Three Tests of $\Lambda$CDM

Carlos Martins
& the CAUP Dark Side Team
Is this a dog?
Is this a dog?
Precision Taxonomy
A Dipole on the Sky?

- New physics or systematics?
  - No known systematic can explain dipole
  - Existing data has been taken with other purposes
  - Need customized analysis pipelines [Thompson et al. 2009]
  - UVES LP first results out soon [Molaro et al. 2012]
The Fine Structure Constant and the CMB Damping Scale

Eloisa Menegoni\textsuperscript{a}, Maria Archidiacono\textsuperscript{b}, Erminia Calabrese\textsuperscript{c}, Silvia Galli\textsuperscript{d}, C. J. A. P. Martins\textsuperscript{e}, and Alessandro Melchiorri\textsuperscript{b}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\alpha/\alpha_0$</th>
<th>$\alpha/\alpha_0 + N_{\text{eff}}$</th>
<th>$\alpha/\alpha_0 + N_{\text{eff}} + Y_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.0218 $\pm$ 0.0004</td>
<td>0.0224 $\pm$ 0.0005</td>
<td>0.0223 $\pm$ 0.0007</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1144 $\pm$ 0.0034</td>
<td>0.1302 $\pm$ 0.0095</td>
<td>0.1303 $\pm$ 0.0094</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.086 $\pm$ 0.014</td>
<td>0.088 $\pm$ 0.015</td>
<td>0.088 $\pm$ 0.016</td>
</tr>
<tr>
<td>$H_0$</td>
<td>68.9 $\pm$ 1.4</td>
<td>71.52 $\pm$ 2.0</td>
<td>71.8 $\pm$ 2.1</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.976 $\pm$ 0.013</td>
<td>0.991 $\pm$ 0.013</td>
<td>0.992 $\pm$ 0.016</td>
</tr>
<tr>
<td>$\log[10^{10} A_s]$</td>
<td>3.193 $\pm$ 0.037</td>
<td>3.169 $\pm$ 0.040</td>
<td>3.167 $\pm$ 0.042</td>
</tr>
<tr>
<td>$A_{SZ}$</td>
<td>$&lt; 2.00$</td>
<td>$&lt; 2.00$</td>
<td>$&lt; 2.00$</td>
</tr>
<tr>
<td>$A_C$</td>
<td>$&lt; 16.0$</td>
<td>$&lt; 15.8$</td>
<td>$&lt; 14.8$</td>
</tr>
<tr>
<td>$A_P$</td>
<td>$&lt; 24.7$</td>
<td>$&lt; 24.9$</td>
<td>$&lt; 22.4$</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>0.7137 $\pm$ 0.0070</td>
<td>0.7020 $\pm$ 0.0094</td>
<td>0.704 $\pm$ 0.013</td>
</tr>
<tr>
<td>$Age/Gyr$</td>
<td>13.76 $\pm$ 0.24</td>
<td>13.18 $\pm$ 0.38</td>
<td>13.15 $\pm$ 0.37</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.2863 $\pm$ 0.0070</td>
<td>0.2980 $\pm$ 0.0094</td>
<td>0.296 $\pm$ 0.013</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.836 $\pm$ 0.023</td>
<td>0.862 $\pm$ 0.028</td>
<td>0.859 $\pm$ 0.034</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>10.7 $\pm$ 1.2</td>
<td>11.0 $\pm$ 1.3</td>
<td>11.0 $\pm$ 1.3</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>$-$</td>
<td>$4.10^{+0.24}_{-0.29}$</td>
<td>$4.19^{+0.31}_{-0.35}$</td>
</tr>
<tr>
<td>$Y_p$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.215 \pm 0.096$</td>
</tr>
<tr>
<td>$\chi^2_{min}$</td>
<td>7600.2</td>
<td>7596.8</td>
<td>7596.5</td>
</tr>
</tbody>
</table>

*arXiv:1202.1476*
Would You Like an ESPRESSO?
Would You Like an ESPRESSO?

http://espresso.astro.up.pt
Would you like an ESPRESSO?

- ESPRESSO is...
  - 380-800nm spectral coverage in one shot
  - Highest-resolution instrument on a 10m-class telescope
  - Wavelength calibration far more accurate than any other facility
  - Cleanest, best-quality spectra both at high and low SNR
  - A spectrograph on a 16m telescope (largest visible until ELTs)
  - Ultra-high resolution mode, far beyond existing facilities

- >270 nights GTO, over a few years:
  - 80% Rocky Planets, 10% Varying Constants
  - 10% to be decided: ToO + Exquisite Science + (Any ideas?)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard 1-UT</th>
<th>4-UT</th>
<th>Ultra-High Res 1-UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>380-800 nm</td>
<td>380-800 nm</td>
<td>380-800 nm</td>
</tr>
<tr>
<td>Resolving power</td>
<td>140'000</td>
<td>60'000</td>
<td>225'000</td>
</tr>
<tr>
<td>Aperture on sky</td>
<td>1.0 arcsec</td>
<td>4x1.0 arcsec</td>
<td>0.5 arcsec</td>
</tr>
<tr>
<td>Sampling (average)</td>
<td>3.3 pixels</td>
<td>4.0 pixels (binned x2)</td>
<td>2.1 pixels</td>
</tr>
<tr>
<td>Spatial sampling</td>
<td>6.9 pixels</td>
<td>4.0 pixels (binned x4)</td>
<td>3.5 pixels</td>
</tr>
<tr>
<td>Simultaneous reference</td>
<td>Yes (no sky)</td>
<td>Yes (no sky)</td>
<td>Yes (no sky)</td>
</tr>
<tr>
<td>Sky subtraction</td>
<td>Yes (no sim. ref.)</td>
<td>Yes (no sim. ref.)</td>
<td>Yes (no sim. ref.)</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>10%</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Instrumental RV precision</td>
<td>&lt; 10 cm s⁻¹</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Variation of fundamental parameters and dark energy. A principal component approach

L. Amendola,¹,* A.C.O. Leite,²,³,* C.J.A.P. Martins,³,* N.J. Nunes,¹,* P.O.J. Pedrosa,²,³,* and A. Seganti⁴

* CODEX can constrain dark energy better than SNe
  - Key advantage is huge redshift lever arm
  - ESPRESSO is no slouch either...

arXiv:1109.6793
To Couple or Not To Couple

- Reconstruction using varying fundamental constants requires an assumption on the field coupling...
  - ... but coupling can be measured and compared to local constraints [Menegoni et al. 2011]
  - Inconsistent assumptions can be identified and corrected

- See P. Vielzeuf's poster for 2 explicit examples

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Probing dark energy beyond $z = 2$ with CODEX

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$^3$Université Paul Sabatier—Toulouse III, 118 route de Narbonne 31062 Toulouse Cedex 9, France

Precision measurements of nature’s fundamental couplings and a first measurement of the cosmological redshift drift are two of the key targets for future high-resolution ultra-stable spectrographs such as CODEX. Being able to do both gives CODEX a unique advantage, allowing it to probe dynamical dark energy models (by measuring the behavior of their equation of state) deep in the matter era and thereby testing classes of models that would otherwise be difficult to distinguish from the standard $\Lambda$CDM paradigm. We illustrate this point with two simple case studies.

arXiv:1202.4364
Many astrophysical objects can be used to search for spacetime variations of fundamental couplings

- Population III stars [Ekstrom et al. 2010]
- Neutron stars [Perez-Garcia & Martins 2012]

Probing unification scenarios with neutron stars

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2 Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
(Dated: March 5, 2012)

We discuss the sensitivity of the neutron star equation of state to combined variations of the gravitational, strong and electroweak coupling constants in the context of unification scenarios. We find that current knowledge of the neutron star mass-radius relationship and heavy ion collisions observable measurements constrain the equation of state as described by relativistic field models of interacting matter. In particular, there are unification scenarios that would be incompatible with the existence of these objects. This provides an additional independent constraint on the allowed range of variation of fundamental dimensionless constants.

arXiv:1203.0399
T(z) & Distance Duality

- T(z)=T_0(1+z) is a robust prediction of standard cosmology
  - Adiabatic expansion, photon number conservation
  - Violated in many scenarios, e.g. string theory inspired ones
  - If T(z)=T_0(1+z)^{1-\beta}, find $\beta=-0.01\pm0.03$ [Noterdaeme et al. 2011]

MEASURING THE REDSHIFT DEPENDENCE OF THE CMB MONOPOLE TEMPERATURE WITH PLANCK DATA.
I. de Martino¹, F. Atrio-Barandela¹, A. da Silva², H. Ebeling³, A. Kashlinsky⁴, D. Kocevski⁵, C.J.A.P. Martins²

Draft version March 9, 2012

ABSTRACT

We study the power of PLANCK data to constrain deviations of the Cosmic Microwave Background black body temperature from adiabatic evolution using the thermal Sunyaev-Zeldovich anisotropy induced by clusters of galaxies. We consider two types of data sets: the cosmological signal is removed in the Time Ordered Information or is removed from the final maps; and two different statistical estimators, based on the ratio of temperature anisotropies at two different frequencies and on a fit to the spectral variation of the cluster signal with frequency. To test for systematics, we construct a template from clusters drawn from a hydro-simulation included in the pre-launch Planck Sky Model. We demonstrate that, using a proprietary catalog of X-ray selected clusters with measured redshifts, electron densities and X-ray temperatures, we can constrain deviations of adiabatic evolution, measured by the parameter $\alpha$ in the redshift scaling $T(z) = T_0(1+z)^{1-\alpha}$, with an accuracy of $\sigma_{\alpha} = 0.011$ in the most optimal case and with $\sigma_{\alpha} = 0.016$ for a less optimal case. These results represent a factor 2-3 improvement over similar measurements carried out using quasar spectral lines and a factor 6-20 with respect to earlier results using smaller cluster samples.

arXiv:1203.1825
T(z) & Distance Duality

- \( T(z) = T_0 (1+z) \) is a robust prediction of standard cosmology:
  - Adiabatic expansion, photon number conservation
  - Violated in many scenarios, e.g. string theory inspired ones
  - If \( T(z) = T_0 (1+z)^{1-\beta} \), find \( \beta = -0.01 \pm 0.03 \) [Noterdaeme et al. 2011]

- \( d_L = (1+z)^2 d_A \) is a robust prediction of standard cosmology:
  - Metric theory of gravity, photon number conservation
  - Violated if there's photon dimming, absorption or conversion
  - If \( d_L = (1+z)^{2+\varepsilon} d_A \), find \( \varepsilon = -0.04 \pm 0.08 \) [Avgoustidis et al. 2010, ...]

- In fact, in many models the two are not independent: \( \beta = -2\varepsilon/3 \), so distance duality tests also constrain \( \beta \)
  - A generalized relation exists for any redshift dependence
Constraints on the CMB temperature-redshift dependence from SZ and distance measurements

A. Avgoustidis, G. Luzzi, C.J.A.P. Martins and A.M.R.V.L. Monteiro

JCAP 02 (2012) 013
arXiv:1112.1862
So What's Your Point?

- Observational evidence for the acceleration of the universe demonstrates that canonical theories of cosmology and particle physics are incomplete, if not incorrect
  - Several few-sigma hints: smoke but no smoking gun

- Forthcoming high-resolution ultra-stable spectrographs will enable new generation of precision consistency tests
  - Also: Equivalence Principle tests, Redshift drift
  - Interesting synergies with other facilities, including Euclid