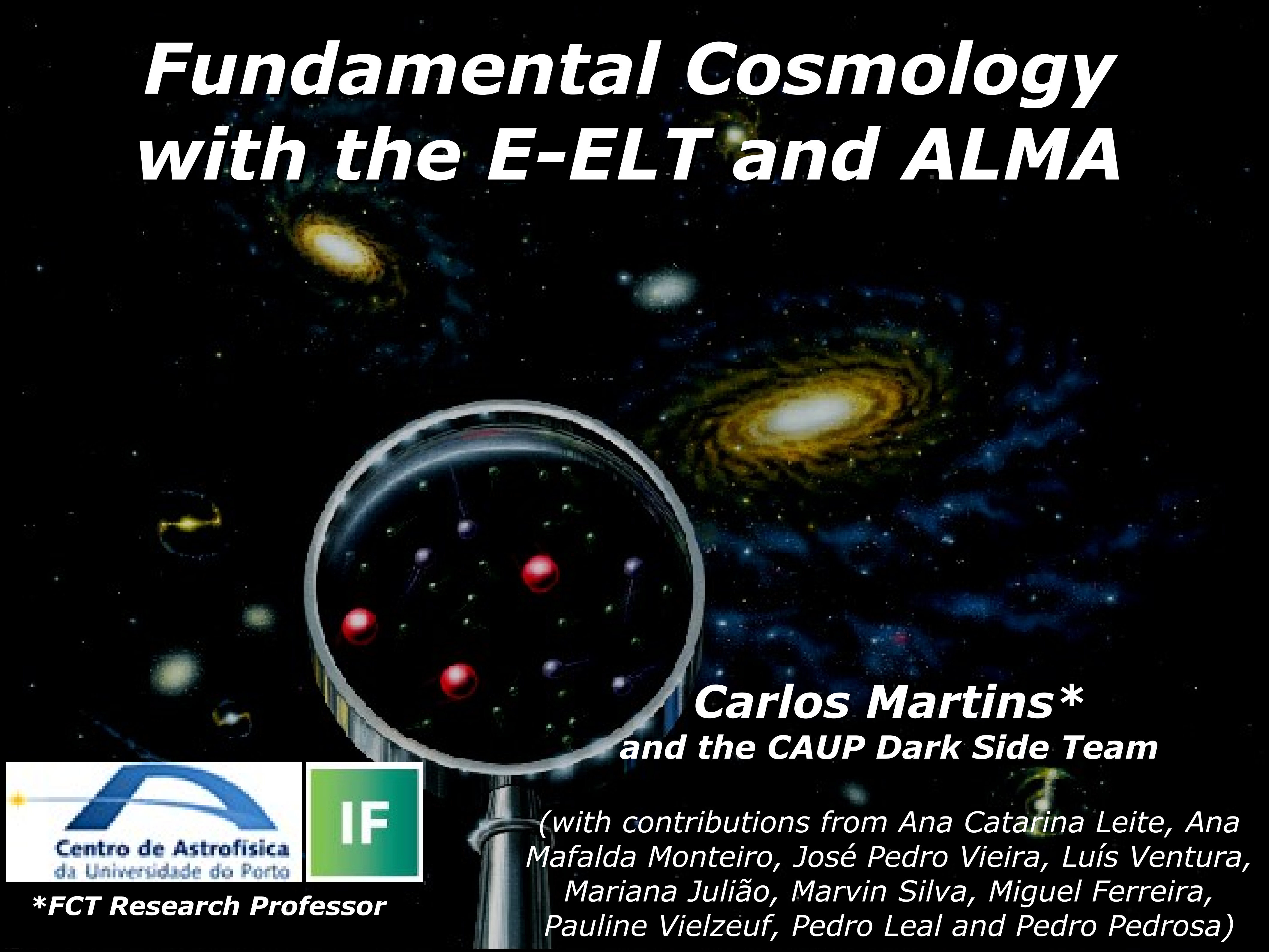
Fundamental Cosmology with the E-ELT and ALMA



Carlos Martins*

and the CAUP Dark Side Team

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

Centro de Astrofísica da Universidade do Porto

IF

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.

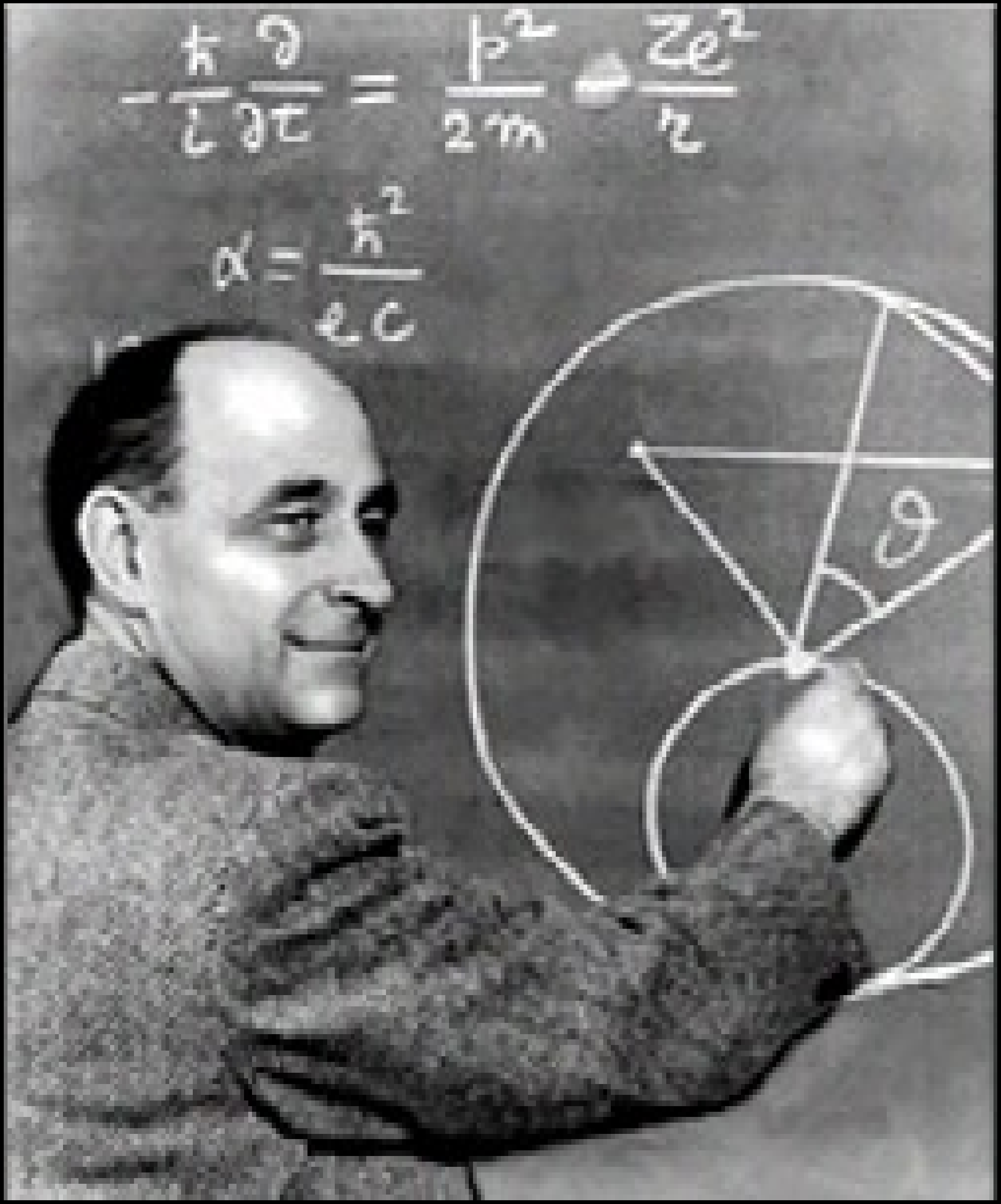
Fundamental Scalar Fields

- 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
- More important than each of these is the fact that they don't occur alone: this allows key consistency tests

So What's Your Point?

- We all know that fundamental couplings run with energy
- Moreover, in many (or arguably most?) models they will equally naturally roll in time and ramble in space
- Therefore astrophysical (and local) tests of their stability provide us with optimal probes of fundamental cosmology

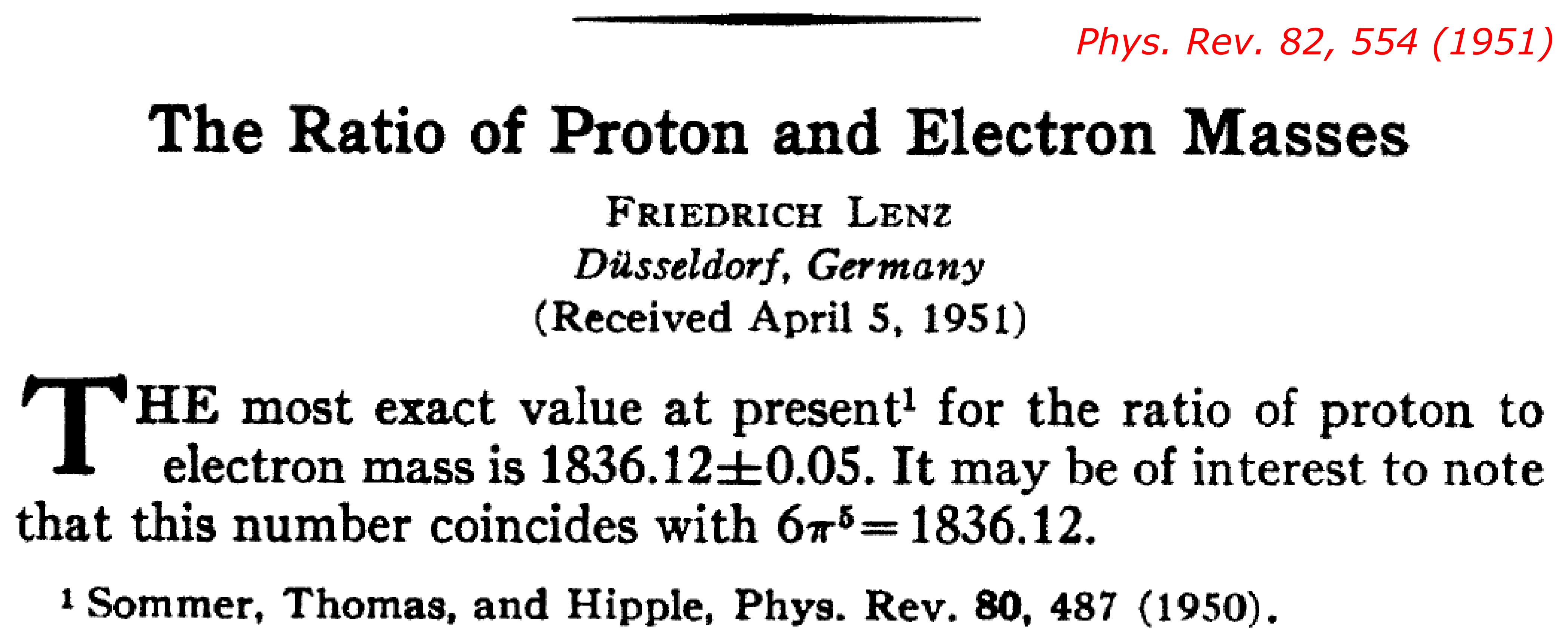
Varying Fundamental Couplings



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, yet we have no theory for them
- 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

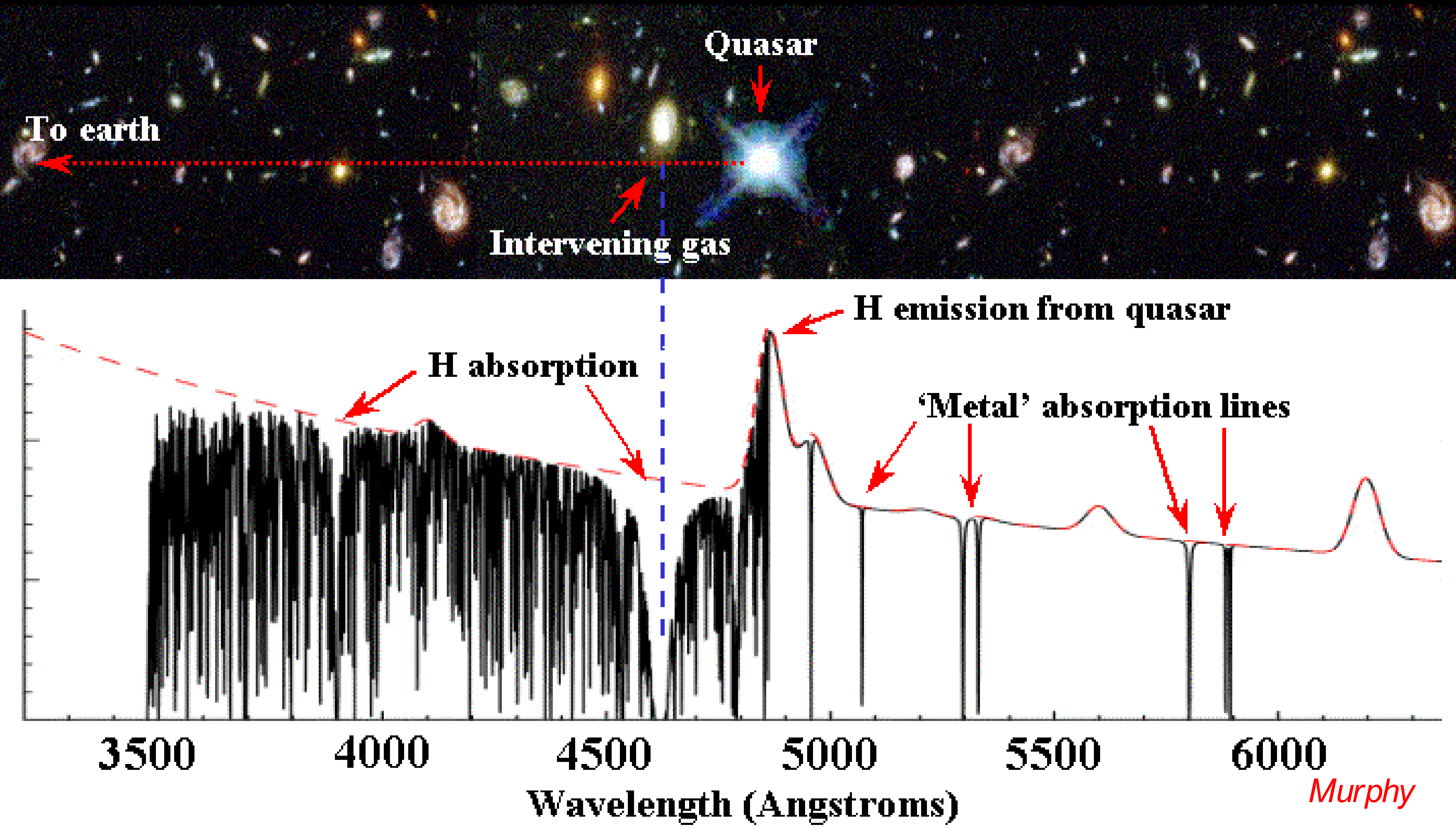
FRIEDRICH LENZ
Düsseldorf, Germany

(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).

Measuring α from Quasars



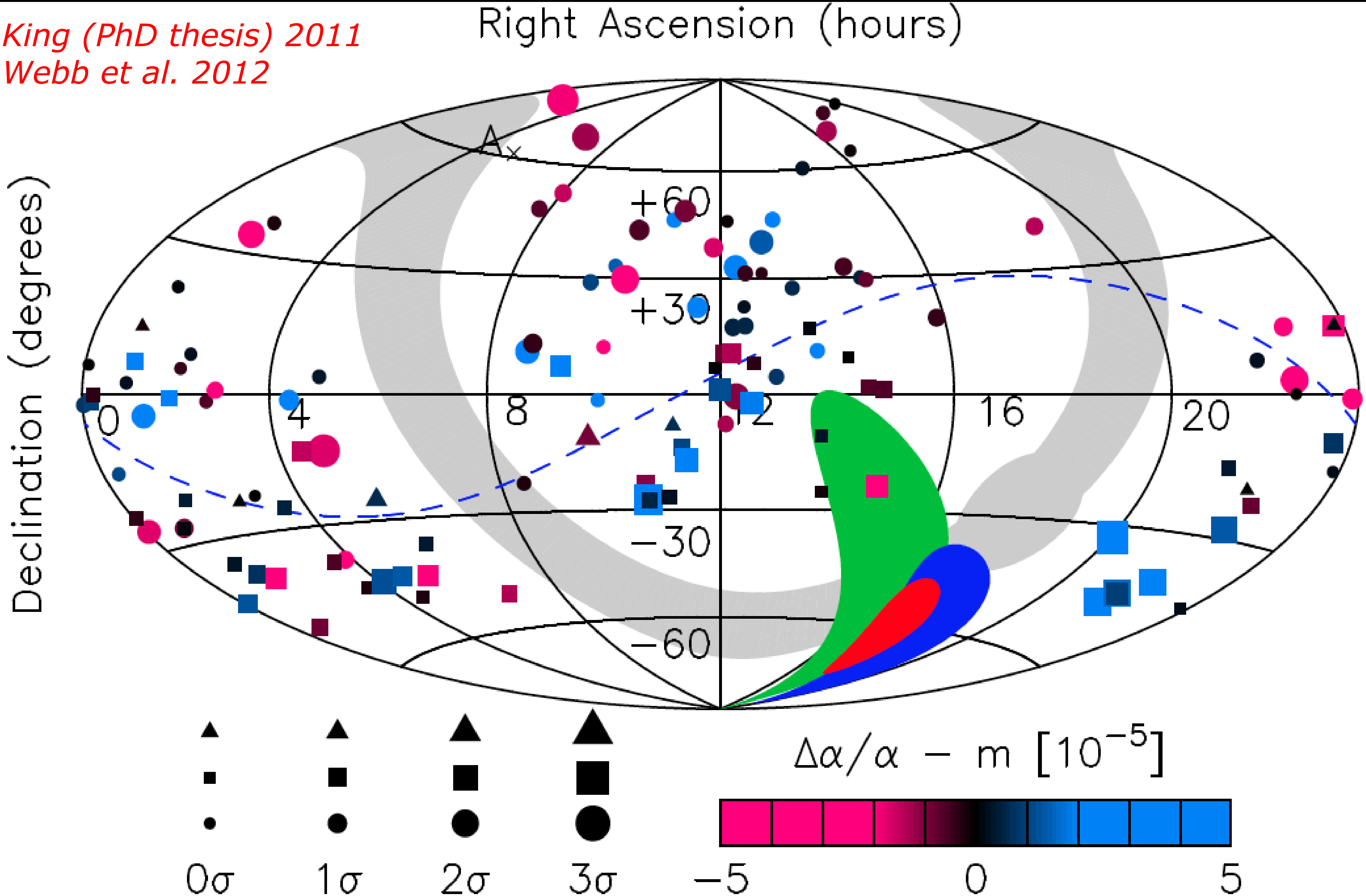
Murphy

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
- …

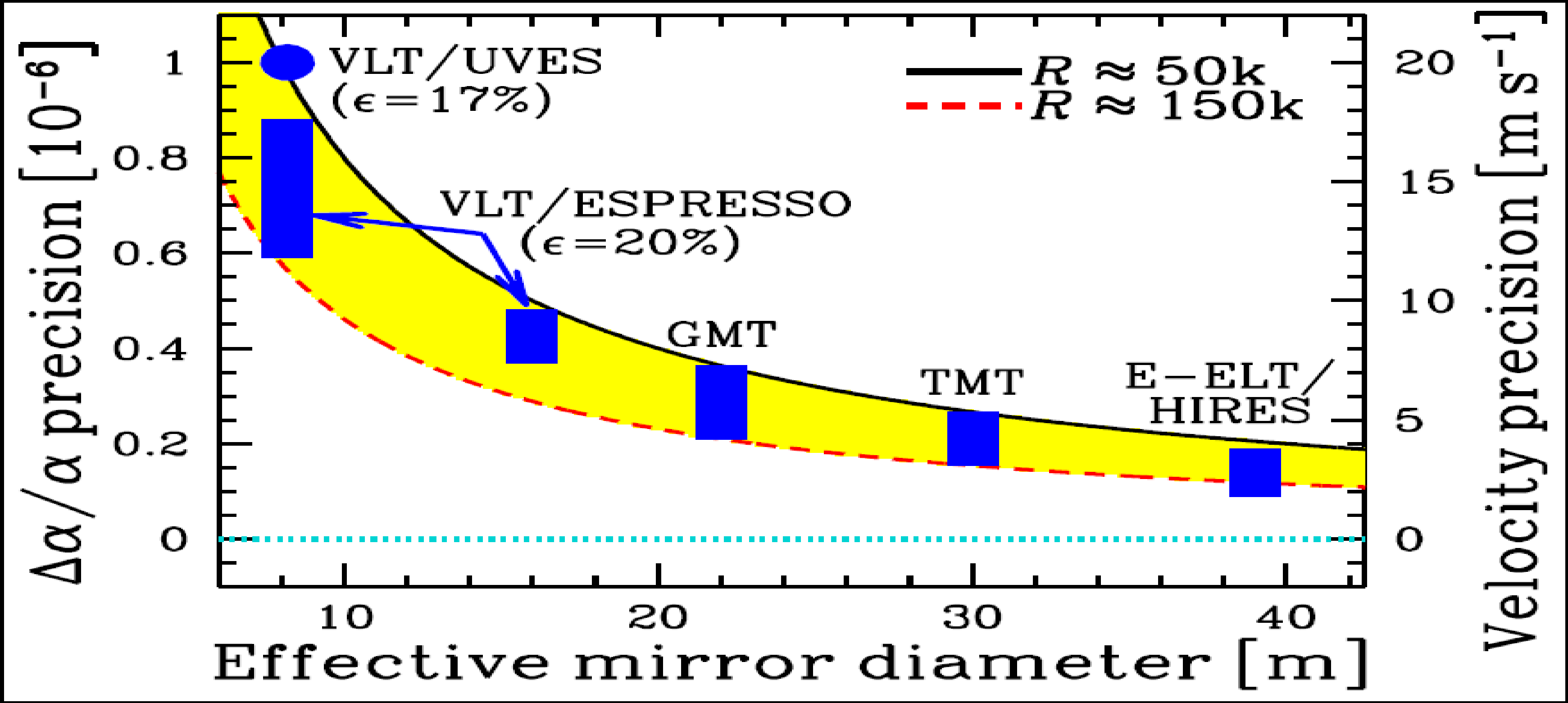
A Dipole on the Sky?

King (PhD thesis) 2011
Webb et al. 2012

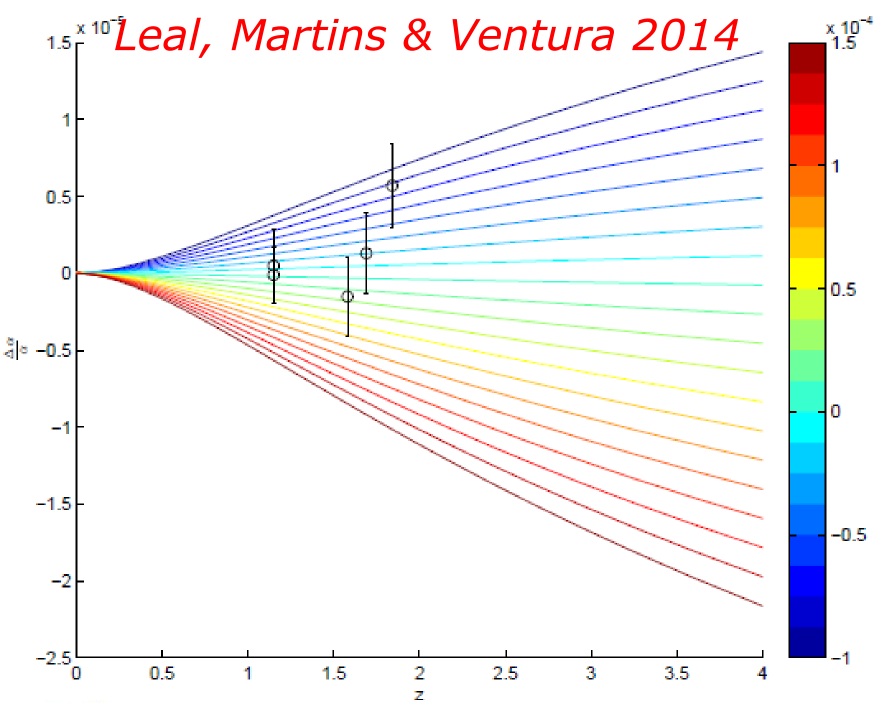


A Dipole on the Sky?

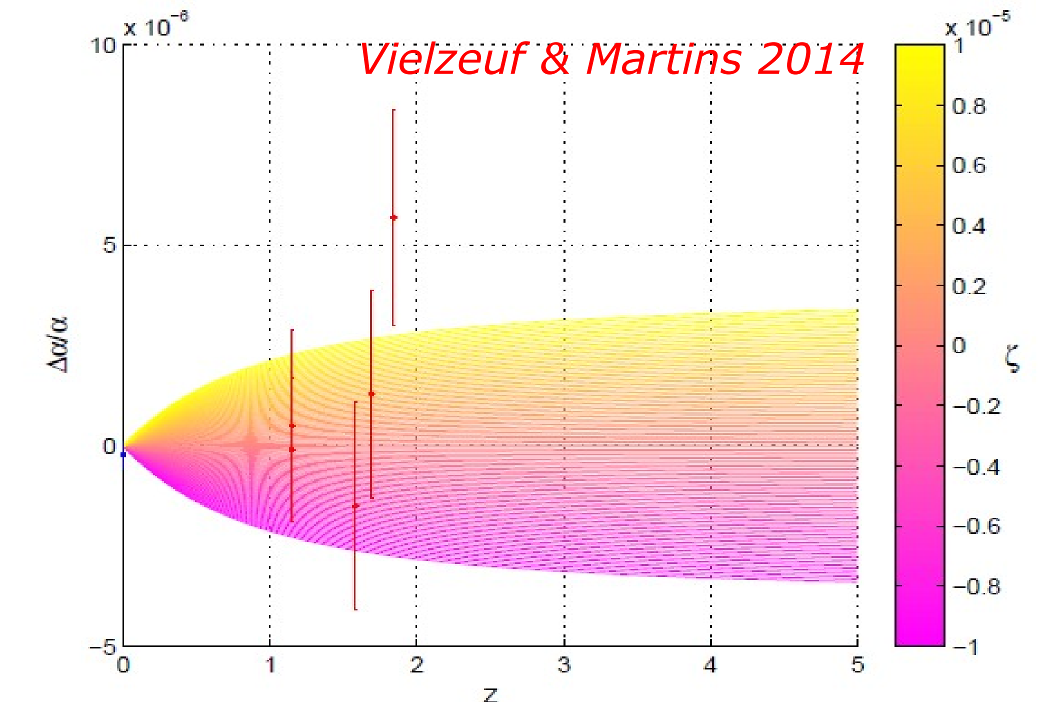
- >4 sigma evidence for a dipole; new physics or systematics?
  - Unclear if pure spatial dipole or dependent on lookback time
  - No known systematic can explain dipole, but difficult to model
  - A concern: archival data, taken for other purposes
- Key driver for ESPRESSO (VLT) and the ELT-HIRES
  - Better precision, and much better control of systematics



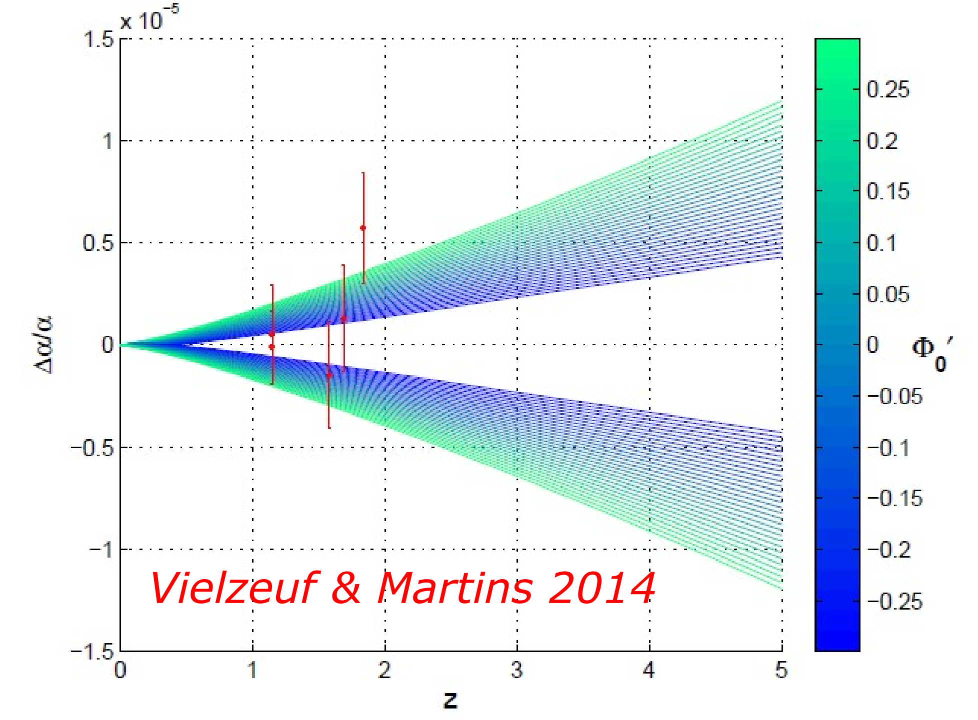
The Zoo of Models



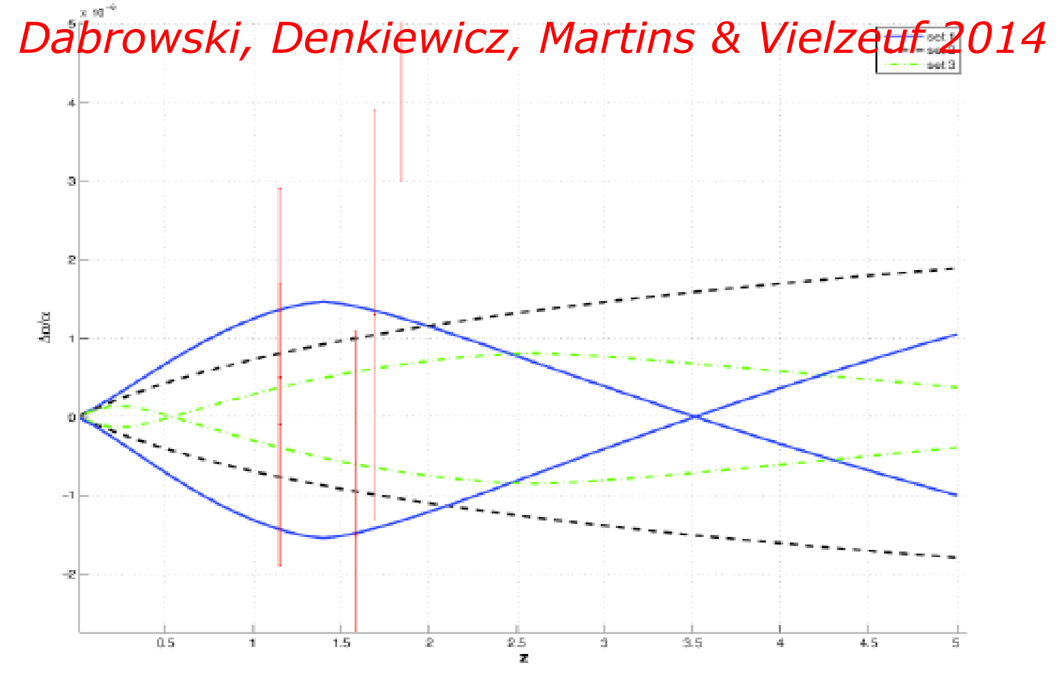
Leal, Martins & Ventura 2014



Vielzeuf & Martins 2014

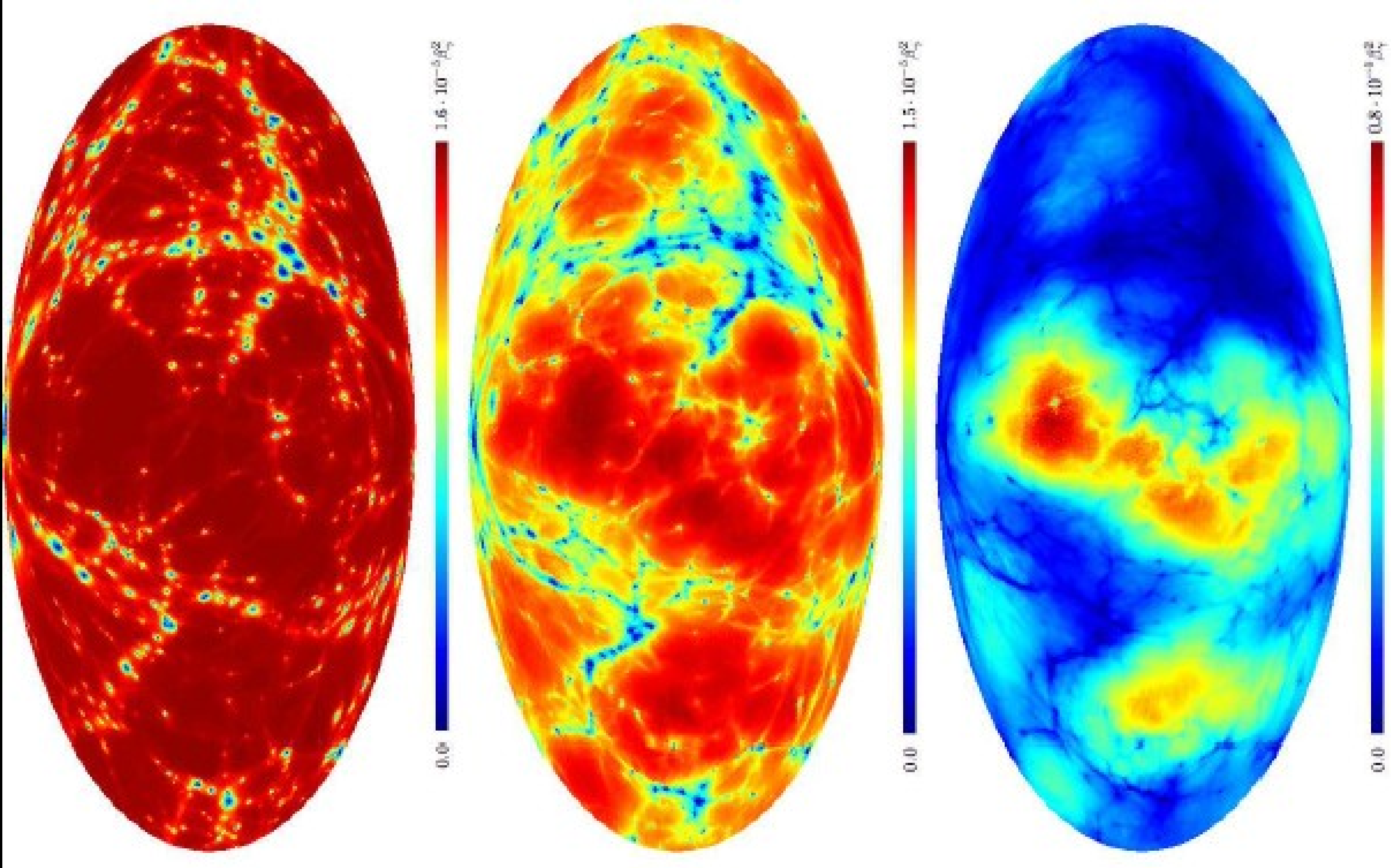


Vielzeuf & Martins 2014



Dabrowski, Denkiewicz, Martins & Vielzeuf 2014

Varying α from Symmetrons



[See Marvin Silva et al., Phys.Rev. D89 (2014) 024025]

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]*

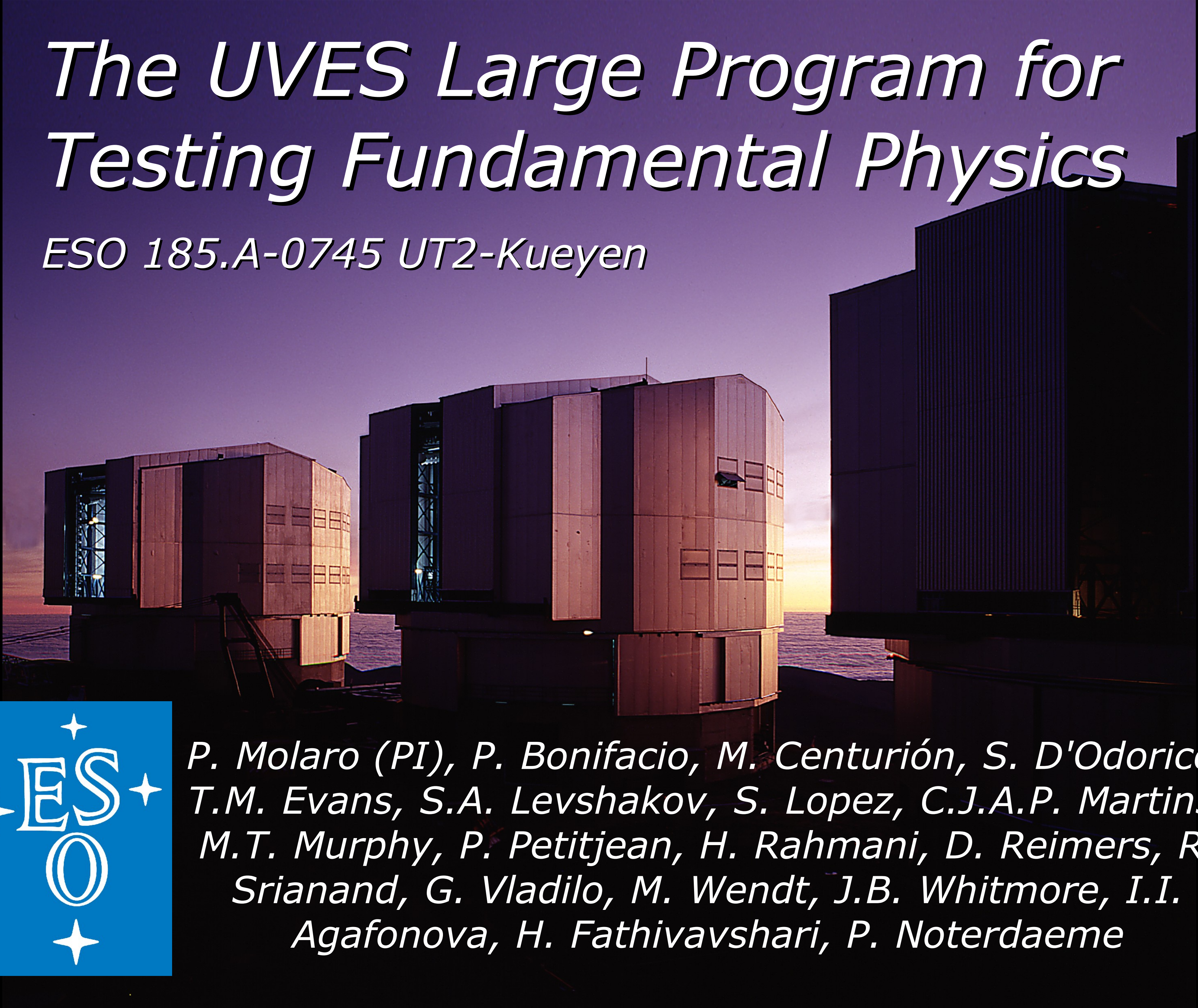
$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1+S)]\frac{\Delta\alpha}{\alpha}$$

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

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

The UVES Large Program for Testing Fundamental Physics

ESO 185.A-0745 UT2-Kueyen

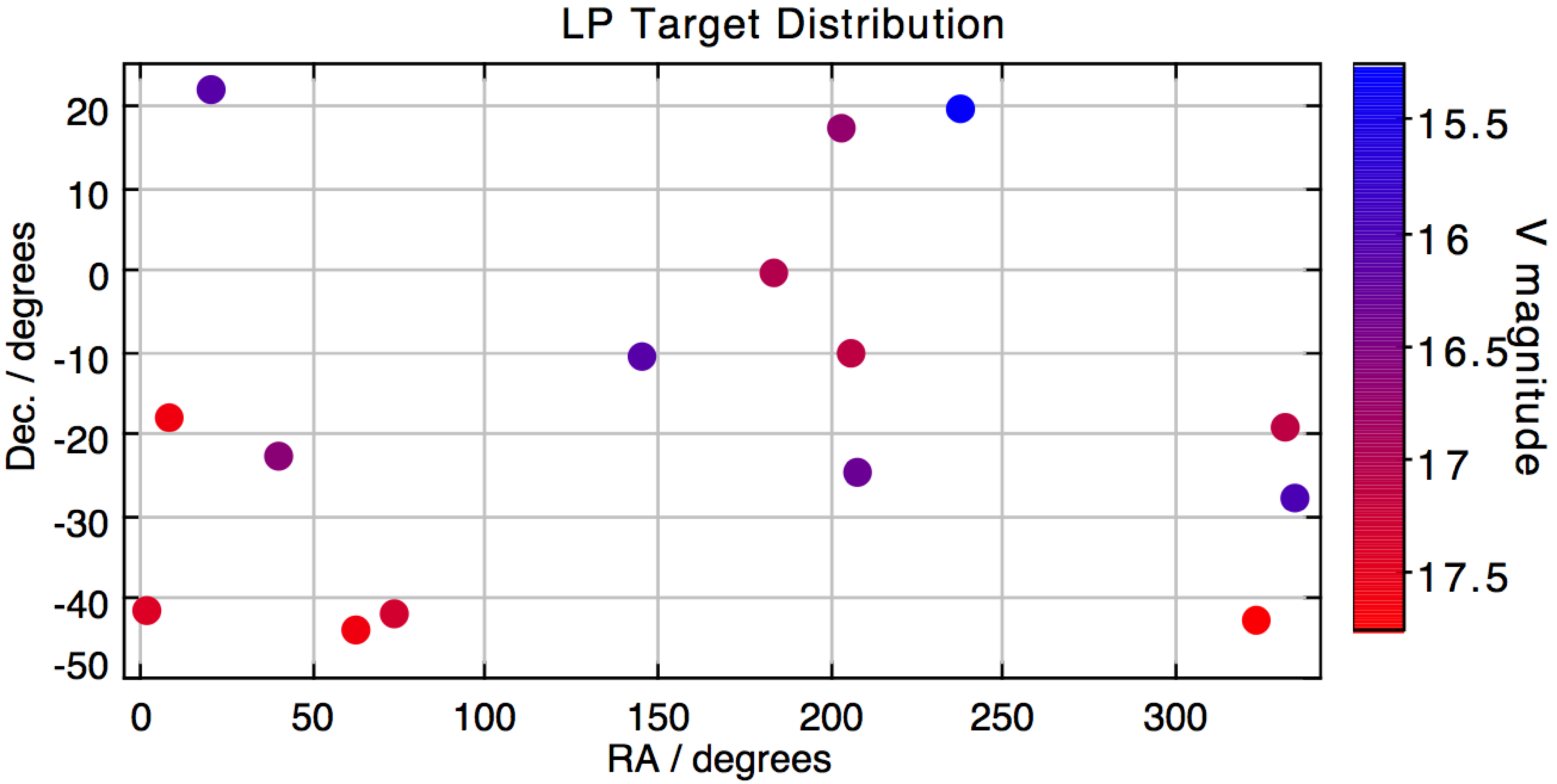


P. Molaro (PI), P. Bonifacio, M. Centurión, S. D'Odorico, T.M. Evans, S.A. Levshakov, S. Lopez, C.J.A.P. Martins, M.T. Murphy, P. Petitjean, H. Rahmani, D. Reimers, R. Srianand, G. Vladilo, M. Wendt, J.B. Whitmore, I.I. Agafonova, H. Fathivavshari, P. Noterdaeme

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

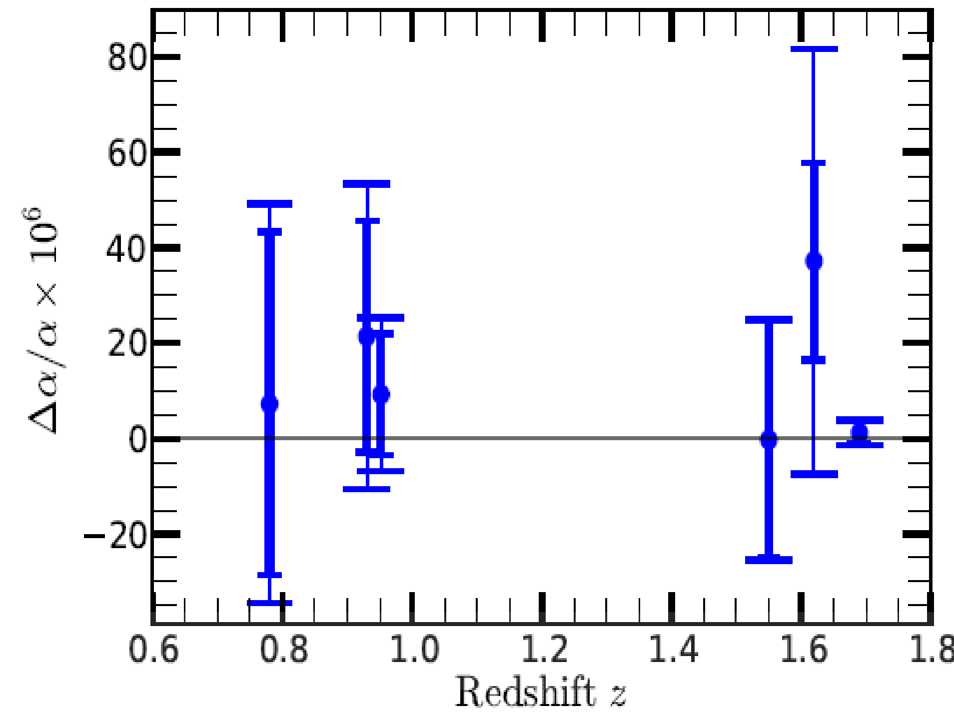
Target Selection & Status



- 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: first results on HE2217-2818 and HE0027-1836
    - Most raw data already in the ESO public archive, and reduced data products will also be made public – have fun!

First Results

- HE2217-2818, z_{abs}~1.69:
  $\Delta\alpha/\alpha$ = 1.3 ± 2.4$_{sta}$ ± 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

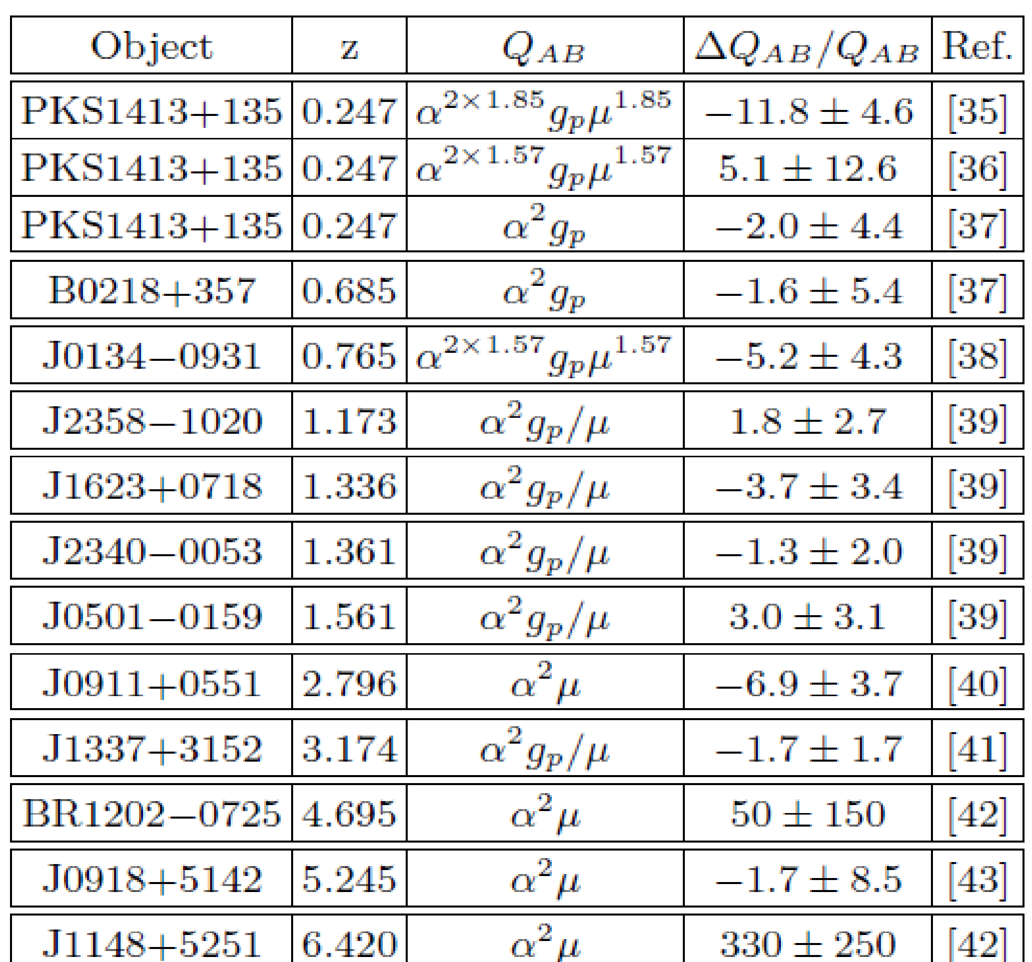


- HE0027-1836, z_{abs}~2.40: $\Delta\mu/\mu$ = -7.6 ± 8.1$_{sta}$ ± 6.3$_{sys}$ ppm
  - Paper II: H. Rahmani et al., MNRAS 435 (2013) 861
  - Identified wavelength-dependent velocity drift (corrected with bright asteroid data)
- Bottleneck: intra-order distortions (~200m/s) & long-range distortions on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

Current Dedicated Measurements

- Direct measurements of α and μ can be obtained in the UV/optical; in the radio band one can measure combinations
  - Parts per million sensitivity is nominally much easier to reach in the radio, though at significantly lower redshifts

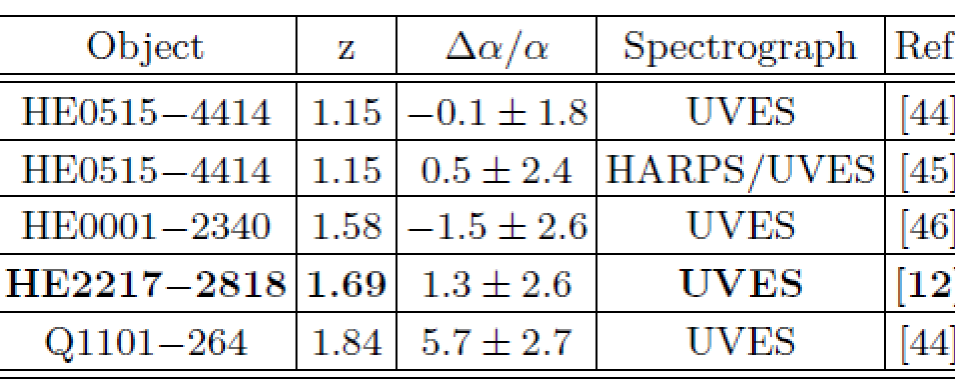
- Radio band sensitivity is even better within Galaxy (z=0), where one can search for environmental dependencies
  - No variation seen at the 0.1 ppm level for α *[Truppe et al. 2013]*
  - No variation seen at the 0.05 ppm level for μ *[Levshakov et al. 2013]*



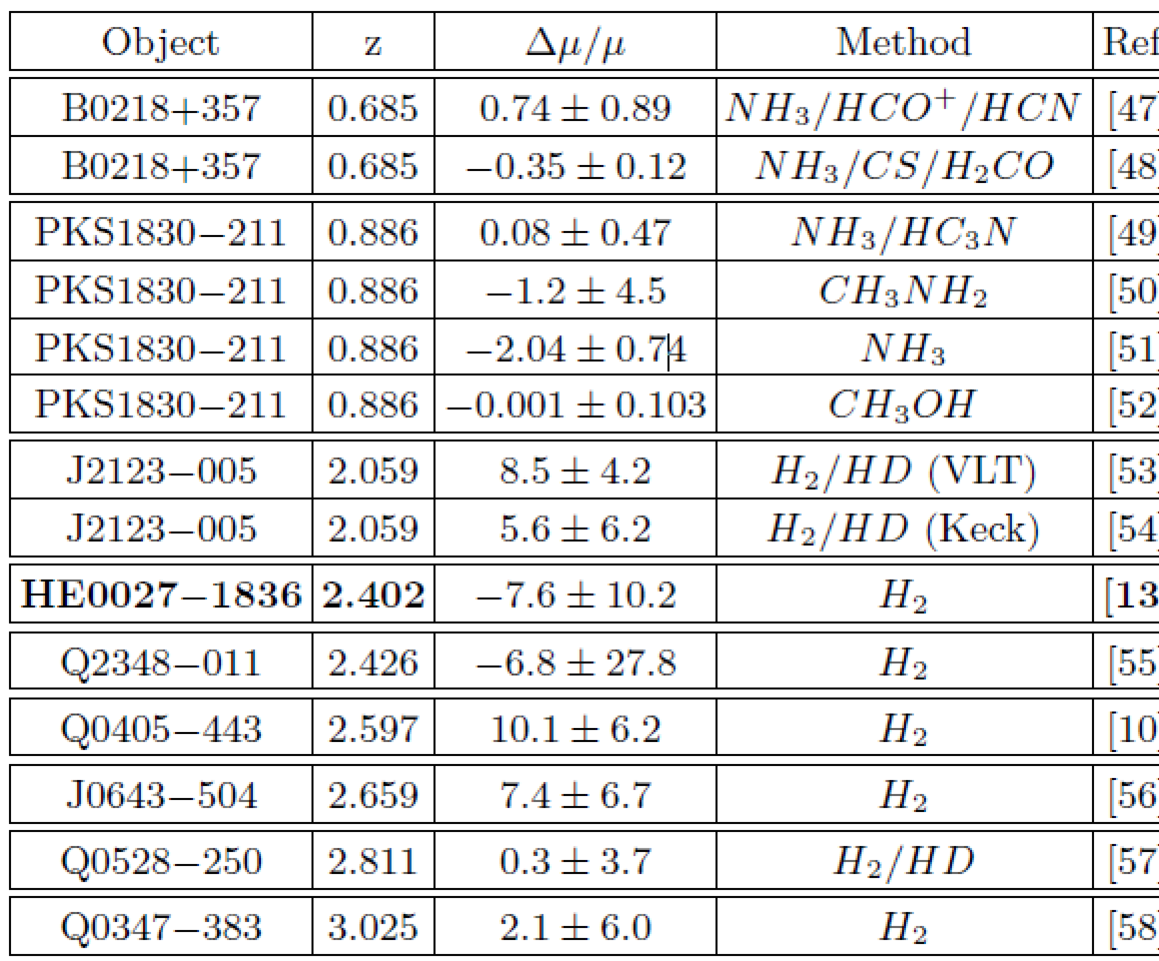
Object	z	Q_{AB}	$\Delta Q_{AB}/Q_{AB}$	Ref.
PKS1413+135	0.247	$\alpha^{2\times1.85} g_p \mu^{1.85}$	-11.8 ± 4.6	[35]
PKS1413+135	0.247	$\alpha^{2\times1.57} g_p \mu^{1.57}$	5.1 ± 12.6	[36]
PKS1413+135	0.247	$\alpha^2 g_p$	-2.0 ± 4.4	[37]
B0218+357	0.685	$\alpha^2 g_p$	-1.6 ± 5.4	[37]
J0134−0931	0.765	$\alpha^{2\times1.57} g_p \mu^{1.57}$	-5.2 ± 4.3	[38]
J2358−1020	1.173	$\alpha^2 g_p/\mu$	1.8 ± 2.7	[39]
J1623+0718	1.336	$\alpha^2 g_p/\mu$	-3.7 ± 3.4	[39]
J2340−0053	1.361	$\alpha^2 g_p/\mu$	-1.3 ± 2.0	[39]
J0501−0159	1.561	$\alpha^2 g_p/\mu$	3.0 ± 3.1	[39]
J0911+0551	2.796	$\alpha^2 \mu$	-6.9 ± 3.7	[40]
J1337+3152	3.174	$\alpha^2 g_p/\mu$	-1.7 ± 1.7	[41]
BR1202−0725	4.695	$\alpha^2 \mu$	50 ± 150	[42]
J0918+5142	5.245	$\alpha^2 \mu$	-1.7 ± 8.5	[43]
J1148+5251	6.420	$\alpha^2 \mu$	330 ± 250	[42]

Current Dedicated Measurements

- Direct measurements of α and μ can be obtained in the UV/optical; in the radio band one can measure combinations
  - Parts per million sensitivity is nominally much easier to reach in the radio, though at significantly lower redshifts



Object	z	$\Delta\alpha/\alpha$	Spectrograph	Ref
HE0515−4414	1.15	-0.1 ± 1.8	UVES	[44]
HE0515−4414	1.15	0.5 ± 2.4	HARPS/UVES	[45]
HE0001−2340	1.58	-1.5 ± 2.6	UVES	[46]
HE2217−2818	**1.69**	$\mathbf{1.3 \pm 2.6}$	**UVES**	**[12**
Q1101−264	1.84	5.7 ± 2.7	UVES	[44]



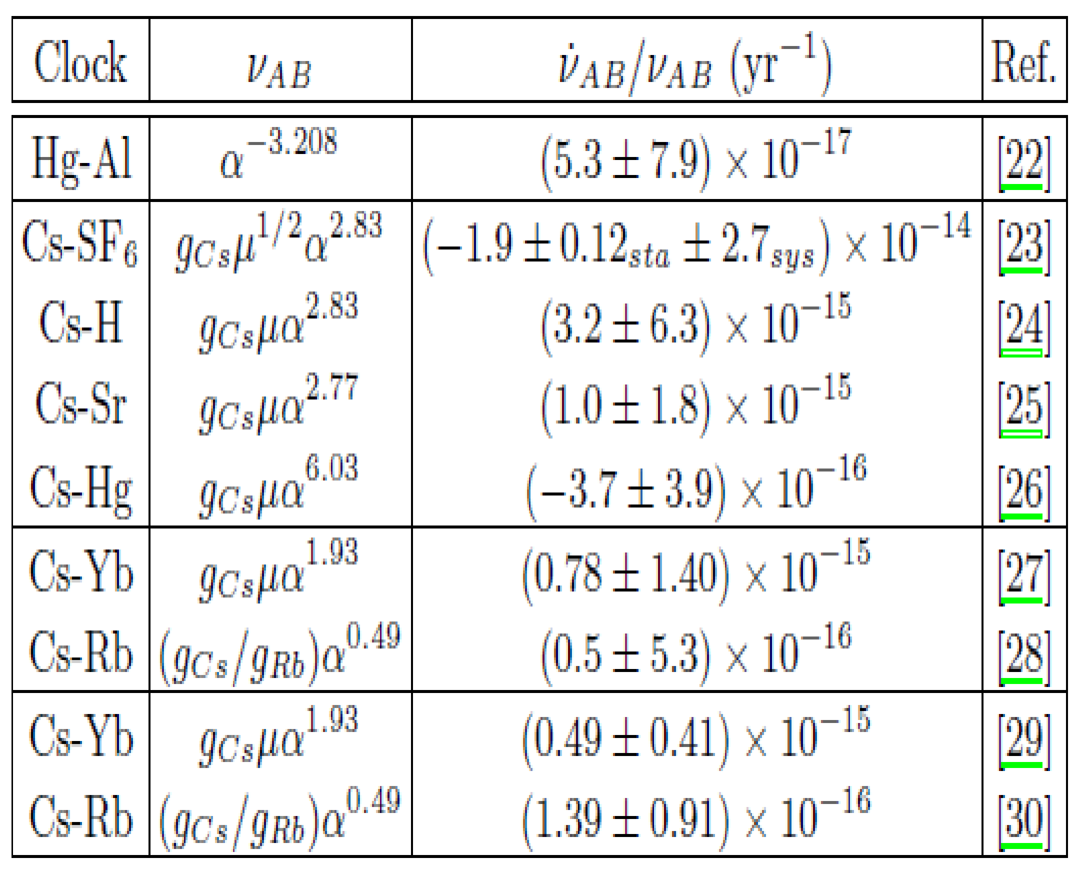
Object	z	$\Delta\mu/\mu$	Method	Ref
B0218+357	0.685	0.74 ± 0.89	$NH_3/HCO^+/HCN$	[47
B0218+357	0.685	-0.35 ± 0.12	$NH_3/CS/H_2CO$	[48
PKS1830−211	0.886	0.08 ± 0.47	NH_3/HC_3N	[49
PKS1830−211	0.886	-1.2 ± 4.5	CH_3NH_2	[50
PKS1830−211	0.886	-2.04 ± 0.74	NH_3	[51
PKS1830−211	0.886	-0.001 ± 0.103	CH_3OH	[52
J2123−005	2.059	8.5 ± 4.2	H_2/HD (VLT)	[53
J2123−005	2.059	5.6 ± 6.2	H_2/HD (Keck)	[54
HE0027−1836	**2.402**	$\mathbf{-7.6 \pm 10.2}$	H_2	**[13**
Q2348−011	2.426	-6.8 ± 27.8	H_2	[55
Q0405−443	2.597	10.1 ± 6.2	H_2	[10
J0643−504	2.659	7.4 ± 6.7	H_2	[56
Q0528−250	2.811	0.3 ± 3.7	H_2/HD	[57
Q0347−383	3.025	2.1 ± 6.0	H_2	[58

- Joint analysis of all the available data suggests some inconsistencies

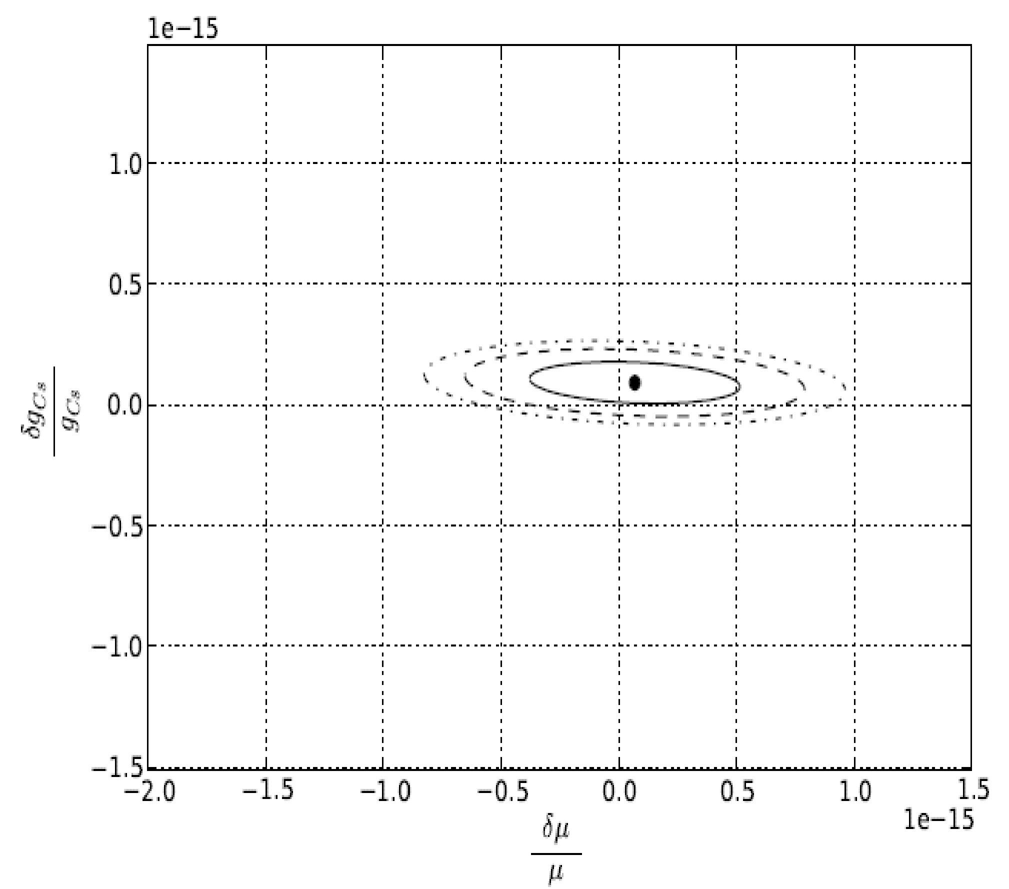
  [See Ferreira, Frigola, Martins, Monteiro & Solà, Phys. Rev. D89 (2014) 083011]

Low-redshift Constraints

- Atomic clocks: sensitivity of fewx10^{-17}/yr *[Rosenband et al. 2008]*
  - Future: molecular & nuclear clocks, 10^{-21}/yr achievable?



Clock	ν_{AB}	$\dot{\nu}_{AB}/\nu_{AB}$ (yr^{-1})	Ref.
Hg-Al	$\alpha^{-3.208}$	$(5.3 \pm 7.9) \times 10^{-17}$	[22]
Cs-SF$_6$	$g_{Cs}\mu^{1/2}\alpha^{2.83}$	$(-1.9 \pm 0.12_{sta} \pm 2.7_{sys}) \times 10^{-14}$	[23]
Cs-H	$g_{Cs}\mu\alpha^{2.83}$	$(3.2 \pm 6.3) \times 10^{-15}$	[24]
Cs-Sr	$g_{Cs}\mu\alpha^{2.77}$	$(1.0 \pm 1.8) \times 10^{-15}$	[25]
Cs-Hg	$g_{Cs}\mu\alpha^{6.03}$	$(-3.7 \pm 3.9) \times 10^{-16}$	[26]
Cs-Yb	$g_{Cs}\mu\alpha^{1.93}$	$(0.78 \pm 1.40) \times 10^{-15}$	[27]
Cs-Rb	$(g_{Cs}/g_{Rb})\alpha^{0.49}$	$(0.5 \pm 5.3) \times 10^{-16}$	[28]
Cs-Yb	$g_{Cs}\mu\alpha^{1.93}$	$(0.49 \pm 0.41) \times 10^{-15}$	[29]
Cs-Rb	$(g_{Cs}/g_{Rb})\alpha^{0.49}$	$(1.39 \pm 0.91) \times 10^{-16}$	[30]



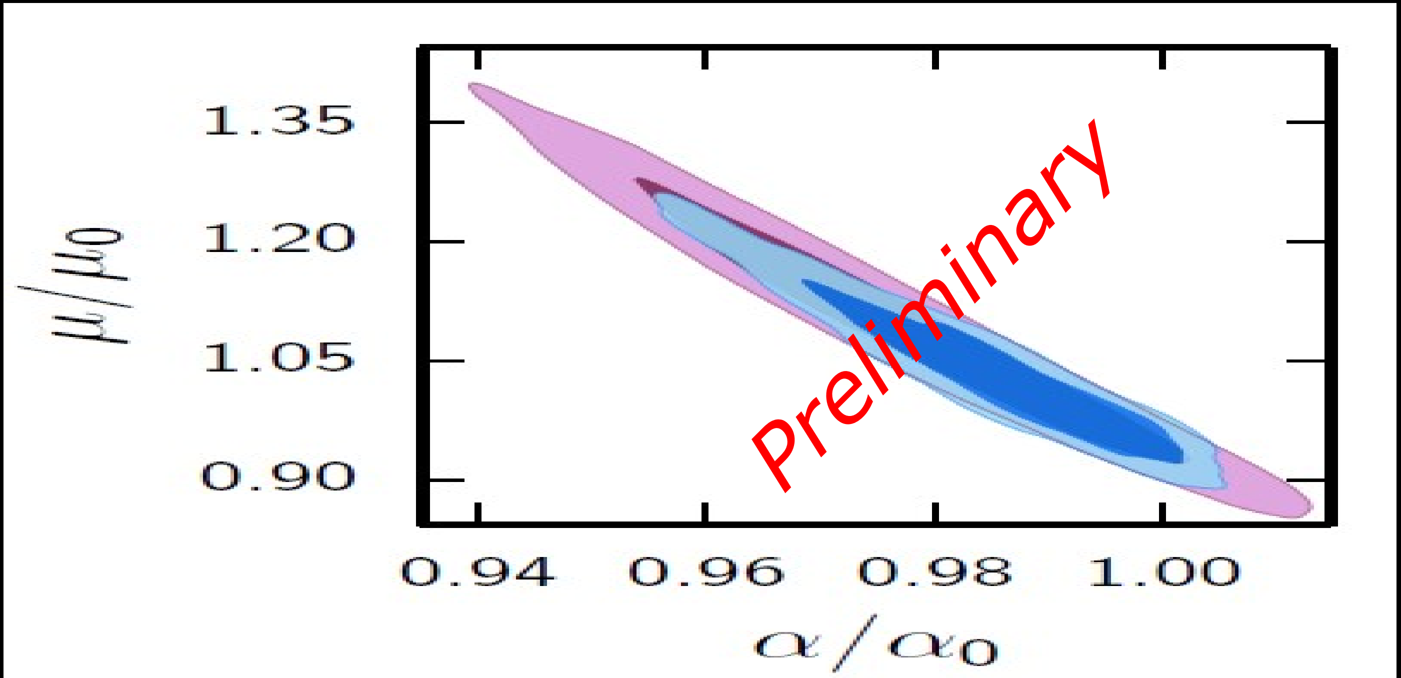
[See Ferreira, Julião, Martins & Monteiro, PRD86 (2012) 125025]

Low-redshift Constraints

- Atomic clocks: sensitivity of fewx10^{-17}/yr *[Rosenband et al. 2008]*
  - Future: molecular & nuclear clocks, 10^{-21}/yr achievable?
- Compact objects used to constrain environmental dependencies; limiting factor usually comes from nuclear physics uncertainties
  - Population III stars *[Ekstrom et al. 2010]*, sensitivity ~fewx10^{-5}
  - Neutron stars *[Pérez-García & Martins 2012]*, sensitivity ~10^{-4}
  - Solar-type stars *[Vieira et al. 2012]*, sensitivity ~10^{-4} or better?
  - White dwarfs *[Berengut et al. 2013]*, sensitivity ~10^{-4} or better?
- Oklo (natural nuclear reactor, z~0.14): nominal sensitivity of fewx10^{-8} *[Davis et al. 2014],* but not a 'clean' measurement
  - Assumptions somewhat simplistic; effectively constrains α_s
- Clusters of galaxies (z<1): compare SZ and X-ray observations: 0.8% sensitivity *[Galli 2013]*
  - Promising with larger numbers of clusters

High-redshift Constraints

- Ionization history (and hence the cosmic microwave background) affected by varying constants
  - Clean probe, but relatively weak bounds due to degeneracies
  - Current α-only bound *[Planck 2013, paper XVI]* is 0.4%
- More realistic approach: allow both α and particle masses to vary, in generic unification scenarios *[Galli & Martins, 2014]*
  - Constraints on unification can be combined with low-z ones



High-redshift Constraints

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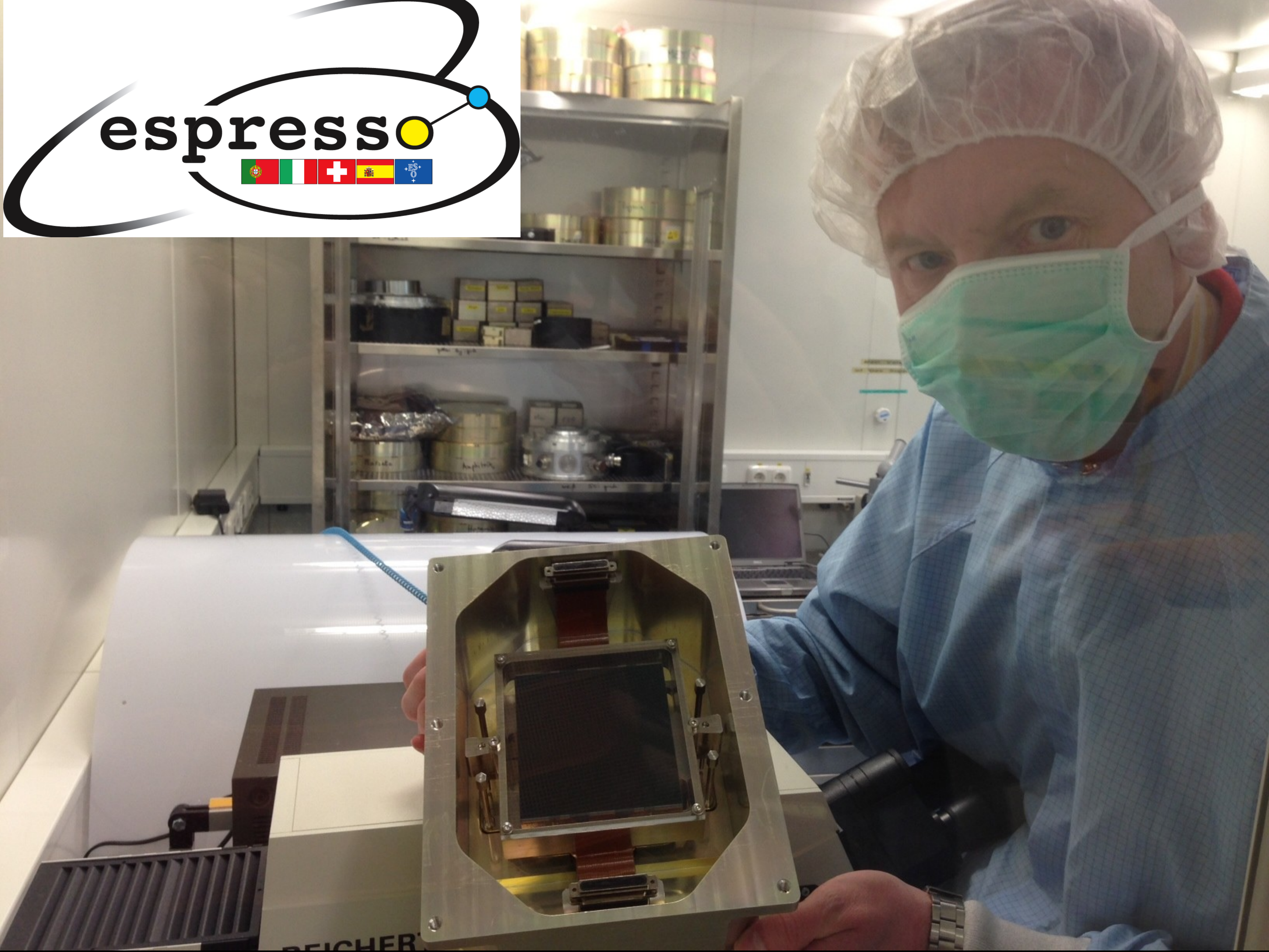
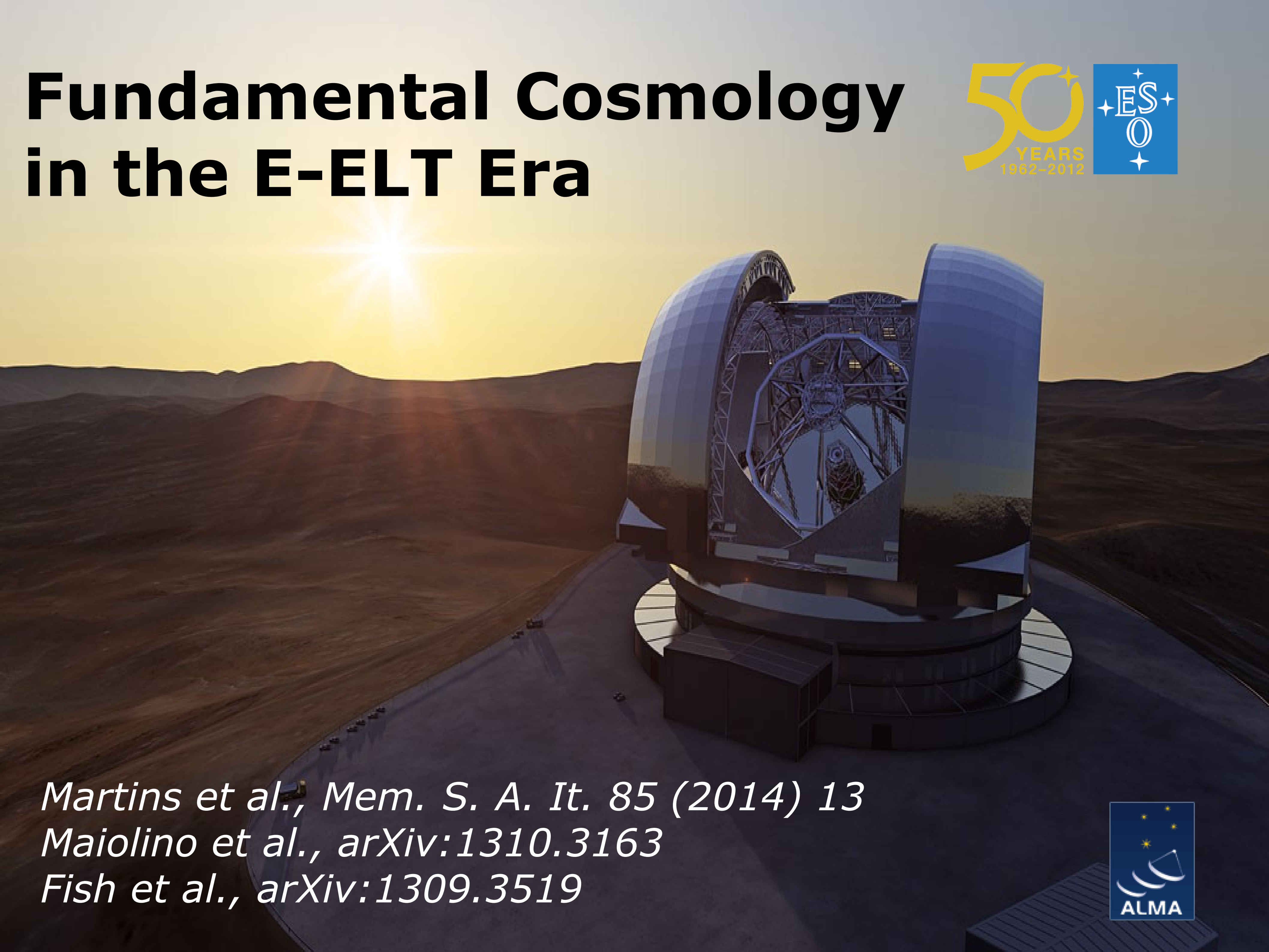
- More realistic approach: allow both α and particle masses to vary, in generic unification scenarios *[Galli & Martins, 2014]*
  - Constraints on unification can be combined with low-z ones
- At higher redshifts constraints can be obtained from Big Bang nucleosynthesis, but they will necessarily be model-dependent
  - Current constraints are at around the 1% level, for relatively generic models *[Martins et al. 2010]*
  - Tighter constraints can be obtained for more specific choices of model *[Coc et al. 2007, etc.]*
  - Lithium problem might be removed in some GUT scenarios *[Stern (PhD thesis) 2008]*, but in-depth analysis remains to be done

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 Era

Martins et al., Mem. S. A. It. 85 (2014) 13
Maiolino et al., arXiv:1310.3163
Fish et al., arXiv:1309.3519

The E-ELT Vision

Enabling discovery is achieved by opening parameter space

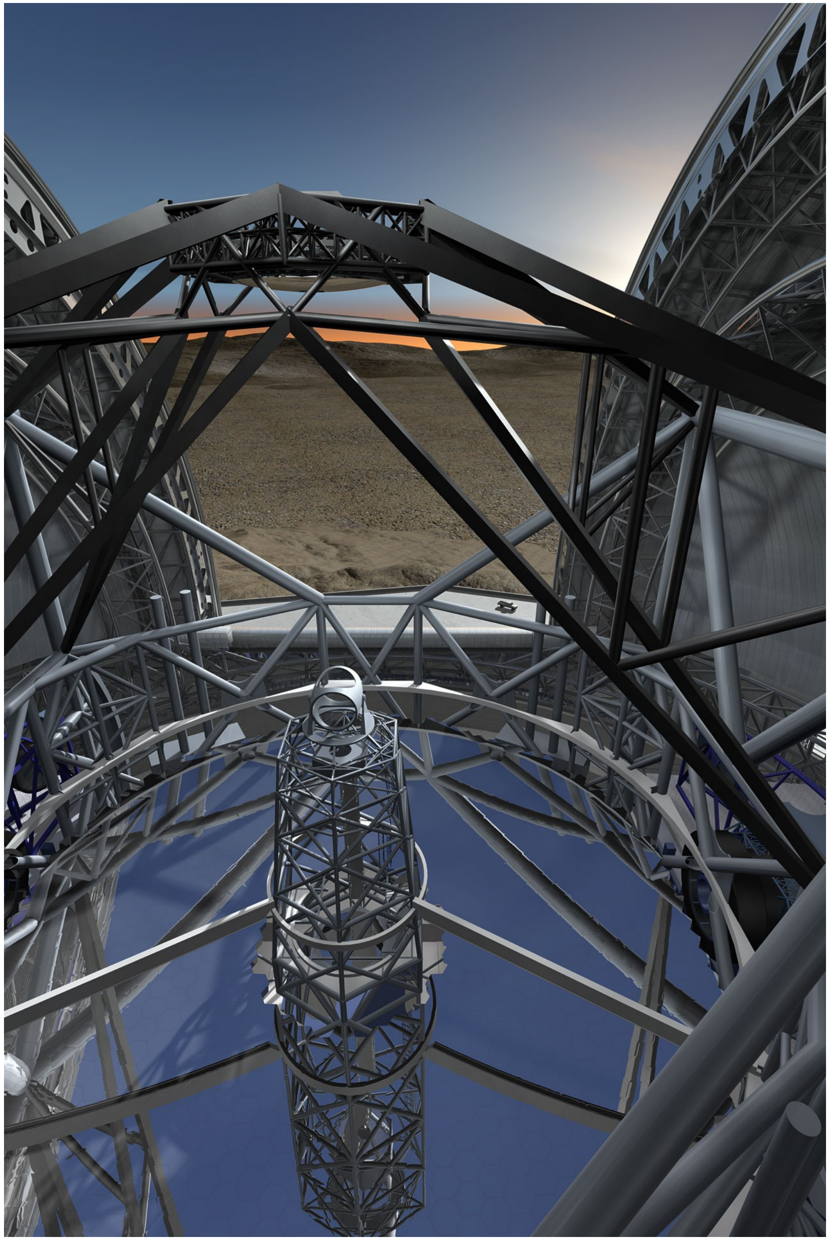
The E-ELT excels

- in collecting power

- in spatial resolution

These should not be compromised; they should be pushed into a range unattained previously

The E-ELT is *not* a survey telescope, indeed it's not a 'classical' telescope at all: it's an *exquisite science experiment*



ALMA & E-ELT Instruments

- **Diffraction-limited NIR camera**
- **ELT-CAM (PI Davies) cf. MICADO+MAORY**
  - First strong gravity tests around the galactic black hole (possibly others too)
  - Dynamical measurements of gravitational potential near event horizon
  - Direct (astrometric) test of no-hair 'theorem' *[Will 2008]*
  - ***ALMA: further strong-gravity tests of GR and the no-hair theorem***

- **Single-field wideband IFU NIR spectrometer**
- **ELT-IFU (PI Thatte), cf. HARMONI+ATLAS**
  - Spectroscopic characterization of Type Ia supernovas in $1<z<5$ *[Hook 2012]*
  - JWST (through NIRcam imaging) should find them and measure light curves

- **High-resolution, ultra-stable Optical/IR spectrograph**
- *ELT-HIRES, details tbc ('CODEX+SIMPLE') [cf. arXiv:1309.7758,1310.3163]*
  - Redshift drift: watching the universe expand in real time
  - Fundamental couplings: mapping the dark universe
  - The CMB temperature: mapping the bright universe
  - **ALMA: further measurements of T(z) and various combinations of couplings (mostly at low redshift)**

Was Einstein Right?

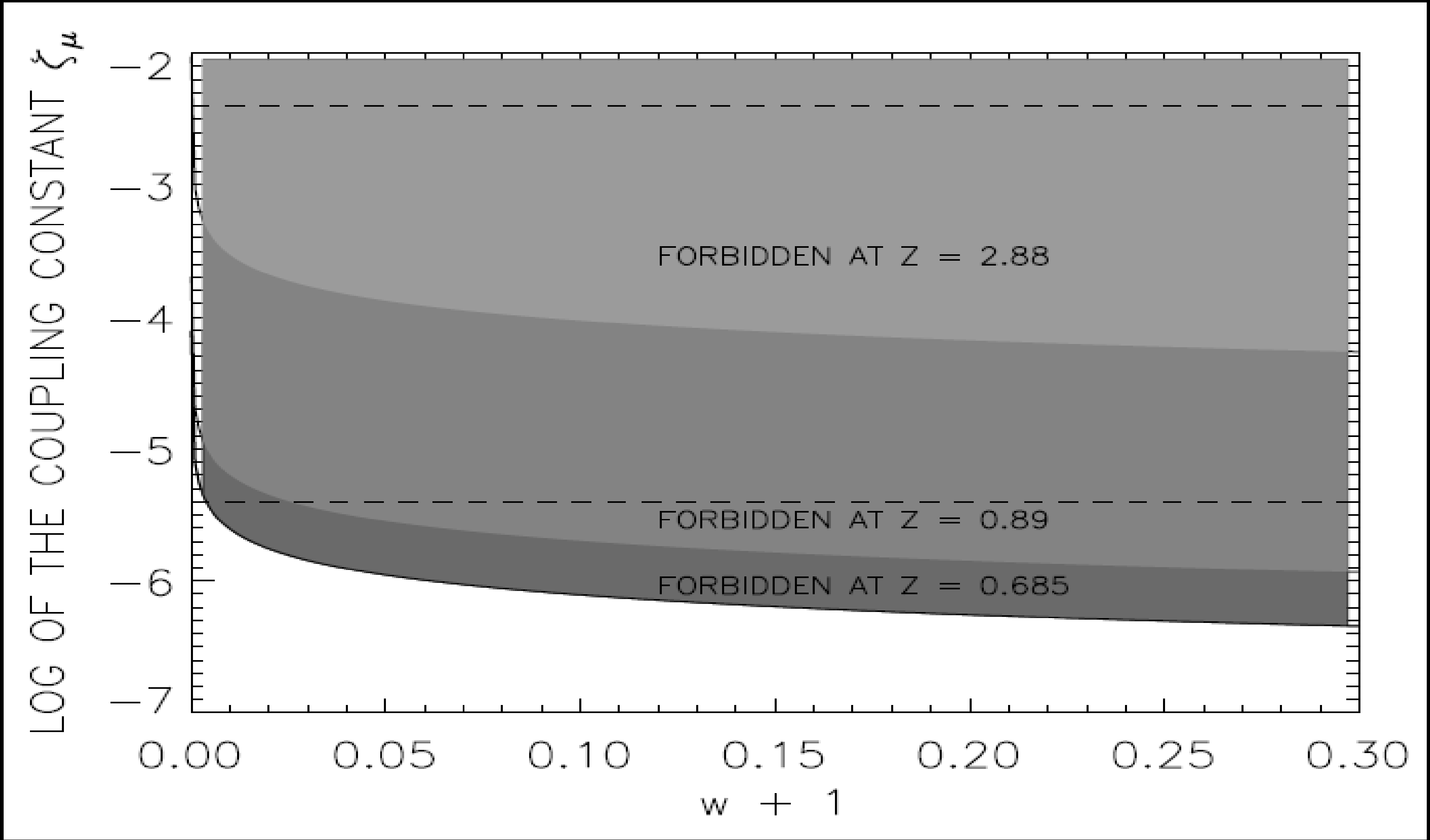
Dark Energy & Varying Couplings

- 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 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
  - This ensures a 'minimum guaranteed science'

Taxonomy: Class I

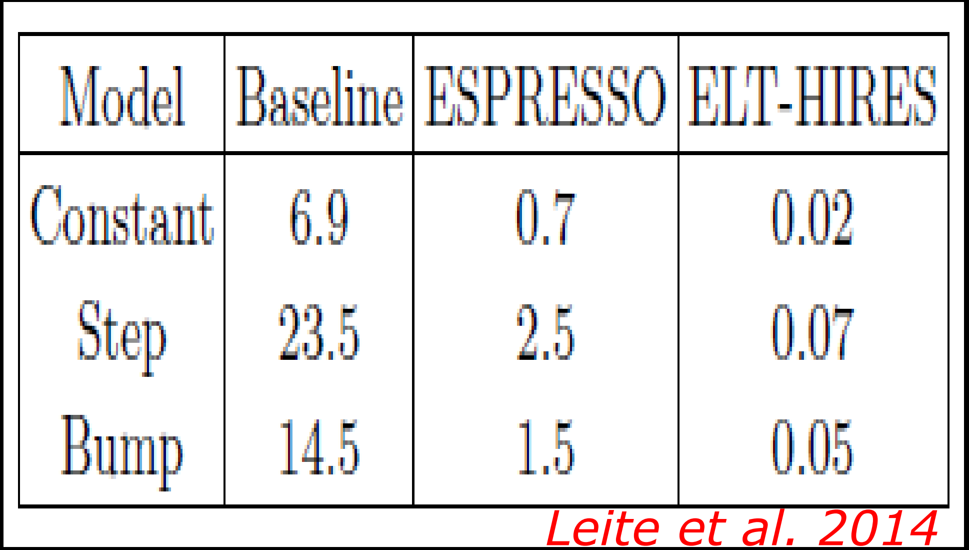
- If the same degree of freedom is responsible for dark energy and varying α, the latter's evolution is parametrically determined

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



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
  - Fundamental couplings ideally probe scalar field dynamics beyond the domination regime *[Nunes & Lidsey 2004]*
- ALMA, ESPRESSO and ELT-HIRES will map dark energy 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)

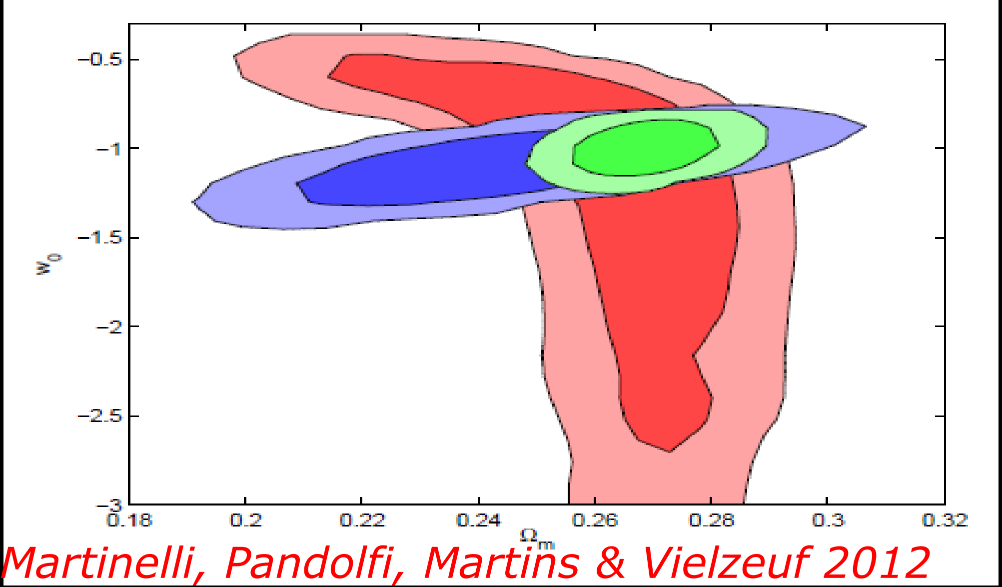


Model	Baseline	ESPRESSO	ELT-HIRES
Constant	6.9	0.7	0.02
Step	23.5	2.5	0.07
Bump	14.5	1.5	0.05

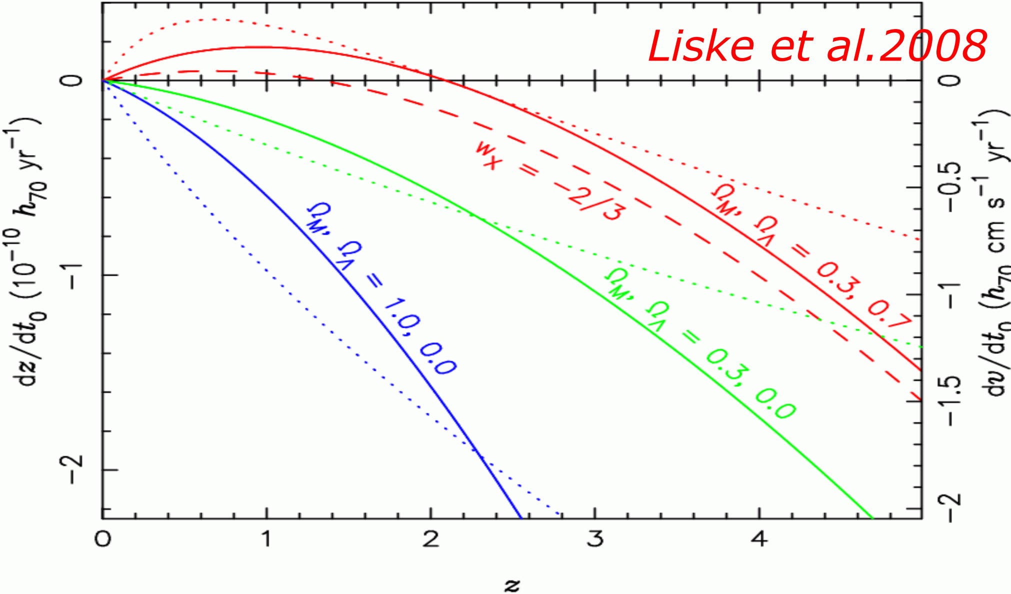
Leite et al. 2014

The Redshift Drift

- Direct probe of dynamics of the universe *[Sandage 1962]*
  - No assumptions on gravity, geometry, or clustering
  - Crucial for consistency tests, breaks CMB degeneracies



Martinelli, Pandolfi, Martins & Vielzeuf 2012

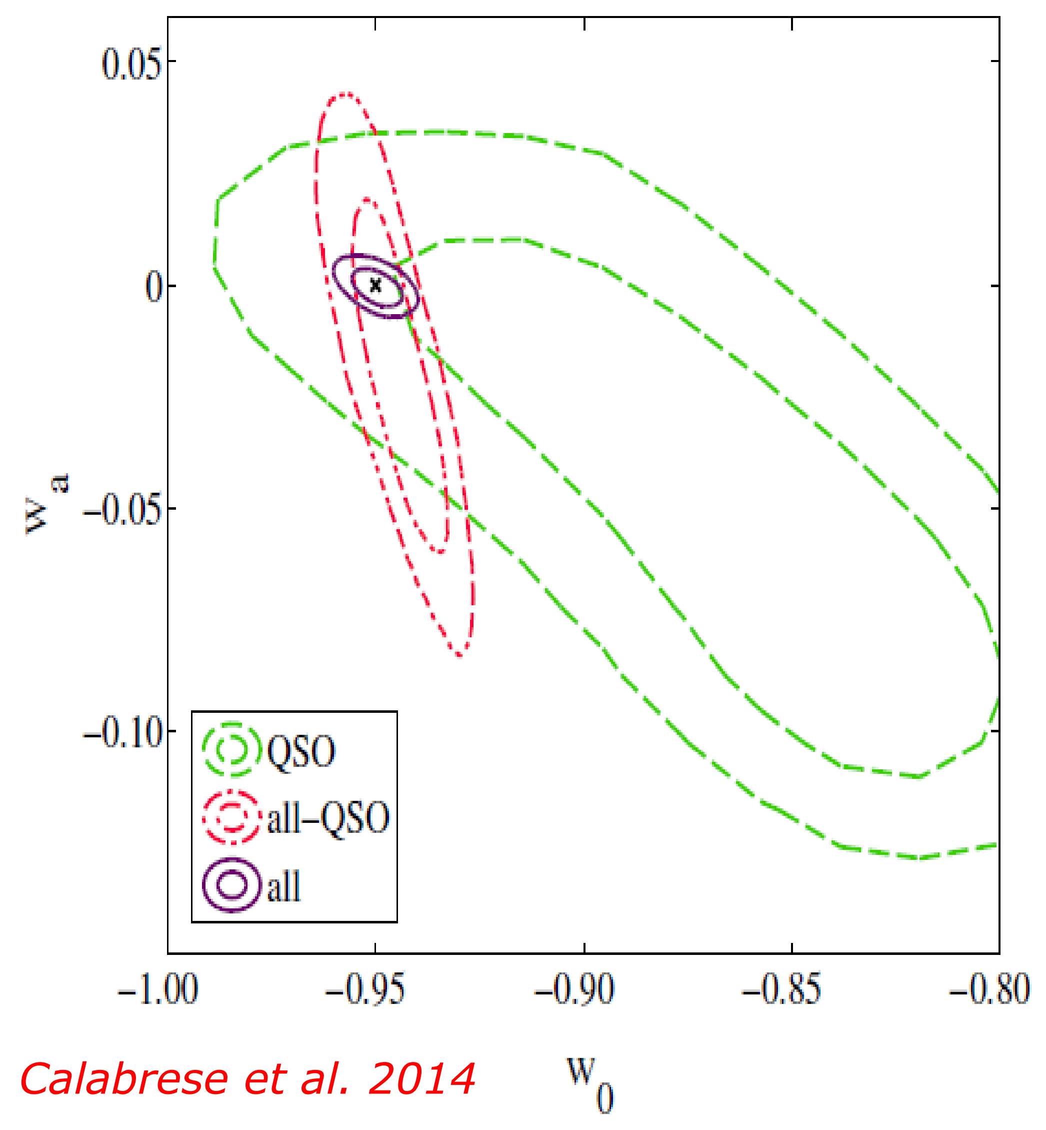


Liske et al.2008

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

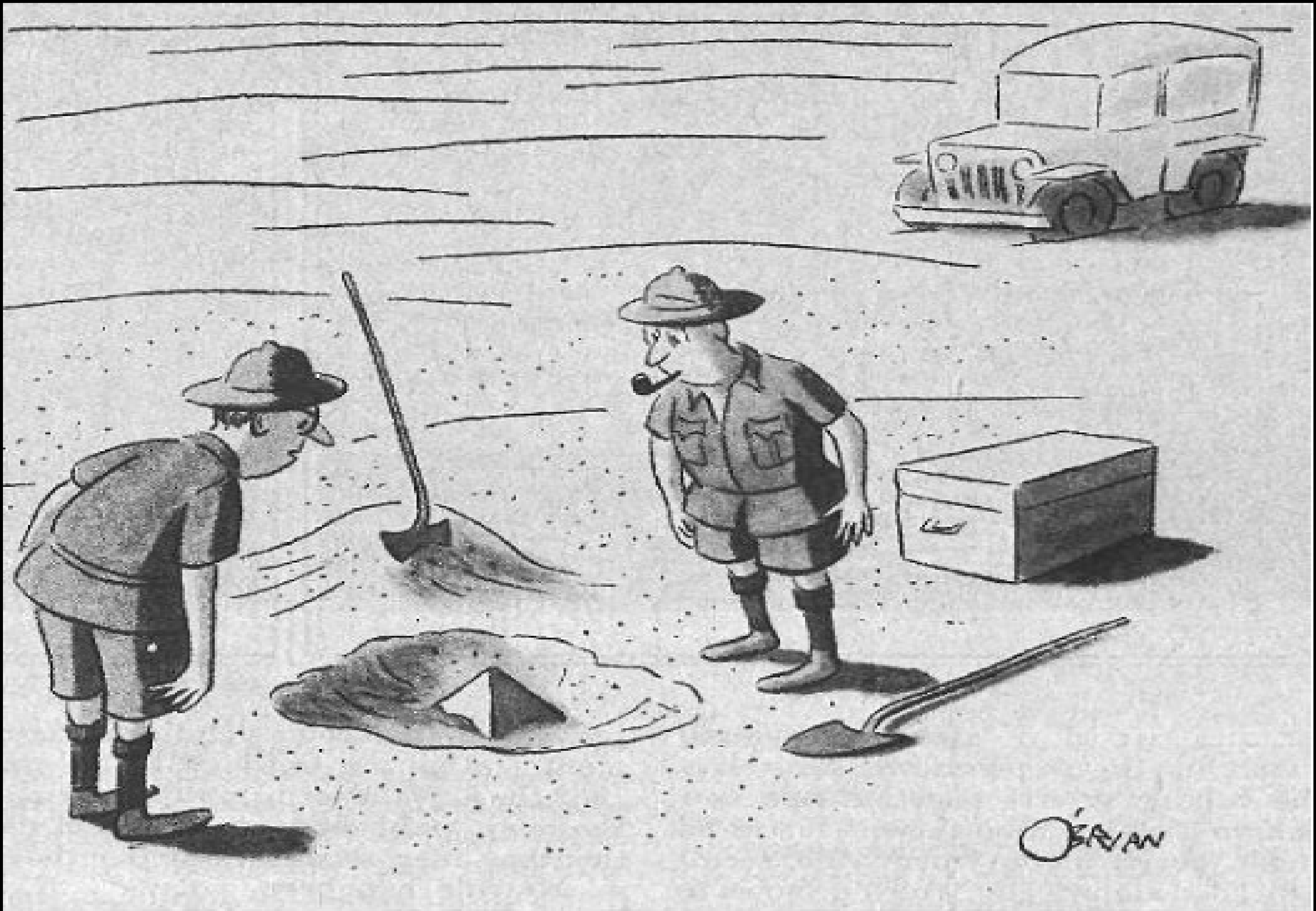
Euclid & Varying α

- The weak lensing shear power spectrum (a Euclid primary probe) + Type Ia Supernovas 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]*



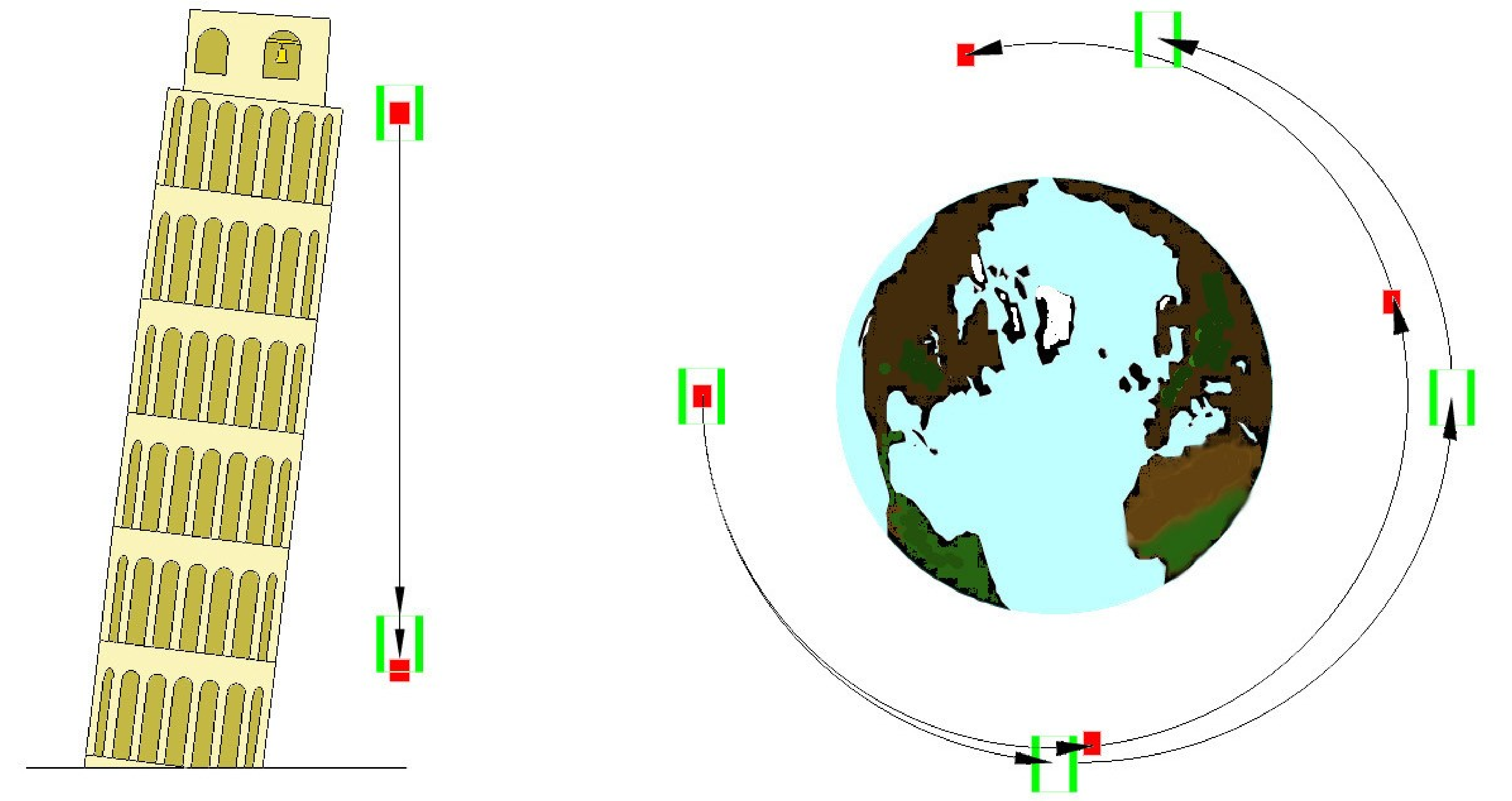
Calabrese et al. 2014

The Quest for Redundancy



"This could be the discovery of the century. Depending, of course, on how far down it goes."

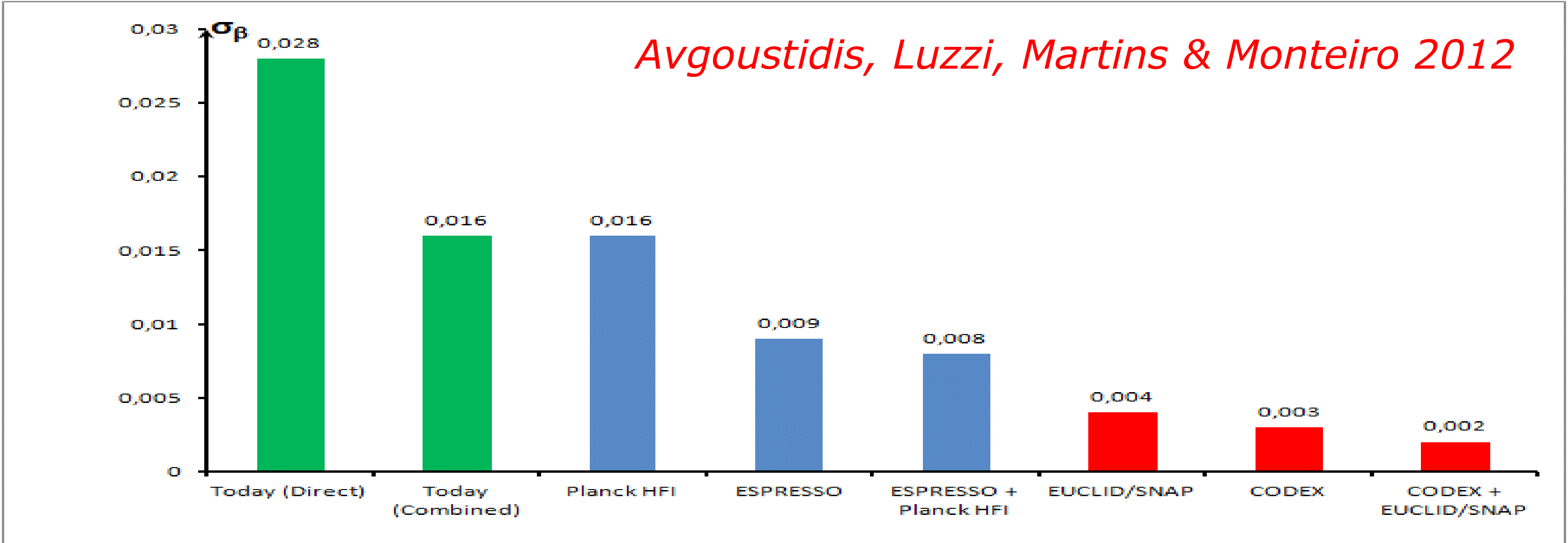
Equivalence Principle Tests



- Variations of α at few ppm level naturally lead to Weak Equivalence Principle violations within 1 order of magnitude of current bound on the Eotvos parameter *[Damour 2003]*
    - E.g., MICROSCOPE satellite should detect violations

A Consistency Test

- $T(z)=T_0(1+z)$ is a robust prediction of standard cosmology
  - Adiabatic expansion, photon number conservation
  - 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
  - If $d_L=(1+z)^{2+\varepsilon} d_A$, find $\varepsilon=-0.04\pm0.08$ *[Avgoustidis et al. 2010]*
- In such models $\beta=-2\varepsilon/3$, but the T-d_L relation is more generic: distance duality also constrains β



Avgoustidis, Luzzi, Martins & Monteiro 2012

Taxonomy: Class II

- Models where α field does not provide all dark energy can be identified via consistency tests *[Vielzeuf & Martins 2012]*
  - Examples include runaway dilaton models *[Damour et al. 2002 Vielzeuf & Martins 2014]* and Bekenstein-type toy models *[Sandvik et al. 2002, Leal, Martins & Ventura 2014]*
- For the latter class 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 may be relevant for Planck data analysis; also true for disformal couplings (but not for chameleons)
- 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 number non-conservation will change T(z), the distance duality relation, etc. How do these models weaken constraints on cosmological parameters?
- Euclid can (even on its own, if it does a SN survey) constrain dark energy while allowing for photon number non-conservation *[Avgoustidis et al. 2013]*
  - 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...

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 are less 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