# Testing long range self-interactions in the dark sector

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w/ Bottaro, Costa, Archidiacono, Redigolo, Salvioni

based on arXiv:2204.08484 (JCAP) and 2309:11496 (PRL) and to appear

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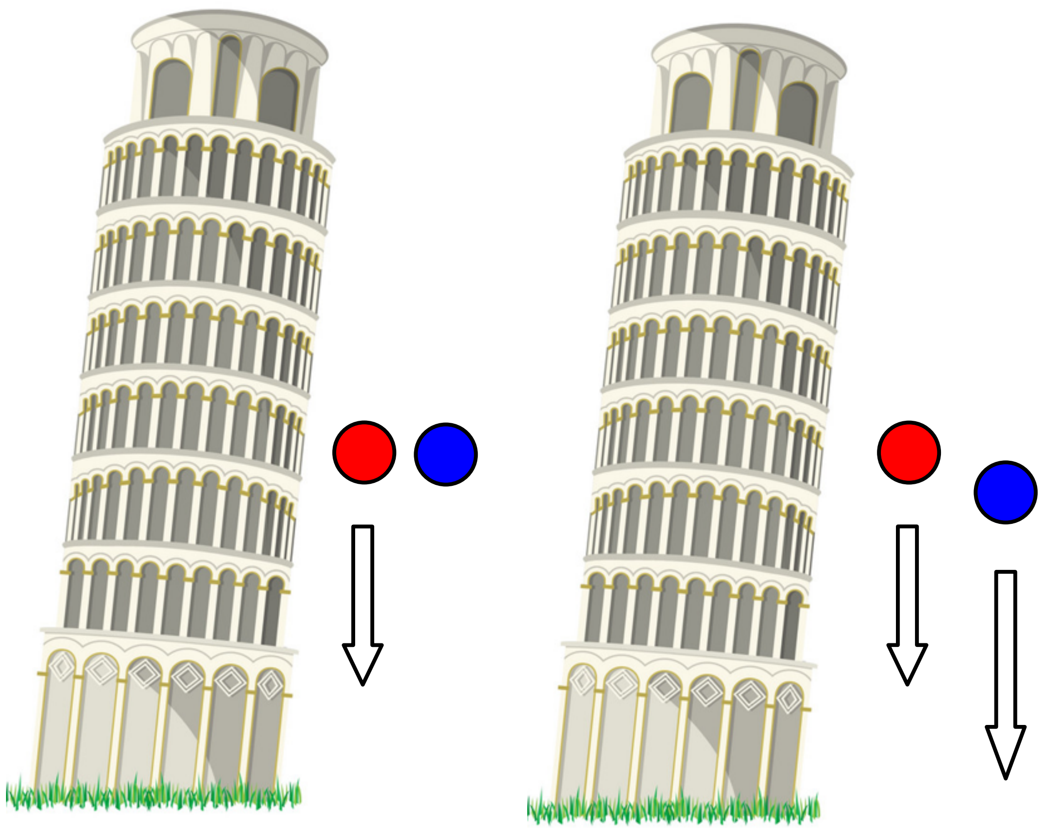
# In Galileo's words



Universality of free fall established at the % level in 1600s

'Accordingly I took two balls, one of lead and one of cork, the former more than a hundred times heavier than the latter, and suspended them by means of two equal fine threads, each four or five cubits long. Pulling each ball aside from the perpendicular, I let them go at the same instant, and they, falling along the circumferences of circles having these equal strings for semi-diameters, passed beyond the perpendicular and returned along the same path. This free vibration [per lor medesime le andate e le tornate] repeated a hundred times showed clearly that the heavy body maintains so nearly the period of the light body that neither in a hundred swings nor even in a thousand will the former anticipate the latter by as much as a single moment [minimo momento], so perfectly do they keep step.'

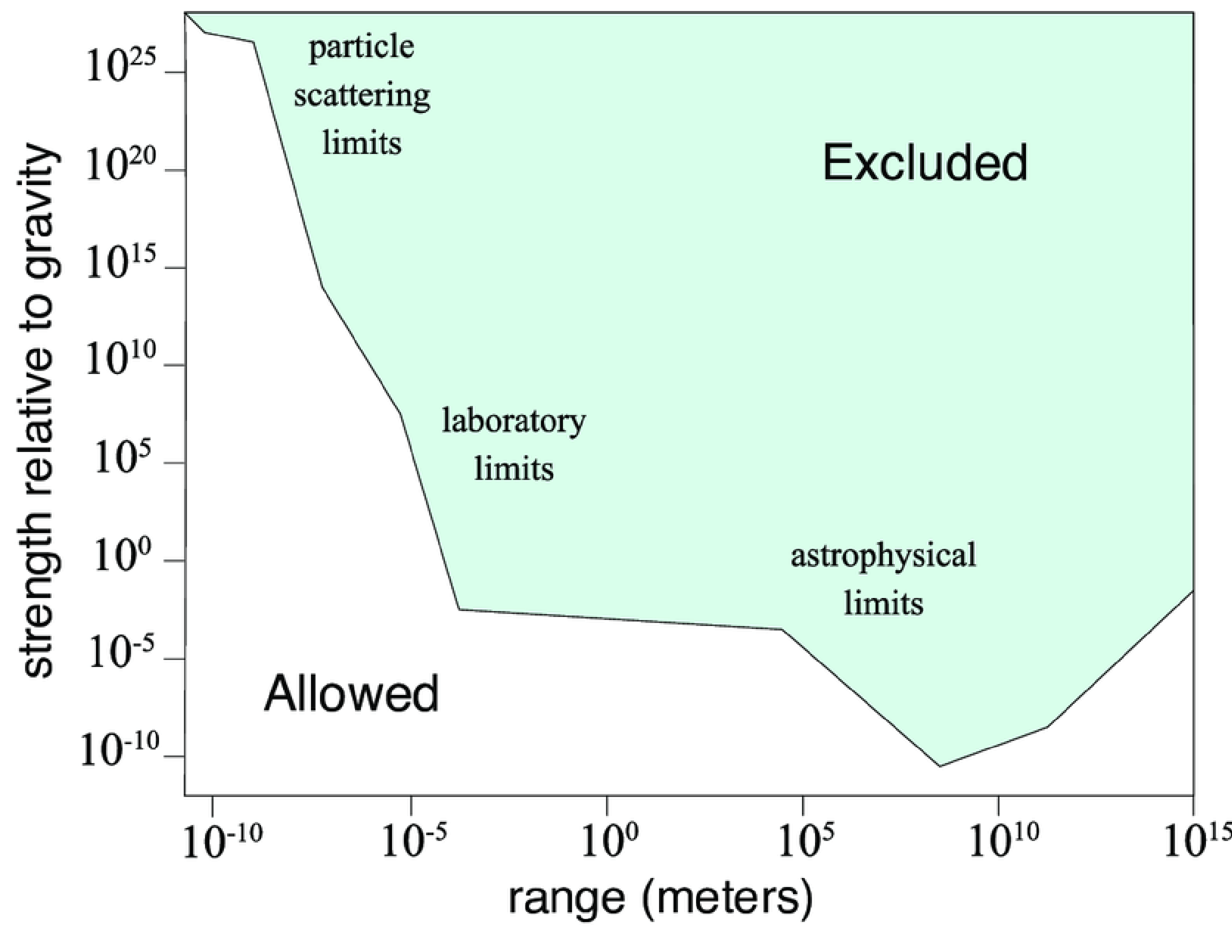
# Current bounds on visible fifth forces

$$V = -G_N m_A m_B \frac{e^{-m_\varphi r}}{r} \left[1 + \alpha_A \alpha_B\right] \qquad m_\varphi \sim 1/\lambda$$

Two types of constraints :

- Departures from 1/r

Carroll21



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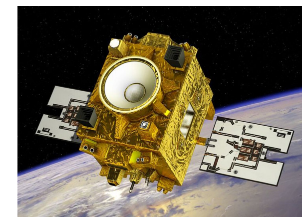


- Departures from 1/r

- Equivalence Principle Violations

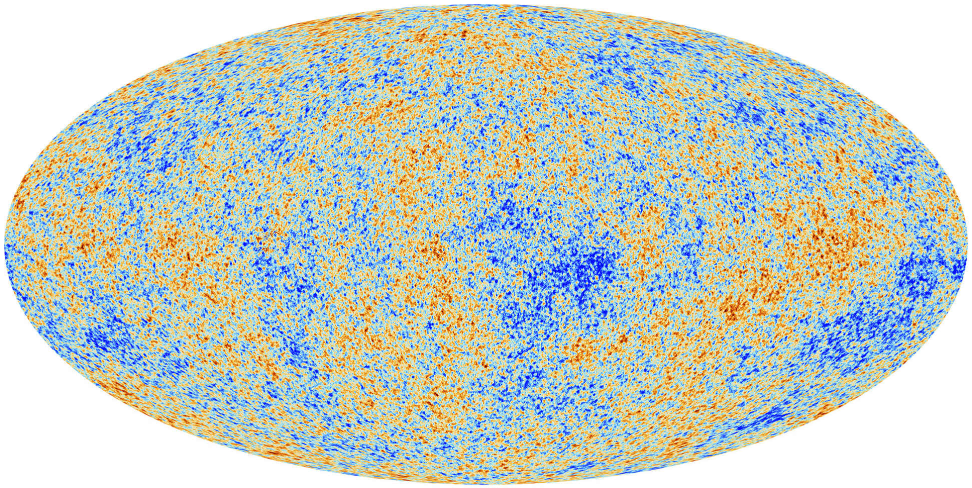
$$\frac{\Delta a}{a}\Big|_{\mathrm{Ti-Pt}} = (-1 \pm 13) \times 10^{-15}$$

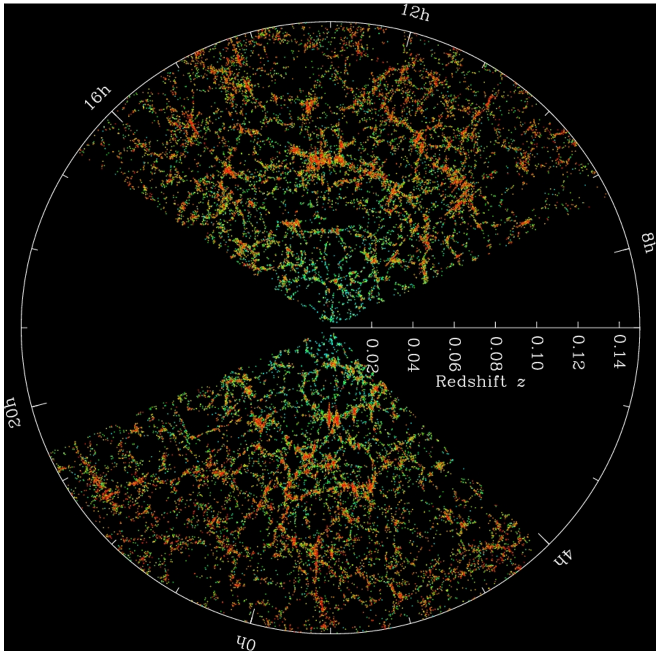
Current best bounds from MICROSCOPE

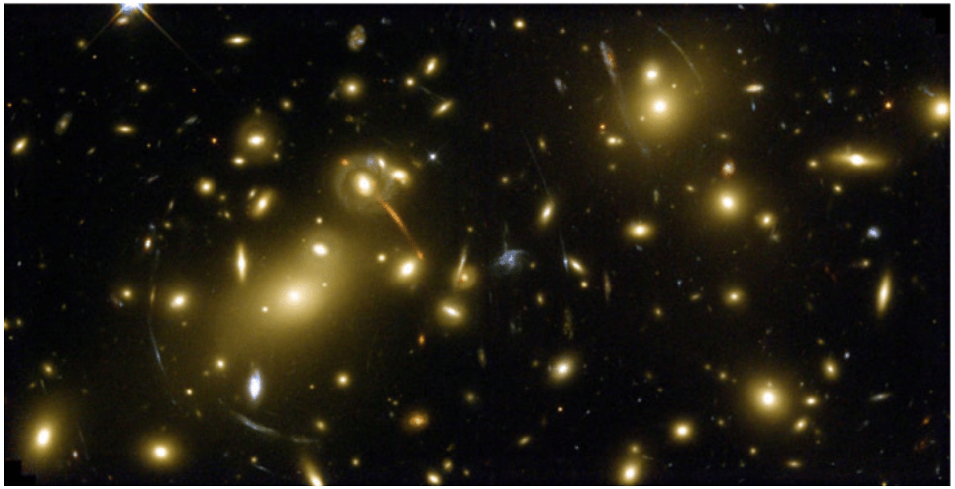
Eot-Wash Group awarded Breakthrough prize for fundamental physics in 2020

The visible sector does not allow for the presence of new long range forces

# Enters Dark Matter





+ overwhelming evidence at smaller scales

# Back to the acronym

**C**old **D**ark **M**atter

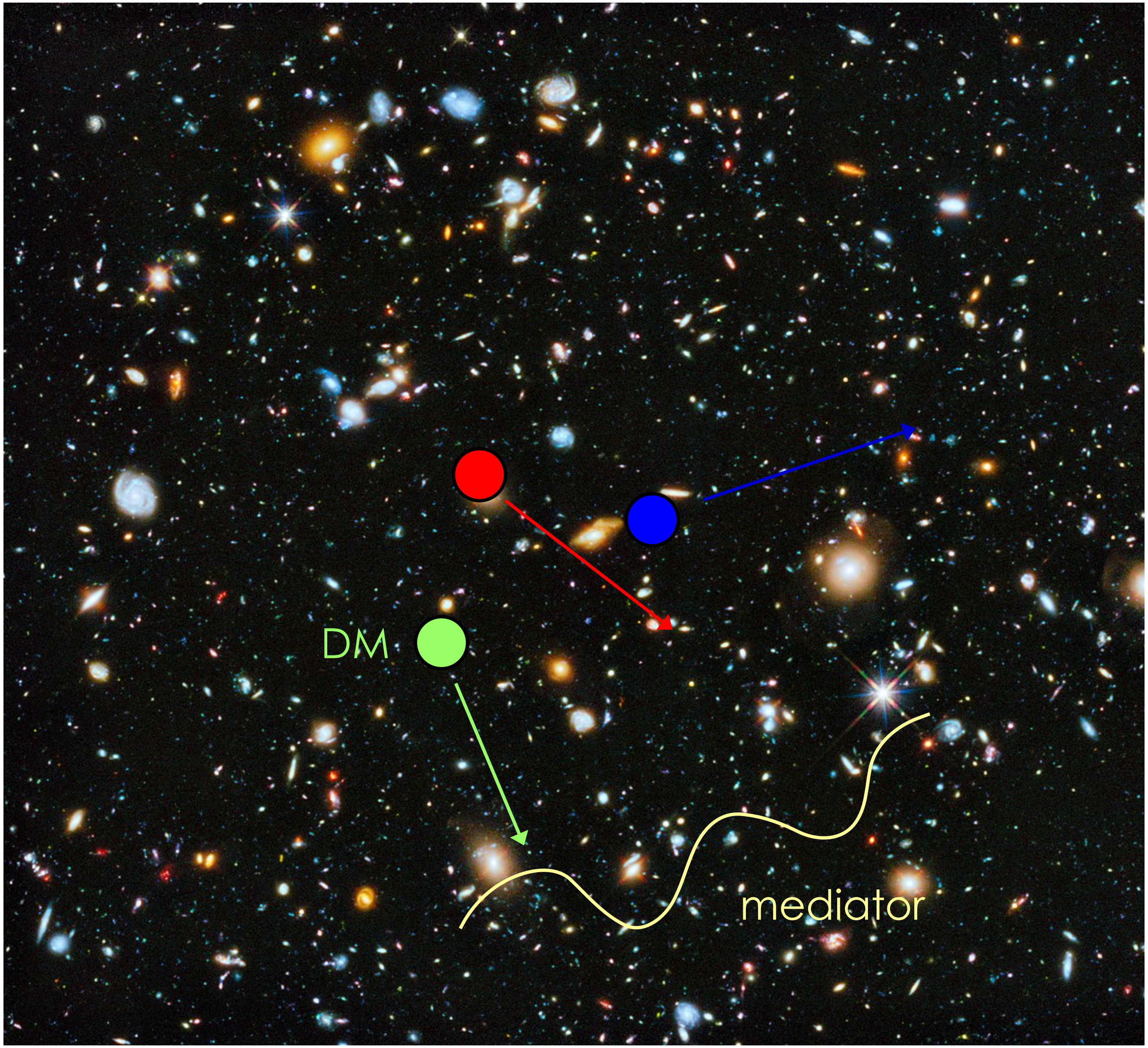
Studied in great details, ~ no room for warm and/or charged DM

Are O(1) violation of the EP in the dark sector possible ?

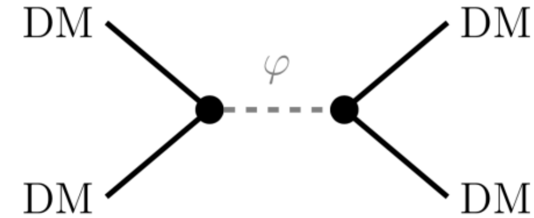
What is the parameter space of DM long-range Interactions ?

What about the M ? If it is a particle we always assume it obeys the EP

# The Universe as a scale



# Dark matter interactions




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

Field dependent mass

$$m_\chi^2(s) = m_\chi^2(1+2s)$$

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

Self-interactions can be neglected

$$\beta \equiv \frac{\rm New\ Force}{\rm Gravity} = \frac{G_s}{4\pi G_{\rm N}}$$

Self-consistently include DM and mediator evolution @ bkg and perturbation level

# Particle dynamics

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

Strassler94, Farrar&Peebles04

- DM particles still move trying to extremize their proper time

- The DM mass depends on the space-time configuration of the new mediator ‘s’

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

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NR limit

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

New interactions couple to the number density, not the energy density

# The cosmological background

The energy momentum tensor of DM is not conserved anymore, like in E&M or GR

$$\nabla_\mu (T^{\mu\nu}_\chi + T^{\mu\nu}_s) = 0$$

At the background level

$$\bar{\rho}'_\chi + 3\mathcal{H}\bar{\rho}_\chi = \bar{\rho}_\chi \frac{\partial \log m_\chi(s)}{\partial s} \bar{s}' \longrightarrow \rho_\chi \not\propto a^{-3} \quad \rho_\chi \sim m_\chi(s) n_\chi$$

$$\bar{s}'' + 2\mathcal{H}\bar{s}' + a^2 m^2 \bar{s} + G_s a^2 \bar{\rho}_\chi \frac{\partial \log m_\chi(s)}{\partial s} = 0 \longrightarrow$$

5fth force evolves with time, s'<0

$$\beta \equiv \frac{G_s}{4\pi G_{\rm N}}$$

Is the only new parameter of the model (for $m_s \ll H_0$ )

Case I

$$m/H_0 \ll 1$$

# Time on our side

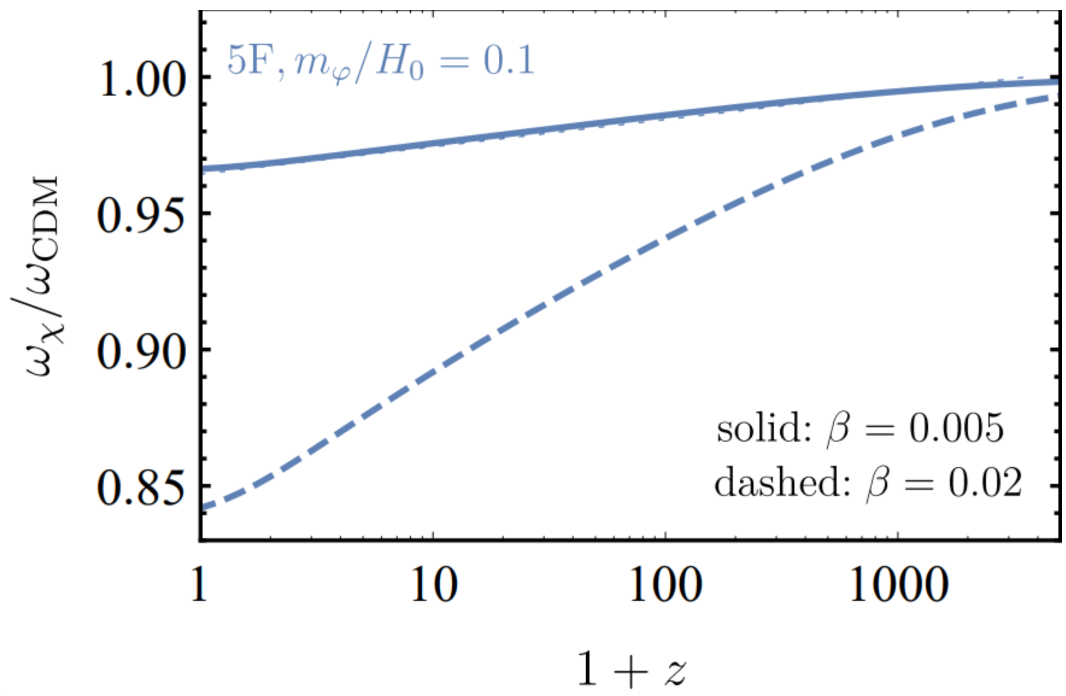
Small violations of EP can lead to large changes in parameters over cosmic time.

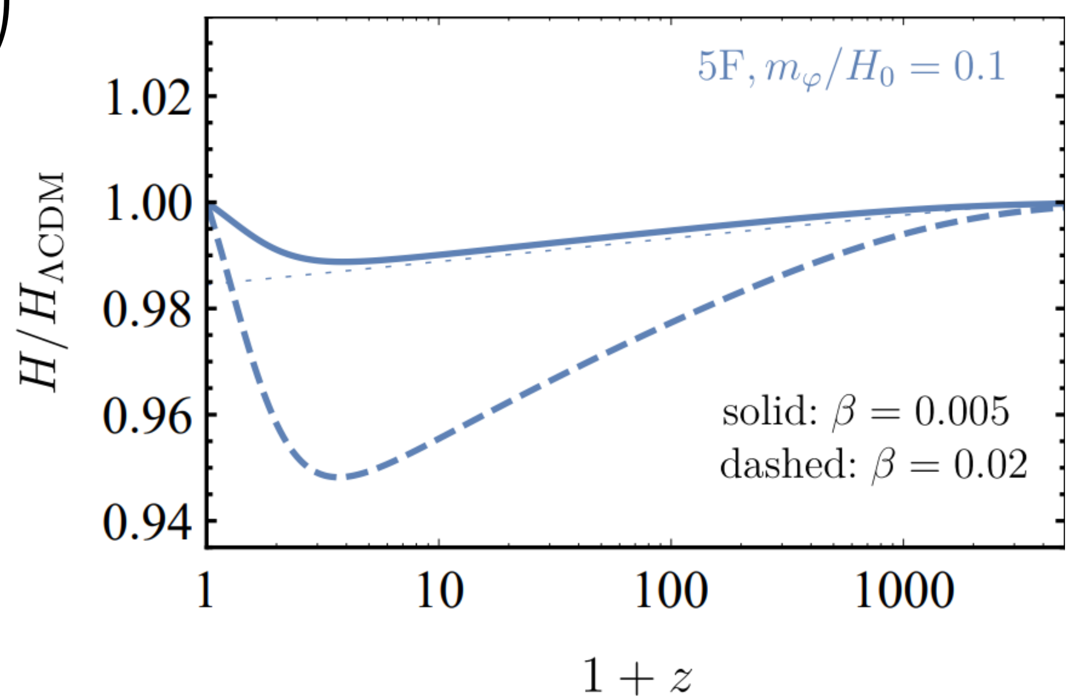
$$\frac{\omega_\chi(a)}{\omega_\chi(a_{\rm eq})} \sim 1 - \beta f_\chi \log\frac{a}{a_{\rm eq}}$$

$$H(a) \sim H_{\Lambda{\rm CDM}}\left(1 - \frac{\beta}{2} f_\chi^2 \log\frac{a}{a_{\rm eq}}\right)$$

Logs brings a factor of 8 enhancement

Reduced by the relative fraction of DM



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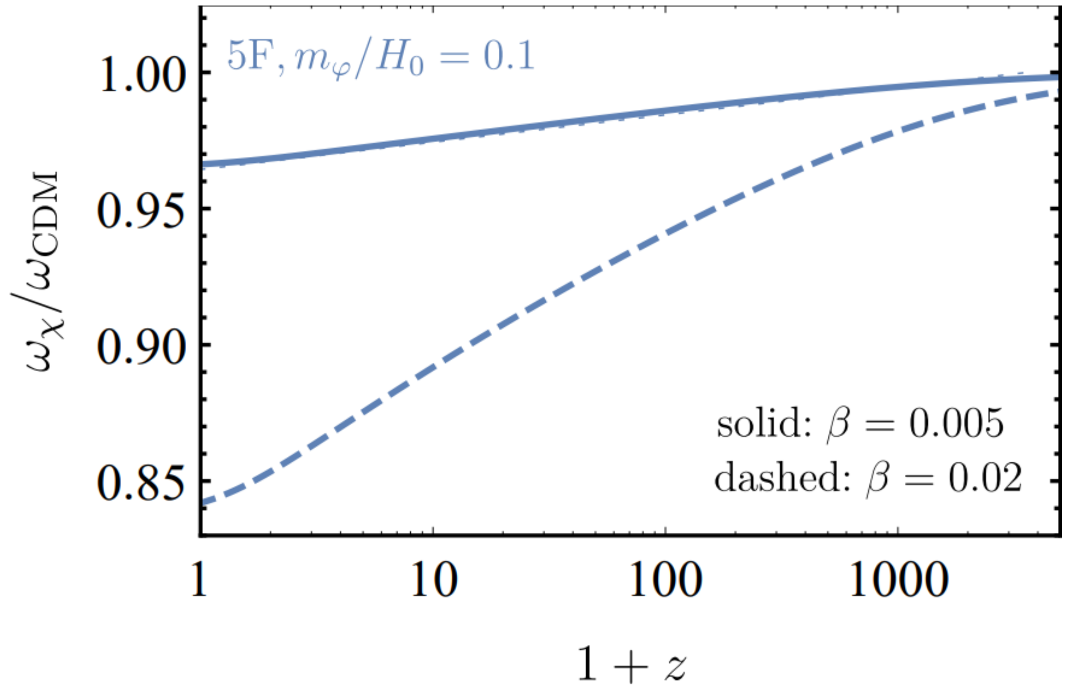
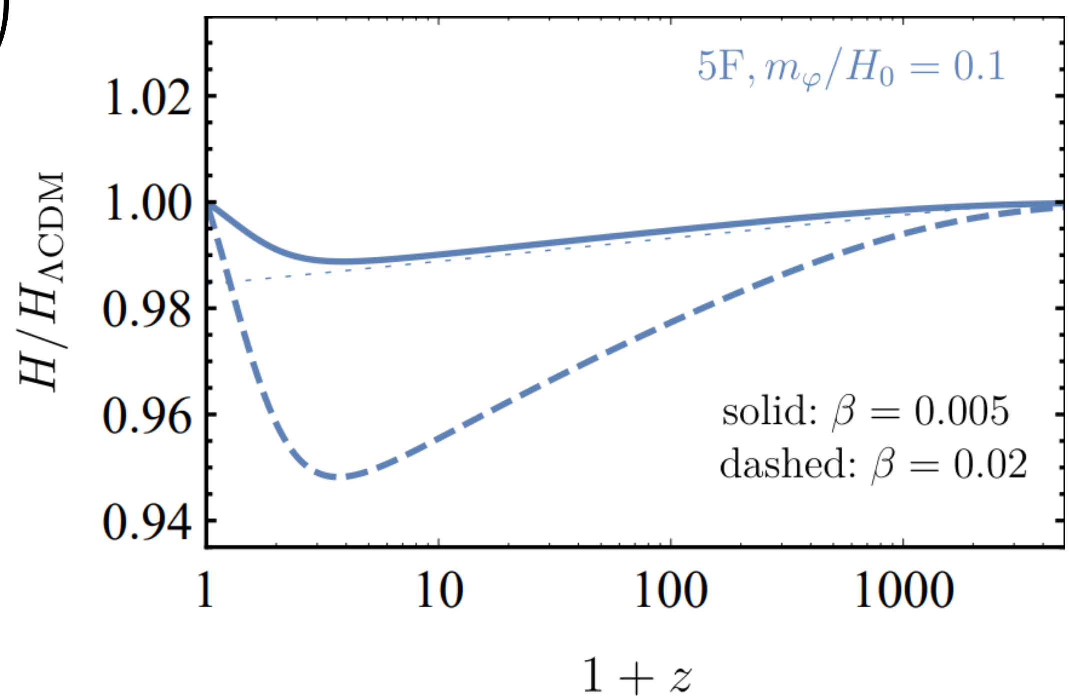
Energy transfer to the mediator implies an upper bound on the coupling

$$\beta \equiv \frac{G_s}{4\pi G_N} \lesssim 0.10$$



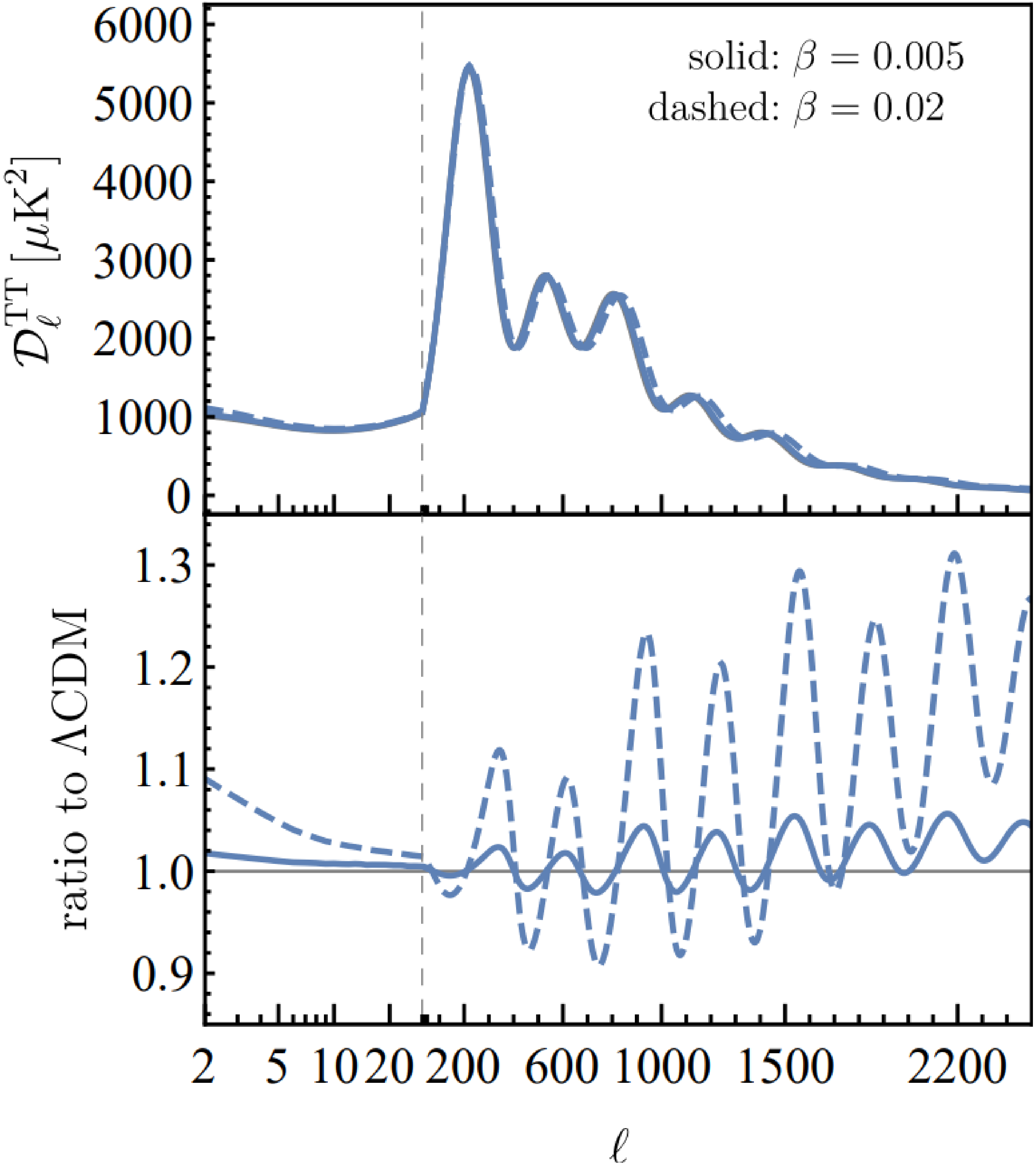
# CMB

Physical scales at decoupling mostly unchanged.

Differences are due to projections

Again, differences much larger than naive scaling of $\mathcal{O}(\beta)$

CMB is not the ultimate probe of 5th forces !

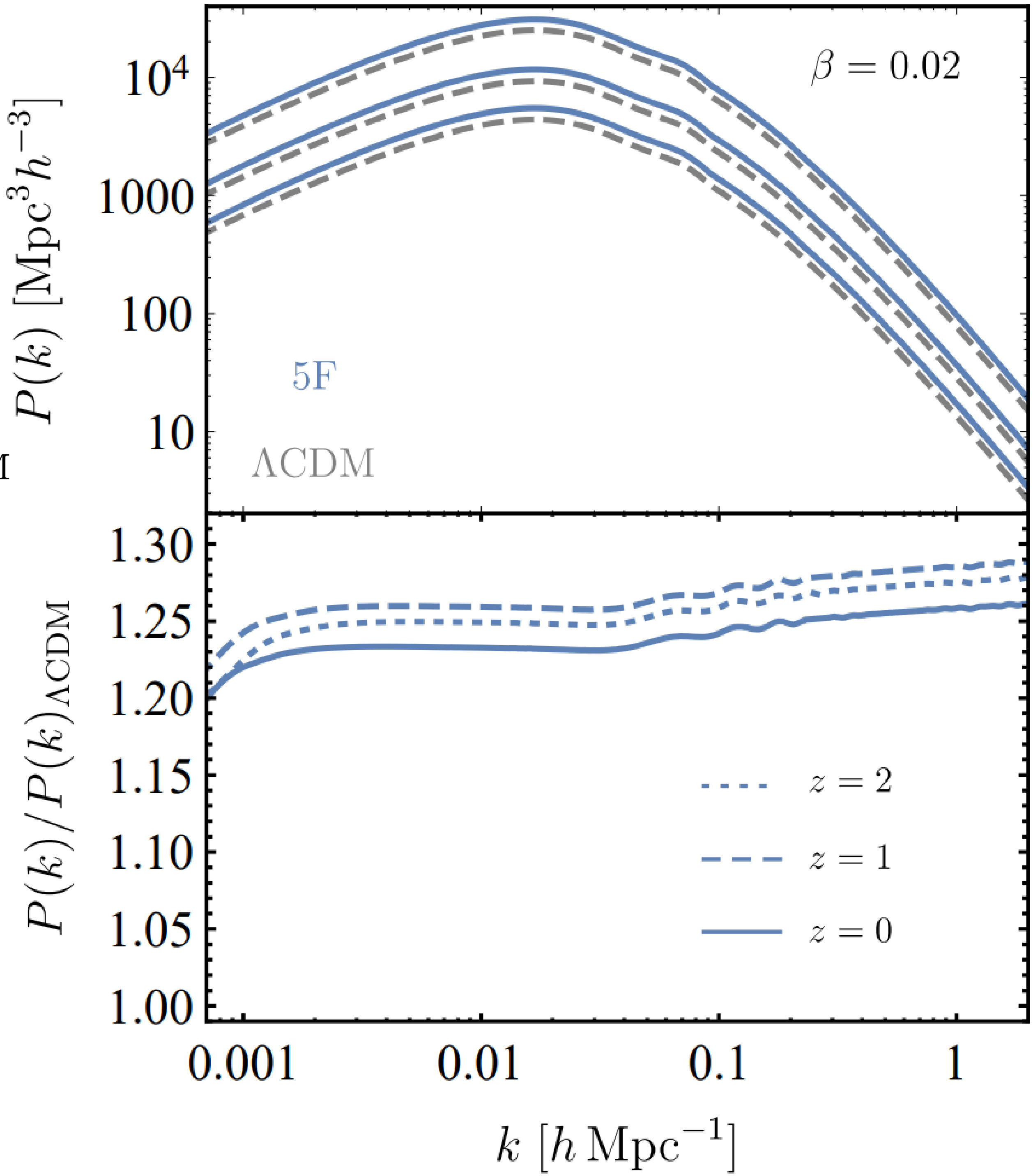


# Total matter P(k)

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

$$\delta_m \sim \left(1 + \frac{6}{5}\beta \log \frac{a}{a_{\rm eq}}\right) \delta_m^{\rm CDM}$$

- Differences are large and decrease with redshift
- Minor changes in BAO (more soon)



# The EFT of New Physics

$$\varepsilon \equiv \beta f_\chi = \frac{G_s f_\chi}{4\pi G_{\rm N}}$$

$$\delta_m' + \theta_m = -\nabla_i(\delta_m v_m^i)\,,$$

$$\theta_m' + \mathcal{H}(1 - \underline{f_\chi \varepsilon})\theta_m + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_m (1 + \underline{f_\chi \varepsilon}) = -\nabla_i(v_m^j \nabla_j v_m^i)\,,$$

$$\delta_r' + \theta_r = -\nabla_i(\delta_m v_r^i + \delta_r v_m^i)\,,$$

$$\theta_r' + \mathcal{H}\theta_r - \underline{\varepsilon \mathcal{H}\left(\theta_m - \frac{3}{2}\Omega_m \mathcal{H}\delta_m\right)} = -\nabla_i(v_m^j \nabla_j v_r^i) - \nabla_i(v_r^j \nabla_j v_m^i)$$

$$\delta_r = \delta_\chi - \delta_b \quad , \quad v_r^i = v_b^i - v_\chi^i$$

For the first time, the perturbative LSS evolution with new DM dynamics

# The EFT of New Physics

$$\delta^{(n)}(\mathbf{k}) \sim D^{(n)}(\tau) \int_{\mathbf{q}_1 \ldots \mathbf{q}_n} \delta_D[\mathbf{k} - (\mathbf{q}_1 + ... + \mathbf{q}_n)] F_n(\mathbf{q}_1, ..., \mathbf{q}_n) \delta(\mathbf{q}_1) ... \delta(\mathbf{q}_n)$$

Time dependence is 'simple'

$$D^{(n)}(\tau) = a_n [D^{(1)}(\tau)]^n + b_n(\tau)\beta$$

↑

$$(\beta log \tau)^n$$

Implications for many BSM scenarios, e.g. light relics.

# The EFT of New Physics

$$\delta^{(n)}(\mathbf{k}) \sim D^{(n)}(\tau) \int_{\mathbf{q}_1 \ldots \mathbf{q}_n} \delta_D[\mathbf{k} - (\mathbf{q}_1 + \ldots + \mathbf{q}_n)] F_n(\mathbf{q}_1, \ldots, \mathbf{q}_n) \delta(\mathbf{q}_1) \ldots \delta(\mathbf{q}_n)$$

Scale dependence is relatively 'simple'

$$F_n^{(m)} \sim F_n^{\Lambda CDM} + \varepsilon \Delta F_n$$

$$F_n^{(r)} \sim \varepsilon \Delta F_r$$ ← IR divergent $$\nabla_i \Phi \sim \frac{\nabla_i}{\nabla^2} \delta \sim \frac{i q_i}{q^2} \delta(q)$$

Long wavelength modes produce observable effects if EP is broken

New counterterms in the EFT, much stronger UV sensitivity $\sim k^0 P_{\rm mm}$

# The EFT of New Physics

BSM generates new operators absent in ΛCDM

Can I observe relative fluctuations ?

$$\delta_g = b_1\delta_m + b_r\delta_r + b_\theta\theta_r + \ \ldots$$

$$b_{mr}\delta_m\delta_r + b_{\delta\theta}\delta_m\theta_r + b_{\nabla\delta}\nabla_i\delta_m v_r^i + b_K K^{ij}\nabla_i v_r^j + b_{Kr}K_{ij}\frac{\nabla^i\nabla^j}{\nabla^2}\delta_r$$

The galaxy n-point functions are sensitive to relative perturbations

$$\langle\, \delta_A(\mathbf{p})\delta_B(\mathbf{k}_1)\delta_A(\mathbf{k}_2)\,\rangle \sim -\frac{\mathbf{k_1}\cdot\mathbf{p}}{p^2}\frac{7}{6}\varepsilon P(p)P(k_1)(b_{r,A}-b_{r,B})$$

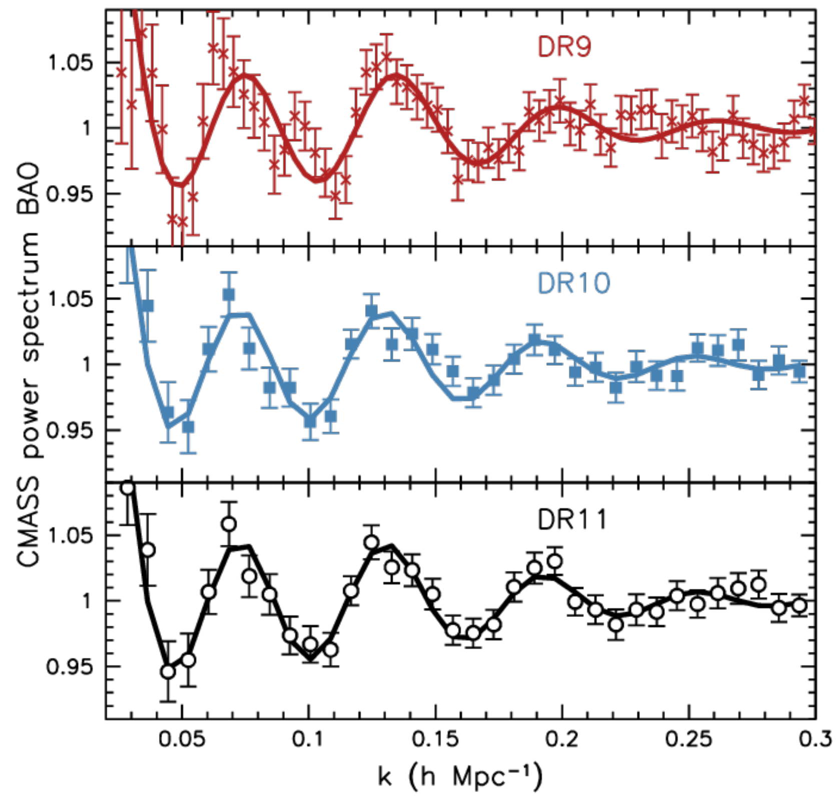
- Signal-to-noise in the pole is too small

# Subtleties about the BAO

Everyone expected shifts due to EP violations

Shifts ~ $\mathcal{O}(\beta)$

Up to % level given CMB bounds.



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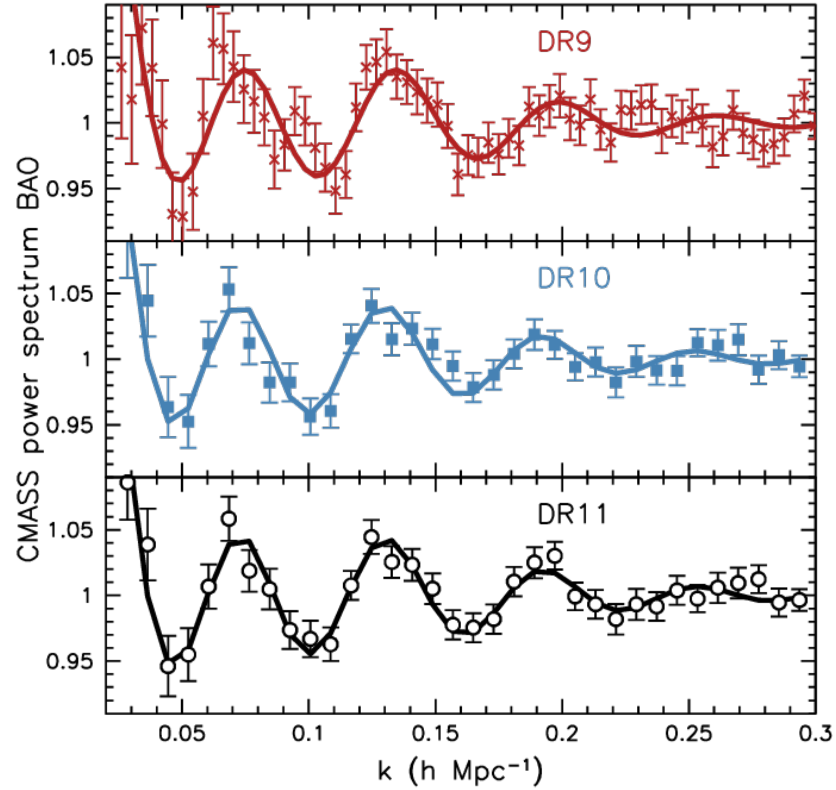


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Why ?

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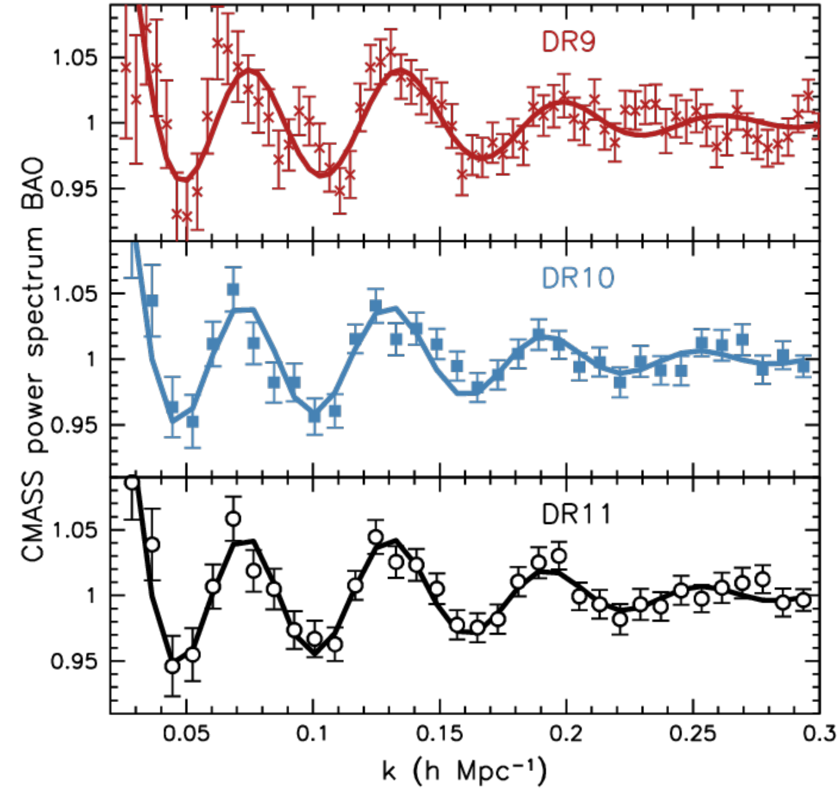


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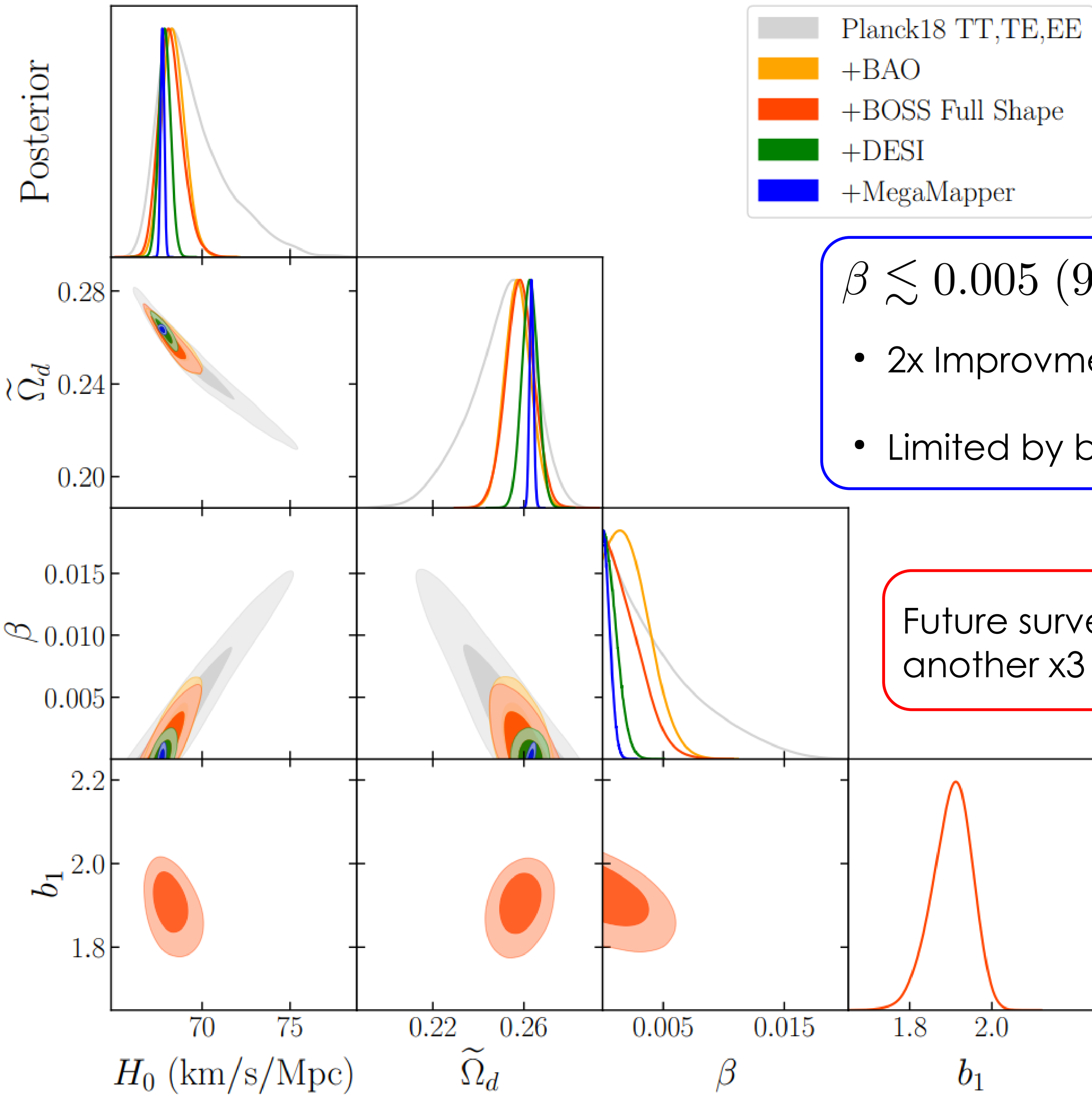
Why ?

By translational invariance (only manifest in LPT)

$$P_g \supset \delta_{ij} v_r^i v_r^j \sim \mathcal{O}(\beta^2)$$

# LSS bounds




$\beta \lesssim 0.005$ (95%) Planck + BOSS

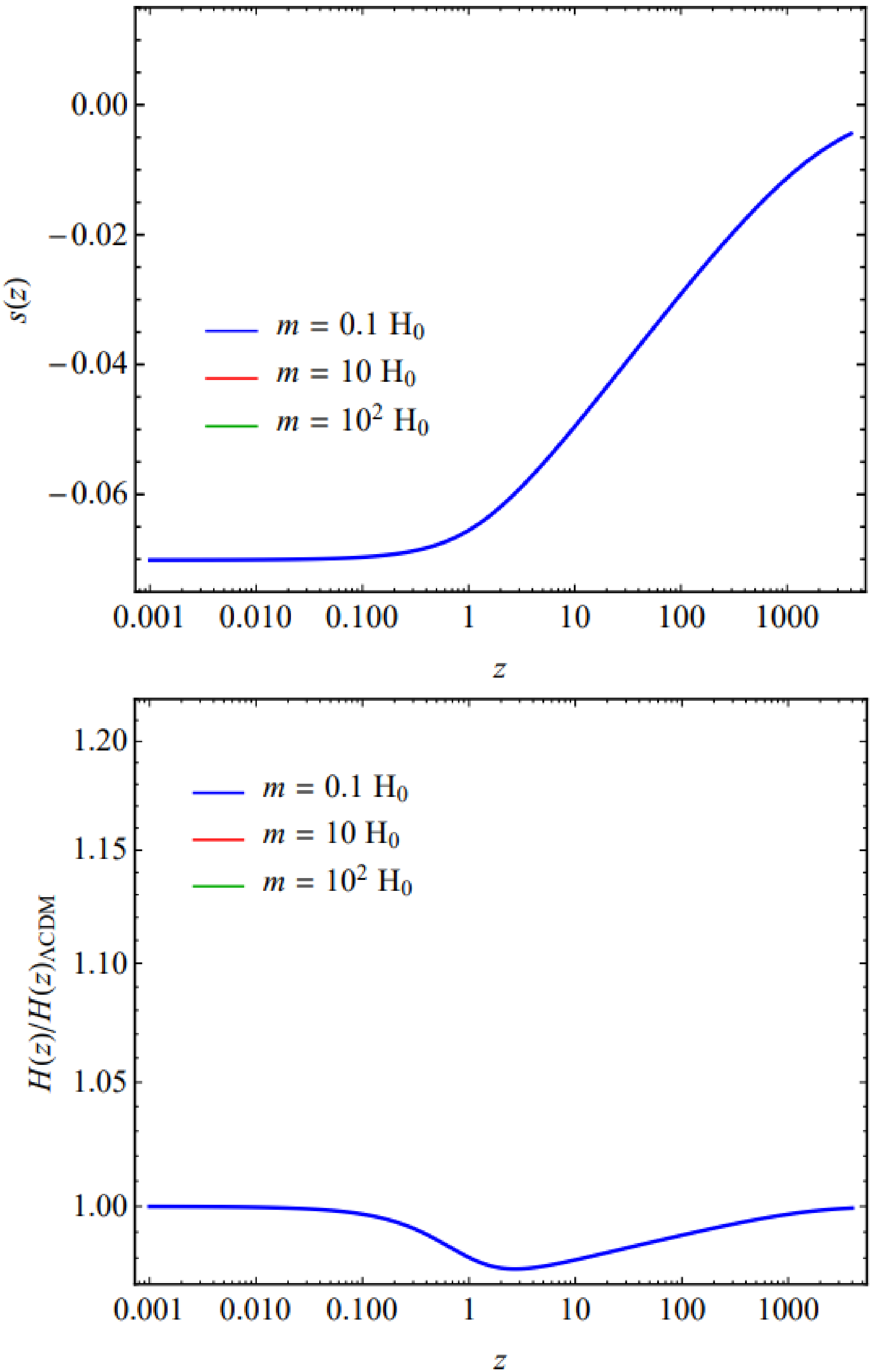
- 2x Improvment over CMB
- Limited by bias parameters

Future surveys could improve by another x3

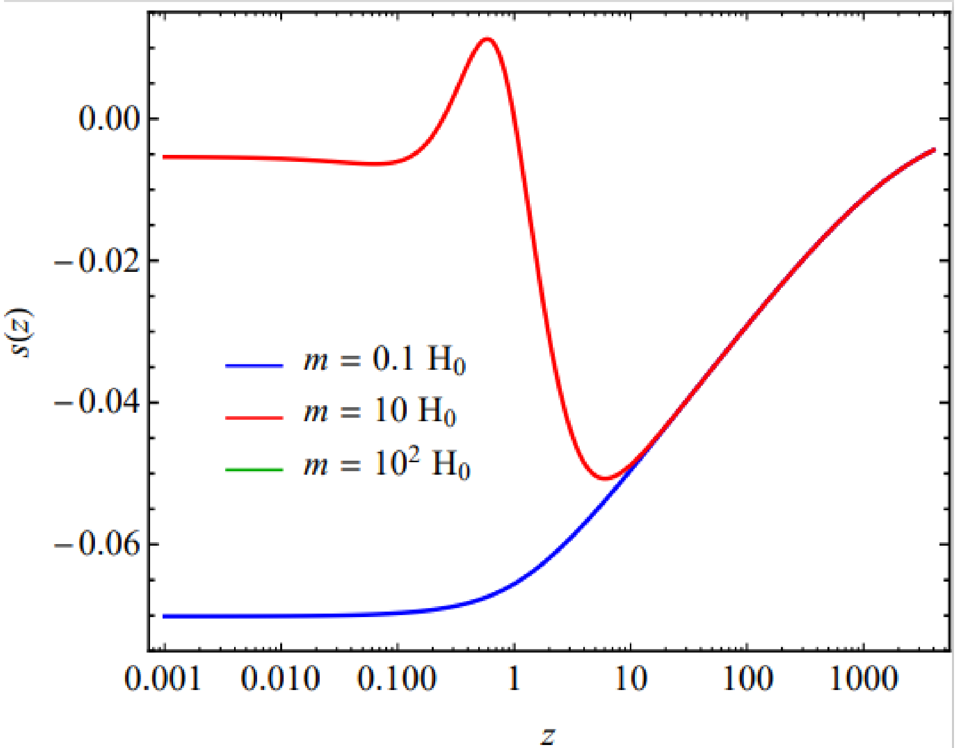
Does not include any Bispectrum, CMB lensing, x-corr

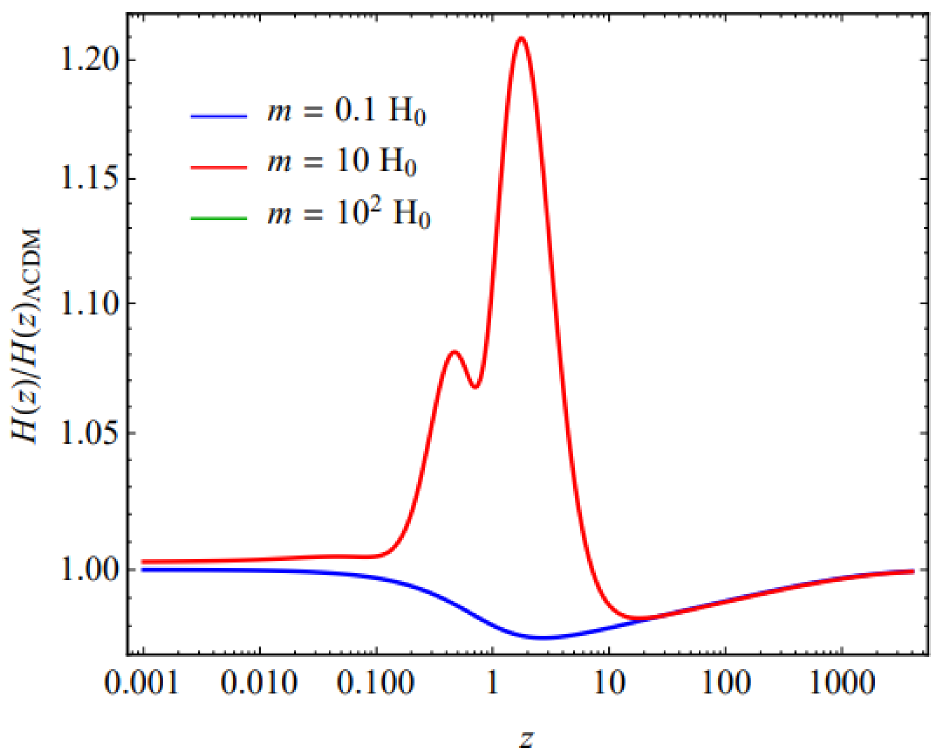
# Case II

$$m/H_0 > 1$$

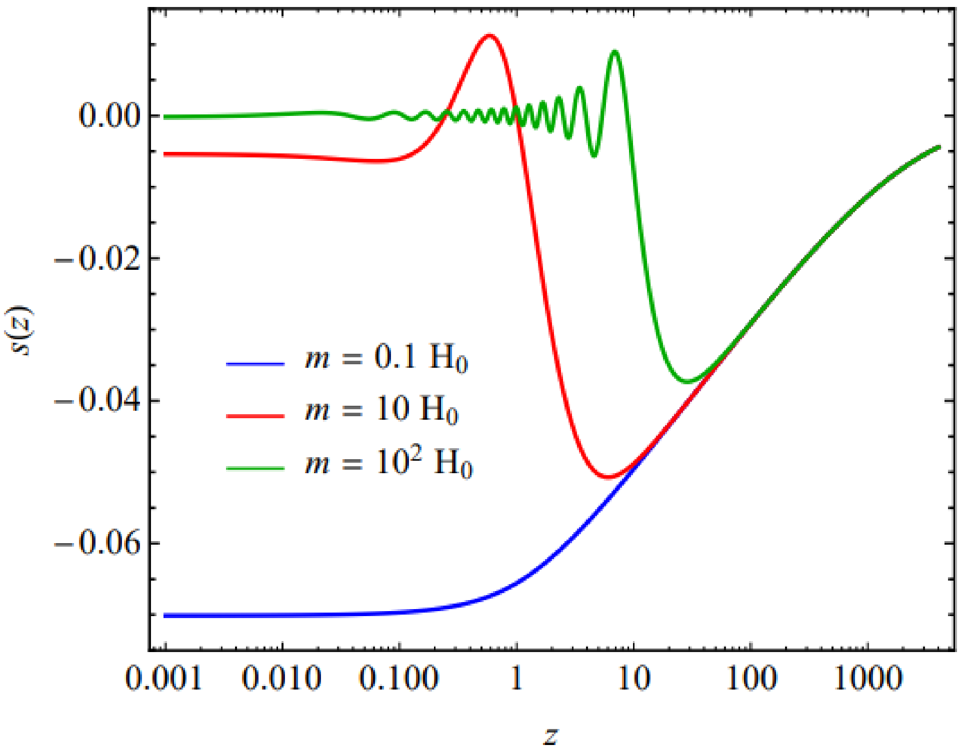


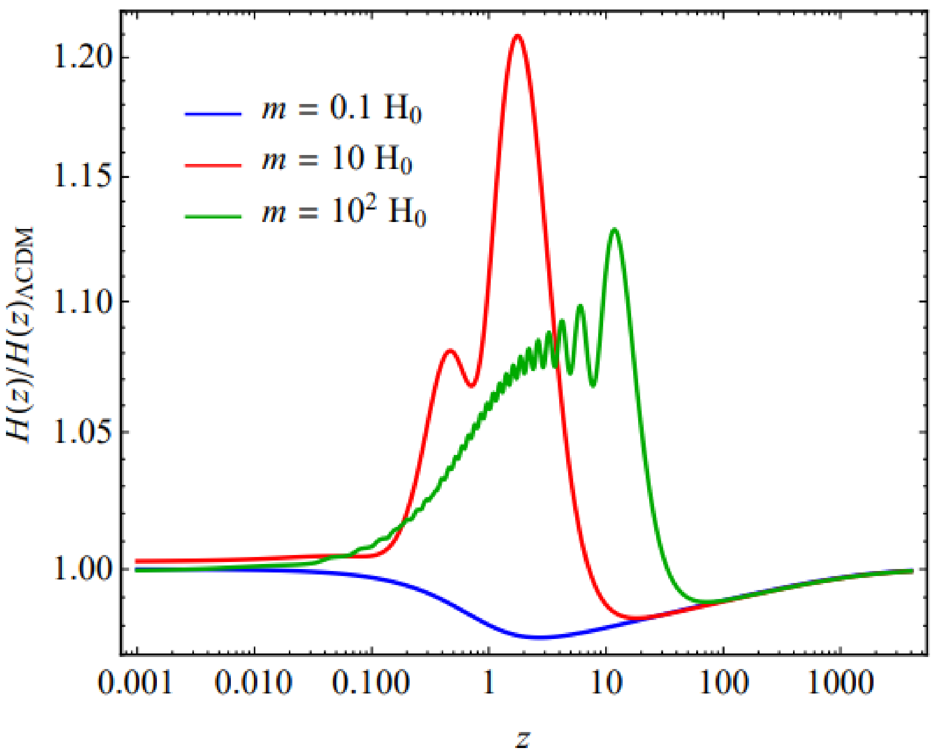

- When m<H energy is transferred from DM to the mediator




- When m<H energy is transferred from DM to the mediator
- When m>H, the mediator starts oscillating around the new mimimum of its potential, releasing energy back into Hubble
- The new force disappears

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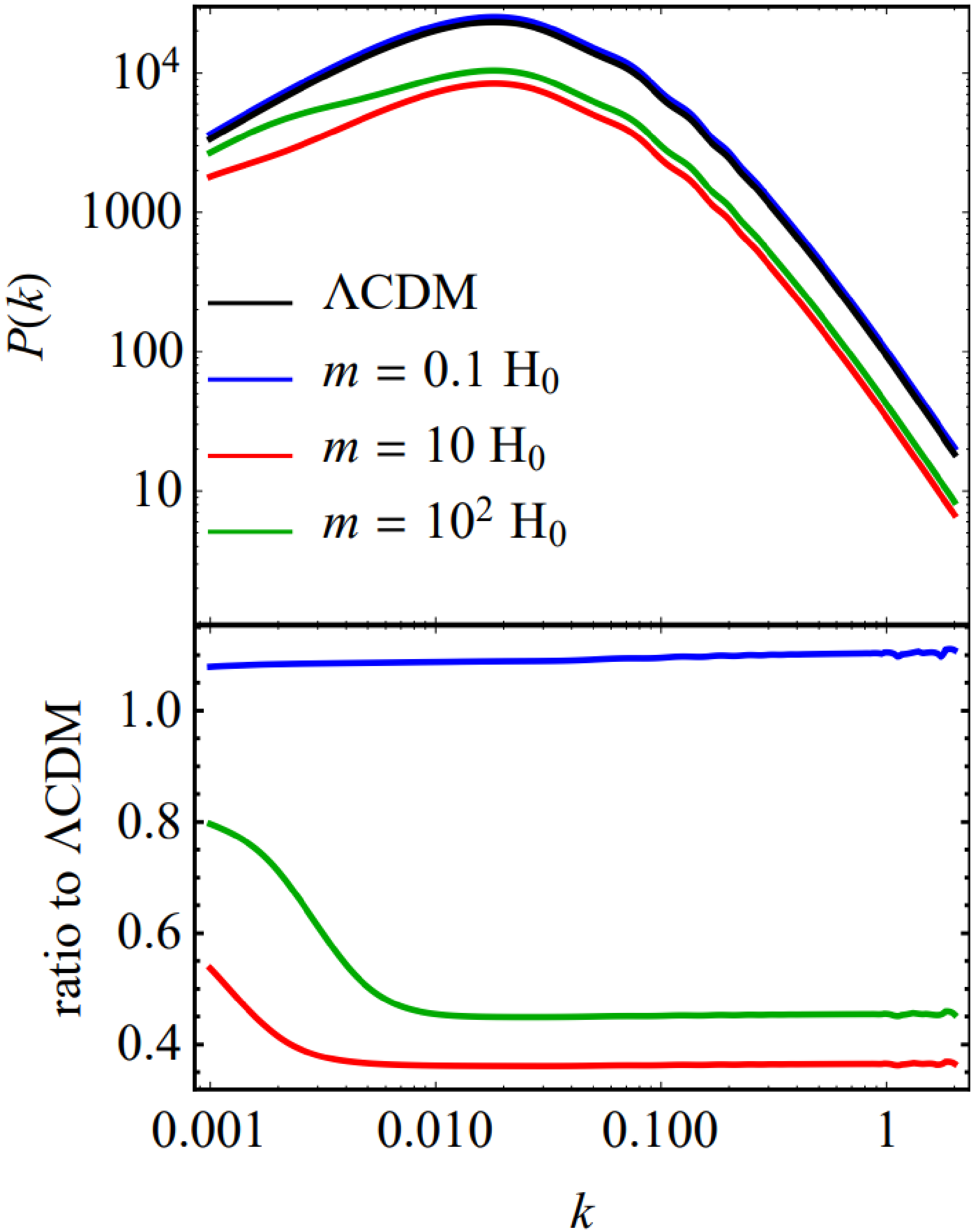
- The new force disappears
- The mediator then becomes a fraction of DM today

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



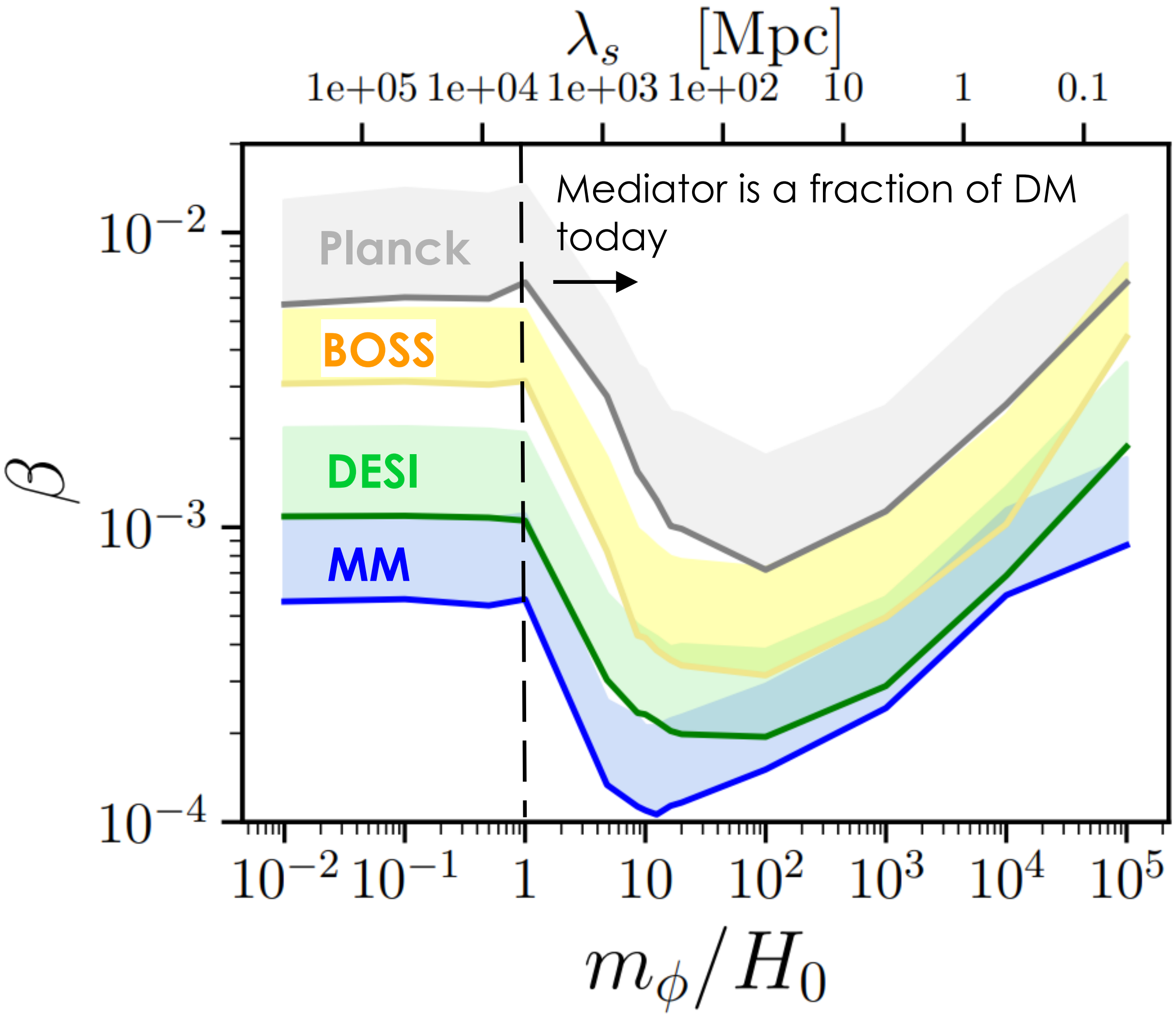

- At late times the mediator becomes an ULA, suppressing growth

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

- At low masses, EFTofLSS is doable
- For m>>H, the Jeans scales is right into the perturbative regime

  Not yet available ⟶ Stop at 10^5H_0

# Summary and Outlook




- We can probe new long-range forces at 0.1 % level with LSS data

  Orders of magnitude better than with small scales

- Analysis of relative fluctuations in progress…

  fractions of DM and bias

- Extending the EFT of LSS for massive mediators will allow to probe down to 1 pc (till kJ > kNL )

- Optimizing Spec-S5 for new DS dynamics is an open problem

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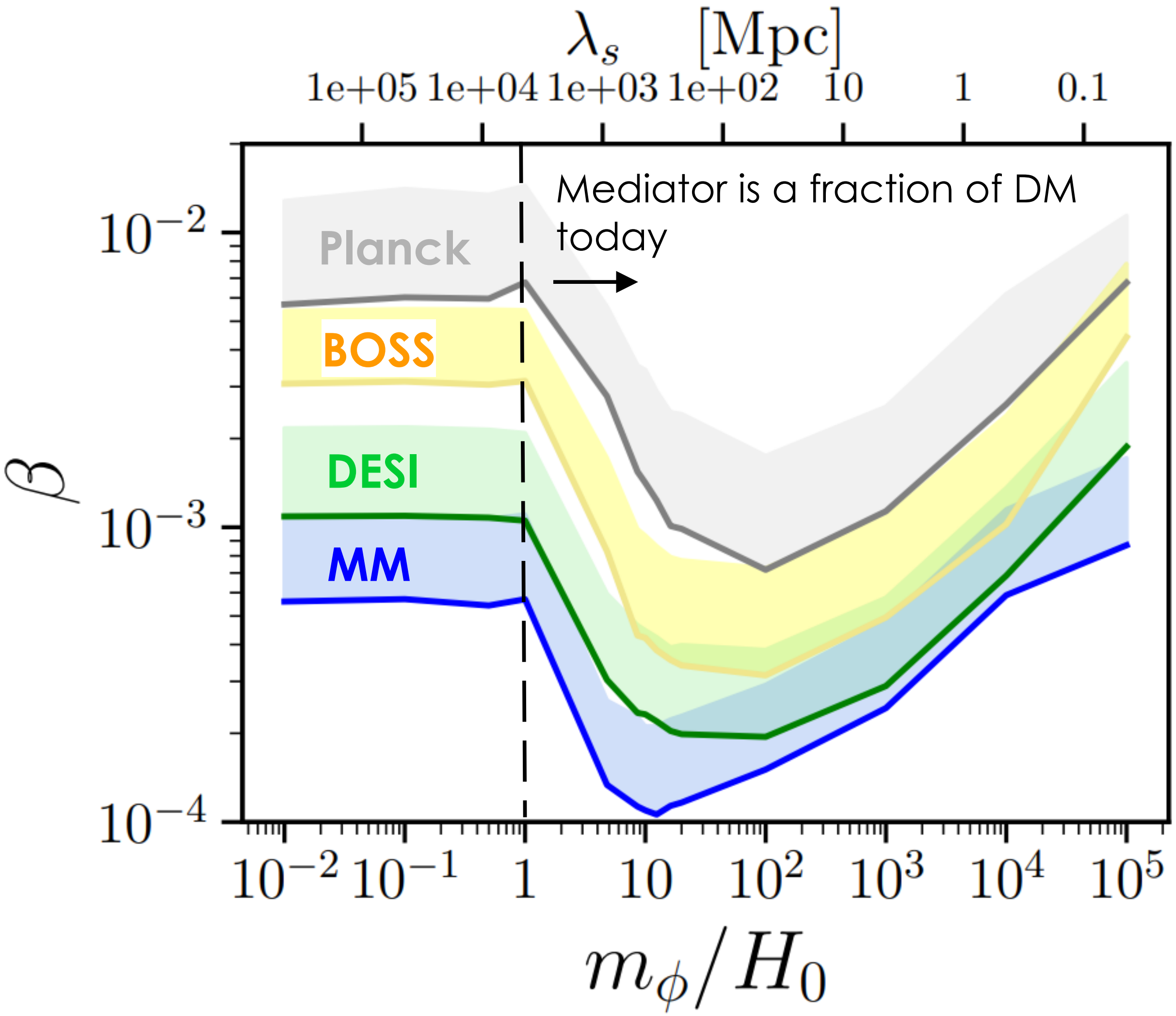


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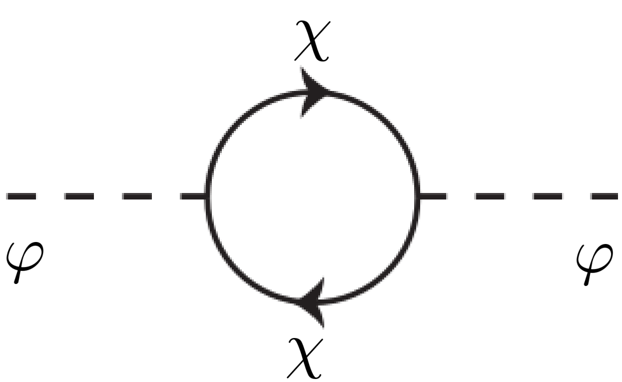
**Thank you for your attention!**

# Implications for the visible sector: Naturalness

We are interested in cosmologically relevant fifth forces

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




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

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

DM has to be light, an axion ?, unless one accepts a massive fine tuning.
Different than Farrar&Bovy08

# Implications for the visible sector

For atoms A and B

$$V = -G_N m_A m_B \frac{e^{-m_\varphi r}}{r} \left[1 + \alpha_A \alpha_B\right]$$

$$\frac{\Delta a}{a} \sim (\alpha_A - \alpha_B) \sim 10^{-14}$$

Coupling to photons

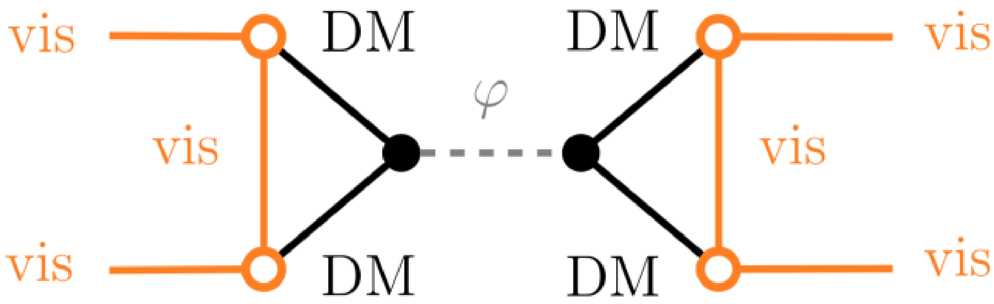
$$d_e \lesssim 2.1 \times 10^{-4}$$

Coupling to gluons

$$d_g \lesssim 2.9 \times 10^{-6}$$

Q: if DM violates the EP and also talks to the Standard model, can this induce EP violations in the visible sector ?

# Implications for the visible sector : loops




We expect violation of the EP in the visible sector

$$\mathcal{O}(\beta^{1/2} \times g^2_{\mathrm{DM-SM}})$$

For the axion-like particle coupled to photons and gluons

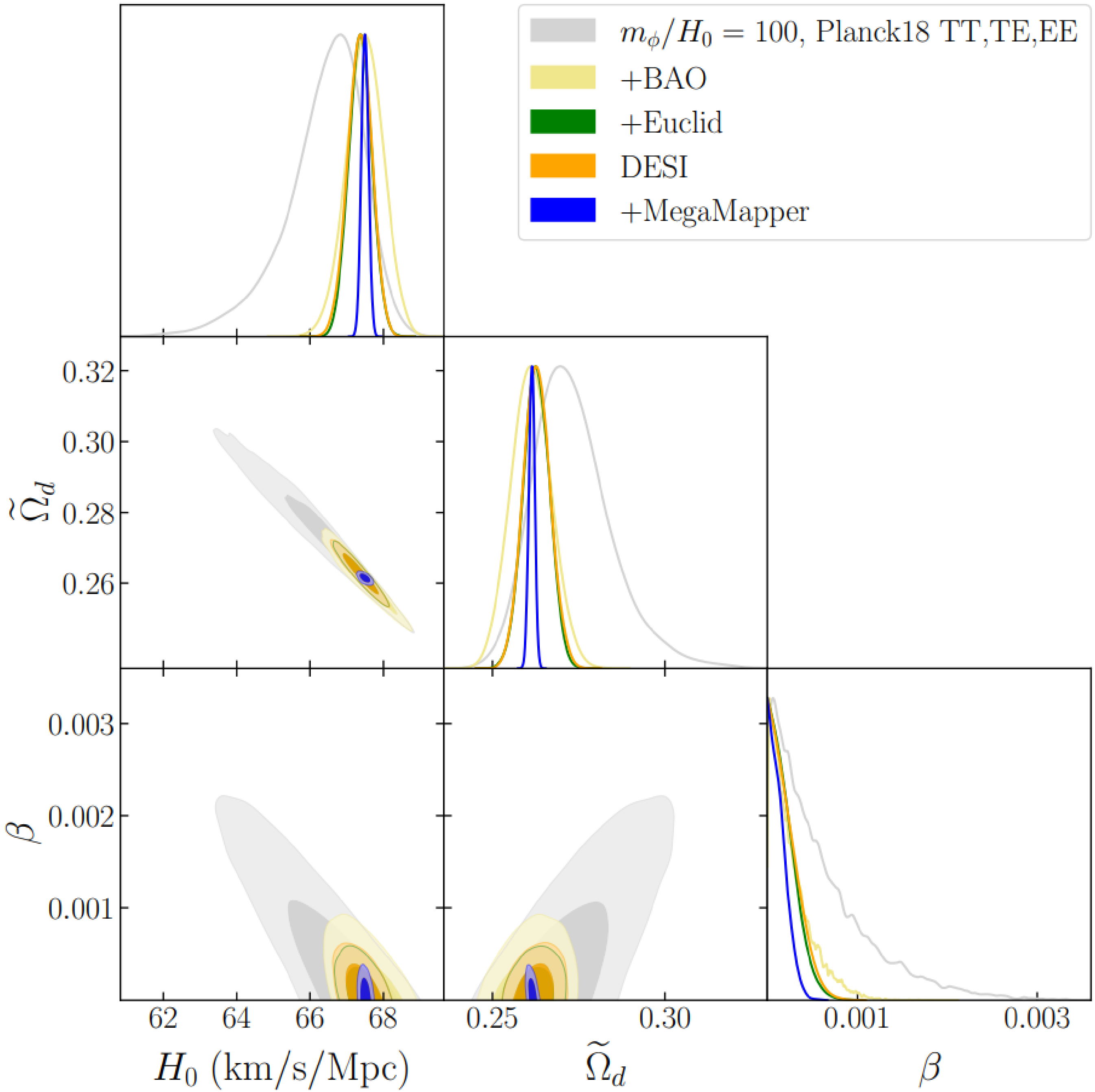
$$d_e \simeq \; 2 \times 10^{-10} \sqrt{\frac{\beta}{0.01}} \left(\frac{m_a}{f_a}\right)^2 \lesssim 2.1 \times 10^{-4}$$

$$d_g \simeq \; 3 \times 10^{-6} \sqrt{\frac{\beta}{0.01}} \left(\frac{m_a}{f_a}\right)^2 \lesssim 2.9 \times 10^{-6}$$

$$\left(\frac{m_a}{f_a}\right) \ll 1$$

Axions could realize parametrically large fifth forces.

Accepting fine tuning could imply DM can never be detected



$m_\phi/H_0 = 100$, Planck18 TT,TE,EE
+BAO
+Euclid
DESI
+MegaMapper
0.32
0.30
0.28
0.26
$\widetilde{\Omega}_d$
0.003
0.002
0.001
$\beta$
62
64
66
68
$H_0$ (km/s/Mpc)
0.25
0.30
$\widetilde{\Omega}_d$
0.001
0.003
$\beta$