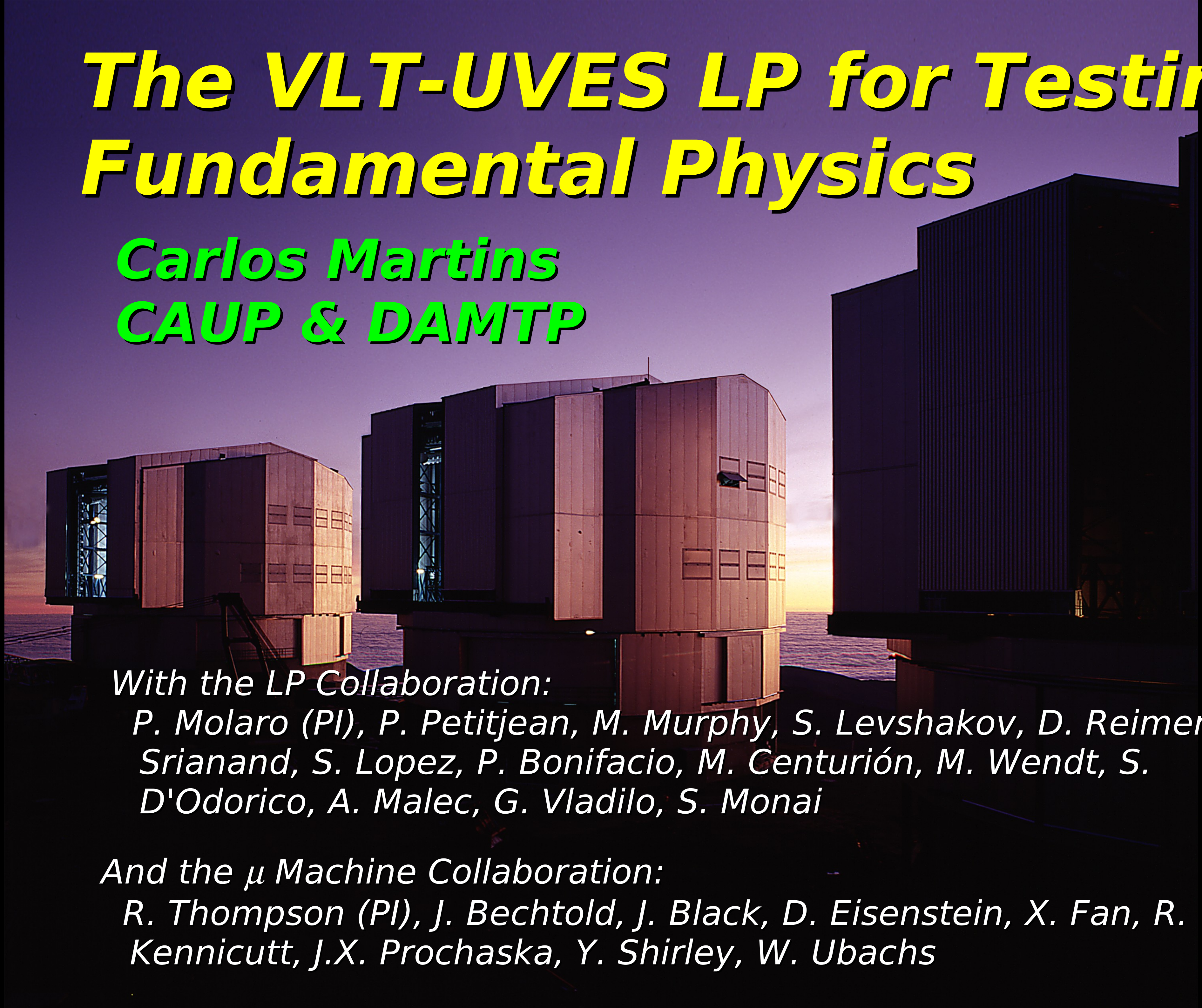

The VLT-UVES LP for Testing Fundamental Physics

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And the μ Machine Collaboration:
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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 as a whole.
    - If they vary, all the physics we know is incomplete
- Improved null results are important and useful; a detection would be revolutionary!
    - Natural scale for cosmological evolution would be Hubble time, but current bounds are 6 orders of magnitude stronger
    - Varying non-gravitational constants imply a violation of the Einstein Equivalence Principle, a 5^{th} force of nature, etc

The Ratio of Proton and Electron Masses

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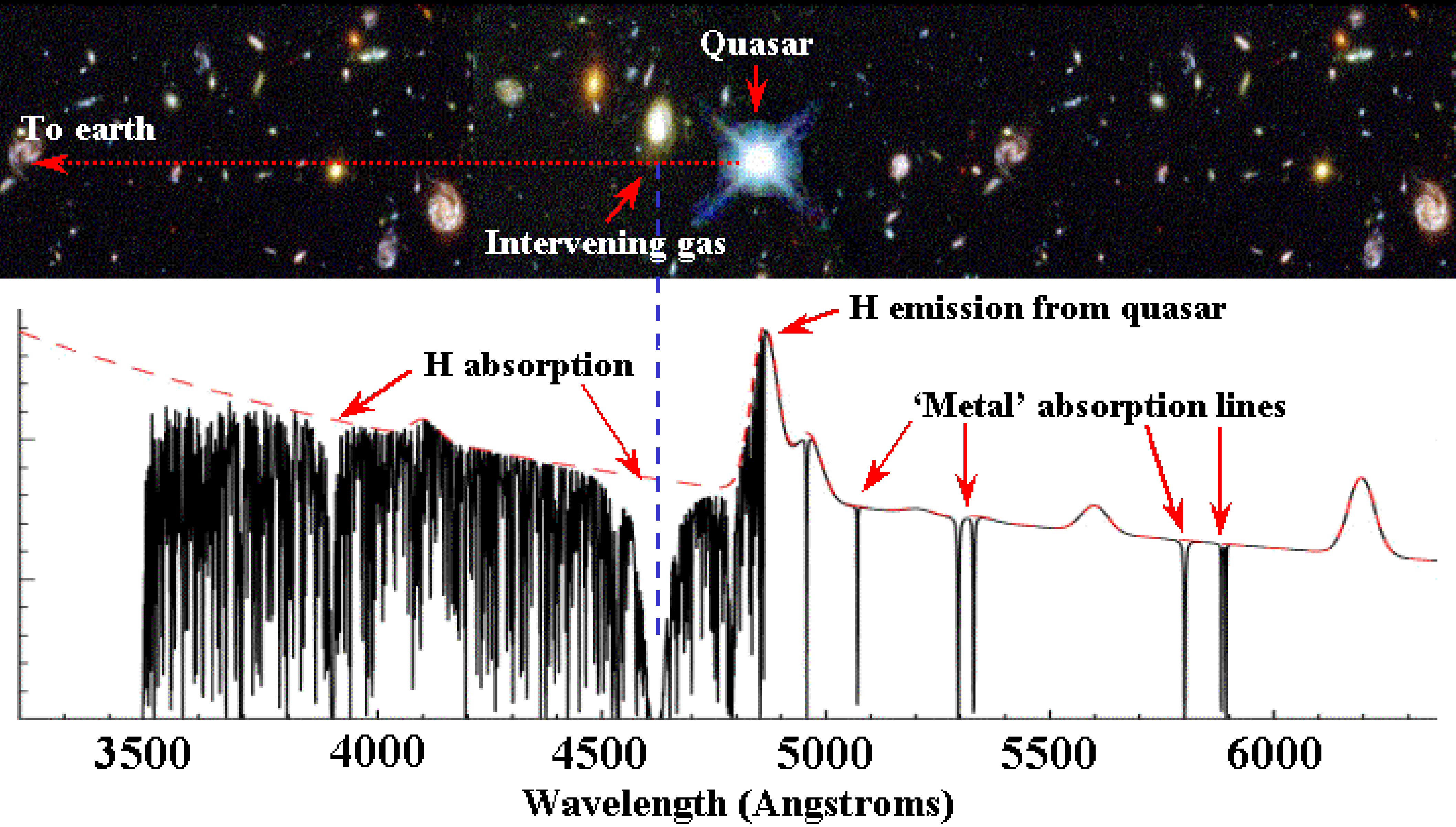
(Received April 5, 1951)

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



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.'04]* $\Delta\alpha/\alpha=-5.7\pm1.1$ppm
  - ... $\Delta\alpha/\alpha=-0.1\pm1.5$ ppm *[Petitjean et al.'09]*
  - *[Ubachs et al.'07]* $\Delta\mu/\mu=25.6\pm5.8$ppm
  - ... $\Delta\mu/\mu=2.6\pm3.0$ppm *[King et al.'08],* $\Delta\mu/\mu=-7\pm8$ppm *[Thompson et al.'09]*
  - Radio ($z<1$): null results at few x ppm level *[Kanekar'08]*
- Can also use emission: cleaner but less sensitive measurements, similar z range! *[Brinchmann et al.'04]*

Reinhold et al.

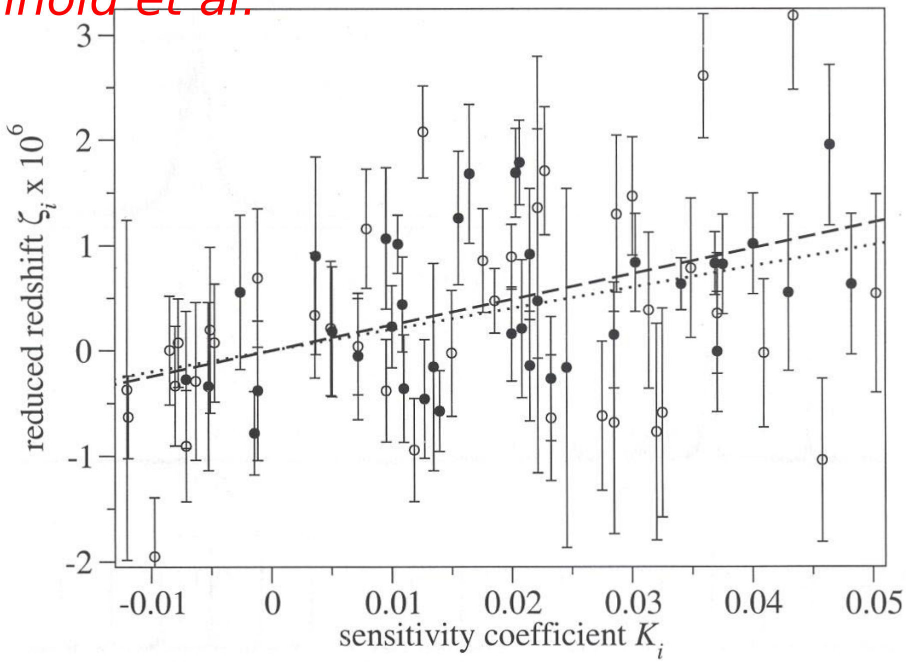
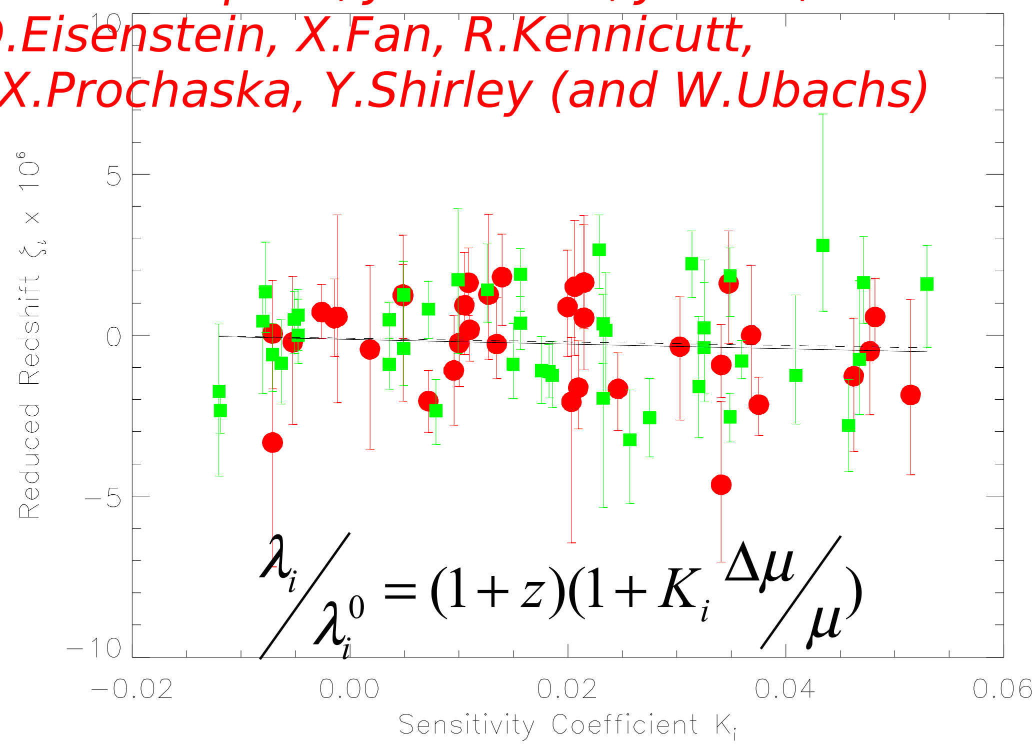


FIG. 2: Linear fit to reduced redshift of quasar absorption lines ζ as defined by Eq. 9. I
Q 0347-383, $z = 3.0248970$; open circles: Q 0405-443, $z = 2.5947325$. The error-weigh
is shown by a dashed line, the unweighted fit by a dotted line.

- In principle, can match H_2 absorption line wavelengths against the pattern of shifts predicted by the sensitivity coefficients.
- In practice the available signal to noise and resolution allows only a fit to the trend of the predicted shifts.

w/ R.Thompson, J.Bechtold, J.Black, D.Eisenstein, X.Fan, R.Kennicutt, J.X.Prochaska, Y.Shirley (and W.Ubachs)



$$\lambda_i / \lambda_i^0 = (1+z)(1+K_i \, \Delta\mu / \mu)$$

- Systematic wavelength errors in the old UVES reduction pipeline may be the source of the previous indication of a positive change in μ.

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!
- Measurement of fundamental constants requires observing procedures beyond what is done in standard observations.
  - Existing data has been generally taken with other purposes and does not have the necessary quality to fully exploit UVES capabilities.
- Need customized wavelength calibration procedures beyond those supplied by standard pipelines *[Thompson et al.'09]*.
  - Ultimately should 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 be needed to resolve the issue:
  - Shortly: Maestro (R~90000) at MMT, PEPSI (R~300000) at LBT
  - Near future: ESPRESSO at VLT, ...
  - Later on: CODEX at E-ELT, ...

The VLT-UVES LP

- New observations of a selected sample, taken with a specifically optimized methodology.
    - Calibration lamps attached to science exposures, ie 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, no line broadening/saturation
- Potential UVES accuracy is 1-2ppm per system, where photon noise and wavelength calibration errors are comparable.
    - Our goal: 2ppm per system, 0.5ppm for sample of 22 systems.
- 41 nights secured over 9 observation periods (4.5 years)
    - 4 nights already in (September 19-23, 2009), results out soon…

μ Machine Milestones

- The existing μ measurements come from VLT R~70000 spectra, analyzed with the standard UVES pipeline
- Developed new optimized techniques and re-reduced existing UVES/VLT and HIRES/Keck H2 data, to more accurately measure μ
- A second step is using Maestro/MMT (R~90000) a PEPSI/LBT (R~300,000) to obtain better spectra of northern hemisphere systems
  - We should measure μ to ten times higher accuracy at look-back times from a few to 12 billion years (ca. 14 systems)
- Third short-term goal is design of a laser frequency comb wavelength calibration system for PEPSI
- A strategic goal is to design a dedicated facility for ultra-high resolution ($R \sim 10^6$) and signal to noise spectra of point objects for measuring both α and μ

Would you like an ESPRESSO?

- Echelle Spectrograph for PREcision Super Stable Observations
  - Geneve-OAT-IAC-CAUP-ESO
  - PI Pepe, PM Mégevand, PS Molaro
  - 2009 Phase A, 2010 start, 2014 op
- Instrument specifications:
  - Radial Velocity Accuracy 10cm/s, R > 120000 for 1UT (4 UT lower)
  - HARPS: Vacuum Tank, No moving parts, Mechanically stable, Controlled environment, Simultaneous Calibration, Fibre Fed
- Key scientific goals:
  - Measure high precision radial velocity for search for rocky planets
  - Search for variation of physical constants
  - Also: Chemical compositions, stellar oscillations, IGM, ...
- ESPRESSO is an ideal instrument for varying constants
  - Resolution + Photons (4UT) + stability = $\sigma(\Delta\alpha/\alpha) \sim 0.5$ ppm

So What's Your Point?

- Everyone agrees that nothing varies at 10^{-5} level; this is starting to be constraining (cf. Cassini bound)
- We'll get to 10^{-6} soon (PEPSI, ESPRESSO, ...) and to 10^{-7} later
  - Need customized observation procedures, laser frequency comb calibration, purpose-built data reduction pipelines.
  - Doing things right is quite tricky, so be patient (if something is varying today, it will be varying tomorrow...)
- Recall the dark energy lesson: it's clear that a detection will only be believed when there's redundancy
  - Equivalence Principle tests
  - Laboratory measurements, spatial variations, T(z), etc
- Need other astrophysical probes (SZ, helioseismology?)
- Varying constants are a powerful (and low-cost) way to probe fundamental physics and dark energy