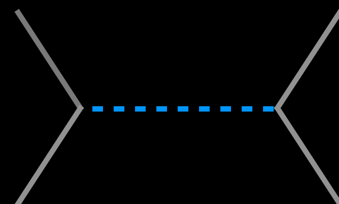
Probing the dark sector with Large Scale Structure



2204.08484 [JCAP] with Archidiacono, Castorina, Redigolo
2309.11496 [PRL] with Bottaro, Castorina, Costa, Redigolo
+ to appear

Ennio Salvioni

CERN, 14/06/2024

University of Sussex

Outline

- Intro: why Large Scale Structure now

- LSS in the standard cosmological model

- Beyond the standard model: dark forces

[Archidiacono, Castorina, Redigolo, Salvioni 2204.08484]
[Bottaro, Castorina, Costa, Redigolo, Salvioni 2309.11496]
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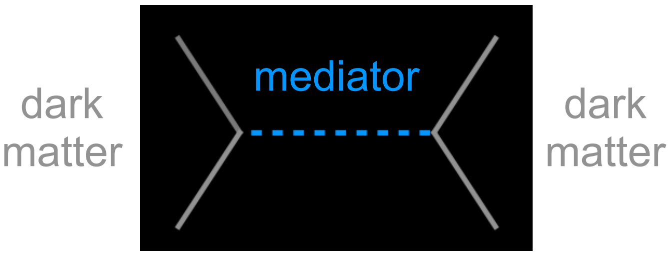
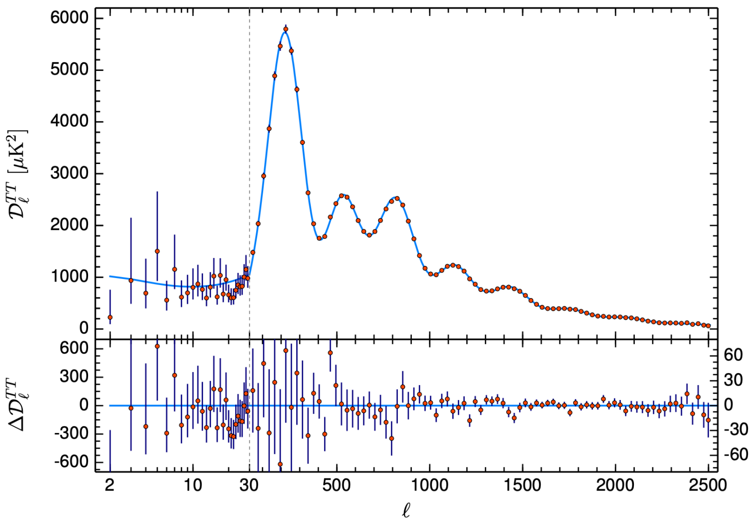


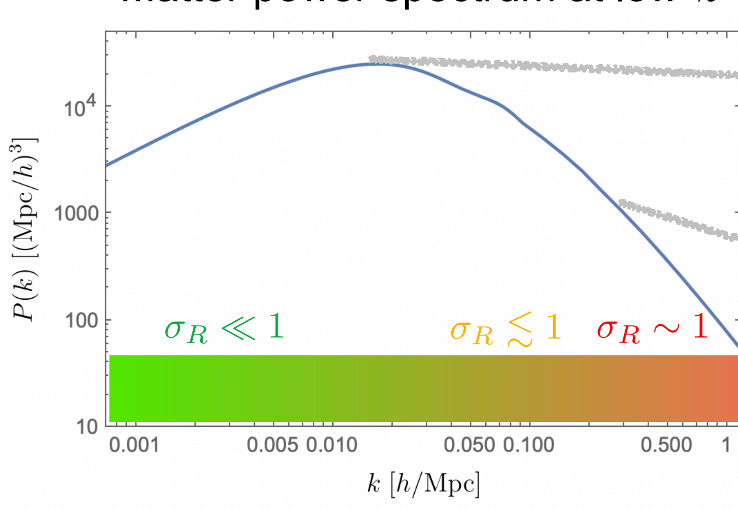
Sources of cosmological information

CMB anisotropies

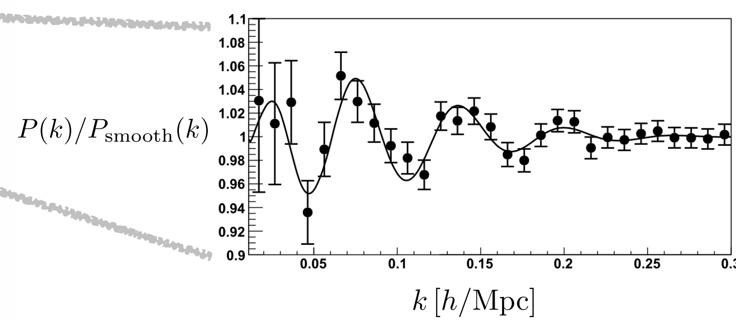


Planck 2018

Matter power spectrum at low z



Baryon acoustic oscillations



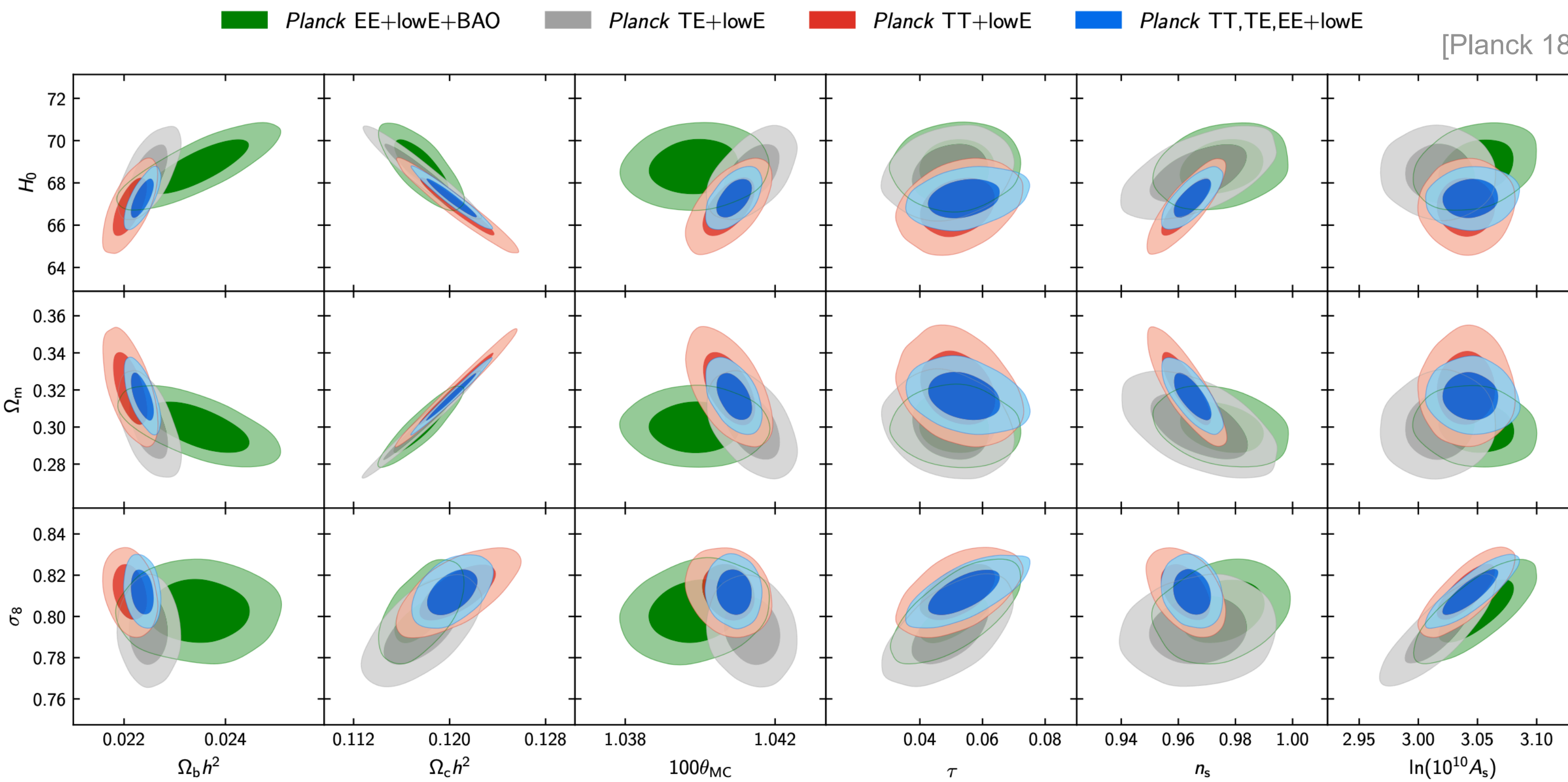
BOSS 2016

(DESI 2024)

$$\sigma_R^2 = \frac{1}{2\pi^2}\int_0^{1/R} dk\, k^2 P_L(k)$$

Precision cosmology

For standard cosmological model, Planck constrains parameters to sub-percent level:



[Planck 1807.06209]

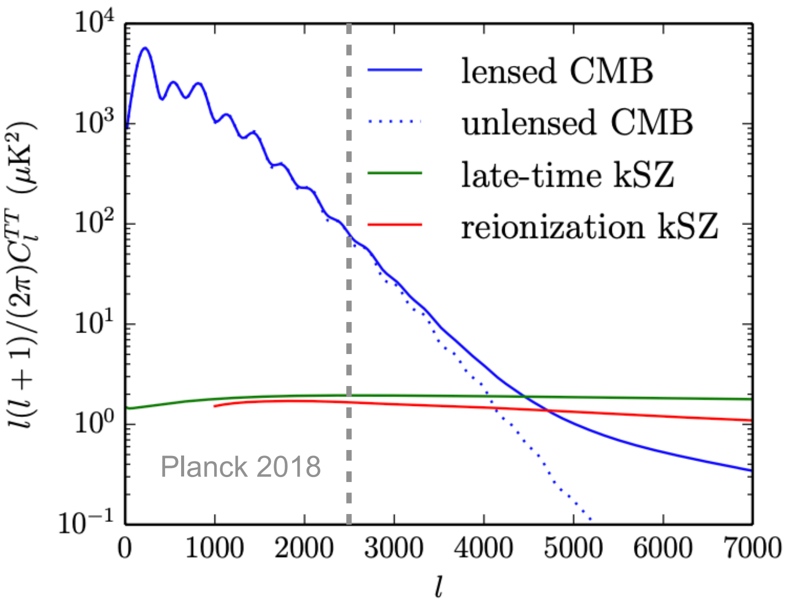
Power spectrum information helps to improve precision,

by breaking geometric degeneracies of CMB (H_0 vs Ω_m)

CMB vs LSS

CMB is a 2D surface

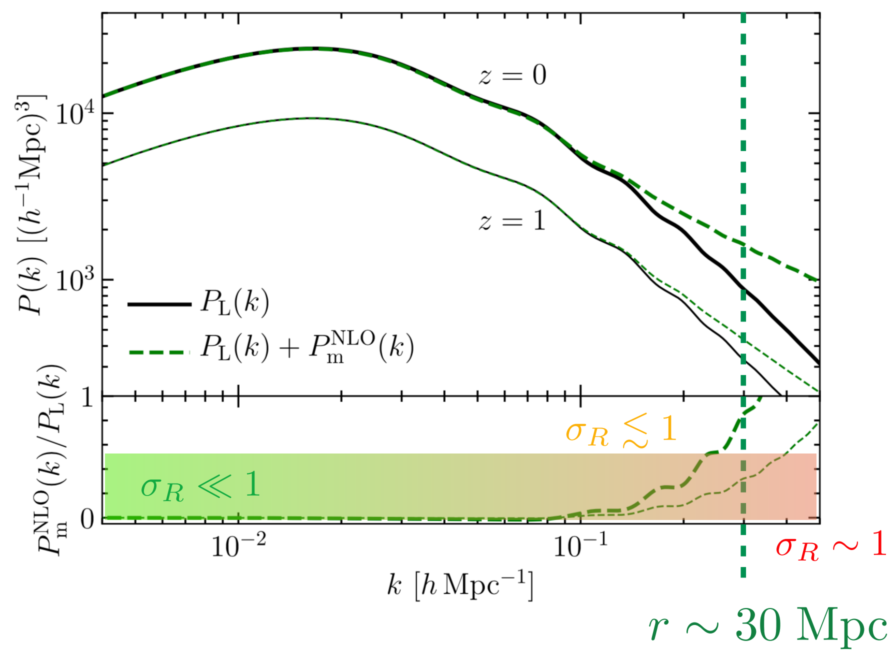
$$N_{\rm modes}^{\rm CMB} \sim \ell_{\rm max}^2 \sim (2500)^2$$



At large ℓ, limited by fluctuations of late-time origin

Large Scale Structure (LSS) probes a 3D volume

$$N_{\rm modes}^{\rm LSS} \sim k_{\rm max}^3 \,{\rm Volume}$$



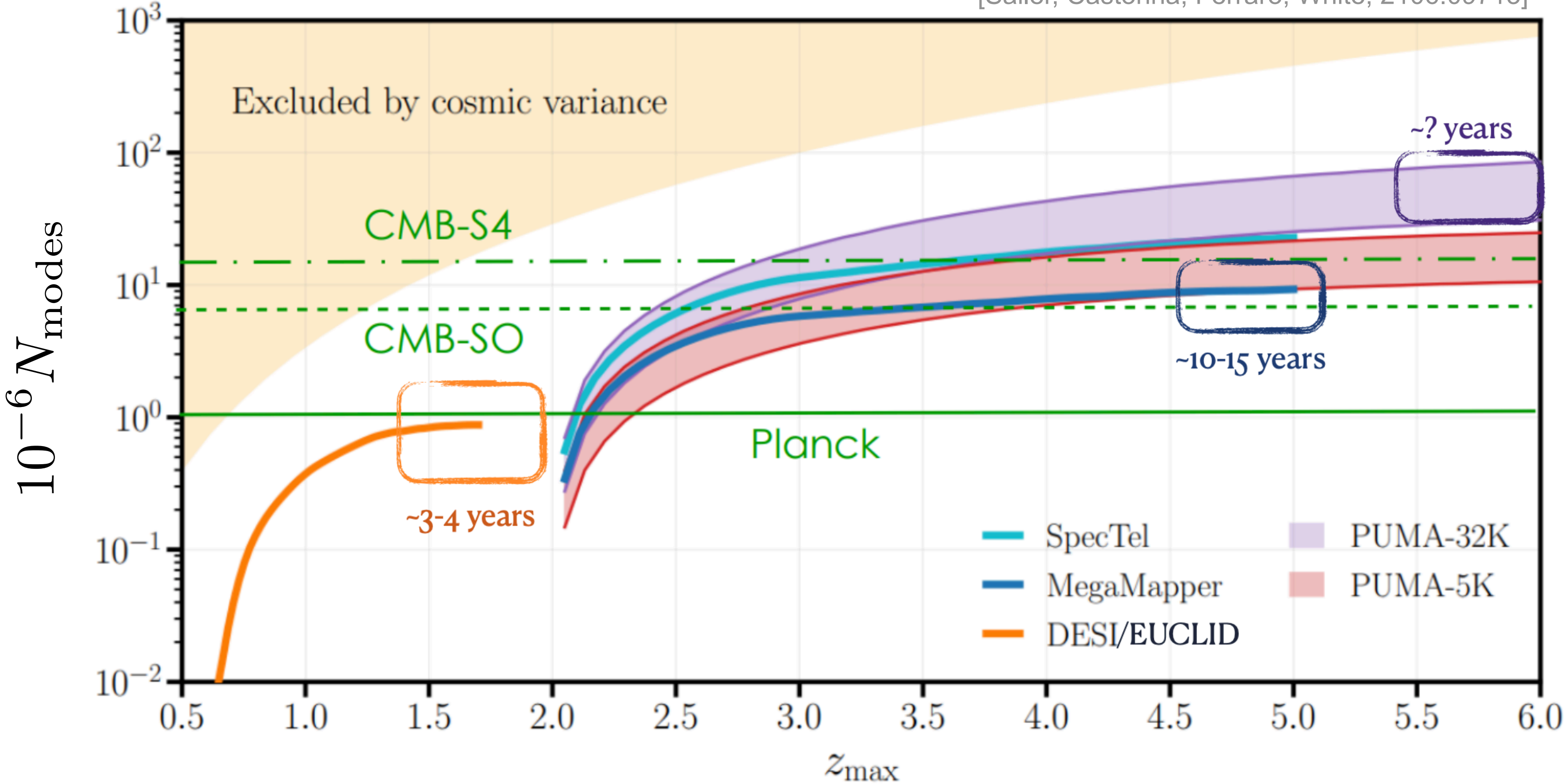
At large k, limited by our ability to make robust predictions on mildly non-linear scales

[Smith, Ferraro, 1607.01769]

[Dodelson, Schmidt, 2020]

Looking ahead: estimate number of modes

[Sailer, Castorina, Ferraro, White, 2106.09713]



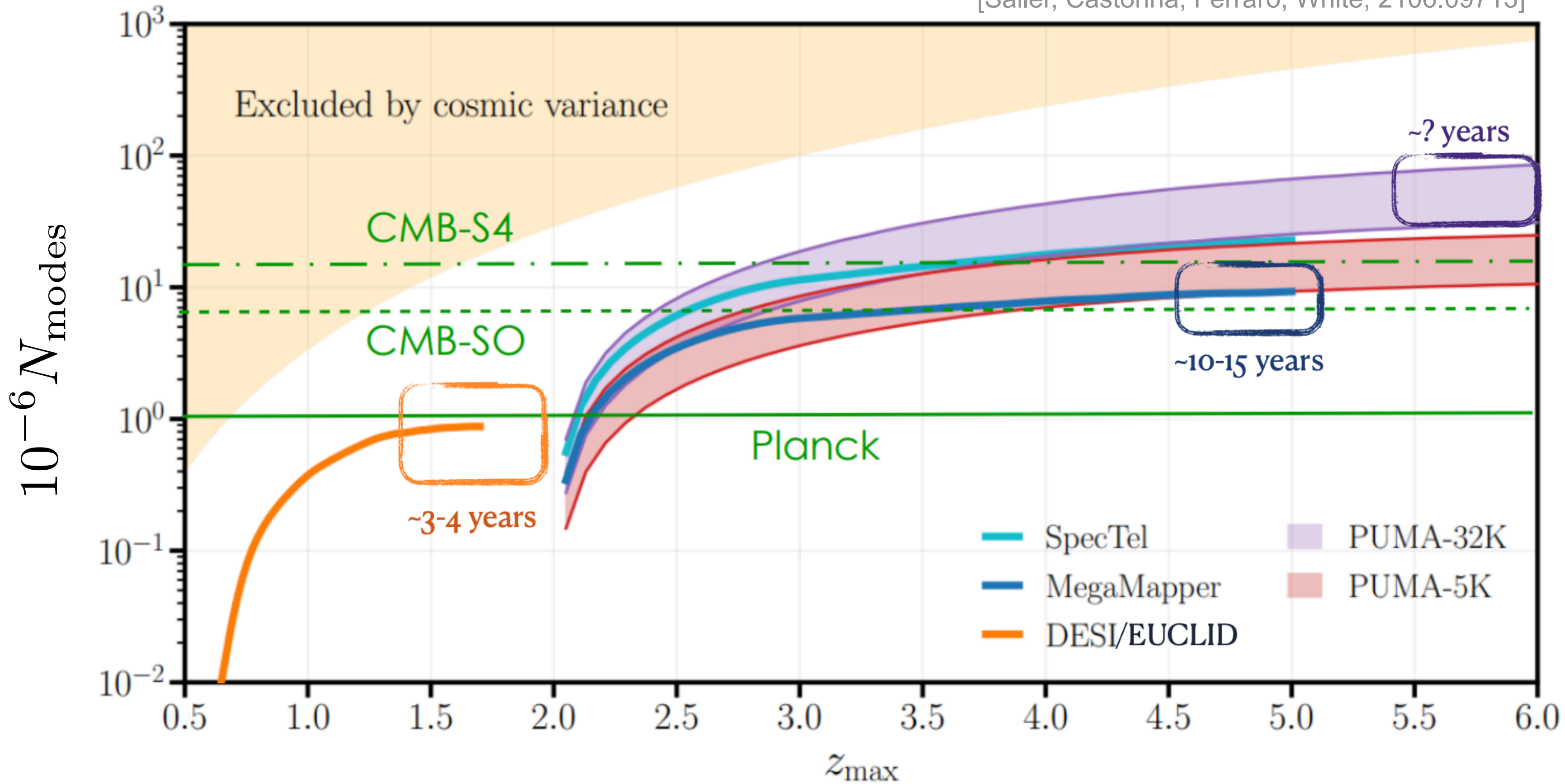
Very soon, LSS will become competitive with CMB

DESI: first data release 2024

Euclid: first data release 2025

Looking ahead: estimate number of modes

[Sailer, Castorina, Ferraro, White, 2106.09713]



Very soon, LSS will become competitive with CMB

Prospects for a S5 spectroscopic survey are encouraging

DESI: first data release 2024

Euclid: first data release 2025

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  [Archidiacono, Castorina, Redigolo, Salvioni 2204.08484]
  [Bottaro, Castorina, Costa, Redigolo, Salvioni 2309.11496]
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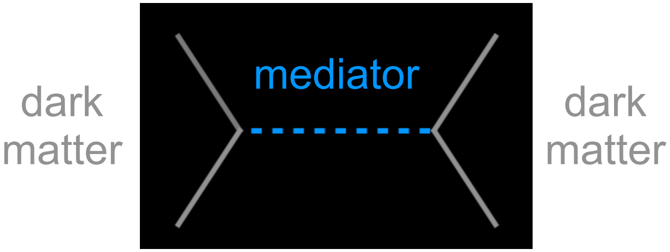
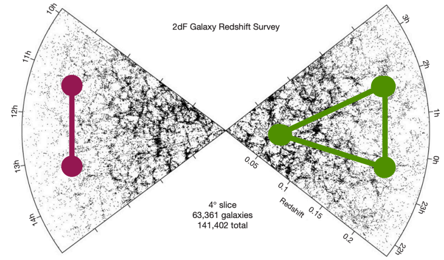


Calculating LSS observables



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

But we observe galaxies (angle and redshift): $\delta_g(\vec{k}, a) = \dfrac{\delta n_g}{\bar{n}_g}$

$$\langle \delta_g(\vec{k}_1)\delta_g(\vec{k}_2)\rangle = (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P_g(k_1)$$

power spectrum

$$\langle \delta_g(\vec{k}_1)\delta_g(\vec{k}_2)\delta_g(\vec{k}_3)\rangle = (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B_g(k_1, k_2, k_3)$$

bispectrum

$$\ldots$$

Galaxy overdensities track matter overdensities: systematic expansion

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

$K_{ij} \equiv (\nabla_i \nabla_j / \nabla^2 - \delta_{ij}/3)\delta_m$

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

galaxy correlators are expressed in terms of correlators of underlying field(s)

[our analysis is in redshift space; here show real space for simplicity]

Calculating LSS observables in LCDM

Start from Boltzmann equation for collision-less fluid, in matter domination

for sub-horizon scales:

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

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

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

effective stress-energy tensor, accounting for short-scale physics (not a perfect fluid)

EFT of LSS

[Senatore; Baumann, Nicolis, Zaldarriaga, Carrasco, Hertzberg, 2010-2012]

$$\nabla_i\nabla_j \tau^{ij}_{\rm eff} = \bar{\rho}_m \, c_s^2 \nabla^2 \delta_m + \ldots$$

counterterm

Calculating LSS observables in LCDM

Start from Boltzmann equation for collision-less fluid, in matter domination for sub-horizon scales:

$$(\theta_m \equiv \nabla_i v_m^i)$$

$$\delta_m' + \theta_m + \nabla_i(\delta_m v_m^i) = 0 \,,$$

$$\theta_m' + \mathcal{H}\theta_m + \frac{3}{2}\mathcal{H}^2\delta_m + \nabla_i(v_m^j \nabla_j v_m^i) = \frac{1}{\bar{\rho}_m}\nabla_i\nabla_j\tau_{\rm eff}^{ij}$$

Perturbative solution has the form

initial fluctuation, at ~ matter/radiation equality

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

linear growth factor:

$$D_{1m}^{\rm CDM}(a) = a$$

time- and space-dependences factorize

All time dep. encoded by linear growth factor

LCDM non-linear kernels

(mode coupling)

[Bernardeau, Colombi, Gaztañaga, Scoccimarro 2001]

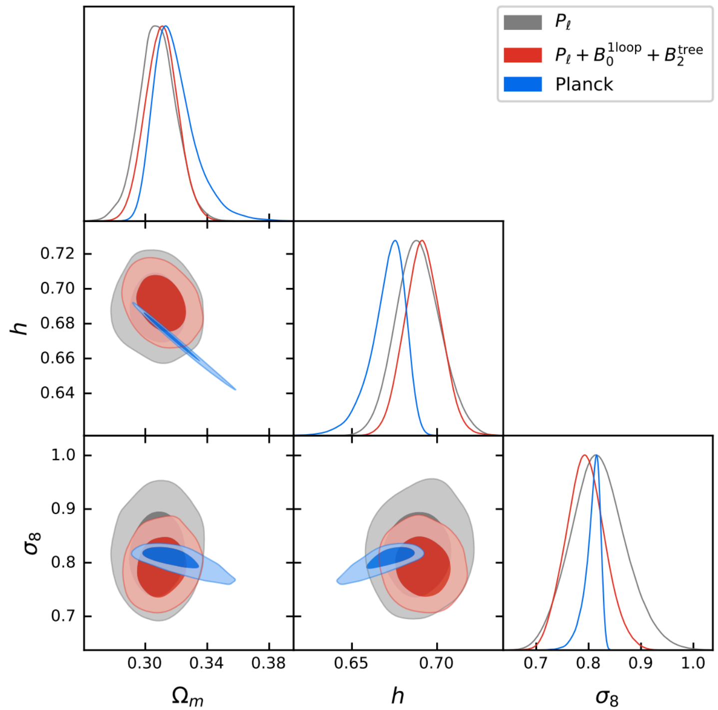
Success of LSS program for LCDM

These results enabled perturbative calculation of galaxy correlation functions

- Modeling of power spectrum and bispectrum at one loop, up to $k_{\max} \simeq 0.2\, h\, \mathrm{Mpc}^{-1}$
- Bias coefficients and counterterms are treated as nuisance parameters and fit to data → very robust approach

Full-shape analysis of BOSS data with BBN prior adds important new information beyond Planck

[D'Amico, Lewandowski, Senatore, Zhang + …]
[Ivanov, Philcox, Simonović, Zaldarriaga + …]
…

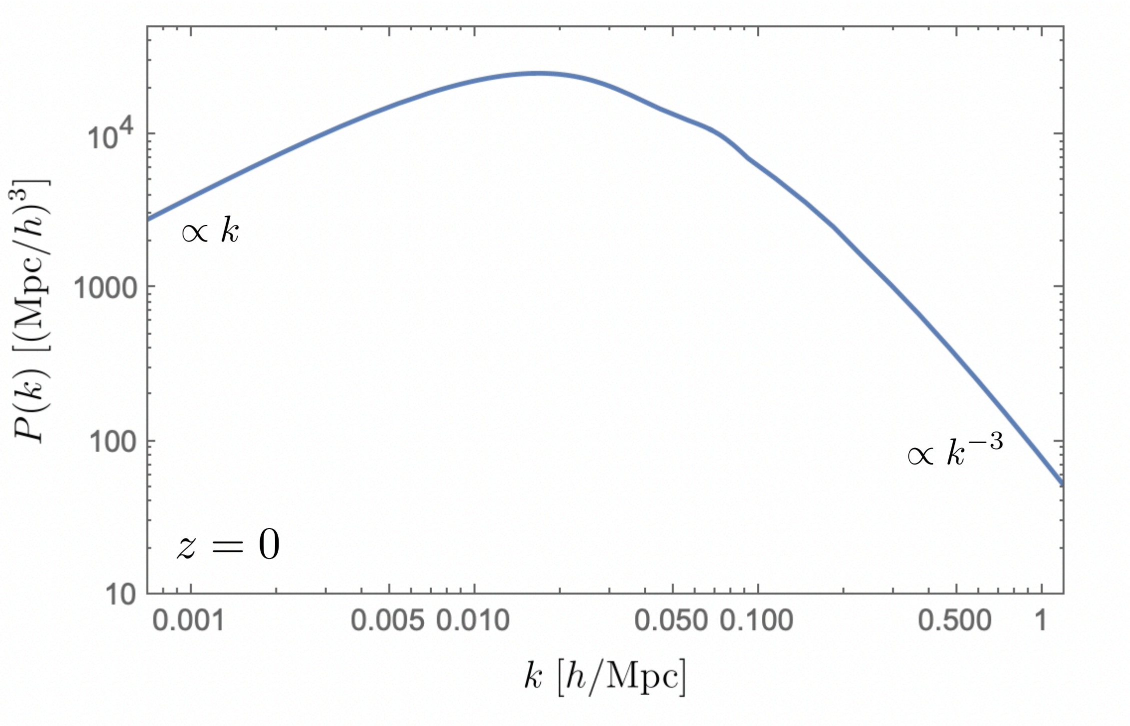


[D'Amico, Donath, Lewandowski, Senatore, Zhang, 2206.08327]

Going BSM

EFT of LSS has been applied with great success within LCDM.

With DESI & Euclid data in sight, what new physics can be probed?

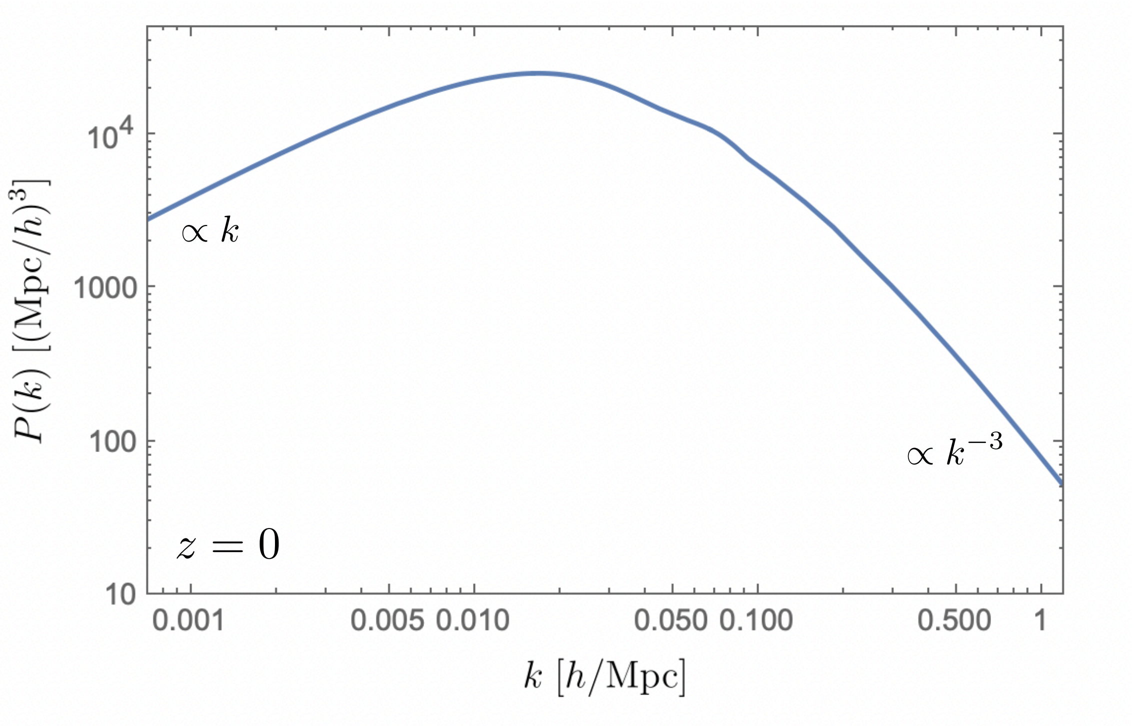


Examples: drop/rise at small scales, new features in BAO, DM self-interactions, …

Going BSM

EFT of LSS has been applied with great success within LCDM.

With DESI & Euclid data in sight, what new physics can be probed?



Extending EFT of LSS to BSM allows us to use info from full shape of power spectrum

→ robust discovery potential

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[Archidiacono, Castorina, Redigolo, Salvioni 2204.08484]
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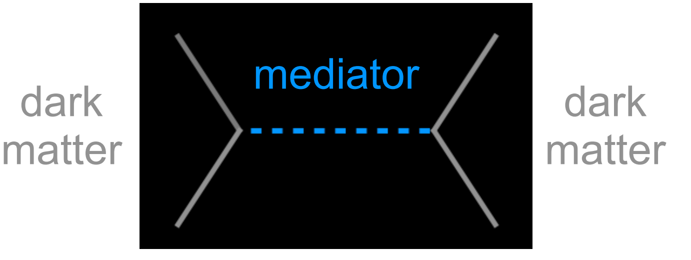
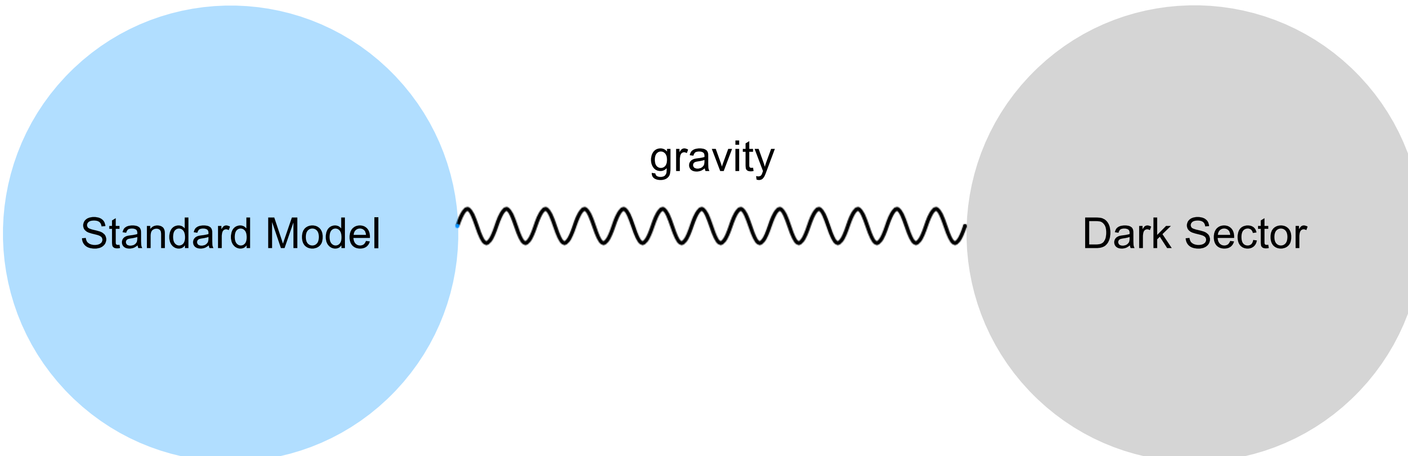
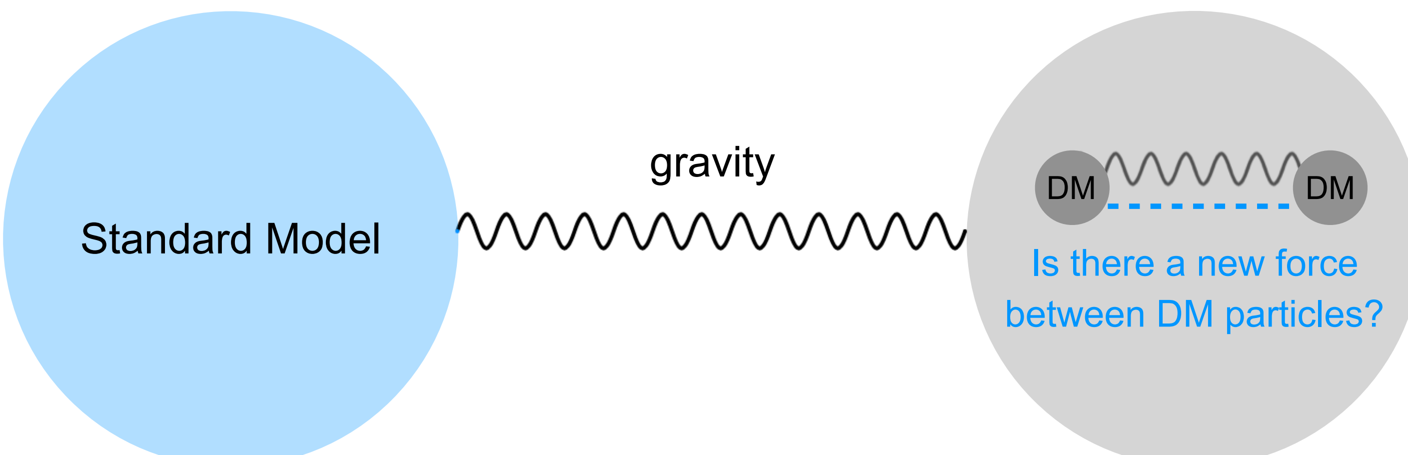


Dark forces

(Nightmare) scenario:

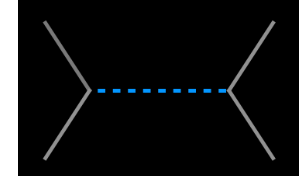


But cosmology and astrophysics can still probe nature of dark sector:



(DM produced non-thermally)

A toy model



scalar mediator

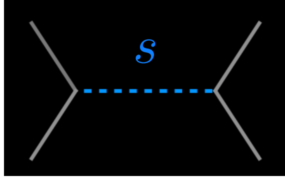
$$2\mathcal{L} \supset -m_\chi^2 \chi^2 - \kappa \varphi \chi^2$$

DM

→ effect of interaction can be seen as field-dependent mass for DM

[Damour, Gibbons, Gundlach, 1990]
[Farrar, Peebles, 2003]

A toy model



scalar mediator

$$2\mathcal{L} \supset -m_\chi^2 \chi^2 - \kappa \varphi \chi^2$$

DM

→ effect of interaction can be seen as field-dependent mass for DM

Define new scalar potential $s = G_s^{1/2} \varphi$ $\quad G_s \equiv \frac{\kappa^2}{m_\chi^4}$

$$2\mathcal{L} = -(\partial\chi)^2 - m_\chi^2(s)\chi^2 - \frac{1}{2G_s}(\partial s)^2 - \frac{1}{2G_s} m_s^2 s^2 + \mathcal{O}(1/G_s^2)$$

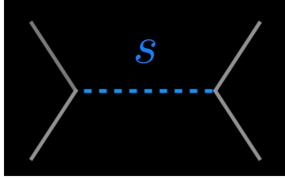
field-dependent DM mass $\qquad$ scalar mediator

self-scattering of mediator is negligible

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

[Damour, Gibbons, Gundlach, 1990]
[Farrar, Peebles, 2003]

A toy model



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field-dependent DM mass $\qquad$ scalar mediator

Three parameters

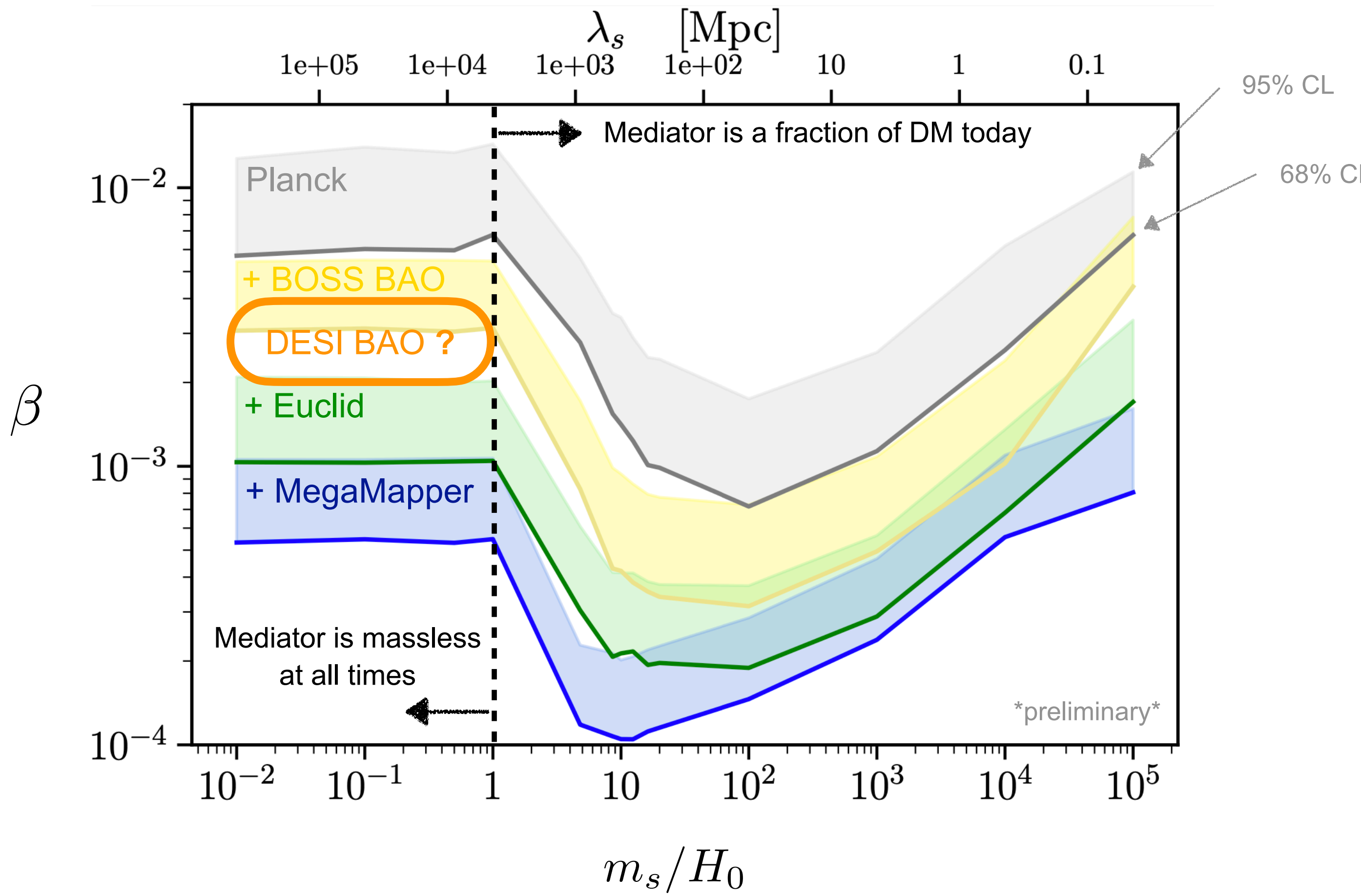
1. Strength of dark force, $\beta \equiv \frac{G_s}{4\pi G_N}$
2. Range of dark force, m_s
3. Fraction of DM that is interacting, f_χ

Here focus on

- long-range interactions $m_s/H_0 \lesssim 10^5$
- 100% of DM is interacting $f_\chi \simeq 1$

$H_0 \approx 10^{-33}$ eV

Results

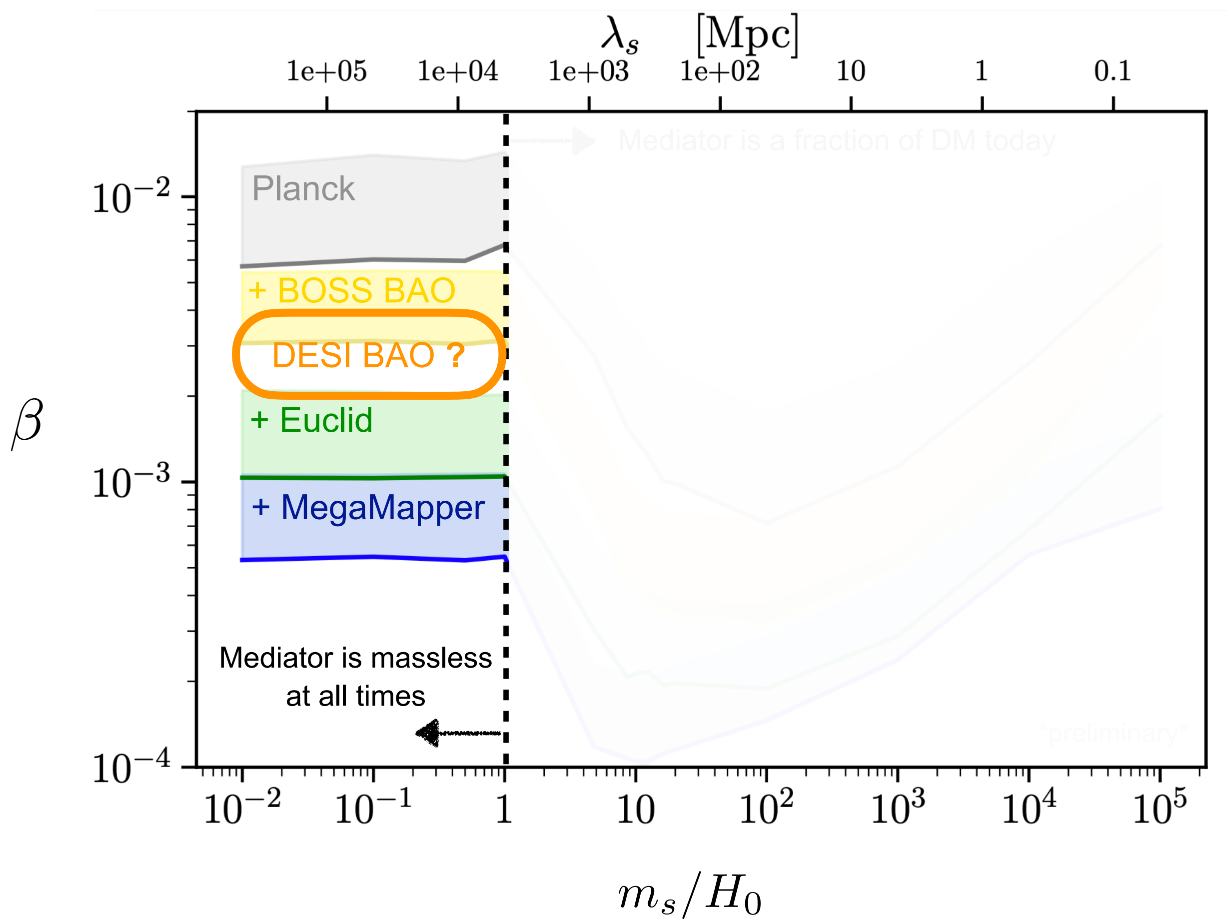


Full-shape of power spectrum will probe strength of new forces

at least down to 0.002 x gravity

[Bottaro, Castorina, Costa, Redigolo, Salvioni to appear]

Results

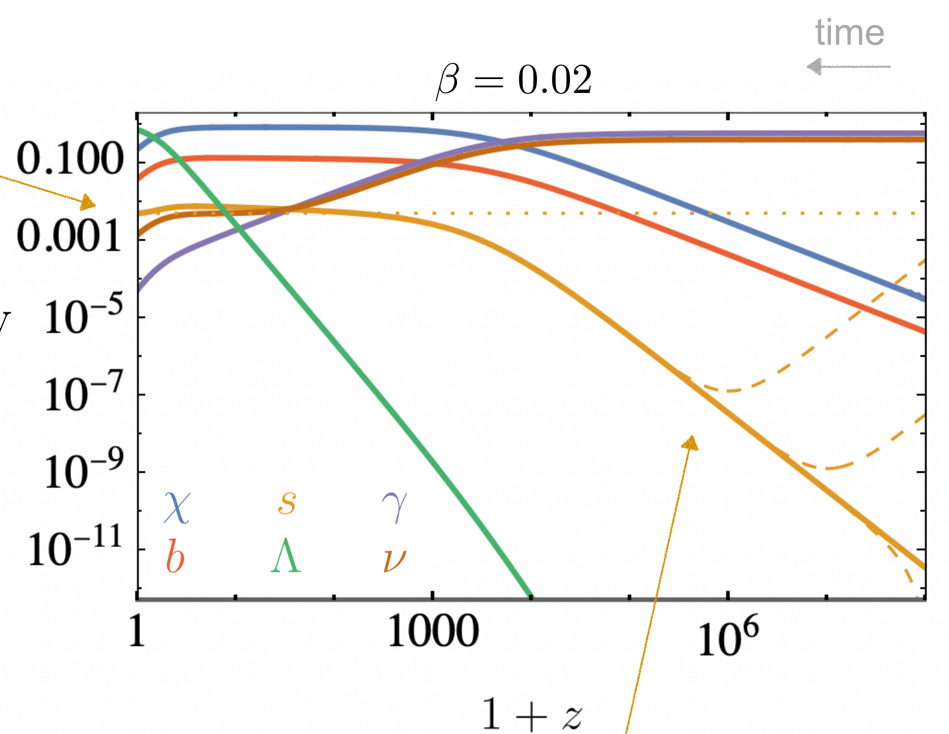


$$m_s \lesssim H_0$$

[Bottaro, Castorina, Costa, Redigolo, Salvioni to appear]

Evolution of scalar background

Present density is subleading effect,
s is only a force mediator



Dominated by kinetic energy at all times,

$$w_s = \overline{\mathcal{P}}_s / \bar{\rho}_s \simeq +1$$

s is sourced by DM density,

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

$$(m_s \lesssim H_0)$$

[Damour, Gibbons, Gundlach 1990]
[Farrar, Peebles 2003]

Main physical effects

1) Modified background evolution impacts cosmological distances: $\text{distance}\,(z) \propto H^{-1}$

DM transfers energy to scalar → DM energy density redshifts faster $\bar{\rho}_\chi \propto a^{-(3+\beta f_\chi)}$ → $\frac{H}{H_{\rm CDM}} = 1 - \frac{\beta f_\chi^2}{2} \log \frac{a}{a_{\rm eq}}$

large log (~ 8 at small redshift)
due to long-range nature of force

2) Enhanced growth of matter fluctuations

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

Relative fluctuations between DM and baryons also generated: EP violation

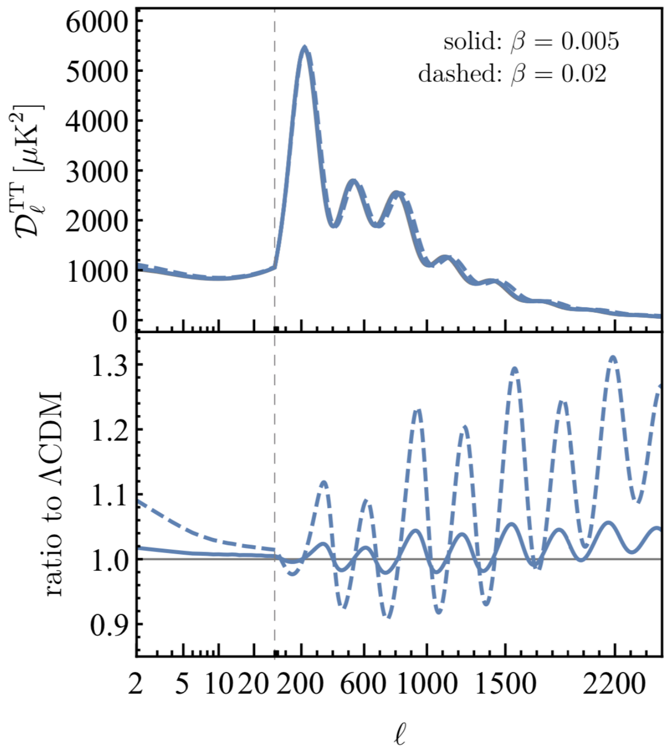
$$\delta_r(\vec{k}, a) = \frac{5}{3}\beta f_\chi \delta_m^{\rm CDM}(\vec{k}, a)$$

$$(\delta_r = \delta_\chi - \delta_b)$$

but not log-enhanced: subleading (for $f_\chi \simeq 1$)

Effects on linear cosmology

CMB



Physical scales are little affected at last scattering (effects of new force negligible until equality)

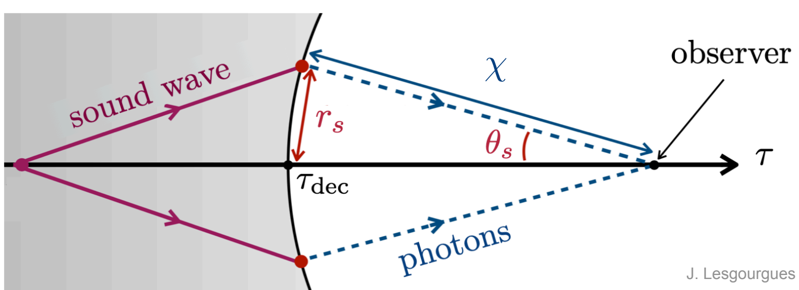
Main effect is modification of distance from today to last scattering

↓

peaks and troughs shift compared to LCDM

$$\theta_s = \frac{r_s}{\chi}$$

$$\chi(z) = \int_0^z \frac{dz'}{H(z')}$$



Effects on linear cosmology

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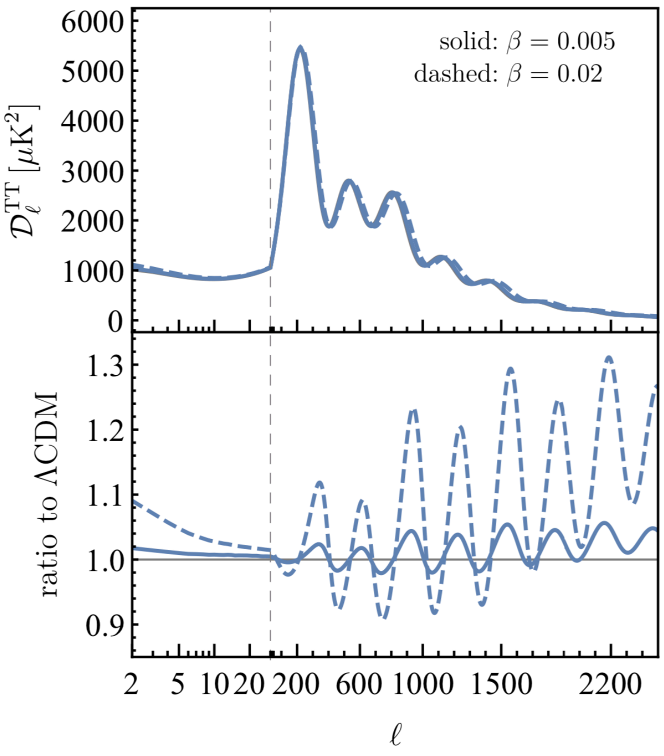
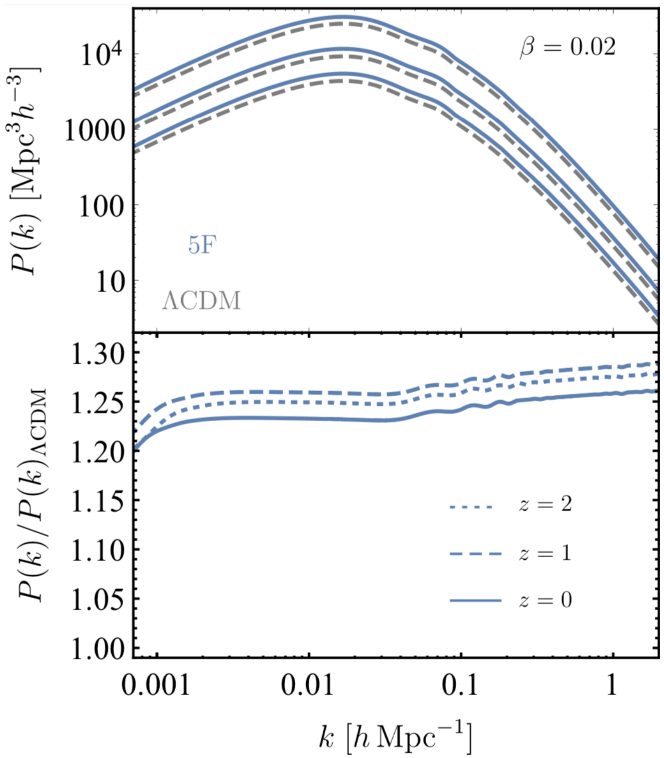


Matter power spectrum



scale-independent increase of linear power spectrum

$$P_{m,L}(k,a) \simeq \left(1 + \frac{12}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}\right) P_{m,L}^{\rm CDM}(k,a)$$

Non-linear predictions

One-loop calculation of galaxy power spectrum is needed to compare to data

→ consistently develop EFT of LSS for long-range dark forces

Keeping only leading log-enhanced terms, structure of nonlinear corrections is same as LCDM,

but with modified linear growth factor

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

$$D_{1m}(a) = \left(1 + \frac{6}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}\right) D_{1m}^{\rm CDM}(a)$$

same nonlinear kernels as in LCDM

[modulo not-log-enhanced corrections]

[Bottaro, Castorina, Costa, Redigolo, Salvioni 2309.11496, Appendices]

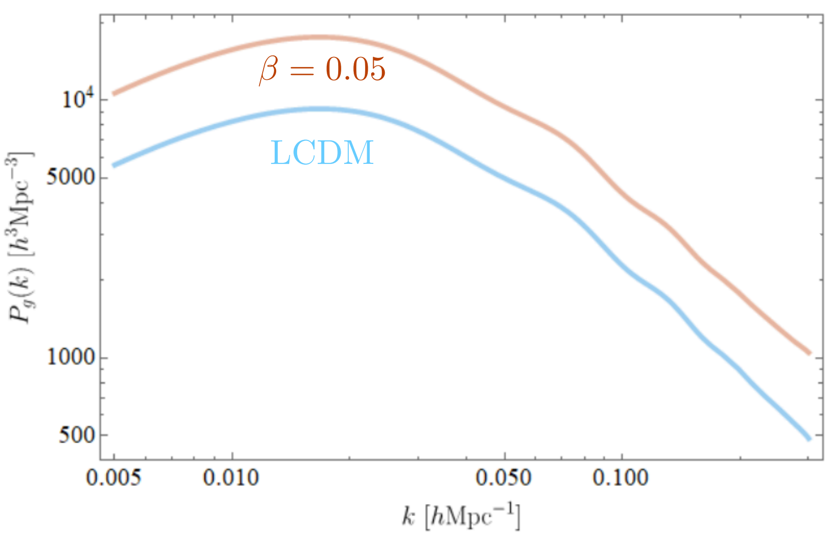
Dark force vs galaxy bias

One-loop galaxy power spectrum:

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

$$\propto \left(1 + \frac{12}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}\right) \qquad \propto \left(1 + \frac{24}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}\right)$$

$(\delta_g = b_1 \delta_m + \ldots)$



At linear level, increase of power can be absorbed by bias parameter

$$b_1^2 \to \frac{b_1^2}{1 + \frac{12}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}}$$

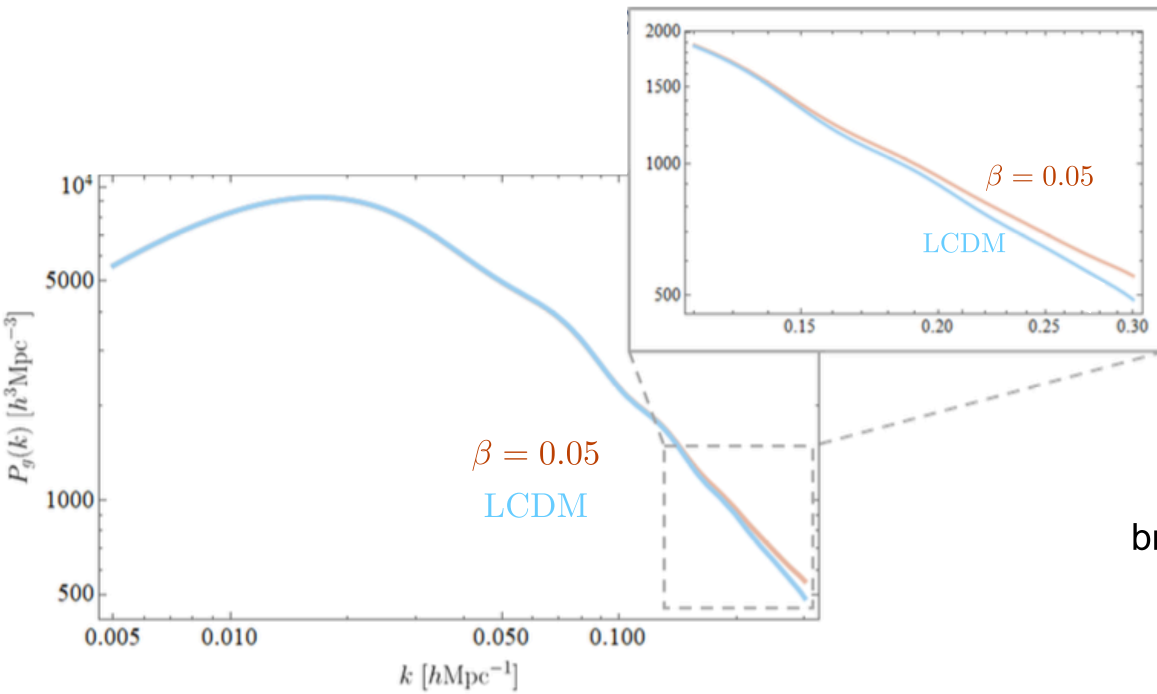
Dark force vs galaxy bias

One-loop galaxy power spectrum:

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

$$\propto \left(1 + \frac{12}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}\right) \qquad \propto \left(1 + \frac{24}{5}\beta f_\chi^2 \log\frac{a}{a_{\rm eq}}\right)$$

$(\delta_g = b_1\delta_m + \ldots)$



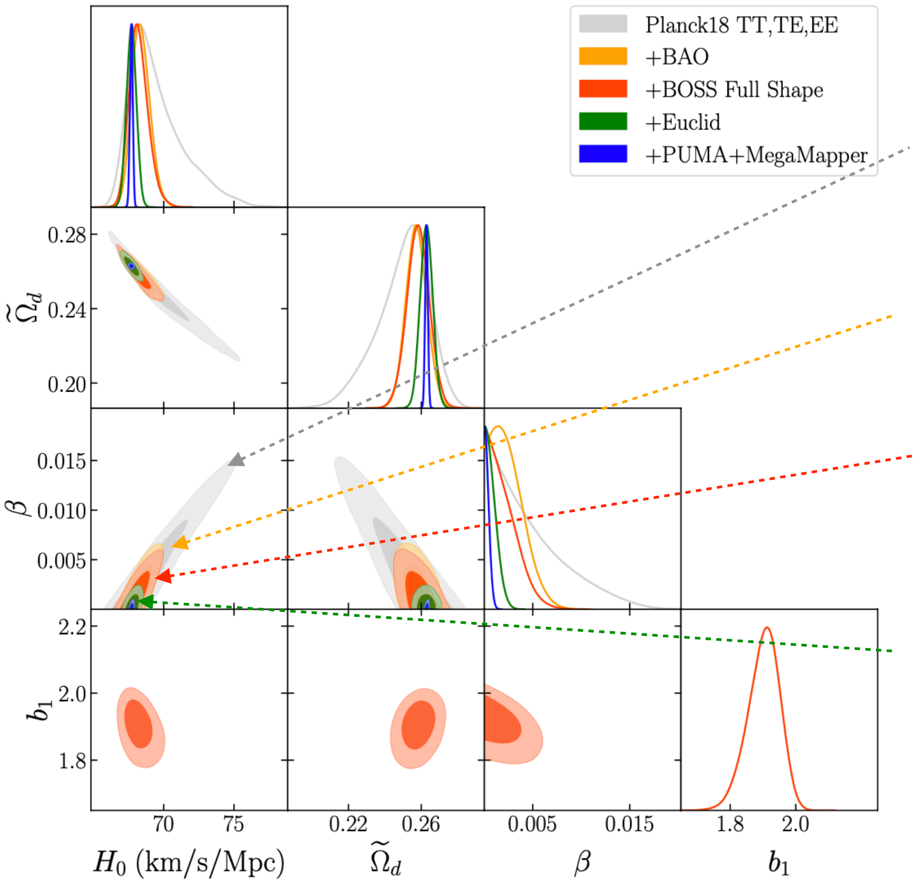
One-loop correction

breaks b_1 - β degeneracy

↓

separate new physics from astrophysics

Results



CMB alone gives $\beta \lesssim 0.01$, but suffers from the geometric Ω_m - H_0 degeneracy

BAO breaks degeneracy, improving constraint by factor 2

Including full shape of BOSS power spectrum gives limited improvement, because b_1 is poorly measured in BOSS

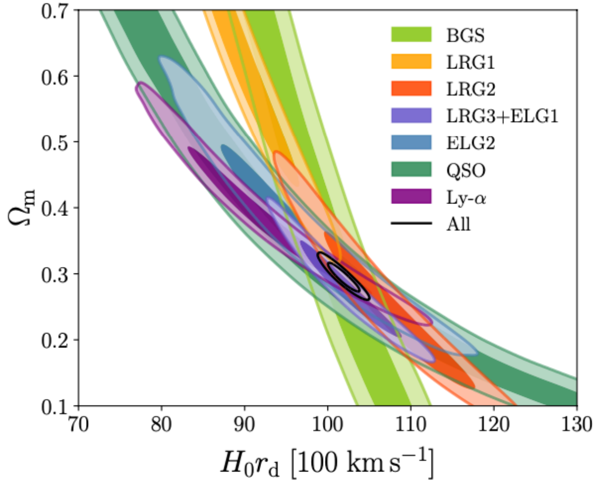
Euclid will improve constraint strongly, thanks to increased precision on b_1 : $\beta < 0.002$

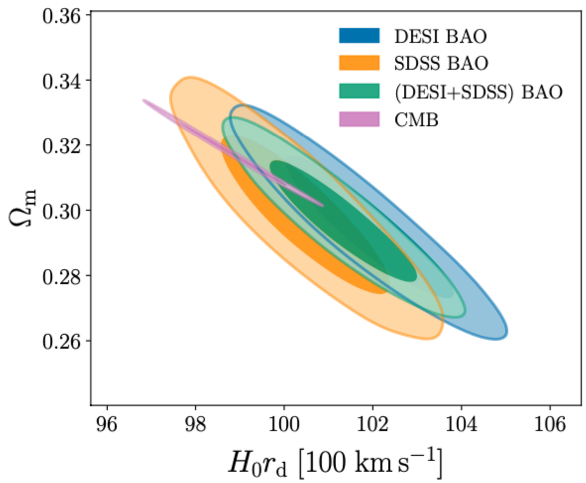
BOSS analysis with PyBird [D'Amico, Senatore, Zhang 2003.07956]
Forecasts with FishLSS [Sailer, Castorina, Ferraro, White 2106.09713]

The Ω_m - H_0 degeneracy of CMB is enhanced by new physics: $\beta \uparrow$ $H_0 \uparrow$ $\Omega_m \downarrow$

DESI BAO

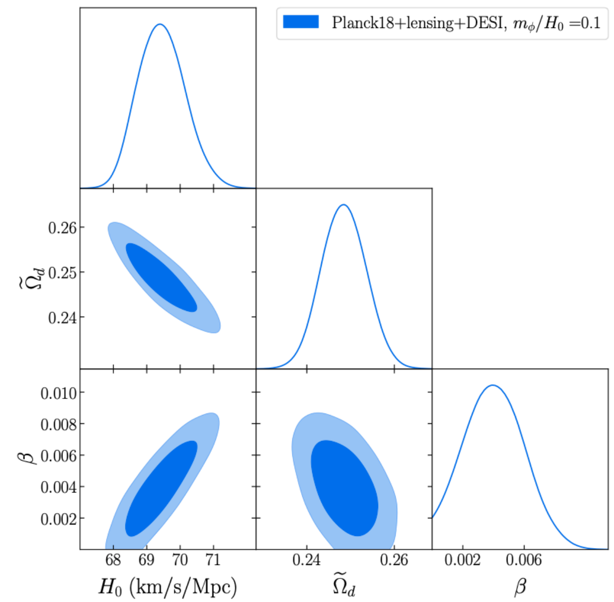
[DESI 2404.03002]





First DESI results,
April 2024

LRG2 sample @ $z_{\text{eff}} \approx 0.7$ drives
mild preference for higher H_0 than BOSS

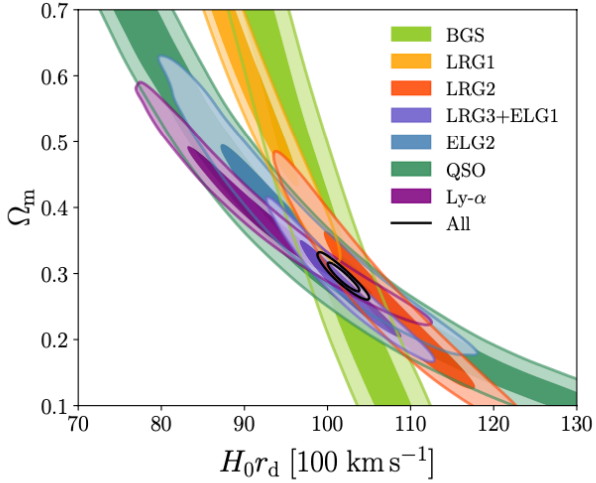


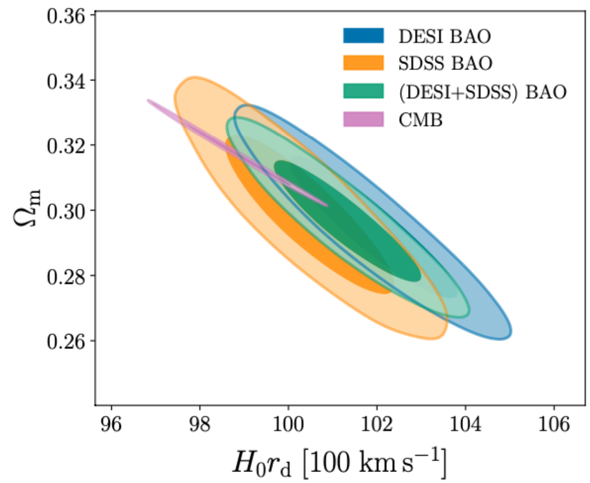
$\beta \sim 0.004 \pm 0.002$

See also [Craig, Green, Meyers, Rajendran 2405.00836],
(modification of background cosmology was not included)

DESI BAO

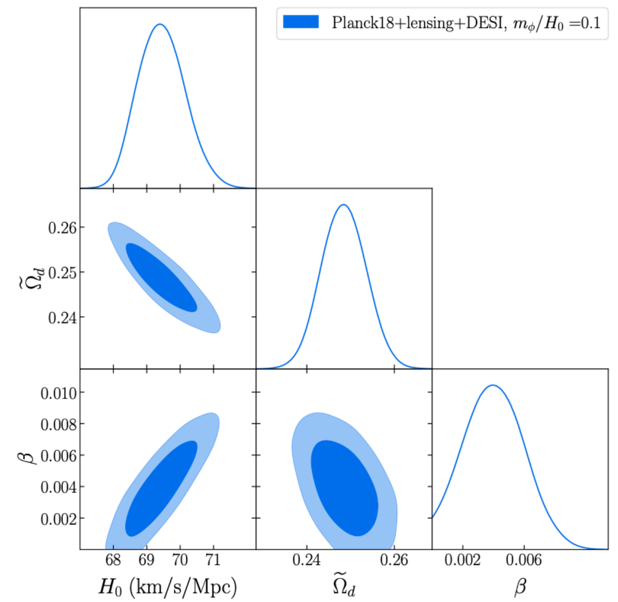
[DESI 2404.03002]

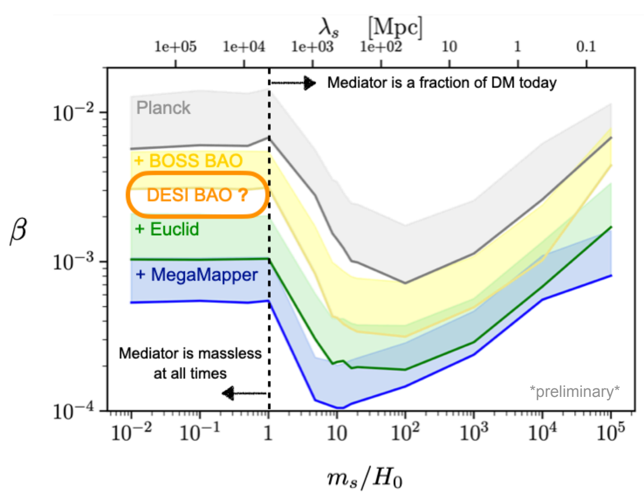




First DESI results,
April 2024

LRG2 sample @ $z_{\rm eff} \approx 0.7$ drives
mild preference for higher H_0 than BOSS





$\beta \sim 0.004 \pm 0.002$

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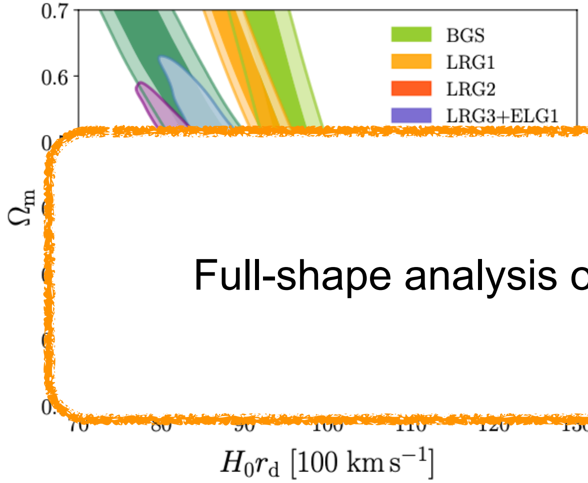
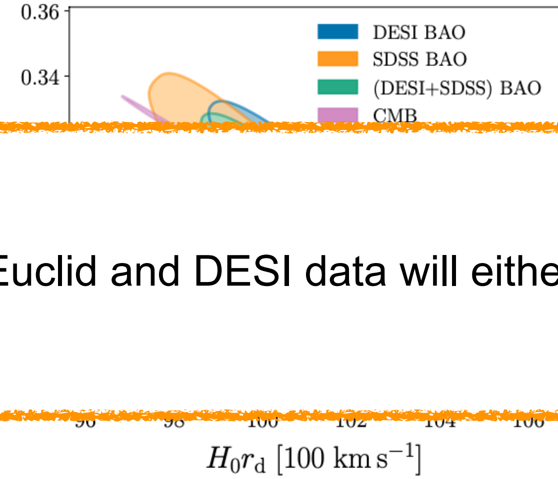
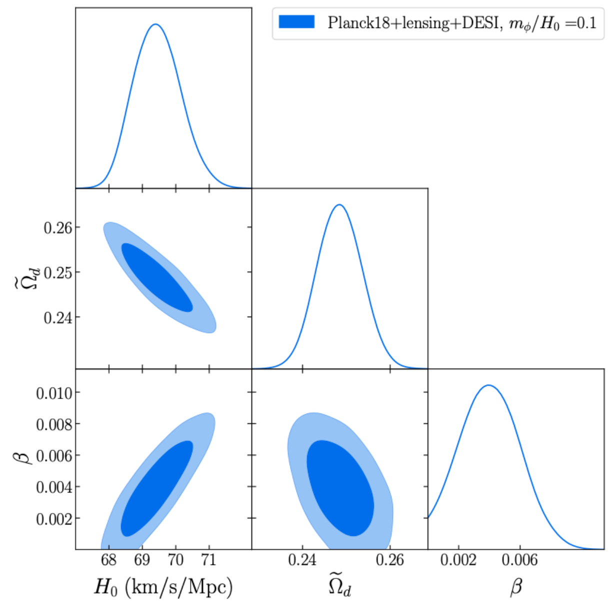




Full-shape analysis of Euclid and DESI data will either disprove or confirm this

LRG2 sample @ $z_{\rm eff} \approx 0.7$ drives mild preference for higher H_0 than BOSS



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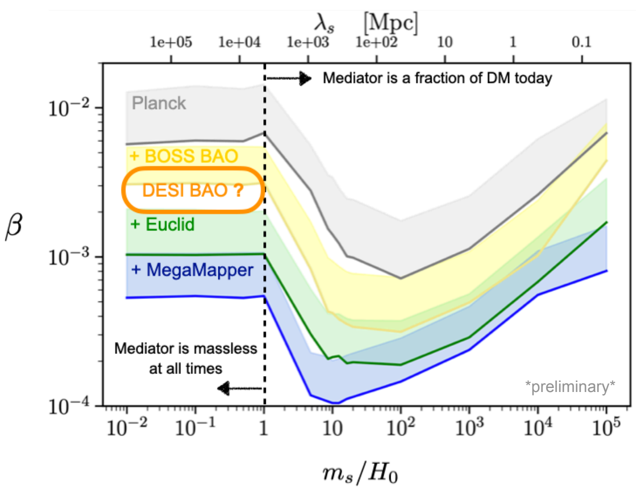
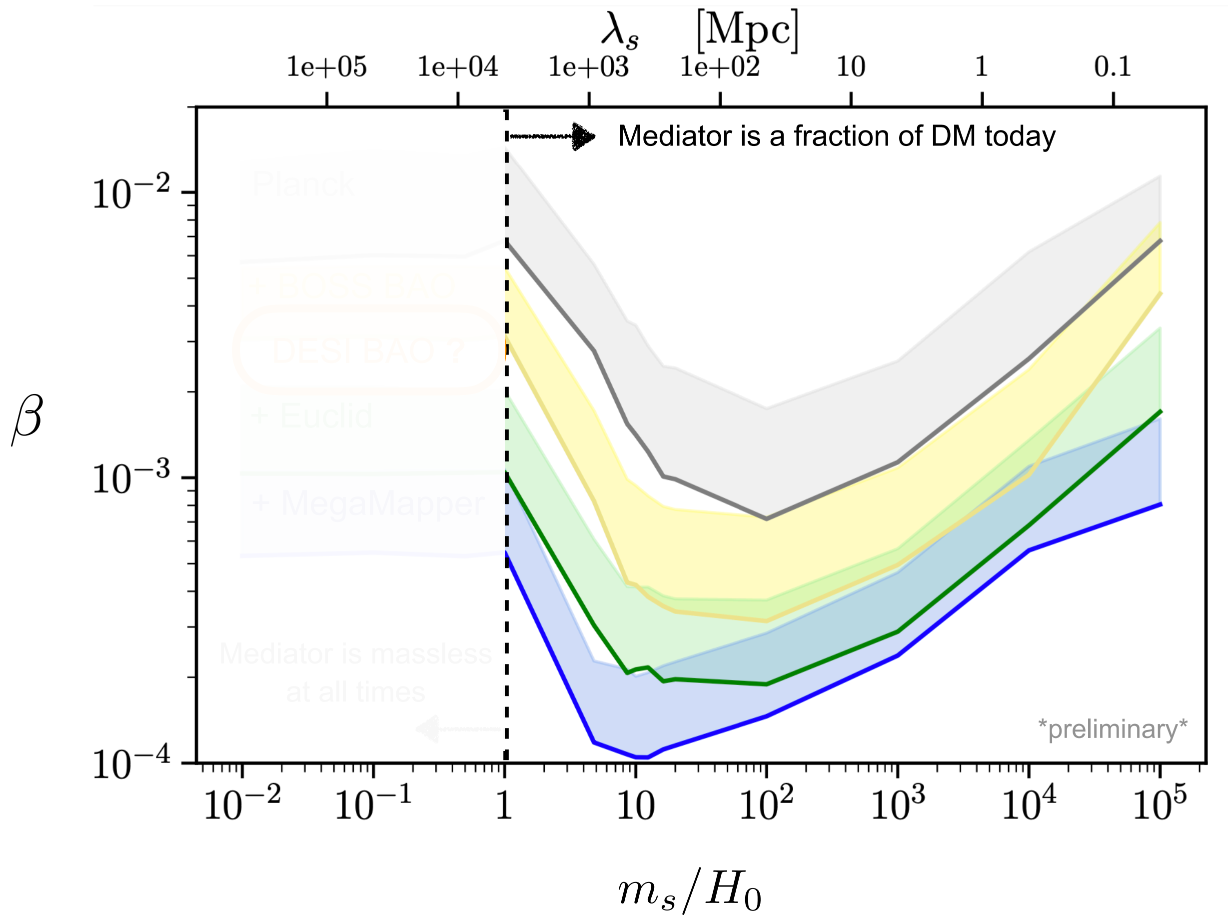


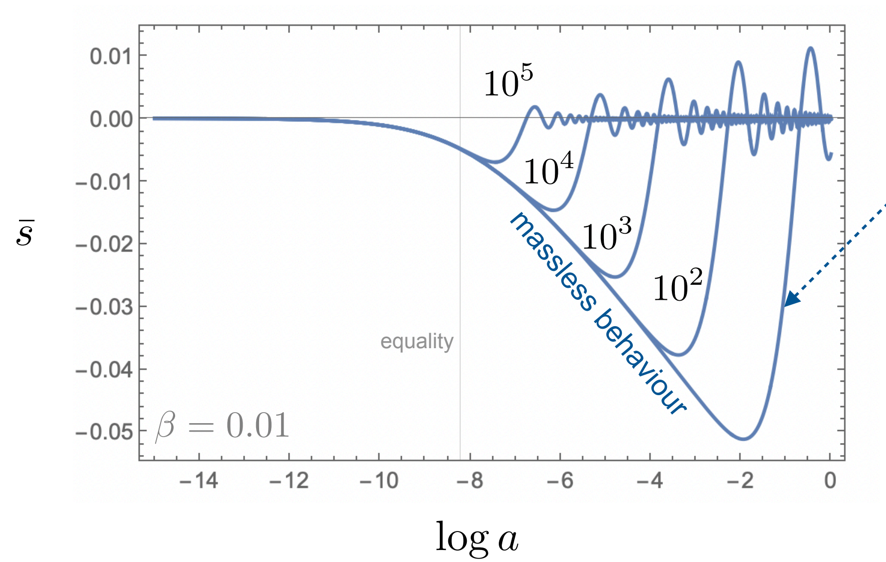
Results



$$m_s > H_0$$

[Bottaro, Castorina, Costa, Redigolo, Salvioni to appear]

Mediator heavier than H_0

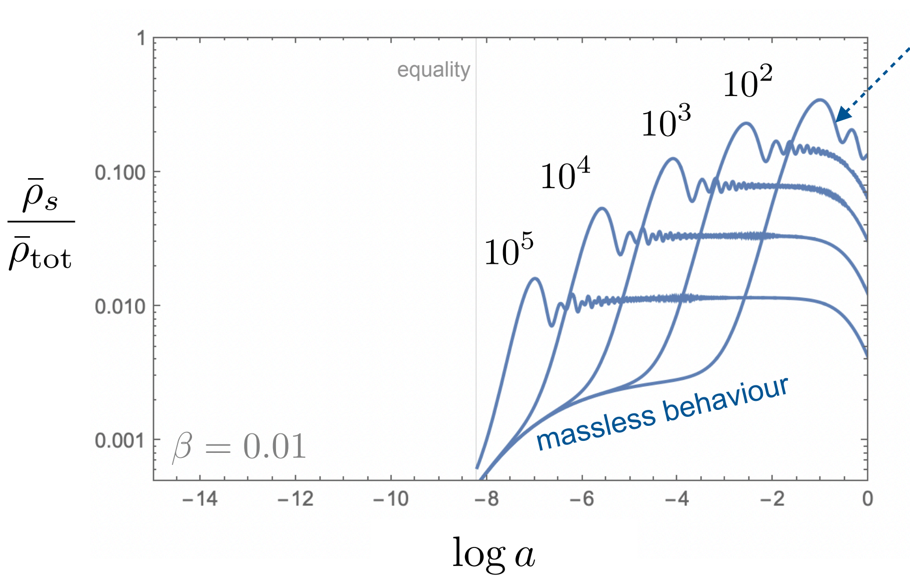


$\frac{m_s}{H_0} = 10$

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

When mass term and DM source term become comparable, scalar begins to oscillate

→ transition from $w_s = +1$ to $(w_s)_{\text{eff}} = 0$



$\frac{m_s}{H_0} = 10$

At late times, fraction of energy density in mediator is strongly enhanced wrt massless case,

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

$(f_s^{\text{massless}} = \beta f_\chi^2/3)$

Power spectrum

Matter fluctuations receive two corrections:

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

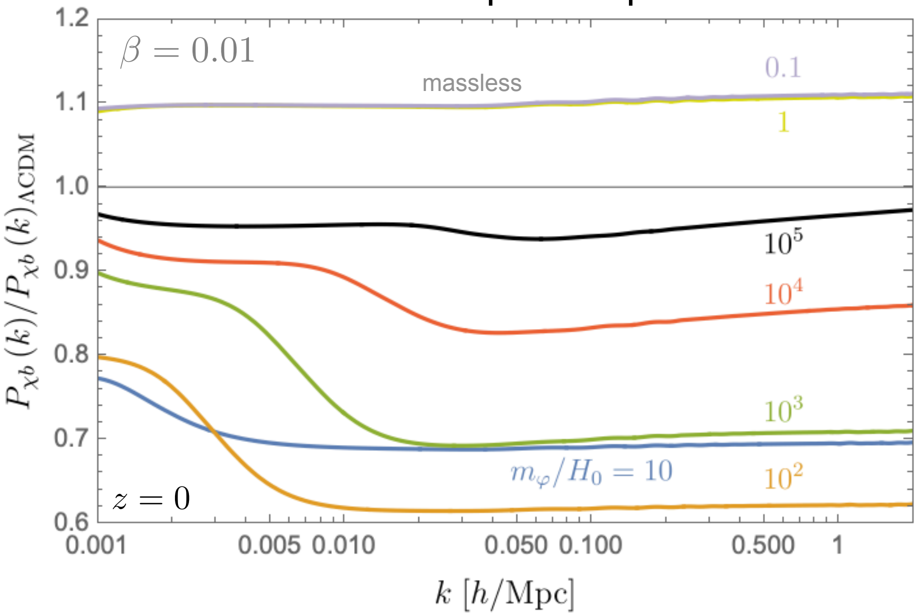
Enhanced growth as long as mediator is massless

Late-time suppression due to s fraction which does not cluster

↓

dominates due to $\log^2$ - enhanced s fraction

ratio to LCDM power spectrum

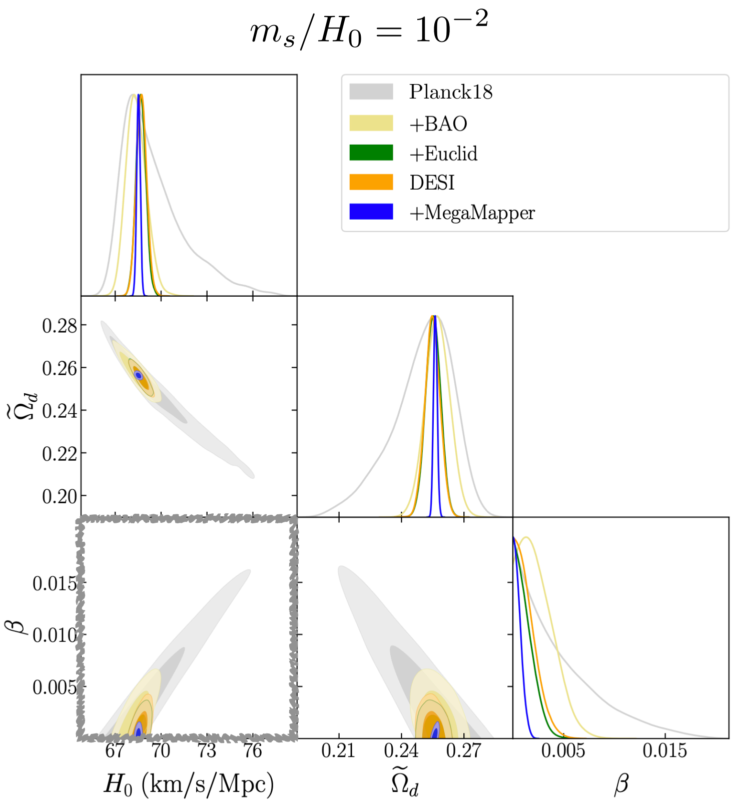


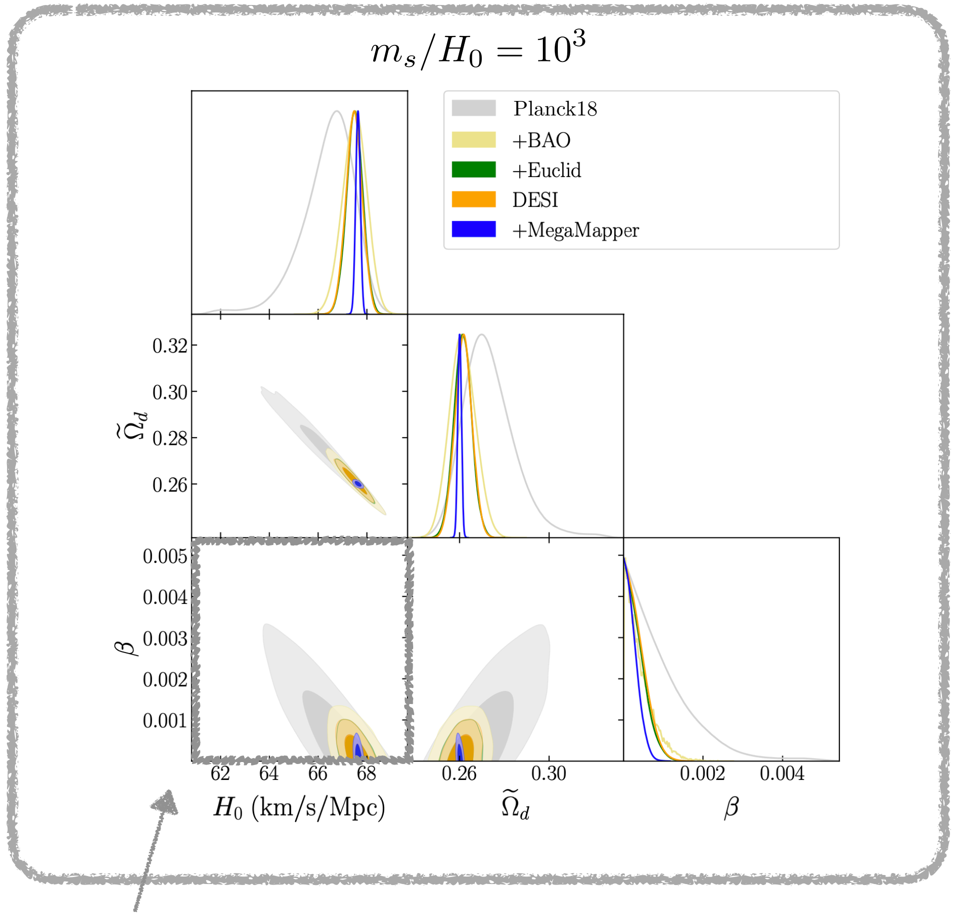
Jeans scale of the mediator

$$k_J(a) \approx 4\times 10^{-4}\, a^{1/4}\left(\frac{m_s}{H_0}\right)^{1/2} h\ \mathrm{Mpc}^{-1}$$

For the mass range considered $k_J \lesssim k_{\rm eq}$ so EFT of LSS does not require modification wrt massless case

Results





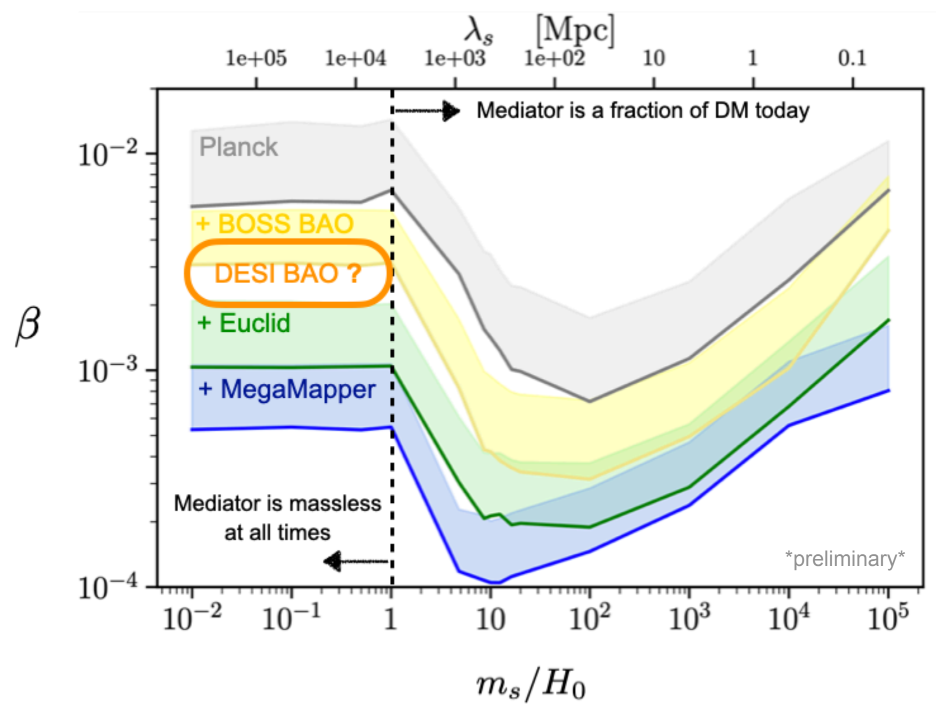
Opposite behaviour along the Ω_m - H_0 degeneracy:

$$\beta \uparrow \qquad H_0 \downarrow \qquad \Omega_m \uparrow$$

(DESI corresponds to pure Fisher forecast)

Conclusion

- EFT of LSS applied successfully in standard cosmology
- DESI / Euclid data are here / imminent, time to put BSM ideas to test
- Extending EFT of LSS to BSM is robust path to potential discoveries



- Extend EFT of LSS to massive mediators

  → probe larger masses for which $k_J \gg k_{\rm eq}$

  [in progress]

- Full analysis including relative fluctuations

  → probe DM fraction $f_\chi \ll 1$ [in progress]

Conclusion

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https://indico.cern.ch/event/1375290

New Physics from Galaxy Clustering III

4–8 Nov 2024
Centro Congressi S. Elisabetta, Parma
Europe/Rome timezone

Enter your search term

Florence 2025

https://www.ggi.infn.it/showevent.pl?id=513

Event at Galileo Galilei Institute

Workshop

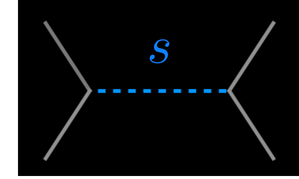
New Physics from Galaxy Clustering at GGI

Aug 25, 2025 - Oct 03, 2025

Apply (deadline: May 31, 2025)

Backup slides

Naturalness



scalar mediator

$$2\mathcal{L} \supset -m_\chi^2\chi^2 - \kappa\varphi\chi^2$$

DM

→ effect of interaction can be seen as field-dependent mass for DM

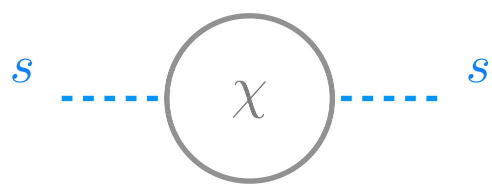
Define new scalar potential $s = G_s^{1/2}\varphi$ $\qquad G_s \equiv \frac{\kappa^2}{m_\chi^4}$

$$2\mathcal{L} = -(\partial\chi)^2 - m_\chi^2(s)\chi^2 - \frac{1}{2G_s}(\partial s)^2 - \frac{1}{2G_s}m_s^2 s^2 + \mathcal{O}(1/G_s^2)$$

field-dependent DM mass $\qquad$ scalar mediator

$H_0 \approx 10^{-33}$ eV

Scalar mass should be at least of size generated by DM loops

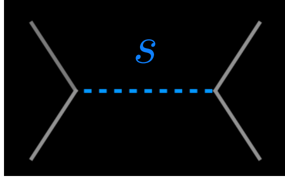


$$m_s^2 \gtrsim \frac{\beta}{(4\pi)^2}\frac{m_\chi^4}{M_{\rm Pl}^2}$$

$$m_\chi \lesssim \frac{(4\pi m_s M_{\rm Pl})^{1/2}}{\beta^{1/4}} \sim \frac{10^{-2}\ {\rm eV}}{\beta^{1/4}}\left(\frac{m_s}{H_0}\right)^{1/2}$$

expect DM to be a light boson

Naturalness



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field-dependent DM mass scalar mediator

$H_0 \approx 10^{-33}$ eV

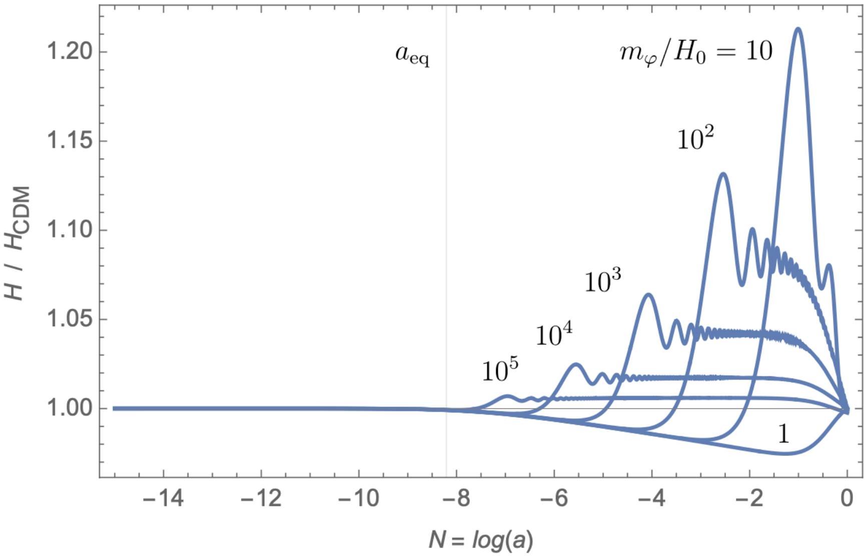
$\kappa = g_D m_\chi$

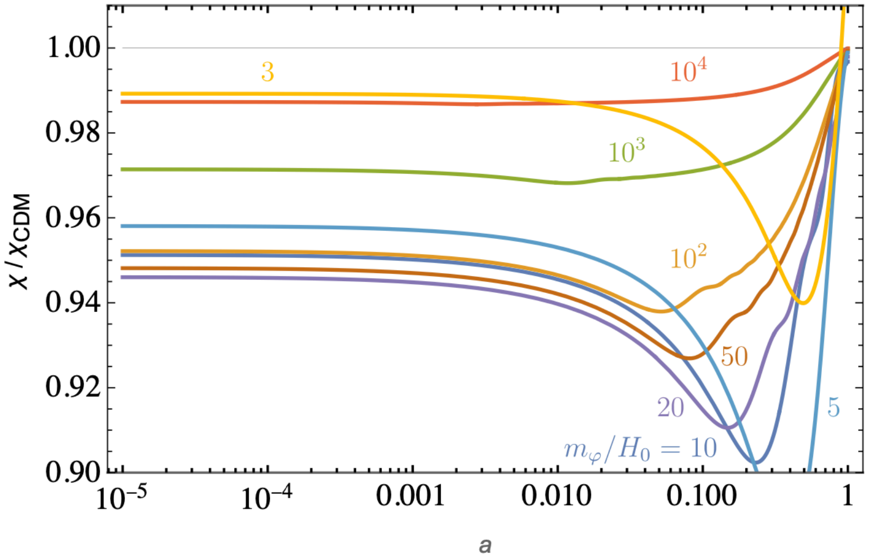
$\beta < 0.005$ → $g_D < 2\times 10^{-32}\left(\frac{m_\chi}{10^{-3}\ \mathrm{eV}}\right)$

current bound

Hubble and distances

$\beta = 0.01$
$h = 0.67$

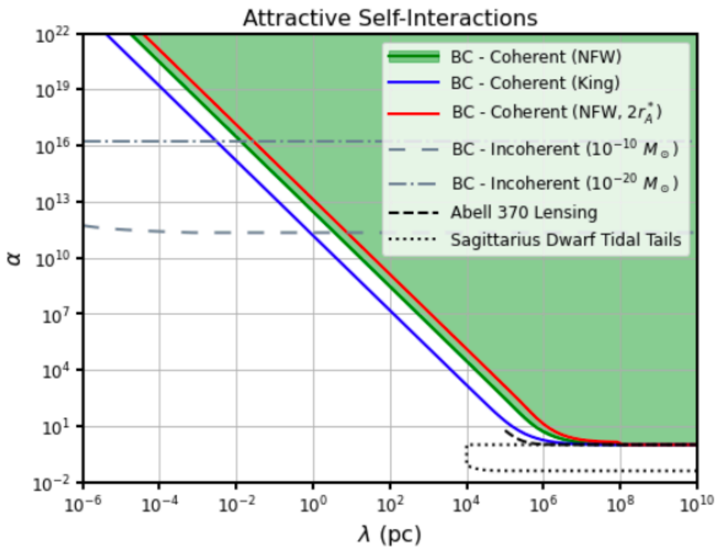


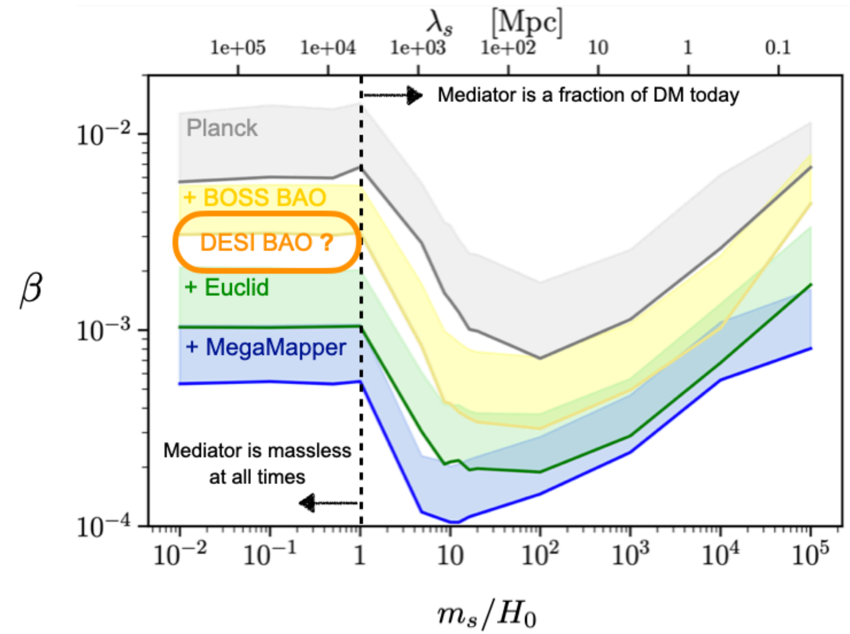


$$\theta_s = \frac{r_s}{\chi} \qquad \chi(z) = \int_0^z \frac{dz'}{H(z')}$$

Comparison to bullet cluster constraints

[Bogorad, Graham, Ramani 2311.07648]





$$\alpha = \beta$$