# Spectroscopic constrains on variation of fundamental constants in astrophysics

M G Kozlov

*Petersburg Nuclear Physics Institute*

*&*

*Petersburg Electrotechnical University "LETI"*

New ideas in low-energy tests of fundamental physics

16 - 20 June 2014

# Sesto Conference

*Varying fundamental constants and dynamical dark energy*

**July 2013 (Italy)**

# Fundamental constants in atomic physics

Fundamental constants, which influence atomic and molecular spectra:

- Fine structure constant $\alpha = e^2/(\hbar c)$ is a coupling constant in QED.
- Electron to proton mass ratio $\mu = m_e/m_p$. Because $m_p$ is proportional to $\Lambda_{QCD}$, $\mu \sim m_e/\Lambda_{QCD}$.
- Nuclear gyromagnetic ratio $g_n$ can be expressed in terms of $\Lambda_{QCD}$ and quark masses, but for atomic physics $g_n$ is independent constant. It always enters in combination $g_n\mu$. According to Flambaum & Tedesco (2006) the dependence of $g_n$ on quark masses is weak.

# Dimensionless sensitivity coefficients

If fundamental constants change, the frequency of any atomic transition also change:

$$\omega = \omega_0 \left[1 + Q_\alpha \frac{\delta\alpha}{\alpha} + Q_\mu \frac{\delta\mu}{\mu} + Q_g \frac{\delta g_n}{g_n}\right],$$

$$\frac{\delta\omega}{\omega} = \frac{\delta F}{F}, \qquad F = \alpha^{Q_\alpha} \mu^{Q_\mu} g_n^{Q_g}.$$

In order to detect this variation we need to compare at least two transition frequencies:

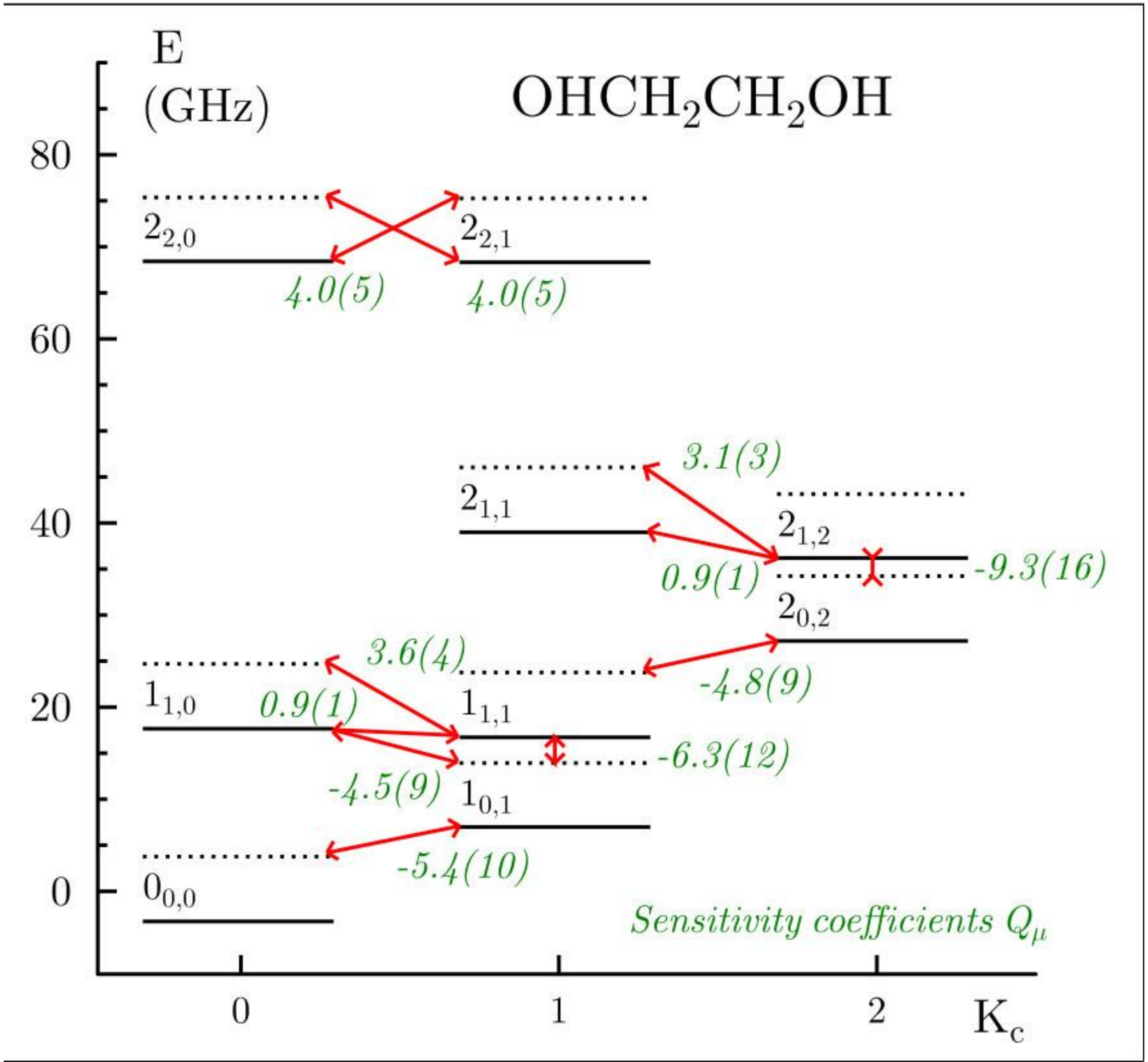
$$\frac{\omega_i}{\omega_k} = \left(\frac{\omega_i}{\omega_k}\right)_0 \left[1 + \Delta Q_\alpha \frac{\delta\alpha}{\alpha} + \Delta Q_\mu \frac{\delta\mu}{\mu} + \Delta Q_g \frac{\delta g_n}{g_n}\right].$$

# Sensitivity coefficients for different wavebands (in a.u.)

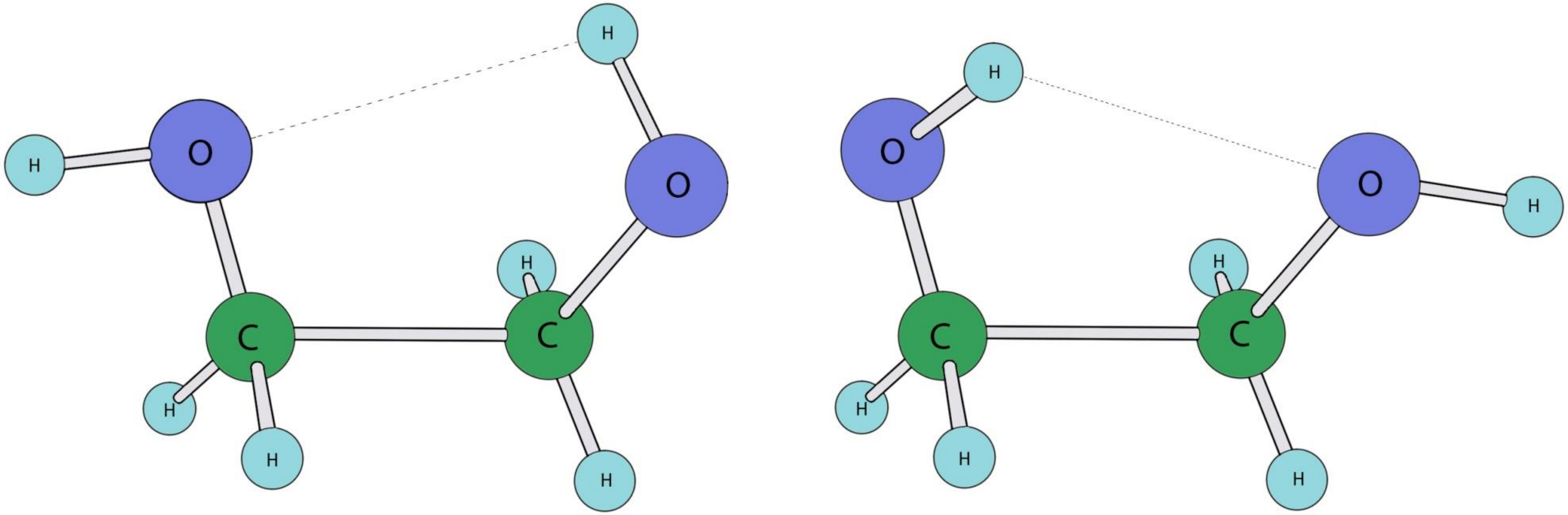
- For optical transitions in atoms and molecules with nuclear charge $Z \leq 30$, all sensitivities are small, $Q_\alpha, Q_\mu, Q_g \ll 1$.
- Optical transitions in Highly Charged Ions: $|Q_\alpha| \gg 1$.
- Fine structure (IR, FIR): $\sim \alpha^2 \quad \Rightarrow \quad Q_\alpha = 2$.
- Vibrational structure (IR): $\sim \mu^{1/2} \quad \Rightarrow \quad Q_\mu = \frac{1}{2}$.
- Rotational structure (FIR, microwave): $Q_\mu = 1$.
- Magnetic hyperfine structure (microwave): $Q_\alpha = 2$; $Q_\mu = 1$; $Q_g = 1$.
- Tunneling transitions in polyatomic molecules (FIR, microwave): $1 \lesssim Q_\mu \lesssim 10$.
- Microwave mixed tunneling-rotational lines: $|Q_\mu| \gg 1$.
- Microwave $\Lambda$-doublet, $\Omega$-doublet, and $K$-doublet lines in linear radicals: $|Q_\alpha|, |Q_\mu| \gg 1$.

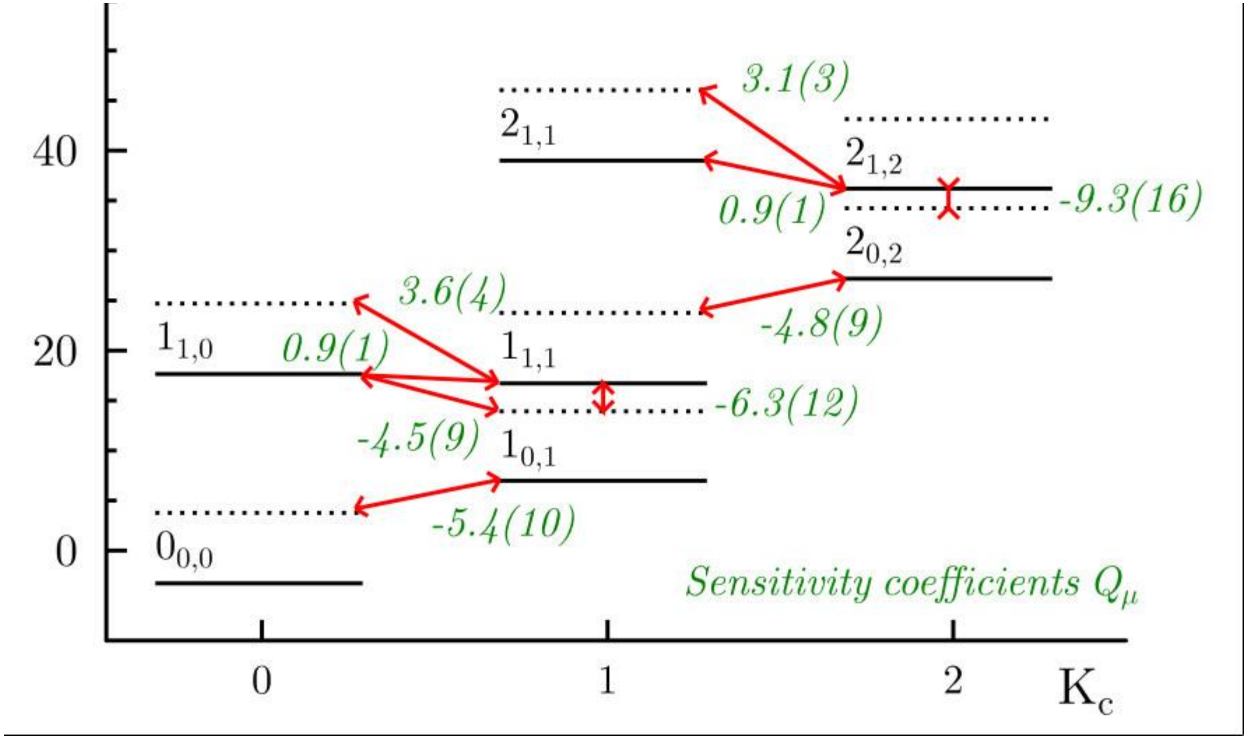
# Tunneling-rotational spectrum of Ethylene glycol

*[A Viatkina & MK 2014]*

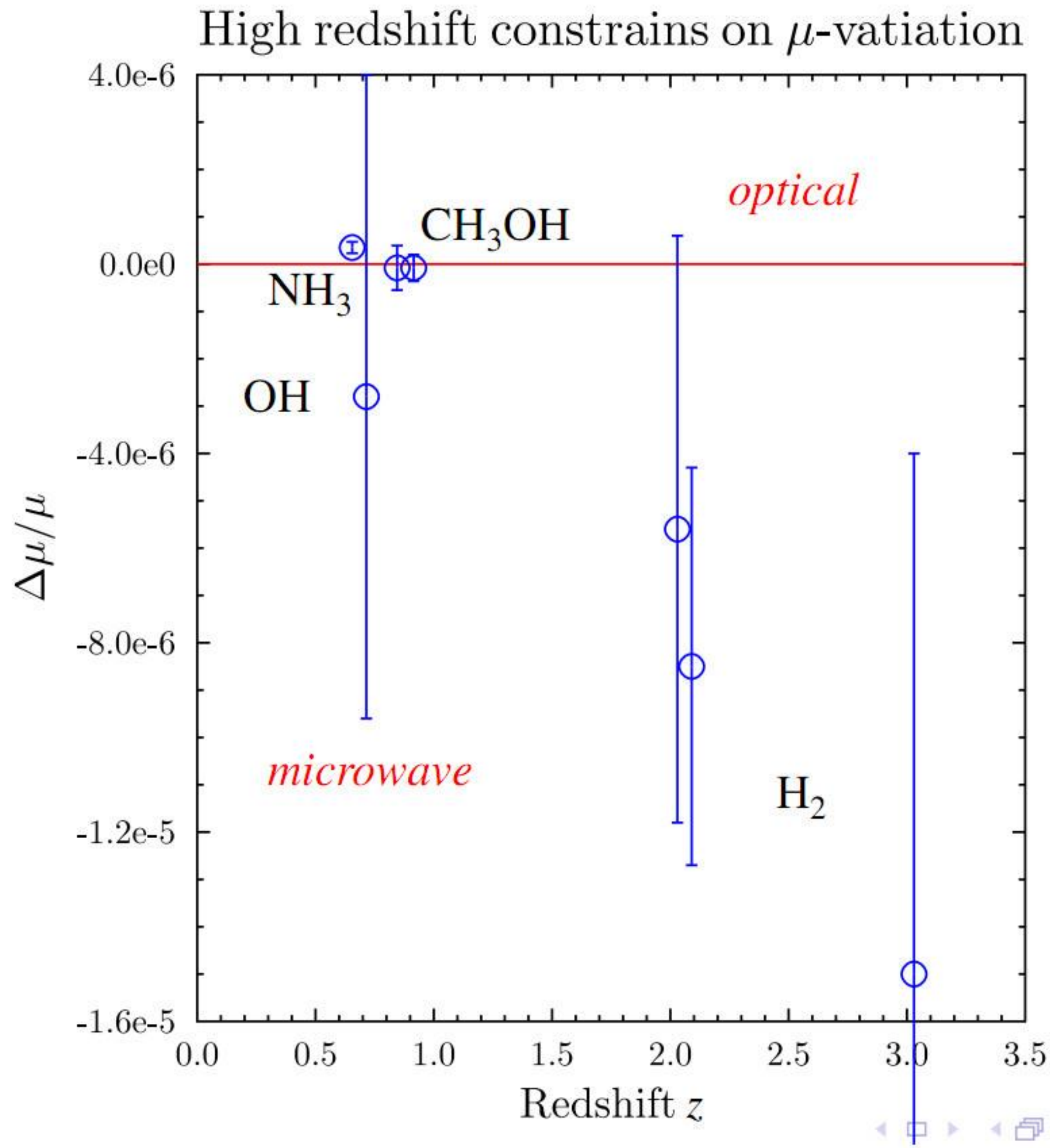


# Tunneling-rotational spectrum of Ethylene glycol



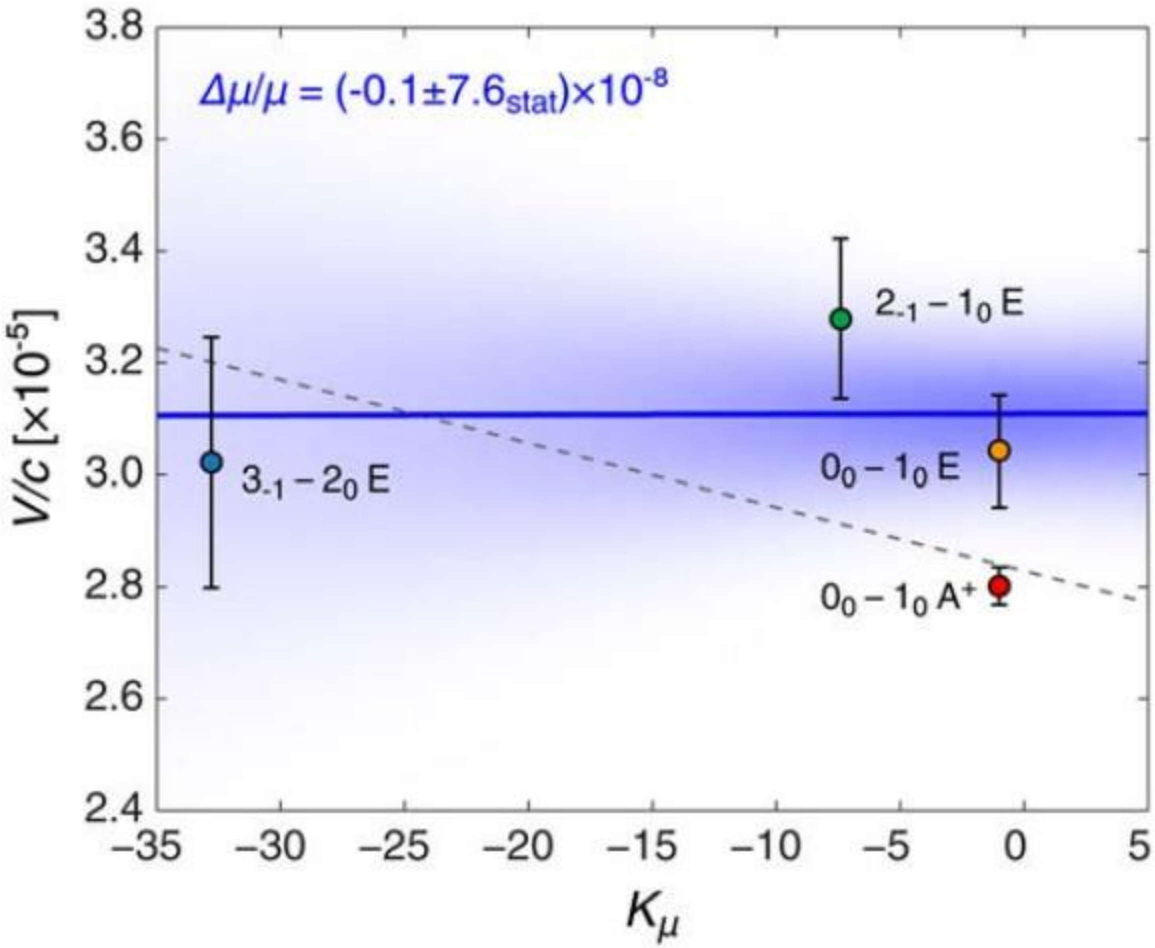



# Ограничения на вариацию $\mu$ на больших $z$



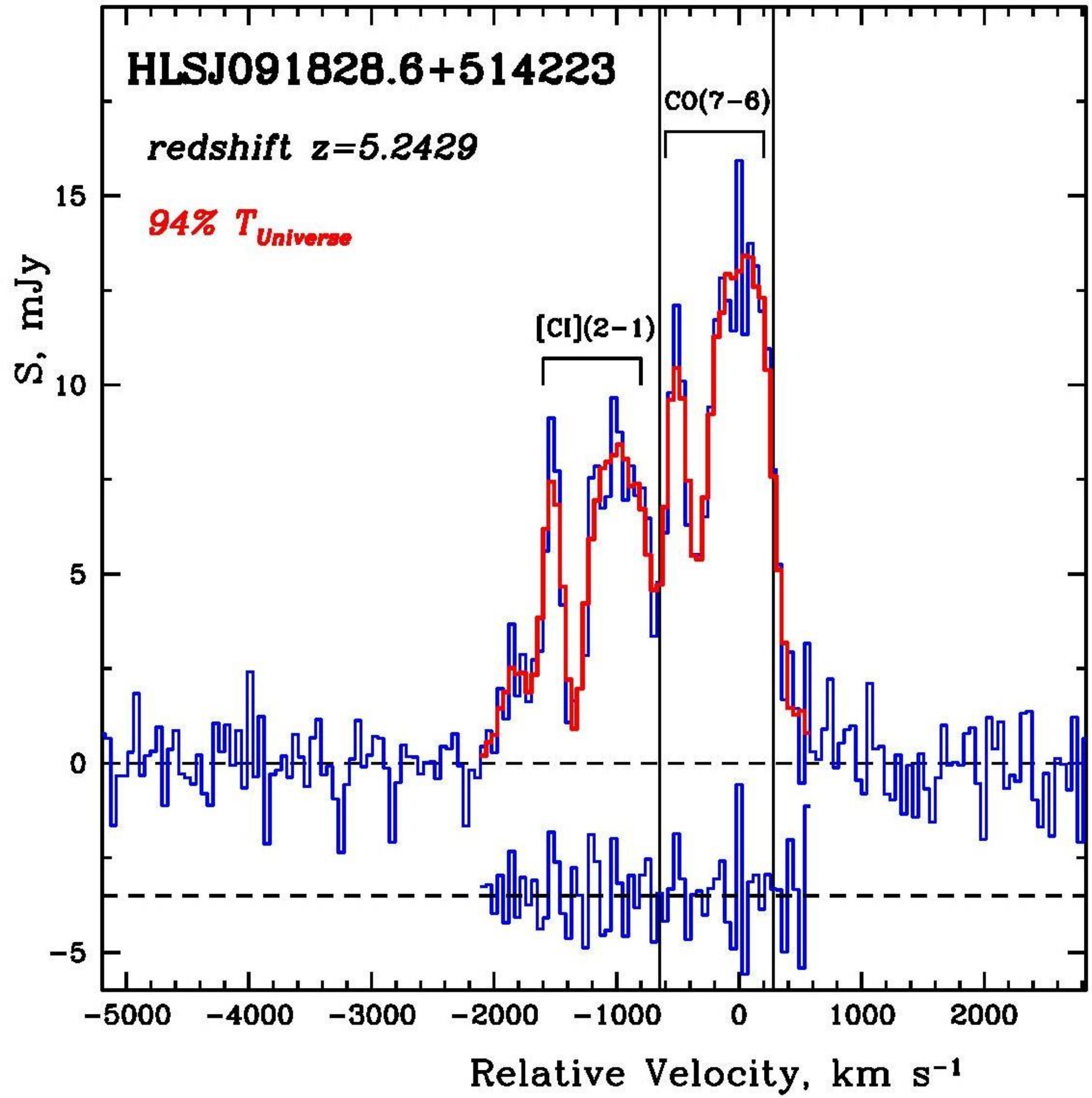
# Constrain on μ-variation from observation of methanol lines at redshift z=0.89

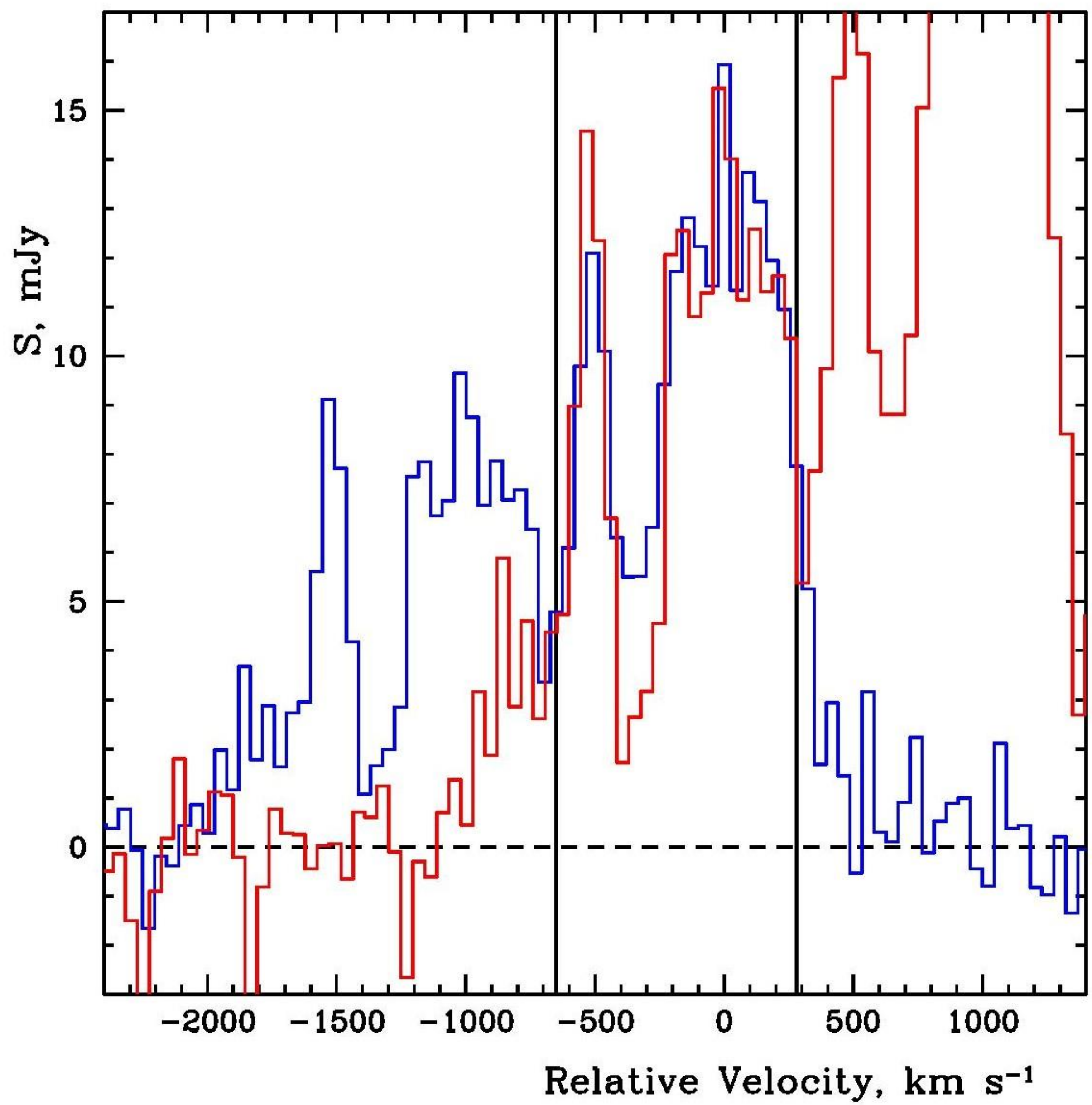
*[Bagdonaite et al. Science 339, 46 (2013)]*



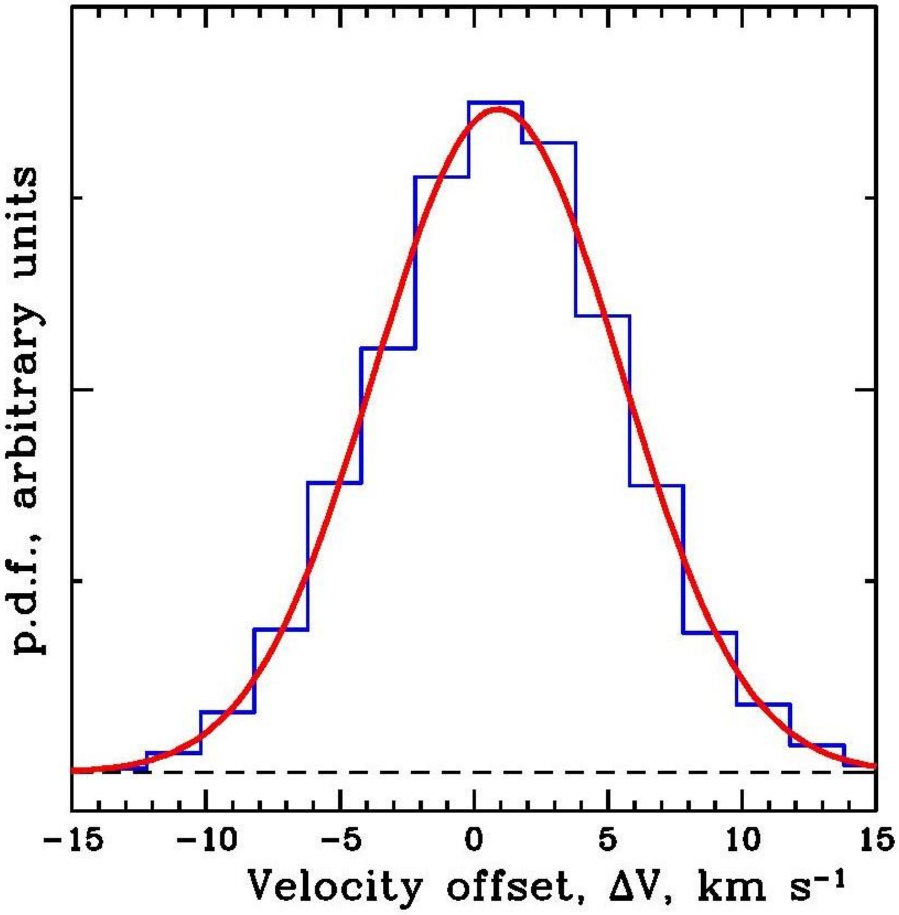
# $^3P_2$-$^3P_1$ fine structure transition in C I at the redshift z=5.2

(S. A. Levshakov et al *Astron. Astrophys*., 2012, 540, L9)


HLSJ091828.6+514223
redshift z=5.2429
94% T_Universe
CO(7-6)
[CI](2-1)
S, mJy
15
10
5
0
-5
-5000
-4000
-3000
-2000
-1000
0
1000
2000
Relative Velocity, km s-1



15
10
5
0
S, mJy
−2000
−1500
−1000
−500
0
500
1000
Relative Velocity, km s⁻¹



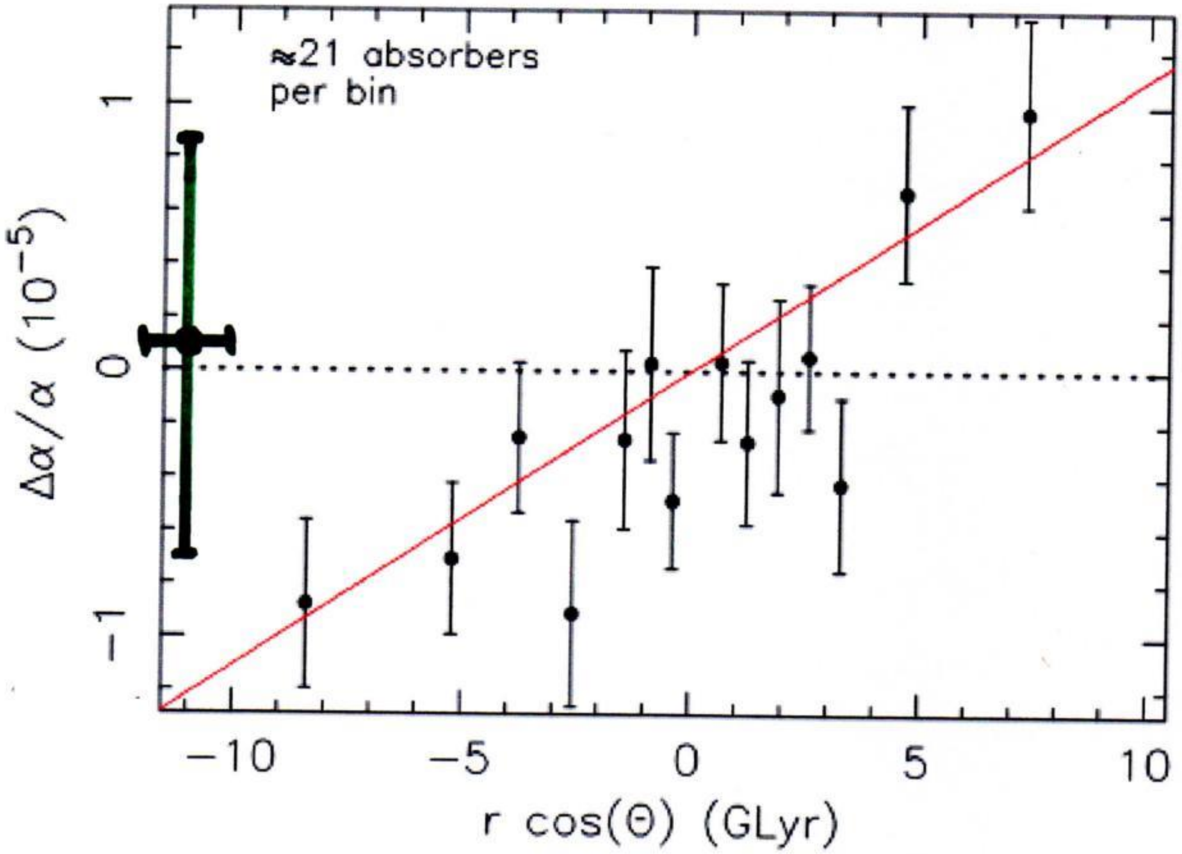

$\Delta V = (1 \pm 5)$ km/s

$F = \alpha^2/\mu$

$\Delta F/F < 2 \times 10^{-5}$

# Australian dipole

(Webb et al, *Phys. Rev. Lett.*, **2011**, *107*, 191101)



# $NH_3$ and CH molecules in cold interstellar clouds in the Milky Way

*Testing chameleon models of the Dark energy*

Tunneling transition in $NH_3$ is highly sensitive to μ-variation, while Ω-doublet transitions in CH are sensitive to variation of both μ and α.

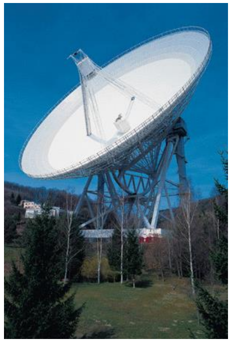
# Radio astronomical observations of $NH_3$

*[Levshakov et al, 2014]*

32m MEDICINA
Italy

$NH_3$ , $HC_3N$

100m EFFELSBERG
Germany



$NH_3$ , $HC_3N$, $HC_5N$, $HC_7N$

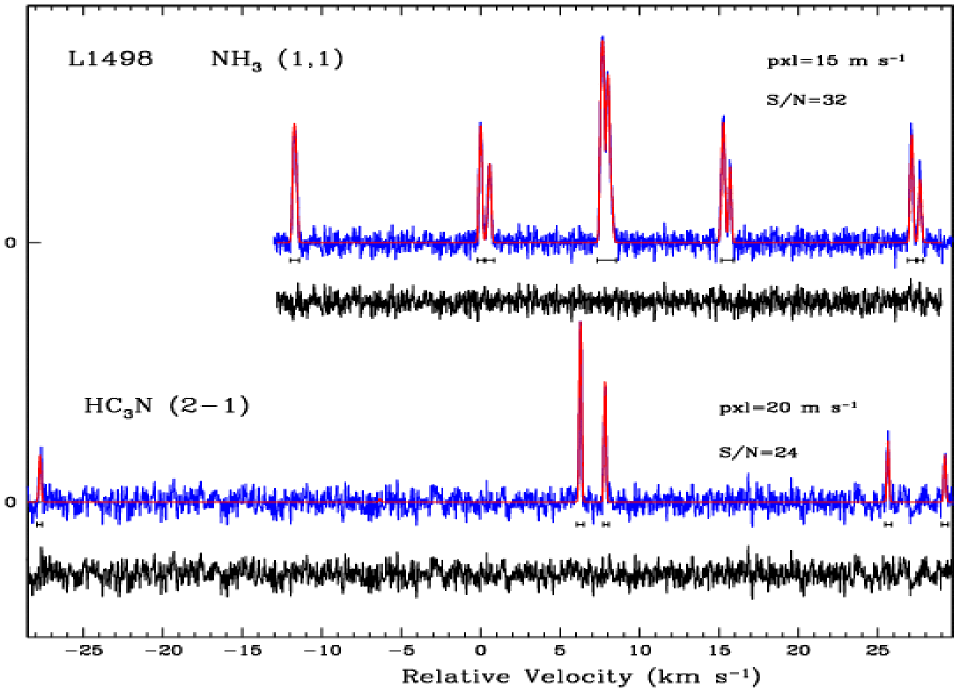
45m NOBEYAMA
Japan

$NH_3$ , $N_2H^+$

41 molecular cores
in Taurus

52 molecular cores
in Aquila

# Effelsberg 100-m



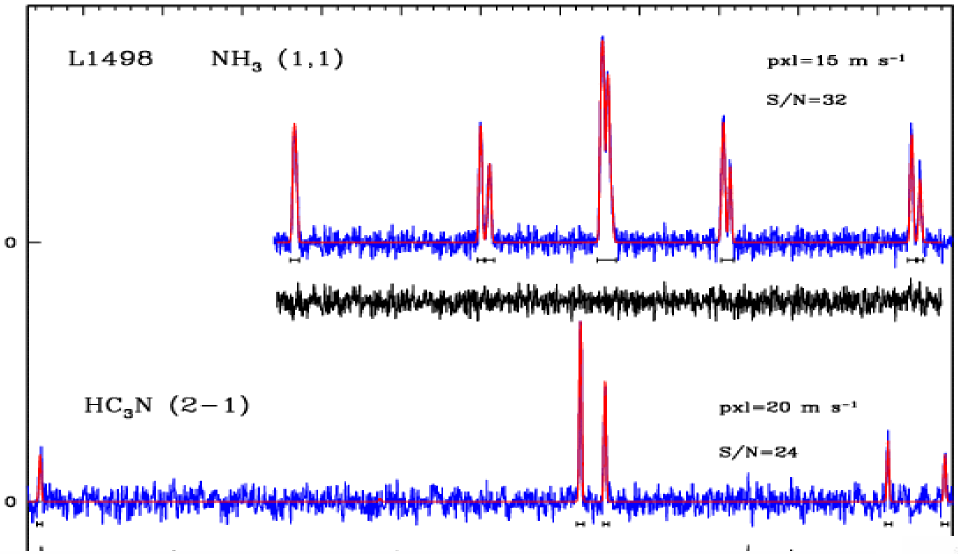

## Line width:

**FWHM=200 m/s**
**σ ~ 1 m/s**

**FWHM=150 m/s**
**σ ~ 5 m/s**

**Line position uncertainty**

# Effelsberg 100-m

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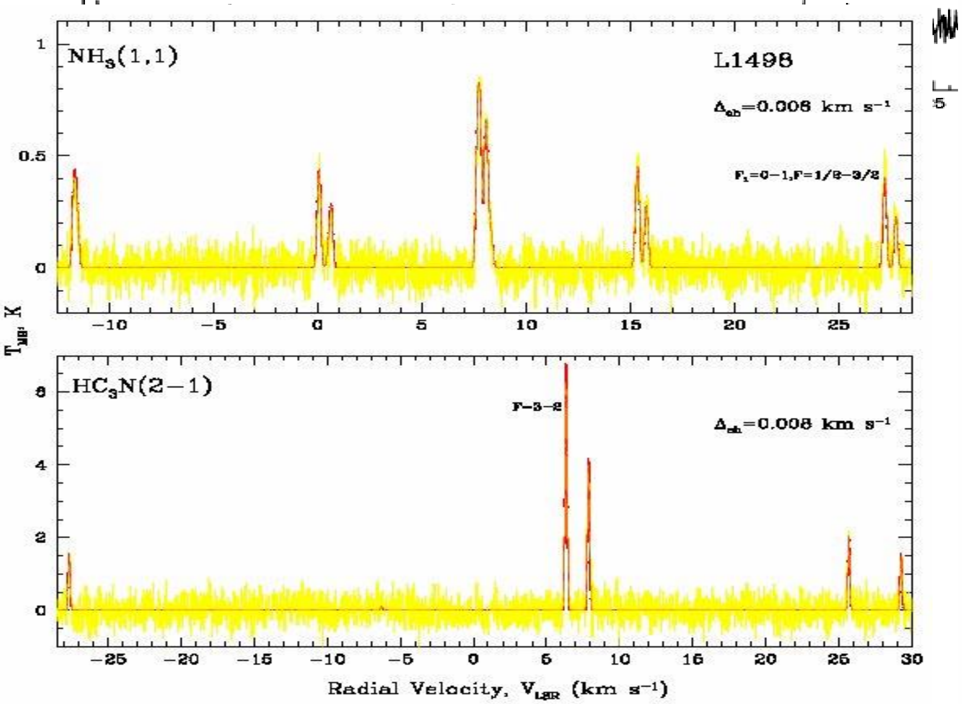
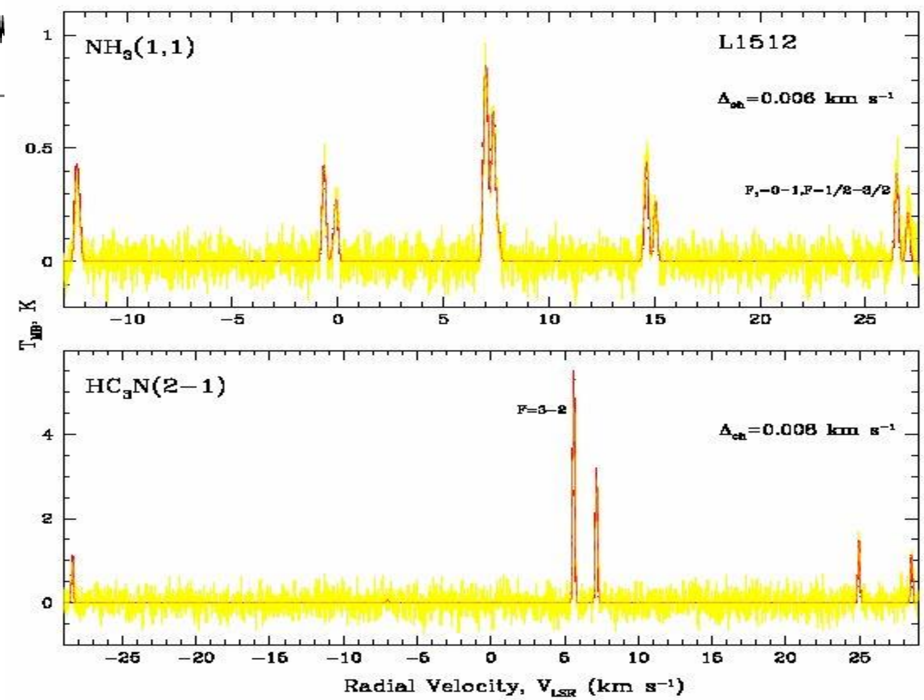
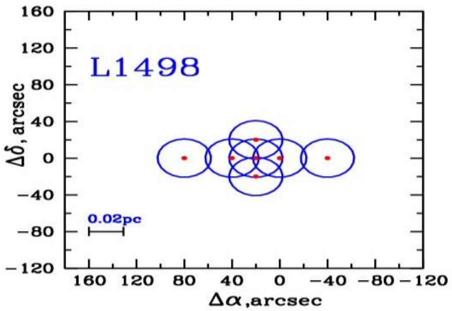
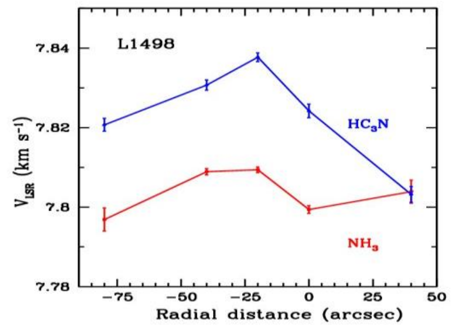


## Effelsberg, 2010
## mapping



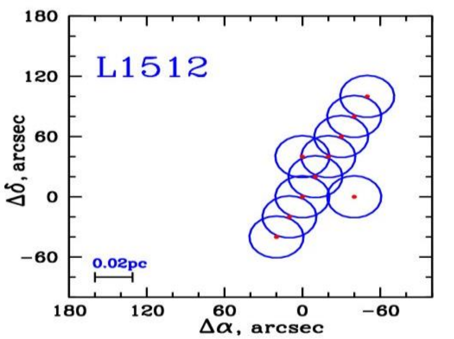



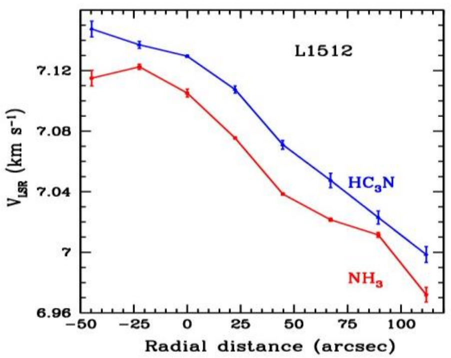

## L1498+L1512

**Jan, 2010:**

**ΔV = 27 +/- 1 +/- 3 m/s**

**Δμ/μ = 26 +/- 1 +/- 3 ppb**



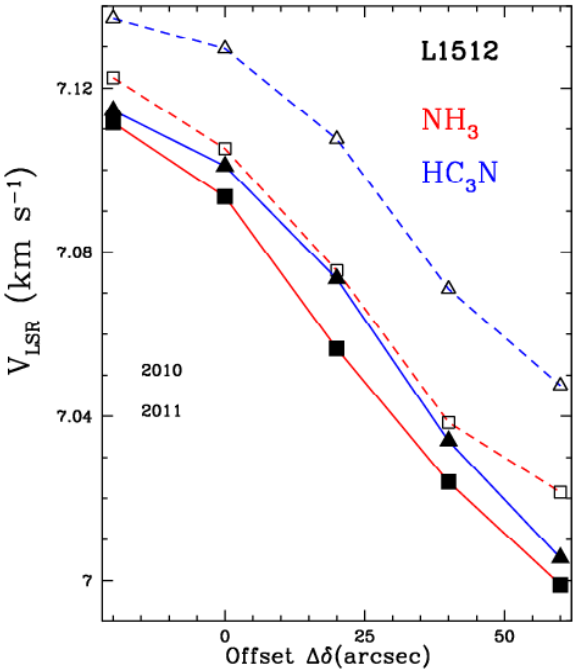

**Feb, 2009:**

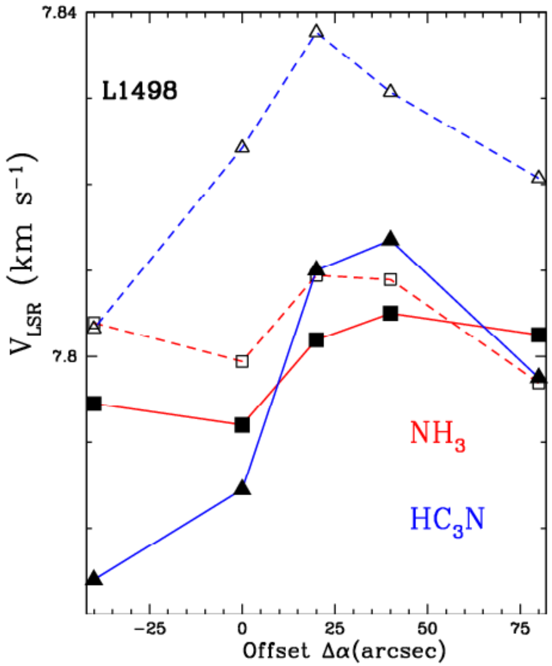
**ΔV = 26 +/- 4 +/- 3 m/s**

**Δμ/μ = 26 +/- 4 +/- 3 ppb**

# additional tests:
# data reproducibility

## Effelsberg, 2011
## mapping

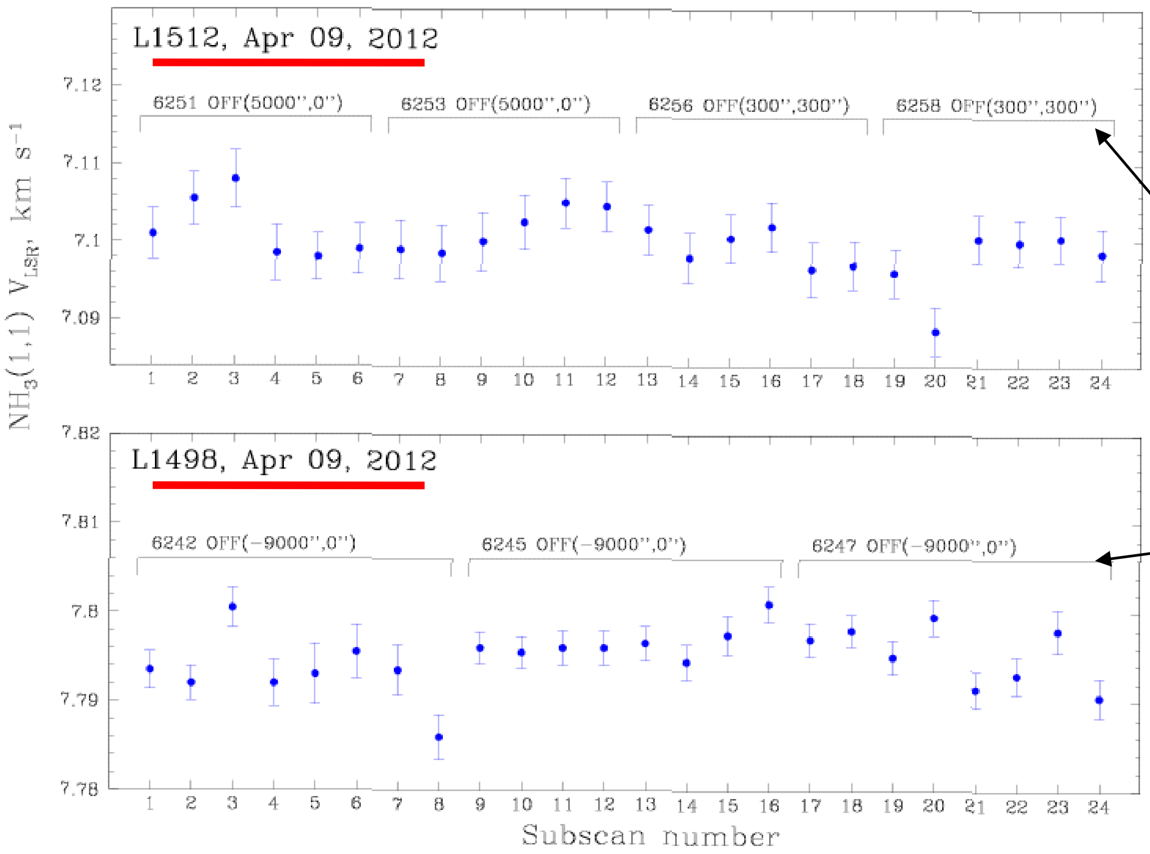



**FFTS (fast fourier transform spectrometer)**

# Time series

## Effelsberg, 2012




**New spectrometer:**

**XFFTS (eXtended FFTS)**

**Exposure time:**

**30 min/scan (ON+OFF)**

**PSW**

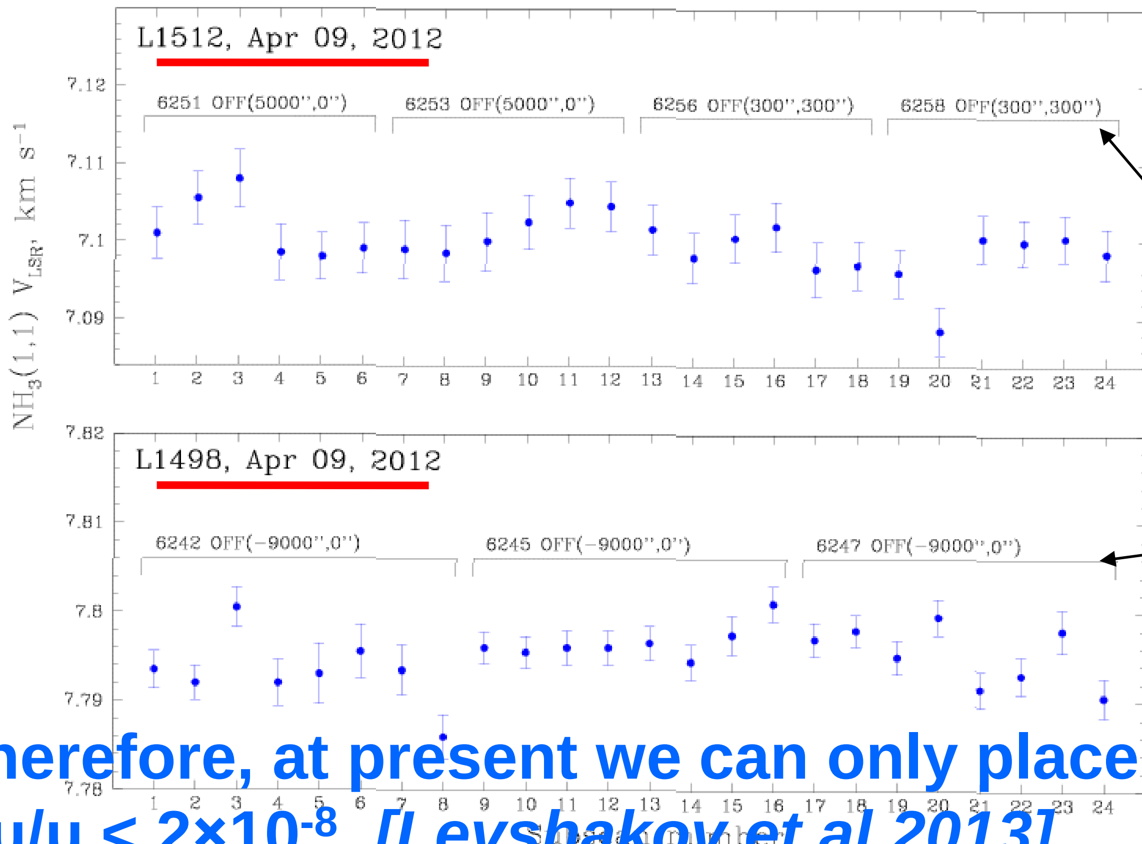
**150 sec/point**

**instability of δV ~ 10 m/s detected**

**independently checked by Benjamin Winkel (MPIfR)**

# Time series

**Effelsberg, 2012**




**New spectrometer:**

**XFFTS (eXtended FFTS)**

**Exposure time:**

**30 min/scan (ON+OFF)**

**PSW**

**150 sec/point**

**Therefore, at present we can only place an upper bound:**
**$\Delta\mu/\mu < 2\times10^{-8}$ *[Levshakov et al 2013]***

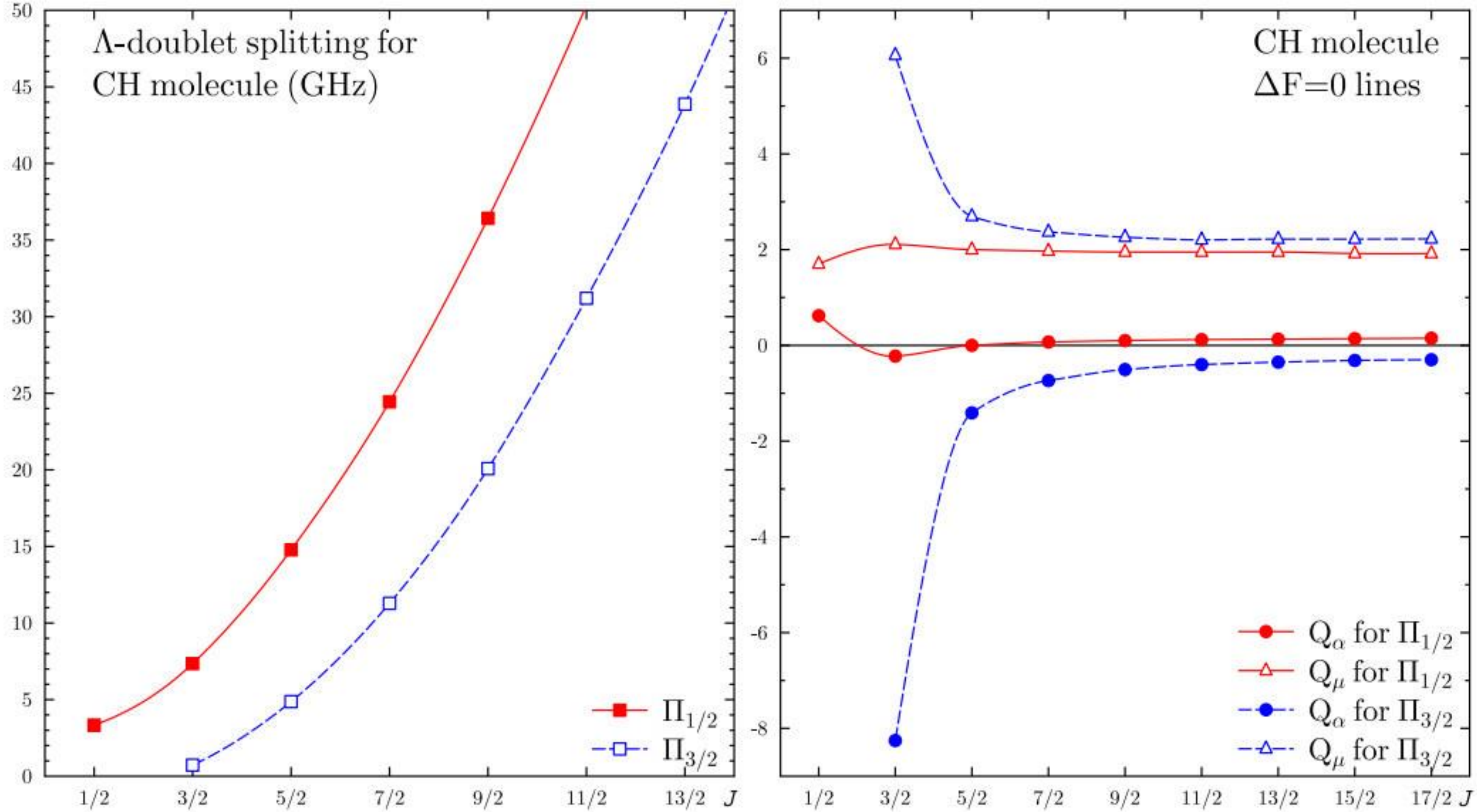
**instability of $\delta V \sim 10$ m/s detected**

**independently checked by Benjamin Winkel (MPIfR)**

# Λ-doublet, or Ω-doublet transitions in CH

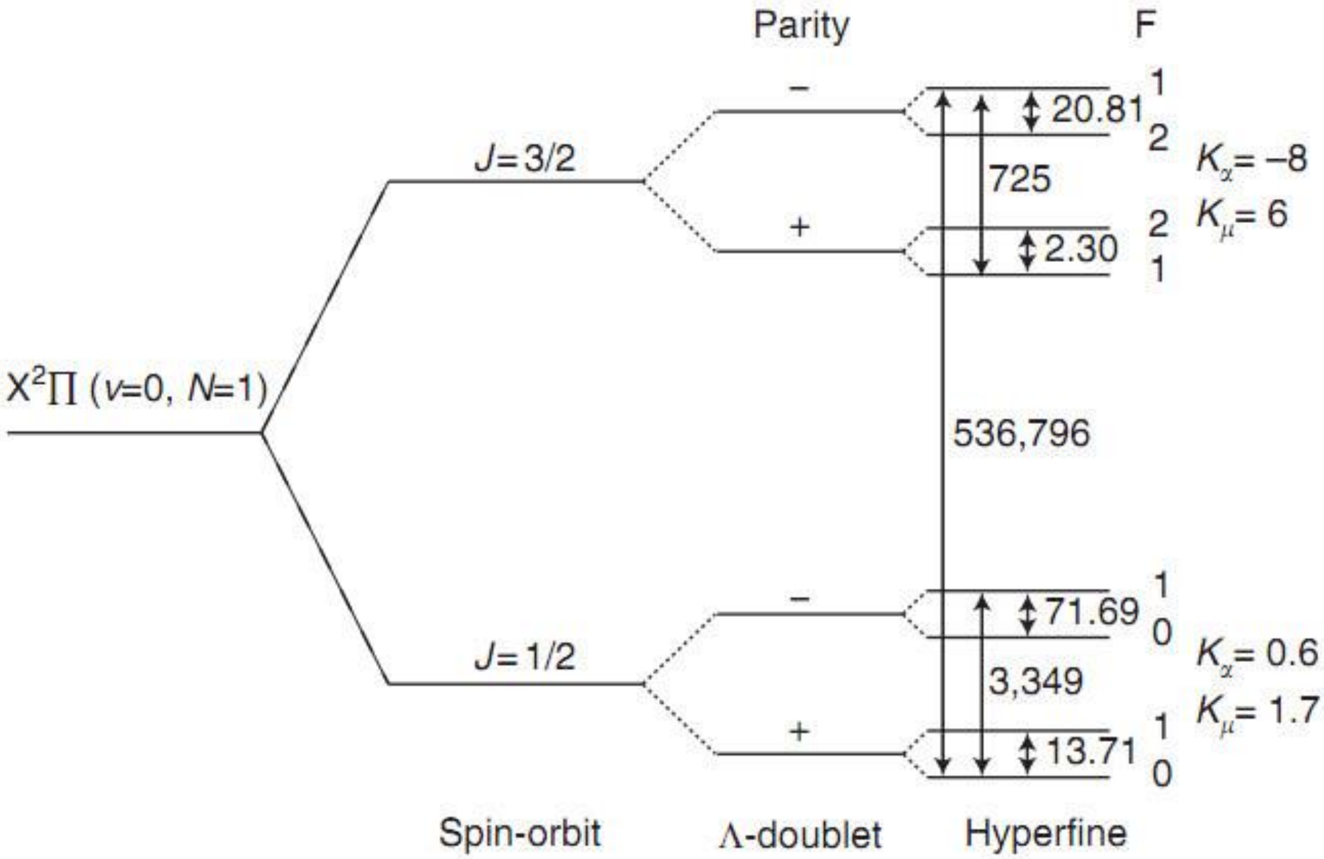
Spin-orbit interaction couples electron spin to the molecular axis. When rotational energy grows, electron spin decouples from the axis. Then quantum number Ω is substituted by Λ. Competition between Coriolis and SO interactions leads to strong dependence of the doubling splitting on α and μ.

# Frequencies & sensitivities of Λ-transitions in CH



# Detection of Λ-doublet transitions in CH

*[Truppe et al, Nat. Commun. 4, 2600 (2013)]*



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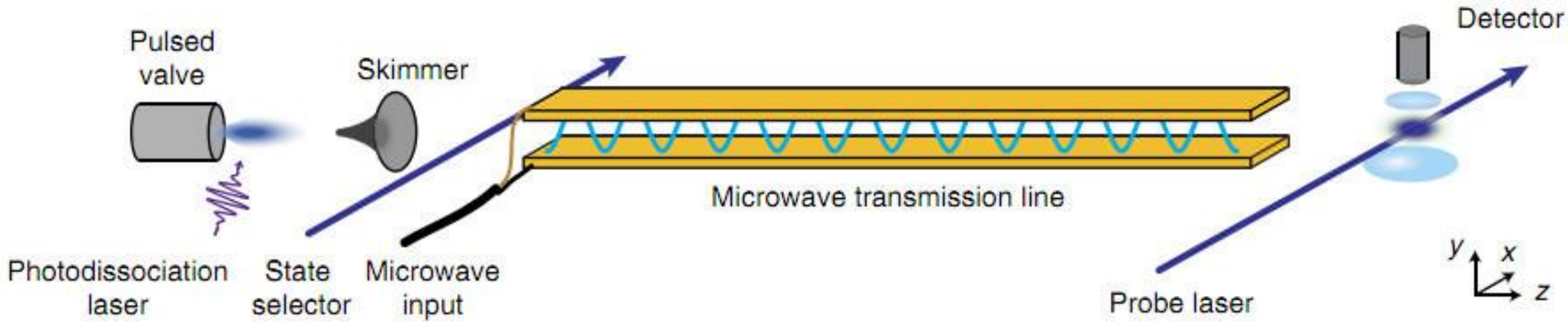

# Detection of Λ-doublet transitions in CH

*[Truppe et al, Nat. Commun. 4, 2600 (2013)]*

**Table 1 | Measured Λ-doublet frequencies with 1σ uncertainties.**

| Transition | Frequency (Hz) |
|---|---|
| $(1/2^{+},1)-(1/2^{-},1)$ | 3,335,479,356 ± 3 |
| $(1/2^{+},0)-(1/2^{-},1)$ | 3,349,192,556 ± 3 |
| $(1/2^{+},1)-(1/2^{-},0)$ | 3,263,793,447 ± 3 |
| $(3/2^{+},2)-(3/2^{-},2)$ | 701,677,682 ± 6 |
| $(3/2^{+},1)-(3/2^{-},1)$ | 724,788,315 ± 16 |
| $(3/2^{+},1)-(3/2^{-},2)$ | 703,978,340 ± 21 |
| $(3/2^{+},2)-(3/2^{-},1)$ | 722,487,624 ± 16 |

Levels are labelled with the notation ($J^{p}$, $F$).

**Table 2 | Analysis of astronomical data.**

| Source | Transition 1 | Transition 2 | $v$ (km s$^{-1}$) | $\Delta v_{12}$ (km s$^{-1}$) | $\Delta v'_{12}$ (km s$^{-1}$) | $\frac{\Delta\alpha}{\alpha}$ ($10^{-7}$) | $\frac{\Delta\mu}{\mu}$ ($10^{-7}$) | Ref. |
|---|---|---|---|---|---|---|---|---|
| G111.7 − 2.1(CasA) | CH(3264, 3335, 3349) | OH(1667) | − 1.4, 0 | − 0.01 (0.09) | − 0.08 (0.11) | 1.5 (2.0) | − 3.1 (4.1) | 30,32 |
| G265.1 + 1.5(RCW36) | CH(3264, 3335) | OH(1612, 1665, 1667, 1721) | 6.8 | 0.06 (0.19) | 0.04 (0.16) | 0.9 (3.1) | 1.9 (6.4) | 34 |
| G174.3 − 13.4(Heiles2) | CH(3264, 3335, 3349) | OH(1612, 1665, 1667, 1721) | 5.8 | 0.00 (0.19) | − 0.02 (0.19) | 0.6 (3.6) | − 1.2 (7.4) | 32,43 |
| G6.0 + 36.7(L134N) | CH(3264, 3335, 3349) | OH(1665, 1667) | 2.5 | 0.05 (0.13) | − 0.12 (0.13) | 2.3 (2.4) | − 4.8 (5.0) | 32,43 |
| G49.5 − 0.4(W51) | CH(702) | CH(3264, 3335, 3349) | 65 | − 0.85 (0.53) | − 0.48 (0.55) | − 1.8 (2.0) | 3.6 (4.1) | 36 |

# Conclusions

- In the recent years there was gradual shift of emphasis from optical to microwave waveband in the quest for the variation of the fundamental constants.
- At present there is no reliable evidence of the variation of constants either in space, or in time.
- Astrophysical data leads to very strict upper limits on the variation of constants.
- State of the art laboratory techniques are essential to provide high accuracy rest frame frequencies of important molecular transitions.
- New observations of microwave spectra at high redshifts are likely to lead to even stronger limits in the near future.