# Fundamental Cosmology in the E-ELT Era


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***and the CAUP Dark Side Team***

*(with key contributions from Ana Catarina Leite, Ana Mafalda Monteiro, Mariana Julião, Miguel Ferreira, Pauline Vielzeuf and Pedro Pedrosa)*

***FCT Research Professor***

# Based On...

- Amendola, Leite, Martins, Nunes, Pedrosa & Seganti, PRD 86 (2012) 063515
- Avgoustidis, Luzzi, Martins & Monteiro, JCAP 1202 (2012) 013
- Avgoustidis, Martins, Monteiro, Vielzeuf & Luzzi, arXiv:1305.7031
- Ferreira, Julião, Martins & Monteiro, Phys. Rev. D86 (2012) 125025
- Ferreira, Julião, Martins & Monteiro, Phys. Lett. B724 (2013) 1
- Martinelli, Pandolfi, Martins & Vielzeuf, Phys. Rev. D86 (2012) 123001
- Molaro, Centurión, Whitmore, Evans, Murphy, Agafonova, Bonifacio, D'Odorico, Levshakov, López, Martins, Petitjean, Rahmani, Reimers, Srianand, Vladilo & Wendt, A&A 555 (2013) A68
- Rahmani, Wendt, Srianand, Noterdaeme, Petitjean, Molaro, Whitmore, Murphy, Centurión, Fathivavasari, D'Odorico, Evans, Levshakov, López, Martins, Reimers & Vladilo, MNRAS (in press)
- Thompson, Martins & Vielzeuf, MNRAS 428 (2013) 2232
- Vielzeuf & Martins, Phys. Rev. D85 (2012) 087301
- + work @ Euclid Cosmology Theory SWG & ESO ELT-PST

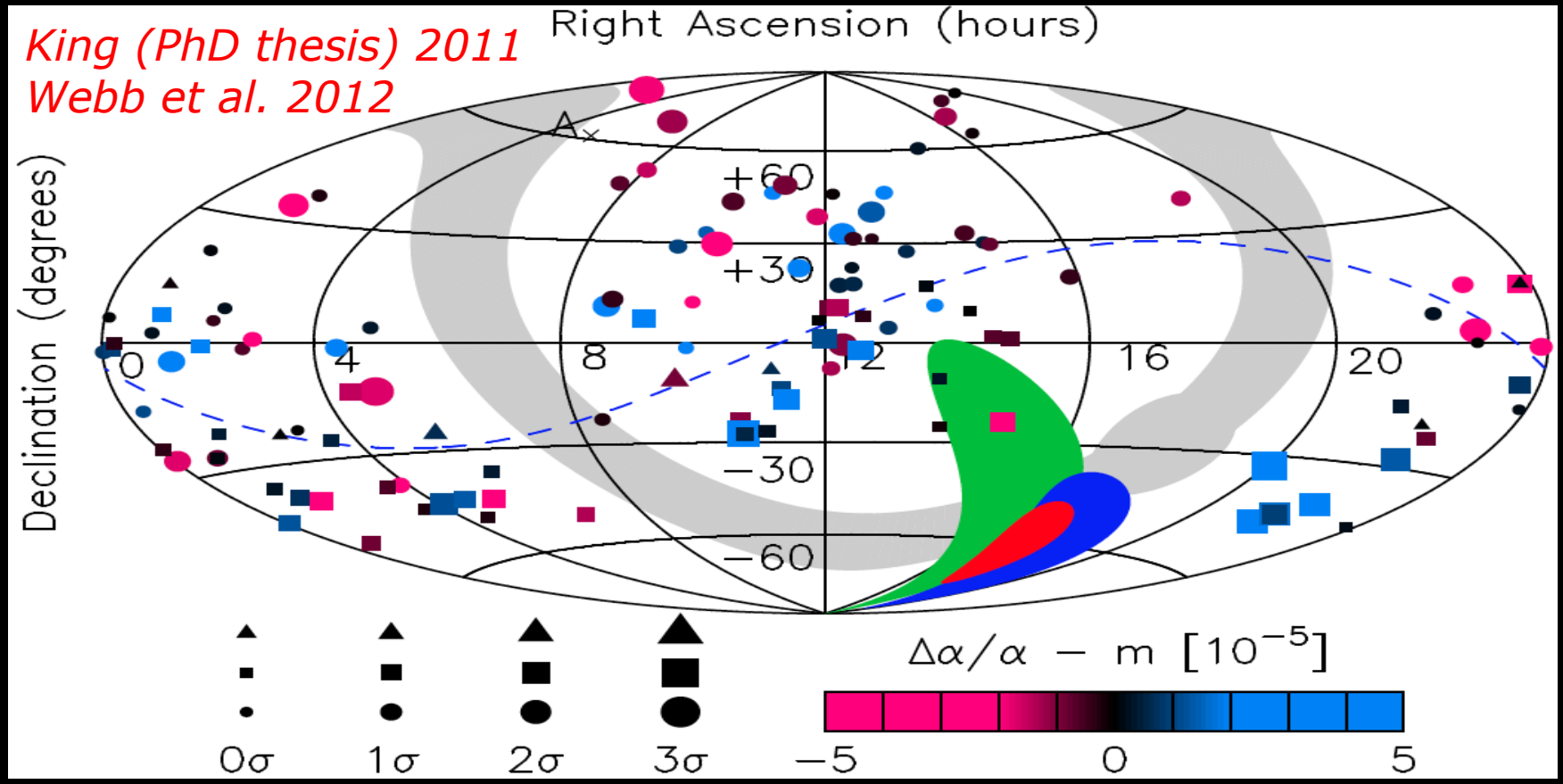
***Disclaimer: I am a member of the E-ELT Project Science Team. Views expressed in this talk are my own, not those of the PST.***

# Rationale

- Universe dominated by component whose gravitational behavior is similar to that of a cosmological constant.
  - A dynamical scalar field is arguably more likely
- Such a field must be slow-rolling (mandatory for $p<0$) and be dominating the dynamics around the present day.
- Couplings of this field lead to potentially observable long-range forces and varying constants *[Carroll 1998]*.
  - These measurements (whether they are detections of null results) will constrain fundamental physics and cosmology

# A Dipole on the Sky?

- New physics or systematics?
  - Hard to model, but no known systematic can explain dipole
  - Archival data, need customized pipelines *[Thompson et al. 2009]*




- Key driver for ESPRESSO and ELT-HIRES
  - Better precision & better control of systematics

# Just Checking…

- Ongoing VLT Large Program: one paper published, one accepted, many more to come
  - Paper I: A&A 555 (2013) A68
  - Paper II: MNRAS in press (arXiv next week)

**The UVES Large Program for Testing Fundamental Physics: I Bounds on a change in $\alpha$ towards quasar HE 2217−2818 ⋆**

P. Molaro[1,7], M. Centurion[1], J. B. Whitmore[2], T. M. Evans[2], M. T. Murphy[2], I. I. Agafonova[3], P. Bonifacio[4], S. D'Odorico[5], S. A. Levshakov[3,12], S. Lopez[6], C. J. A. P. Martins[7], P. Petitjean[8], H. Rahmani[10], D. Reimers[9], R. Srianand[10], G. Vladilo[1], M. Wendt[11,9]

**The UVES Large Program for Testing Fundamental Physics II: Constraints on a Change in $\mu$ Towards Quasar HE 0027−1836⋆**

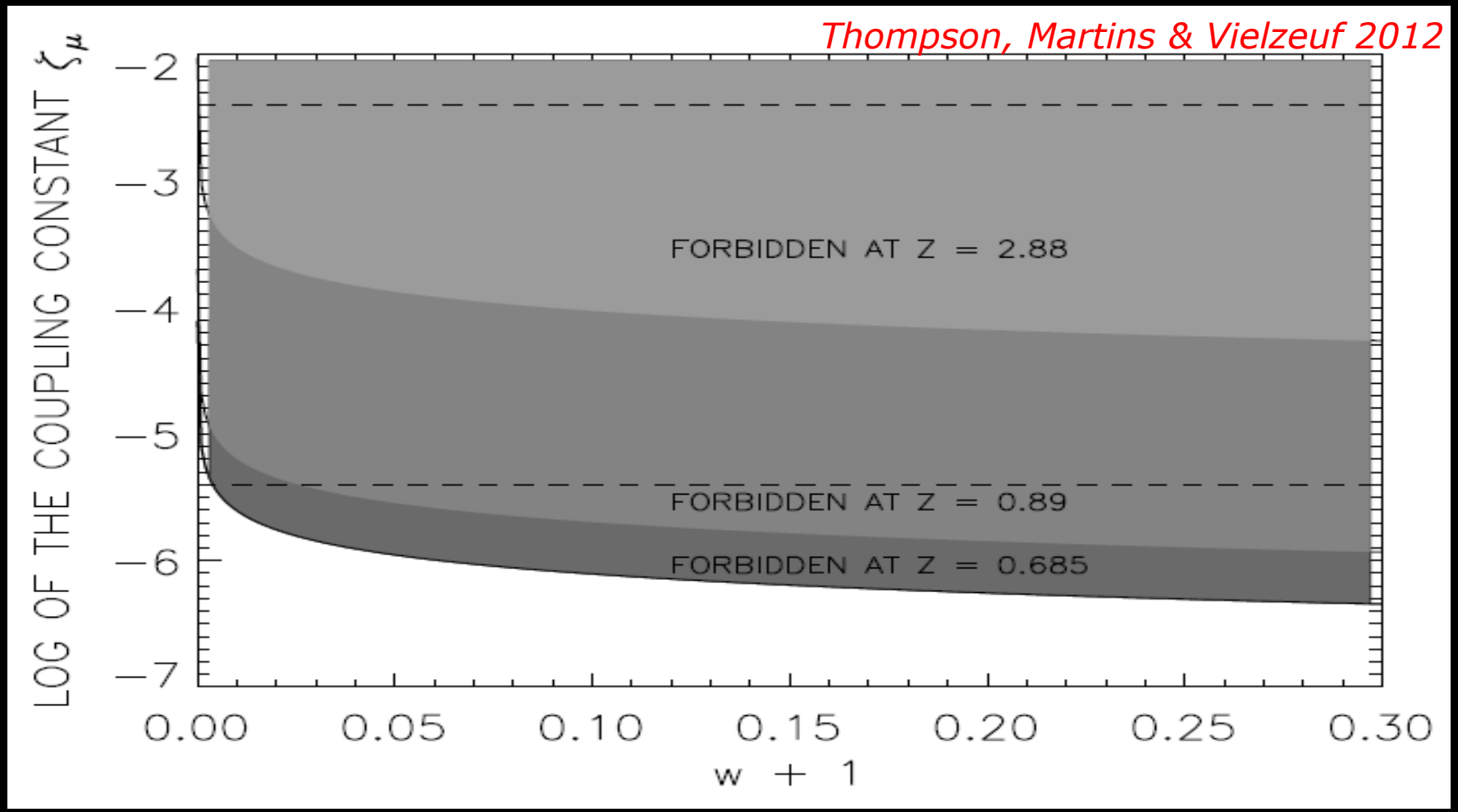
H. Rahmani[1], M. Wendt[2,3], R. Srianand[1], P. Noterdaeme[4], P. Petitjean[4], P. Molaro [5,6], J. B. Whitmore[7], M. T. Murphy[7], M. Centurion[5], H. Fathivavsari[8], S. D'Odorico[9], T. M. Evans[7], S. A. Levshakov[10,11], S. Lopez[12], C. J. A. P. Martins[6], D. Reimers[2], and G. Vladilo[5]

- Bottleneck: intra-order distortions (~200m/s) & possible long-range distortions on UVES
  - Also identified in HARPS and Keck-HIRES

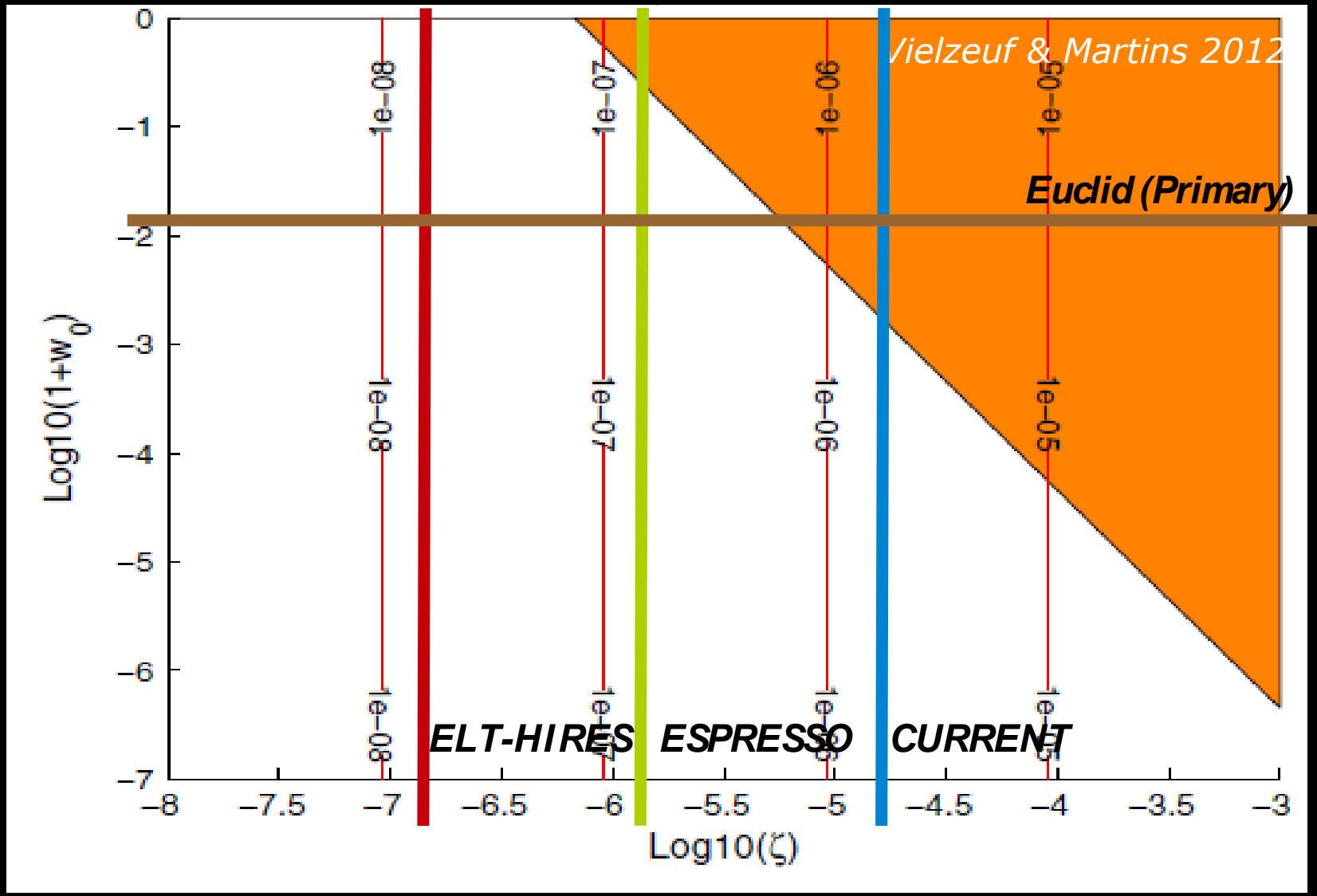
# Taxonomy: Class I

- If the varying $\alpha$ field also provides the dark energy, its evolution is parametrically determined

$$\frac{\Delta\alpha}{\alpha}(z) = \zeta \int_0^z \frac{\sqrt{\Omega_\phi(z')\,[1+w(z')]}}{1+z'} dz'$$



# The Future is Bright




- ELT-HIRES will either find variations or rule out (at more than 10 sigma) the simplest classes of these models

# Going Further

- Standard methods (SNe, etc) are of limited use as dark energy probes *[Maor et al. 2001, Upadhye et al. 2005, etc]*
  - Since the field is slow-rolling when dynamically important, a convincing detection of w(z) will be tough at low z.
- We must probe the deep matter era regime, where the dynamics of the hypothetical scalar field is fastest.
  - Varying fundamental couplings are ideal for probing scalar field dynamics beyond the domination regime *[Nunes & Lidsey 2004]*
- ALMA, ESPRESSO & ELT-HIRES can map this up to z~4 and possibly beyond
  - Plus measurements of the redshift drift...
  - Plus deep matter era Type Ia supernovas (ELT-IFU)...

# The Future is Bright

| Constant, Baseline | SNe Only | SNe + ESPRESSO | SNe + ELT-HIRES |
|---|---|---|---|
| SNAP | *3.324* | *3.442* | *5.021* |
| SNAP + E-ELT | *3.578* | *3.714* | *5.021* |
| SNAP + TMT | *3.541* | *3.677* | *5.034* |

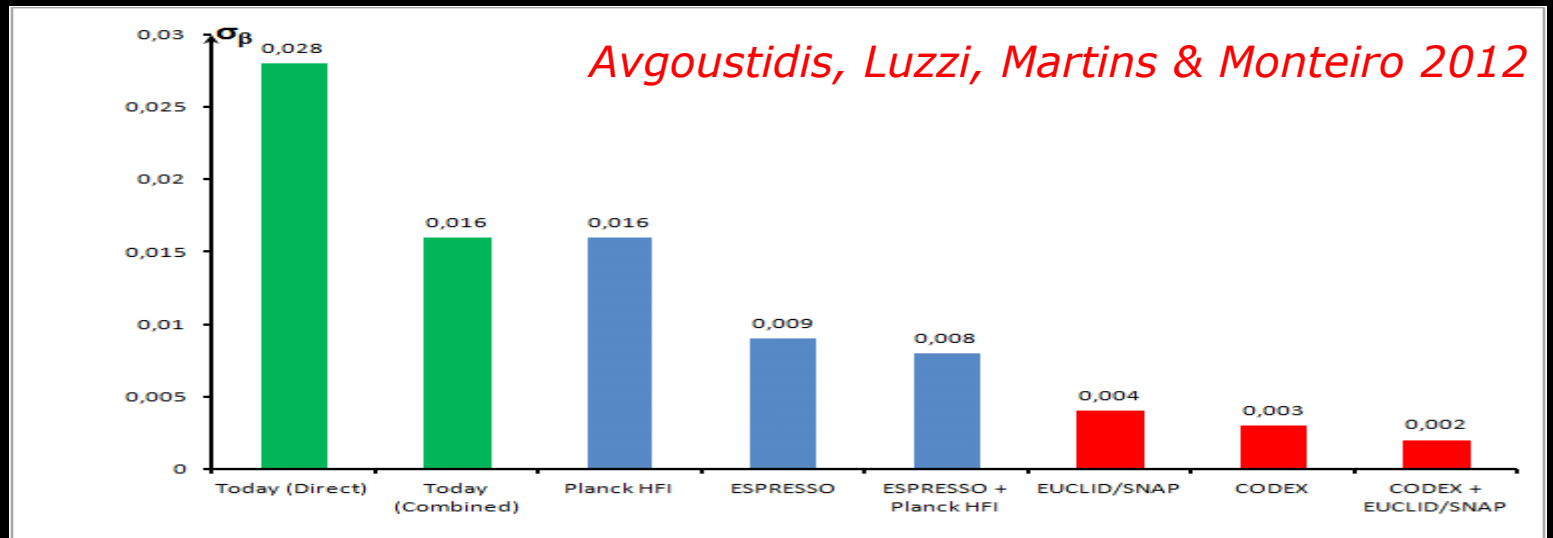
| Early Dark Energy, Ideal | SNe Only | SNe + ESPRESSO | SNe + ELT-HIRES |
|---|---|---|---|
| SNAP | *3.240* | *5.599* | *8.222* |
| SNAP + E-ELT | *3.619* | *5.860* | *8.523* |
| SNAP + TMT | *3.456* | *5.599* | *8.222* |

*Leite et al. (in progress)*

- ELT-HIRES can constrain dark energy better than supernovas, but optimized mapping strategy is needed (and it's not trivial)
  - To get best PCA mode <1 with 16 $\alpha$ measurements you need 45 nights on UVES, 24 nights on ESPRESSO, 5 nights on ELT-HIRES

# A Consistency Test

- $T(z)=T_0(1+z)$ 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]*
- $d_L=(1+z)^2 d_A$ 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 $\varepsilon=-0.04\pm0.08$ *[Avgoustidis et al. 2010, ...]*
- In many models $\beta=-2\varepsilon/3$: distance duality also constrains $\beta$



# Taxonomy: Class II

- Models where the degree of freedom responsible for the varying constants does not provide (all of) the dark energy can be identified through (in)consistency tests
- For example, in Bekenstein-type models one has

$$\frac{T(z)}{T_0} = (1+z)\left(\frac{\alpha(z)}{\alpha_0}\right)^{1/4} \sim (1+z)\left(1+\frac{1}{4}\frac{\Delta\alpha}{\alpha}\right)$$

*Avgoustidis, Martins, Monteiro, Vielzeuf & Luzzi 2013*

$$d_L(z) = d_A(z)(1+z)^2\left(\frac{\alpha(z)}{\alpha_0}\right)^{3/8} \sim d_A(z)(1+z)^2\left(1+\frac{3}{8}\frac{\Delta\alpha}{\alpha}\right)$$

  - ...which is relevant for Planck data analysis
  - holds for disformal couplings, opposite sign for chameleons
- Note that even if this degree of freedom does not dominate at low redshifts it can still bias cosmological parameter estimations

# Scalar-Photon Couplings

- Photon number non-conservation will change T(z), the distance duality relation, etc. We quantify how these models weaken constraints on cosmological parameters

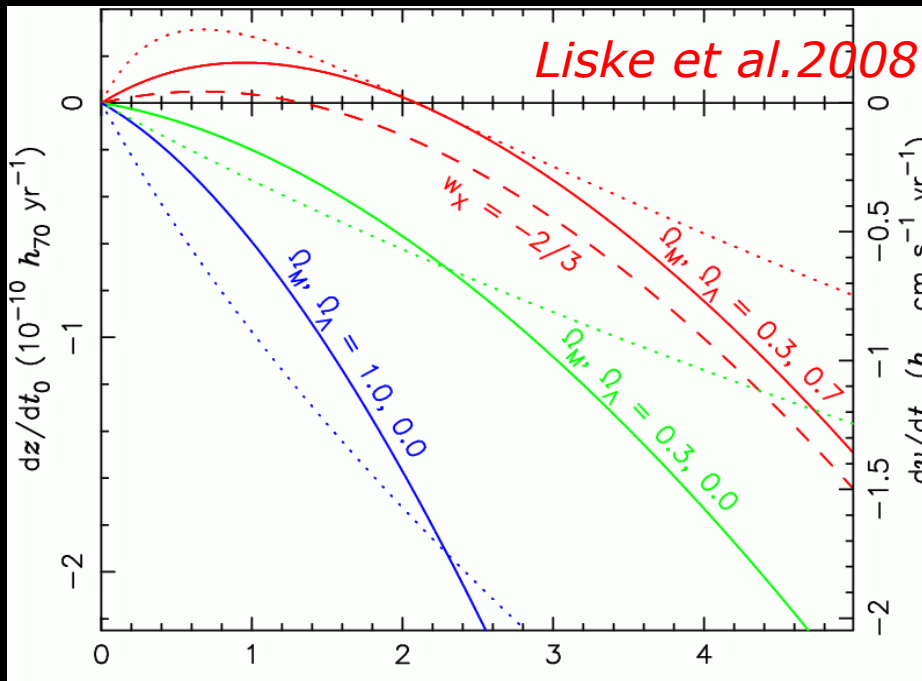
| Dataset | $\delta w_0$ | $\delta w_a$ | $\delta\Omega_m$ | $\delta k$ |
|---|---|---|---|---|
| Current (weak) | 0.25 | 1.3 | 0.06 | $1.2\times10^{-6}(10^{-5})$ |
| Current (strong) | 0.22 | 0.65 | 0.06 | $1.2\times10^{-6}(10^{-5})$ |
| Euclid(BAO)+SNAP | 0.15(0.35) | 0.4(1.6) | 0.03 | $10^{-6}(1.1\times10^{-5})$ |
| Euclid only (BAO+SN) | 0.15(0.35) | 0.6(1.6) | 0.03 | – |
| Euclid(BAO+SN)+SNAP | 0.14(0.35) | 0.8(1.5) | 0.025 | $8\times10^{-7}(9\times10^{-6})$ |
| Euclid(BAO)+SNAP+E-ELT | 0.13(0.3) | 0.75(1.45) | 0.023 | $8\times10^{-7}(8\times10^{-6})$ |
| Euclid(BAO)+SNAP+TMT | 0.13(0.25) | 0.4(1.3) | 0.024 | $6\times10^{-7}(8\times10^{-6})$ |

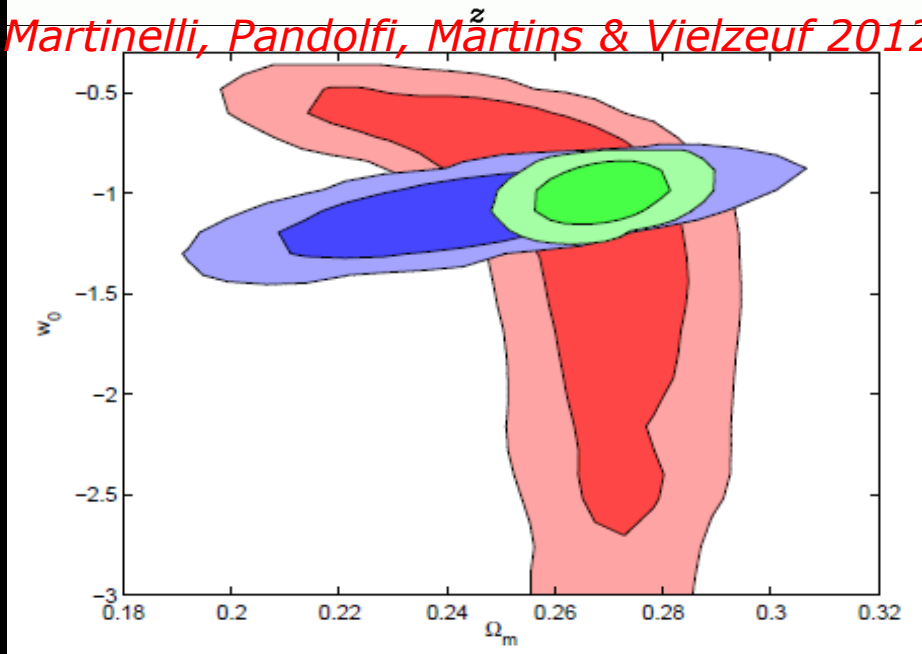
*Avgoustidis, Martins, Monteiro, Vielzeuf & Luzzi, arXiv:1305.7031*

- Euclid can, even on its own, constrain dark energy while allowing for photon number non-conservation
  - Stronger constraints in combination with other probes
- T(z) measurements are crucial for breaking degeneracies: they can be obtained with ALMA, ESPRESSO & ELT-HIRES (also Planck clusters now – and PRISM later)

# The Redshift Drift

- Standard dark energy probes are geometric and/or probe localised density perturbations
  - No measurements of the global dynamics so far
- Redshift drift yields clean signal *[Sandage 1962, Loeb 1998]*
  - Caveat: signal is tiny!
- Does not map out our (present-day) past light-cone, but directly measures evolution by comparing past light cones at different times
  - Ideal probe of dark sector in deep matter era, complements supernovas and constants
  - Also breaks CMB degeneracies



# 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
  - Keep in mind the dark energy lesson: redundancy is crucial!

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