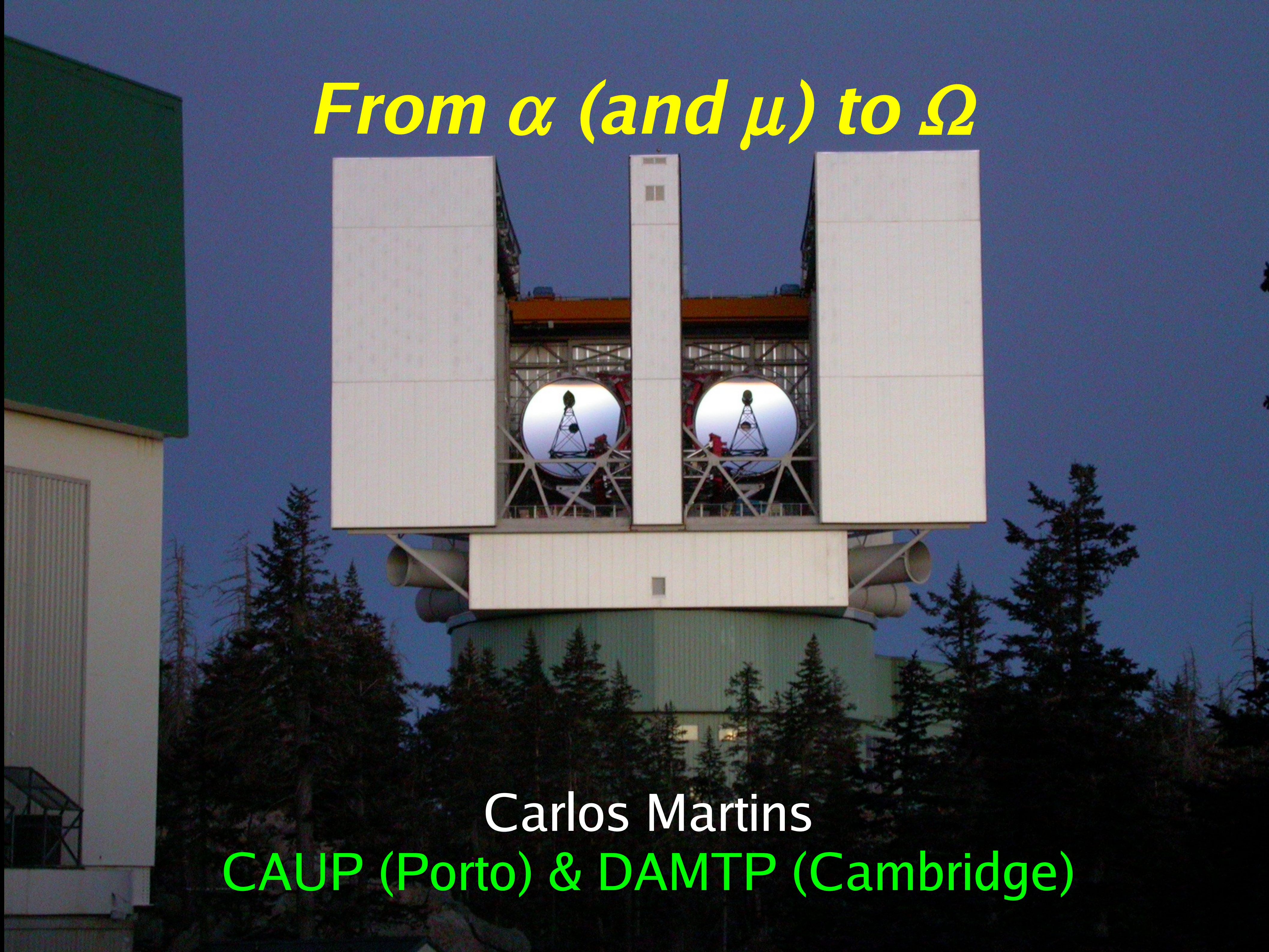


From α (and μ) to Ω

Carlos Martins

CAUP (Porto) & DAMTP (Cambridge)

The Quest for Scalar Fields

- The fields of Nature:
  - Observed particles are described by Fermi spinors
  - Gauge forces are described by boson vector fields
  - Einstein gravity uses only a 2-tensor (the metric)
  - Is there anything else (such as fundamental scalar fields)?
- Scalar fields have long been part of the standard model of particle physics (cf. the Higgs particle).
- Recent developments suggest that they could be equally important in astrophysics and cosmology.
- ***Yet neither side has so far produced definitive experimental or observational evidence for them…***

Hints of New Physics

- For each of these observables the SM makes very specific statements, failing however to reproduce the experimental evidence:
  - Neutrino masses
  - Dark matter
  - Size of baryon asymmetry
- It's precisely 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 cosmology.***

Scalar Fields in Cosmology

- Scalar fields play a key role in most paradigms of modern cosmology, yielding *inter alia*
  - Exponential expansion of the early universe (inflation)
  - Relics of cosmological phase transitions (cosmic defects)
  - Dynamical dark energy powering current acceleration phase
  - Varying fundamental couplings
- ***Even more important than each of these paradigms is the fact that they usually don't occur alone – this will be crucial for future consistency tests!***

Dark Energy & Varying Couplings

- Universe dominated by component whose gravitational behavior is similar to that of a cosmological constant.
- Required cosmological constant value is so small that a dynamical scalar field is arguably more likely.
- Slow-roll (mandatory for $p<0$) and present-day domination imply (if $V_{min}=0$) that *[Carroll 1998]*
  - The field VEV today is of order m_{Pl}
  - Field excitations are very light, $m \sim H_0 \sim 10^{-33}$ eV
- ***Hence couplings of this field lead to observable long-range forces and time dependence of the constants of nature.***

Key Consequences

- Bounds on varying couplings therefore restrict the evolution of the scalar field and provide constraints on dark energy and extra dimensions that are complementary (and in some sense more powerful than) those obtained by traditional means
- A space-time varying scalar field coupling to matter mediates a new interaction: if varying α is explained by a dynamical scalar field, this necessarily implies the existence of a new force
- ***It then unavoidably follows that the Einstein Equivalence Principle is violated: gravity can't be geometry!***
- Several space-based missions (ACES, μSCOPE, STEP) will soon improve existing bounds by as much as 6 orders of magnitude, and must find violations if current data is correct

Constants & Extra Dimensions

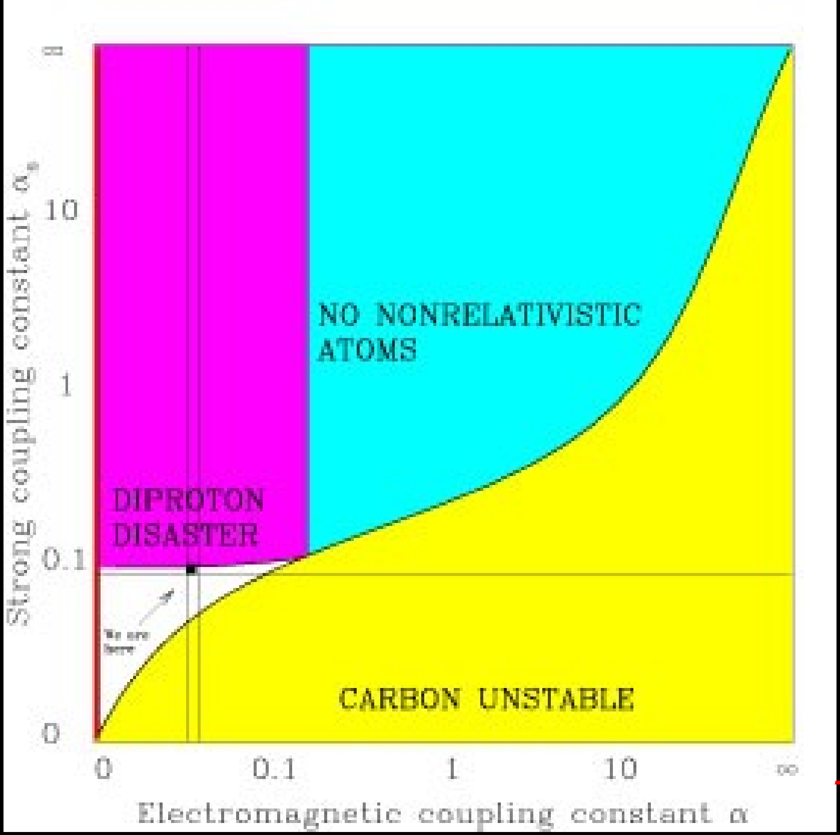
- Unification of fundamental forces requires additional space-time dimensions; in such models, true fundamental constants are defined in higher dimensions
- (3+1)D constants are effective quantities, typically related to the true constants via characteristic sizes of the extra dimensions
- *Hence expect space-time variation of such effective coupling constants. Inter alia, a varying α is unavoidable in string theory*
- Many simple examples exist, e.g. in
  - Kaluza-Klein models *[Chodos & Detweiler 1980, Marciano 1981]*
  - Superstring theories *[Wu & Wang 1986]*
  - Brane worlds *[Kiritsis 1999, Alexander 2000]*

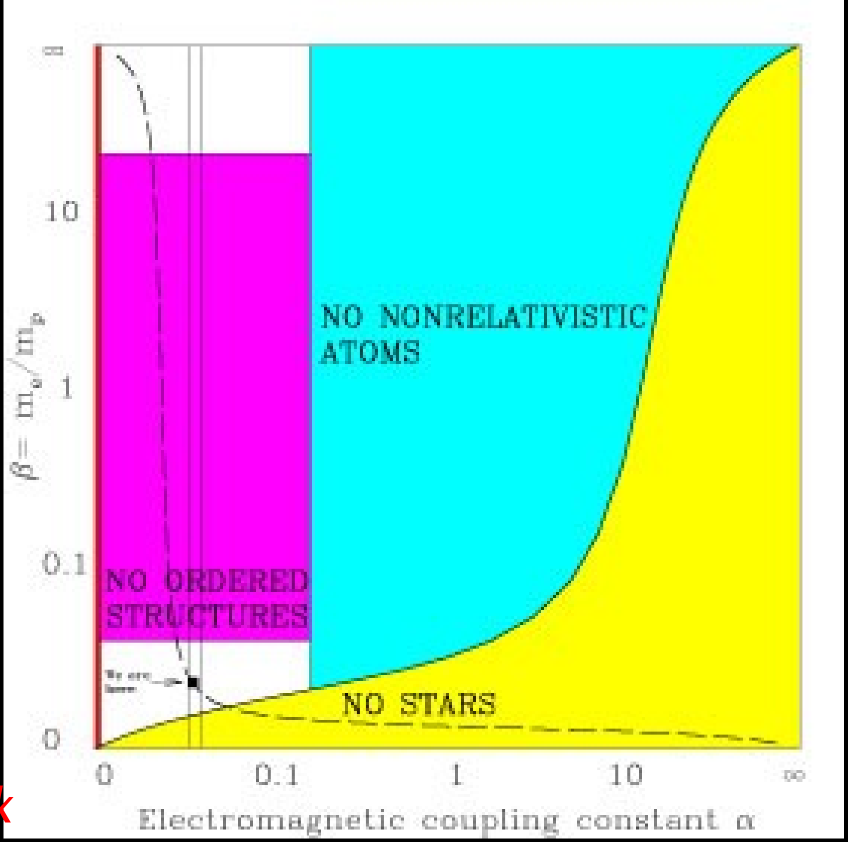
The Role of Constants

- A completely unsolved issue: no 'theory of constants' exists! *[Duff et al. 2002, Martins 2002]*
- Asymptotic states?
  - c: Limit velocity of massive particle in flat space-time
  - G: Limit potential for mass not forming black hole in curved space-time
  - h: Limit uncertainty (quantum of action)
- Convenient conversion factors?
  - Can't be pushed arbitrarily far...
- Pointers to the emergence of new phenomena
- **How many are fundamental? *(The story so far: 3)* Will they be fixed by consistency conditions, or remain arbitrary?**

Metrology Matters

- *One can only measure dimensionless combinations of relevant quantities*
- *Any such measurements are necessarily local*





Tegmark

Relating Measurements

- Different methods of measurement probe different epochs and environments (cf. absorption vs. emission, spatial variations), so comparisons are not trivial!
- Face-value comparisons of measurements at different redshifts are too naive, and often manifestly incorrect
- Most such comparisons are model-dependent: a cosmological model and one for $\alpha(z)$ are both needed
- Assuming $d\alpha/dt$=const (and providing a 'measurement' of it) is useless: no sensible particle physics model will ever have such dependence over any significant redshift range

Atomic Clock Basics

- Clock = Oscillator + Counter
- In an atomic clock, ticker is quantum-mechanical: a photon is absorbed by an atom's last electron, causing it to flip its spin and magnetic field
- Key ongoing developments include:
  - Laser-cooled, atomic fountain clocks
  - Clocks based on a single atom (as opposed to an ensemble)
  - Optical clocks (THz, as opposed to GHz – microwave)
  - Micro-gravity (use dedicated satellites or the ISS)

Local Constraints & Expectations

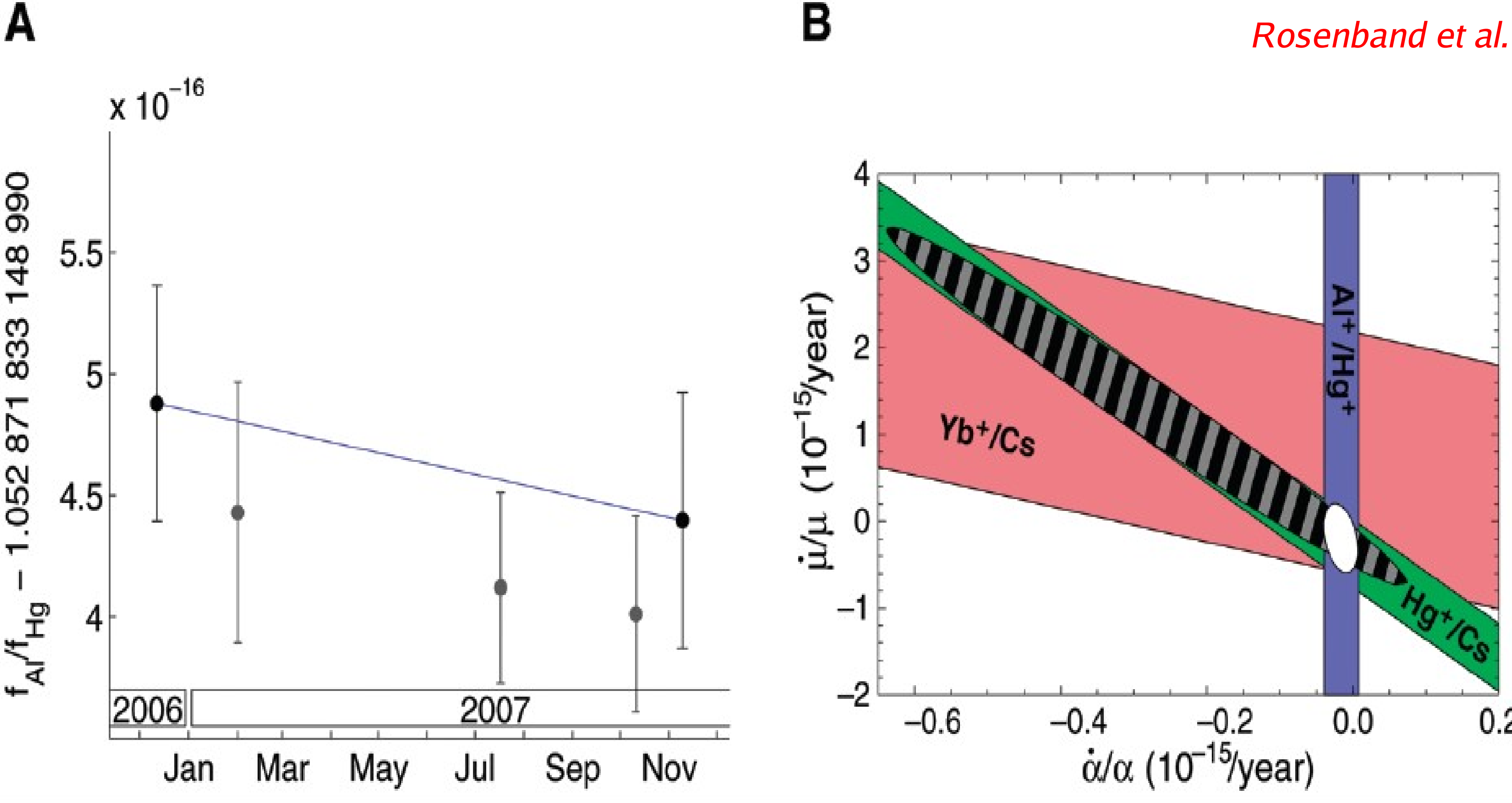
- Direct constraint by the NIST group *[Rosenband et al. 2008]* comparing single-atom Al+ and Hg+ optical clocks over a period of a year yields

  $d/dt(\ln \alpha) = (-1.6 \pm 2.3) \times 10^{-17}\ \mathrm{yr}^{-1}$

- Direct local constraints on μ are significantly weaker: *[Shelkovnikov et al. 2008]* comparing molecular and Cs clocks over 2 years, find

  $d/dt(\ln \mu) = (-3.8 \pm 5.6) \times 10^{-14}\ \mathrm{yr}^{-1}$

- Key future experiments and expected improvements in orders of magnitude (note integration times small):
  - ACES (French-Swiss project, at the ISS, 2012): 1 o.m.
  - μSCOPE (mostly a CNES satellite, 2010): 2 o.m.
  - GG (Italian, ?): 3 o.m.?
  - STEP (a joint ESA-[NASA] cryo-satellite, ?): 5 o.m.
- These apply both to various aspects of the EEP and (indirectly) to α



Rosenband et al.

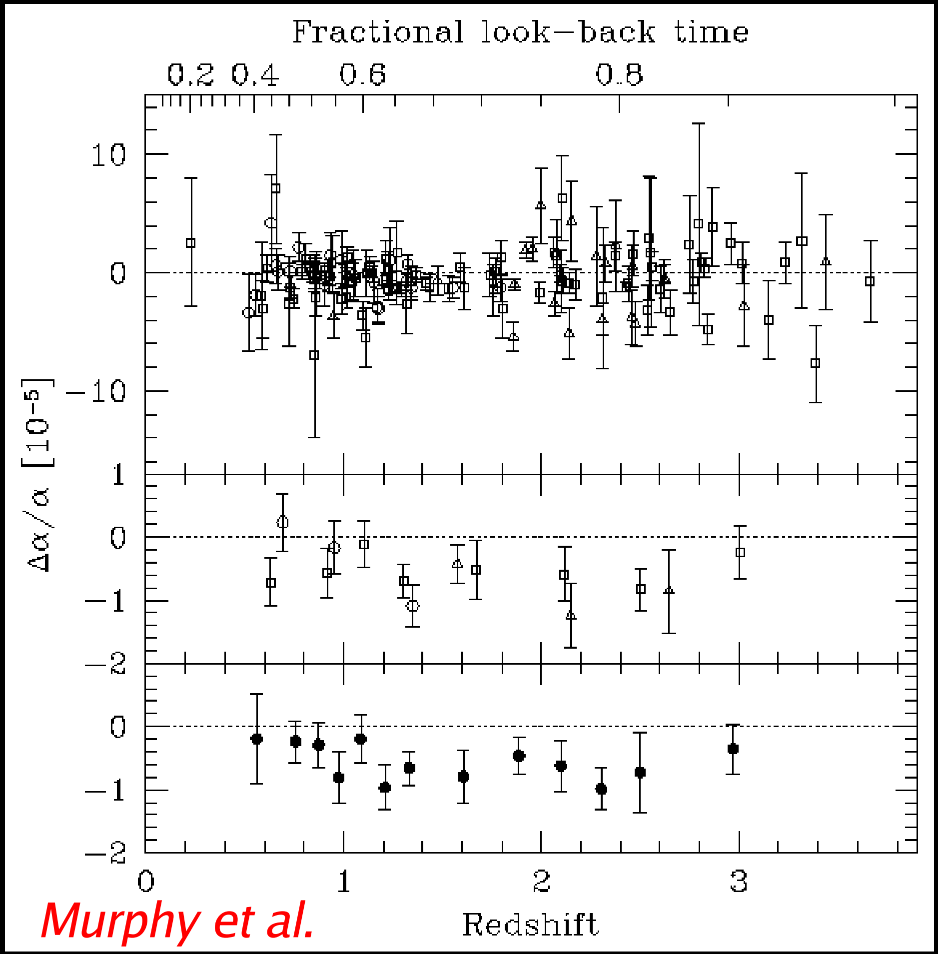
The Oklo Reactor

- Natural nuclear reactor at a mine in Gabon, went off about 1.8 billion years ago ($z\sim0.14$); ran for 10^5 years in few-second bursts.
- Observable is Samarium abundance depletion, highly sensitive to neutron cross sections: key resonance E~97.3meV, is well below the typical energy scale of nuclear physics due to near-cancellation of Coulomb and nuclear strong interactions
- First MCNP analysis *[Petrov et al. At. Energy 98:296, 2005, PRC74:064610,2006]* highlights shortcomings of previous studies, and finds $\Delta\alpha/\alpha=(0.6+6.2)\times10^{-8}$
- Independent analysis finds consistent result $\Delta\alpha/\alpha=(0.7+1.8)\times10^{-8}$ *[Gould et al. PRC74:024607, 2006]*
- Measurement is not 'clean': naive assumptions on behavior of other quantities must be made

Searching for Varying Constants

- Absorption line measurements include
  - α_{em}: Fine-structure doublet
  - μ: Molecular Rotational *vs.* Vibrational modes
  - g_p: Fine-structure doublet *vs.* Hyperfine H
  - $\alpha_{em} g_p \mu$: Hyperfine H *vs.* Fine-structure
  - And many more…
- The observational story so far
  - *[Murphy et al. 2004]* $\Delta\alpha/\alpha=(-0.57\pm0.11)\text{x}10^{-5}$
  - *[Ubachs et al. 2007]* $\Delta\mu/\mu=(2.56\pm0.58)\text{x}10^{-5}$
  - Radio ($z<1$): null results at few x 10^{-6} level *[Kanekar 2008]*
- Can also use emission lines: typically cleaner measurements, but less sensitive – redshift range is similar! *[Brinchmann et al. 2004]*

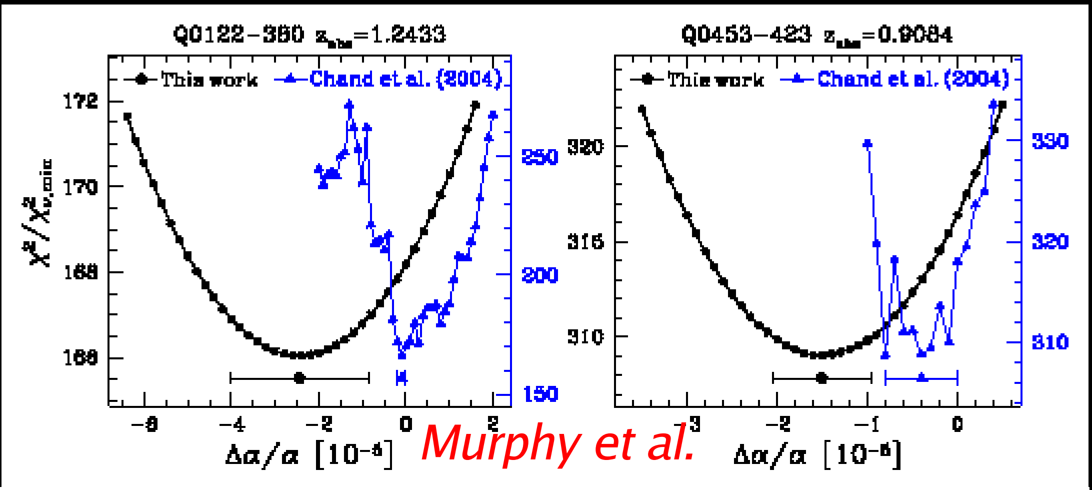
The *Webb et al.* Results



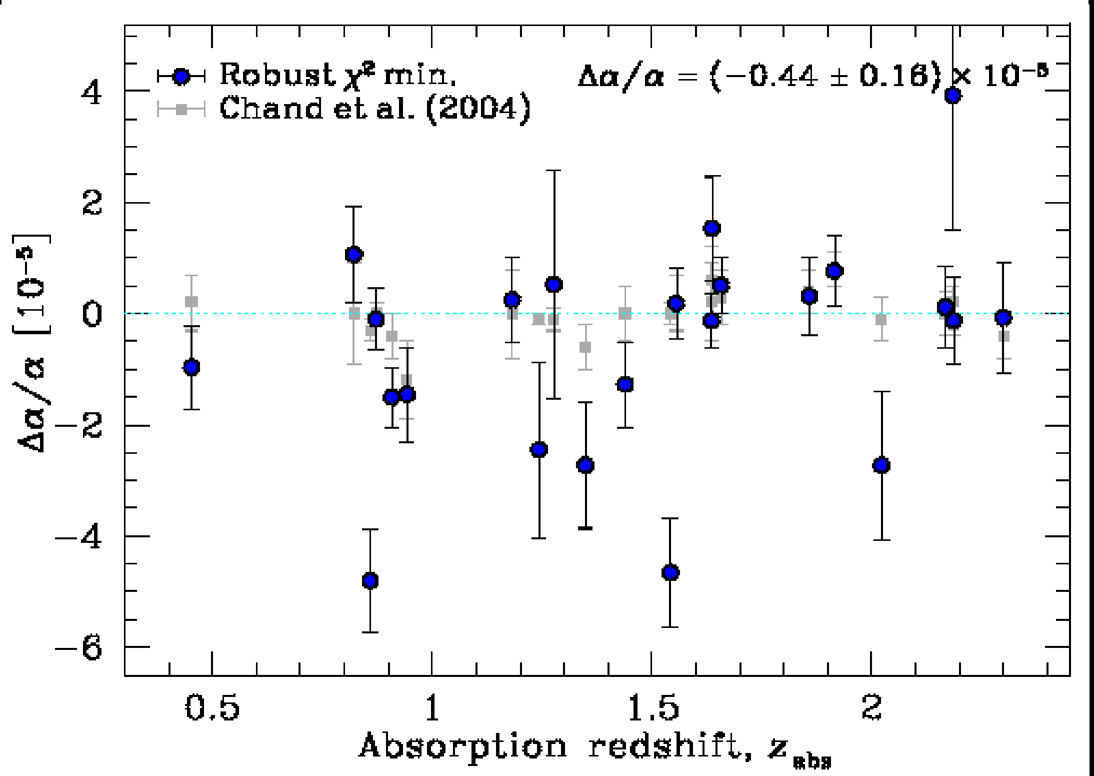
Murphy et al.

- 128 absorption systems, 68 QSOs in range $0.2 < z_{abs} < 3.7$, observed with Keck/HIRES
- Combines lines from many doublets and systems, exploits enhanced sensitivity of ground state (Many Multiplet Method)
- Weighted mean *[Murphy et al. 2004]* $\Delta\alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}$
- Evidence for variation is only strong beyond z~1, and no significant evidence for spatial variations (such as a dipole)

The *Chand et al.* Results



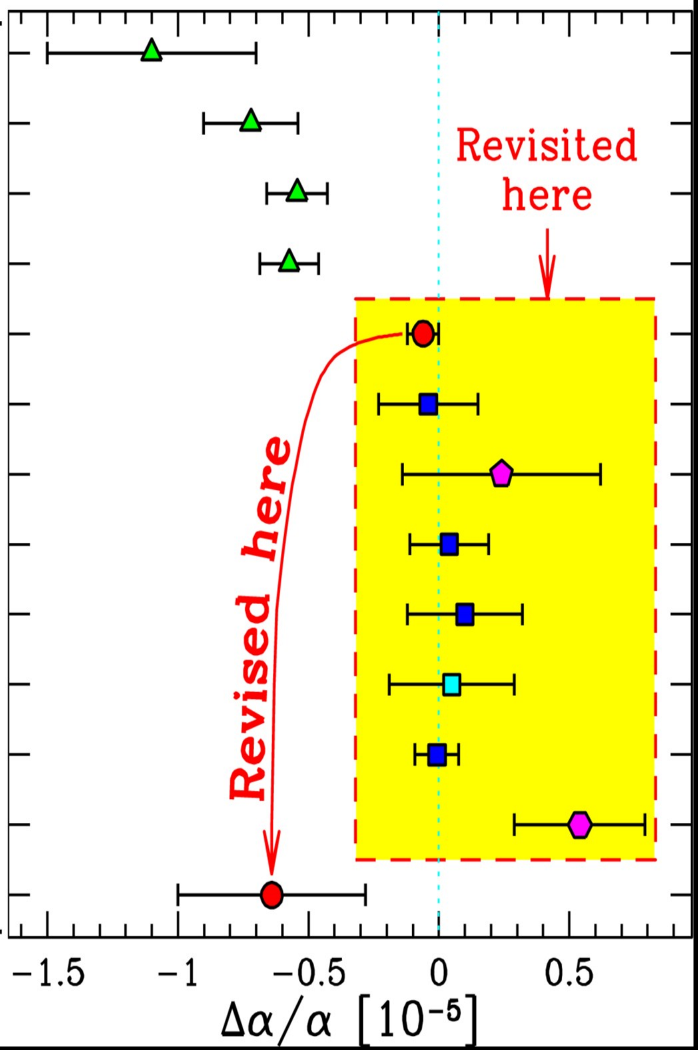
Murphy et al.



- Using a 'few multiplet' method, *[Chand et al. 2005]* claim a null result $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$
- But the analysis pipeline is flawed
  - Parameter estimation methods
  - Selection of velocity components
  - Wavelength calibration
- Re-analysis *[Murphy et al. 2006]* yields $\Delta\alpha/\alpha = (-0.44 \pm 0.16) \times 10^{-5}$
  - Scatter in individual values higher than expected, which signals further (hidden) errors…

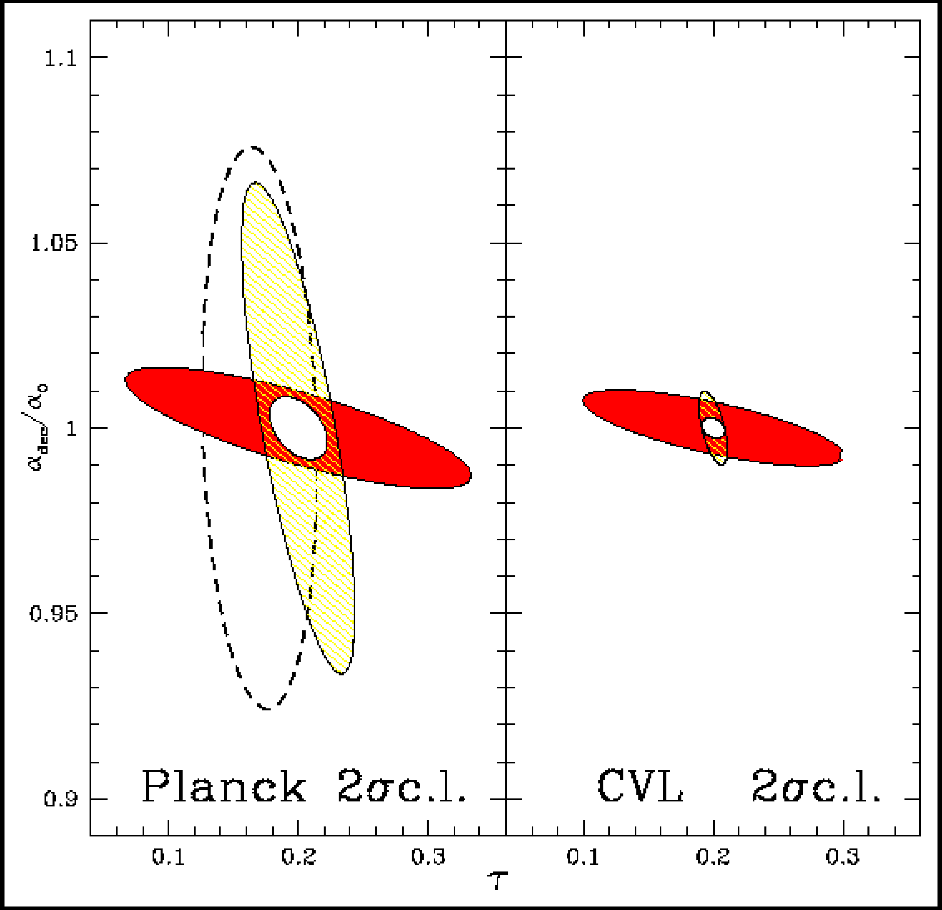
The Controversy Continues…

Instrument	N_{abs}	z_{abs}	$\Delta\alpha/\alpha$ $[10^{-5}]$	Reference
HIRES	30	0.5–1.6	−1.100 ± 0.400	Webb et al. (1999)
HIRES	49	0.5–3.5	−0.720 ± 0.180	Murphy et al. (2001a)
HIRES	128	0.2–3.7	−0.543 ± 0.116	Murphy et al. (2003)
HIRES	143	0.2–4.2	−0.573 ± 0.113	Murphy et al. (2004)
UVES	23	0.4–2.3	−0.060 ± 0.060	Chand et al. (2004)
UVES	1	1.151	−0.040 ± 0.190 ± 0.270	Quast et al. (2004)
UVES	1	1.839	+0.240 ± 0.380	Levshakov et al. (2005)
UVES	1	1.151	+0.040 ± 0.150	Levshakov et al. (2005)
UVES	1	1.151	+0.100 ± 0.220	Chand et al. (2006)
HARPS	1	1.151	+0.050 ± 0.240	Chand et al. (2006)
UVES	1	1.151	−0.007 ± 0.084 (± 0.100)	Levshakov et al. (2006)
UVES	1	1.839	+0.540 ± 0.250	Levshakov et al. (2007)
UVES	23	0.4–2.3	−0.640 ± 0.360	This work



Murphy et al.

Varying α and the CMB



- Changes ionization history
  - Energy levels & binding energies are shifted: changes z_{dec}
  - Changes the Thomson cross-section for all species: effect goes as α^2
- WMAP yields *[Martins et al. 2004]*

$$0.95 < \alpha_{dec}/\alpha_0 < 1.02$$

- A cosmic variance limited CMB experiment can measure α to 0.1% accuracy (can do much better adding other datasets) *[Rocha et al. 2004]*

The Strong Sector, α & μ

- In theories where a dynamical scalar field is responsible for varying α, the other gauge and Yukawa couplings are also expected to vary
  - In GUTs the variation of α is related to that of Λ_{QCD}, whence nucleon mass varies when measured in energy scale independent of QCD
  - Expect varying $\mu=m_p/m_e$, which can be measured using H_2 *[Thompson 1975]*
- Wide range of possible α-μ relations makes this a unique discriminating tool between competing models.
- Observationally, μ measurements much cleaner:
  - α measurements compare line shifts from different atoms, ionizations, or excitations; H_2 has many lines with different shifts from the same lower state
  - H_2 measurements immune to contamination by other isotopic species
  - Expected change in μ is much larger than that of α (but model-dependent)
  - Only 17 DLAs known with H_2 absorption, in $1.15 < z < 4.22$

An Example

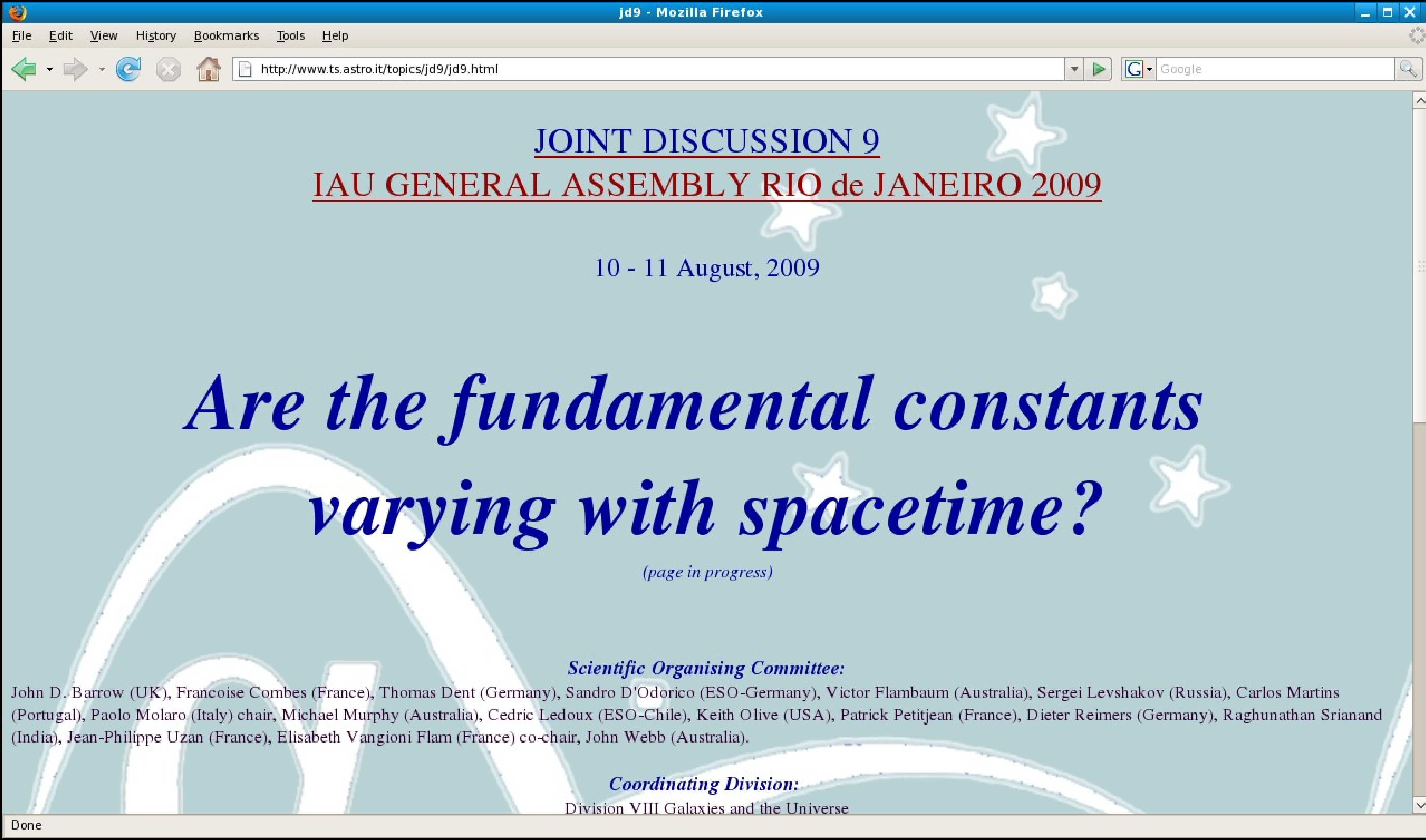
- For the MSSM embedded on a GUT

$$(d \ln \mu / dt) \sim R\, (d \ln \alpha / dt)$$

- If α varies due to a varying unified coupling, $R>0$ (typically 40); if due to varying unification scale, $R<0$ (typically -50)
- Can build say SU(5) models with $-500<R<600$ *[Calmet & Fritzsch 2002]*. $|R|$ typically large: fine-tuning needed for $|R|<1$
- Large numbers arise simply because the strong coupling and the Higgs VEV run (exponentially) faster than α
- *By probing $\alpha(z)$ and $\mu(z)$ we can test GUT scenarios without needing to detect any GUT model particles at accelerators!*

Why is it so hard?

- Akin to finding exoplanets, except that only a few lines can be used and QSOs are much fainter than stellar sources!
- The measurement of fundamental constants requires observing procedures beyond what is done in standard observations.
  - The data so far available have been generally taken with other purposes and do not have the necessary quality to fully exploit UVES capabilities.
- Need customized wavelength calibration procedures beyond those supplied by standard pipelines *[Thompson et al. 2009]*.
  - Ultimately should calibrate with laser frequency combs, not ThAr lamps or I cells *[Li et al. 2008, Steinmetz et al. 2008]*!
- A new generation of high-resolution, ultra-stable spectrographs will be needed to resolve the issue:
  - Shortly: Maestro at MMT, PEPSI at LBT
  - Near future: HRUSS (ESPRESSO) at VLT, ...
  - Later on: CODEX at E-ELT, ...



JOINT DISCUSSION 9

IAU GENERAL ASSEMBLY RIO de JANEIRO 2009

10 - 11 August, 2009

Are the fundamental constants varying with spacetime?

(page in progress)

Scientific Organising Committee:

John D. Barrow (UK), Francoise Combes (France), Thomas Dent (Germany), Sandro D'Odorico (ESO-Germany), Victor Flambaum (Australia), Sergei Levshakov (Russia), Carlos Martins (Portugal), Paolo Molaro (Italy) chair, Michael Murphy (Australia), Cedric Ledoux (ESO-Chile), Keith Olive (USA), Patrick Petitjean (France), Dieter Reimers (Germany), Raghunathan Srianand (India), Jean-Philippe Uzan (France), Elisabeth Vangioni Flam (France) co-chair, John Webb (Australia).

Coordinating Division:

Division VIII Galaxies and the Universe

Dynamical Dark Energy

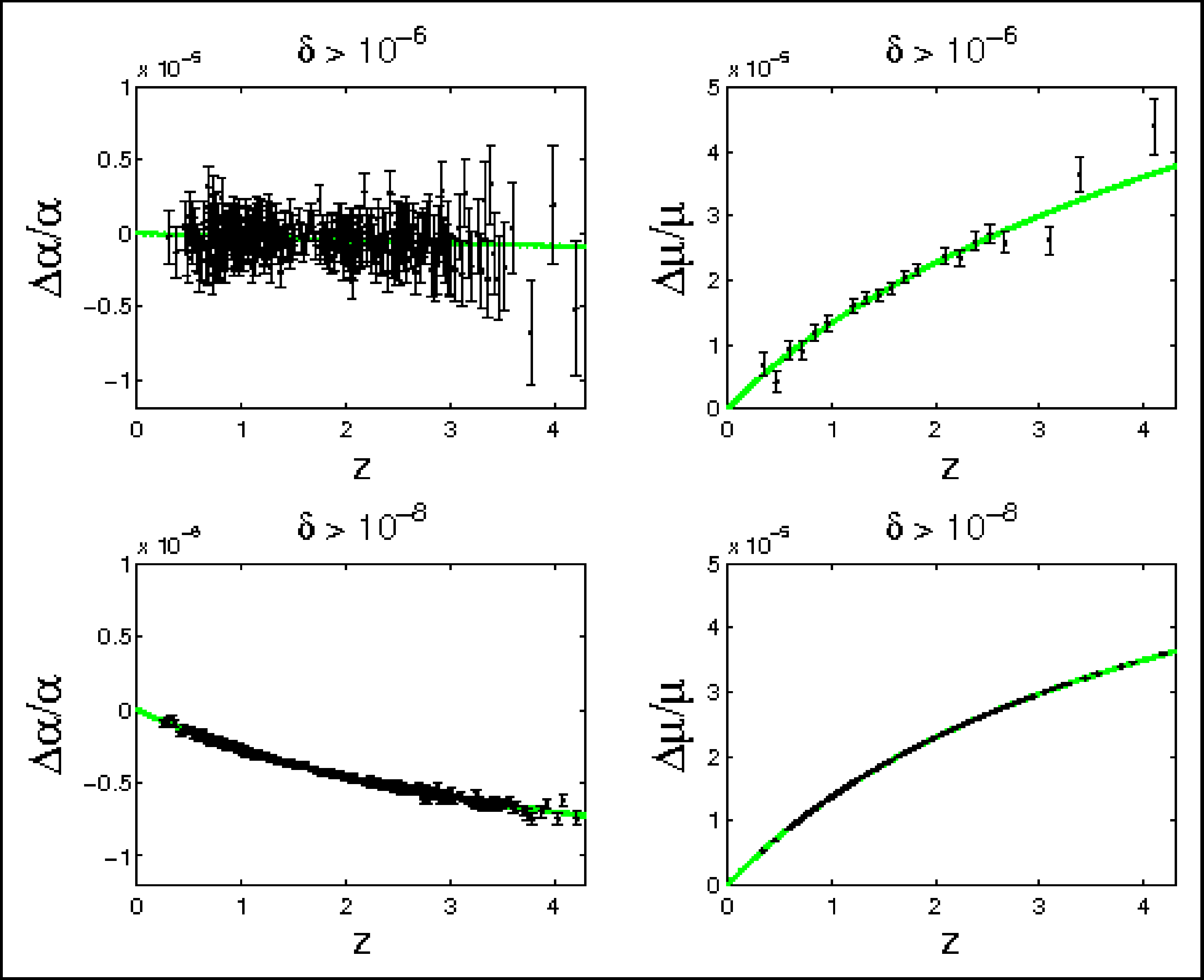
- Universe dominated by component whose gravitational behavior is similar to that of a cosmological constant.
- Required cosmological constant value is so small that a dynamical scalar field is arguably more likely.
- Slow-roll (mandatory for $p<0$) and present-day domination imply *[Carroll 1998]* that couplings of this field lead to observable long-range forces and time dependence of the constants of nature.
- Standard methods (SNe, Lensing, etc) are of limited use as dark energy probes *[Maor et al. 2001, Upadhye et al. 2005].*
  - Clear detection of a varying $w(z)$ is key to convincing result, since $w_0 \sim -1$
- ***Since the field is slow-rolling when dynamically important, a convincing detection of w(z) is very unlikely even with EUCLID or JDEM (SNAP, DESTINY, JEDI, …)***

From $\alpha(z)$ - and $\mu(z)$ - to $w(z)$

- Scalar field yielding dark energy must give varying couplings. They can be used to reconstruct $w(z)$ *[Nunes & Lidsey 2004].*
  - Analogous to reconstructing the 1D potential for the classical motion of a particle, given its trajectory
- Will complement and easily be competitive with standard methods.
- Key Advantages:
  - ***Direct probe of Grand Unification and fundamental physics***
  - ***Directly distinguishes Λ from dynamical field (no false positives)***
  - ***Huge z lever arm, probes otherwise unaccessible z range where scalar field dynamics is expected to be fastest (deep matter era)***
  - ***Cheaper, ground-based (~100 good nights on VLT, Keck, LBT, …)***
  - ***We can start now!***

Reconstruction: In Practice

With P. Avelino, N. Nunes, K. Olive, PRD74, 083508



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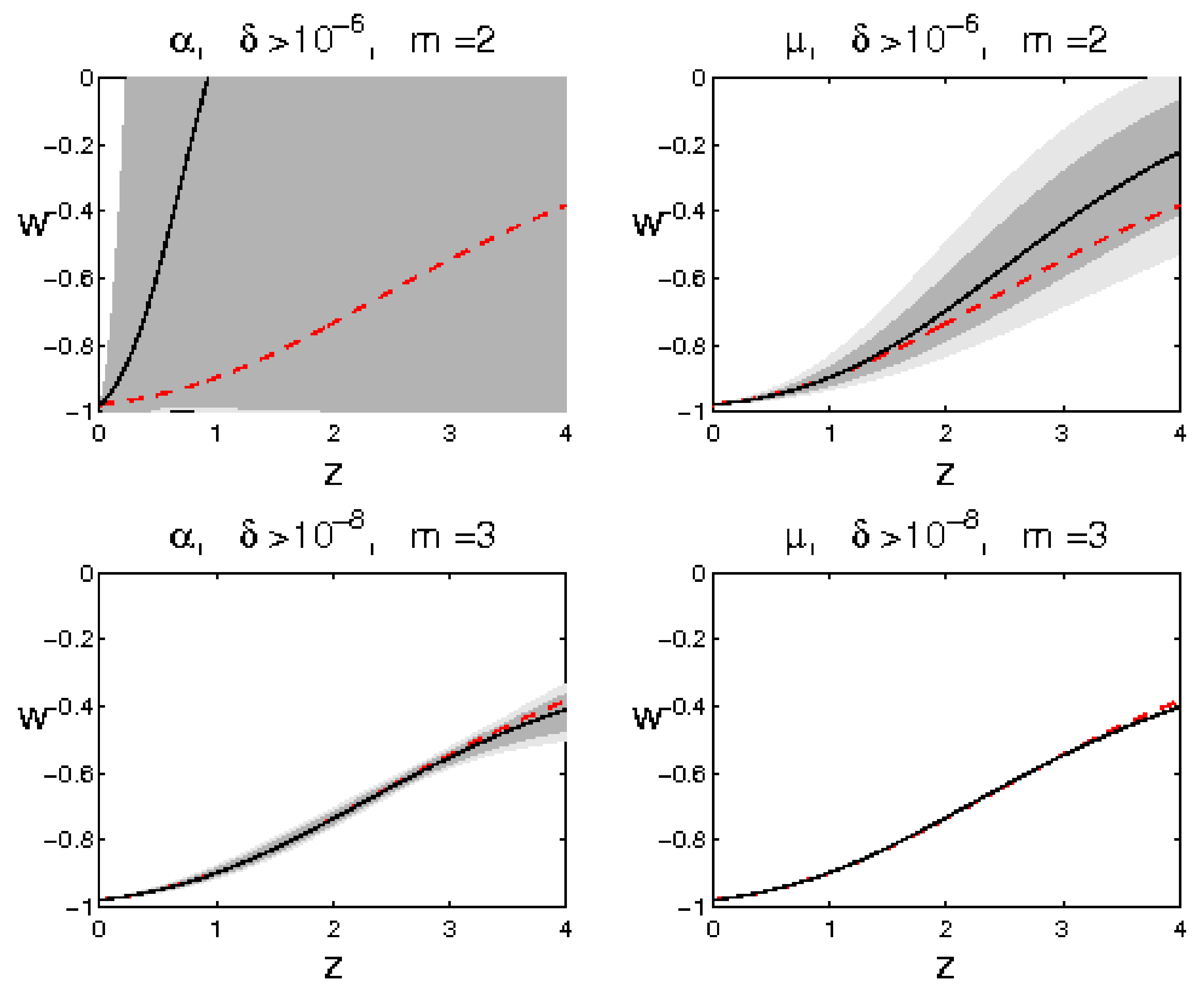

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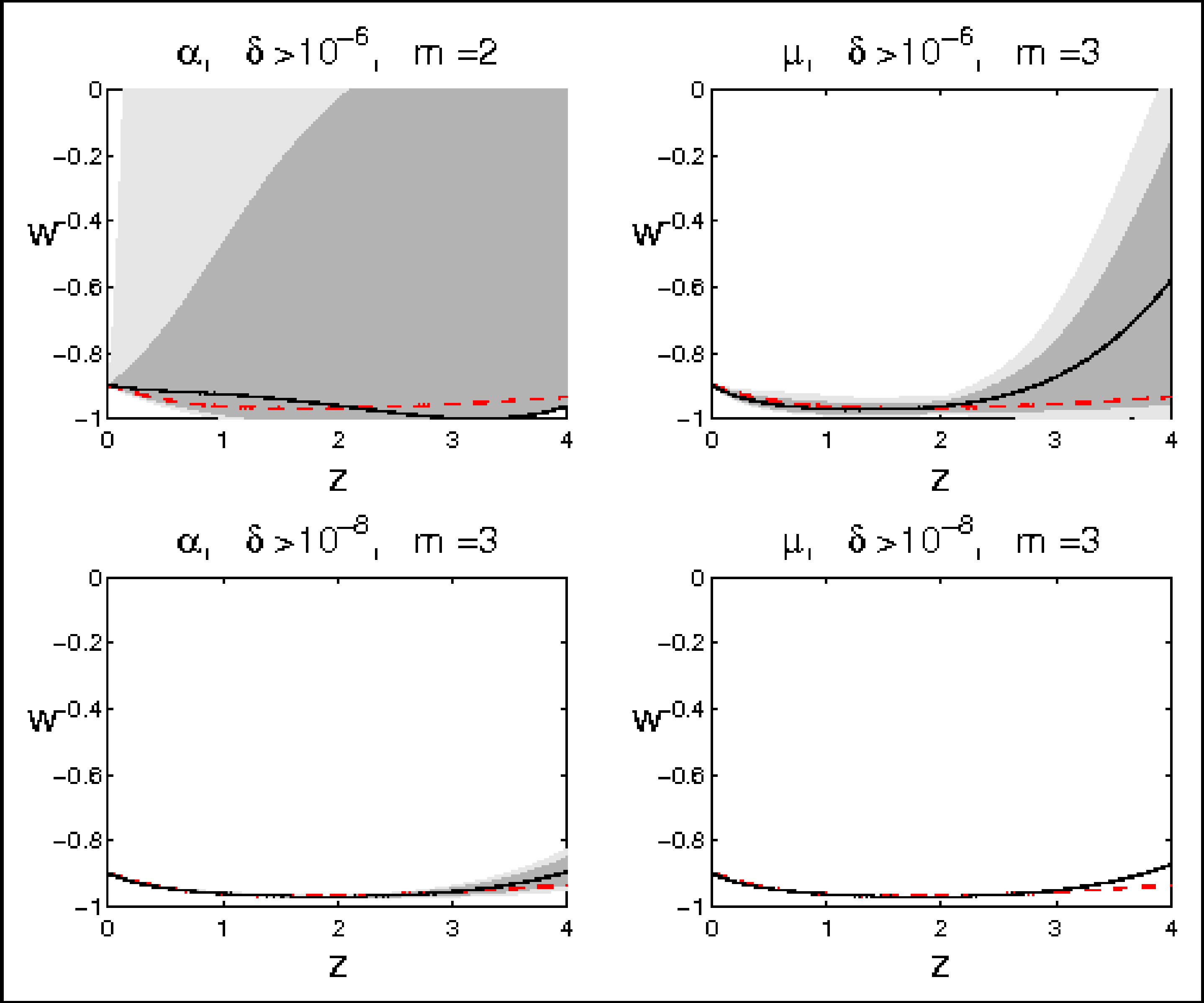
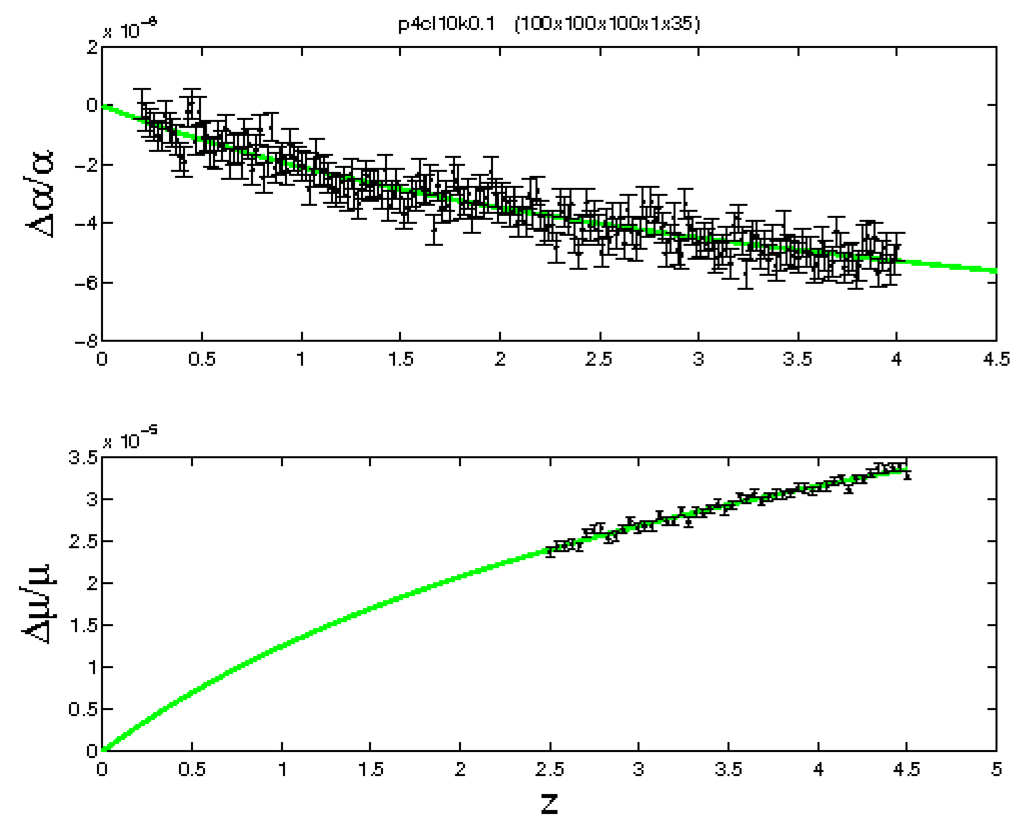
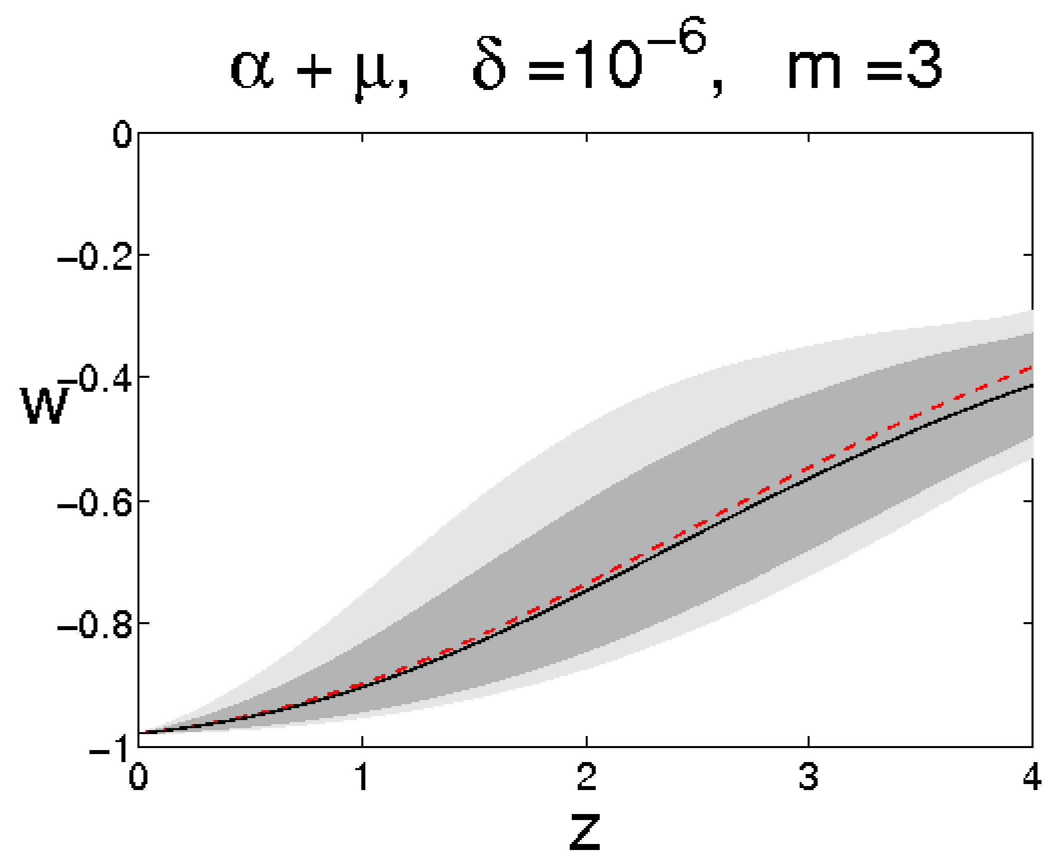


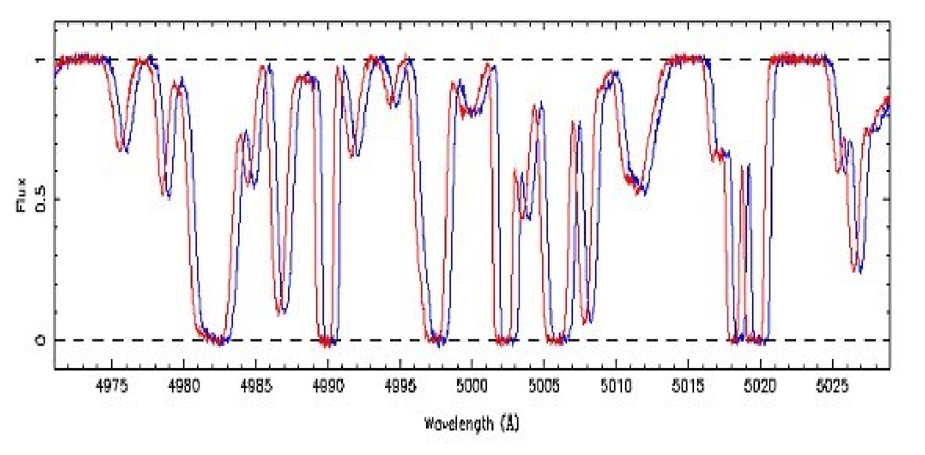
Reconstruction: ESPRESSO

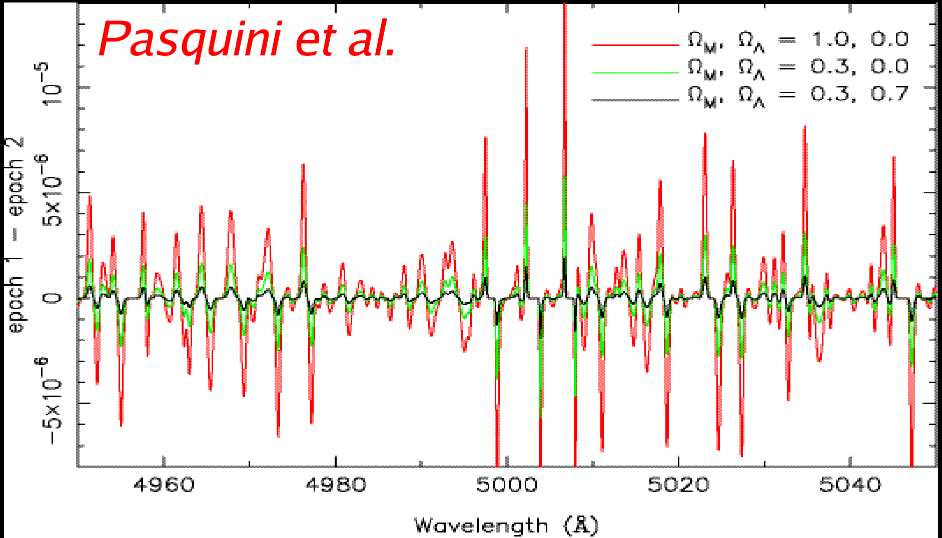




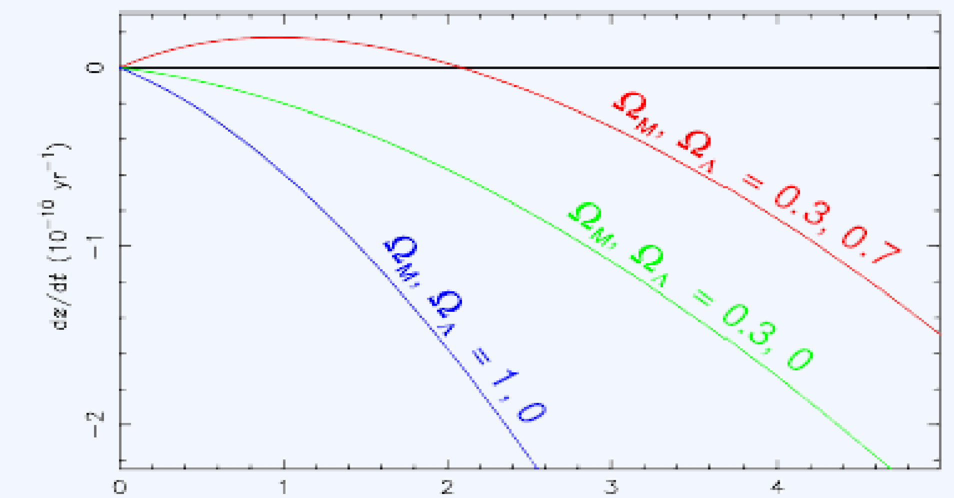
CODEX: Direct Probe of Dynamics

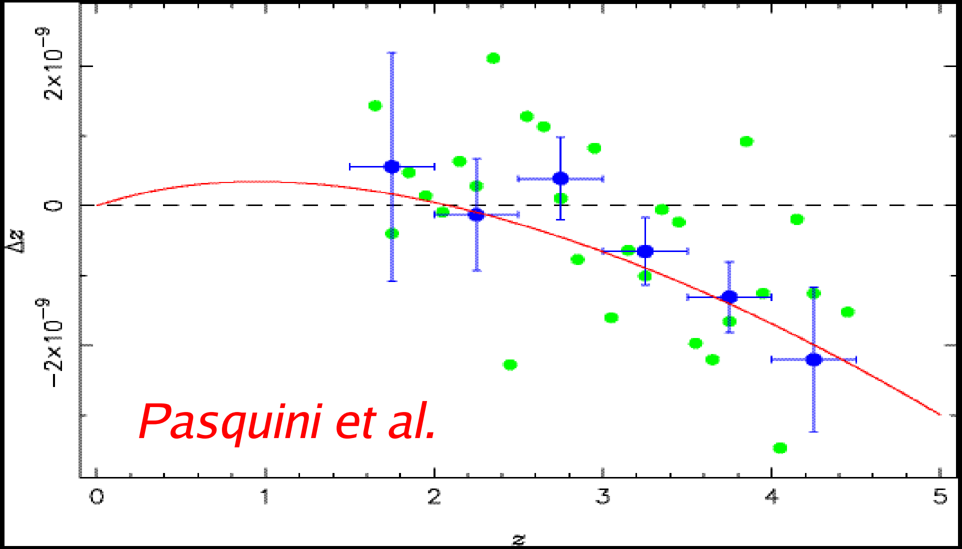
- Direct dynamical measurement of the expansion of the universe. (No geometry, clustering, gravity.)
- Acquire two sets of spectra with $\delta t \sim 10$ yr on lines towards $z=1$-4 quasars, measure shift in the Ly-α forest and metallic lines due to the changing cosmic expansion rate.
- Key figures: $R \sim 150000$, $S/N \sim 2000$, 500 nights over 15 years at E-ELT, $\lambda \sim 400$-680nm, $\sigma_v \sim 1$cm/s on 10 yr, HW cost 24 M€, for 12 years.
- Also: BBN, planets, etc…




Pasquini et al.

CODEX Cosmology





Pasquini et al.

- If GR is correct on large scales, $dz/dt=(1+z)H_0-H(z)$
- For EdS universe, redshift of an object at fixed coordinate distance always decreases with time, but for flat models with dark energy it increases for objects at low z
- Also get 2 orders of magnitude improvement on α measurement
- Proof-of-concept (ESPRESSO) will be at VLT in 5 years
- For more information, see the ESO CODEX Book