Long-range massive dark matter self-interactions in cosmology

Based on Archidiacono, Castorina, Redigolo, Salvioni 2204.08484
Bottaro, Castorina, MC, Redigolo, Salvioni 2309.11496
Bottaro, Castorina, MC, Redigolo, Salvioni 2407.18252

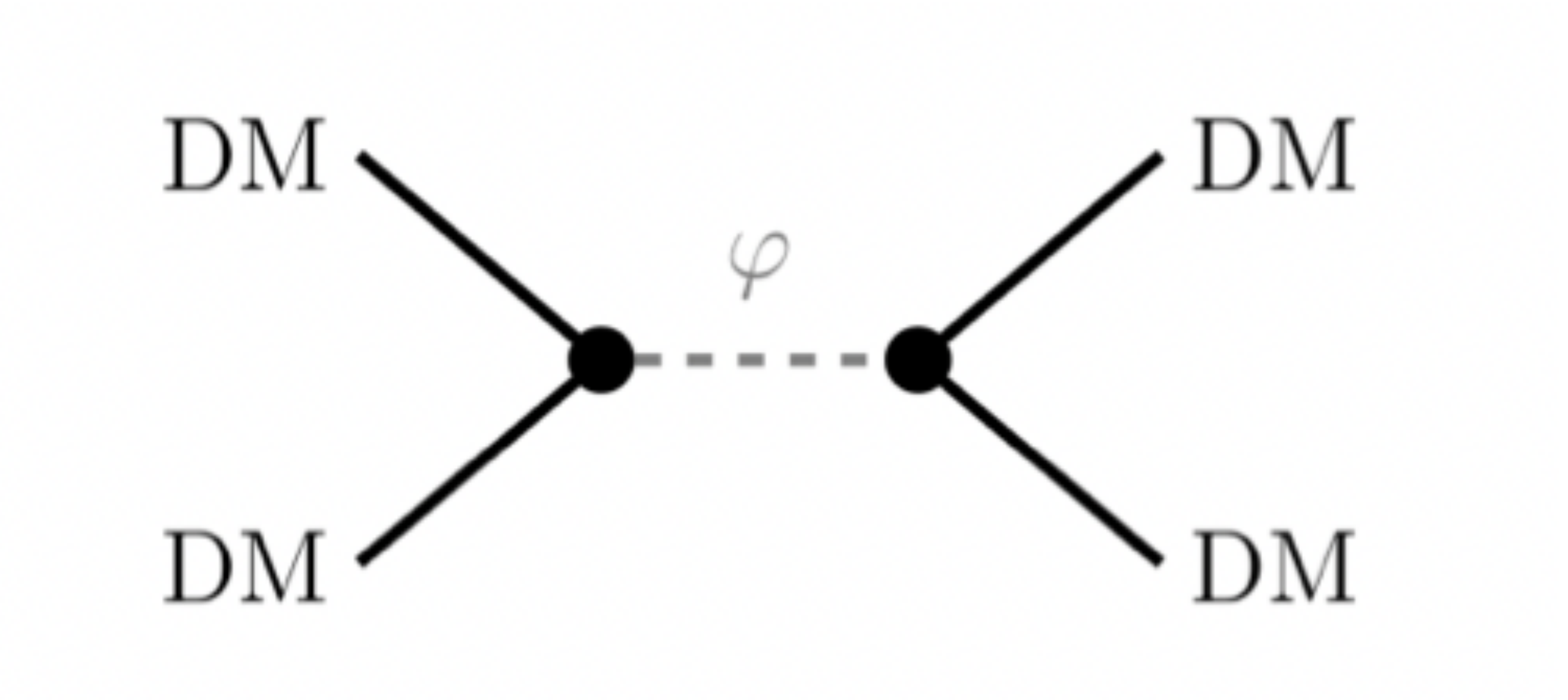
PERIMETER INSTITUTE

Marco Costa (Perimeter Institute),

Dark force model

Yukawa interaction

$$\mathscr{L}_{\rm int} = \kappa\chi^2\varphi$$



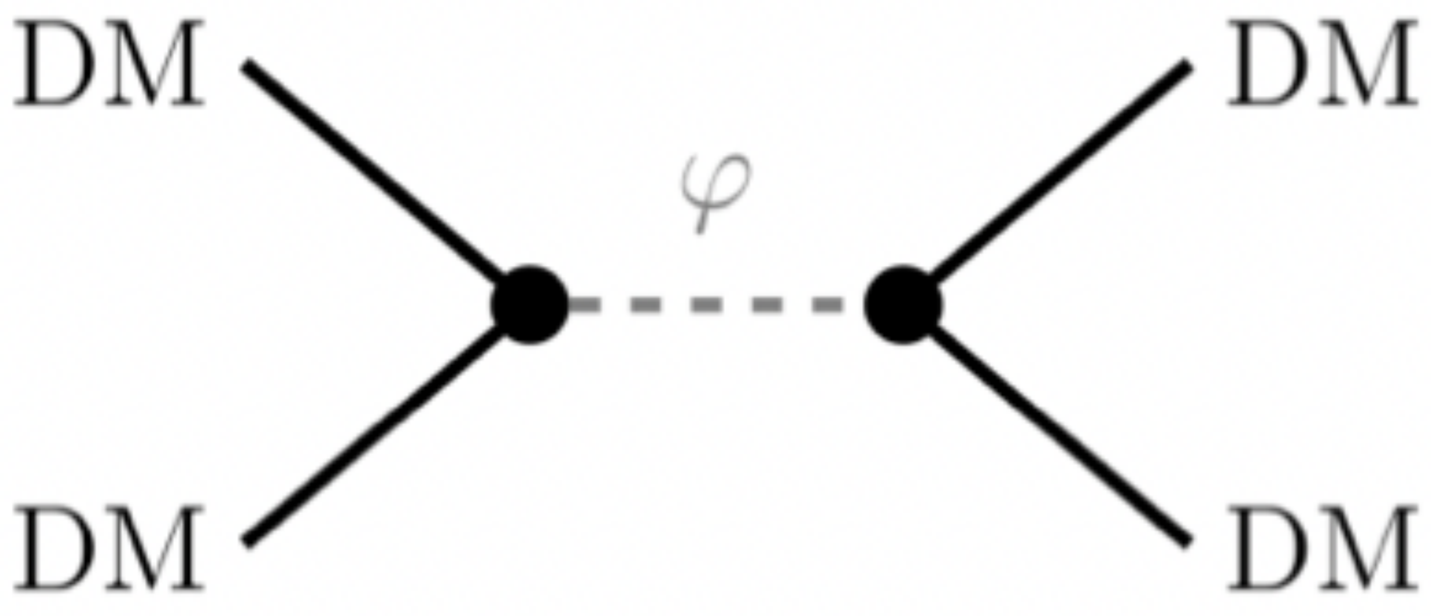
Scalar mediator

$$V_\chi = -4\pi G_N \beta \frac{m_1 m_2}{r} e^{-m_\varphi r}$$

β relative strength compared to gravity

Dark force model

Yukawa interaction



Scalar mediator

$$V_\chi = -4\pi G_N \beta \frac{m_1 m_2}{r} e^{-m_\varphi r}$$

β relative strength compared to gravity $\quad \beta \equiv \frac{G_S}{4\pi G_N}$

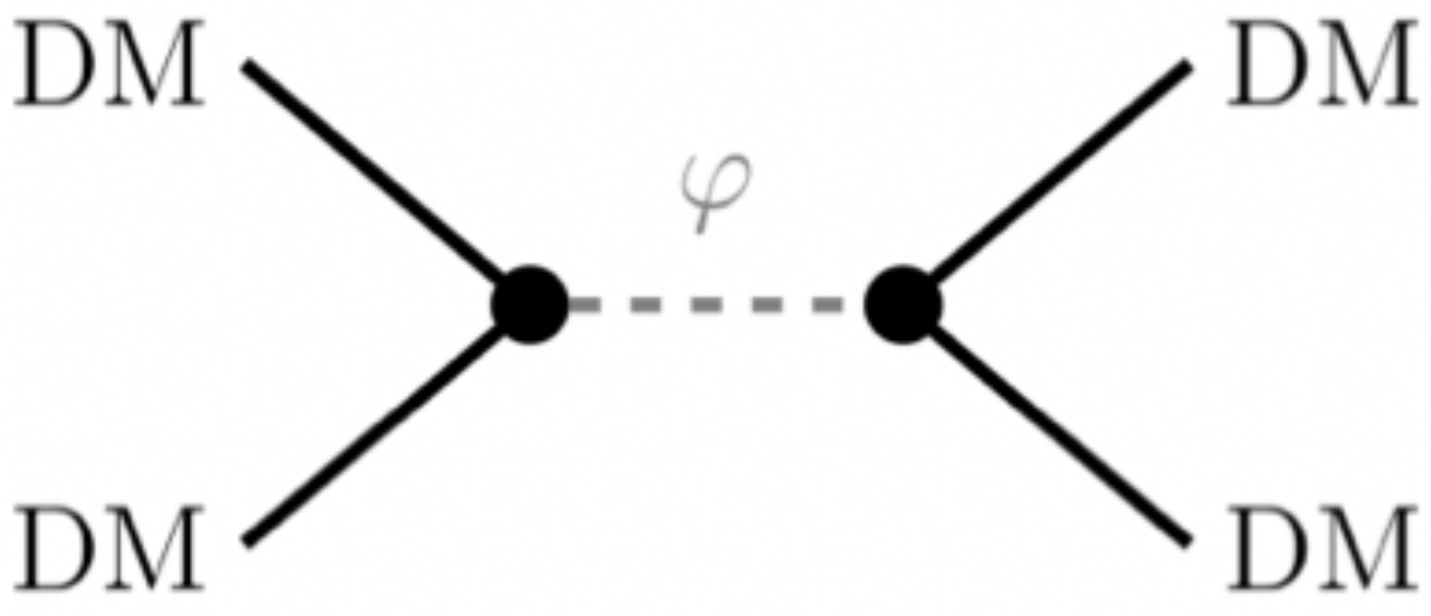
$$\mathcal{L}_{\rm int} = \kappa \chi^2 \varphi \xrightarrow[G_s \equiv \kappa^2/m_\chi^4]{\varphi \equiv G_s^{-1/2} s} \mathcal{L}_{\rm int} = m_{\chi,0}^2 \chi^2 s$$

s induced mass $m_\chi^2 \equiv m_{\chi,0}^2 (1 + 2\bar{s})$

χ sources $V_s \sim \frac{1}{2G_s} m_\varphi^2 s^2 + \bar{\rho}_\chi s$

Dark force model

Yukawa interaction



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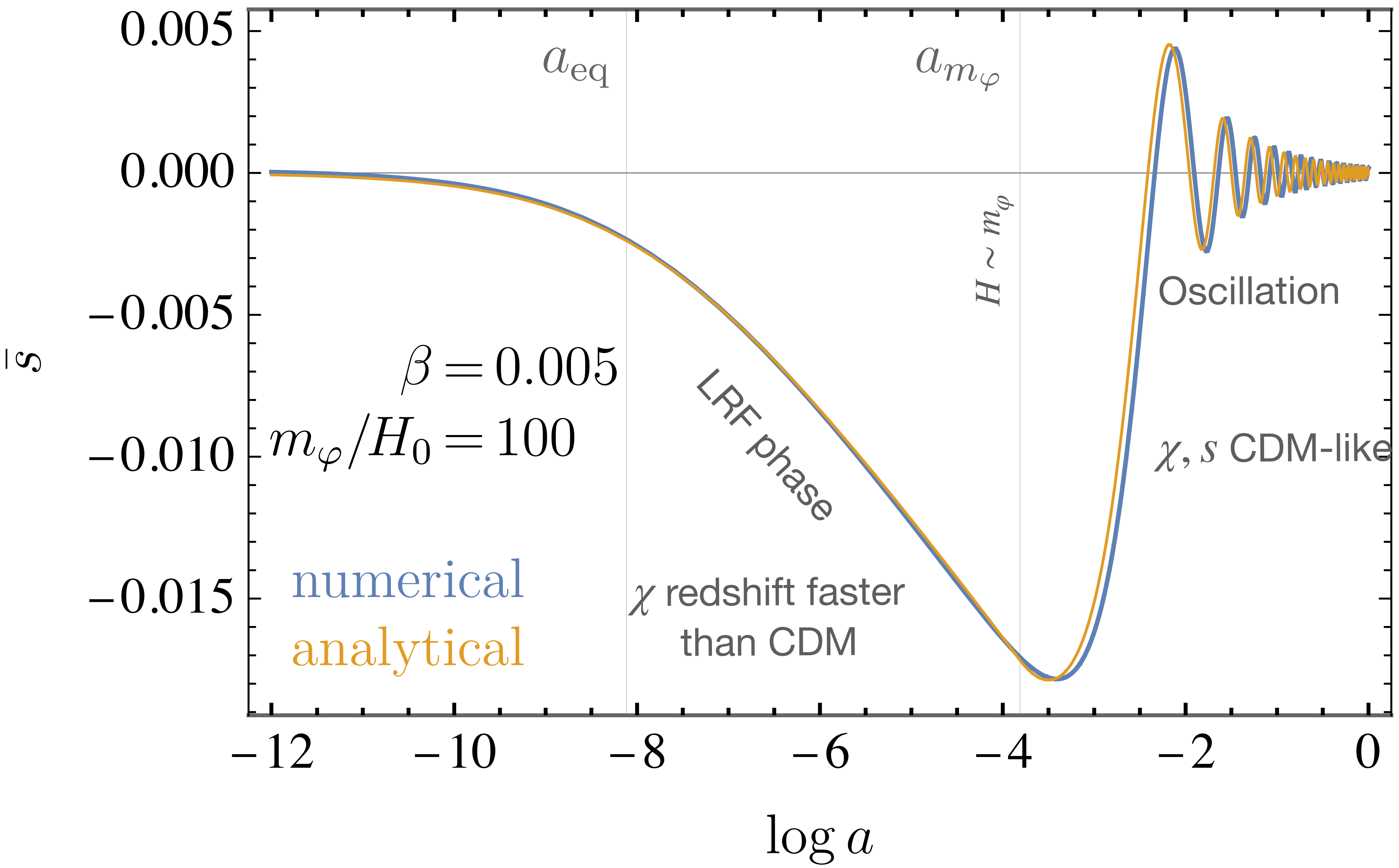
β relative strength compared to gravity $\beta \equiv \frac{G_S}{4\pi G_N}$

Working assumptions:

- Light mediator $m_\varphi < H_{\rm eq}$
- All DM self interacting $f_\chi \simeq 1$
- Perturbative regime: $\beta \ll 1$
- Only new params: β, m_φ

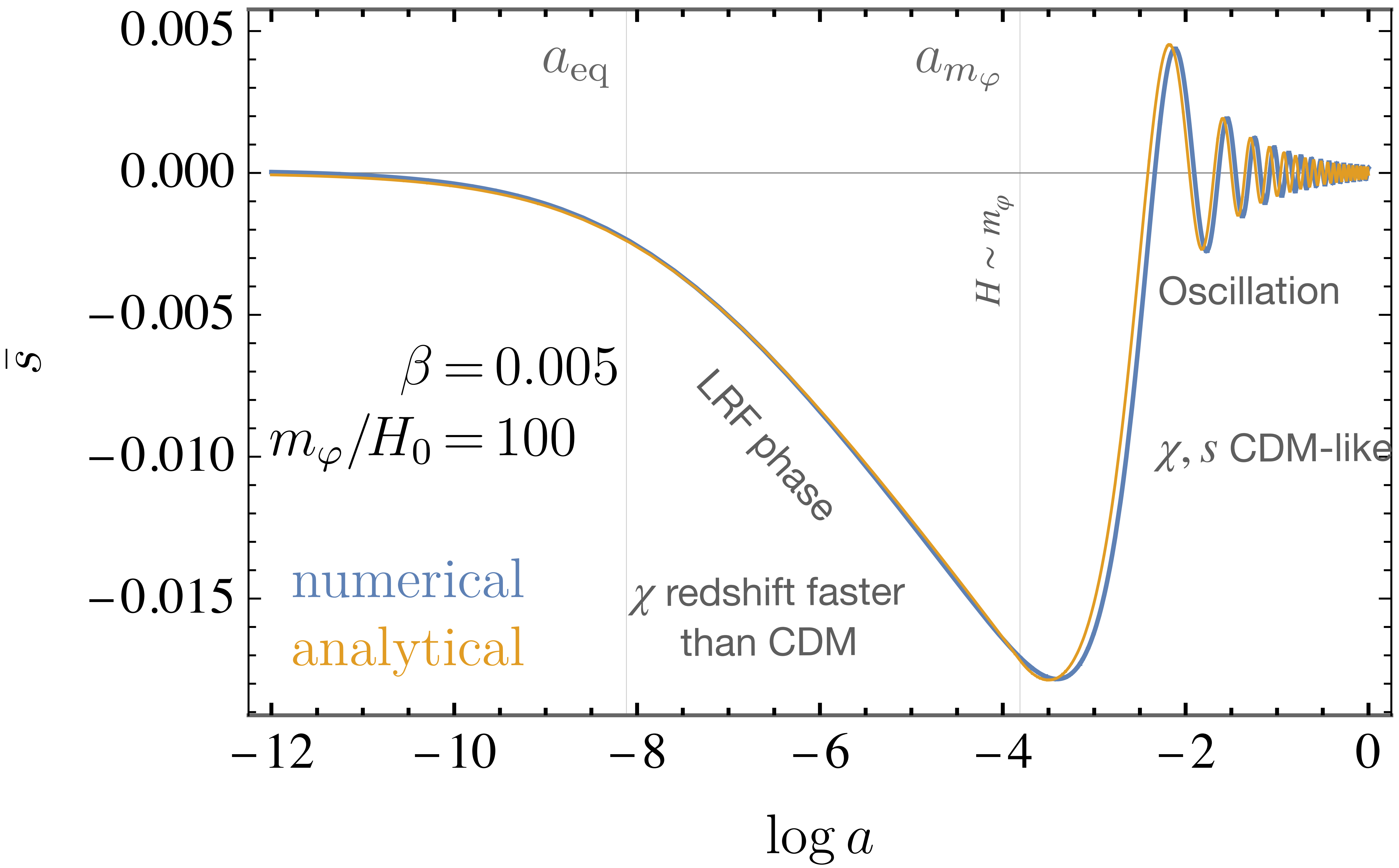
Mediator background evolution

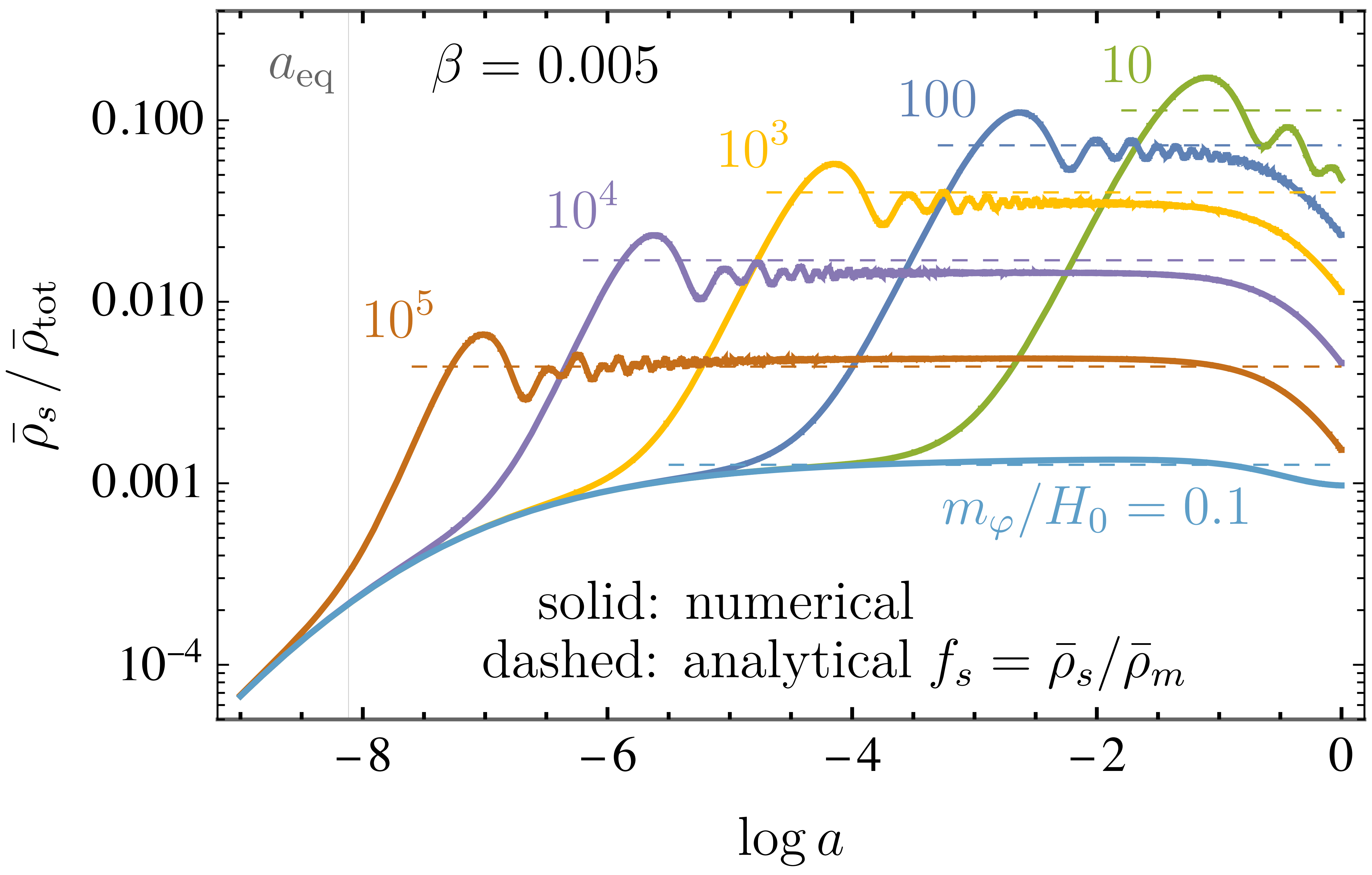


$$\Omega_\chi = a^{-3}(1 - \beta \log a/a_{\rm eq})$$

$\rightarrow \mathcal{O}(10)$

Mediator background evolution





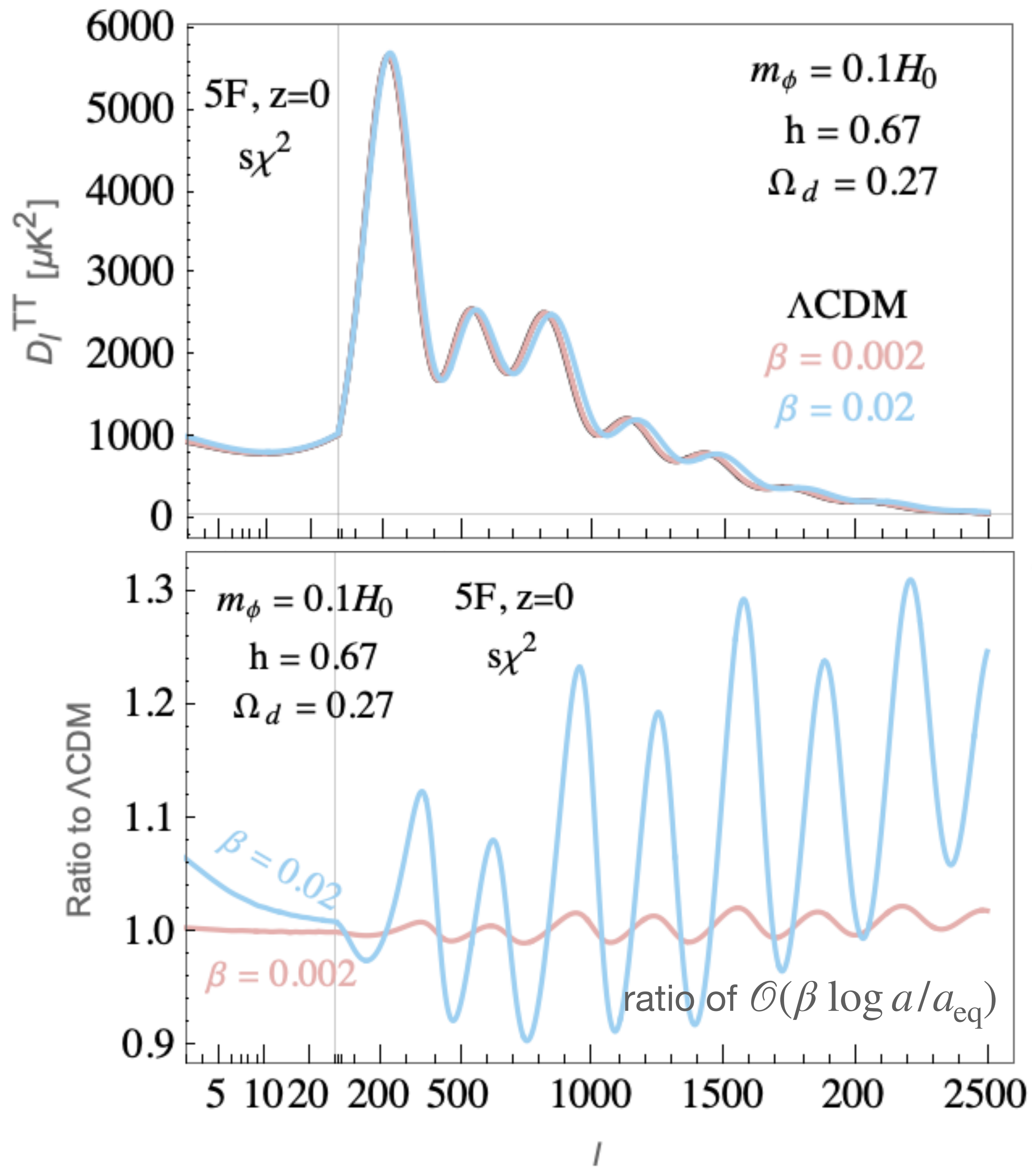
$$\Omega_\chi = a^{-3}(1 - \beta \log a/a_{\rm eq})$$

$$f_s \simeq \frac{5}{4} f_s^{\rm massless} \log^2 \frac{H_{\rm eq}}{m_\varphi} \qquad H_{\rm eq} \gg m_\varphi \gg H_0$$

$$f_s^{\rm massless} \simeq \beta f_\chi^2/3$$

Observables: CMB

Massless mediator

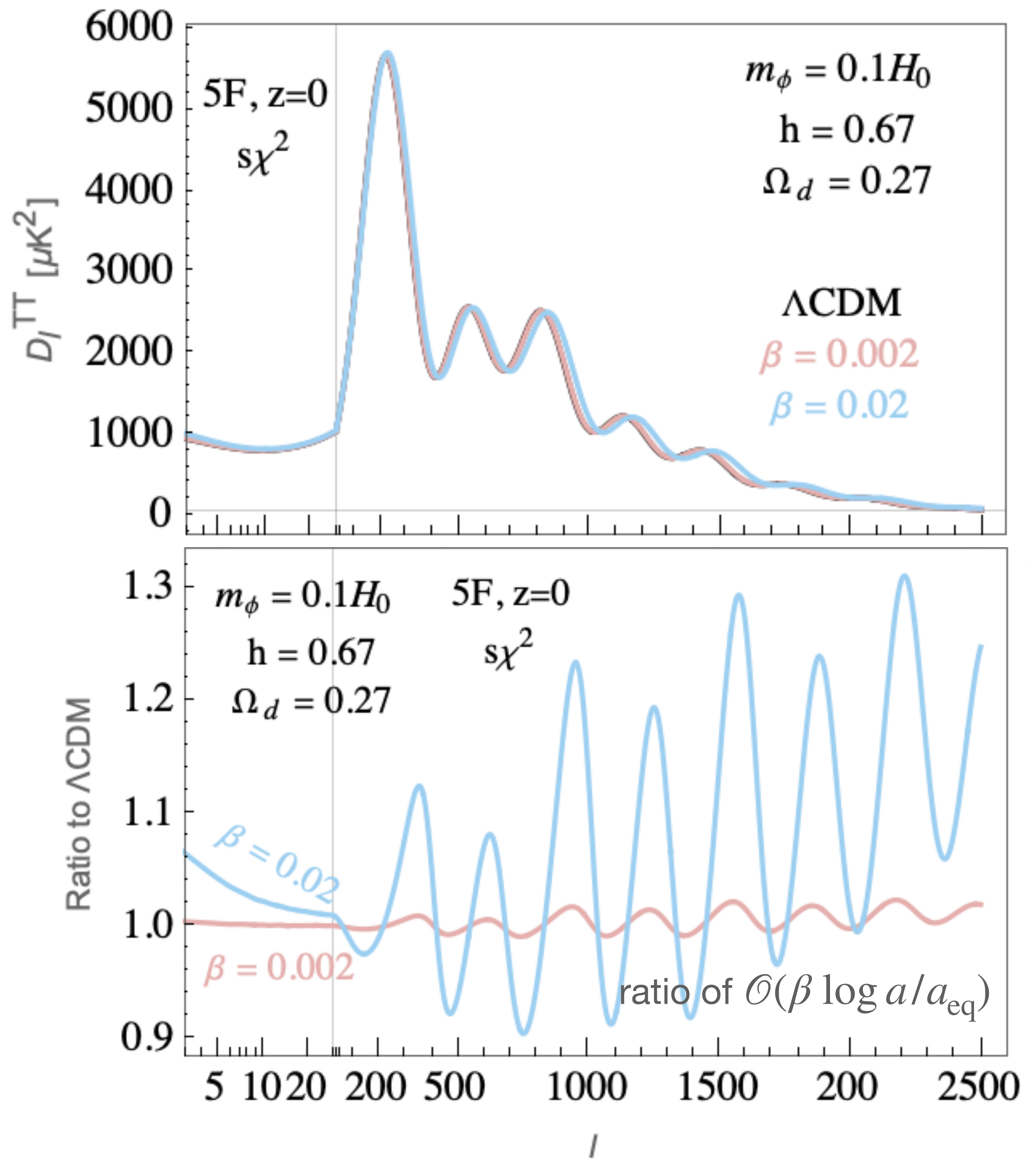


$$l_n \approx \frac{n\pi}{c_s t_{rec}} \propto \int_0^{z_{rec}} \mathrm{d}\,z \frac{1}{H_{\Lambda CDM}(z) + \Delta H(z)}$$

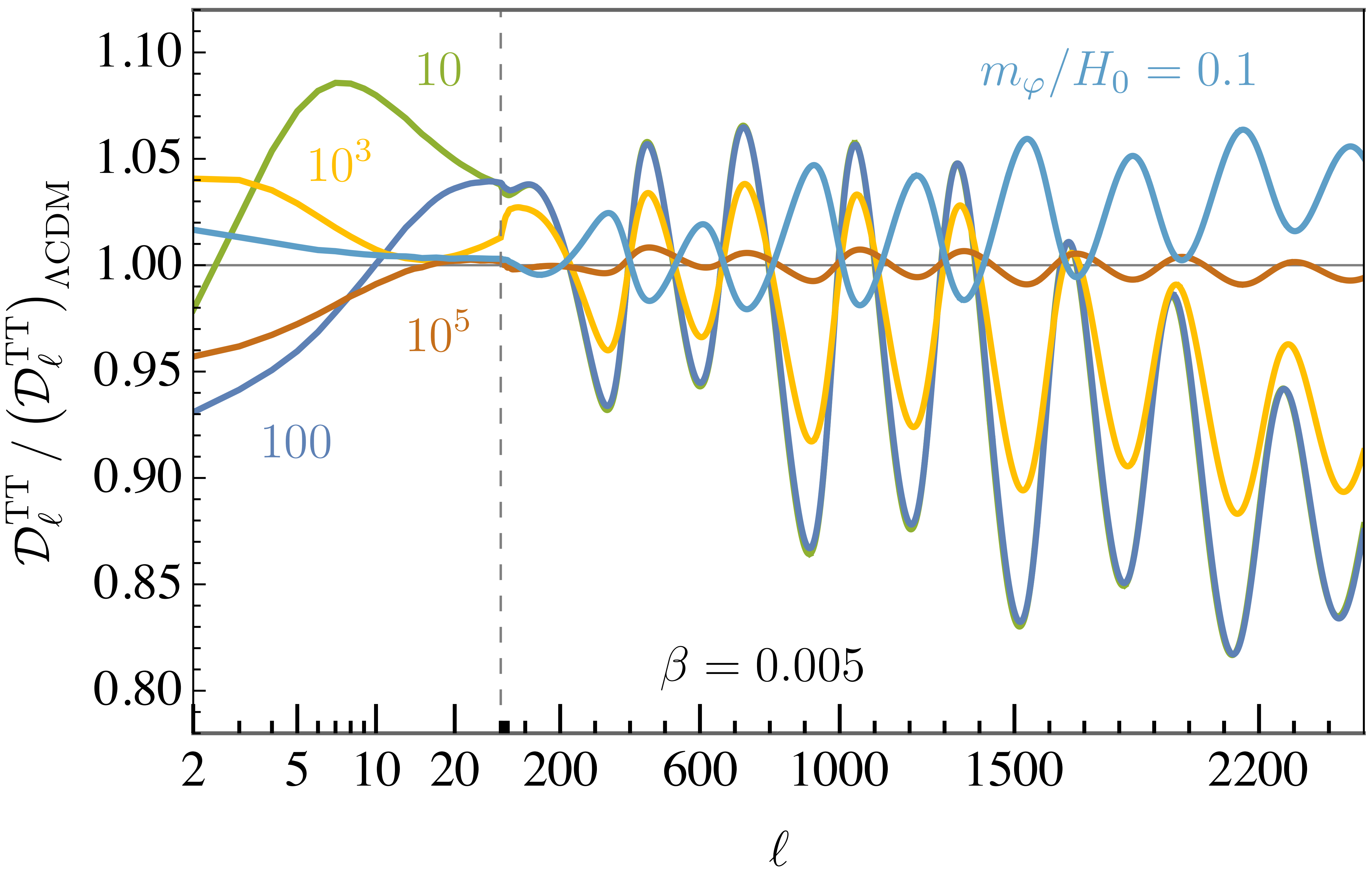
$\beta < 0.015$ from CMB alone

Observables: CMB

Massless mediator



Massive meditator



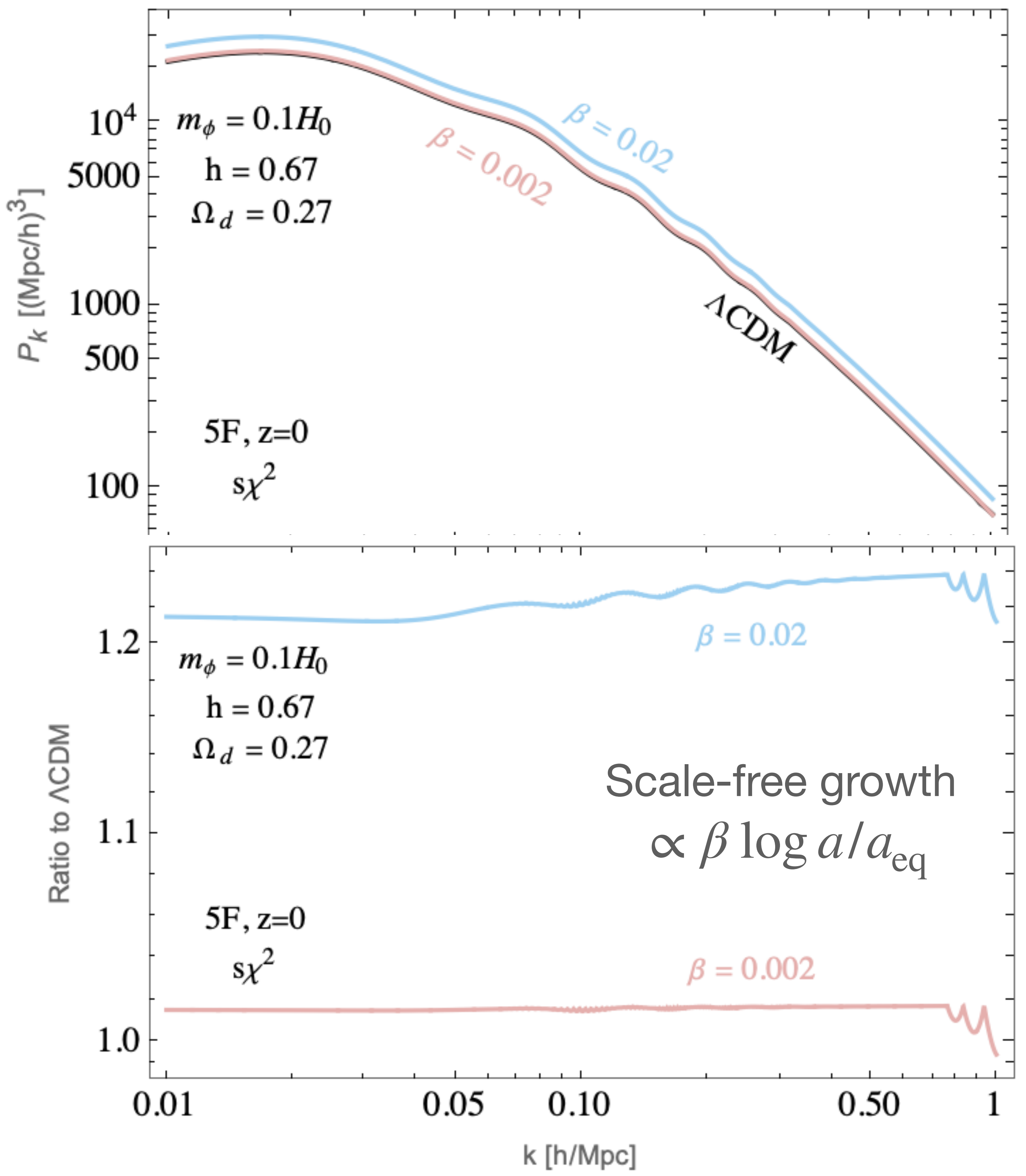
$$l_n \approx \frac{n\pi}{c_s t_{rec}} \propto \int_0^{z_{rec}} dz \frac{1}{H_{\Lambda CDM}(z) + \Delta H(z)}$$

Opposite phase shift!

$\beta < 0.015$ from CMB alone

Observables: Power spectra

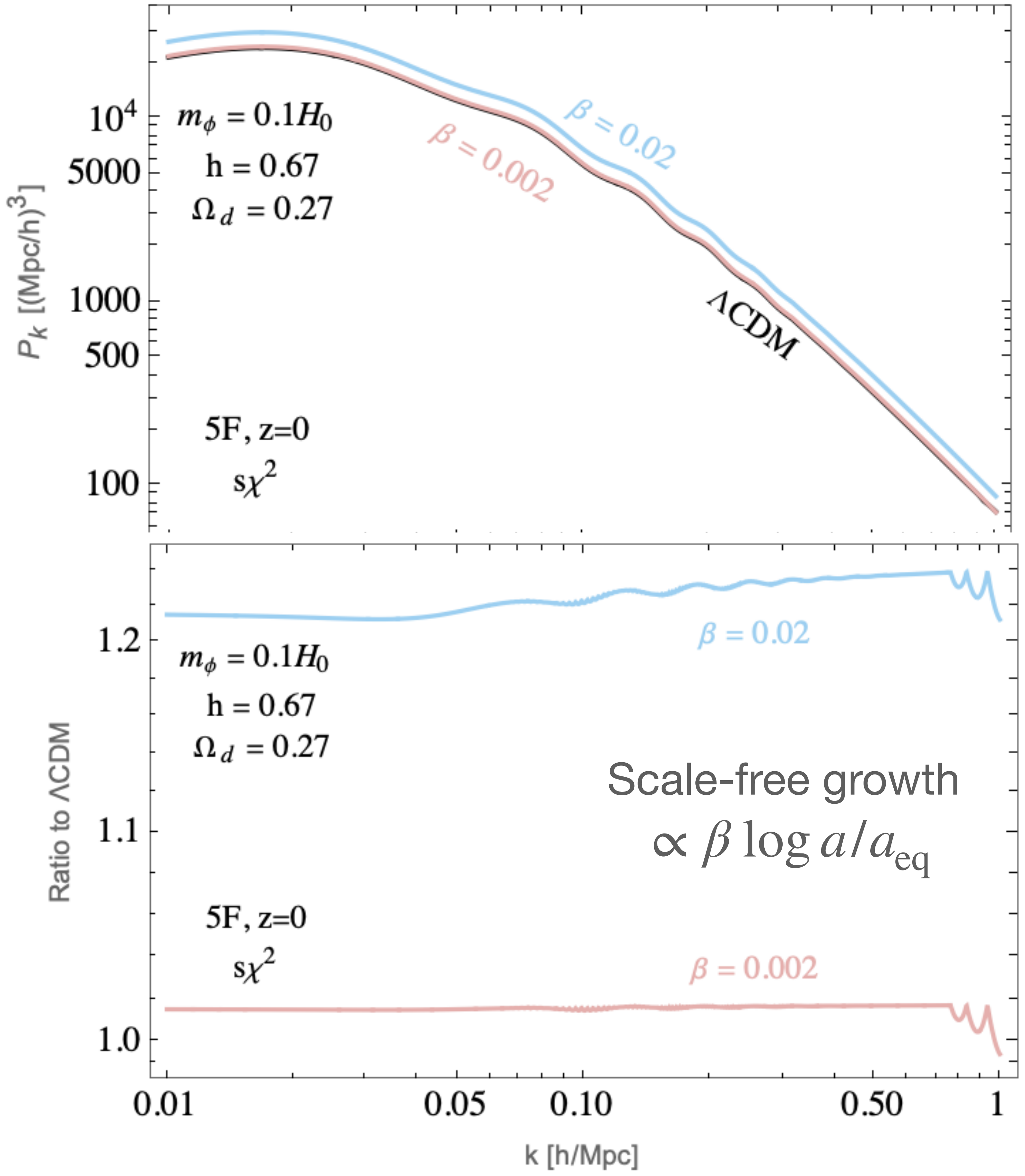
Massless mediator



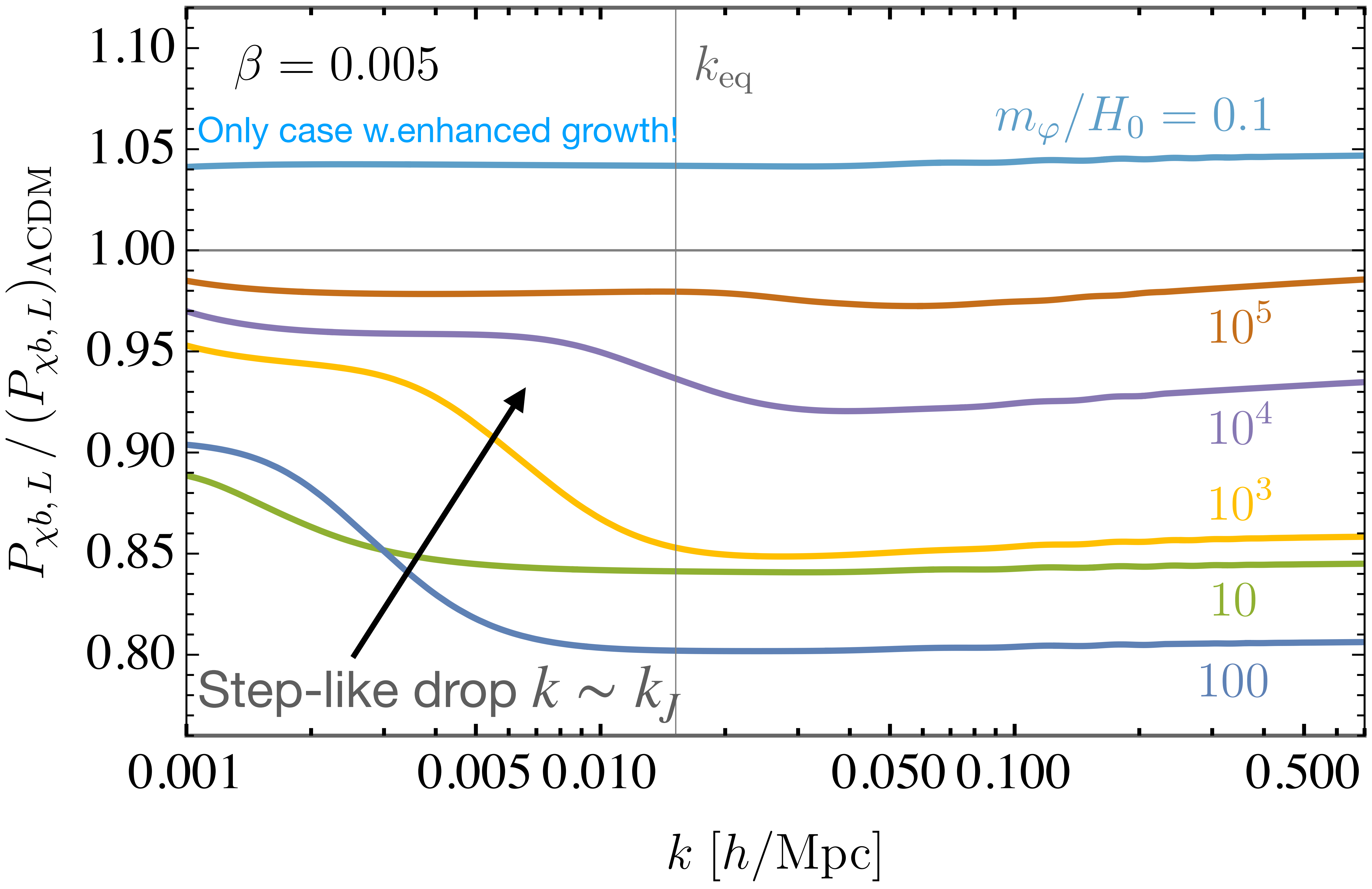
At $\mathcal{O}(\beta \log a/a_{\text{eq}})$ PT+EFT same as in ΛCDM

Observables: Power spectra

Massless mediator



Massive meditator

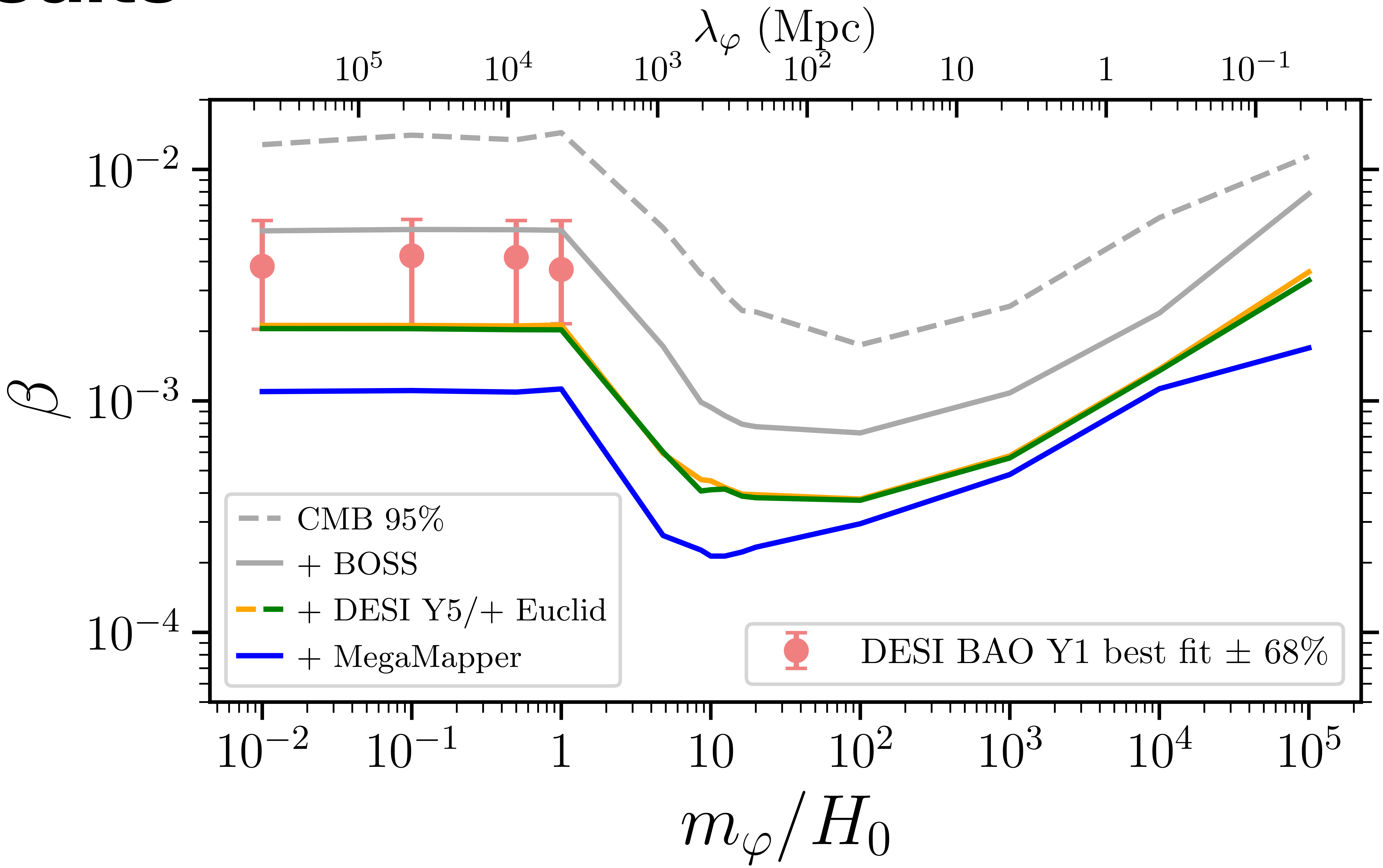


At $\mathcal{O}(\beta \log a/a_{\rm eq})$ PT+EFT same as in ΛCDM

φ doesn't cluster at scales $k \gg k_{\rm eq}$

Reduced gravitational potential for χ, b

Results



Current BOSS FS data doesn't help much

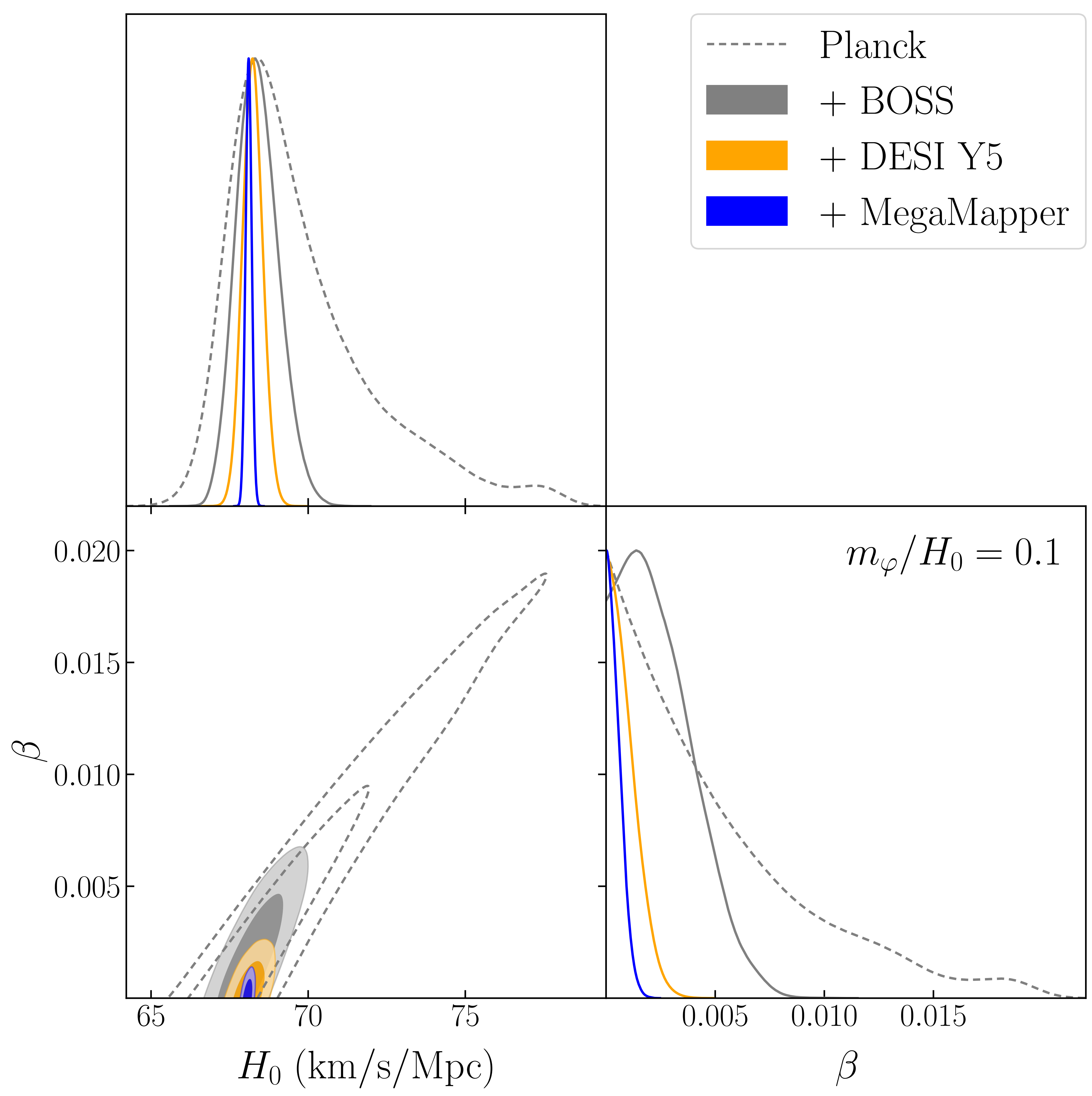
Conclusions

- We studied the effect of long-range attractive scalar force between DM
- Mediator evolution is crucial to understand cosmology of Dark Forces
- Bounds valid for ranges up to 100 kpc, factor 5 stronger for $m_\varphi/H_0 \sim 10^2$
- **CMB+BAO:** $\beta < 5 \times 10^{-3}$, forecasted **+FS**: $\beta \lesssim 10^{-3}$
- **Outlook:** if $f_\chi \ll 1/8$, $\mathcal{O}(\beta f_\chi) > \mathcal{O}(\beta f_\chi^2 \log)$: need to change EFT+PT structure!
- **Outlook:** matching mediator to fluid for $m_\varphi \gg H_{\rm eq}$

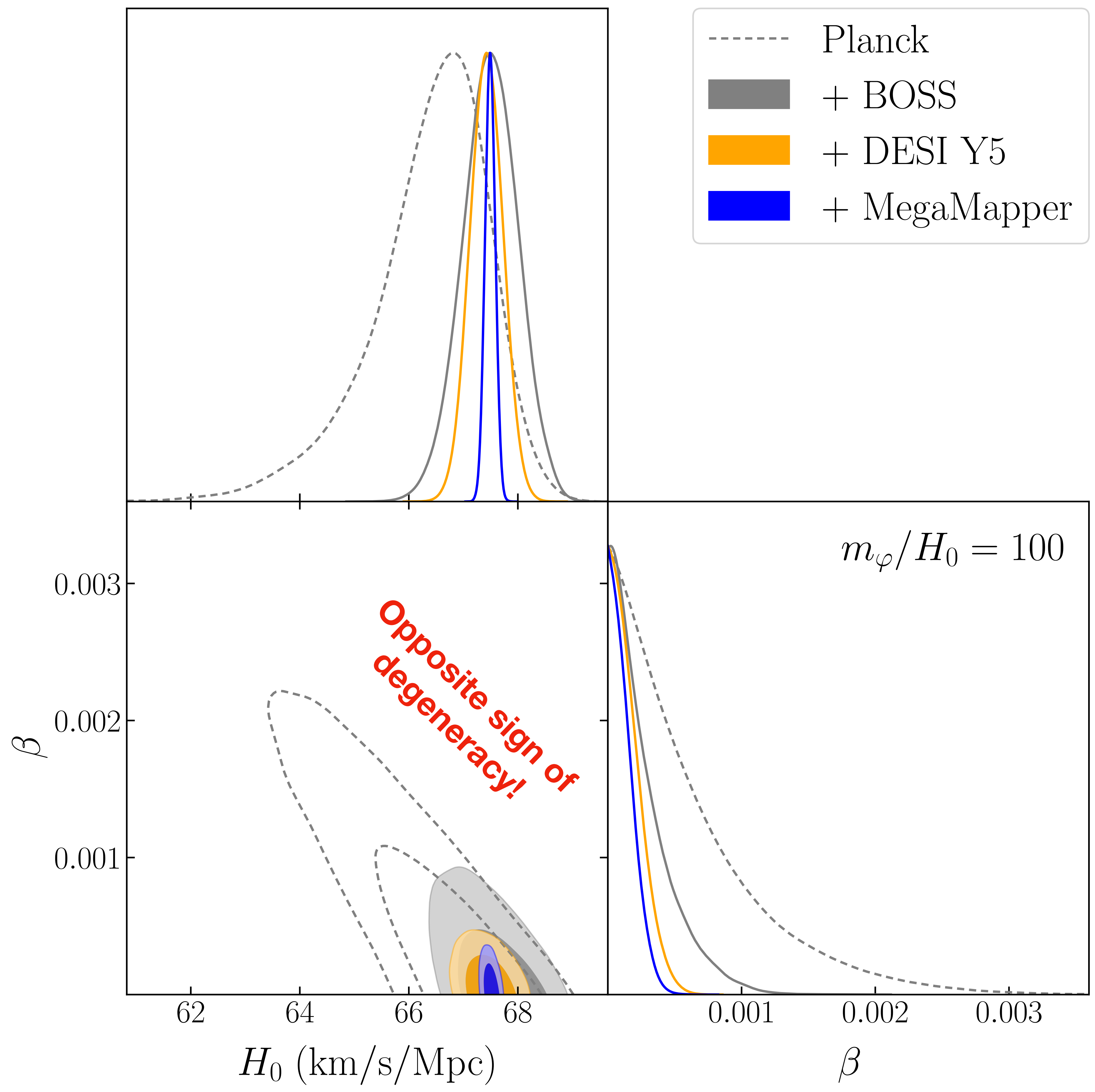
Thanks for the attention!

Backup

Results

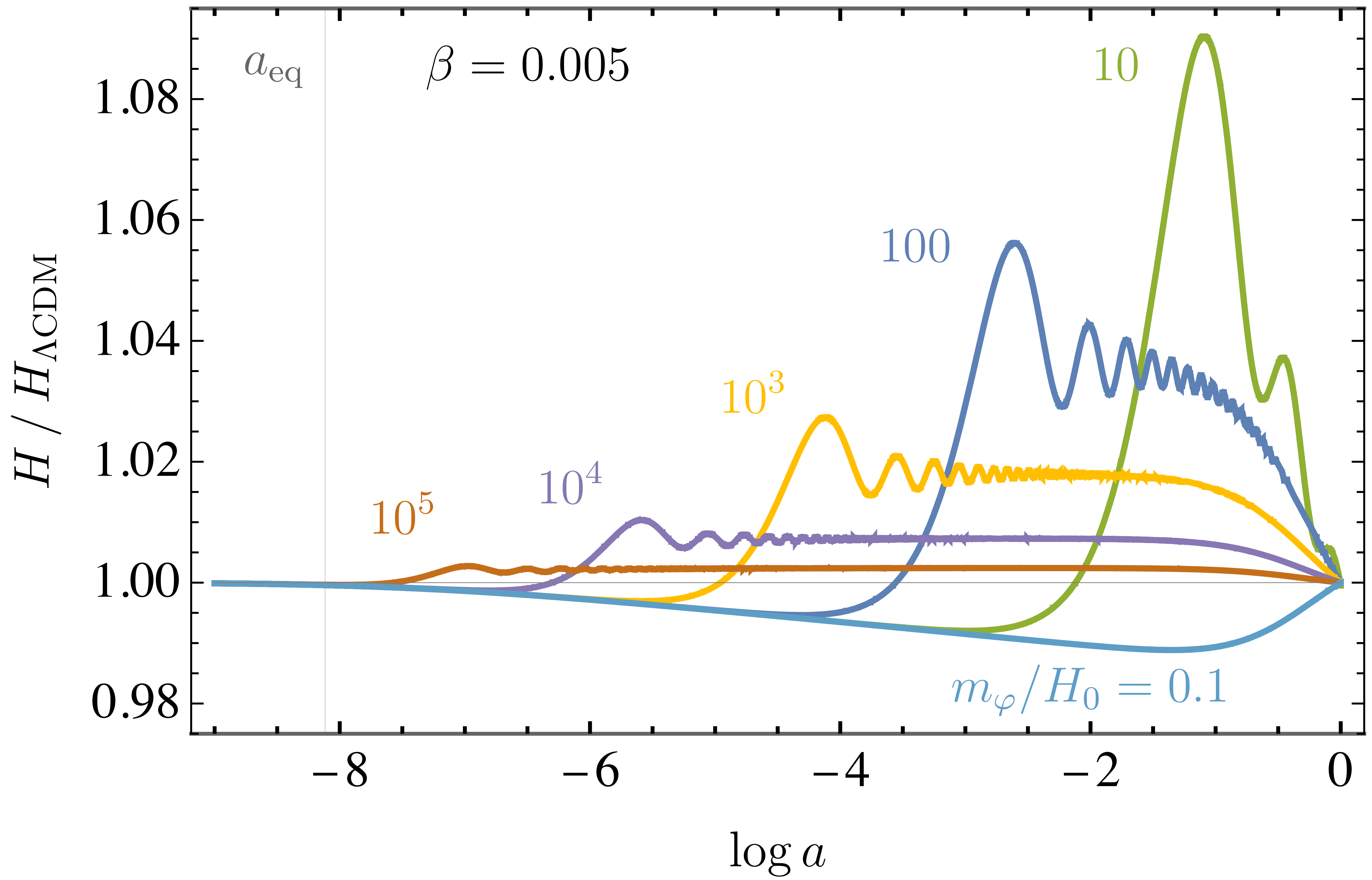


Planck
+ BOSS
+ DESI Y5
+ MegaMapper
$m_\varphi/H_0 = 0.1$
0.020
0.015
0.010
0.005
β
65
70
75
H_0 (km/s/Mpc)
0.005
0.010
0.015
β



Planck
+ BOSS
+ DESI Y5
+ MegaMapper
$m_\varphi/H_0 = 100$
Opposite sign of degeneracy!
0.003
0.002
0.001
β
62
64
66
68
H_0 (km/s/Mpc)
0.001
0.002
0.003
β

Massive mediator details



H larger in massive case: smaller distance

$$f_s \simeq \frac{5}{4} f_s^{\rm massless} \log^2 \frac{H_{\rm eq}}{m_\varphi}$$

$$H_{\rm eq} \gg m_\varphi \gg H_0$$

$$f_s^{\rm massless} \simeq \beta f_\chi^2 / 3$$

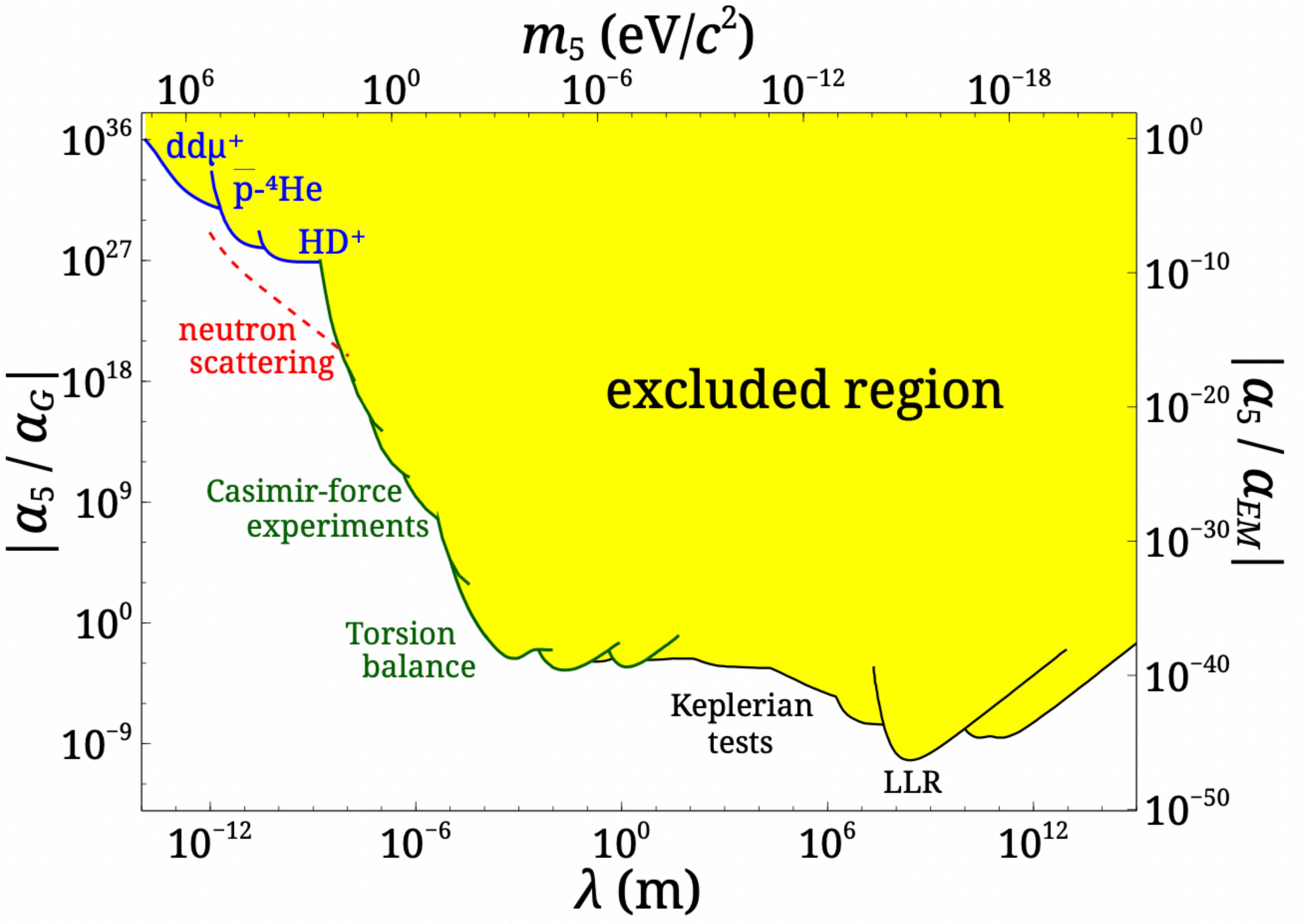
A step back: new baryonic forces

Time dependent background: tested via atomic clocks

$$V \sim \frac{\alpha_5(t)}{r} e^{r/\lambda}$$

Corrections to coupling strength

Corrections to 1/r

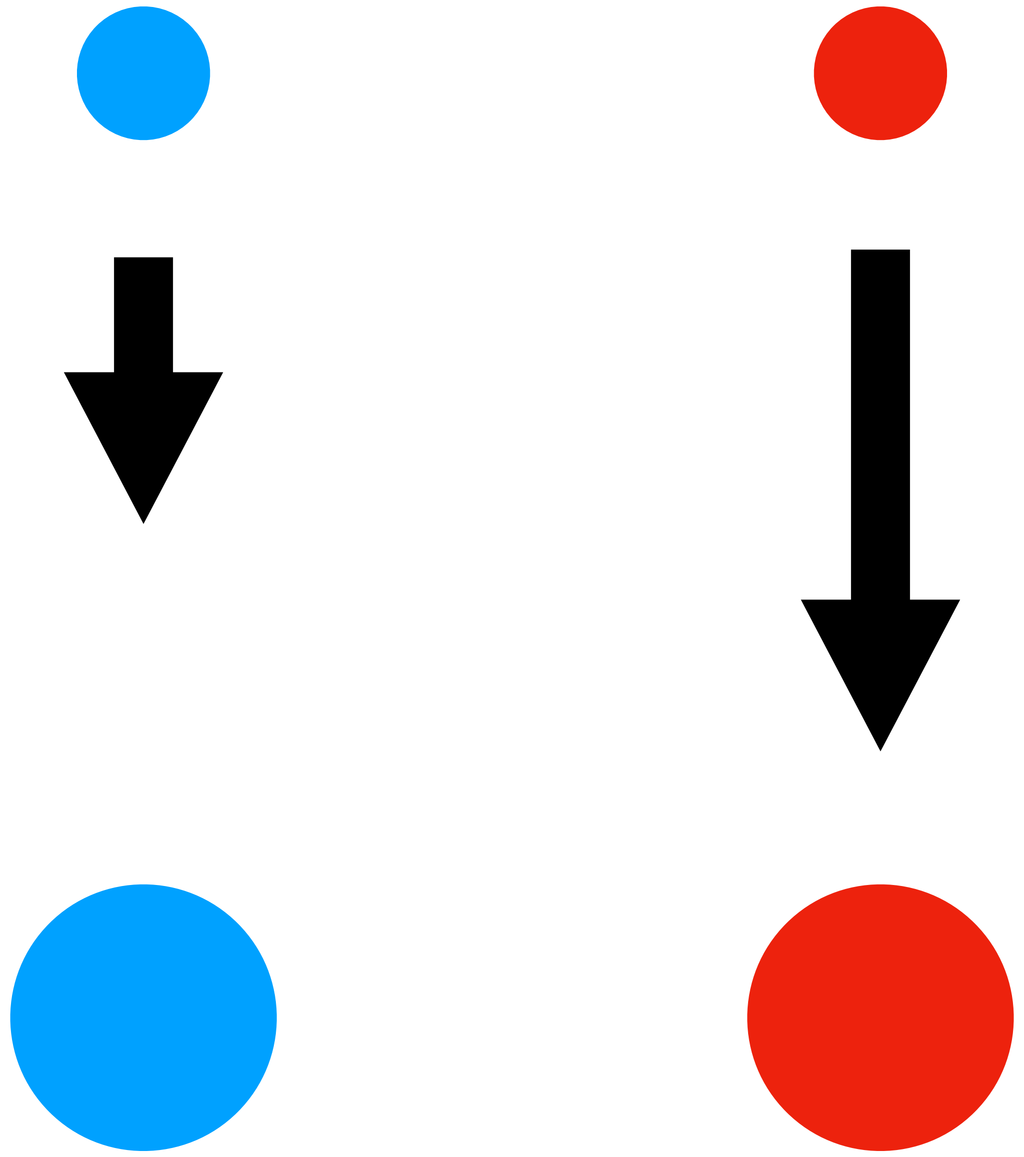


Salumbides Ubachs Korobov 1308.1711

What do we know about DM forces?

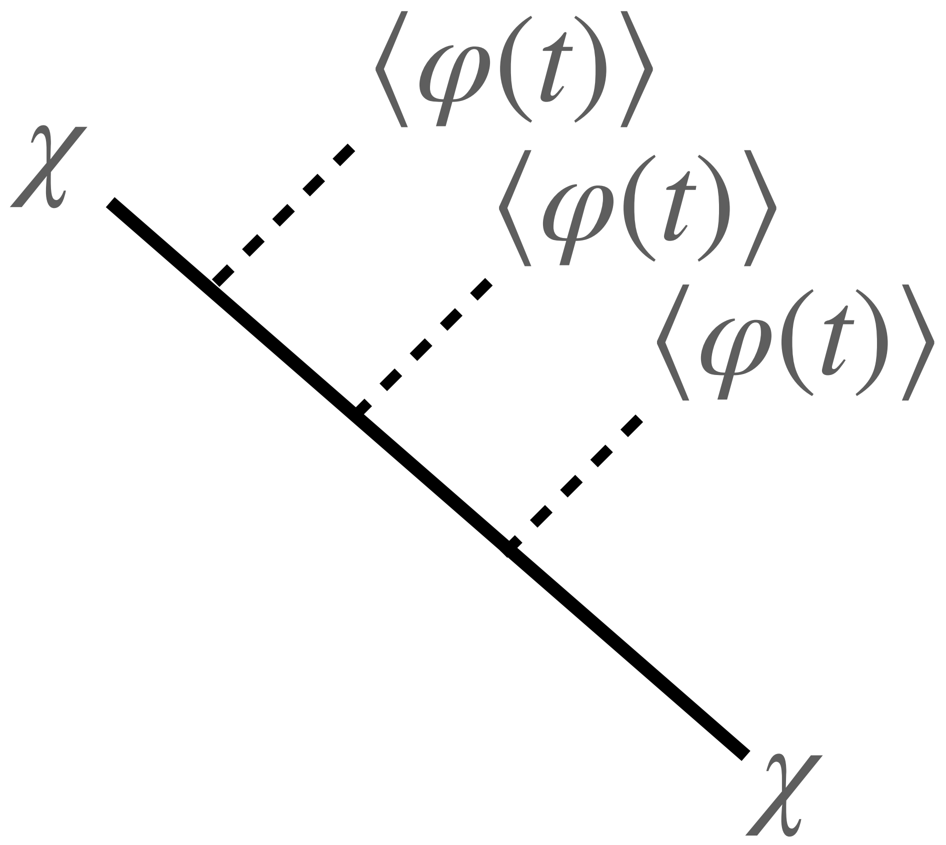
$$\delta_r \equiv \delta_\chi - \delta_b$$

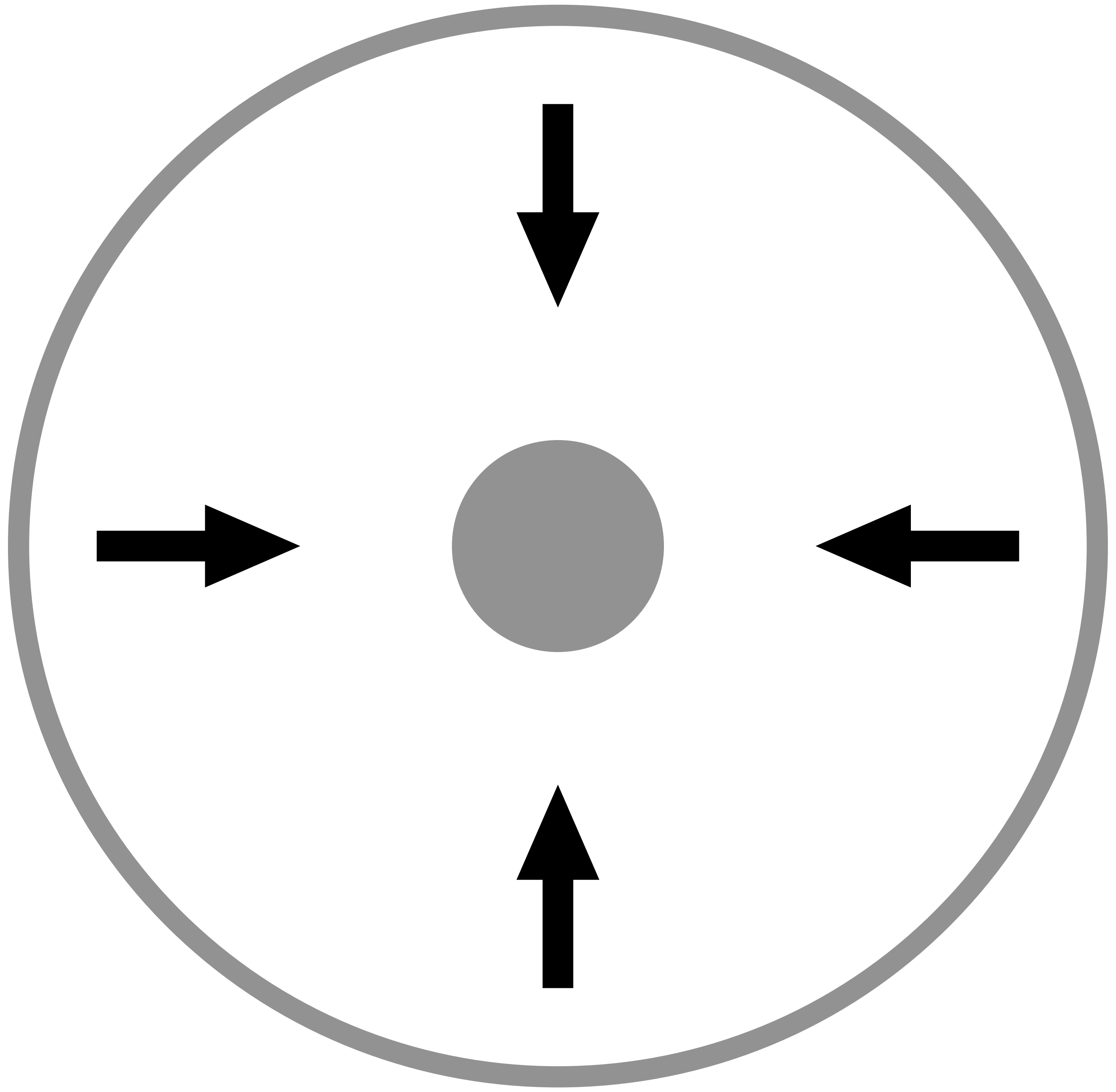
$$\delta_m = f_\chi \delta_\chi + f_b \delta_b$$



EP violation: sensitive to $\alpha_{5,\chi} \neq \alpha_{5,b}$

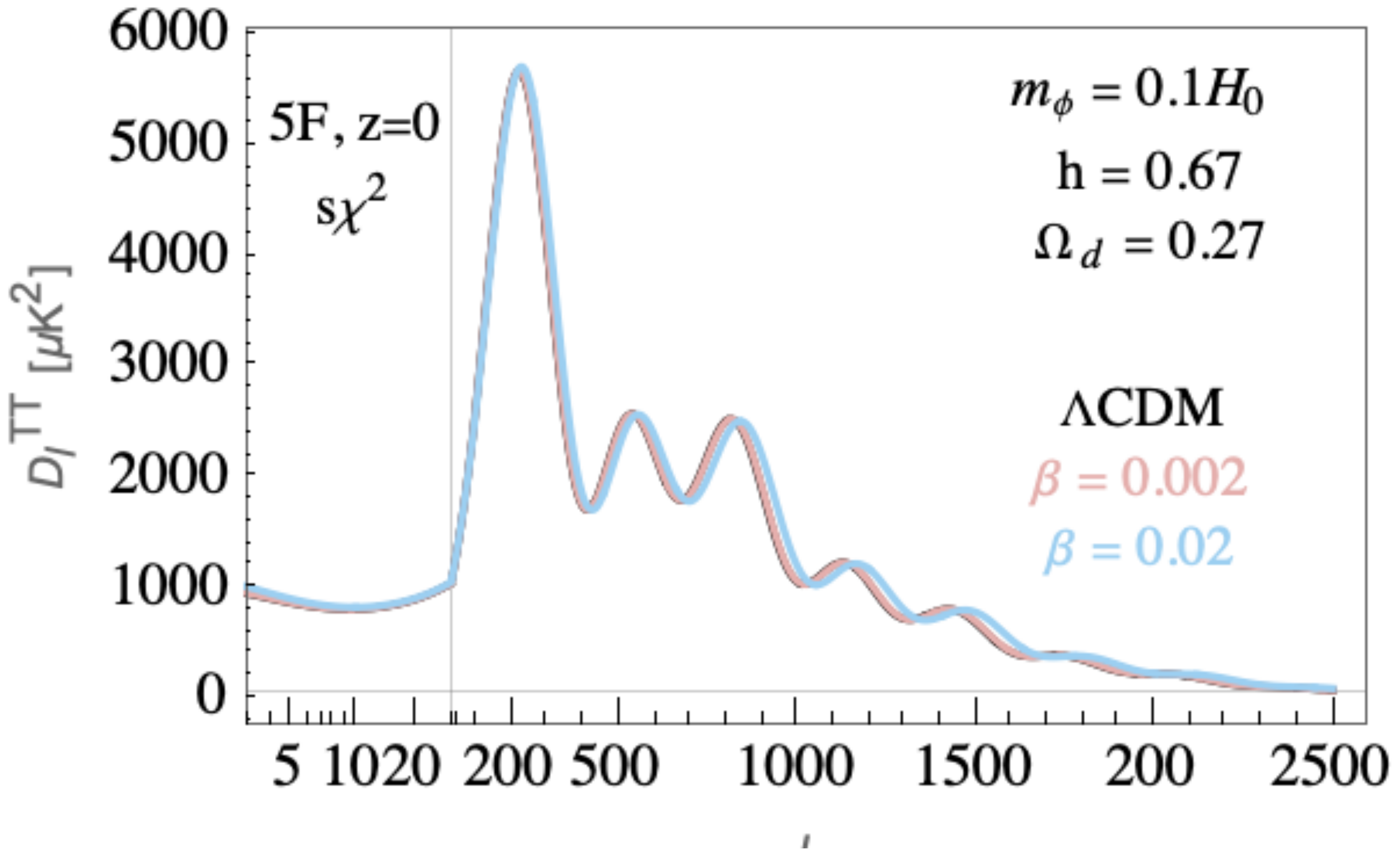
We will actually see there is another unforeseen effect: mediator background time dependence!



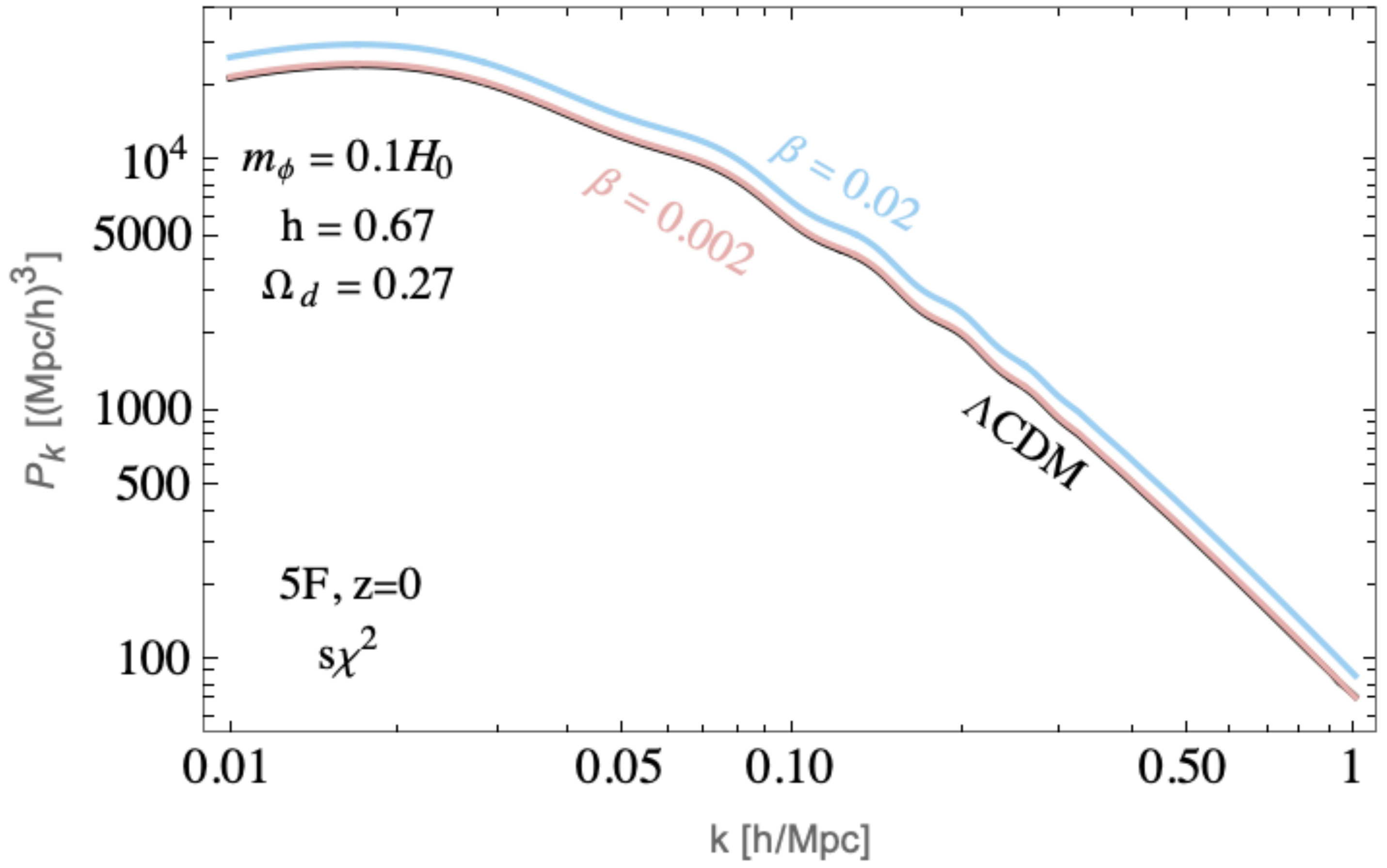


Growth: sensitive to 1/r modifications

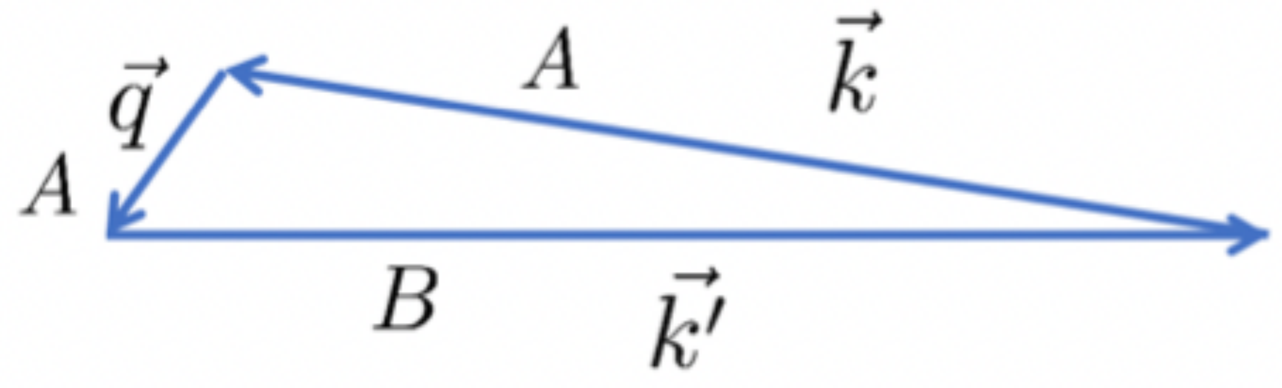
What can cosmology measure?



- Background time dependence: CMB, BAO



- Total clustering δ_m : Full shape Power spectrum



- EP violation δ_r : Higher point functions

Why now?

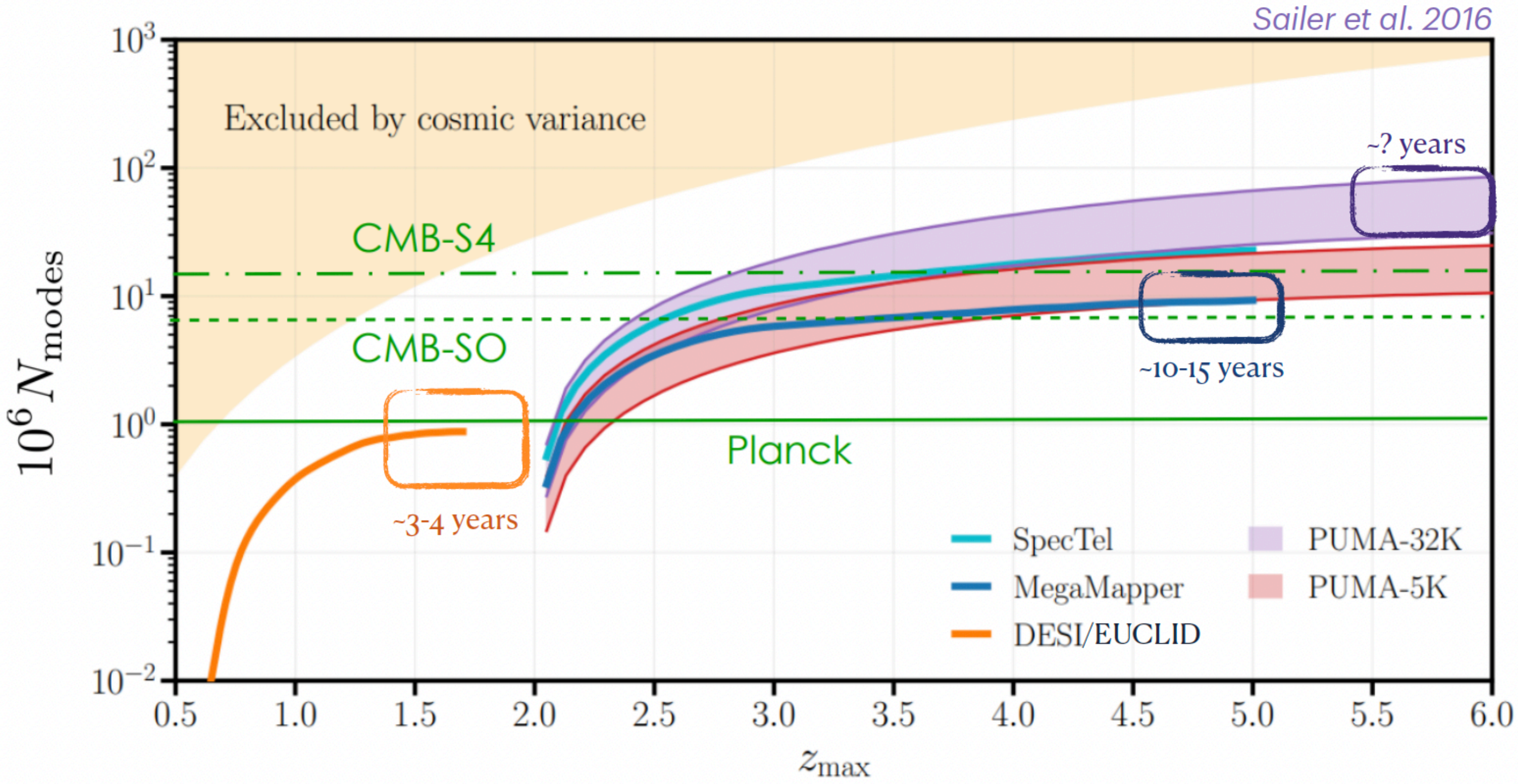
Galaxy clustering data will soon be available, need to properly model for BSM!

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

CMB anisotropies are 2D info!
Limited by small scale noise

$$(S/N)_{\rm LSS} \sim N_{\rm modes,LSS} \sim k^3_{\rm max}{\rm Vol}$$

Galaxy clustering provide 3D info!
Limited by theoretical modeling!



Particle motion

$$S_\chi = -\int m_\chi(s)\, d\tau = -\int \mathrm{d}\,\lambda_\chi(s)\sqrt{-g_{\mu\nu}\frac{\mathrm{d}x^\mu}{\mathrm{d}\lambda}\frac{\mathrm{d}x^\nu}{\mathrm{d}\lambda}}$$

NR "geodesic"

$$\ddot{x}^i = -\nabla^i\Psi - \frac{\partial \log m_\chi(s)}{\partial s}\nabla^i s$$

$$\equiv \tilde{m} = \frac{1}{1+2\bar{s}} \simeq 1$$

Change in EOS: different redshift!

$$\rho_\chi = m_\chi(s) n_\chi$$

Full relativistic geodesic

$$\frac{\mathrm{d}P^\mu}{\mathrm{d}\lambda} + \Gamma^\mu_{\nu\rho} P^\nu P^\rho + \frac{1}{2}\frac{\partial m_\chi^2(s)}{\partial s} g_{\mu\nu} \frac{\partial s}{\partial x^\nu} = 0$$

Perturbations: Boltzmann equations

$$\delta_{\chi,b} = \rho_{\chi,b}/\bar{\rho}_{\chi,b} - 1 \qquad \theta_{\chi,b} = \nabla^i v^i_{\chi,b}$$

$$\delta_m = f_\chi \delta_\chi + (1 - f_\chi)\delta_b \qquad \delta_r = \delta_\chi - \delta_b$$

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

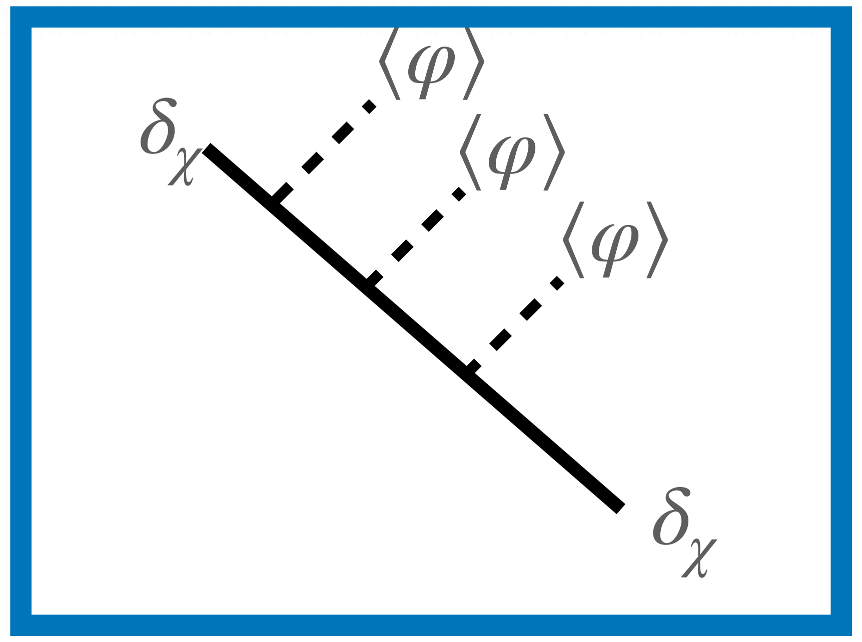
$$\theta'_m + \left(\mathcal{H} + f_\chi \frac{\partial \log m_\chi(s)}{\partial s}\bar{s}'\right)\theta_m = k^2 \frac{\partial \log m_\chi(s)}{\partial s} f_\chi \delta s + k^2\Psi - \nabla_i(v^j_m \nabla_j v^i_m)$$

$$\delta'_r + \theta_r = -\nabla_i(\delta_m v^i_r + \delta_r v^i_m)$$

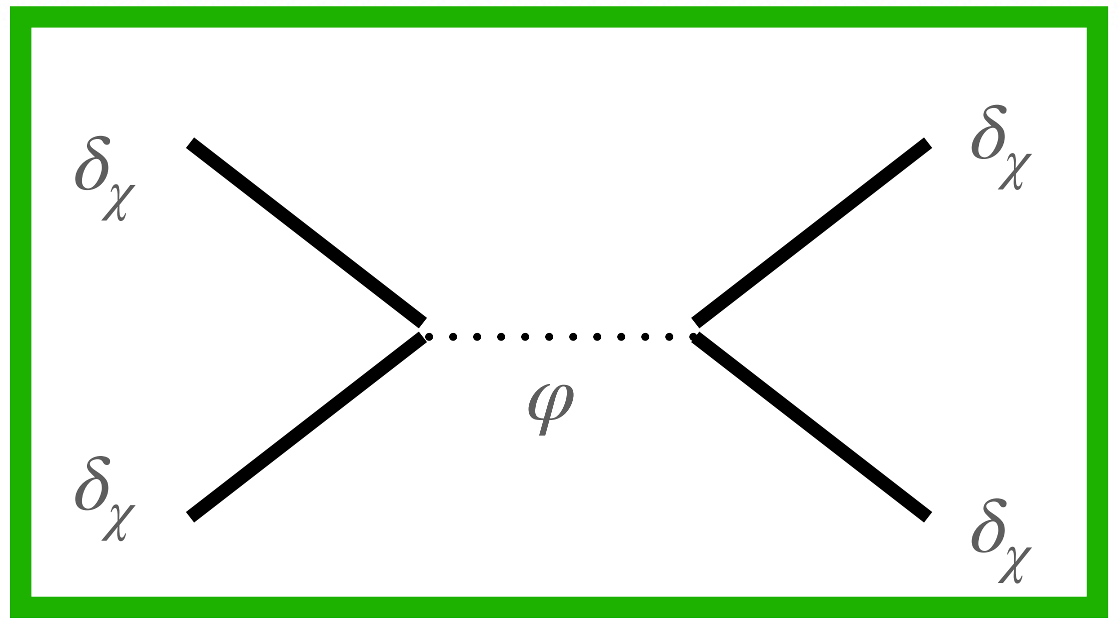
$$\theta'_r + \mathcal{H}\theta_r = -\frac{\partial \log m_\chi(s)}{\partial s}\bar{s}'\theta_m + k^2 \frac{\partial \log m_\chi(s)}{\partial s}\delta s - \nabla_i(v^j_m \nabla_j v^i_r) - \nabla_i(v^j_r \nabla_j v^i_m)$$

+ EFT counterterms

Background corrections



Fifth force corrections (Modified Poisson)



Linear solution

$k \gg H$

Fifth force $\equiv D_{1m}$ Background correction

$$\delta_m^{(1)}(\vec{k}) = D_{1m}^{\Lambda\mathrm{CDM}}\left(1 + \frac{3}{5}\beta f_\chi^2 \frac{\partial \log m_\chi(s)}{\partial s}\log\frac{a}{a_{\mathrm{eq}}} + \frac{3}{5}\beta f_\chi^2 \frac{\partial \log m_\chi(s)}{\partial s}\log\frac{a}{a_{\mathrm{eq}}}\right)\delta_0(\vec{k})$$

$$\delta_r^{(1)}(\vec{k}) = D_{1m}^{\Lambda\mathrm{CDM}}\left(1 + \frac{2}{3}\right)\beta f_\chi \frac{\partial \log m_\chi(s)}{\partial s}\delta_0(\vec{k})$$

$\sim \mathcal{O}(10)$

Total matter growth is log-enhanced compared to naive expectation
EP violation effect non enhanced!

Toward the non-linear galaxy Power Spectrum

To properly model full shape modes $k \simeq 0.2h\mathrm{Mpc}^{-1}$ we need to properly compute mild non-linearities and relate matter to galaxy

1. Bias expansion to compute galaxy field δ_g
2. Perturbative loop expansion of Boltzmann equation
3. EFT counterterms to account for deviation from ideal fluid
4. Redshift space distortions

Carrasco at al 2012, Baumann et al 2012

This has been done assuming CDM cosmology
What about new forces?

D'Amico. Lewandowski, Senatore, Zhang et al
Ivanov, Philcox, Simonovic, Zaldarriaga et al

LSS Observables

Galaxy Power Spectrum

P_m **not directly observable…**

$$P_g(\overrightarrow{k}, z) \sim \langle \delta_g(\overrightarrow{k}, z)\, \delta_g(-\overrightarrow{k}, z) \rangle$$

Galaxy over density : "Composite" Field

Fundamental fields:

$$\delta_m \equiv f_\chi \delta_\chi + (1 - f_\chi)\delta_b = \left(1 + \frac{6}{5}\beta f_\chi^2 \log(z_{\text{eq}}/z)\right) D_{1m}^{\text{CDM}}(z)\delta_0(k)$$

$$\delta_r \equiv \delta_\chi - \delta_b = \beta f_\chi D_{1m}^{\text{CDM}}(z)\delta_0(k)$$

Negligible feature if
$f_\chi > \log z_{\text{eq}}/z \simeq 1/8$

LSS Observables

Galaxy Power Spectrum

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$f_\chi > \log z_{\rm eq}/z \simeq 1/8$

Bias expansion: based on symmetries of theory

$$\delta_g = b_1\delta_m + b_r\delta_r + b_\theta\theta_r + \frac{b_2}{2}\delta_m^2 + b_s(K_{ij}\delta_m)^2 \;\ldots$$

LSS Observables

Galaxy Power Spectrum

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

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Example: tree level P_g real space

$$P_g \simeq b_1^2 P_{mm} \simeq b_1^2 \left(1 + \frac{12}{5}\beta f_\chi^2 \log(z_{\rm eq}/z)\right) P_m^{\rm CDM}(k)$$

Second order kernels

$$\delta_g^{(2)}(\mathbf{k},a) = (D_{1m})^2 \int_{\mathbf{k}} \mathrm{d}k_{12} \Big(F_{2,g}(\mathbf{k}_1,\mathbf{k}_2) + \varepsilon F_{2r,g}(\mathbf{k}_1,\mathbf{k}_2) \Big) \,,$$

where

$$\varepsilon \equiv \beta f_\chi \tilde{m}$$

$$F_{2,g}(\mathbf{k}_1,\mathbf{k}_2) = b_1 F_2(\mathbf{k}_1,\mathbf{k}_2) + \frac{b_2}{2} + b_{K^2}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - \frac{1}{3}\right) ,$$

$$F_{2r,g}(\mathbf{k}_1,\mathbf{k}_2) = b_r F_{2r}(\mathbf{k}_1,\mathbf{k}_2) \; - \; b_1\frac{6f_\chi}{35}\left(1 - \frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2}\right) + \frac{5}{3}b_{mr} + \frac{5}{3}b_{Kr}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - \frac{1}{3}\right)$$
$$- \mathcal{H}\left[b_\theta G_{2r}(\mathbf{k}_1,\mathbf{k}_2) + \frac{5}{3}b_{\nabla\delta}\frac{\mathbf{k}_1\cdot\mathbf{k}_2}{2}\left(\frac{1}{k_1^2} + \frac{1}{k_2^2}\right) + \frac{5}{3}b_{\delta\theta} + \frac{5}{3}b_K\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - \frac{1}{3}\right)\right]$$

Computing Non-linearities with 5F

At non-linear level 5th forces symmetries = CDM symmetries at $\mathcal{O}(\beta \log)$ (if $f_\chi \gtrsim 1/8$)

- Can use existing pipeline as **PyBird** for **BOSS** P_g w. RSD and **FishLSS** for Fisher Forecast

D'Amico Senatore Zhang 20

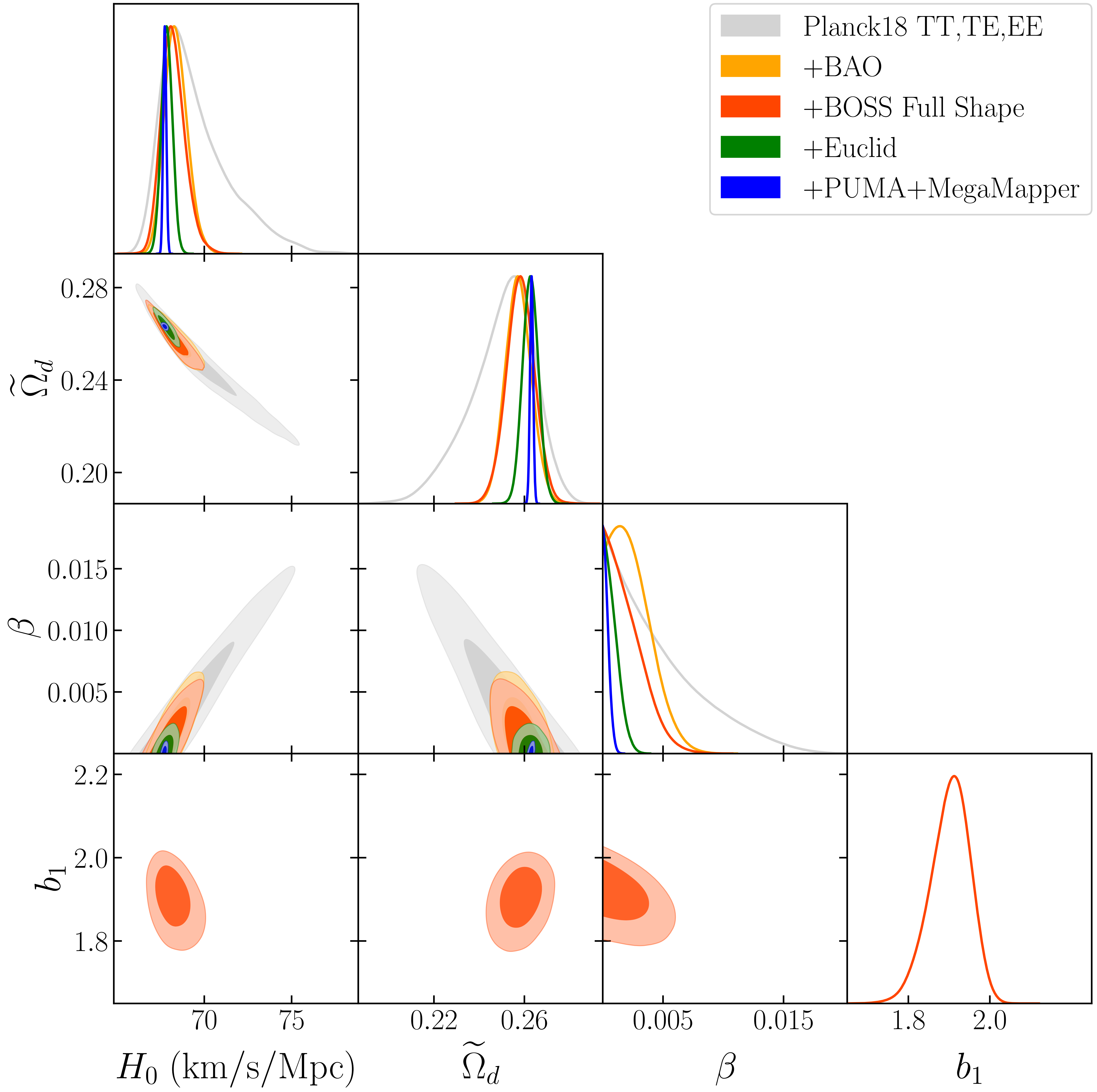
Sailer Castorina Ferraro White 21

- Use CLASS with 5fth Force (2204.08484) for P_m
- (Also RSD kernel is the same at $\mathcal{O}(\beta \log)$!)
- 6 CDM pars $(\Omega_b, \tilde{\Omega}_\chi, H_0, \tau, n_s, A_s)$ + β +(CT, biases, SN)x z bin

Results

FS@1-loop+EFT, RSD

- CMB only: $\beta \lesssim 0.015$ @ 95%
- + BAO (w.reco): $\beta \lesssim 5 \times 10^{-3}$
- + BOSS FS no improvement: strong degeneracies between β, b
- Future surveys FS will improve bound!
  - +Euclid: $\beta \lesssim 2 \times 10^{-3}$
  - + PUMA+MM: $\beta \lesssim \times 10^{-3}$



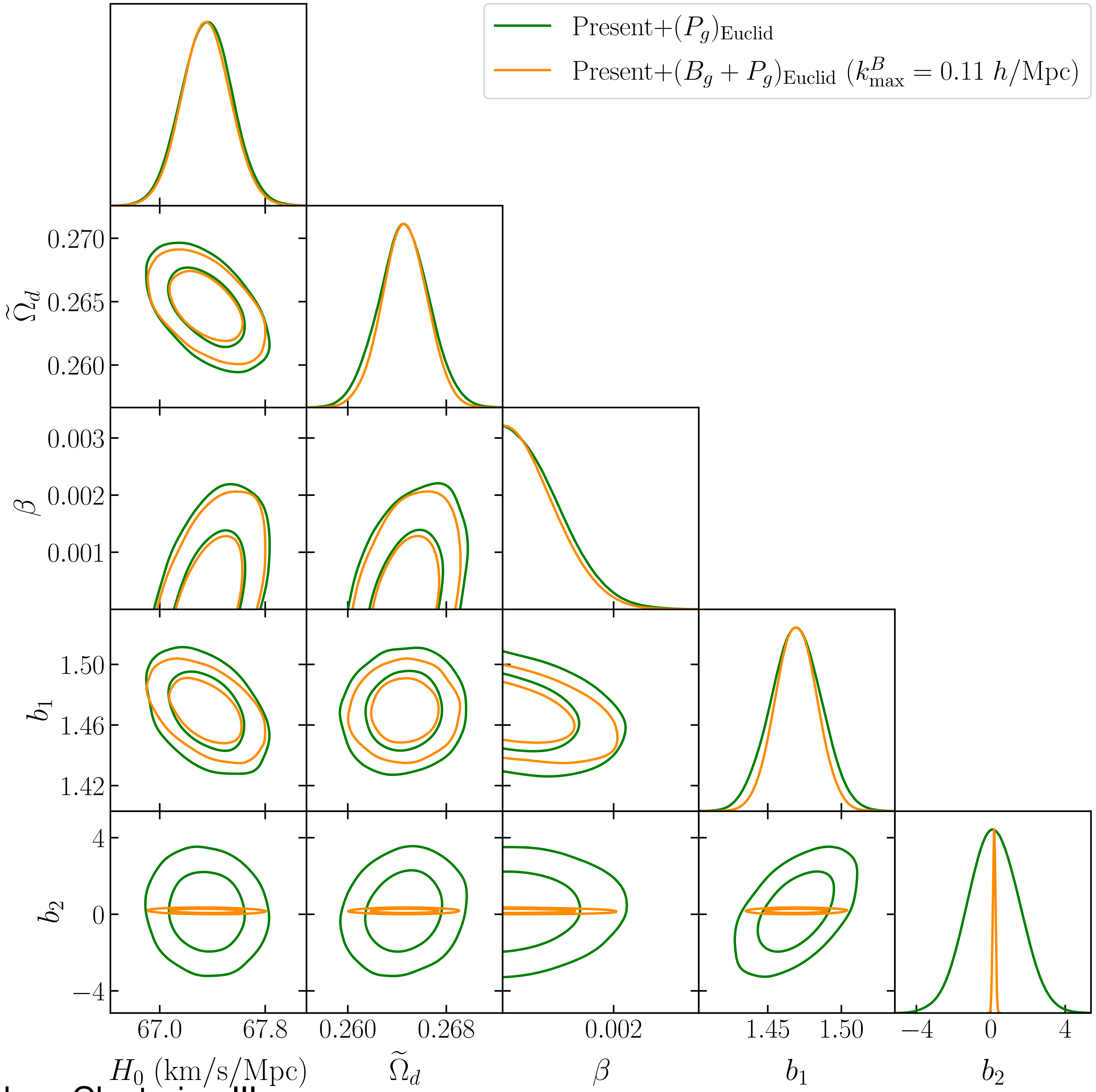
Bispectrum

Real Space, Tree level

$$B_g(k_1, k_2, k_3) \sim \langle \delta_g(k_1)\ \delta_g(k_2)\delta_g(k_3) \rangle$$

$$\sim \left(1 + \frac{24}{5}\beta \tilde{m}^2 f_\chi^2 \log \frac{a}{a_{\rm eq}}\right) B_g^{\rm CDM}$$

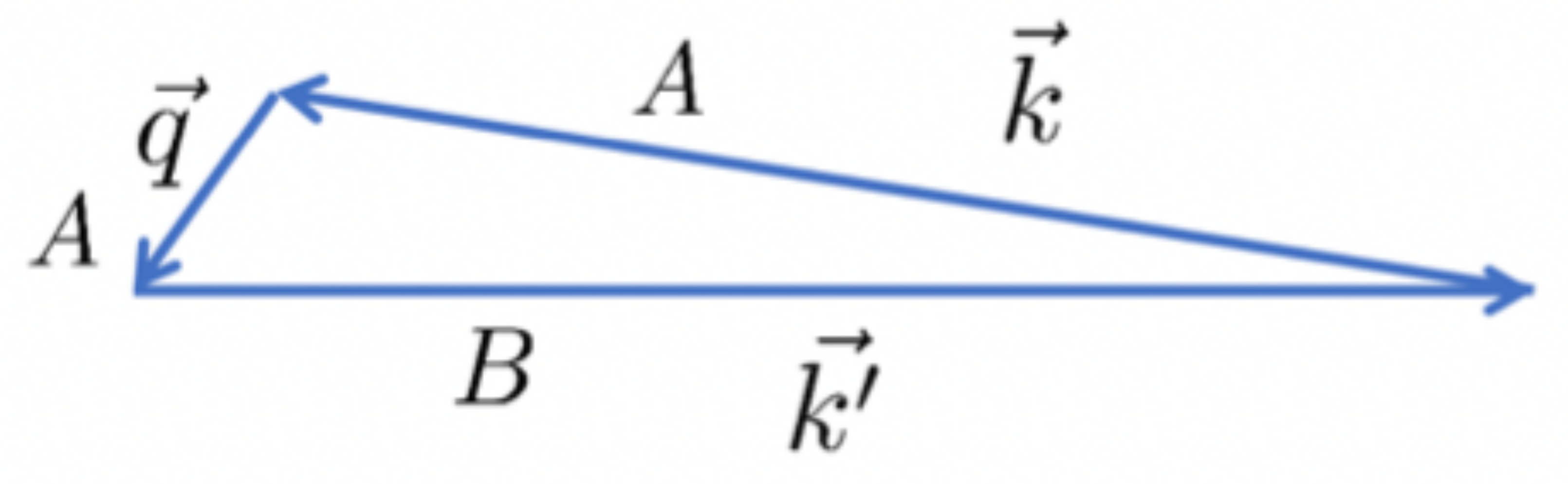
- Potentially more modes than P_g !
- For linear modes, improve only NL bias



Multi-tracer Bispectrum

Real Space, Tree level

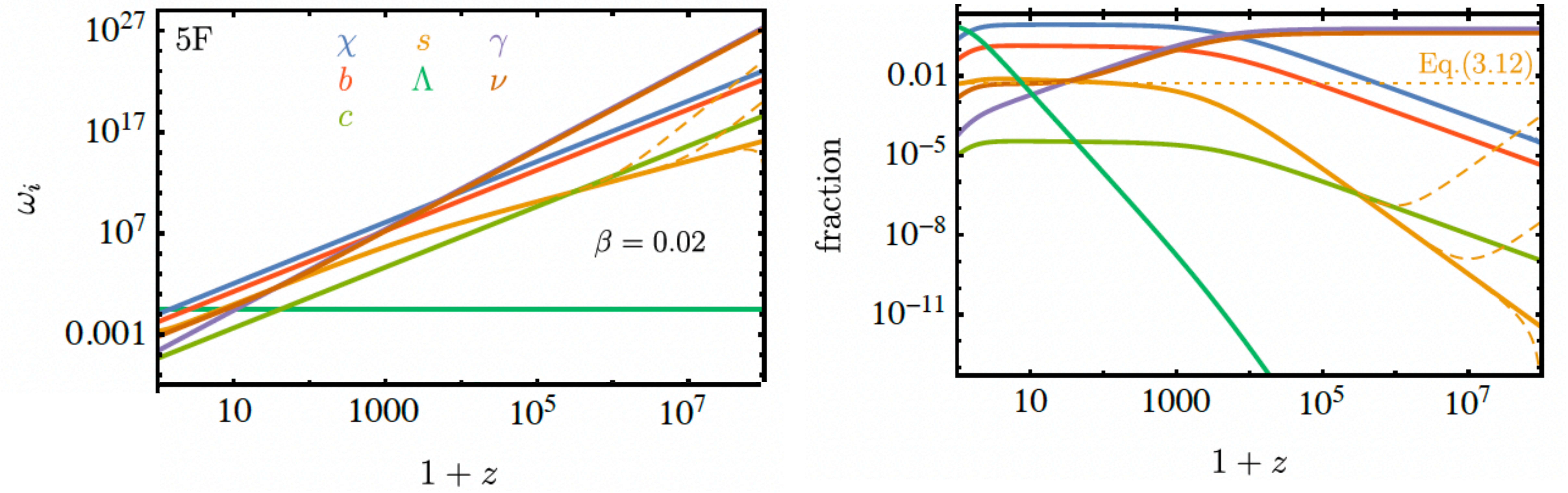
$$B_g^{AAB}(\vec{q}, \vec{k}, \vec{k}') \sim \langle \delta_g^A(\vec{q})\, \delta_g^A(\vec{k})\delta_g^B(\vec{k}')\rangle$$



- Violation of EP: squeezed limit pole (different infall rate in long mode bkg)
- Not log-enhanced (as expected)
- Still subleading for $f_\chi \sim 1$ not enough modes, pole cutoff by $k_{\rm min} \sim 1/V^{1/3}$

$$\frac{\Delta B_g^{AAB}(\vec{q}, \vec{k}, \vec{k}')}{P_m^{\rm CDM}(k)P_m^{\rm CDM}(q)} \sim \beta f_\chi \frac{\vec{q}\cdot\vec{k}}{q^2} b_1^A(b_1^A b_r^B - b_1^B b_r^A)$$

Energy density evolution

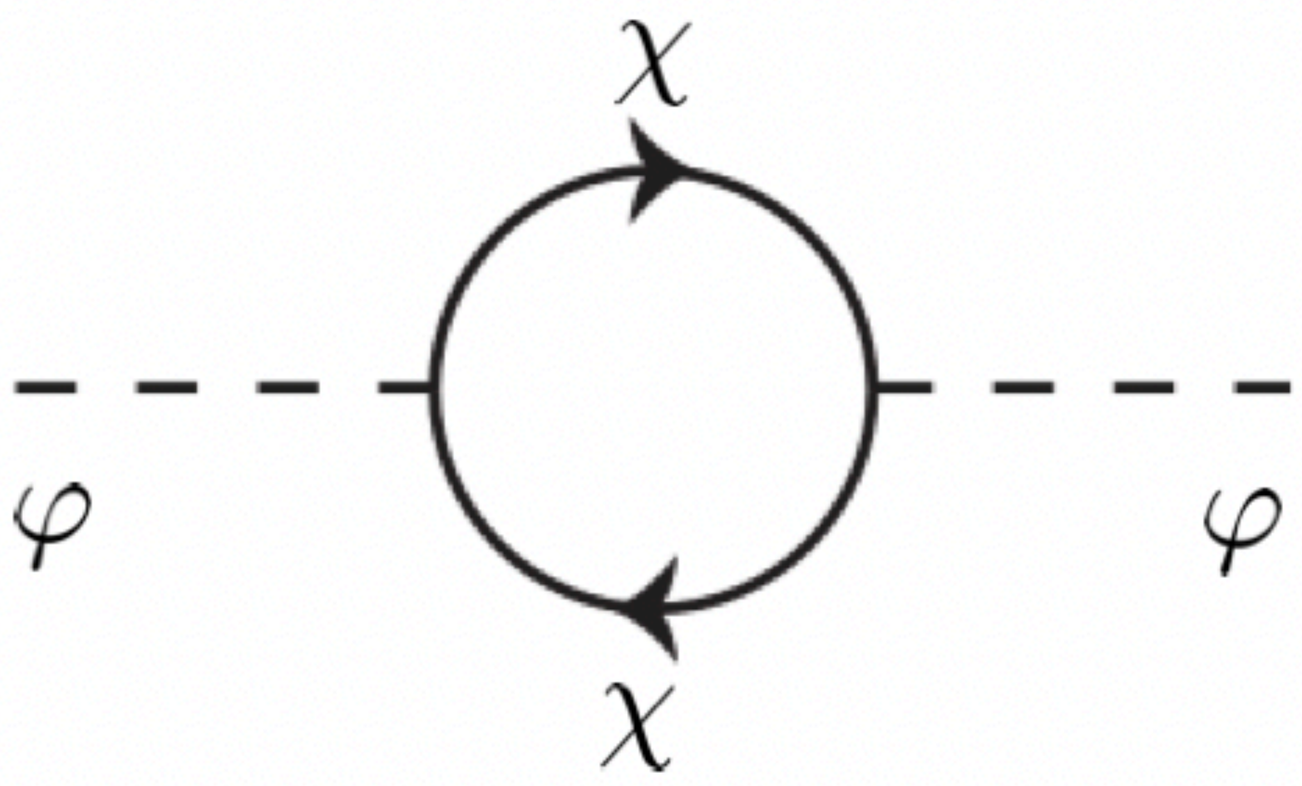


Different models

Model	$\frac{\partial \log m(s)}{\partial s}$	Small $s_{\rm ini}$	Large $s_{\rm ini}$
$s\chi^2$ (super-renormalizable)	$\frac{1}{1+2s}$	1	$1/s_{\rm ini}$
$\frac{1}{2}s^2\chi^2$ (marginal)	$\frac{s}{1+s^2}$	s	$1/s_{\rm ini}$
$\frac{1}{n!}s^n\chi^2$ (non-renormalizable)	$\frac{ns^{n-1}}{2(1+s^n)}$	s^{n-1}	$1/s_{\rm ini}$

Naturalness of light mediator

$$m_\varphi \lesssim H_0 \sim 10^{-33}\,\mathrm{eV}$$



$$\delta m_\varphi^2 \sim \frac{g_D^2}{(4\pi)^2} m_\chi^2 \lesssim m_\varphi^2$$

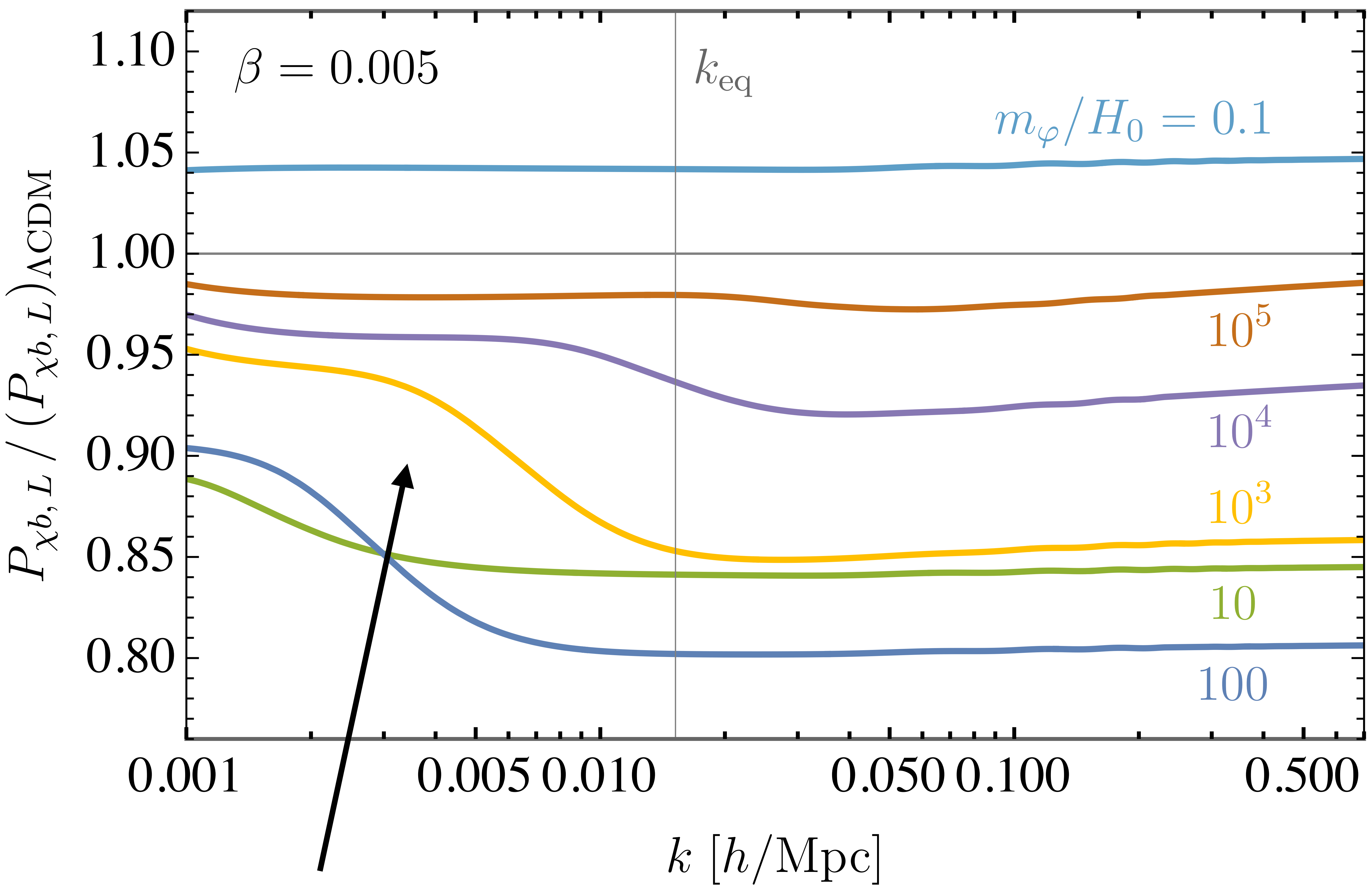
$$m_\chi \lesssim \beta^{-1/4}\,(4\pi\, m_\varphi M_{\mathrm{Pl}})^{1/2} \approx 0.02\,\mathrm{eV}\left(\frac{0.01}{\beta}\right)^{1/4}\left(\frac{m_\varphi}{H_0}\right)^{1/2}$$

Power spectrum details

When $m_\varphi \gg H$ mediator behaves like ULA

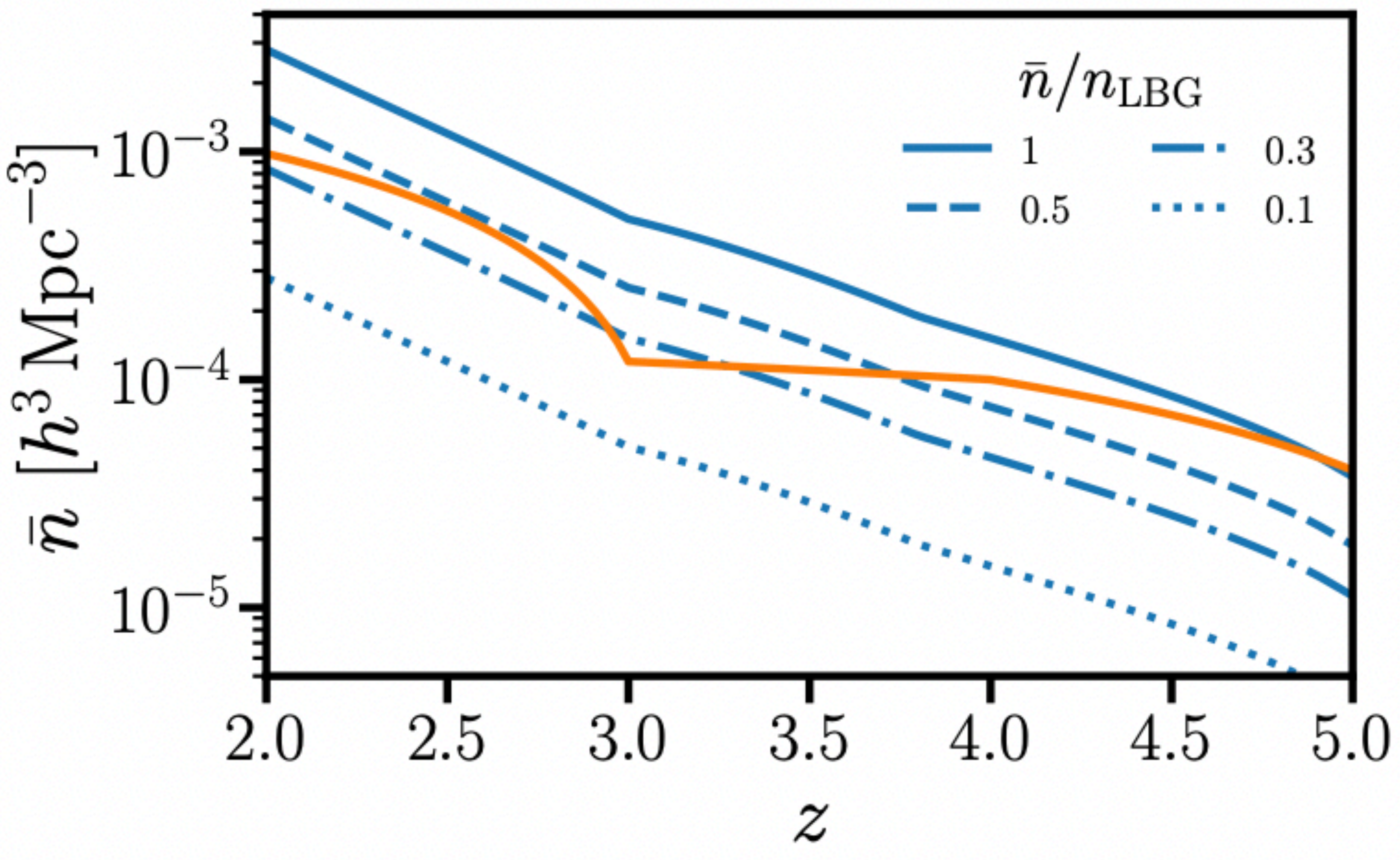
$$k_J \approx 3.9 \times 10^{-4} a^{1/4} \left(\frac{m_\varphi}{H_0}\right)^{1/2} \left(\frac{\Omega_m^0}{0.3}\right)^{1/4} h\,\mathrm{Mpc}^{-1}$$

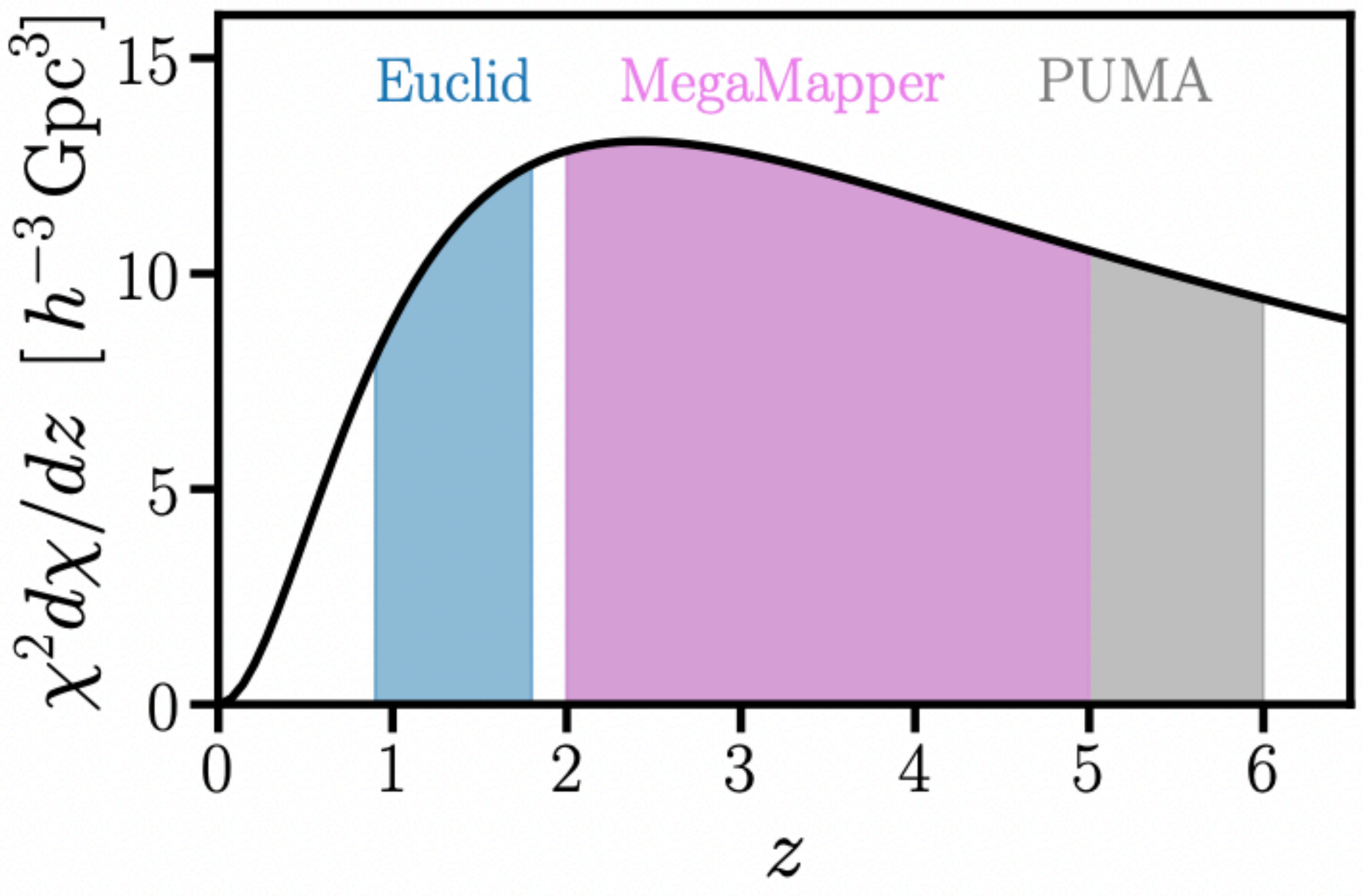
For $m_\varphi \ll H_{\rm eq}$ LSS modes: $k \gg k_J$



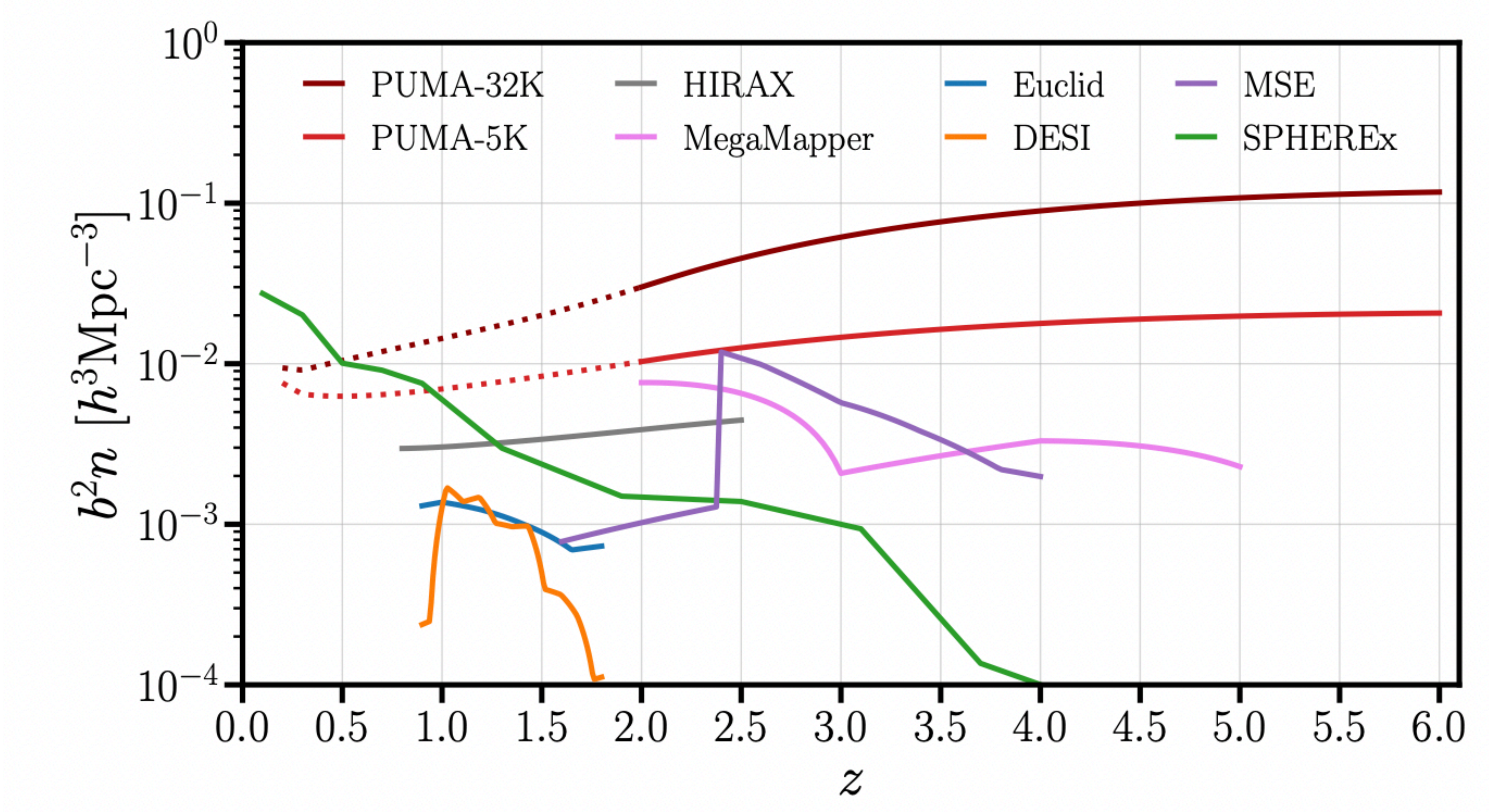
Step-like drop $k \sim k_J$

Surveys


$\bar{n}/n_{\rm LBG}$
1
0.5
0.3
0.1
$\bar{n}$ [h^3 Mpc^{-3}]
10^{-3}
10^{-4}
10^{-5}
2.0
2.5
3.0
3.5
4.0
4.5
5.0
z


Euclid
MegaMapper
PUMA
$\chi^2 d\chi/dz$ [h^{-3} Gpc^3]
15
10
5
0
1
2
3
4
5
6
z

Surveys



PUMA-32K
PUMA-5K
HIRAX
MegaMapper
Euclid
DESI
MSE
SPHEREx
$b^2 n\ [h^3 \mathrm{Mpc}^{-3}]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
z

Computing Non-linearities

Also at non-linear level (loop, EFTofLSS)
Dark force = CDM symmetries at
$\mathcal{O}(\beta f_\chi^2 \log)$ **(if** $f_\chi \gtrsim 1/8$ **)**

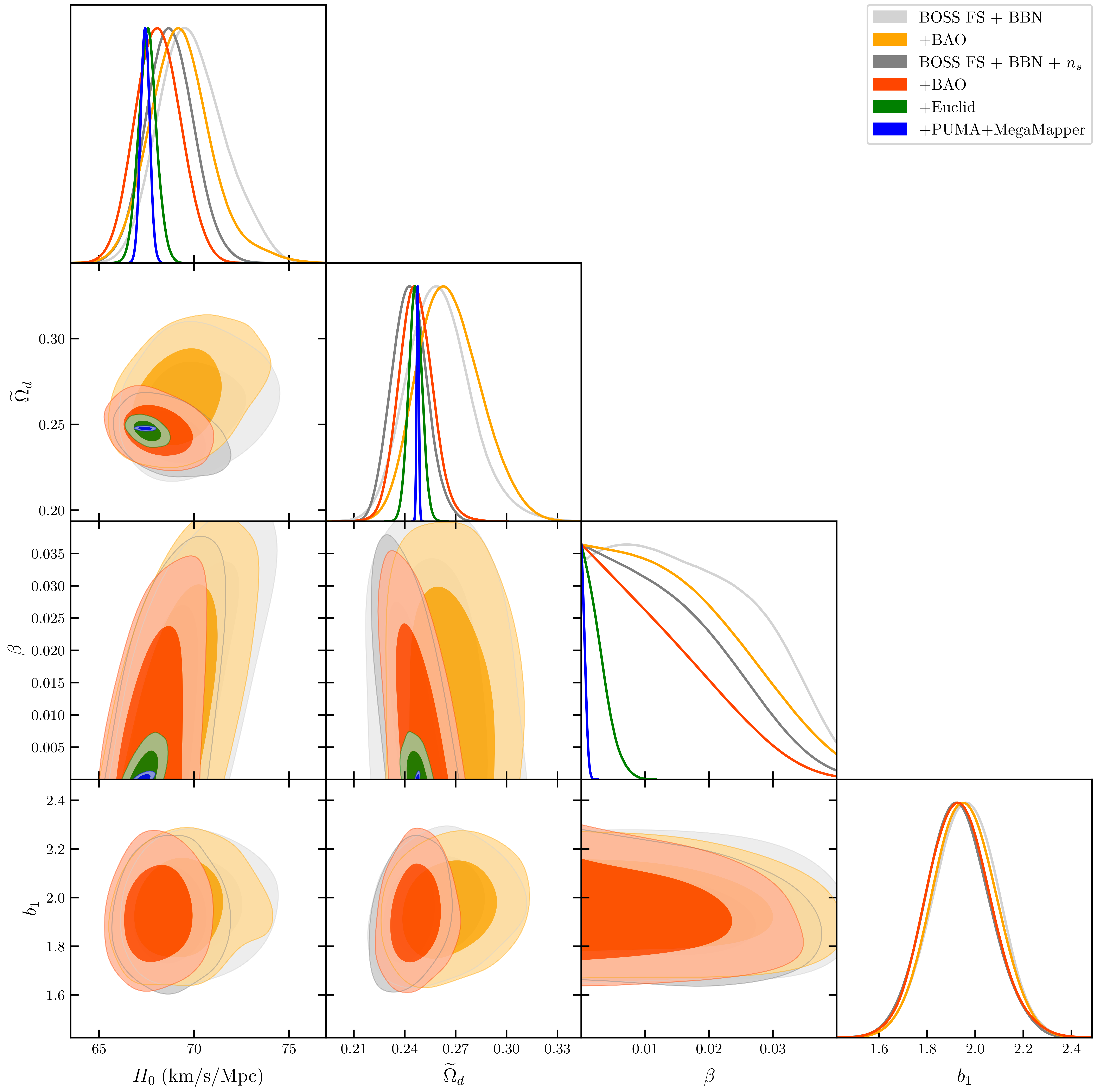
- Can use existing pipeline as **PyBird** for **BOSS** P_g w. RSD and **FishLSS** for Fisher Forecast
- (Also RSD kernel is the same at $\mathcal{O}(\beta \log)$!)

Sailer Castorina Ferraro White 21

D'Amico Senatore Zhang 20

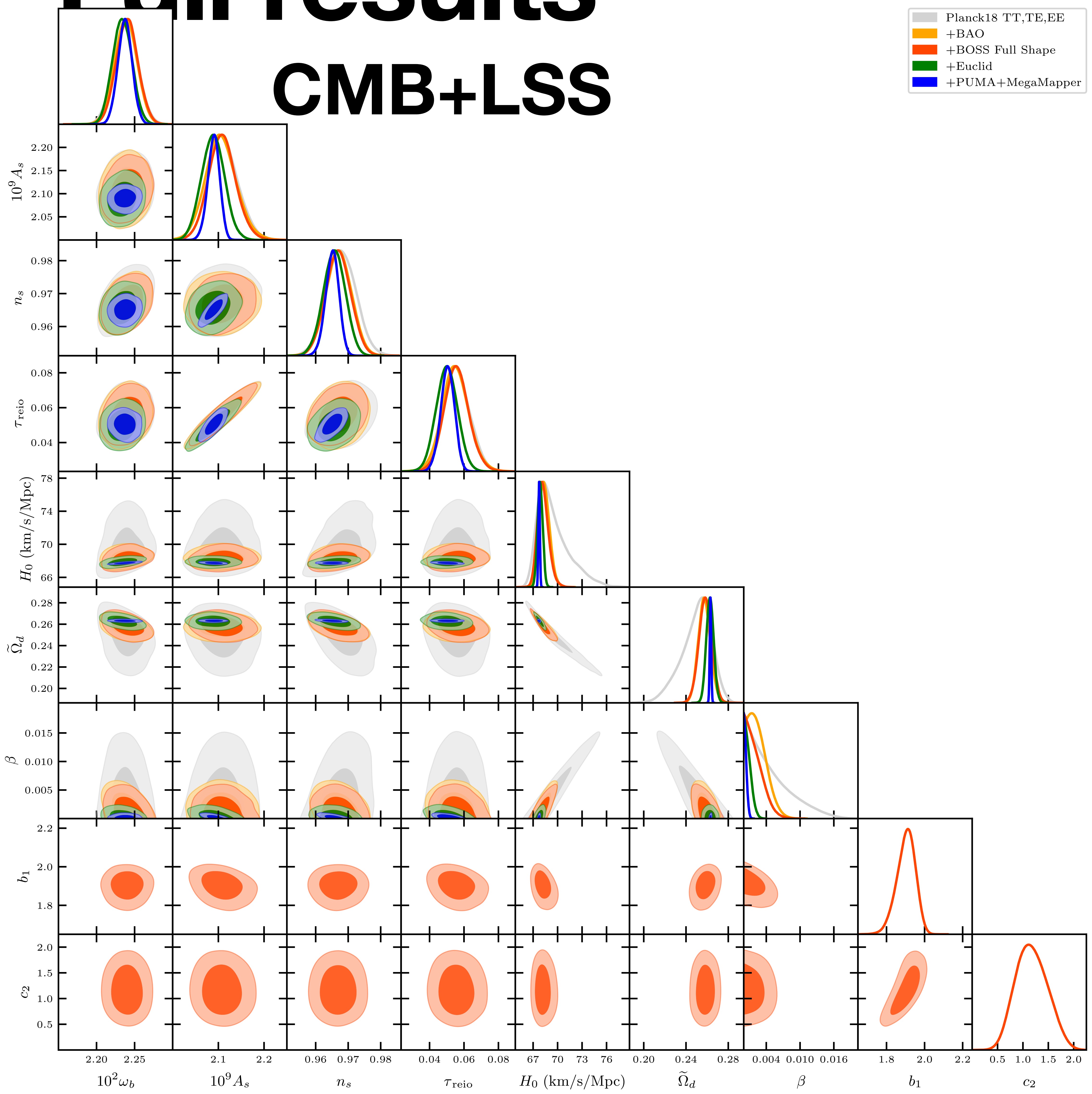
LSS only results

- BOSS FS + BAO with no n_s prior comparable with CMB alone bound

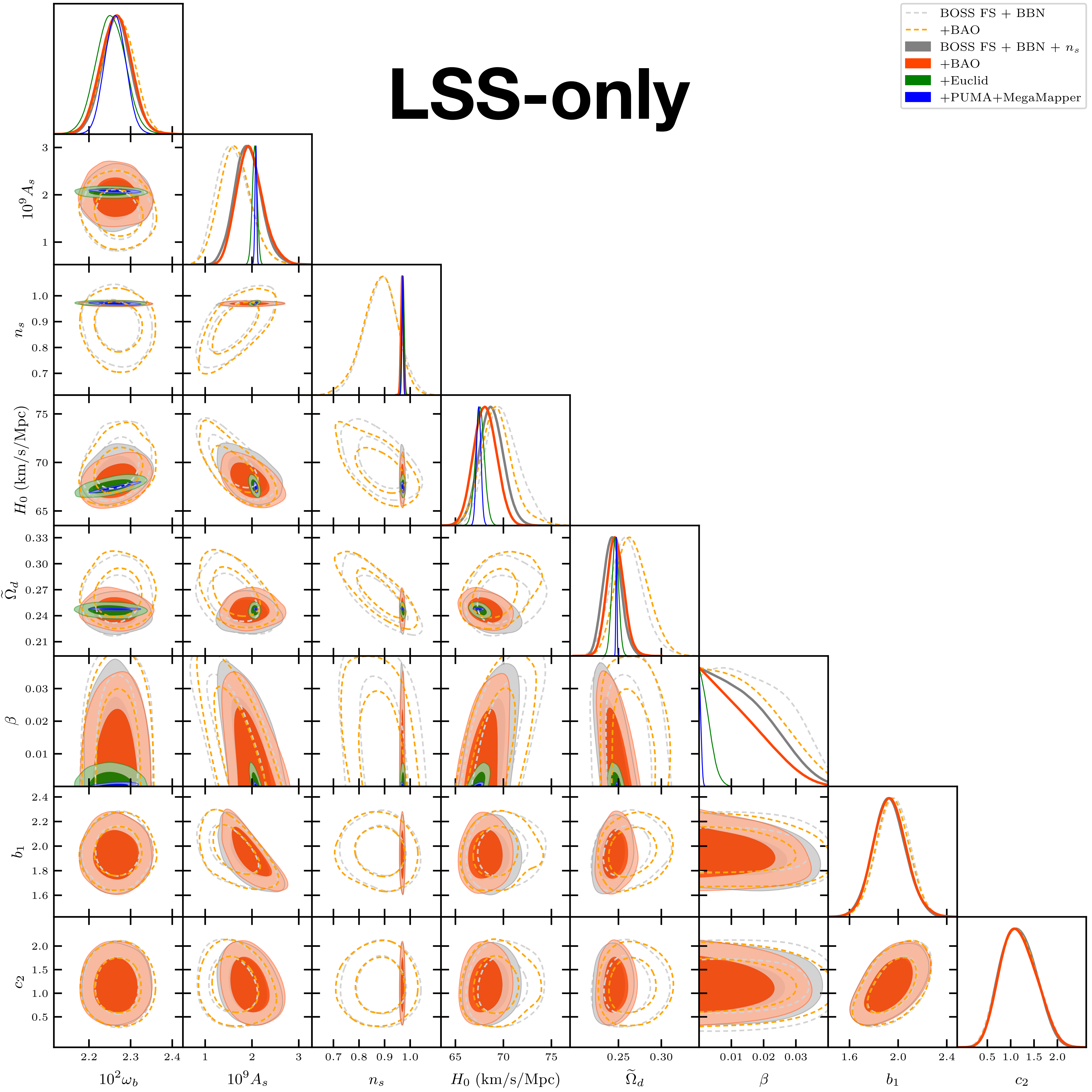


Full results

CMB+LSS

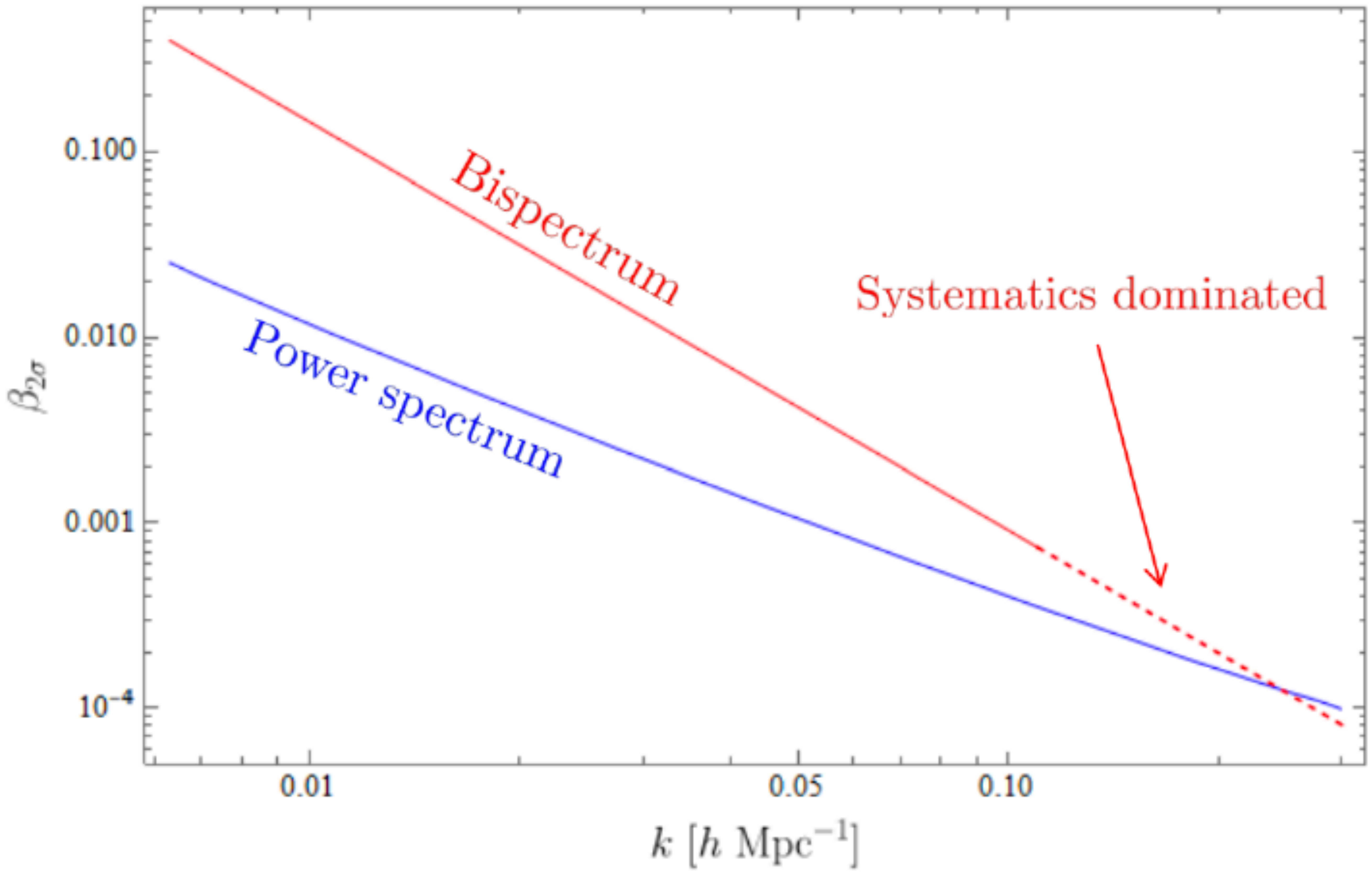


LSS-only

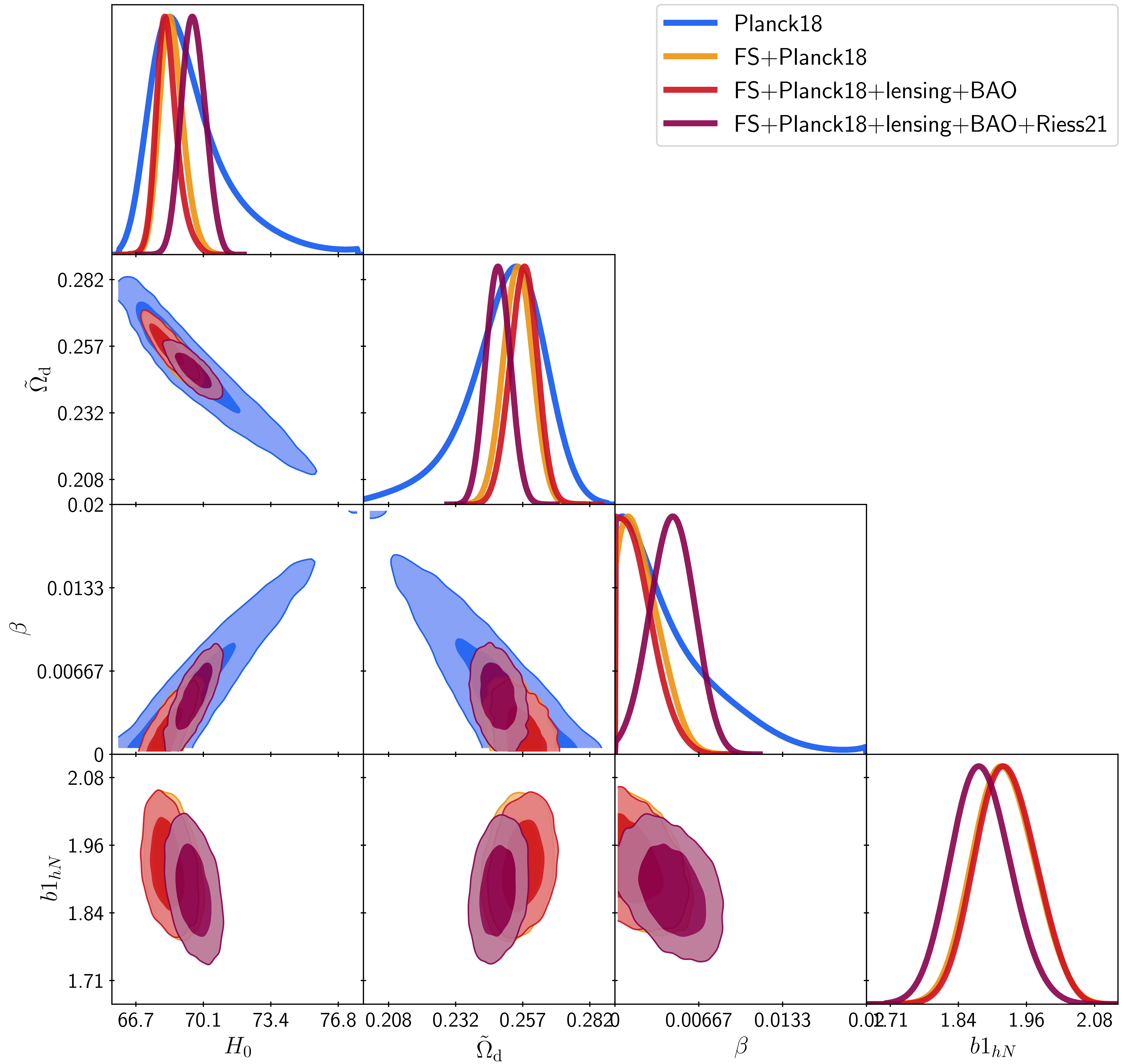


1D analytic estimates

- $\beta_{2\sigma,P} \propto (k_{\rm min}/k_{\rm max})^{1.5}$
- $\beta_{2\sigma,B} \propto (k_{\rm min}/k_{\rm max})^{2.2}$
- $B_g \sim P_g$ when $k_{\rm max} \gtrsim 0.2h/{\rm Mpc}$: need 1-loop computation!



H0 tension


Planck18
FS+Planck18
FS+Planck18+lensing+BAO
FS+Planck18+lensing+BAO+Riess21
0.282
0.257
0.232
0.208
0.02
0.0133
0.00667
0
2.08
1.96
1.84
1.71
66.7
70.1
73.4
76.8
0.208
0.232
0.257
0.282
0.00667
0.0133
1.84
1.96
2.08

DESI bestfit