Current State of $m_p/m_e=\mu$ Measurements Versus Cosmic Time

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Motivation

- Pure intellectual interest in establishing the value of a fundamental “constant” in the early universe
- Input and information to guide our way through the vast landscape (10^{500}?) of elementary particle and dark energy theories

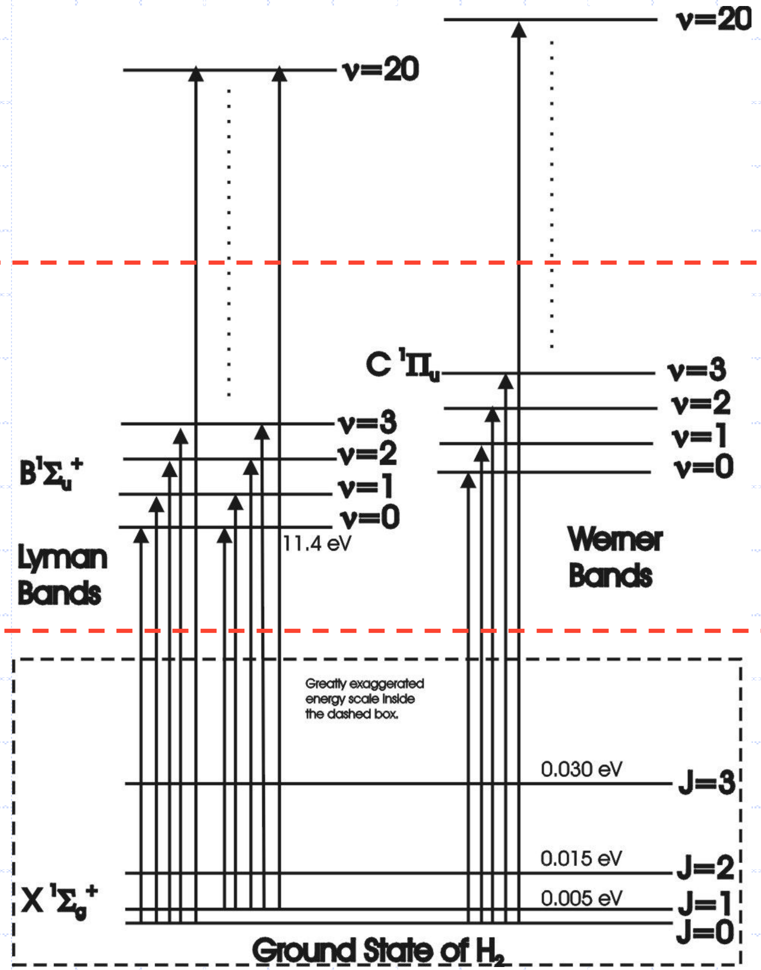
Bottom Line

- $\Delta\mu/\mu \leq 10^{-5}$ at a look back time of ~11Gyr

Concept

- A change in μ produces a calculable change in the rotational and vibrational energies of a molecule relative to the electronic energy (Thompson 1975).
- These changes in the energy levels alter the spectra of the molecules in a way that can not be duplicated by a redshift.
- The value of μ at high redshift can be determined from the absorption spectra of H_2 in high redshift DLA systems

H_2 Energy Levels



Overlap areas are very important.

$\Delta J=0,+/-1$

$\Delta v=$ any integer

Sensitivity Constants

- Although implicit in previous work, Varshalovich and Levshakov (1993) explicitly developed the sensitivity constant which for a line i is defined as

$$K_i = \frac{d \ln \lambda_i}{d \ln \mu} = \frac{\mu}{\lambda_i}\frac{d \lambda_i}{d \mu} = -\frac{\mu}{\nu_i}\frac{d \nu_i}{d \mu}$$

- The rest frame wavelengths are related to the observed wavelengths by

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

- Each line has a unique sensitivity constant K_i which can be slightly negative, zero or positive.
- The higher the vibrational quantum number the larger the sensitivity constant.
- The overlap of the Lyman and Werner bands places lines with very different sensitivity constants in close proximity to each other.

Sensitivity Constants cont.

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

Redshift vs. Sensitivity Coefficients

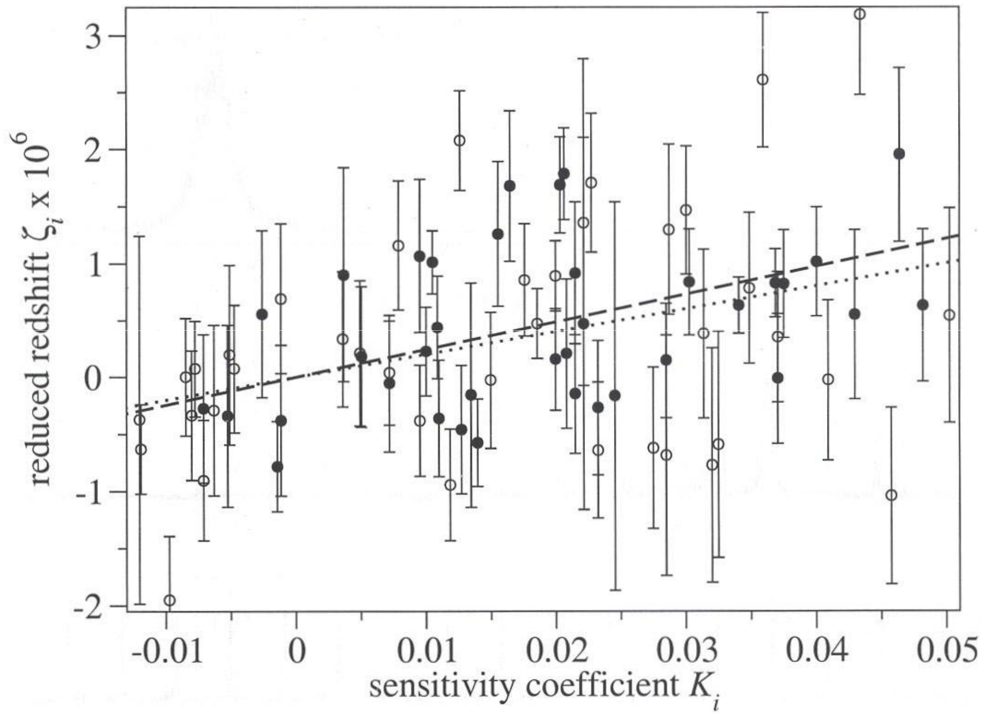


FIG. 2: Linear fit to reduced redshift of quasar absorption lines ζ as defined by Eq. 9. Filled circles: Q 0347-383, $z = 3.0248970$; open circles: Q 0405-443, $z = 2.5947325$. The error-weighted linear fit is shown by a dashed line, the unweighted fit by a dotted line.

From Reinhold et al. 2006

Observational History

- Historically there have been 3 types of observations
  - Optical observations of redshifted absorption lines of the electronic transitions of H_2 in DLAs.
  - Radio observations of rotational and inversion transitions of molecules in molecular clouds.
  - Laboratory measurement of the current rate of change of μ.

H_2 Observations

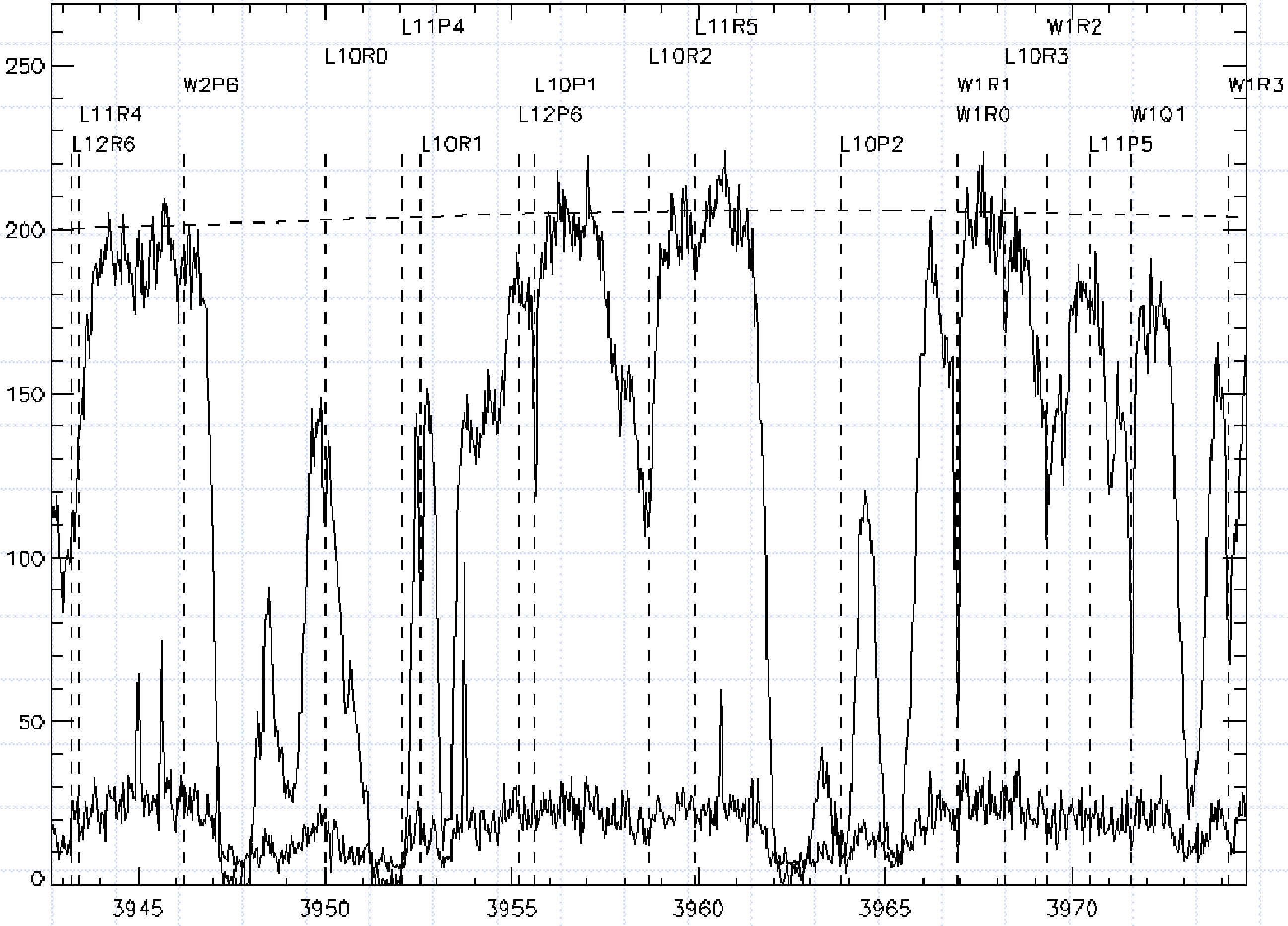
- When first proposed in 1975 the method required 3 advances to be practical
  - Larger telescopes
  - More sensitive and higher resolution astronomical spectrometers
  - More accurate measurements of the rest wavelengths of the transitions
- All of these have now occurred

H_2 Difficulties

- Very few DLAs contain measurable amounts of H_2.
  - Only about a dozen known
- The Lyman and Werner lines lie in the Ly alpha Forest of atomic absorption lines
- The primary shift is in the vibrational and rotational levels. These shifts are diluted by the electronic energy.
  - Typical K_i are about 10^{-2}.

Sample Spectrum and Difficulties

Q0347-383



Wavelength in Å

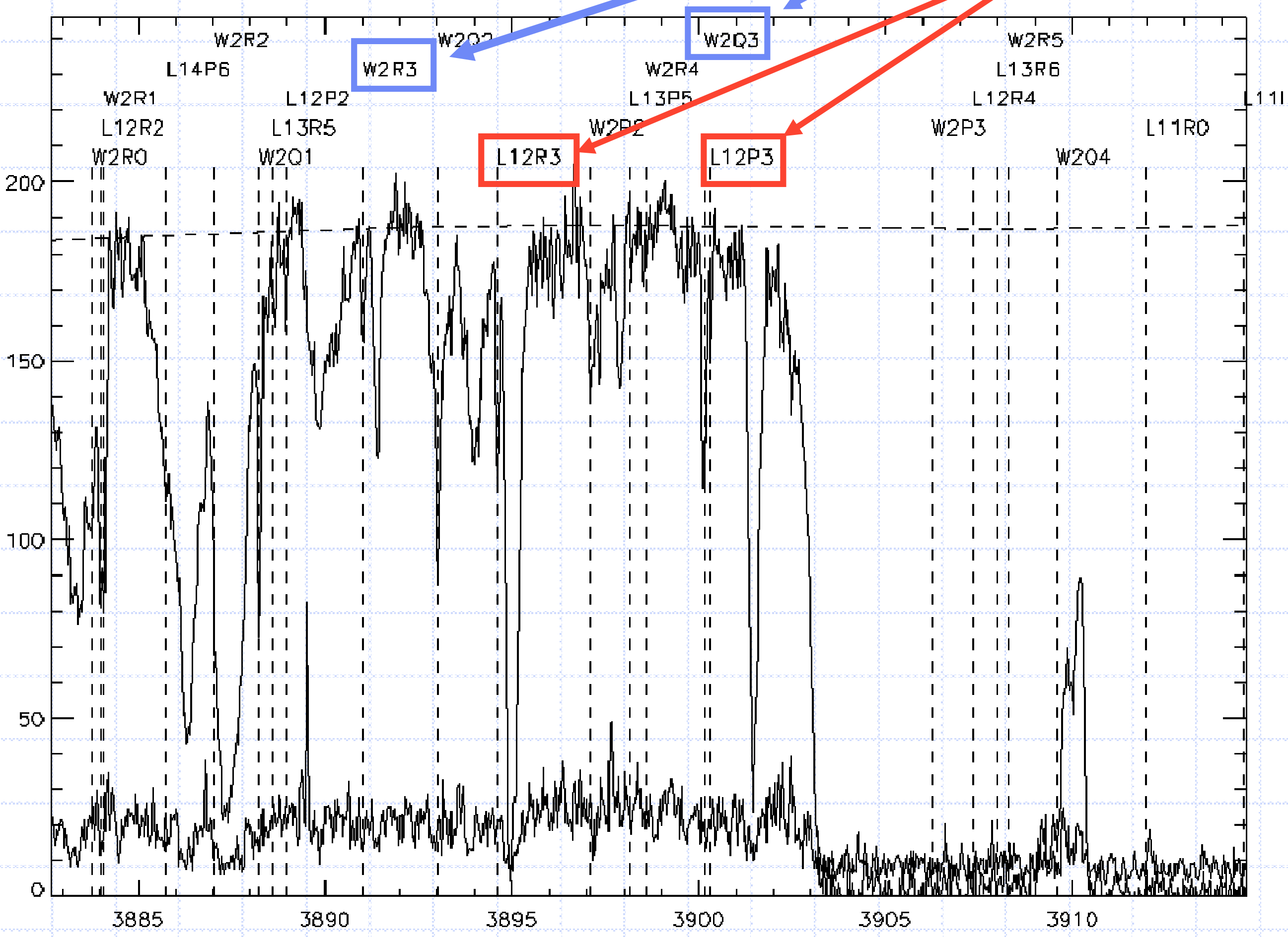
H_2 Advantages

- Potential for many lines from the same ground state
- Well measured rest wavelengths
  - (Ubachs et al. 2007)
- Lines with significantly different sensitivity factors in close spectral proximity
  - Mix of Lyman and Werner lines

Some Opportunities

Low Shift Lines

High Shift Lines



All 4 lines have the same ground state.

Very Few Systems Actually Studied

- PKS 0528-250= Q0528-250 (z = 2.811)
  - Foltz et al. (1988), Cowie & Songaila(1995), Potekhin et al. (1998), King et al. (2008)
- Q1232+082 (z=2.338)
  - Ivanchik et al. (2002)
- Q0347-383 (z=3.025) and Q0405-443 (z=2.595)
  - D'Odorico(2001), Ivanchik et al.(2002,2003,2005), Levshakov et al.(2002), Ubachs & Reinhold(2004), Reinhold et al.(2006), Ubachs et al.(2007), King et al. (2008), Wendt & Reimers(2008),Thompson et al.(2009)
- Q1331+170 (z=1.776)
  - Cui et al. (2006)
- J2123-0050 (z=2.059)
  - Malec et al. 2010

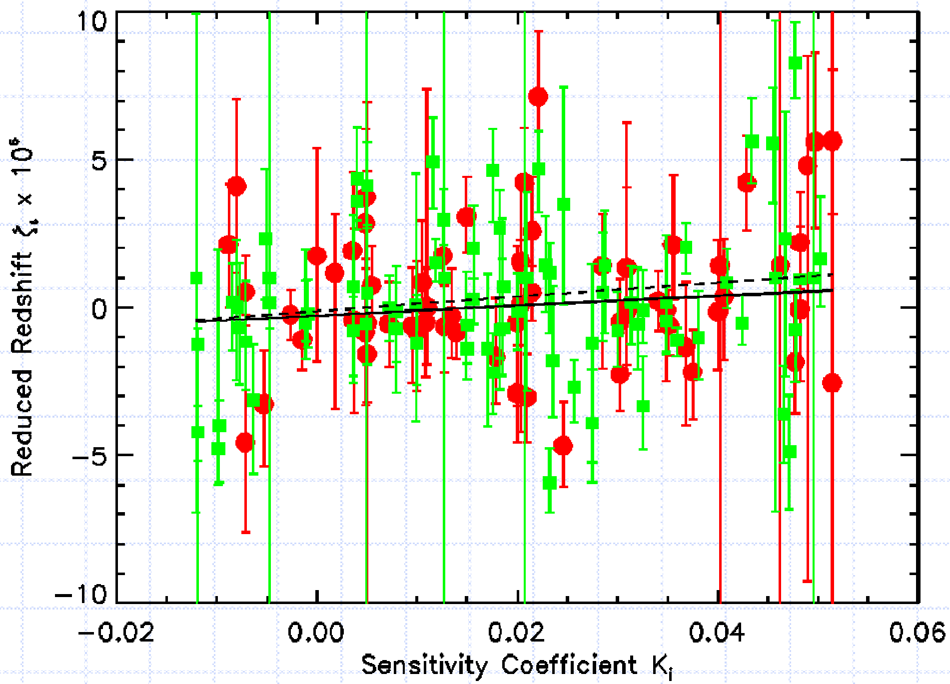
- A total of 6 systems in all

Sources of Systematic Errors

- Systematic errors in the wavelength calibration
  - The sensitivity factors K_i are roughly proportional to the vibrational quantum number of the upper state (ground state is always $v = 0$)
  - The higher the upper vibrational quantum number the shorter the wavelength
  - Systematic wavelength errors therefore translate into positive or negative changes in μ
  - Partially mitigated by the mixture of Lyman and Werner bands.

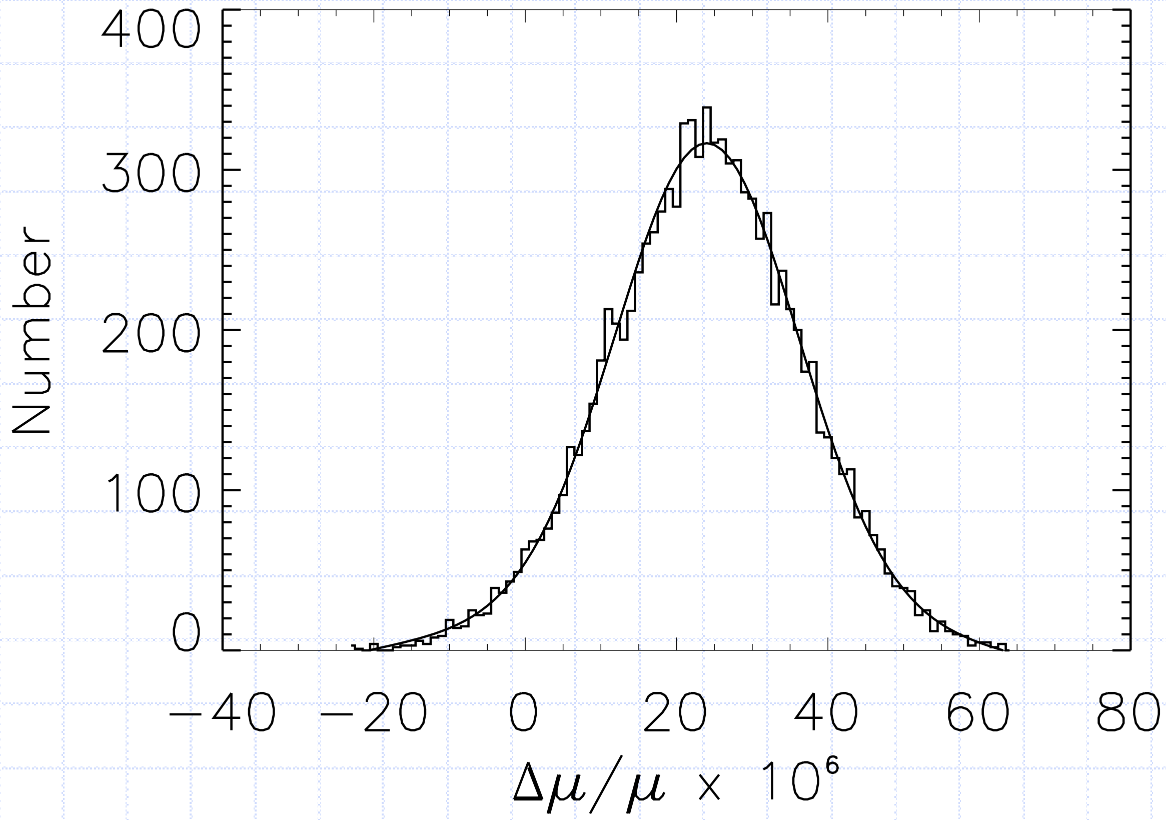
Application to the Positive Detection

- Systematic wavelength errors in the old UVES reduction pipeline may be the source of the previous positive result for a change in μ.
- New results from the same data (Thompson et al. 2009)
  - See also King et al. (2008)



$\Delta\mu/\mu = (1.6 +\backslash- 1) \times 10^{-5}$

Bootstrap Statistics

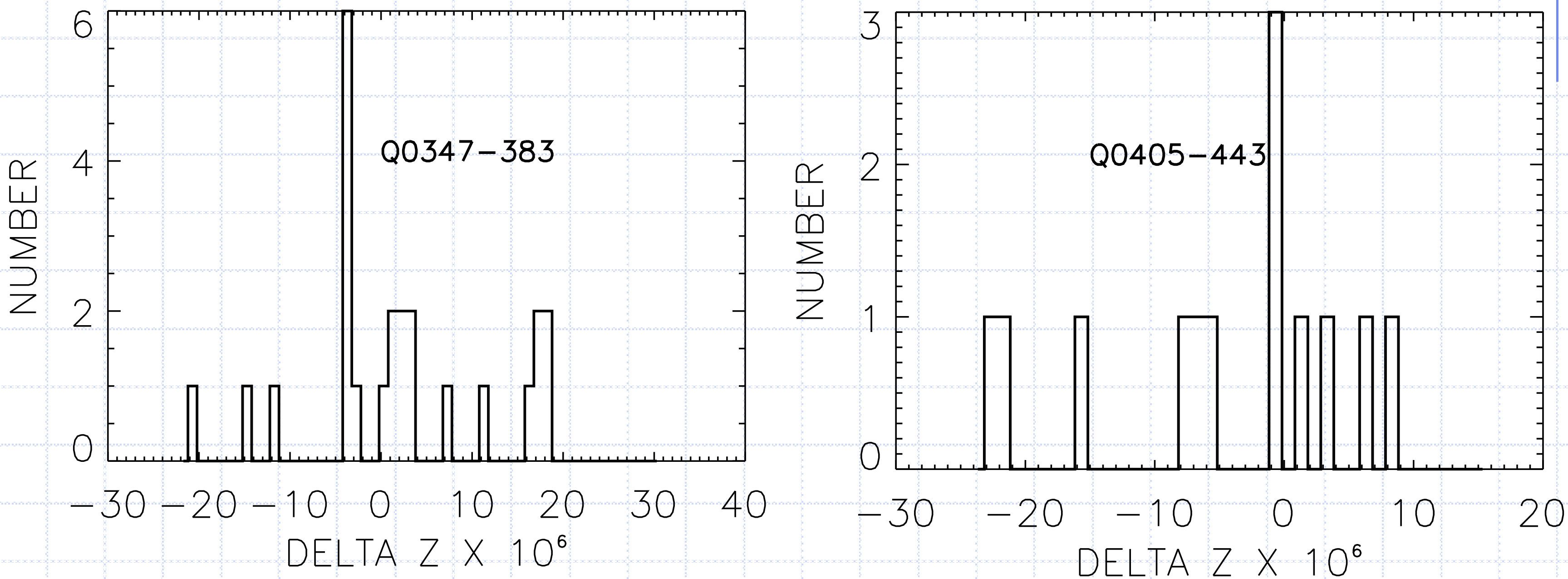


10,000 bootstrap realizations have a Gaussian Distribution

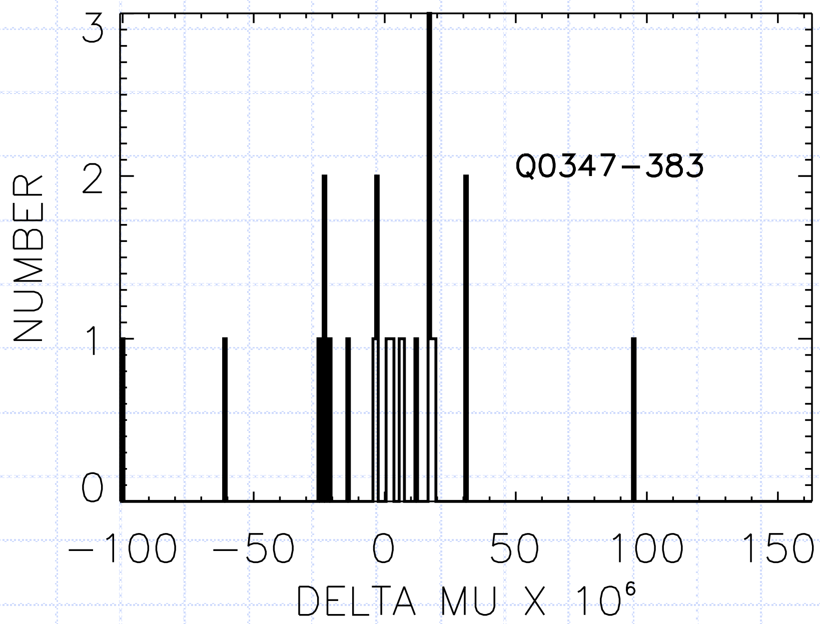
Lyman Werner Pairs

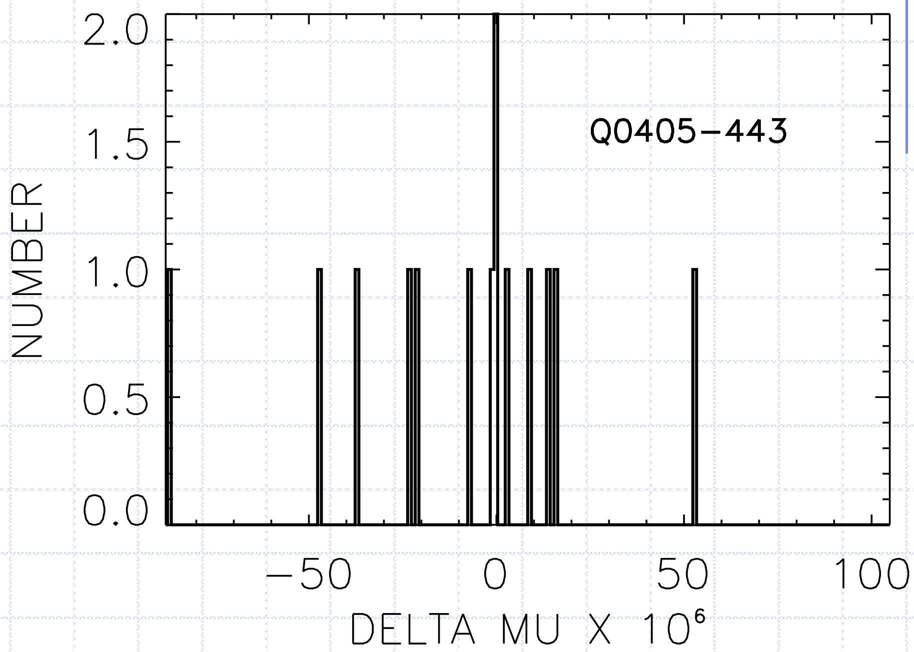
- The superposition of Lyman and Werner lines produces closely spaced pairs with very different sensitivity factors.
- We looked at the $\Delta\mu/\mu$ values for these pairs in Q0347-383 and Q0405-443.
- The $\Delta\mu/\mu$ values are uniformly distributed around 0.

Δz values for Lyman-Werner Pairs



Δμ For Lyman-Werner Pairs





$\Delta\mu/\mu = (0.7 \pm 5) \times 10^{-5}$

$\Delta\mu/\mu = (0.1 \pm 4) \times 10^{-5}$

Instrument Systematics

- In most spectrometers the light path of the calibration lamp is not the same as the object light path
  - Different angles between the object and calibration lamp principal rays can introduce systematic wavelength differences.

Other systematics

- Errors in rest wavelength
  - Errors in rest wavelength $\Delta\lambda$ produce errors in $\Delta\mu/\mu$ of $(1/K_i)\Delta\lambda/\lambda$.
  - Typical K_i are 0.02, typical $\Delta\lambda/\lambda$ are 10^{-8}.
  - Errors are then $\sim 5 \times 10^{-7}$ which may limit future high resolution observations
- Errors in the sensitivity constants.
  - Errors in the sensitivity factor K_i result in errors in $\Delta\mu/\mu$ proportional to $\Delta K_i/K_i$.

Systematics Continued

- Mixing of different rotational quantum number lower states
  - Cold and hot gas can have different kinematics.
  - The effect would be slight since the lower rotational J levels do not have a large influence on the sensitivity factors.

Summary of the State of H_2 Studies

- Except for Q0347-383 and Q0405-443 there have been no claims of a detected shift in μ.
- Reanalysis of the Q0347-383 and Q0405-443 data by two groups find no shift.
- From H_2 data $\Delta\mu/\mu < 10^{-5}$ for a lookback time of 10.5 gigayears ($z \sim 3.1$).

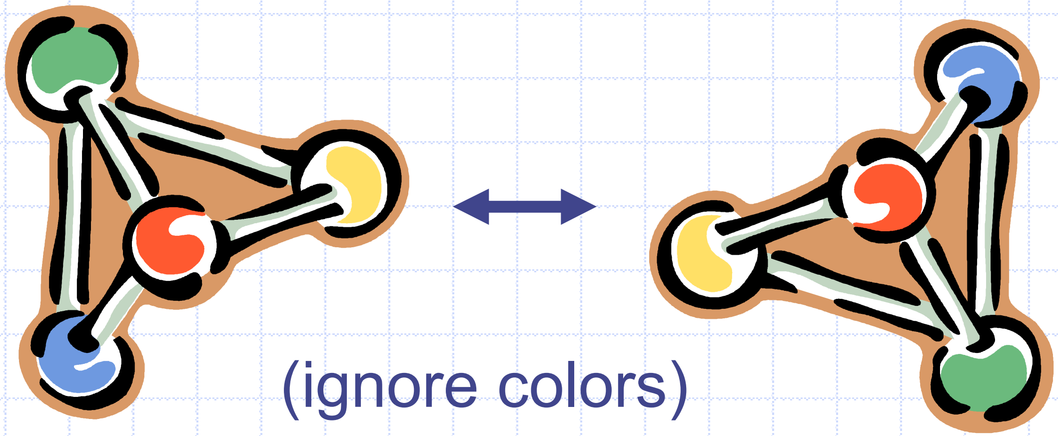
Table of Recent Measurements

Group	Objects	$\Delta\mu/\mu$
Thompson et al (2009)	Q0347-383, Q0405-443	$(7 +/- 8)x10^{-6}$
King et al (2009)	Q0347-383, Q0405-443, Q0528-250*	$(2.6+/- 3)x10^{-6}$
Malec et al (2010)	J2124-0050	$(5.5+/- 6)x10^{-6}$

* Dominates Result

History of Radio Molecular Studies

- Radio studies of μ are much more recent than the first optical studies of H_2
- Studies have concentrated on the inversion transition of ammonia



Advantages of Radio Measurements

- Radio telescopes are capable of high frequency resolution
  - $\Delta\nu/\nu < 10^{-7}$
- Radio molecular transitions have high sensitivity factors
  - $K_{NH_3} = 4.46$ for inversion transitions
  - $K_i \sim 1.$ for rotational transitions

Disadvantages of Radio Observations

- In general there are not multiple lines from the same ground state
  - Often a different molecule is used as the reference
  - This is a particular problem in systems that have multiple close spaced velocity components. If the abundance ratios between the two components is different between the two molecules, errors occur.
- To date observations have been limited to redshifts less than 1

Observations of NH_3 to Determine $\Delta\mu/\mu$

- Absorption system in the spectrum of B0218+357 at z = 0.68466
  - Flambaum and Kozlov (2007), Murphy et al. (2008)
- Find $|\Delta\mu/\mu| < 1.8 \times 10^{-6}$ at z=0.68466
  - From Murphy et al. 2008 who used HCN and HCO^+ as the wavelength standard
  - The universe is ~1/2 its present age at this point and in the transition between matter dominated and dark energy dominated epochs.

OH Observations

- Four observed transitions that have different dependencies on μ, α and g_p (the proton g factor).

$$\nu_{1665} + \nu_{1667} \propto \mu^{2.57} \alpha^{-1.14},$$

$$\nu_{1667} - \nu_{1665} \propto \mu^{2.44} \alpha^{-0.88} g_{\mathrm{p}},$$

$$\nu_{1720} - \nu_{1612} \propto \mu^{0.72} \alpha^{2.56} g_{\mathrm{p}},$$

Spatial variations of μ within the Milky Way

- Levshakov, Molaro and Kozlov (2008) find $\Delta\mu/\mu$ values of $(4\text{-}14)\times10^{-8}$ for various locations in the Milky Way
- They compare NH_3 emission lines with those of HC_3N and N_2H^+

State of Radio Observations

- Most accurate limits on $\Delta\mu/\mu$ but at redshifts below 1
- H_2 not available at radio wavelengths
- The lower abundance of other molecules is a limiting factor
- Hard to find transitions from a common ground state to eliminate kinematic effects

Conclusions

- Optical H_2 measurements limit $\Delta\mu/\mu$ to less than 10^{-5} at redshifts up to 3
- Radio measurements are pushing $\Delta\mu/\mu$ to less than 10^{-6} at redshifts below 1
- Future large telescopes and spectrometers should be able to measure $\Delta\mu/\mu$ to less than 10^{-6} in the near future
- These limits will impact both dark energy and dark matter theories.