Interacting Dark Energy in light of PLANCK experiment results

Valentina Salvatelli
with A. Marchini, L. Lopez-Honorez, O. Mena

"La Sapienza" Università di Roma
Theoretische Natuurkunde, Vrije Universiteit Brussel
IFIC, Universidad de Valencia-CSIC

Cosmology on the beach, Cabo San Lucas, Mexico
14 January 2014
General Introduction

Planck results (1st release)

Standard cosmological model in good agreement with data but ...

Valentina Salvatelli

Interacting Dark Energy in light of Planck results
Hubble constant tension

... some tensions exist!

- Hubble Constant value

Measurement from Planck (assuming standard cosmology)

\[ H_0 = 67.3 \pm 1.2 \text{ km/s/Mpc} \]

Local measurement from Hubble Space Telescope

\[ H_0 = 73.8 \pm 2.4 \text{ km/s/Mpc} \]

AN HINT FOR NEW PHYSICS ????

From Planck Collaboration. XVI. 2014 arXiv:1403.5076
Dark matter-Dark energy interacting models

Models where we allow an energy-momentum transfer between fluids

\[ \nabla_{\mu} T_{(\text{dm})\nu}^\mu = Q_\nu \quad \nabla_{\mu} T_{(\text{de})\nu}^\mu = -Q_\nu \]

Tantalizing scenario to investigate!

- **ALLOWED BY OBSERVATIONS**
  (only the interaction with ordinary matter is strongly constrained)

- **CAN ALLEVIATE THE COINCIDENCE PROBLEM**

- **POSSIBLE EXPLANATION TO THE TENSION BETWEEN LOCAL AND HIGH-REDSHIFT MEASUREMENTS OF THE HUBBLE CONSTANT**
Energy Momentum Transfer frame

2 alternatives frames to define the energy-momentum exchange

**DEvel**

\[ Q_{\nu} = Q u_{\nu}^{(de)}/a \]

- No momentum transfer to the DE frame
- Change in DM peculiar velocity
- “Fifth force” effect \( \rightarrow \)
- Effectively modified gravity models

**DMvel**

\[ Q_{\nu} = Q u_{\nu}^{(dm)}/a \]

- No momentum transfer to DM frame
- No violation of the weak equivalence principle

Interaction rate

4-velocity

Scale factor
**Background evolution** (in a flat universe)

**Modified background equations**

\[
\begin{align*}
\dot{\rho}_{dm} + 3\mathcal{H}\rho_{dm} &= Q \\
\dot{\rho}_{de} + 3\mathcal{H}\rho_{de}(1 + w) &= -Q
\end{align*}
\]

\[
\mathcal{H} = \dot{a}/a
\]

- The background evolution does not depend on the frame
- If \( Q<0 \) DM passes energy to DE, that implies \( \rho_{dm}^0 | Q<0 < \rho_{dm}^0 | Q=0 \)

**Effective equations of state**

\[
\begin{align*}
w_{dm}^{\text{eff}} &= -\frac{Q}{3\mathcal{H}\rho_{dm}} \\
w_{de}^{\text{eff}} &= w + \frac{Q}{3\mathcal{H}\rho_{de}}
\end{align*}
\]

- Coupling imitates dynamical dark energy even if \( w \) is constant
- \( Q<0 \) yields to more negative effective \( w \)
- \( Q<0 \) acts as a positive pressure in the dark matter EoS
Linear Perturbation theory

\[ \delta \equiv \frac{\delta \rho}{\rho} \quad \theta \equiv \partial_i v^i \]

Baryons not coupled \( \Rightarrow \) equations do not change

\[
\dot{\delta}_{dm} = - (\theta_{dm} - 3\dot{\Phi}) + \frac{Q}{\rho_{dm}} \left( \frac{\delta Q}{Q} - \delta_{dm} + \Psi \right) \\
\dot{\theta}_{dm} = - \mathcal{H} \theta_{dm} + k^2 \Psi + (1 - b) \frac{Q}{\rho_{dm}} (\theta_{de} - \theta_{dm})
\]

\[
\dot{\delta}_{de} = -(1 + w)(\theta_{de} - 3\dot{\Phi}) - 3\mathcal{H} \left( \dot{c}_{s de}^2 - w \right) \times \\
\left[ \delta_{de} + \mathcal{H} \left( 3(1 + w) + \frac{Q}{\rho_{de}} \right) \frac{\theta_{de}}{k^2} \right] - \frac{Q}{\rho_{de}} \left( \frac{\delta Q}{Q} - \delta_{de} + \Psi \right) \\
\dot{\theta}_{de} = - \mathcal{H} \left( 1 - 3\dot{c}_{s de}^2 - \frac{\dot{c}_{s de}^2 + b}{1+w} \frac{Q}{\mathcal{H} \rho_{de}} \right) \theta_{de} + \frac{k^2}{1+w} \dot{c}_{s de}^2 \delta_{de} + k^2 \Psi - b \frac{Q}{\rho_{de}} \frac{\theta_{dm}}{1+w}
\]

\[ b = 0 \quad \text{if} \quad Q \nu \propto u^{(de)}_\nu \]
\[ b = 1 \quad \text{if} \quad Q \nu \propto u^{(dm)}_\nu \]

Euler equation only changes in DEvel models
MODEL “PROS”:

- Viable scenario
- No instabilities (if $Q<0$ and $w>-1$)
- Analytic form of $H(z)$
- Changes in background and growth evolution ($\rho_{dm}(z) \not\propto (1+z)^3$)

\[ Q_\nu = (\xi)H\rho_{de}u_{\nu}^{dm} \]

DMvel frame

Dimensionless coupling parameter

Credits to Laura Lopez-Honorez
• Decreased amplitude of the spectrum
• Peaks shifted towards lower multipoles
### Interacting Dark Energy Constraints

#### PLANCK Constraints

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PLANCK + ΛCDM</th>
<th>PLANCK + ξ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best fit</td>
<td>68% limit</td>
</tr>
<tr>
<td>$Ω_bh^2$</td>
<td>0.02203</td>
<td>0.02205 ± 0.00028</td>
</tr>
<tr>
<td>$Ω_ch^2$</td>
<td>0.1204</td>
<td>0.1199 ± 0.0027</td>
</tr>
<tr>
<td>100$θ$</td>
<td>1.04119</td>
<td>1.04131 ± 0.00063</td>
</tr>
<tr>
<td>$τ$</td>
<td>0.093</td>
<td>0.089±0.012</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9619</td>
<td>0.9603 ± 0.0073</td>
</tr>
<tr>
<td>log(10$^{10}A_s$)</td>
<td>3.098</td>
<td>3.089±0.024</td>
</tr>
<tr>
<td>$ξ$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$Ω_m$</td>
<td>0.318</td>
<td>0.315±0.016</td>
</tr>
<tr>
<td>$Ω_Λ$</td>
<td>0.682</td>
<td>0.685±0.018</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>11.4</td>
<td>11.1 ± 1.1</td>
</tr>
<tr>
<td>$H_0$[km/s/Mpc]</td>
<td>67.0</td>
<td>67.3 ± 1.2</td>
</tr>
<tr>
<td>Age/Gyr</td>
<td>13.824</td>
<td>13.817 ± 0.048</td>
</tr>
<tr>
<td>$χ^2_{min}/2$</td>
<td>4902.95</td>
<td>4902.45</td>
</tr>
</tbody>
</table>

- $A_L = 1 \quad w = -0.999 \quad N_{eff} = 3.046 \quad \sum m_ν = 0.06$ eV

- An interacting scenario is compatible with data and not disfavoured
- The degeneracy between $H_0$ and $ξ$ favours larger values for $H_0$, the tension with HST is solved

---

Valentina Salvatelli

Interacting Dark Energy in light of Planck results

10/14

### PLANCK+HST constraints

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PLANCK + HST + $\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02201 \pm 0.00027$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.0450$</td>
</tr>
<tr>
<td>$\Omega_{de} h^2$</td>
<td>$0.9586 \pm 0.0070$</td>
</tr>
<tr>
<td>$\log(10^{10} A_s)$</td>
<td>$3.070 \pm 0.027$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$-0.58 \pm 0.090$</td>
</tr>
<tr>
<td>$\Omega_{m}$</td>
<td>$0.127 \pm 0.033$</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>$0.873 \pm 0.033$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.080 \pm 0.017$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.988 \pm 0.014$</td>
</tr>
<tr>
<td>$100\theta$</td>
<td>$10.9 \pm 1.1$</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>$10.2$</td>
</tr>
<tr>
<td>$H_0 [\text{km/s/Mpc}]$</td>
<td>$73.0 \pm 2.0$</td>
</tr>
<tr>
<td>$\text{Age/Gyr}$</td>
<td>$13.720 \pm 0.051$</td>
</tr>
<tr>
<td>$\chi^2_{min}/2$</td>
<td>4902.52</td>
</tr>
</tbody>
</table>

- If we include the HST prior a zero coupling is excluded at 95% c.l.

\[ H_0 = 73.8 \pm 2.4 \text{ km/s/Mpc} \]

---

• If we include BAO a zero coupling is excluded at 68% c.l and the H0 tension is alleviated.
Is the $H_0$ tension an evidence for coupling?

The tension between the Hubble constant value measured by the Hubble Space Telescope and measured by PLANCK is solved in this dark coupled scenario.
To summarize

For the interacting dark energy scenario that we have investigated we can conclude that:

• it is compatible with PLANCK and with PLANCK combined with low redshift measurements

• it can solve the tension between PLANCK and HST measurements of the Hubble constant value

• a null interaction is excluded at 95% c.l. if we consider the combined constraint from PLANCK+HST
Thank you!

For questions or comments:
valentina.salvatelli@uniroma1.it
Valentina Salvatelli

Interacting Dark Energy and Modified Gravity in light of Planck results

Coupling Constraints varying w

\[ \Omega_c h^2 \quad 100\theta \quad \Omega_m \quad H_0 \]

\text{PLANCK} 

\text{PLANCK} + \text{HST} 

\text{PLANCK} + \text{BAO} 

Coupling Posterior distributions
Evolution of energy densities in interacting scenarios

Credits to Laura Lopez-Honorez

Fine tuning problem is worsened in this case

CMB is sensitive to densities at recombination
Further indication from Supernovae

Combined constraints from CMB and Supernovae

\[ w = -1.13^{+0.13}_{-0.14} \quad 95\% \text{ c.l.} \]

Reconstructed dark energy equation of state if the real universe is coupled and we use standard equations
Constraints on DM-baryons interactions


Values inside the coloured contours are ruled out!
### Coupled Quintessence Constraints

**Models in the DEvel frame**

\[ Q = -\beta \rho_c \phi', \]

- **Green** = Planck + WP + BAO
- **Blue** = Planck + WP + HST

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PlanckWP + BAO</th>
<th>PlanckWP + HighL + BAO</th>
<th>PlanckWP + HST</th>
<th>PlanckWP + HighL + HST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{m}h^2$</td>
<td>0.02204 ± 0.00028</td>
<td>0.0221 ± 0.000269</td>
<td>0.0220 ± 0.00029</td>
<td>0.0221 ± 0.000281</td>
</tr>
<tr>
<td>$\Omega_{c}h^2$</td>
<td>0.1165 ± 0.0019</td>
<td>0.1169 ± 0.00197</td>
<td>0.1114 ± 0.00332</td>
<td>0.1121 ± 0.00338</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>1.0415 ± 0.000579</td>
<td>1.0415 ± 0.000576</td>
<td>1.0418 ± 0.000595</td>
<td>1.0418 ± 0.000611</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.09037 ± 0.0132</td>
<td>0.0904 ± 0.01287</td>
<td>0.0913 ± 0.0135</td>
<td>0.0936 ± 0.0126</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9629 ± 0.0062</td>
<td>0.9603 ± 0.00583</td>
<td>0.9077 ± 0.00673</td>
<td>0.9655 ± 0.00678</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.0364 ± 0.01626</td>
<td>0.0346 ± 0.0155</td>
<td>0.0660 ± 0.0182</td>
<td>0.0611 ± 0.0188</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.03132 ± 0.0360</td>
<td>0.0146 ± 0.0164</td>
<td>0.0564 ± 0.0240</td>
<td>0.0708 ± 0.0235</td>
</tr>
<tr>
<td>$\Omega_{de}$</td>
<td>0.2895 ± 0.1062</td>
<td>0.2837 ± 0.105</td>
<td>0.2932 ± 0.1055</td>
<td>0.2681 ± 0.0996</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.437 ± 1.250</td>
<td>67.267 ± 1.247</td>
<td>71.123 ± 2.109</td>
<td>70.737 ± 2.093</td>
</tr>
</tbody>
</table>

Valentina Salvatelli  
Interacting Dark Energy and Modified Gravity in light of Planck results