Hunting for New physics in Large Scale Structure of the Universe

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The relevance of LSS today...

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
$\Omega_{\rm b}h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_{\rm c}h^2$	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
$\ln(10^{10}A_{\rm s})$	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
$n_{\rm s}$	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
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
$\Omega_{\rm m}$	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056

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CMB already measures the cosmological parameters
at the sub percent level

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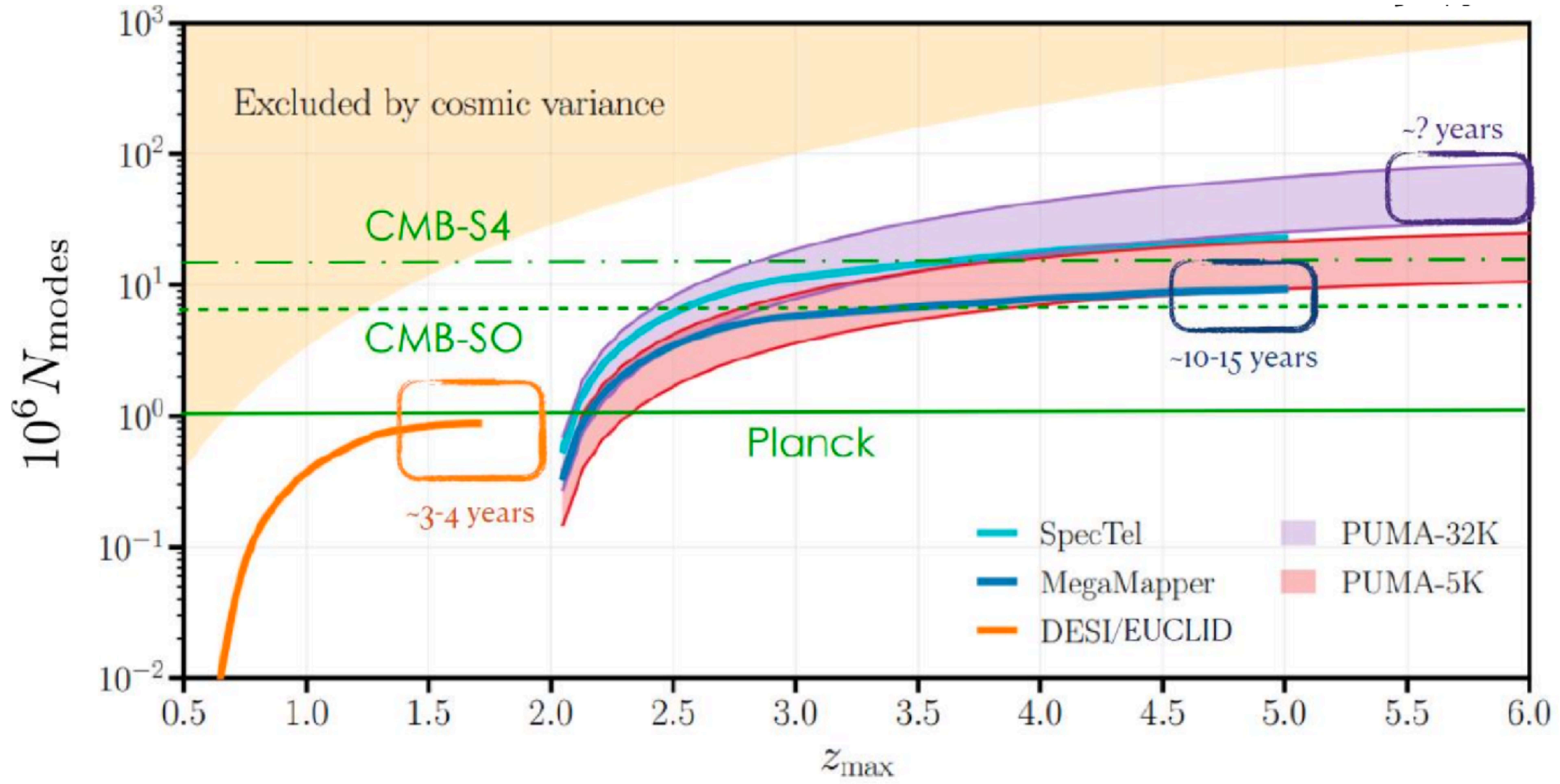
Information from matter power spectrum breaks degeneracies

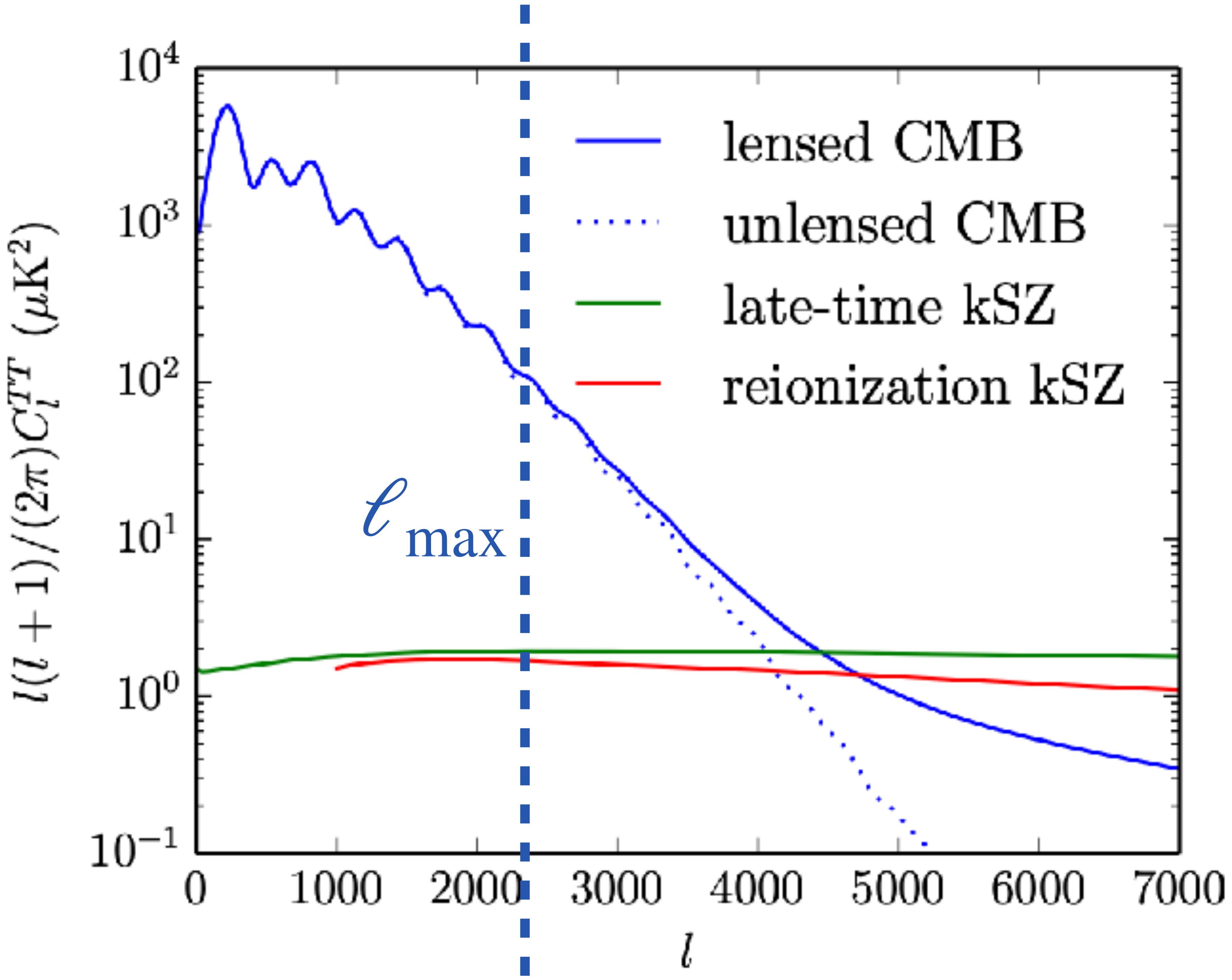
... and in the (very) near future!



… and in the (very) near future!

CMB is a 2D surface

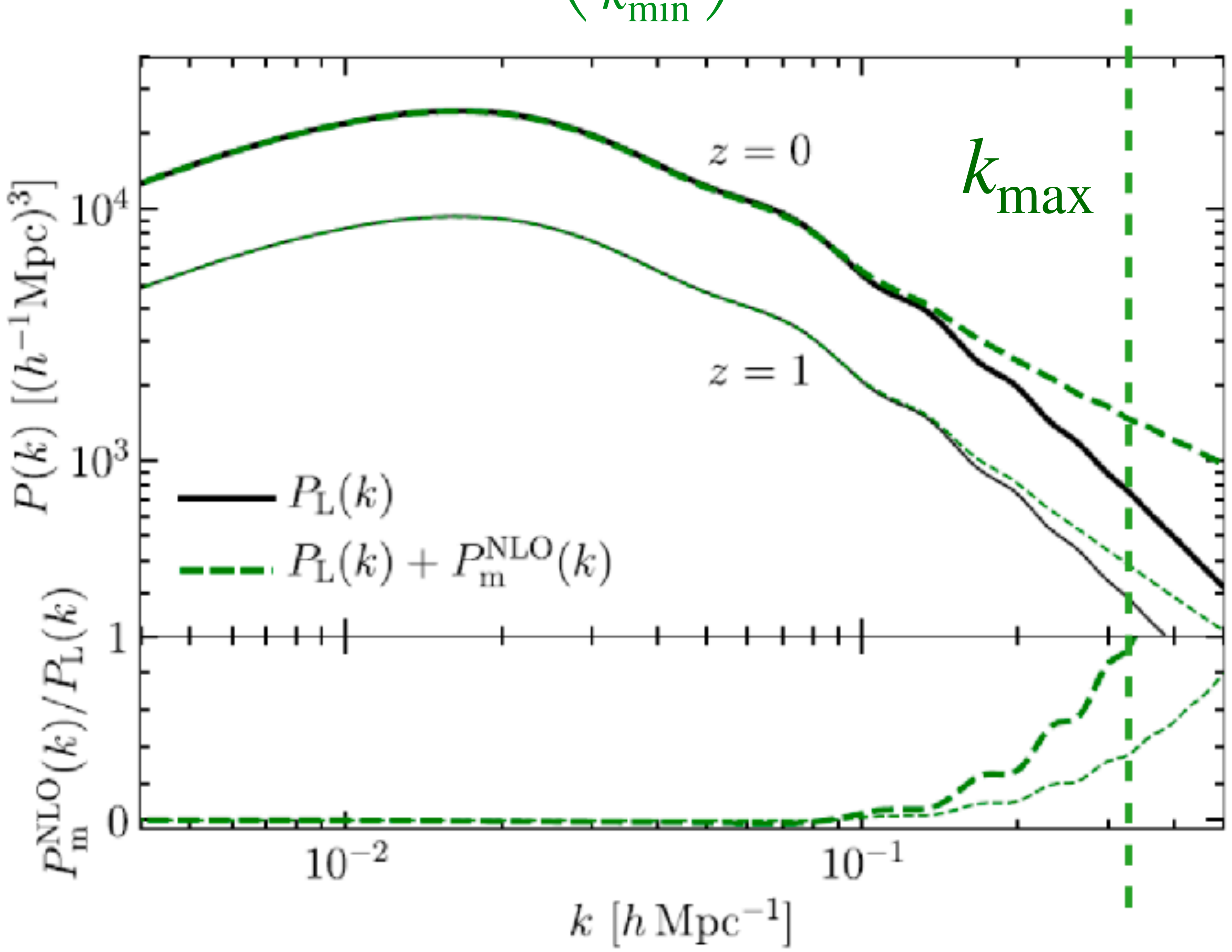
$$N_{\mathrm{modes}}^{\mathrm{CMB}} \approx \ell_{\mathrm{max}}^2 \approx (2200)^2$$



Limited by small-scale fluctuations

LSS probes a 3D volume

$$N_{\mathrm{modes}}^{\mathrm{LSS}} \approx \left(\frac{k_{\mathrm{max}}}{k_{\mathrm{min}}}\right)^3 \leq 10^9$$



Limited by convergence of perturbative series

From theory to observations

Theory predicts $\delta_m = \dfrac{\delta\rho_m}{\bar{\rho}_m}$

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We observe galaxies $\delta_g = \frac{\delta n_g}{\bar{n}_g} = b_1 \delta_m + \frac{b_2}{2} \delta_m^2 + b_K K_{ij} K^{ij} + \ldots$

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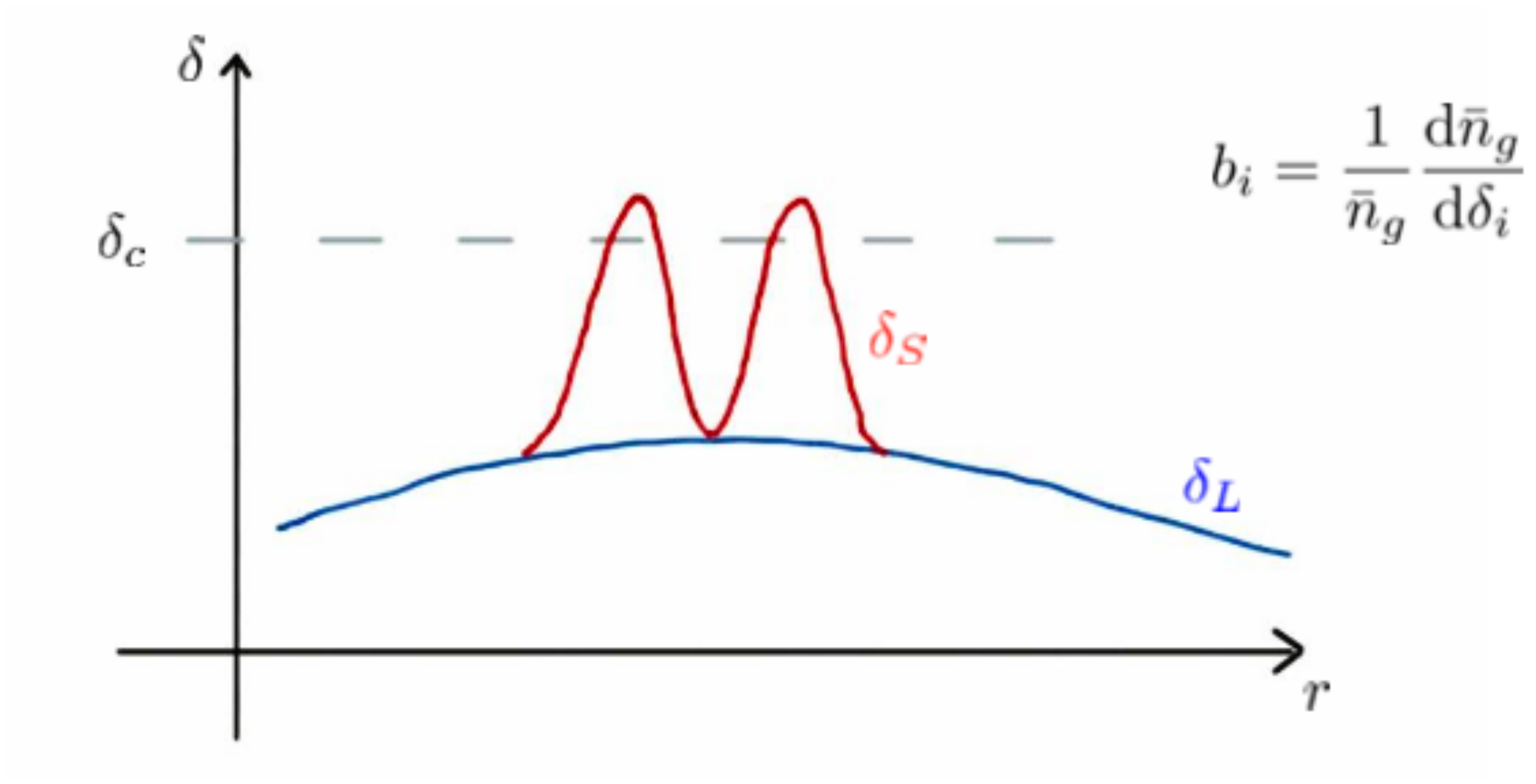
Bias expansion



Long-range fluctuations affect collapse

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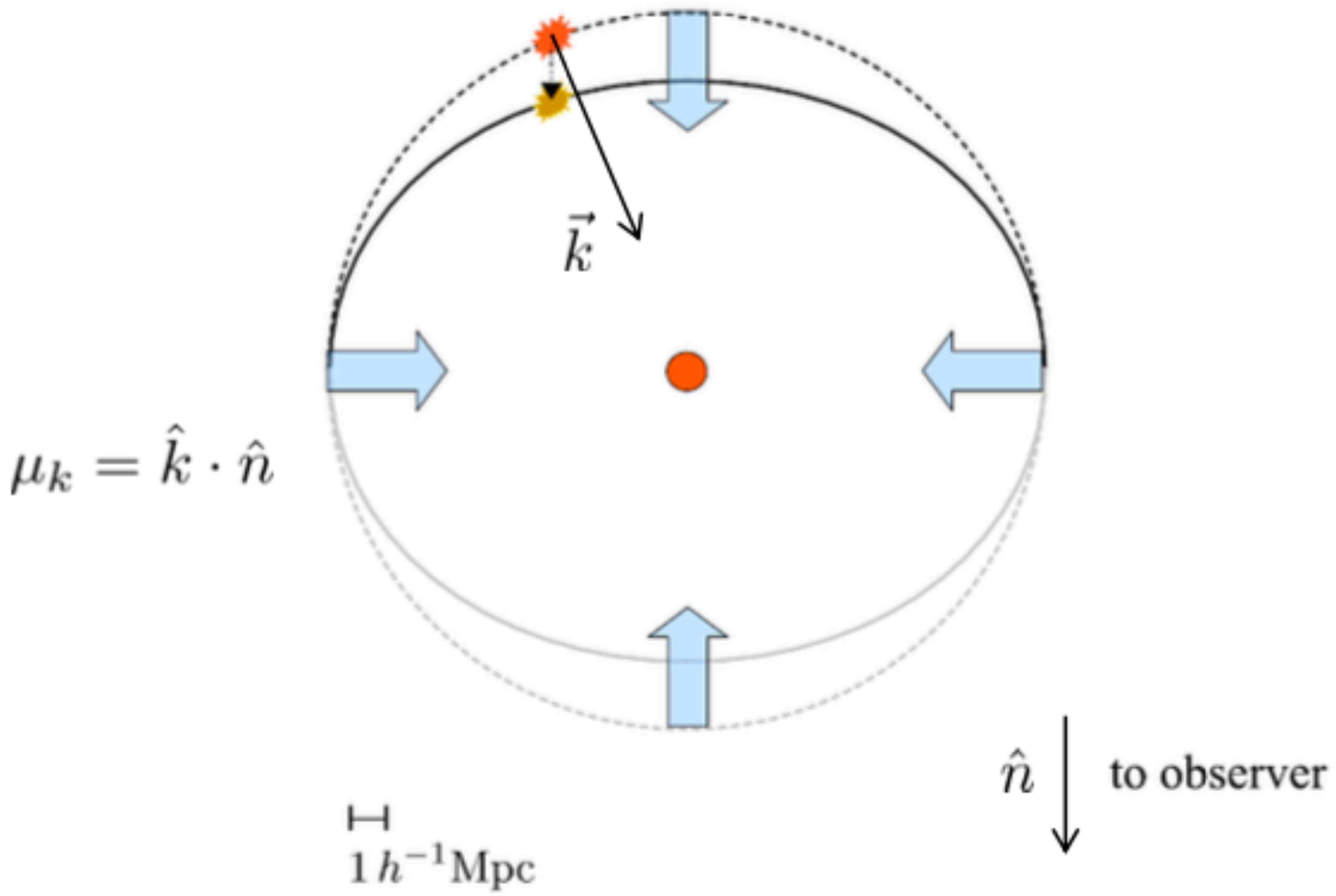
Redshift-space distortions



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We measure correlation functions of $\delta_g^{\rm RSD}$

$$\begin{cases} \langle \delta_g^{\rm RSD}(\vec{k}_1)\delta_g^{\rm RSD}(\vec{k}_2)\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1+\vec{k}_2)P_g^{\rm RSD}(k_1) \\ \ldots \end{cases}$$

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How to make precise predictions?

$$\begin{cases} \delta_m' + \theta_m + \vec{\nabla}(\delta_m \vec{v}_m) = 0, \quad \theta_m = \vec{\nabla}\vec{v}_m & \text{Continuity} \\ \theta_m' + \mathscr{H}\theta_m + \frac{3}{2}\mathscr{H}^2\delta_m + \partial_i(v_m^j \partial_j v_m^i) = 0 & \text{Euler} \end{cases}$$

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↓ Solved iteratively, order by order

$$\delta_m(a,\vec{k}) = D_m(a)\delta_0(\vec{k}) + \sum_{n=2}^{\infty} D^n_m(a) \int \prod_{i=1}^{n} \frac{d^3k_i}{(2\pi)^3} \delta_0(\vec{k}_i)\delta^{(3)}\left(\vec{k} + \sum_{i=1}^{n}\vec{k}_i\right) F_n(\vec{k}_1, \ldots, \vec{k}_n)$$

How to make precise predictions?

Continuity
$$\delta'_m + \theta_m + \vec{\nabla}(\delta_m \vec{v}_m) = 0, \quad \theta_m = \vec{\nabla}\vec{v}_m$$

Euler
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Linear growth factor

How to make precise predictions?

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Linear growth factor

Initial fluctuation at equality

Non-linear kernels

How to make precise predictions?

Continuity / Euler

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Non-linear kernels

Compute correlation functions at any order

How to make precise predictions?

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Compute correlation functions at any order → Wrong predictions!

How to make precise predictions?

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Wrong model!

How to make precise predictions?

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DM is not collisionless at small scales!

$$\partial_i\partial_j\tau^{ij}_{\rm eff} = c_s^2 \nabla^2 \delta_m + \cdots$$

Encodes short-scale backreaction on long modes

New expansion in powers of $\frac{k^2}{k_{\rm NL}^2}$

Counterterms extracted from data

How to make precise predictions?

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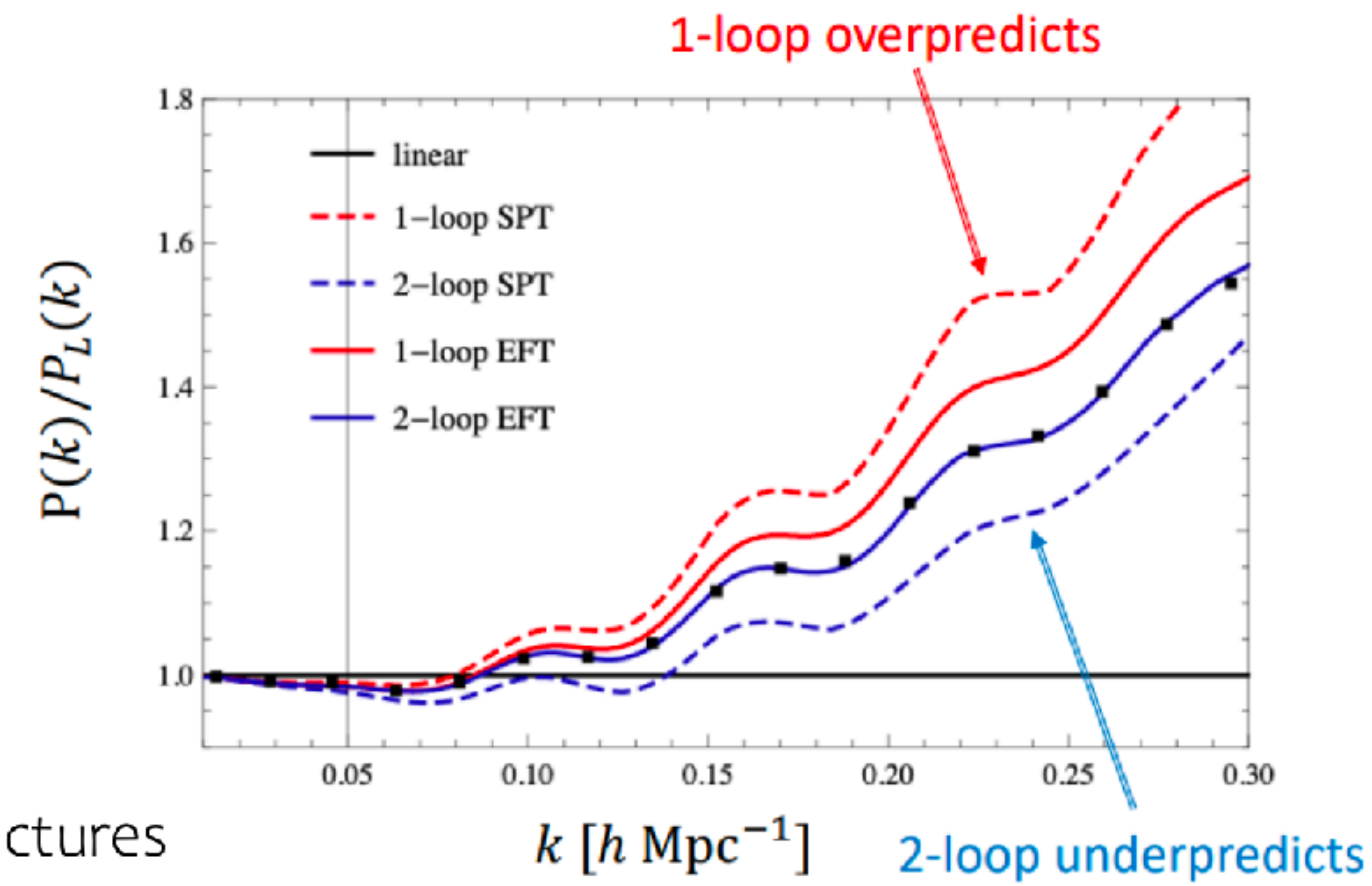
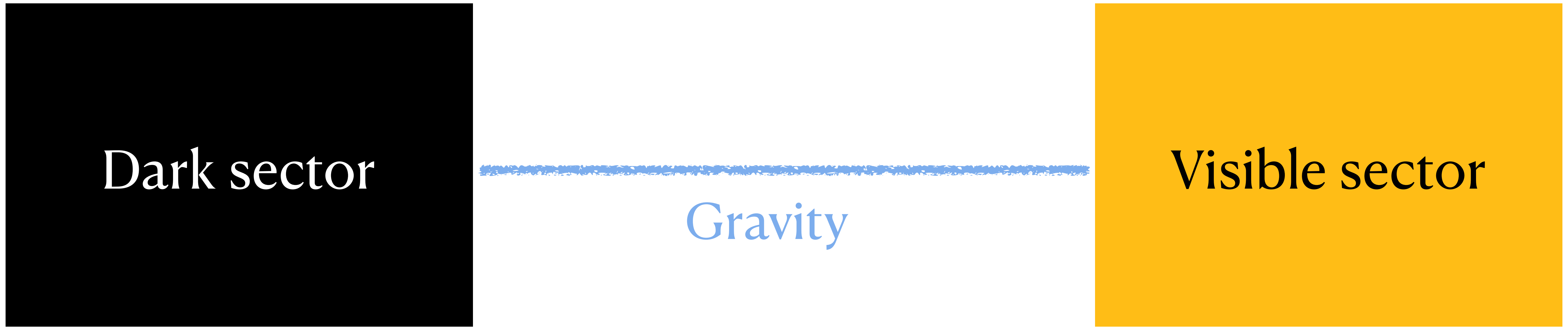


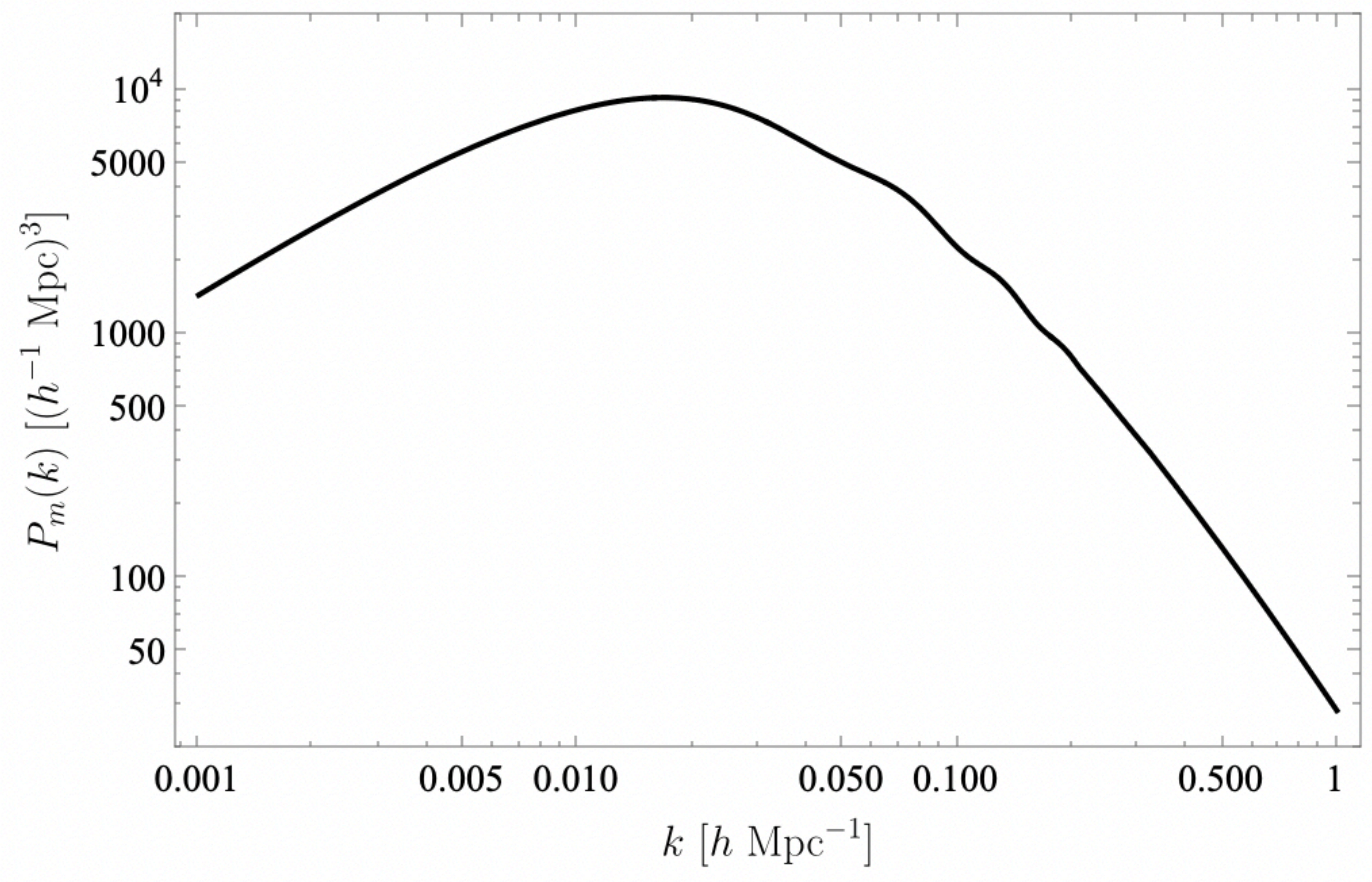
Baldauf lectures

Can we see in the dark?



Cosmology is the only way to probe completely secluded dark sectors!

What can we find in the Power Spectrum?



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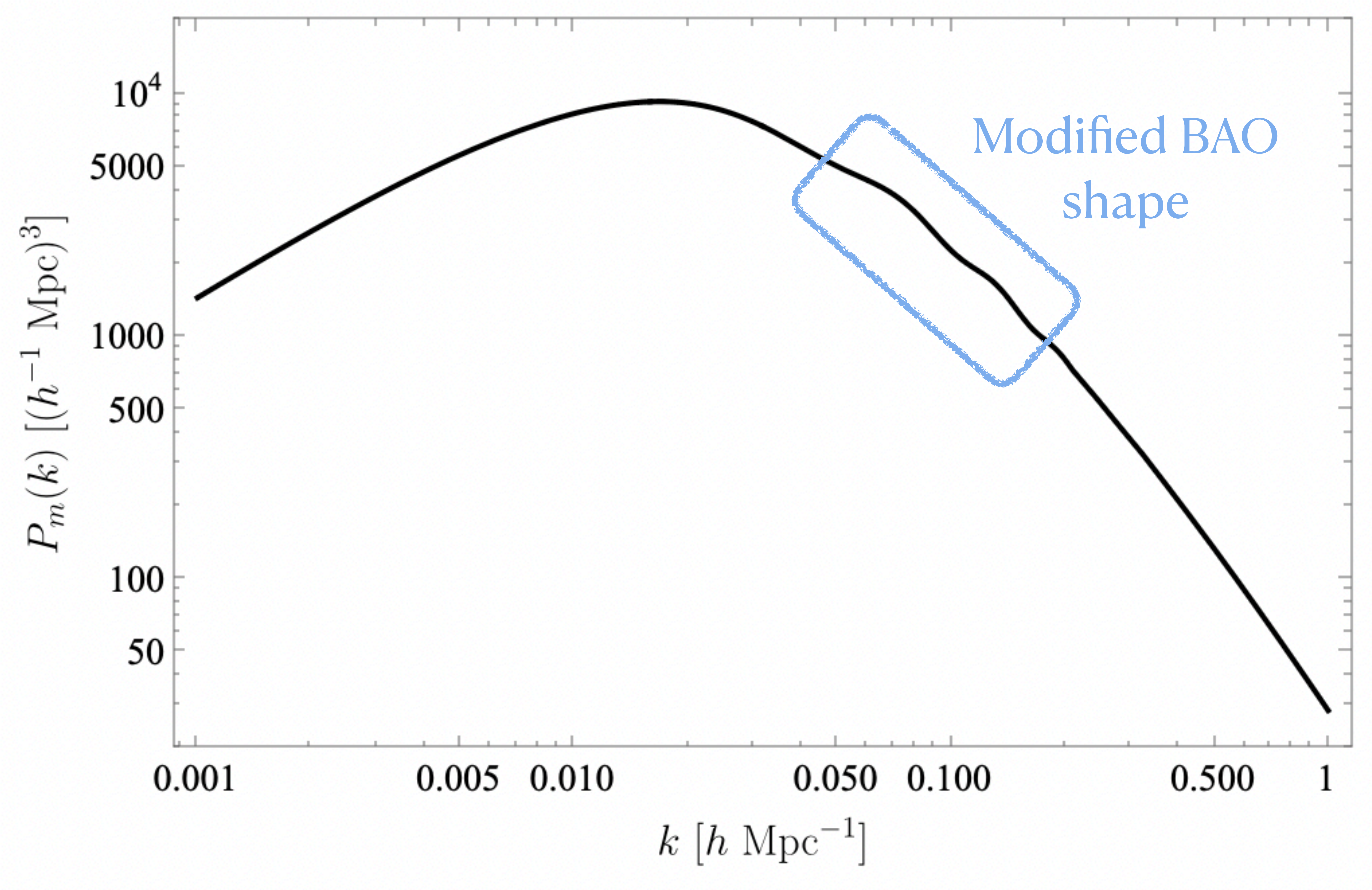

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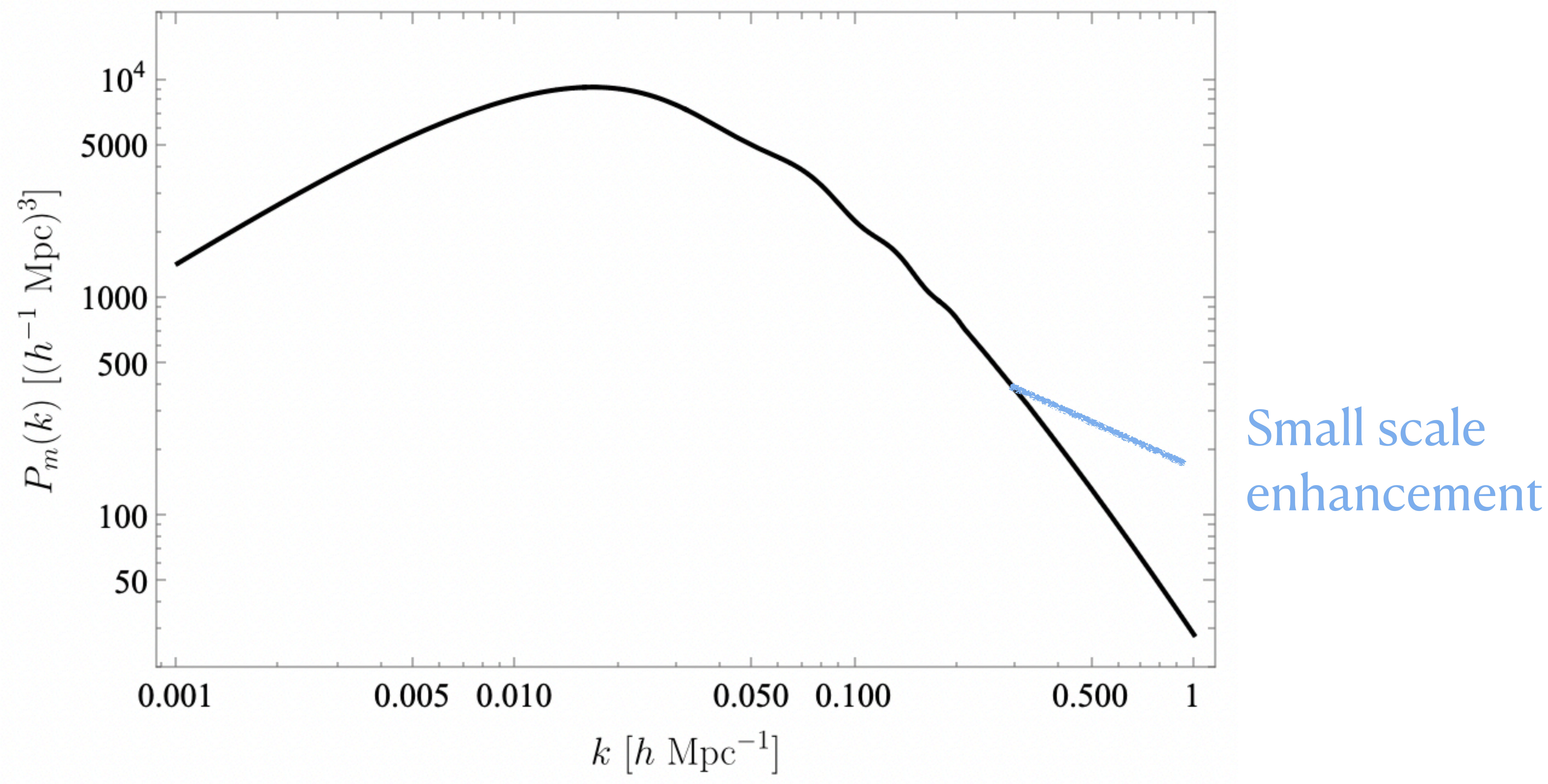

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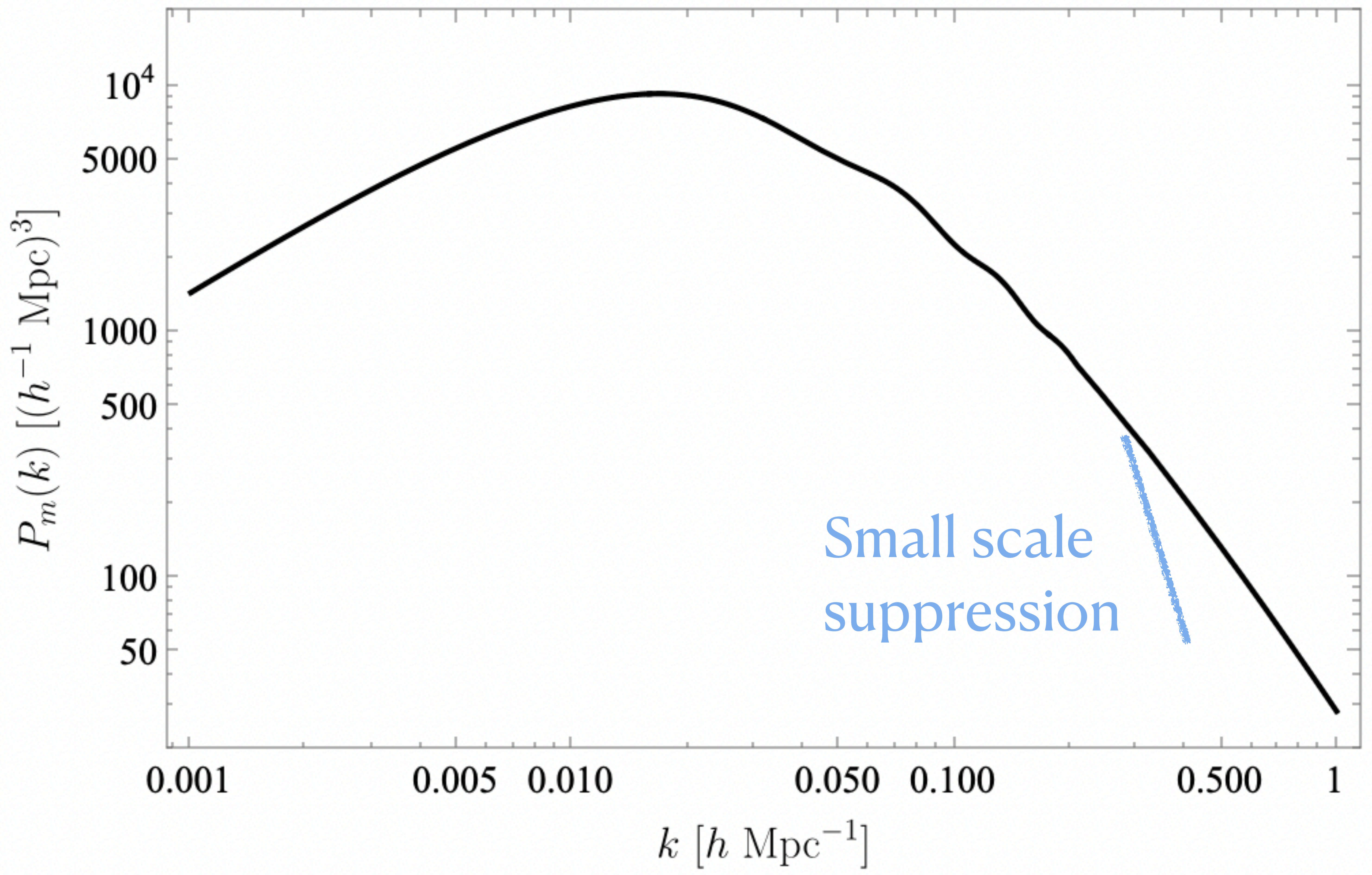

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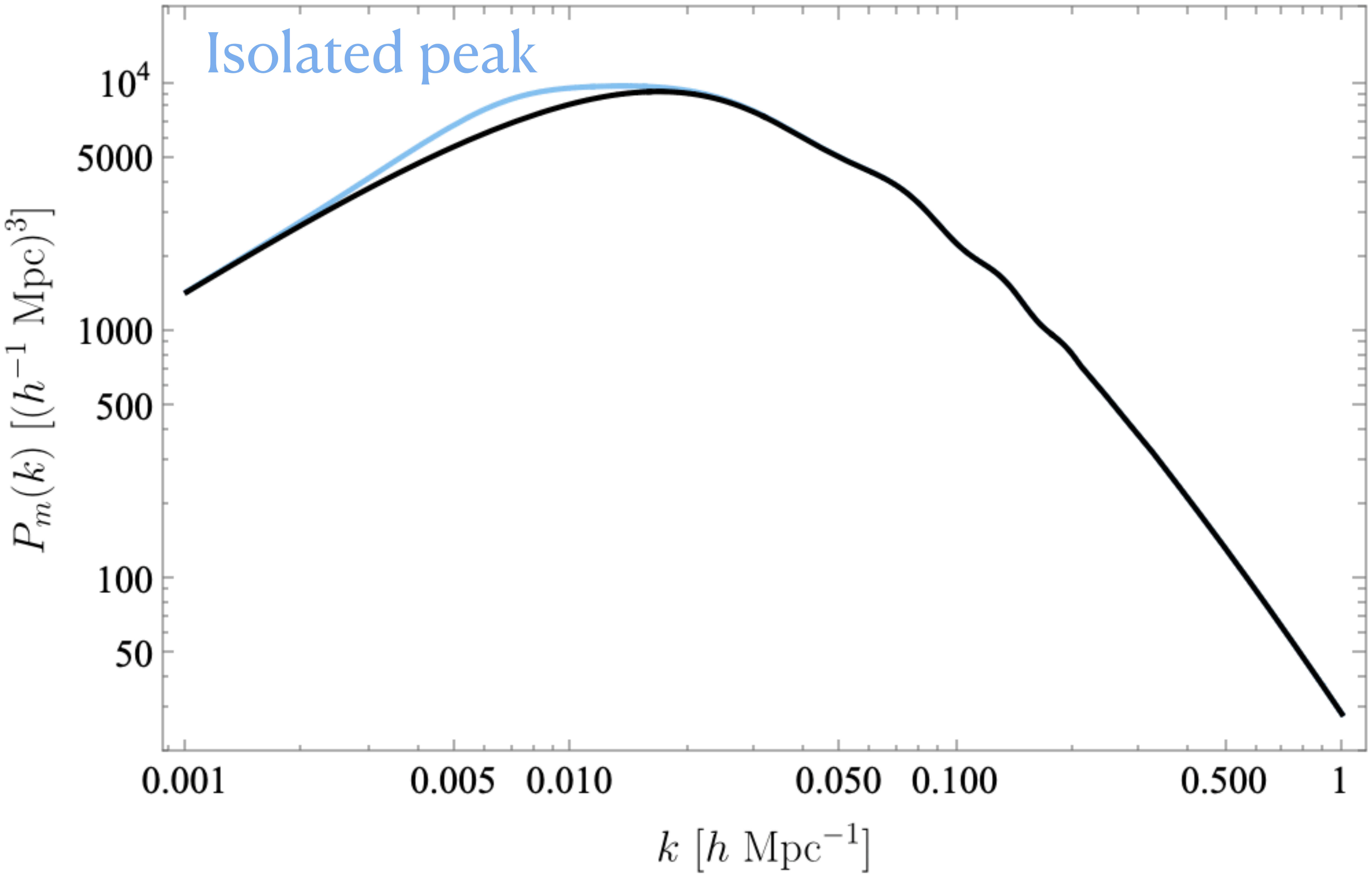

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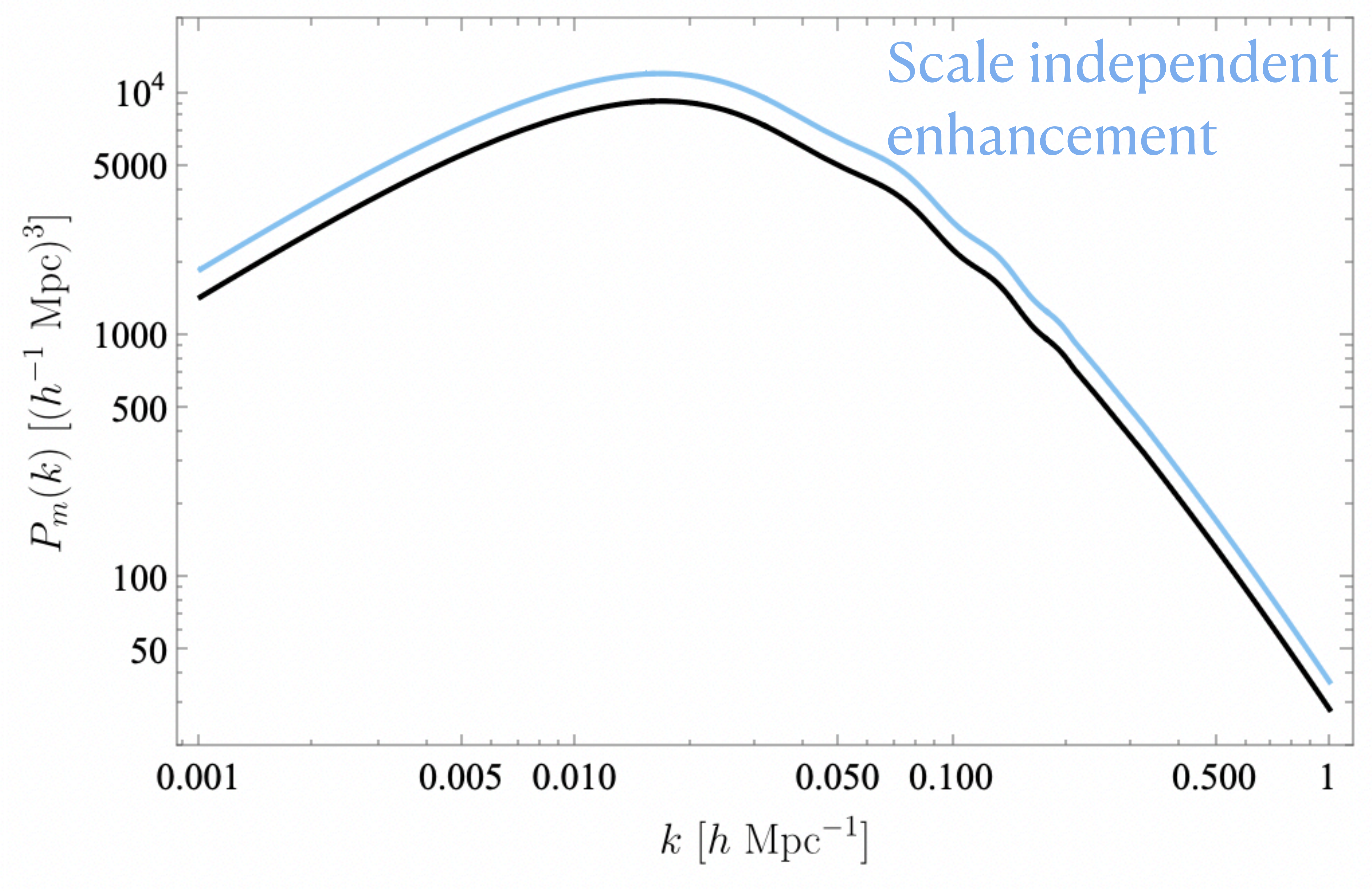

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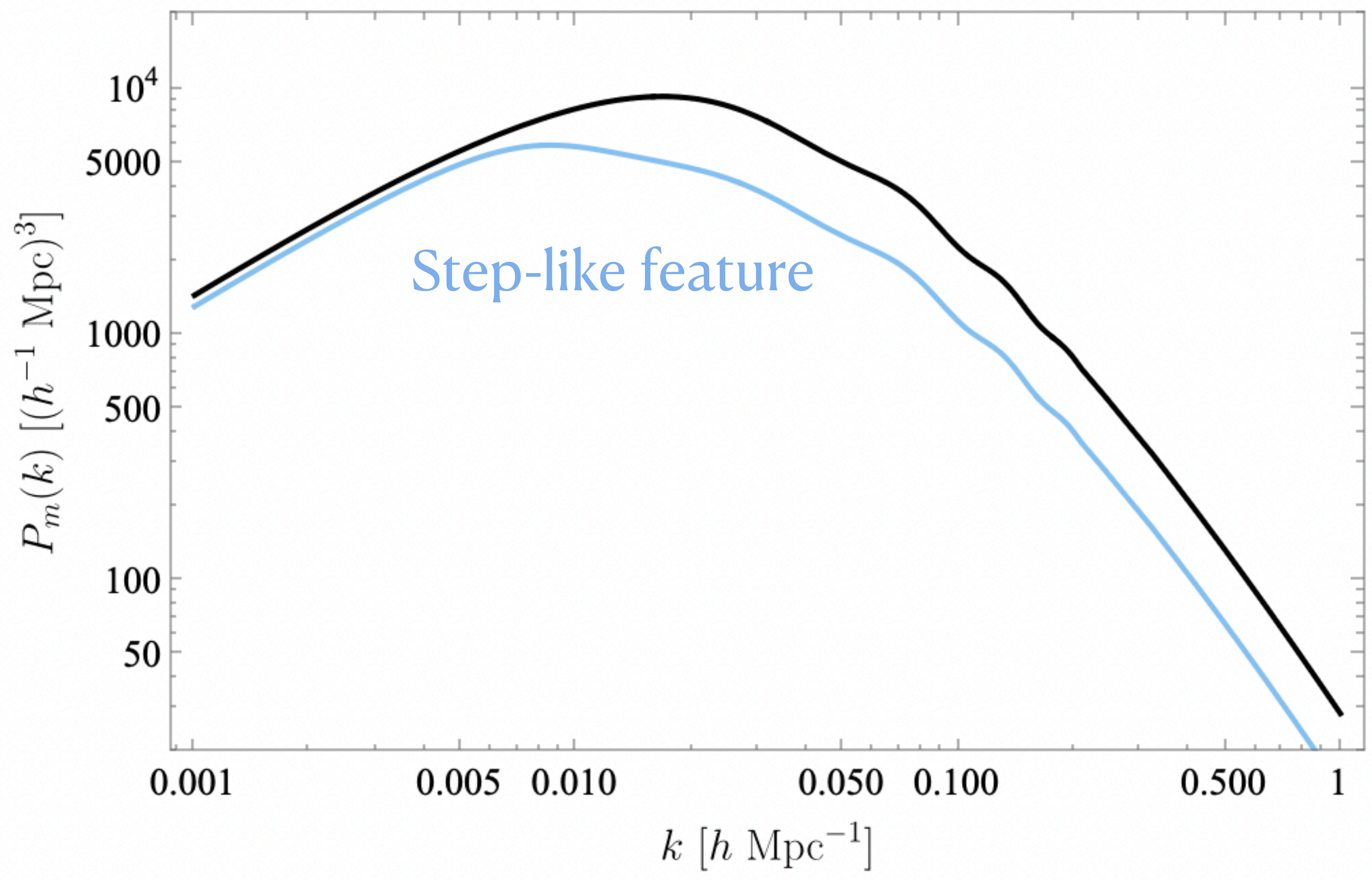

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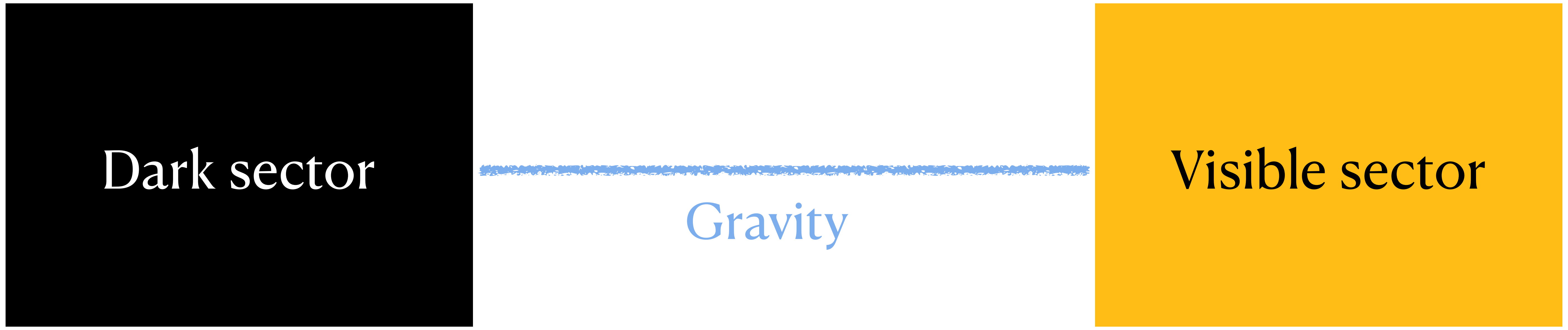


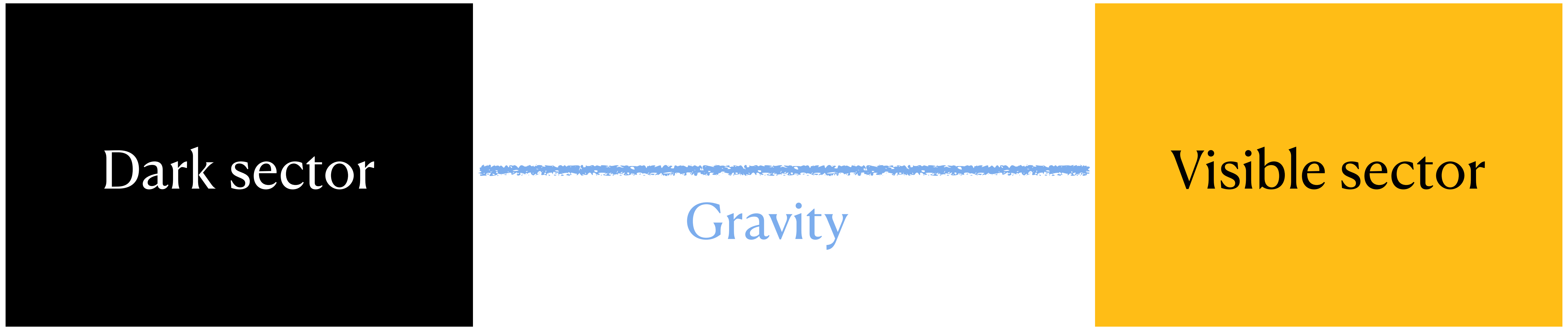
Cosmology is the only way to probe completely secluded dark sectors!

Examples in this talk

Long-range dark forces

Late-time dark phase transitions

Can we see in the dark?



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Examples in this talk

SB et al. 2309.11496
SB et al. 2407.18252
Just al. 2204.08484

Long-range dark forces

Late-time dark phase transitions

A simple model

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \chi)^2 + \frac{1}{2G_s}(\partial_\mu s)^2 + \frac{1}{2G_s} m_s^2 s^2 + \frac{1}{2} m_\chi^2 (1 + 2s)\chi^2, \quad G_s = \frac{\kappa^2}{m_\chi^4}$$

Dark matter

Scalar dark force mediator

Interaction term: s-dependent DM mass

A simple model

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Dark matter | Scalar dark force mediator | Interaction term: s-dependent DM mass

Dynamics determined by three parameters

1. Scalar mass m_s
2. Dark Matter fraction f_χ
3. Strength of the dark force $\beta = \frac{G_s}{4\pi G_N}$

Upper bound on m_χ from naturalness $m_\chi \lesssim 0.02 \text{ eV} \left(\frac{0.01}{\beta}\right)^{\frac{1}{4}} \left(\frac{m_s}{H_0}\right)^{\frac{1}{2}}$

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Dark matter — Scalar dark force mediator — Interaction term: s-dependent DM mass

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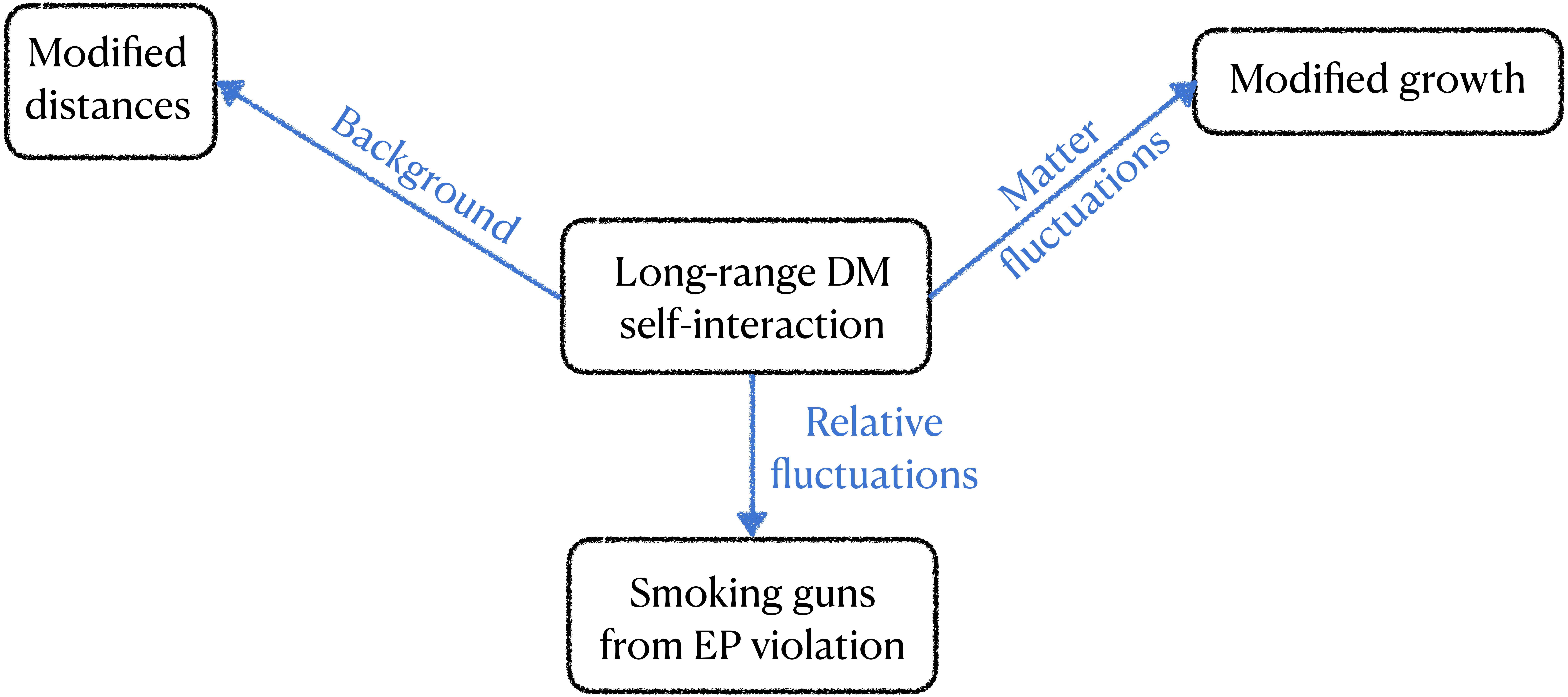
Working assumptions →

$m_s \leq H_{\rm eq} \approx 10^{-28}$ eV

$f_\chi \approx f_{\rm cdm}$

Upper bound on m_χ from naturalness $m_\chi \lesssim 0.02 \text{ eV} \left(\frac{0.01}{\beta}\right)^{\frac{1}{4}} \left(\frac{m_s}{H_0}\right)^{\frac{1}{2}}$

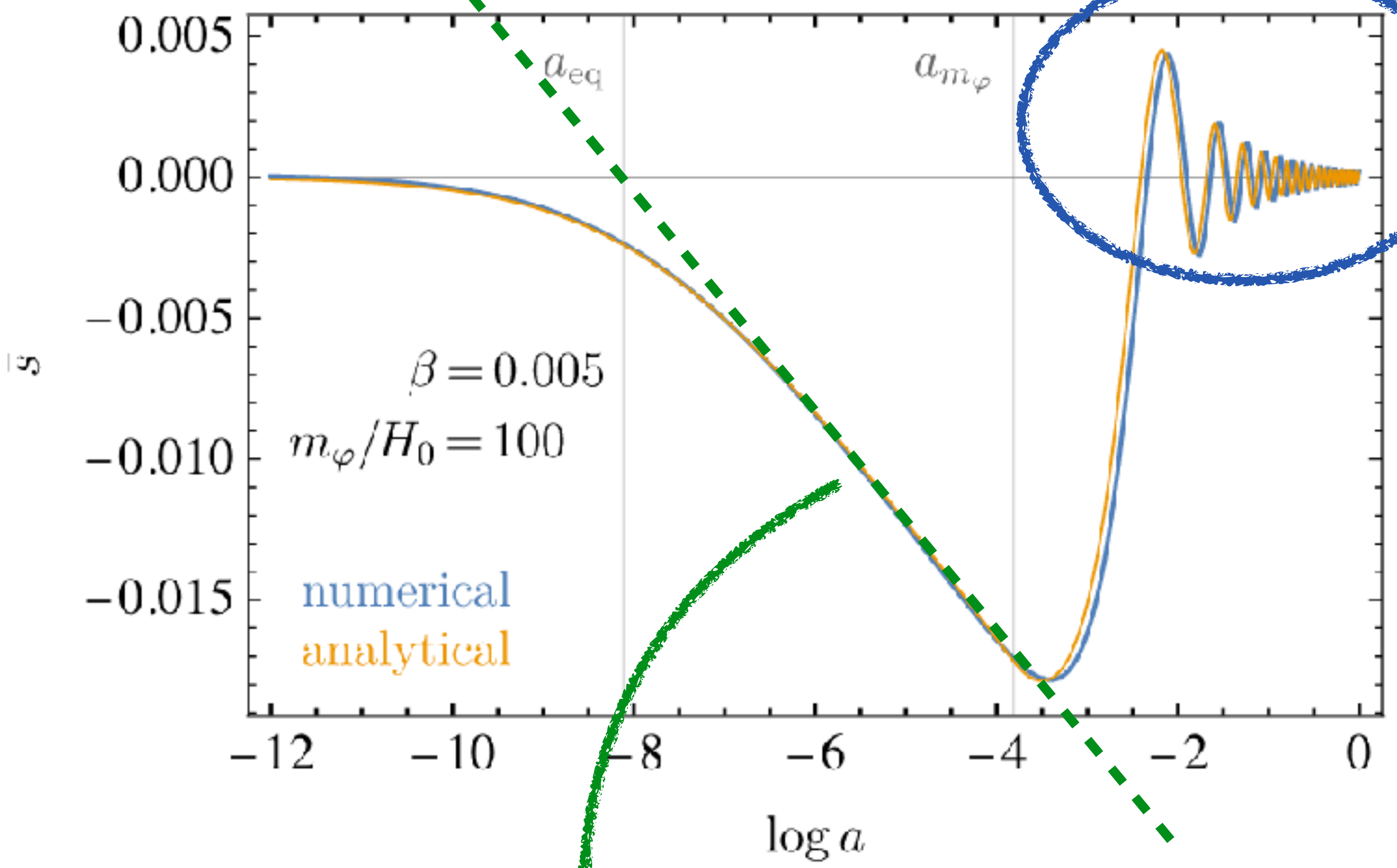
Dark force dynamics

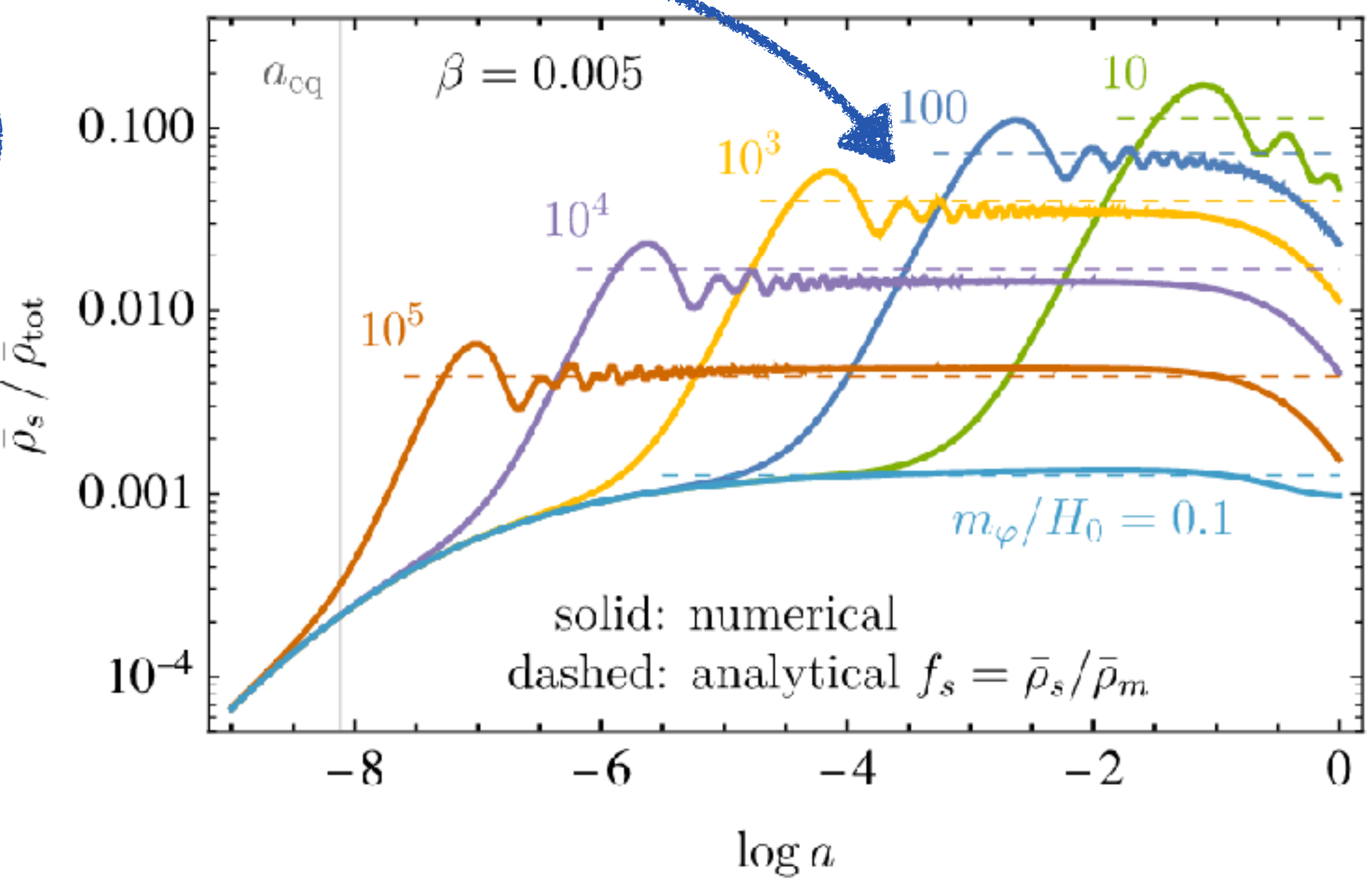


Background dynamics

Behaves as CDM with fraction $f_s \sim \beta f_\chi^2 \log \frac{m_s^2}{H_0^2}$

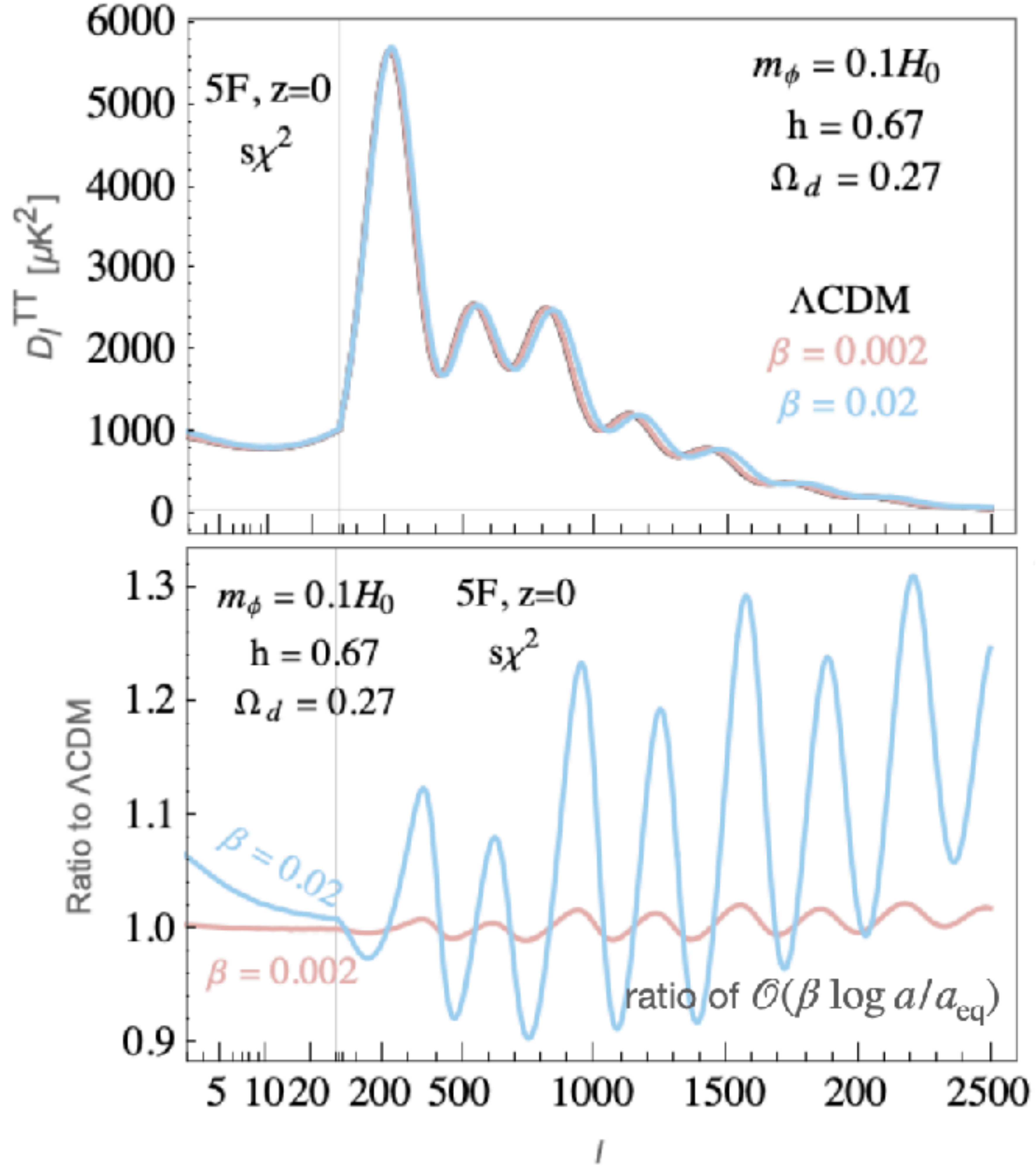
$\bar{s} \sim \beta f_\chi \log a$





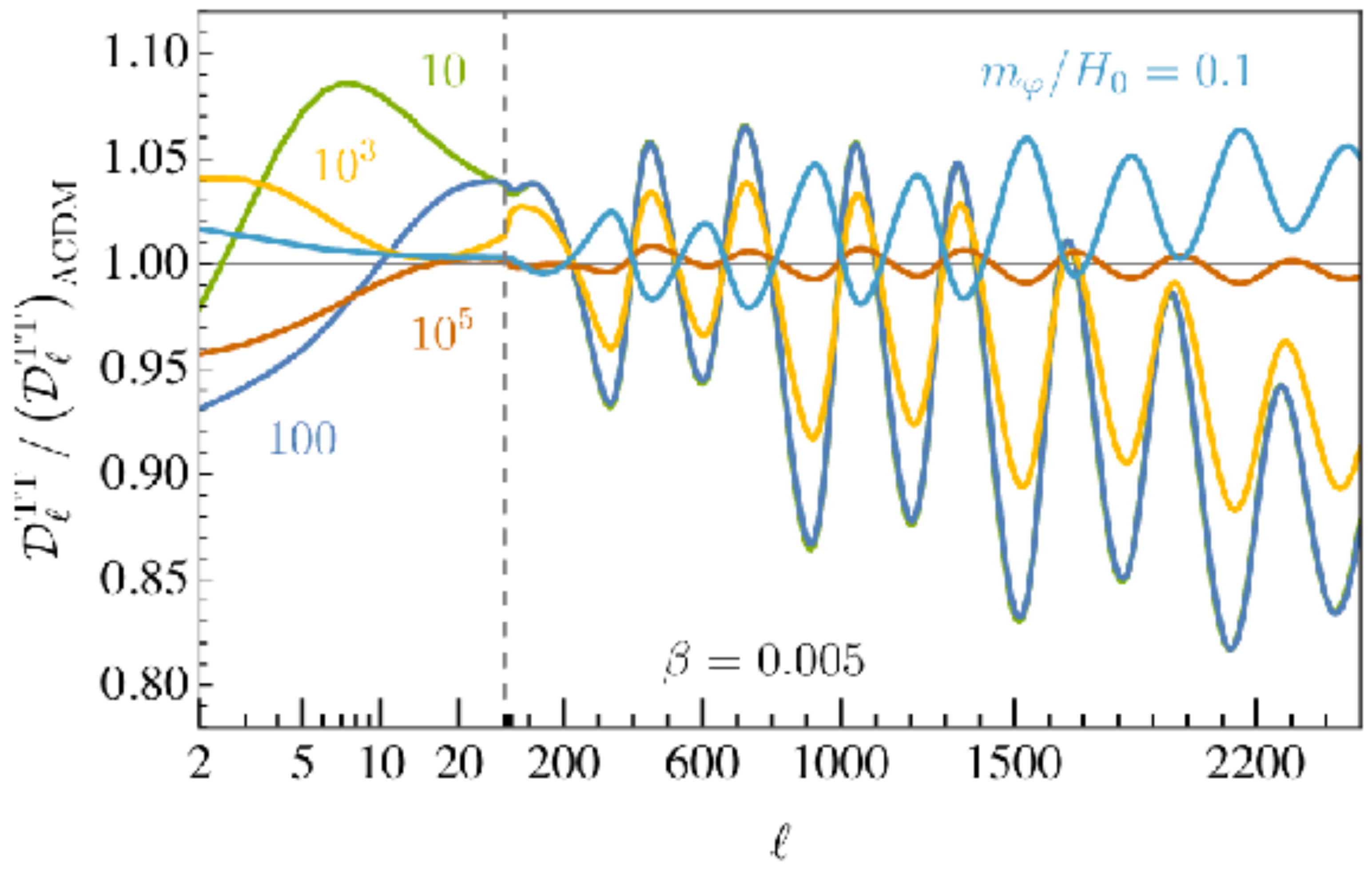
DM redshifts faster $\Omega_\chi \simeq a^{-3}\left(1 - \beta f_\chi \log \frac{a}{a_{eq}}\right)$

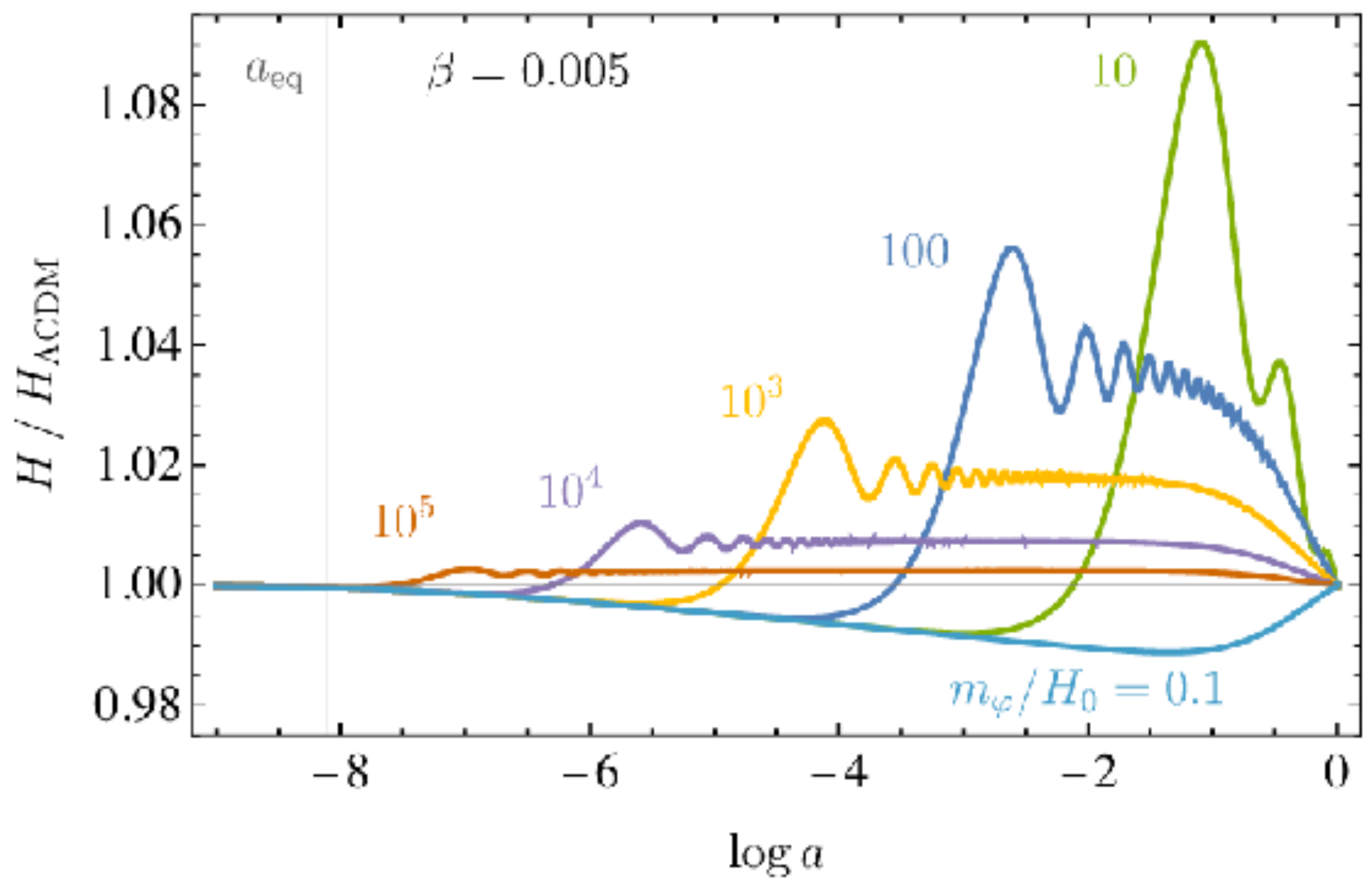
Effects on CMB



Pure shift from bkg evolution

$$\ell_n \approx \frac{n\pi}{c_s \chi_{\rm rec}} \propto \int_0^{\rm rec} dz \frac{1}{H_{\Lambda CDM}(z) + \Delta H(z)}$$





Effects on Matter Power Spectrum

Two contrasting effects

Enhancement from new attractive force

Suppression from mediator Jeans scale

$$k_{Js} \approx 5 \times 10^{-4} \left(\frac{m_s}{H_0} \right)^{\frac{1}{2}} h \text{ Mpc}^{-1}$$

Effects on Matter Power Spectrum

Two contrasting effects

Enhancement from new attractive force

$m_s \leq H_0$

$$\begin{cases} \delta'_m + \theta_m + \vec{\nabla}(\delta_m \vec{v}_m) = 0, \quad \theta_m = \vec{\nabla}\vec{v}_m \\ \theta'_m + \mathscr{H}(1-\beta f_\chi^2)\theta_m + \frac{3}{2}\mathscr{H}^2(1+\beta f_\chi^2)\delta_m + \partial_i(v_m^j \partial_j v_m^i) = -\frac{1}{\bar{\rho}_m}\partial_i\partial_j\tau^{ij}_{\text{eff}} \end{cases}$$

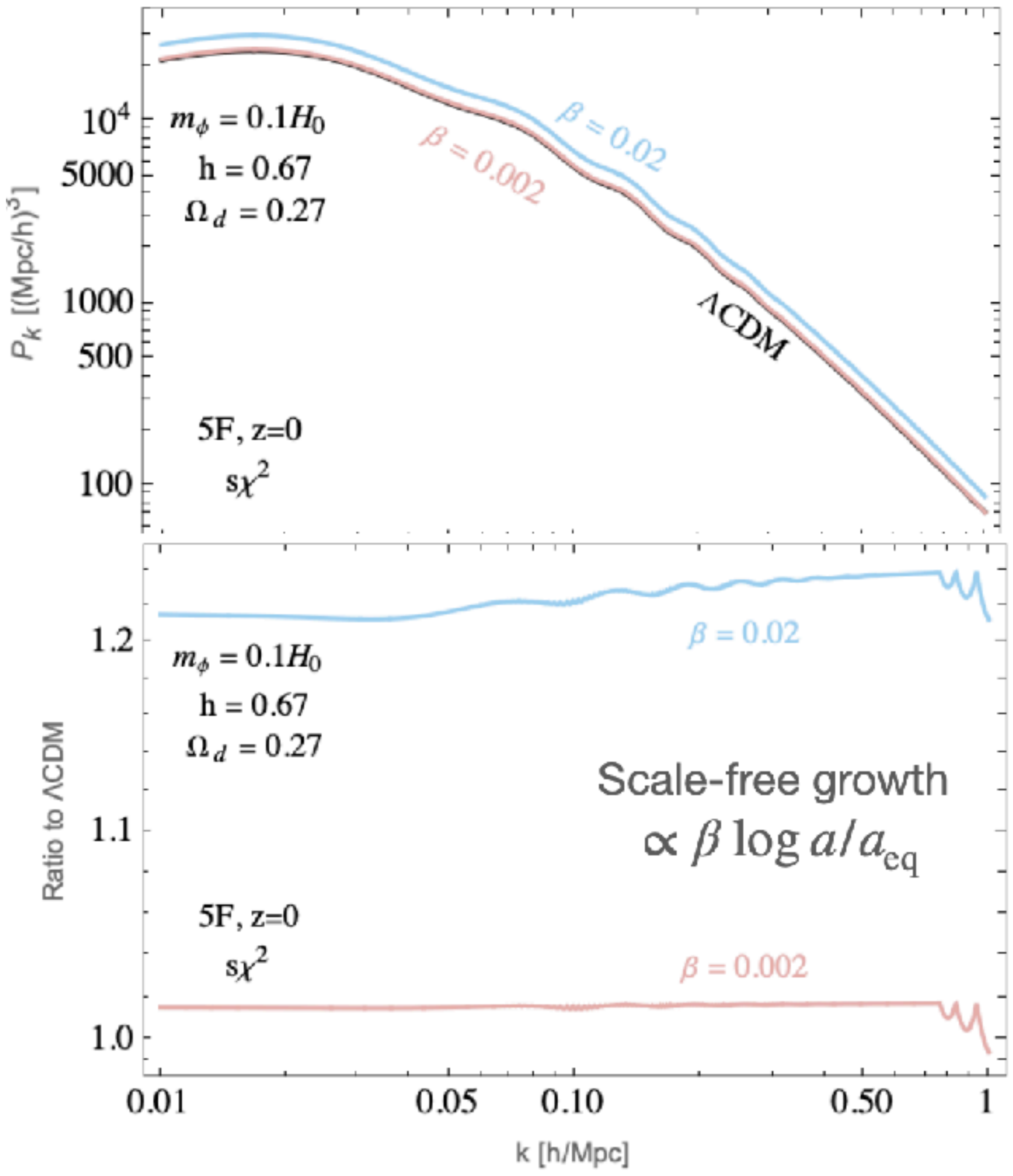
Suppression from mediator Jeans scale

$$k_{Js} \approx 5 \times 10^{-4} \left(\frac{m_s}{H_0}\right)^{\frac{1}{2}} h\ \text{Mpc}^{-1}$$

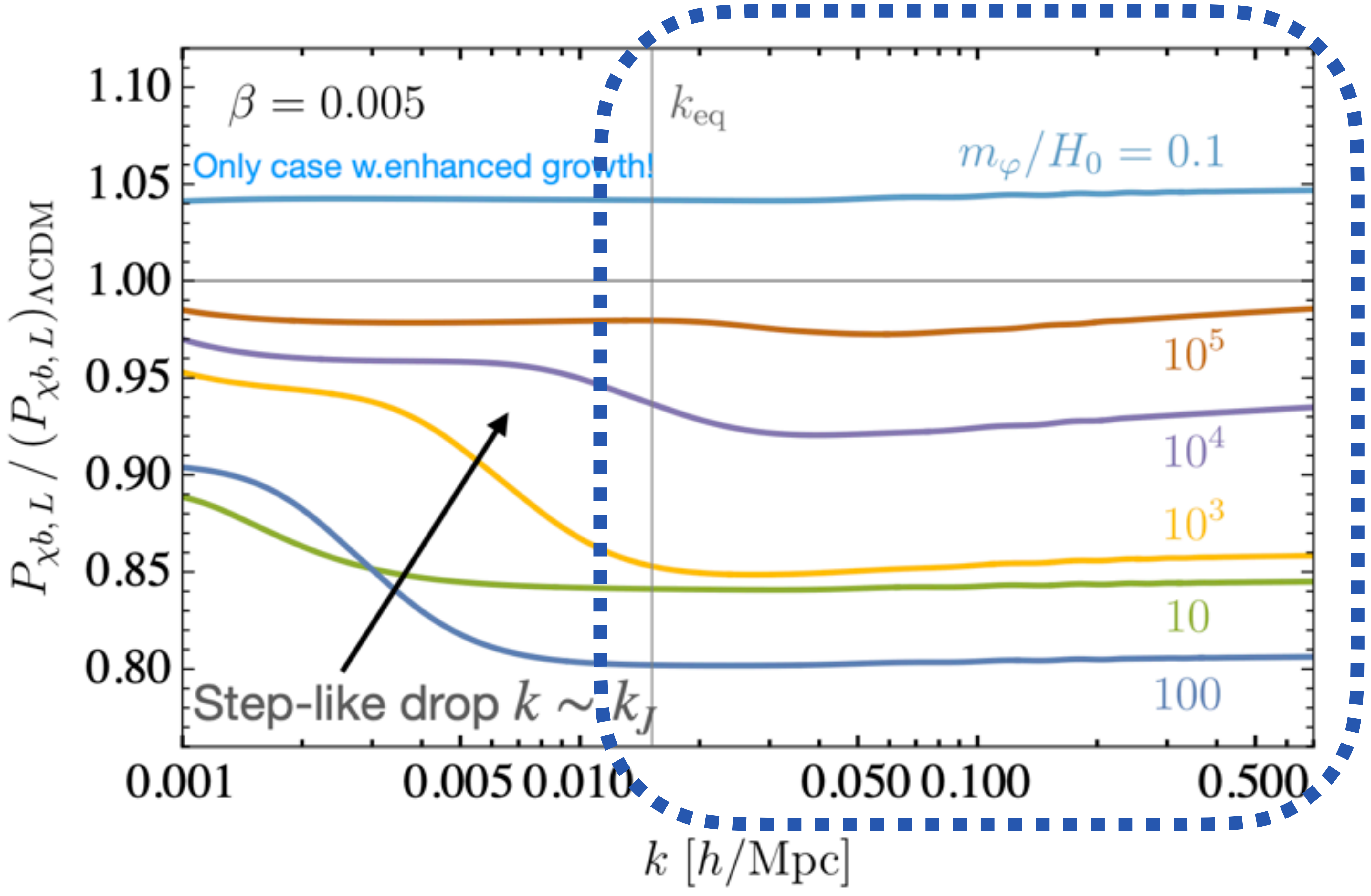
$k_{Js} \leq k_{\text{eq}}$ **if** $m_s \leq H_{\text{eq}}$

Scale independent growth factor at the scales relevant for LSS

Effects on Matter Power Spectrum

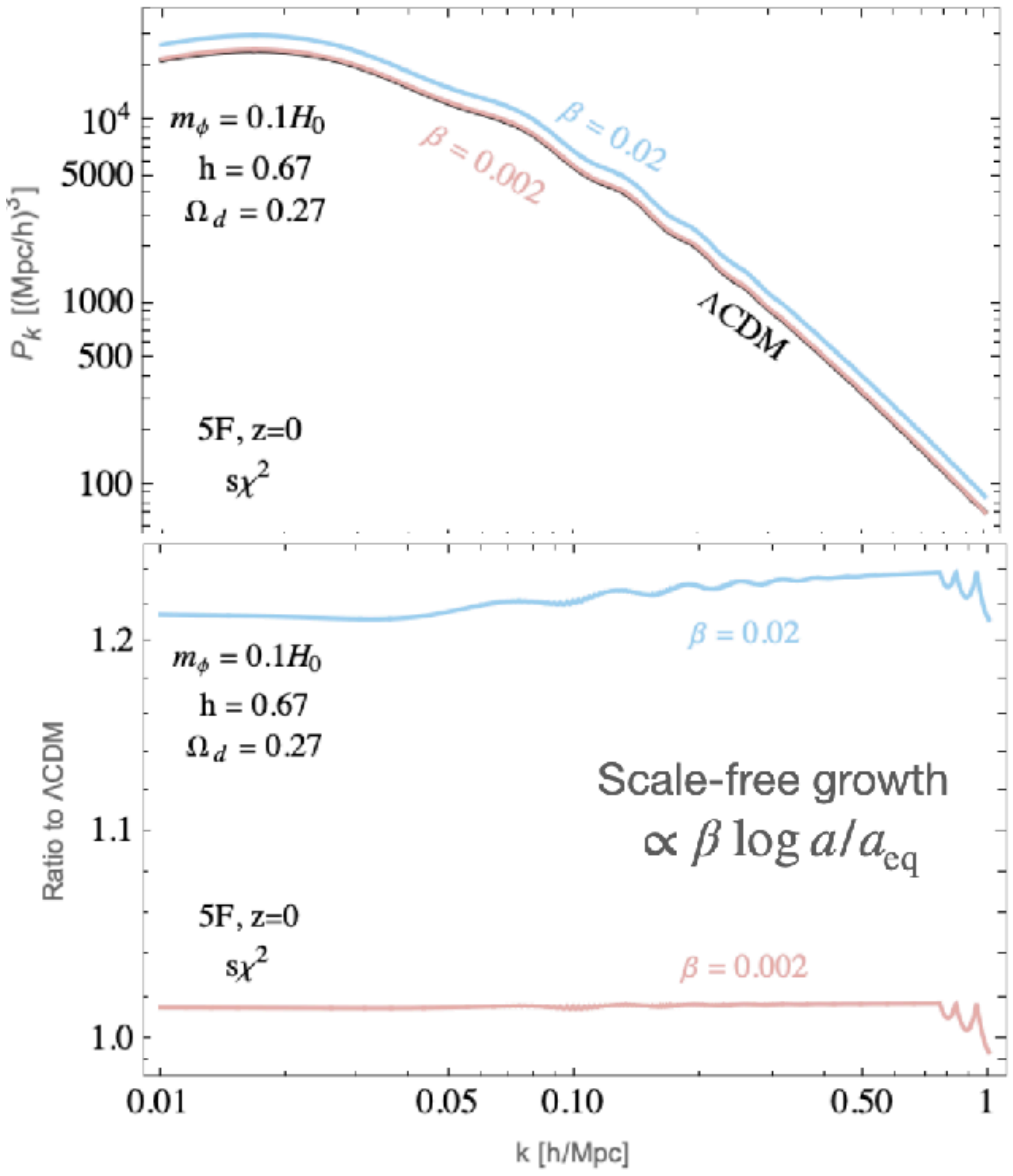


Scale-free growth factor at scales relevant for LSS

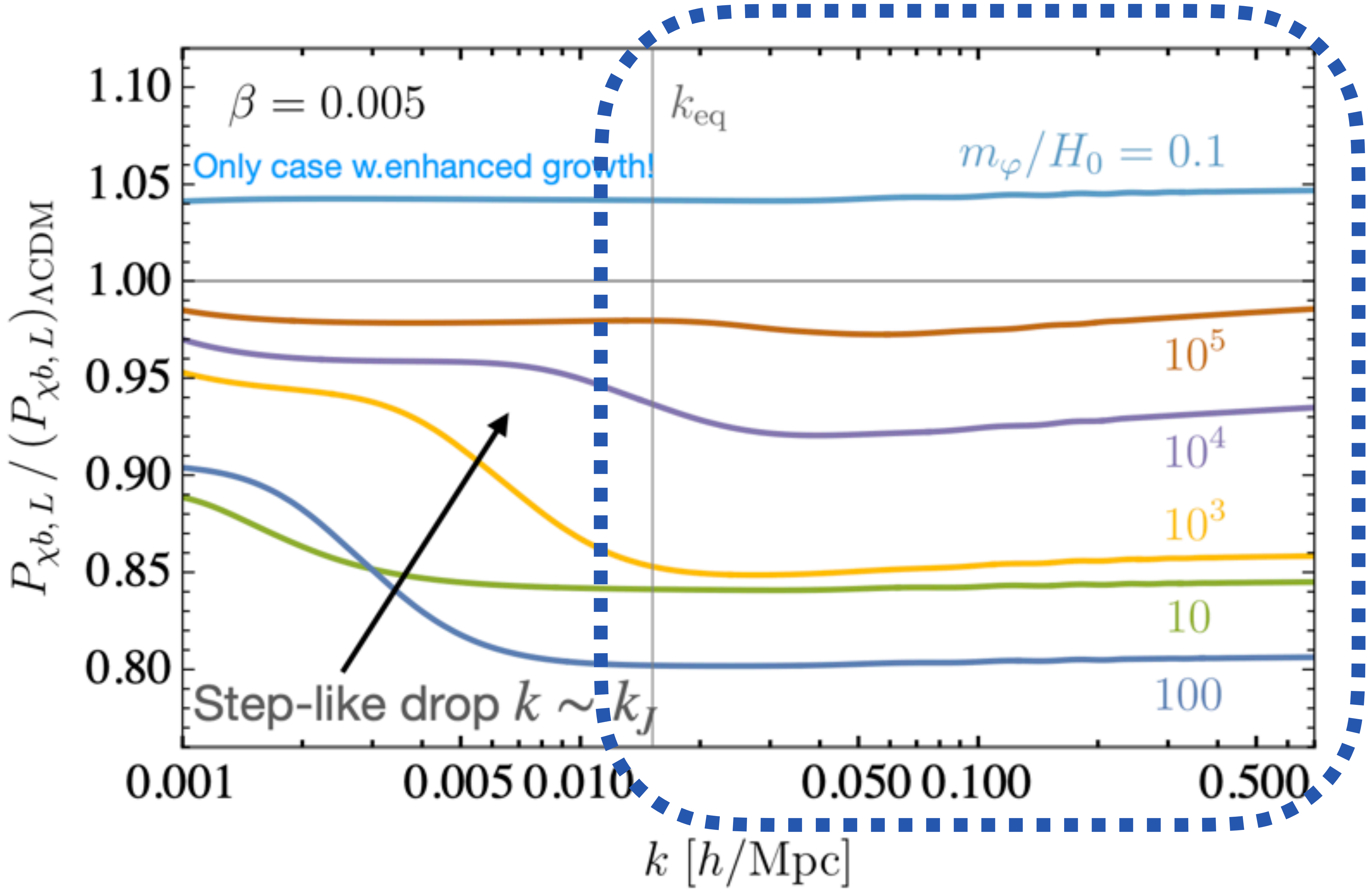


$$\frac{\delta_m(a)}{\delta_m^{\rm CDM}(a)} - 1 \simeq \frac{6}{5}\beta \tilde{m}_s^2 f_\chi^2 \log\frac{a_{m_\varphi}}{a_{\rm eq}} - f_s - \frac{3}{5} f_s \log\frac{a}{a_{m_\varphi}}$$

Effects on Matter Power Spectrum



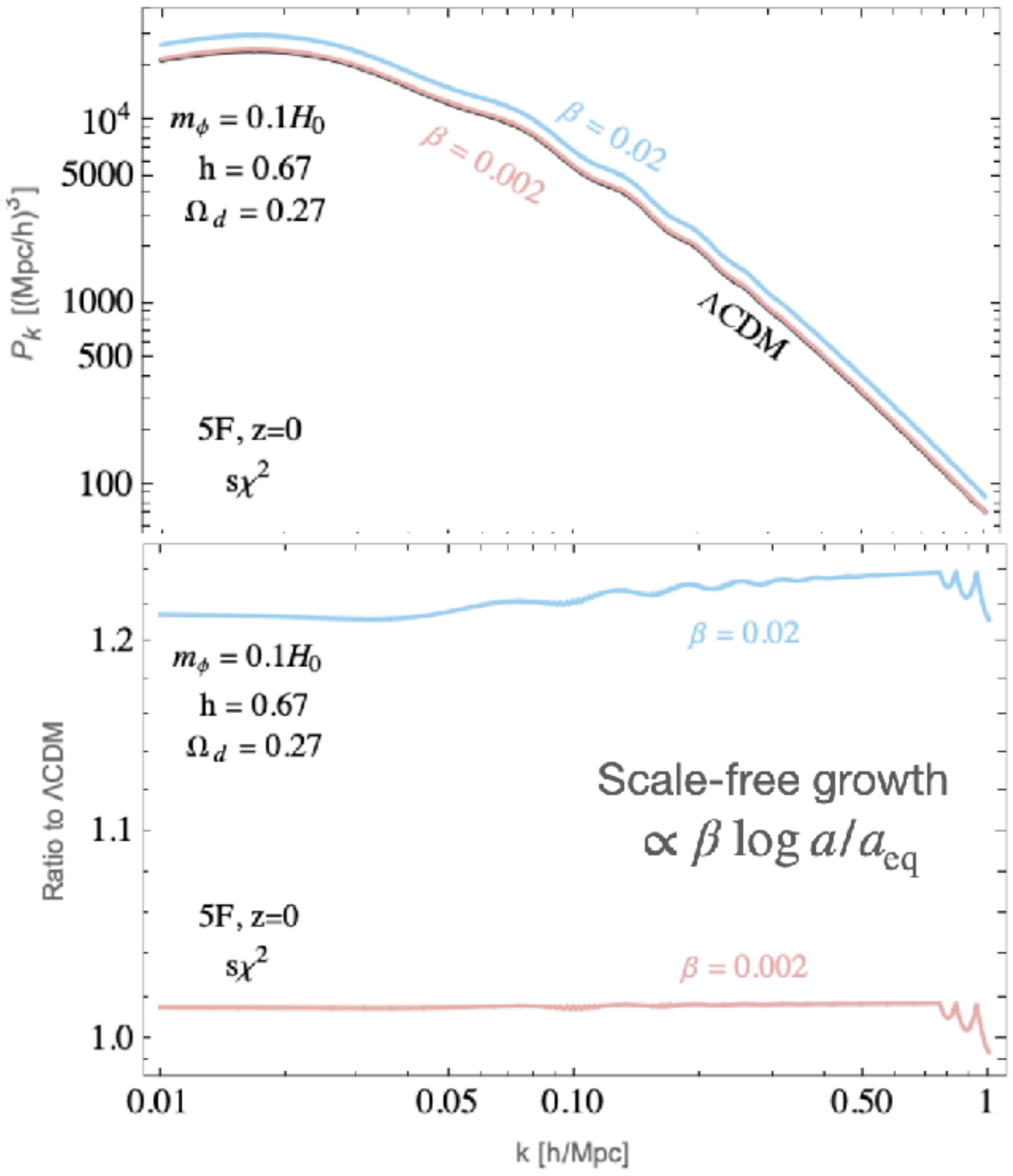
Scale-free growth factor at scales relevant for LSS



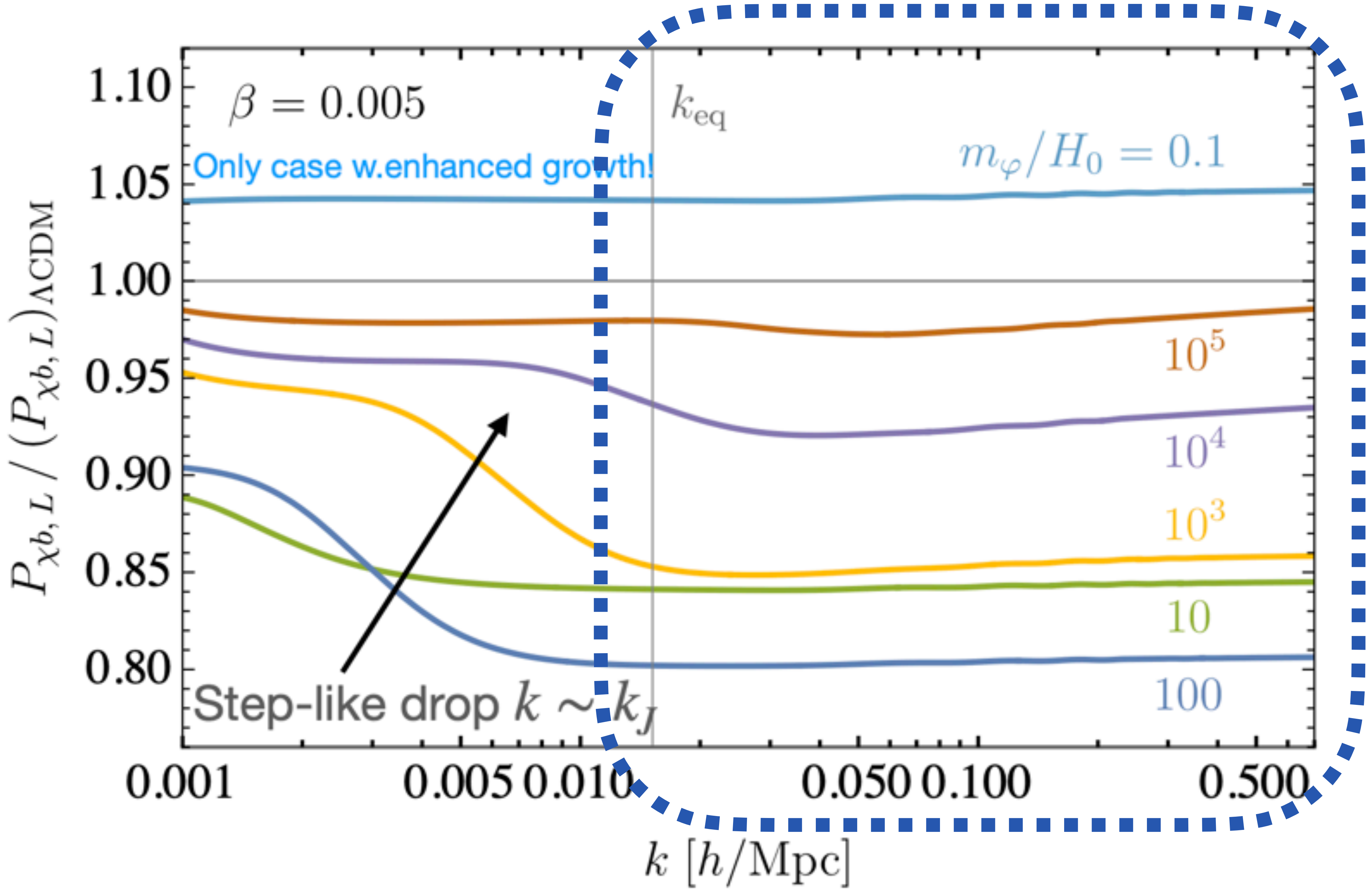
$$\frac{\delta_m(a)}{\delta_m^{\rm CDM}(a)} - 1 \simeq \frac{6}{5}\beta \tilde{m}_s^2 f_\chi^2 \log\frac{a_{m_\varphi}}{a_{\rm eq}} - f_s - \frac{3}{5} f_s \log\frac{a}{a_{m_\varphi}}$$

Enhanced growth

Effects on Matter Power Spectrum



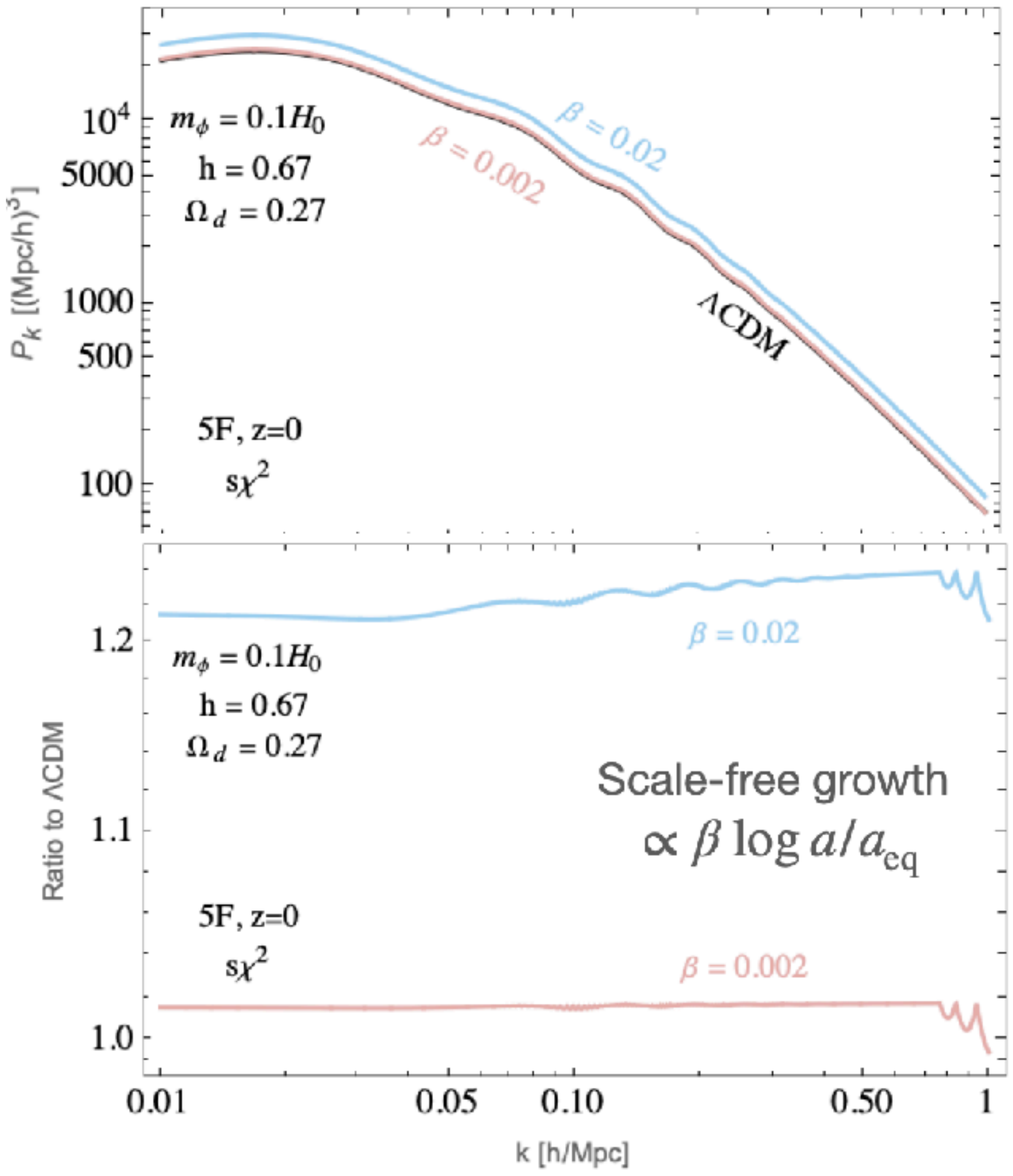
Scale-free growth factor at scales relevant for LSS



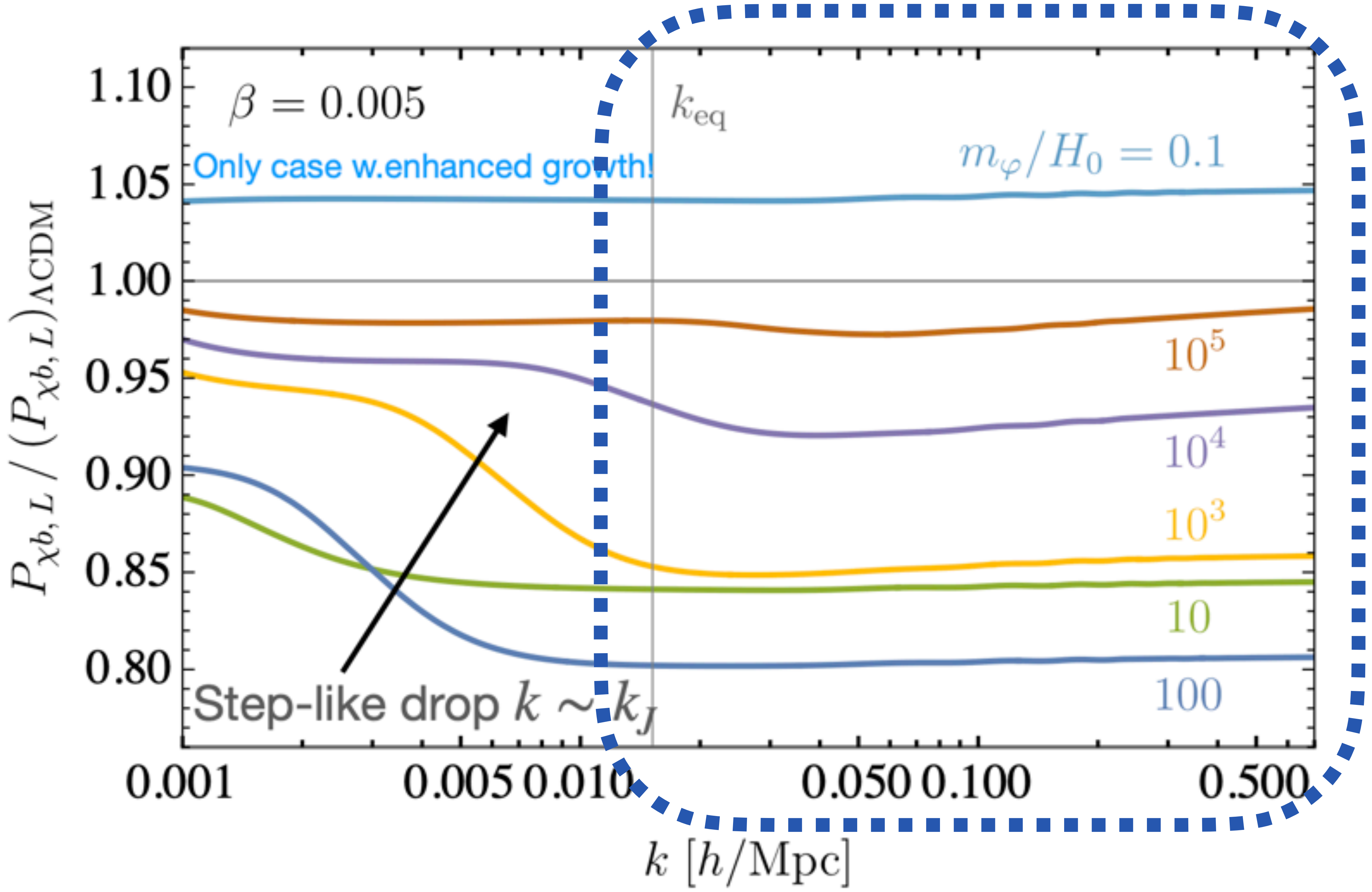
$$\frac{\delta_m(a)}{\delta_m^{\rm CDM}(a)} - 1 \simeq \frac{6}{5}\beta \tilde{m}_s^2 f_\chi^2 \log\frac{a_{m_\varphi}}{a_{\rm eq}} - f_s - \frac{3}{5} f_s \log\frac{a}{a_{m_\varphi}}$$

Mediator not clustering

Effects on Matter Power Spectrum



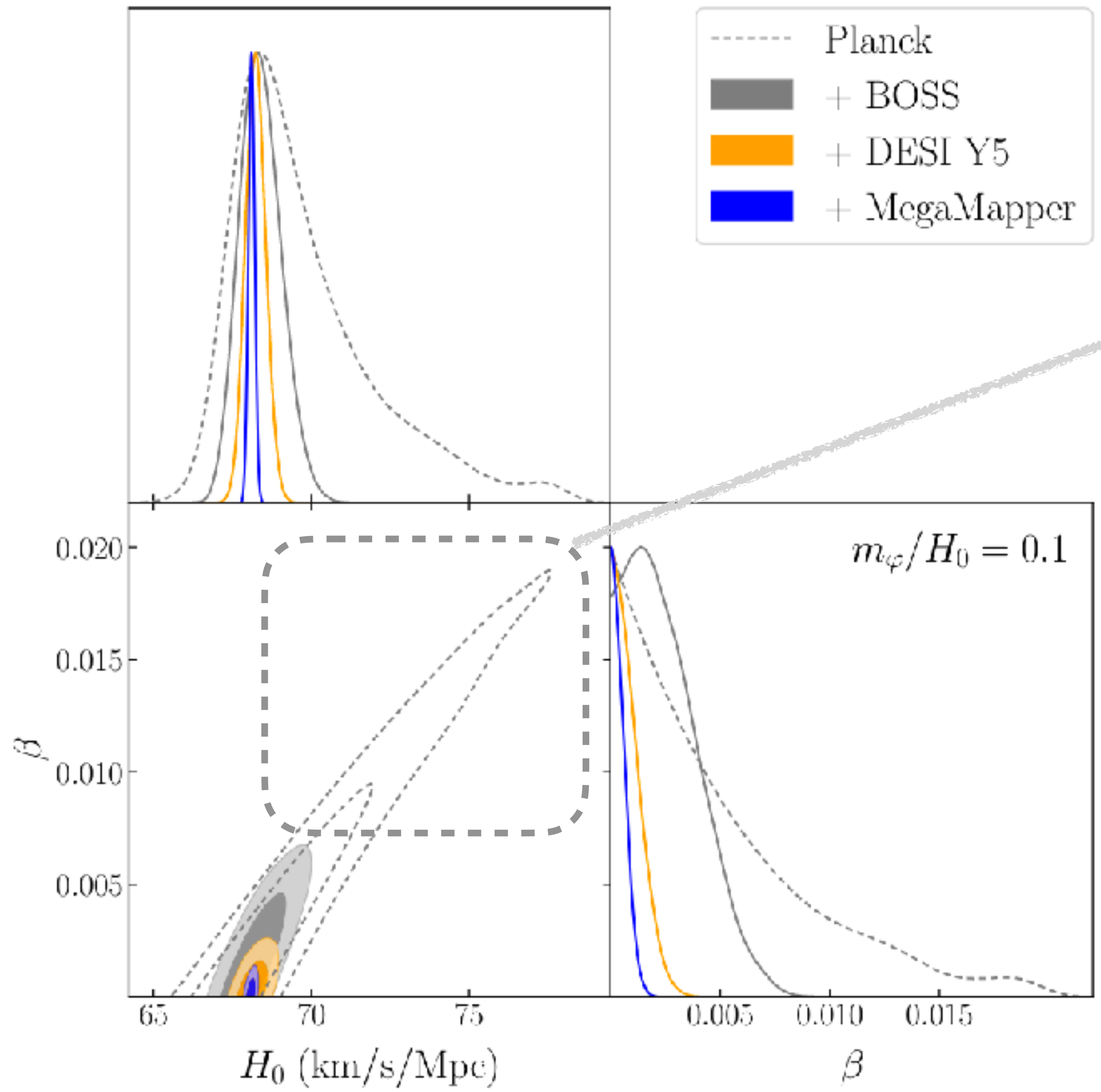
Scale-free growth factor at scales relevant for LSS



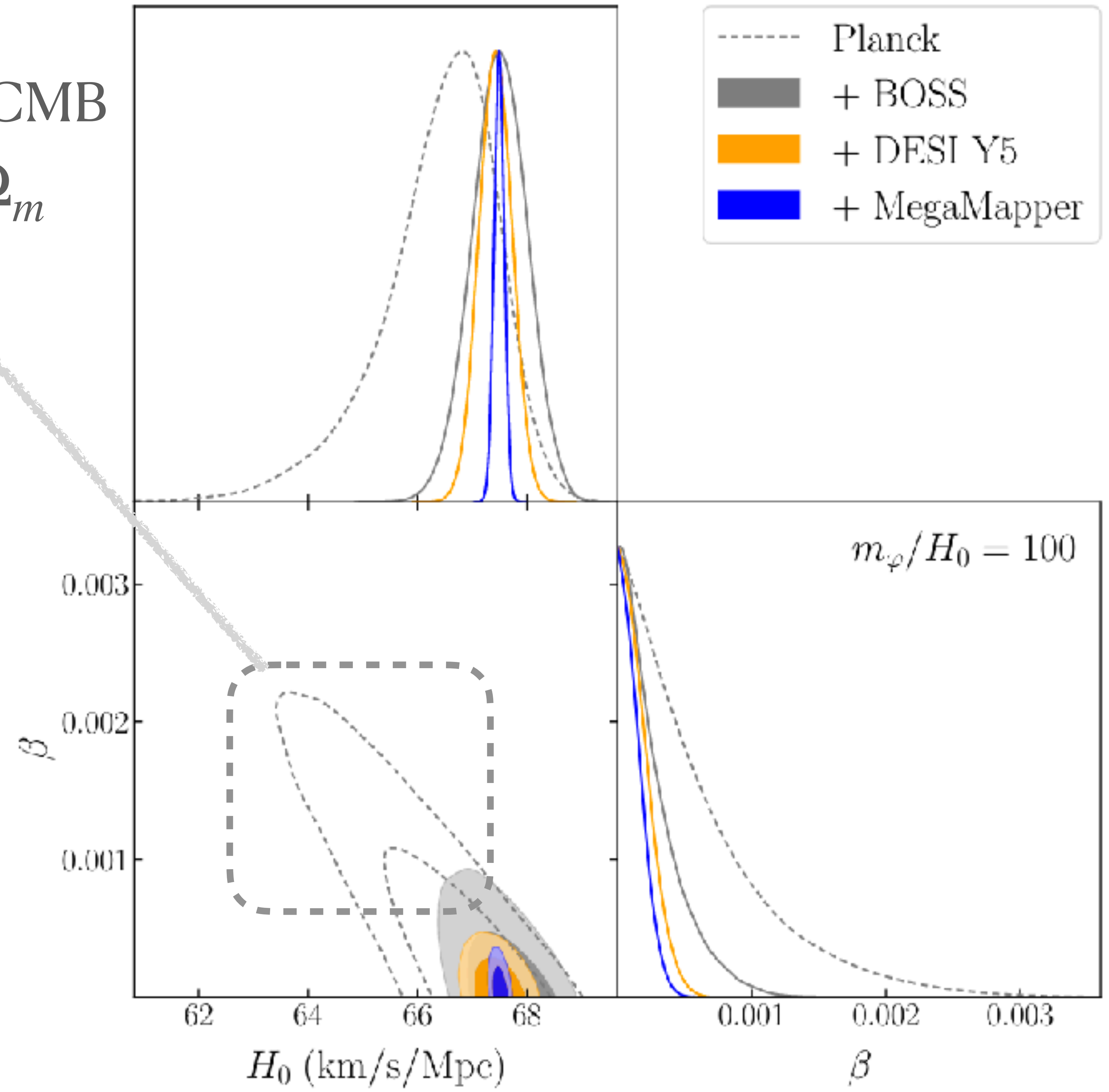
$$\frac{\delta_m(a)}{\delta_m^{\rm CDM}(a)} - 1 \simeq \frac{6}{5}\beta \tilde{m}_s^2 f_\chi^2 \log\frac{a_{m_\varphi}}{a_{\rm eq}} - f_s - \frac{3}{5} f_s \log\frac{a}{a_{m_\varphi}}$$

Reduced gravitational potential

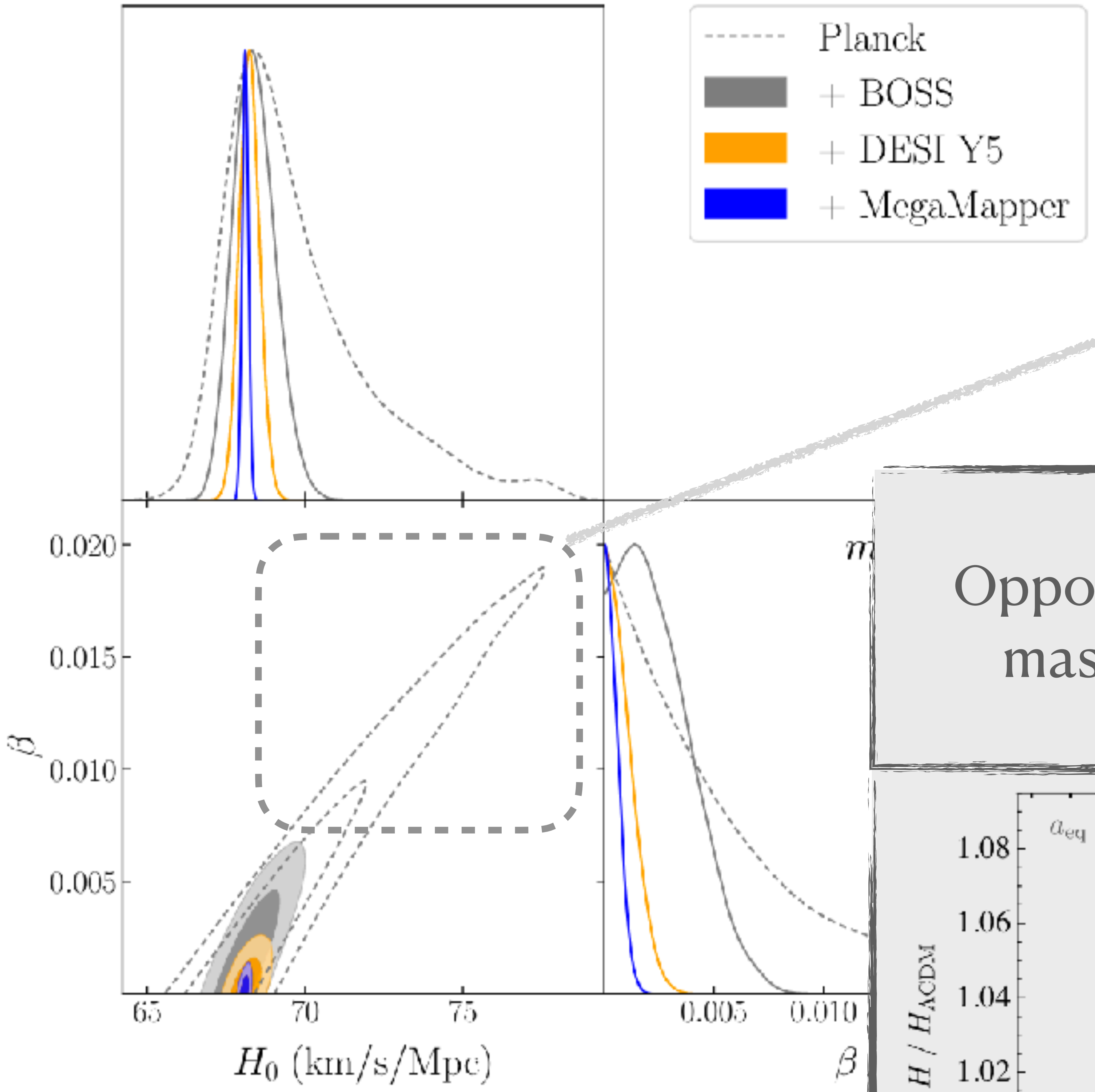
Results



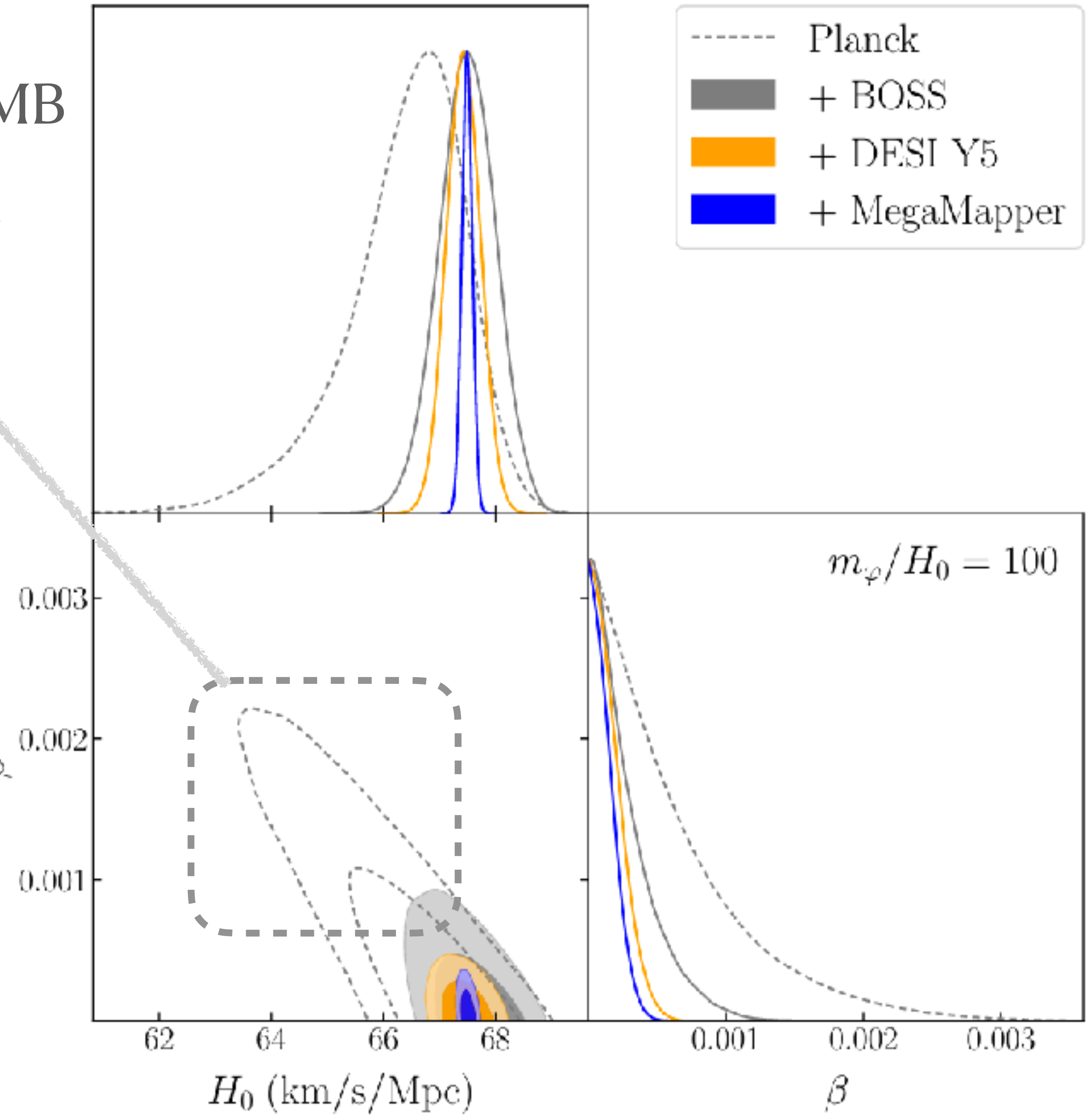
Strong constraints from CMB but plagued by $H_0 - \Omega_m$ degeneracy



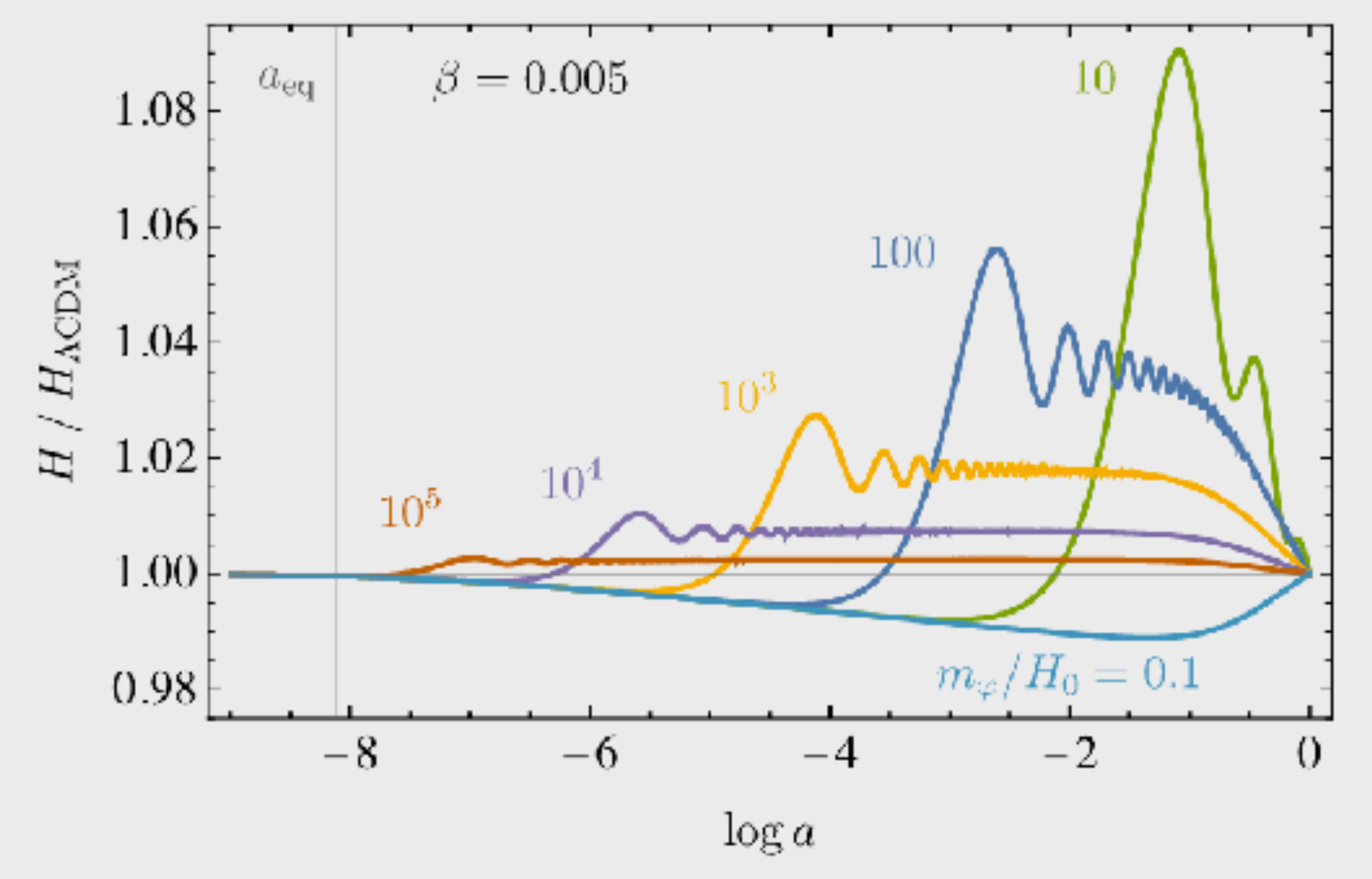
Results



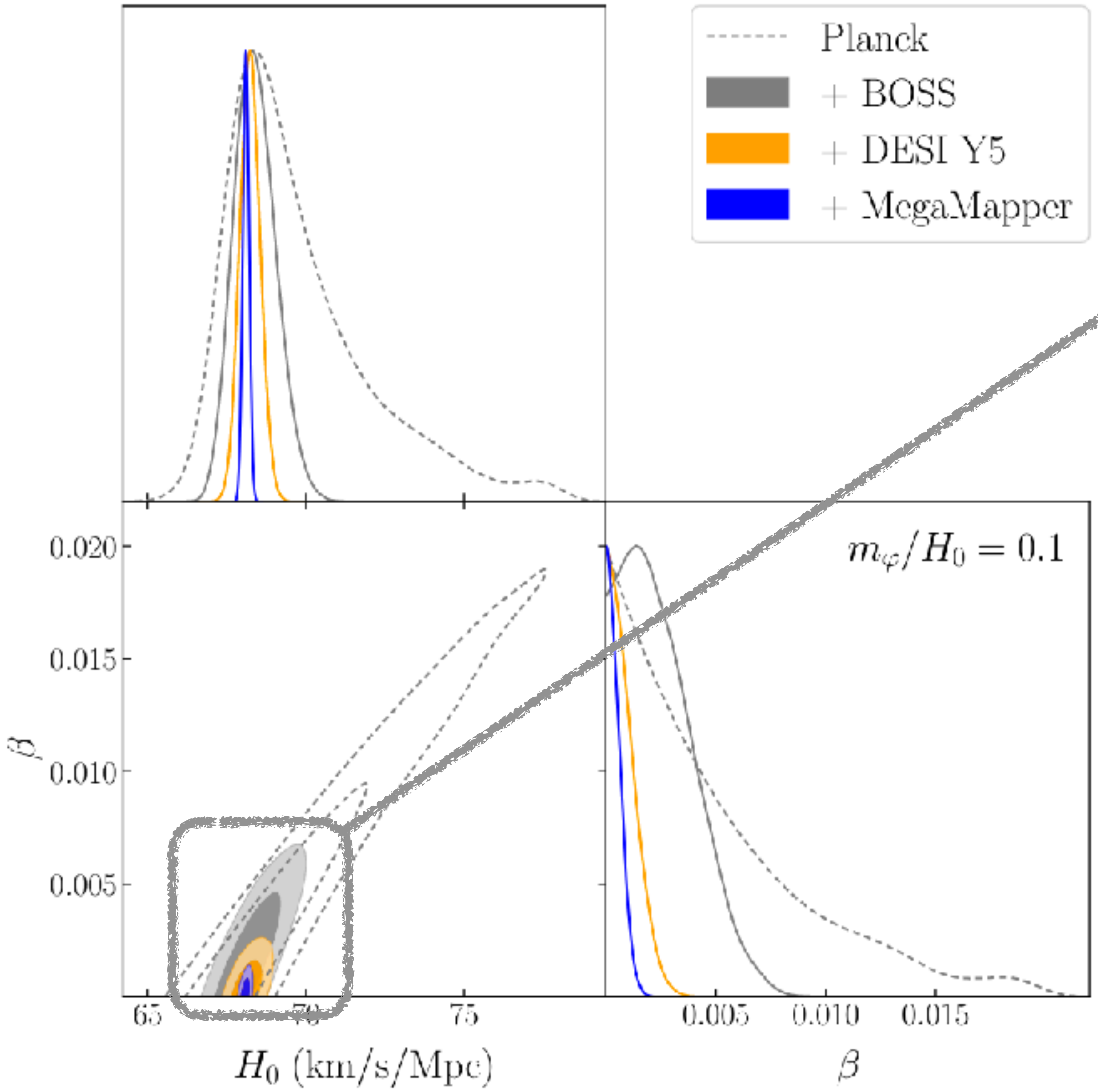
Strong constraints from CMB but plagued by $H_0 - \Omega_m$ degeneracy



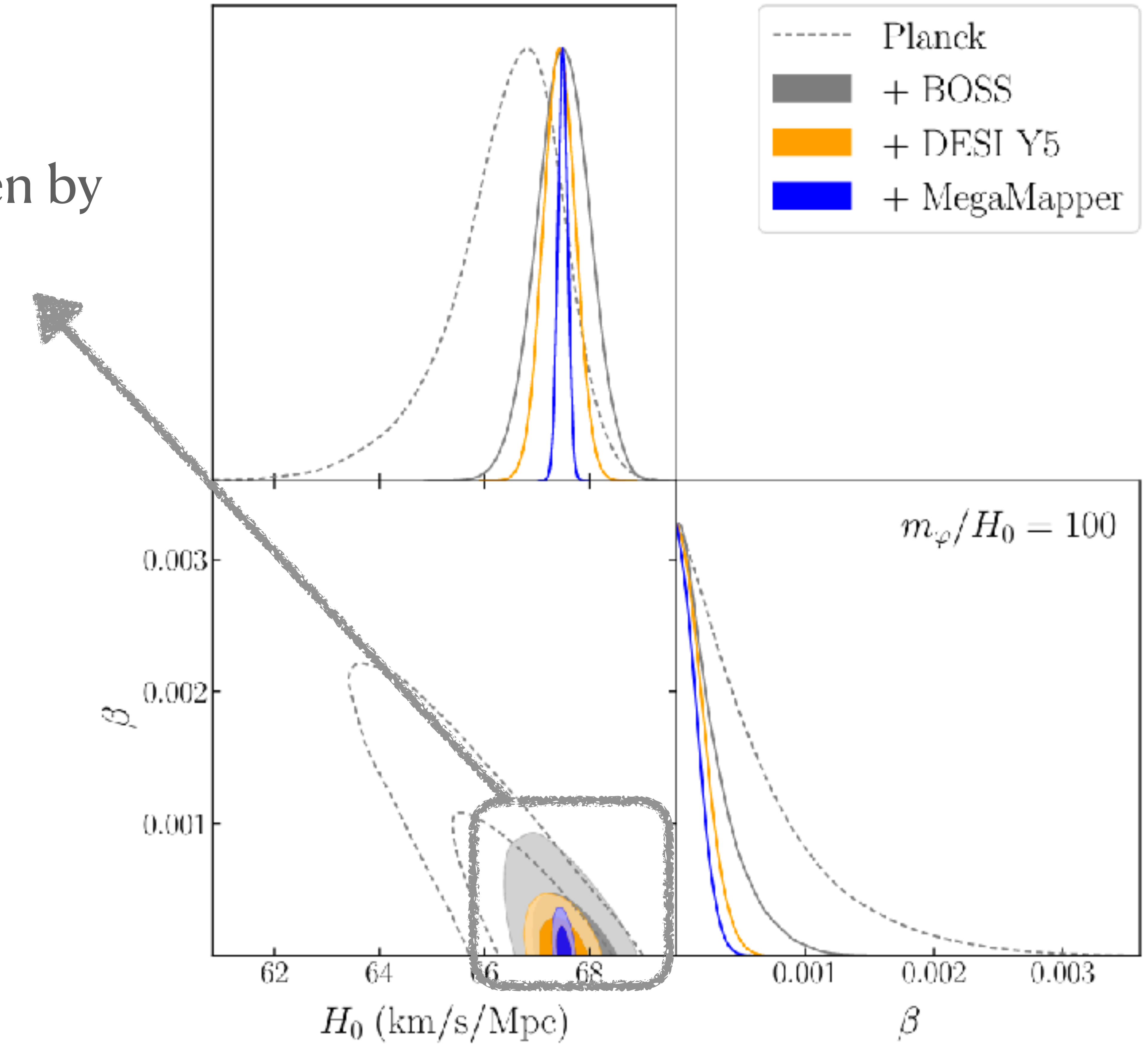
Opposite degeneracy between massless and massive case



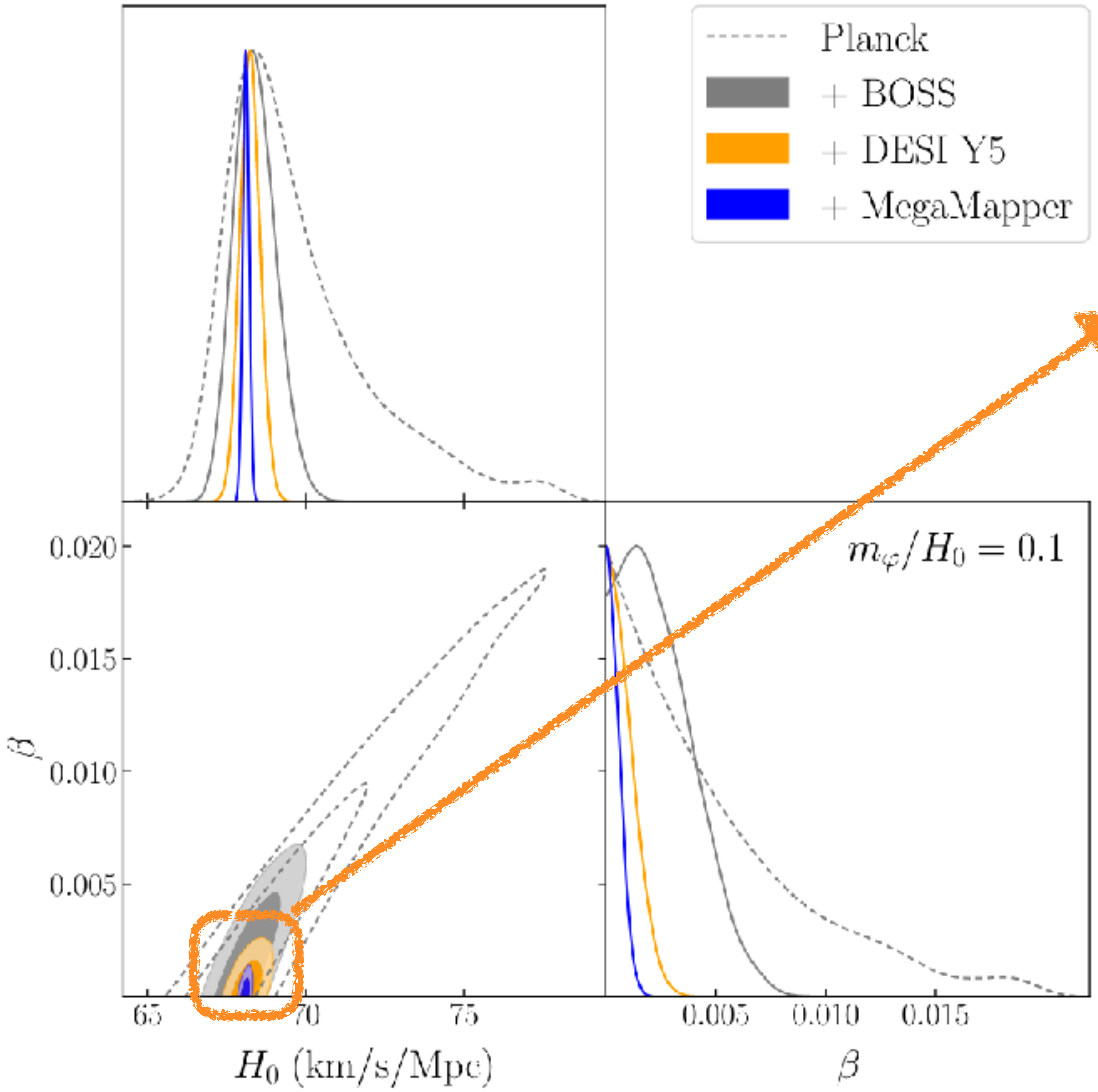
Results



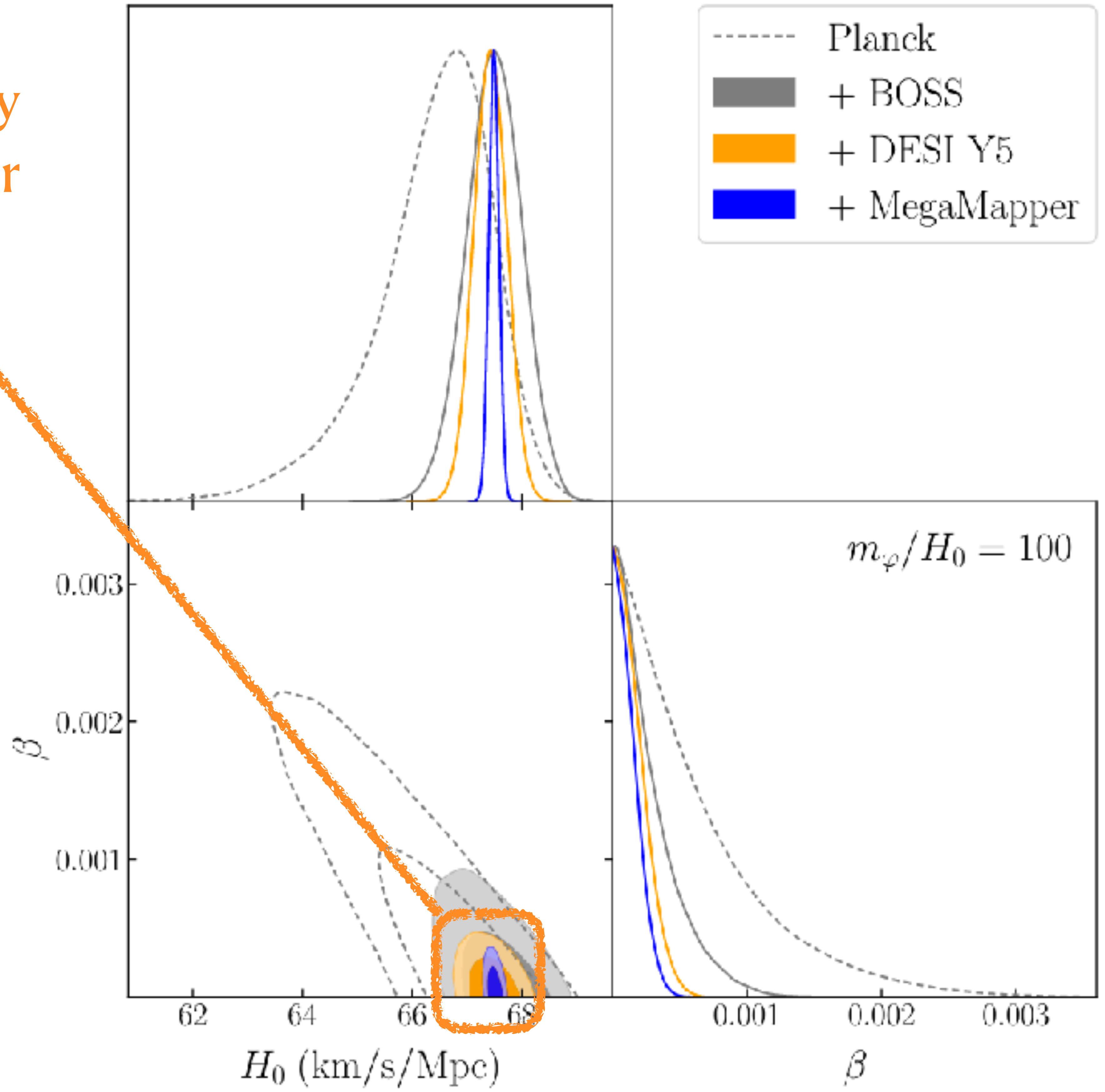
Degeneracy broken by BAO



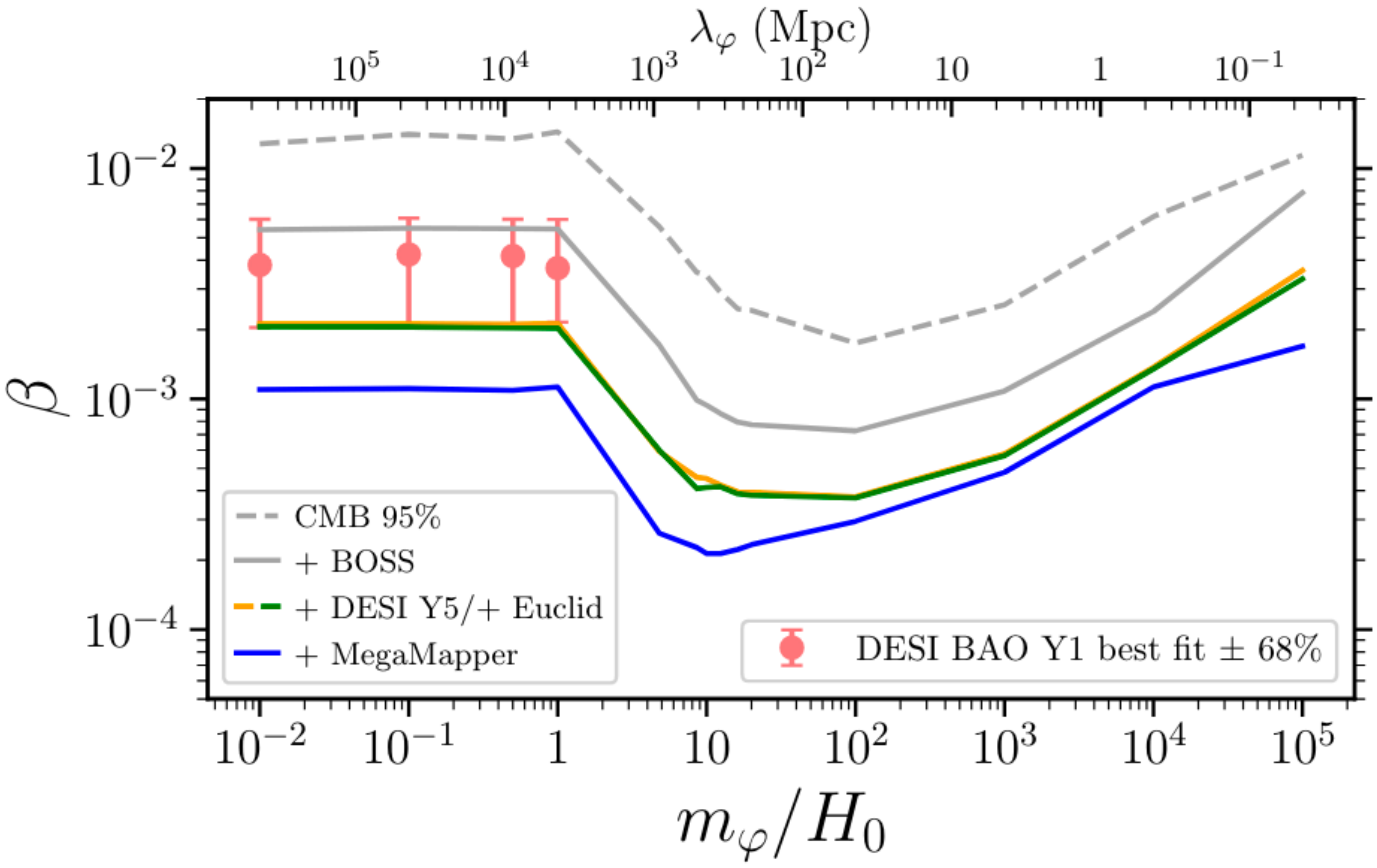
Results



DESI improves bounds by a factor 2 thanks to better determination of b_1



Results



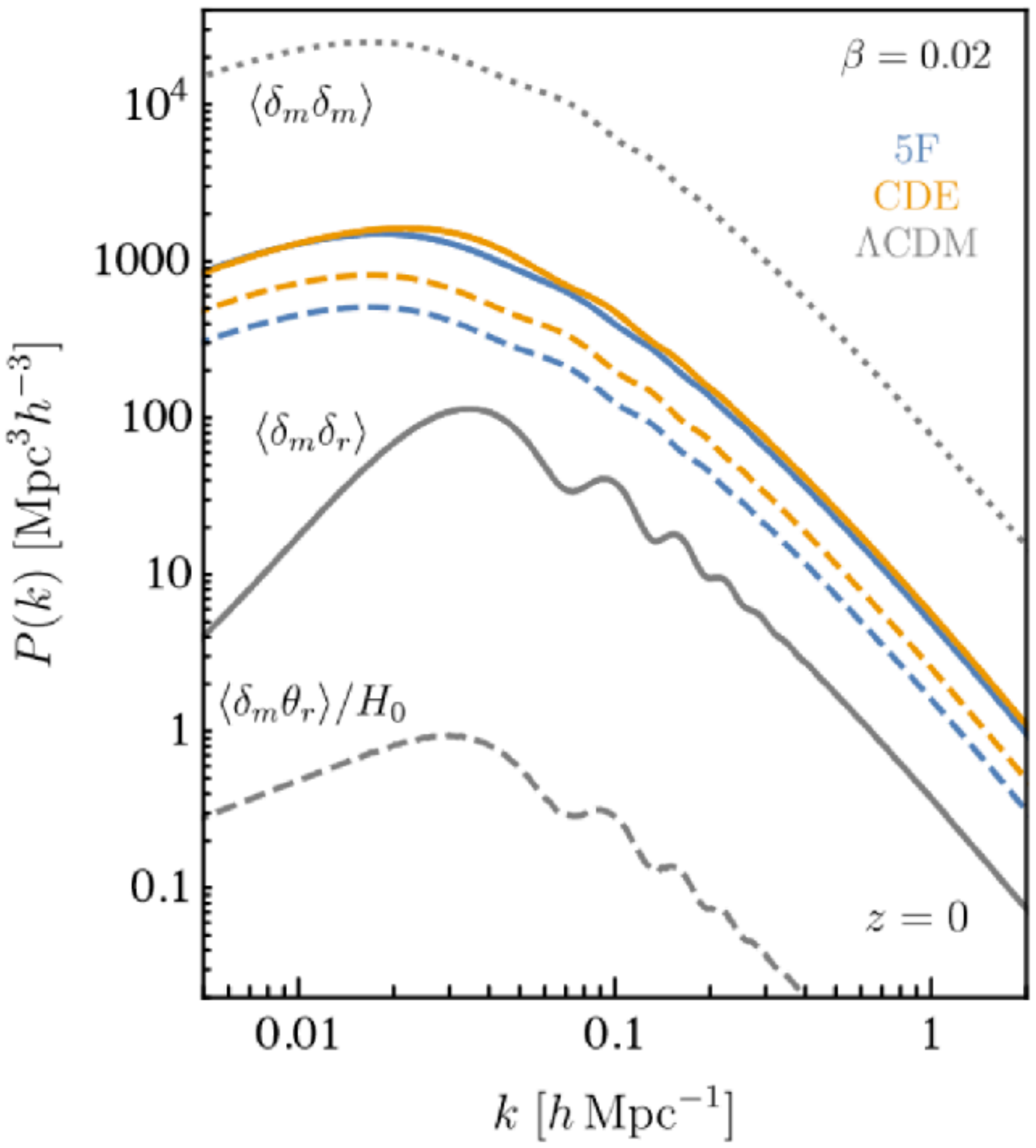
λ_φ (Mpc)
10^5 10^4 10^3 10^2 10 1 10^{-1}
β
10^{-2}
10^{-3}
10^{-4}
CMB 95%
+ BOSS
+ DESI Y5/+ Euclid
+ MegaMapper
DESI BAO Y1 best fit ± 68%
10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5
m_φ/H_0

When are relative fluctuations important?

Relative fluctuations $\delta_r \equiv \delta_\chi - \delta_b$

Grow with scale factor

$$\delta_r(a) = \frac{5}{3}\beta f_\chi \delta_m^{\Lambda\mathrm{CDM}}(a)$$



When are relative fluctuations important?

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Grow with scale factor

$$\delta_r(a) = \frac{5}{3}\beta f_\chi \delta_m^{\Lambda\mathrm{CDM}}(a)$$

New bias

$$\delta_g \supset b_r\delta_r + b_{\theta r}\theta_r + \dots$$

When are relative fluctuations important?

Relative fluctuations $\delta_r \equiv \delta_\chi - \delta_b$

Grow with scale factor

$$\delta_r(a) = \frac{5}{3}\beta f_\chi \delta_m^{\Lambda\mathrm{CDM}}(a)$$

New bias

$$\delta_g \supset b_r\delta_r + b_{\theta r}\theta_r + \ldots$$

New non-linear structures

$$\delta_r(a,\vec{k}) = \beta f_\chi \left(\frac{5}{3} D_m^{\Lambda\mathrm{CDM}}(a)\delta_0(\vec{k}) + \sum_{n=2}^{\infty} D_m^{\Lambda\mathrm{CDM},n}(a) \int \prod_{i=1}^{n} \frac{d^3k_i}{(2\pi)^3}\delta_0(\vec{k}_i)\delta^{(3)}\left(\vec{k} + \sum_{i=1}^{n}\vec{k}_i\right) F_n^{(r)}(\vec{k}_1,\ldots,\vec{k}_n) \right)$$

Crucial features: no log enhancement, only linear scaling with f_χ

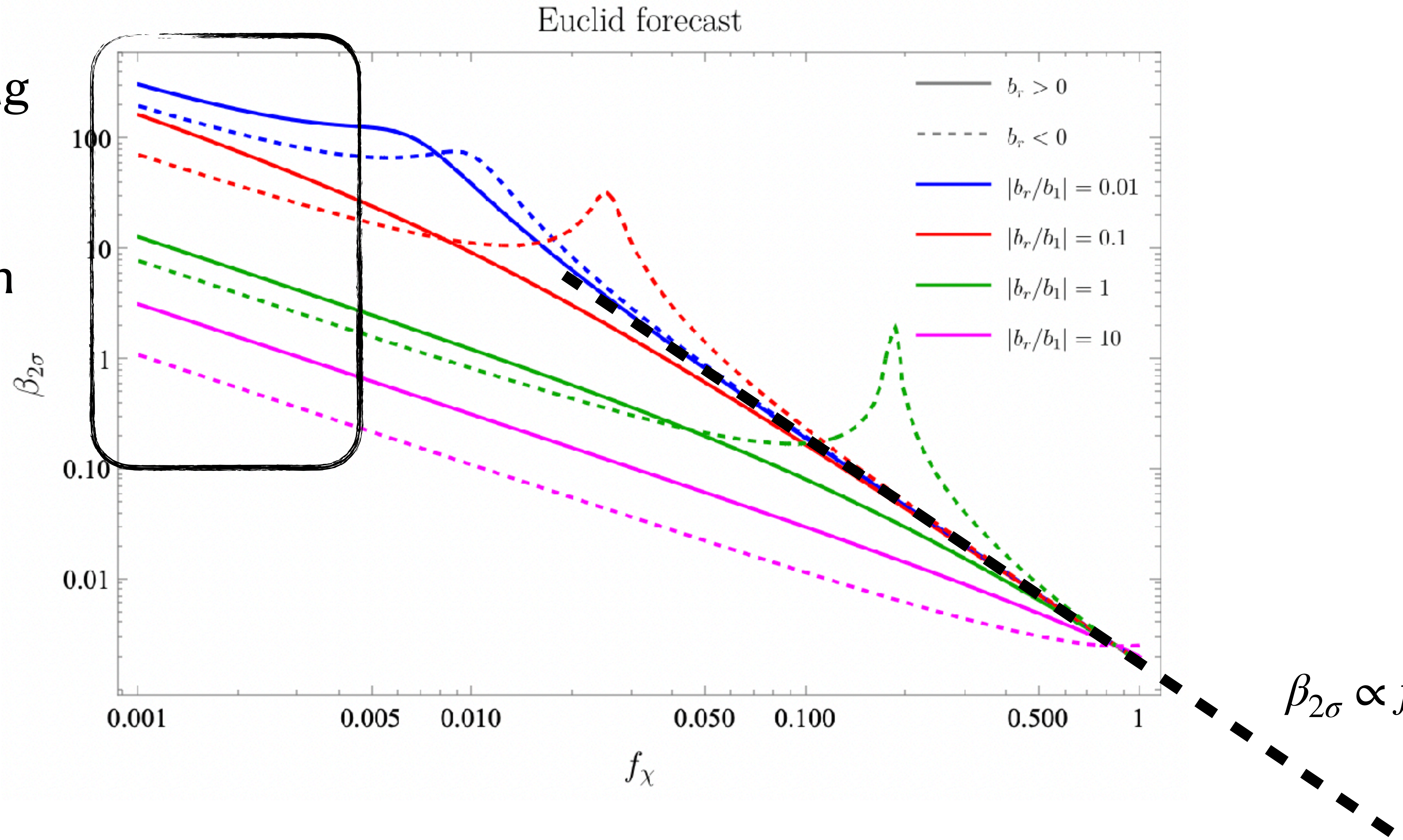
When are relative fluctuations important?

Different scaling

$$\beta_{2\sigma} \propto f_\chi^{-1}$$

expected when

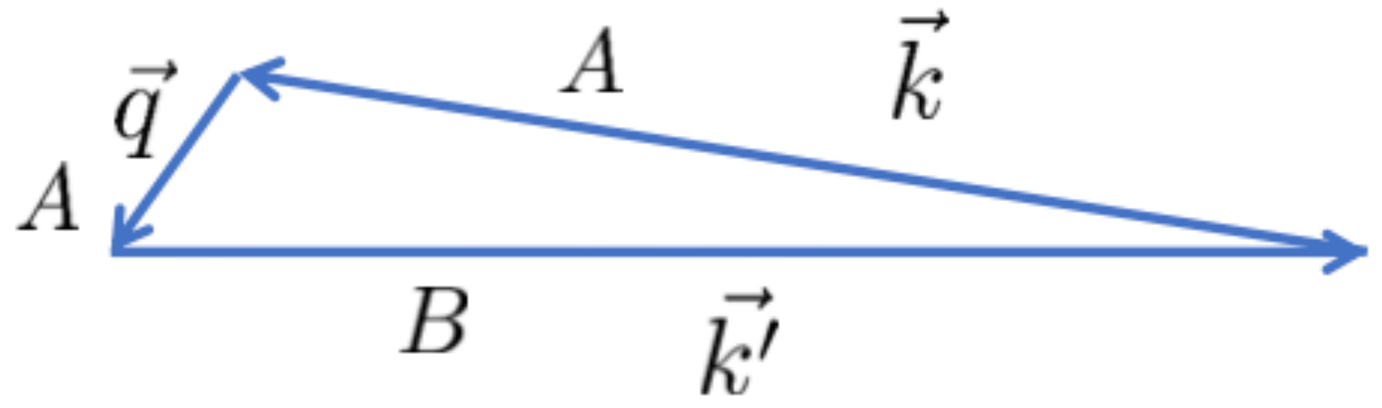
$$f_\chi \lesssim \frac{b_r}{b_1}\frac{1}{\log}$$



$$\beta_{2\sigma} \propto f_\chi^{-2}$$

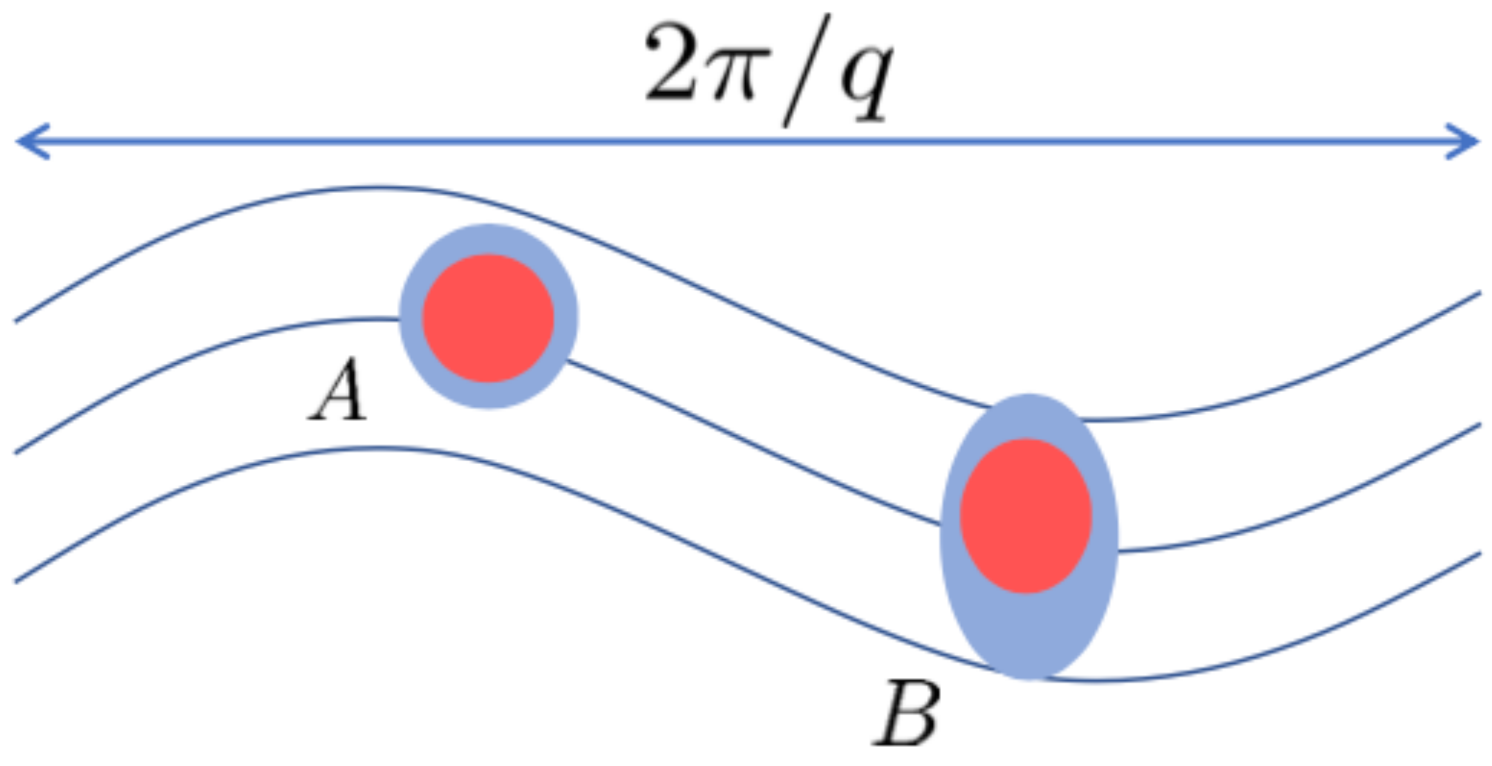
Smoking guns: Pole of the bispectrum

Pole emerging in the squeezed limit of the bispectrum for two different tracers



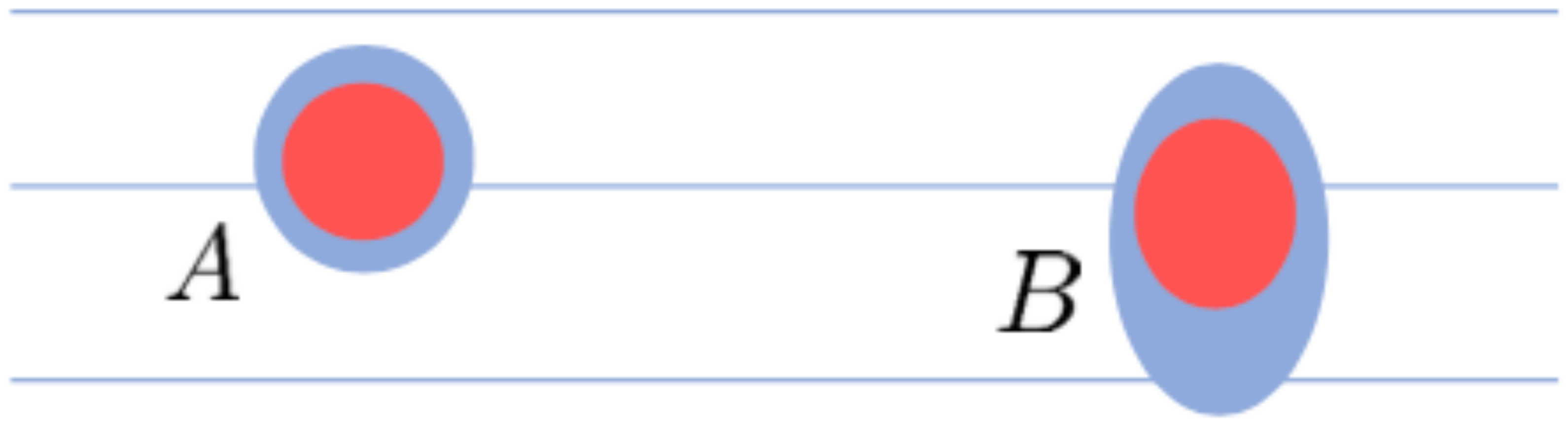
$$\lim_{q\to 0} \Delta B(q,k,k') \propto \Delta_{AB} \frac{\vec{q}\cdot\vec{k}}{q^2} P^{\rm lin}(k) P^{\rm lin}(q)$$

$$\Delta_{AB} = b_1^A (b_1^A b_r^B - b_1^B b_r^A)$$

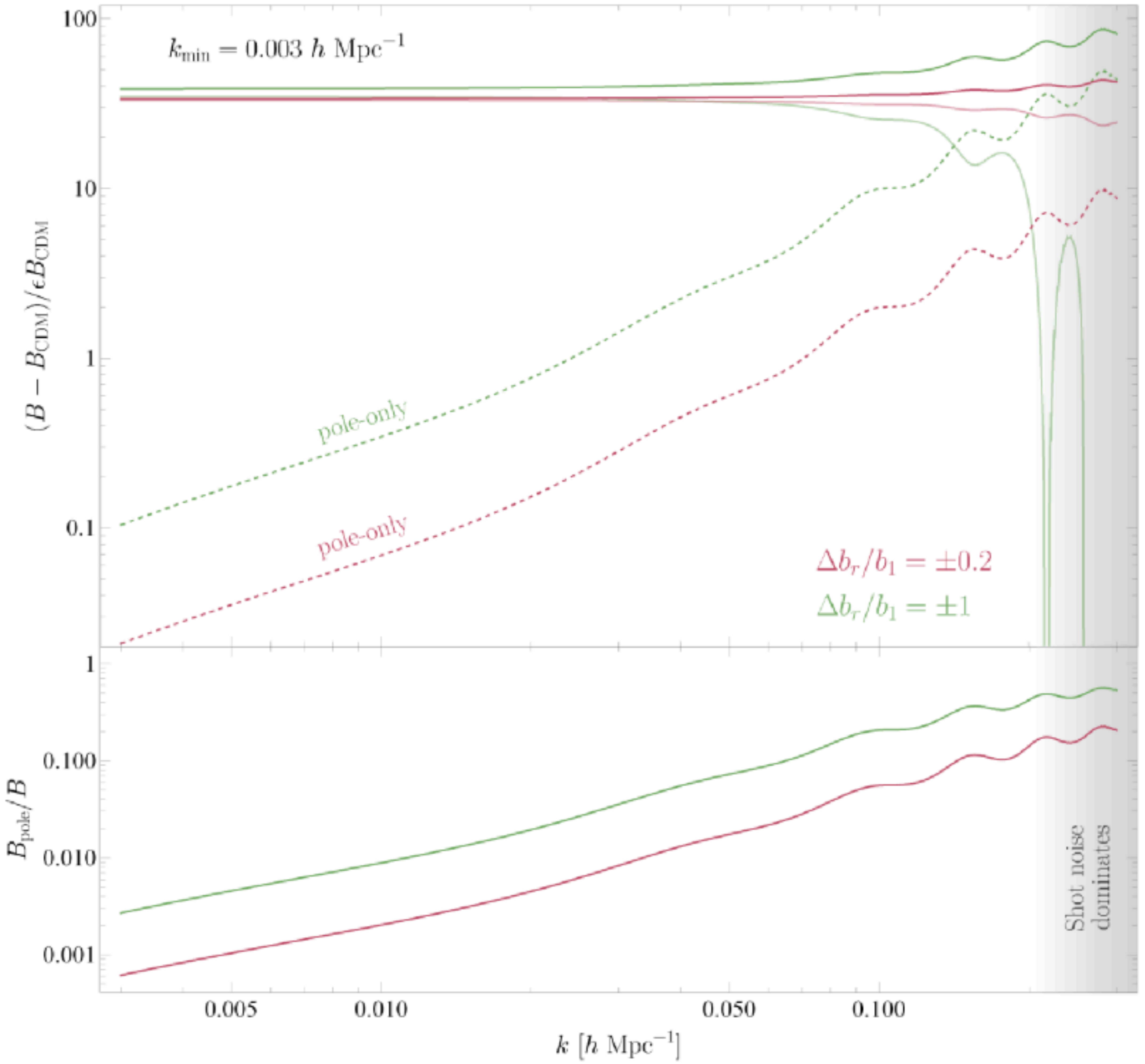


Boost to free-fall system

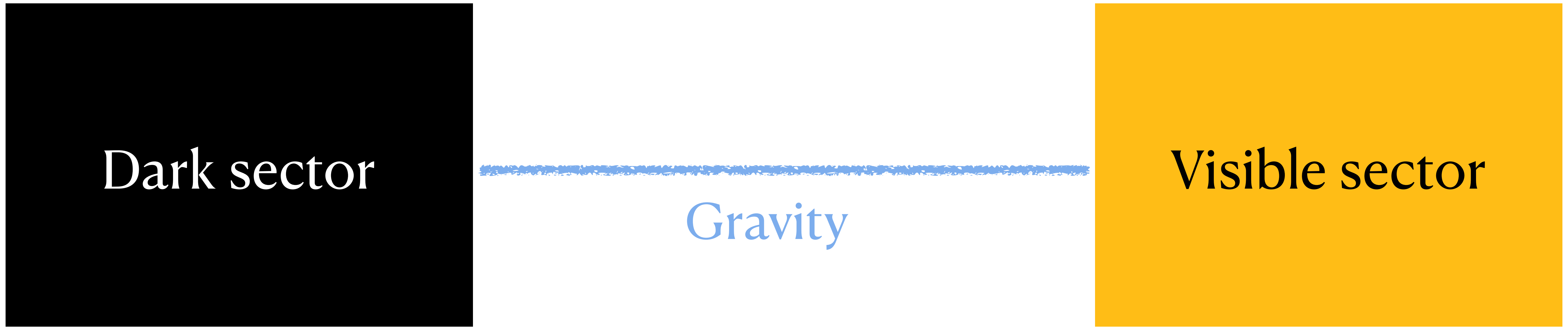
Still feel a non-zero potential!



Smoking guns: Pole of the bispectrum



Can we see in the dark?



Cosmology is the only way to probe completely secluded dark sectors!

Examples in this talk

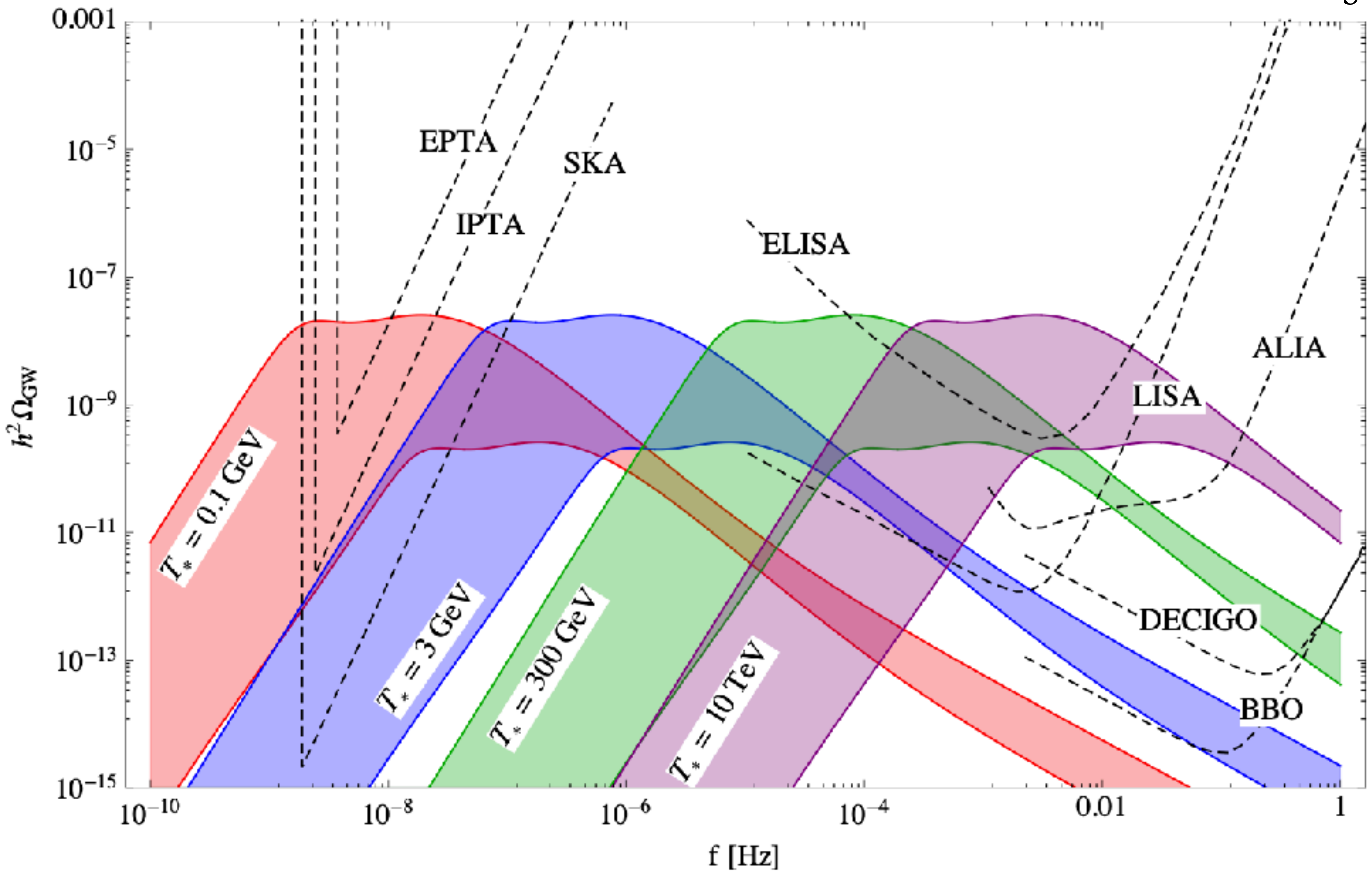
Long-range dark forces

Late-time dark phase transitions

Can we test late-time PT?

PT happening at $T \gtrsim 1$ eV produce GWs in the sensitivity range of future interferometers

Schwaller '15



What about later PT? Imprints left on cosmological observables!

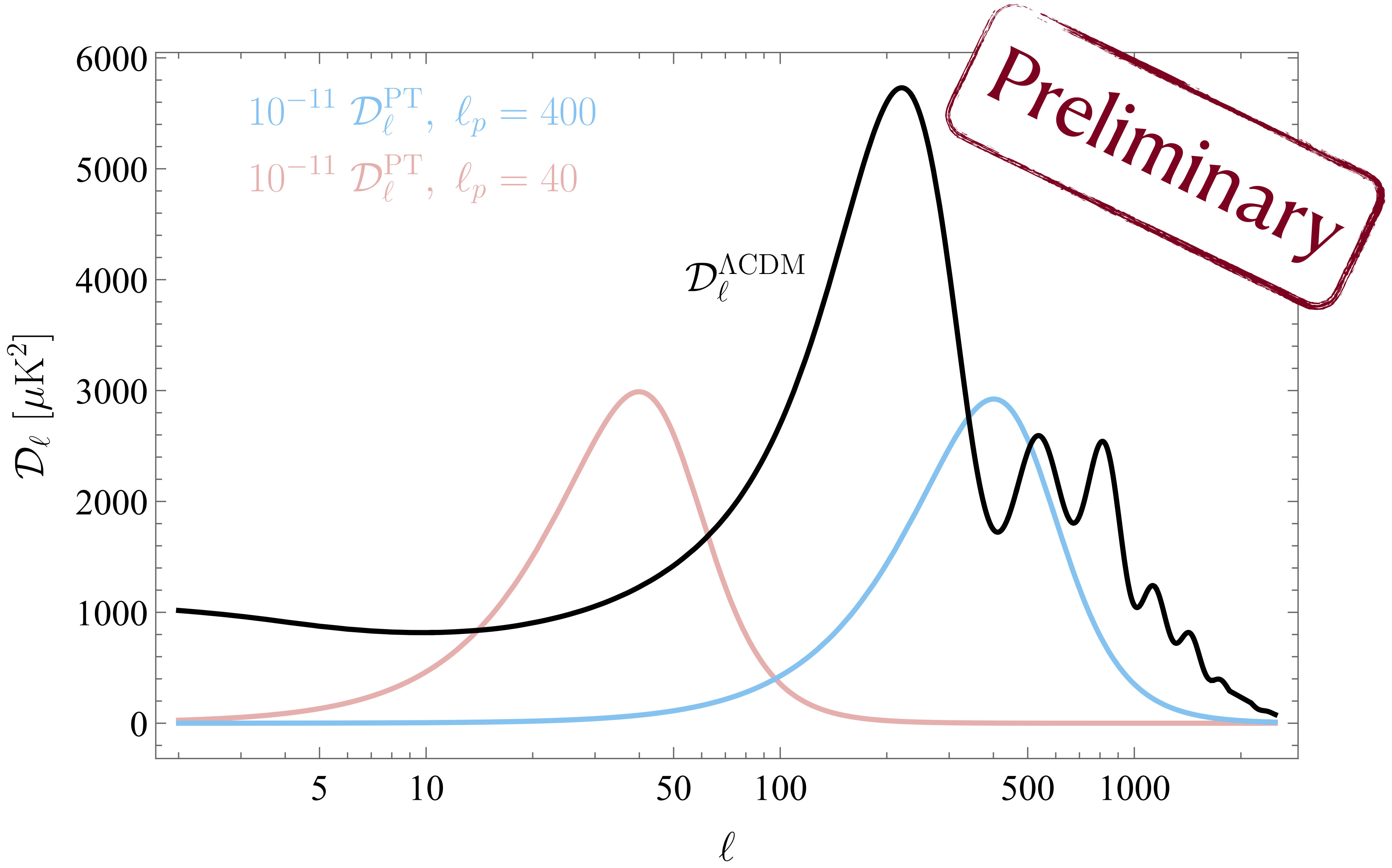
Dynamics of a Late PT

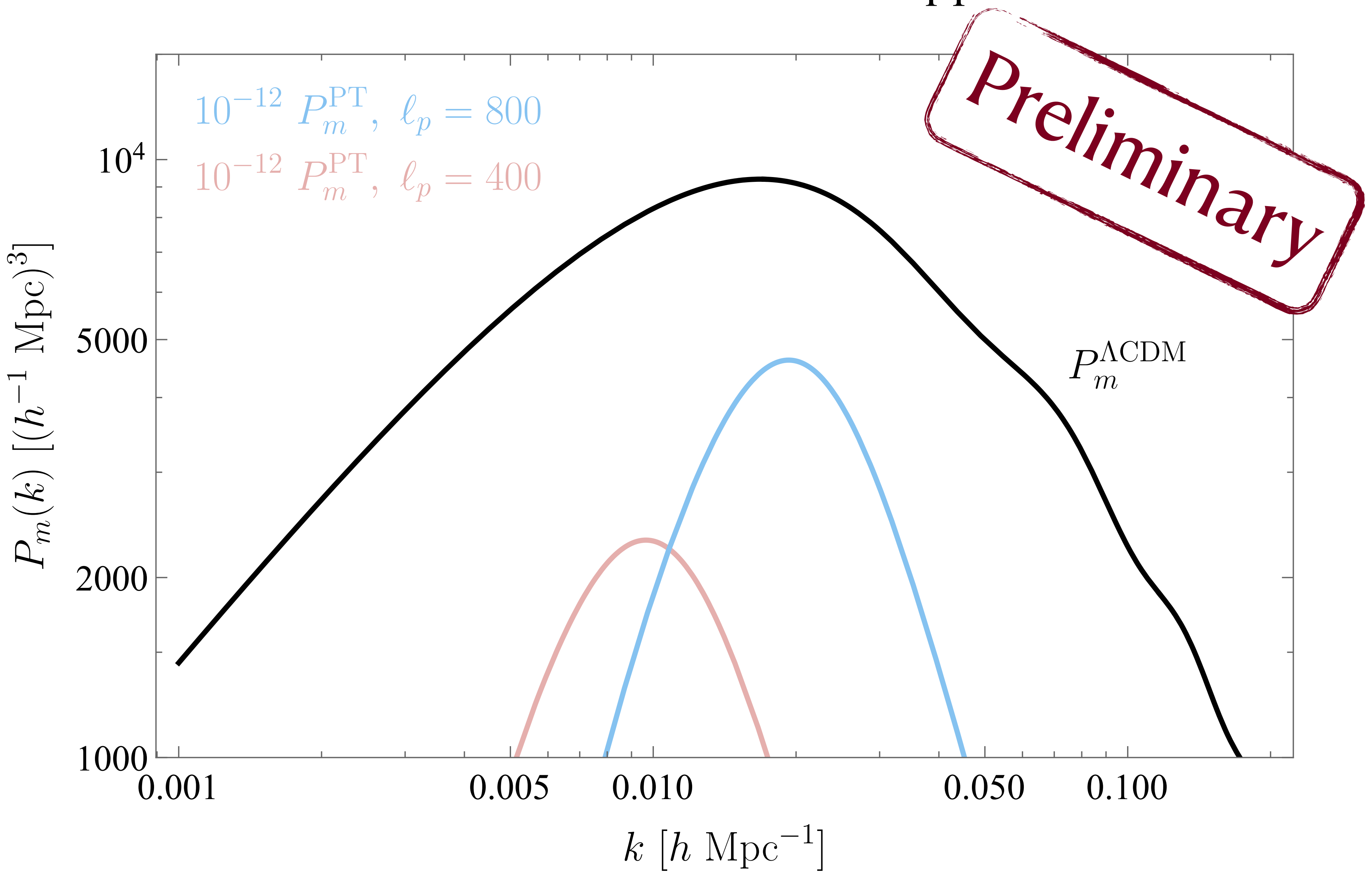
Features of the Signal

Both ISW and matter power peak at a scale set by β_H and z_{PT}

$$\ell_p \simeq 4.3\,\sqrt{z_{PT}}\;\beta_H \sim \frac{\chi_{PT}\,H_{PT}\,\beta_H}{1+z_{PT}}$$

$$k_p \simeq \frac{H_0\,\ell_p}{13} \sim \frac{H_{PT}\,\beta_H}{1+z_{PT}}$$

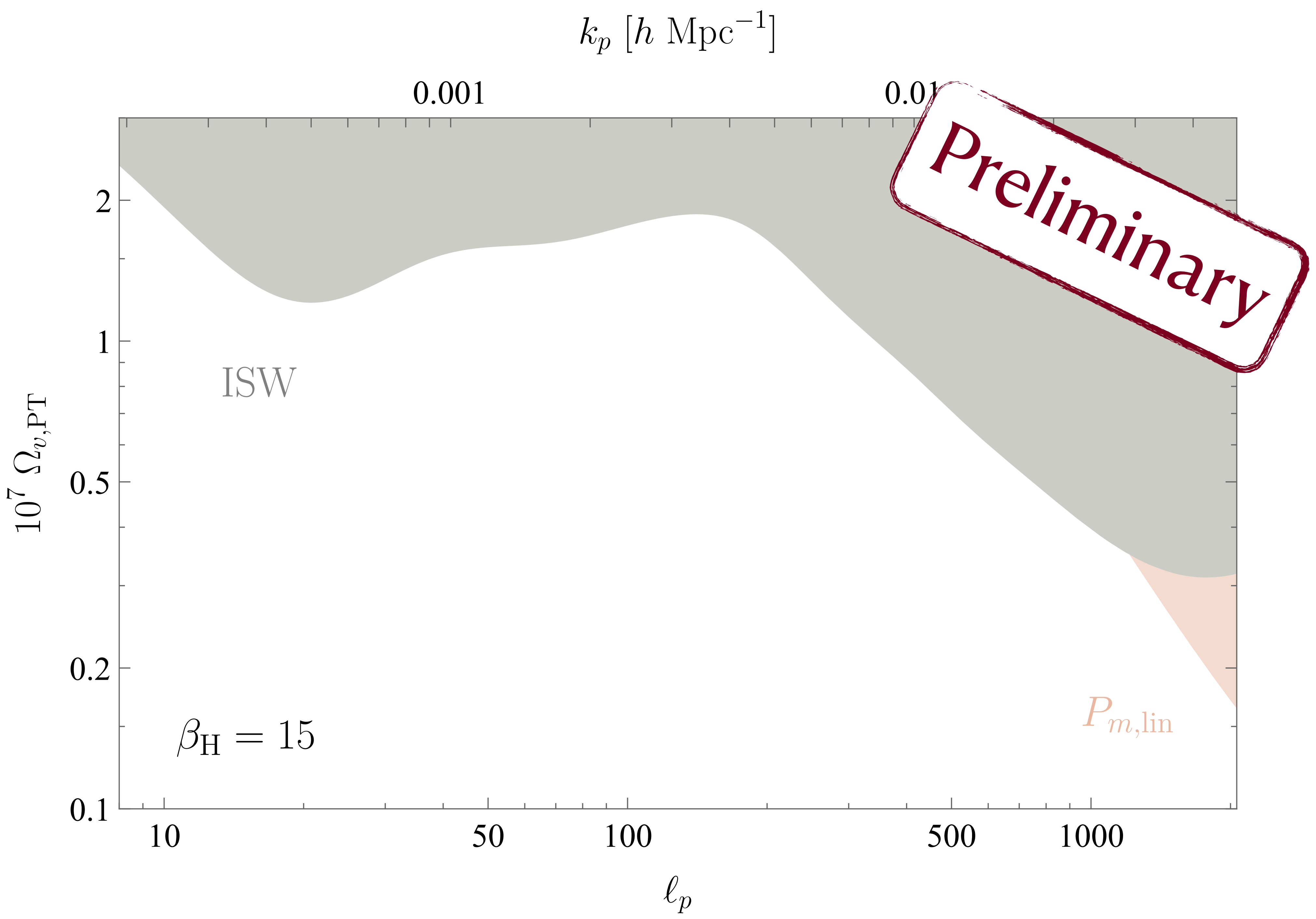


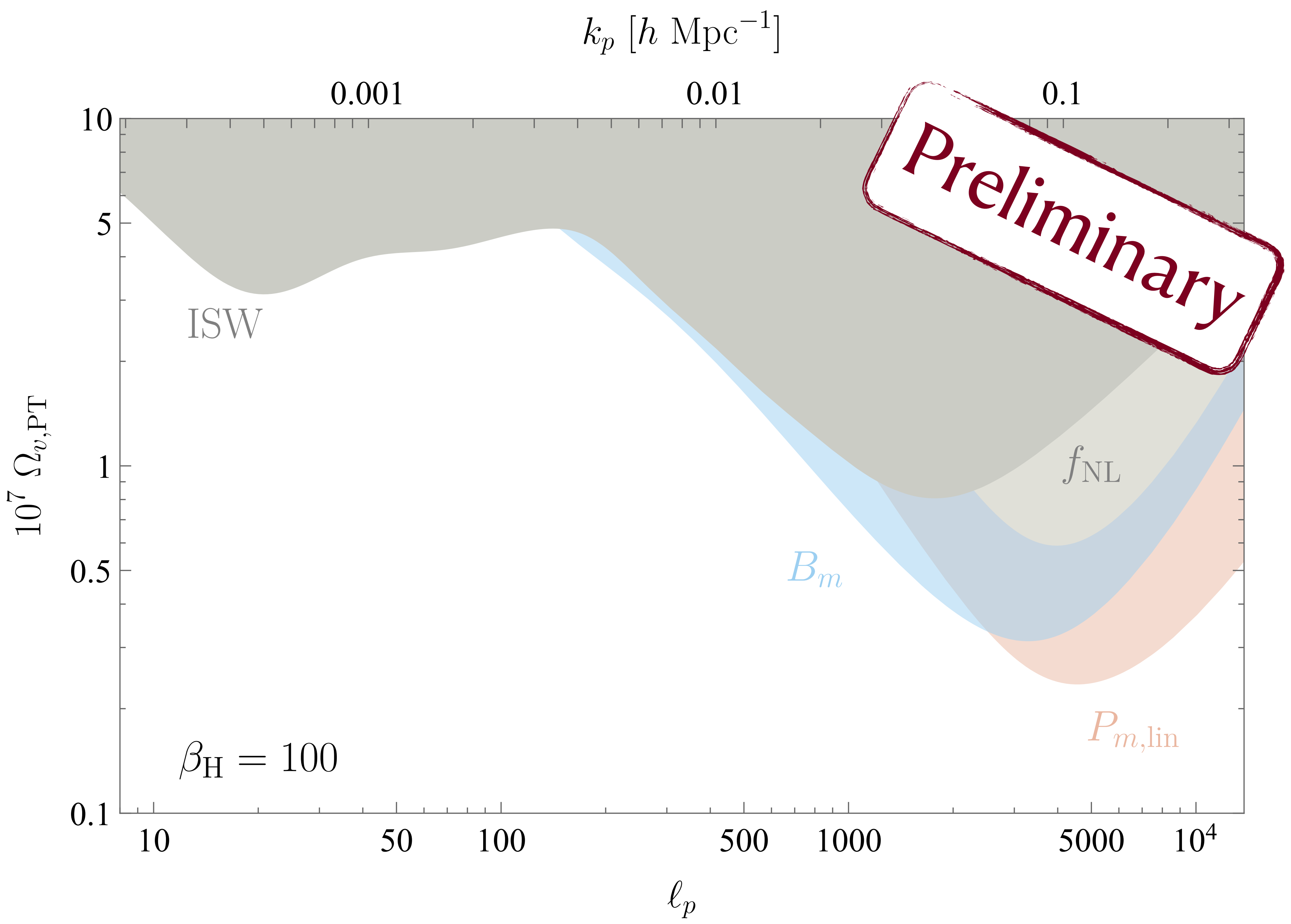


→ Negligible degeneracies with cosmological parameters

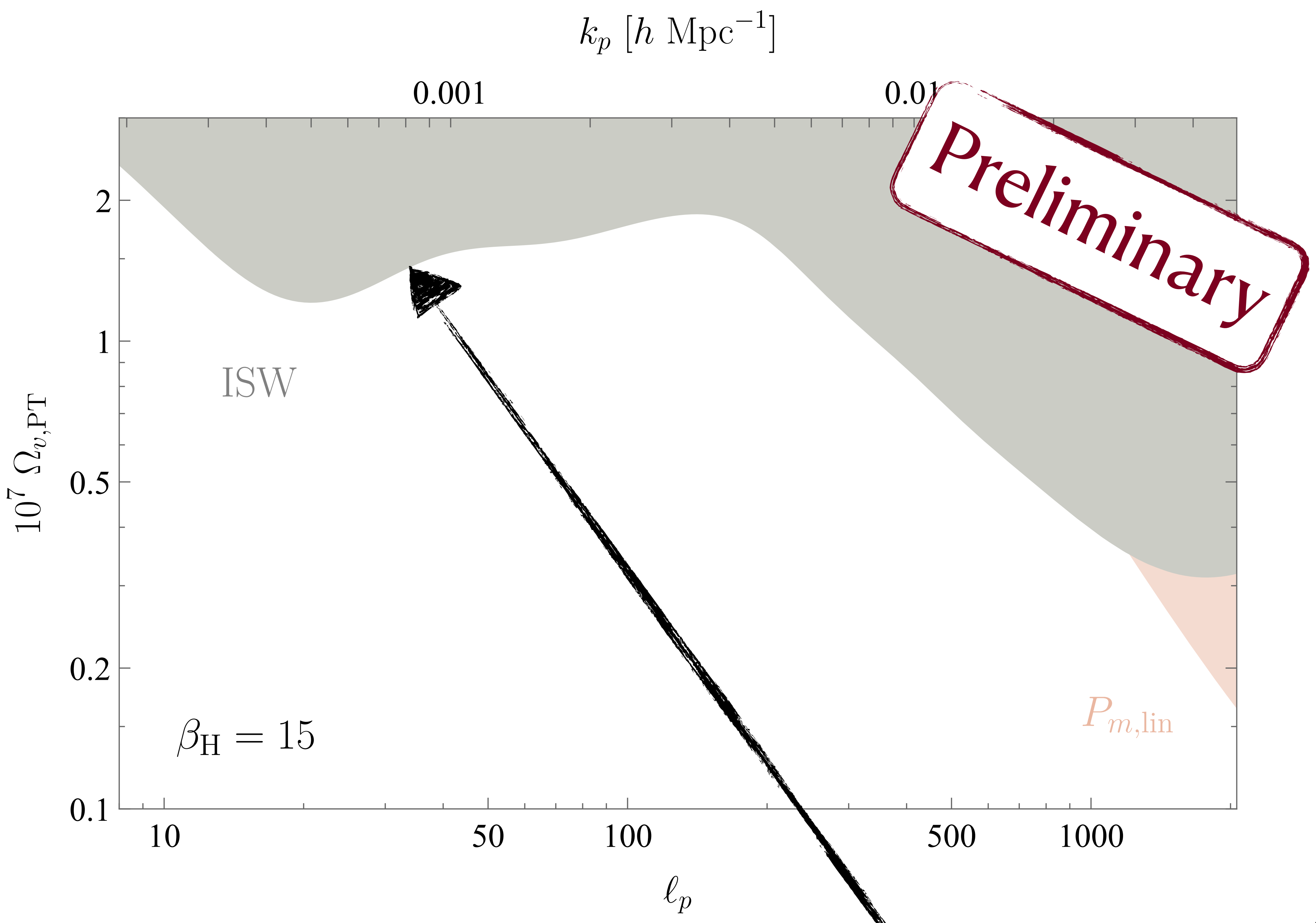
Significant non-Gaussianities are produced $\langle\Phi\Phi\Phi\rangle^2 \approx \langle\Phi\Phi\rangle^3$ → Constraints from bispectrum and f_{NL}

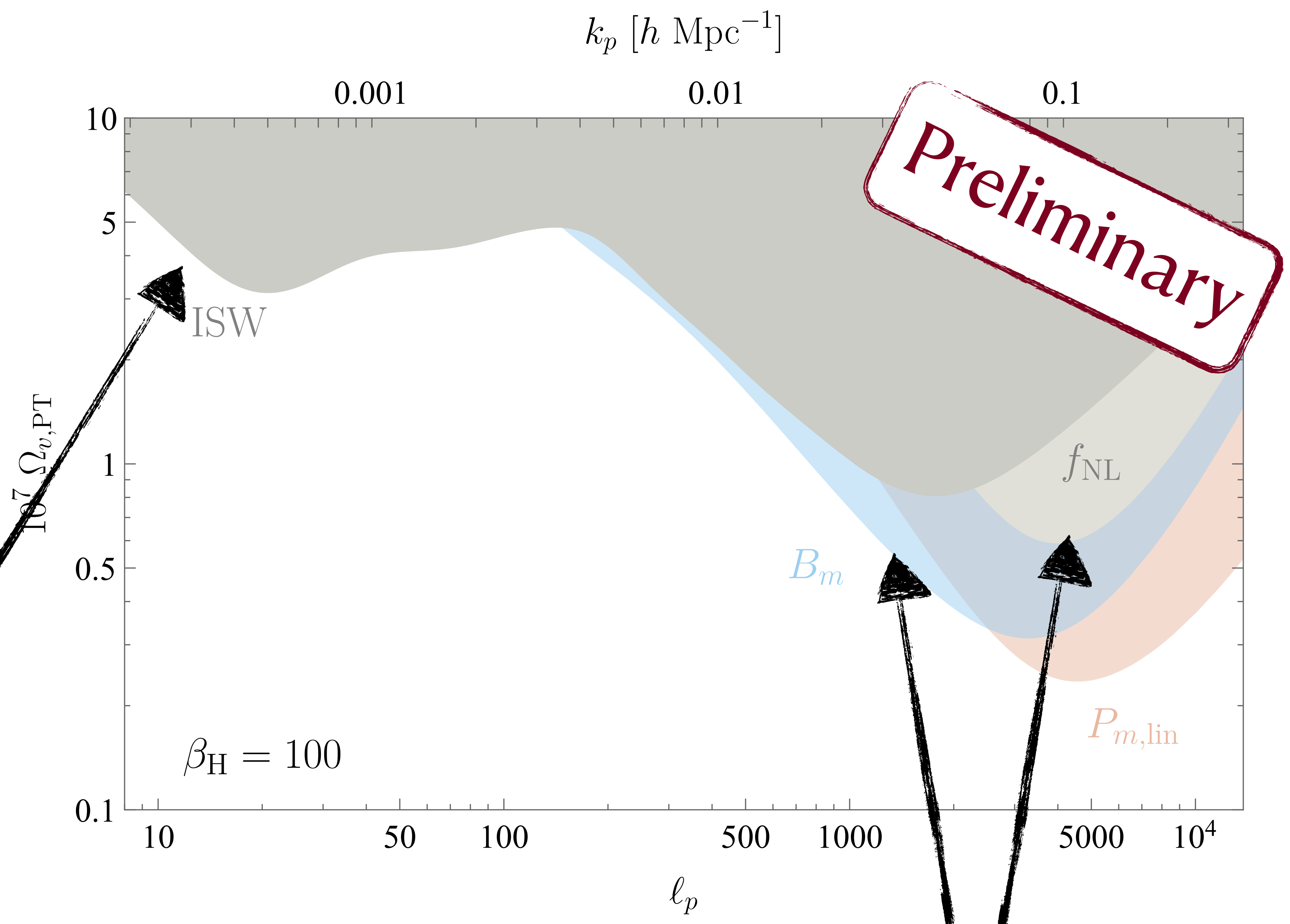
Bounds and Projections





Bounds and Projections





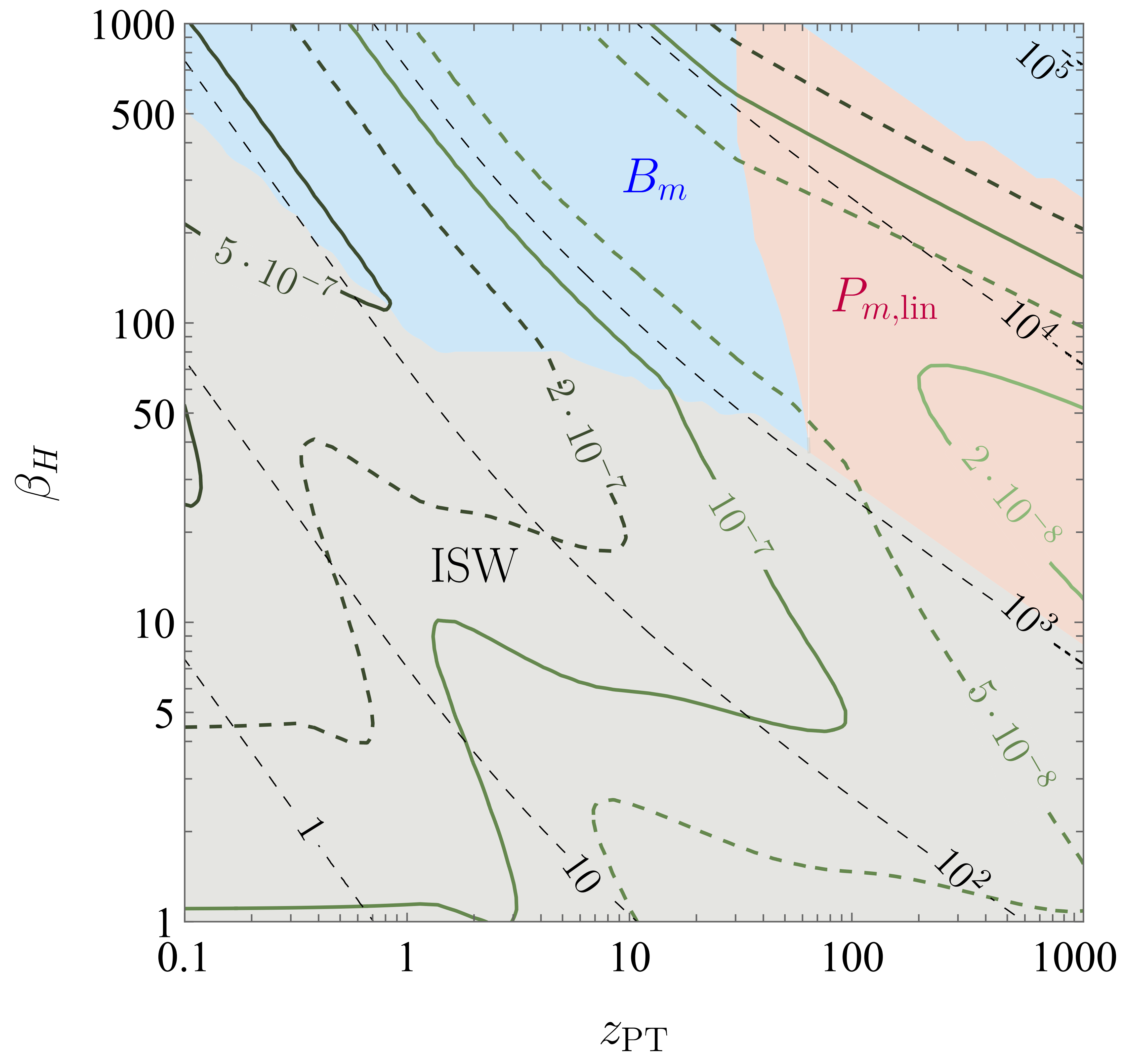
$\mathscr{D}_\ell^{\mathrm{PT}},\ P_{m,\mathrm{lin}}^{\mathrm{PT}} \simeq \Omega_{\mathrm{PT}}^2\ \beta_H^{-1}\ F(\ell_p)$

$B_m^{\mathrm{PT}},\ f_{\mathrm{NL}} \simeq \Omega_{\mathrm{PT}}^3\ F(\ell_p)$

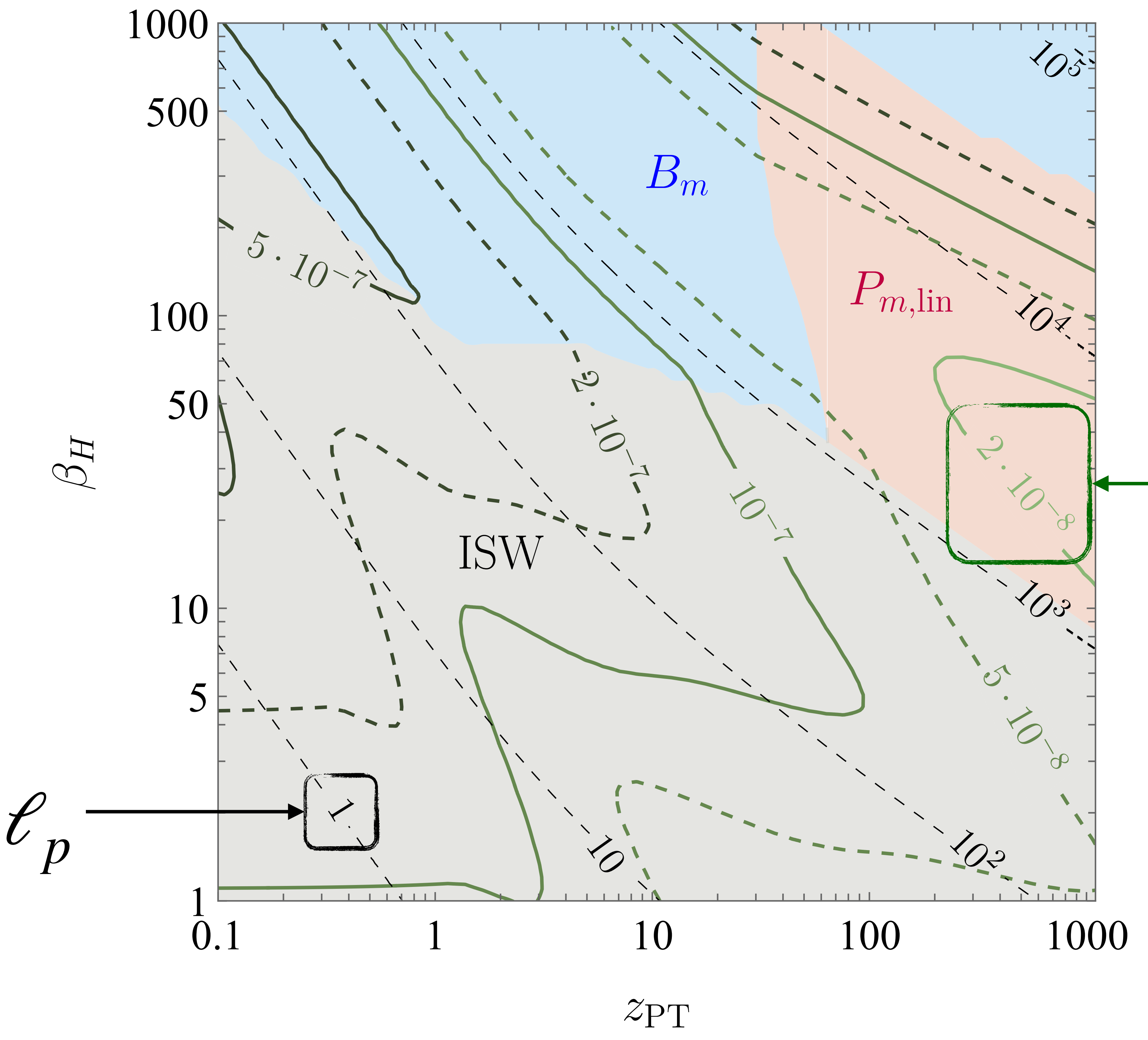
Bispectrum breaks residual degeneracies of matter and CMB power spectrum

Phase transition can be fully characterized and $\Omega_{\mathrm{PT}} \equiv \dfrac{\Delta\rho_{\mathrm{PT}}}{\rho_{\mathrm{cr,PT}}}$ can be probed at $\mathcal{O}(10^{-7})$

Bounds and Projections



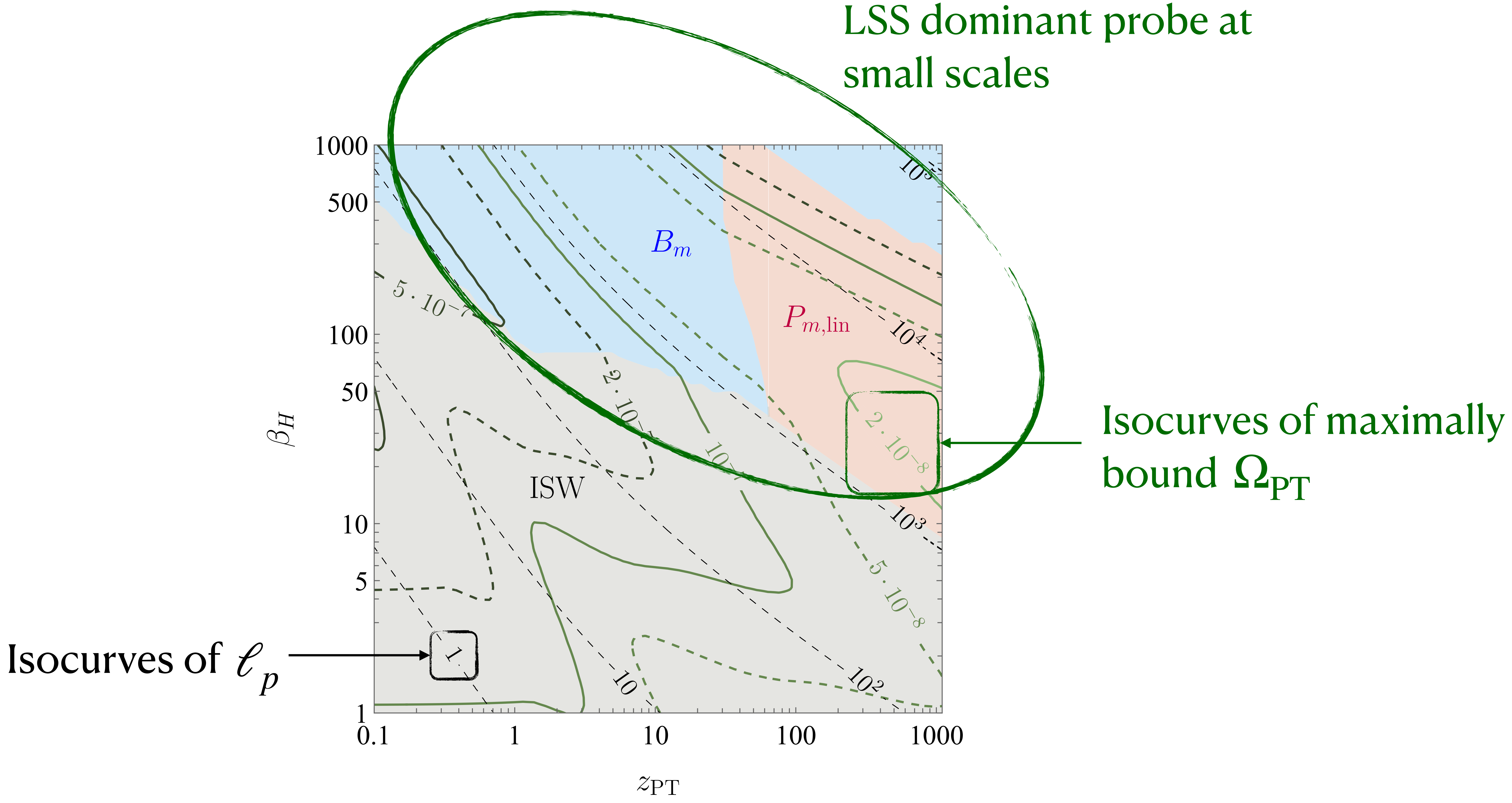
Bounds and Projections



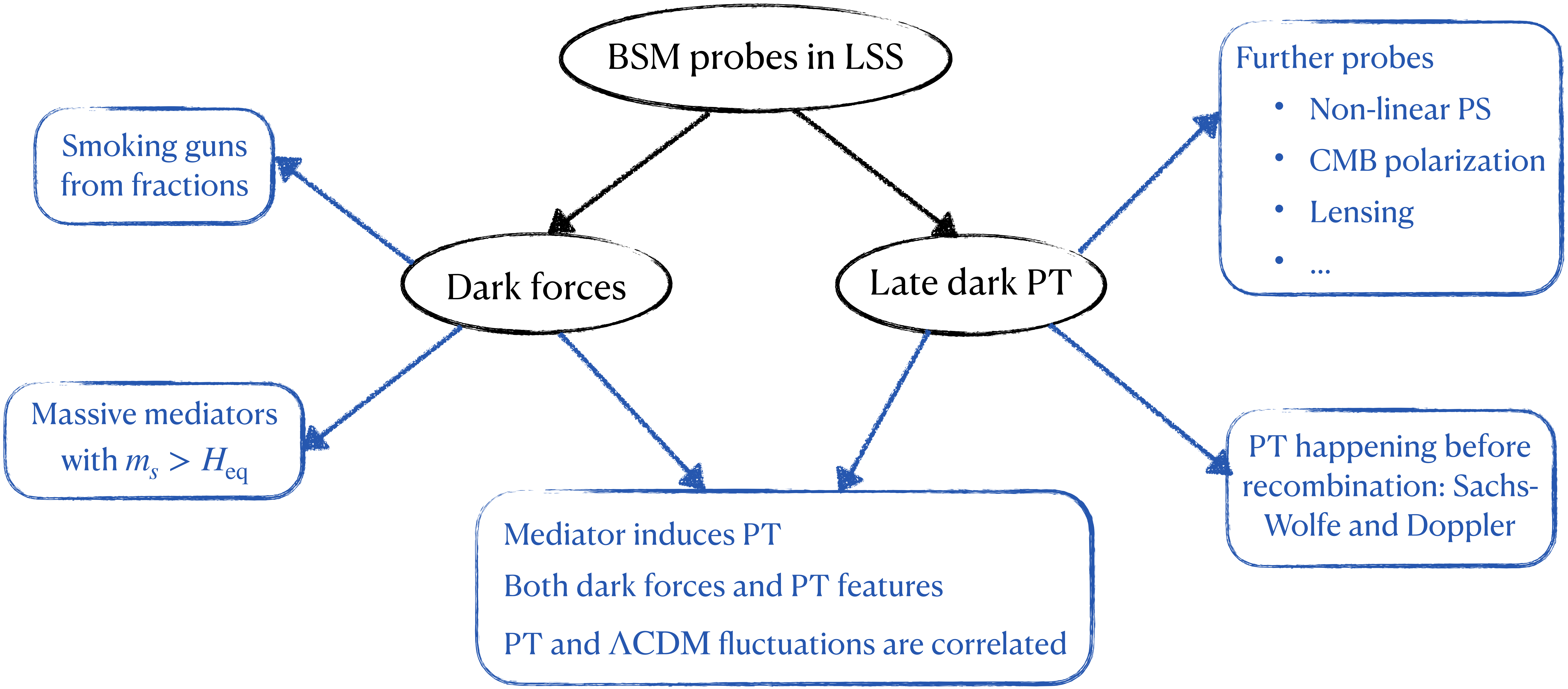
Isocurves of maximally bound $\Omega_{\rm PT}$

Isocurves of ℓ_p

Bounds and Projections



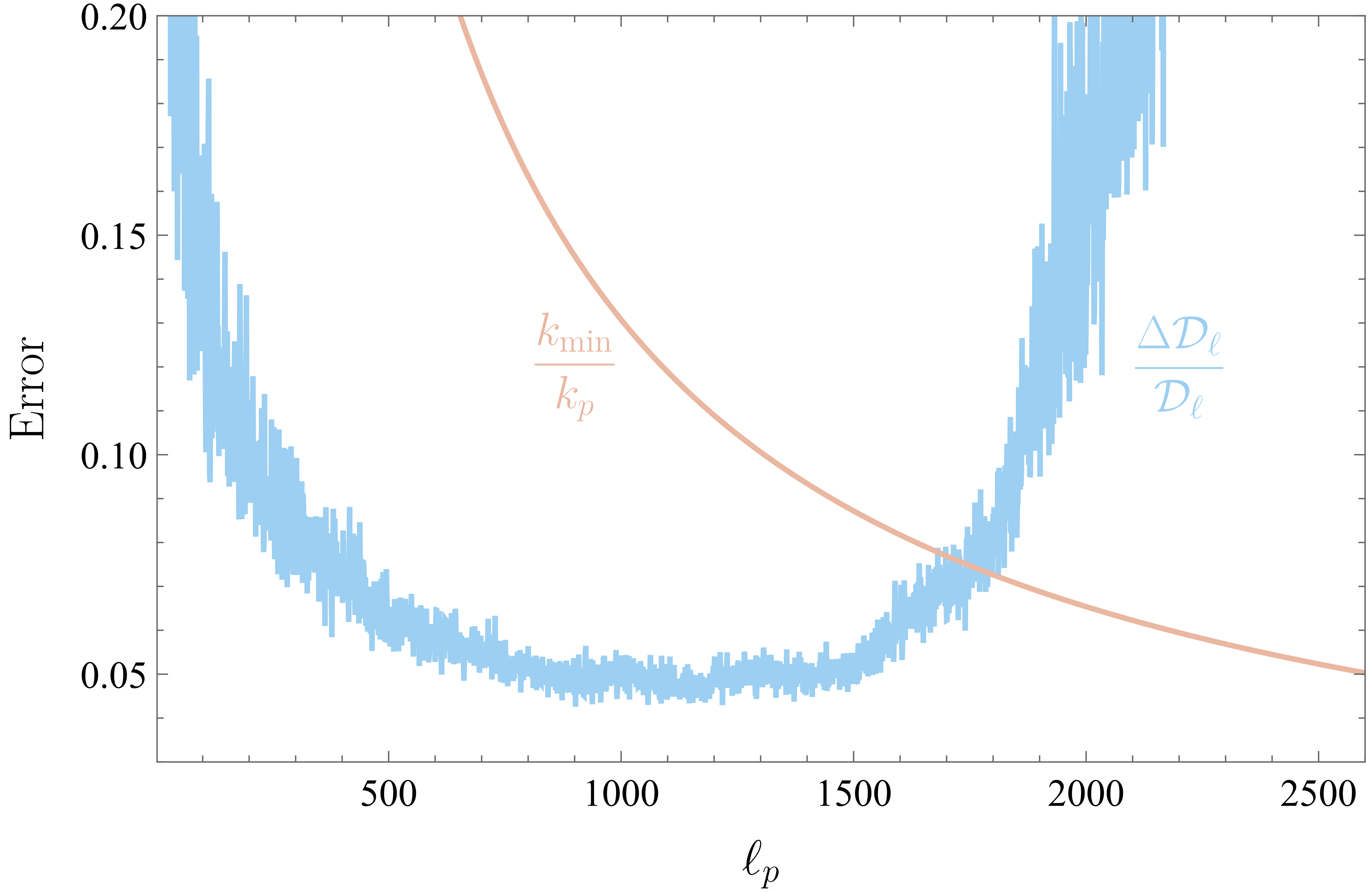
Outlook



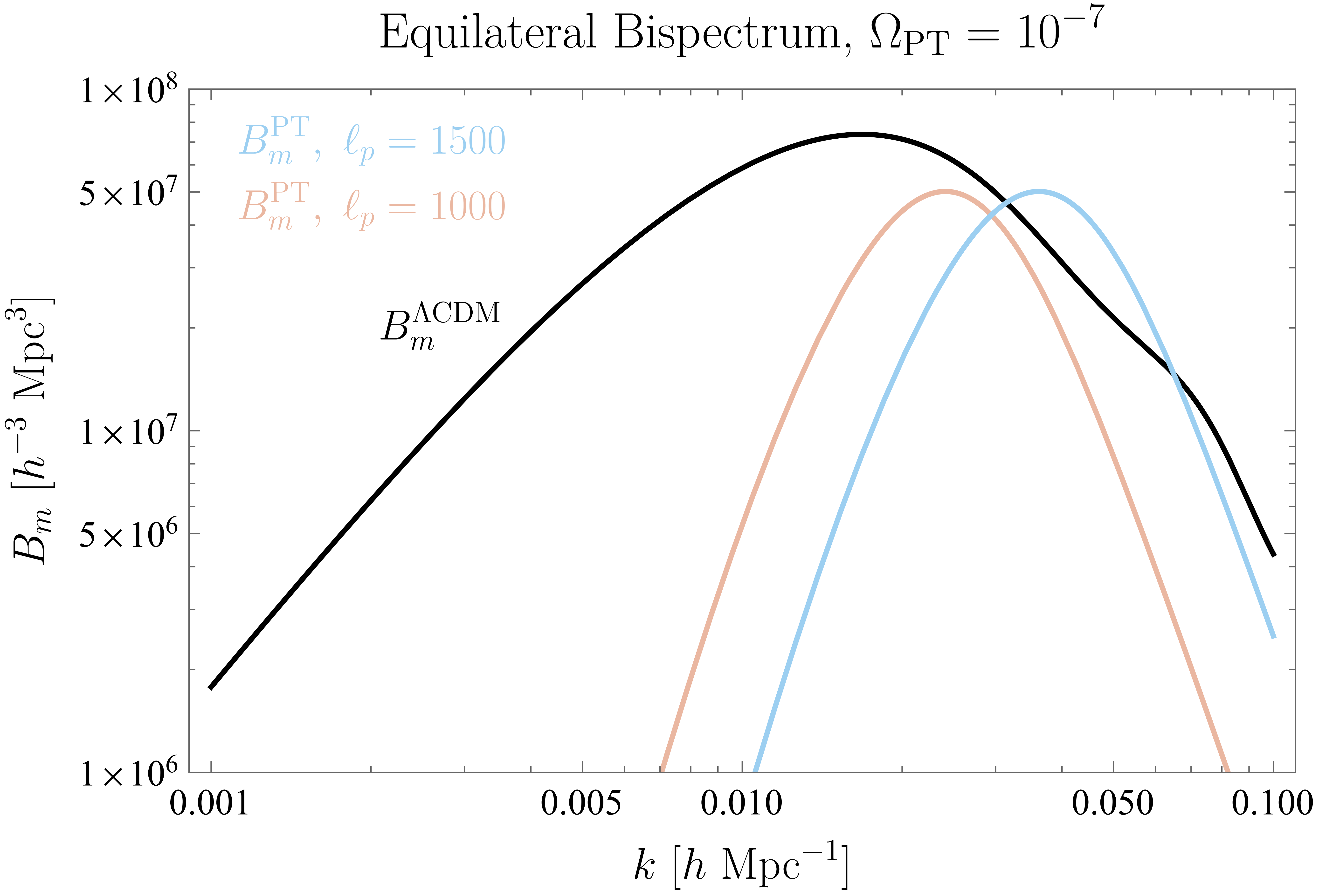
BSM probes in LSS
Dark forces
Late dark PT
Smoking guns from fractions
Massive mediators with $m_s > H_{eq}$
Mediator induces PT
Both dark forces and PT features
PT and ΛCDM fluctuations are correlated
Further probes
• Non-linear PS
• CMB polarization
• Lensing
• ...
PT happening before recombination: Sachs-Wolfe and Doppler

Back-up

CMB vs. Power spectrum

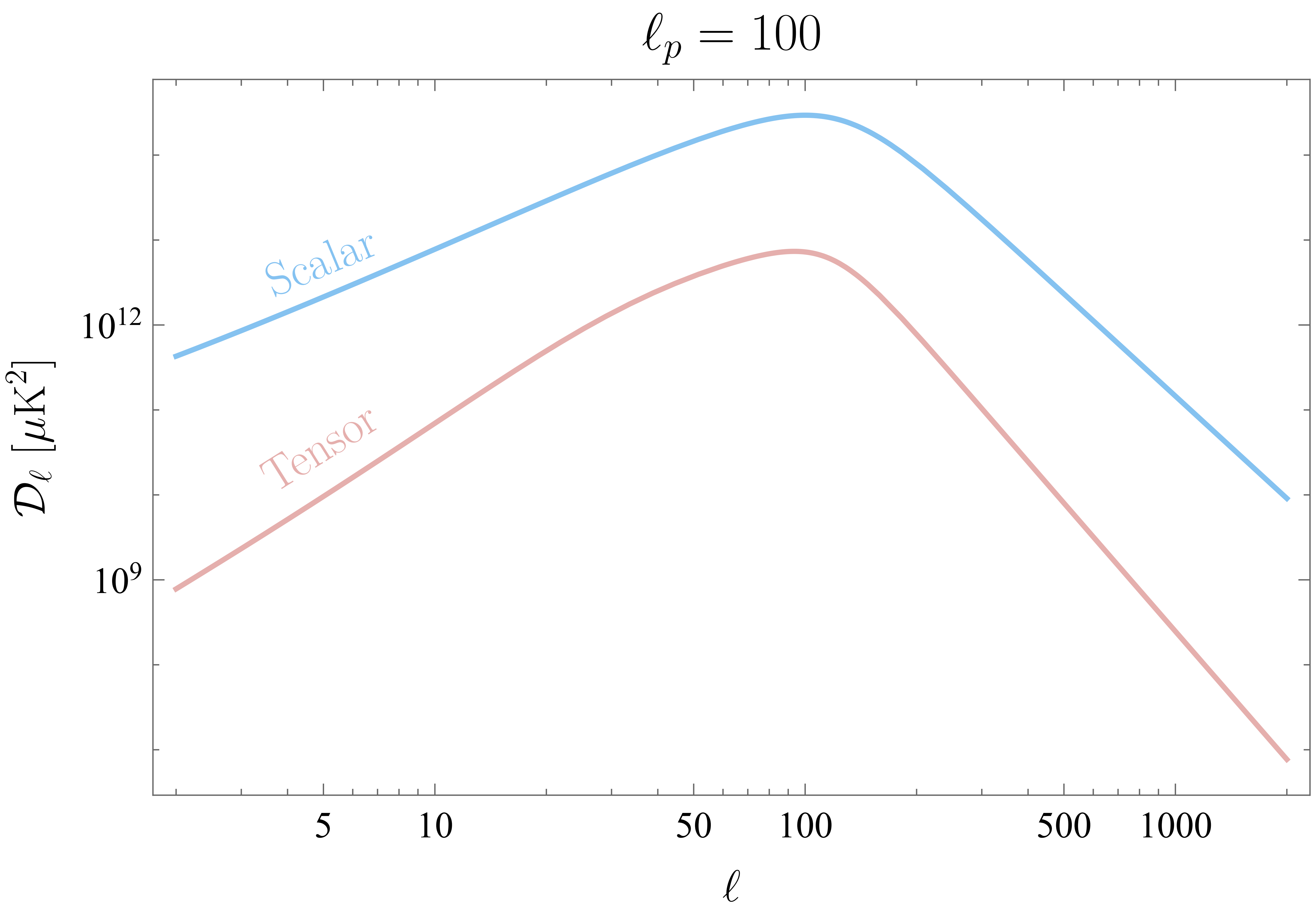


Bispectrum



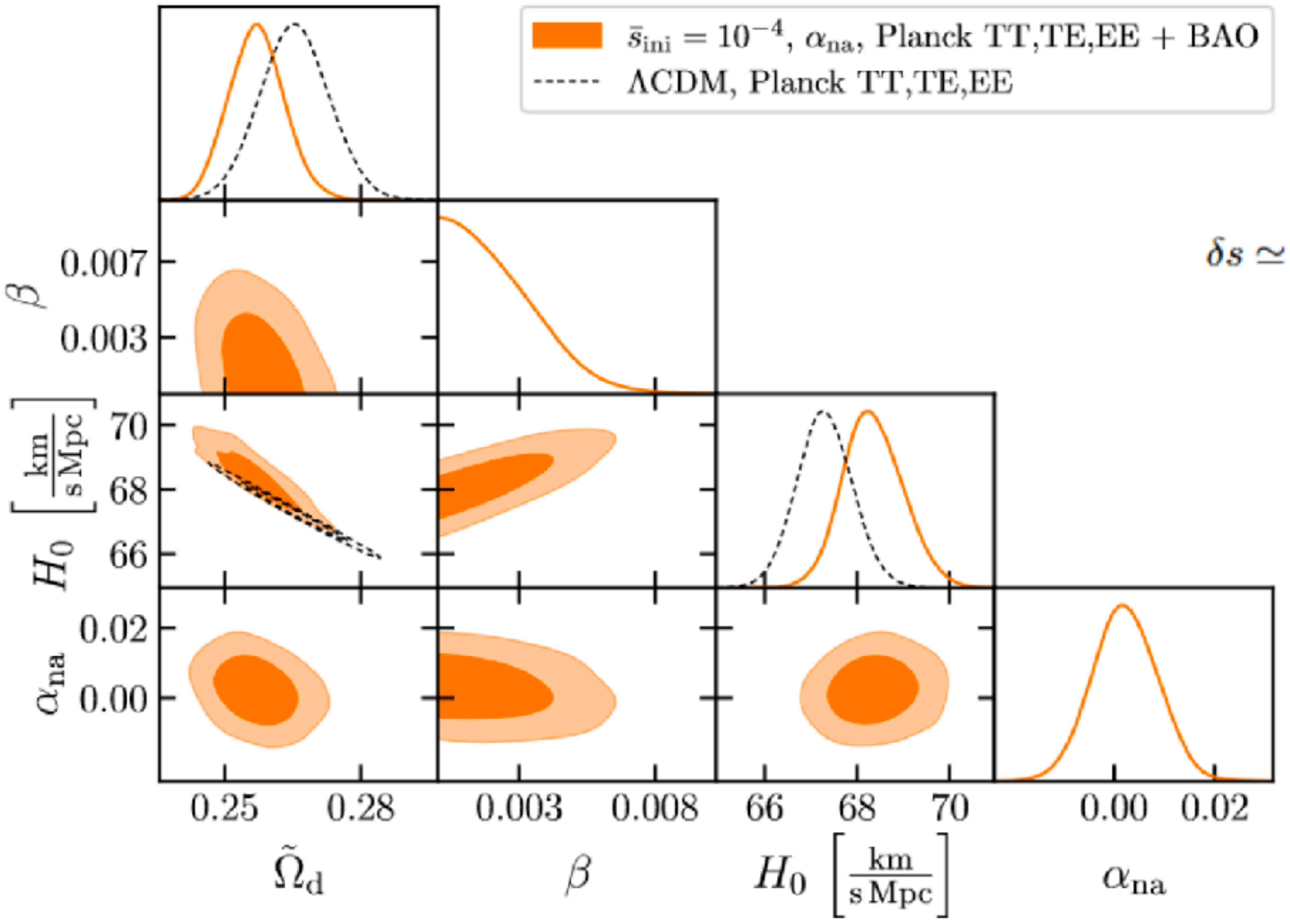
Equilateral Bispectrum, $\Omega_{PT} = 10^{-7}$
B_m^{PT}, $\ell_p = 1500$
B_m^{PT}, $\ell_p = 1000$
$B_m^{\Lambda CDM}$
1×10^8
5×10^7
1×10^7
5×10^6
1×10^6
0.001
0.005
0.010
0.050
0.100
B_m $[h^{-3}\ \mathrm{Mpc}^3]$
k $[h\ \mathrm{Mpc}^{-1}]$

ISW from GWs



$\ell_p = 100$
Scalar
Tensor
10^{12}
10^{9}
$\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
5
10
50
100
500
1000
ℓ

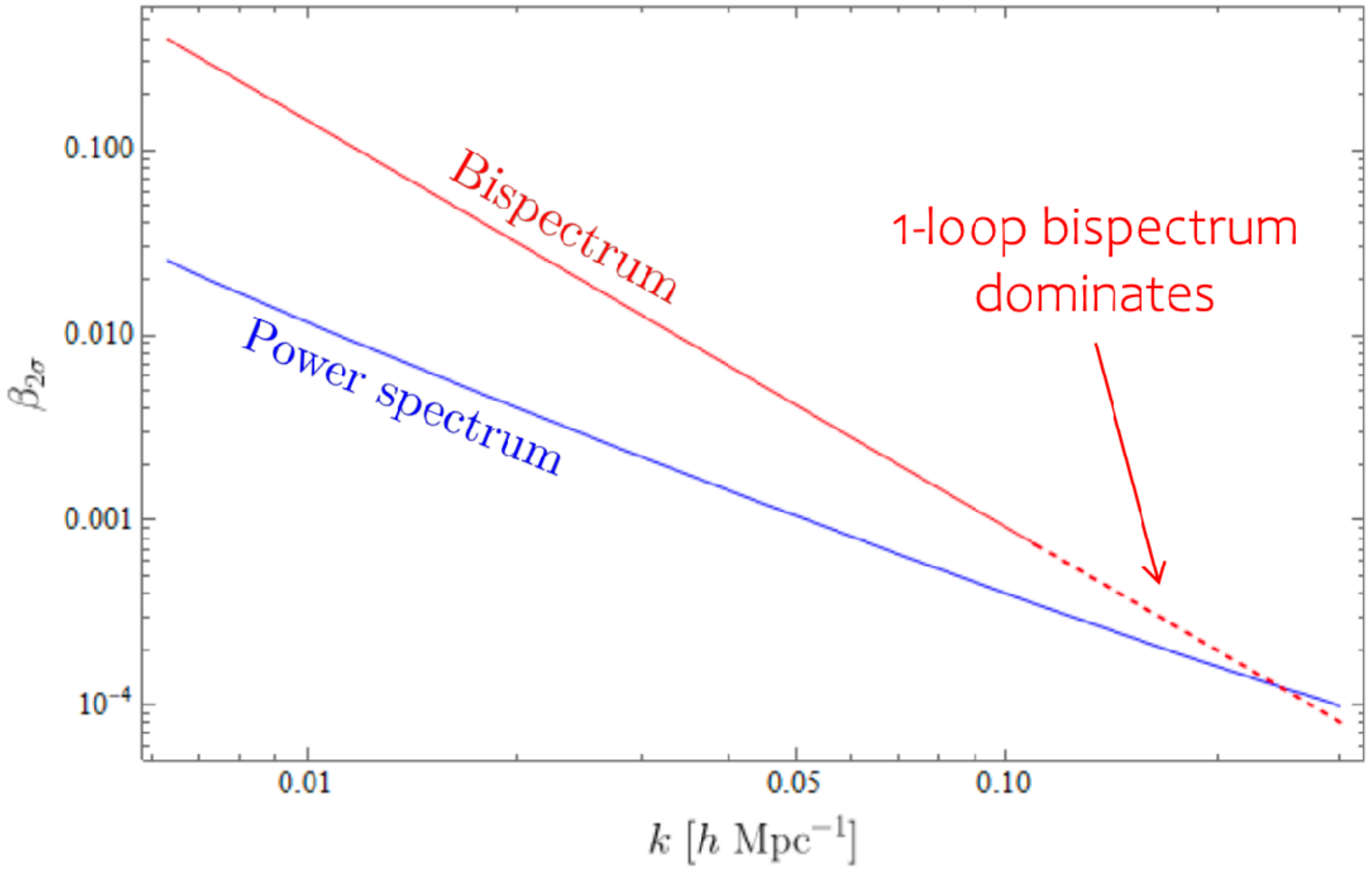
Non-adiabatic ICs



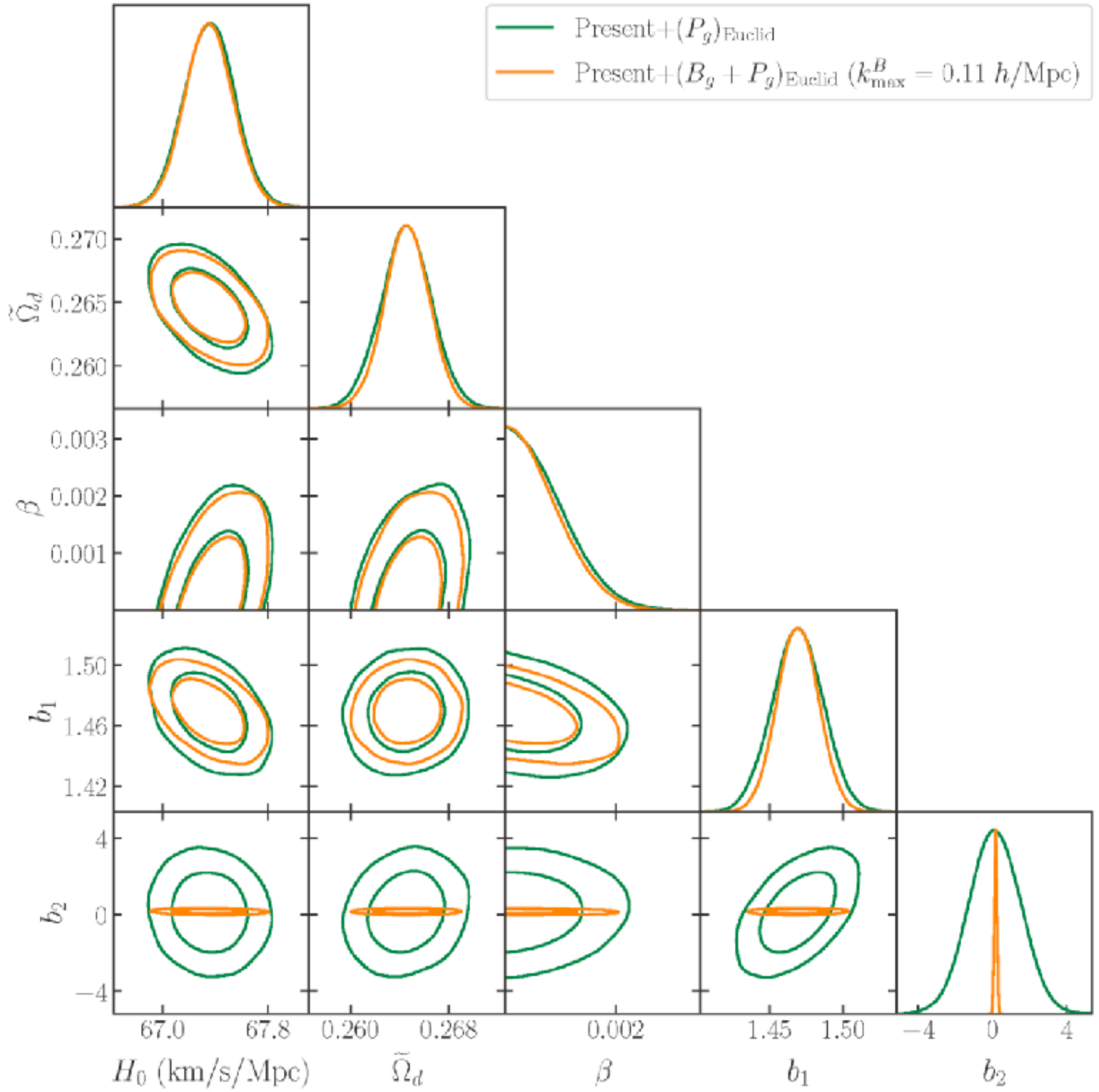
$$\delta s \simeq (\delta s)_{\rm ad} + \alpha_{\rm na}\left(1 + \frac{\partial^2 \log m_\chi(s)/\partial s^2}{\partial \log m_\chi(s)/\partial s}\bar{s}'\tau + \mathcal{O}(\bar{s}'^2\tau^2)\right)$$

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

Bispectrum vs. Power spectrum



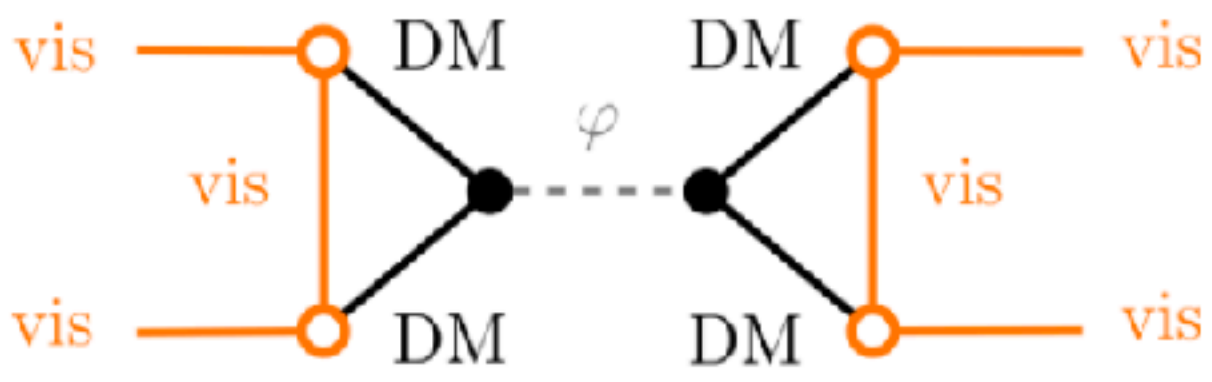
Bispectrum vs. Power spectrum



Relations with 5th force experiments

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

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



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

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

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

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