Constraining the interactions in the dark sector with cosmological data

Adrià Gómez-Valent

MG16, DM1 session
July 6, 2021

This talk is based on...

- **Update on coupled dark energy and the H_0 tension**
  A. Gómez-Valent, V. Pettorino and L. Amendola.
  Phys. Rev. D, 101, 123513 (2020) [arXiv:2004.00610]
- **Running vacuum against the H_0 and σ_8 tensions**
  J. Solà Peracaula, A. Gómez-Valent, J. de Cruz Pérez and C. Moreno-Pulido
  Europhys. Lett., 134, 19001 (2021) [arXiv:2102.12758]

Outline

1. Coupled quintessence
   - The basics. Background dynamics
   - P(k) and CMB temperature anisotropies
   - Data and statistical analysis
   - Results
2. Ricci Running Vacuum Models
   - Basic equations
   - Results for the RRVM
3. Conclusions

Coupled quintessence

Lagrangian density for the dark sector:

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with

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In a flat FLRW universe:

$$\beta\kappa a^2\rho_{dm} = \phi'' + 2\mathcal{H}\phi' + a^2\frac{\partial V}{\partial\phi}$$

$$\rho'_{dm} + 3\mathcal{H}\rho_{dm} = -\beta\kappa\rho_{dm}\phi'$$

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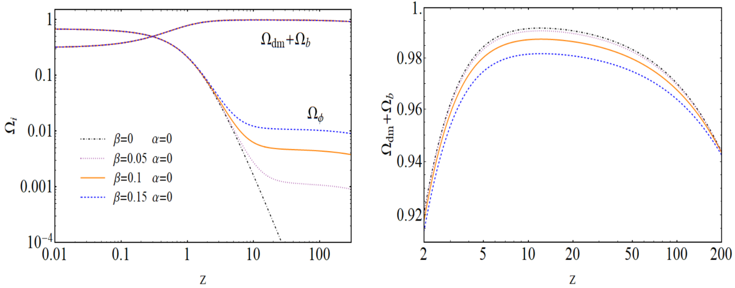
$$\beta = const. > 0 \qquad ; \qquad V(\phi) = V_0 \phi^{-\alpha} \quad (\text{with}\, \alpha > 0)$$

By solving the conservation equation for DM one finds:

$$m(\phi) = m^{(0)} e^{\beta\kappa(\phi^{(0)} - \phi)}$$

Scaling behavior in the MDE, $\Omega_\phi = 2\beta^2/3$ and $q = \frac{1}{2} + \beta^2$.



Linear perturbations

Equation for the DM density contrast:

$$\delta''_{dm} + (\mathcal{H} - \beta\kappa\phi')\delta'_{dm} - 4\pi G a^2[\rho_b\delta_b + \rho_{dm}\delta_{dm}(1+2\beta^2)] = 0$$

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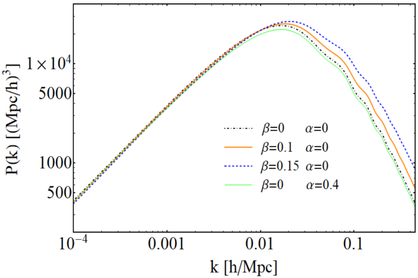

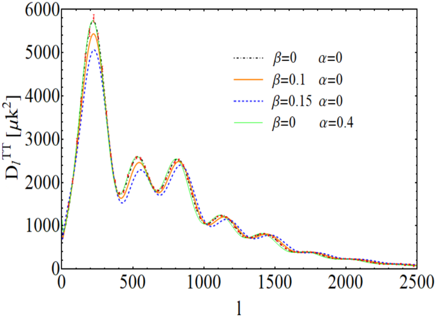

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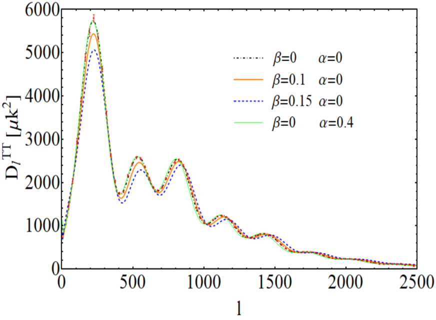

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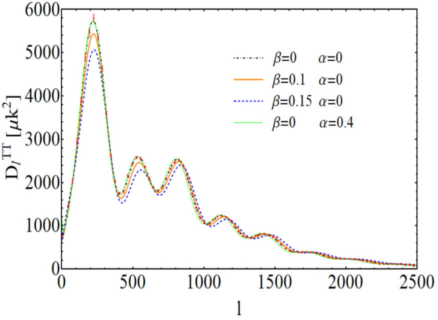

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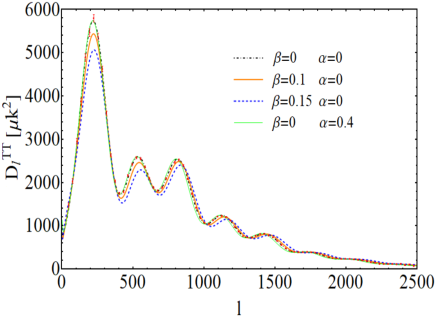

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- The coupling affects lensing of CMB by large-scale structure.
- The amplitude is suppressed, because of the decrease of ρ_b/ρ_{dm} at recombination.
- The interaction also shifts the position of the acoustic peaks to larger multipoles due to the decrease of the sound horizon at the baryon-drag epoch, which is caused by the increase of the mass of the DM particles.

Number of parameters and nested models

Our coupled quintessence model has 9 parameters:

- 6 ΛCDM parameters (ω_{dm},ω_b,τ,n_s,A_s,H_0).
- α, β and ϕ_{ini}.

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and three nested models:

- ΛCDM: $\alpha=\beta=0$
- Peebles-Ratra model: $\beta=0$
- Coupled dark energy with flat potential: $\alpha=0$.

Data

- Planck 2018 TT,TE,EE likelihood (P18); when CMB lensing is also included (P18lens).
- Pantheon+MCT compilation of SNIa.
- Data on BAO from various galaxy surveys.
- Data on $H(z_i)$ from cosmic chronometers.
- SH0ES prior on $H_0 = (74.03 \pm 1.42)$ km/s/Mpc.
- Angular diameter distances measured with the strong lensed quasars from HOLICOW.
- Redshift space distortions, $f(z_i)\sigma_8(z_i)$.

Occam's razor and model comparison

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Bayes ratio:

$$\frac{P(\mathrm{CDE}|\mathcal{D})}{P(\Lambda\mathrm{CDM}|\mathcal{D})} = \frac{\mathcal{E}(\mathcal{D}|\mathrm{CDE})}{\mathcal{E}(\mathcal{D}|\Lambda\mathrm{CDM})} \equiv B_{\mathrm{CDE},\Lambda}$$

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Bayesian evidence:

$$\mathcal{E}(\mathcal{D}|M_i) = \int \mathcal{L}(\mathcal{D}|\vec{p}^{M_i}, M_i)\pi(\vec{p}^{M_i})d^n p^{M_i}$$

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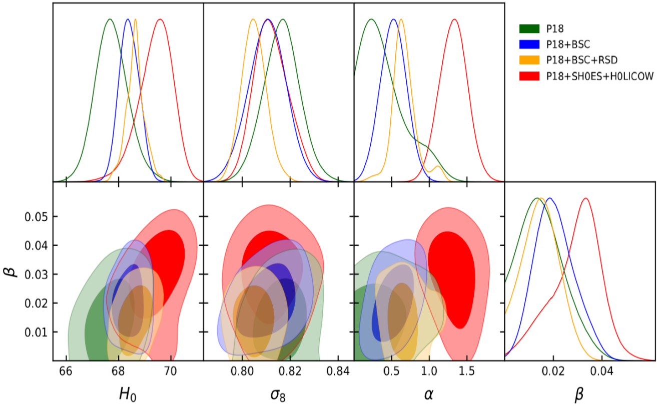
We computed the evidences with the Python code `MCEvidence`, Heavens et al. [arXiv:1704.03472].

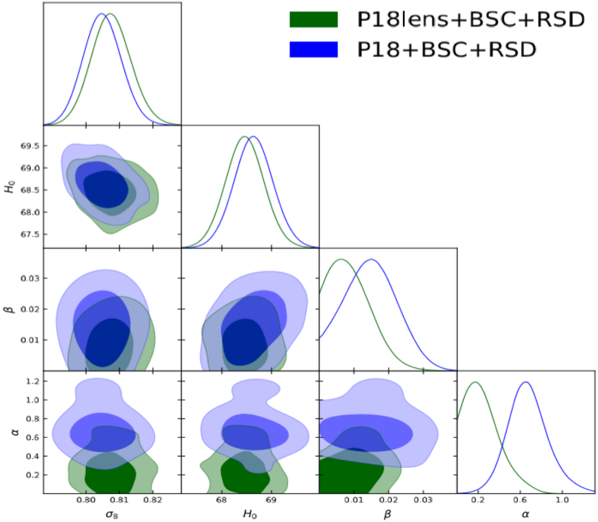
Jeffreys' scale

$\ln\, B_{i,\Lambda} > 5$	Very strong evidence for model i
$3 < \ln\, B_{i,\Lambda} \geq 5$	Strong evidence for model i
$1 < \ln\, B_{i,\Lambda} \geq 3$	Moderate evidence for model i
$-1 < \ln\, B_{i,\Lambda} \geq 1$	Not conclusive
$-3 < \ln\, B_{i,\Lambda} \geq -1$	Moderate evidence for model ΛCDM
$-5 < \ln\, B_{i,\Lambda} \geq -3$	Strong evidence for model ΛCDM
$\ln\, B_{i,\Lambda} \geq -5$	Very strong evidence for model ΛCDM


P18
P18+BSC
P18+BSC+RSD
P18+SH0ES+H0LICOW
β
0.05
0.04
0.03
0.02
0.01
66
68
70
H_0
0.80
0.82
0.84
σ_8
0.5
1.0
1.5
α
0.02
0.04
β

Parameter	P18	P18+BSC	P18+SH0ES+H0LICOW	P18+BSC+RSD	P18lens+BSC+RSD	P18+BSC+SH0ES+H0LICOW	P18lens+SH0ES+H0LICOW
$\Omega^{(0)}_{dm}h^2$	$0.1207^{+0.0014}_{-0.0013}$	0.1192 ± 0.0008	$0.1172^{+0.0012}_{-0.0014}$	0.1187 ± 0.0008	0.1191 ± 0.0007	0.1185 ± 0.0008	$0.1182^{+0.0011}_{-0.0010}$
$\Omega^{(0)}_{b}h^2$	0.02237 ± 0.00015	$0.02242^{+0.00010}_{-0.00015}$	$0.02262^{+0.00016}_{-0.00014}$	$0.02253^{+0.00010}_{-0.00012}$	$0.02253^{+0.00013}_{-0.00011}$	$0.02253^{+0.00011}_{-0.00013}$	$0.02259^{+0.00014}_{-0.00016}$
τ	0.0538 ± 0.0070	$0.0532^{+0.0075}_{-0.0087}$	0.0594 ± 0.0074	0.0501 ± 0.0052	$0.0525^{+0.0052}_{-0.0064}$	$0.0579^{+0.0069}_{-0.0078}$	$0.0637^{+0.0065}_{-0.0096}$
H_0	$67.74^{+0.57}_{-0.66}$	68.41 ± 0.38	$69.43^{+0.72}_{-0.53}$	$68.64^{+0.30}_{-0.38}$	68.45 ± 0.34	$68.79^{+0.35}_{-0.40}$	68.99 ± 0.51
n_s	$0.9654^{+0.0035}_{-0.0042}$	0.9690 ± 0.0038	0.9731 ± 0.0042	$0.9701^{+0.0029}_{-0.0033}$	0.9685 ± 0.0034	0.9705 ± 0.0034	0.9713 ± 0.0037
σ_8	0.8164 ± 0.0076	0.8104 ± 0.0076	$0.8121^{+0.0065}_{-0.0080}$	0.8048 ± 0.0052	$0.8073^{+0.0048}_{-0.0056}$	0.8120 ± 0.0074	0.8160 ± 0.0068
α	< 0.50	0.52 ± 0.17	1.32 ± 0.18	$0.67^{+0.11}_{-0.16}$	$0.25^{+0.09}_{-0.20}$	$0.73^{+0.11}_{-0.27}$	$0.33^{+0.19}_{-0.23}$
β	$0.0158^{+0.0067}_{-0.0120}$	$0.0206^{+0.0070}_{-0.0095}$	$0.0294^{+0.0120}_{-0.0076}$	$0.0151^{+0.0073}_{-0.0083}$	$0.0095^{+0.0030}_{-0.0087}$	$0.0206^{+0.0076}_{-0.0100}$	$0.0197^{+0.0094}_{-0.0084}$
$\chi^2_{min,\mathrm{CDE}} - \chi^2_{min,\Lambda}$	-0.02	-0.28	-0.58	-1.56	-0.90	-1.34	-1.46
$\ln B_{\mathrm{CDE},\Lambda}$	-8.05	-9.95	-7.57	-8.33	-7.83	-7.95	-8.75

Effect of CMB lensing



Results with exponential potential

What happens if we consider $V = V_0 e^{-\kappa\lambda\phi}$ instead of the Peebles-Ratra potential?

Parameter	P18+BSC	P18+SH0ES+H0LICOW	P18lens+BSC+RSD
H_0	$67.86^{+0.64}_{-0.46}$	69.29 ± 0.61	67.67 ± 0.62
σ_8	$0.8090^{+0.0110}_{-0.0090}$	0.8097 ± 0.0086	0.7994 ± 0.0084
λ	$0.40^{+0.20}_{-0.24}$	< 0.163	$0.54^{+0.24}_{-0.17}$
β	$0.0198^{+0.0100}_{-0.0120}$	$0.0240^{+0.0150}_{-0.0120}$	$0.0167^{+0.0085}_{-0.0100}$
$\ln B_{\rm CDE,\Lambda}$	-5.88	-6.54	-5.33

Results for the nested models

Parameter	ΛCDM	Peebles-Ratra	CDE with $\alpha = 0$	CDE
$\Omega_{dm}^{(0)} h^2$	0.1188 ± 0.0008	$0.1180^{+0.0010}_{-0.0009}$	$0.1187^{+0.0006}_{-0.0008}$	0.1187 ± 0.0008
$\Omega_b^{(0)} h^2$	0.02252 ± 0.00012	0.02257 ± 0.00014	0.02253 ± 0.00011	$0.02253^{+0.00010}_{-0.00012}$
τ	$0.0508^{+0.0048}_{-0.0072}$	$0.0532^{+0.0063}_{-0.0079}$	0.0496 ± 0.0047	0.0501 ± 0.0052
H_0 [km/s/Mpc]	68.50 ± 0.34	$67.68^{+0.61}_{-0.52}$	$68.55^{+0.38}_{-0.31}$	$68.64^{+0.30}_{-0.38}$
n_s	0.9696 ± 0.0034	0.9719 ± 0.0038	$0.9700^{+0.0032}_{-0.0037}$	$0.9701^{+0.0029}_{-0.0033}$
σ_8	0.8033 ± 0.0057	$0.7880^{+0.0110}_{-0.0097}$	0.8022 ± 0.0054	0.8048 ± 0.0052
α	-	$0.096^{+0.038}_{-0.071}$	-	$0.67^{+0.11}_{-0.16}$
β	-	-	$0.0040^{+0.0012}_{-0.0032}$	$0.0151^{+0.0073}_{-0.0083}$
$\chi^2_{min,i} - \chi^2_{min,\Lambda}$	-	-1.74	-1.02	-1.56
$\ln B_{i,\Lambda}$	-	-1.67	-5.14	-8.33

Ricci Running Vacuum Model

Vacuum energy density:

$$\rho_{\rm vac}(\mathcal{R}) = \frac{3}{8\pi G_N}\left(c_0 + \frac{\nu}{12}\mathcal{R}\right)$$

with

$$\dot{\rho}_{dm} + 3H\rho_{dm} = -\dot{\rho}_{\rm vac}\,.$$

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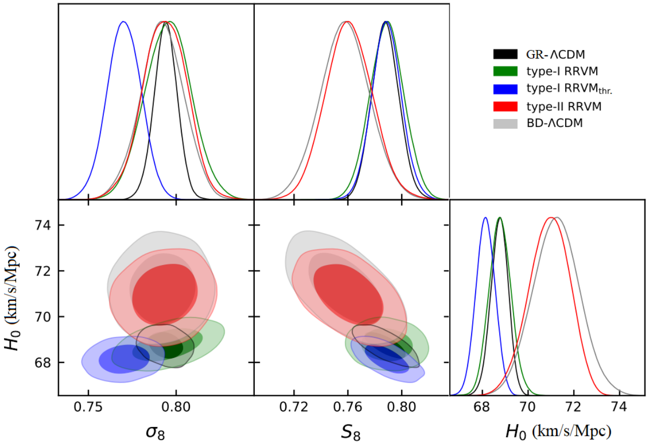
We can solve the system and obtain:

$$\rho_{dm}(a) = \rho_m^0 a^{-3\xi} - \rho_b^0 a^{-3} \qquad ; \qquad \rho_{\rm vac}(a) = \rho_{\rm vac}^0 + \left(\frac{1}{\xi} - 1\right)\rho_m^0\left(a^{-3\xi} - 1\right)$$

where $\xi = 1 - \frac{\nu}{4} + \mathcal{O}(\nu^2)$.


GR-ΛCDM
type-I RRVM
type-I RRVM$_{thr.}$
type-II RRVM
BD-ΛCDM
H_0 (km/s/Mpc)
74
72
70
68
0.75
0.80
σ_8
0.72
0.76
0.80
S_8
68
70
72
74
H_0 (km/s/Mpc)

Baseline + H_0

Parameter	ΛCDM	type I RRVM	type I RRVM$_{\rm thr.}$	type II RRVM	BD-ΛCDM
H_0 (km/s/Mpc)	$68.75^{+0.41}_{-0.36}$	$68.77^{+0.49}_{-0.48}$	$68.14^{+0.43}_{-0.41}$	$70.93^{+0.93}_{-0.87}$	$71.23^{+1.01}_{-1.02}$
ω_b	$0.02240^{+0.00019}_{-0.00021}$	$0.02238^{+0.00021}_{-0.00023}$	$0.02243^{+0.00019}_{-0.00018}$	$0.02269^{+0.00025}_{-0.00024}$	$0.02267^{+0.00026}_{-0.00023}$
ω_{dm}	$0.11658^{+0.00080}_{-0.00083}$	$0.11661^{+0.00084}_{-0.00085}$	$0.12299^{+0.00197}_{-0.00203}$	$0.11602^{+0.00162}_{-0.00163}$	$0.11601^{+0.00161}_{-0.00157}$
$\nu_{\rm eff}$	-	$-0.00005^{+0.00040}_{-0.00038}$	$0.02089^{+0.00553}_{-0.00593}$	$0.00038^{+0.00041}_{-0.00044}$	-
$\epsilon_{\rm BD}$	-	-	-	-	$-0.00130^{+0.00136}_{-0.00140}$
$\varphi_{\rm ini}$	-	-	-	$0.938^{+0.018}_{-0.024}$	$0.928^{+0.024}_{-0.026}$
φ_0	-	-	-	$0.930^{+0.022}_{-0.029}$	$0.919^{+0.028}_{-0.033}$
$\tau_{\rm reio}$	$0.050^{+0.008}_{-0.007}$	$0.049^{+0.009}_{-0.008}$	$0.058^{+0.008}_{-0.009}$	0.052 ± 0.008	0.052 ± 0.008
n_s	$0.9718^{+0.0035}_{-0.0038}$	0.9714 ± 0.0046	$0.9723^{+0.0040}_{-0.0039}$	$0.9868^{+0.0072}_{-0.0074}$	$0.9859^{+0.0073}_{-0.0072}$
σ_8	0.794 ± 0.007	0.795 ± 0.013	0.770 ± 0.010	$0.794^{+0.013}_{-0.012}$	$0.792^{+0.013}_{-0.012}$
S_8	$0.788^{+0.010}_{-0.011}$	0.789 ± 0.013	0.789 ± 0.011	$0.761^{+0.018}_{-0.017}$	$0.758^{+0.019}_{-0.018}$
r_s (Mpc)	$147.97^{+0.29}_{-0.31}$	$147.94^{+0.35}_{-0.36}$	$147.88^{+0.33}_{-0.29}$	$143.00^{+1.54}_{-1.96}$	$142.24^{+1.99}_{-2.12}$
$\chi^2_{\rm min}$	2302.14	2301.90	2288.82	2296.38	2295.36
ΔDIC	-	-2.36	+10.88	+5.52	+6.25

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- $\rho_{dm}(z_{dec})$ is very strongly constrained by the CMB data. This limits the ability of these models to alleviate the cosmological tensions.
- The mass of the DM particles is restricted to be $m(a_{ini})/m(a=1)-1 \lesssim \mathcal{O}(1)\%$ in the CDE model.
- Applying Occam's razor we conclude that ΛCDM is preferred by the current cosmological data.

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- It is also curious to see how some regions of parameter space in CDE with a significant late-time DE dynamics and non-negligible interactions with DM give rise to a phenomenology almost indistinguishable from the ΛCDM.

Thanks for your attention!