From Precision Spectroscopy to Fundamental Cosmology

[or: Testing GR and the Equivalence Principle, 100 years on]

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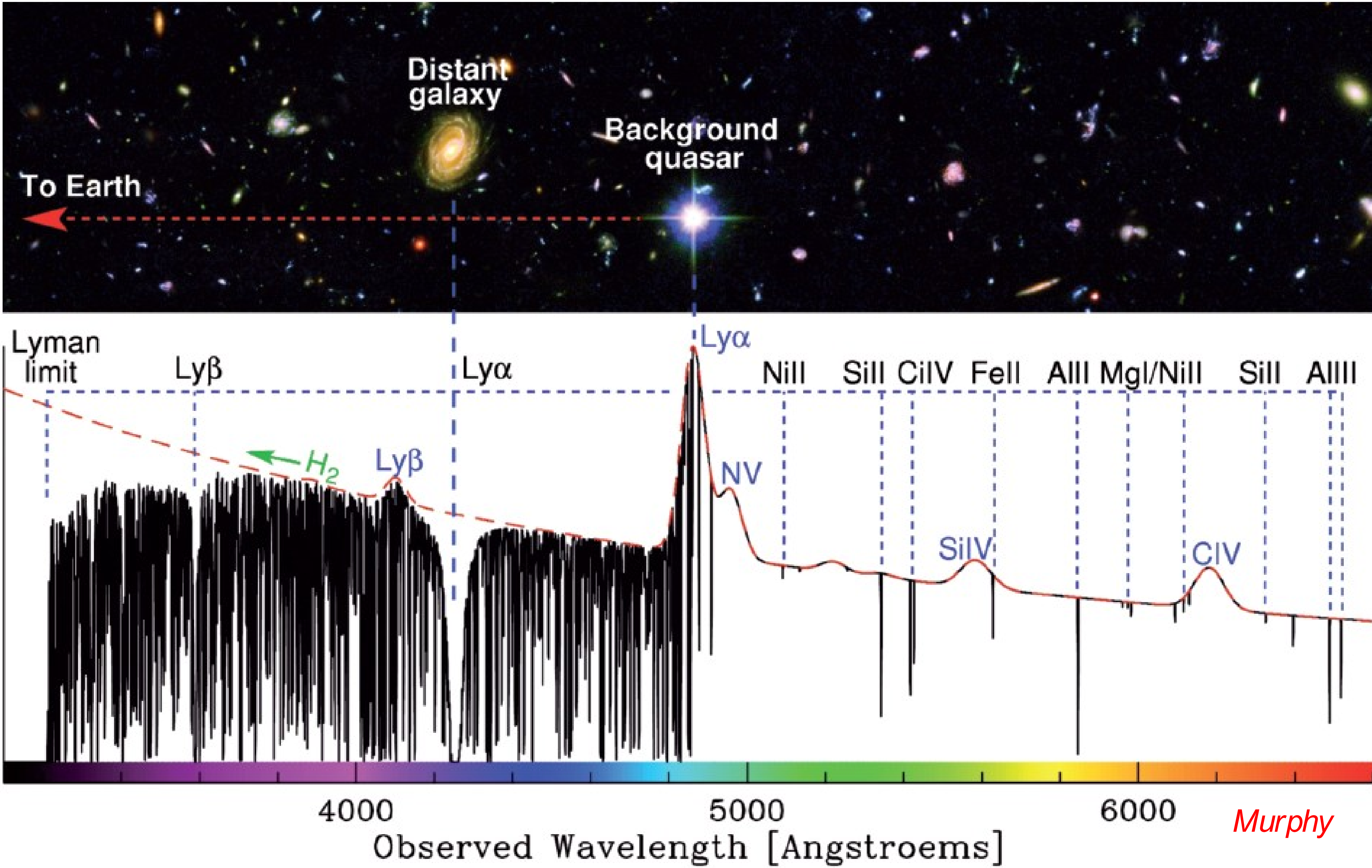
with Ana Catarina Leite, Ana Marta Pinho, Catarina Rocha, David Corre, Mar Pino, Max von Wietersheim, Miguel Ferreira, Rui Alves and the UVES Fundamental Physics LP Team

Is this a dog?

Is this a dog?

Precision Taxonomy

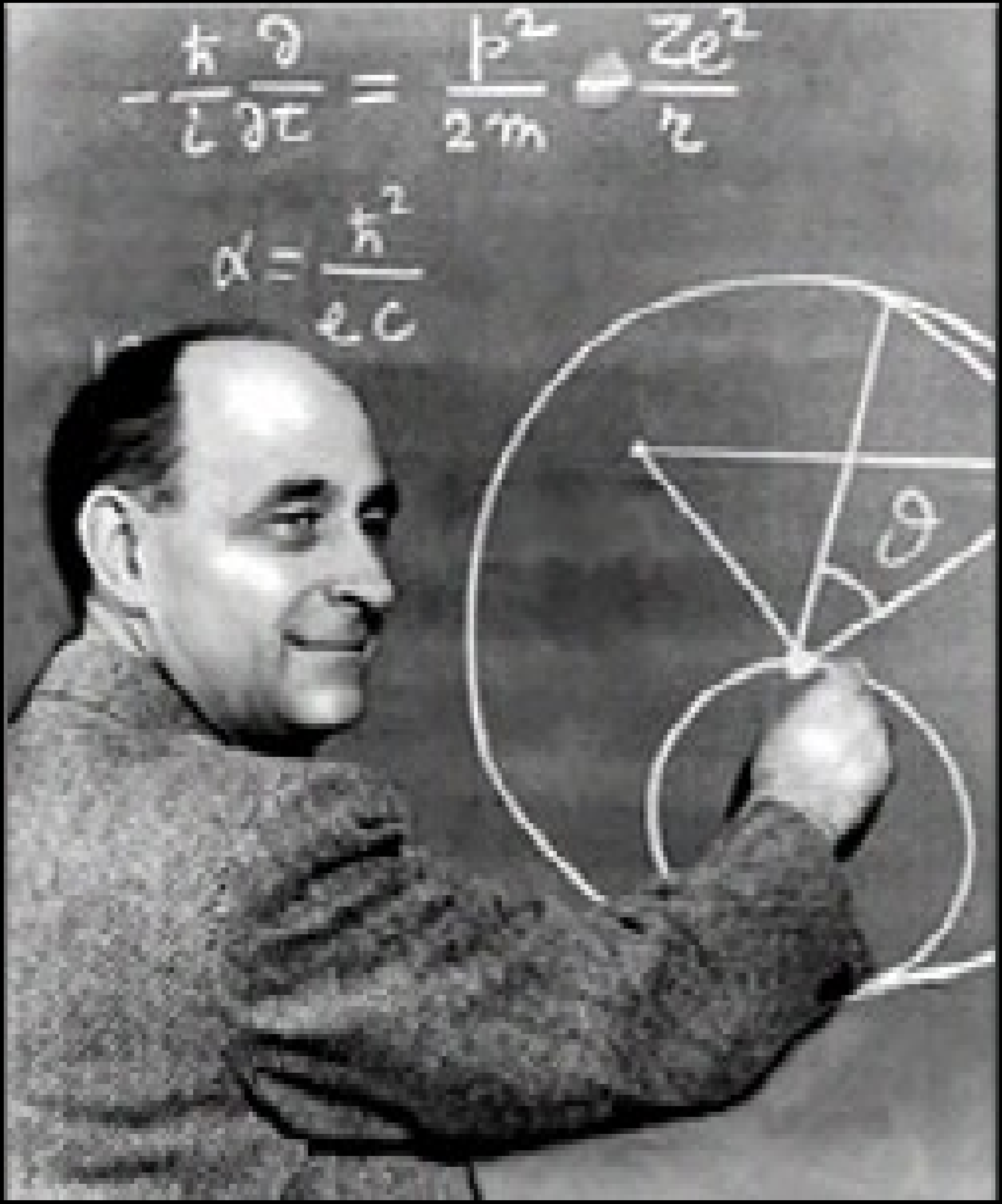
Precision Spectroscopy



So what's your point?

- We now know (from the LHC) that fundamental scalar fields are among Nature's building blocks
  - ...and that fundamental couplings run with energy
- These fields will naturally couple to the rest of the model
  - (unless there is an unknown principle to suppress them)
  - Couplings can therefore roll in time and ramble in space
- These couplings will lead to potentially observable long-range forces and varying couplings *[Carroll 1998, ...]*
  - These measurements (whether they are detections or null results) will constrain fundamental physics and cosmology
  - This ensures a quantifiable 'minimum guaranteed science'

Varying Fundamental Couplings



Fundamental? Varying?

- Nature is characterized by some physical laws and 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
- We have no 'theory of constants'
  - They determine properties of atoms, cells and the universe...
  - ...and if they vary, all the physics we know is incomplete
- Improved null results are important and very 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 dimensionless physical constants imply a violation of the Einstein Equivalence Principle, a 5th force of nature, etc

How low should one go?

- Dark energy equation of state vs. Relative variation of α

  $(1+w_0)$ is naively $O(1)$ — Observationally $< 10^{-1}$

  $(\Delta\alpha/\alpha)$ is naively $O(1)$ — Observationally $< 10^{-5}$

  - If not O(1), no 'natural' scale for variation: either fine-tuning...
  - ...or a new (currently unknown) symmetry forces it to be zero

- So is it worth pushing beyond ppm? Certainly yes!
  - Strong CP Problem in QCD: a parameter naively O(1) is known to be $<10^{-9}$, leading to postulate of Peccei-Quinn symmetry and axions
  - Sufficiently tight bound would indicate either no dynamical fields in cosmology...
  - ...or a new symmetry to suppress the couplings – whose existence would be as significant as that of the original field

Phys. Rev. 82, 554 (1951)

The Ratio of Proton and Electron Masses

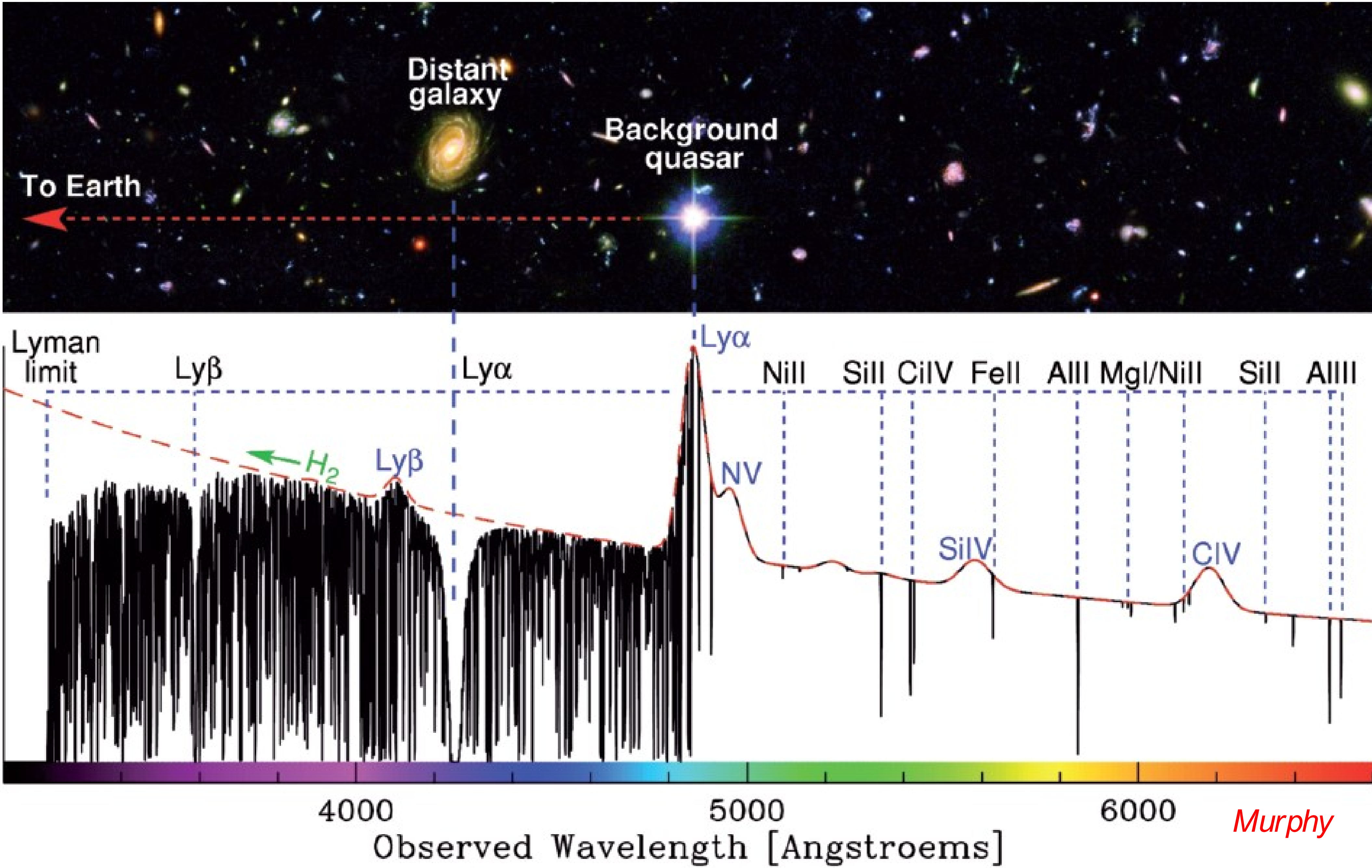
FRIEDRICH LENZ
Düsseldorf, Germany

(Received April 5, 1951)

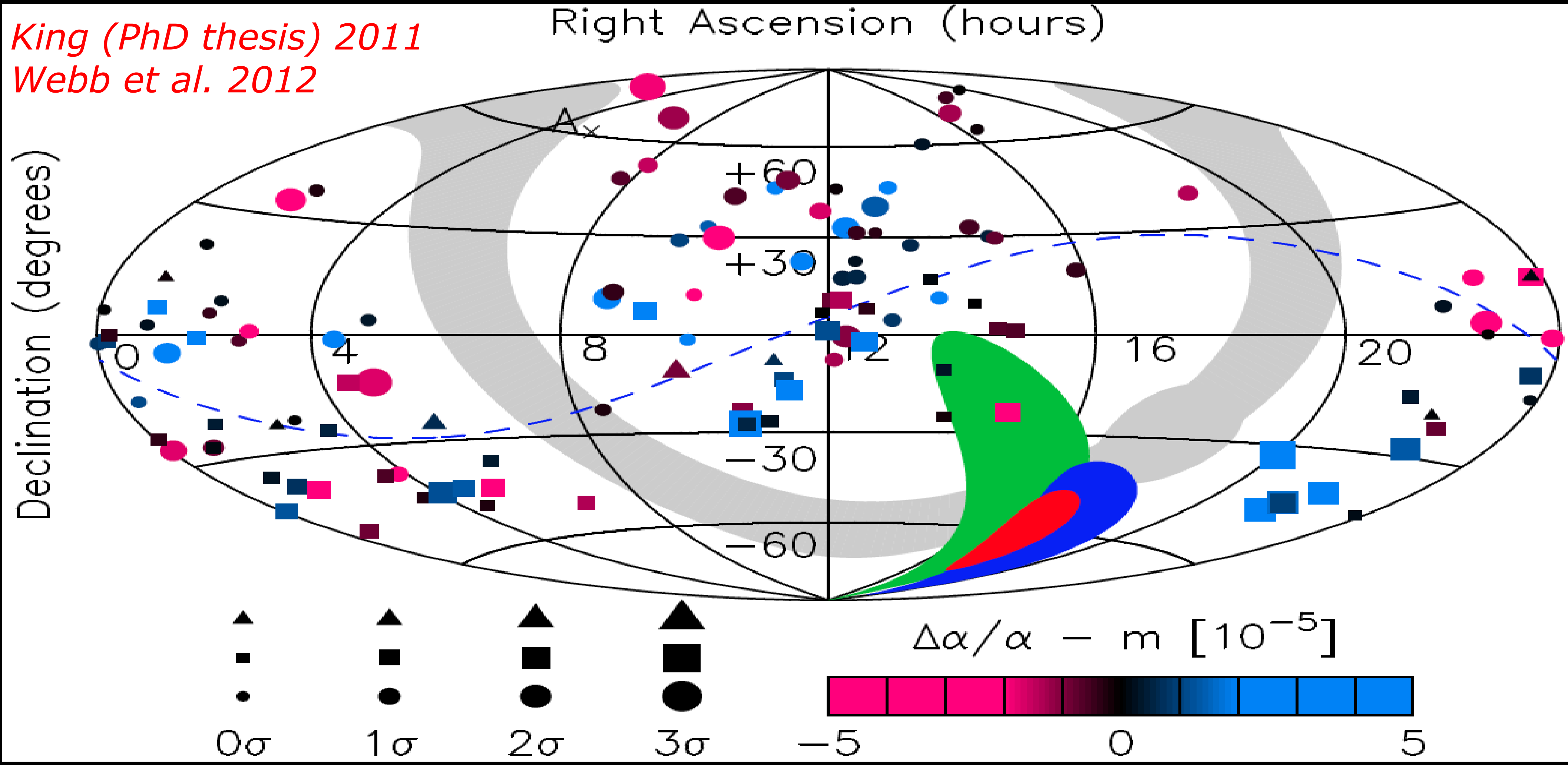
THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12 ± 0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

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

Measuring α from Quasars



A Dipole on the sky?



- >4 sigma evidence for a dipole; new physics or systematics?
  - Unclear if pure spatial dipole or dependent on lookback time
  - Main concern: archival data, taken for other purposes
  - Key driver for ESPRESSO and ELT-HIRES

$\alpha(z)$, $\mu(z)$, $T(z)$ and Beyond

- In theories where a dynamical scalar field yields varying α, other couplings are also expected to vary, including $\mu=m_p/m_e$
  - In GUTs the variation of α is related to that of Λ_{QCD}, whence m_{nuc} 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
- Also, there will be violations of the $T(z)$ law and the distance duality (Etherington) relation *[Avgoustidis et al. 2012, ...]*
- Wide range of possible α-μ-T relations makes this a unique discriminating tool between competing models
  - Sensitive probe of fundamental physics and unification scenarios *[Coc et al. 2007, Luo et al. 2011, Ferreira et al. 2012, Ferreira et al. 2013, ...]*

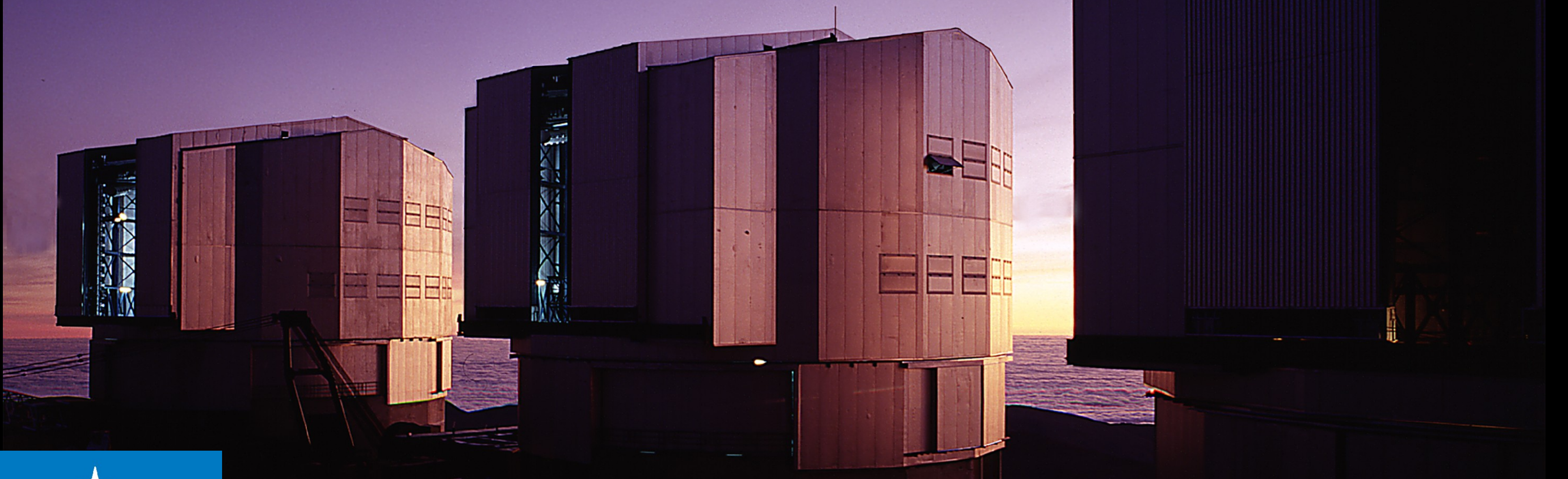
$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1+S)]\frac{\Delta\alpha}{\alpha}$$

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

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

The UVES Large Program for Testing Fundamental Physics

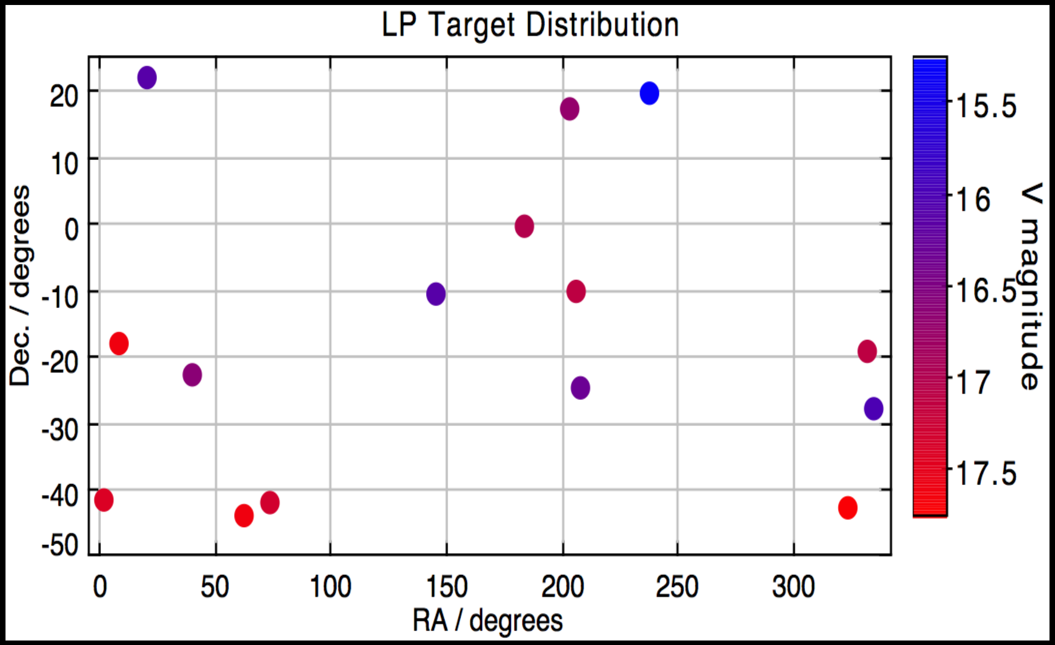
ESO 185.A-0745 UT2-Kueyen



P. Molaro (PI), P. Bonifacio, M. Centurión, S. D'Odorico, T.M. Evans, S.A. Levshakov, S. Lopez, C.J.A.P. Martins, M.T. Murphy, P. Petitjean, H. Rahmani, D. Reimers, R. Srianand, G. Vladilo, M. Wendt, J.B. Whitmore, I.I. Agafonova, H. Fathivavsari, P. Noterdaeme, ...

Goals, Targets, Status

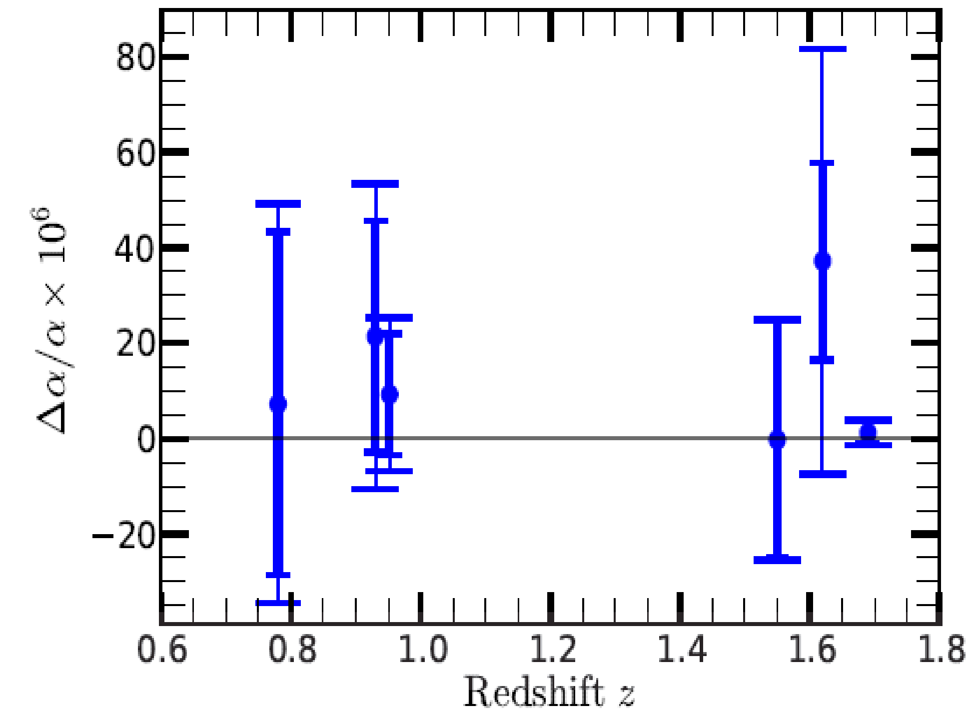
- Only large program dedicated to varying couplings, with optimized sample & methodology: ca. 40 nights in 2010-13
- R~60000, S/N~100; potential accuracy is 1-2ppm/system, where photon noise and calibration errors are comparable
  - Our goal: 2ppm per system, 0.5ppm for full sample
  - All 3 active observational groups involved
  - Compare/check/optimize different analysis pipelines (incl. blinds)



- 13 α targets, 2 μ targets
  - Selected before dipole known *[Bonifacio et al. 2014]*
  - Out: HE2217-2818, HE0027-1836, HS1519+1919
  - Raw data in the ESO public archive, and reduced data products will also be made public – have fun!

Understanding the Data

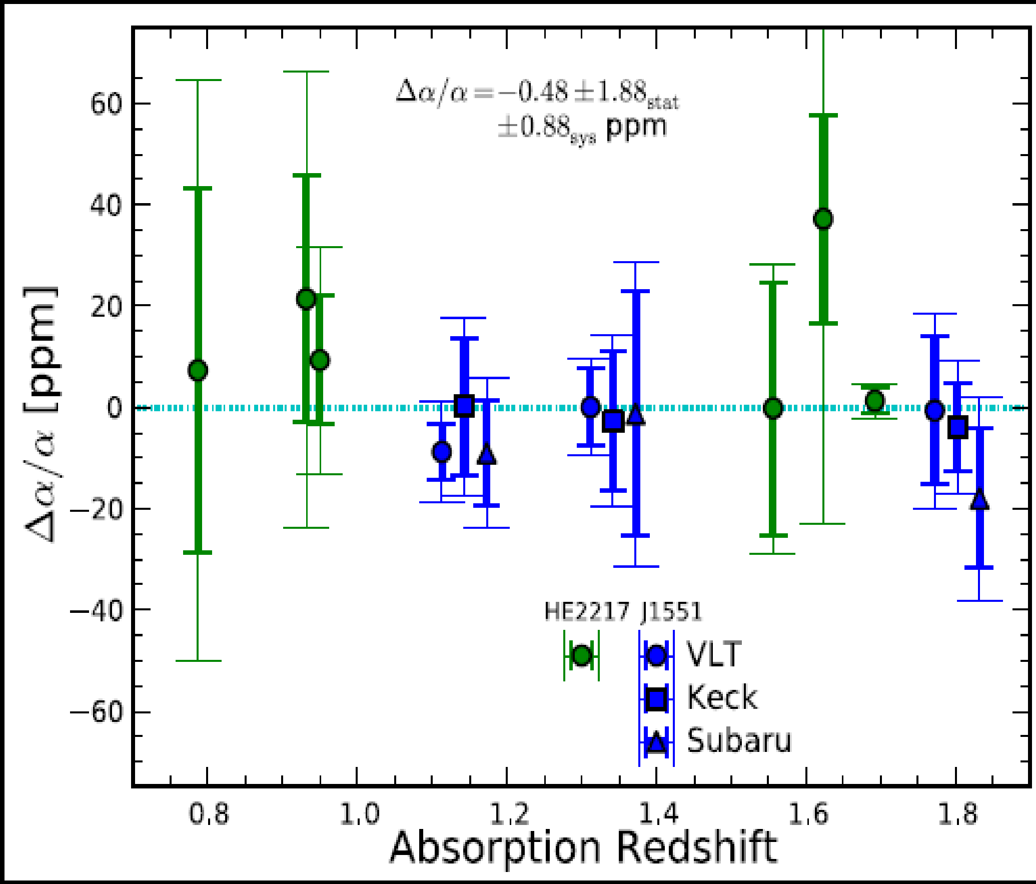
- HE2217-2818, z_{abs}~1.69:
  $\Delta\alpha/\alpha = 1.3 \pm 2.4_{sta} \pm 1.0_{sys}$ ppm
  - Paper I: P. Molaro et al., A&A 555 (2013) A68
  - Dipole fit: (3.2–5.4)±1.7 ppm depending on model; our measurement does not confirm this, but is not inconsistent with it either



- HE0027-1836, z_{abs}~2.40: $\Delta\mu/\mu$ = -7.6 $\pm$ 8.1$_{sta}$ $\pm$ 6.3$_{sys}$ ppm
  - Paper II: H. Rahmani et al., MNRAS 435 (2013) 861
  - Identified wavelength-dependent velocity drift (corrected with bright asteroid data)
- Bottleneck: intra-order distortions (~200m/s) & long-range distortions on UVES, discussion in Paper IV *[Whitmore et al.]*
  - Also identified in HARPS and Keck-HIRES

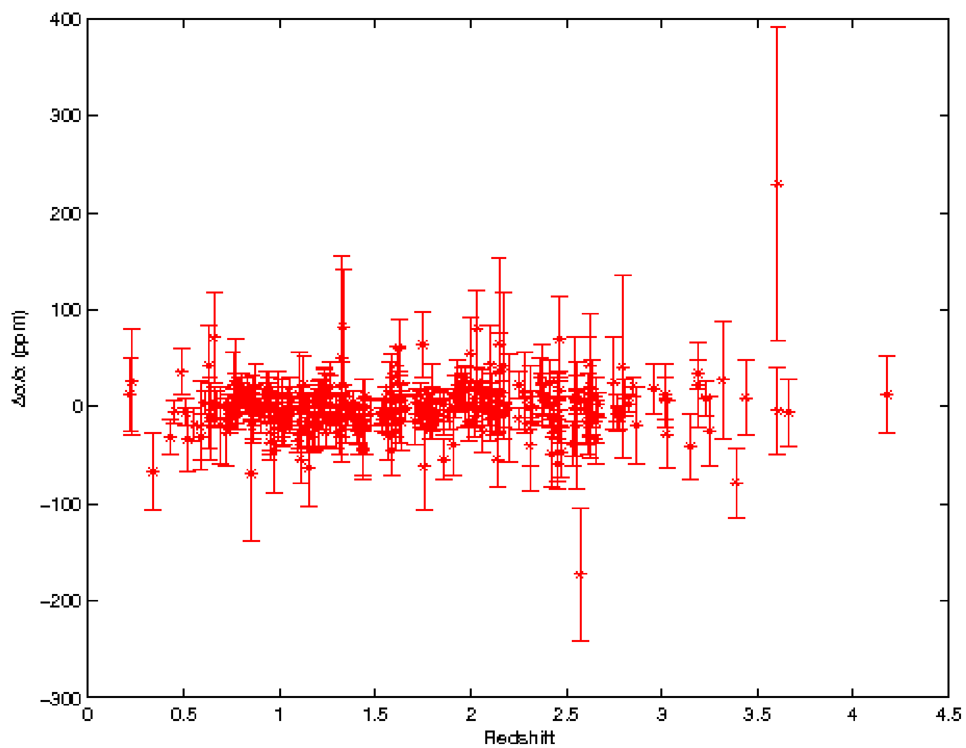
A Triple Check

- HS1519+1919: 3 absorbers at z_{abs}~1.1, 1.3 & 1.8, observed with the 3 top optical telescopes (VLT/UVES, Keck/HIRES and Subaru/HDS): $\Delta\alpha/\alpha = -5.4 \pm 3.3_{sta} \pm 1.5_{sys}$ ppm
  - Paper III: T. Evans et al., MNRAS 445 (2014) 128
  - Directly comparing spectra and 'supercalibrating' with asteroid and iodine-cell tests, allows removal of long-range distortions



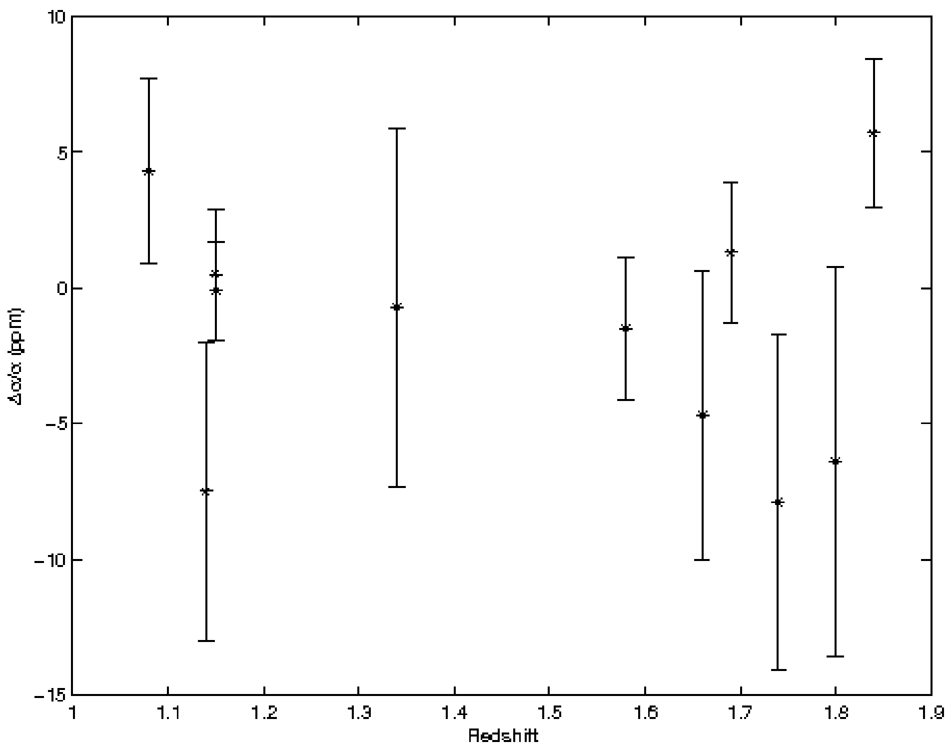
- Current status: compatible with null result and dipole...
  - Full sample analysis ongoing
  - Papers IV-VII should be appearing soon

From COSMO-10 to COSMO-15



- *Webb et al. 2011*
  - 293 archival absorbers
  - Nominal weighted mean
    $\sigma_{stat} \sim 2$ ppm
  - ...but inferred $\sigma_{sys} \sim 9$ ppm

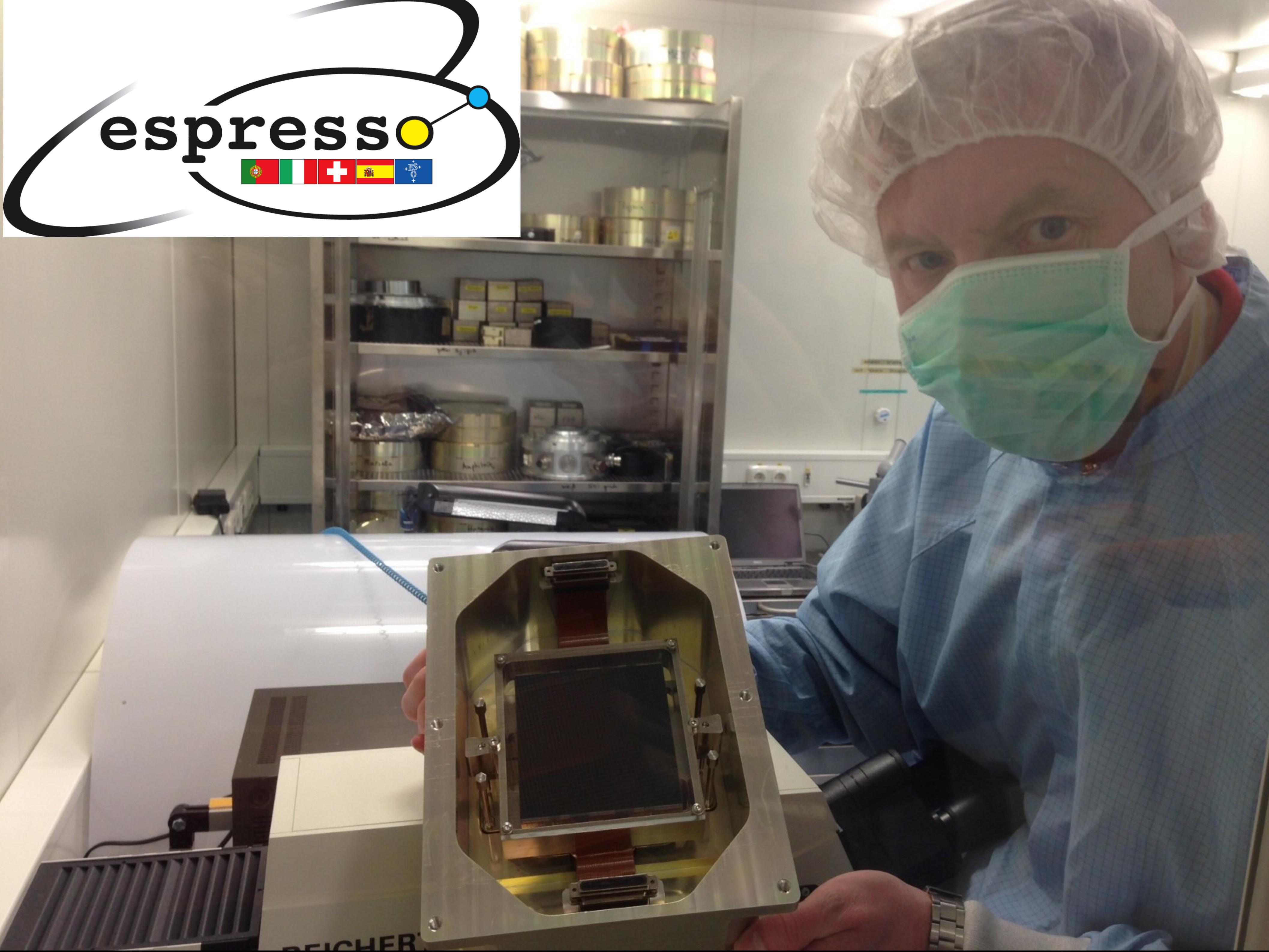
- *Large Program et al., @2015*
  - 11 dedicated measurements
  - Nominal weighted mean
    0.37 ± 0.94 ppm
  - Systematics floor 1 ppm



What's taking you so long?

- Akin to finding exoplanets, except much harder!
  - Much fainter sources, only a few lines clean
- Measurements of fundamental couplings require observing procedures – and instruments – beyond current facilities
  - Need customized data reduction pipelines, including careful wavelength calibration procedures *[Thompson et al. 2009]*
  - Must calibrate with laser frequency combs, not ThAr lamps or I2 cells *[Li et al. 2008, Steinmetz et al. 2008]*
- New generation of high-resolution, ultra-stable spectrographs has these measurements as key driver
  - 'Shortly': PEPSI at the LBT
  - 2016: ESPRESSO at the VLT (1 or 4 UT)
  - 2025+: ELT-HIRES at the E-ELT

Would you like an ESPRESSO?

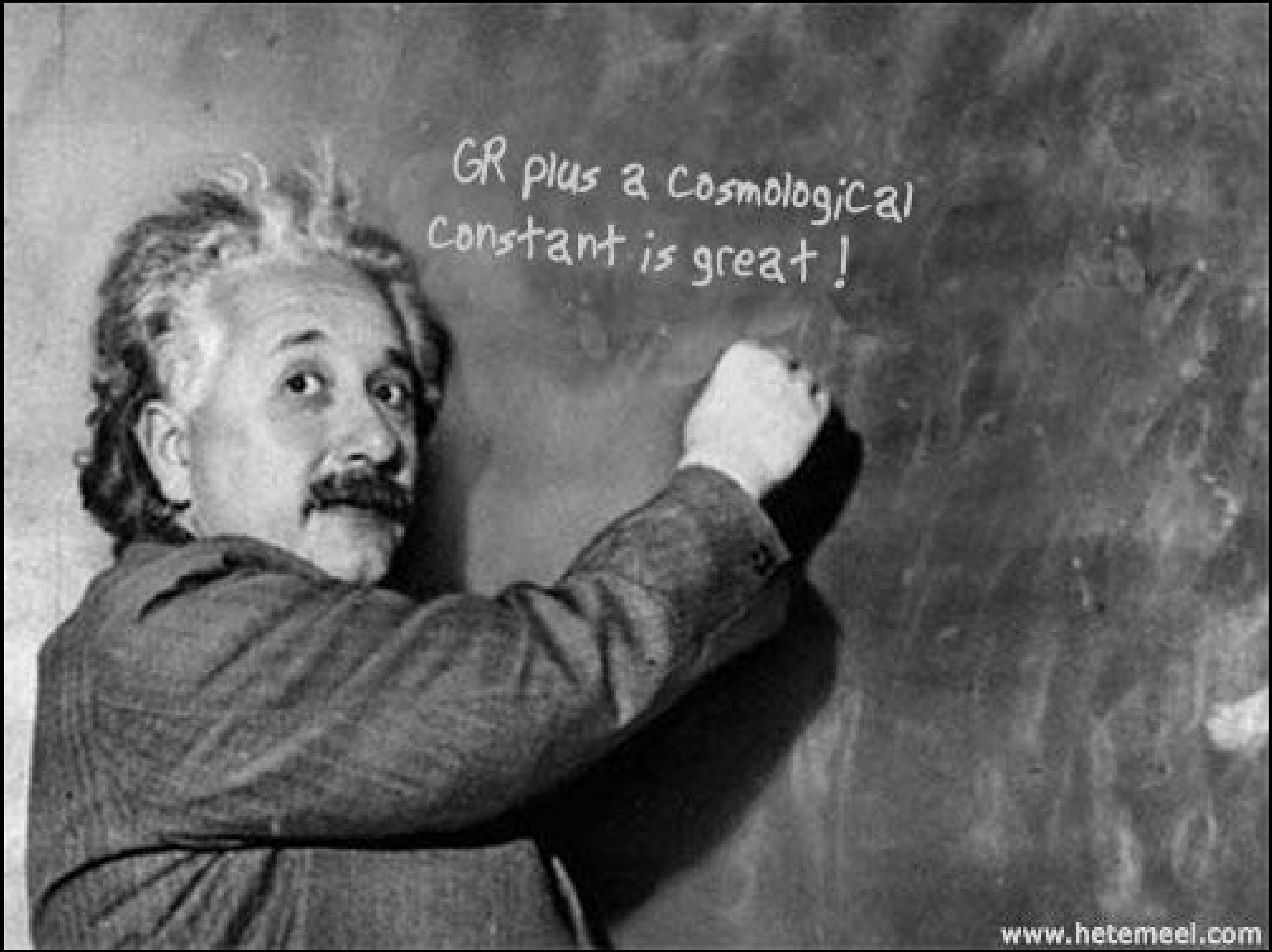

espresso

Fundamental Cosmology in the E-ELT Era

Martins, GRG 47 (2015) 1843

Fish et al., arXiv:1309.3519
Tilanus et al., arXiv:1406.4650

Was Einstein Right?



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 will lead to potentially observable long-range forces and varying 'constants' *[Carroll 1998, Wetterich 1998, Damour 2004, ...]*
  - Current measurements already provide competitive constraints on fundamental physics and cosmology
  - Key science (and design) driver for forthcoming ESO facilities

Taxonomy: Class I

- If the same degree of freedom is responsible for dark energy and varying α, the latter's evolution is parametrically determined

$$\frac{\Delta\alpha}{\alpha}(z) = \zeta \int_0^z \sqrt{3\Omega_\phi(z')[1+w_\phi(z')]}\frac{dz'}{1+z'}$$

- Current QSO + Clocks + Cosmo 1D marginalized constraints are *[Martins & Pinho 2015, Martins et al. 2015]*
  - $|\zeta| < 5\times10^{-6}$ (2 sigma) and $|1+w_0| < 0.06$ (3 sigma)
  - 12 ESPRESSO GTO measurements (cf. Ana Catarina Leite's talk): $|\zeta| < 3\times10^{-6}$ (2 sigma) and $|1+w_0| < 0.04$ (3 sigma)
  - ...or >3 sigma detection of ζ
- Bound on Eotvos parameter $\eta < 3\times10^{-14}$ *[Martins et al. 2015]*
  - Cf. *[Dvali & Zaldarriaga 2002, Chiba & Kohri 2002, Uzan 2011, ...]*
  - > 10x tighter than direct bounds (but testable by MICROSCOPE)
  - ESPRESSO can reach few$\times10^{-16}$, best until STEP or ELT-HIRES

Aiming Higher (i.e., Deeper)

- Standard methods (SNe, etc) are of limited use as dark energy probes *[Maor et al. 2001, Upadhye et al. 2005, ...]*
  - Since the field is slow-rolling when dynamically important, a convincing detection of w(z) will be tough at low z
  - Must probe deep matter era – fundamental couplings ideal
- ALMA, ESPRESSO & ELT-HIRES will map dark energy to z=4 *[Amendola et al. 2012, ...]*
  - Enables unambiguous consistency test of underlying assumptions

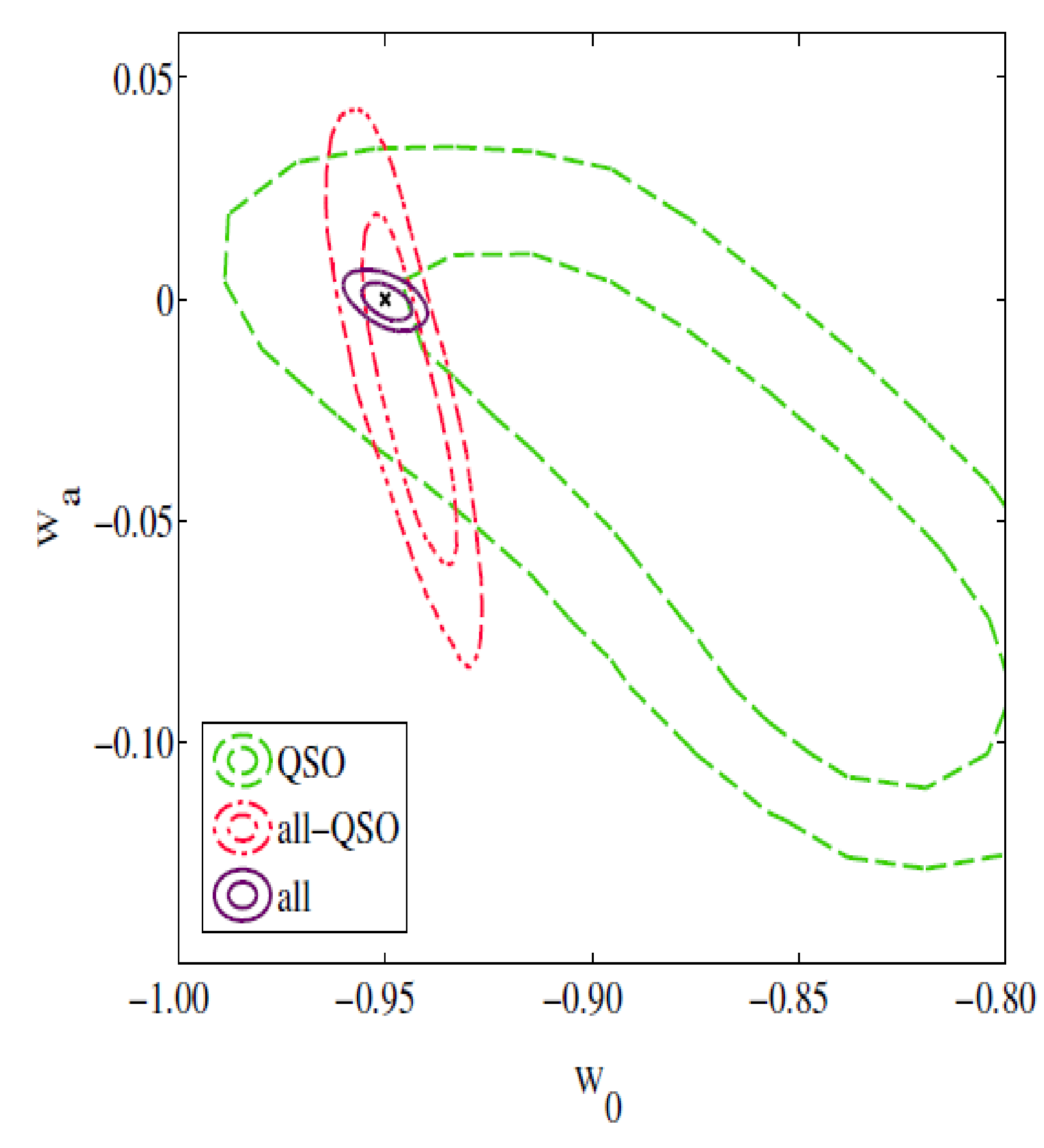
Leite et al. 2014

Model	ESPRESSO	ELT-HIRES
Constant	649.8	19.5
Step	2231.6	66.9
Bump	1420.1	42.6

- Redshift drift: direct non-geometric model-independent measurement of expansion history *[Liske et al. 2008]*
  - Rather than mapping our (present-day) past light-cone, it directly maps evolution by comparing past light-cones at different times
  - ELT-HIRES will map 2<z<5, SKA (possibly) z<1

Euclid & Varying α

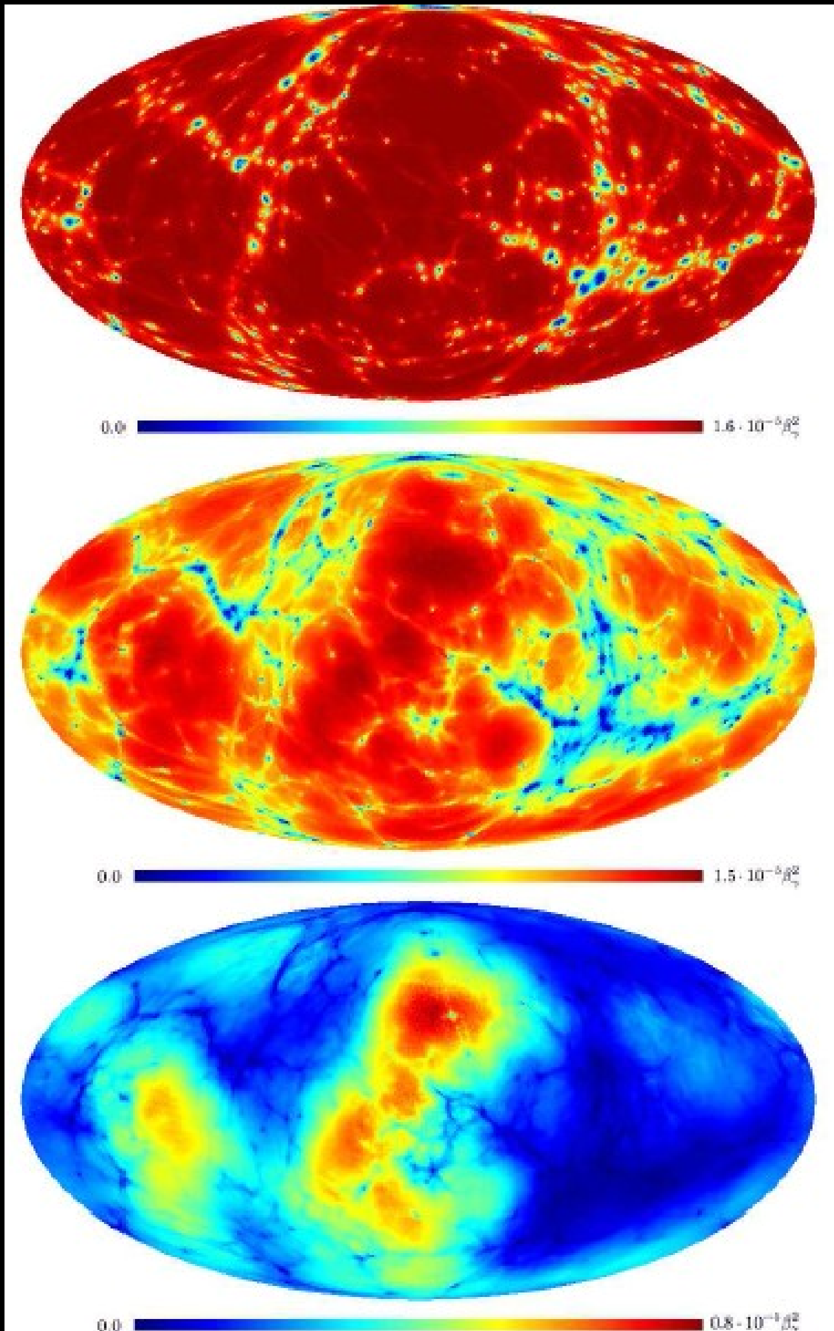
- The weak lensing shear power spectrum + Type Ia SNe can constrain Class I models
  - …with external datasets
- Example for a CPL fiducial
  - Euclid WL + DESIRE SN Ia data *[Astier et al. 2014]*
  - ELT spectroscopic data (+ atomic clock prior)
- For a full analysis see *[Calabrese et al. 2014]*
  - Synergies between Euclid and the various E-ELT instruments should be further quantified



Taxonomy: Class II

- Models where α field does not provide all dark energy can be identified via consistency tests *[Vielzeuf & Martins 2012, ...]*
  - Compare different reconstructions, or use redshift drift
  - Examples: BSBM models *[Sandvik et al. 2002, Leal et al. 2014]* and Runaway dilatons *[Damour et al. 2002, Martins et al. 2015]*
  - For both of these, the current WEP bound from α is $\eta < 5\times10^{-14}$
- Even if the field does not dominate at low z, photon number nonconservation will bias cosmological parameter estimation
  - Several effects already quantified, e.g. within Euclid Consortium *[Calabrese et al. 2014, Avgoustidis et al. 2014]*
  - T(z) data breaks degeneracies in these models *[Avgoustidis et al. 2012, de Martino et al. 2015, Luzzi et al. 2015]*
- ESPRESSO (and ALMA) measurements of α and T(z) will further constrain these models (and be useful for Euclid)

Spatial Variations?



[Silva et al., PRD89 (2014) 024025]

- A sub-type of Class II models has environmental dependencies stronger than time variations
  - Observed as spatial variations
- Models can be built consistent with Webb *et al.* dipole, but all require very considerable fine-tuning
  - Symmetrons, galileons, massive gravity, chameleons, ...
- ESPRESSO GTO will constrain the maximal amplitude of any such dipole, but can't really distinguish among these possible models
  - ...that would require several hundreds of telescope nights (for a few ppm amplitude)

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
  - Fundamental coupling stability is optimal probe of new physics
- The story so far: nothing is varying at ~ 10^{-5} level, already a very significant constraint (stronger than the Cassini bound)
  - Things less clear at 10^{-6} level, but improvements are coming...
  - ...and these already provide the world's best WEP constraints
- New dedicated instruments (ESPRESSO and ELT-HIRES) will lead to a new generation of precision consistency tests
  - Implications for dark energy and fundamental physics
  - Complementarity: Equivalence Principle, Redshift drift, T(z) ...
  - Synergies with other facilities, including ALMA, Euclid & SKA

IberiCos 2016

29-31 March 2016, Porto, Portugal

IberiCos 2016, the XI Iberian Cosmology Meeting, will take place near Porto around Easter 2016. Registration is expected to start on October 1st. Further information (including the venue) will appear here soon.

SOC

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Juan Garcia-Bellido (Madrid)
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