The UVES Large Program for Testing Fundamental Physics

(latest results, cosmological implications, and the road ahead)

Carlos Martins*

and the CAUP Dark Side Team

(with key contributions from Ana Catarina Leite, Ana Mafalda Monteiro, Luís Ventura, Mariana Julião, Marvin Silva, Miguel Ferreira, Pauline Vielzeuf, Pedro Leal and Pedro Pedrosa)

Centro de Astrofísica da Universidade do Porto

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***FCT Research Professor**

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

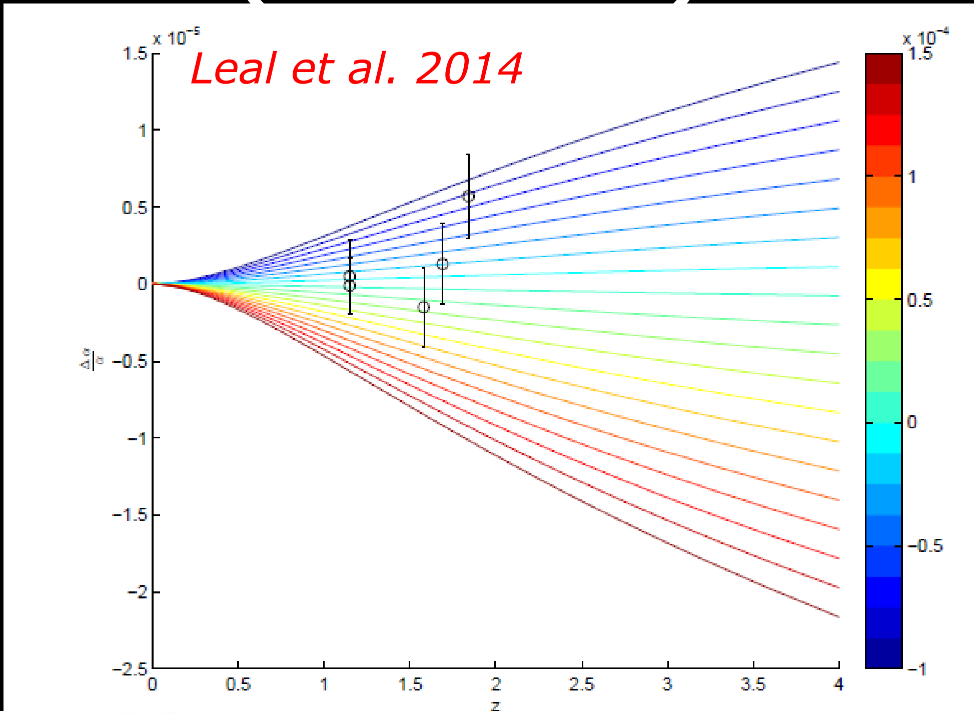
Scalar Fields, Since They're There

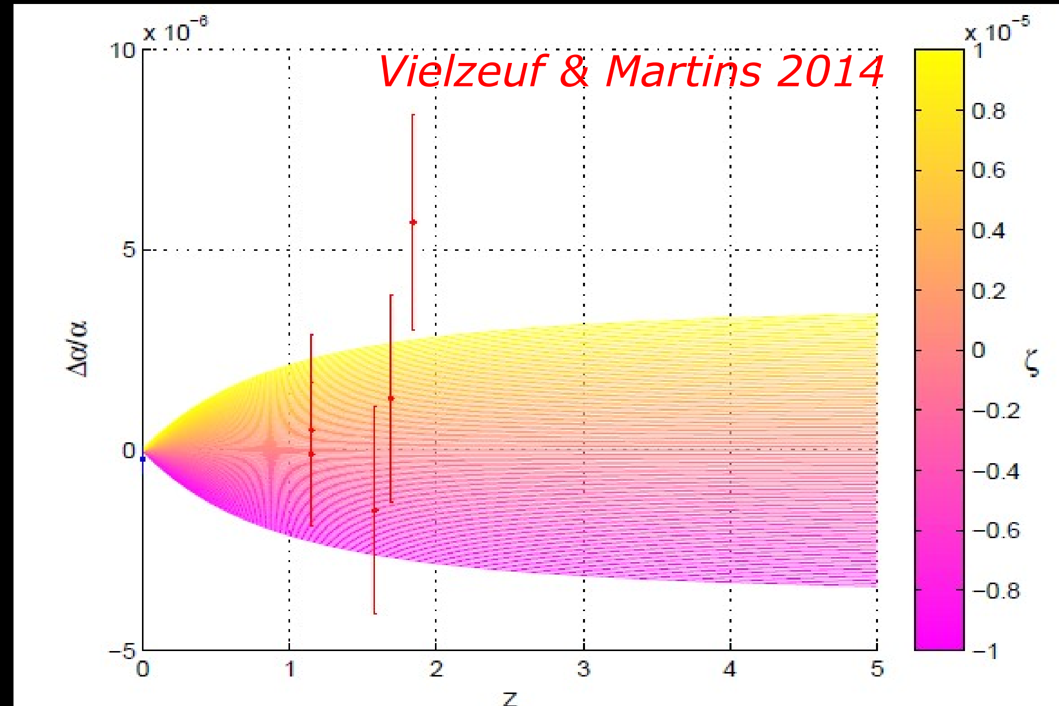
- We now know that fundamental scalar fields are part of Nature's building blocks
    - Does the Higgs have a cosmological counterpart?
- Scalar fields play a key role in most paradigms of modern cosmology, yielding *inter alia*
    - Exponential expansion of the early universe (inflation)
    - Cosmological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

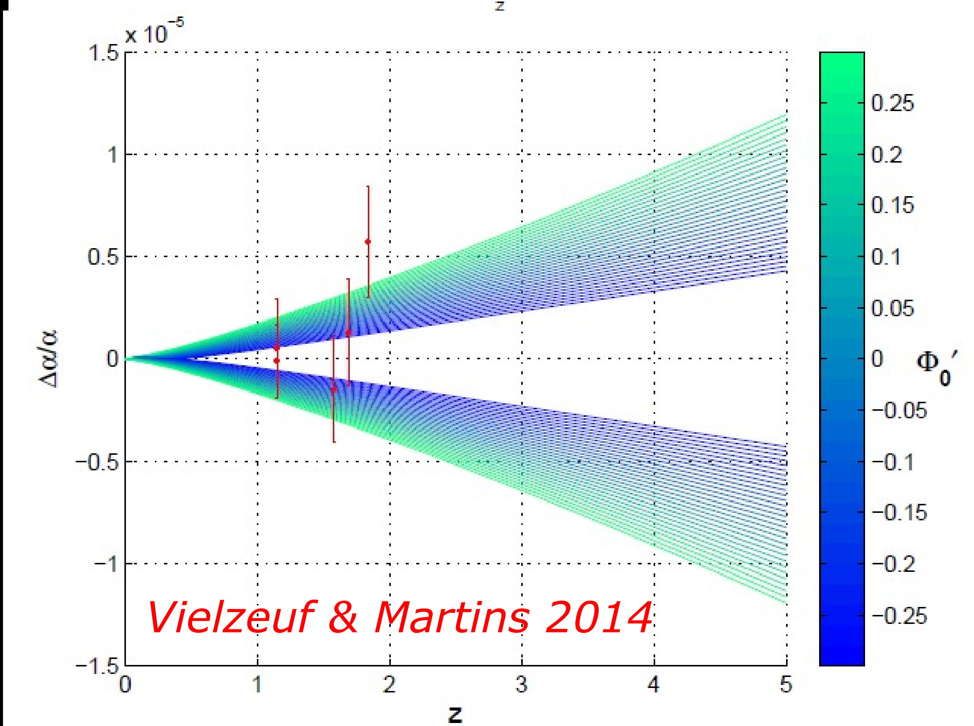
Fundamental Couplings?

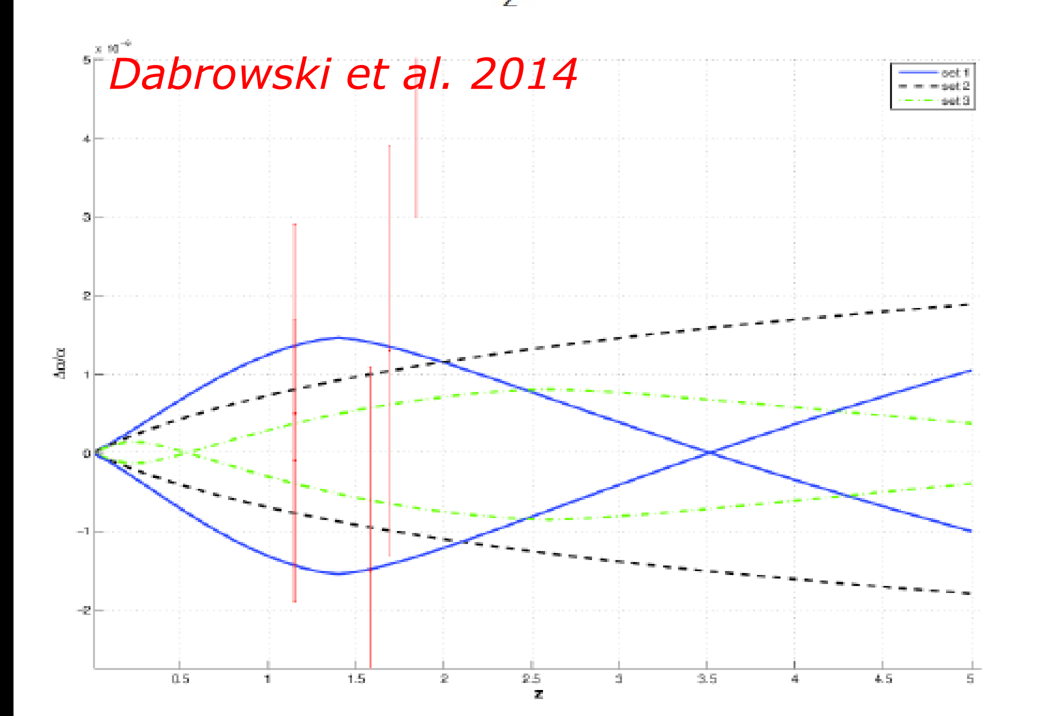
- Nature is characterized by a set of physical laws and fundamental dimensionless couplings, which historically we have assumed to be spacetime-invariant
  - For the former, this is a cornerstone of the scientific method
  - For latter, a simplifying assumption without further justification
- These couplings 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

(Part of) The Zoo of Models

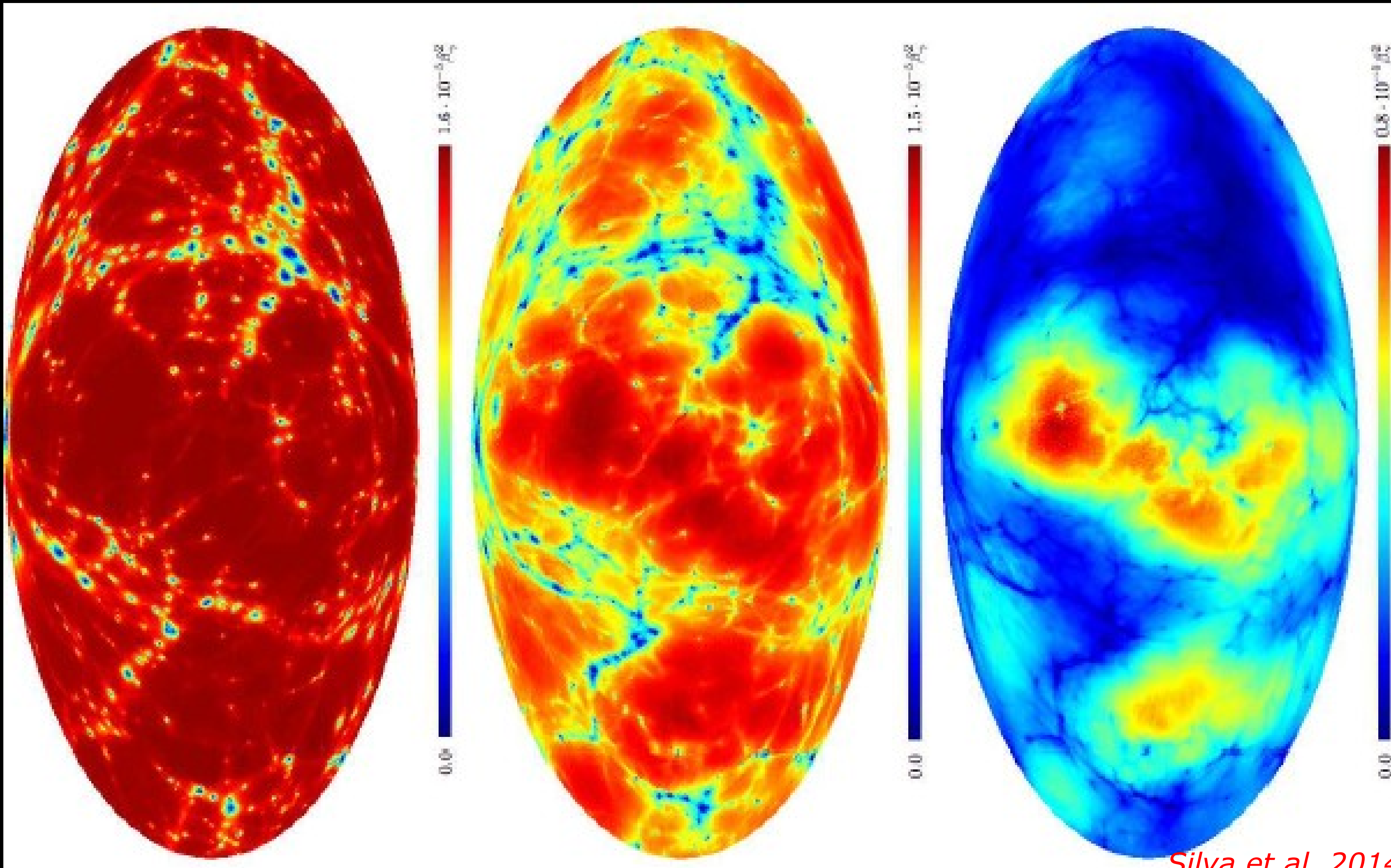








… and Spatial Variations Too



α, μ and Beyond

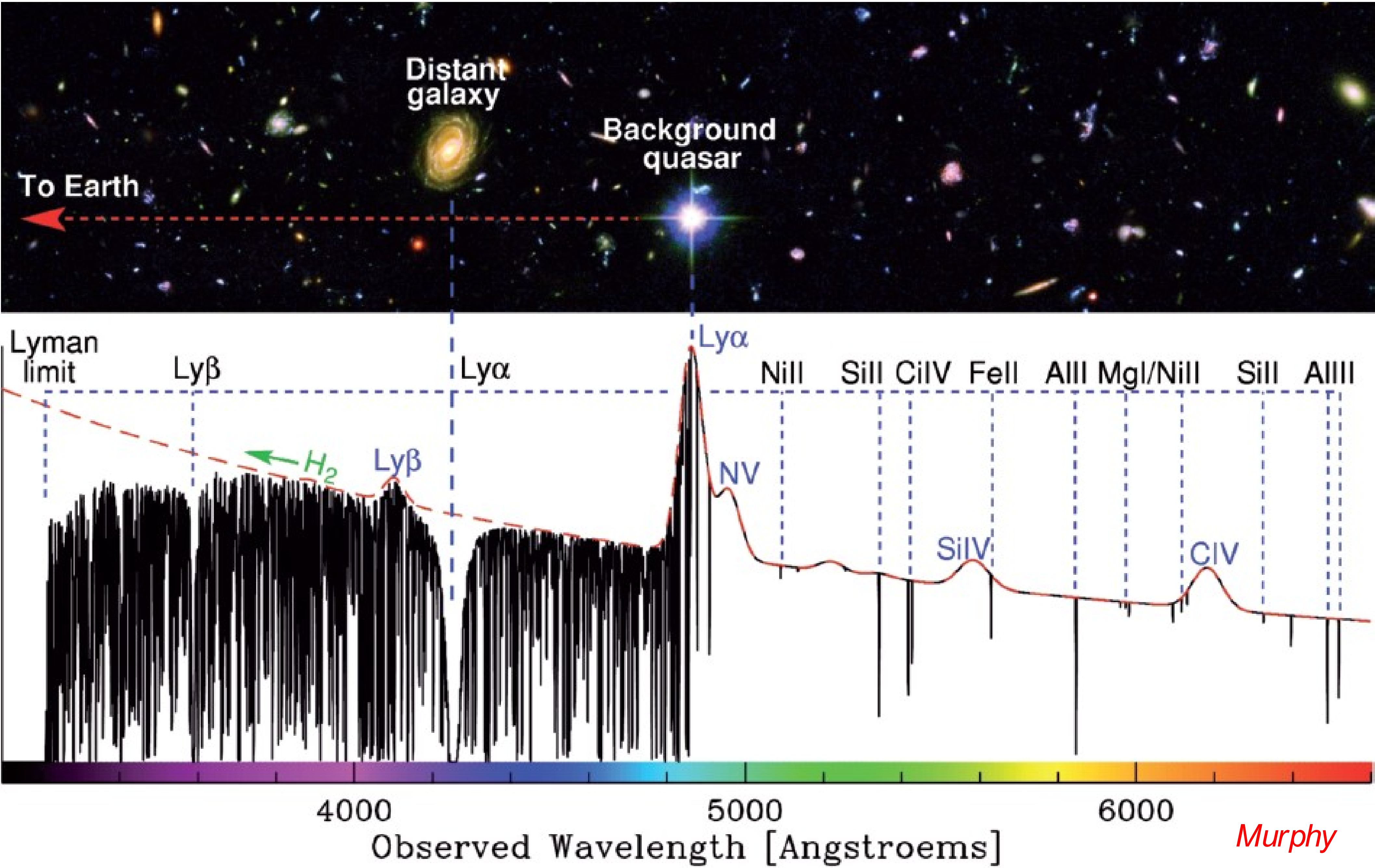
- In theories where a dynamical scalar field yields varying α, other gauge and Yukawa couplings are also expected to vary
  - In GUTs the variation of α is related to that of Λ_{QCD}, whence m_{nuc} varies when measured in energy scale independent of QCD
  - Expect a varying $\mu=m_p/m_e$, which can be probed with H_2 *[Thompson 1975]* and other molecules
- Wide range of possible α-μ relations makes this a unique discriminating tool between competing models
  - Find systems where various constants can be simultaneously measured, or where one can be measured in various ways
  - Sensitive probe of fundamental physics and unification scenarios *[Coc et al. 2007, Luo et al. 2011, Ferreira et al. 2012, Ferreira et al. 2013, ...]*

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

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

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

Precision Spectroscopy

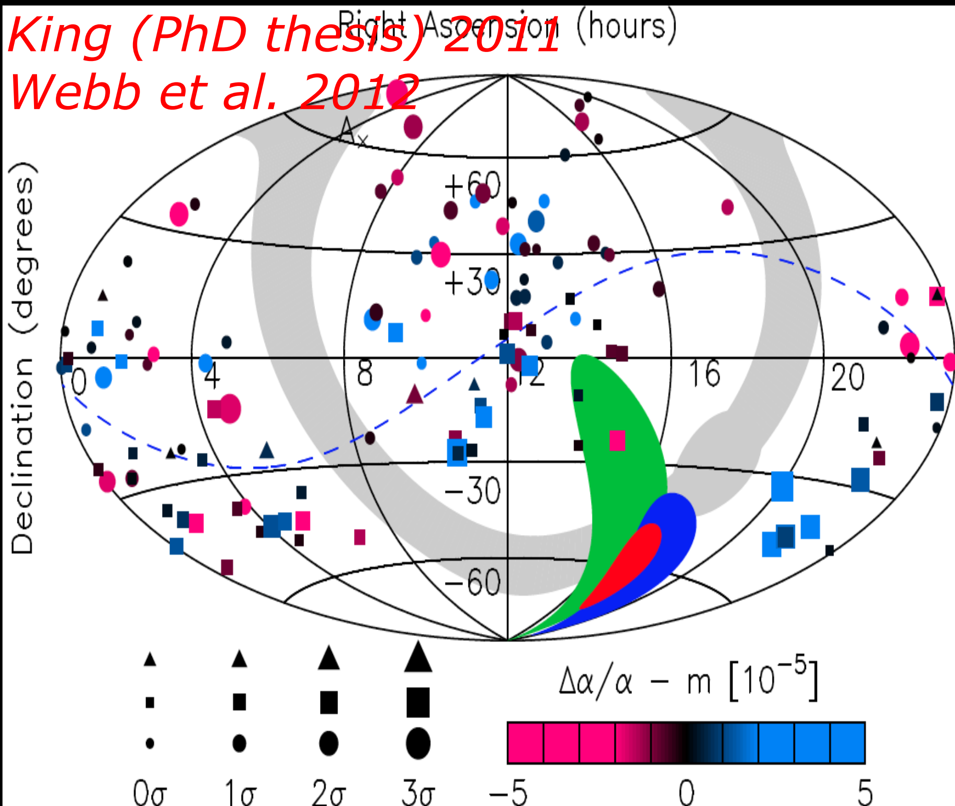


Murphy

Constraints from Absorption Lines

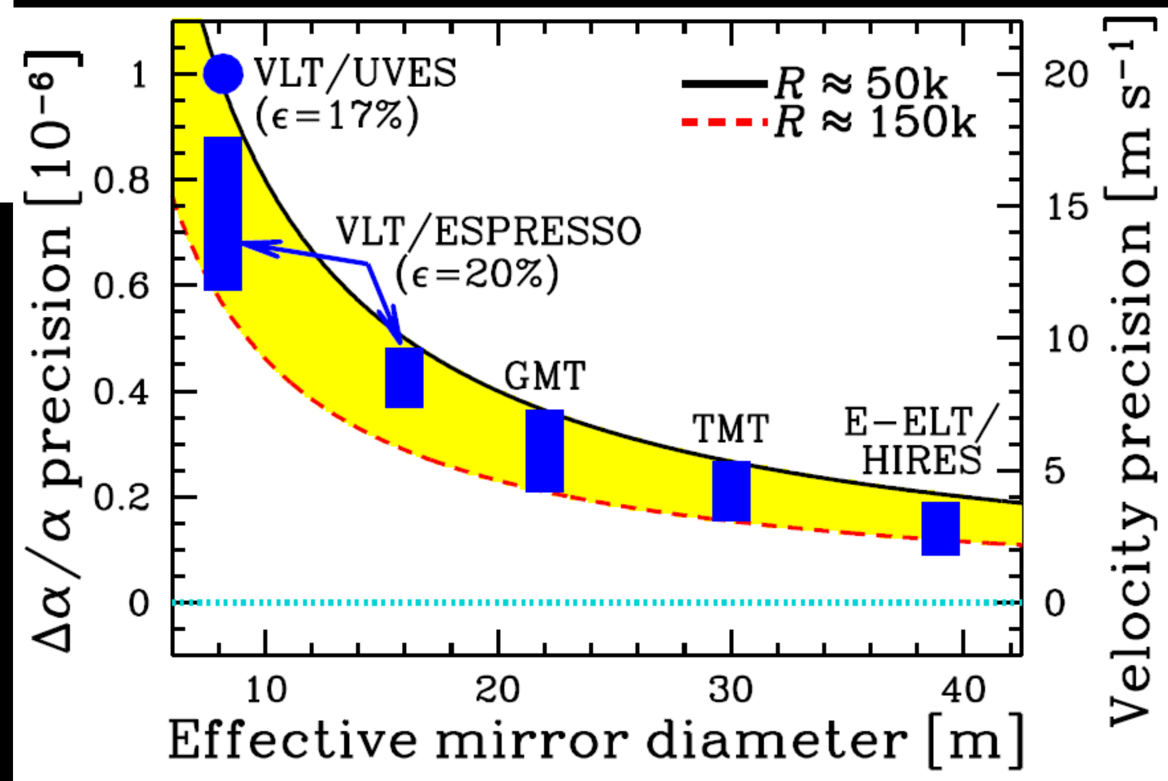
- α_{em}: Fine-structure doublet
- $\mu = m_p/m_e$: Molecular Rotational *vs.* Vibrational modes
- $\alpha_{em}^2 g_p$: Rotational modes *vs.* Hyperfine H
- $\alpha_{em} g_p \mu$: Hyperfine H *vs.* Fine-structure
- $\alpha_{em}^2 g_p \mu$: Hyperfine H *vs.* Optical
- ...

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 (VLT) and the ELT-HIRES
  - Better precision, and much better control of systematics



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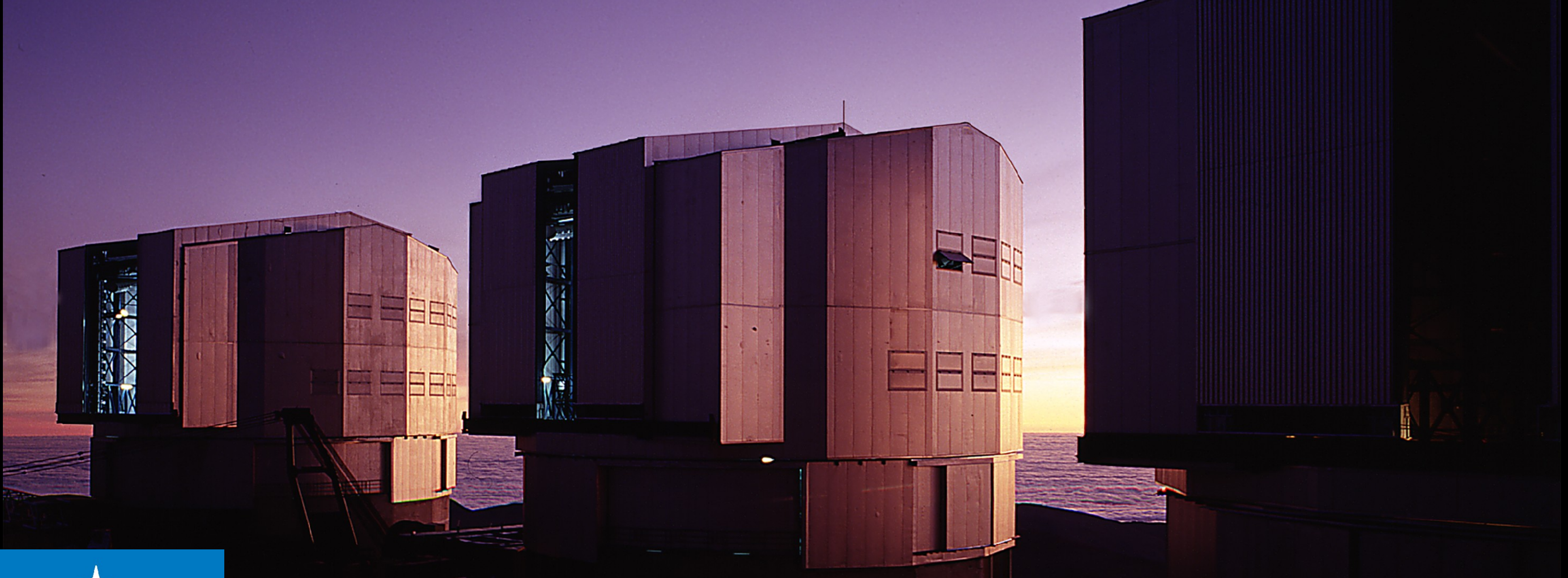
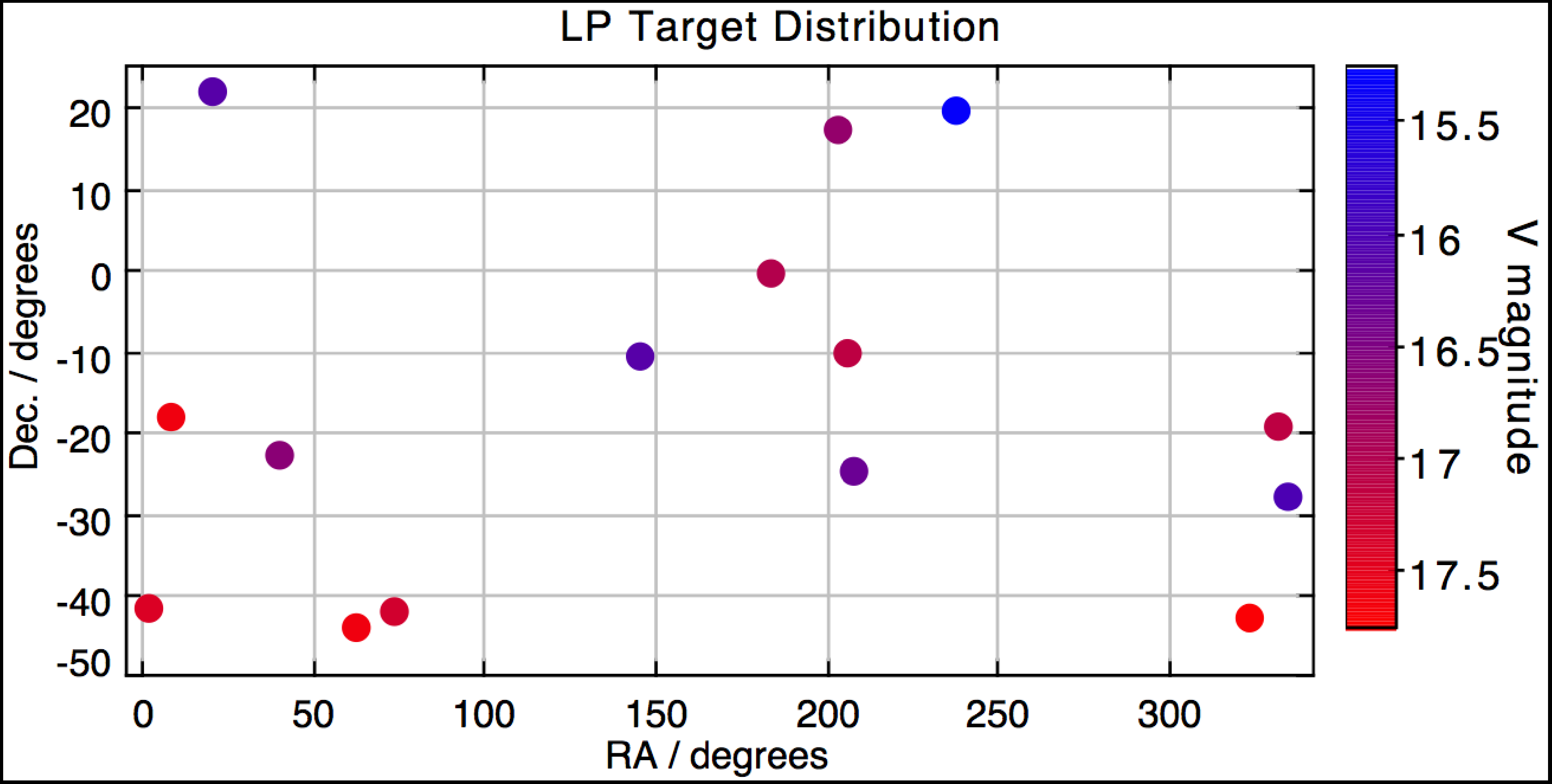


P. Molaro (PI), P. Bonifacio, M. Centurión, S. D'Odorico, T.M. Evans, S.A. Levshakov, S. Lopez, C.J.A.P. Martins, M.T. Murphy, P. Petitjean, H. Rahmani, D. Reimers, R. Srianand, G. Vladilo, M. Wendt, J.B. Whitmore, I.I. Agafonova, H. Fathivavsari, T. Misawa, P. Noterdaeme

LP Plan & Goals

- Only large program dedicated to varying constants, optimized sample & methodology, ca. 40 nights in 2010-13
  - Calibration lamps attached to science exposures (in same OB): don't reset x-disperser encoding position for each exposure
  - Observe bright (mag 9-11) asteroids at twilight, to monitor radial velocity accuracy of UVES and the optical alignments
  - Sample: Multiple absorption systems, brightness (S/N), high redshift (FeII 1608), simplicity, narrow components at sensitive wavelengths, no line broadening/saturation
- 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
  - Also compare/check/optimize different analysis pipelines
  - Introduce blind analysis techniques

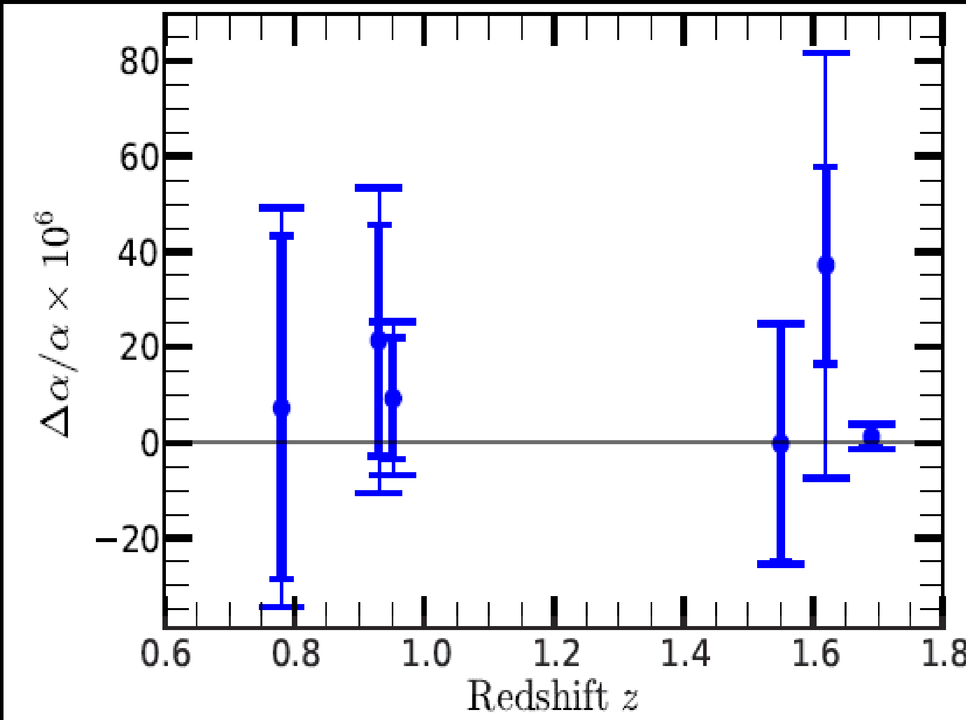
Target Selection & Status



- Selected before alpha dipole was known *[Bonifacio et al. 2014]*
  - 13 targets for α, 2 targets for μ=mp/me (QSO 0405-443, HE 0027-1836)
  - Already out: results on HE2217-2818 HE0027-1836, HS1519+1919
  - Raw data already in the ESO public archive, and the reduced data products will also be made public in due course – 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

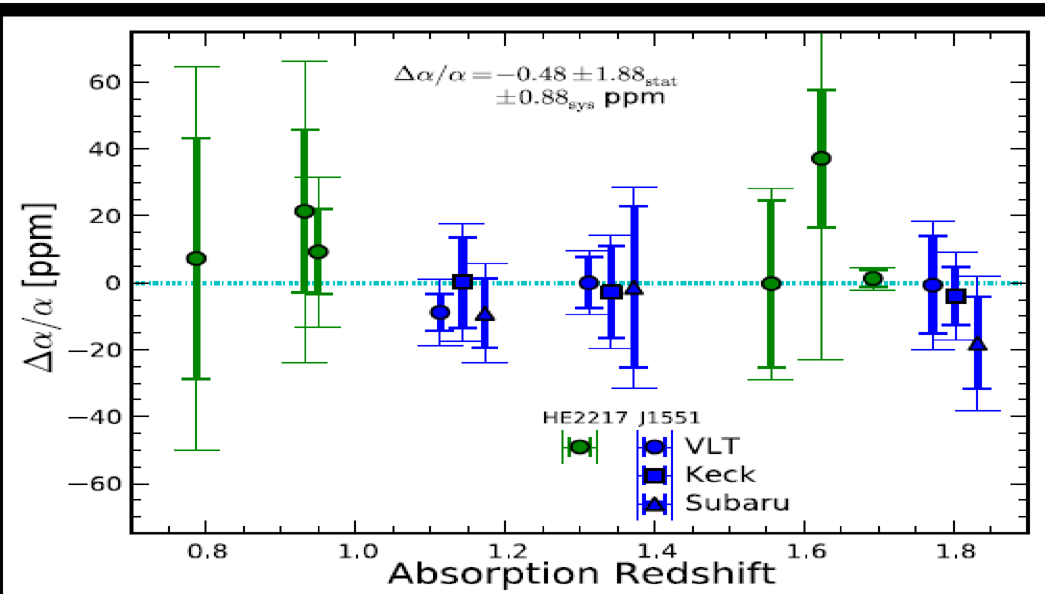


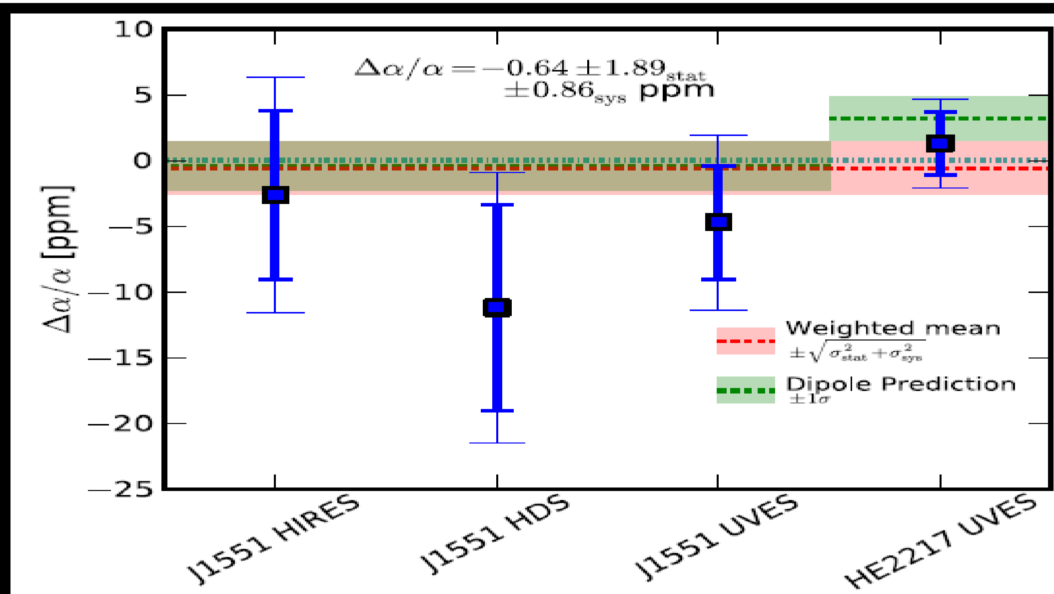
- HE0027-1836, z_{abs}~2.40: $\Delta\mu/\mu$ = -7.6 $\pm$ 8.1$_{sta}$ $\pm$ 6.3$_{sys}$ ppm
  - Paper II: H. Rahmani et al., MNRAS 435 (2013) 861
  - Identified wavelength-dependent velocity drift (corrected with bright asteroid data)
- Bottleneck: UVES intra-order (~200m/s) & long-range distortions,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

A Triple Check of Distortions

- HS1519+1919: 3 absorbers at z_{abs}~1.1, 1.3 & 1.8, observed with 3 top optical telescopes: $\Delta\alpha/\alpha = -5.4 \pm 3.3_{sta} \pm 1.5_{sys}$ 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

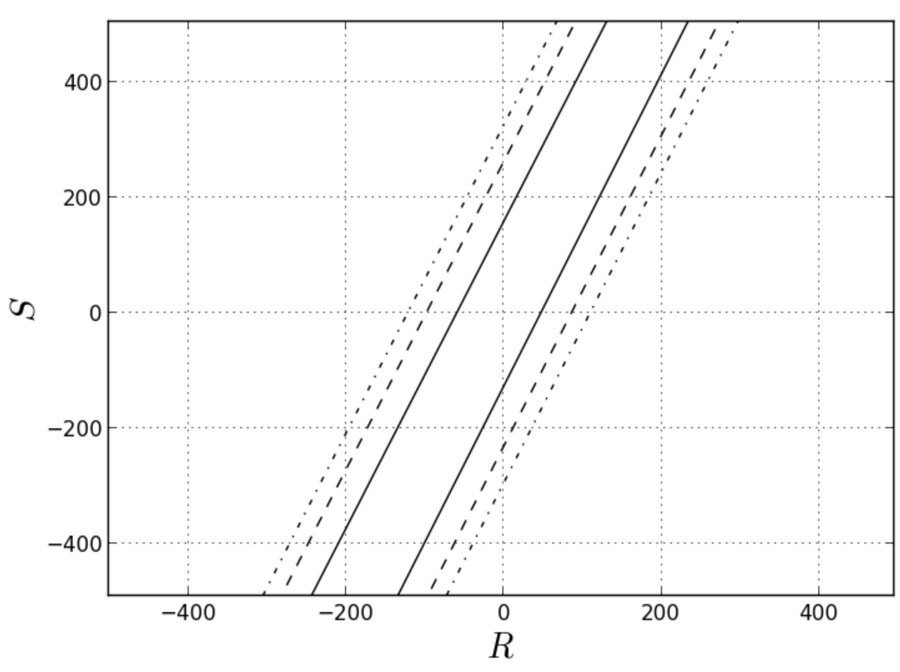
	$\Delta\alpha/\alpha \pm \sigma_{\rm stat} \pm \sigma_{\rm sys}$ [ppm]														
Absorption Redshift	Keck/HIRES			χ^2_ν	VLT/UVES			χ^2_ν	Subaru/HDS			χ^2_ν	Absorber Average		
$z_{\rm abs} = 1.143$	+0.20	13.63	3.97	1.18	−8.80	5.60	4.36	1.45	−9.04	10.41	4.34	1.59	−7.49	4.63	3.02
$z_{\rm abs} = 1.342$	−2.77	13.71	3.16	1.20	+0.02	7.64	1.85	1.53	−1.29	24.04	6.04	1.23	−0.70	6.43	1.55
$z_{\rm abs} = 1.802$	−3.92	8.61	4.69	0.75	−0.66	14.65	4.54	0.98	−17.98	13.67	6.45	0.76	−6.42	6.52	3.16
Weighted mean	−2.64	6.43	2.54	–	−4.71	4.31	2.36	–	−11.20	7.83	2.44	–	−5.40	3.25	1.53



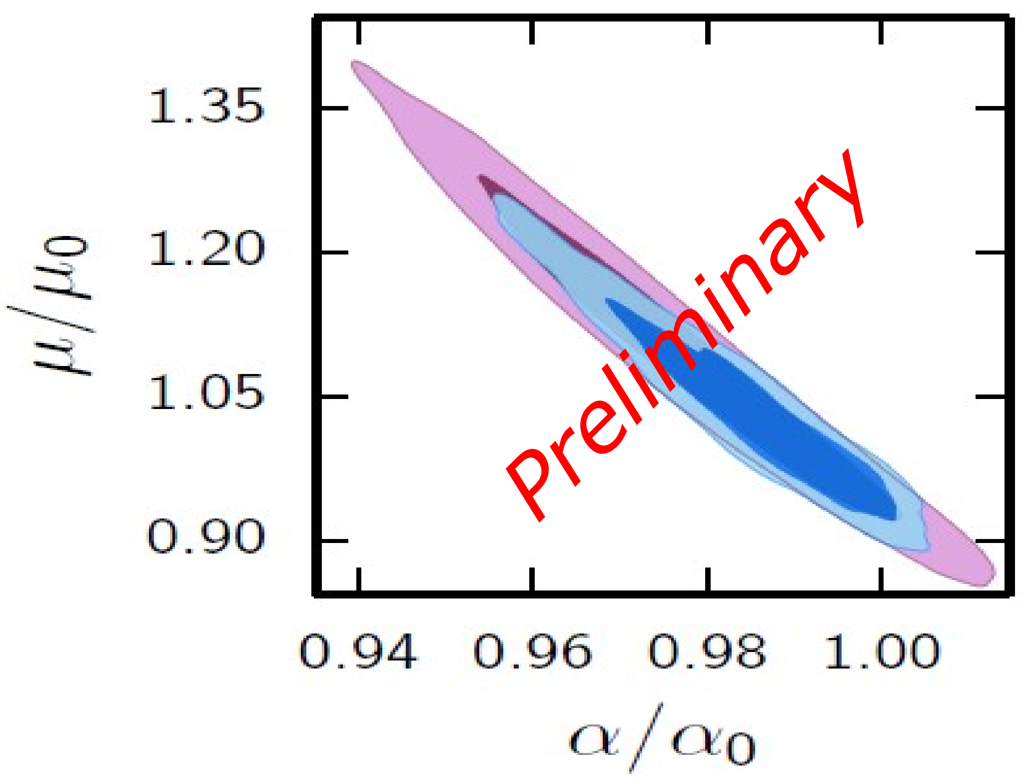


Aside: Other Measurements

- Atomic clocks: α drift sensitivity $\sim 10^{-17}$/yr *[Rosenband et al. 2008]*
- Radio μ sensitivity in Galaxy ~0.02 ppm *[Levshakov et al. 2013]*
- Compact objects: ~50 ppm sensitivity *[Ekstrom et al. 2010, Vieira et al. 2012, Berengut et al. 2013, Bagdonaite et al. 2014, ...]*
- CMB is a clean probe, but 2000 ppm sensitivity only competitive for a few selected models *[Planck 2014, Galli & Martins 2014]*

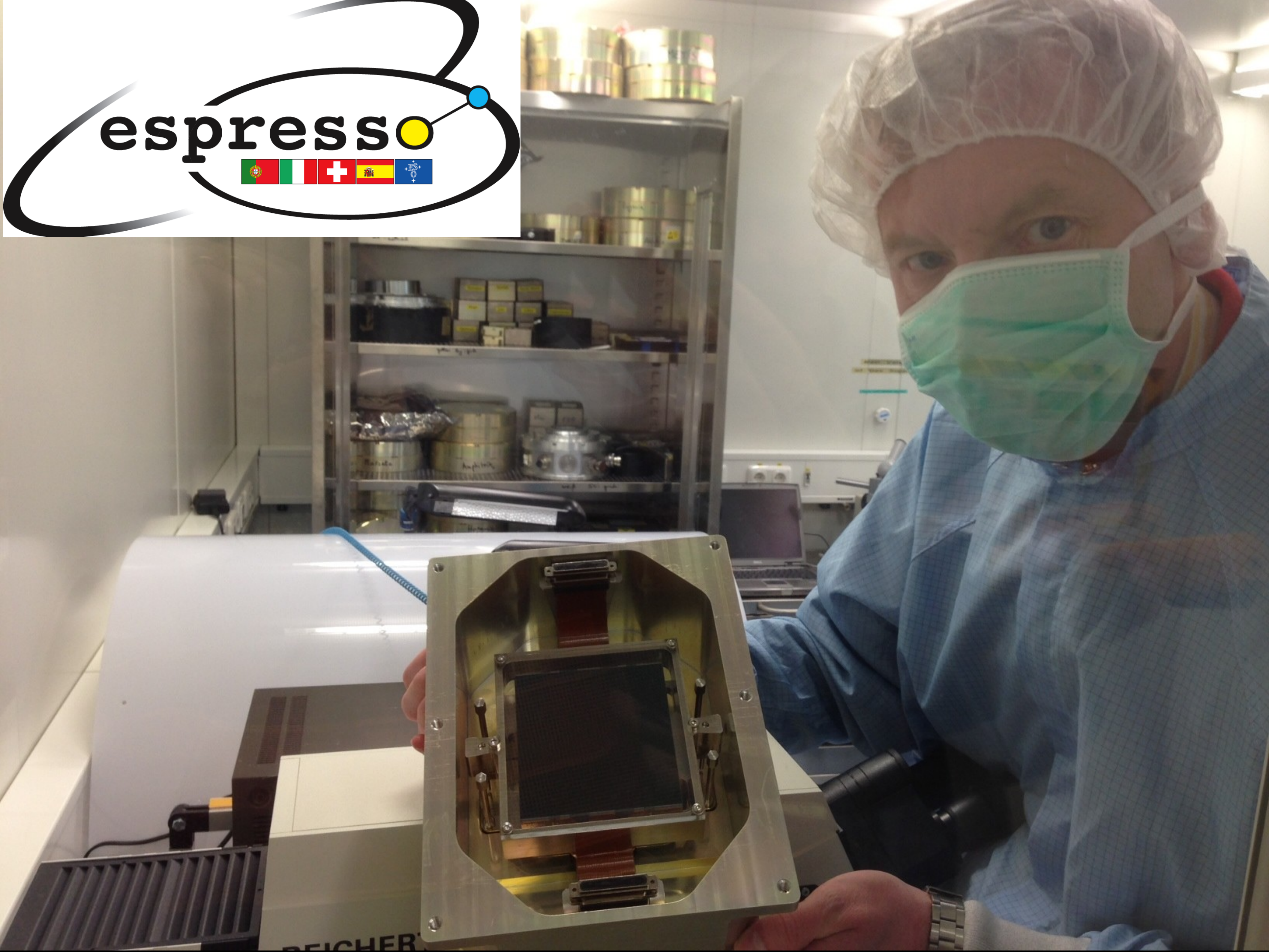


Ferreira et al. 2012

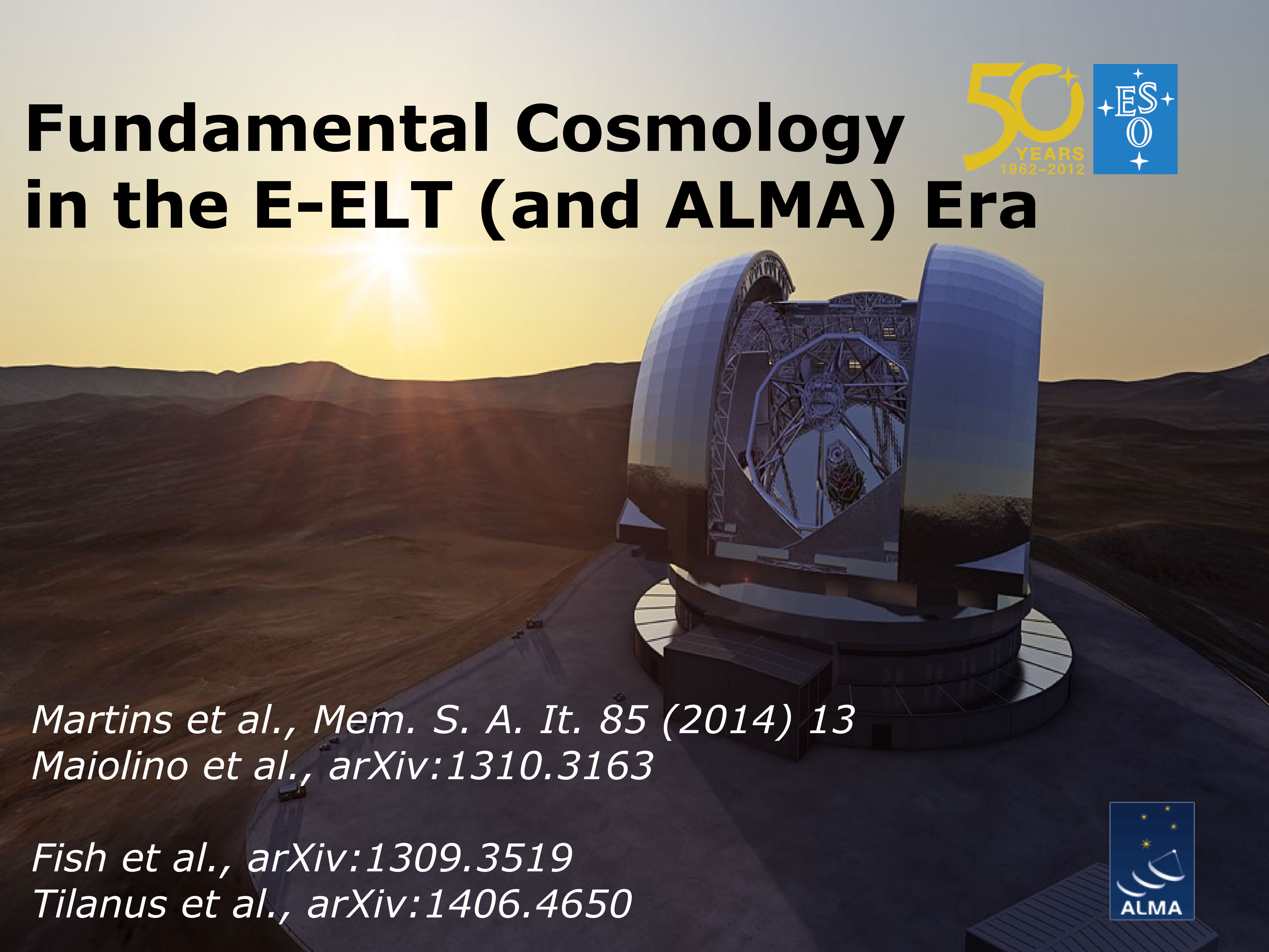


Why is it so hard?

- Akin to finding exoplanets, except much harder!
  - Much fainter sources, only a few lines clean
- Measurements of fundamental constants 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, ...]*
- A new generation of high-resolution, ultra-stable spectrographs will have these measurements as key driver
  - Shortly: PEPSI at LBT, 2016: ESPRESSO at VLT, Later: ELT-HIRES


espresso

Fundamental Cosmology in the E-ELT (and ALMA) Era



Martins et al., Mem. S. A. It. 85 (2014) 13
Maiolino et al., arXiv:1310.3163

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

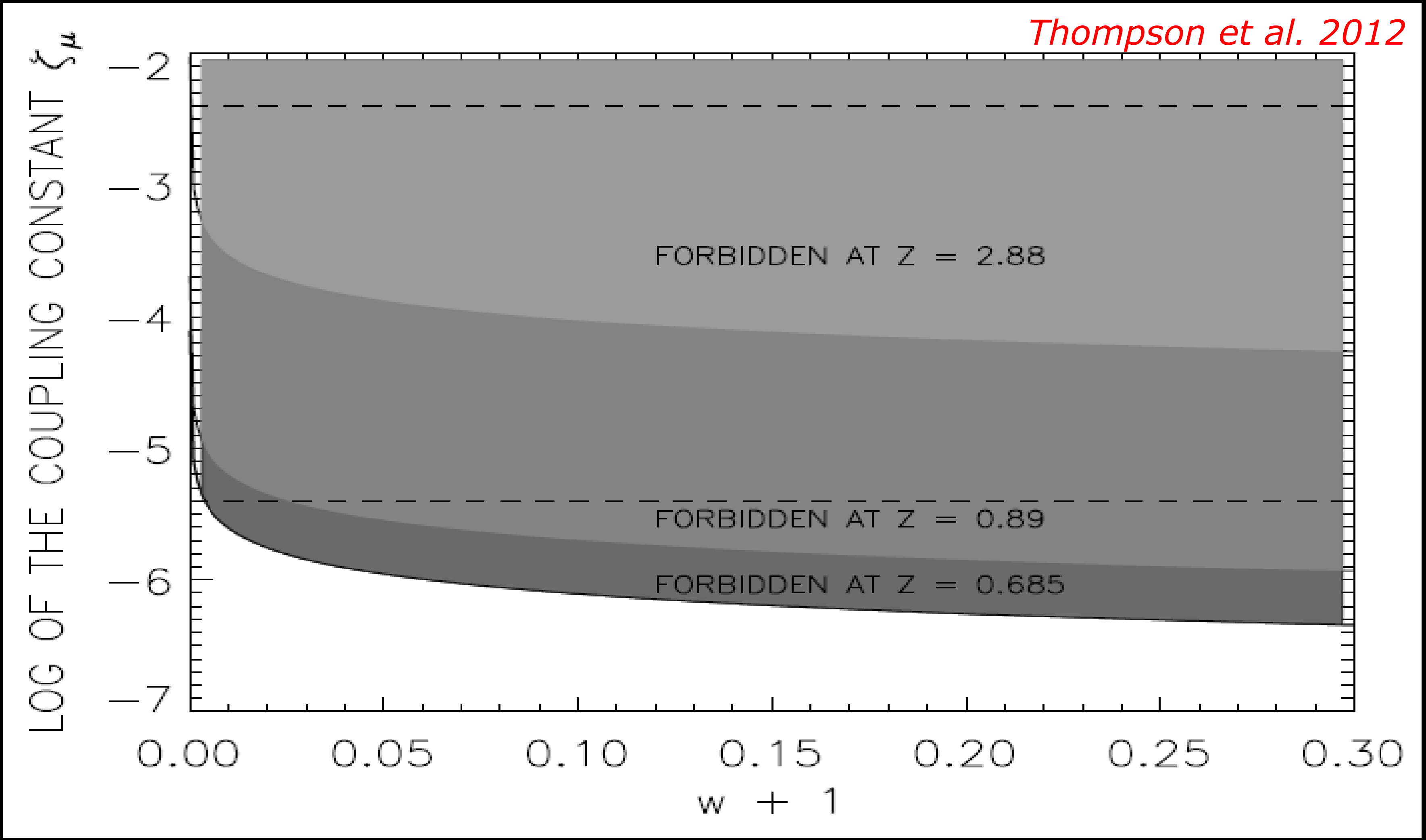
Dark Energy & Varying Couplings

- 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 varying couplings *[Carroll 1998, Wetterich 1998, ...]*
  - These measurements (whether they are detections of null results) will constrain fundamental physics and cosmology
  - This ensures a 'minimum guaranteed science'

Taxonomy: Class I

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

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



Aiming Higher (i.e., Deeper)

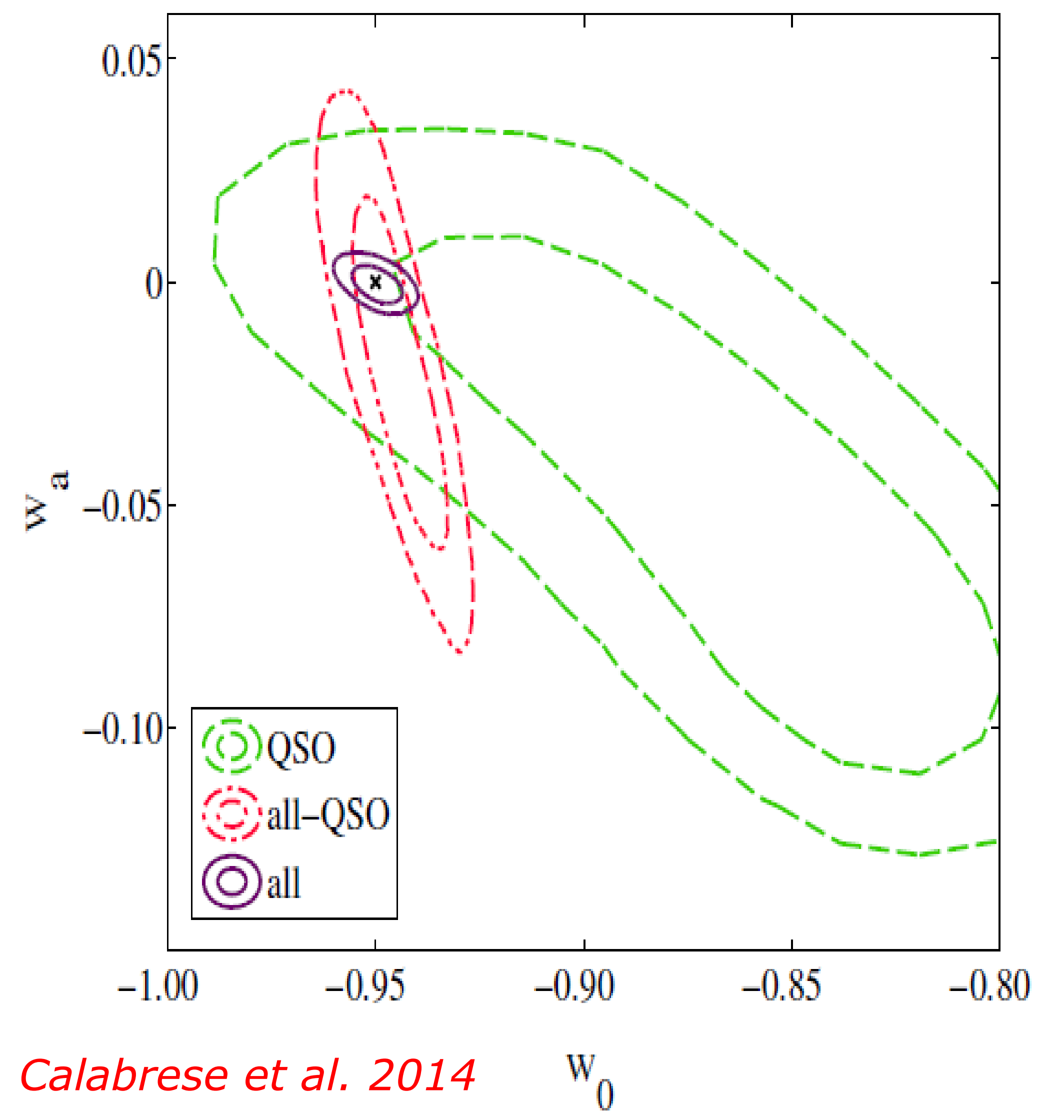
- Standard methods (SNe, etc) are of limited use as dark energy probes *[Maor et al. 2001, Upadhye et al. 2005, ...]*
  - Since the field is slow-rolling when dynamically important, a convincing detection of w(z) will be tough at low z
- We must probe the deep matter era regime, where the dynamics of the hypothetical scalar field is fastest
  - Fundamental couplings ideally probe scalar field dynamics beyond the domination regime *[Nunes & Lidsey 2004]*
- ALMA, ESPRESSO and ELT-HIRES will map the dark side out to z~4 *[Amendola et al. 2012, Leite et al. 2014]*
  - Key synergies with redshift drift and with other E-ELT instruments (e.g., high-z supernovas from ELT-IFU)

Leite et al. 2014

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

Euclid & Varying α

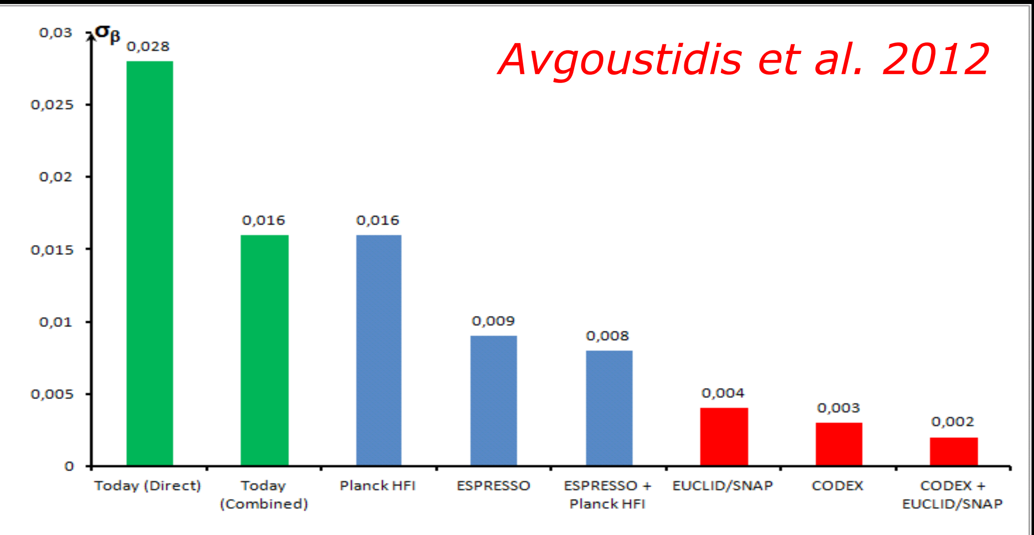
- The weak lensing shear power spectrum + Type Ia SNe can constrain Class I models
  - …with external datasets
- Example for a CPL fiducial
  - Euclid WL
  - Euclid SN Ia *[Astier et al.]*
  - ELT Redshift drift & α data
  - + atomic clock bound
- Key synergy between Euclid and the E-ELT
  - Redshift drift & QSO data are crucial for breaking degeneracies *[Vielzeuf & Martins 2012]*

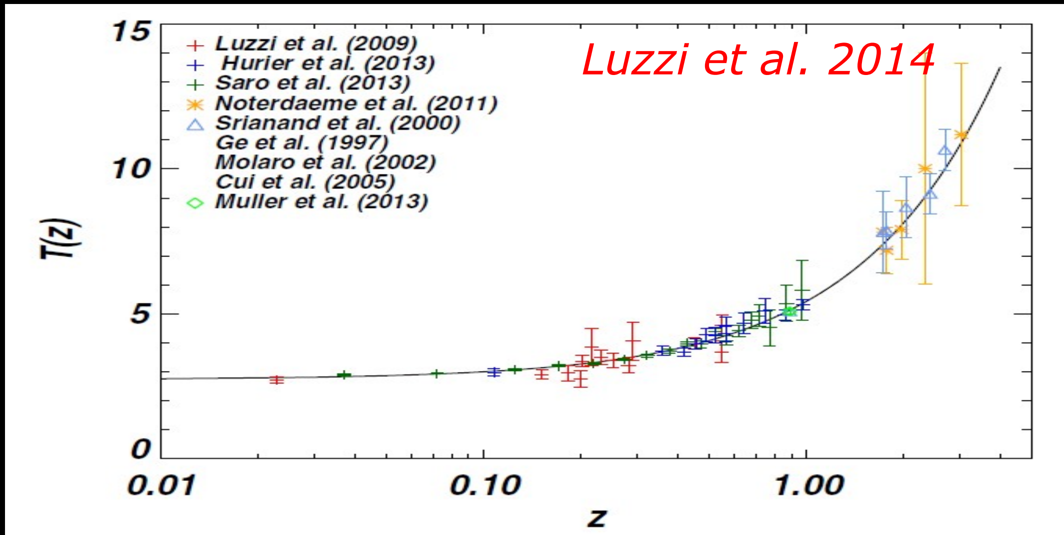


Calabrese et al. 2014

Taxonomy: Class II

- Models where α field does not provide all dark energy can be identified via w(z) consistency tests *[Vielzeuf & Martins 2012]*
  - E.g., runaway dilatons *[Damour et al. 2002, Vielzeuf & Martins 2014]* and BSBM models *[Sandvik et al. 2002, Leal et al. 2014]*
- Further test: subclass-dependent consistency relations for $\alpha(z)$, $T_{CMB}(z)$ and $d_L/d_A(z)$ *[Avgoustidis et al. 2012, 2013, ...]*
  - ...which may be relevant for Planck data analysis
- Even if this degree of freedom does not dominate at low z, it can bias cosmological parameter estimations (cf. Euclid)





Euclid & Scalar-Photon Couplings

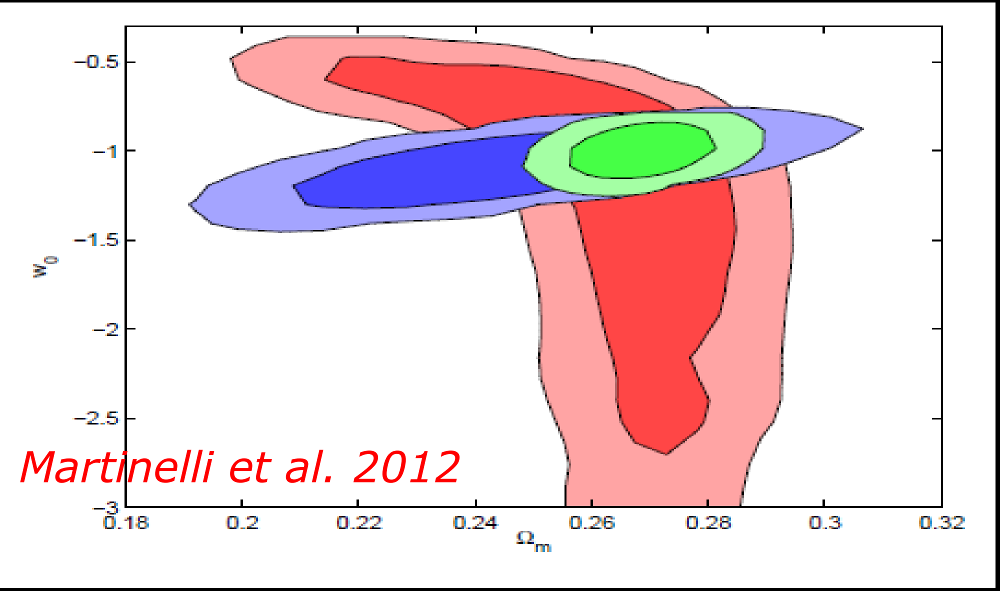
- Photon non-conservation changes T(z), the distance duality relation, etc. How do these weaken cosmological constraints?
- Euclid can (even on its own, with a SN survey) constrain dark energy in these scenarios *[Avgoustidis et al. 2014]*
    - Stronger constraints in combination with other probes
- T(z) measurements are crucial for breaking degeneracies: they can be obtained with ALMA, ESPRESSO & ELT-HIRES
    - Also Planck clusters now, and hopefully COrE+ later

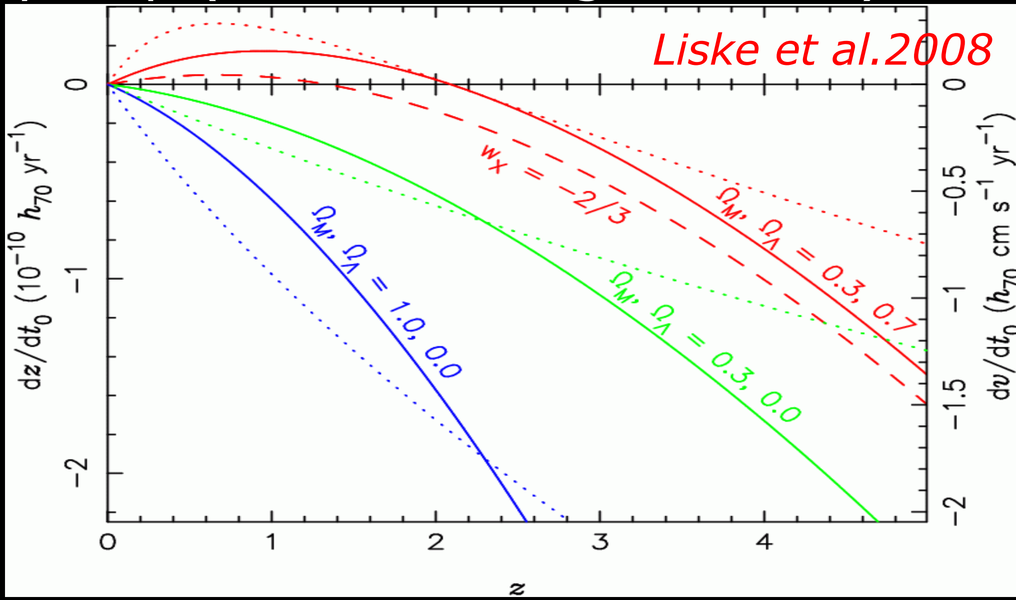
Avgoustidis et al. 2014

Dataset	δw_0	δw_a	$\delta\Omega_m$	δk (2-σ)
Current (weak)	0.25	1.3	0.06	10^{-5}
Current (strong)	0.22	0.65	0.06	10^{-5}
Euclid(BAO)+SNAP	0.15(0.35)	0.4(1.6)	0.03	1.1×10^{-5}
Euclid only (BAO+SN)	0.15(0.35)	0.6(1.6)	0.03	–
Euclid(BAO+SN)+SNAP	0.14(0.35)	0.4(1.5)	0.025	9×10^{-6}
Euclid(BAO)+SNAP+E-ELT	0.13(0.3)	0.4(1.45)	0.023	8×10^{-6}
Euclid(BAO)+SNAP+TMT	0.13(0.25)	0.4(1.3)	0.024	8×10^{-6}

The Redshift Drift

- Direct probe of dynamics of the universe *[Sandage 1962]*
  - No assumptions on gravity, geometry, or clustering
  - Crucial to close the consistency loop (and break degeneracies)





- Key ELT-HIRES driver (probing $2<z<5$) *[Liske et al. 2008]*
  - Uses Ly-α forest, plus various metal absorption lines
- SKA-2 may do it with HI ($z<1$ in emission, $z>8$ in absorption)
  - Several recent claims *[Darling 2012, Kloeckner et al. 2013, Yu et al. 2014, ...]*, more detailed studies ongoing

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)
  - At 10^{-6} level, things not yet clear: exponential growth in activity
  - 2-3 orders of magnitude improvement in sensitivity is coming...
  - ...but doing things properly is tough (so be patient)
- Dedicated instruments are coming, leading to a new generation of precision consistency tests
  - Redshift drift, T(z), Distance Duality, Equivalence Principle, ...
  - Synergies with other facilities, including ALMA, Euclid & SKA