Ruling out Interacting Holographic Dark Energy with Hubble scale cutoff
+
New constraints on Interacting Dark Energy

Ricardo G. Landim

Based on 2206.10205 [Phys.Rev.D 106 (2022)]
and work in progress (in collaboration with G. Hoerning, L. Ponte)

Progress on Old and New Themes in cosmology – 3 May 2023

UNIVERSITY OF PORTSMOUTH

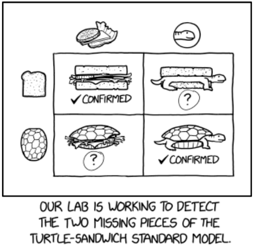
The best theories so far . . .

Gravitational interaction:

- General Relativity is running well . . . `[GR-Result: 0 Errors, xx Warnings, yy Bad Boxes]`

Strong and Electro-Weak interactions:

- Standard Model of particle physics is running . . . `[SM-Result: xx Errors, yy Warnings, zz Bad Boxes]` (+ neutrino masses + . . .)



https://xkcd.com/2301/

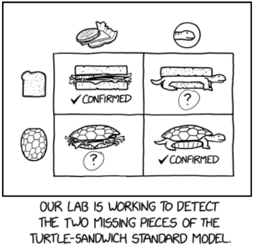
The best theories so far ...

Gravitational interaction:

- General Relativity is running well ... [GR-Result: 0 Errors, xx Warnings, yy Bad Boxes]

Strong and Electro-Weak interactions:

- Standard Model of particle physics is running ... [SM-Result: xx Errors, yy Warnings, zz Bad Boxes] (+ neutrino masses + ...)



https://xkcd.com/2301/

- \make{ theory SM+GR} ... [fatal error occurred! no output produced]

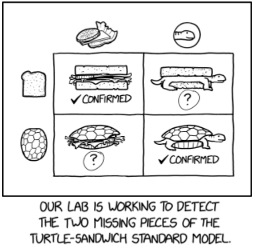
The best theories so far ...

Gravitational interaction:

- General Relativity is running well ... [GR-Result: 0 Errors, xx Warnings, yy Bad Boxes]

Strong and Electro-Weak interactions:

- Standard Model of particle physics is running ... [SM-Result: xx Errors, yy Warnings, zz Bad Boxes] (+ neutrino masses + ...)



https://xkcd.com/2301/

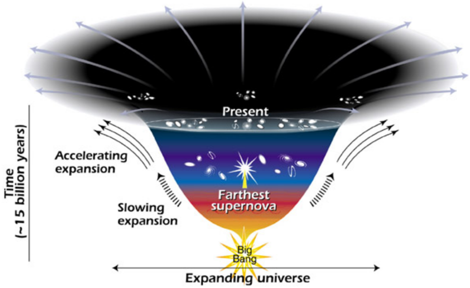
- \make{ theory SM+GR} ... [fatal error occurred! no output produced]

BUT there is not only light, there is the dark side

- $SU(3) \times SU(2) \times U(1)$ (5%)
- Universe is expanding at accelerated rate (68%)
- Dark matter (27%)

Cosmological constant problem

- Universe expanding at an accelerated rate.
- $\rho_{\Lambda}^{(obs)} \approx 10^{-47}\text{GeV}^4$.
- $\rho_{vac} \approx 10^{74}\text{GeV}^4$.
- Famous 120-orders-of-magnitude discrepancy.
- Coincidence ‘problem’ - why are dark energy and matter densities of the same order today?



Source: Wikipedia

Dark energy candidates

It's been a long road...

- Scalar or vector fields
- Modified gravity
- Metastable DE
- Extra dimensions
- Exotic fluids
- etc

Symmetry Magazine: Artwork by Sandbox Studio, Chicago

Interacting dark energy

$$\dot{\rho_d} + 3H(\rho_d + p_d) = -\mathcal{Q}, \tag{1}$$

$$\dot{\rho_m} + 3H\rho_m = \mathcal{Q}, \tag{2}$$

$$\dot{\rho_r} + 4H\rho_r = 0, \tag{3}$$

The case of $\mathcal{Q} > 0$ corresponds to dark energy transformation into dark matter, while $\mathcal{Q} < 0$ is the transformation in the opposite direction.

Holographic principle

Degrees of freedom of a physical system scales with its boundary area rather than its volume.

- 't Hooft
- Susskind
- Thorn and Bekenstein

Cohen, Kaplan & Nelson [1998] suggested the following relationship:

$$L^3\Lambda^4 \lesssim LM_P^2 \tag{4}$$

$$\rho_D = 3c^2 M_{pl}^2 L^{-2} \tag{5}$$

HDE Hubble cutoff

- First (obvious) choice [Hsu, 2004]: $L \sim H^{-1}$, BUT

$$3H^2 = \rho_D + \rho_m = 3c^2H^2 + \rho_m \tag{6}$$

$$\rho_m = 3H^2(1 - c^2) \tag{7}$$

ρ_m scales with a^{-3}, as so ρ_D $\rightarrow w_D = 0$

HDE Particle horizon

- $L = R_H$

$$\rho_D = 3c^2 M_{pl}^2 L^{-2}, \quad R_H = a\int_0^t \frac{dt}{a}, \quad w_D = -\frac{1}{3} + \frac{2}{3c} > -\frac{1}{3} \tag{8}$$

HDE Future event horizon

- $L = R_E$ [Li 2004]

$$\rho_D = 3c^2 M_{pl}^2 L^{-2}, \quad R_E = a\int_t^\infty \frac{dt}{a}, \quad w_D = -\frac{1}{3} - \frac{2}{3c} \tag{9}$$

Interacting HDE

$$\rho_d = 3c^2 M_{pl}^2 H^2 \tag{10}$$

Constant c.

- $\mathcal{Q} = H(\lambda_1 \rho_{\rm dm} + \lambda_2 \rho_{\rm de})$

$$w = -\frac{1}{3}\left(\lambda_1 + \frac{\lambda_2}{r}\right)(1+r)\,. \tag{11}$$

$r \equiv \rho_m/\rho_d = (1-c^2)/c^2 \rightarrow c^2 = (1+r_0)^{-1}$

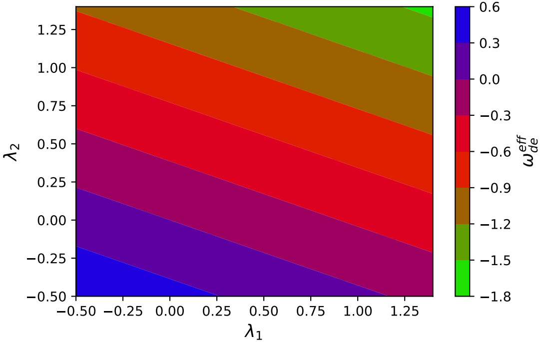
- Equation of state is no longer a free parameter
- When the coupling constants are zero, a pressureless fluid is recovered

$$\rho_{\rm dm} = \rho_{\rm dm,0}\, a^{-3+\lambda_1+\frac{\lambda_2}{r_0}}\,, \quad (12)$$

$$\rho_{\rm de} = \rho_{\rm de,0}\, a^{-3+\lambda_1+\frac{\lambda_2}{r_0}}\,. \quad (13)$$

$$\Rightarrow w_{\rm de}^{\rm eff} = w_{\rm dm}^{\rm eff} = -1/3(\lambda_1 + \lambda_2/r_0)$$

- Both fluids will have the same evolution
  - CDM (with $\lambda_1 = \lambda_2 \simeq 0$) (*remember previous slides*)
  - DE ($w_{\rm de}^{\rm eff} < -1/3$)



1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
λ_2
−0.50 −0.25 0.00 0.25 0.50 0.75 1.00 1.25
λ_1
0.6
0.3
0.0
−0.3
−0.6
−0.9
−1.2
−1.5
−1.8
ω_{de}^{eff}

$$\dot{\delta}_{\rm dm} = -\theta_{\rm dm} - \frac{\dot{h}}{2} + \mathcal{H}\lambda_2\frac{\rho_{\rm de,0}}{\rho_{\rm dm,0}}(\delta_{\rm de} - \delta_{\rm dm}) + \left(\lambda_1 + \lambda_2\frac{\rho_{\rm de,0}}{\rho_{\rm dm,0}}\right)\left(\frac{kv_T}{3} + \frac{\dot{h}}{6}\right), \quad (14)$$

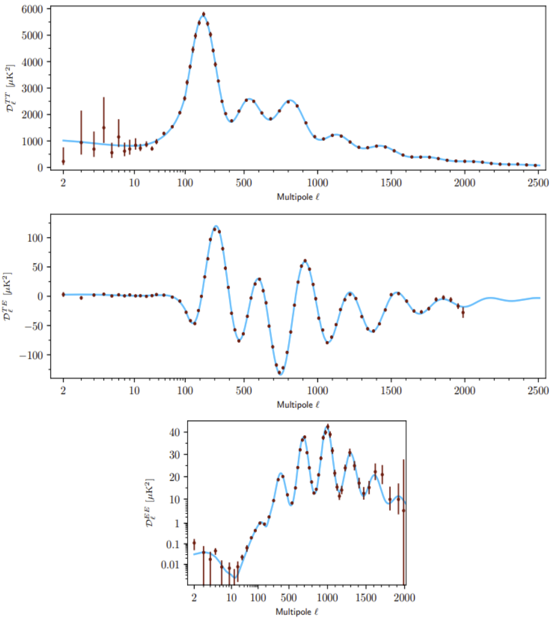
$$\dot{\theta}_{\rm dm} = -\mathcal{H}\theta_{\rm dm} - \left(\lambda_1 + \lambda_2\frac{\rho_{\rm de,0}}{\rho_{\rm dm,0}}\right)\mathcal{H}\theta_{\rm dm}\,, \quad (15)$$

$$\begin{aligned}\dot{\delta}_{\rm de} =& -(1+w)\left(\theta_{\rm de} + \frac{\dot{h}}{2}\right) - 3\mathcal{H}(1-w)\delta_{\rm de} + \mathcal{H}\lambda_1\frac{\rho_{\rm dm,0}}{\rho_{\rm de,0}}(\delta_{\rm de} - \delta_{\rm dm}) \\ & - 3\mathcal{H}(1-w)\left[3(1+w) + \lambda_1\frac{\rho_{\rm dm,0}}{\rho_{\rm de,0}} + \lambda_2\right]\frac{\mathcal{H}\theta_{\rm de}}{k^2} - \left(\lambda_1\frac{\rho_{\rm dm,0}}{\rho_{\rm de,0}} + \lambda_2\right)\left(\frac{kv_T}{3} + \frac{\dot{h}}{6}\right), \quad (16)\end{aligned}$$

$$\dot{\theta}_{\rm de} = 2\mathcal{H}\theta_{\rm de}\left[1 + \frac{1}{1+w}\left(\lambda_1\frac{\rho_{\rm dm,0}}{\rho_{\rm de,0}} + \lambda_2\right)\right] + \frac{k^2}{1+w}\delta_{\rm de}\,, \quad (17)$$

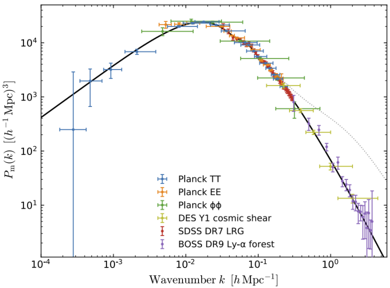
$$(1+w_T)v_T = \sum_a (1+w_a)\Omega_a v_a\,. \quad (18)$$

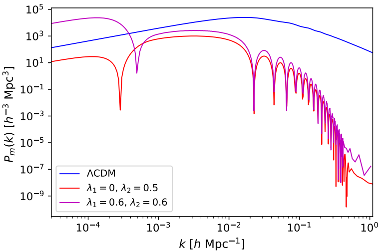
Inclusion of term δH for interaction (*absent in other works!*)

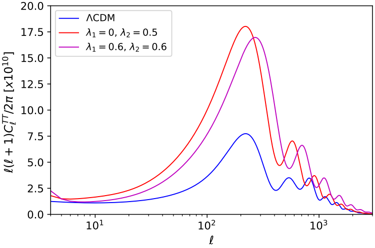

6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
2
10
100
500
1000
1500
2000
2500
Multipole ℓ
100
50
0
−50
−100
$\mathcal{D}_\ell^{TE}$ [μK^2]
Multipole ℓ
40
30
20
10
1
0.1
0.01
$\mathcal{D}_\ell^{EE}$ [μK^2]
Multipole ℓ

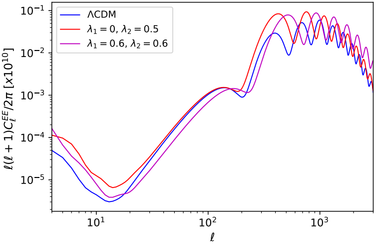
Planck 2018

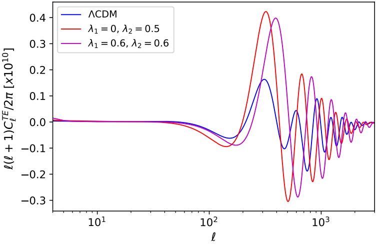
Results

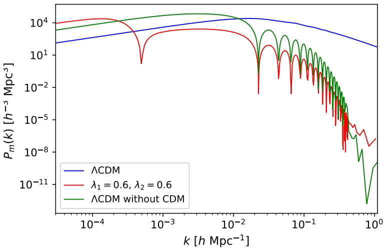

Planck TT
Planck EE
Planck ϕϕ
DES Y1 cosmic shear
SDSS DR7 LRG
BOSS DR9 Ly-α forest
$P_m(k)$ $[(h^{-1}\,\mathrm{Mpc})^3]$
Wavenumber k $[h\,\mathrm{Mpc}^{-1}]$

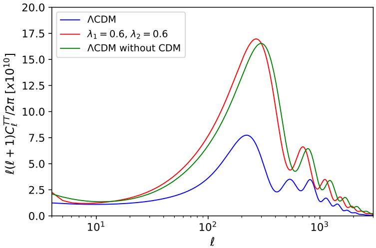

ΛCDM
$\lambda_1 = 0, \lambda_2 = 0.5$
$\lambda_1 = 0.6, \lambda_2 = 0.6$
$P_m(k)$ $[h^{-3}\,\mathrm{Mpc}^3]$
k $[h\,\mathrm{Mpc}^{-1}]$


ΛCDM
$\lambda_1 = 0, \lambda_2 = 0.5$
$\lambda_1 = 0.6, \lambda_2 = 0.6$
$\ell(\ell+1)C_\ell^{TT}/2\pi$ [x10^{10}]
ℓ


ΛCDM
$\lambda_1 = 0, \lambda_2 = 0.5$
$\lambda_1 = 0.6, \lambda_2 = 0.6$
$\ell(\ell+1)C_\ell^{EE}/2\pi$ [x10^{10}]
ℓ


ΛCDM
$\lambda_1 = 0, \lambda_2 = 0.5$
$\lambda_1 = 0.6, \lambda_2 = 0.6$
$\ell(\ell+1)C_\ell^{TE}/2\pi$ [x10^{10}]
ℓ





All parameter space excluded!

- Why new constraints?

- Why new constraints?
- – (Not very) New data (Planck 2018, BAO, Pantheon+)

- Why new constraints?
- – (Not very) New data (Planck 2018, BAO, Pantheon+)
- – Inclusion of term δH for interaction (*absent in other works!*)

- Why new constraints?
- – (Not very) New data (Planck 2018, BAO, Pantheon+)
- – Inclusion of term δH for interaction (*absent in other works!*)

$$\dot{\rho}_{\rm dm} + 3\mathcal{H}\rho_{\rm dm} = a^2 Q^0_{\rm dm} = aQ\,, \tag{19}$$

$$\dot{\rho}_{\rm de} + 3\mathcal{H}(1+w)\rho_{\rm de} = a^2 Q^0_{\rm de} = -aQ\,, \tag{20}$$

$$Q = H(\lambda_1 \rho_{\rm dm} + \lambda_2 \rho_{\rm de})$$

- $\lambda_1 \neq 0$, $\lambda_2 = 0$
- $\lambda_1 = 0$, $\lambda_2 \neq 0$
- $\lambda_1 = \lambda_2$

- $\lambda_1 \neq 0$, $\lambda_2 = 0$

$$\rho_{\rm dm} = \rho_{\rm dm,0} a^{-3(1+w_1^{\rm eff})}\,, \tag{21}$$

$$\rho_{\rm de} = \rho_{\rm de,0} a^{-3(1+w)} + \lambda_1 \frac{\rho_{\rm dm,0} a^{-3(1+w)}}{3(w - w_1^{\rm eff})}\left[1 - a^{3(w-w_1^{\rm eff})}\right]\,, \tag{22}$$

where $w_1^{\rm eff} = -\lambda_1/3$.

- $\lambda_1 = 0$, $\lambda_2 \neq 0$ [Lucca, 2020]

$$\rho_{\rm dm} = \rho_{\rm dm,0} a^{-3} + \lambda_2 \frac{\rho_{\rm de,0} a^{-3}}{3 w_2^{\rm eff}}\left[1 - a^{-3w_2^{\rm eff}}\right]\,, \tag{23}$$

$$\rho_{\rm de} = \rho_{\rm de,0} a^{-3(1+w_2^{\rm eff})}\,, \tag{24}$$

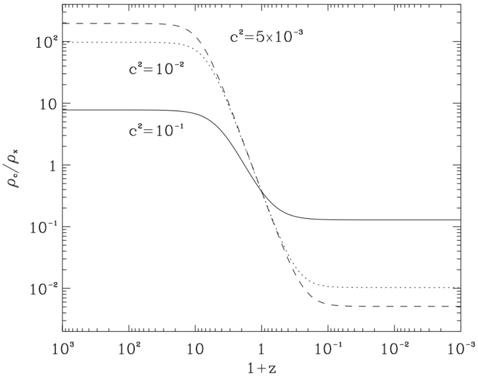
where $w_2^{\rm eff} = w + \lambda_2/3$.

- $\lambda_1 = \lambda_2$ [Olivares, 2005]

$$\rho_{\rm dm} = w_{\rm eff}^{-1}\left\{\left[\left(1+w+\frac{\lambda}{3}\right)\rho_{\rm dm,0}+\frac{\lambda}{3}\rho_{\rm de,0}\right](a^{S_-}-a^{S_+})+\rho_{\rm dm,0}(S_-a^{S_-}-S_+a^{S_+})\right\}, \quad (25)$$

$$\rho_{\rm de} = w_{\rm eff}^{-1}\left\{\left[\frac{\lambda}{3}\rho_{\rm dm,0}-\left(1-\frac{\lambda}{3}\right)\rho_{\rm de,0}\right](a^{S_+}-a^{S_-})+\rho_{\rm de,0}(S_-a^{S_-}-S_+a^{S_+})\right\}, \quad (26)$$

where $w_{\rm eff} = (w^2 + 4\lambda w/3)^{1/2}$ and $S_\pm = -(1+w/2) \mp w_{\rm eff}/2$.



Olivares 2005

$\Rightarrow \dot{r} = 0$

$$\lambda_1 r_+ = -\frac{3}{2}\left(w + \frac{\lambda_1}{3} + \frac{\lambda_2}{3}\right) + \frac{3}{2}\sqrt{w^2 + \frac{2}{3}w(\lambda_1 + \lambda_2) + \frac{1}{9}(\lambda_1 - \lambda_2)^2}\,, \tag{27}$$

$$\lambda_1 r_- = -\frac{3}{2}\left(w + \frac{\lambda_1}{3} + \frac{\lambda_2}{3}\right) - \frac{3}{2}\sqrt{w^2 + \frac{2}{3}w(\lambda_1 + \lambda_2) + \frac{1}{9}(\lambda_1 - \lambda_2)^2}\,. \tag{28}$$

$$\dot{\delta}_{\rm dm} = -\,\theta_{\rm dm} - \frac{\dot{h}}{2} + \mathcal{H}\lambda_2 \frac{\rho_{\rm de}}{\rho_{\rm dm}}(\delta_{\rm de} - \delta_{\rm dm}) + \left(\lambda_1 + \lambda_2 \frac{\rho_{\rm de}}{\rho_{\rm dm}}\right) \underbrace{\left(\frac{kv_T}{3} + \frac{\dot{h}}{6}\right)}_{\propto\, \delta H}\,, \tag{29}$$

$$\dot{\theta}_{\rm dm} = -\,\mathcal{H}\theta_{\rm dm} - \left(\lambda_1 + \lambda_2 \frac{\rho_{\rm de}}{\rho_{\rm dm}}\right)\mathcal{H}\theta_{\rm dm}\,, \tag{30}$$

$$\begin{aligned}\dot{\delta}_{\rm de} =& -(1+w)\left(\theta_{\rm de} + \frac{\dot{h}}{2}\right) - 3\mathcal{H}(1-w)\delta_{\rm de} + \mathcal{H}\lambda_1 \frac{\rho_{\rm dm}}{\rho_{\rm de}}(\delta_{\rm de} - \delta_{\rm dm}) \\ & - 3\mathcal{H}(1-w)\left[3(1+w) + \lambda_1 \frac{\rho_{\rm dm}}{\rho_{\rm de}} + \lambda_2\right]\frac{\mathcal{H}\theta_{\rm de}}{k^2} - \left(\lambda_1 \frac{\rho_{\rm dm}}{\rho_{\rm de}} + \lambda_2\right)\underbrace{\left(\frac{kv_T}{3} + \frac{\dot{h}}{6}\right)}_{\propto\, \delta H}\,,\end{aligned} \tag{31}$$

$$\dot{\theta}_{\rm de} = 2\mathcal{H}\theta_{\rm de}\left[1 + \frac{1}{1+w}\left(\lambda_1 \frac{\rho_{\rm dm}}{\rho_{\rm de}} + \lambda_2\right)\right] + \frac{k^2}{1+w}\delta_{\rm de}\,, \tag{32}$$

$Q \propto \rho_{\rm dm} + \rho_{\rm de}$

$$\delta_{\rm de}^{(i)} = \frac{3}{4}\delta_r^{(i)}\left(1 + w + \frac{\lambda_1}{3}r + \frac{\lambda_2}{3}\right), \quad (33)$$

$$\delta_{\rm dm}^{(i)} = \frac{3}{4}\delta_r^{(i)}\left(1 - \frac{\lambda_1}{3} - \frac{\lambda_2}{3}\frac{1}{r}\right), \quad (34)$$

$$v_{\rm de}^{(i)} = v_r^{(i)}, \quad (35)$$

$Q \propto \rho_{\rm dm}$

$$\delta_{\rm de}^{(i)} = \delta_{\rm dm}^{(i)} = \frac{3}{4}\delta_r^{(i)}\left(1 - \frac{\lambda_1}{3}\right), \quad (36)$$

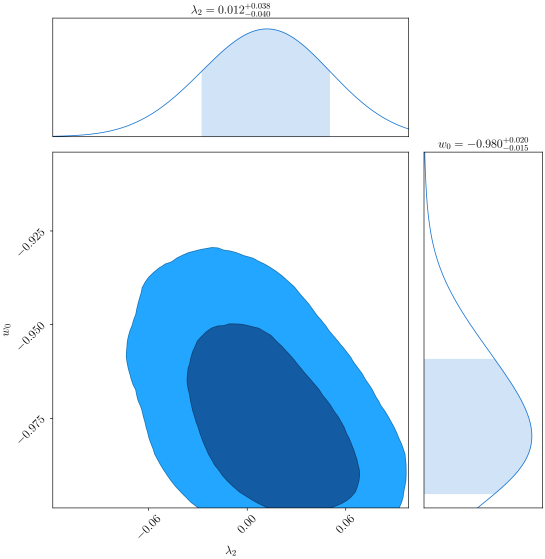
$Q \propto \rho_{\rm de}$

$$\delta_{\rm de}^{(i)} = \frac{3}{4}\delta_r^{(i)}\left(1 + w + \frac{\lambda_2}{3}\right), \quad (37)$$

$$\delta_{\rm dm}^{(i)} = \frac{3}{4}\delta_r^{(i)}. \quad (38)$$

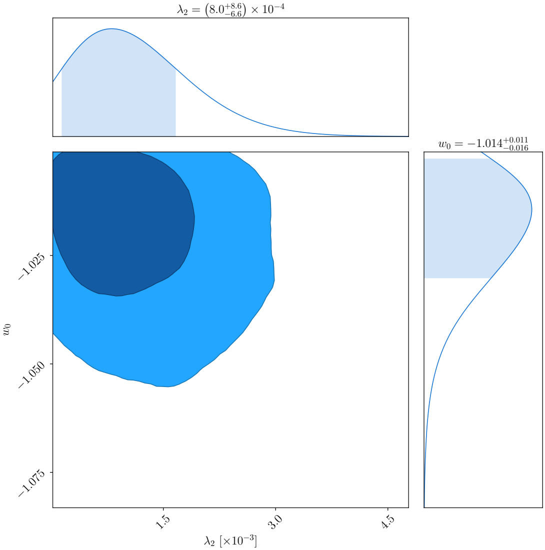
- $Q \propto \rho_{\rm dm}$: $0 \leq \lambda_1 < -3w$ and $w < -1$
- $Q \propto \rho_{\rm de}$: $\lambda_2 < -w$
- $Q \propto \rho_{\rm dm} + \rho_{\rm de}$: $\lambda \leq -3w/4$ and $w < -1$

Preliminary



BAO, Pantheon+, Planck ($\lambda_2 \neq 0$)

Preliminary



BAO, Pantheon+, Planck ($\lambda_1 \neq 0$)

Thank you very much for your attention!

ricardo.landim@port.ac.uk