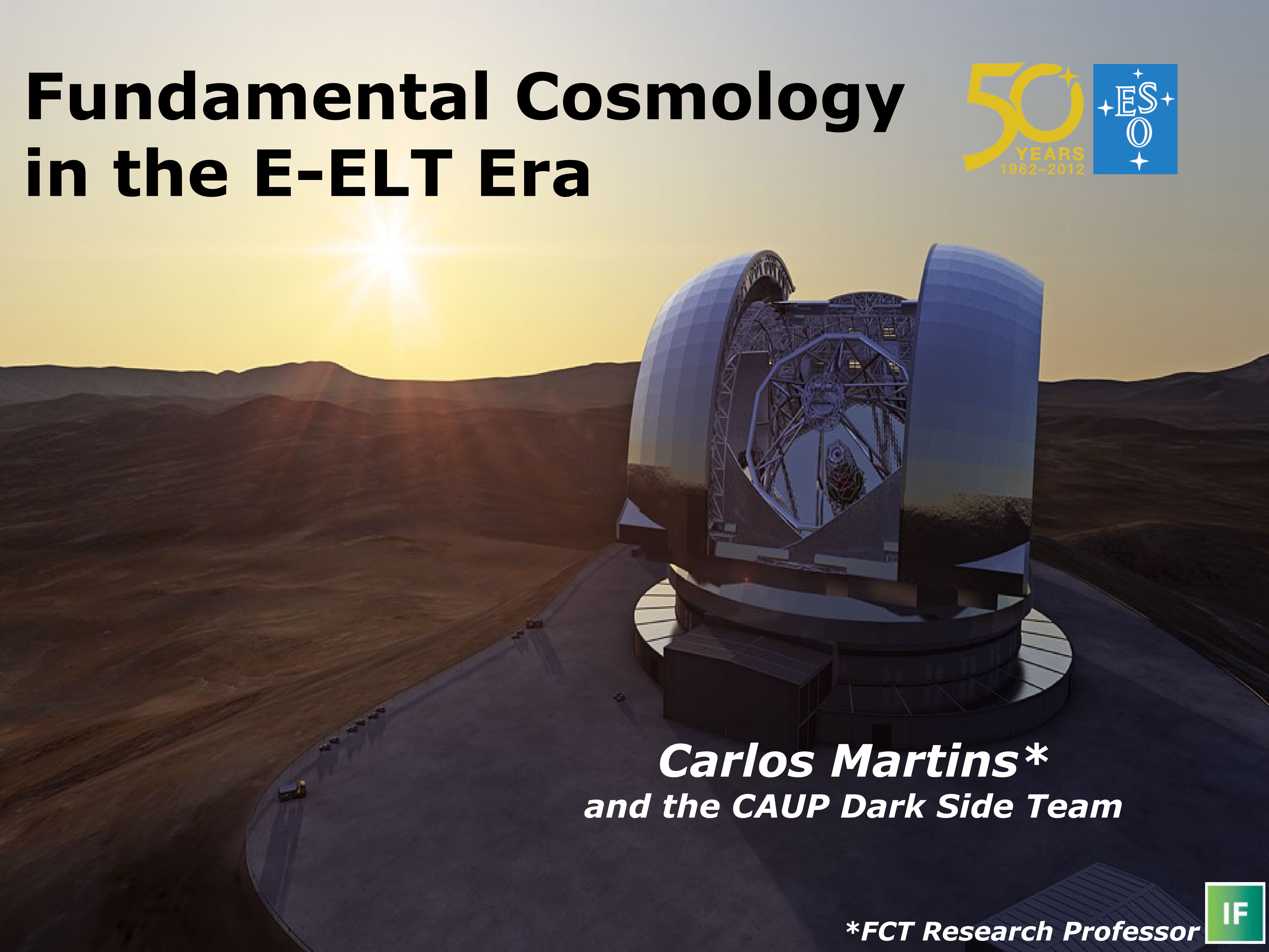
Fundamental Cosmology in the E-ELT Era



*Carlos Martins**

and the CAUP Dark Side Team

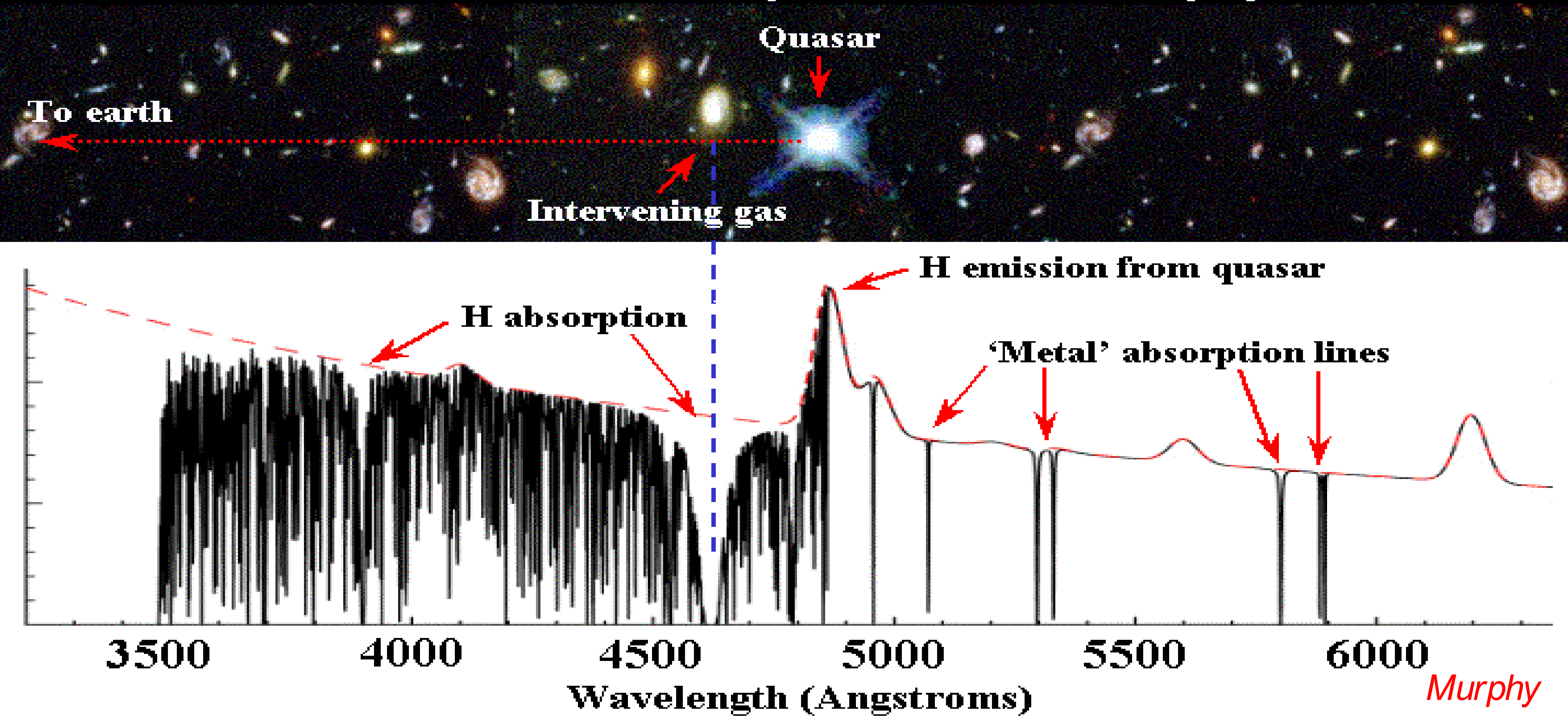
**FCT Research Professor*

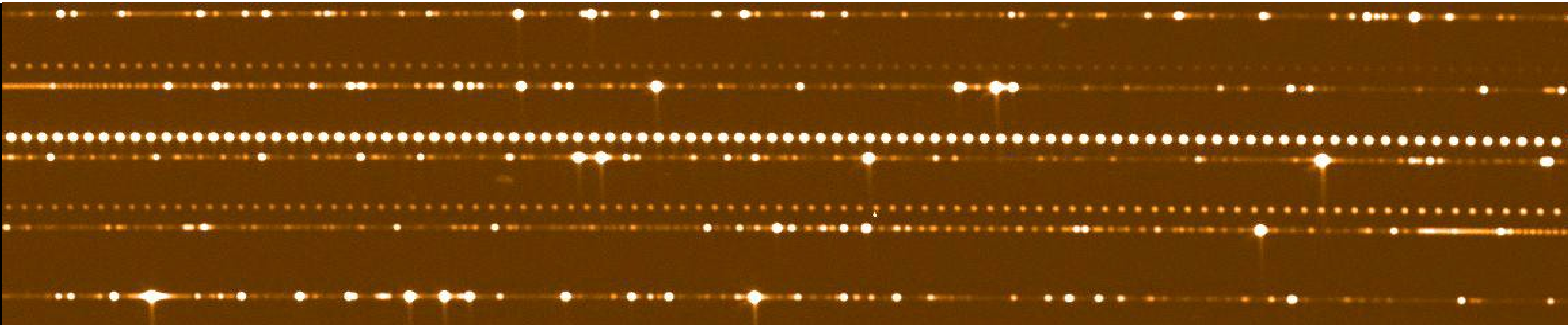
Is this a dog?

Is this a dog?

Precision Taxonomy

Precision Spectroscopy





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.

Fundamental Scalar Fields

- We now know that fundamental scalar fields are part of Nature's building blocks
    - Does the Higgs have a cosmological counterpart?
- Scalar fields play a key role in most paradigms of modern cosmology, yielding *inter alia*
    - Exponential expansion of the early universe (inflation)
    - Cosmological phase transitions & their relics (cosmic defects)
    - Dynamical dark energy powering current acceleration phase
    - Varying fundamental couplings
- ***Even more important than each of these paradigms is the fact that they don't occur alone: this will be crucial for future consistency tests!***

The Constants of Nature

- Nature is characterized by a set of physical laws and fundamental dimensionless couplings, which historically we have assumed to be spacetime-invariant
    - For the former, this is a cornerstone of the scientific method
    - For latter, a simplifying assumption without further justification
- These couplings determine the properties of atoms, cells, planets and the universe as a whole
    - If they vary, all the physics we know is incomplete
- Improved null results are important and useful; a detection would be revolutionary
    - Natural scale for cosmological evolution would be Hubble time, but current bounds are 6 orders of magnitude stronger
    - Varying non-gravitational constants imply a violation of the Einstein Equivalence Principle, a 5th force of nature, etc

Phys. Rev. 82, 554 (1951)

The Ratio of Proton and Electron Masses

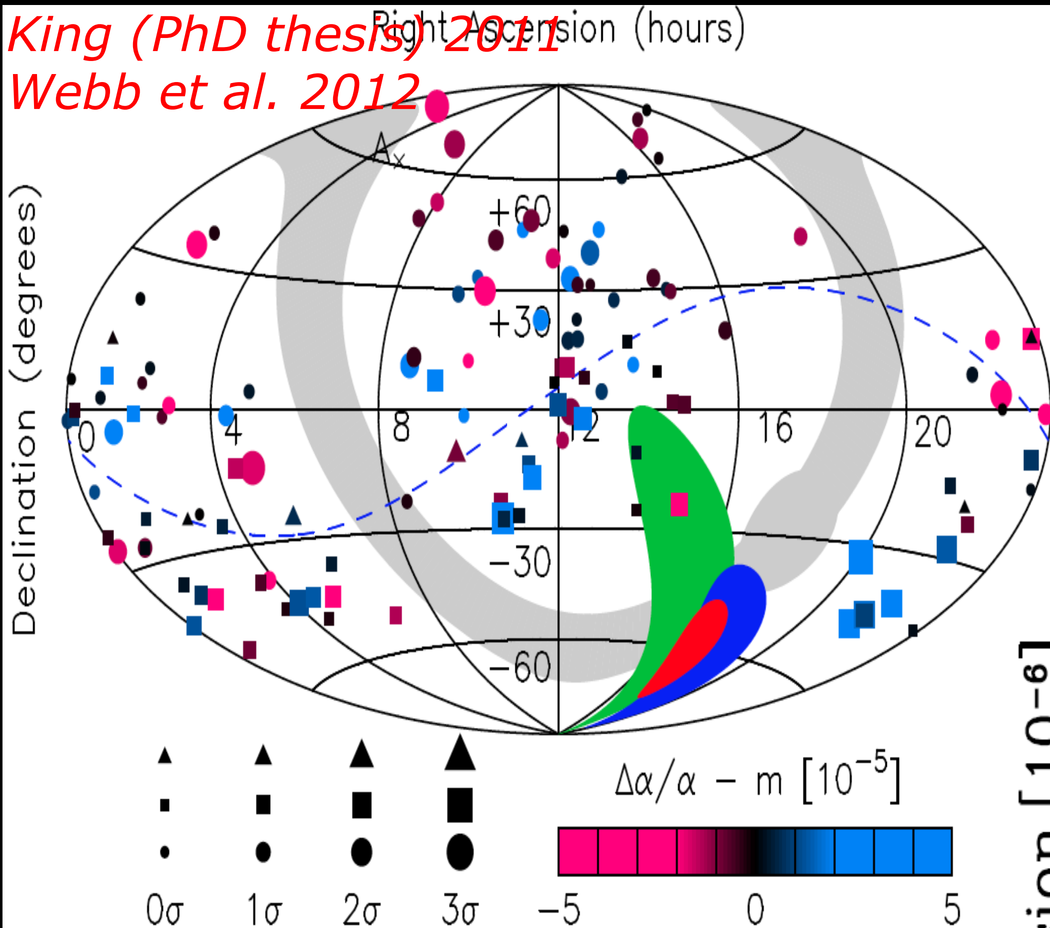
FRIEDRICH LENZ
Düsseldorf, Germany

(Received April 5, 1951)

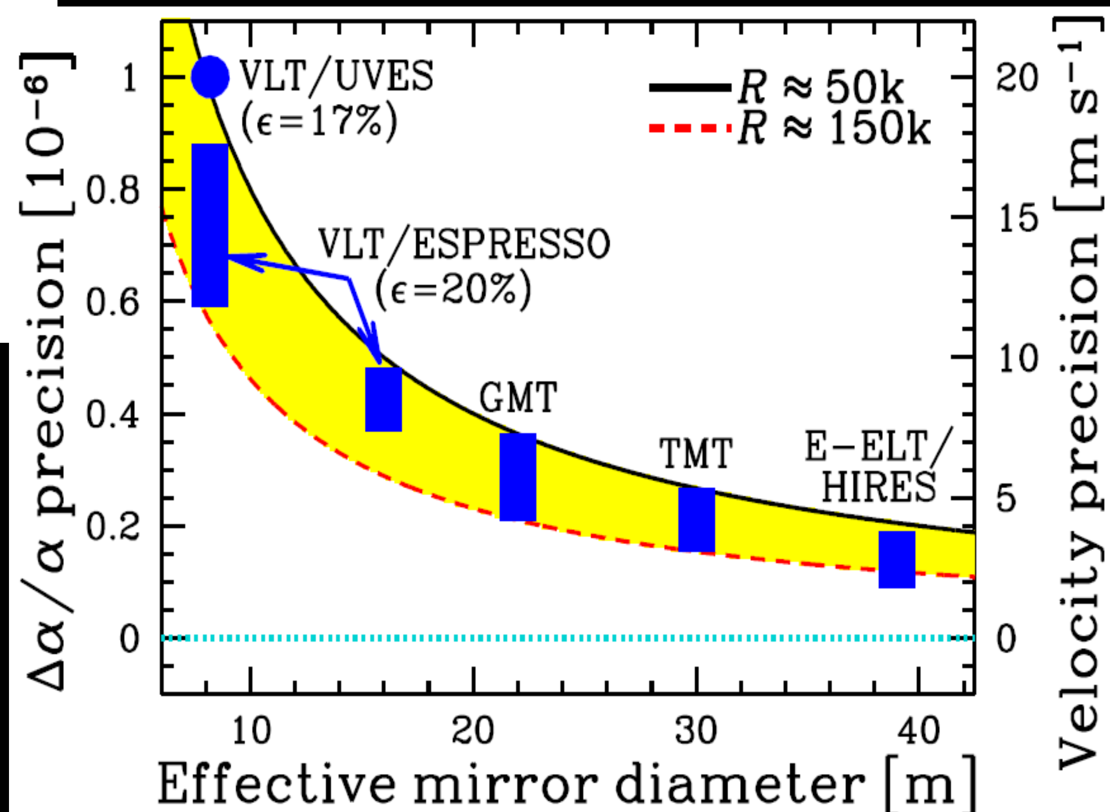
THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12 ± 0.05. It may be of interest to note that this number coincides with $6\pi^5=1836.12$.

[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

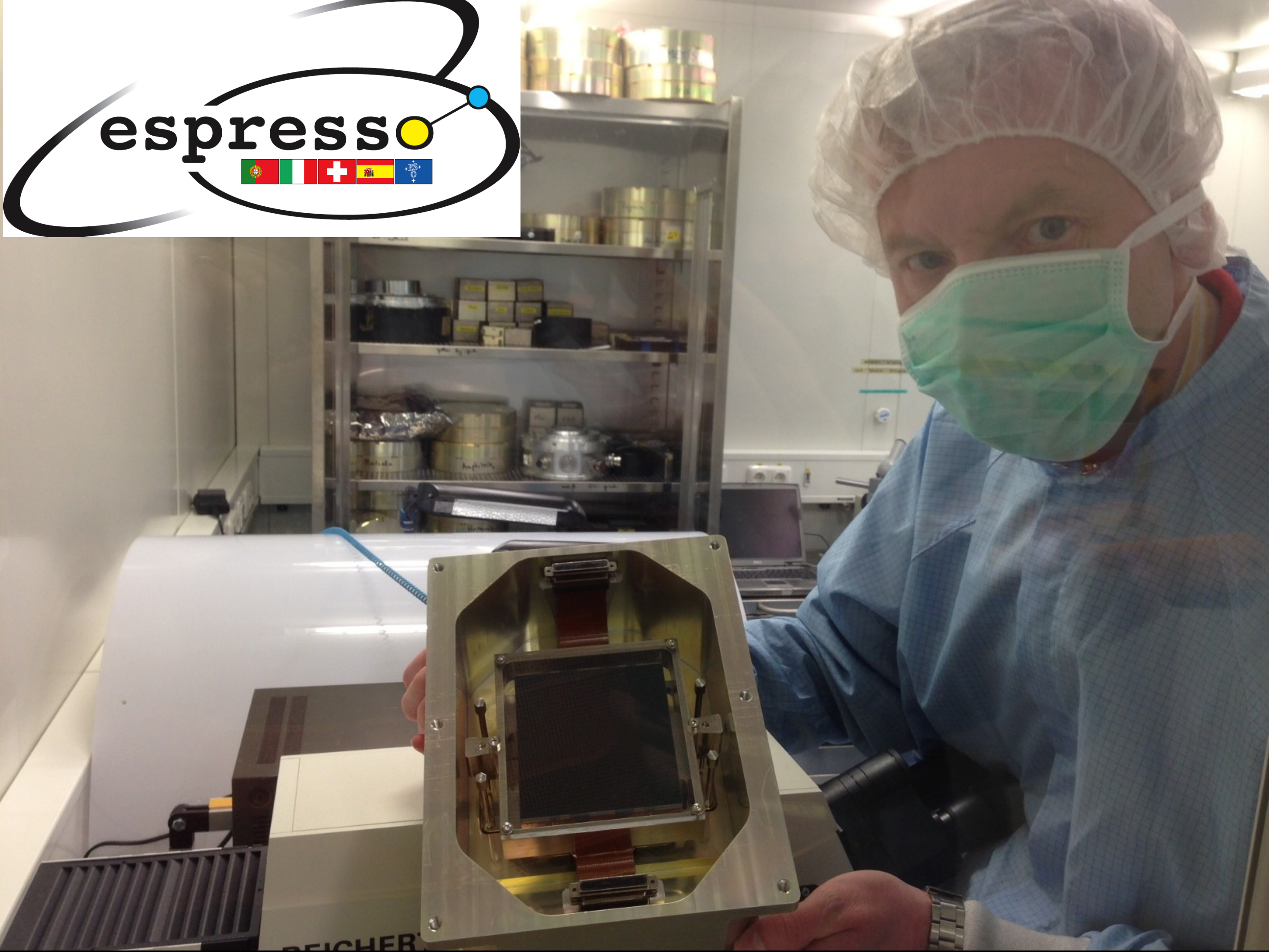
A Dipole on the Sky?



- New physics or systematics?
  - No known systematic can explain dipole
  - Most current data taken for other purposes
  - Need customized pipelines *[Thompson et al. 2009]*



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


espresso

arXiv:1305.1884
A&A, in press

[more soon...]

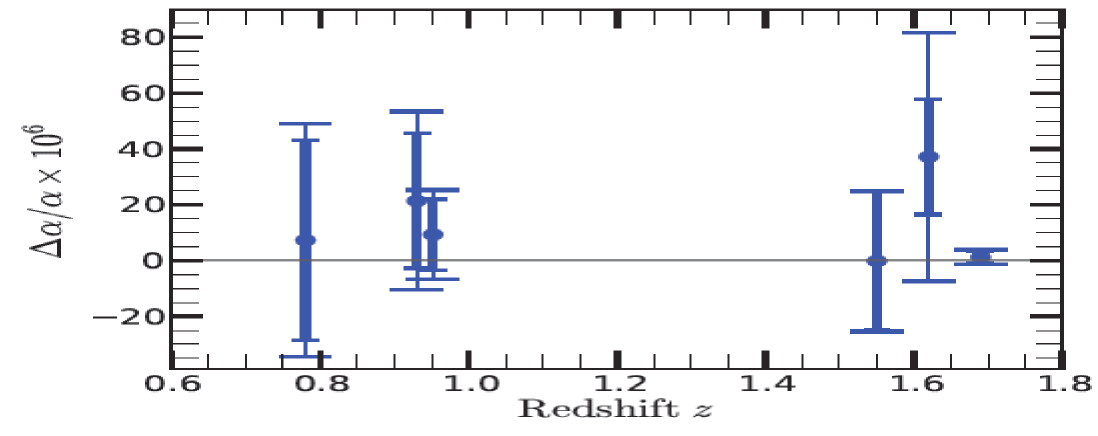


Fig. 8. Summary of $\Delta\alpha/\alpha$ measurements towards HE 2217−2818. Each

The UVES Large Program for Testing Fundamental Physics: I Bounds on a change in α 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]

Aims. To test these claims we are conducting a "Large Program" of observations with the Very Large Telescope's Ultraviolet and Visual Echelle Spectrograph (UVES). We are obtaining high-resolution ($R \approx 60000$) and high signal-to-noise ratio (S/N $\approx$ 100) UVES spectra calibrated specifically for this purpose. Here we analyse the first complete quasar spectrum from this Program, that of HE 2217−2818.
Methods. We apply the Many Multiplet method to measure α in 5 absorption systems towards this quasar: $z_{\rm abs}$ = 0.7866, 0.9424, 1.5558, 1.6279 and 1.6919.
Results. The most precise result is obtained for the absorber at $z_{\rm abs}$ = 1.6919 where 3 Fe II transitions and Al II λ1670 have high S/N and provide a wide range of sensitivities to α. The absorption profile is complex, with several very narrow features, and requires 32 velocity components to be fitted to the data. We also conducted a range of tests to estimate the systematic error budget. Our final result for the relative variation in α in this system is $\Delta\alpha/\alpha = +1.3 \pm 2.4_{\rm stat} \pm 1.0_{\rm sys}$ ppm. This is one of the tightest current bounds on α-variation from an individual absorber. A second, separate approach to the data-reduction, calibration and analysis of this system yielded a slightly different result of $-3.8 \pm 2.1_{\rm stat}$ ppm, possibly suggesting a larger systematic error component than our tests indicated. This approach used an additional 3 Fe II transitions, parts of which were masked due to contamination by telluric features. Restricting this analysis to the Fe II transitions only and using a modified absorption profile model, gave a result consistent with the first approach, $\Delta\alpha/\alpha = +1.1 \pm 2.6_{\rm stat}$ ppm. The other 4 absorbers have simpler absorption profiles, with fewer and broader features, and offer transitions with a smaller range of sensitivities to α. Therefore, they provide looser bounds on $\Delta\alpha/\alpha$ at the $\gtrsim$10 ppm precision level.
Conclusions. The absorbers towards quasar HE 2217−2818 reveal no evidence for variation in α at the 3-ppm precision level (1-σ confidence). If the recently-reported 10-ppm dipolar variation of α across the sky were correct, the expectation at this sky position is (3.2–5.4) ± 1.7 ppm depending on dipole model used. Our constraint of $\Delta\alpha/\alpha = +1.3 \pm 2.4_{\rm stat} \pm 1.0_{\rm sys}$ ppm is not inconsistent with this expectation.

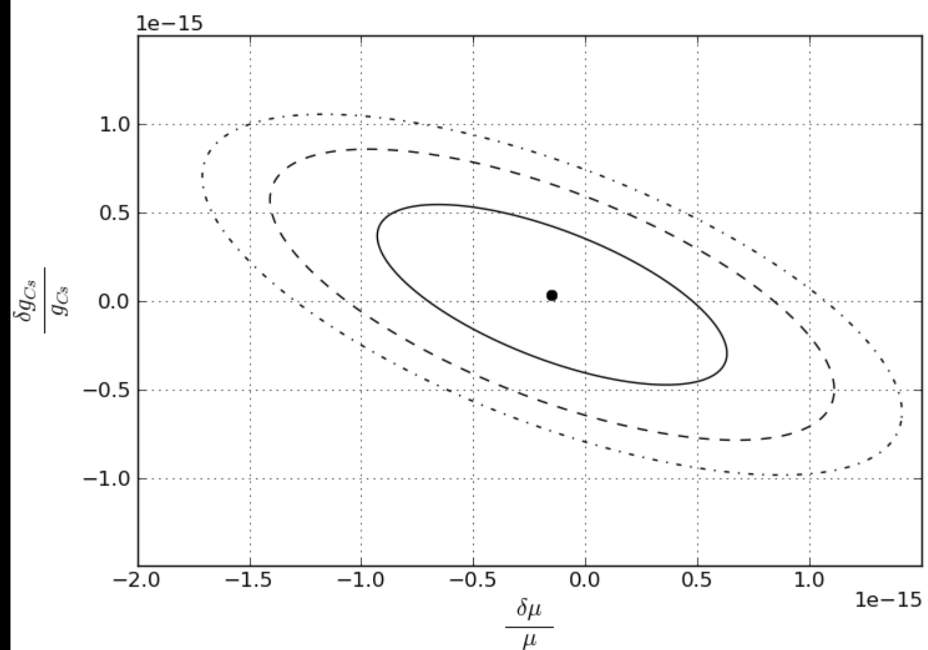
α, μ and Beyond

- In theories where a dynamical scalar field yields varying α, other gauge and Yukawa couplings are also expected to vary
  - In GUTs the variation of α is related to that of Λ_{QCD}, whence nucleon mass varies when measured in energy scale independent of QCD
  - Expect a varying $\mu = m_p/m_e$, which can be probed with H_2 *[Thompson 1975]* and other molecules.
- Wide range of possible α-μ relations makes this a unique discriminating tool between competing models.
  - Look for systems where various constants can be simultaneously measured.
  - Look for systems where a constant can be measured in several independent ways.

Atomic Clocks & Varying Couplings

- Varying constants can be constrained locally by comparing atomic clocks
  - Clocks are sensitive to different couplings
- Combined analysis of all existing measurements:

Clock	ν_{AB}	$\dot{\nu}_{AB}/\nu_{AB}$ (yr^{-1})
Hg-Al	$\alpha^{-3.208}$	$(5.3 \pm 7.9) \times 10^{-17}$
Cs-SF$_6$	$g_{Cs}\mu^{1/2}\alpha^{2.83}$	$(-1.9 \pm 0.12_{sta} \pm 2.7_{sys}) \times 10^{-14}$
Cs-H	$g_{Cs}\mu\alpha^{2.83}$	$(3.2 \pm 6.3) \times 10^{-15}$
Cs-Sr	$g_{Cs}\mu\alpha^{2.77}$	$(1.0 \pm 1.8) \times 10^{-15}$
Cs-Hg	$g_{Cs}\mu\alpha^{6.03}$	$(-3.7 \pm 3.9) \times 10^{-16}$
Cs-Yb	$g_{Cs}\mu\alpha^{1.93}$	$(0.78 \pm 1.40) \times 10^{-15}$
Cs-Rb	$(g_{Cs}/g_{Rb})\alpha^{0.49}$	$(0.5 \pm 5.3) \times 10^{-16}$



Luo, Olive & Uzan 2011

Atomic Clocks & Varying Couplings

- Varying constants can be constrained locally by comparing atomic clocks
  - Clocks are sensitive to different couplings
- Combined analysis of all existing measurements:

$$\frac{\dot{\alpha}}{\alpha} = (-1.7 \pm 4.9) \times 10^{-17}\,\mathrm{yr}^{-1}$$

$$\frac{\dot{\mu}}{\mu} = (6.8 \pm 57.6) \times 10^{-17}\,\mathrm{yr}^{-1}$$

$$\frac{\dot{g}_p}{g_p} = (-7.2 \pm 8.9) \times 10^{-17}\,\mathrm{yr}^{-1}$$

Clock	ν_{AB}	$\dot{\nu}_{AB}/\nu_{AB}$ (yr^{-1})
Hg-Al	$\alpha^{-3.208}$	$(5.3 \pm 7.9) \times 10^{-17}$
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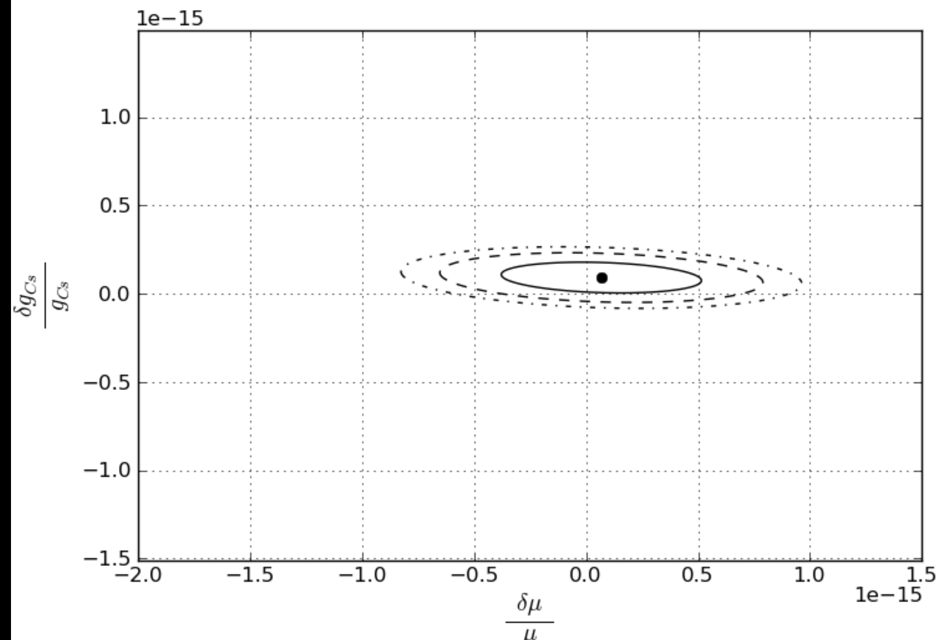

Ferreira, Julião, Martins & Monteiro 2012

Atomic Clocks & Unification

- These can be translated into bounds on classes of unification scenarios
  - A 'systematic' uncertainty comes from nuclear physics calculations
- Generic parametrization with only 2 free parameters:

$$\frac{\Delta m_e}{m_e} = \frac{1}{2}(1+S)\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1+S)]\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta g_p}{g_p} = [0.10R - 0.04(1+S)]\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta g_n}{g_n} = [0.12R - 0.05(1+S)]\frac{\Delta\alpha}{\alpha}$$

Clock	ν_{AB}	$\dot{\nu}_{AB}/\nu_{AB}$ (yr^{-1})
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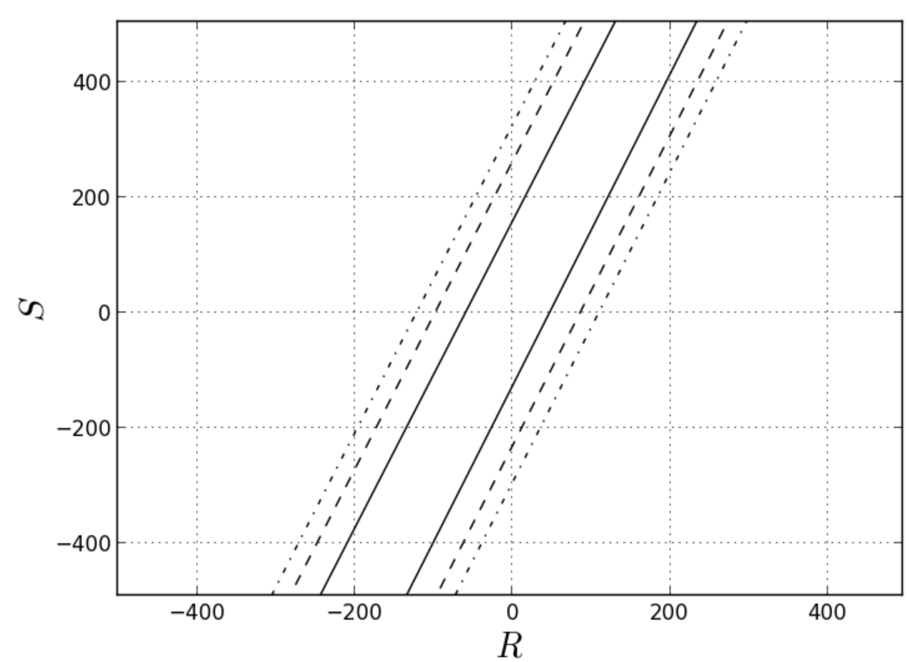
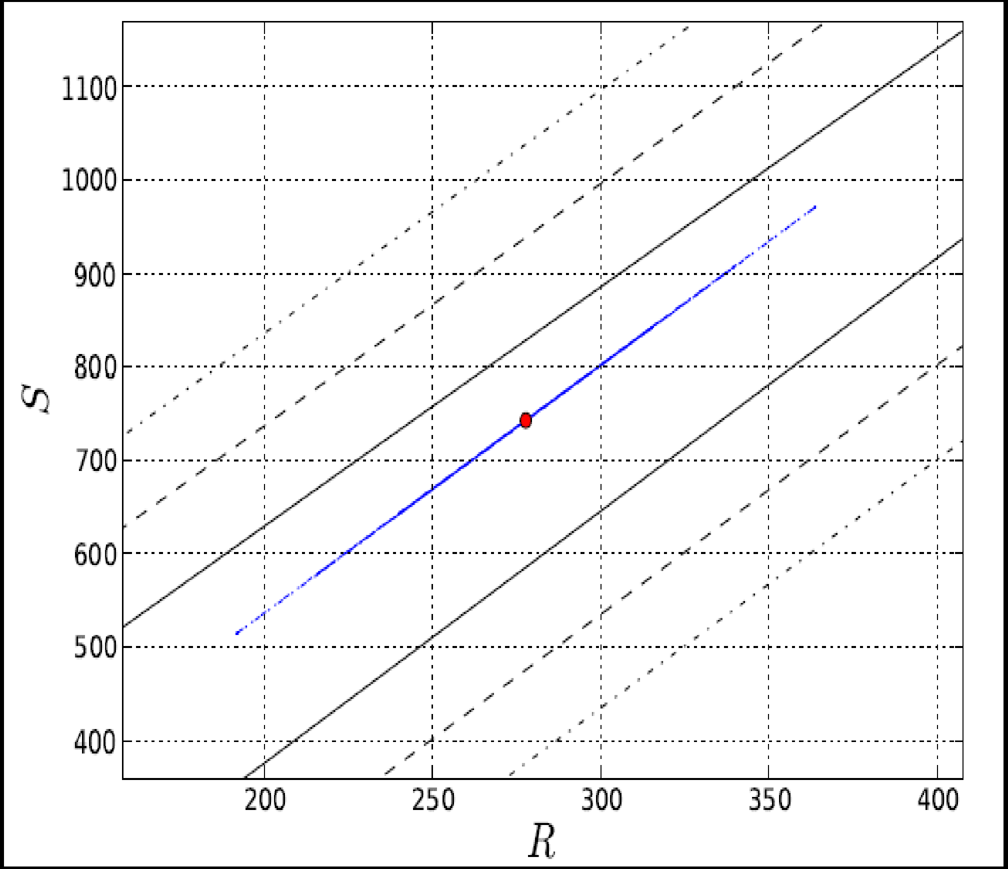


Ferreira, Julião, Martins & Monteiro 2012

PKS1413+135

- Edge-on radio source at z=0.247, yields individual constraints on α, μ and g_p
  - Current sensitivity can't test the spatial dipole scenario
- Taken at face value, yields R=277±24, S=742±65... worth a check (with better measurements)



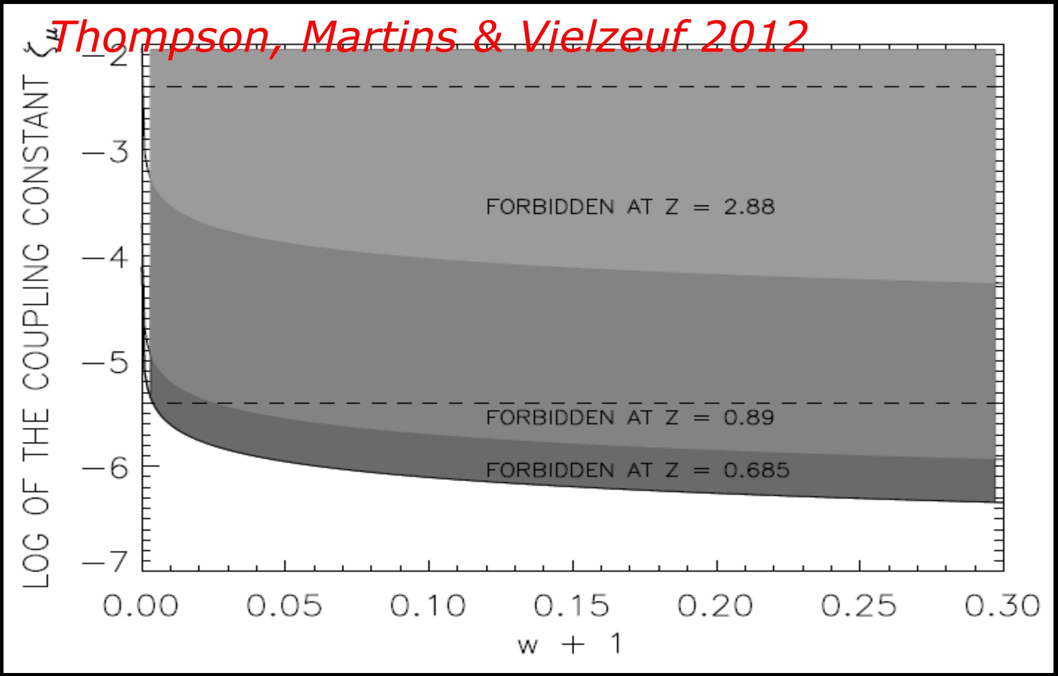
Q_{AB}	$\Delta Q_{AB}/Q_{AB}$	Reference
$\alpha^2 g_p$	$(-2.0 \pm 4.4) \times 10^{-6}$	Murphy *et al.* [5]
$\alpha^{2\times1.57} g_p \mu^{1.57}$	$(5.1 \pm 12.6) \times 10^{-6}$	Darling [6]
$\alpha^{2\times1.85} g_p \mu^{1.85}$	$(-11.8 \pm 4.6) \times 10^{-6}$	Kanekar *et al.* [7]

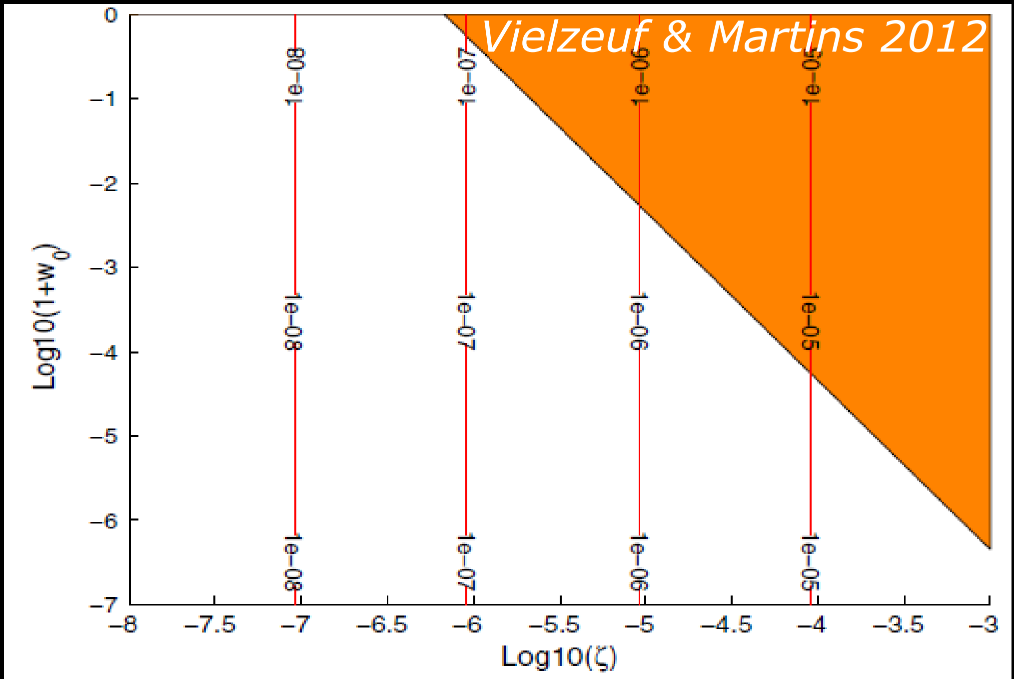
$$\frac{\Delta\alpha}{\alpha} = (-5.1 \pm 4.3) \times 10^{-5},$$
$$\frac{\Delta\mu}{\mu} = (4.1 \pm 3.9) \times 10^{-5},$$
$$\frac{\Delta g_p}{g_p} = (9.9 \pm 8.6) \times 10^{-5},$$

Ferreira, Julião, Martins & Monteiro 2013

Dark Energy & Varying Couplings

- 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]*.





Dynamical Dark Energy

- 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]*

Amendola, Leite, Martins et al. 2012

	Baseline	Ideal	Control
Supernovas	2	2	2
ESPRESSO (α only)	0	1	0
Supernovas + ESPRESSO	2	3	2
HIRES (α only)	2	8	3
Supernovas + HIRES	4	10	5

- ELT-HIRES can constrain dark energy better than supernovas
  - Plus measurements of the redshift drift...
  - Plus deep matter era Type Ia supernovas (ELT-IFU)...

Dynamical Dark Energy

Supernovas	SN Only	SN + ESPRESSO	SN + ELT-HIRES
SNAP	*43*	*52*	*324*
SNAP + E-ELT	*62*	*72*	*330*
SNAP + TMT	*59*	*68*	*330*

Ana Catarina Leite (work in progress)

Amendola, Leite, Martins et al. 2012

	Baseline	Ideal	Control
Supernovas	2	2	2
ESPRESSO (α only)	0	1	0
Supernovas + ESPRESSO	2	3	2
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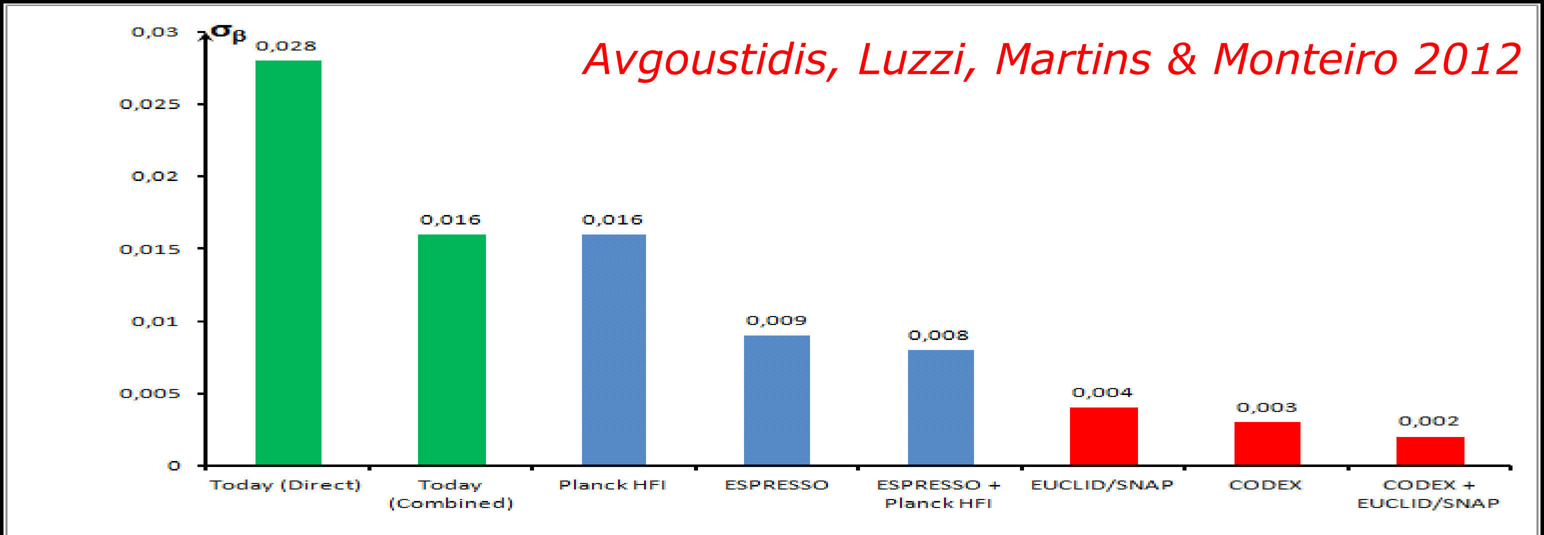
A Consistency Test

- $T(z)=T_0(1+z)$ 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 β



Scalar-Photon Couplings

Euclid Consortium

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

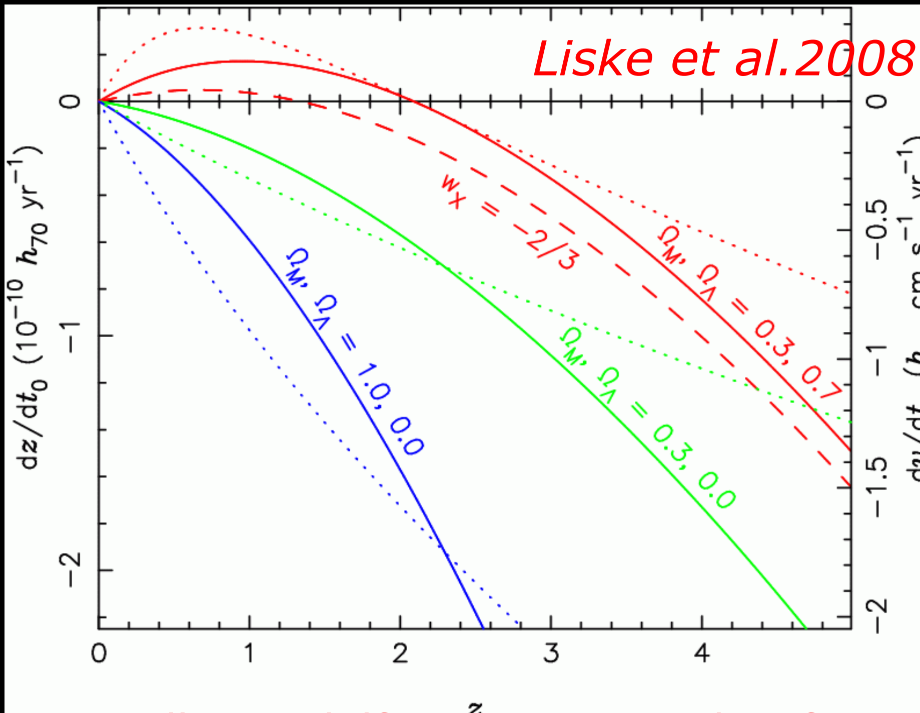
Dataset	δw_0	δw_a	$\delta \Omega_m$	δk
Current (weak)	0.25	1.3	0.06	$1.2\times10^{-6}(10^{-5})$
Current (strong)	0.22	0.65	0.06	$1.2\times10^{-6}(10^{-5})$
Euclid(BAO)+SNAP	0.15(0.35)	0.4(1.6)	0.03	$10^{-6}(1.1\times10^{-5})$
Euclid only (BAO+SN)	0.15(0.35)	0.6(1.6)	0.03	–
Euclid(BAO+SN)+SNAP	0.14(0.35)	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

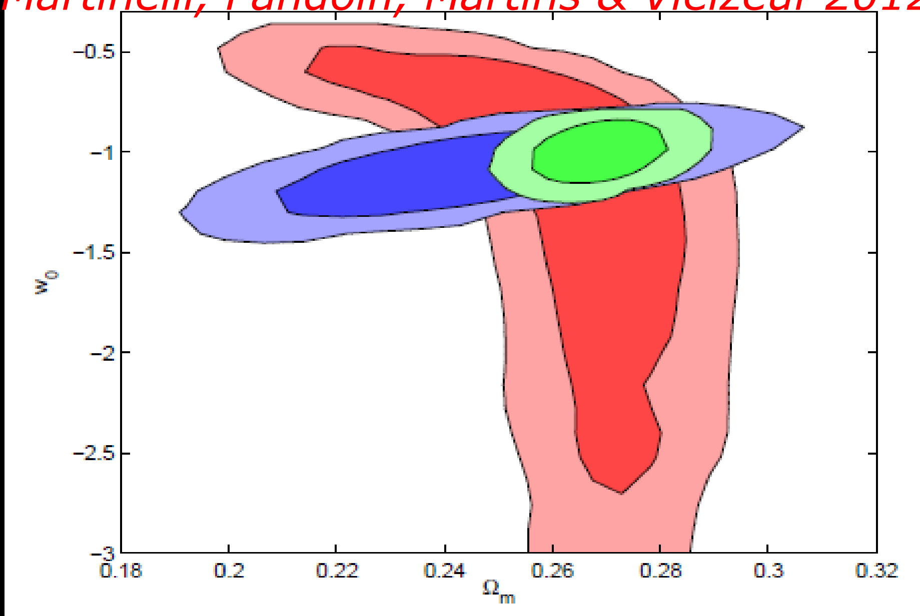
- Euclid can, even on its own, constrain dark energy while allowing for photon number non-conservation
  - Stronger constraints in combination with other probes
- T(z) measurements are crucial for breaking degeneracies: they can be obtained with ALMA, ESPRESSO & ELT-HIRES (also Planck clusters now –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



Martinelli, Pandolfi, Martins & Vielzeuf 2012



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