Fundamental Cosmology in the E-ELT Era

(Part I: Theoretical motivation & the status quo)

Carlos.Martins@astro.up.pt

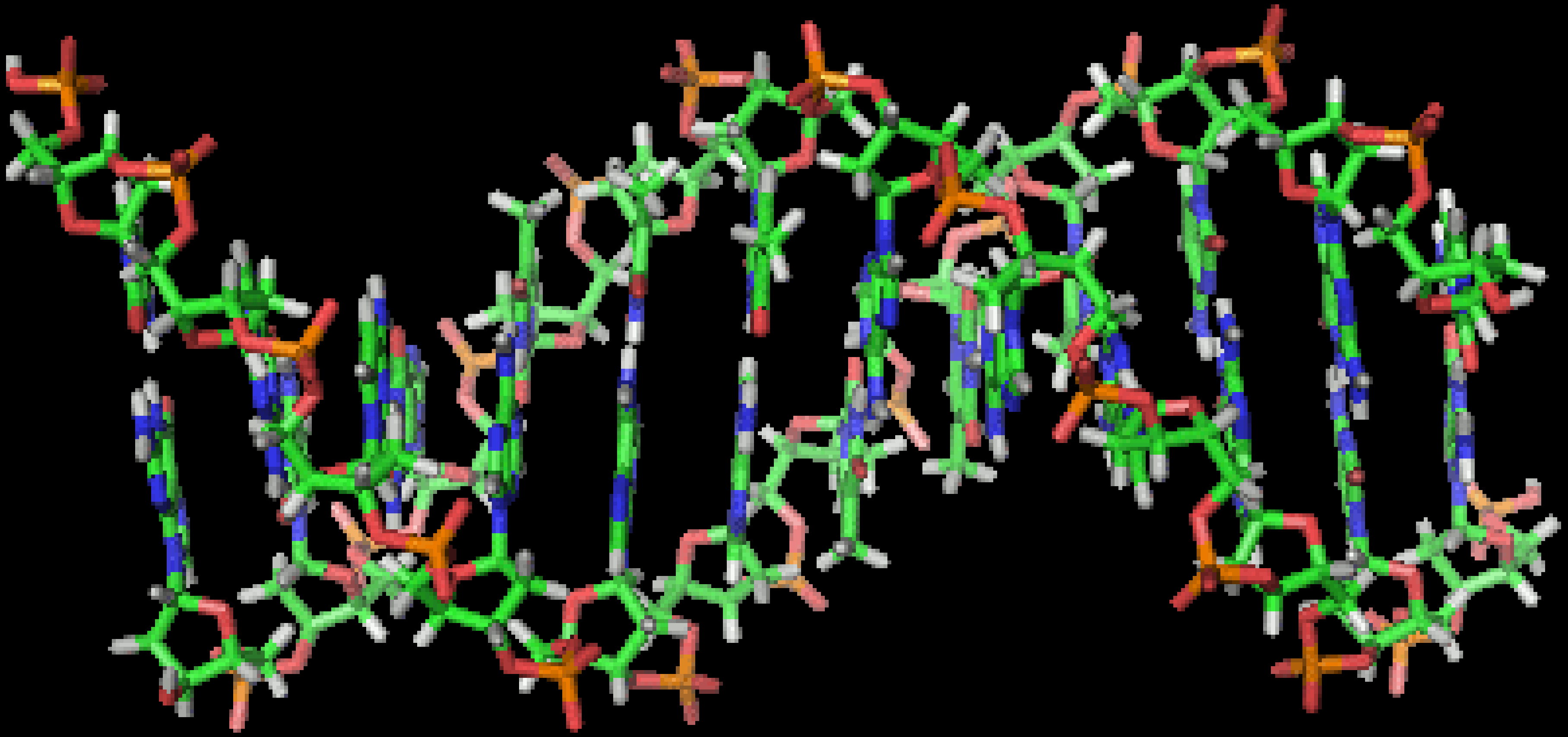
with Ana Catarina Leite, Ana Marta Pinho, Catarina Rocha, David Corre, Mar Pino, Max von Wietersheim, Miguel Ferreira, Rui Alves, and the UVES Fundamental Physics LP team

Erice, September 1996

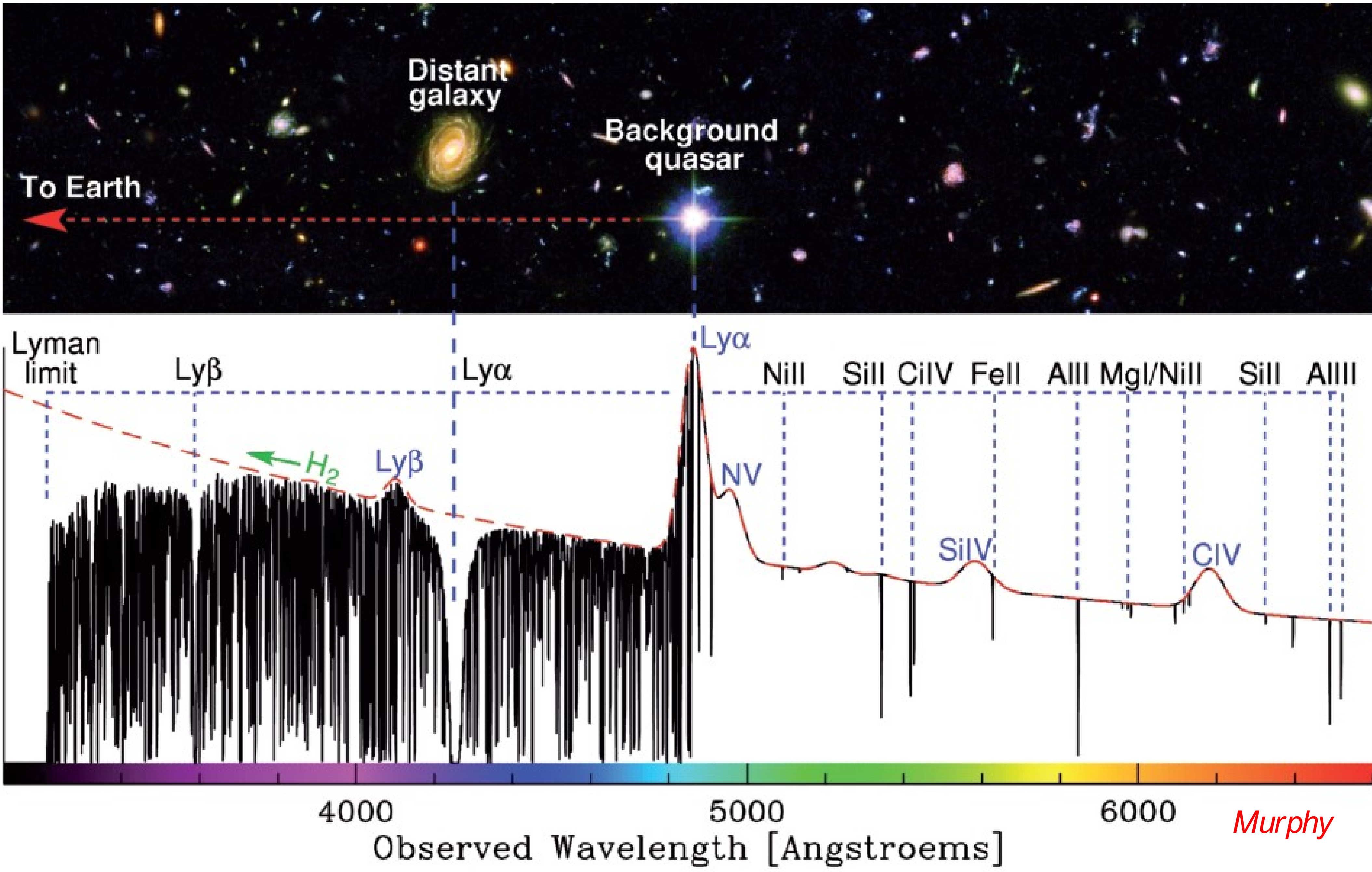
Is this a dog?

Is this a dog?

Precision Taxonomy



Precision Spectroscopy



So What's Your Point?

- Observational evidence for the acceleration of the universe shows that canonical theories of cosmology and particle physics are at least incomplete (and possibly incorrect)
- Is dark energy a cosmological constant (i.e. vacuum energy)?
  - If yes, it's 10^{120} times below Quantum Field Theory expectations
  - If no, the Einstein Equivalence Principle is violated
- New physics is out there, waiting to be discovered; the most pressing task for forthcoming astrophysical facilities is to search for, identify and characterize this new physics
- I will highlight the E-ELT's unique role in this quest
  - I will mostly focus on ELT-HIRES science
  - ...but will also say a few words about MICADO, HARMONI and synergies with other facilities (such as ALMA, Euclid and SKA)
  - Full disclosure: I'm a member of the E-ELT PST, ESPRESSO, Euclid, and the ELT-HIRES, COrE+ and eLISA collaborations

What is Fundamental Physics?

- Tests of fundamental laws/symmetries
  - Equivalence principle, Laws of Gravity, Spacetime structure and dimensionality, Foundations of quantum mechanics
- Search for/characterization of fundamental constituents
  - Scalar fields (Higgs, dark energy, …), new particles for dark matter, magnetic monopoles, fundamental strings, etc.
- Fundamental cosmology pursues these goals through astrophysical observations
- Fundamental theories (string theory, quantum gravity, extra dimensions, …) often lead to violations of standard principles
  - Space-time structure modified, violating Lorentz invariance
  - Fundamental couplings dynamical, violating Equivalence principle
  - Gravity laws modified at large and/or small scales

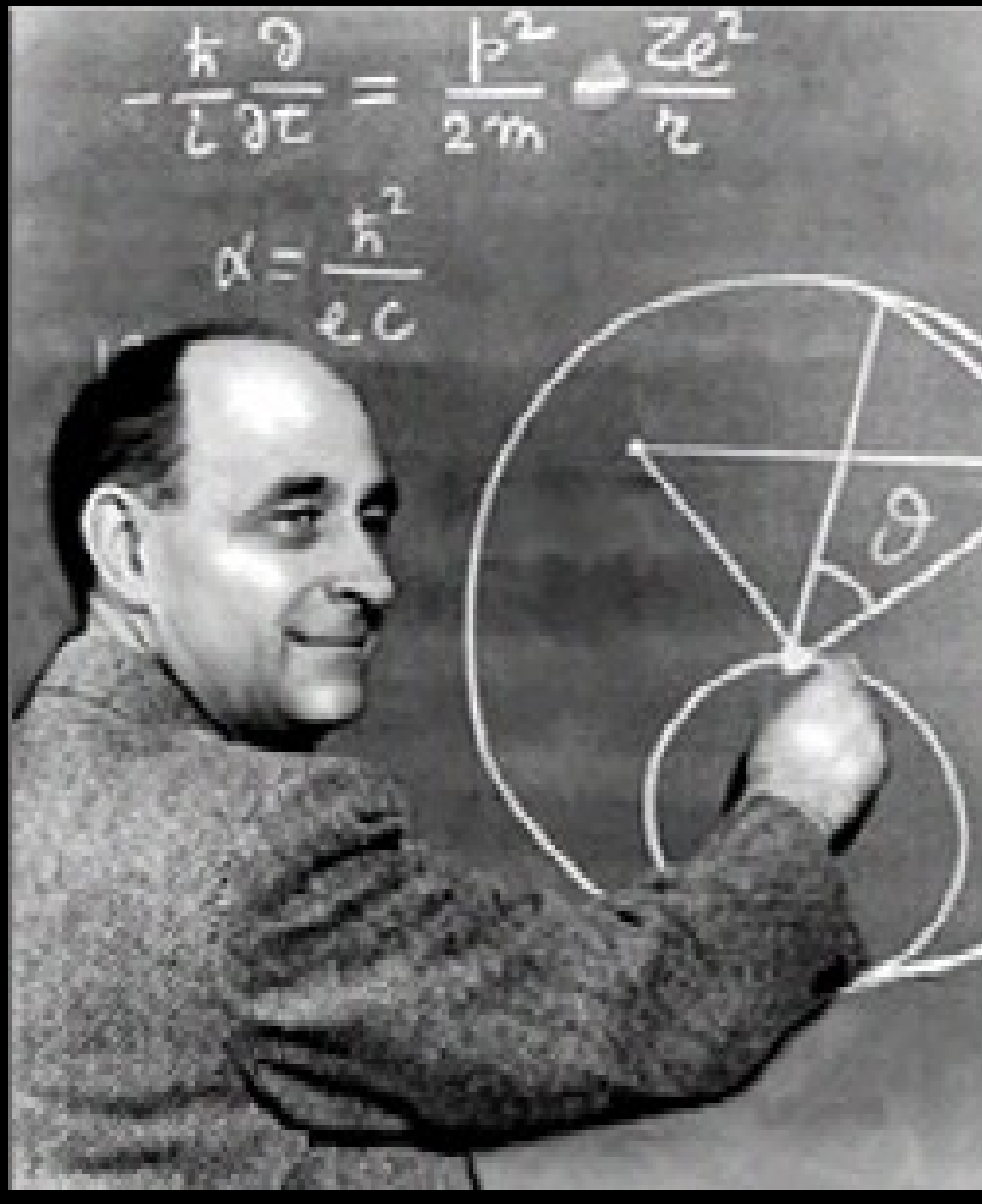
Hints of New Physics

- Three firmly established facts that the standard model of particle physics can't explain:
  - Neutrino masses: Key recent result in particle physics, needs new ad-hoc conservation law or phenomena beyond current framework
  - Dark matter: no Standard Model object can account for the dark matter required by observations
  - Size of baryon asymmetry: A BAU mechanism does exist, but fails given the measured values of the parameters controlling it
- Our confidence in the standard model that leads us to the expectation that there must be new physics beyond it
    - All have obvious astrophysical and cosmological implications!
- Progress in fundamental particle physics increasingly depends on progress in observational cosmology

Scalars, Because They're There

- Fundamental scalar fields are among Nature's building blocks
    - Does the Higgs have a cosmological counterpart?
    - Scalar fields are popular because they can preserve Lorentz invariance (vectors or fermions would break it, and give you problems with Special Relativity)
- 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 enables key consistency tests

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)

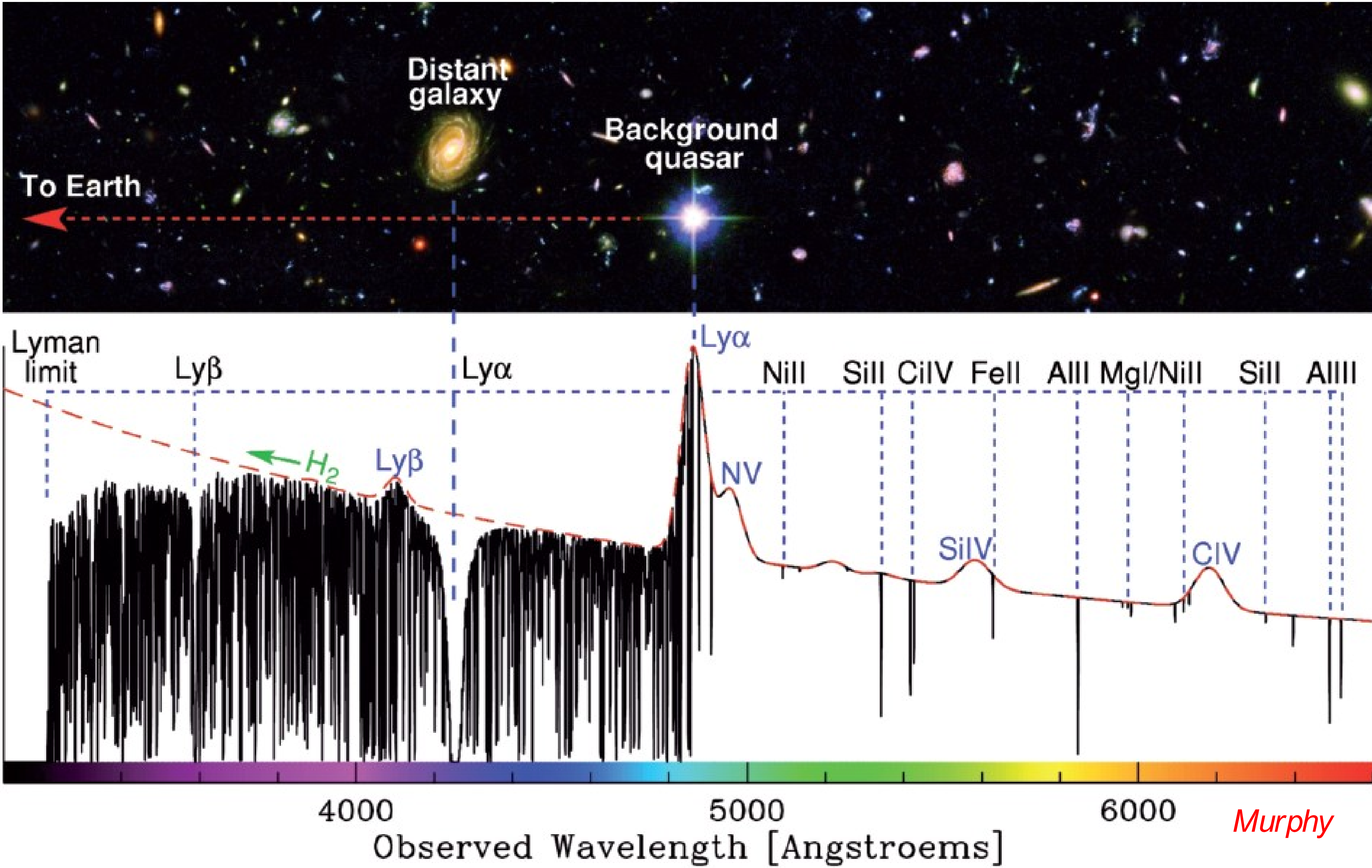
The Ratio of Proton and Electron Masses

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).

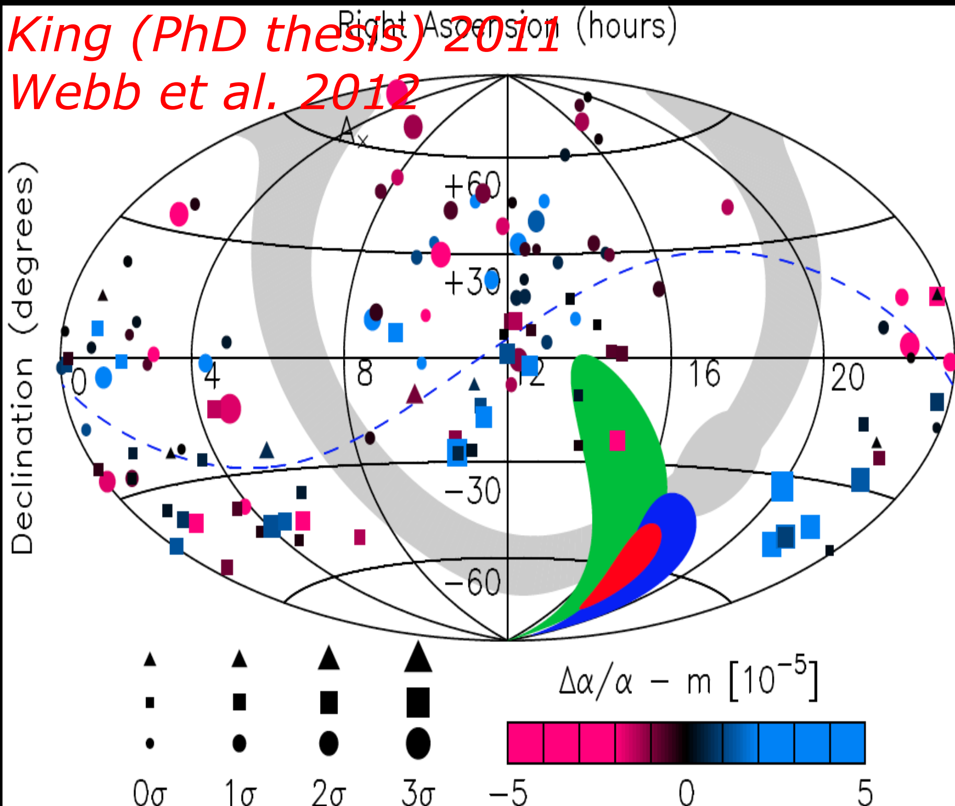
Measuring α from Quasars



Spectroscopic Constraints

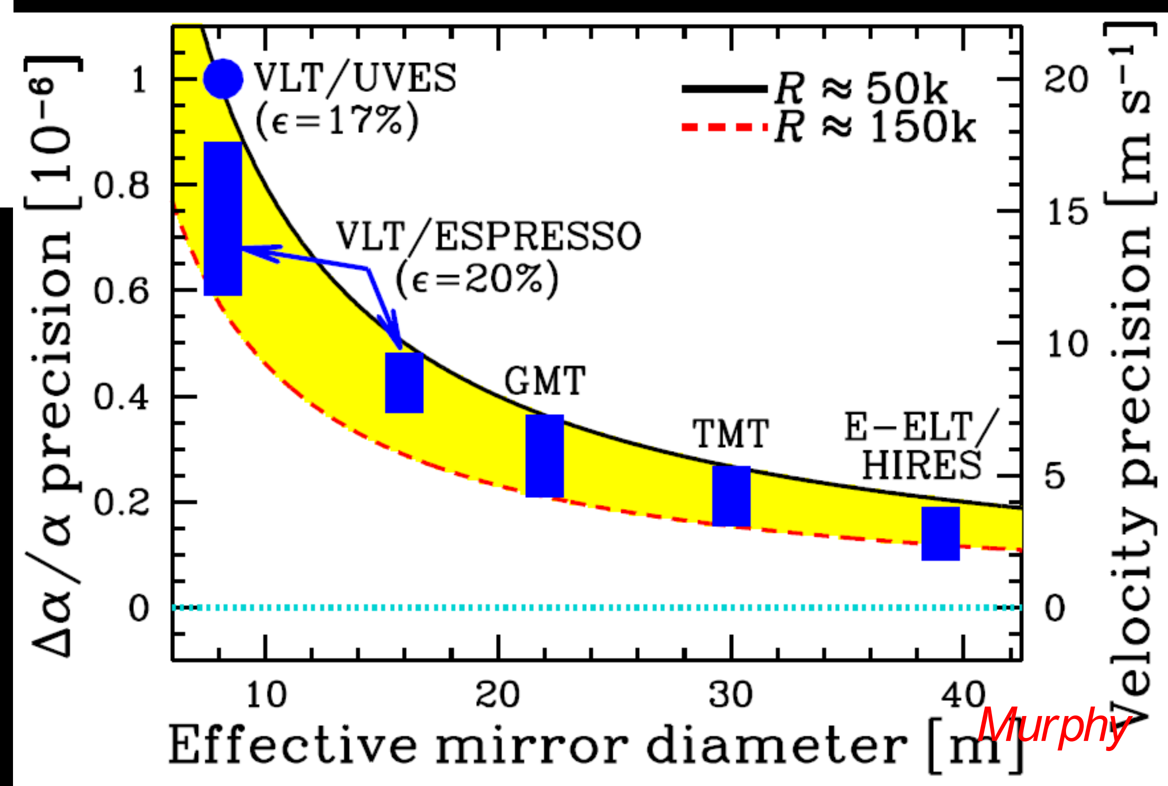
- α_{em}: Fine-structure doublet
- $\mu = m_p/m_e$: Molecular Rotational *vs.* Vibrational modes
- $\alpha_{em}^2 g_p$: Rotational modes *vs.* Hyperfine H
- $\alpha_{em} g_p \mu$: Hyperfine H *vs.* Fine-structure
- $\alpha_{em}^2 g_p \mu$: Hyperfine H *vs.* Optical
- …
- NB: Emission measurements are more straightforward than absorption ones, but much less sensitive *[Albareti et al. 2015]*; the available redshift range is similar *[Brinchmann et al. 2004, …]*

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



$\alpha(z)$, $\mu(z)$, $T(z)$ 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 – on which more tomorrow
- Molecular observations measure the inertial masses (not the gravitational ones) and they may or may not be probing μ...
  - H_2 measurements do probe m_p/m_e; more complicated molecules probe $m_{nuc}/m_e \sim$ few m_p/m_e: but beware composition-dependent forces!
  - The E-ELT could ultimately constrain these forces (H_2 vs HD vs …)

So What's Your Point?

- Wide range of possible α-μ-T relations makes this a unique discriminating tool between competing models
  - Sensitive probe of unification scenarios *[Coc et al. 2007, Luo et al. 2011, Ferreira et al. 2012, Ferreira et al. 2013, …]*

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

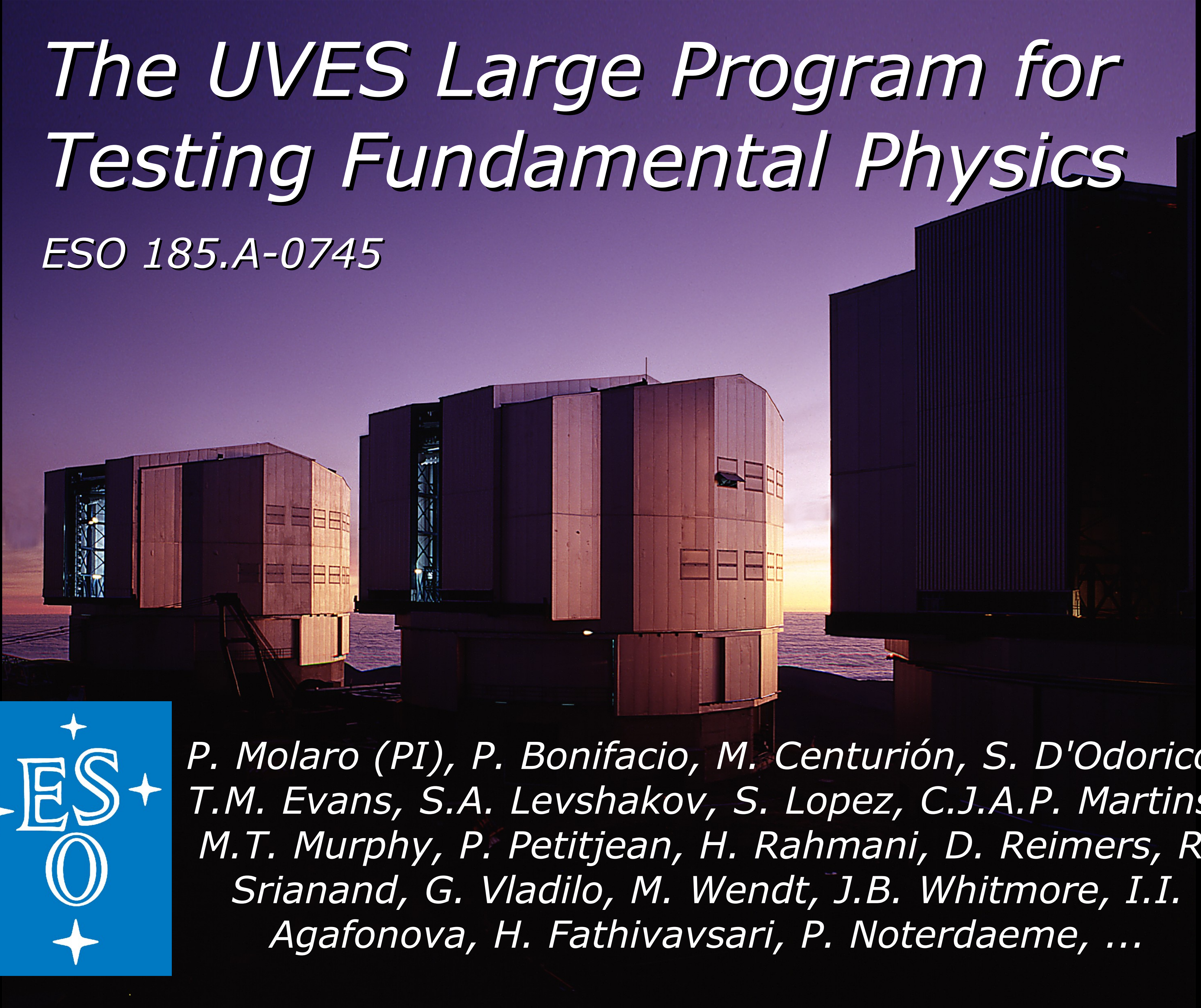
$$\frac{\Delta g_p}{g_p} = [0.10R - 0.04(1+S)]\frac{\Delta\alpha}{\alpha}$$

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

- Theoretically, not all targets are equally useful – must actively search for ideal ones (with ALMA, APEX, …), where
  - Several parameters can be measured simultaneously (e.g., μ+T relatively common both in optical/UV and radio/mm)
  - Occasionally can even measure α, μ and g_p in the same system
  - One or more parameters can be measured in several independent ways (e.g., μ measured from various molecules)

The UVES Large Program for Testing Fundamental Physics

ESO 185.A-0745

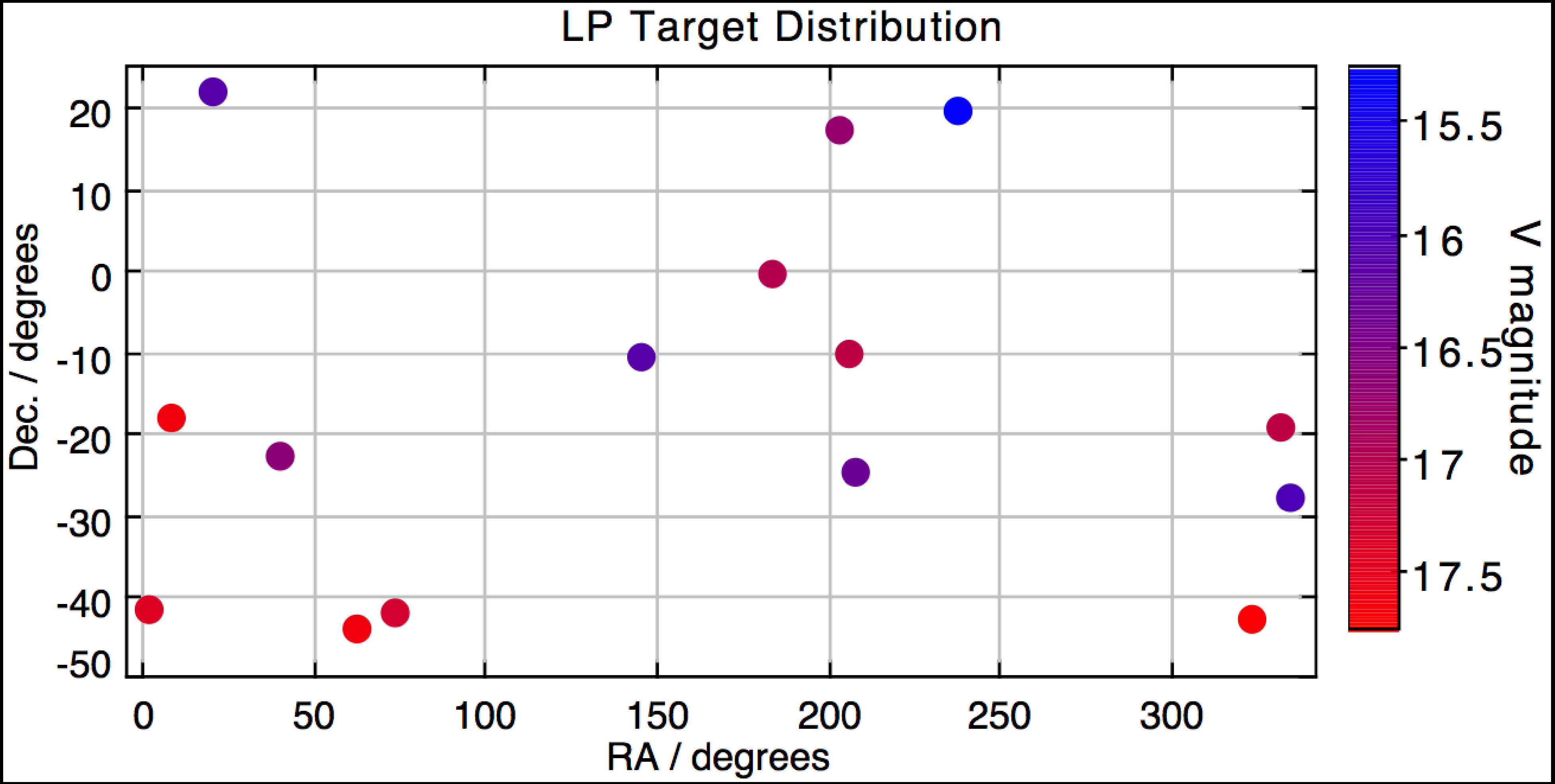


P. Molaro (PI), P. Bonifacio, M. Centurión, S. D'Odorico, T.M. Evans, S.A. Levshakov, S. Lopez, C.J.A.P. Martins, M.T. Murphy, P. Petitjean, H. Rahmani, D. Reimers, R. Srianand, G. Vladilo, M. Wendt, J.B. Whitmore, I.I. Agafonova, H. Fathivavsari, P. Noterdaeme, ...

LP Plan & Goals

- Only large (ca. 40 nights) program dedicated to varying couplings, with optimized sample & methodology
  - 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 active observational groups involved
  - Also compare/check/optimize different analysis pipelines
  - Introduce blind analysis techniques

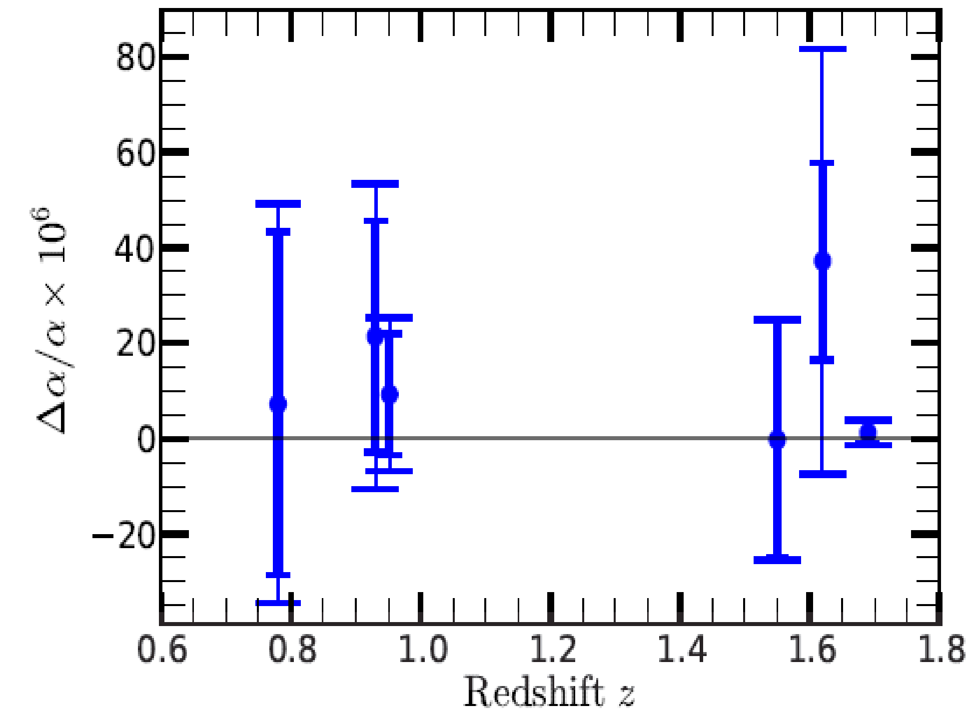
Target Selection & Status



- Selected before dipole was known *[Bonifacio et al. 2014]*
  - 13 targets for α, 2 targets for μ (QSO 0405-443, HE 0027-1836)
  - Already out: HE2217-2818, HE0027-1836 and HS1519+1919

Understanding the Data

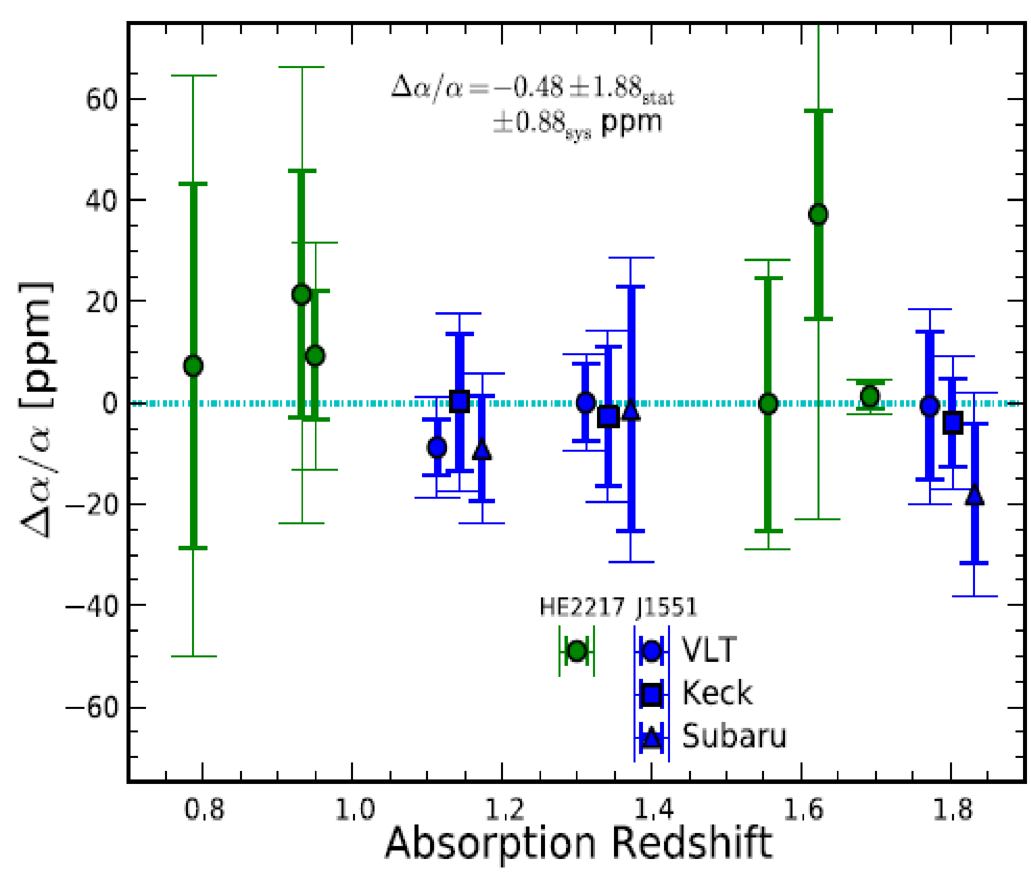
- HE2217-2818, z_{abs}~1.69:
  $\Delta\alpha/\alpha$ = 1.3 $\pm$ 2.4$_{sta}$ $\pm$ 1.0$_{sys}$ ppm
  - Paper I: P. Molaro et al., A&A 555 (2013) A68
  - Dipole fit: (3.2–5.4)±1.7 ppm depending on model; our measurement does not confirm this, but is not inconsistent with it either



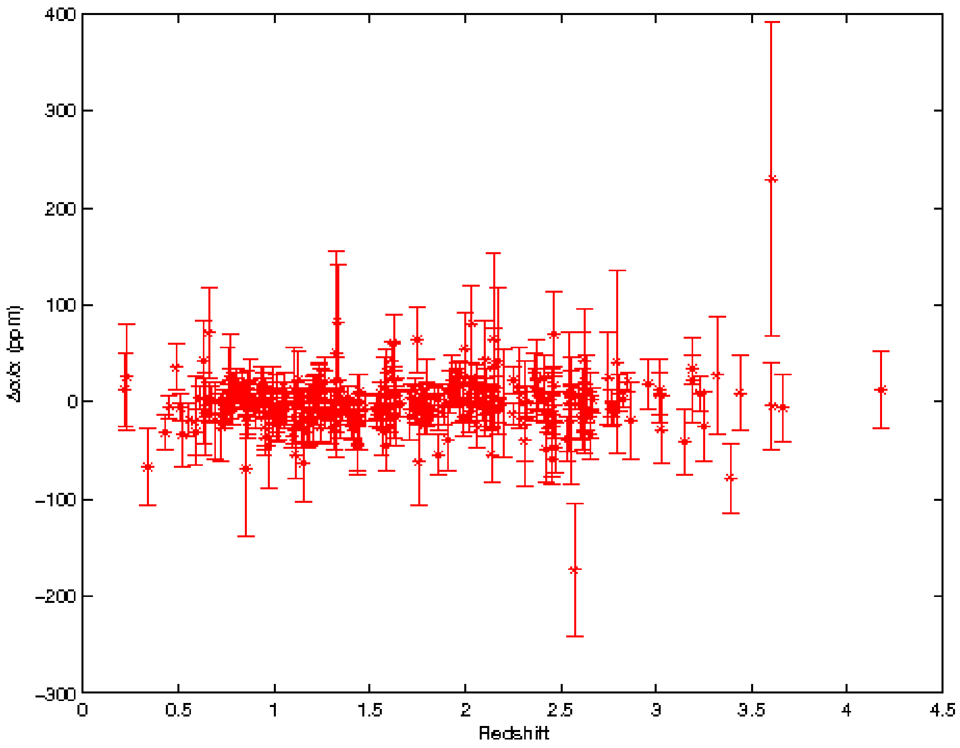
- HE0027-1836, z_{abs}~2.40: $\Delta\mu/\mu$ = -7.6 $\pm$ 8.1$_{sta}$ $\pm$ 6.3$_{sys}$ ppm
  - Paper II: H. Rahmani et al., MNRAS 435 (2013) 861
  - Identified wavelength-dependent velocity drift (corrected with bright asteroid data)
- Bottleneck: intra-order distortions (~200m/s) & long-range distortions on UVES, discussed in *[Whitmore & Murphy 2015]*
  - 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 data allows removal of long-range distortions
- Current status: compatible with null result and dipole…
  - Full sample analysis ongoing
  - Additional papers should be appearing soon – watch this space…

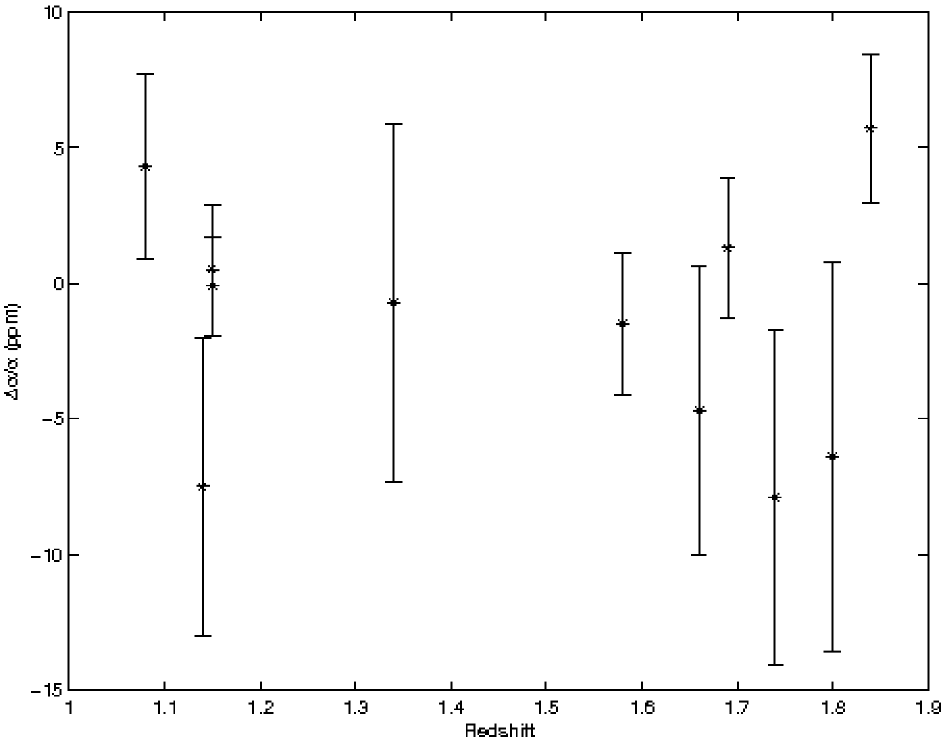


From 2010 to 2015



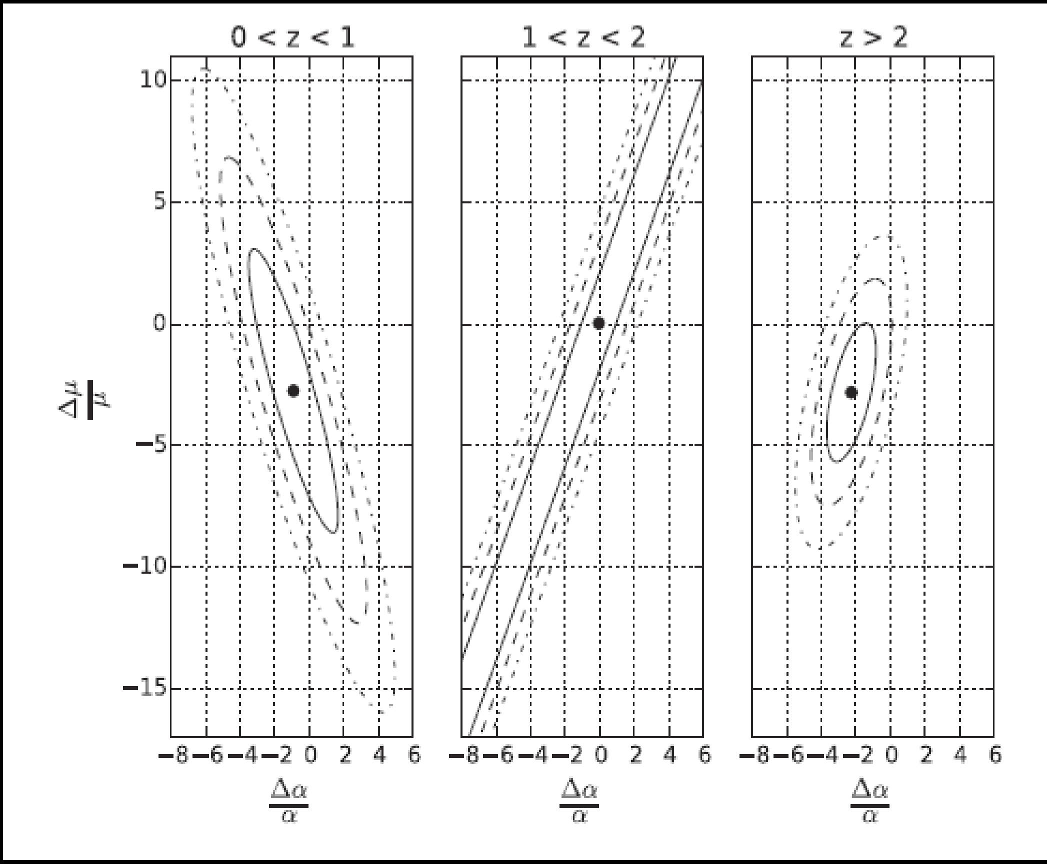
- *Webb et al. 2011*
  - 293 archival absorbers
  - Nominal weighted mean $\sigma_{stat} \sim 2$ ppm
  - ...but inferred $\sigma_{sys} \sim 9$ ppm

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



Consistency Tests

- α and μ can be measured in the UV/optical; in the radio/mm one usually measures combinations
  - μ measurements in radio currently restricted to 2 targets at z<1
  - ppm sensitivity nominally easier in the radio, though at significantly lower redshift



- Radio sensitivity even better within the Galaxy (i.e., at z=0), where one can search for environmental dependencies
  - No variation at 0.1 ppm level for α *[João et al. 2015]*
  - No variation at 0.05 ppm level for μ *[Levshakov et al. 2013]*

Consistency Tests

TABLE V. One-dimensional marginalized two-sigma constraints for μ and g_p, for the data in Table I, assuming Eq. (6) as prior on α, for the full sample and various redshift bins. All constraints are in ppm.

Sample	$\Delta\mu/\mu$	$\Delta g_p/g_p$
$0 < z < 1$	-0.1 ± 6.8	-2.5 ± 4.5
$z > 1$	-3.1 ± 5.9	-4.2 ± 6.7
$0 < z < 2$	-1.1 ± 3.6	-1.9 ± 3.2
$z > 2$	-3.1 ± 5.9	-5.6 ± 8.6
Full	-3.3 ± 3.3	-4.2 ± 3.6

TABLE VI. One-dimensional marginalized two-sigma constraints for α and g_p, for the data in Table I, assuming Eqs. (7)–(8) as low- and high-redshift priors on μ, for the full sample and various redshift bins. All constraints are in ppm.

Sample	$\Delta\alpha/\alpha$	$\Delta g_p/g_p$
$0 < z < 1$	0.5 ± 7.6	-2.8 ± 16.6
$z > 1$	-2.9 ± 3.0	8.9 ± 6.9
$0 < z < 2$	-0.1 ± 7.4	-0.6 ± 15.2
$z > 2$	-2.9 ± 3.0	7.5 ± 8.9
Full	-4.0 ± 3.3	6.9 ± 7.5

- Joint analysis of optical/UV and radio/mm data yields ~2-sigma inconsistencies
  - Details are in *[Ferreira & Martins 2015]*
- This is especially true for measurements deep in the matter era (z>1)
  - Hidden systematics is the likely explanation, but this should be clarified with ALMA and ESPRESSO
  - Must find μ targets in the radio/mm (a task for APEX or ALMA)

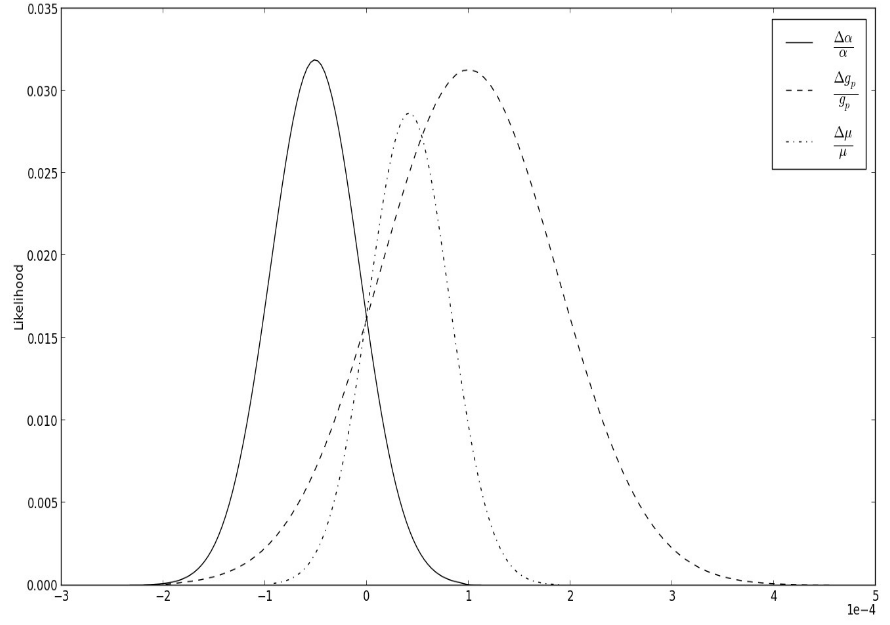
PKS1413+135

- Edge-on radio source at z=0.247, only currently known target to yield individual constraints on α, μ and g_p
  - Current sensitivity too poor to test the spatial dipole scenario

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



- Taken at face value, yields marginalized constraints on unification parameters R=277±24, S=742±65
- Well worth another look!

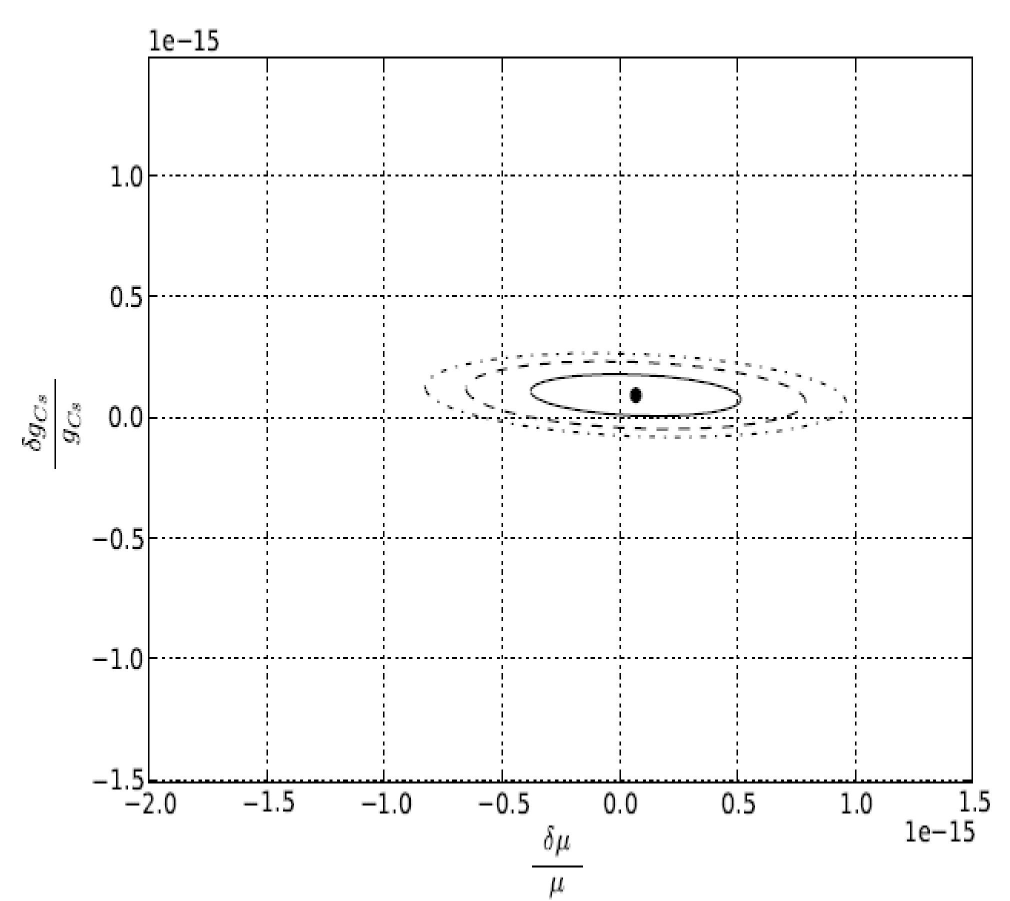
What's Taking You So Long?

- 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, ...]*
- A new generation of high-resolution, ultra-stable spectrographs has these measurements as key driver
  - 2017: ESPRESSO@VLT (1 or 4 UT), >2025: ELT-HIRES
  - NB: To fully exploit ELT sensitivity, lab wavelengths of most atomic/molecular transitions will need to be re-measured

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]



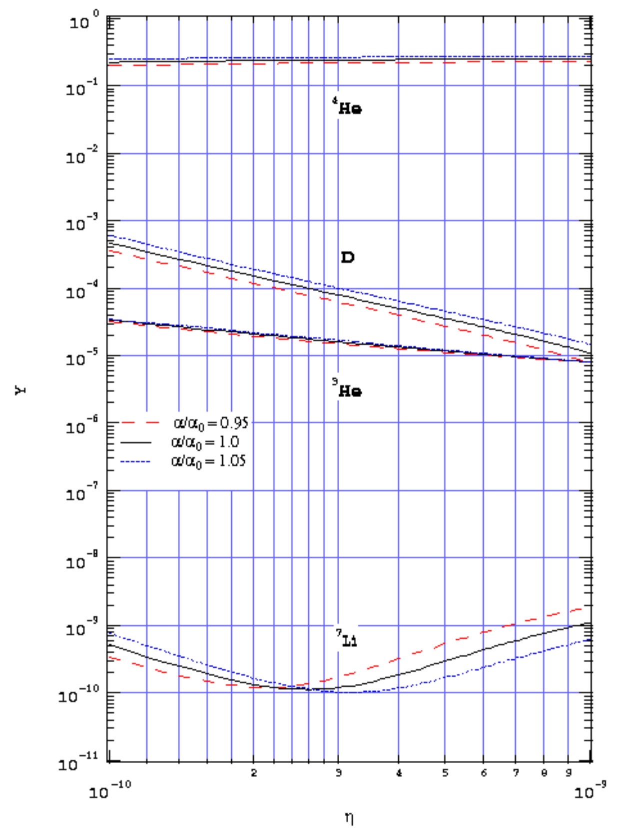
[See Ferreira, Julião, Martins & Monteiro, PRD86 (2012) 125025]

Low-redshift Constraints

- Atomic clocks: sensitivity of few$\times10^{-17}$/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 ~few$\times10^{-5}$
  - Neutron stars *[Pérez-García & Martins 2012]*, sensitivity ~10^{-4}
  - Solar-type stars *[Vieira et al. 2012]*, sensitivity ~10^{-4} or better?
  - White dwarf measurements of α and μ *[Berengut et al. 2013, Bagdonaite et al. 2014]*, sensitivity ~10^{-4}
- Oklo (natural nuclear reactor, z~0.14): nominal sensitivity of few$\times10^{-8}$ *[Davis et al. 2014],* but not a 'clean' measurement
  - Assumptions somewhat simplistic; effectively constrains α_s
- Clusters (z<1): SZ plus X-ray data: 0.8% sensitivity *[Galli 2013]*
  - Possibly competitive with much larger numbers (e.g., with COrE+)

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 nominally 0.4%
- Constraints can be obtained from BBN, 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.]*
  - Li problem could be removed in some GUT scenarios *[Stern (PhD thesis) 2008]*, but an in-depth analysis remains to be done



So What's Your Point?

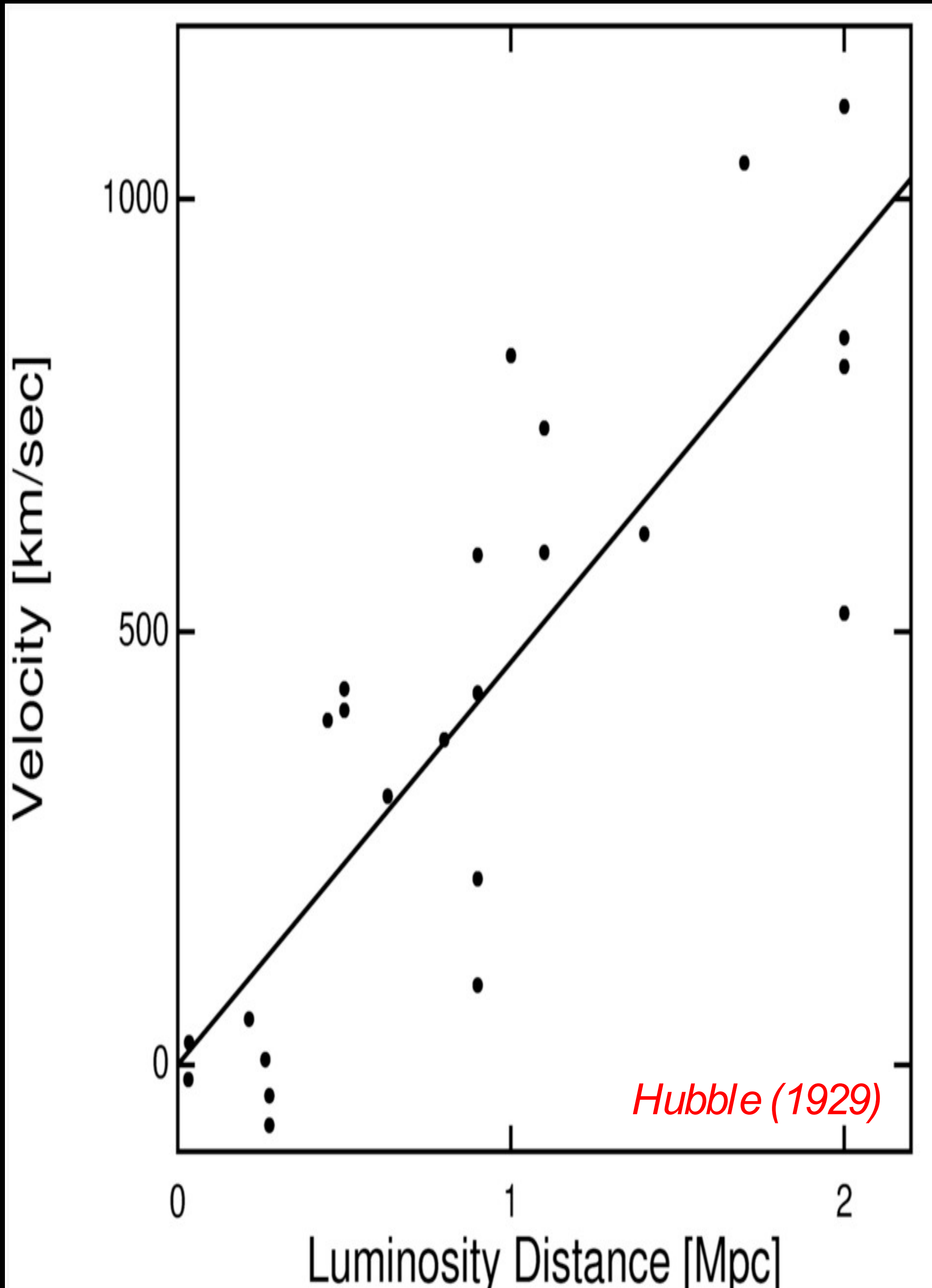
- We now know (from the LHC) that fundamental scalar fields are among Nature's building blocks
  - ...and that fundamental couplings run with energy
- These fields will naturally couple to the rest of the model
  - (unless there is an unknown principle to suppress them)
  - Couplings can therefore roll 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'
  - I'll show you how tomorrow…

Fundamental Cosmology in the E-ELT Era

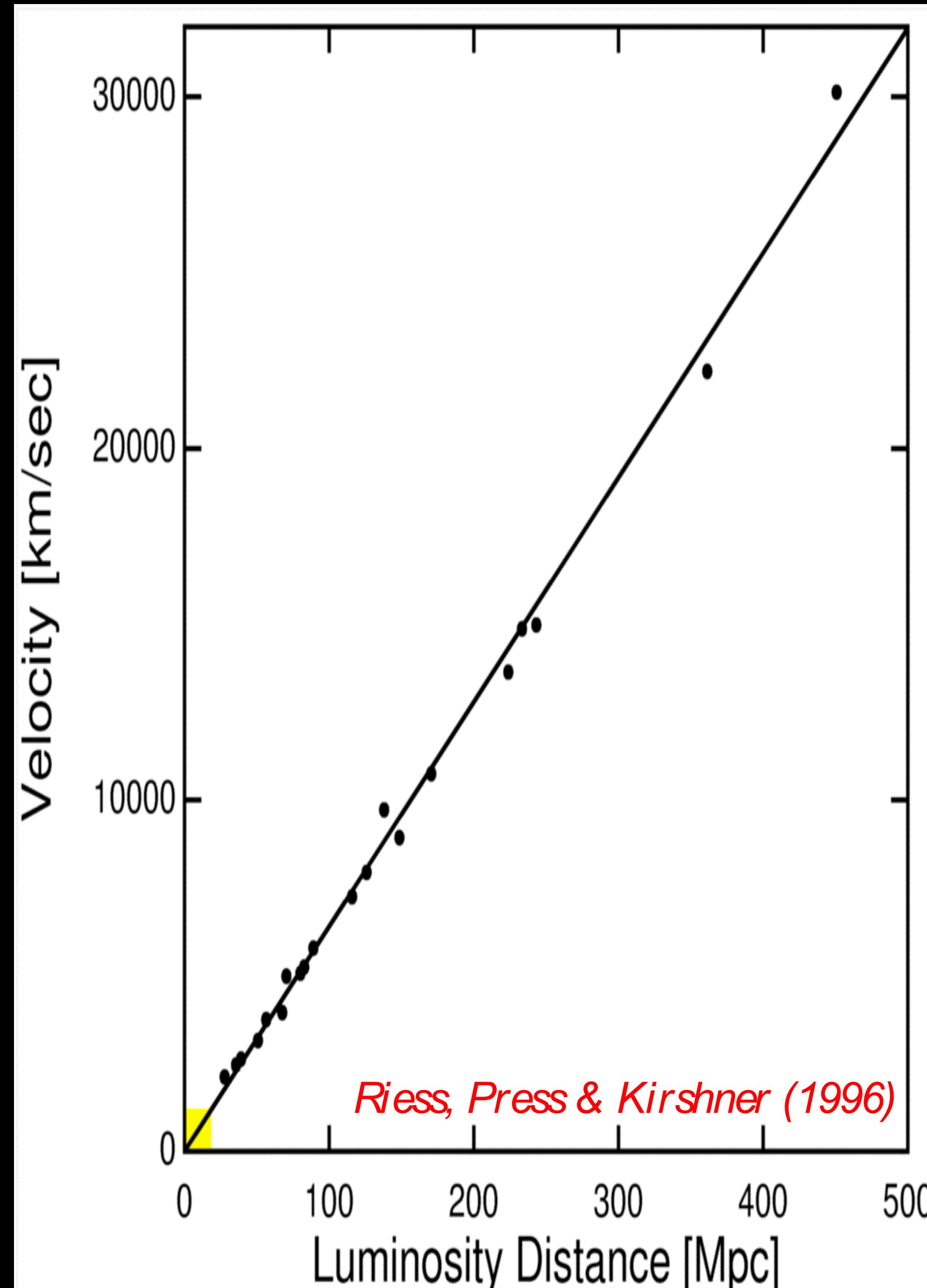
(Part II: The dark side, the E-ELT & the road ahead)

Carlos.Martins@astro.up.pt

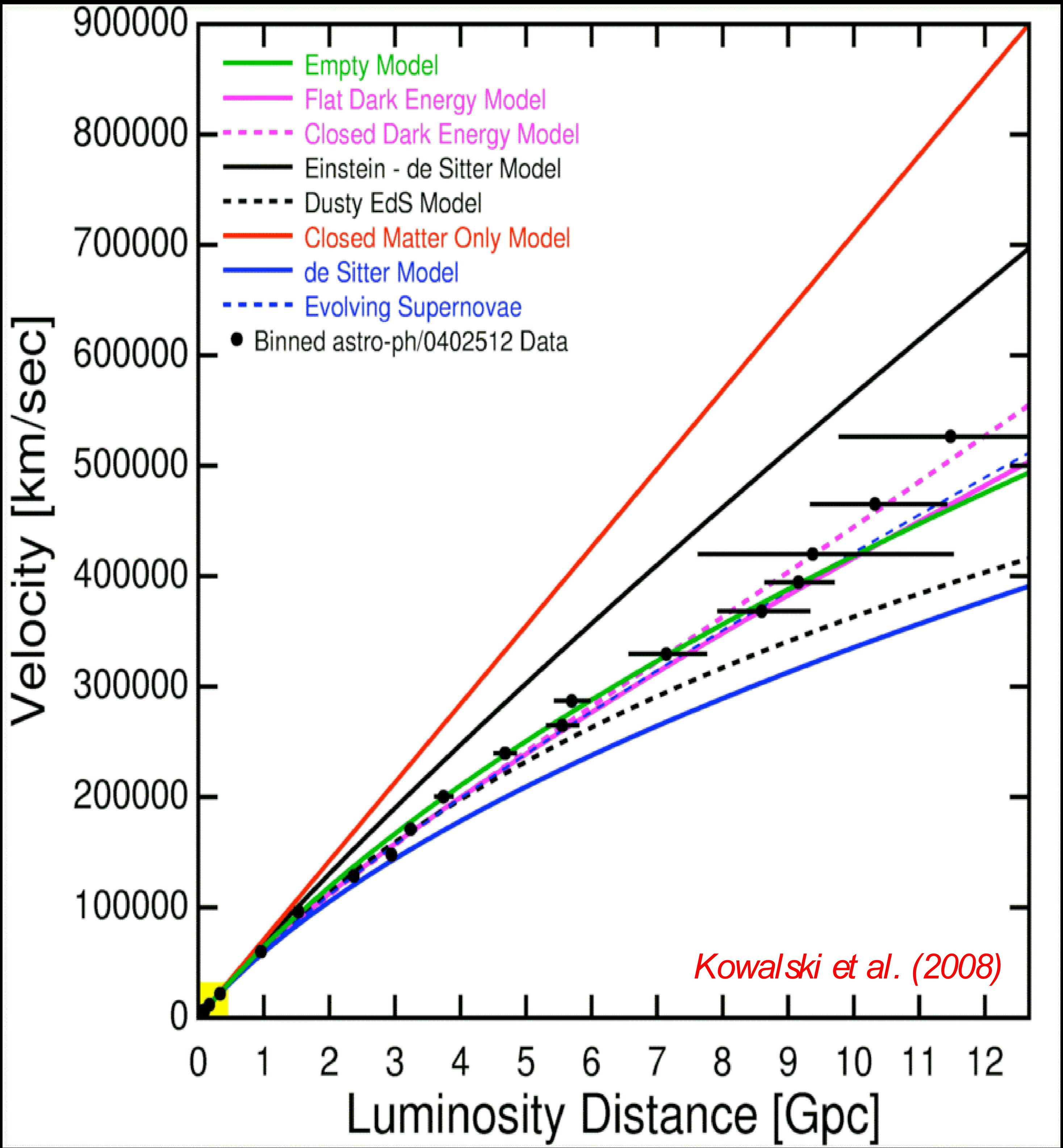
with Ana Catarina Leite, Ana Marta Pinho, Catarina Rocha, David Corre, Mar Pino, Max von Wietersheim, Miguel Ferreira, Rui Alves, and the UVES Fundamental Physics LP team



Velocity [km/sec]
1000
500
0
0
1
2
Luminosity Distance [Mpc]
Hubble (1929)



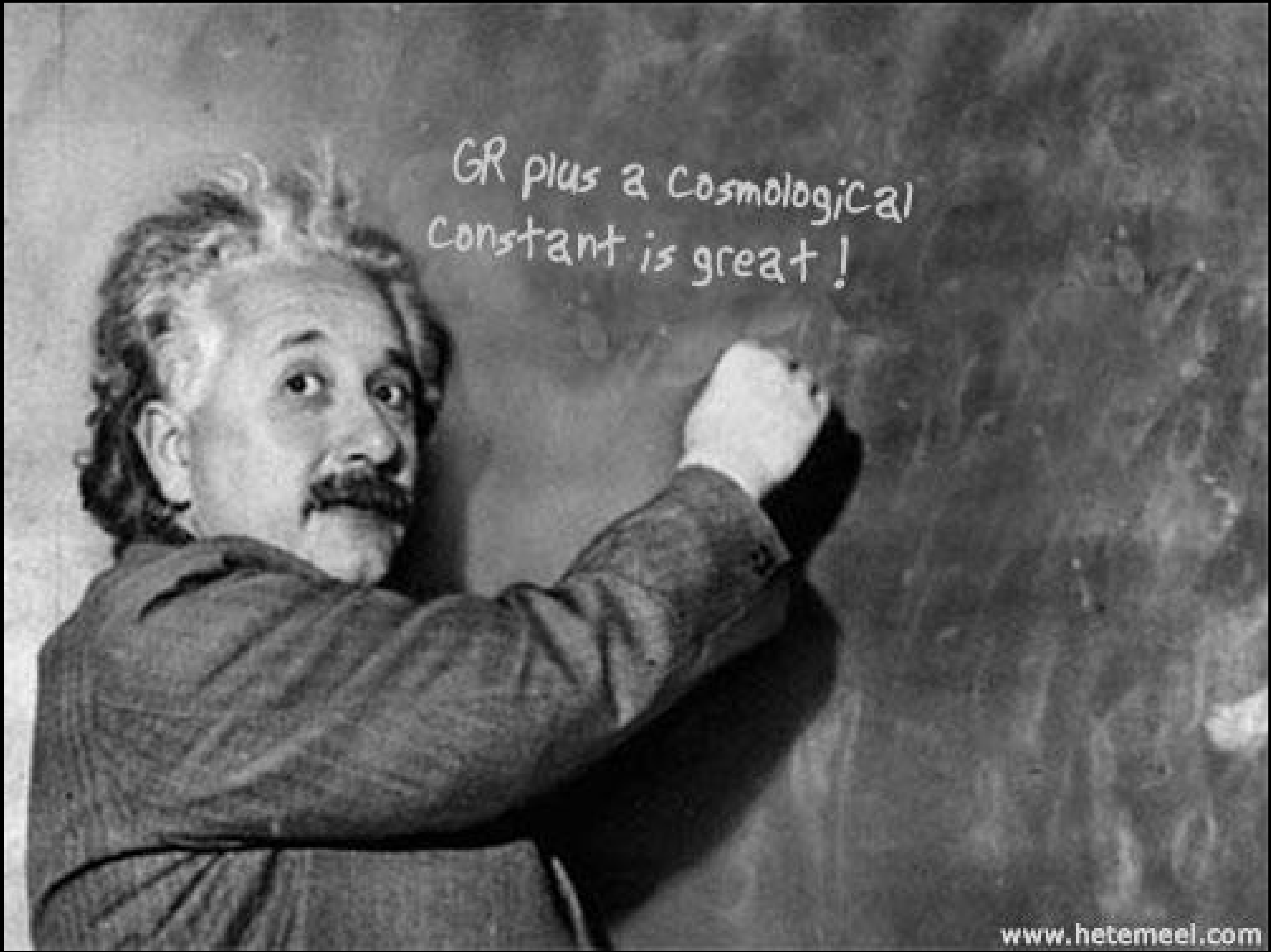
Velocity [km/sec]
30000
20000
10000
0
0
100
200
300
400
500
Luminosity Distance [Mpc]
Riess, Press & Kirshner (1996)


Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned astro-ph/0402512 Data
Kowalski et al. (2008)
Velocity [km/sec]
Luminosity Distance [Gpc]
0
100000
200000
300000
400000
500000
600000
700000
800000
900000
0 1 2 3 4 5 6 7 8 9 10 11 12

Some Matters of Gravity

- ca. 300 BC: Gravity is always attractive. How do we avoid that the sky falls on our heads?
  - Aristotle's answer: A fifth element (a.k.a. aether)
- ca. 1692: Gravity is always attractive. How do we avoid that the stars fall on our heads?
  - Newton's answer: God's initial conditions
- ca. 1917: Gravity is always attractive. How do we avoid that the Universe falls on our heads?
  - Einstein's answer: A cosmological constant modifies GR and prevents collapse, making the universe (nominally) stable

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 dominating the dynamics around the present day
- Couplings of this field will lead to observable long-range forces and varying 'constants' *[Carroll 1998, Wetterich 1998, Damour 2004, …]*
  - Current measurements already provide competitive constraints on fundamental physics and cosmology
  - Minimum guaranteed science for ESPRESSO & ELT-HIRES

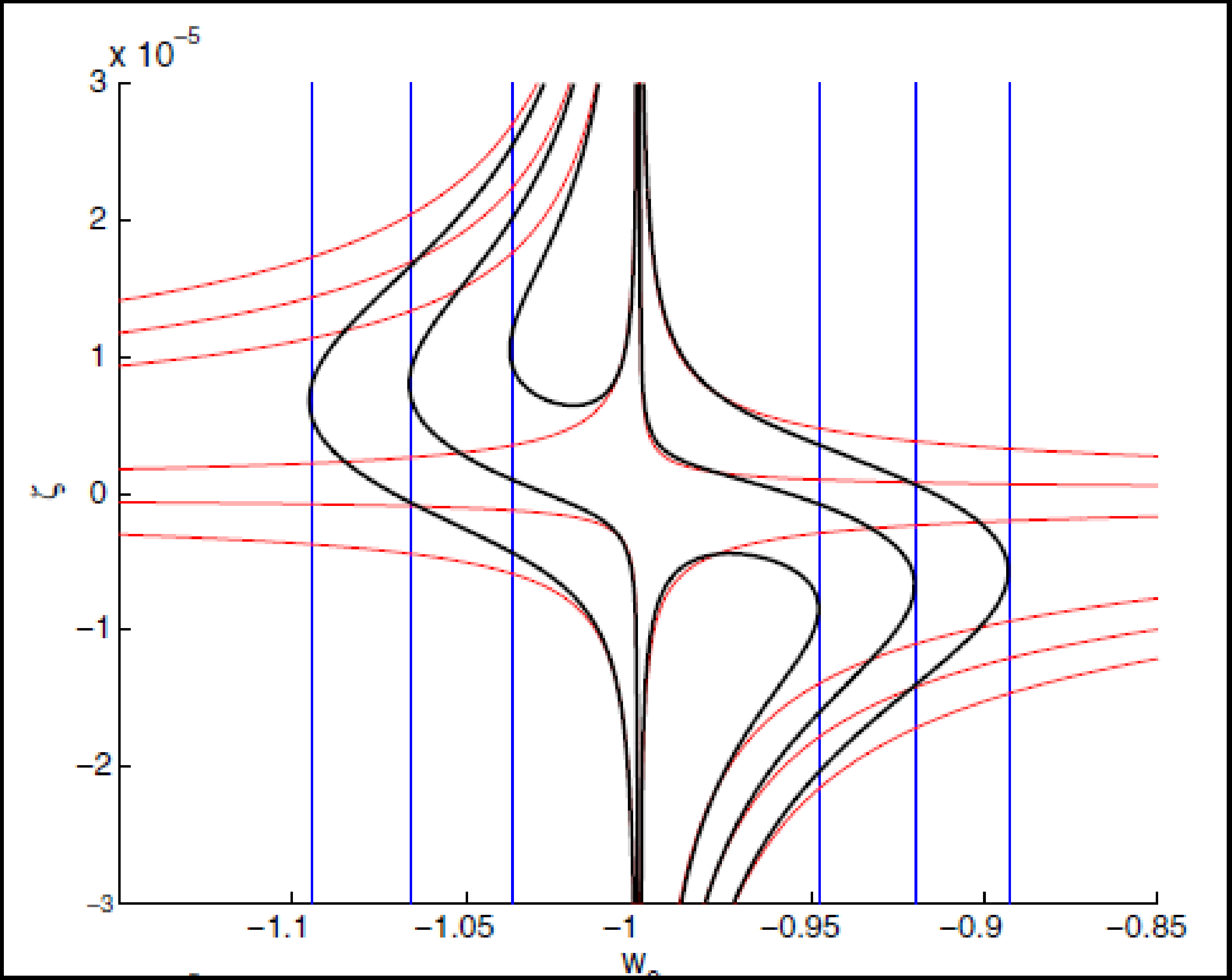
To Couple or Not To Couple

- Any scalar field couples to gravity; it couples to nothing else if a global symmetry $\phi \longrightarrow \phi + $ const. suppresses couplings to the rest of the Lagrangian
  - (If so, only derivatives and derivative couplings will survive)
- Quantum gravity effects don't respect global symmetries, and there's no unbroken global symmetries in (the theory formerly known as) string theory
- Any scalars in the theory will couple to the rest of the model, unless a new (currently unknown) symmetry is postulated

Taxonomy: Class I

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

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



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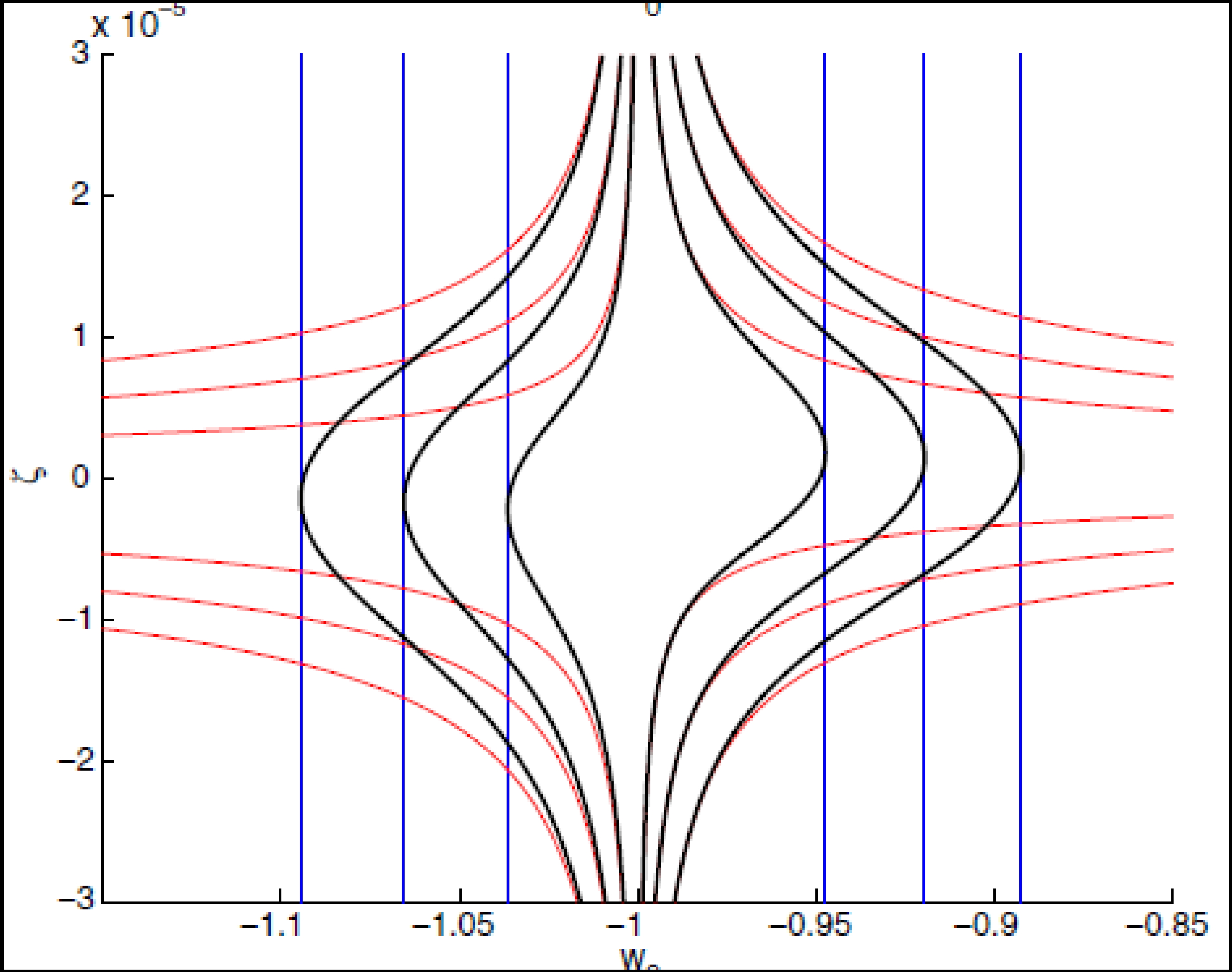

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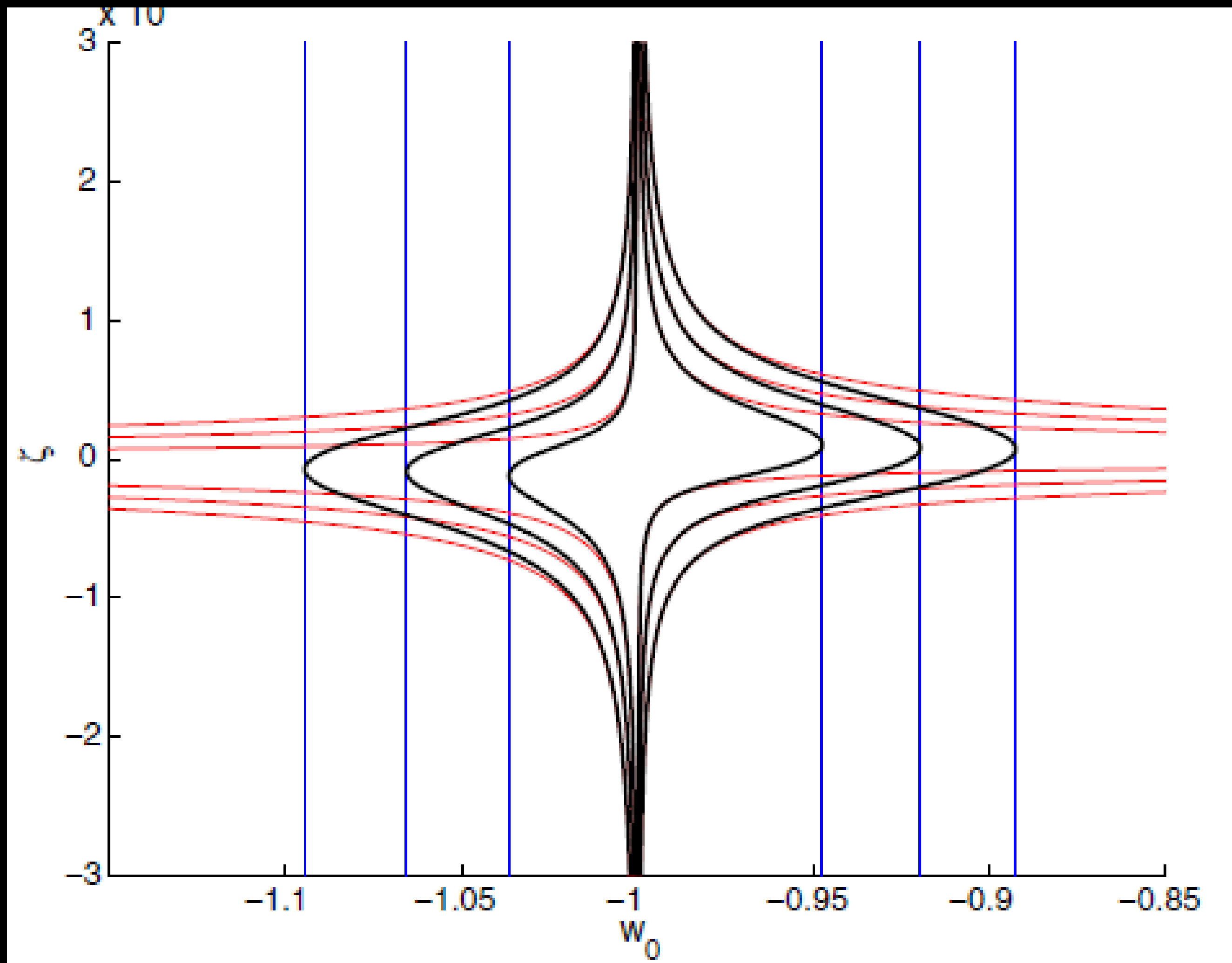

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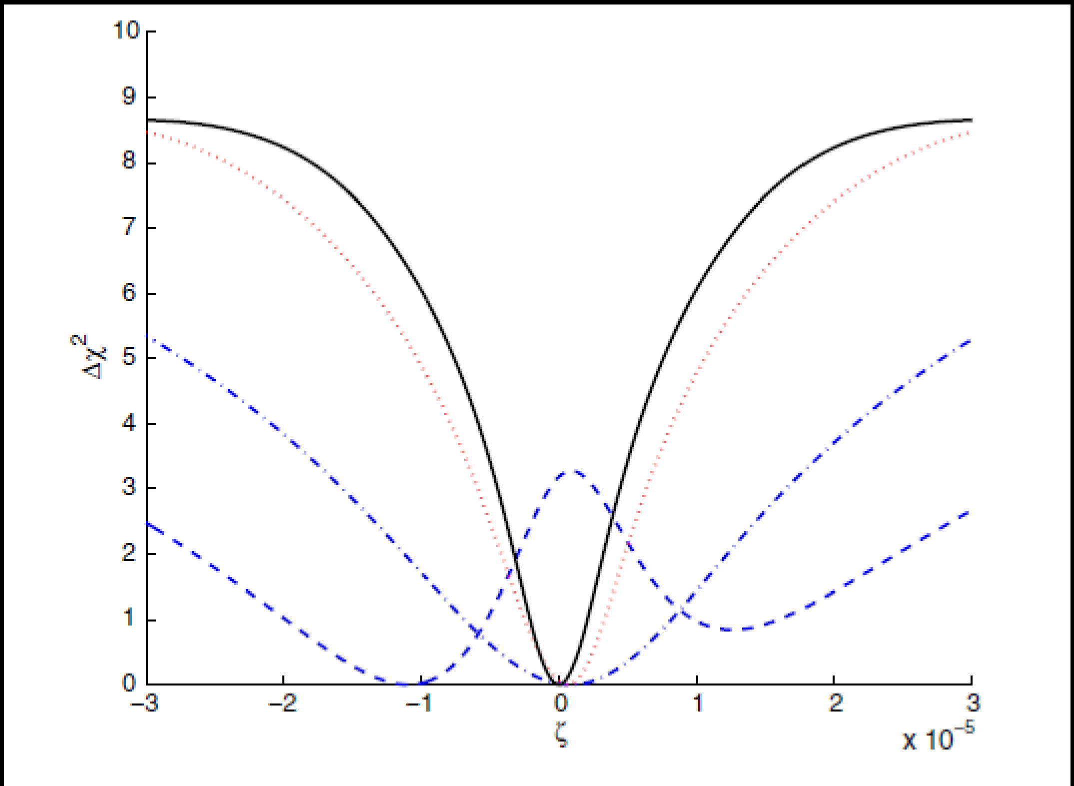

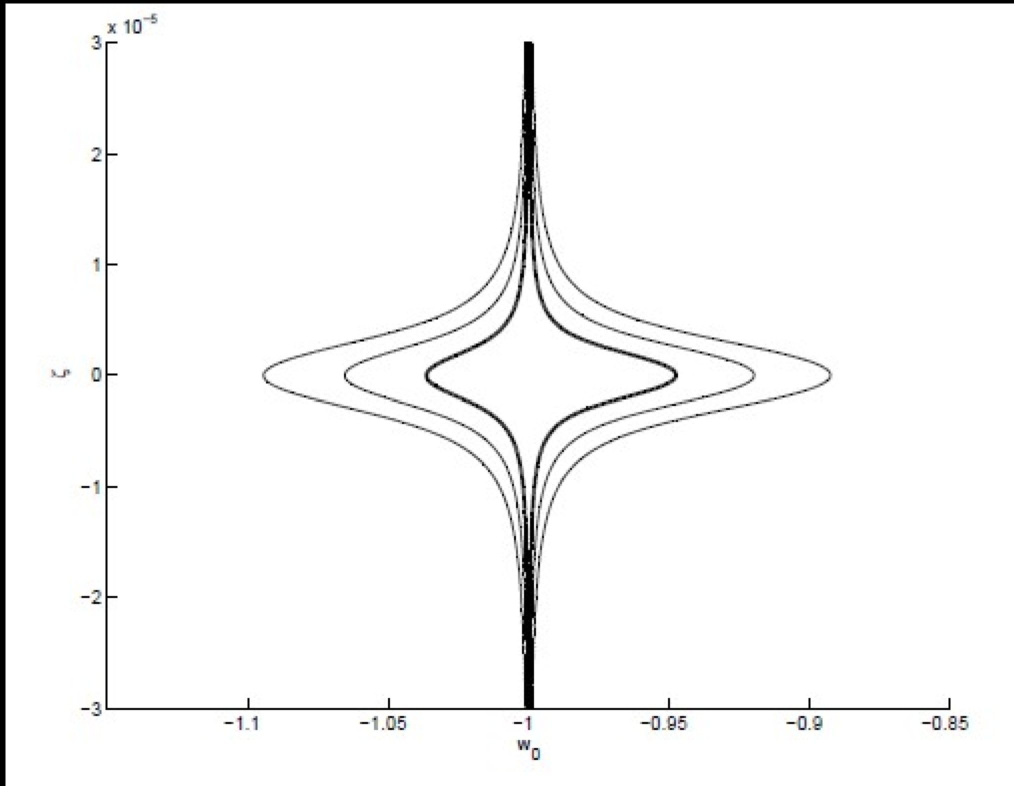

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  - 12 ESPRESSO GTO measurements (cf. Ana Catarina Leite's talk): $|\zeta| < 3\times10^{-6}$ (2 sigma) and $|1+w_0| < 0.04$ (3 sigma)
  - …or >3 sigma detection of ζ
- Bound on Eotvos parameter $\eta < 3\times10^{-14}$ *[Martins et al. 2015]*
  - Cf. *[Dvali & Zaldarriaga 2002, Chiba & Kohri 2002, Uzan 2011, …]*
  - > 10x tighter than direct bounds (but testable by MICROSCOPE)
  - ESPRESSO can reach few$\times10^{-16}$ (better than MICROSCOPE)
  - ELT-HIRES η sensitivity similar to that of the proposed STEP

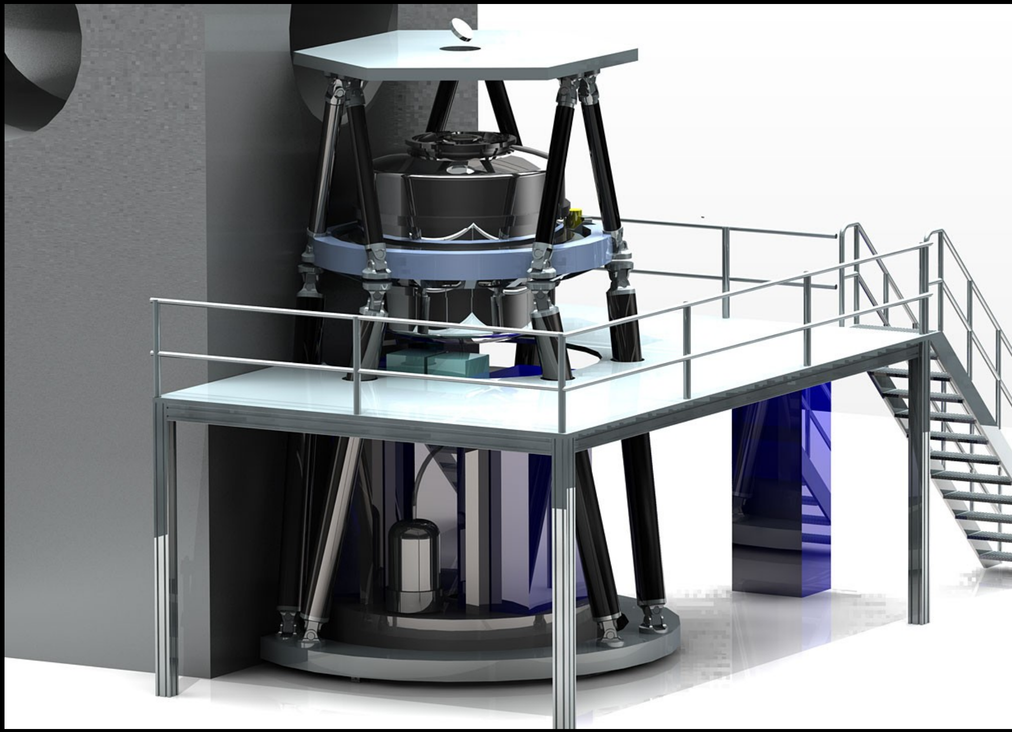
Strong Gravity

- GR well tested in weak field regime (table-top, solar system, pulsars), but two strong-field effects have no weak-field limit
  - Presence of a horizon around collapsed objects
  - No stable circular orbits near a black hole or neutron star
- Strong-field tests of gravity are crucial, and the Galactic Centre is an ideal environment in which to do it
  - Direct test of metric theories (e.g., Kerr black hole solution is not unique to General Relativity)
  - May provide further insight on the nature of spacetime (GR is classical, and may break down in this limit)
- In GR, post-Newtonian effects depend exclusively on distance from center; in alternative theories other factors play a role
  - The closer one gets to the center the stronger the constraints, and the higher the chances of identifying new physics
  - Horizon size of Schwarzschild $4x10^6M_o$ black hole at GC is ~10 μas

Strong Gravity with MICADO

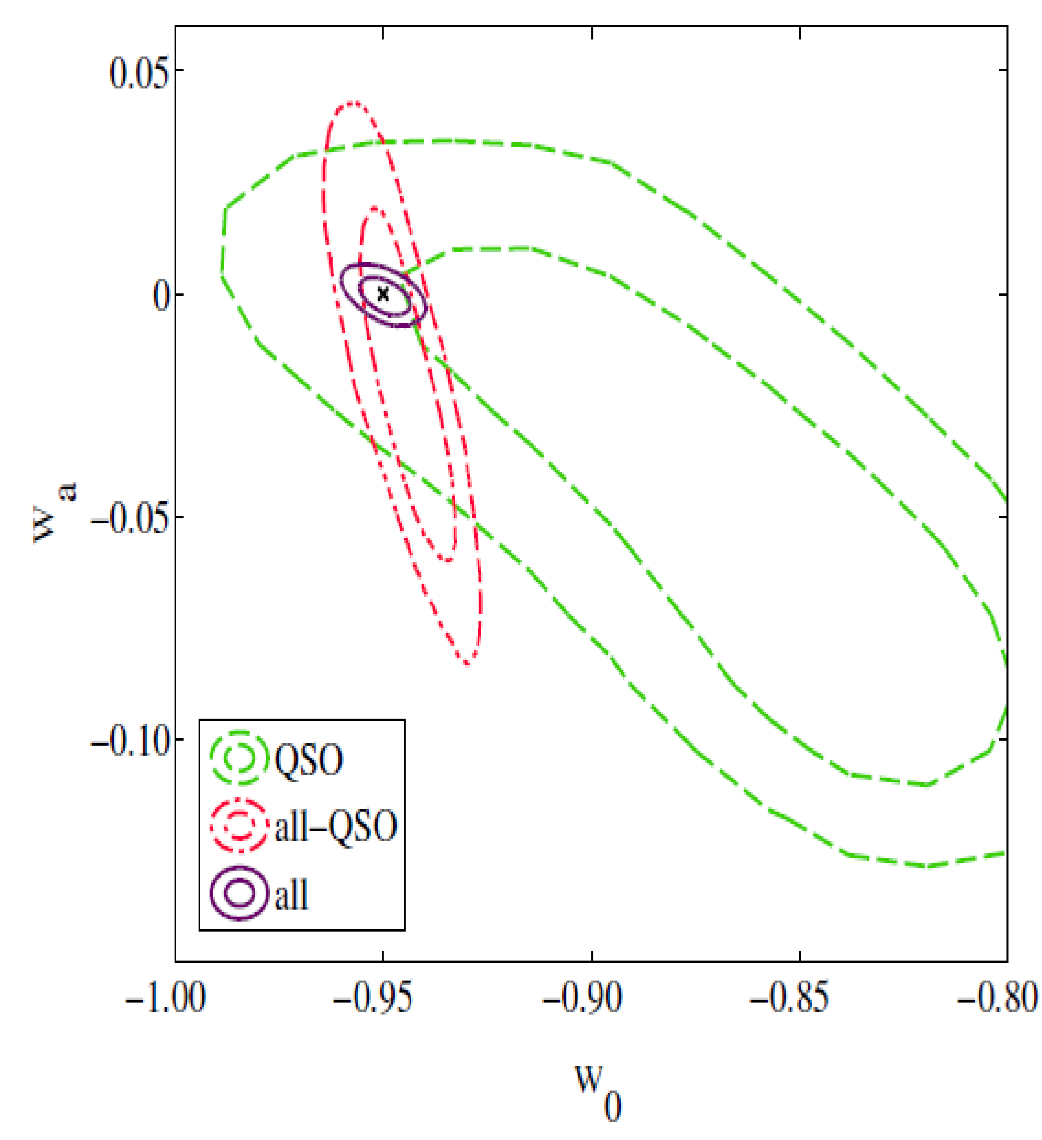
- Stars in highly eccentric orbits with periods of a few months will have detectable precession of their orbital planes
  - Up to 10 μas/year, assuming a black hole rotation rate of at least half the maximum allowed value *[Will 2008]*
- MICADO may directly test the so-called No-hair Theorem*, which would be a direct proof of the presence of a black hole
  - Astrometric observations of 2+ such stars yield a simultaneous measurement of angular momentum and quadrupole moment
  - In geometrized (c=G=1) units, $Q_2=-J^2/M$
  - ALMA may do this too

  * strictly, it's a conjecture



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 E-ELT instruments are being further studied



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, 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]*
  - High-z Type Ia SNe also expected from JWST + HARMONI *[Hook 2012]*

Leite et al. 2014

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

Mapping The Dark Side

- ELT-HIRES can significantly improve dark energy constraints, but careful mapping strategy is needed *[Leite & Martins 2015]*
  - Maximizing the mapped redshift range is always good
  - ...but optimal redshift sampling is model-dependent (and should include cosmology 'priors' plus astrophysical considerations)

TABLE III. Figures of merit for the dark energy equation of state, assuming the 'Constant' fiducial model and the 'Baseline' scenario for α measurements, and 30 redshift bins. For each pair of entries the top and bottom lines respectively assume 20 and 30 redshift bins.

	Sne only	Sne + ESP	Sne + HRS
LOW (20)	539	546	5215
LOW (30)	409	412	3574
LOW + MID (20)	1090	1096	5331
LOW + MID (30)	839	843	3655
LOW + ELT (20)	1194	1215	8055
LOW + ELT (30)	881	888	4947
LOW + MID + ELT (20)	2371	2392	8493
LOW + MID + ELT (30)	1973	1980	5286
LOW + TMT (20)	808	814	5302
LOW + TMT (30)	631	634	3642
LOW + MID + TMT (20)	1581	1586	5520
LOW + MID + TMT (30)	1253	1256	3814

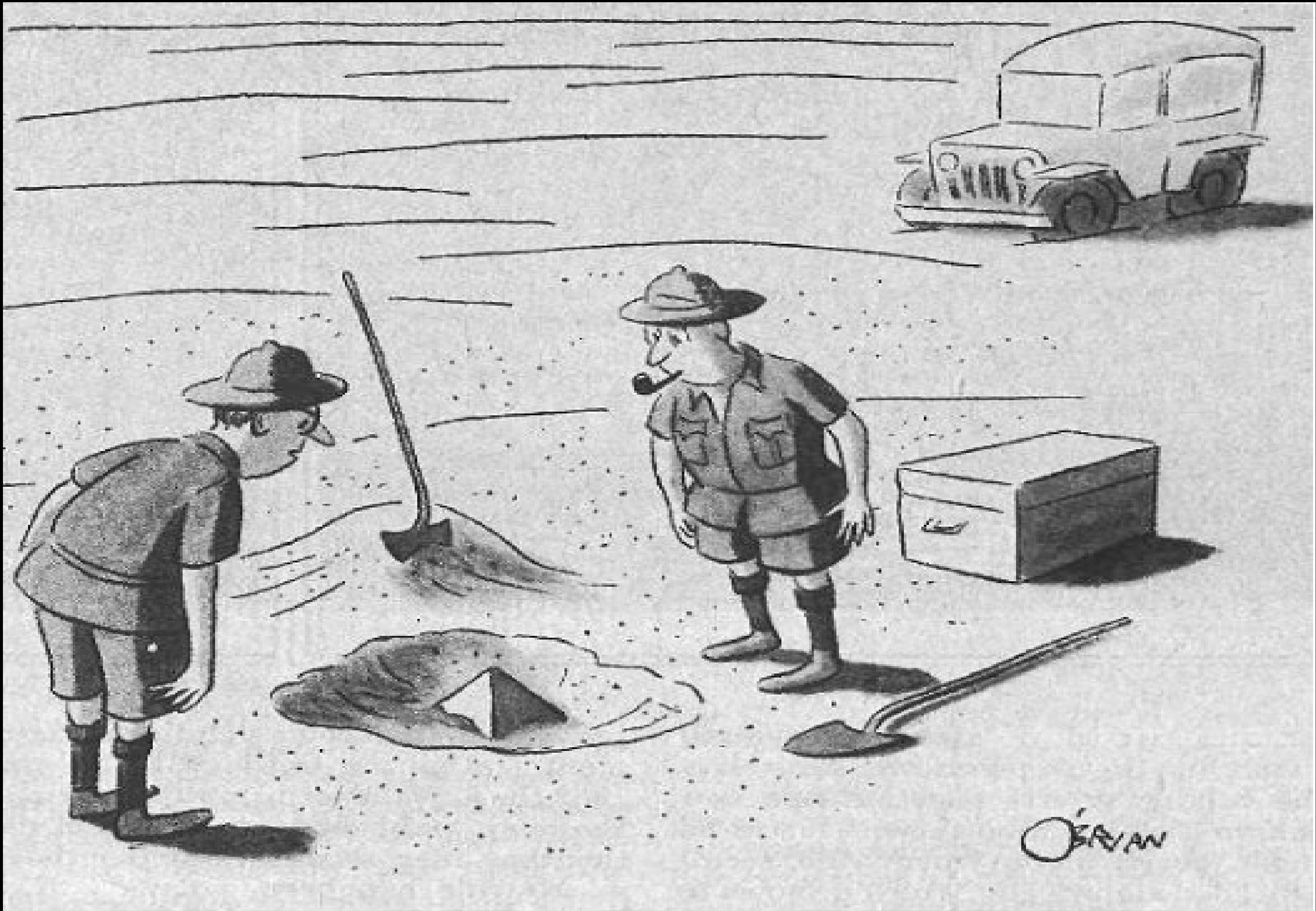
TABLE V. Figures of merit for the dark energy equation of state, assuming the 'Ideal' scenario for α measurements and 30 redshift bins. For each pair of entries the top and bottom lines respectively correspond to the Constant and Step fiducial models.

	Sne only	Sne + ESP	Sne + HRS
LOW (c)	409	996	58684
LOW (s)	404	554	11228
LOW + MID (c)	839	1352	58737
LOW + MID (s)	831	955	11295
LOW + ELT (c)	881	1515	79431
LOW + ELT (s)	881	1064	18176
LOW + MID + ELT (c)	1973	2357	79639
LOW + MID + ELT (s)	1971	2133	18652
LOW + TMT (c)	631	1089	58740
LOW + TMT (s)	634	712	11335
LOW + MID + TMT (c)	1253	1443	58846
LOW + MID + TMT (s)	1260	1328	11514

So What's Your Point?

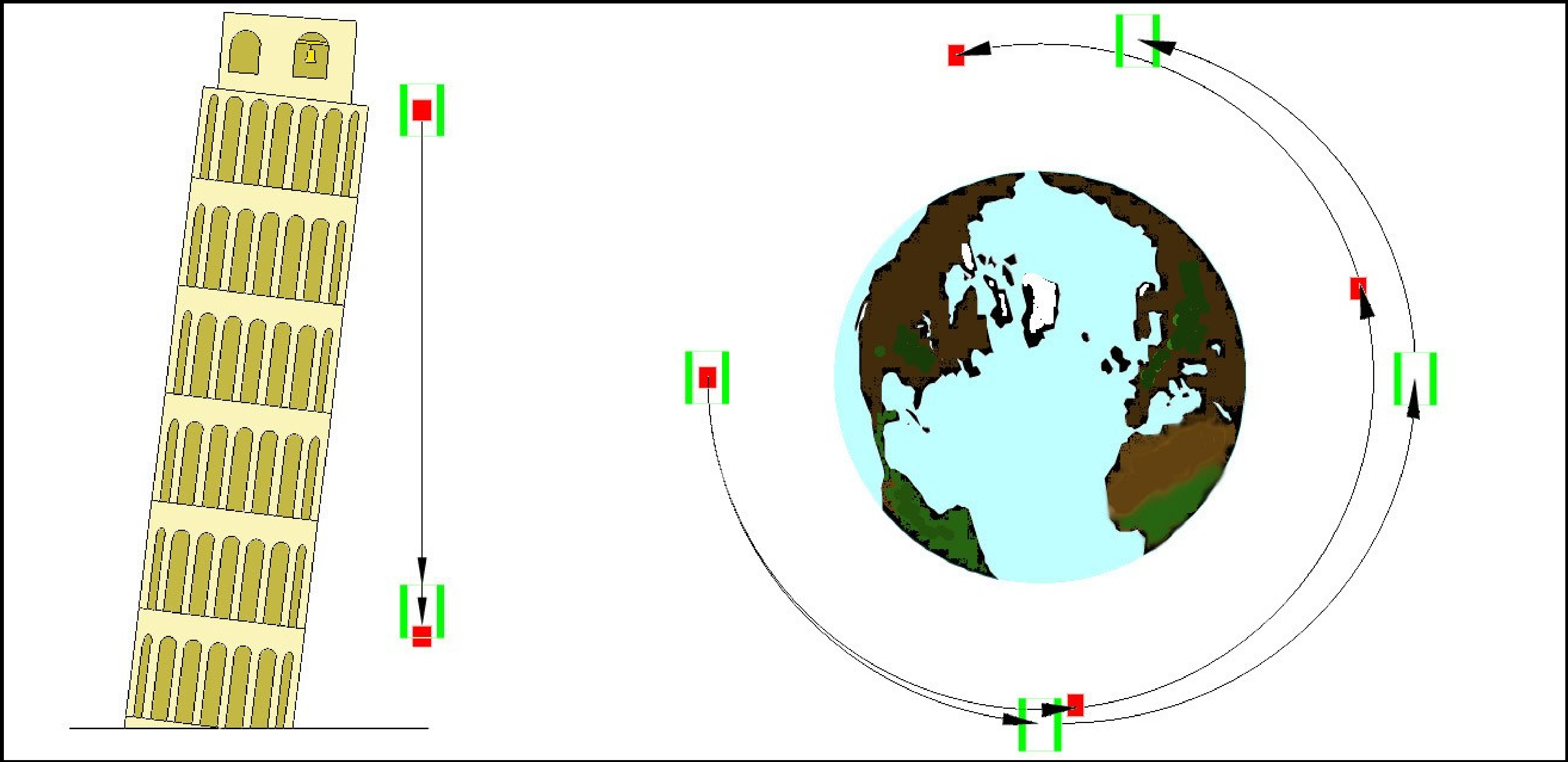
- ELT has the potential to be the most powerful gravity probe in the next few decades
  - Weak Equivalence Principle tests (mostly from α data)
  - Also composition-dependent force tests (mostly from μ data)
  - First strong-field tests (from MICADO)
  - Mapping dark side from z=0 to z=4 (HIRES, plus HARMONI)
  - Weak acceleration 'MOND-like' regime (see Joe's lectures)
- What is needed
  - Some tens of nights of telescope time
  - Identifying additional 'clean' targets (especially for μ)
  - Lab wavelengths of most atomic/molecular transitions will need to be re-measured for HIRES
  - Beyond z=4: go into IR (unclear what sensitivity can be reached) or use lines below 1600 A (not well known in lab)

The Quest for Redundancy



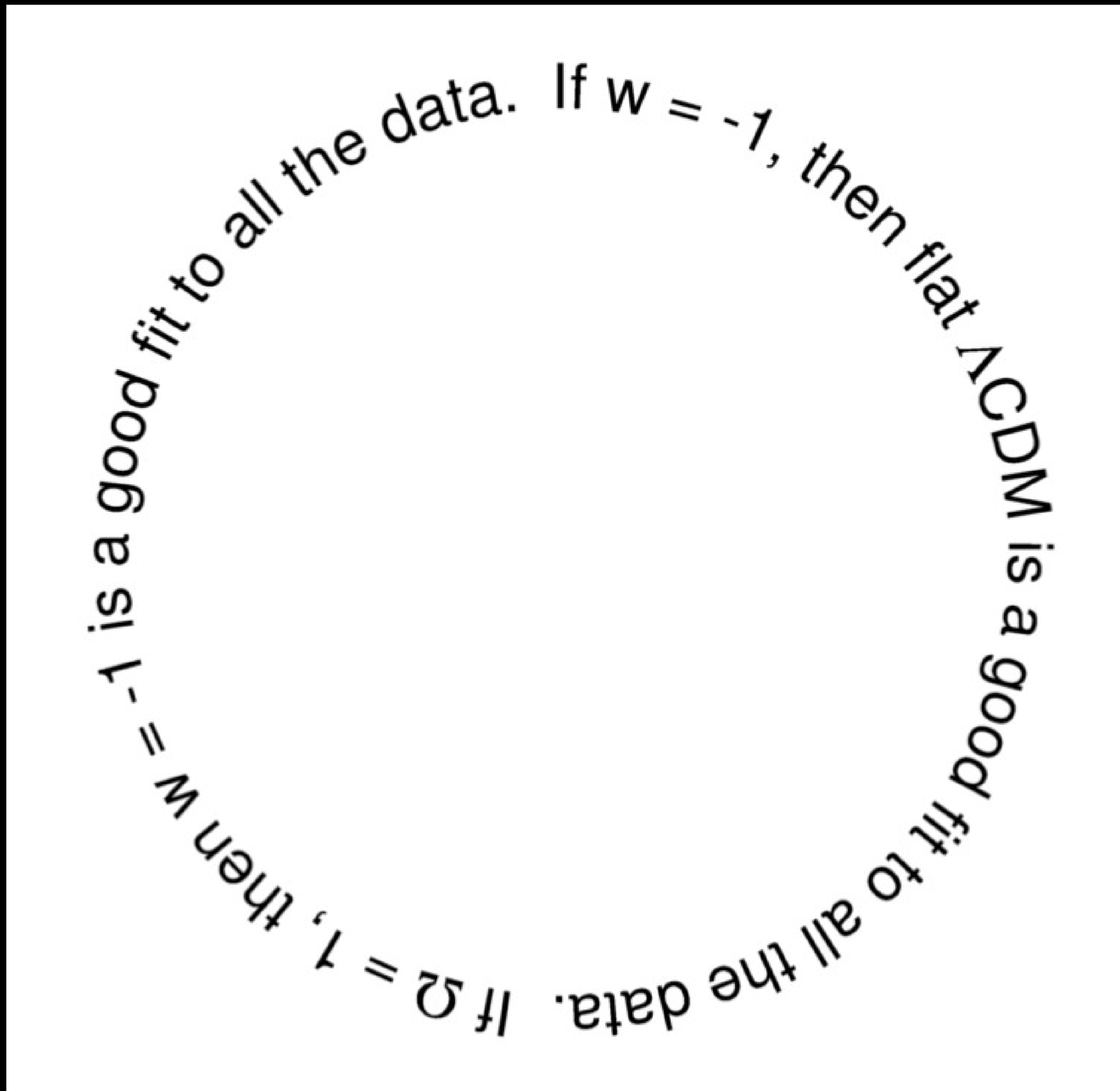
"This could be the discovery of the century. Depending, of course, on how far down it goes."

Equivalence Principle Tests



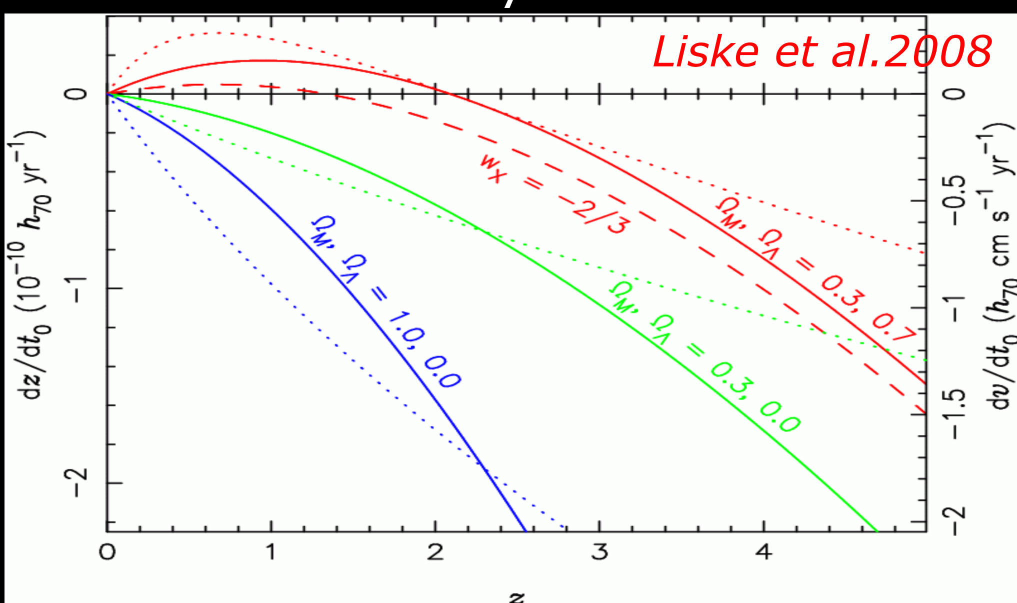
- Variations of α at few ppm level naturally lead to Weak Equivalence Principle violations within 1 o.m. of current direct bound on the Eotvos parameter *[Damour 2003]*
    - E.g., MICROSCOPE satellite should detect violations

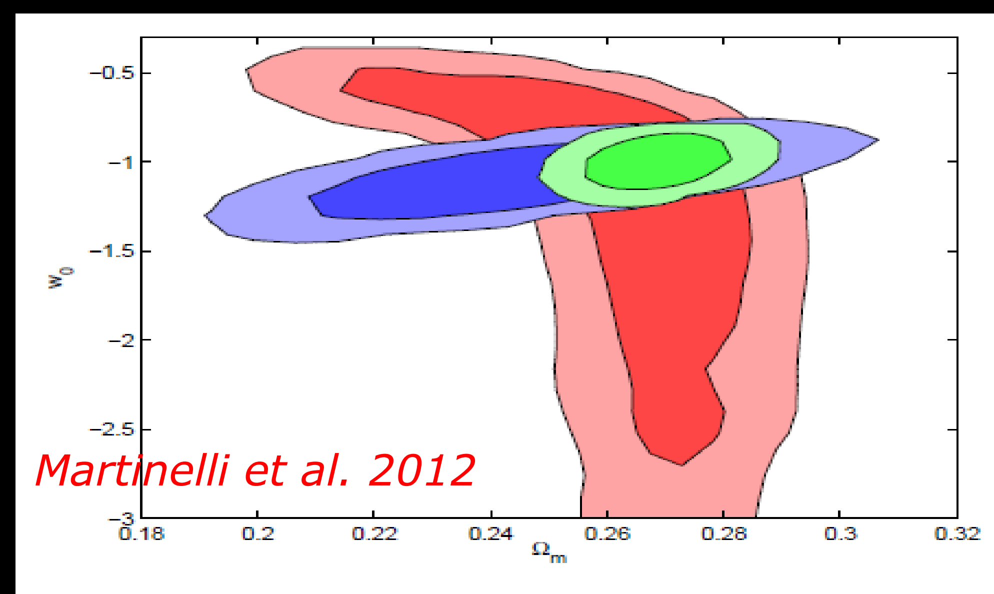
Mind Your (Cosmological) Priors



The Redshift Drift

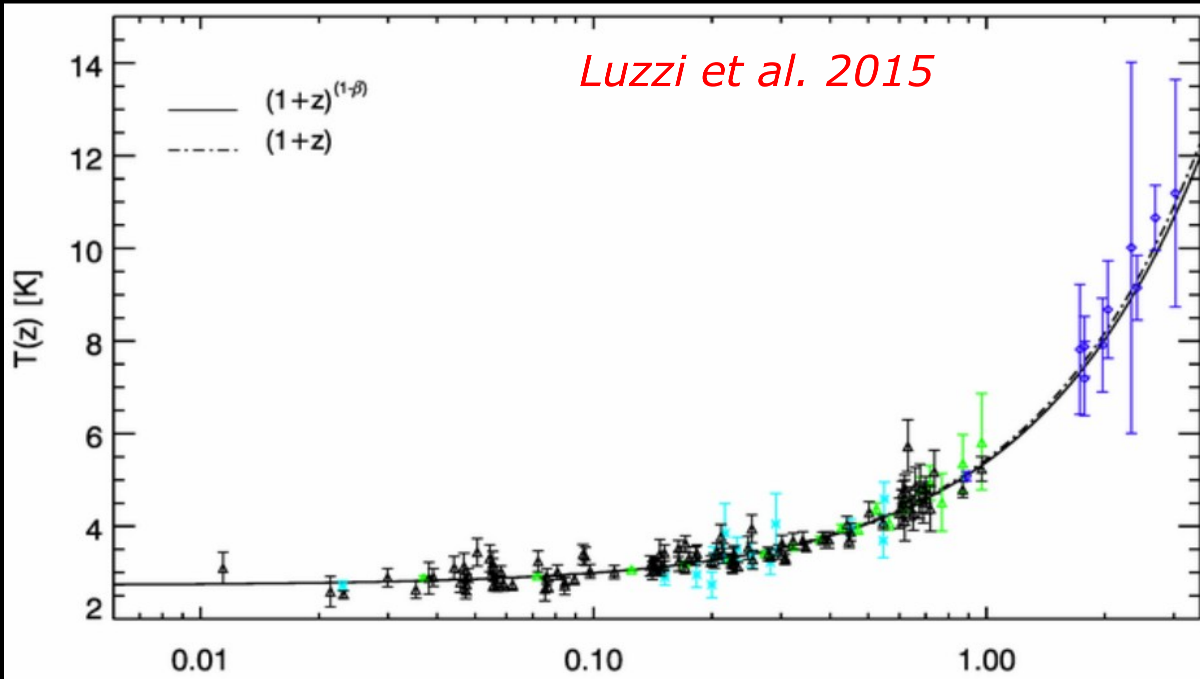
- A direct non-geometric model-independent measurement of the universe's expansion history *[Sandage 1962]*
  - No assumptions on gravity, geometry or clustering
  - Rather than mapping our (present-day) past light-cone, it directly maps evolution by comparing past light-cones at different times
- Key ELT-HIRES driver (probing 2<z<5) *[Liske et al. 2008]*, unique tool to close consistency loop and break degeneracies
  - Uses Ly-α forest, plus various metal absorption lines
  - SKA may also measure it with HI at z<1 *[Kloeckner et al. 2015]*





A Photon Consistency Test

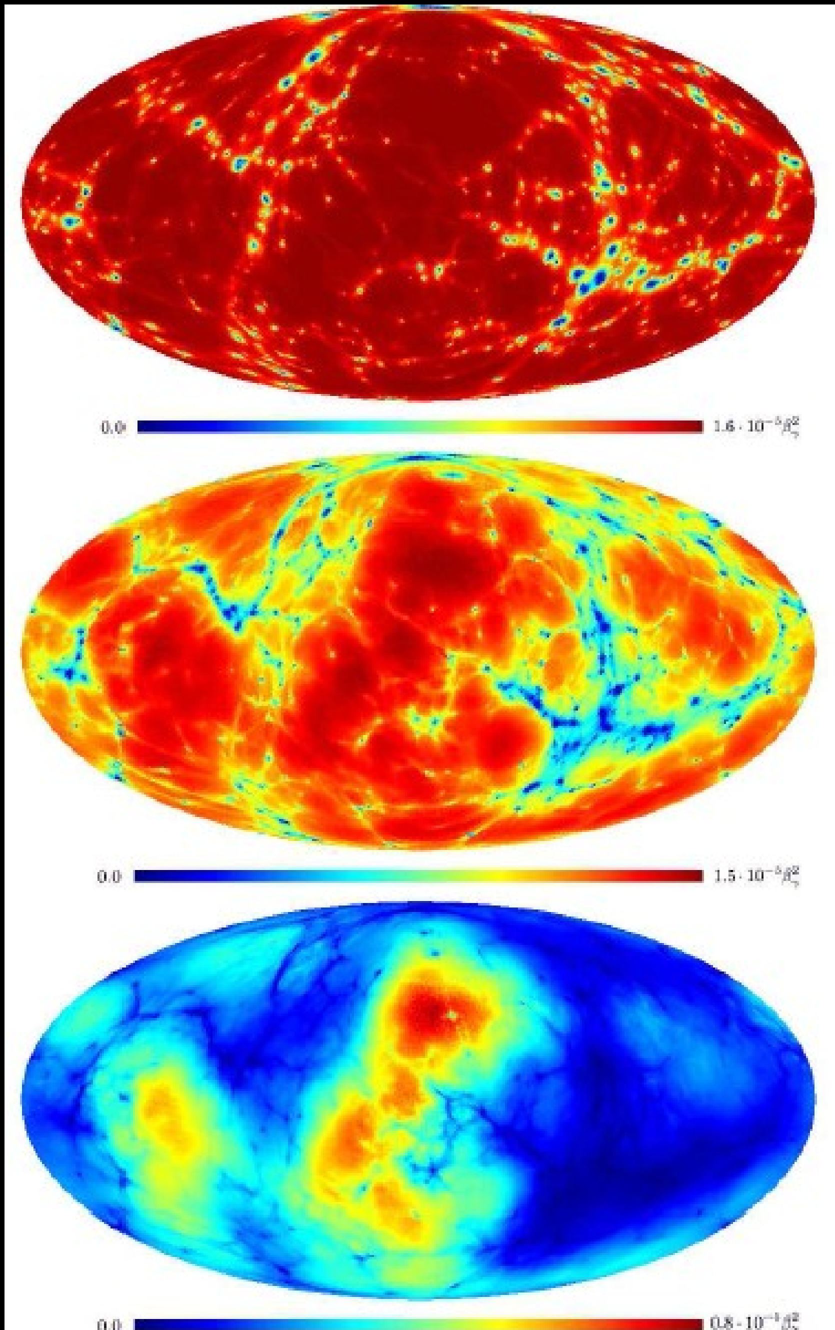
- $T(z)=T_0(1+z)$ is a robust prediction of standard cosmology
  - Assumes adiabatic expansion and photon number conservation
  - If $T(z)=T_0(1+z)^{1-\beta}$, $\beta=-0.01\pm0.03$ *[Noterdaeme et al. 2011, …]*
  - Spectroscopic measurements with CO are S/N limited
- $d_L=(1+z)^2 d_A$ is a robust prediction of standard cosmology
  - Assumes 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 many models $\beta=-2\varepsilon/3$: duality constrains β
  - Current constraint at 1% level, and will be improving…
  - Need more targets for ALMA, ESPRESSO and ELT-HIRES



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) measurements are crucial for breaking degeneracies: they can be obtained with ALMA, ESPRESSO & ELT-HIRES
  - Also from Planck clusters now *[de Martino et al. 2015, Luzzi et al. 2015]*, and hopefully COrE+ later

Spatial Variations?



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

- A particular 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 will constrain amplitude dipole, but can't do model selection
  - limited wavelength range, 100s nights for few ppm amplitude
  - ELT-HIRES would be able to do it in ca. 10 nights (details tbc)

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
  - Precision astrophysical spectroscopy provides and optimal probe of the (still unknown) new physics
- Nothing varying at ~ 10^{-5} level, already a tight constraint (stronger than Cassini bound, best available WEP constraint)
  - Things unclear at 10^{-6} level, ESPRESSO improvements coming…
- The E-ELT will be the flagship tool in a new generation of precision consistency tests
  - Competitive 'guaranteed science' implications for dark energy and fundamental physics
  - Unique value of complementarity, redundancy, and synergies with other facilities (including ALMA, Euclid & SKA)

Let's do it!