Title: Spectroscopic constrains on variation of fundamental constants in astrophysics.

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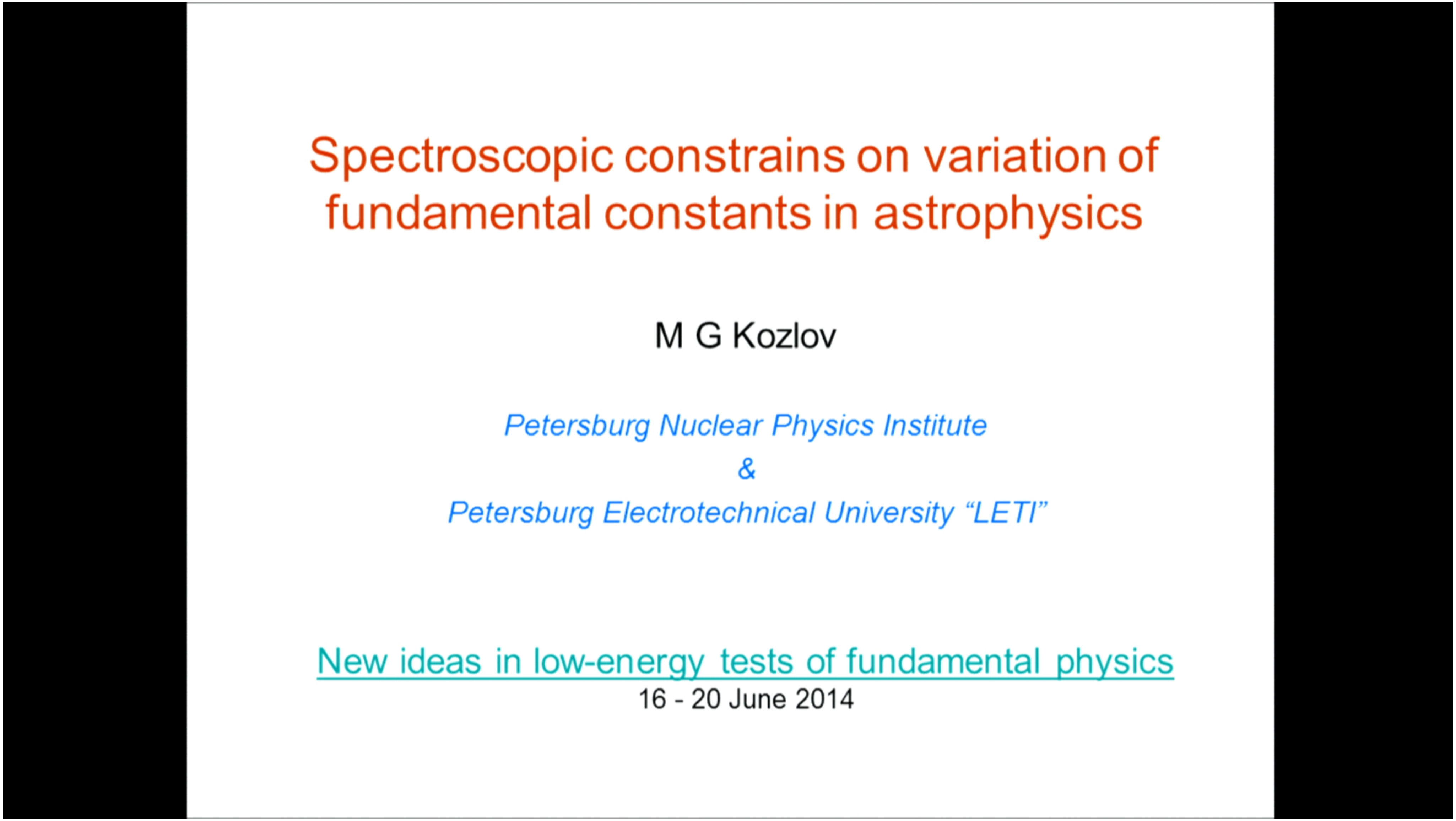
Abstract: I will discuss present limits on the variation of the fine structure constant and the electron to proton mass ratio from the astrophysical data on the spectra from the interstellar gas medium. The emphasis will be made on the infrared and microwave spectra. Such spectra may be 2 - 3 orders of magnitude more sensitive to the variation of constants than optical spectra.



Spectroscopic constrains on variation of fundamental constants in astrophysics

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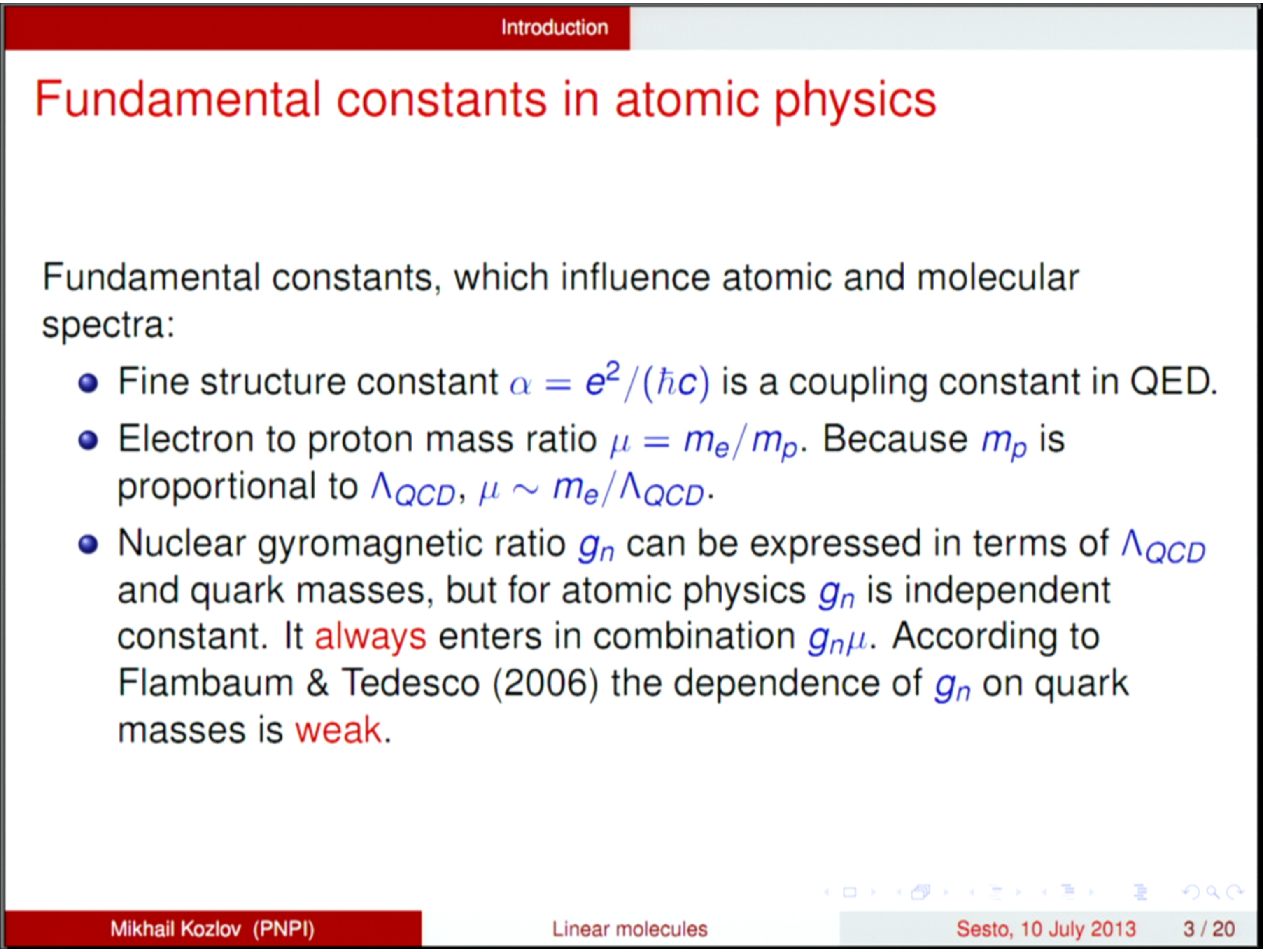
Petersburg Nuclear Physics Institute
&
Petersburg Electrotechnical University “LETI”

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 Λ_{QCD}, $\mu \sim m_e/\Lambda_{QCD}$.
- Nuclear gyromagnetic ratio g_n can be expressed in terms of Λ_{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.

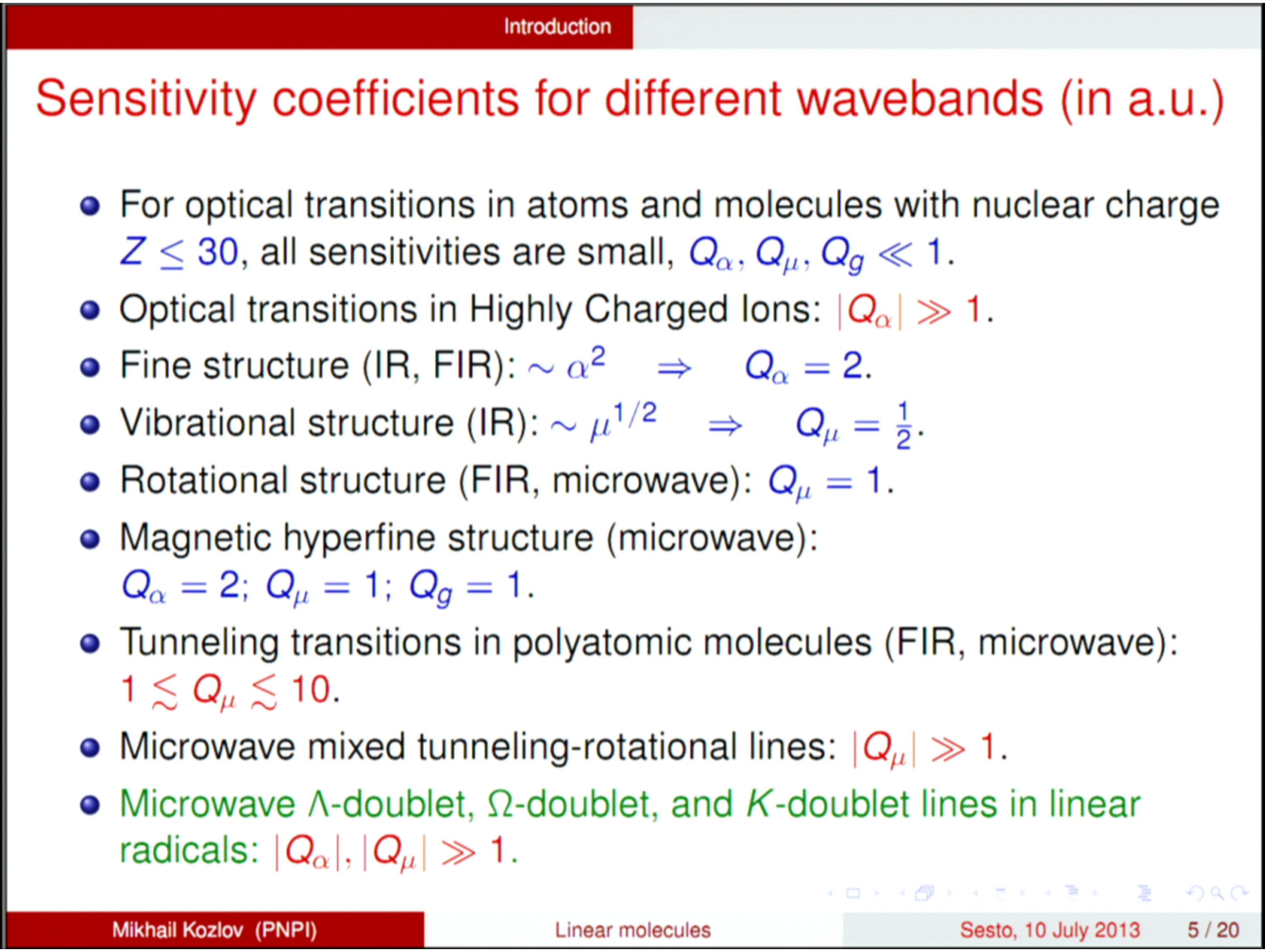
Dimensionless sensitivity coefficients

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

$$\begin{aligned}\omega &= \omega_0\left[1+Q_\alpha\frac{\delta\alpha}{\alpha}+Q_\mu\frac{\delta\mu}{\mu}+Q_g\frac{\delta g_n}{g_n}\right],\\ \frac{\delta\omega}{\omega} &= \frac{\delta F}{F},\qquad F=\alpha^{Q_\alpha}\mu^{Q_\mu}g_n^{Q_g}.\end{aligned}$$

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

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

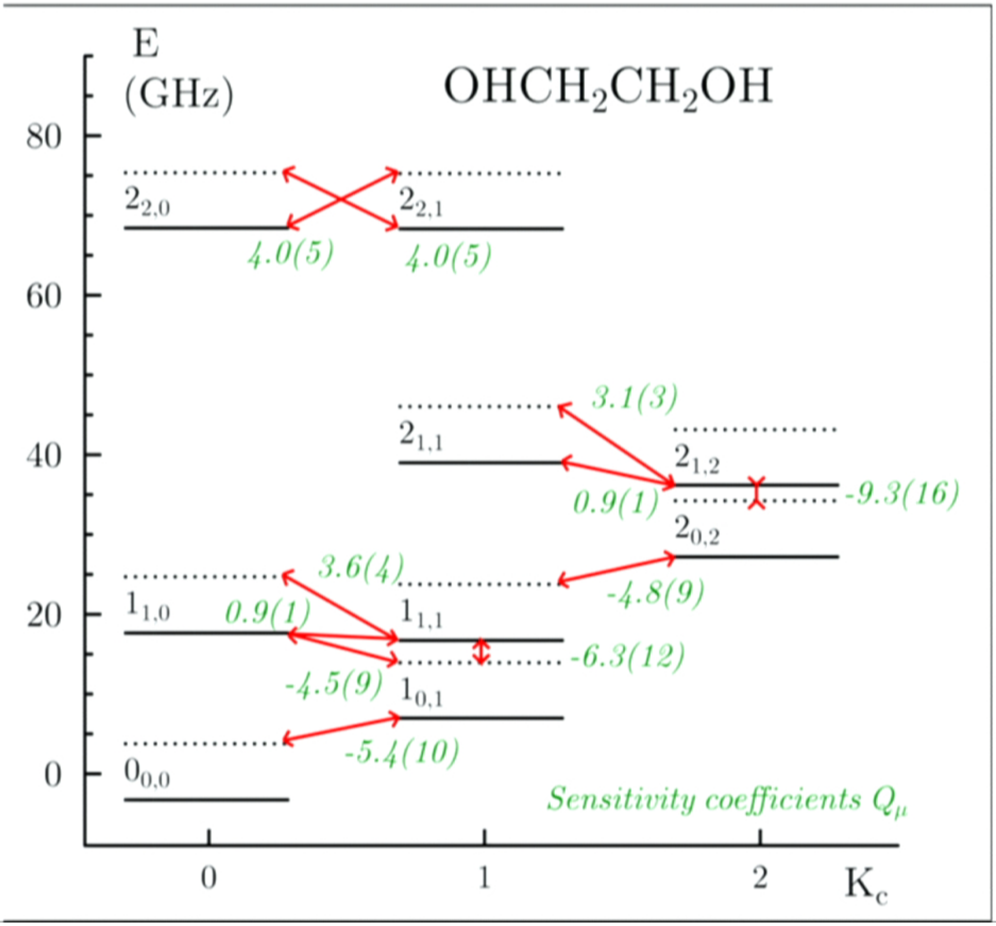


Sensitivity coefficients for different wavebands (in a.u.)

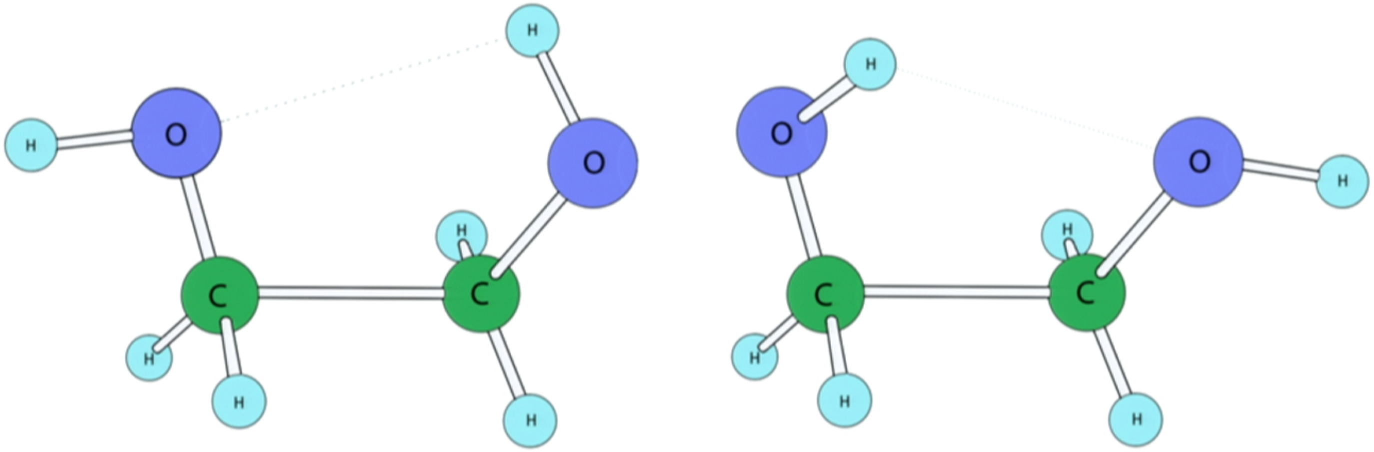
- For optical transitions in atoms and molecules with nuclear charge $Z \leq 30$, all sensitivities are small, $Q_\alpha, Q_\mu, Q_g \ll 1$.
- Optical transitions in Highly Charged Ions: $|Q_\alpha| \gg 1$.
- Fine structure (IR, FIR): $\sim \alpha^2 \quad \Rightarrow \quad Q_\alpha = 2$.
- Vibrational 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 Λ-doublet, Ω-doublet, and K-doublet lines in linear radicals: $|Q_\alpha|, |Q_\mu| \gg 1$.

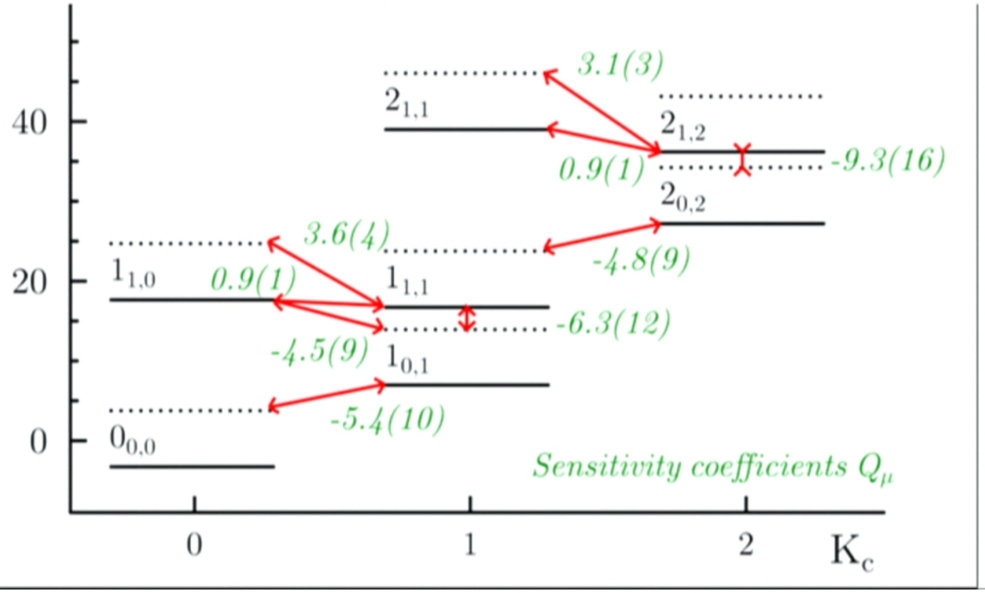
Tunneling-rotational spectrum of Ethylene glycol

[A Viatkina & MK 2014]

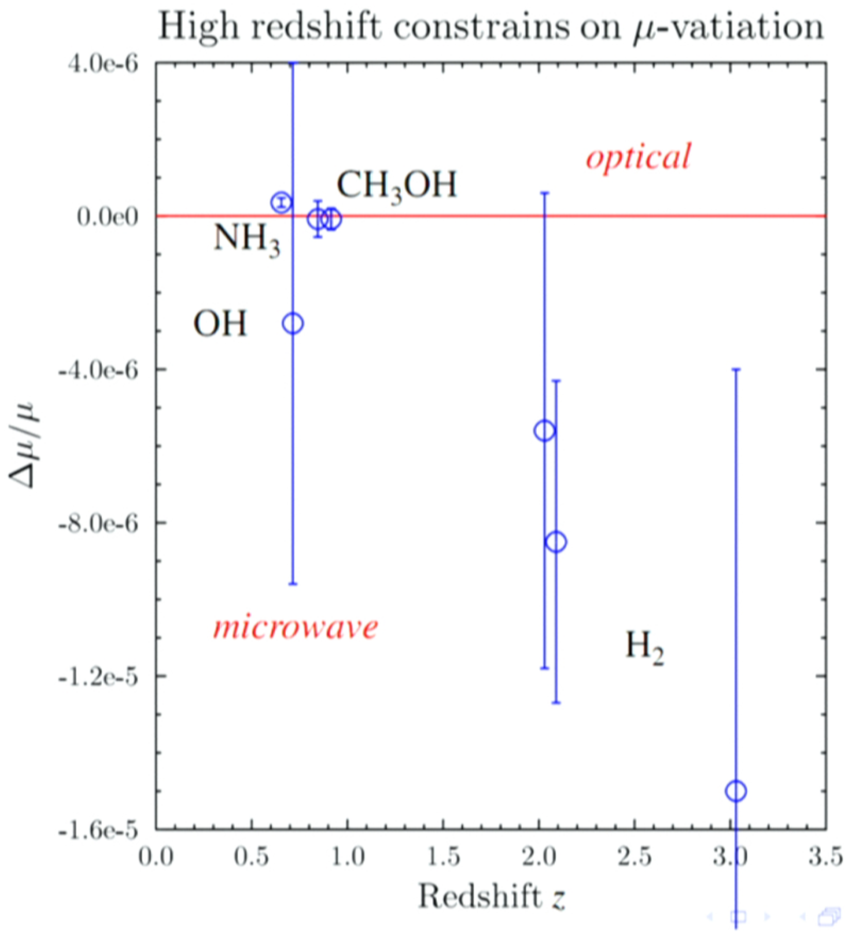


Tunneling-rotational spectrum of Ethylene glycol



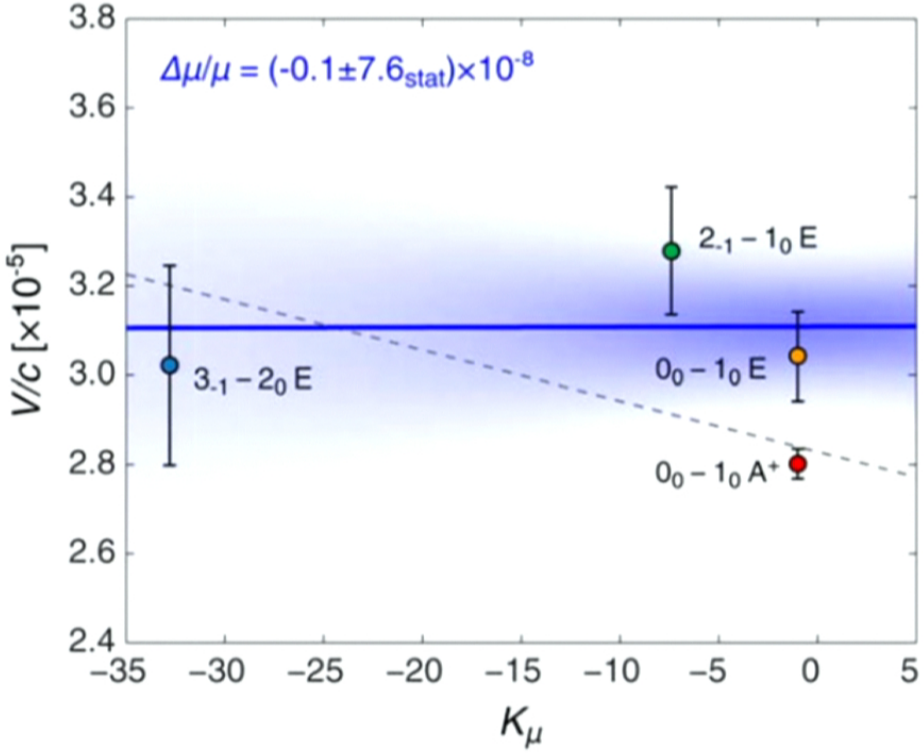


Ограничения на вариацию μ на больших z



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)

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

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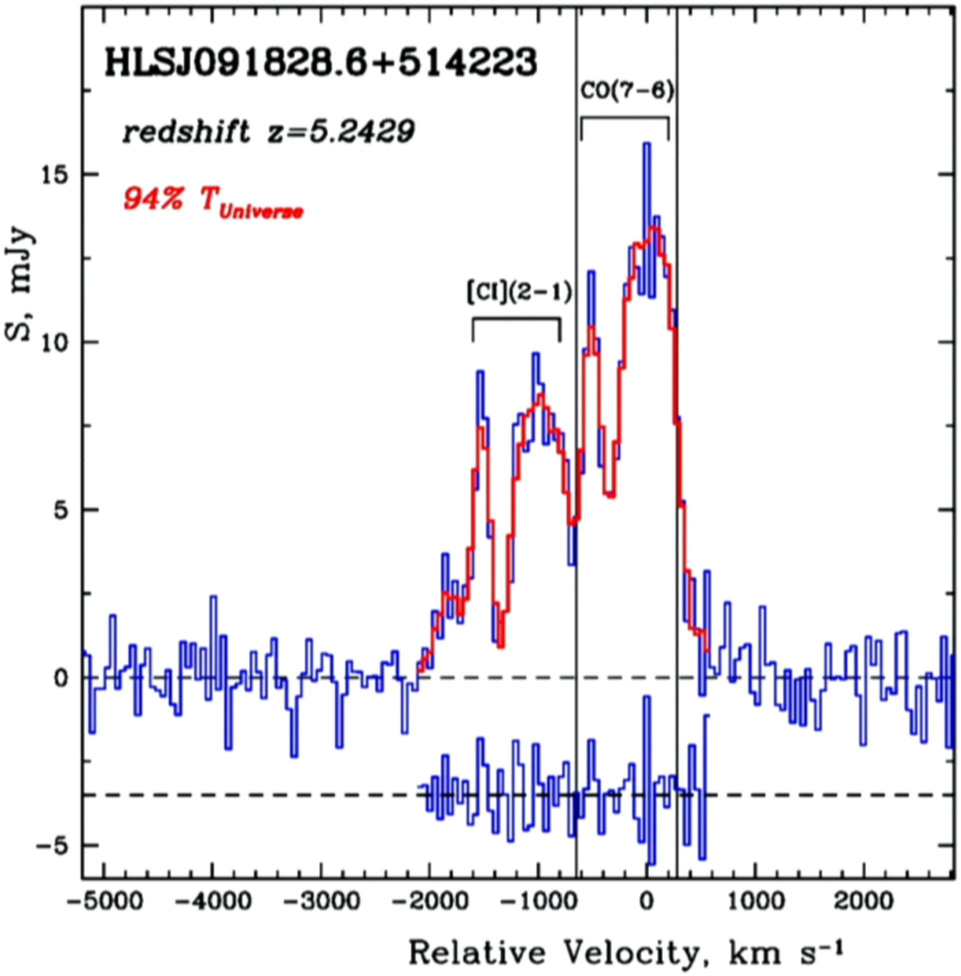
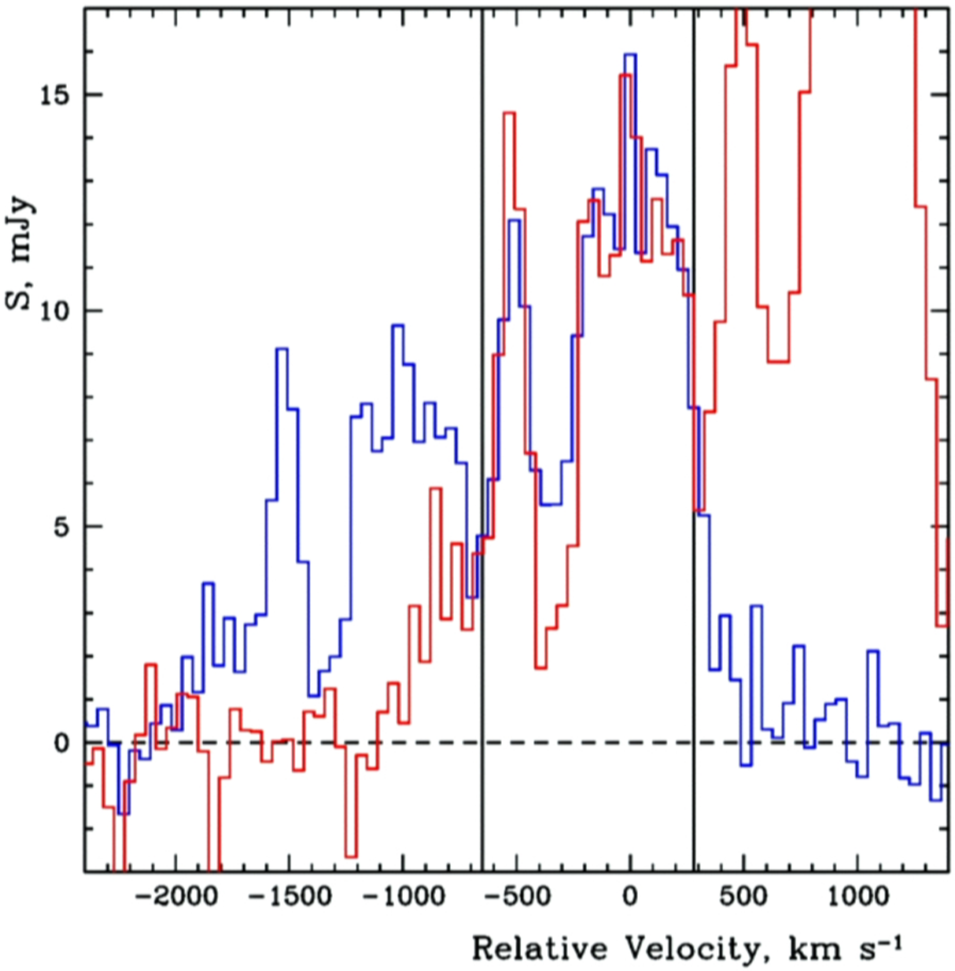
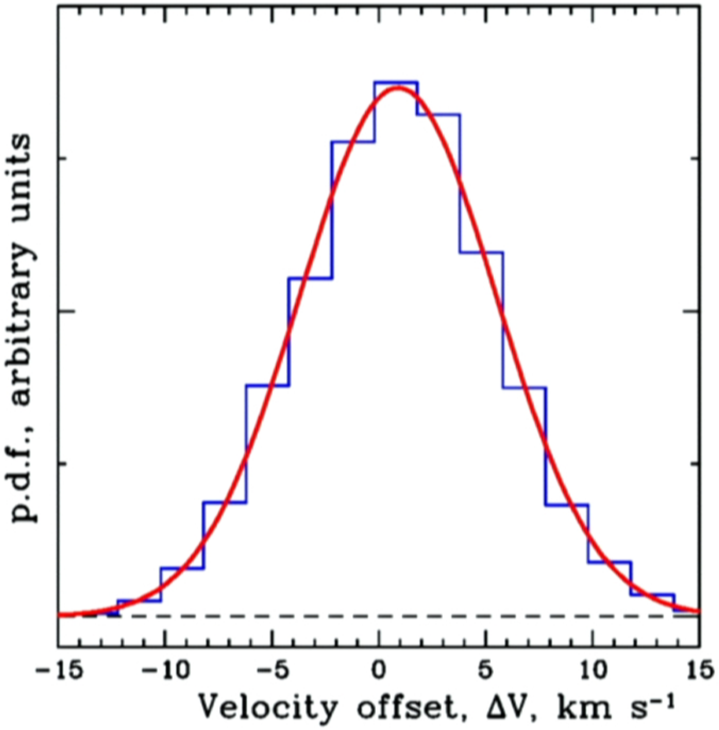

HLSJ091828.6+514223
redshift z=5.2429
94% $T_{Universe}$
CO(7−6)
[CI](2−1)
S, mJy
15
10
5
0
−5
−5000
−4000
−3000
−2000
−1000
0
1000
2000
Relative Velocity, km s^{-1}


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



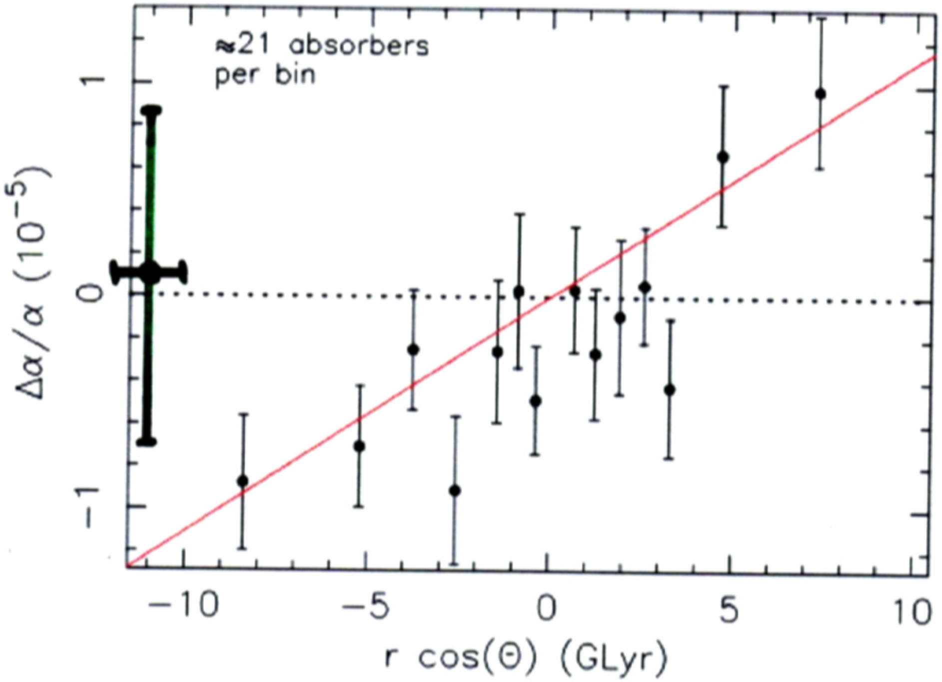
$\Delta V = (1 \pm 5)$ km/s

$F = \alpha^2/\mu$

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

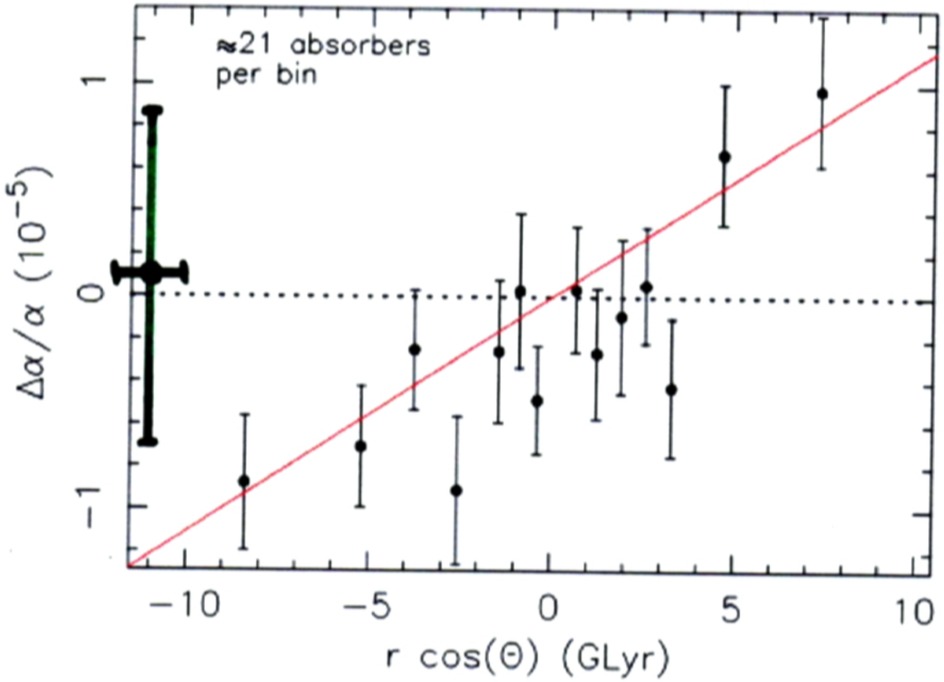
Australian dipole

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



Australian dipole

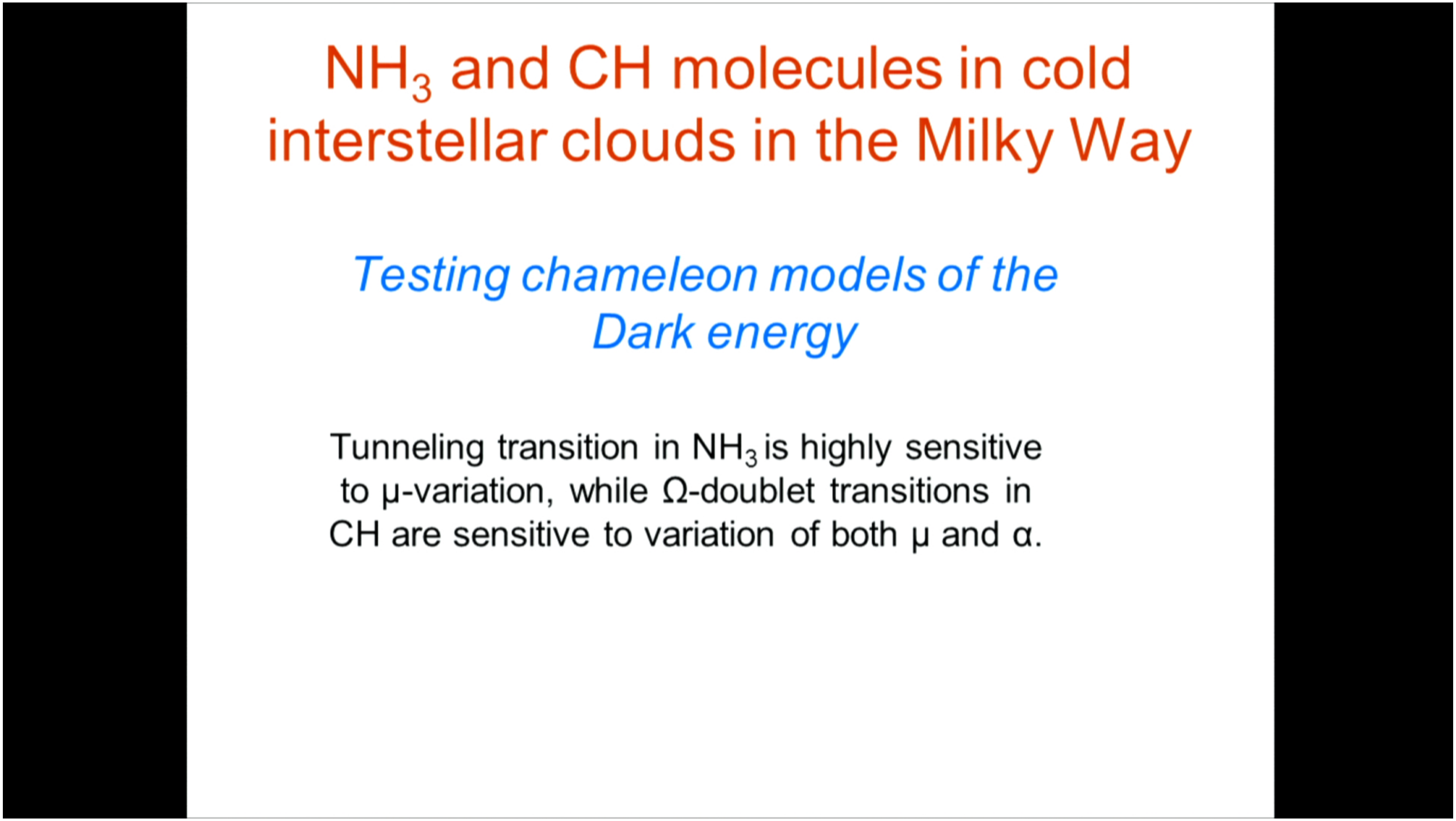
(Webb et al, *Phys. Rev. Lett.*, **2011**, *107*, 191101)



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

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

Testing chameleon models of the Dark energy



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

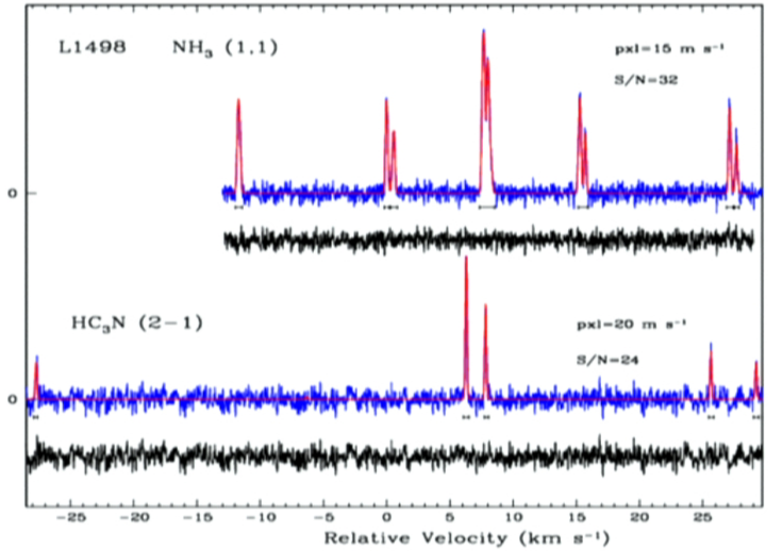
45m NOBEYAMA
Japan

NH_3 , N_2H^+

41 molecular cores
in Taurus

52 molecular cores
in Aquila

Effelsberg 100-m



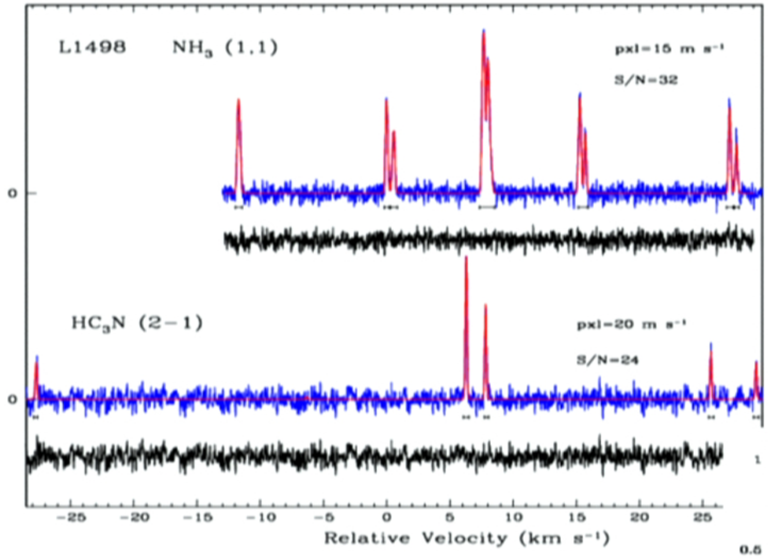
Line width:

FWHM=200 m/s
σ ~ 1 m/s

Line position uncertainty

FWHM=150 m/s
σ ~ 5 m/s

Effelsberg 100-m



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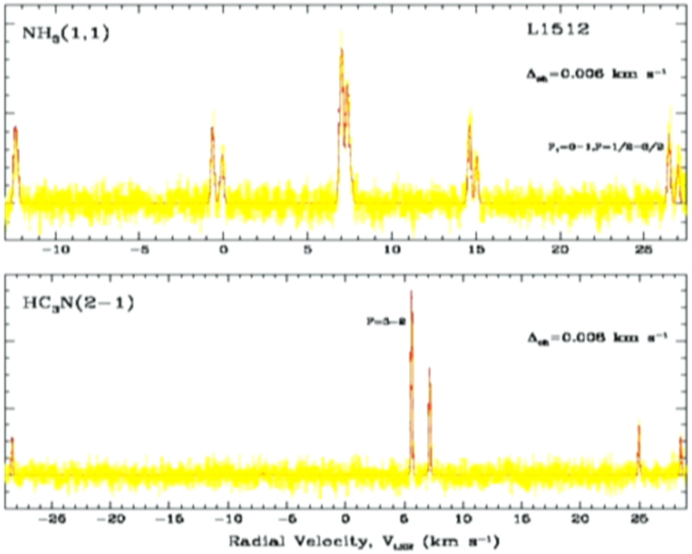
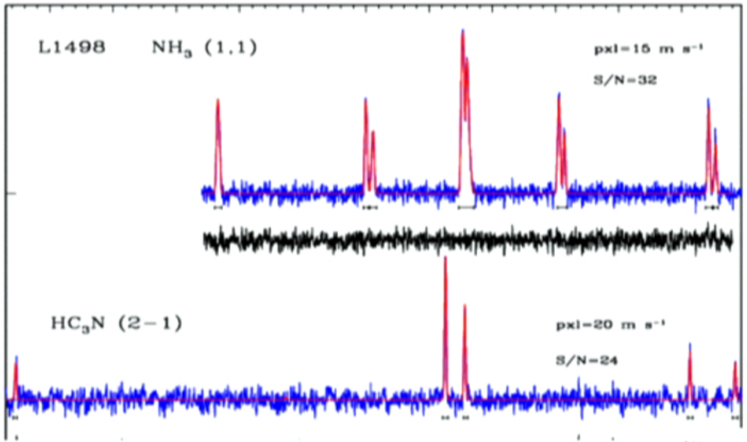


Effelsberg 100-m



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FWHM=200 m/s
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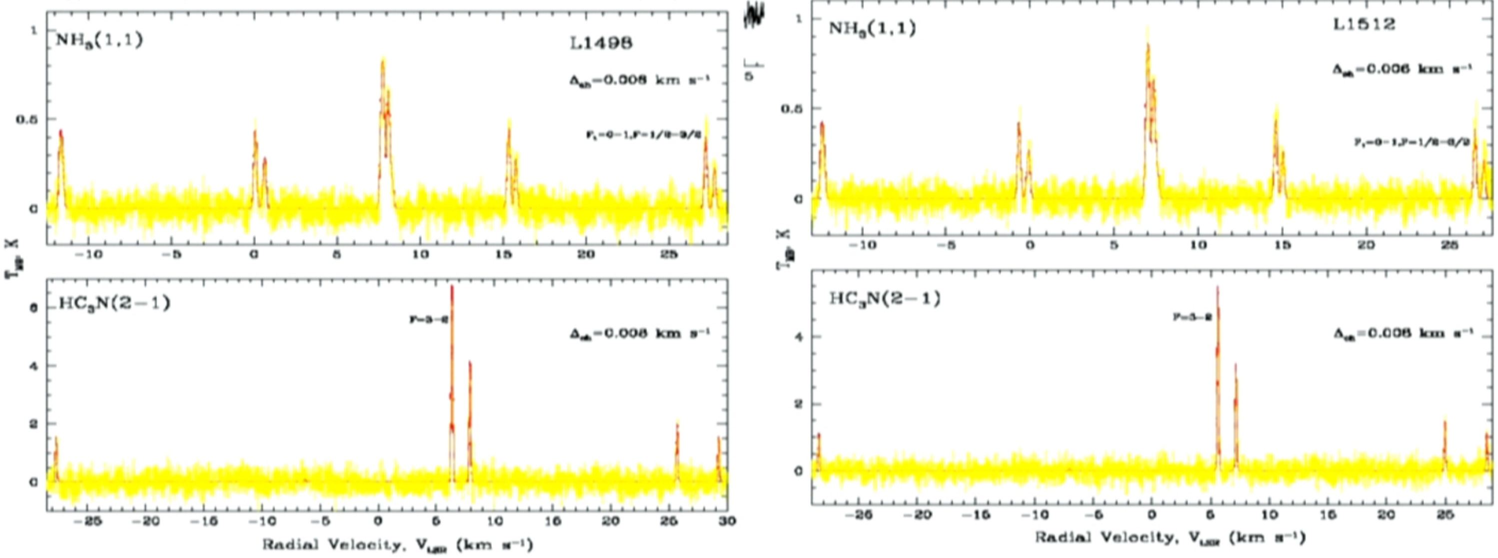
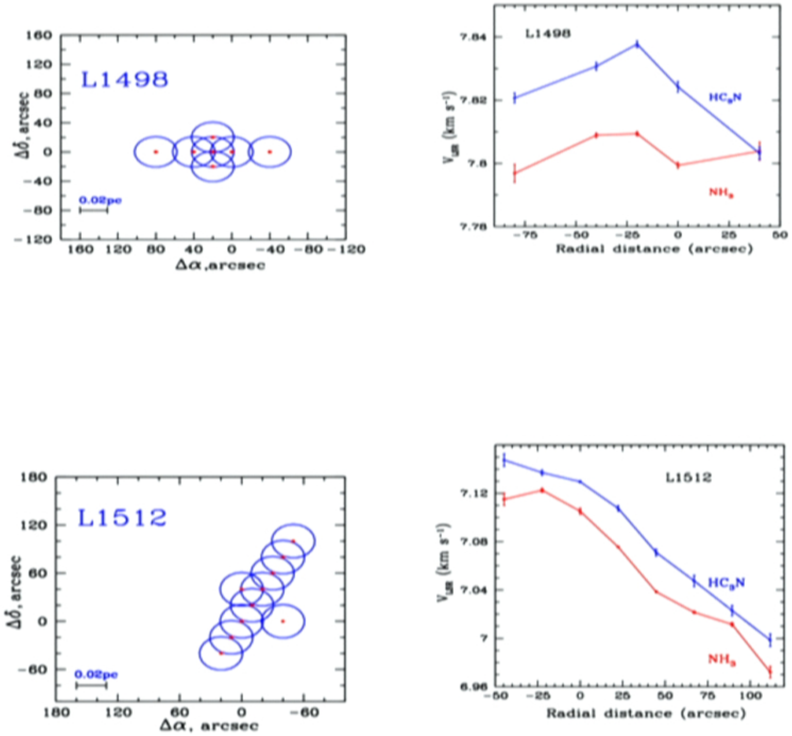


Effelsberg, 2010
mapping



L1498+L1512

Jan, 2010:

ΔV = 27 +/- 1 +/- 3 m/s

Δμ/μ = 26 +/- 1 +/- 3 ppb

Feb, 2009:

ΔV = 26 +/- 4 +/- 3 m/s

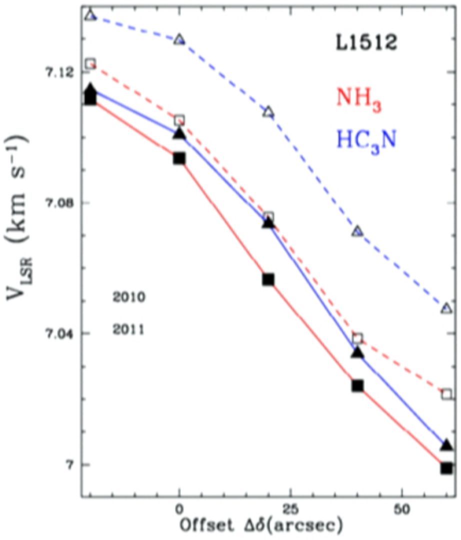
Δμ/μ = 26 +/- 4 +/- 3 ppb

additional tests:
data reproducibility

Effelsberg, 2011
mapping

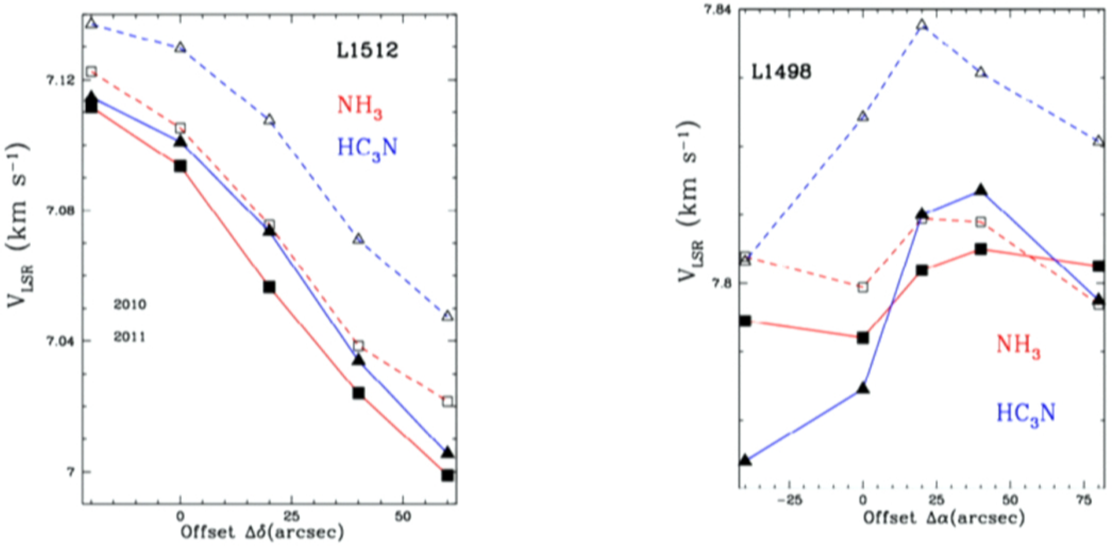
additional tests:
data reproducibility

Effelsberg, 2011
mapping



additional tests:
data reproducibility

Effelsberg, 2011
mapping



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data reproducibility

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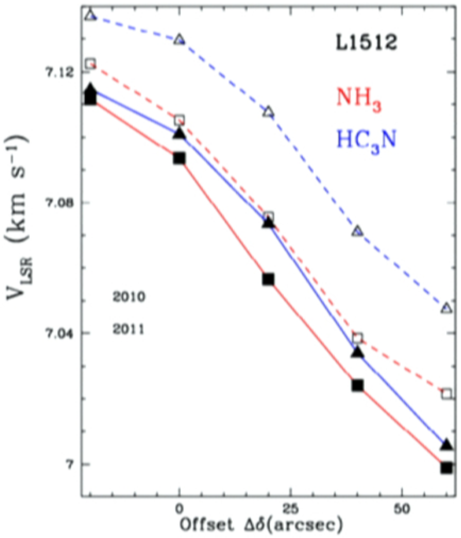
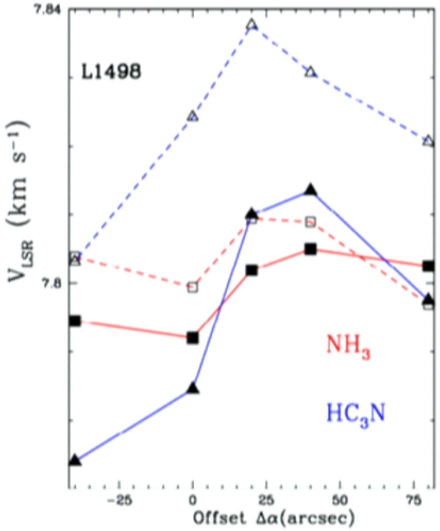
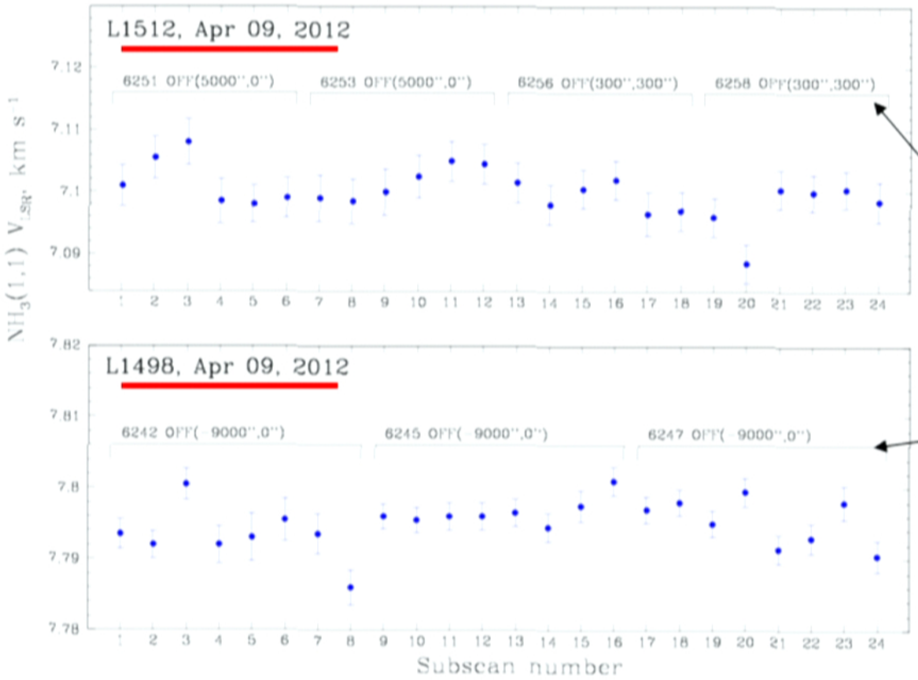




FFTS (fast fourier transform spectrometer)

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)

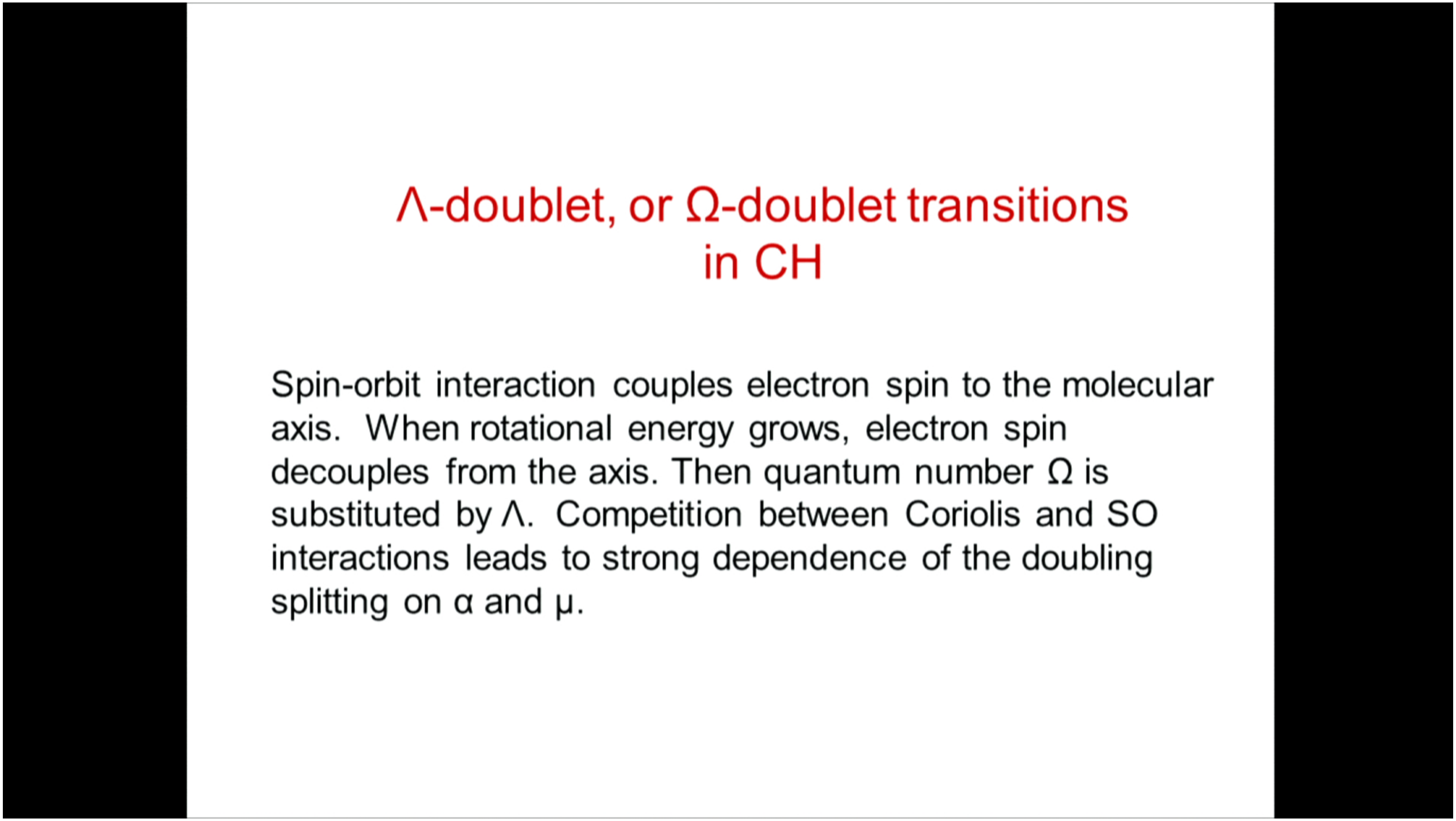
PSW

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

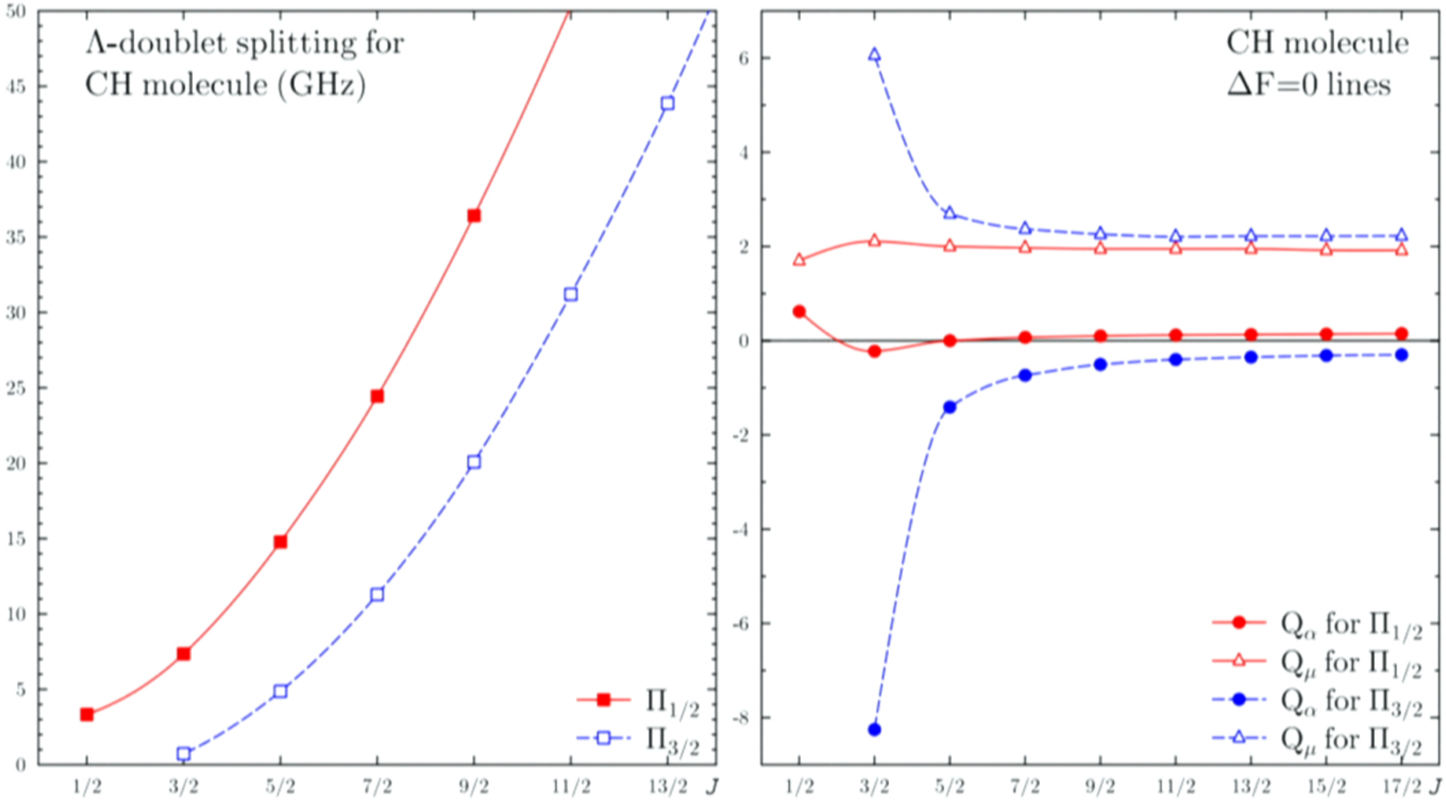
independently checked by Benjamin Winkel (MPIfR)



Λ-doublet, or Ω-doublet transitions in CH

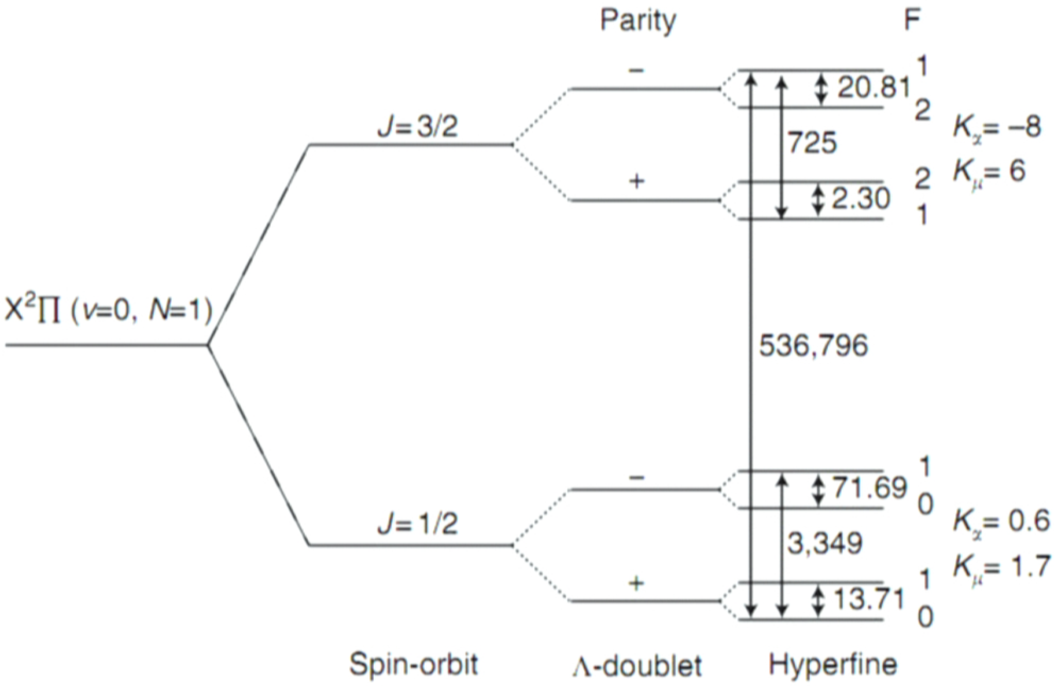
Spin-orbit interaction couples electron spin to the molecular axis. When rotational energy grows, electron spin decouples from the axis. Then quantum number Ω is substituted by Λ. Competition between Coriolis and SO interactions leads to strong dependence of the doubling splitting on α and μ.

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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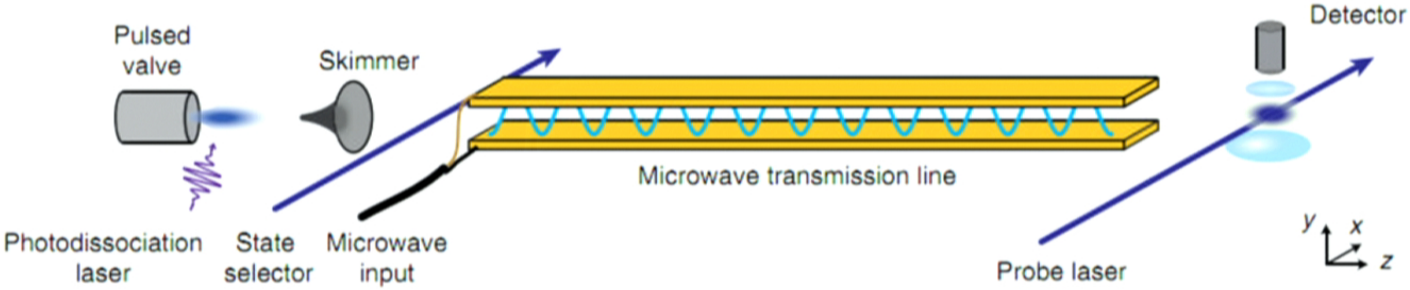

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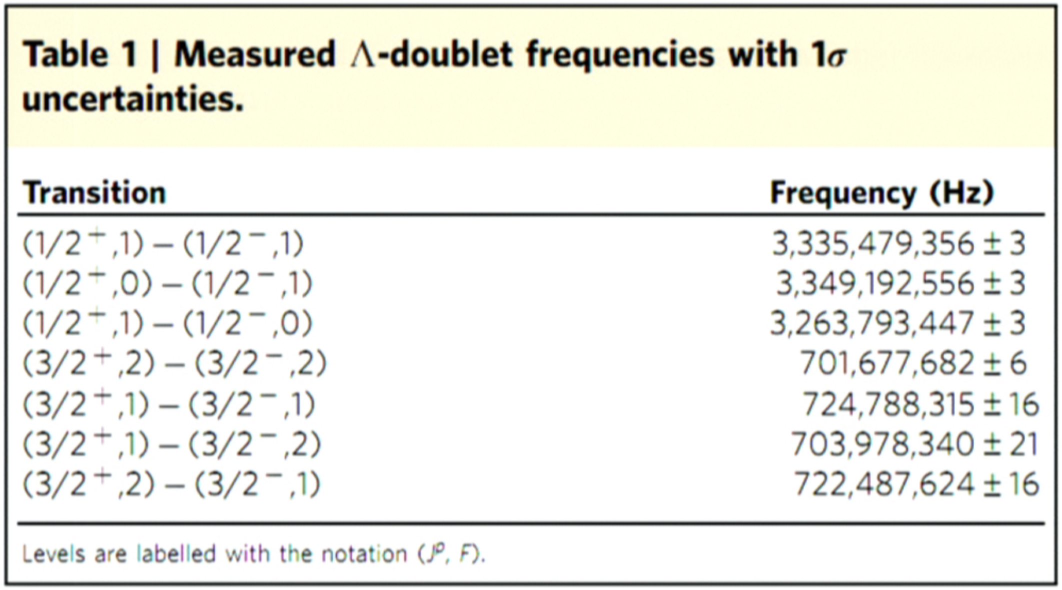

Table 1 | Measured Λ-doublet frequencies with 1σ uncertainties.

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).

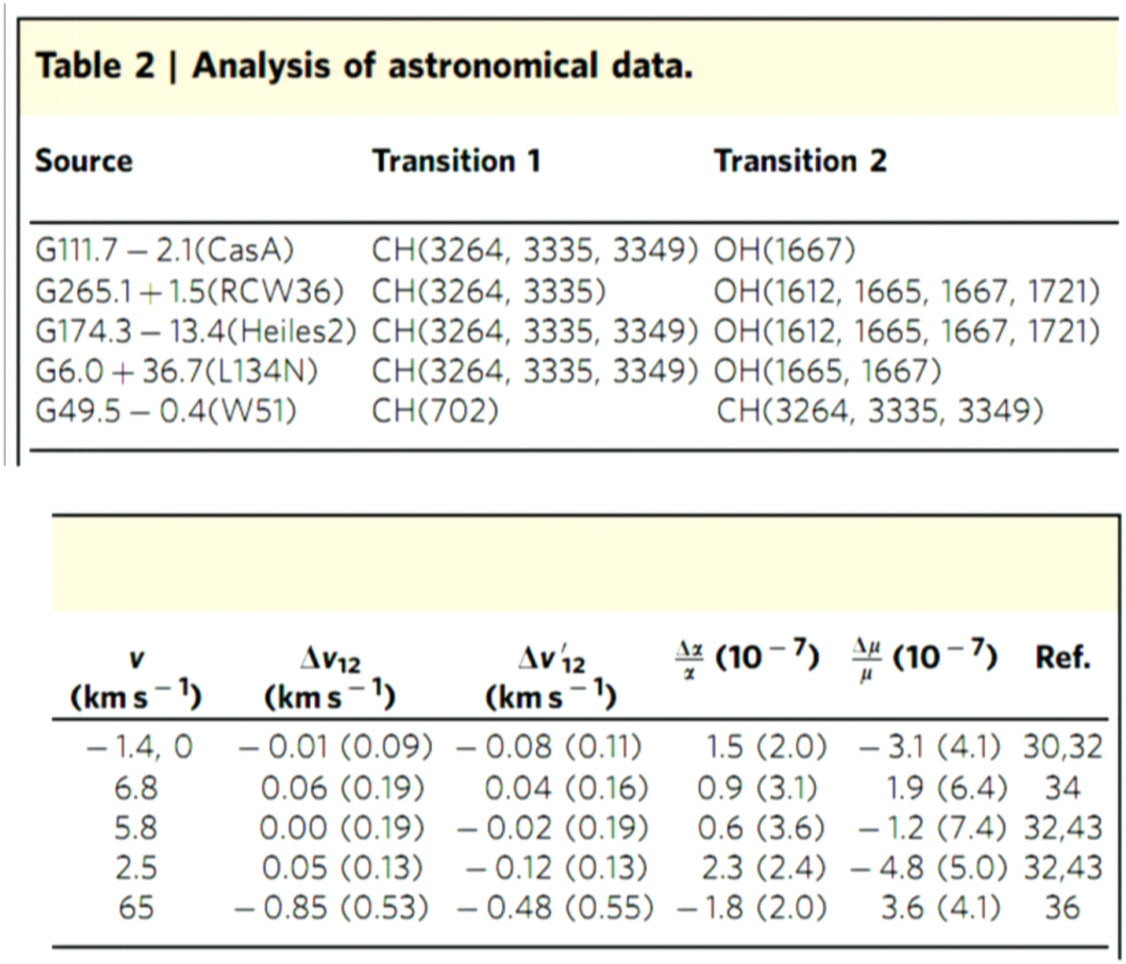

Table 2 | Analysis of astronomical data.

Source	Transition 1	Transition 2	v (km s^{-1})	Δv_{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.