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GRAVITATION COSMOLOGY and group at USAL

PURE MOMENTUM INTERACTIONS IN THE DARK SIDE OF THE UNIVERSE AND THE SIGMA8 TENSION

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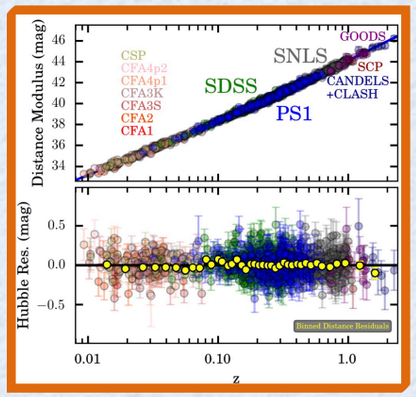
JOSE BELTRÁN JIMÉNEZ

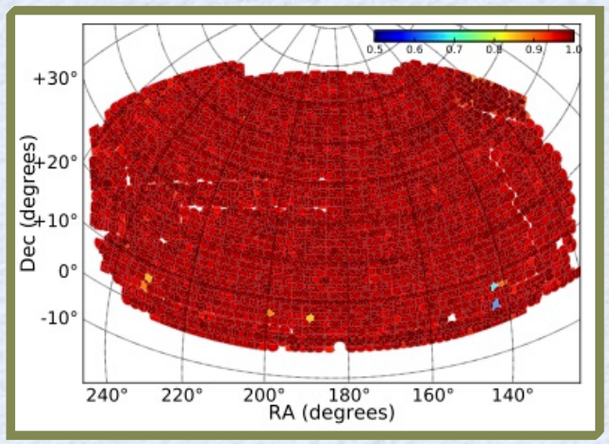
MAIN COLLABORATORS: DAVID FIGUERUELO, DARIO BETTONI AND FLORENCIA A. TEPPA

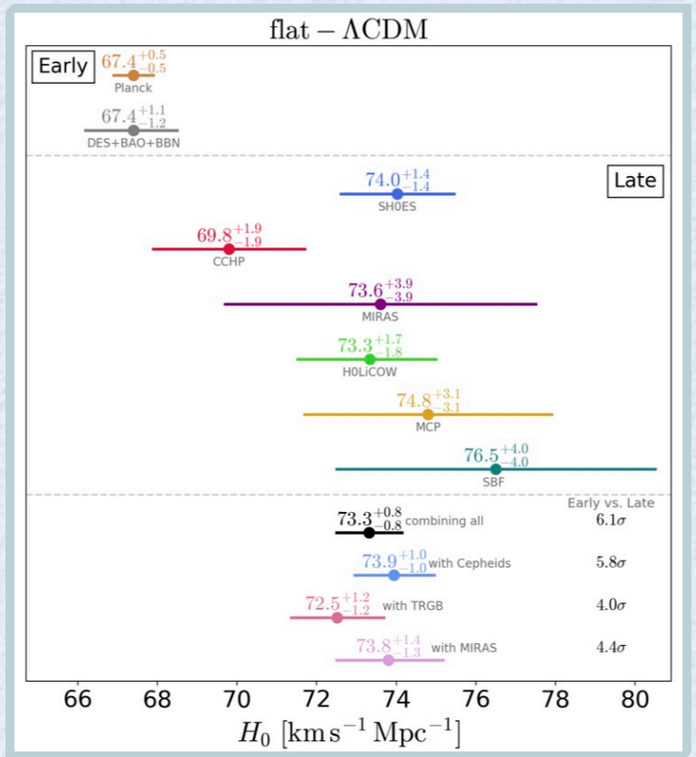
OUTLINE

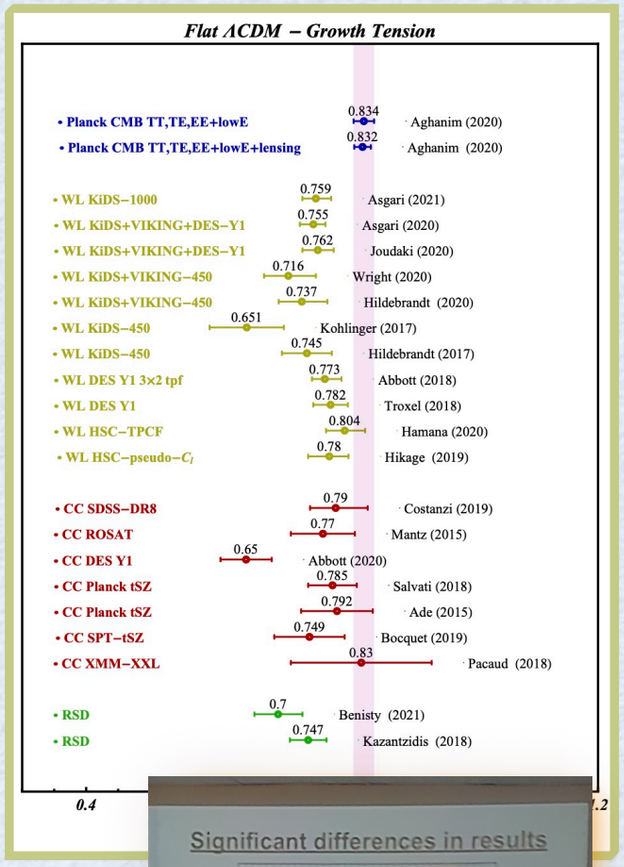
- The concordance model and its tensions
- Elastic interactions in the DSU
- A preference for the interaction from data?
- Forecasts. Is there a smoking gun?
- Non-linear regime
- Conclusions

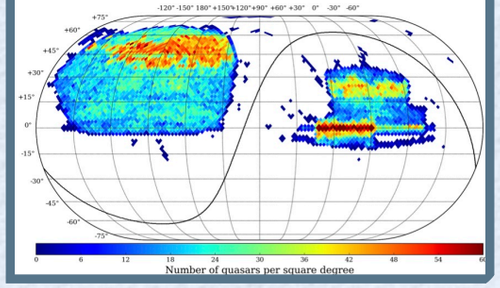
TENSIONS

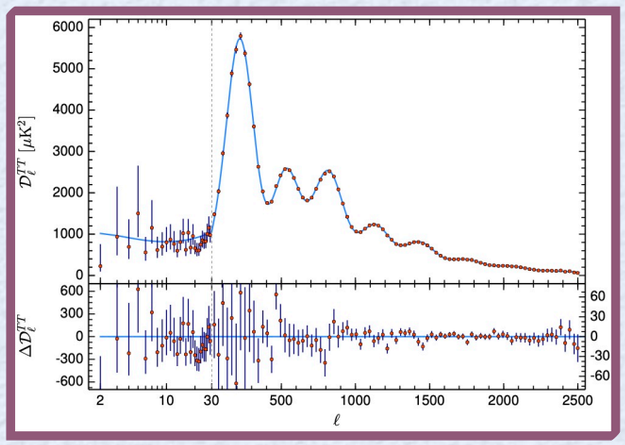


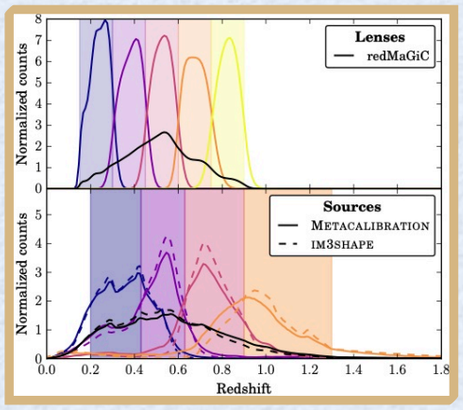


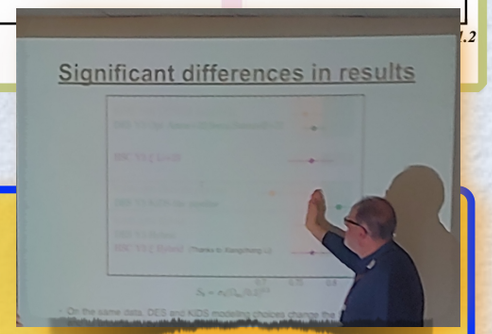








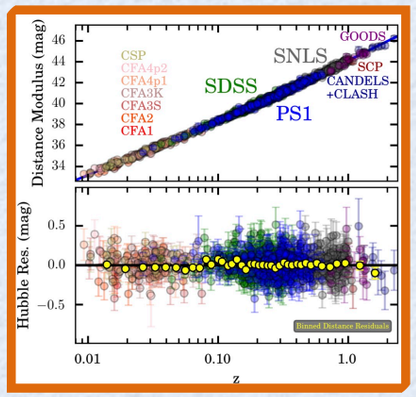


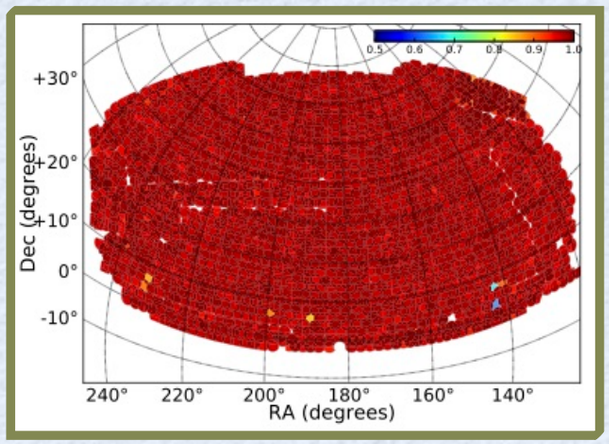


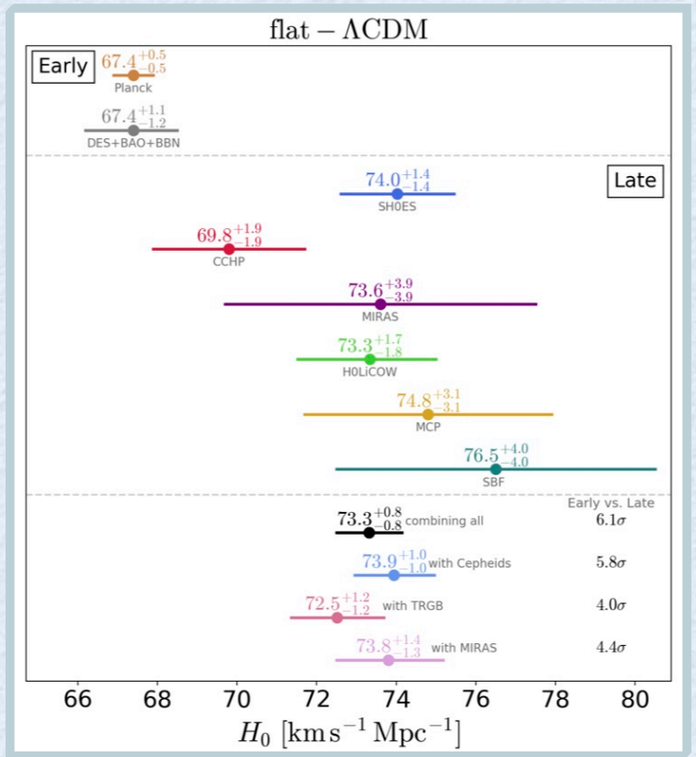
- Unknown systematics.
- Improper calibration or modelling.
- Physics beyond the standard model.

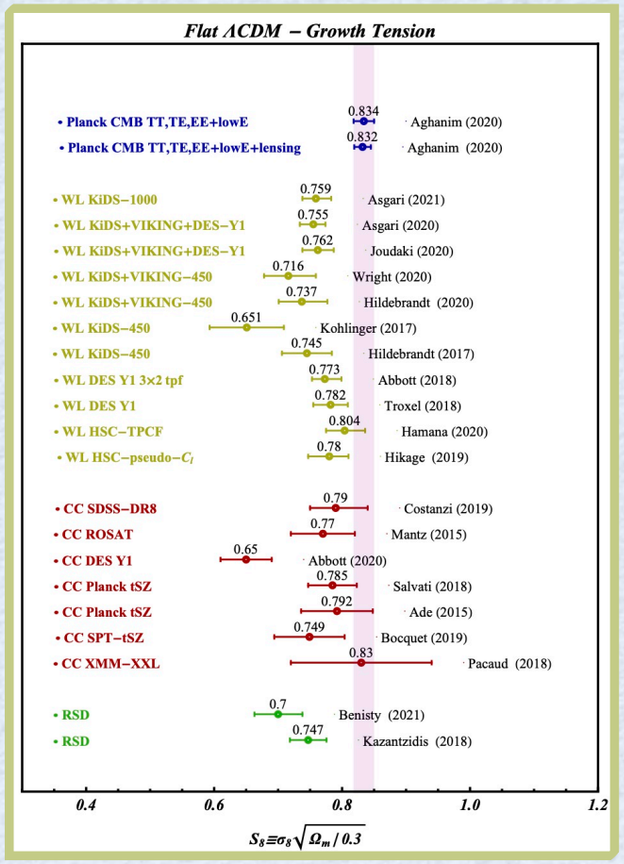
See talks by Ramón Miquel & Elisabeth Krause

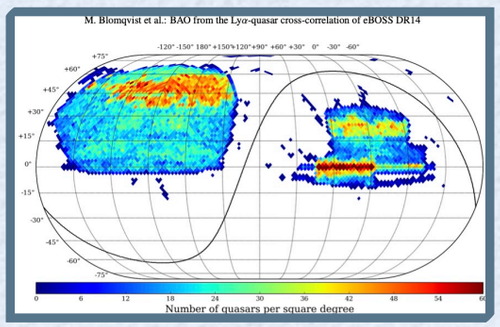
TENSIONS

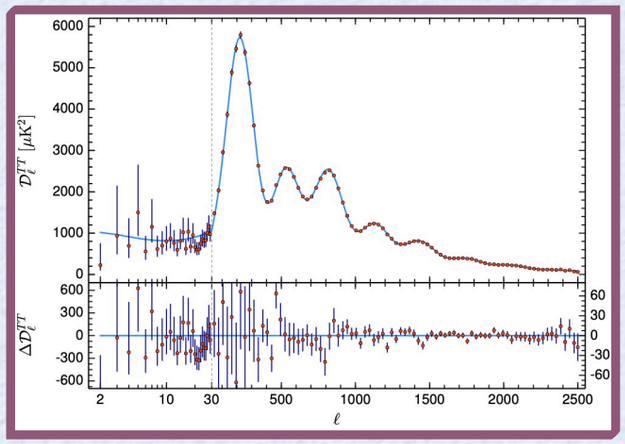


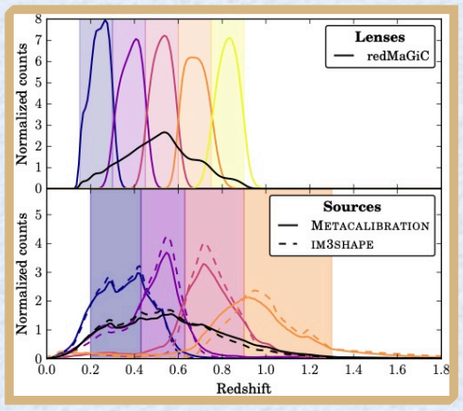












- ☐ Unknown systematics.
- ☐ Improper calibration or modelling.
- ☑ Physics beyond the standard model.

THE SCENARIO

Goal: Late time suppression of the growth of structures while leaving the background unaffected and being minimalist.

Idea: Make DM interact with a pressureful component that prevents clustering without energy exchange.

An elastic interaction in the Dark Side of the Universe

No interaction: Clustering

Interaction: Less clustering

Model I: αCDM

M. Asghari, JBJ, S. Khosravi & D.F. Mota, JCAP (2019)
D. Figueruelo, JBJ, et al. JCAP (2021)

Interacting DM - DE

$$\nabla_\mu T^{\mu\nu}_{\rm dm} = Q^\nu$$

$$\nabla_\mu T^{\mu\nu}_{\rm de} = -Q^\nu$$

We want the interaction to only affect the perturbations

$$Q^\nu = \alpha\left(u^\nu_{\rm dm} - u^\nu_{\rm de}\right)$$

It vanishes for the background owed to the Cosmological Principle

$$\delta'_{\rm dm} = -\theta_{\rm dm} + 3\Phi'$$

$$\delta'_{\rm de} = -3\mathcal{H}\left(c^2_{\rm s} - w\right)\delta_{\rm de} + 3(1+w)\Phi' - \theta_{\rm de}(1+w)\left(1 + 9\mathcal{H}^2\frac{c^2_{\rm s} - w}{k^2}\right)$$

$$\theta'_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\Phi + \Gamma(\theta_{\rm de} - \theta_{\rm dm})$$

$$\theta'_{\rm de} = \left(-1 + 3c^2_{\rm s}\right)\mathcal{H}\theta_{\rm de} + k^2\Phi + \frac{k^2 c^2_{\rm s}}{1+w}\delta_{\rm de} - \Gamma R(\theta_{\rm de} - \theta_{\rm dm})$$

We need $w \neq -1$
to have DE perturbations

Naturally affects at late times

Minimalism: Only 1 extra parameter

Same relation
between δ and θ

Gauge-invariant

Elastic interaction/Pure momentum transfer/Drag

$$\Gamma \equiv \alpha\frac{a}{\rho_{\rm dm}} \propto a^4 \qquad R \equiv \frac{\rho_{\rm dm}}{(1+w)\rho_{\rm de}}$$

Analogous to DM - DE scattering *F. Simpson, PRD (2010)*

$$\Gamma \propto a n_{\rm dm}\sigma$$

Model I: αCDM

$$\delta'_{\rm dm} = -\theta_{\rm dm} + 3\Phi'$$

$$\delta'_{\rm de} = -3\mathcal{H}\left(c_{\rm s}^2 - w\right)\delta_{\rm de} + 3(1+w)\Phi' - \theta_{\rm de}(1+w)\left(1 + 9\mathcal{H}^2\frac{c_{\rm s}^2 - w}{k^2}\right)$$

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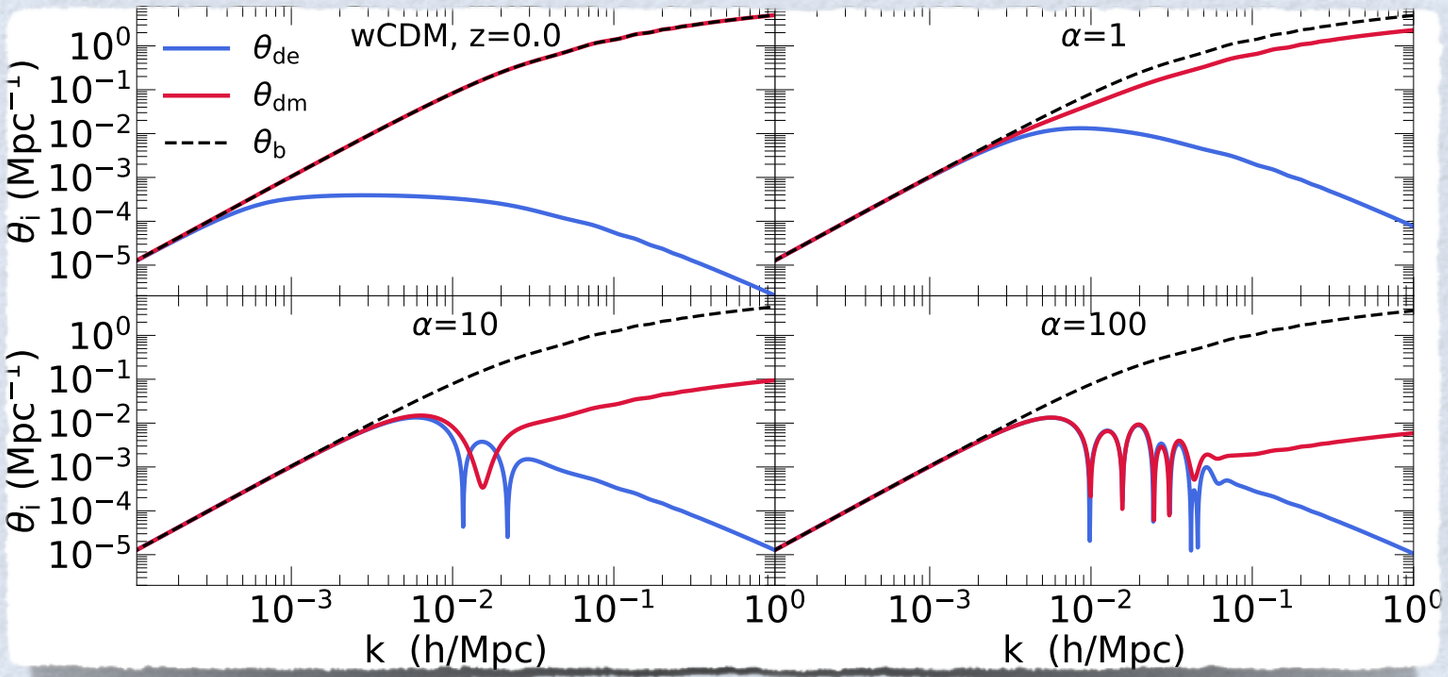
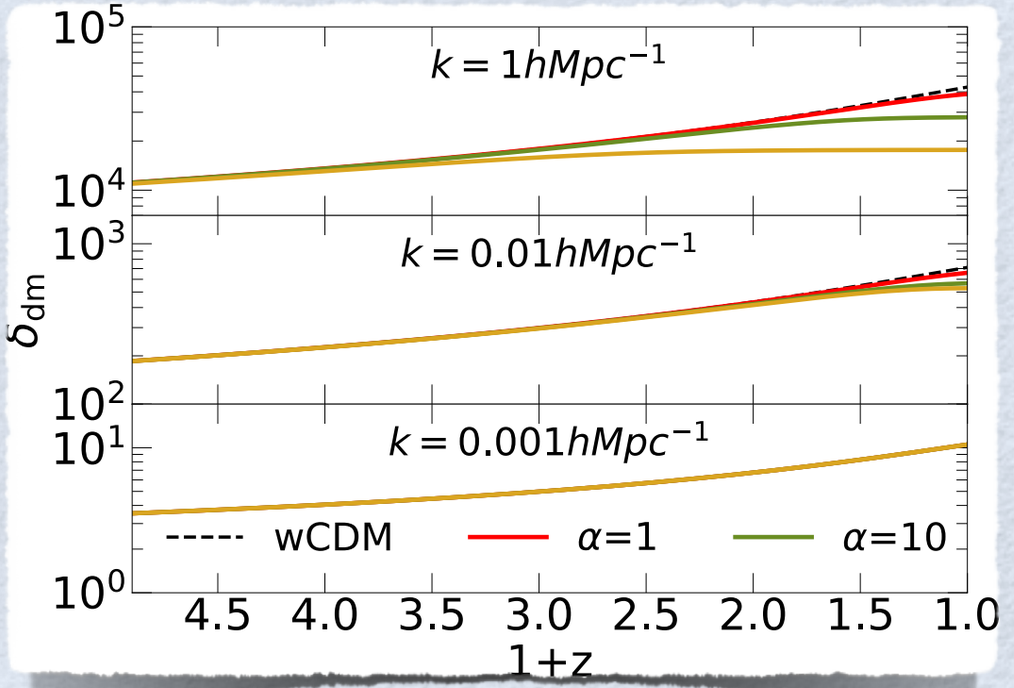
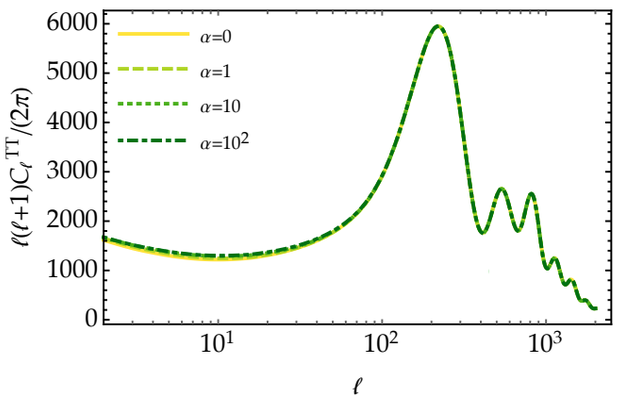
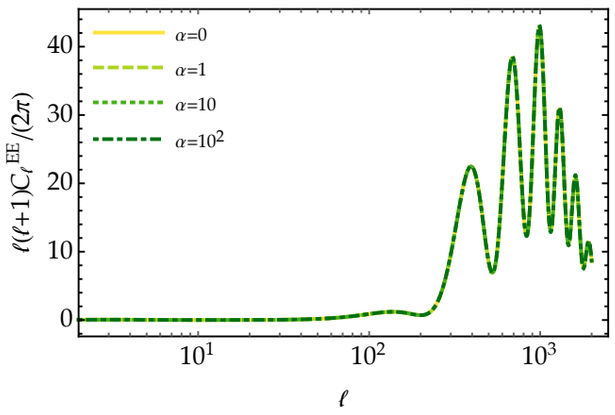


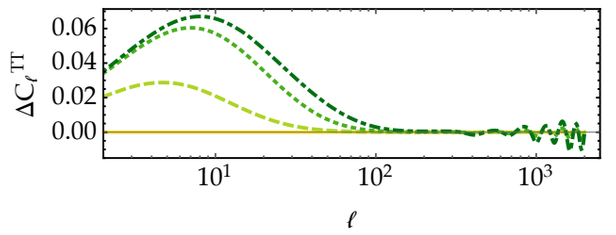


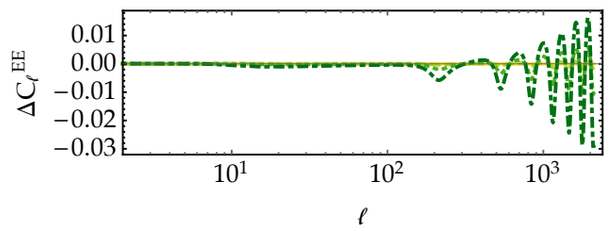
DE drags DM ⇨ reduces DM clustering ⇨ reduces gravitational wells ⇨ reduces baryons clustering

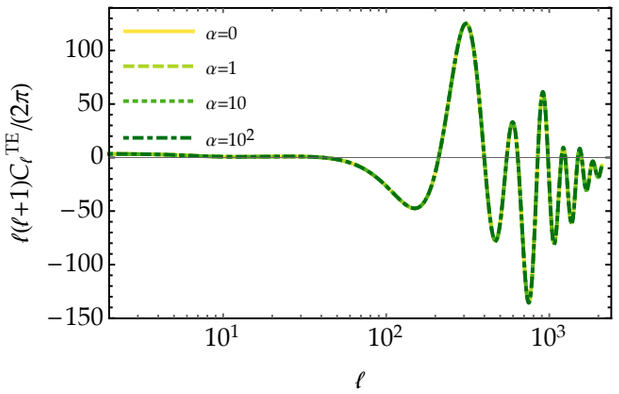
EFFECTS ON THE CMB

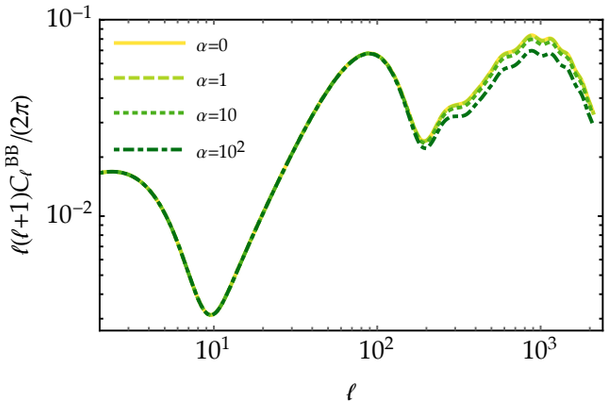


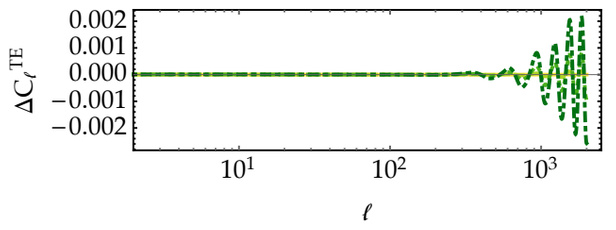


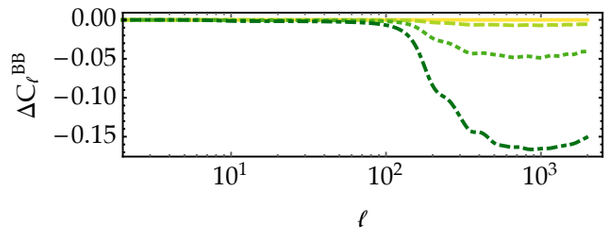










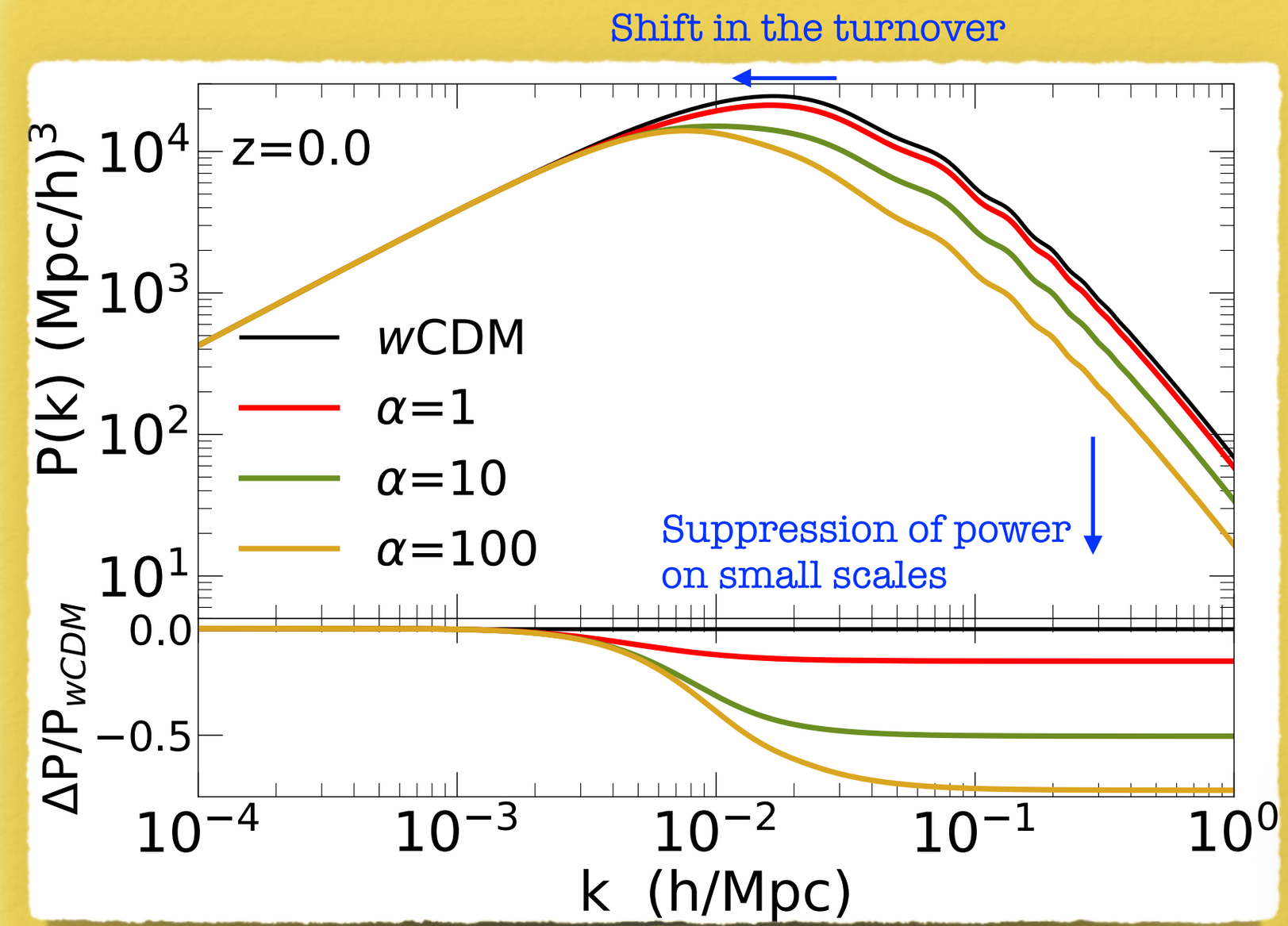


The perturbations evolve as in the standard model for most of the universe history

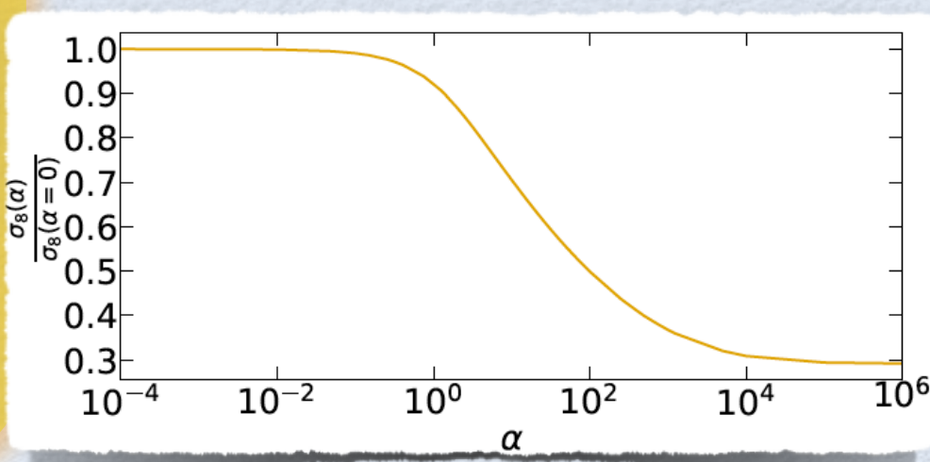
No significant effects on the CMB (only through late-time ISW)

See talk by Blake

SUPPRESSING STRUCTURES



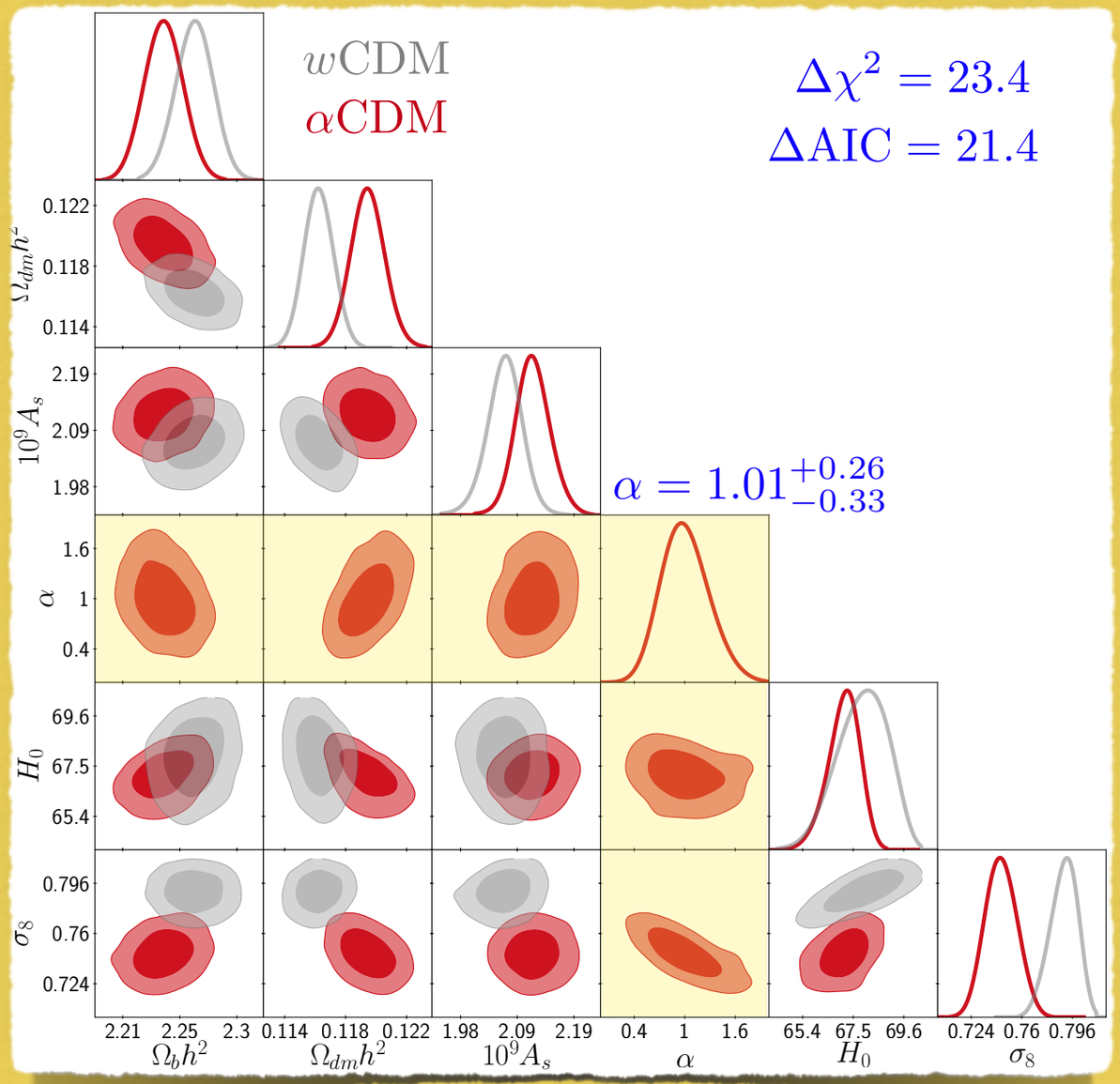
The suppression of a given mode is determined by the time at which it entered the effective sound horizon.



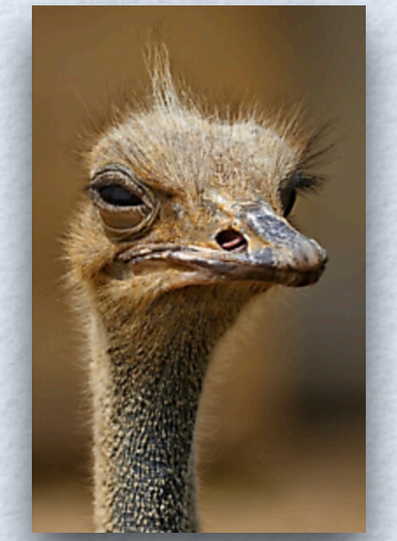
CONFRONTING WITH DATA

Parameters: $\Lambda\text{CDM} + w + \alpha + \text{nuisance parameters}$

Data:
- Planck TT, TE, EE
- BAO: SDSS-III, SDSS-DR7 and 6dF
- SnIa: JLA
- Weak Lensing: CFHTLens and Planck
- Sunyaev-Zeldovich: Planck cluster counts



Detection of an interaction!?



Model II: bCDM

A Lagrangian realisation of the scenario:

JBJ, D. Bettoni, D. Figueruelo, F.A. Teppa Pannia & S. Tsujikawa, JCAP (2021), PRD (2021)

$$\mathcal{S}_{\rm DSU} = -\sum_{I=c,d}\int \mathrm{d}^4x\Big[\underbrace{\sqrt{-g}\,\rho_I(n_I) + J^\mu_I\partial_\mu\ell_I}\Big] + \underbrace{\int \mathrm{d}^4x\sqrt{-g}\,f(Z)}$$

$$Z \equiv g_{\mu\nu}u^\mu_c u^\nu_d$$

Schutz-Sorkin

Velocity-entrainment interaction

Common rest frame at large scales $\bar{Z} = -1$

The interaction only contributes a CC to the background $f(\bar{Z})$

$$\dot{v}_c - 3Hc_c^2v_c - \alpha - c_c^2\frac{\delta\rho_c}{\rho_c+P_c} + \frac{f_{,Z}}{\rho_c+P_c}\left[\dot{v}_d - \dot{v}_c + 3H\left(v_d - v_c\right)\right] = 0$$

$$\dot{v}_d - 3Hc_d^2v_d - \alpha - c_d^2\frac{\delta\rho_d}{\rho_d+P_d} - \frac{f_{,Z}}{\rho_d+P_d}\left[\dot{v}_d - \dot{v}_c + 3H\left(v_d - v_c\right)\right] = 0$$

relative acceleration

relative velocity

$b \equiv f_{,Z}(-1)$

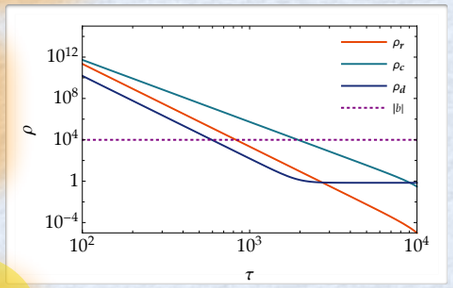
One parameter to describe the whole class of interactions (at linear order)

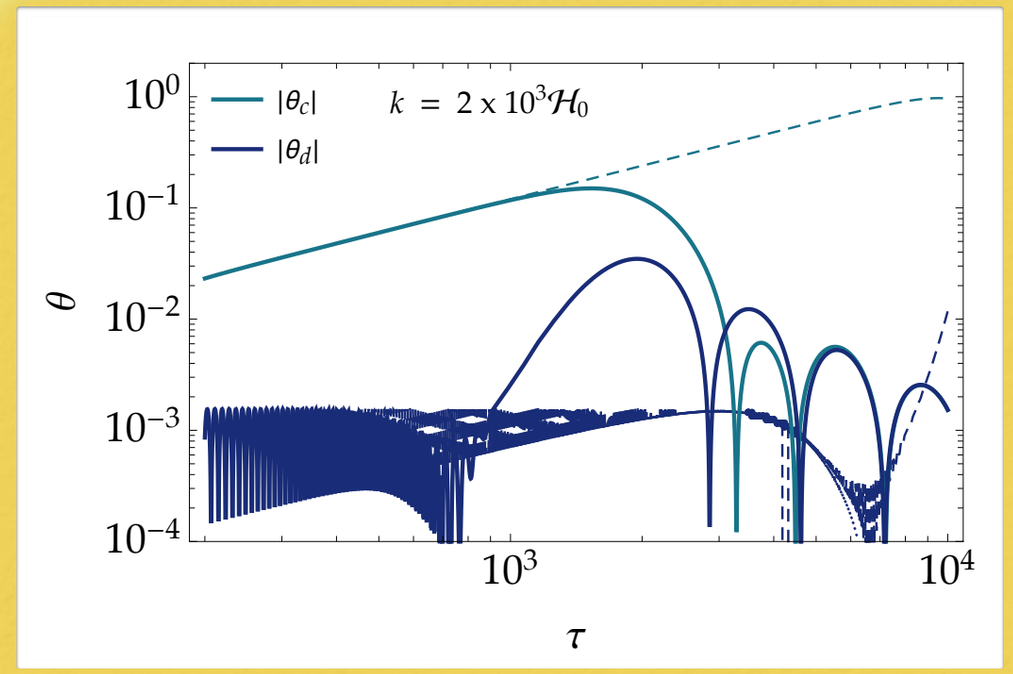
Model II: bCDM

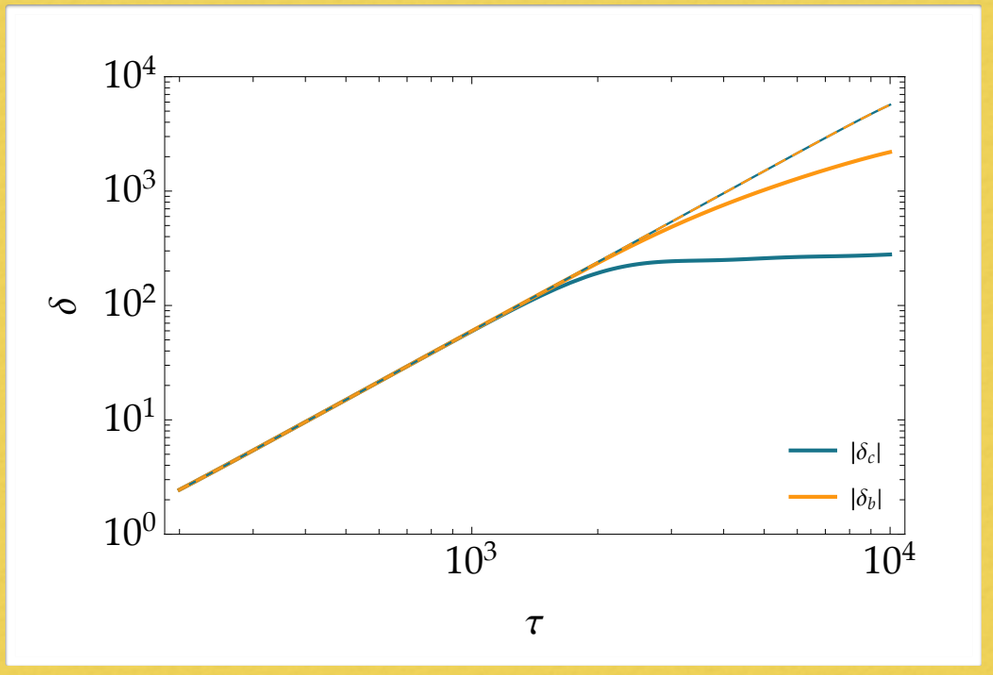
$$\theta'_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\Phi + b\frac{3\mathcal{H}(1+w)\rho_{\rm de}[\theta_{\rm dm} - (1+c^2_{\rm de})\theta_{\rm de}] - k^2c^2_{\rm de}\rho_{\rm de}\delta_{\rm de}}{(1+w)\rho_{\rm de}(\rho_{\rm dm}-b) - b\rho_{\rm dm}} \qquad b \equiv f,z(-1)$$

$$\theta'_{\rm de} = \mathcal{H}(3c^2_{\rm de}-1)\theta_{\rm de} + k^2\Phi + \frac{\rho_{\rm dm}[k^2c^2_{\rm de}\rho_{\rm de}\delta_{\rm de} + 3\mathcal{H}b\{(1+c^2_{\rm de})\theta_{\rm de} - \theta_{\rm dm}\}] - k^2bc^2_{\rm de}\rho_{\rm de}\delta_{\rm de}}{(1+w)\rho_{\rm de}(\rho_{\rm dm}-b) - b\rho_{\rm dm}}$$

Dark energy sector: Λ + Dark Radiation ⇨ Two parameters: Interaction
Initial fraction of DR







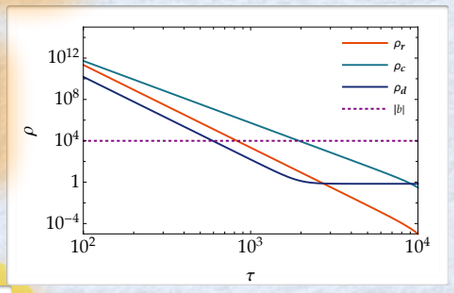
Similar evolution as in αCDM

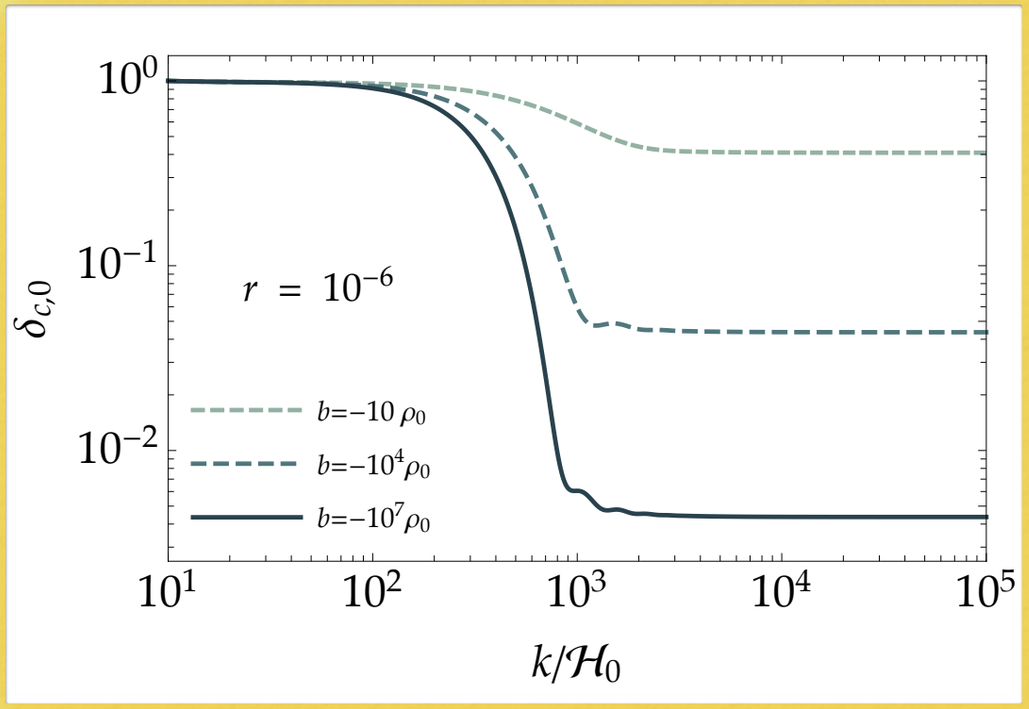
Model II: bCDM

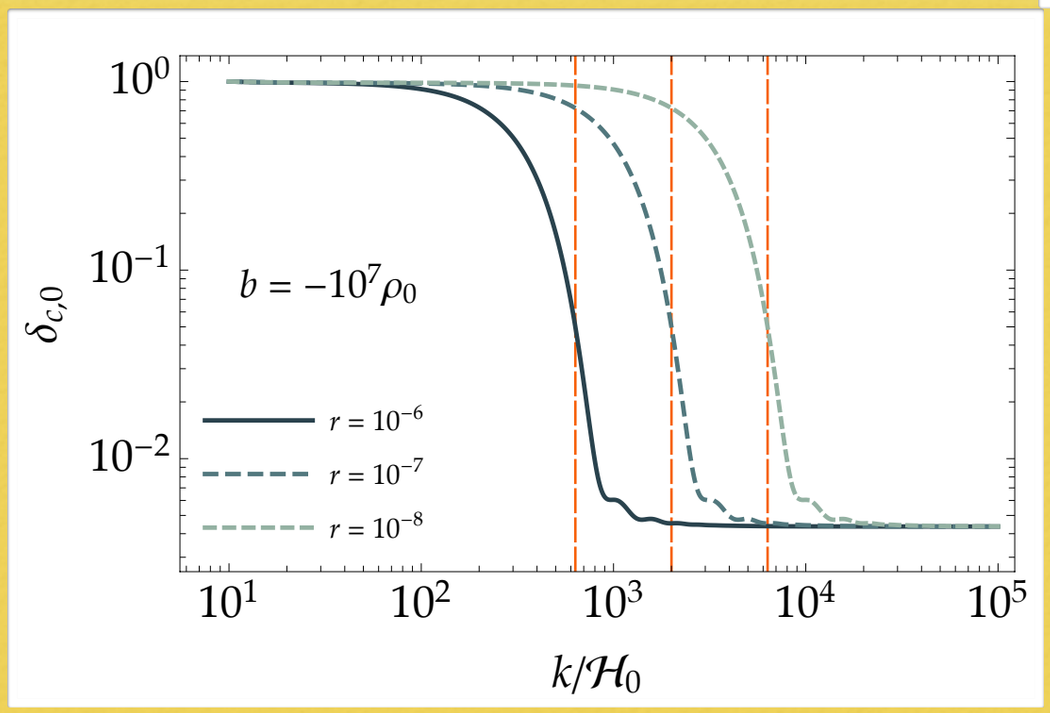
$$\theta'_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\Phi + b\frac{3\mathcal{H}(1+w)\rho_{\rm de}[\theta_{\rm dm} - (1+c^2_{\rm de})\theta_{\rm de}] - k^2c^2_{\rm de}\rho_{\rm de}\delta_{\rm de}}{(1+w)\rho_{\rm de}(\rho_{\rm dm}-b) - b\rho_{\rm dm}} \qquad b \equiv f,z(-1)$$

$$\theta'_{\rm de} = \mathcal{H}(3c^2_{\rm de}-1)\theta_{\rm de} + k^2\Phi + \frac{\rho_{\rm dm}[k^2c^2_{\rm de}\rho_{\rm de}\delta_{\rm de} + 3\mathcal{H}b\{(1+c^2_{\rm de})\theta_{\rm de} - \theta_{\rm dm}\}] - k^2bc^2_{\rm de}\rho_{\rm de}\delta_{\rm de}}{(1+w)\rho_{\rm de}(\rho_{\rm dm}-b) - b\rho_{\rm dm}}$$

Dark energy sector: Λ + Dark Radiation ⇨ Two parameters: Interaction
Initial fraction of DR

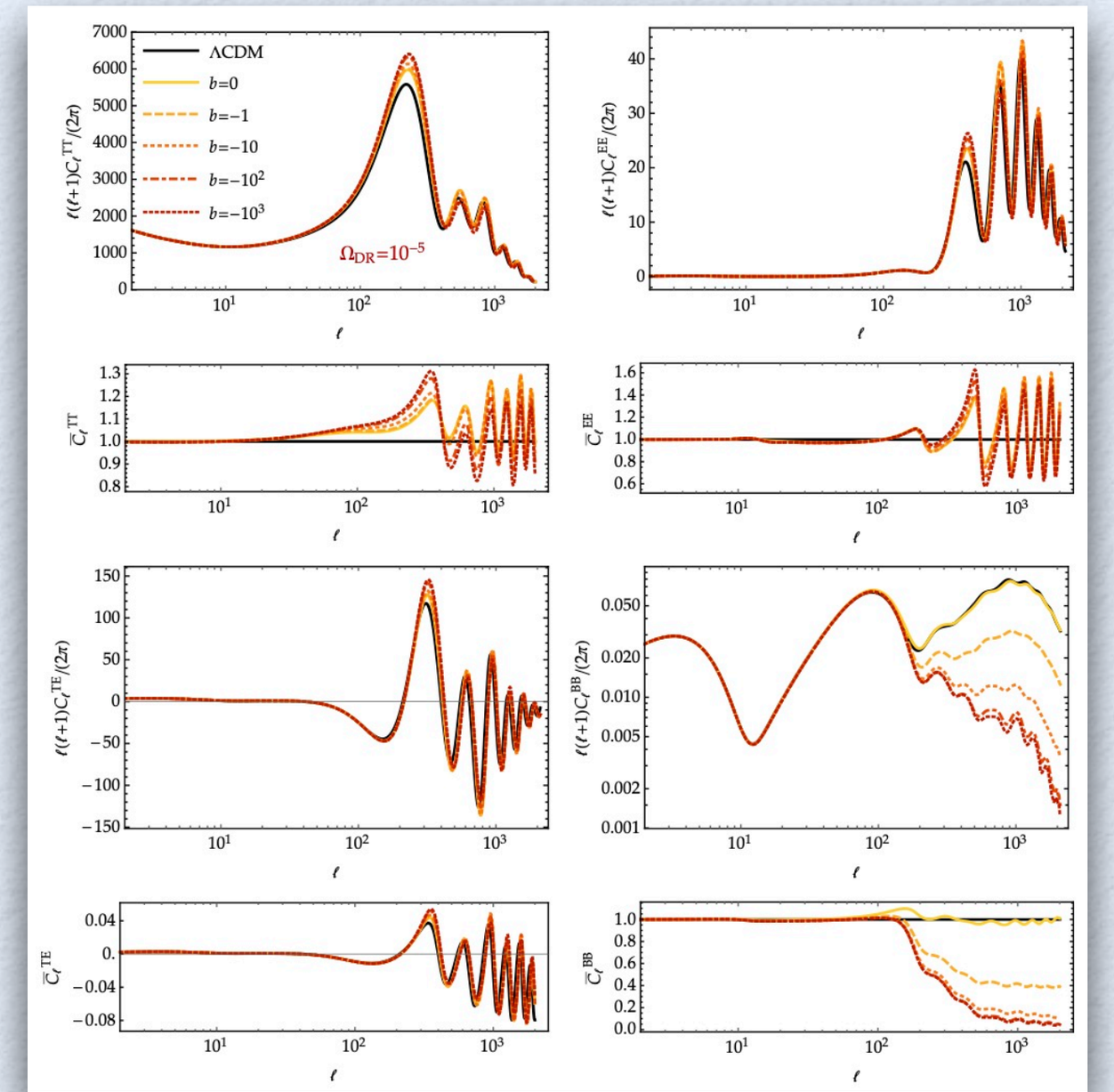


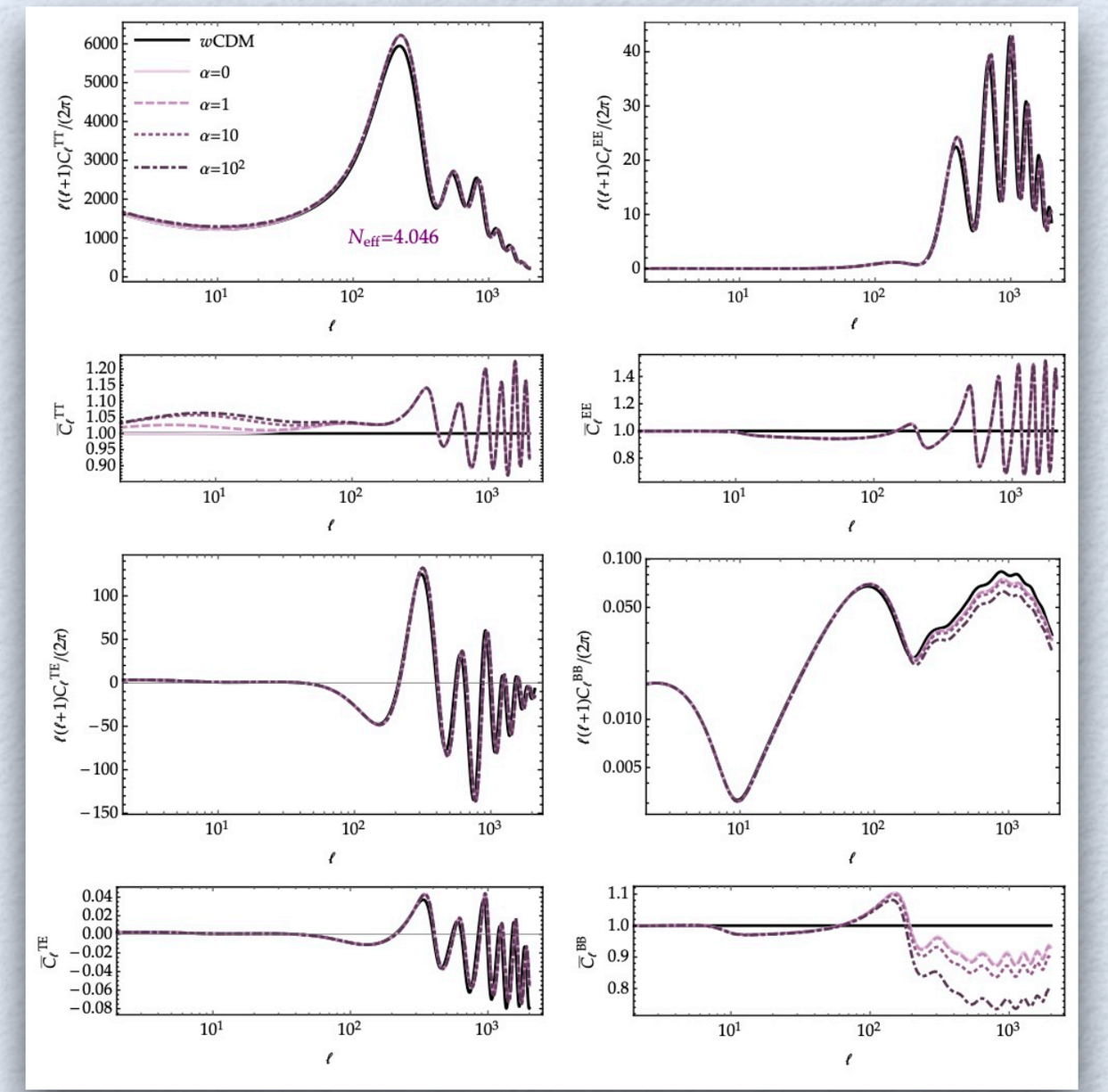




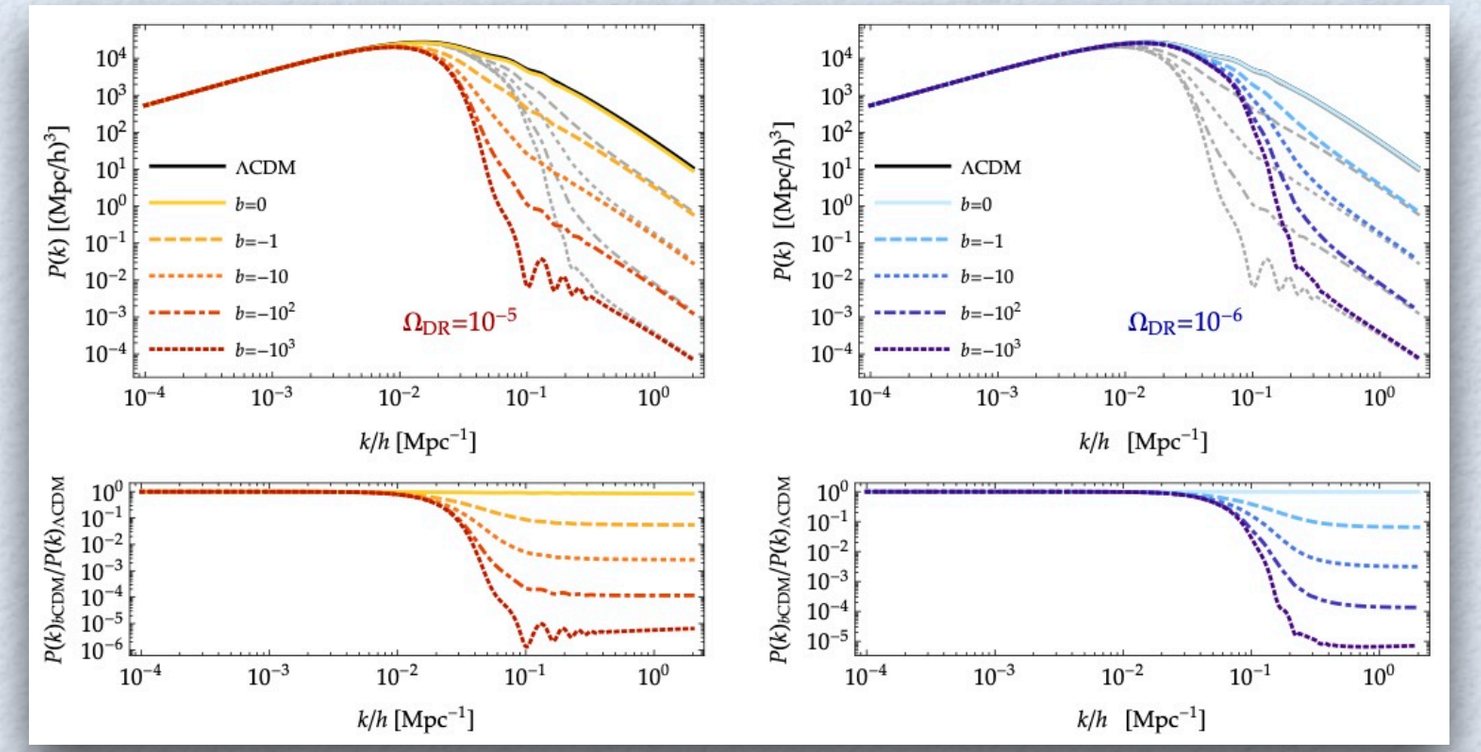
Similar evolution as in αCDM

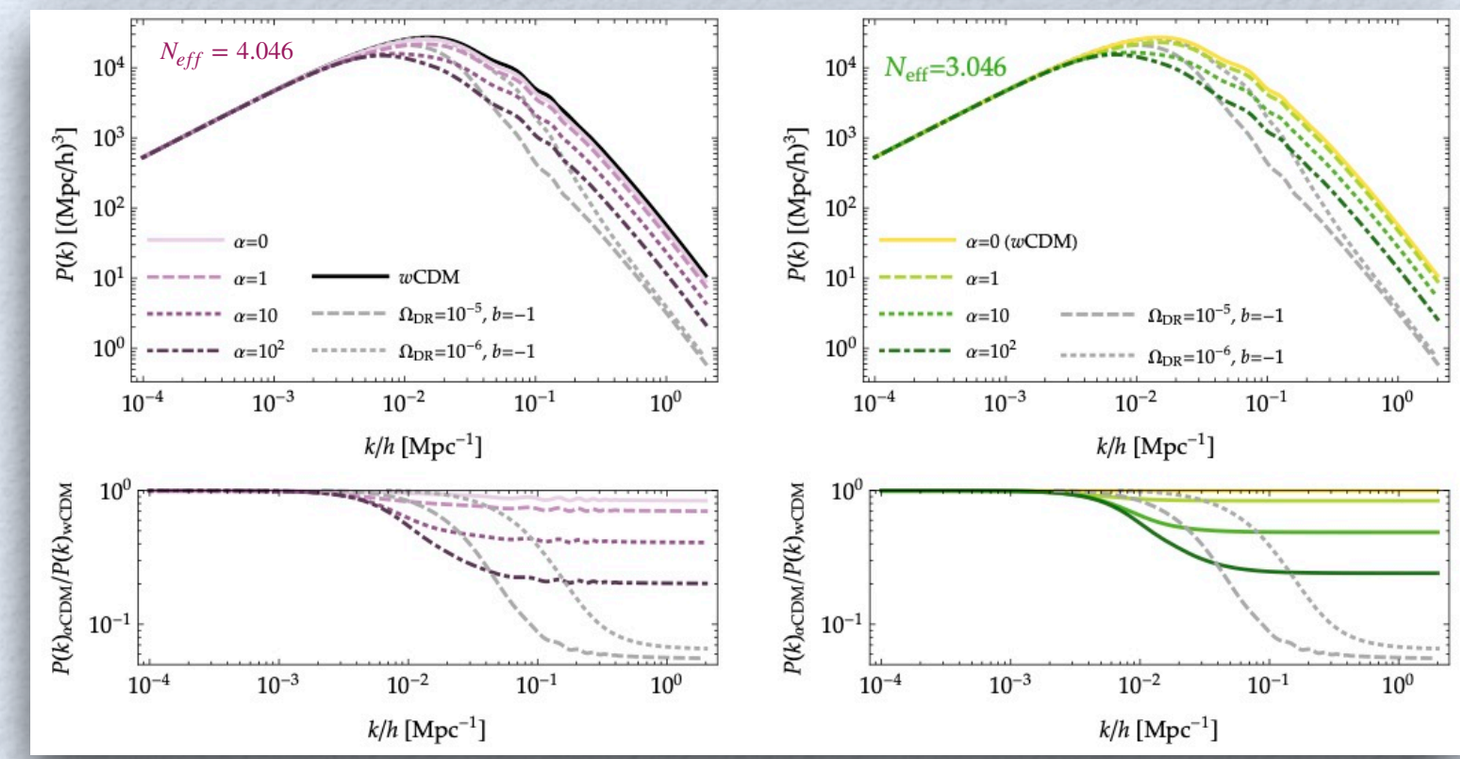
EFFECTS ON THE CMB





EFFECTS ON THE POWER SPECTRUM



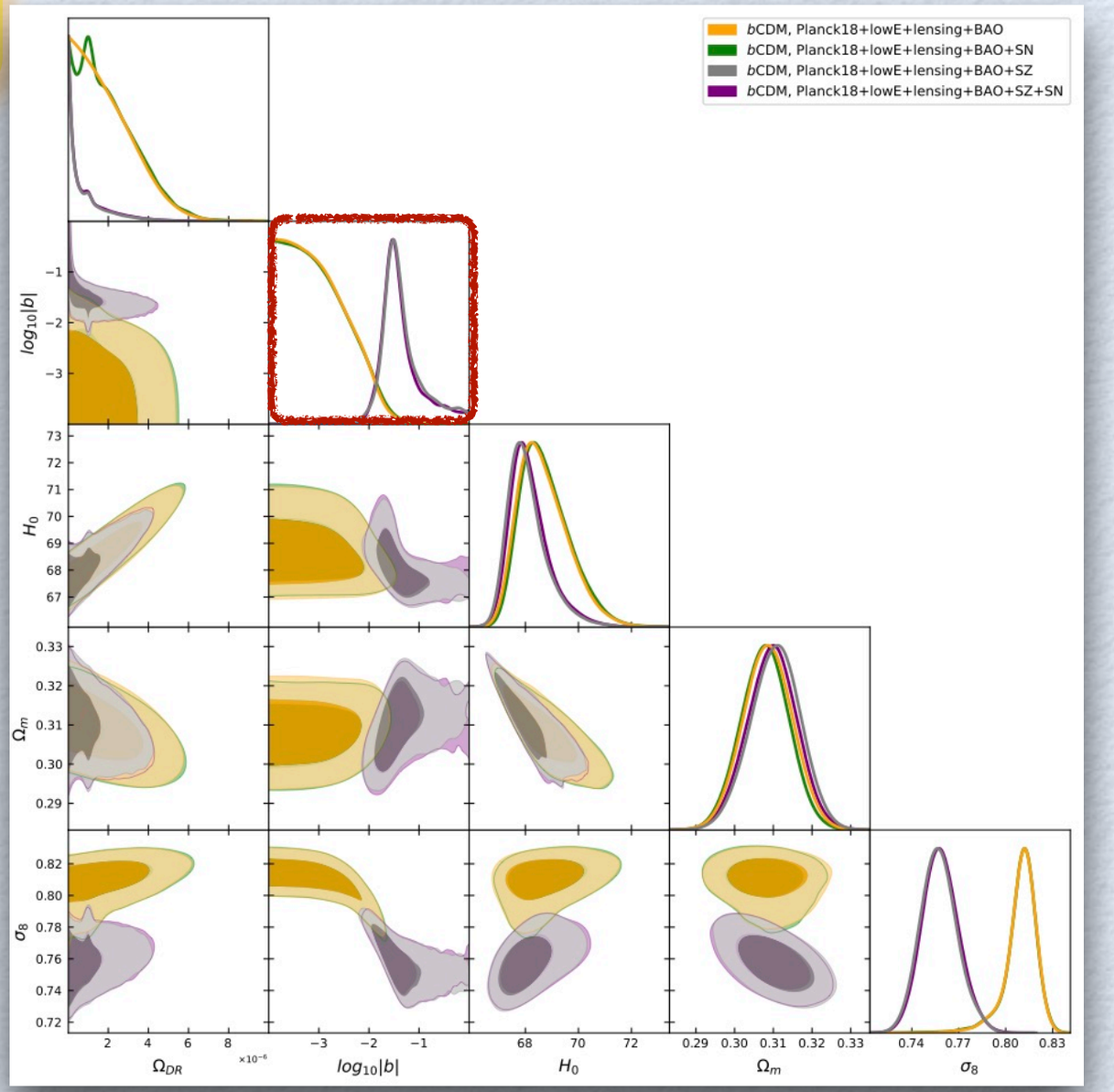


CONFRONTING WITH DATA

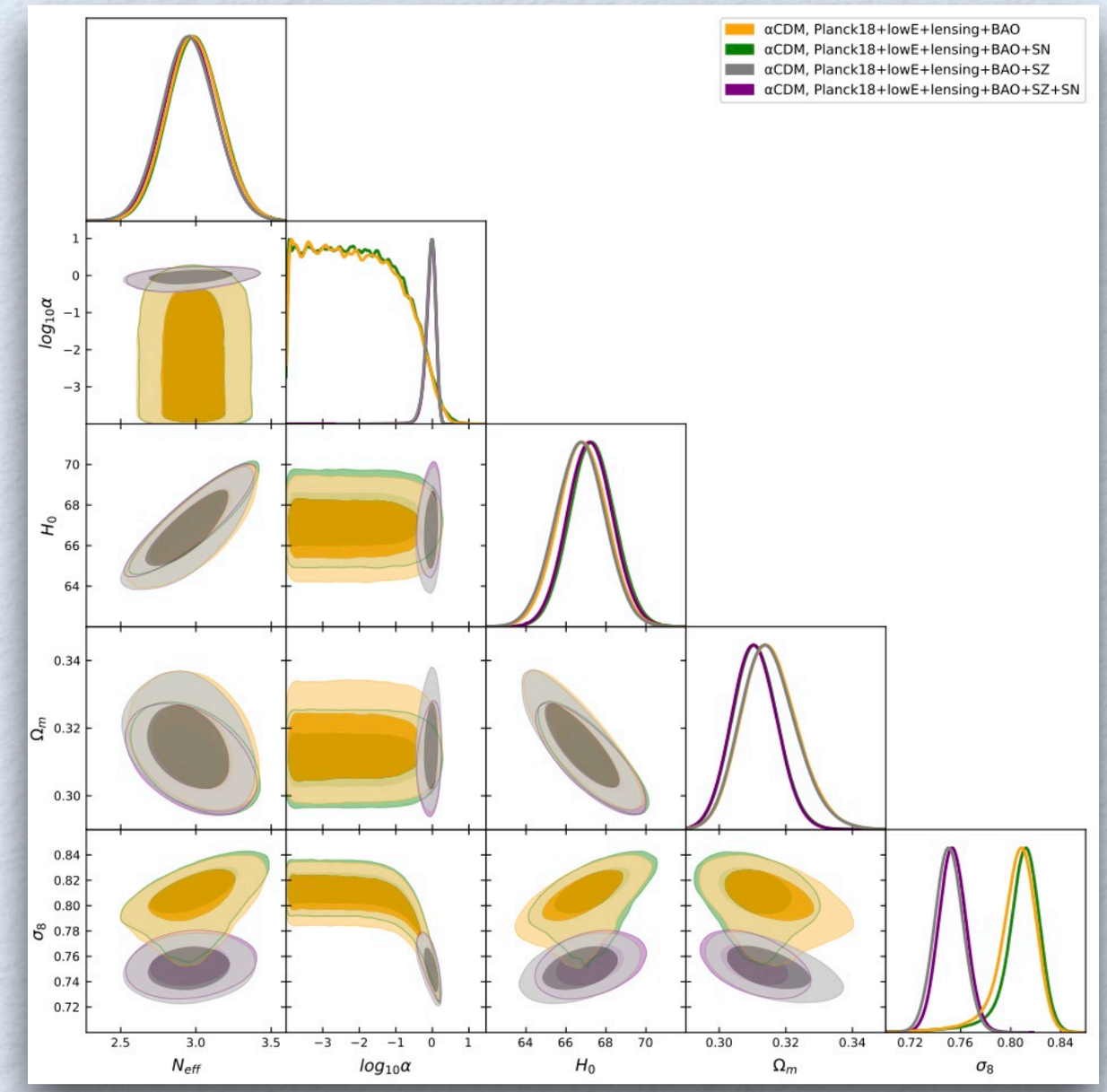
Parameters: $\Lambda\mathrm{CDM} + b + \Omega_{\mathrm{DR}} + \text{nuisance parameters}$

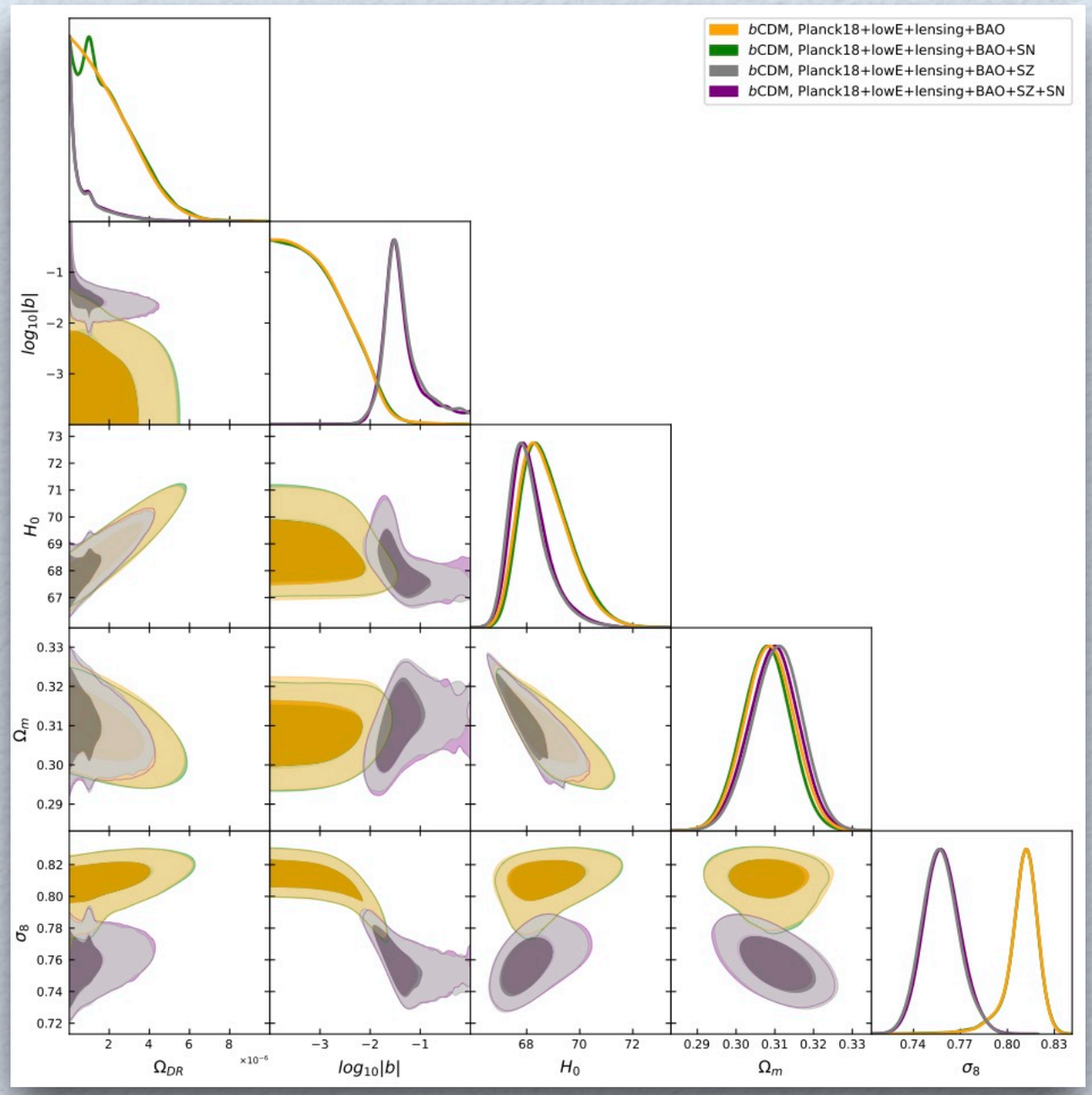
Data:

- Planck TT, TE, EE
- BAO: SDSS-III, SDSS-DR7 and 6dF
- SnIa: JLA
- Weak Lensing: CFHTLens and Planck
- Sunyaev-Zeldovich: Planck cluster counts

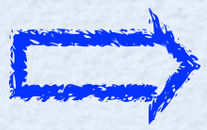


WHAT DRIVES THE DETECTION?





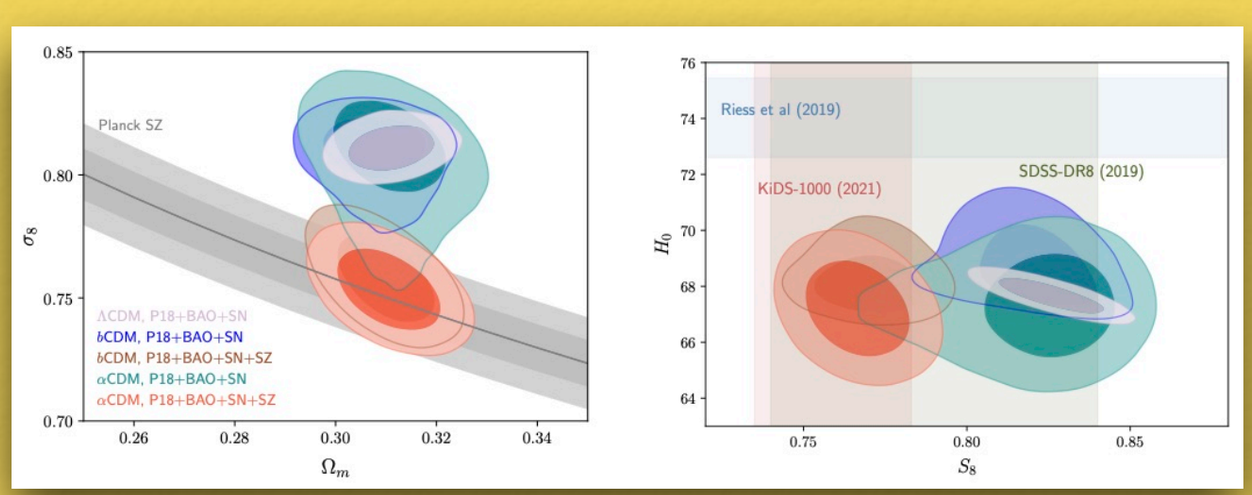
Without SZ, only an upper bound

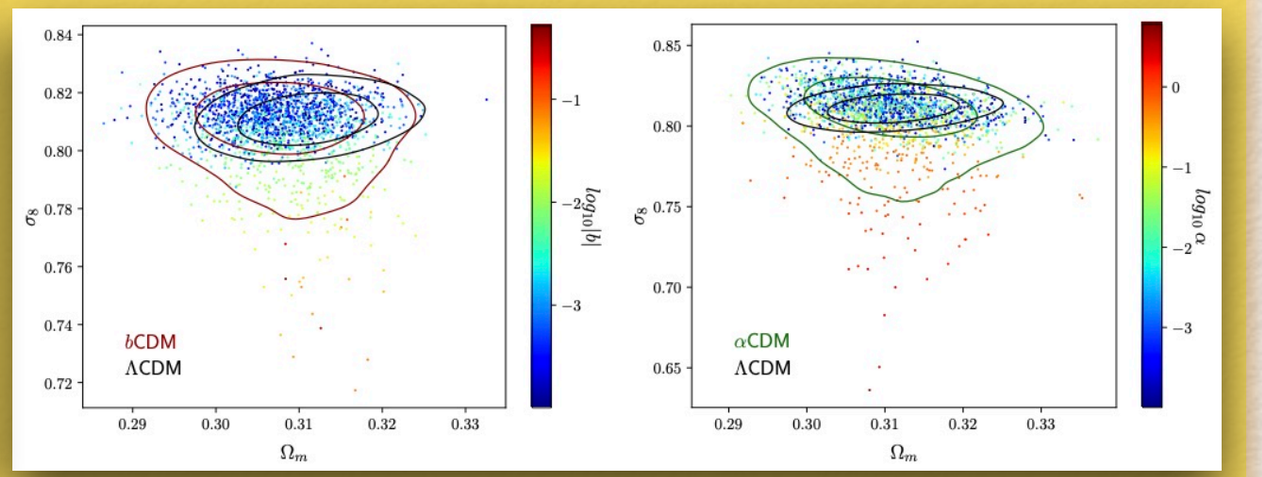


The "detection" is driven by SZ data, i.e., S_8

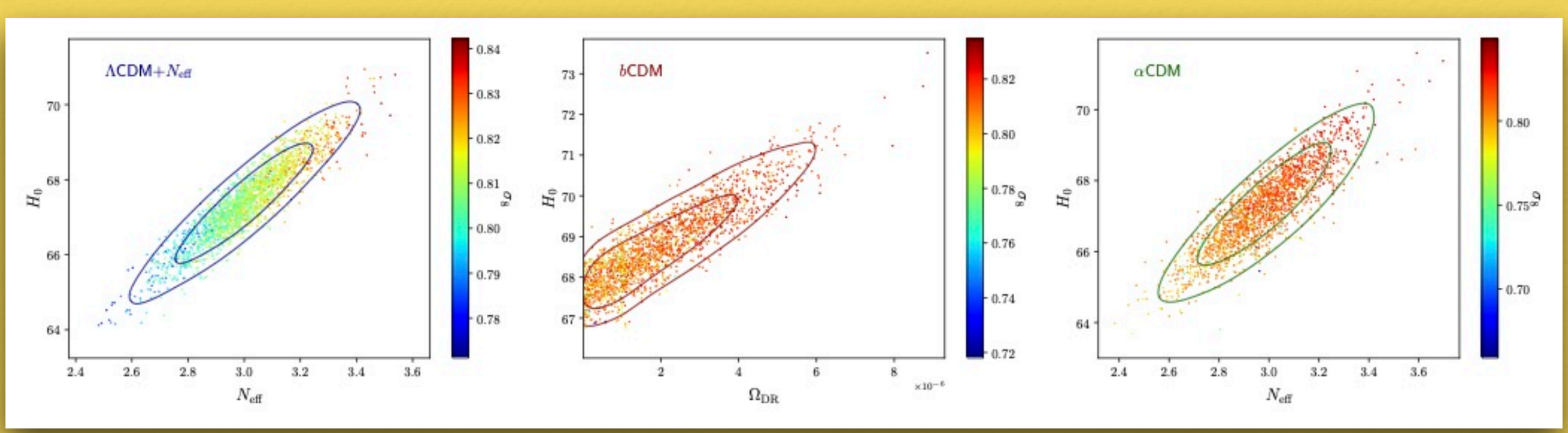
ALLEVIATION OF THE TENSION?

The interaction drives the lowering of the clustering





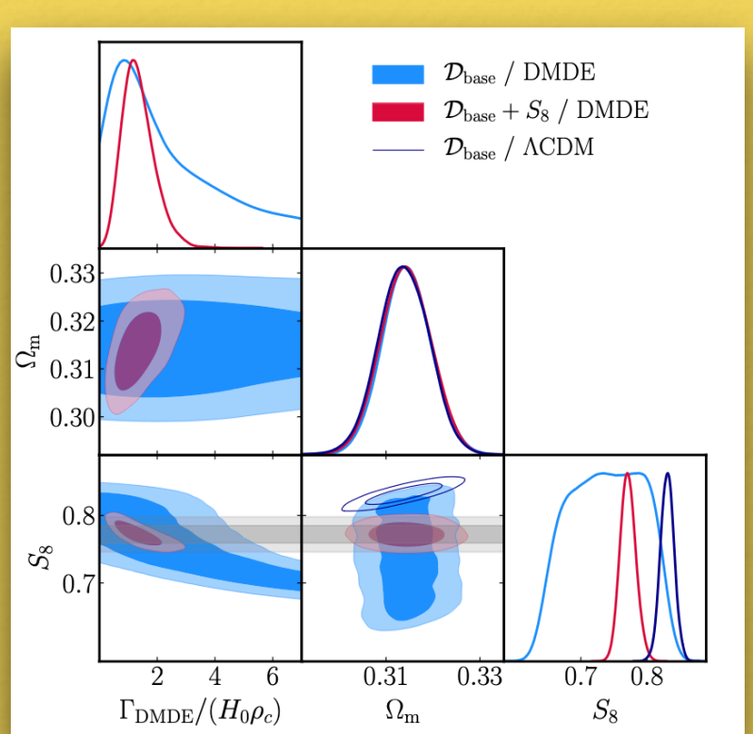
Improving the σ tension does not worsen the H0 tension



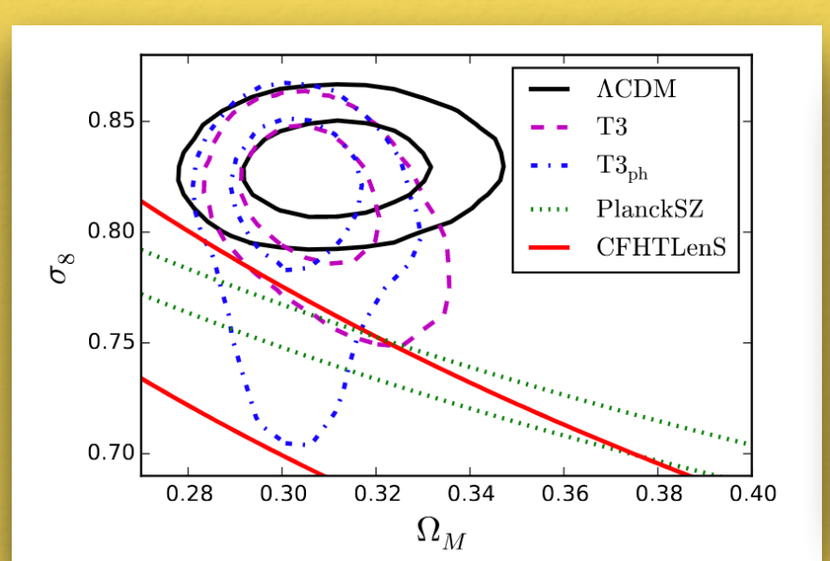
A GENERAL FEATURE

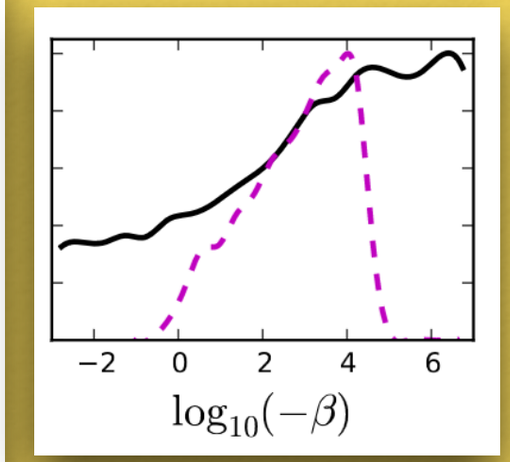
Independent confirmation for αCDM

"The sigma_8 tension is a drag"
V. Poulin, J.L. Bernal, E. Kovetz, M. Kamionkowski, PRD (2023).



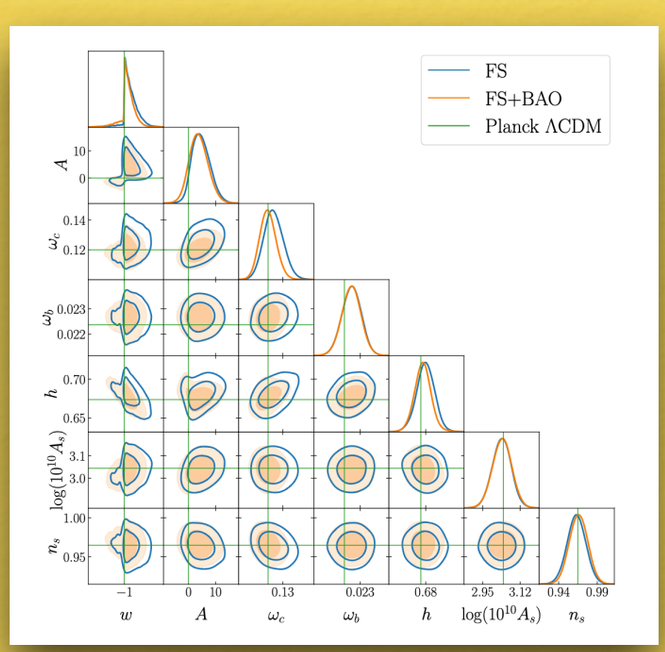
Coupled quintessence with pure momentum interaction *A. Pourtsidou & T. Tram, PRD (2016)*





DM - DE scattering model with Full Shape power spectrum (BOSS DR12)

P. Carrilho, C. Moretti & A. Pourtsidou JCAP (2023)



FORECASTS

Two fiducial models

No interaction

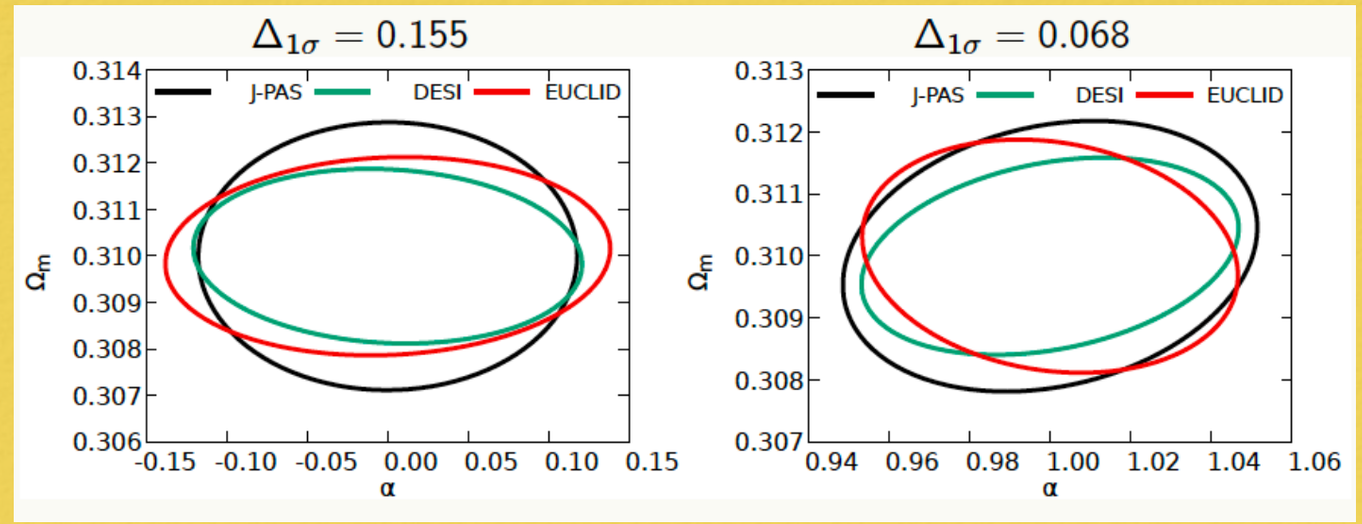
Interaction obtained from present data

Bias:

- Prescription for each survey.
- Marginalization over each redshift bin.

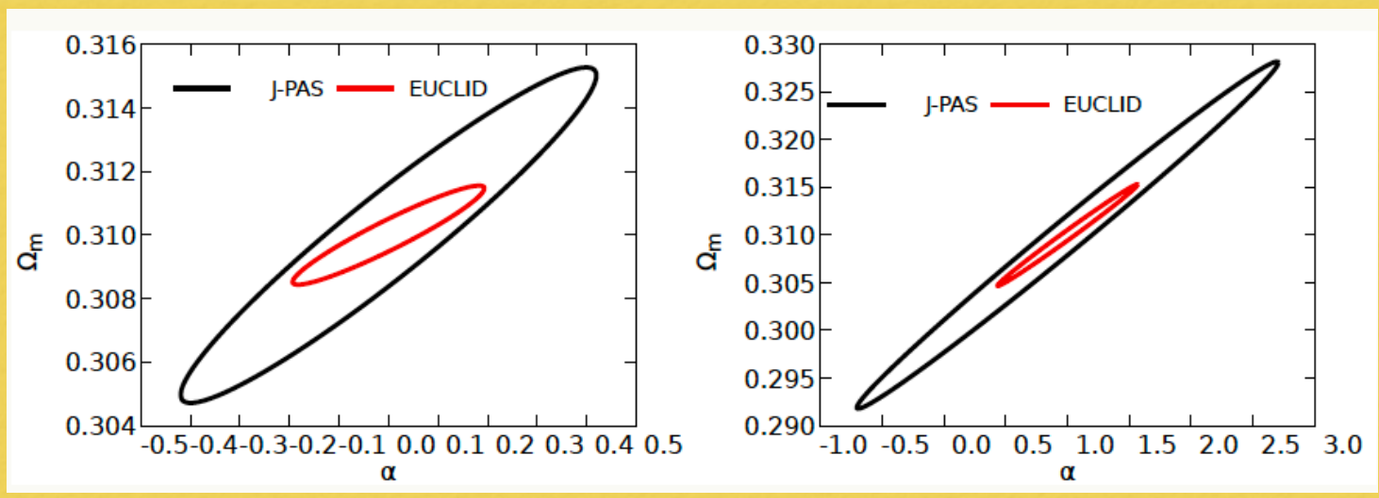
No significant difference.

Clustering



A 10σ detection!

Lensing

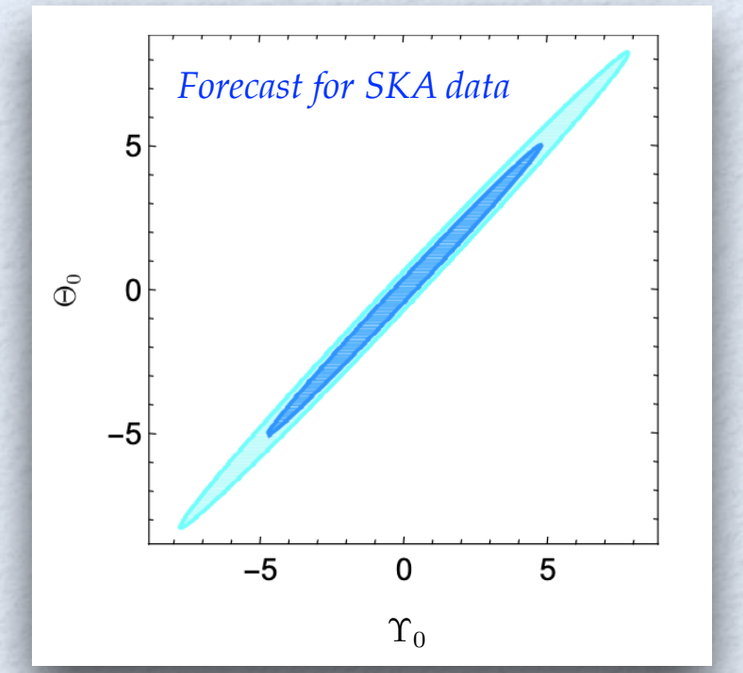


No big improvements from lensing.

A SMOKING GUN?

C. Bonvin & P. Fleury
JCAP (2018)

$$\vec{v}' + \Big[1 + \Theta(t)\Big]\mathcal{H}\vec{v} + \Big[1 + \Upsilon(t)\Big]\vec{\nabla}\Phi = 0$$



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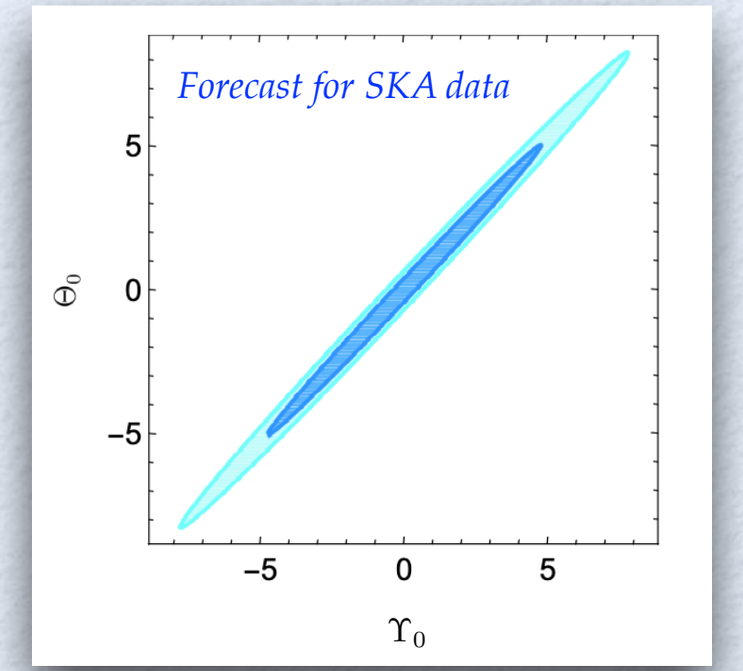
$$\Upsilon(t) = 0$$

αCDM

$$\vec{v}'_{dm} + \mathcal{H}\vec{v}_{dm} + \vec{\nabla}\Phi = \Gamma(\vec{v}_{de} - \vec{v}_{dm})$$

$$\vec{v}_{de} \ll \vec{v}_{dm}$$

$$\Theta(t) = \frac{\Gamma}{\mathcal{H}} = \alpha \frac{aH_0}{\Omega_{dm}(z)\mathcal{H}(z)}$$



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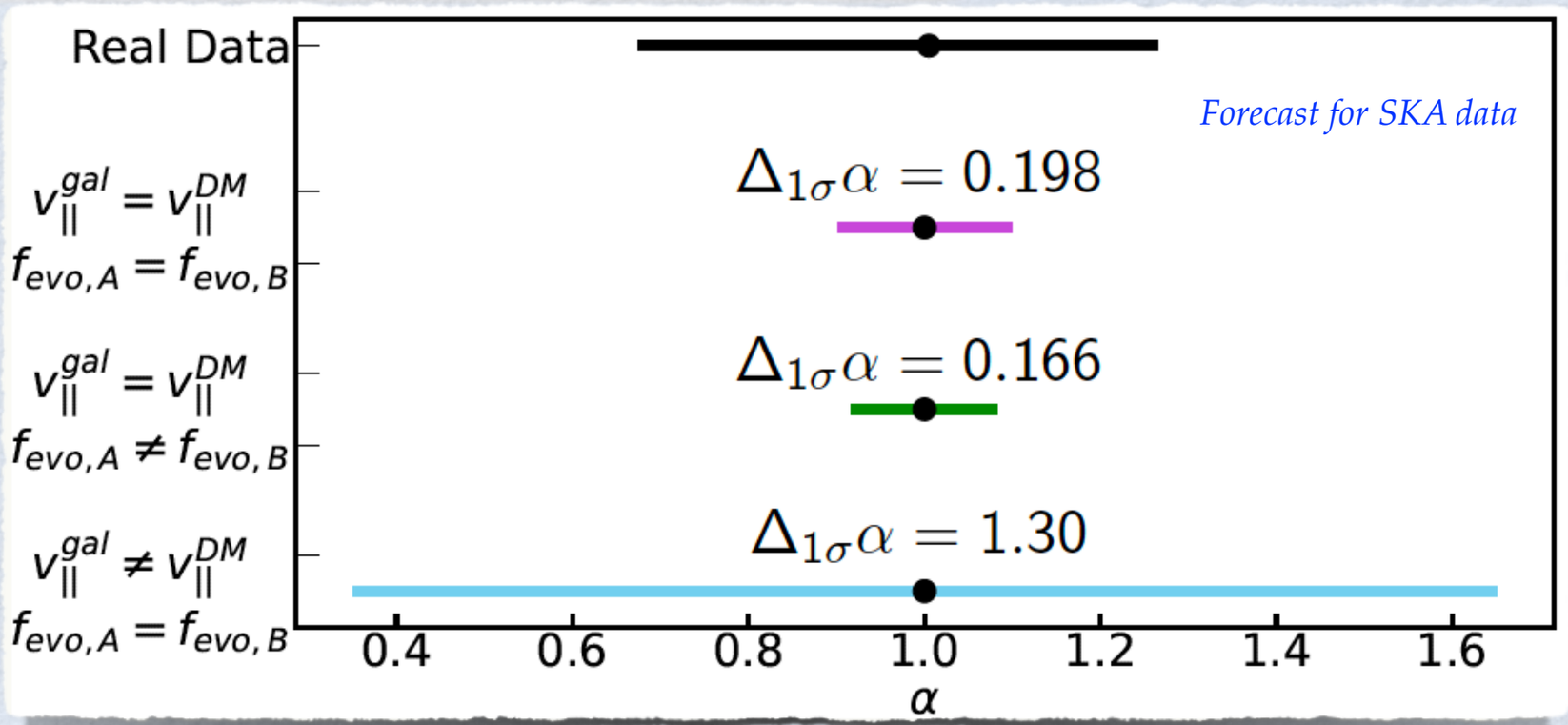
$$\Theta(t) = \frac{\Gamma}{\mathcal{H}} = \alpha \frac{aH_0}{\Omega_{dm}(z)\mathcal{H}(z)}$$

$$P_1^{AB}(k) = if\frac{\mathcal{H}}{k}(b_A - b_B)\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2-5s}{r\mathcal{H}} + 5s - f_{\rm evo} + \Theta\right)P(k) + \mathcal{O}\left(\mathcal{H}^3/k^3\right)$$

Estimator for the dipole in the matter power spectrum from relativistic effects.

Two scenarios:

- Galaxies as DM tracers
- Galaxies as tracers of the gravitational potential



JBJ, E. di Dio & D. Figueruelo (2022)

NON-LINEAR REGIME

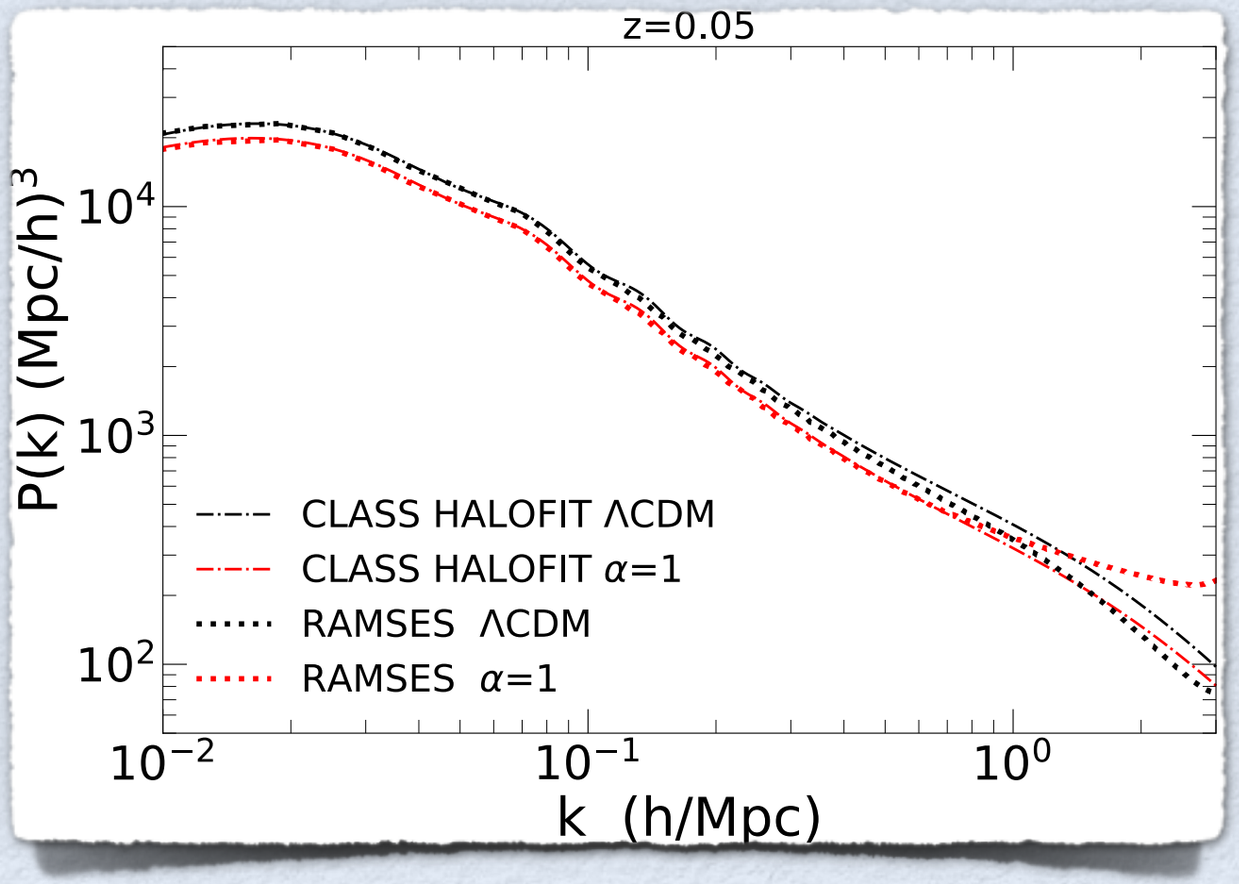
Straightforward implementation in *N*-body codes:
Only one new term for the DM acceleration

Dark Matter: $$\dot{\vec{v}}_i = -H\vec{v}_i + \sum_{j\neq i} \frac{Gm_j\vec{r}_{ij}}{r_{ij}^3} - \alpha\frac{H_0}{\Omega_{\rm dm}(t)}\vec{v}_i$$

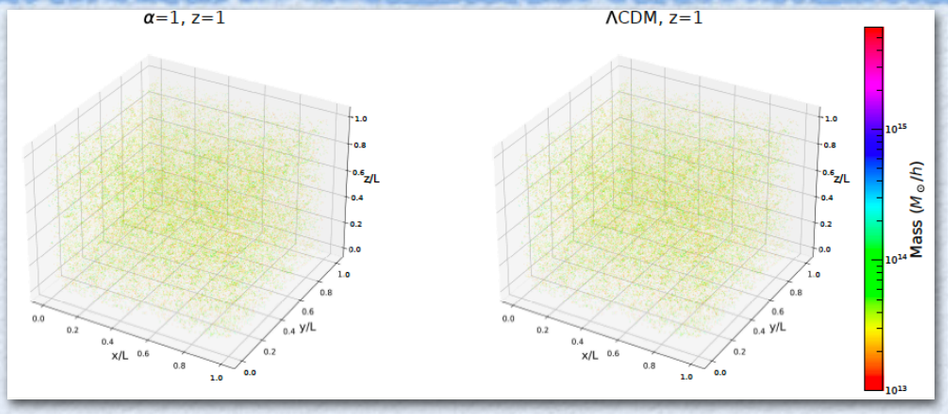
Baryons: $$\dot{\vec{v}}_i = -H\vec{v}_i + \sum_{j\neq i} \frac{Gm_j\vec{r}_{ij}}{r_{ij}^3}$$

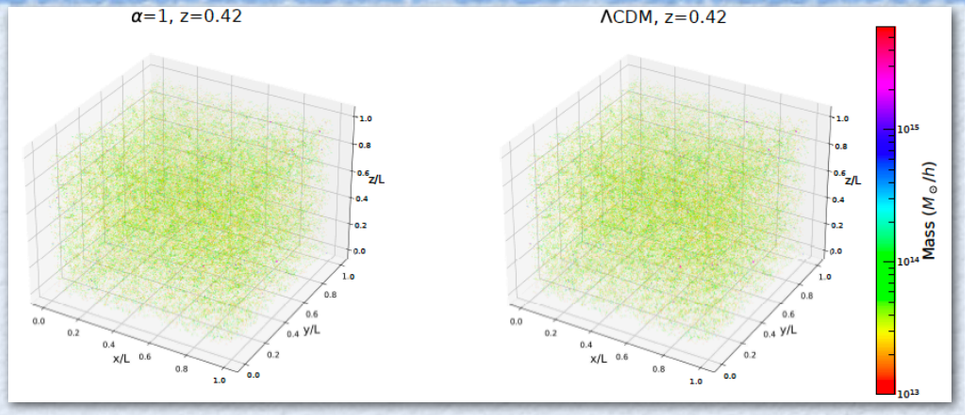
Assumptions:

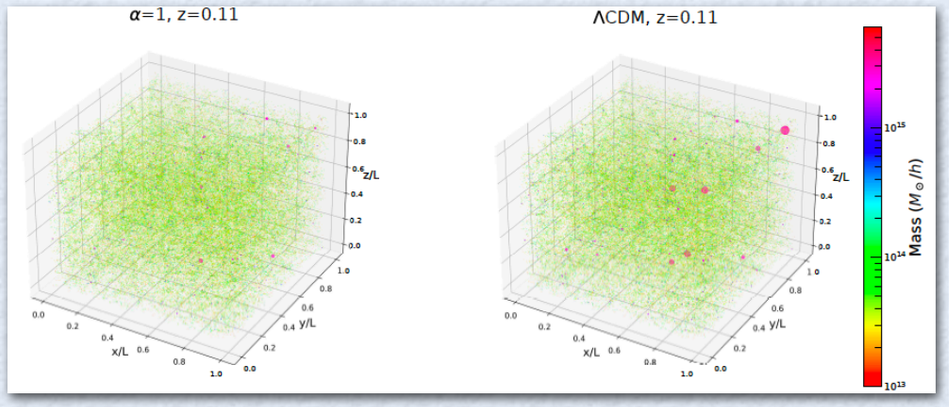
- Same initial conditions as in ΛCDM
- Negligible dark energy velocities.

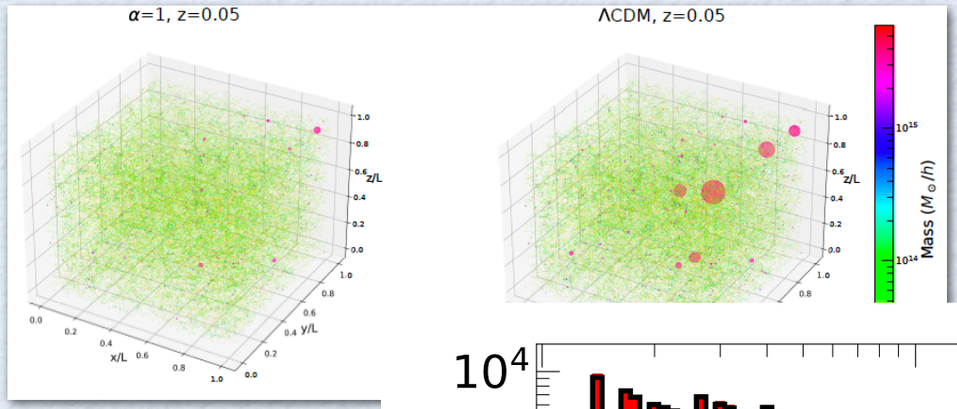


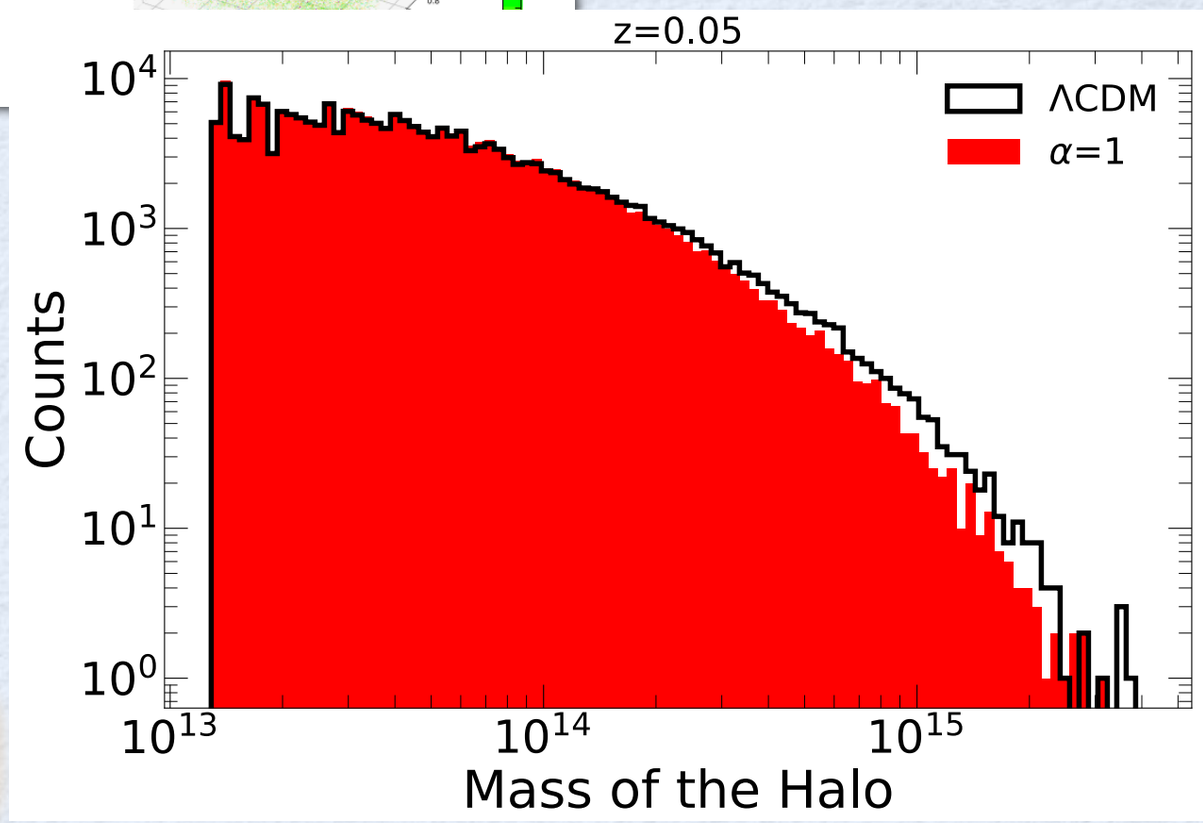
NON-LINEAR REGIME











Fewer massive haloes

CONCLUSIONS/PROSPECTS

- Elastic/Pure momentum interactions make an interesting scenario in the context of the σ_8 tension.

- Clear predictions to be contrasted with future data.

- It makes a very simple and minimal extension of ΛCDM, but with distinctive signatures that can guide the search for deviations.

- A more careful confrontation to data with a better modelling.

- Effects on galaxy bias, velocity bias, DM halo density and velocity profiles...