Fine-structure Constant Constraints on Dark Energy and the Weak Equivalence Principle

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with Ana Catarina Leite, Ana Marta Pinho, Arnau Gusart, Catarina Rocha, David Corre, Fernando Moucherek, Júlia López, Mar Pino, Max von Wietersheim, Miguel Ferreira, Paolo Molaro, Patrícia Carreira, Rui Alves and Stefano Cristiani

Scalars, Because They're There

- We 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) constrain fundamental physics and cosmology
  - This ensures a quantifiable 'minimum guaranteed science'

Fundamental? Varying?

- We have no 'theory of constants': don't know what role they play in physical theories, how many are fundamental, etc.
    - ...but they determine properties of atoms, cells and the universe
- Therefore we also have no compelling reason to assume that they are constant
    - ...but 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 ca. 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

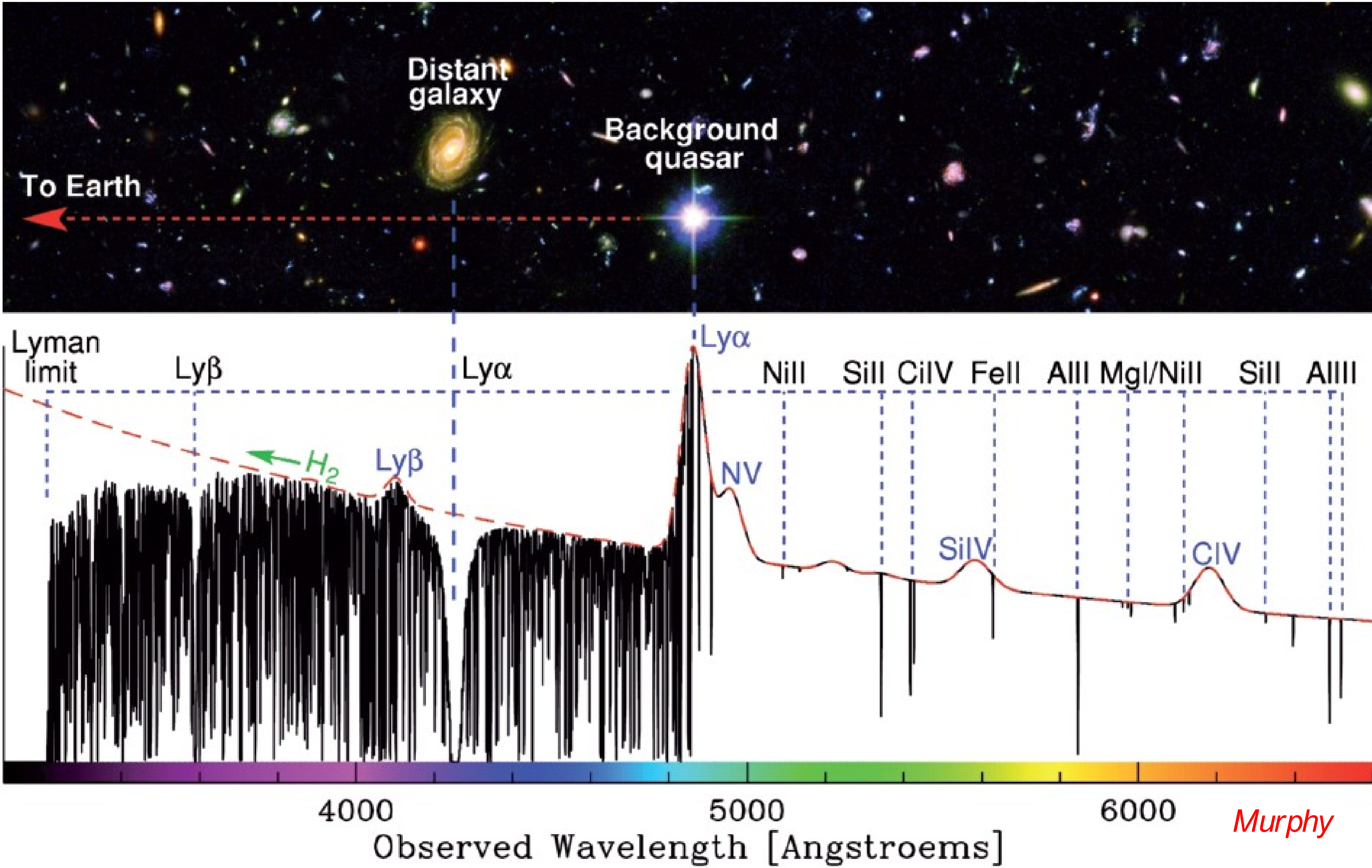
  $(1+w_0)$ is naively $O(1)$ — Observationally $< 10^{-1}$

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

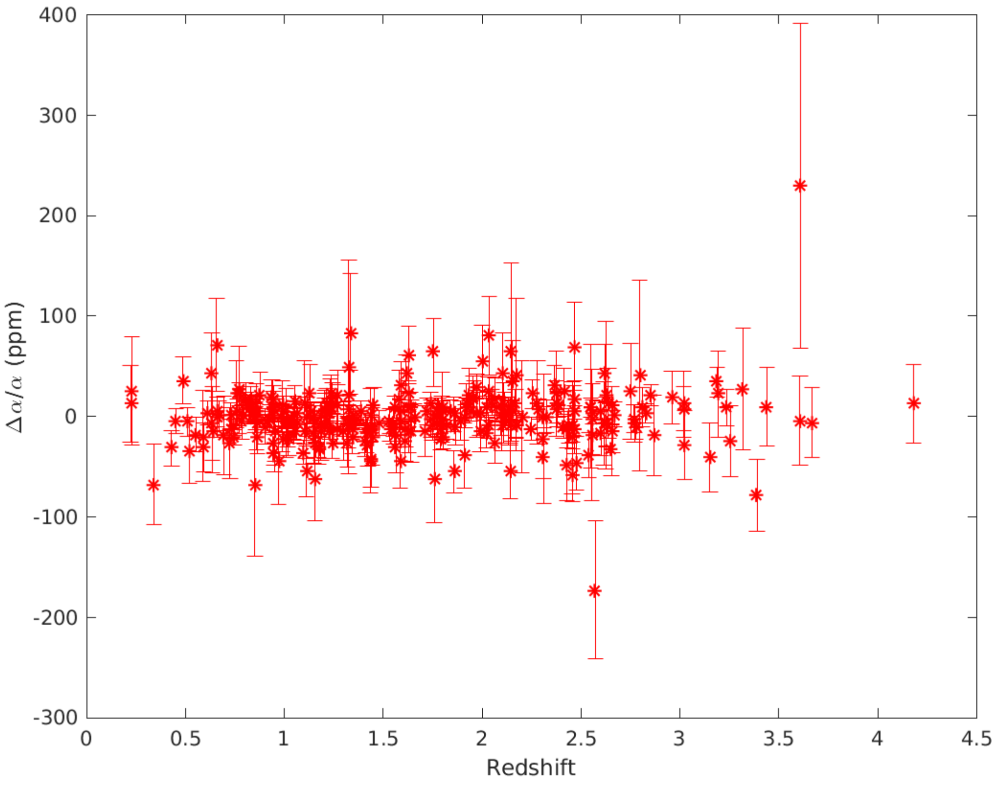
  – If not O(1), no 'natural' scale for variation: either fine-tuning...
  – ...or a new (currently unknown) symmetry forces it to be zero

- So is it worth pushing beyond ppm? Certainly yes!
  – Strong CP Problem in QCD: a parameter naively O(1) is known to be $<10^{-10}$, 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

Measuring α from Quasars

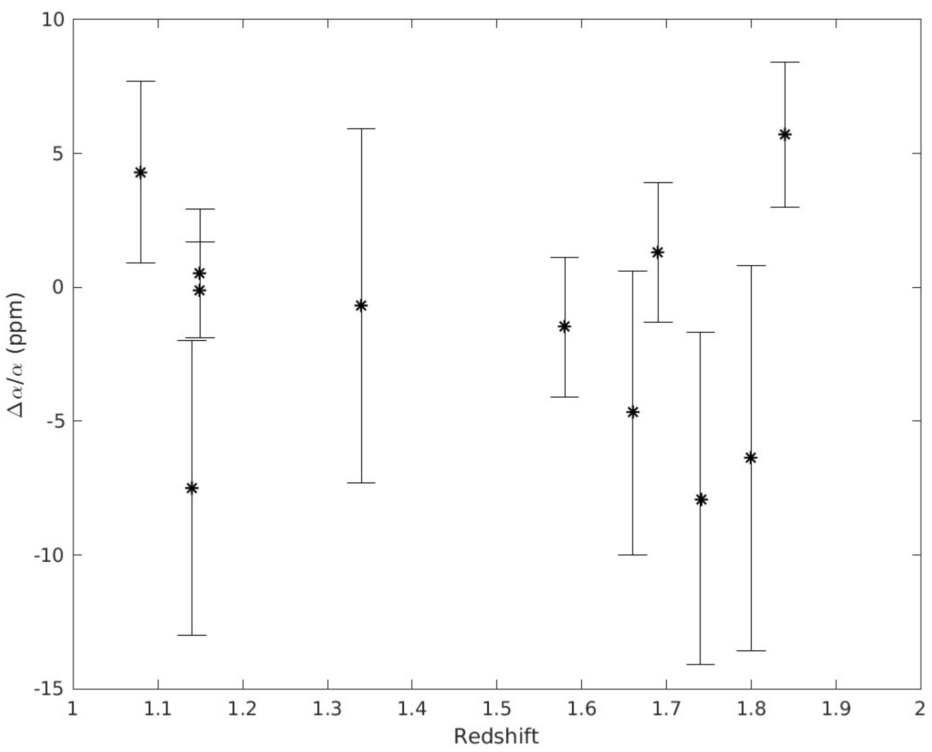


Recent Progress: 2011 to 2016

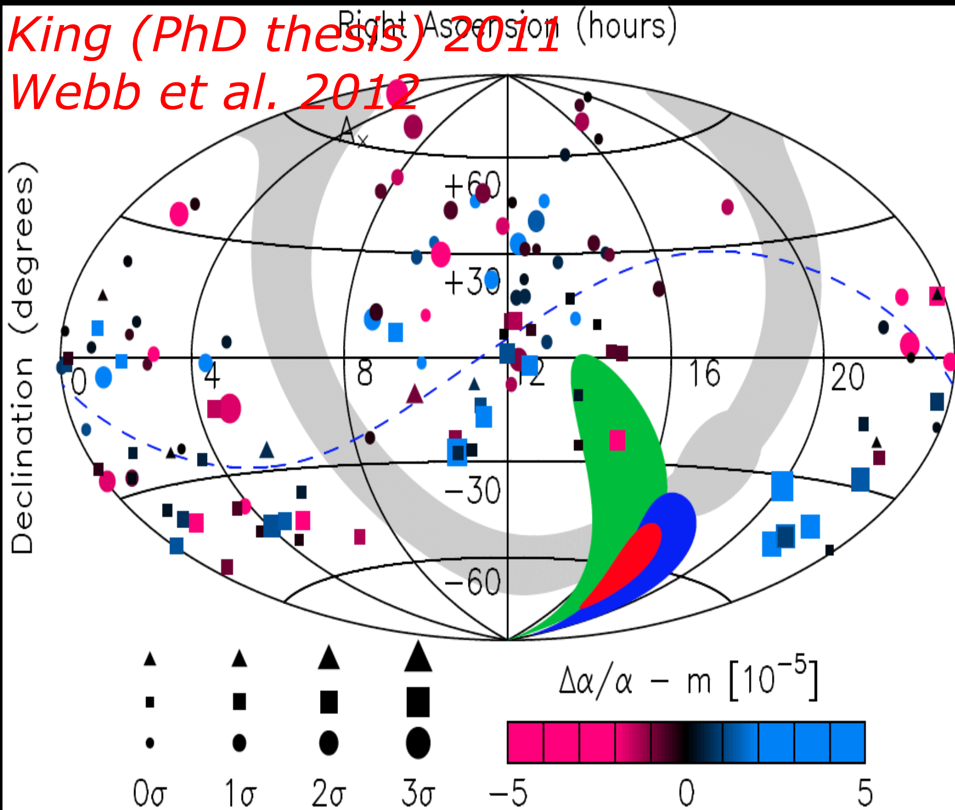


- *Webb et al., 2011*
  - 293 archival absorbers
  - Nominal weighted mean $\sigma_{stat} \sim 2$ ppm
  - ...but inferred $\sigma_{sys} \geq 9$ ppm

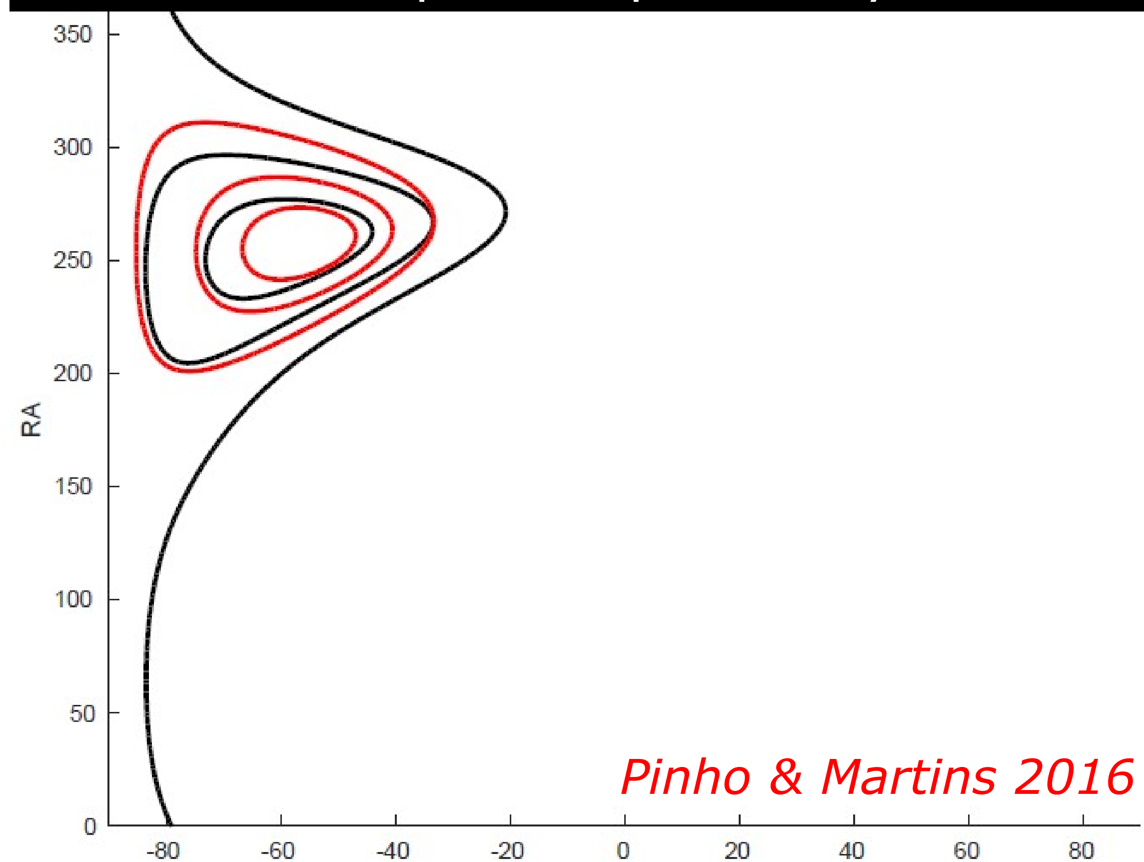
- *Large Program et al., 2016*
  - 11 dedicated measurements (more coming soon)
  - Nominal weighted mean 0.37 ± 0.94 ppm
  - Systematics floor 1 ppm



A Dipole on the Sky?



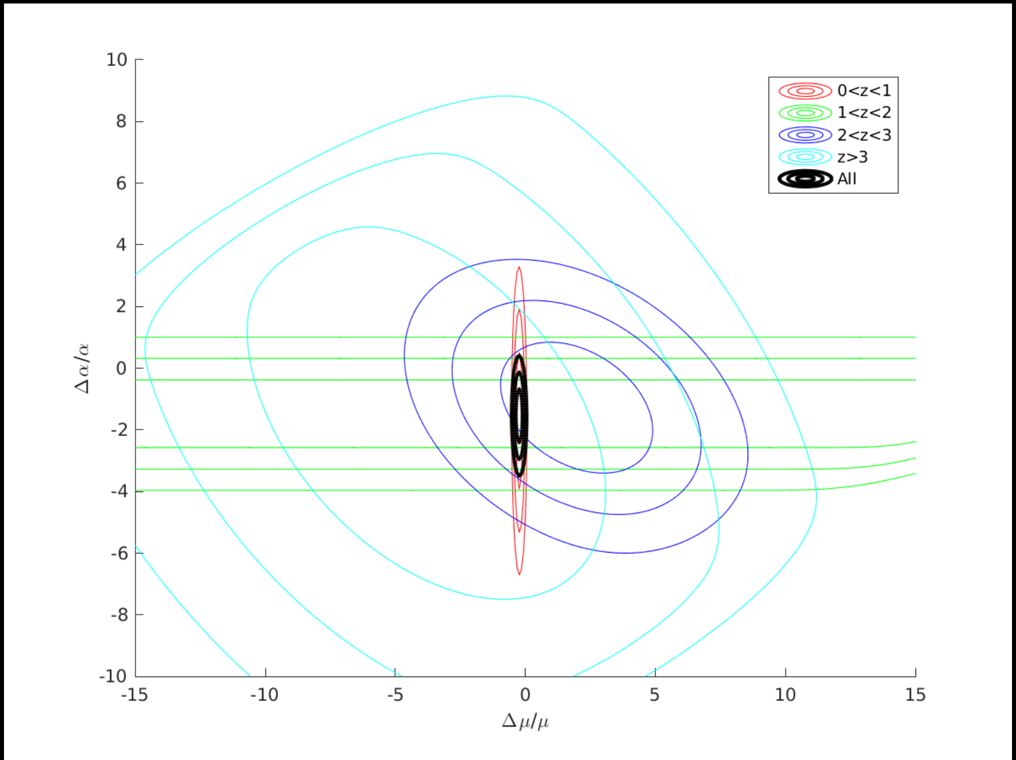
- >4 sigma evidence for a dipole; new physics or systematics?
  - Unclear if pure spatial dipole or dependent on lookback time
  - Recent data reduces allowed dipole amplitude by 20%

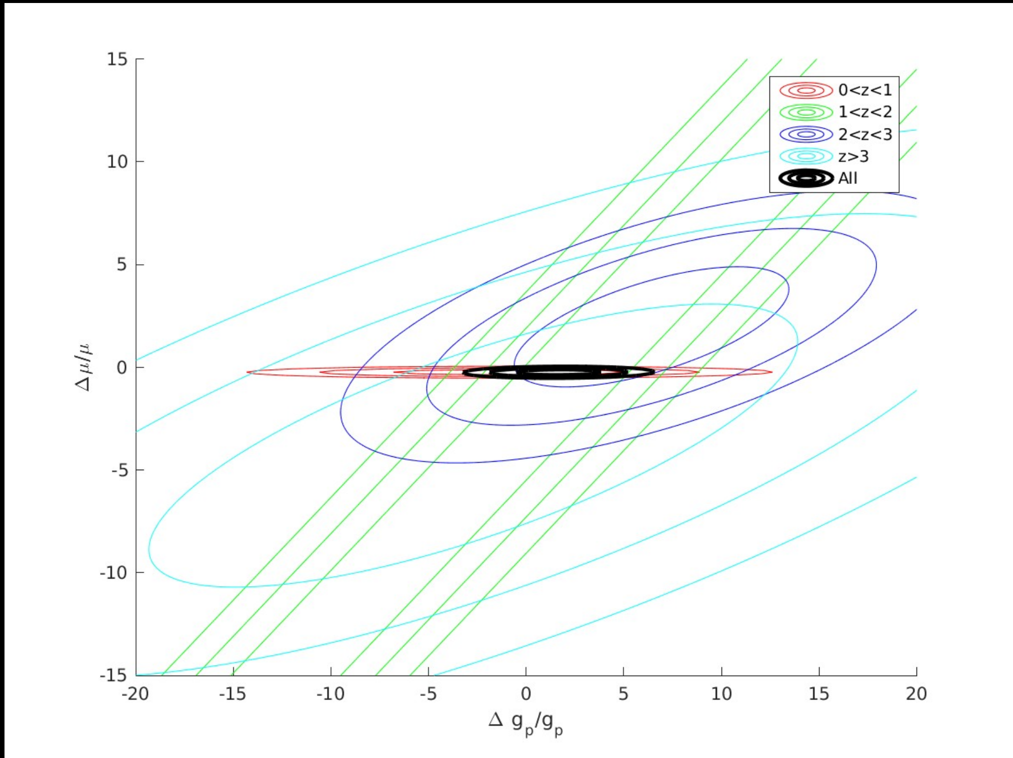


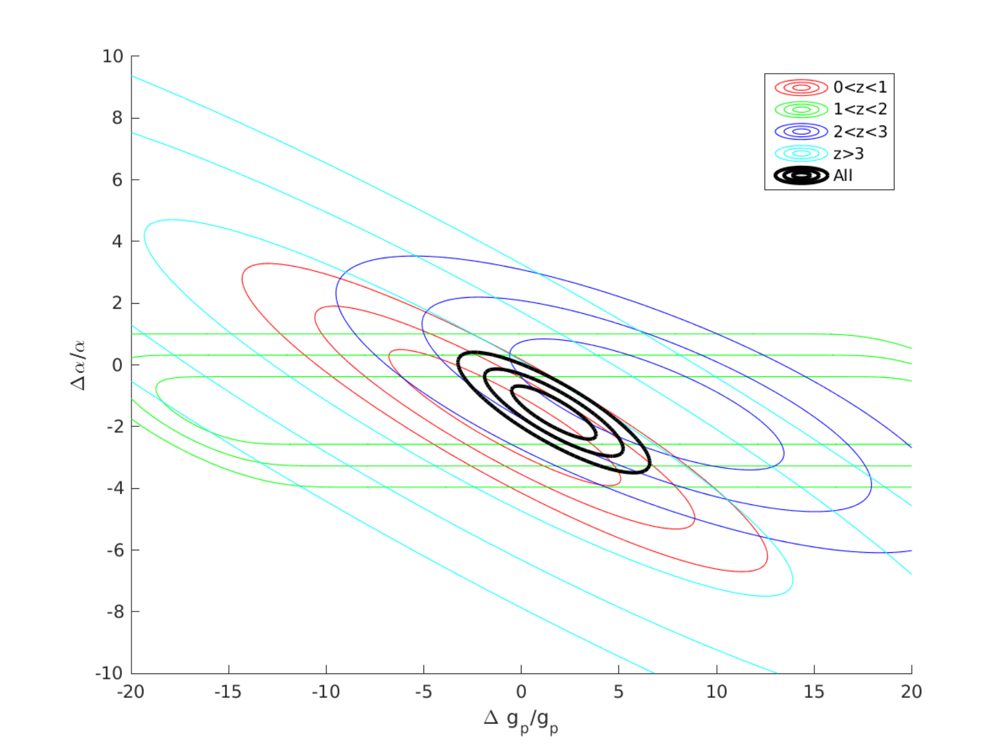
- Key driver for ESPRESSO (VLT) and the ELT-HIRES
  - Better precision, and much better control of systematics

Global Analysis

- Joint analysis optical/UV and radio/mm data yields 1-2σ inconsistencies
  - Especially true for data deep in the matter era
  - To be clarified with APEX, ALMA and ESPRESSO

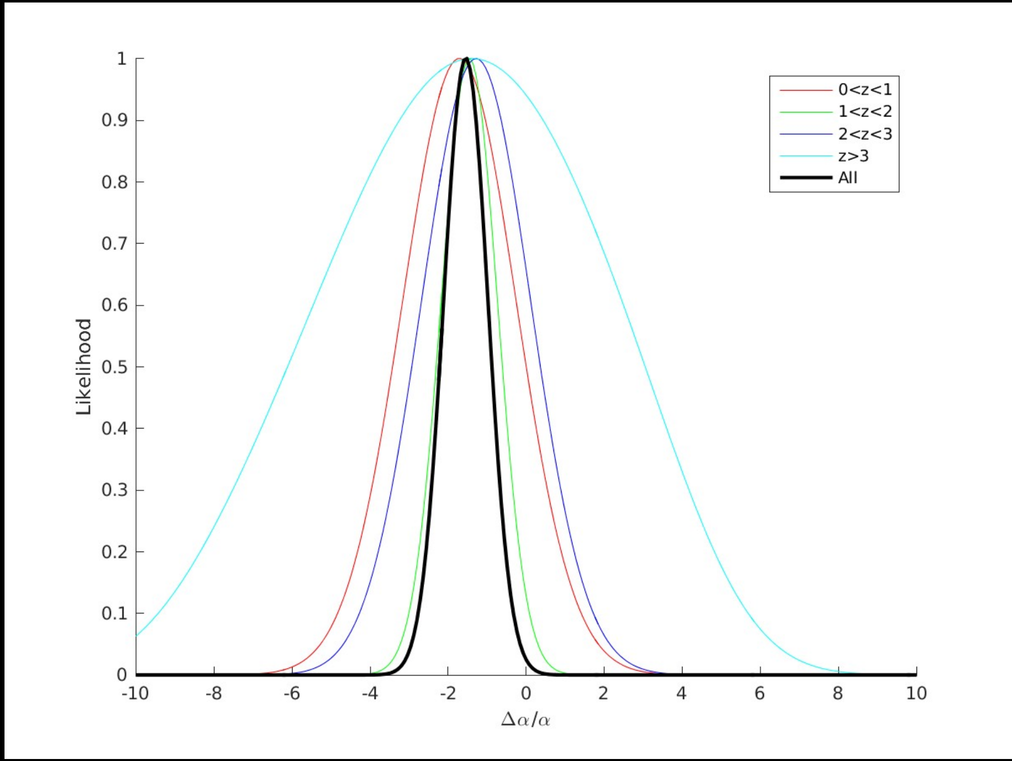


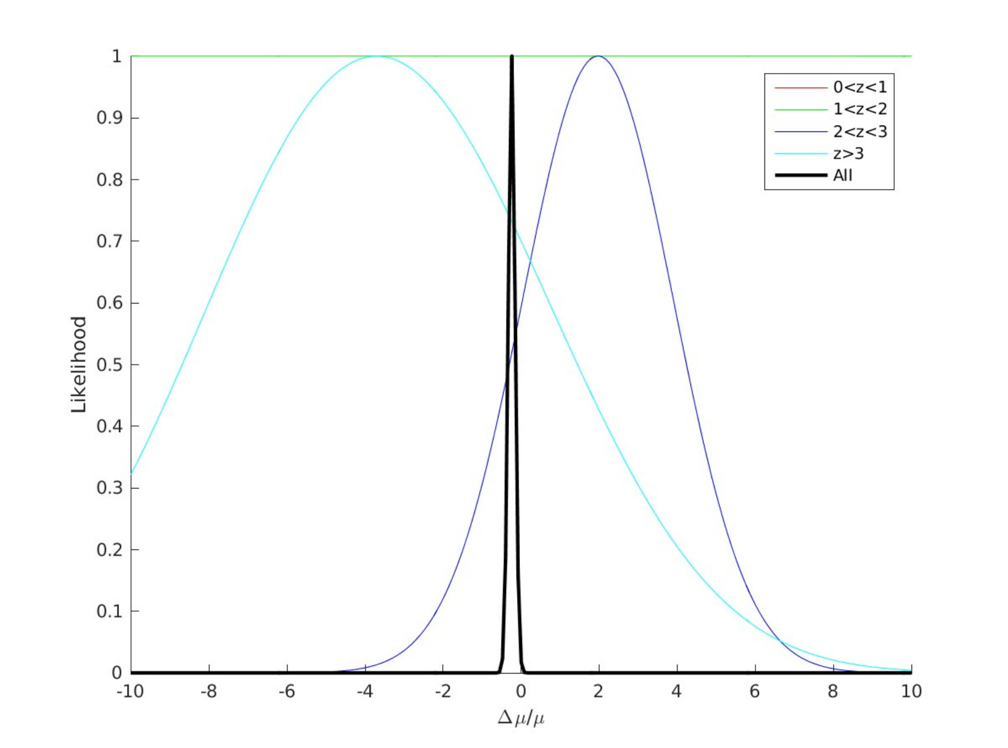


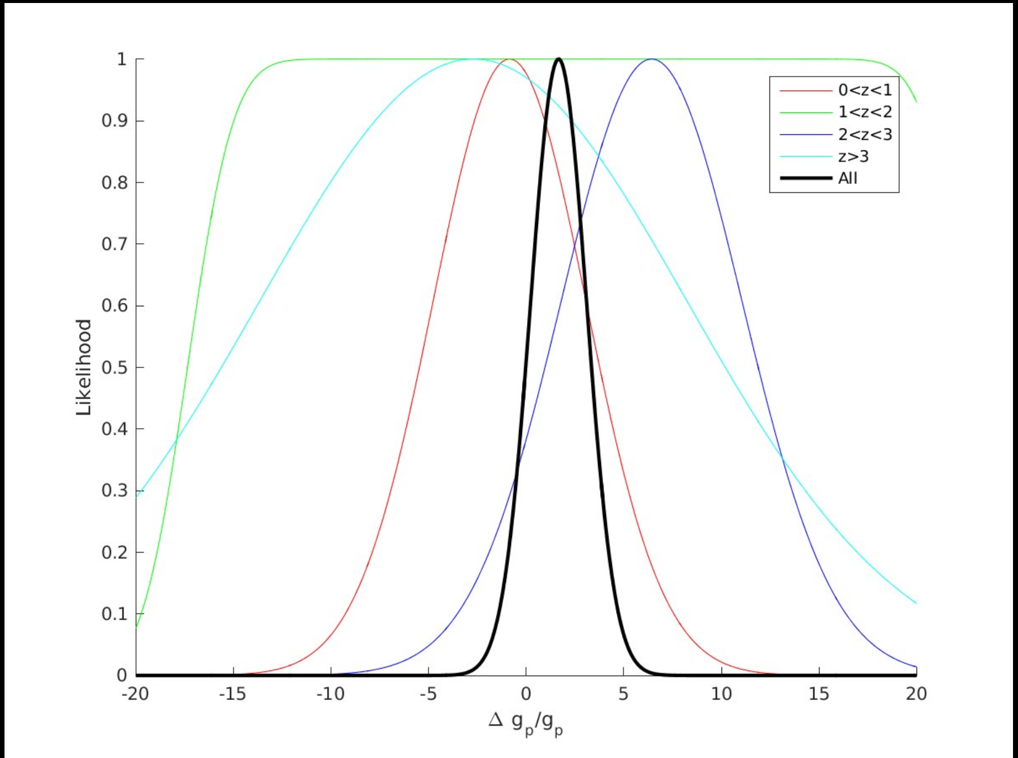


Global Analysis

- Very tight constraint on μ, but only at z<1
  - Best-fit Δα/α ~ -2ppm (not statistically significant)
  - Different behavior in matter and acceleration epochs?







Would You Like an ESPRESSO?

(See Ana Catarina Leite's talk on Thursday)

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 (for $p<0$) and dominate at low z
- 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
- Must probe deep matter era: scalar field dynamics fastest
  - Fundamental couplings ideally probe field dynamics beyond 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

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

Models & Constraints

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

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

- Current QSO + Clocks + Cosmo 1D marginalized constraints for w=const. dark energy model are *[Martins et al. 2015]*
  - $|\zeta| < 5\times10^{-6}$ (2 sigma) and $|1+w_0| < 0.06$ (3 sigma)
  - 12 ESPRESSO GTO measurements (cf. Ana Catarina Leite's talk): improvements by a factor 1.5 (if no variations)...
  - ...or a >3 sigma detection of non-zero ζ
- Results are (mildly) model-dependent *[Martins et al. 2016]*; e.g., for CPL parametrization
  - Weaker constraints on $(1+w_0) = 0.00^{+0.15}_{-0.05}$ (3 sigma)
  - ...hence stronger constraint on coupling $\zeta = (1\pm3)\times10^{-6}$ (2 sigma)

WEP Constraints

- In these models the scalar field will inevitably couple to nucleons (through the α dependence of their masses) and therefore lead to violations of the Weak Equivalence Principle
  - Cf. *[Dvali & Zaldarriaga 2002, Chiba & Kohri 2002, Uzan 2011, …]*
- Eotvos parameter bound: $\eta < 2\text{-}4 \times 10^{-14}$ *[Martins et al. 2015]*
  - > 10x tighter than direct bounds (but testable by MICROSCOPE)
  - In models where dark energy and α variation are due to different physical processes, WEP bound weaker: typically $\eta < 5\text{-}10 \times 10^{-14}$
- Forthcoming high-resolution ultra-stable spectrographs will keep providing competitive constraints
  - ESPRESSO can reach few$\times 10^{-16}$ (i.e., better than MICROSCOPE)
  - ELT-HIRES sensitivity $\eta \sim 10^{-18}$, similar to that of the proposed STEP

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, significant improvements coming
- New dedicated instruments (ESPRESSO and ELT-HIRES) will lead to 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)