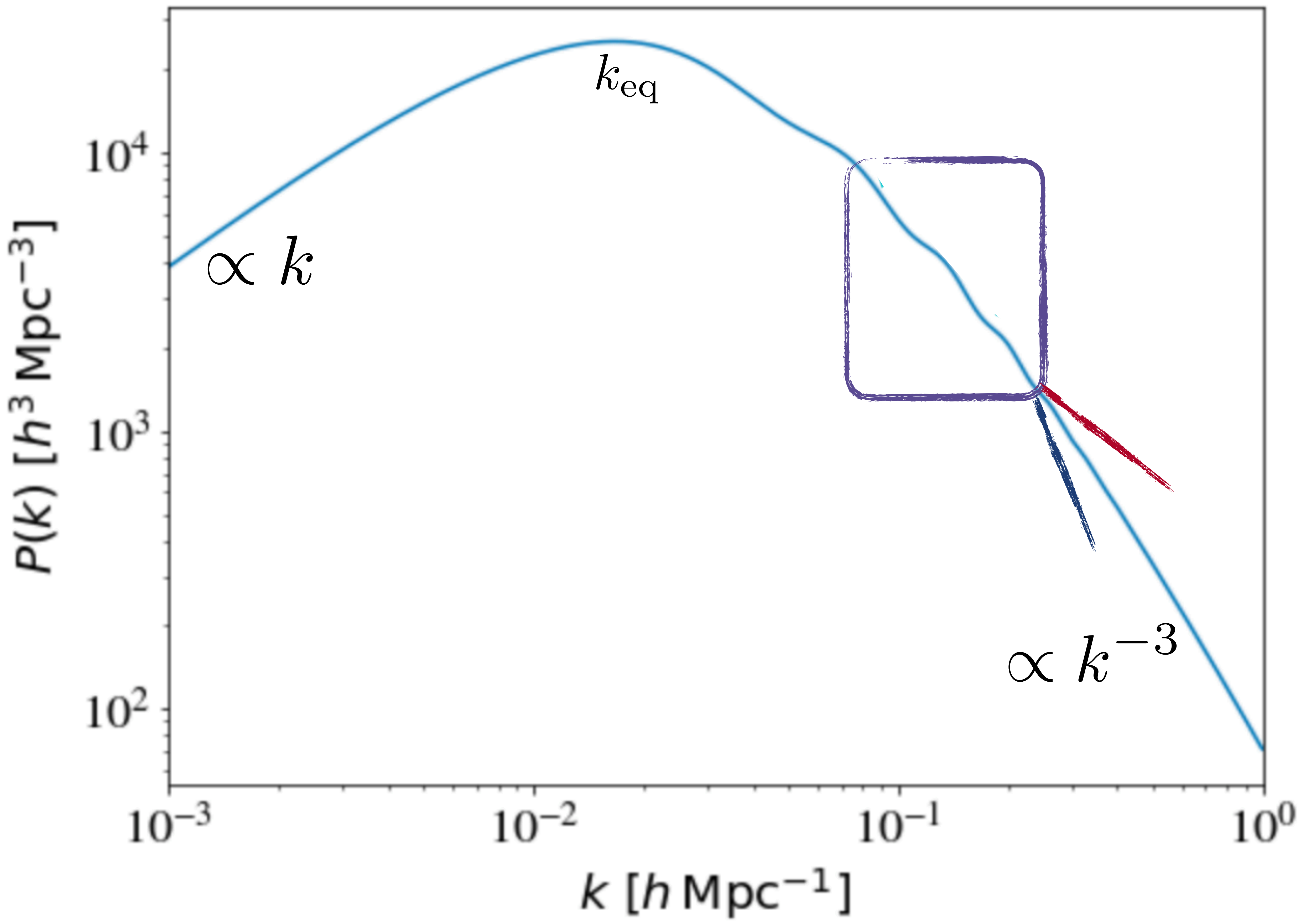
Raise: Isocurvatures, Long range forces,...

Features: dark matter-dark radiation,...

New features in the Power Spectrum



Drop: new relativistic species, fuzzy dark matter, dark radiation...

Raise: Isocurvatures, Long range forces,...

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Extending the EFTofLSS to BSM allows to use the full shape information of the power spectrum

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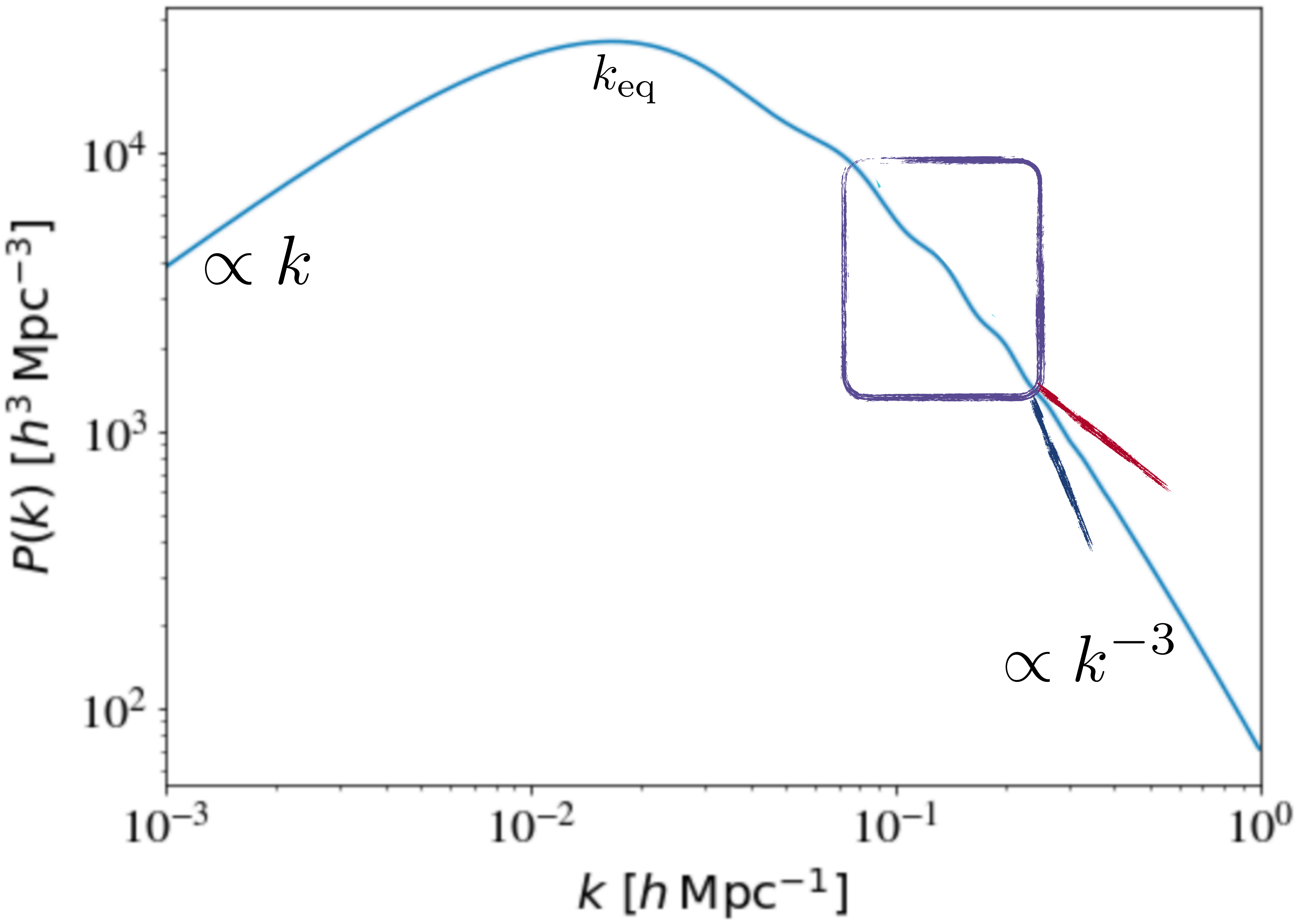

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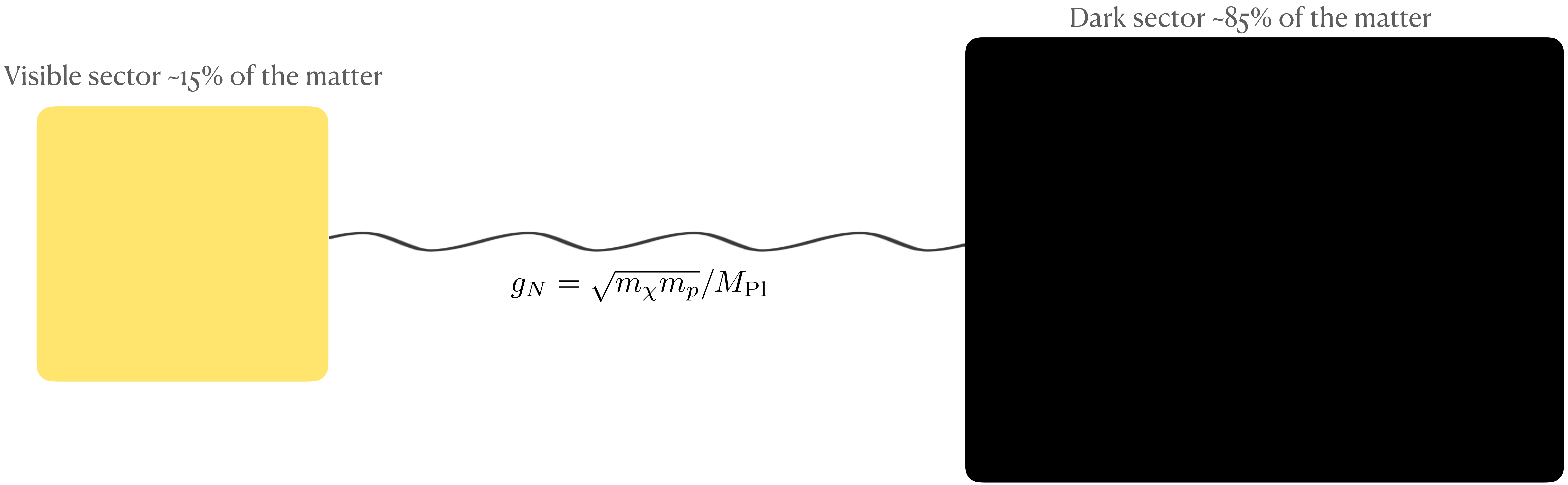
Is there room for discovery something new @ DESI & EUCLID?

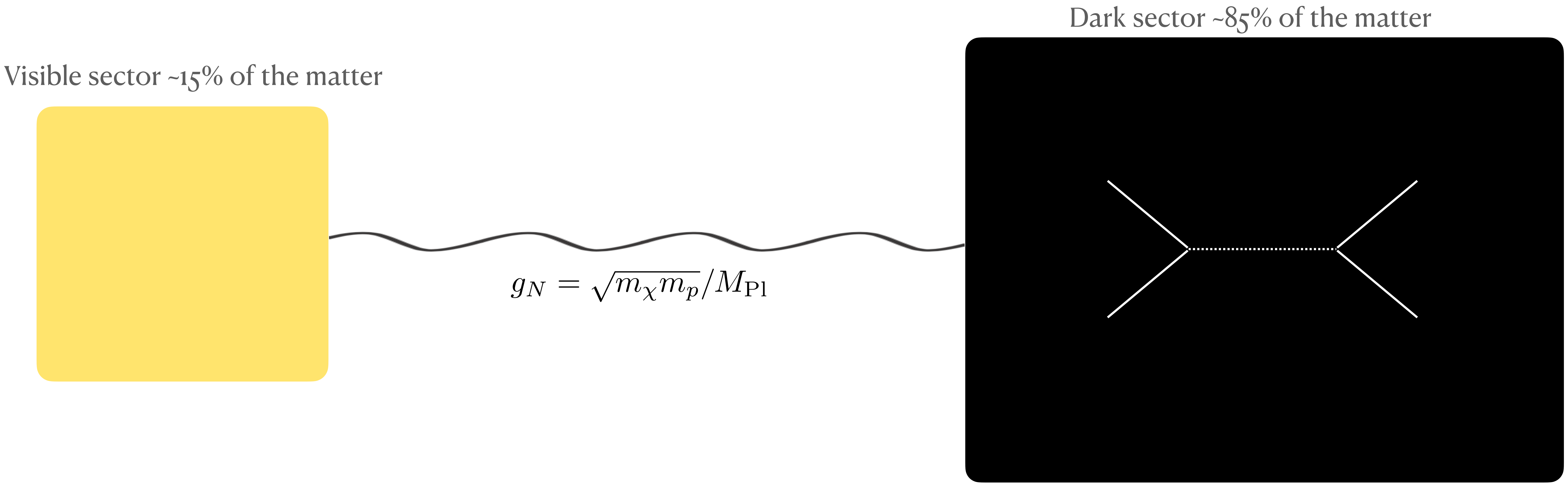
The Dark Sector might be Dark

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

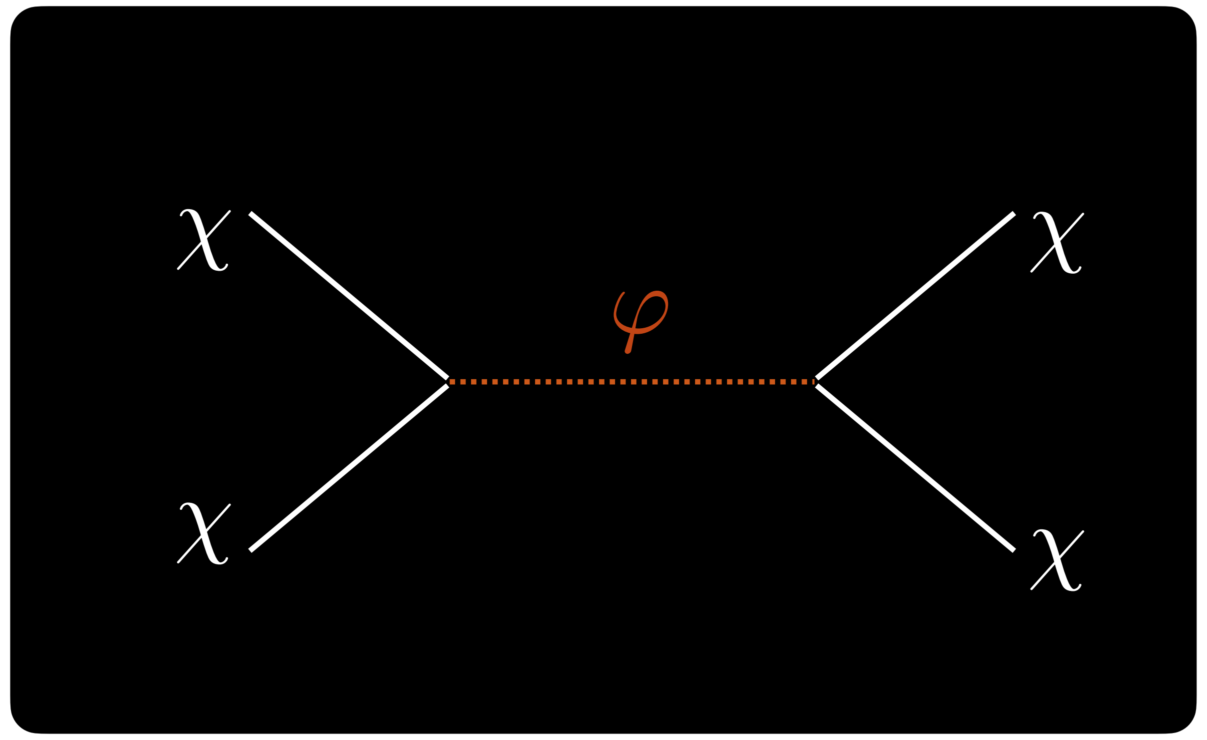


The Dark Sector might be Dark

Is the Dark Matter (or a fraction of it) self-interacting? At what range?



Toy Model

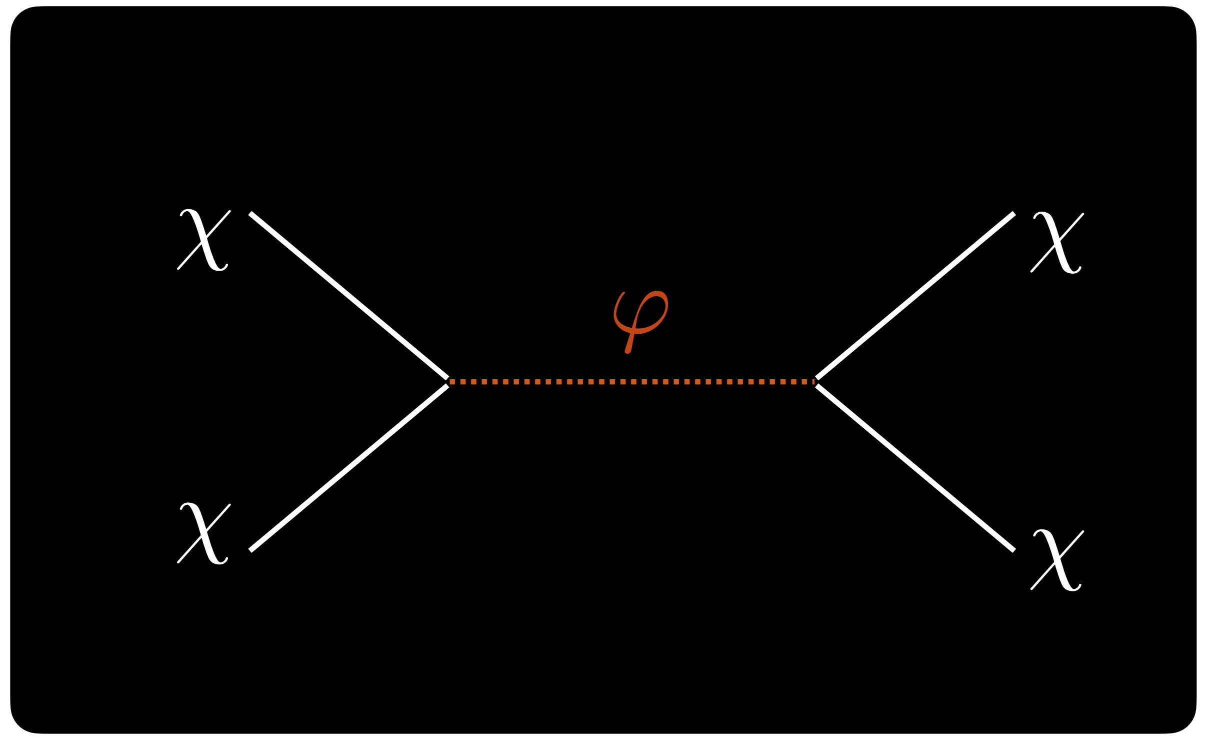


$$(m_\chi^2 + \kappa\varphi)\chi^2$$

Effective Newton constant for the new mediator

$$G_s \equiv \kappa^2/m_\chi^4 = 4\pi\beta G_N$$

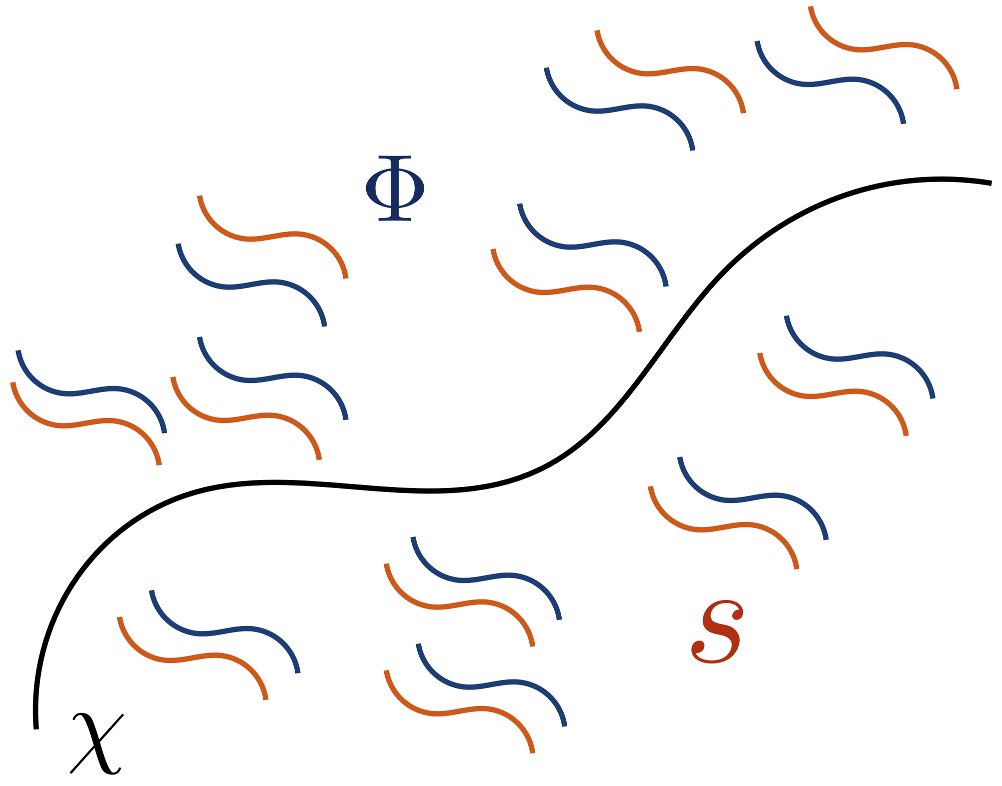
Toy Model



$$(m_\chi^2 + \kappa\varphi)\chi^2$$

$$m_\chi^2(s)\chi^2$$

self-interaction = field dependent DM mass



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Define a new scalar potential, s

$$s \equiv \sqrt{G_s}\varphi$$

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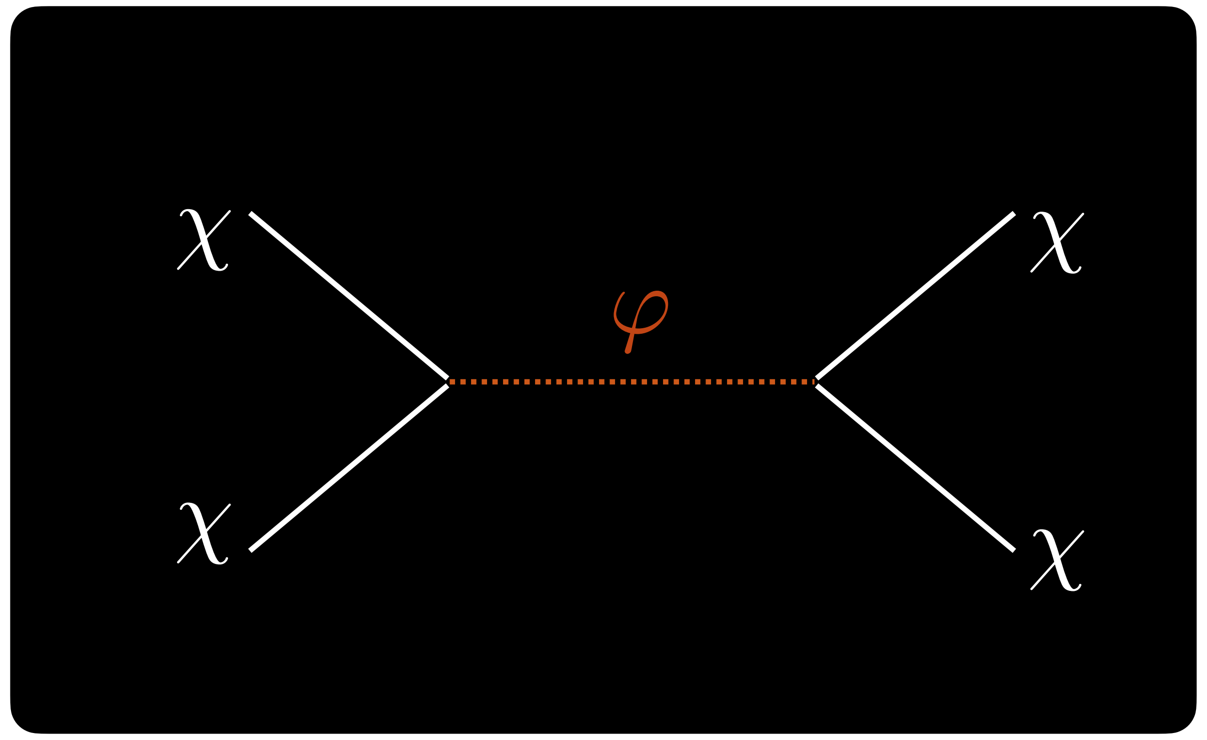

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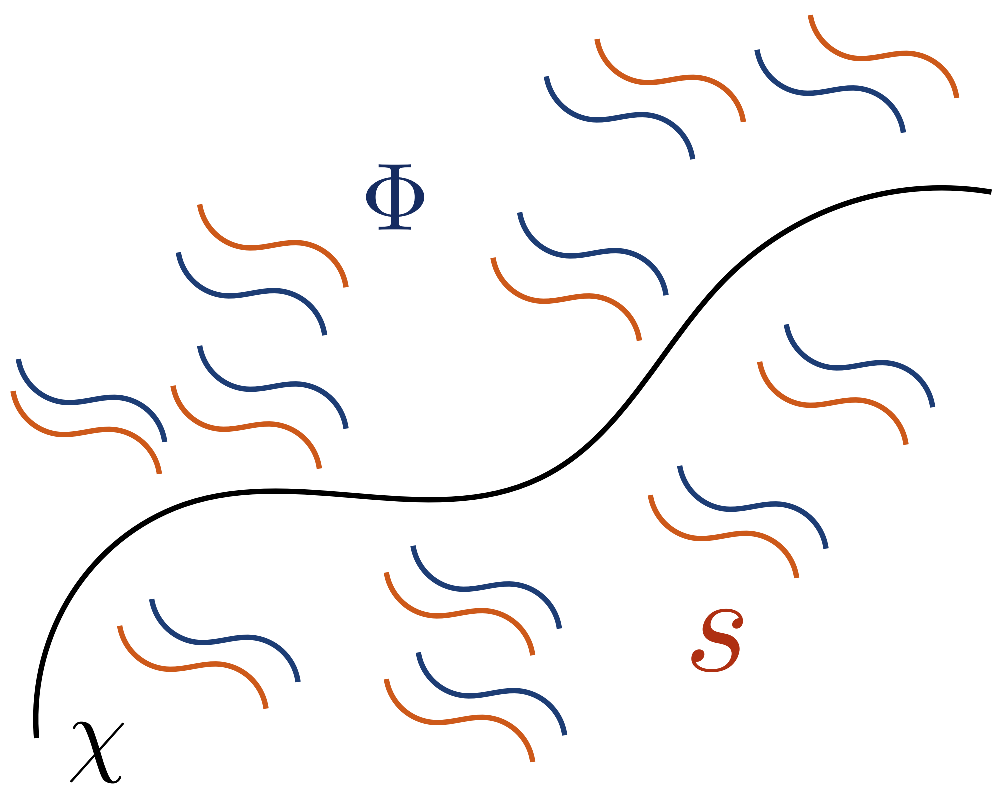

$$2G_s\mathcal{L}_s = (\partial s)^2 + m_s^2 s^2 + \mathcal{O}(1/G_s)$$

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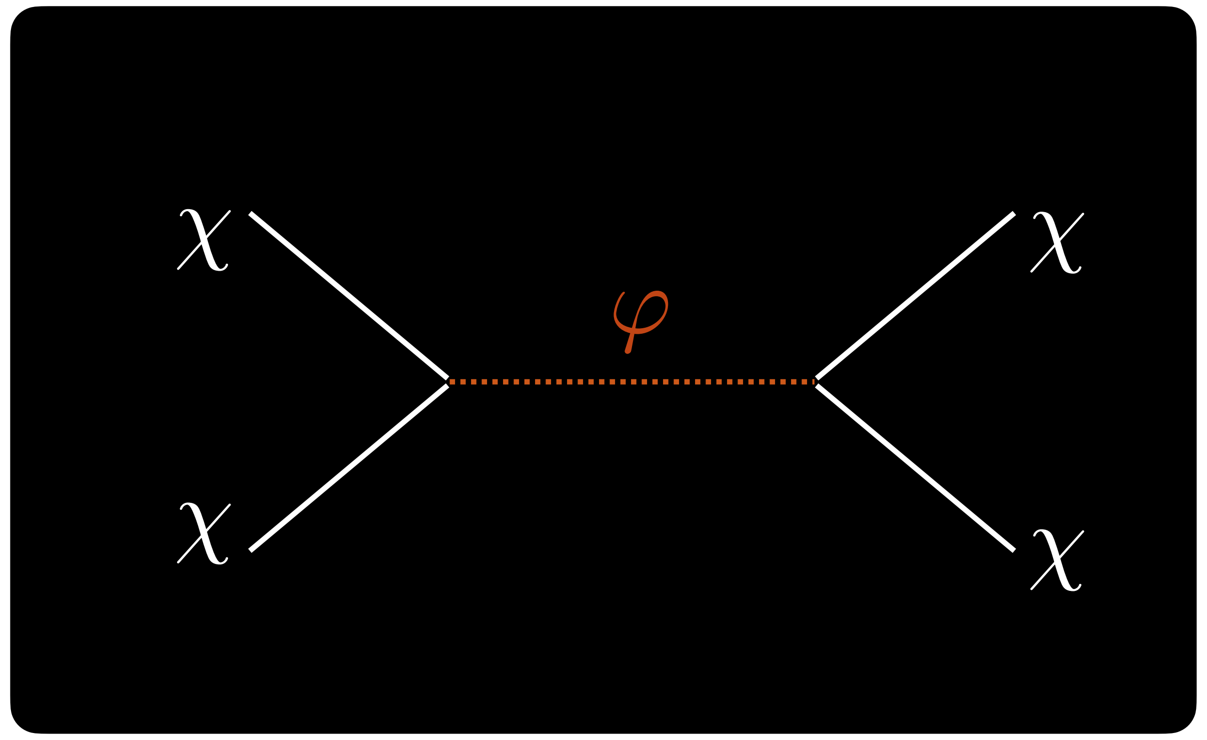
Self-interactions are negligile

$$\Gamma_{\varphi\varphi\to\varphi\varphi} \ll H_0$$

Toy Model



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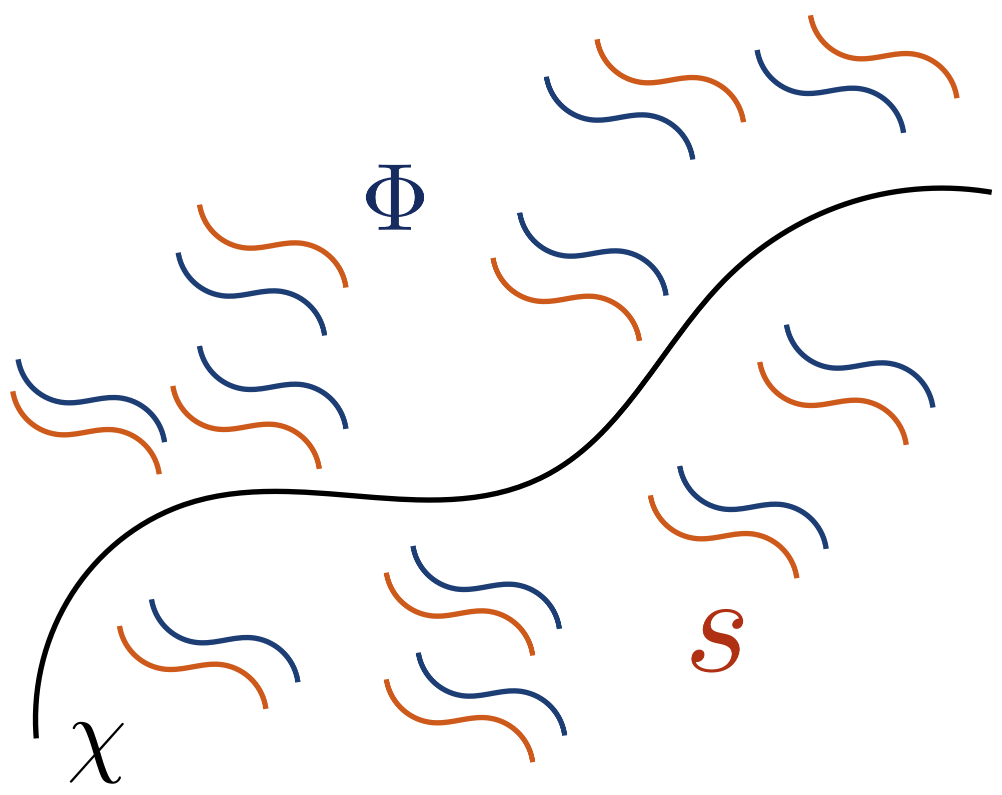

$$2G_s\mathcal{L}_s = (\partial s)^2 + m_s^2 s^2 + \mathcal{O}(1/G_s)$$

- Long range interactions $m_s/H_0 \in (1, 10^5)$
- The whole DM is interacting $f_\chi \simeq 1$

Effective Newton constant for the new mediator

$$G_s \equiv \kappa^2/m_\chi^4 = 4\pi\beta G_N$$

Define a new scalar potential, s

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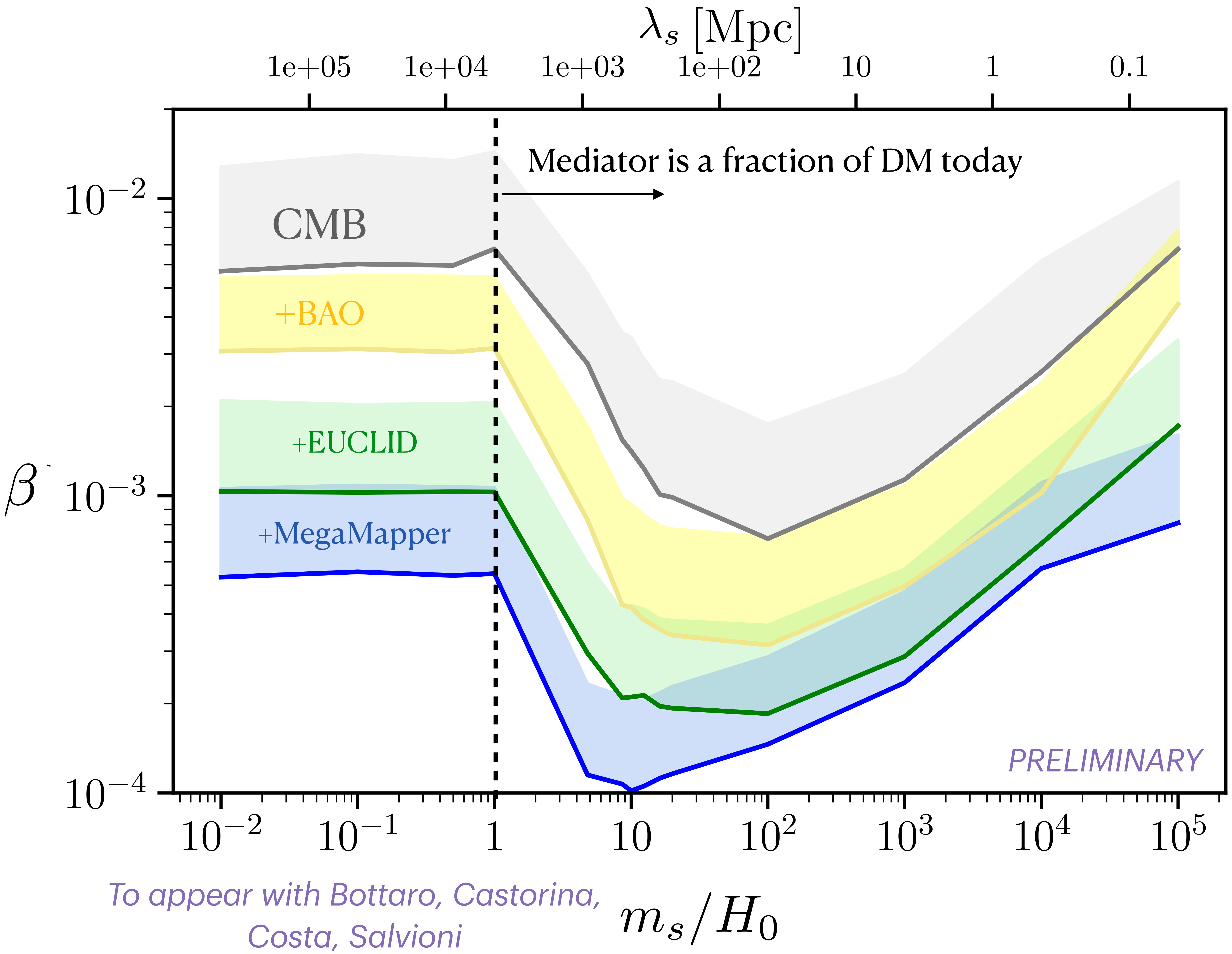
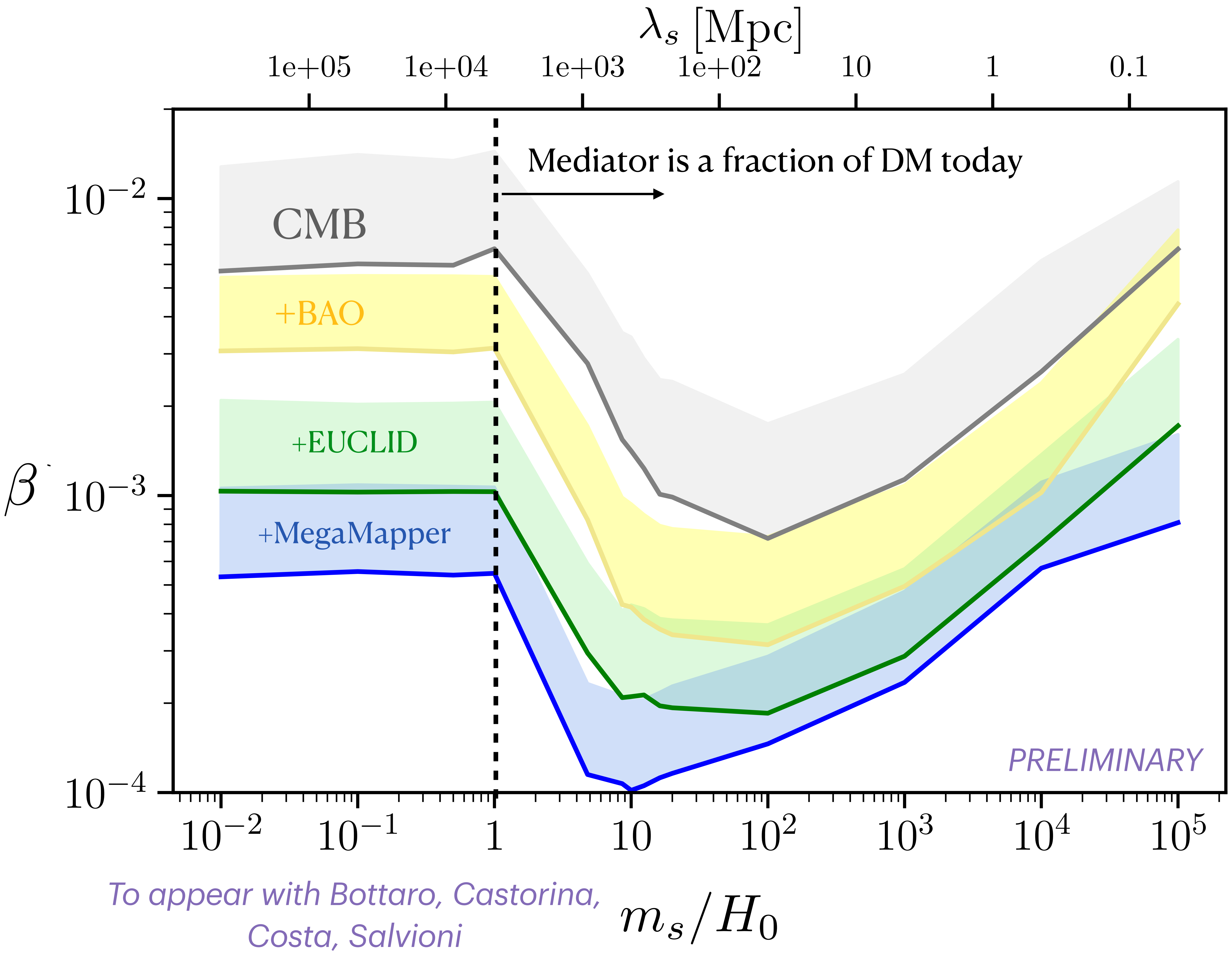
Results



To appear with Bottaro, Castorina, Costa, Salvioni

Precision cosmology will probe the strength of the new forces at least down to permil the strength of gravity

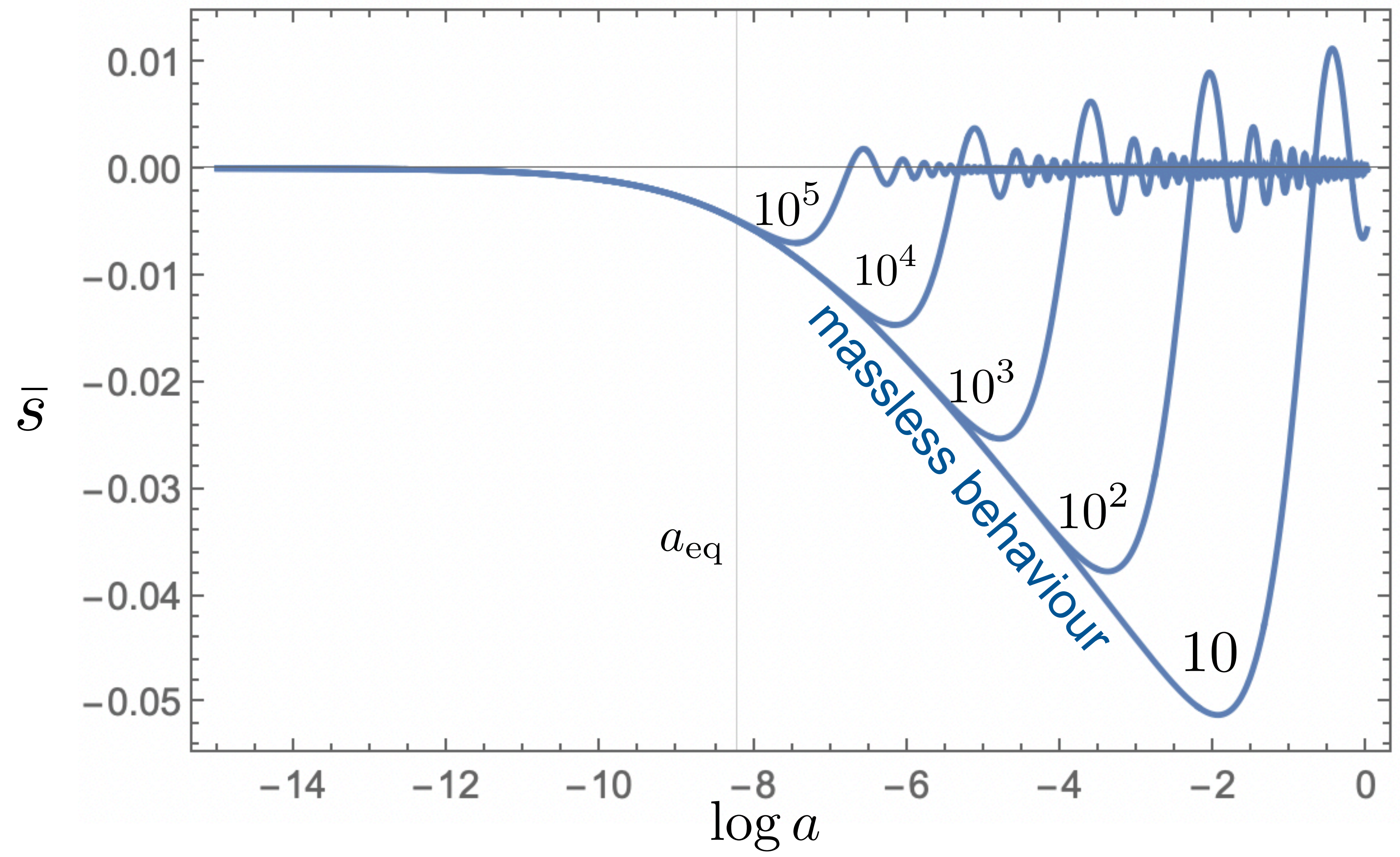
Main effect I



To appear with Bottaro, Castorina, Costa, Salvioni

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

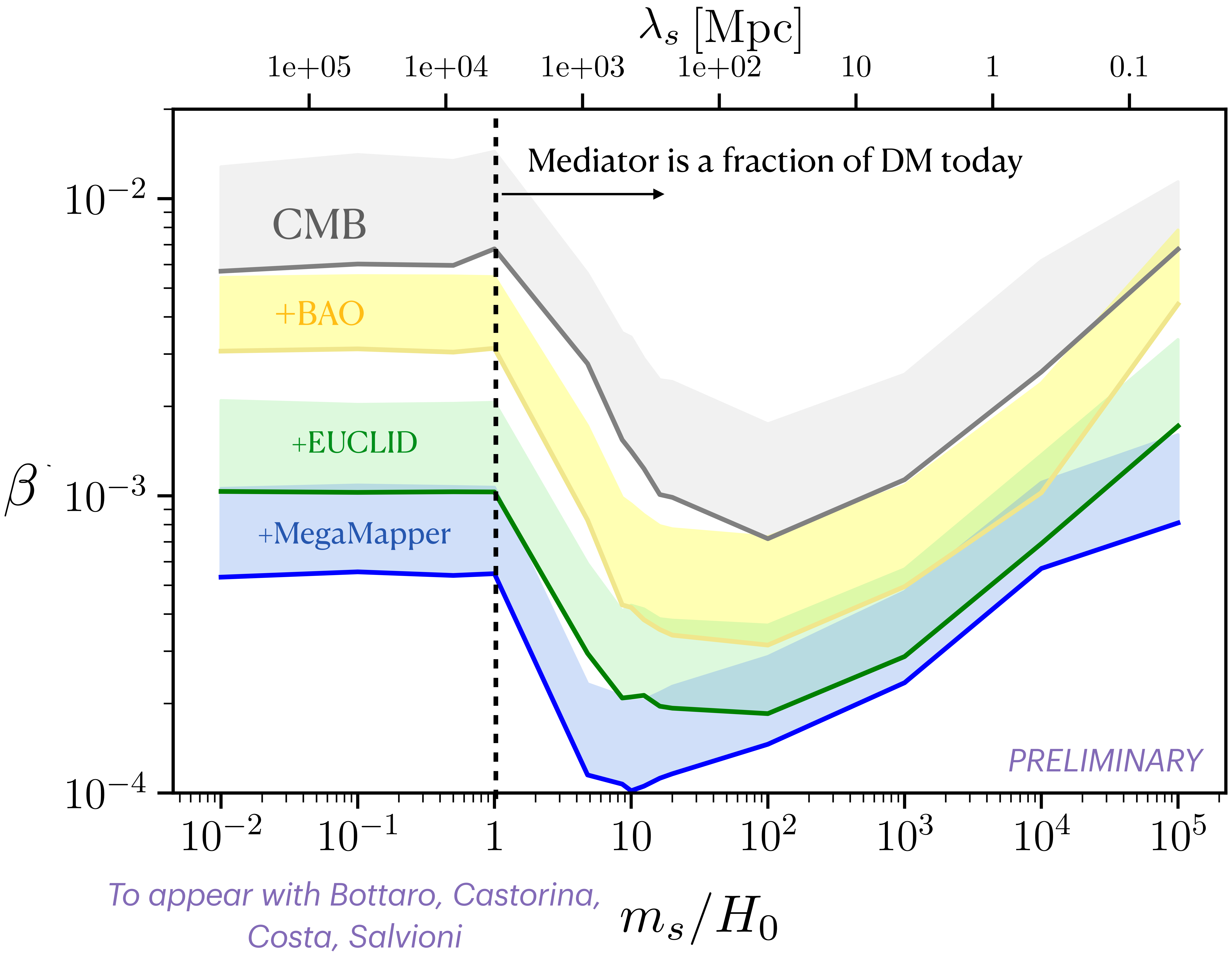
$$\bar{s}'' + 2\mathcal{H}\bar{s}' + \boxed{a^2 m_s^2 \bar{s}} + \boxed{a^2 G_s \rho_\chi} = 0$$



mass << DM source $\quad w_s = 1$

mass ~ DM source $\quad \langle w_s \rangle = 0$

Main effect II



To appear with Bottaro, Castorina, Costa, Salvioni

Matter fluctuations are enhanced as long the mediator is massless $\quad a < a_{m_s}$

$$\delta_m(\vec{k}, a) = \left(1 + \boxed{\frac{6}{5}\beta f_\chi^2 \log \frac{a}{a_{\rm eq}}}\right)\delta_m^{\rm CDM}$$

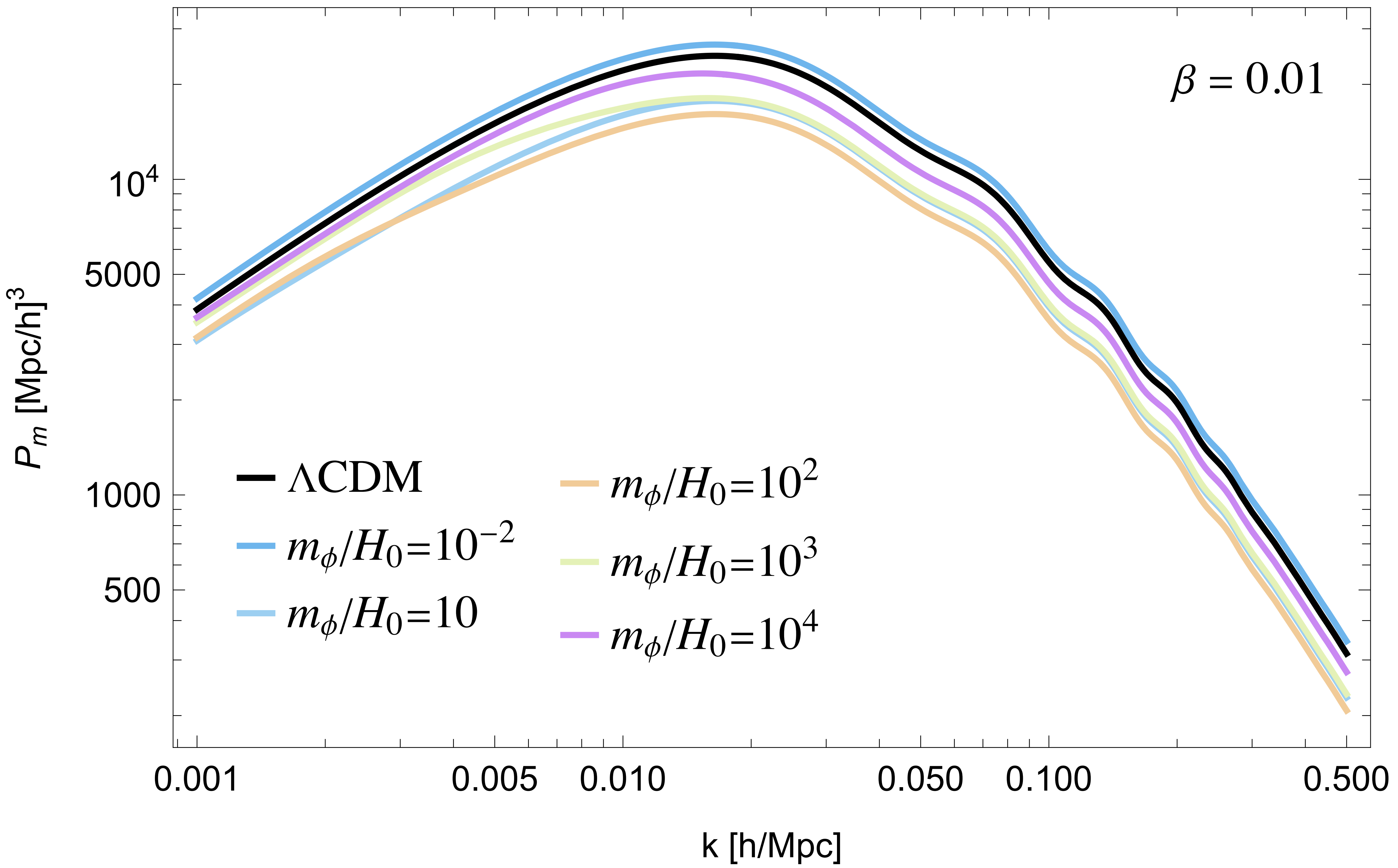
Matter fluctuations are suppressed when s becomes part of the dark matter $\quad a > a_{m_s}$

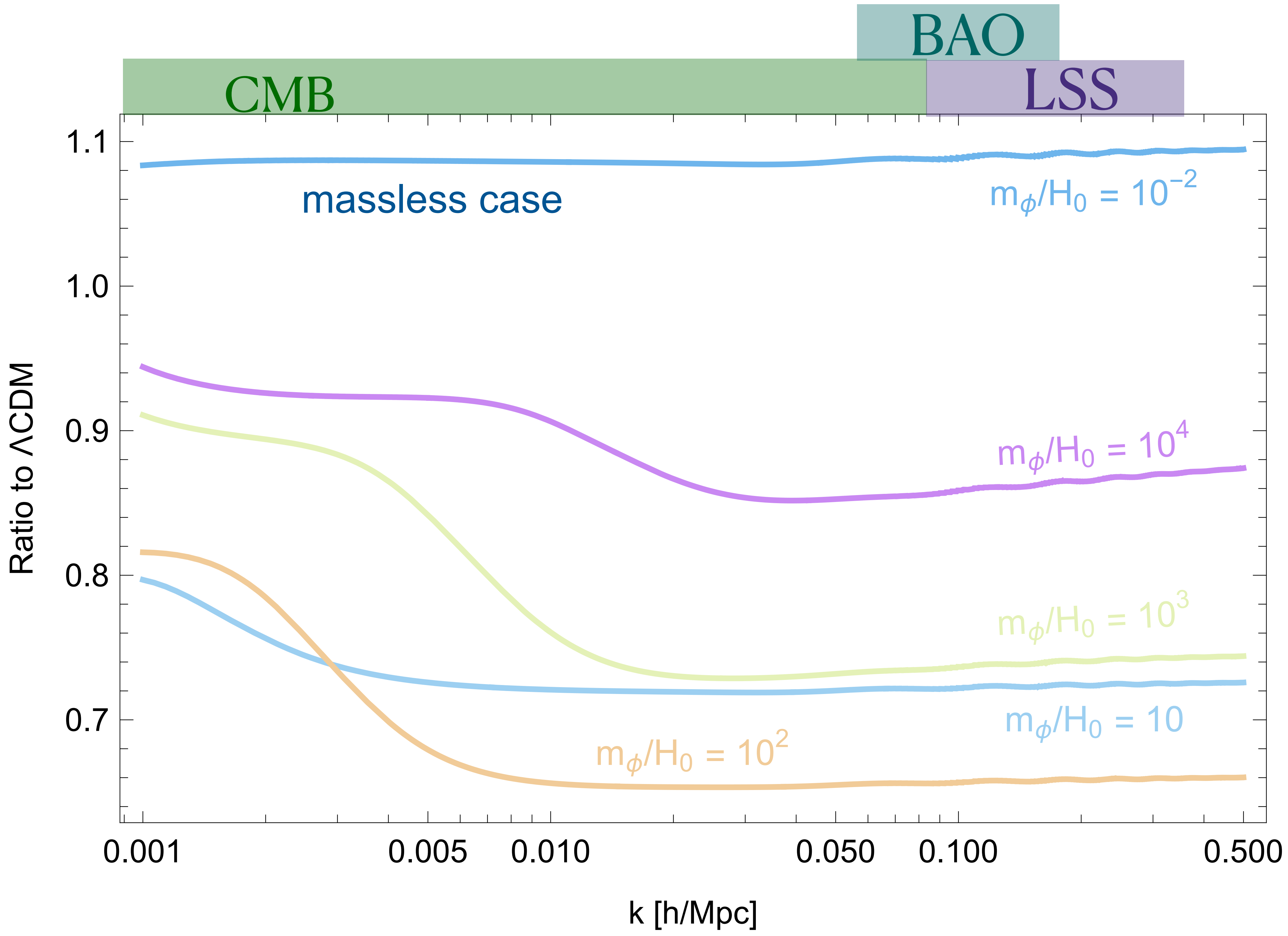
$$\delta_m \simeq \left(1 + \frac{6}{5}\beta f_\chi^2 \log \frac{a_{m_s}}{a_{\rm eq}} \boxed{- \frac{3}{5} f_s \log \frac{a}{a_{m_s}}}\right)\delta_m^{\rm CDM}$$

The suppression dominates as long as $m_s > H_0$

$$f_s^{\rm massive} \simeq \frac{5}{4} f_s^{\rm massless} \times \log^2 \frac{H_{\rm eq}}{m_s}$$

The power spectrum

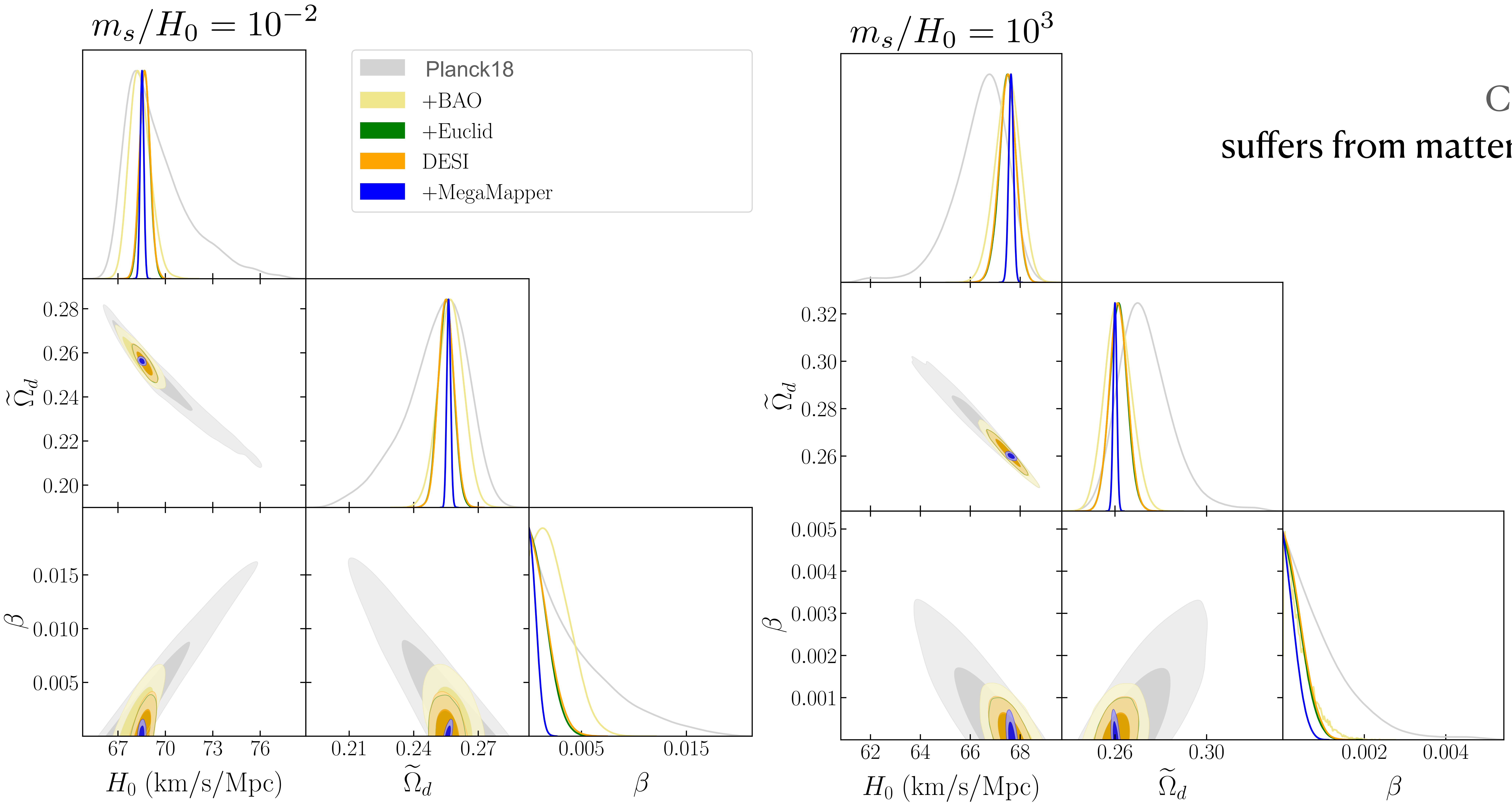




Feature at the jeans scale of the mediator

$$k_J(a) \approx 3.9 \times 10^{-4}\, a^{1/4} \left(\frac{\Omega_m^0}{0.3}\right)^{1/4} \left(\frac{m_\varphi}{H_0}\right)^{1/2} h\ \mathrm{Mpc}^{-1}$$

Massless vs Massive



CMB
suffers from matter-Hubble degeneracy

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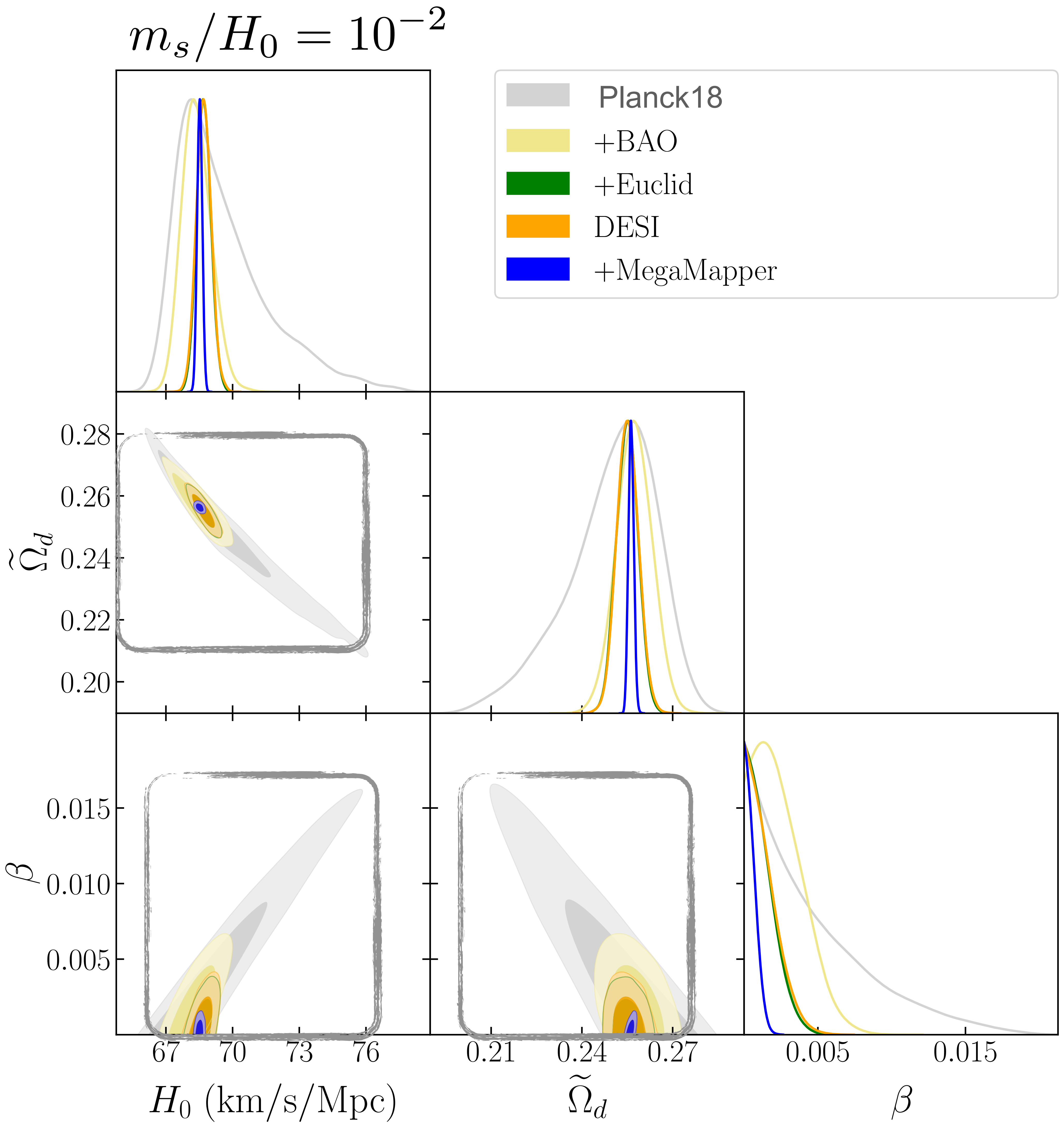

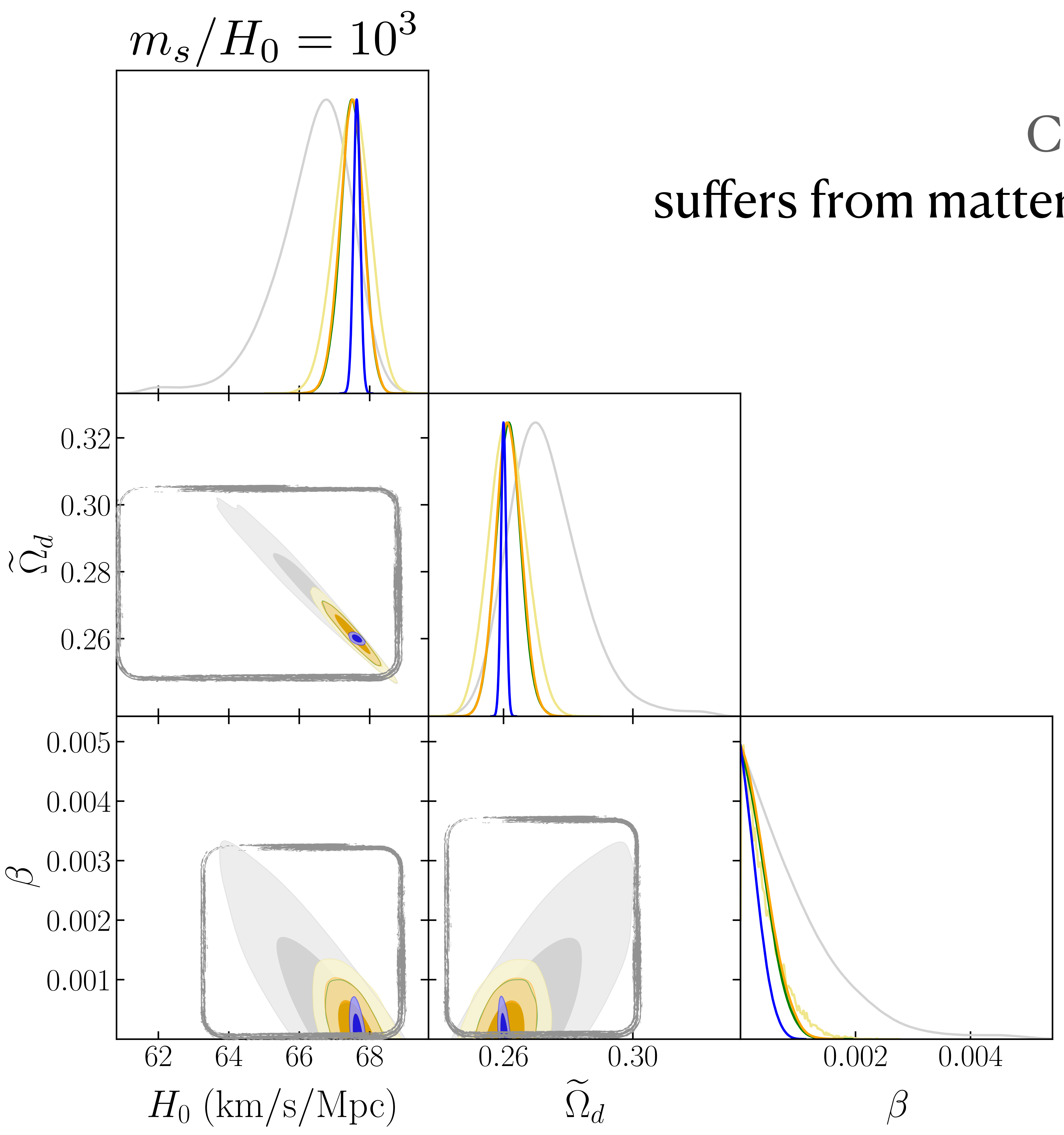

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Strength ↑ , Matter ↓ , H_0 ↑

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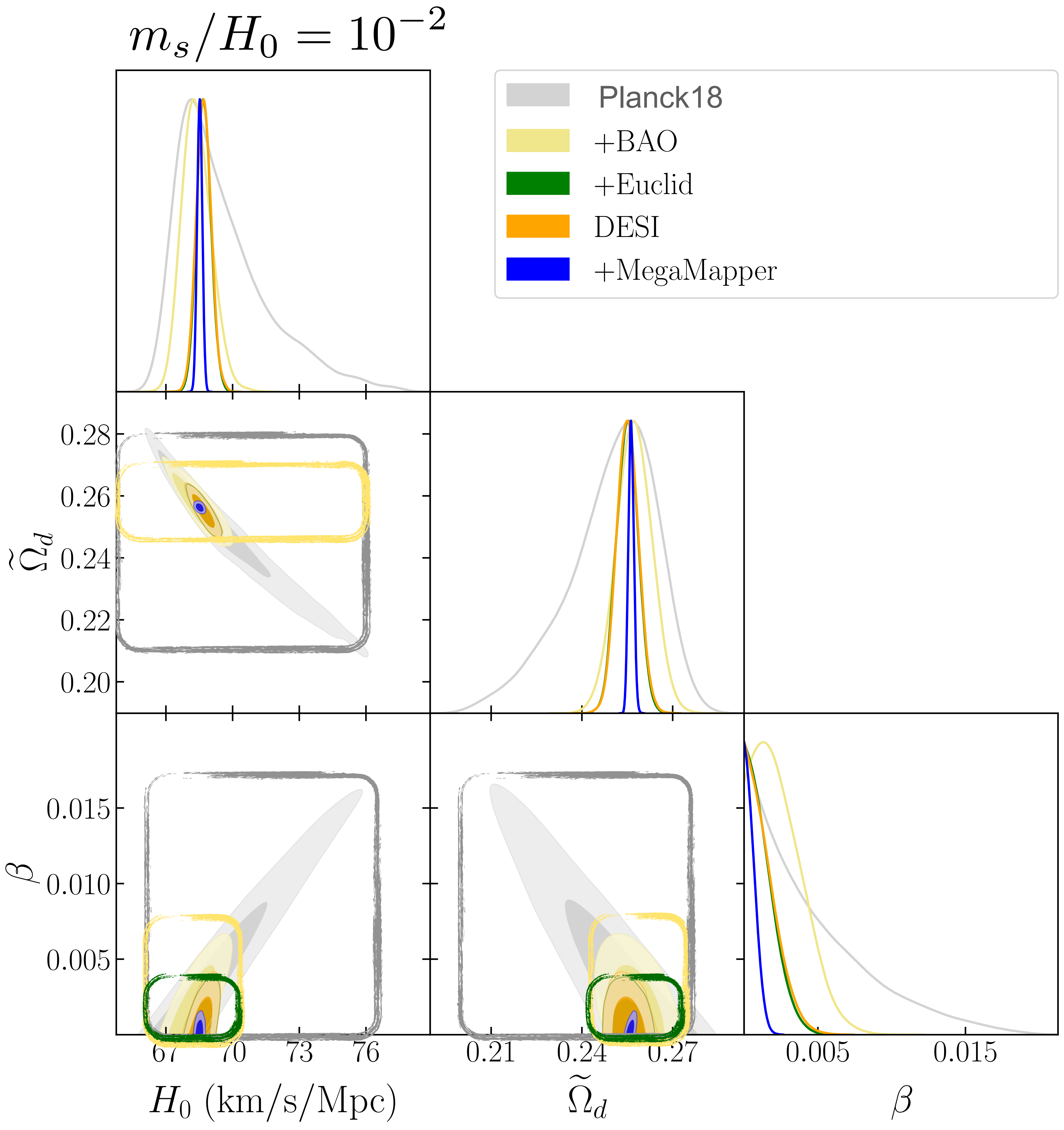

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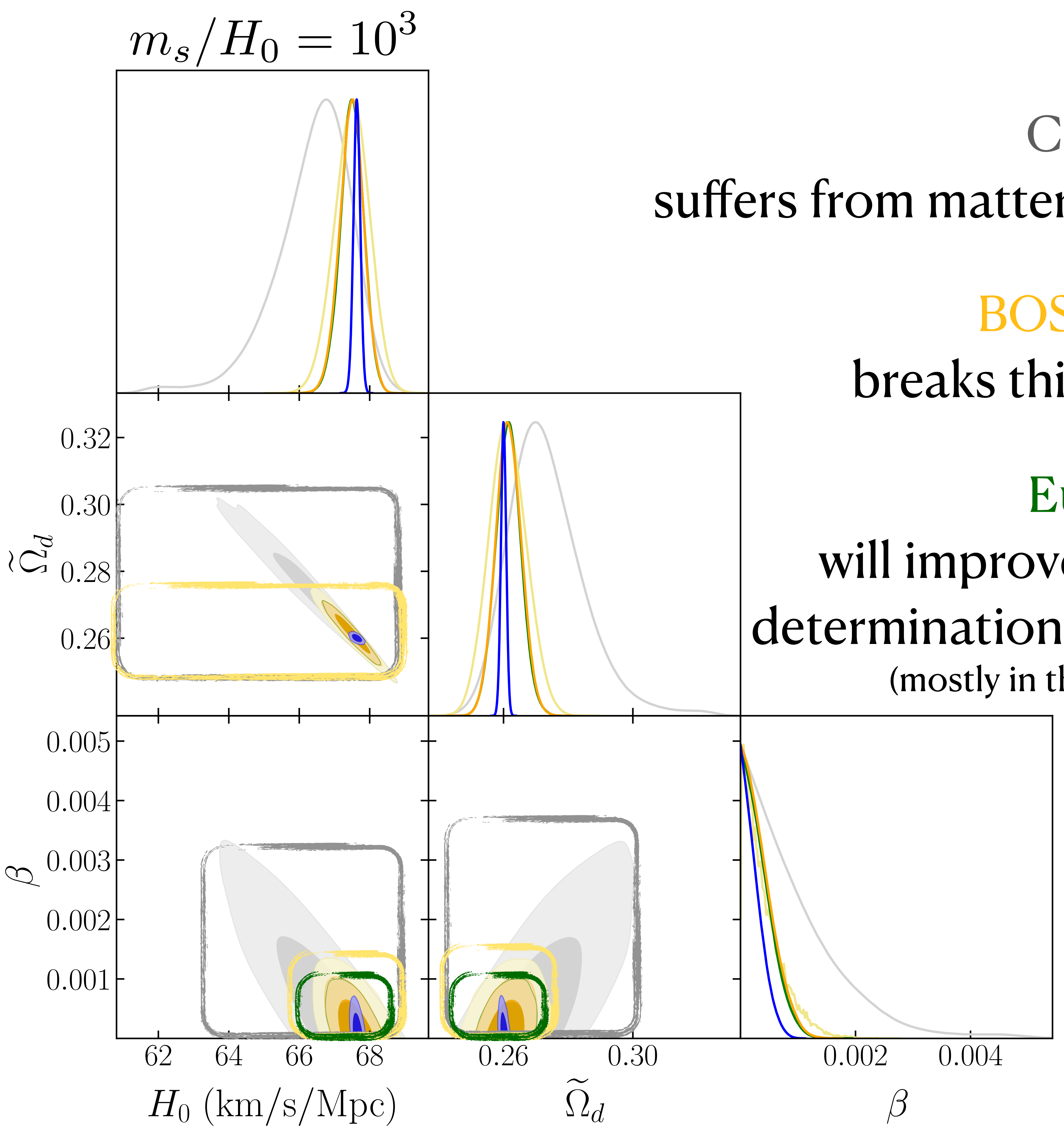

Strength ↑ , Matter ↑ , H_0 ↓

CMB
suffers from matter-Hubble degeneracy

BOSS BAO
breaks this degeneracy

Euclid
will improve with a better determination of the linear bias
(mostly in the masless case)

LSS for long range forces

For the range of masses considered the mediator is massless at the scales of interest $k \gg k_{\rm eq}$

Keeping only leading log-enhanced terms, the structure of nonlinear corrections is same as LCDM, with modified growth factor

$$\delta_m(\vec{k},a) = D_{1m}(a)\delta_0(\vec{k}) + \sum_{n=2} D_{1m}(a)^n \int \prod_{i=1}^{n} \frac{d^3k_i \delta_0(\vec{k}_i)}{(2\pi)^3}(2\pi)^3\delta^{(3)}\Big(\vec{k} - \sum_{i=1}^{n}\vec{k}_i\Big) F_n(\vec{k}_1,\ldots,\vec{k}_n)$$

2309.11496
with Bottaro, Castorina, Costa, Salvioni

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One-loop galaxy power spectrum: $P_g \simeq b_1^2 \left(\frac{D_{1m}}{D_{1m}^{\rm CDM}}\right)^2 P_{m,L}^{\rm CDM} + b_1^2 \left(\frac{D_{1m}}{D_{1m}^{\rm CDM}}\right)^4 P_{m,1\,\rm loop}^{\rm CDM}$

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New physics vs bias

A fully consistent treatment of the EFT allow to disentangle NEW PHYSICS from the ASTROPHYSICS encoded in the biases

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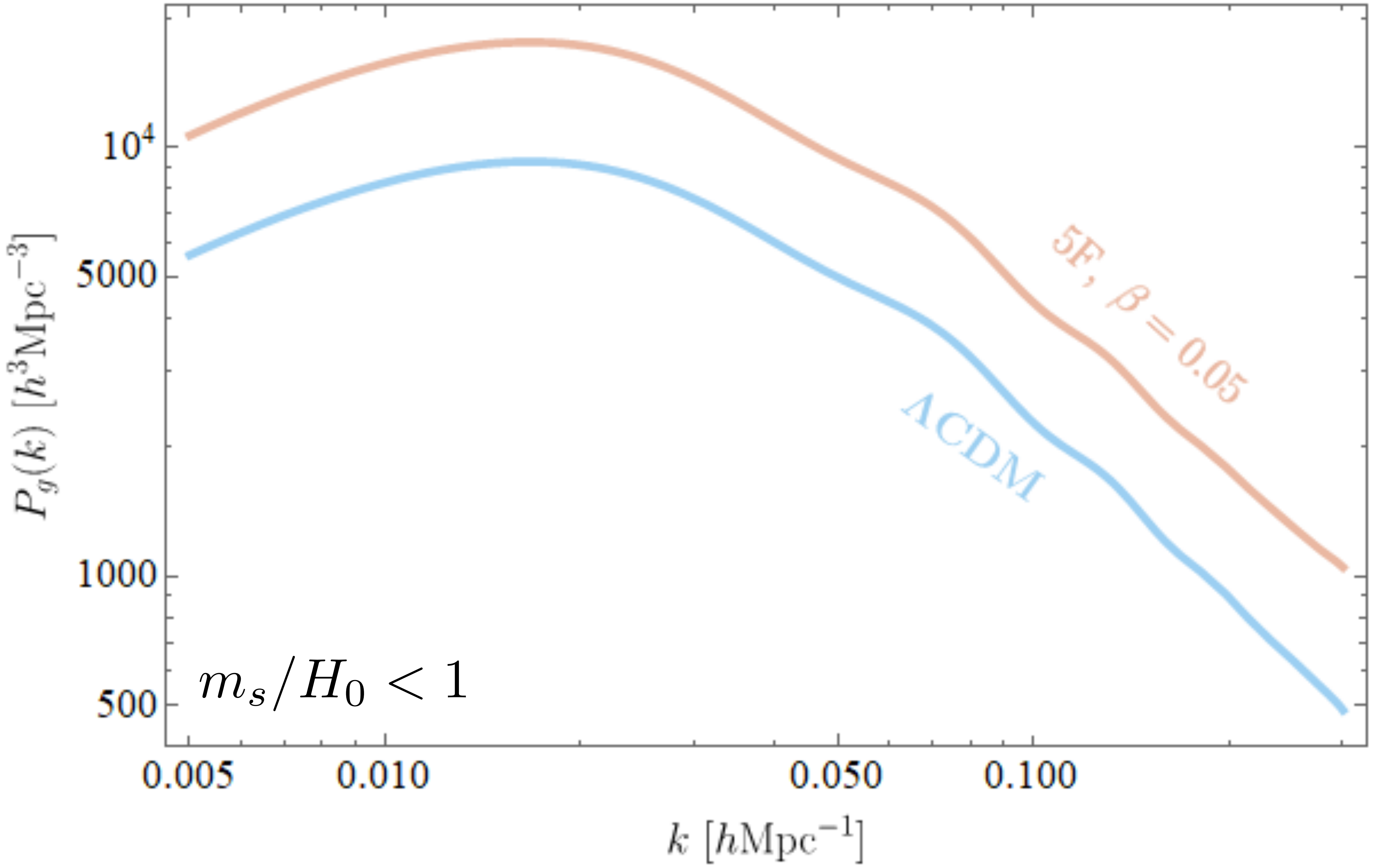
EXAMPLE: massless mediator



@ the linear level we can always reabsorb the increase of power in the linear bias

$$b_1^2 \sim \frac{1}{1 + \frac{12}{5}\beta \log}$$

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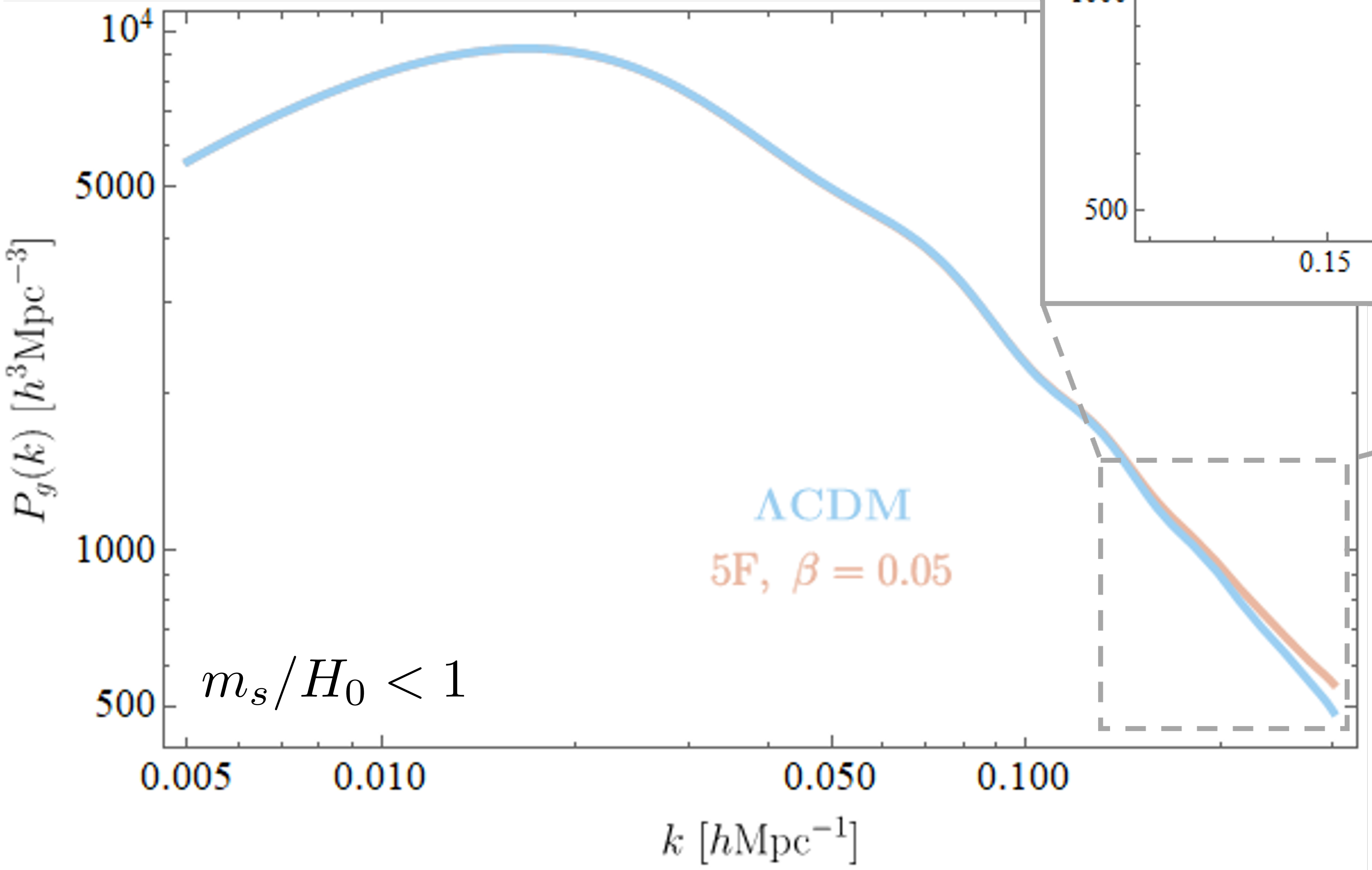

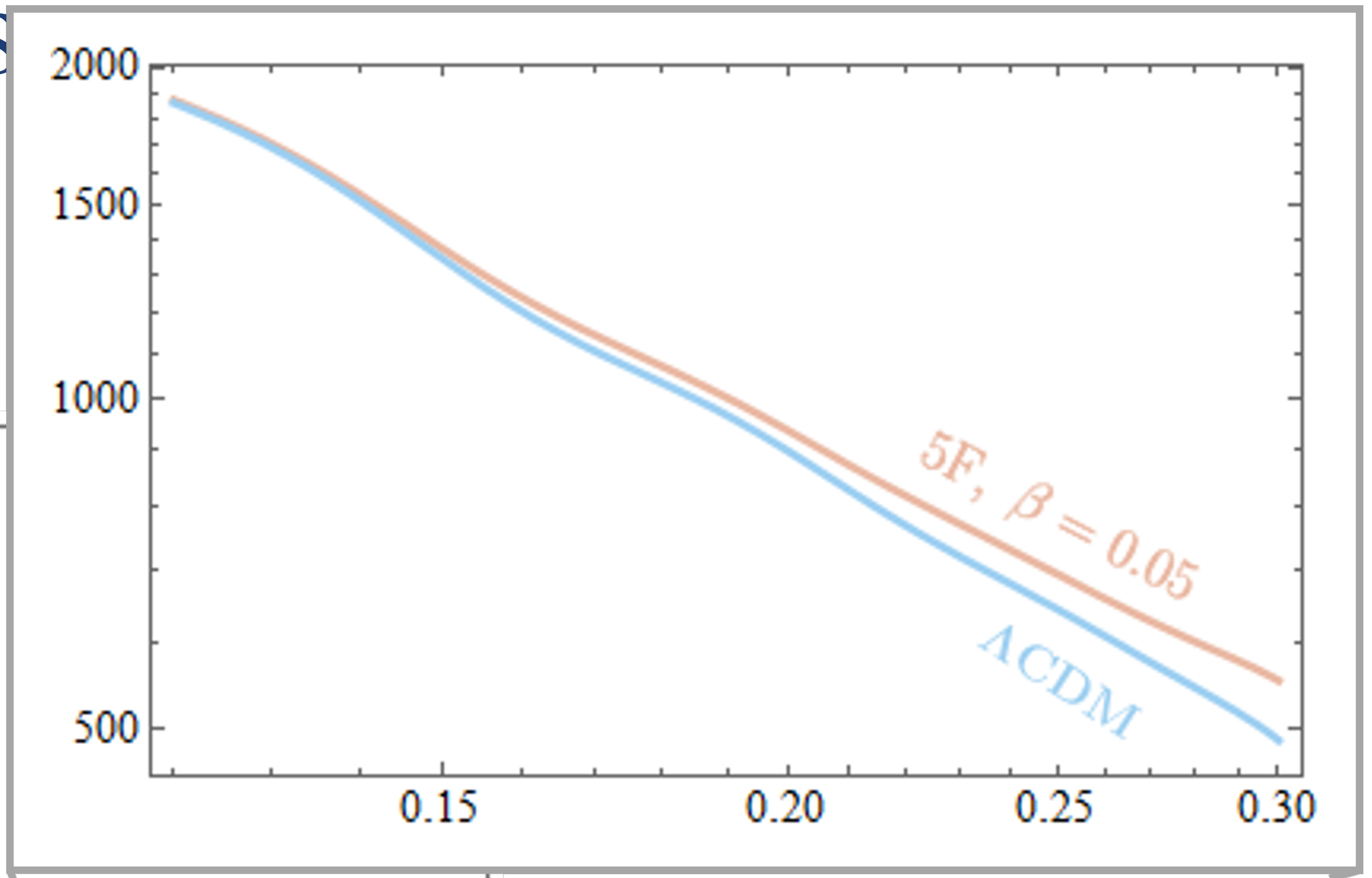

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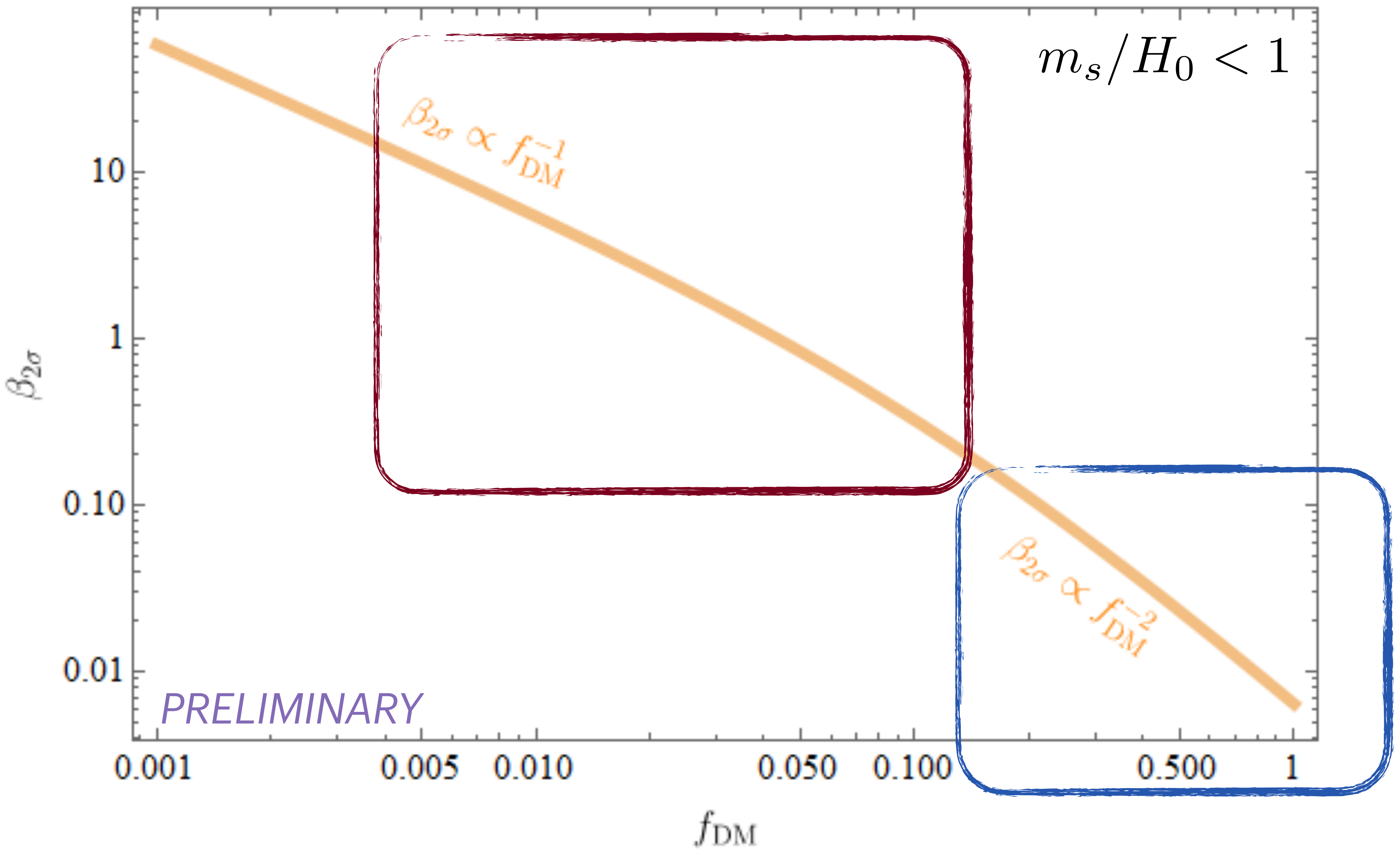
The signal will show up @ non-linear scales!

Relative perturbations/velocities

The dark force sources relative fluctuations between the DM and the baryons



$$\delta_r = \frac{5}{3}\beta f_\chi \delta_m \qquad \delta_r \equiv \delta_m - \delta_b$$

$f_\chi \lesssim 10\%$ relative densities dominate the signal for a massless mediator

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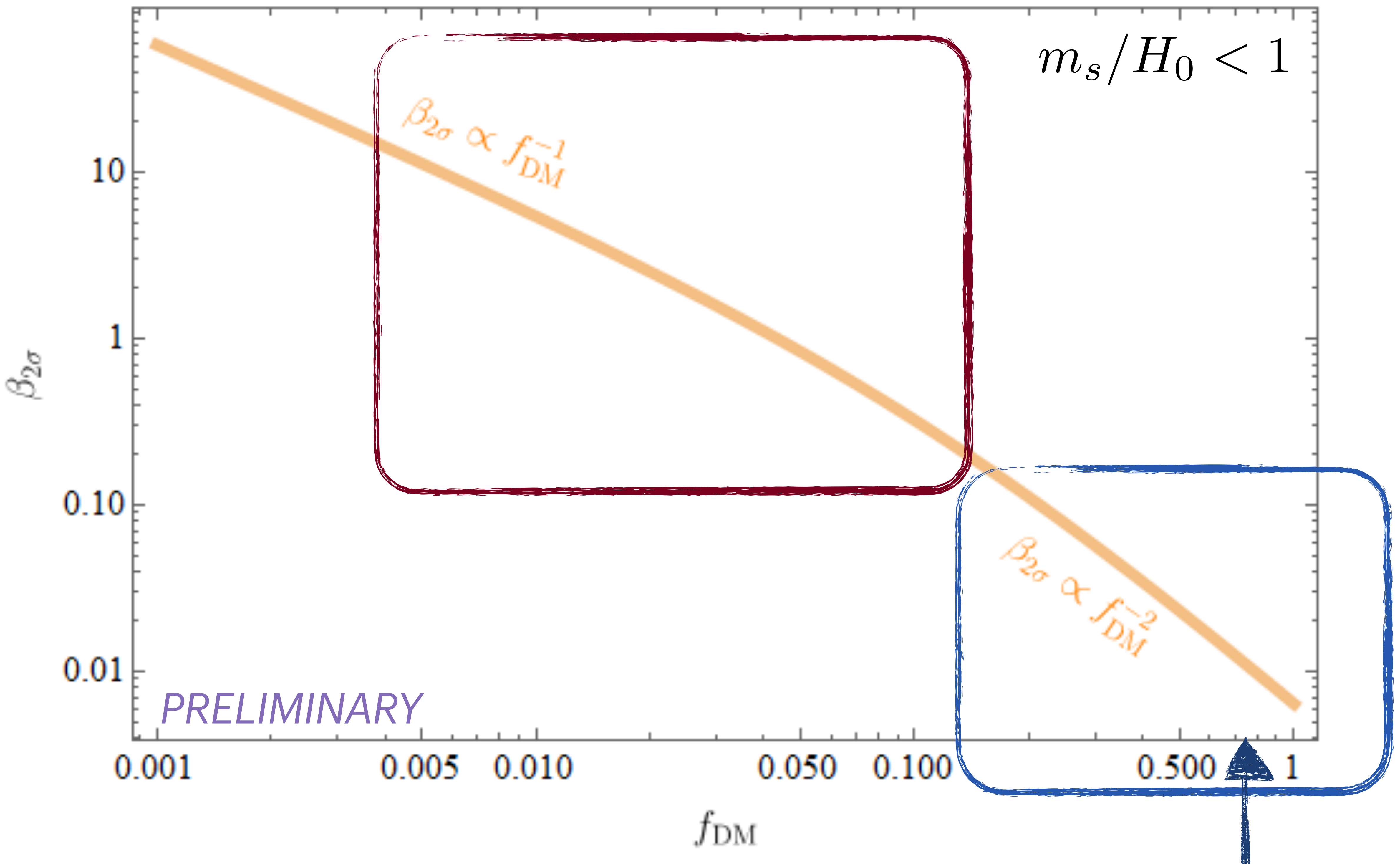

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[fraction]

Log-enhanced effects go like ~[fraction]^2

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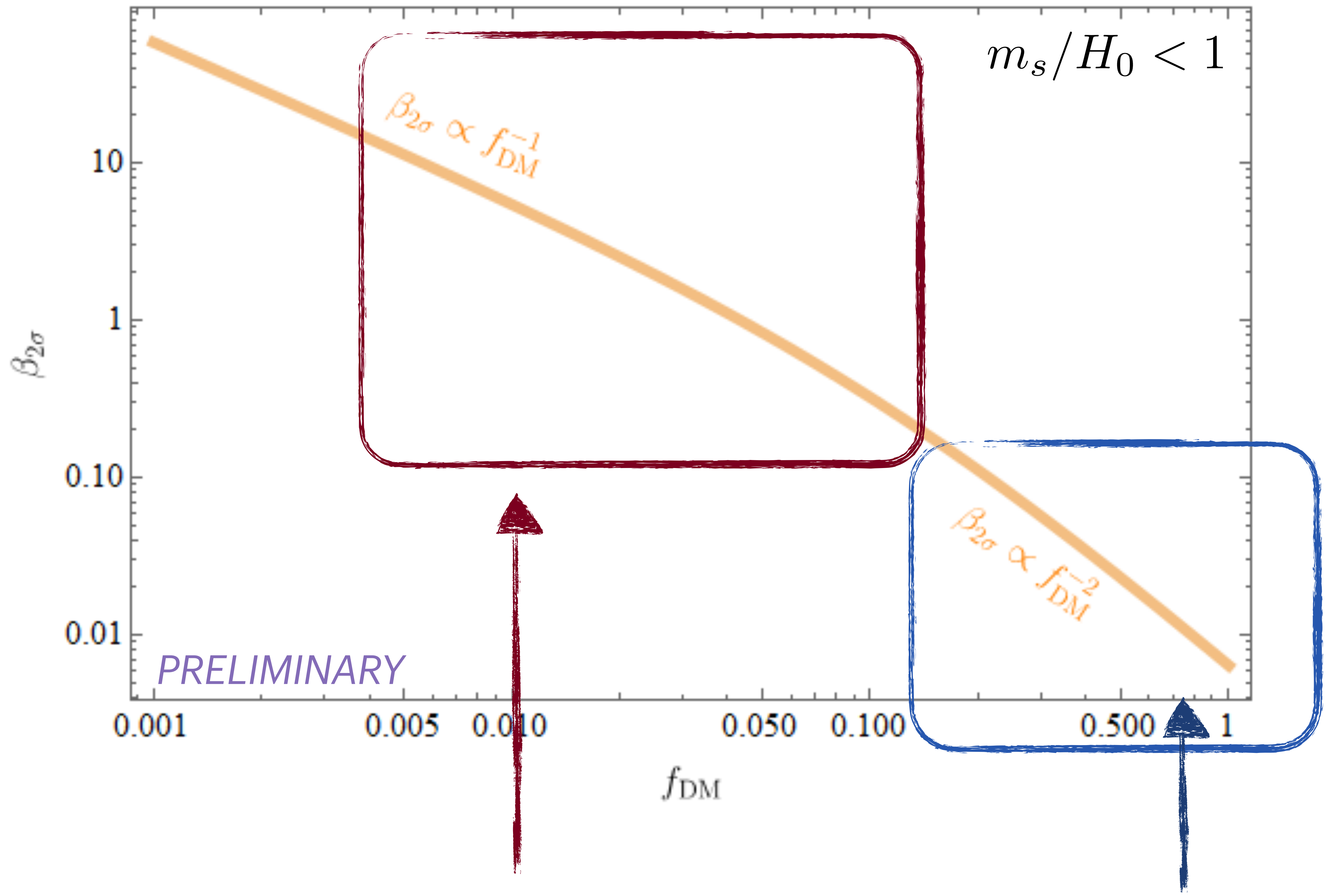

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Relative density effects go like ~ $[\text{fraction}]$

Log-enhanced effects go like ~ $[\text{fraction}]^2$

LSS with relative perturbations

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

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

Relative perturbations will generate genuinely NEW SPATIAL FEATURES

$$\delta_r(\vec{k}, a) = \beta f_\chi \left[\frac{5}{3} D_{1m}^{\rm CDM}(a) \delta_0(\vec{k}) + \sum_{n=2} D_{1m}^{\rm CDM}(a)^n \int \prod_{i=1}^{n} \frac{d^3 k_i \delta_0(\vec{k}_i)}{(2\pi)^3} (2\pi)^3 \delta^{(3)}\left(\vec{k} - \sum_{i=1}^{n} \vec{k}_i\right) F_{nr}(\vec{k}_1, \dots, \vec{k}_n) \right]$$

These generate VIOLATION OF EQUIVALENCE PRINCIPLE & NEW SIGNALS!

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NEW compared to
Schmidt 2016

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Schmidt 2016

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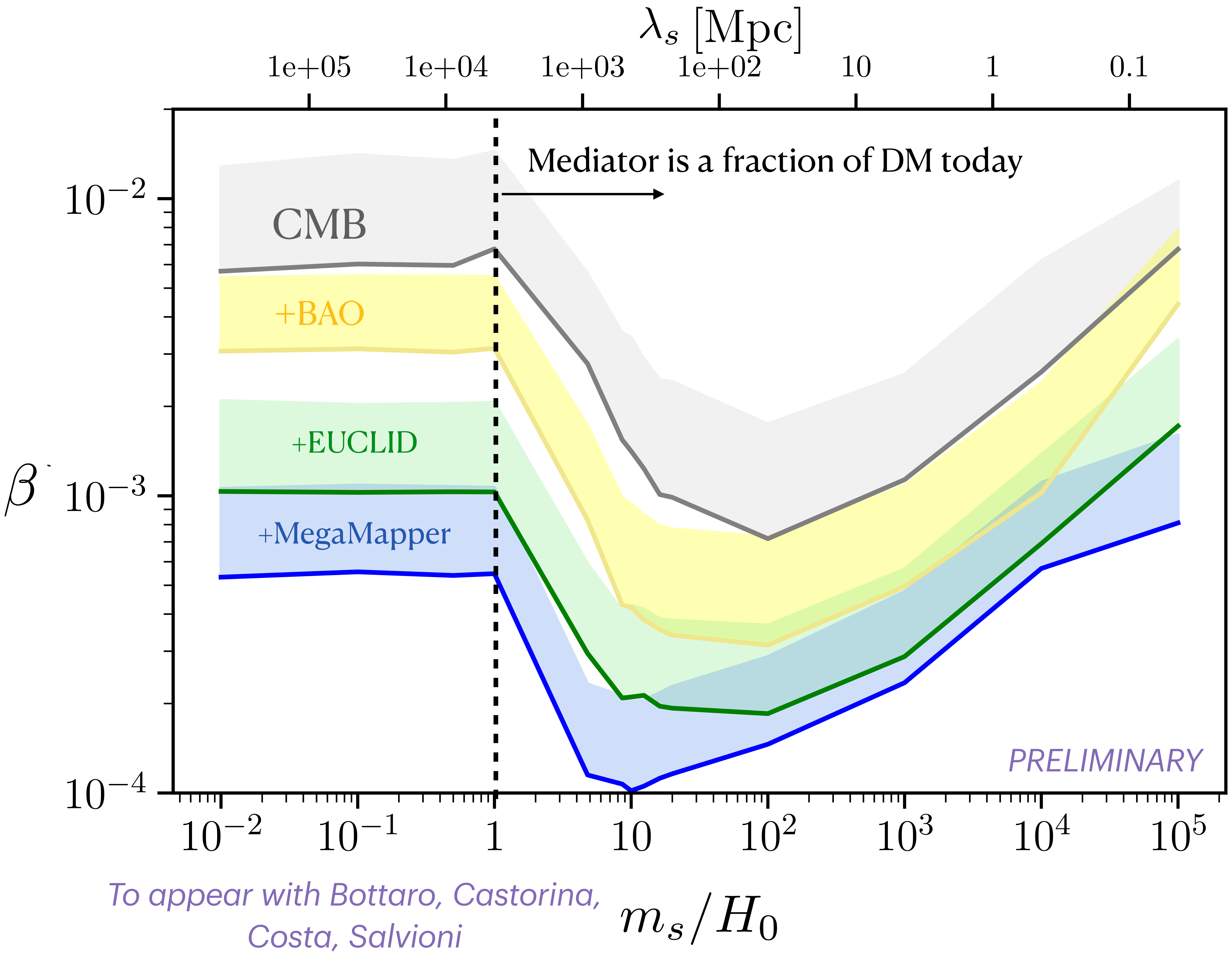
NEW non-linear kernels

These generate VIOLATION OF EQUIVALENCE PRINCIPLE & NEW SIGNALS!

2309.11496
with Bottaro, Castorina, Costa, Salvioni

Summary and to do list



To appear with Bottaro, Castorina, Costa, Salvioni

- Full analysis with relative fluctuations *In progress...*
- Extending the EFT of LSS for massive mediators will allow to probe other 4-5 orders of magnitude in mass (till $k_J > k_{\rm NL}$) *In progress...*

This plan will give a clear picture of self-interaction of dark matter (or a fraction) well beyond the present extrapolated bounds from the bullet cluster

Bogorad, Graham, Ramani 2023

Backup

New Smoking guns

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

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

New Smoking guns

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

Enhanced growth

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

New Smoking guns

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

Enhanced growth

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

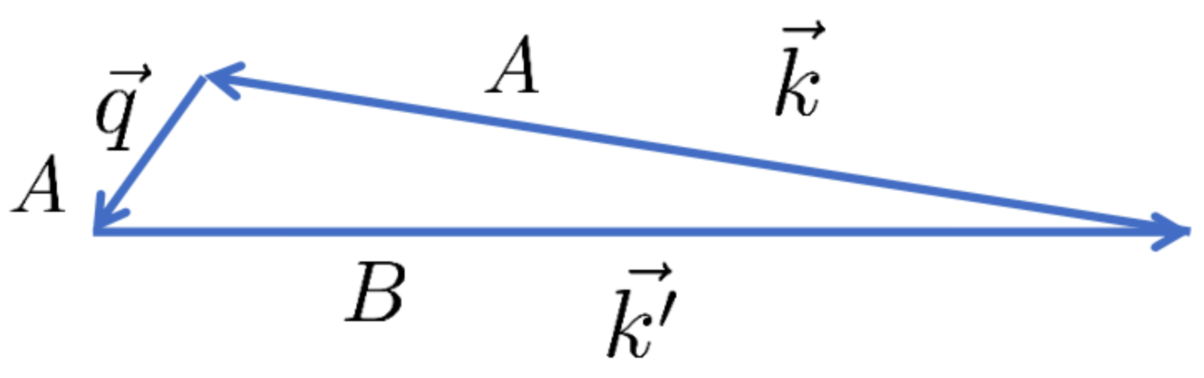
Relative densities and velocities induce

NEW SPATIAL FEATURES

+ VIOLATION OF CONSISTENCY RELATIONS (violation of the EP)

Peloso et al 2013, Creminelli et al. 2013

The double tracer bispectrum

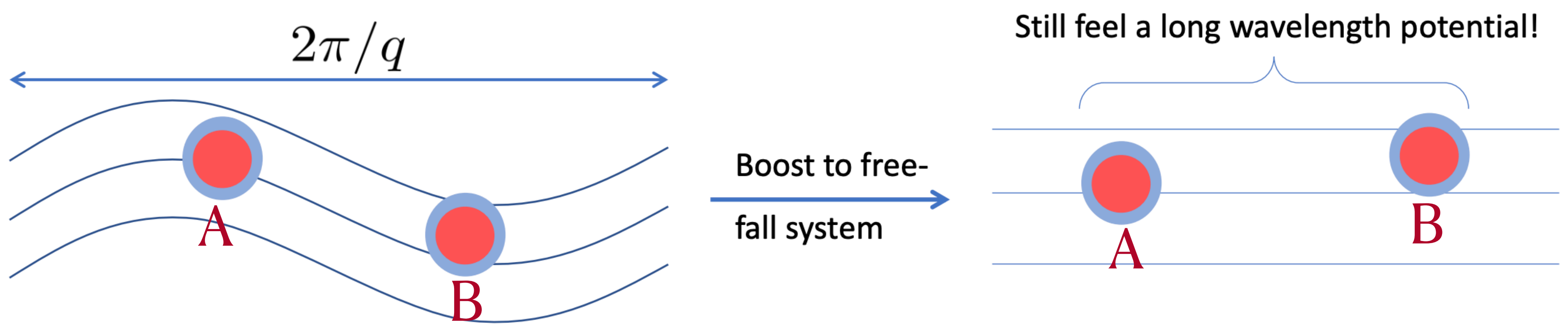


$$\lim_{q\to 0} \Delta\mathcal{B}_{AAB}(q,k,k') \propto \underbrace{\frac{\vec{q}\cdot\vec{k}}{q^2}}_{\frac{7}{6} b_1^A \Delta b^{AB}} P_{\rm lin}(q) P_{\rm lin}(k)$$

The bispectrum has a pole which is zero in $\Lambda\mathrm{CDM}$

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



Creminelli et al. 2013 + many others

The BAO shift

Density and velocity perturbations can shift the BAO scale *Sherwin & Zaldarriaga 2012*

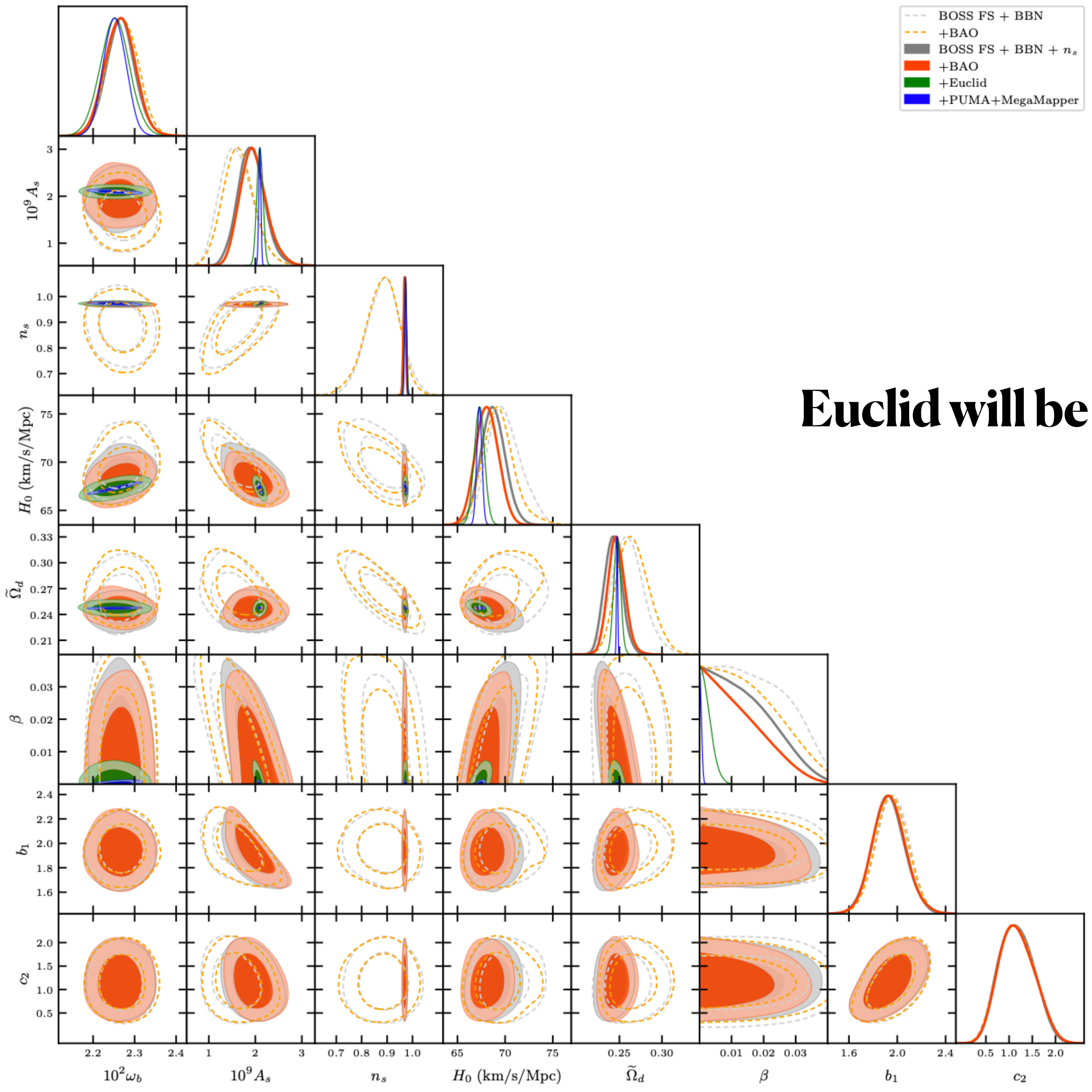
$\text{shift} \sim \mathcal{O}(\beta) \longrightarrow$ Present bounds could allow a detection with future data!

However we find that

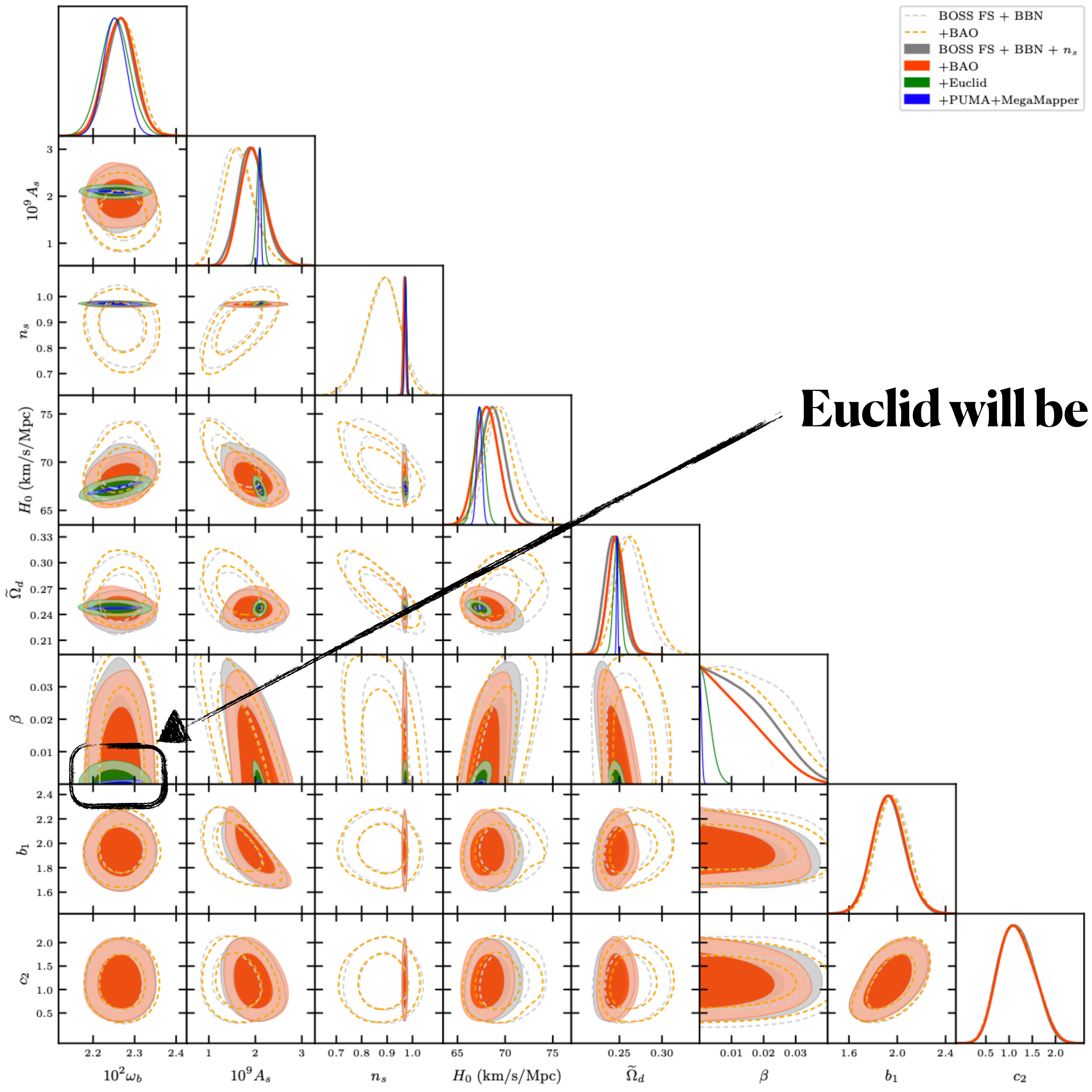
$\text{shift} \sim \mathcal{O}(\beta^2) \longrightarrow P_{mr} = \frac{1}{2}(P_\chi - P_b) + \mathcal{O}(\beta^2)$

For every single fluid we can remove the gravitational force by going to the free-falling frame

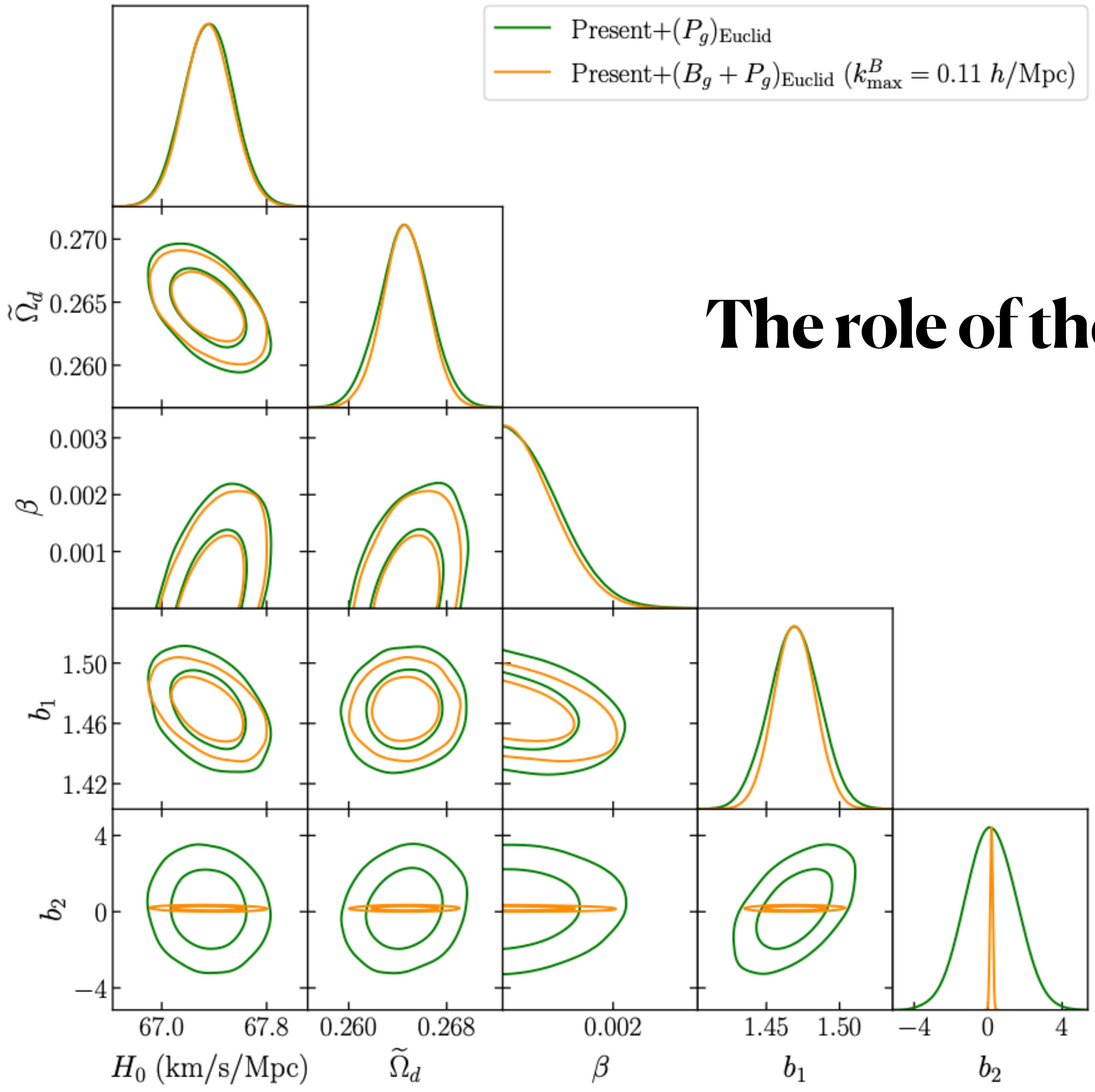
NOT DETECTABLE! :(



Euclid will be competitive even without CMB!

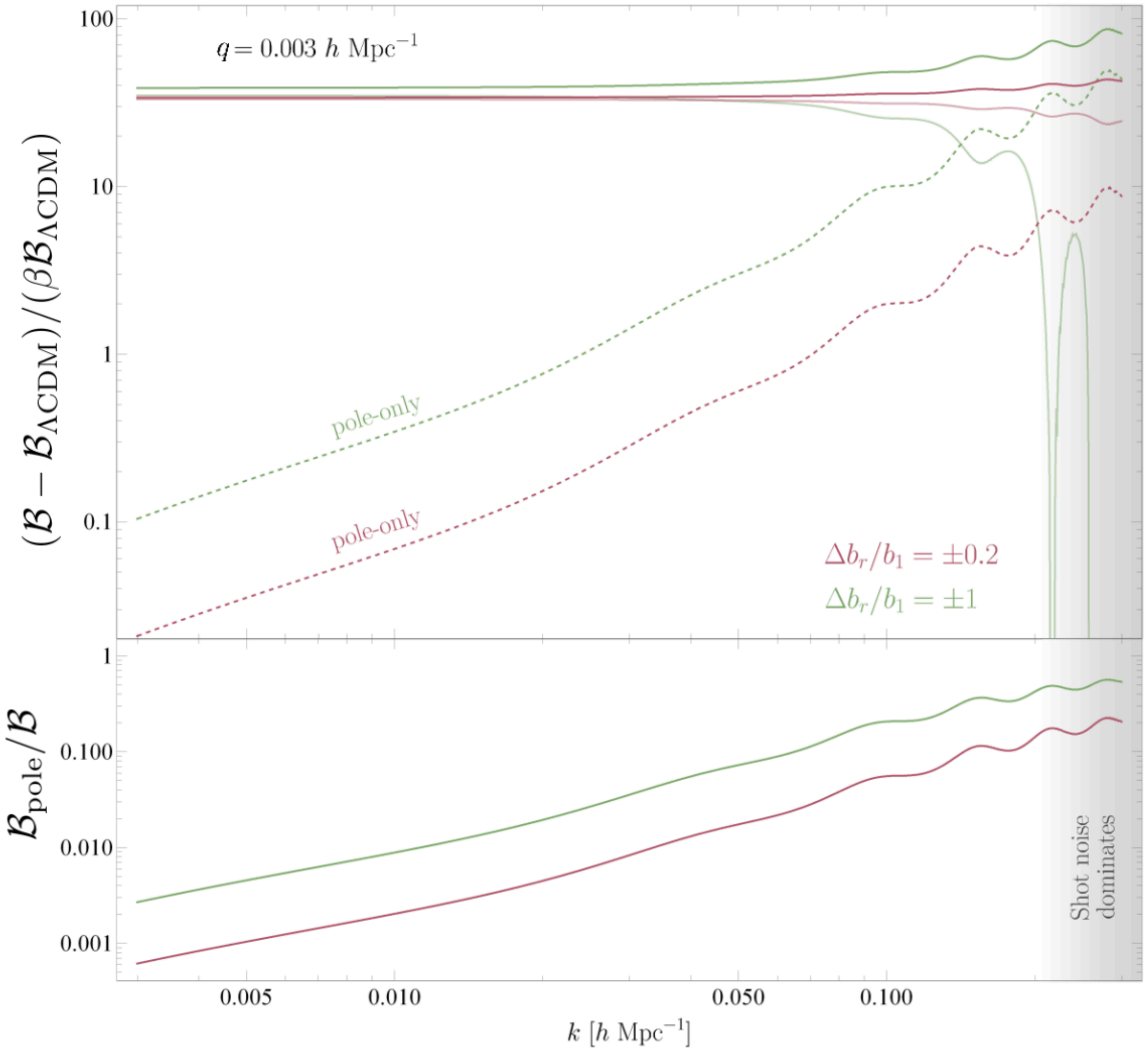


Euclid will be competitive even without CMB!



The role of the bispectrum with k~0.1 is to fix the non-linear bias

Can we see the pole?



1) The log-enhancement covers the pole

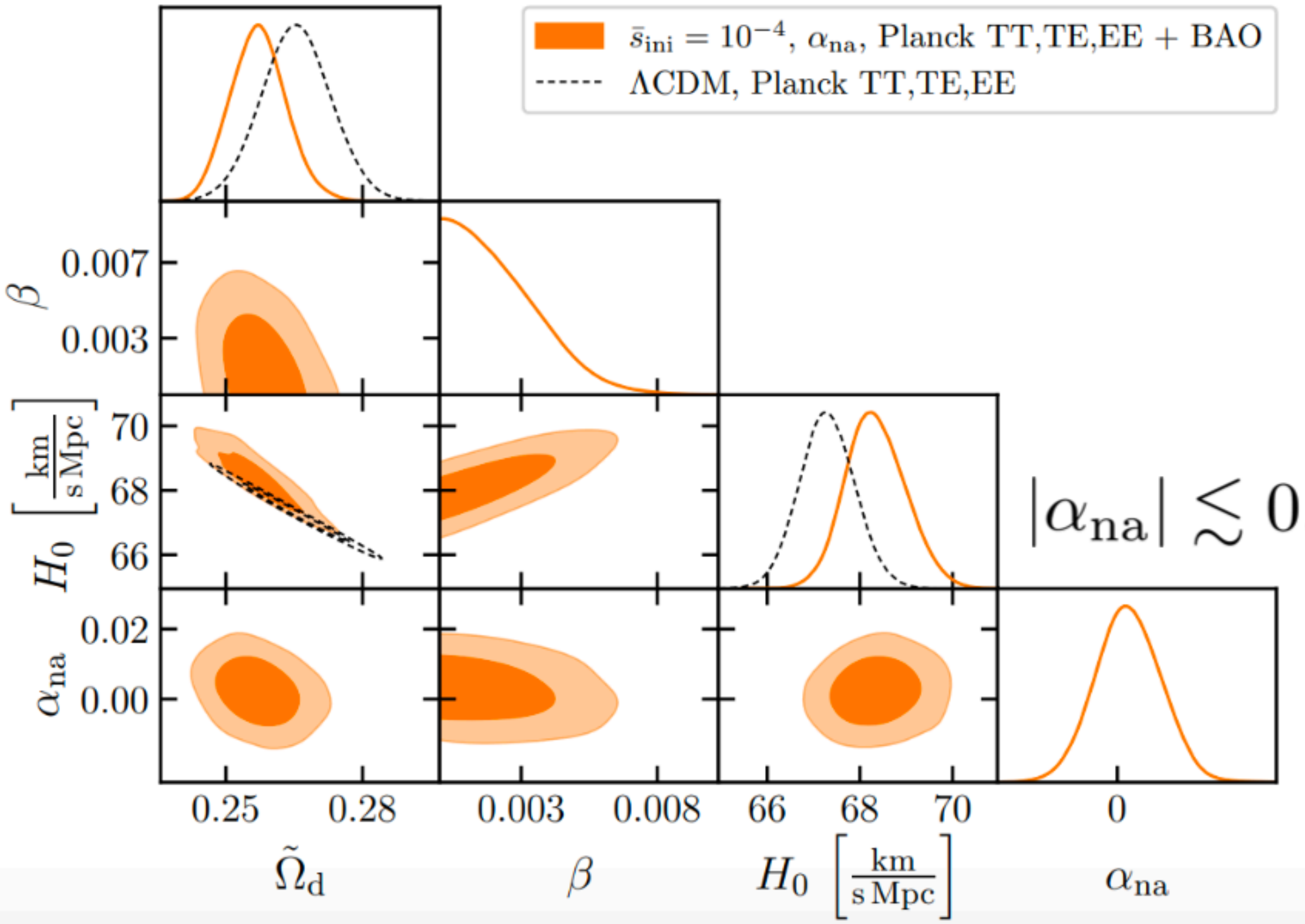
2) The prominence of the pole depend on the relative BIAS

3) Depending on the relative sign signal is suppressed/enhanced

An extra experimental difficulty
is to have two very different tracers in spectroscopic surveys

Isocurvature constraints

$$\theta_\chi = (\theta_\chi)_{\rm ad} + \frac{\alpha_{\rm na}}{2}\frac{\partial \log m_\chi(s)}{\partial s} k(k\tau)$$



$|\alpha_{\rm na}| \lesssim 0.01$

Hp: constant alpha