Observational Tensions in Kinetically Coupled Quintessence

Based on arXiv:2207.13682

Corfu Summer Institute on Elementary Particle Physics and Gravity 2022

Workshop on Tensions in Cosmology 2022, 7th - 12th September

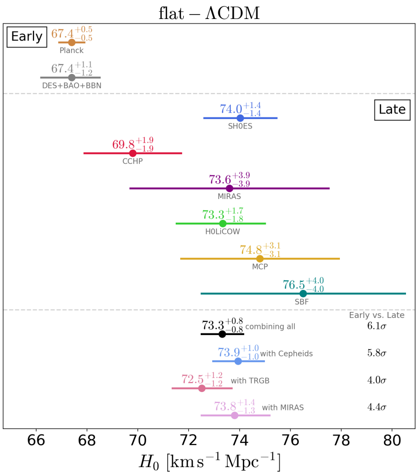
Elsa M. Teixeira

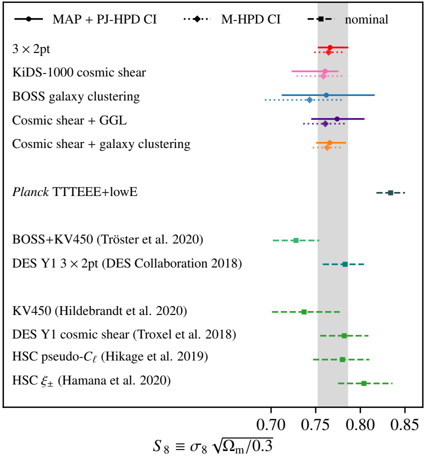
School of Mathematics and Statistics, University of Sheffield

Funded by FCT, SFRH/BD/143231/2019

In collaboration with Bruno J. Barros, Vasco M. C. Ferreira and Noemi Frusciante

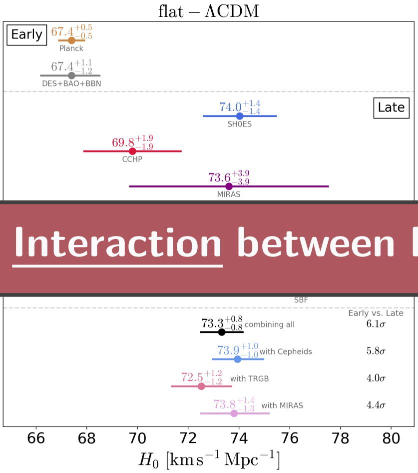
Cosmological Tensions

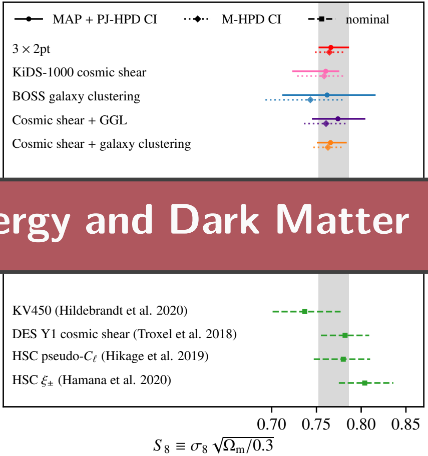




[Verde, Treu, Riess: **Nature Astron. 3 891 (2019)**]

[C. Heymans et al.: **Astron.Astrophys. 646 (2021)**]





Interaction between Dark Energy and Dark Matter

[Verde, Treu, Riess: **Nature Astron. 3 891 (2019)**]

[C. Heymans et al.: **Astron.Astrophys. 646 (2021)**]

Interacting Dark Energy with Kinetic Coupling

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{\mathrm{M}_{\mathrm{Pl}}^2}{2} R + X - V(\phi) + f(\phi, X)\tilde{\mathcal{L}}_c + \mathcal{L}_{\mathrm{SM}}(\psi_i, g_{\mu\nu}) \right]$$

[Barros: **Phys. Rev. D 99, 064051 (2019)**]

Kinetic Model

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- Function $f(\phi, X)$ - how the field couples to the matter species
- Purely kinetic power-law coupling given by $f(X) = \left(\mathrm{M}_{\mathrm{Pl}}^{-4}\, X\right)^{\alpha}$ with $V(\phi) = V_0 e^{-\lambda\phi/\mathrm{M}_{\mathrm{Pl}}}$
- Equivalent to a **conformally coupled** theory with $\tilde{g}_{\mu\nu} = f^2(X) g_{\mu\nu}$

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In an FLRW Universe this gives

$$\begin{cases} 3\mathrm{M}_{\mathrm{Pl}}^2\mathcal{H}^2 = a^2(\rho_c + \rho_b + \rho_r + \rho_\phi) \\ \phi'' + 2\mathcal{H}\phi' + a^2 V_{,\phi} = a^2 Q \\ \rho_c' + 3\mathcal{H}\rho_c = -Q\phi', \quad \rho_\phi' + 3\mathcal{H}(1 + w_\phi)\rho_\phi = Q\phi' \end{cases}$$

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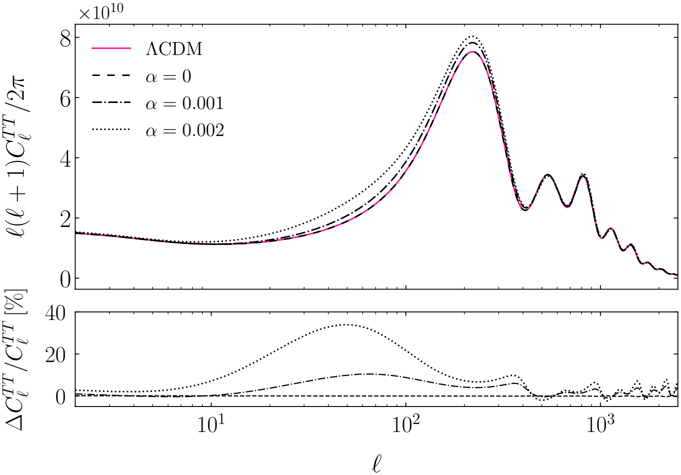
Coupling function regulated by parameter α

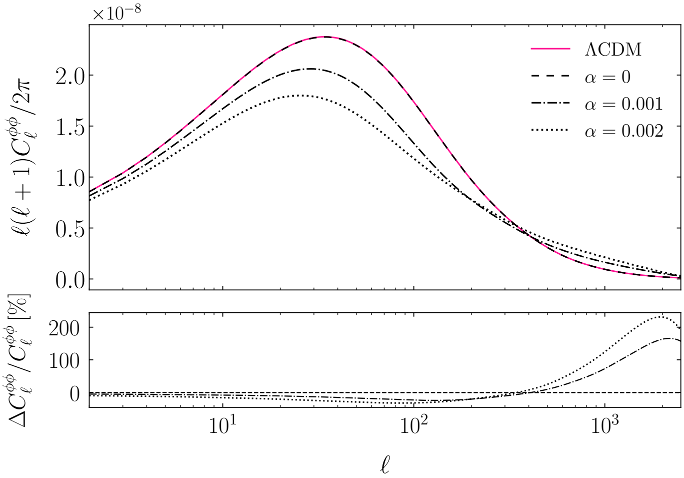
$$Q = 2\alpha\rho_c \frac{3\mathcal{H}\phi' + a^2 V_{,\phi}}{2\alpha a^2\rho_c + (1 + 2\alpha)\,\phi'^2}$$

Cosmological observables



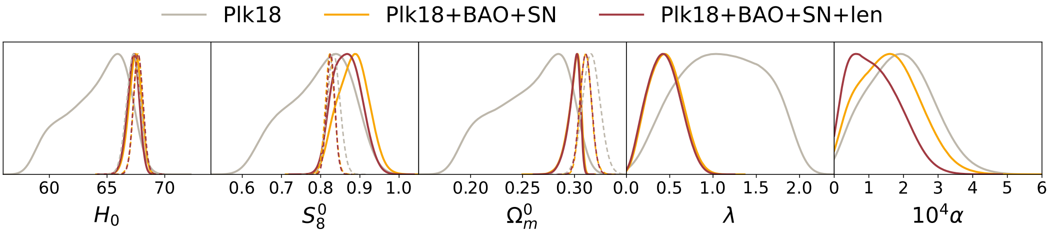
- General **enhancement of TT** power spectrum (ISW effect) - **degeneracy** between H_0 and α

Cosmological observables



- Overall **suppression of the lensing** power spectrum with increasing α

Cosmological Bounds

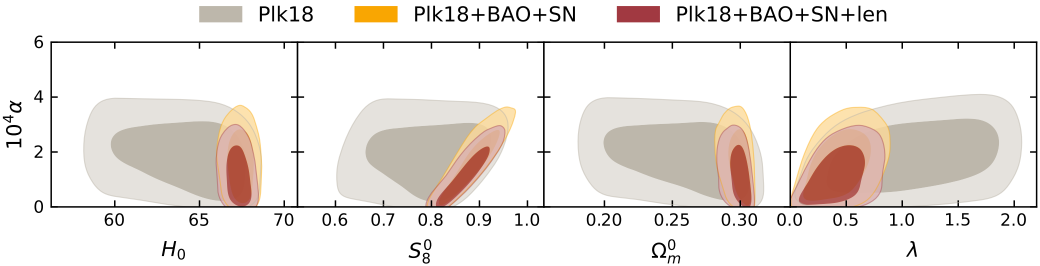


- **Lower** mean values for H_0 and Ω_m^0 in the Kinetic model
- α constrained to be of **order 10^{-4}** for all data combinations (all compatible at 68% C.L.)

Planck data: prefers the higher mean value of α - degeneracies

BAO and SN data: slight decrease of the *best-fit* value of α

CMB lensing data: even lower central value of α - lensing excess



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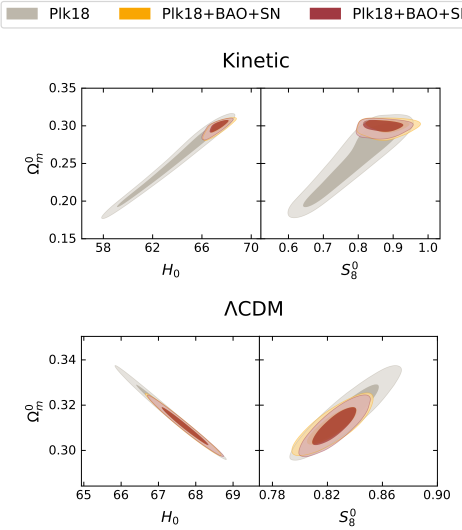
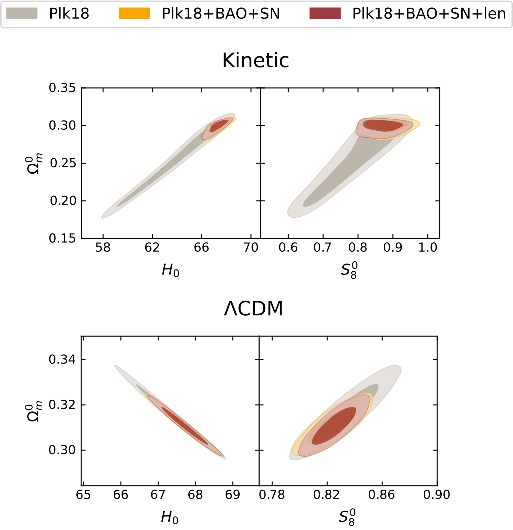
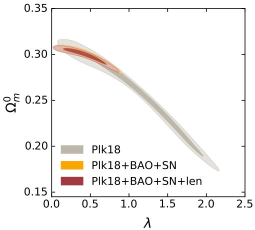
Cosmological Tensions



- **Opposite correlation** between H_0 and Ω_m^0 (positive) - counterbalance the enhancement of the TT power spectrum for $\alpha \neq 0$
- **Positive correlation** between S_8^0 and Ω_m^0
- Planck data: $S_8^0 = 0.793^{+0.11}_{-0.064}$ for the kinetic model and $S_8^0 = 0.833 \pm 0.016$ for the standard scenario - apparent **easing of the S_8 tension**
- Degeneracy broken by BAO and SN data - **Hubble tension is also still present** for all combinations

Cosmological Tensions





- Inclusion of BAO and SN data leads to **narrower constraints** on Ω_m^0, and consequently on H_0, S_8^0 and λ as well
- Anti-correlation between Ω_m^0 and λ: $\Omega_\phi^0 \approx 1 - \Omega_m^0$ and $w_\phi \approx 1 - 2V/3H^2$ - cosmological constant like behaviour today pushes λ towards **smaller values**

	Plk18	Plk18 + BAO + SN	Plk18 + BAO + SN + len
$\Delta\chi^2_{\rm eff}$	-0.9	0.7	1.0
ΔDIC	-0.316	0.7	1.62

- $\Delta\chi^2_{\rm eff}$ to assess the favoured model and **DIC** to quantify the preference
  - Better fit to the data for the **kinetic model** for the **Planck data**, but not overly significant
  - Slight preference for ΛCDM for other data combinations
  - BAO and SN data change the fit to the TT likelihood and the CMB lensing data shows an excess of power – suppression for $\alpha \neq 0$
  - There is **no statistical evidence** in support for **either of the two models**

Model Selection Analysis

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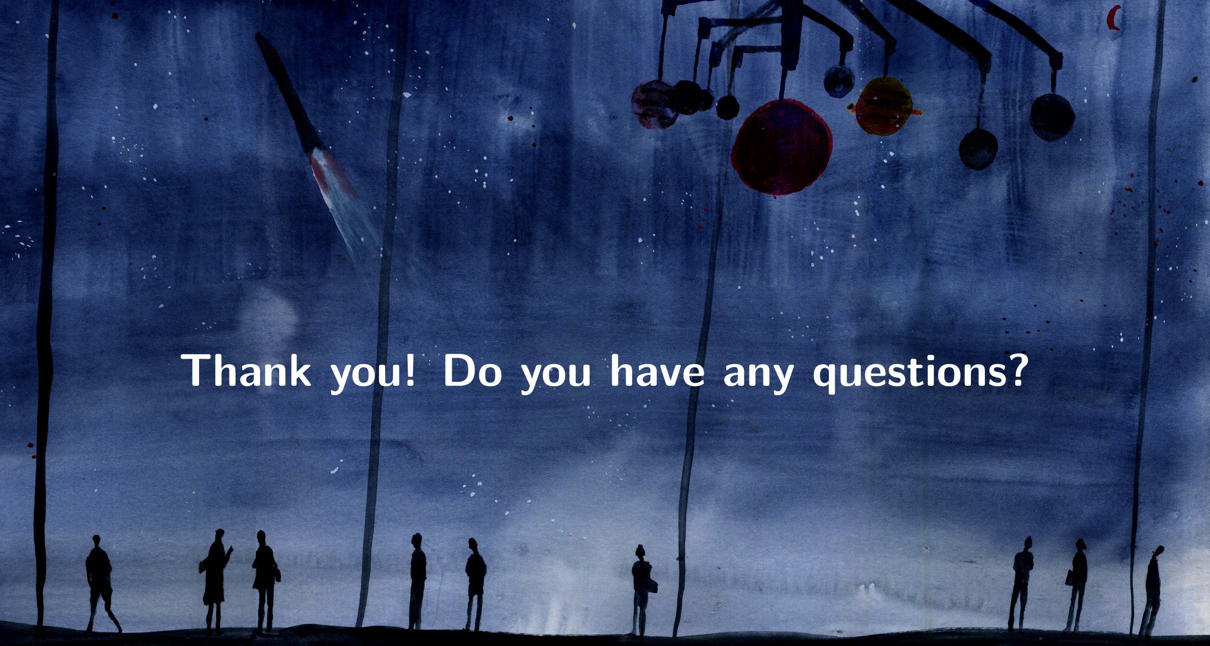
Conclusions

- **Interaction in the dark sector** through a **purely kinetic** coupling function $f(X) = \left(M_{Pl}^{-4} X\right)^{\alpha}$
- Cosmological **constraints on the parameters** of the theory using CMB, CMB lensing, BAO and SN data
- The S_8 tension is apparently **alleviated**, while the H_0 tension is **still present** for all combinations
- The parameter α is consistently constrained to be of the order 10^{-4} but **non-vanishing at 68% C.L.**
- **No clearly statistically favoured model** between ΛCDM and the kinetic model
- It would still be of interest to consider the kinetic models for **further investigations**

[Illustration Credits: Inês Viegas Oliveira]



Thank you! Do you have any questions?

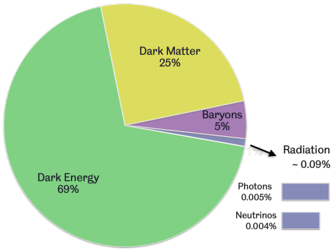
Illustration Credits: Inês Viegas Oliveira (ivoliveira.com)

Standard Model of Cosmology

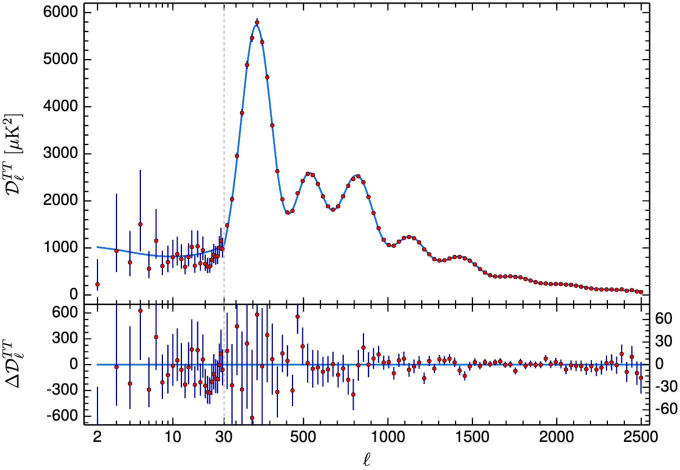
- Overwhelming observational evidence for the **accelerated expansion** of the Universe (CMB, SNe, BAO, ...)
- **ΛCDM model** is the standard model of Cosmology

	Theory of Gravity	Metric Ansatz	Standard Matter
Standard	$G_{\mu\nu} = 8\pi G T_{\mu\nu}$ General Relativity	$ds^2 = -dt^2 + a(t)d\vec{x}^2$ FLRW metric	Baryons, photons, neutrinos
	Late Acceleration	**Inflation**	**Cosmic Structure**
New Physics?	Λ Scalar field? Modified Gravity?	Inflation Inflaton field? Primordial GWs?	Cold Dark Matter Axion? Primordial BH?

[Ezquiaga and Zumalacárregui: **Front.Astron.Space Sci. 5 (2018), 44**]



Standard ΛCDM Model

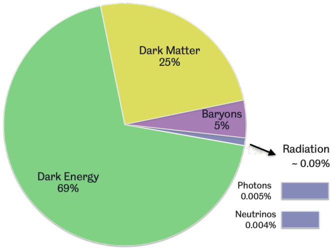


[Aghanim et al.: **Astron.Astrophys. 641 (2020) A6**]

Standard ΛCDM Model

- Overwhelming observational evidence for the **accelerated expansion** of the Universe (CMB, SNe, BAO, ...)
- Standard model of Cosmology based on **6 ingredients**
- **Theoretical simplicity** of the unknown components and fewer number of free parameters
- ΛCDM **correctly predicts** the cosmic background radiation and the large-scale distribution of galaxies
- However: conceptual problems and **observational tensions** Cosmological Constant (Λ): DE fluid whose

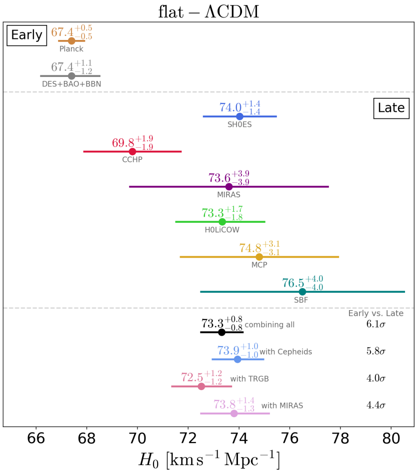
density remains constant with the expansion and has negative pressure ($w = p_\Lambda/\rho_\Lambda = -1$)



Hubble Tension

- **Hubble Tension**: Unreconcilable values for H_0 from the CMB and from direct local distance ladder measurements
- 4.4σ tension between *Planck* 2018 and SH0ES:
  - **CMB (Planck):** $H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$
  - **SNe (SH0ES):** $H_0 = 74.0 \pm 1.4\,\mathrm{km/s/Mpc}$
- The *Planck* 2018 results are a grand confirmation of the ΛCDM model but they are **model dependent**
- **Unlikely** that the discrepancies could be explained by a **single systematic error**
- The magnitude and persistence hints at **standard model flaws**

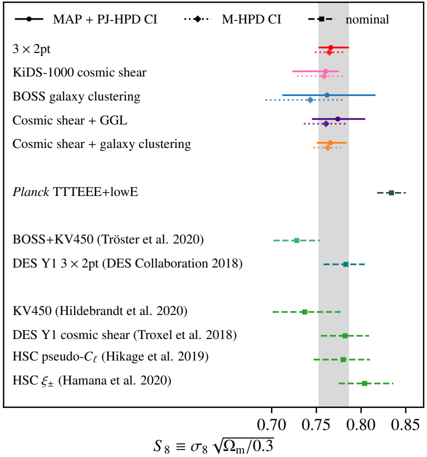
[Di Valentino et al.: **arXiv:2008.11284**]



[Verde, Treu, Riess: **Nature Astron. 3 891 (2019)**]

- **S_8 Tension**: discrepancy between CMB data and weak lensing and redshift surveys on the combined value of Ω_m^0 and σ_8^0, expressed as $S_8^0 = \sigma_8 \sqrt{\Omega_m/0.3}$
- 3σ tension between *Planck* 2018 CMB data and KiDS-1000 combination of Cosmic Shear and Galaxy Clustering:
  - **CMB (Planck):** $S_8^0 = 0.834 \pm 0.016$
  - **CS+GC (KiDS-1000):** $S_8^0 = 0.766^{+0.020}_{-0.014}$
- Could be related to the **excess of lensing** measured by Planck, mimicking a larger S_8^0
- Correlation between the H_0 and S_8 tensions - **conjoined analysis**
- Formulate **extensions** to the standard cosmological framework and test against the relevant constraints

[Di Valentino et al.: **arXiv:2008.11285**]



[C. Heymans et al.: **Astron.Astrophys. 646 (2021)**]

Interacting Dynamical Dark Energy

"Quintessence" (ϕ) - dynamical scalar field that evolves in space and time, as opposed to Λ

New forces between DE and "normal matter" are heavily constrained by observations (e.g. solar system tests)

No fundamental principle which forbids **interactions between the dark species**

Modification to the conservation equations in FLRW Univese:

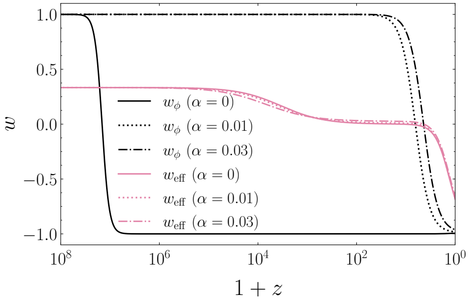
$$\dot{\rho}_{DM} + 3H\rho_{DM} = Q$$
$$\dot{\rho}_{\phi} + 3H\left(1 + w_{\phi}\right)\rho_{\phi} = -Q$$

Changes in the background and linear perturbations evolution could naturally address the H_0 and S_8 tensions

- But how to achieve the **phenomenological coupling**?

Background Cosmology

- EoS parameters w_ϕ and w_{eff}: transition towards accelerating state occurs later for larger values of α
- For a stronger interaction, the field remains frozen in the scaling regime for longer, with $w_\phi = 1$



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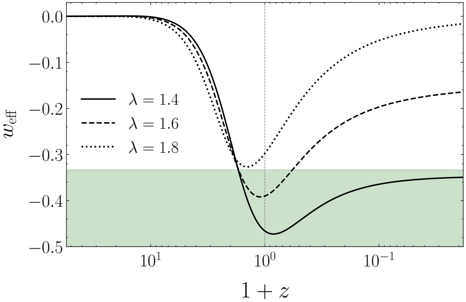

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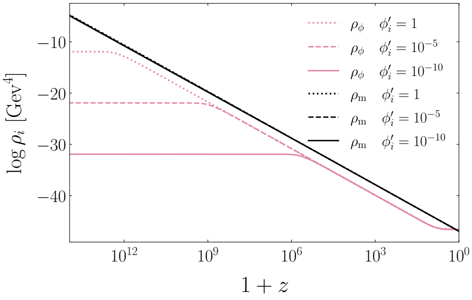
- For a stronger interaction, the field remains frozen in the scaling regime for longer, with $w_\phi = 1$
- Increasing the value of λ decreases the chances of achieving accelerated expansion even if just **transient**
- Increasing ϕ_i' leads to an earlier onset of the scaling regime only, setting the **duration of the scaling** - no influence whatsoever on the dynamics



Linear Perturbations

Scalar perturbations in the conformal Newtonian gauge

$$\mathrm{d}s^2 = a^2(\tau)\left[-(1+2\Psi)\,d\tau^2 + (1-2\Phi)\,\delta_{ij}dx^i dx^j\right]$$

Perturbed continuity and Euler equations for CDM ($\delta_c = \delta\rho_c/\rho_c$ and $\theta_c = \partial_i\partial^i v_c$)

$$\begin{cases} \delta_c' + \theta_c - 3\Phi' = \frac{Q}{\rho_c}\left(\phi'\delta_c - \delta\phi'\right) - \frac{\phi'}{\rho_c}\delta Q \\ \theta_c' + \mathcal{H}\theta_c - k^2\Psi = \frac{Q}{\rho_c}\left(\phi'\theta_c - k^2\delta\phi\right) \end{cases}$$

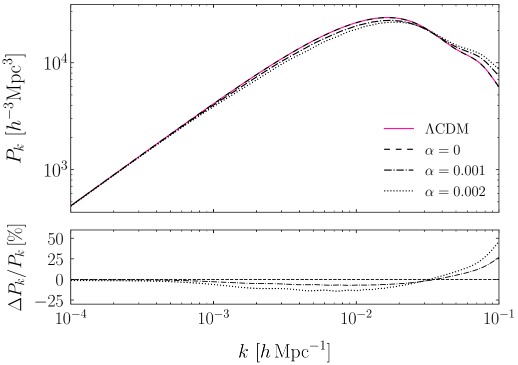
These equations describe the **clustering of matter** that leads to **structure formation**

$$\delta\phi'' + 2\mathcal{H}\delta\phi' + \left(a^2 V_{,\phi\phi} + k^2\right)\delta\phi - \left(\Psi' + 3\Phi'\right)\phi' + 2a^2\Psi V_{,\phi} = a^2\delta Q + 2a^2 Q\Psi$$

$$\delta Q = \frac{2\alpha\rho_c\left\{-3\Phi'\phi' - \phi'\theta_c + \left[3\mathcal{H}\phi' + a^2(V_{,\phi} - Q)\right]\delta_c + \left(2k^2 + a^2 V_{,\phi\phi}\right)\delta\phi - \left[3\mathcal{H}\phi' + 2a^2(V_{,\phi} - Q)\right]\frac{\delta\phi'}{\phi'} + 2a^2\Psi\left(Q - V_{,\phi}\right)\right\}}{2\alpha a^2\rho_c + (1+2\alpha)\phi'^2}$$

Cosmological observables

- **Matter power spectrum** is significantly suppressed at intermediate scales, $10^{-3} < k < 3 \times 10^{-2}$ and enhanced at the smaller scales, $k > 3 \times 10^{-2}$
- The growth of the matter perturbations leads to a **larger** σ_8 for the kinetic model



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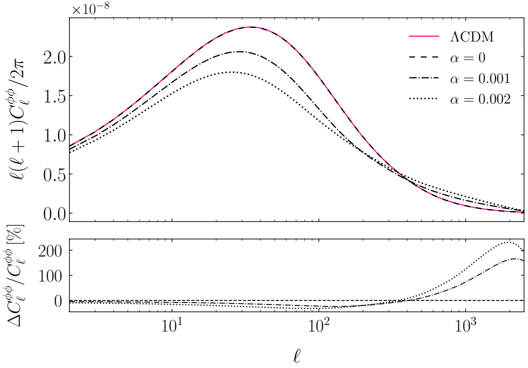

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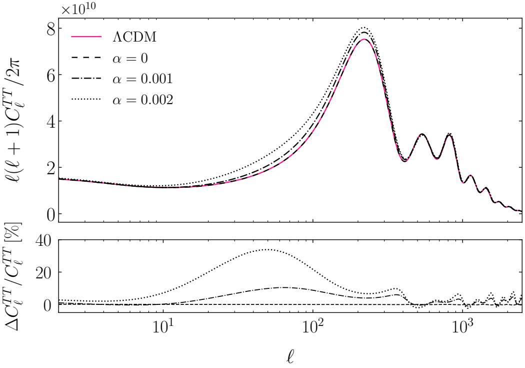
- General **enhancement of TT** power spectrum with greater amplitude and broadness of the first peak - ISW effect



Given a data set d, we want to sample posteriors on the model parameters θ that maximise the likelihood:

Bayes Theorem

$$p(\theta \mid d) = \frac{p(d \mid \theta)\, p(\theta)}{p(d)} \Leftrightarrow \text{Posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

Modified version of Einstein-Boltzmann code `CLASS` interfaced with the `MontePython` sampler

[Blas, Lesgourgues, Tram: **JCAP 1107 (2011) 034**; Audren et al.: **JCAP 1302 (2013) 001**; Brinckmann, Lesgourgues: **Phys. Dark Univ. 24 (2019) 100260**]

Employ an MCMC sampling method and analyse results in `GetDist` [Lewis: **arXiv:2008.11284**]

Sampled Cosmological Parameters

The ΛCDM model is based on 6 free parameters:

- the baryon and dark matter densities $\Omega_b h^2$ and $\Omega_c h^2$
- the angular size of the sound horizon at decoupling θ_s
- the reionisation redshift z_{reio}
- the spectral index n_s and the amplitude A_s of inflationary scalar perturbations

Parameter	Prior
$\Omega_\mathrm{b} h^2$	$[0.005, 0.1]$
$\Omega_\mathrm{c} h^2$	$[0.001, 0.99]$
$100\theta_s$	$[0.5, 10]$
z_{reio}	$[0., 20.]$
n_s	$[0.7, 1.3]$
$\log\left(10^{10} A_s\right)$	$[1.7, 5.0]$

In the **Kinetic Model** scenario we also allow sampling of:

- the effective coupling parameter α and the steepness of the potential λ

$\Longrightarrow$ 2 additional parameters

Parameter	Prior
α	$[0, 1]$
λ	$[0, 2]$

The remaining cosmological parameters are either fixed to standard Planck 2018 values or derived from the main ones

Data Sets

- Baseline data set is **"Plk18"**: CMB Planck 2018 data for large angular scales $\ell = [2, 29]$ and a joint of TT, TE and EE likelihoods for the small angular scales

  [Aghanim et al.: **Astron.Astrophys. 641 (2020) A5**]

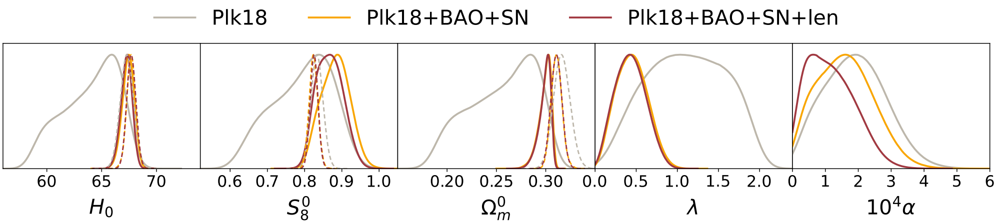
- **"Plk18+BAO+SN"**: "Plk18" plus compilation of baryon acoustic oscillations (BAO) distance and expansion rate measurements and distance moduli measurements of type Ia Supernova (SN) data from Pantheon.

  [Ross et. al: **Mon. Not. Roy. Astron. Soc. 449 (2015) 835**; Beutler et al.: **Mon. Not. Roy. Astron. Soc. 464 (2017) 3409**; Beutler et al.: **Mon. Not. Roy. Astron. Soc. 416 (2011) 3017**; Scolnic et. al: **Astrophys. J. 859 (2018) 101**]

- **"Plk18+BAO+SN+len"**: "Plk18+BAO+SN" plus CMB lensing potential data from Planck 2018

  [Aghanim et al.: **Astron.Astrophys. 641 (2020) A8**]

Cosmological Bounds



Kinetic Model

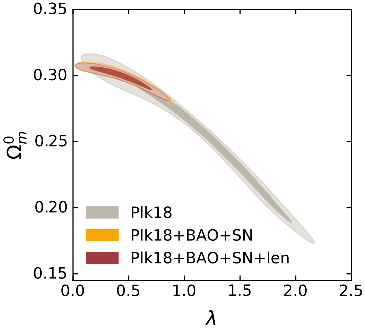
Parameter	Plk18	Plk18+ BAO+SN	Plk18+ BAO+SN+len
S_8^0	$0.793^{+0.11}_{-0.064}$	$0.875^{+0.037}_{-0.043}$	$0.863^{+0.030}_{-0.039}$
Ω_m^0	$0.257^{+0.045}_{-0.025}$	$0.2988^{+0.0072}_{-0.0036}$	$0.2982^{+0.0070}_{-0.0035}$
H_0	$64.0^{+3.3}_{-1.8}$	67.14 ± 0.62	$66.94^{+0.60}_{-0.54}$
λ	1.11 ± 0.48	$0.42^{+0.18}_{-0.21}$	$0.41^{+0.17}_{-0.22}$
$10^4\alpha$	1.88 ± 0.95	$1.37^{+0.67}_{-1.0}$	$1.05^{+0.51}_{-0.87}$

ΛCDM Model

Parameter	Plk18	Plk18+ BAO+SN	Plk18+ BAO+SN+len
S_8^0	0.833 ± 0.016	$0.831^{+0.013}_{-0.015}$	0.834 ± 0.013
Ω_m^0	0.3163 ± 0.0085	$0.3151^{+0.0060}_{-0.0075}$	0.3162 ± 0.0073
H_0	67.31 ± 0.61	$67.39^{+0.53}_{-0.45}$	67.32 ± 0.53

Cosmological Bounds

- Inclusion of BAO and SN data leads to narrower constraints on Ω_m^0, and consequently on H_0, S_8^0 and λ as well
- Anti-correlation between Ω_m^0 and λ: $\Omega_\phi^0 \approx 1 - \Omega_m^0$ and $w_\phi \approx 1 - 2V/3H^2$ - cosmological constant like behaviour today pushes λ towards smaller values
- Better fit to the data for the kinetic model considering the Planck data, although not overly significant
- Slight preference for ΛCDM for other data combinations - inclusion of BAO and SN data changes the fit to the TT likelihood and the CMB lensing data shows an excess of power, while $\alpha \neq 0$ introduces an overall suppression
- There is no statistical evidence in support for either of the two models



	Plk18	Plk18 + BAO + SN	Plk18 + BAO + SN + len
$\Delta\chi^2_{\rm eff}$	-0.9	0.7	1.0
ΔDIC	-0.316	0.7	1.62