Do The Fundamental Constants Change With Time ?

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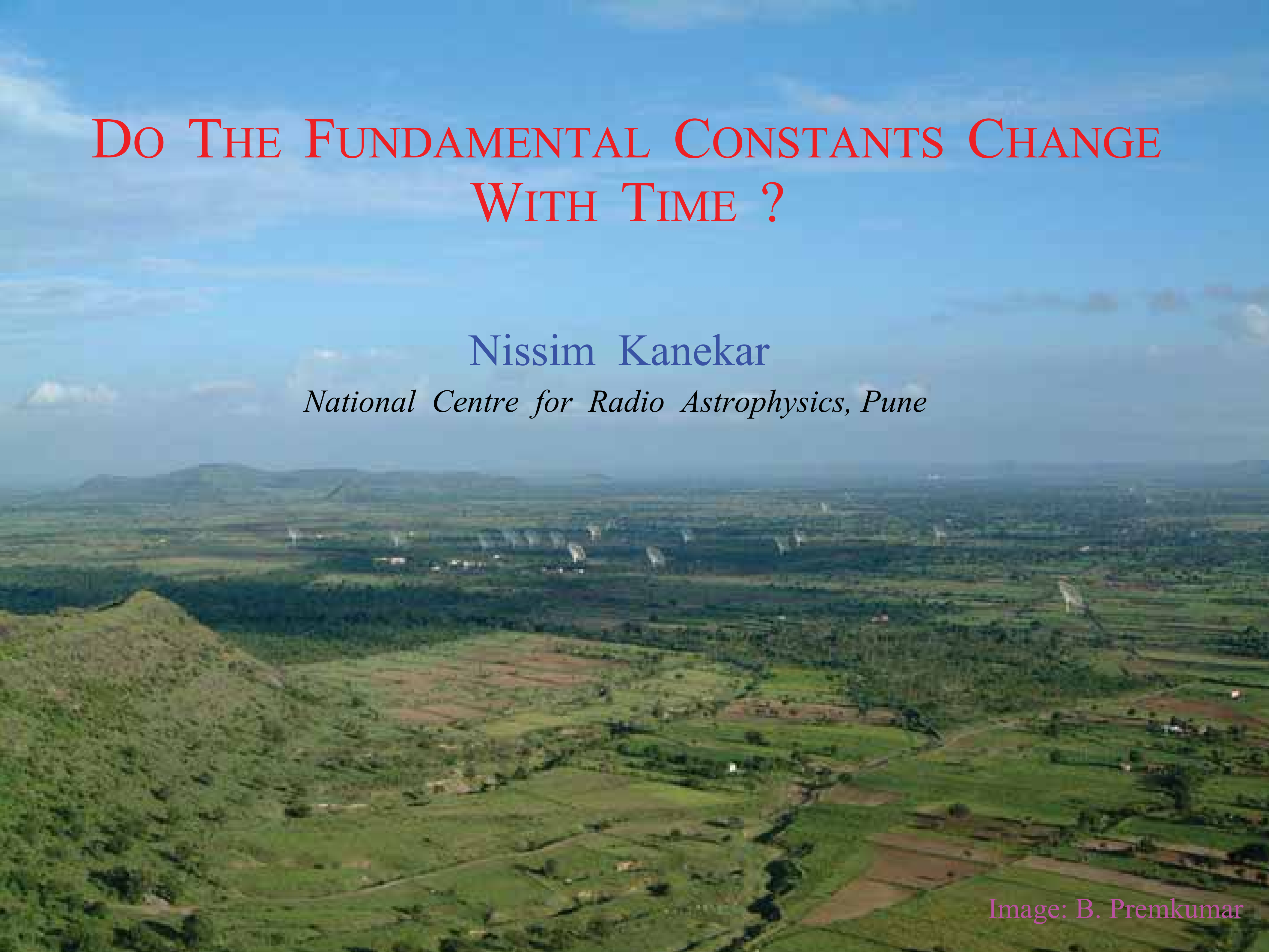


Image: B. Premkumar

FUNDAMENTAL CONSTANT EVOLUTION

- Why do we care ?

  α: *It's one of the greatest damn mysteries of physics!*

  (Feynman 1985, in *QED: The Strange...*)

- General issues: Basic technique, cosmological redshifts.
- Redshifted spectral lines.
- Radio spectroscopic studies.
- The hydroxyl (OH) molecule.
- "Conjugate" OH lines at $z \sim 0.247$.
- The state of the art.

WHY DO WE CARE ?

(e.g. Uzan 2011, Liv. Rev. Rel.)

- Fundamental constants: Free parameters of a theory.

  e.g. c, e, $\hbar$, $\alpha = e^2/\hbar c$, $\mu = m_p/m_e$, *etc.*

- 22 free parameters in the Standard Model & General Relativity!

- Pragmatic view: A test of the basic assumptions of the Standard Model and General Relativity.

- Similar to tests of local position invariance, Lorentz invariance, violation of the equivalence principles, *etc.*

- Changes in the *low-energy* coupling constants "expected" in higher-dimensional unification theories.

(e.g. Bekenstein 1982, Phys. Rev. D; Damour & Polyakov 1994, Phys. Rev. Lett.)

⇨ Low-energy probe of unification theories !

- Timescale of the changes unknown ⇨ Probe timescales ~ 1 day – 10 Gyr.

Basic Technique: Cosmological Redshifts

- Test for changes in *dimensionless* constants (*e.g.* α)! This avoids confusion with units, as the definition of a unit often implicitly assumes that some parameters don't change.

- Approach: Measure the same quantity (e.g. time, redshift) with two methods that have *different dependences* on a constant (e.g. α). If the constant changes, the two techniques would yield different values for the measured quantity.

- *Atomic clocks:* Measurements of time. High sensitivity, good control over systematic effects! But only probe changes over 1 – 2 years, a tiny fraction of the age of the Universe ⇨ Astrophysical techniques.

- *Spectral lines:* Measurements of cosmological redshifts of galaxies. Redshifts due to the expansion of the Universe; more distant galaxies have higher redshifts.

- Finite light speed ⇨ Distant galaxies seen as they were in the past. Higher redshifts $\equiv$ Larger lookback times: $z \sim 0.1 \equiv 1$ Gyr ago; $z \sim 1 \equiv 8$ Gyr ago; $z \sim 6 \equiv 12.8$ Gyr ago.

Spectral Lines

- Line rest frequencies depend on α, μ... Different dependences for different mechanisms (e.g. fine structure, hyperfine structure, rotation, inversion …).

- If λ_{Obs} and λ_{Rest} are the measured and laboratory line wavelengths,

$$\lambda_{Obs} = \lambda_{Rest} \times (1 + z).$$

- But this *assumes* that λ_{Rest} doesn't depend on redshift! If α, and hence λ_{Rest}, depends on z, we would infer the *wrong* redshift!

- If α changes: Two lines from a galaxy, with *different dependences* of λ_{Rest} on α, would yield *different redshifts* for the same galaxy!

(Savedoff 1956, Nature)

- Simple! Identify two lines with different dependences of λ_{Rest} on α, μ..., find the lines in a galaxy, and compare the two redshifts!

- But... Gas clouds in galaxies have internal motions of *few* km/s, adding $(\Delta V/c) \sim 10^{-5}$ to the redshifts. Different velocities for different atoms?

- $[\Delta\alpha/\alpha] \sim \Delta z/(1+z) \approx (\Delta V/c)$. ⇨ Sensitivity limit: $[\Delta\alpha/\alpha] \sim 10^{-5}$.
  ⇨ Average over a large sample of lines ? Or use "special" lines?

Radio Spectroscopic Studies

- Many molecules with different types of transitions (OH, NH_3, CH_3OH, etc.), sensitive to changes in α, μ. Can use *different lines from a single molecule* to reduce systematic effects!
  In thermal equilibrium, all lines would be at the same velocity.

  (e.g. Chengalur & NK 2003, Phys. Rev. Lett.; Darling 2003, Phys. Rev. Lett.; Flambaum & Kozlov 2007, Phys. Rev. Lett.; Jansen et al. 2011, Phys. Rev. Lett.)

- Frequency calibration with errors < 10 m/s.

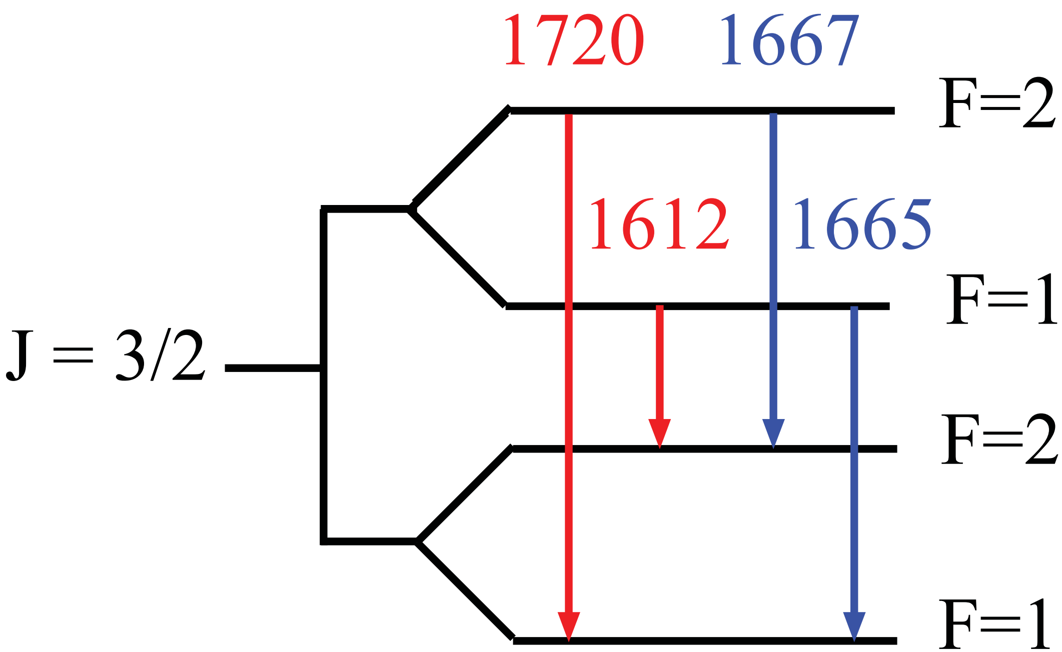
- Two best techniques: "Conjugate satellite" OH lines, CH_3OH lines.

  (NK et al. 2004, Phys. Rev. Lett.; Jansen et al. 2011, Phys. Rev. Lett.)

THE HYDROXYL (OH) MOLECULE

- Common molecule in molecular clouds in galaxies.

(e.g. Weinreb et al. 1963, Nature)



"Main" lines: $\Delta F = 0$
1667 MHz, 1665 MHz.
Strong lines in equilibrium.

"Satellite" lines: $\Delta F = \pm 1$
1720 MHz, 1612 MHz.
Weak lines in equilibrium.

- Arise from a combination of Λ-doubling & hyperfine splitting ⇨ Different dependences on α, μ.

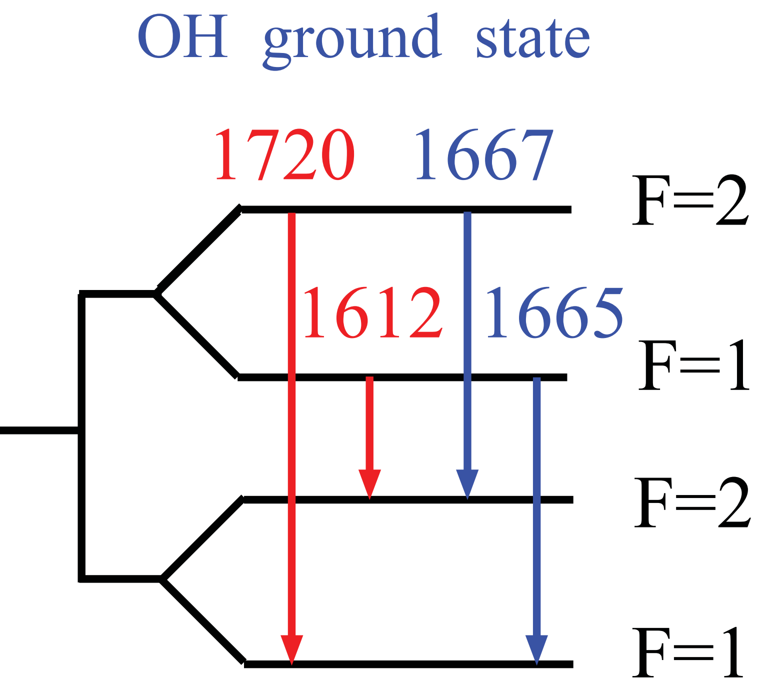
(Chengalur & NK 2003, Phys. Rev. Lett.)

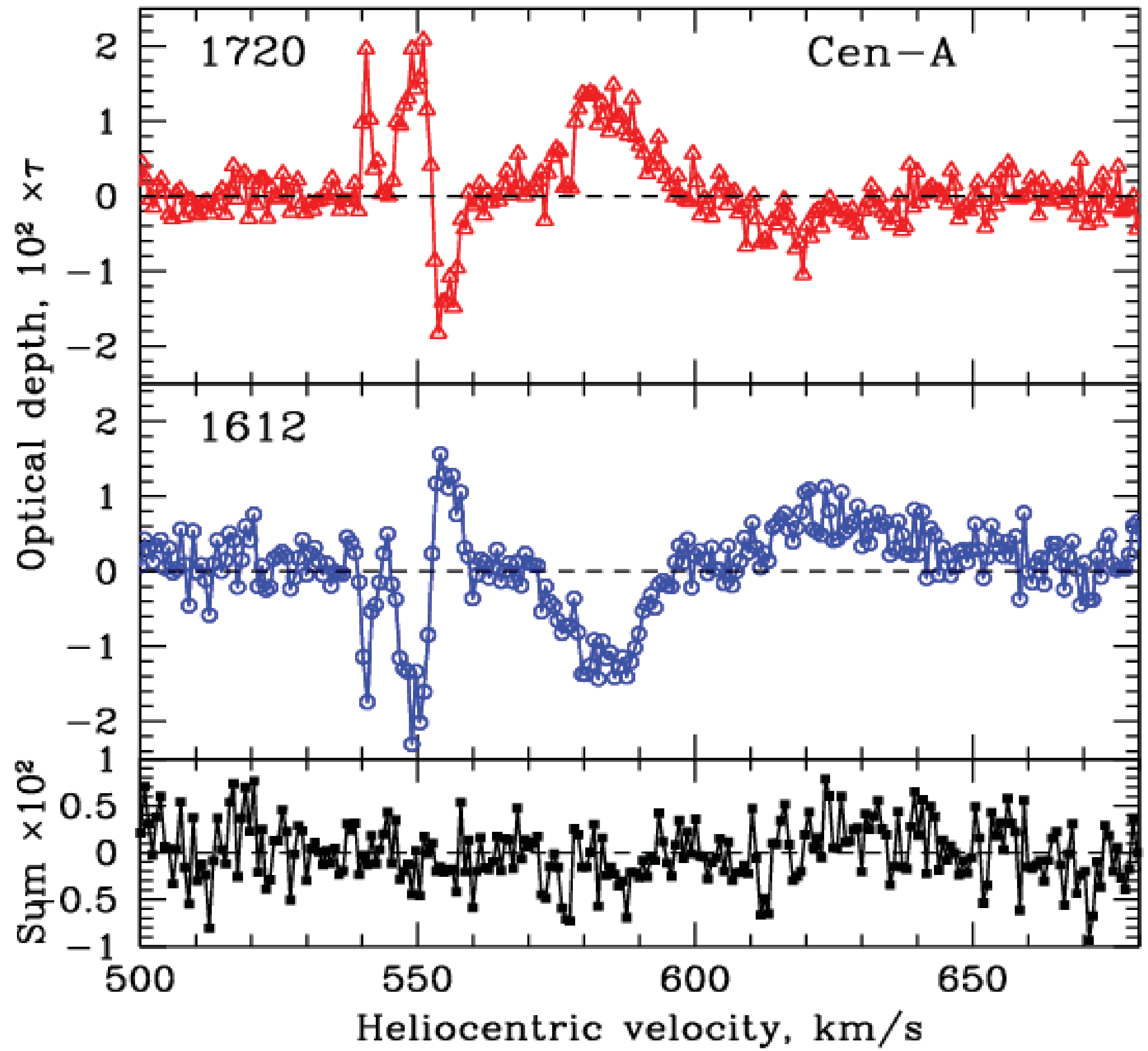
- But... the OH lines in galaxies are rarely in thermal equilibrium. ⇨ "Normal" OH lines may not arise from the same gas.

- Population inversion of F=2 and F=1 levels ⇨ Masing! "Conjugate" satellite lines: Exactly same shape, opposite sign.

Conjugate OH Lines in Cen A: $z \sim 0.002$

(van Langevelde et al. 1995, ApJL)



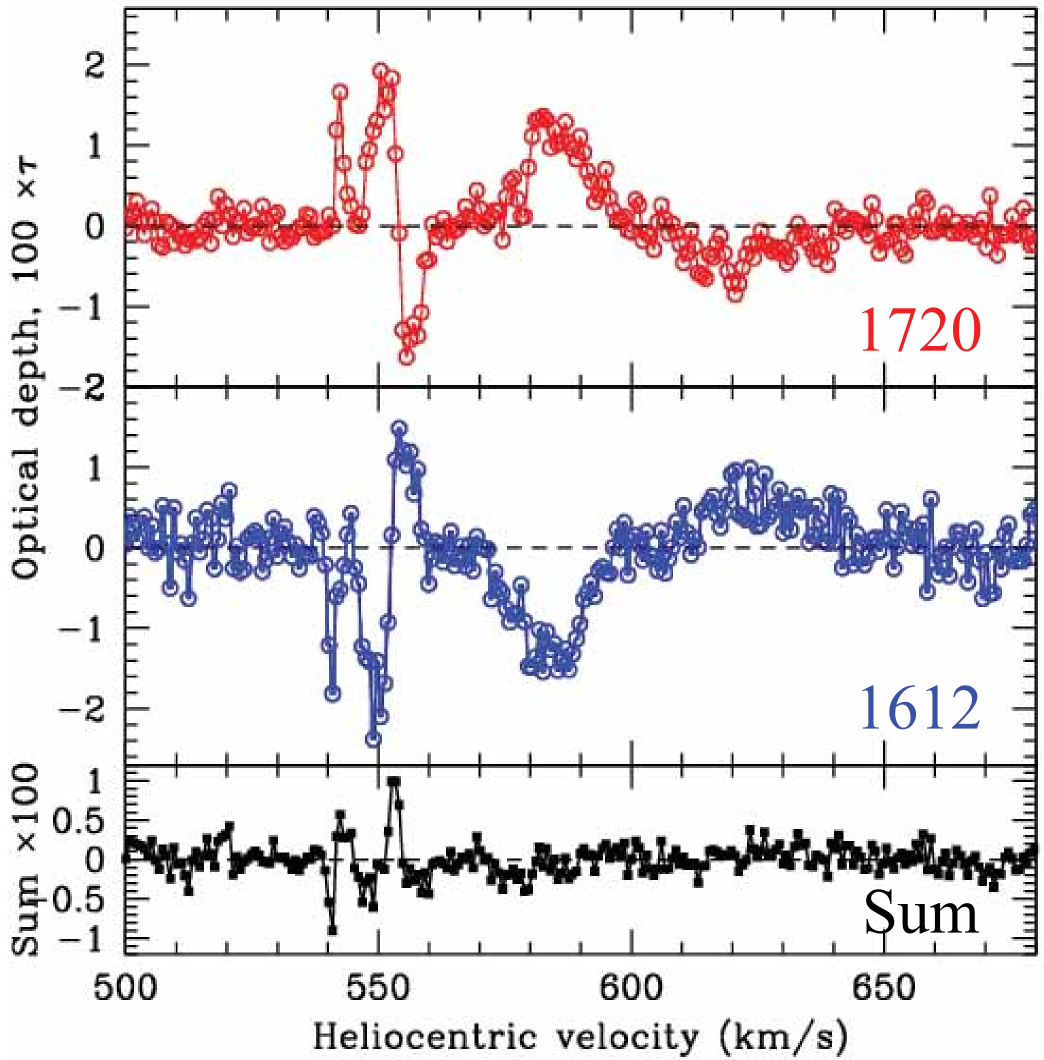


- Quantum mechanical selection rules ⇨ 1720 emission, 1612 absorption, or vice-versa, *with exactly the same shape!*

(Elitzur 1976, ApJ)

Expected Line Profiles for changing α

If $[\Delta\alpha/\alpha] = 1 \times 10^{-5}$ ⇨



- If there are changes in α, μ ⇨ *Same shape, linear translation.*

  ⇨ Excellent to probe changes in α, μ.

- Two known redshifted conjugate systems, at $z \sim 0.25$, 0.77.

(NK et al. 2004, 2005, Phys. Rev. Lett.)

A Deep Arecibo Integration on 1413+135

(with Tapasi Ghosh, Jayaram Chengalur)

- Size matters in astronomy! The Arecibo telescope is the biggest, most sensitive telescope in the world (dish diameter: 305 metres!).

- 125-hour Arecibo observation of the $z \sim 0.247$ OH system toward 1413+135 (2010 – 2012).

- Velocity resolution ~ 90 m/s.

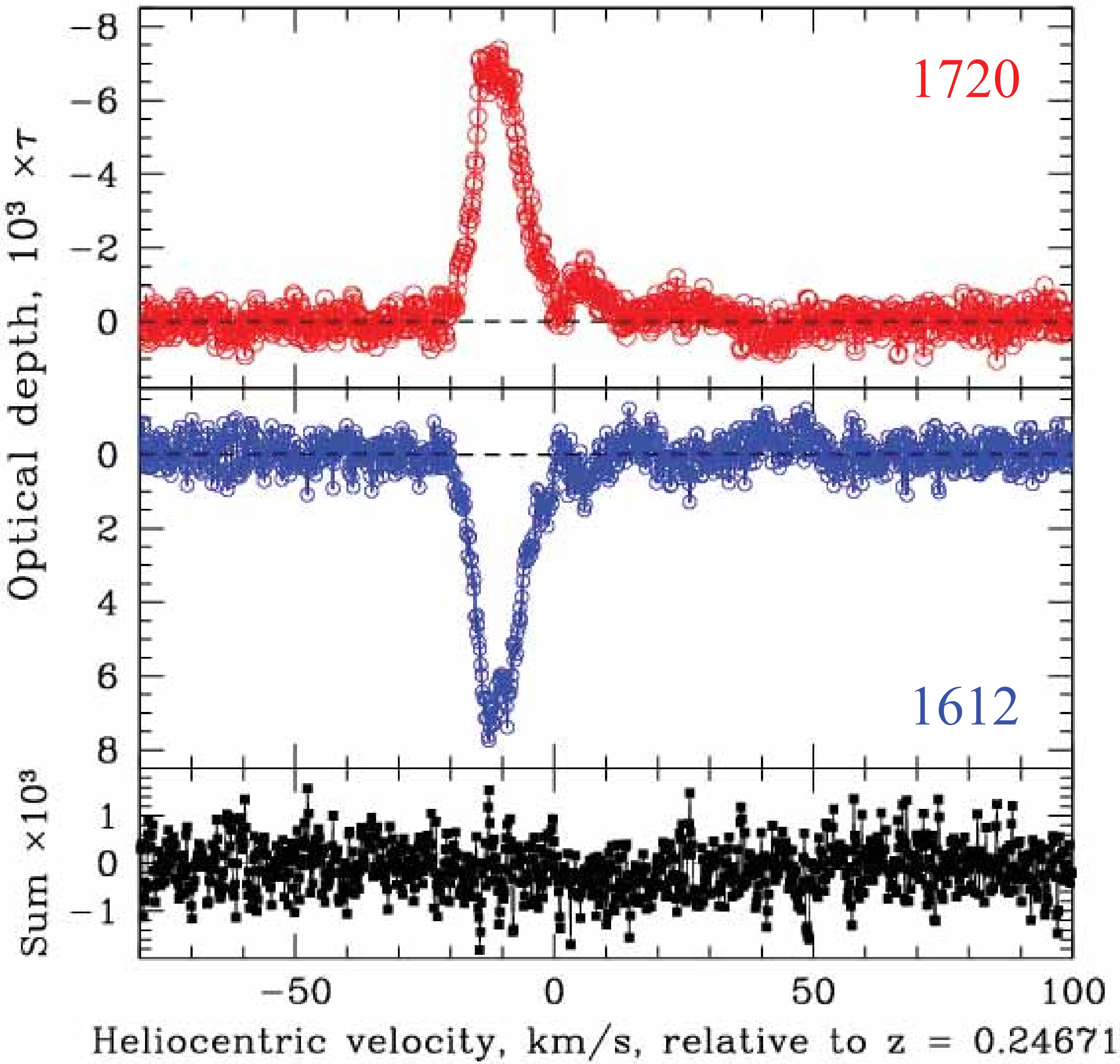
- Simultaneous observations of the satellite OH lines. Same data editing applied to both spectra. ⇨ Exactly simultaneous spectra.

(n.b. Goldeneye was *not* a documentary!)

- Spectral dynamic range ~ 3000 to 1 per 180 m/s channel. The most sensitive radio spectra ever obtained.

A Deep Arecibo Integration on 1413+135

(NK et al. 2018, Phys. Rev. Lett.)



- Conjugate behaviour persists! No evidence of a velocity offset.

RESULTS

(NK et al. 2018, Phys. Rev. Lett.)

- Cross-correlation analysis: More reliable, non-parametric approach!

- Cen. A: Cross-correlation peak at a velocity offset of (50 ± 110) m/s.
  Null result at $z \sim 0$!

- Final Arecibo result on 1413+135: Velocity offset = (-71 ± 51) m/s.

  ⇨ $[\Delta\alpha/\alpha] = (-9.9 \pm 6.6) \times 10^{-7}$.

- At 2σ significance, $[\Delta\alpha/\alpha] < 1.3 \times 10^{-6}$ $(0 < z < 0.25$; 3 Gyr ago).

- Strongest constraint ever on cosmological evolution in α.
  Assuming linear evolution ⇨ $(1/\Delta t)[\Delta\alpha/\alpha] < 4 \times 10^{-16}$ yr^{-1}, over 3 Gyr.

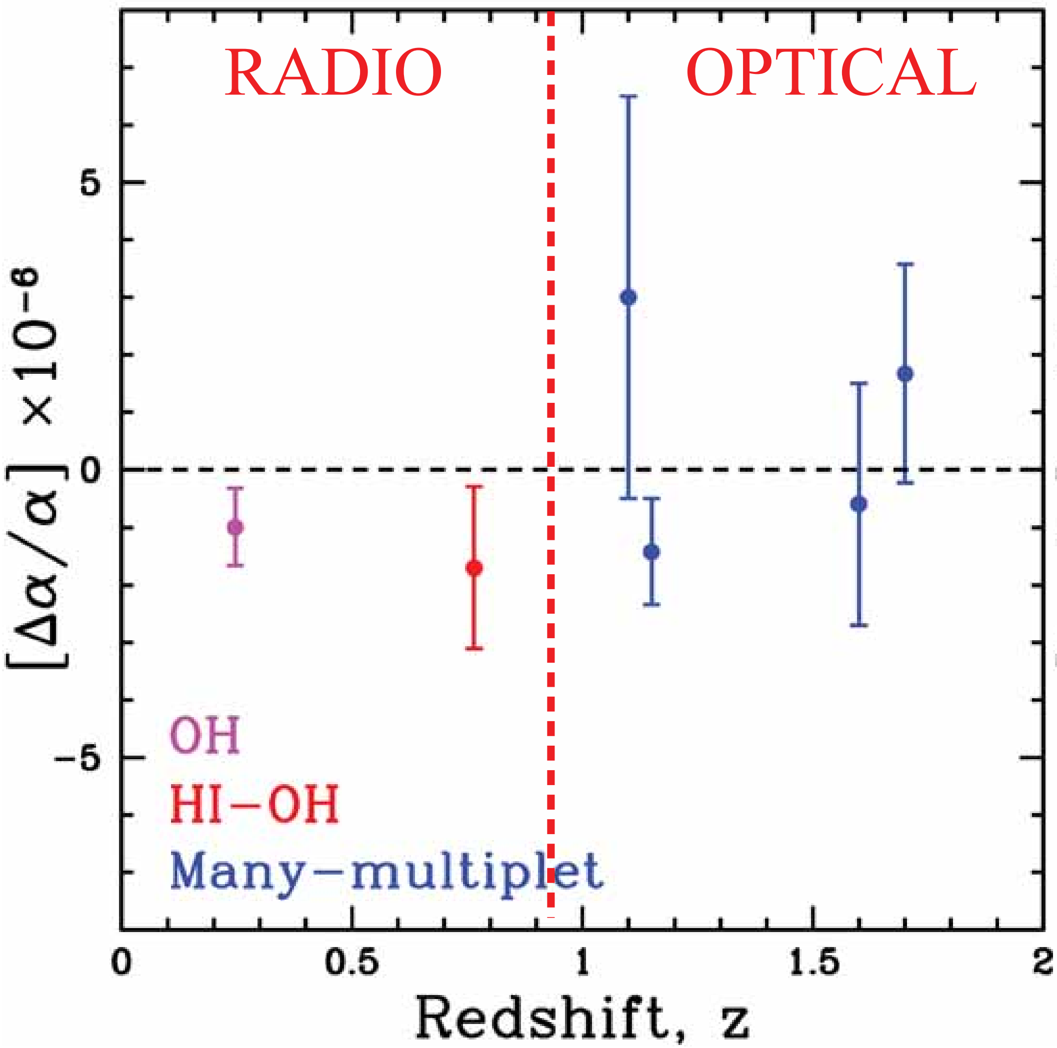
THE STATE OF THE ART

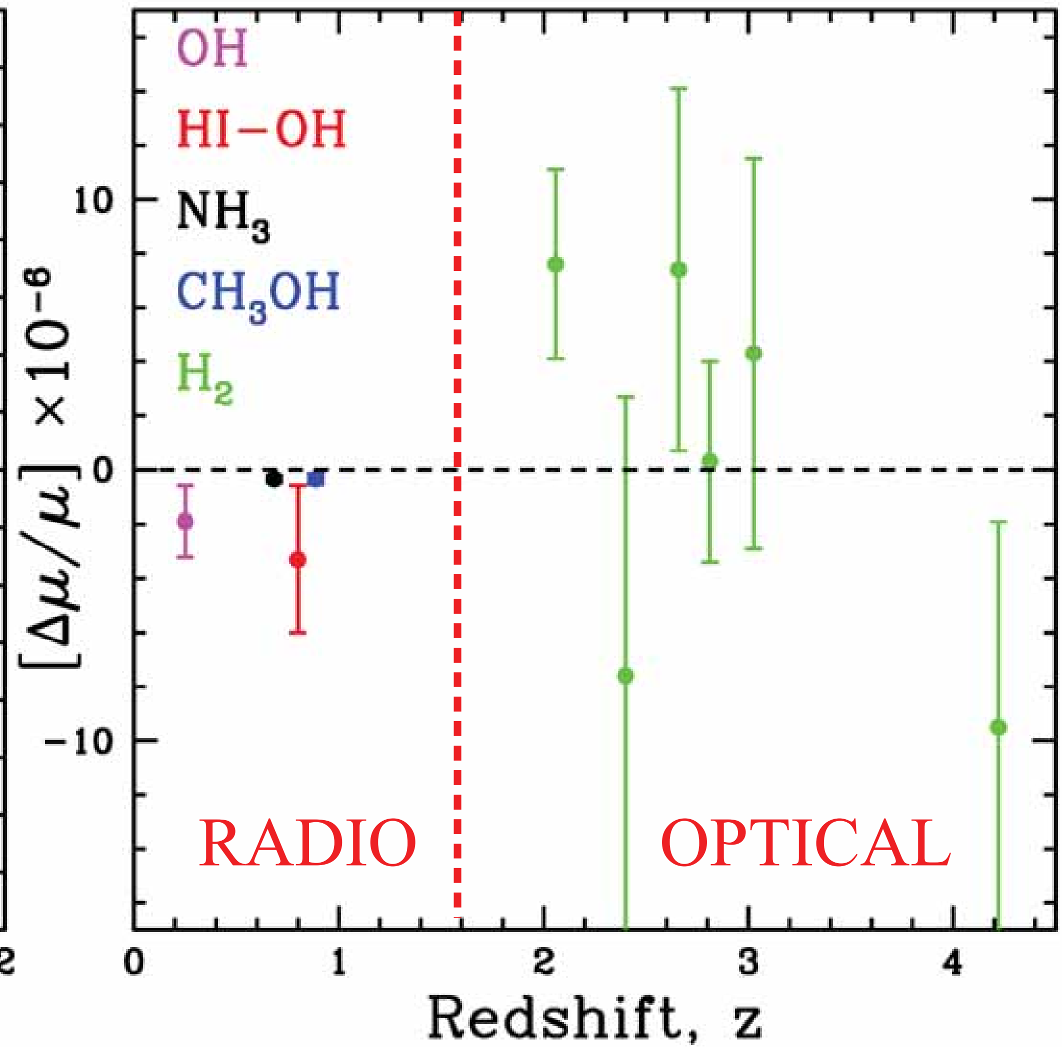
- NH_3, CS & H_2CO lines ($z \sim 0.685$) ⇨ $[\Delta\mu/\mu] = (-3.5 \pm 1.2) \times 10^{-7}$

(NK 2011, ApJL)

- Three CH_3OH lines ($z \sim 0.886$) ⇨ $[\Delta\mu/\mu] = (-2.4 \pm 2.0) \times 10^{-7}$

(NK et al. 2015, MNRAS-Letters)





SUMMARY

- Studies of fundamental constant evolution test the Standard Model, and also provide a window on unification theories, in which the low-energy constants are generically expected to change with time.

- Astronomical studies probe changes in α, μ on Gyr timescales.

- Best current methods: Conjugate satellite OH lines & CH_3OH lines.

- Very Large Array observations of two CH_3OH lines at $z \sim 0.886$:

$$[\Delta\mu/\mu] = [-2.4 \pm 2.0] \times 10^{-7}$$

- 125-hour Arecibo observations of conjugate OH lines at $z \sim 0.247$:

$$[\Delta\alpha/\alpha] = [-9.9 \pm 6.6] \times 10^{-7}$$

- No clear evidence for changes in α or μ. Sensitivity improvements by a factor ~10 within a year, by > 100 over the next decade.