Spatial variations of the electron-to-proton mass ratio: bounds obtained from high-resolution radio spectra of molecular clouds in the Milky Way

S. A. Levshakov

Dept. Theoretical Astrophyscis
A.F. Ioffe Physical-Technical Institute
St. Petersburg

Contents

Atomic & Molecular Discrete Spectra

allow to

probe variability of

$\alpha = e^2/(hc)$ $\mu = m_e/m_p$

through

relativistic corrections to atomic energy, $\omega \propto (\alpha Z)^2 R$

and

corrections for the finite nuclear mass, $\omega \propto \mu R$

less important for atoms

important for molecules

Z – atomic number

R – Rydberg constant

fine-structure levels:

$$\frac{\Delta\omega}{\omega} = 2\frac{\Delta\alpha}{\alpha}$$

molecular rotational transitions:

$$\frac{\Delta\omega}{\omega} = \frac{\Delta\mu}{\mu}$$

atomic levels, in general:

$$\omega' = \omega + qx + \ldots$$

$$\frac{\Delta\omega}{\omega} = 2Q\frac{\Delta\alpha}{\alpha}$$

$\Delta\alpha = \alpha' - \alpha$

$\Delta\mu = \mu' - \mu$

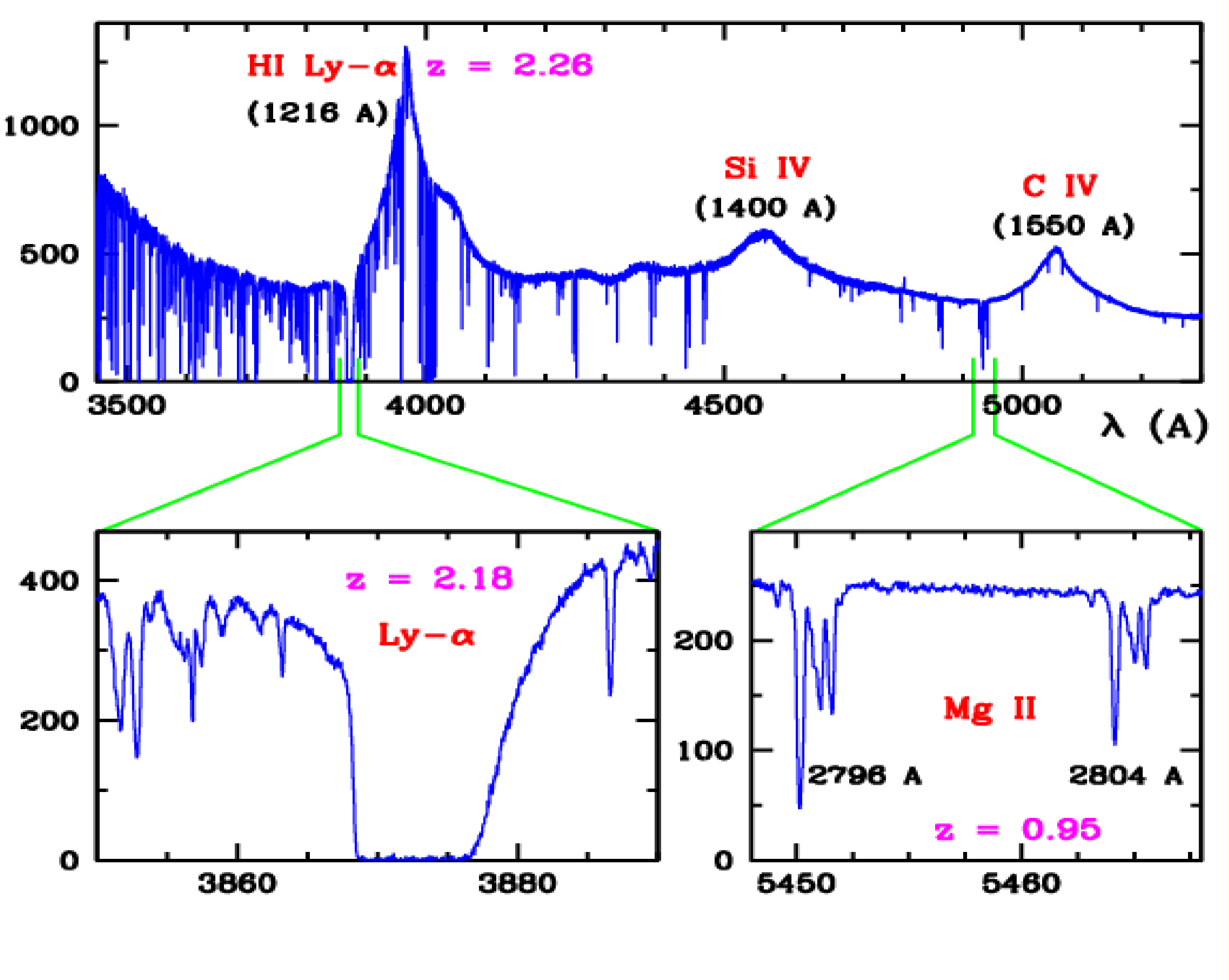
either spatial or temporal differences

$x = (\alpha'/\alpha)^2 - 1$

$Q = q/\omega$ **dimensionless sensitivity coefficient**

q-factor [cm^{-1}] **individual for each atomic transition**

Part I. Cosmological Temporal Variations



Quasar spectra

VLT/UVES

Redshift:

$z = (\lambda - \lambda_0)/\lambda_0$

$z \sim 2 \longrightarrow$

$\Delta t \sim 10^{10}$ yr

Single ion $\Delta\alpha/\alpha$ measurements

$$\boxed{\frac{\Delta\alpha}{\alpha} = \frac{1}{2}\frac{z_1 - z_2}{(Q_2 - Q_1)(1+z)} = \frac{\Delta v}{2c\,\Delta Q}}$$

FeII

2600
2586
2382
2374
2344 | $Q \sim 0.04$

1608 | $Q \sim -0.02$

$\Delta Q \sim 0.06$

FeI

2967
3021 | $Q \sim 0.08$

2484
3441
3720
3861 | $Q \sim 0.03$

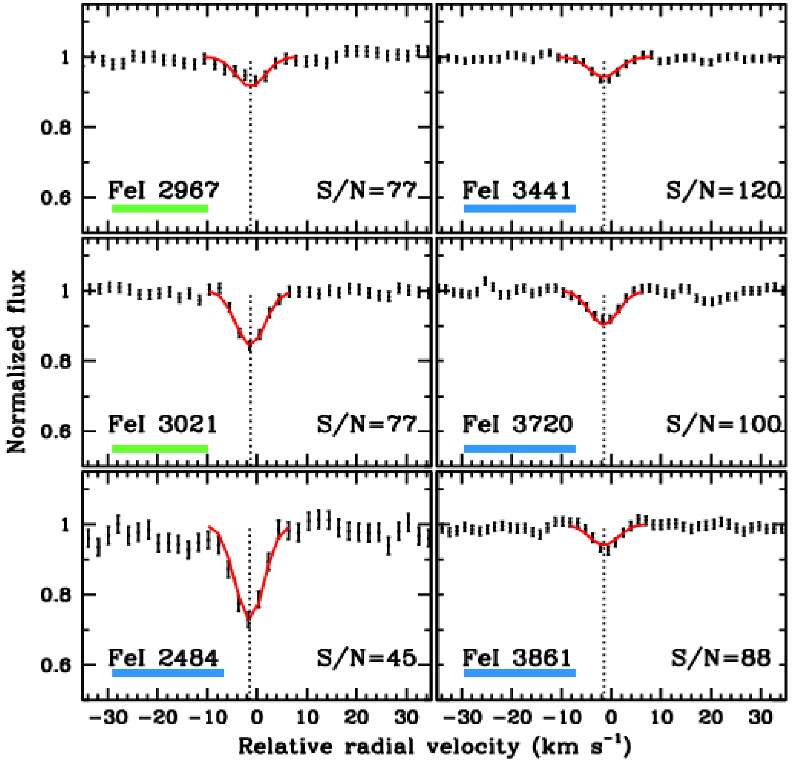
$\Delta Q \sim 0.05$

QSO HE 0001-2340

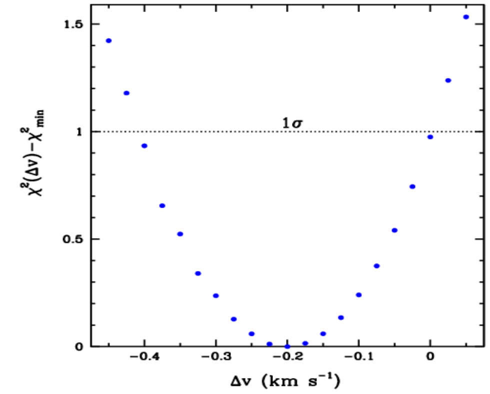
neutral iron FeI resonance transitions at $z=0.45$

Doppler width ≤ 1 km/s (!)

Simple one-component profiles



🟩 **$Q \approx 0.08$** 🟦 **$Q \approx 0.03$**



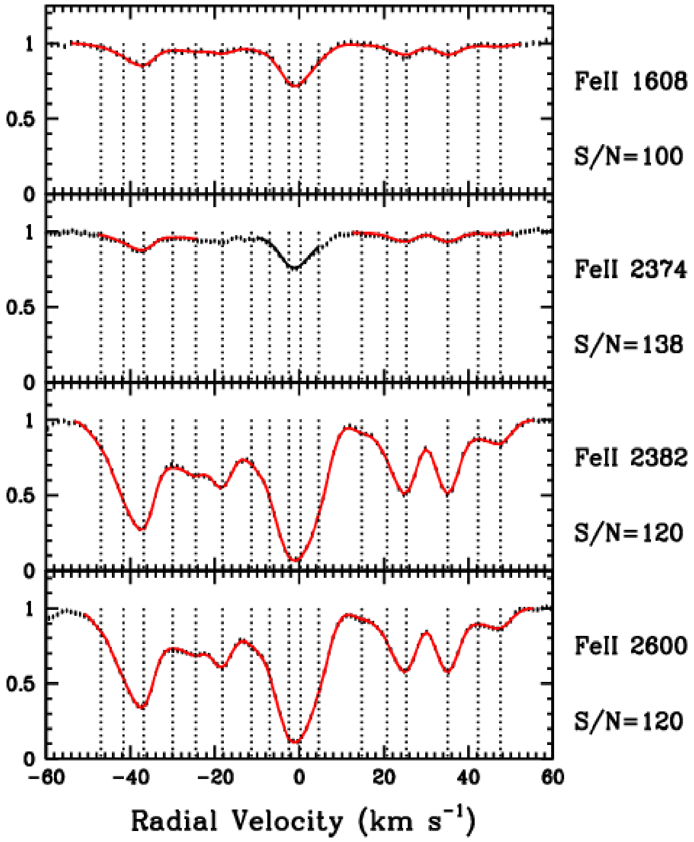
$$\Delta v = -200 \pm 200 \text{ m/s}$$

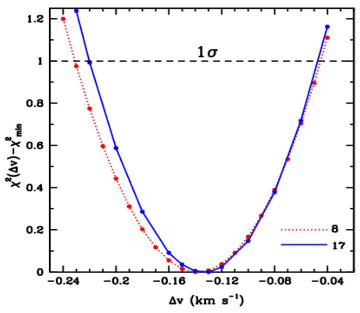
$$\boxed{\Delta\alpha/\alpha = 7 \pm 7 \text{ ppm}}$$

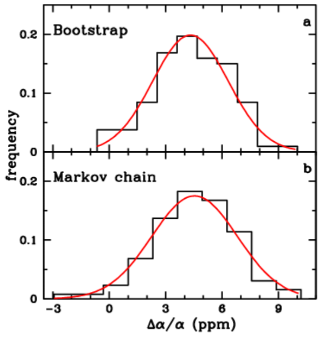
Q 1101-264

the highest resolution spectrum, FWHM = 3.8 km/s

FeII resonance transitions at z=1.84







Current estimate:

Δv = -130 ± 90 m/s

Δα/α = 4.0 ± 2.8 ppm

brightest QSO HE 0515-4414

FeII resonance transitions at z=1.15

34 FeII pairs {1608,X}

X =
2344
2374
2586

Current estimate:

1) updated sensitivity coefficients (Porsev et al.'07)

2) Accounting for correlations between different pairs {1608,X}

$$\boxed{\Delta\alpha/\alpha = -0.12 \pm 1.79 \text{ ppm}}$$

The most stringent limit: $|\Delta\alpha/\alpha| < 2$ ppm

Calibration uncertainty of ~ 50 m/s translates into the error in $\Delta\alpha/\alpha$ of ~ 2 ppm

cf. pixel size ~ 2-3 km/s

Conclusions (Part I)

No cosmological temporal variations of α at the level of 2 ppm have been found

(same for μ)

Part II. Spatial Variations (search for scalar fields)

Chameleon-like scalar field models:

dependence of masses and coupling constants on environmental matter density

$$\alpha = \alpha(\rho)$$

$$\mu = \mu(\rho)$$

ρ - **ambient matter density**

$$\boxed{\rho_{lab} / \rho_{ISM} \sim 10^{14} - 10^{16}}$$

Khoury & Weltman'04

Bax et al.'04

Feldman et al.'06

Olive & Pospelov'08

Ammonia Method to probe m_e/m_p

vibrational, and rotational intervals in molecular spectra

$$E_{vib} : E_{rot} \sim \mu^{1/2} : \mu$$

$$\downarrow$$

$$\Delta\omega_{vib} / \omega_{vib} = 0.5 \; \Delta\mu/\mu$$

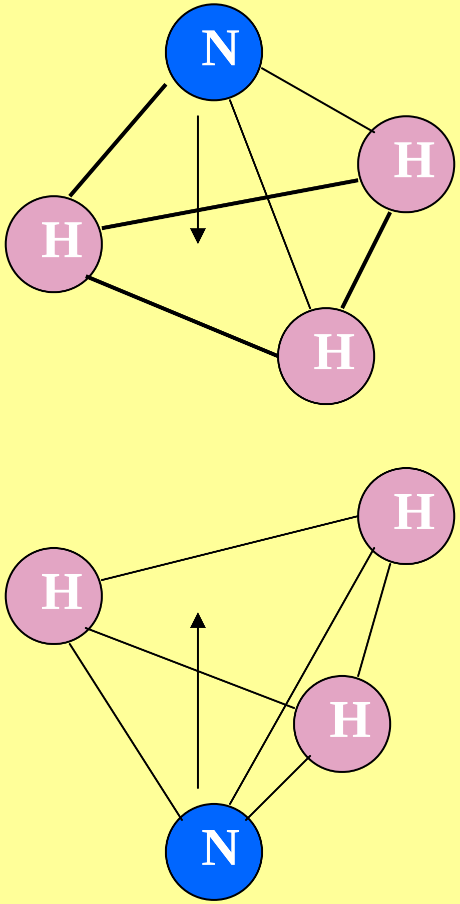
$$\Delta\omega_{rot} / \omega_{rot} = 1.0 \; \Delta\mu/\mu$$

the inversion vibrational transition in ammonia, NH_3, ω_{inv} = 23.7 GHz →

$$\Delta\omega_{inv} / \omega_{inv} = \boxed{4.5} \; \Delta\mu/\mu$$

→ **Flambaum & Kozlov'07**

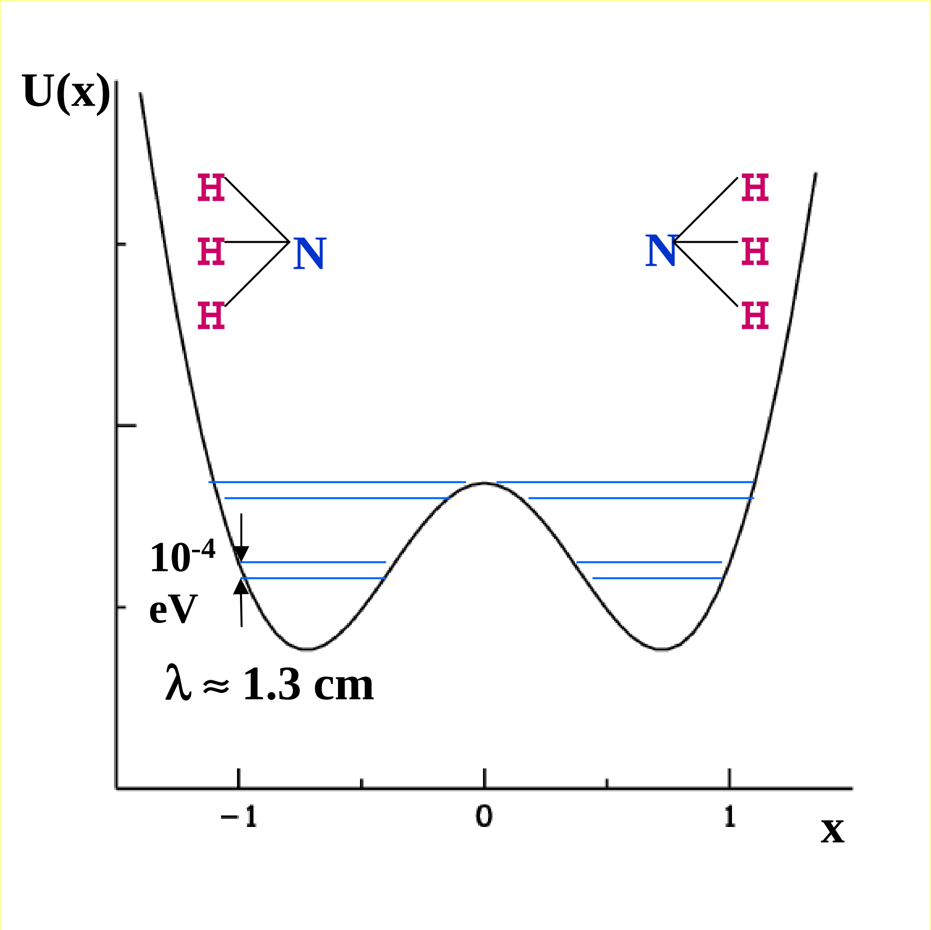
$$Q_{inv} / Q_{vib} = 9$$



Quantum mechanical tunneling

$$\omega_{inv} \sim \exp(-S)$$

the action $S \sim \mu^{-1/2}$



double-well potential of the inversion vibrational mode of NH_3

By comparing the observed inversion frequency of NH_3 with a rotational frequency of another molecule arising *co-spatially* with ammonia, a limit on the spatial variation of $\Delta\mu/\mu$ can be obtained :

$$\Delta\mu/\mu = 0.3(V_{rot} - V_{inv})/c \equiv 0.3\,\boxed{\Delta V}\,/c$$

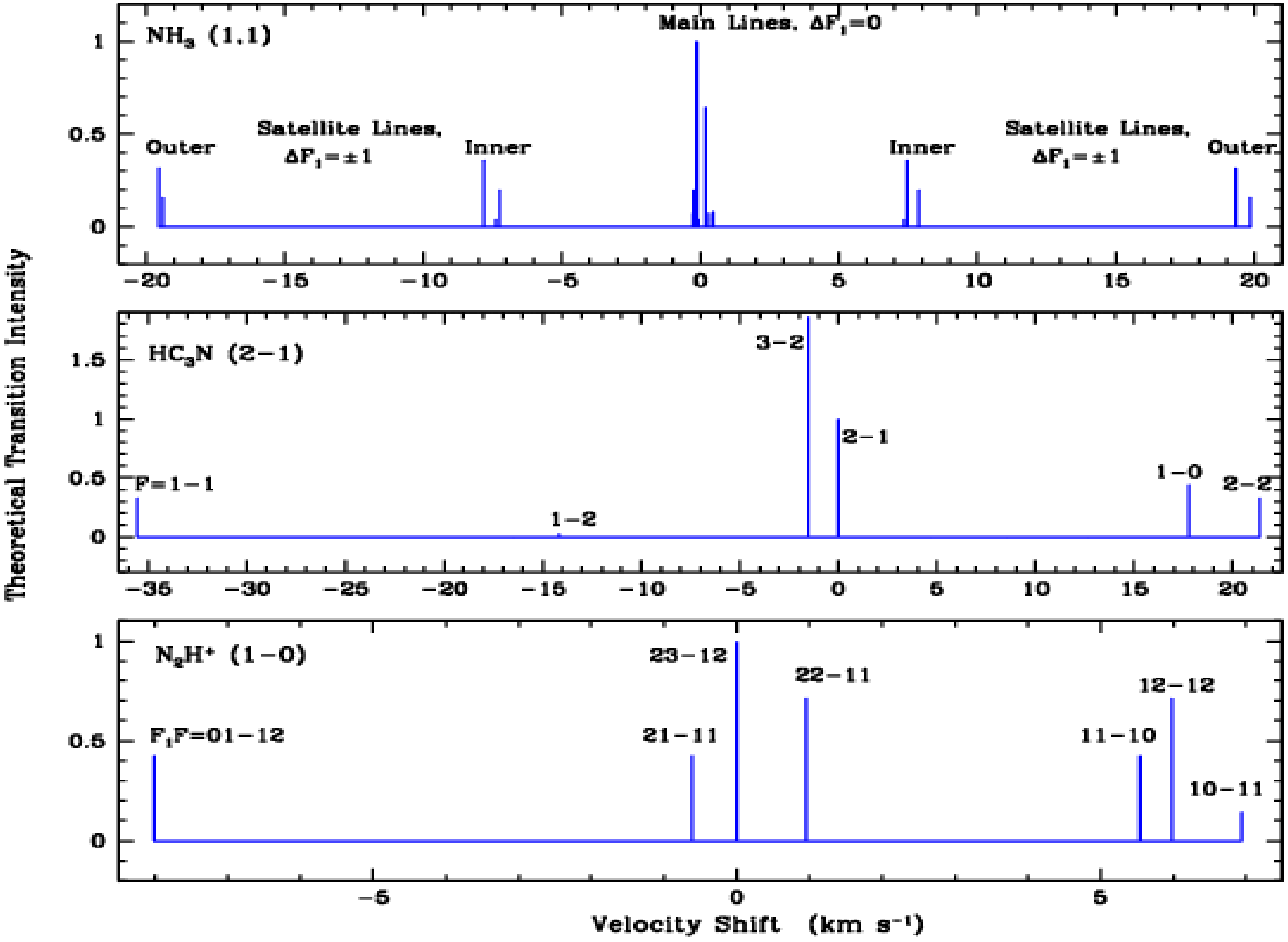
$$\Delta V = \Delta V_{noise} + \Delta V_{\mu}$$

$$\overline{\Delta V}_{noise} = 0$$

$$\overline{\Delta V} = \overline{\Delta V}_{\mu}$$

$$Var(\Delta V) = Var(\Delta V_{noise}) + Var(\Delta V_{\mu})$$

Hyper-fine splittings in NH_3 , HC_3N & N_2H^+

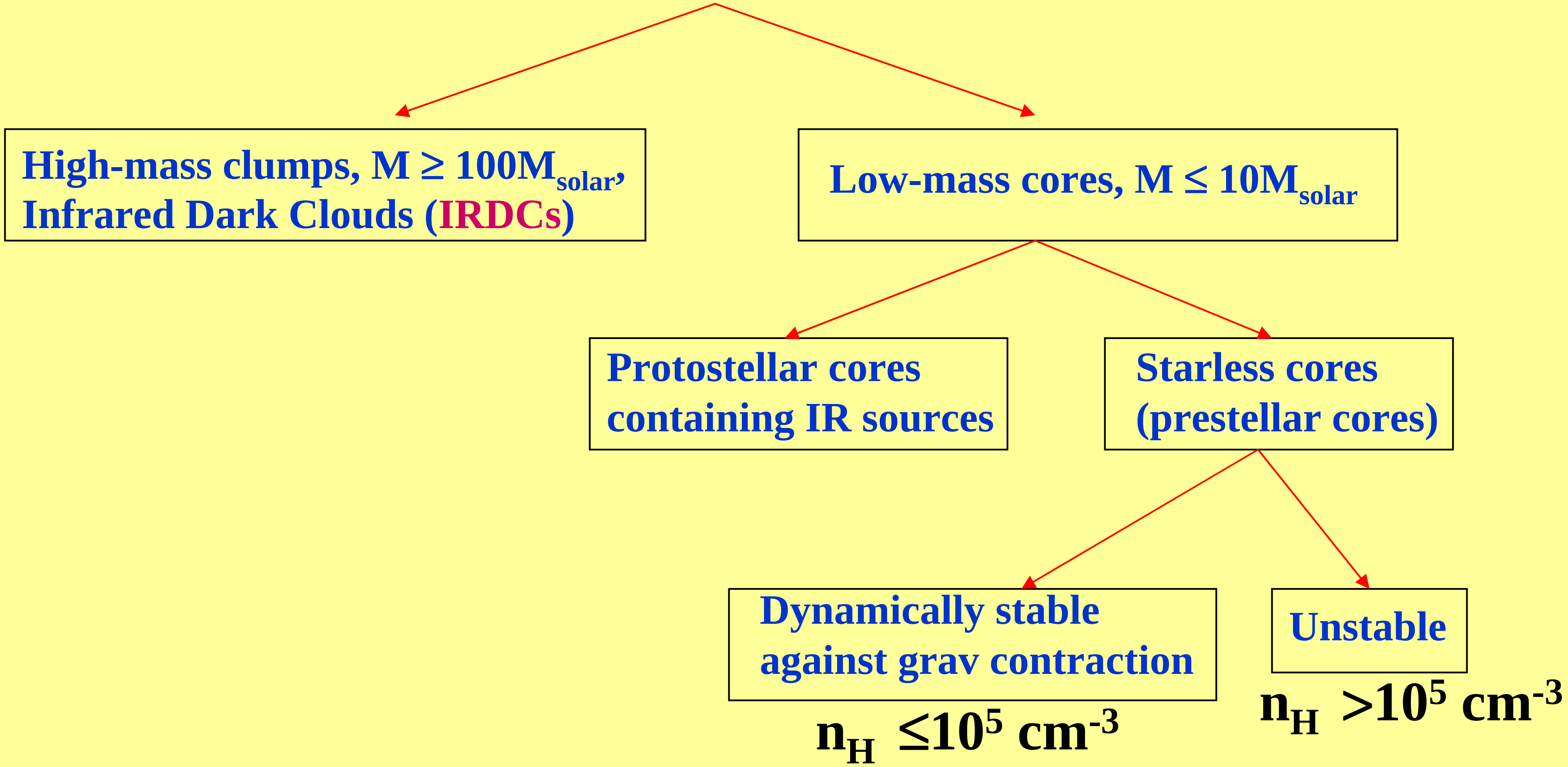


23 GHz

18 GHz

93 GHz

Dense molecular clouds, $n_H \geq 10^4$ cm^{-3}, $T_{kin} \sim 10$K



High-mass clumps, $M \geq 100M_{solar}$,
Infrared Dark Clouds (IRDCs)

Low-mass cores, $M \leq 10M_{solar}$

Protostellar cores containing IR sources

Starless cores (prestellar cores)

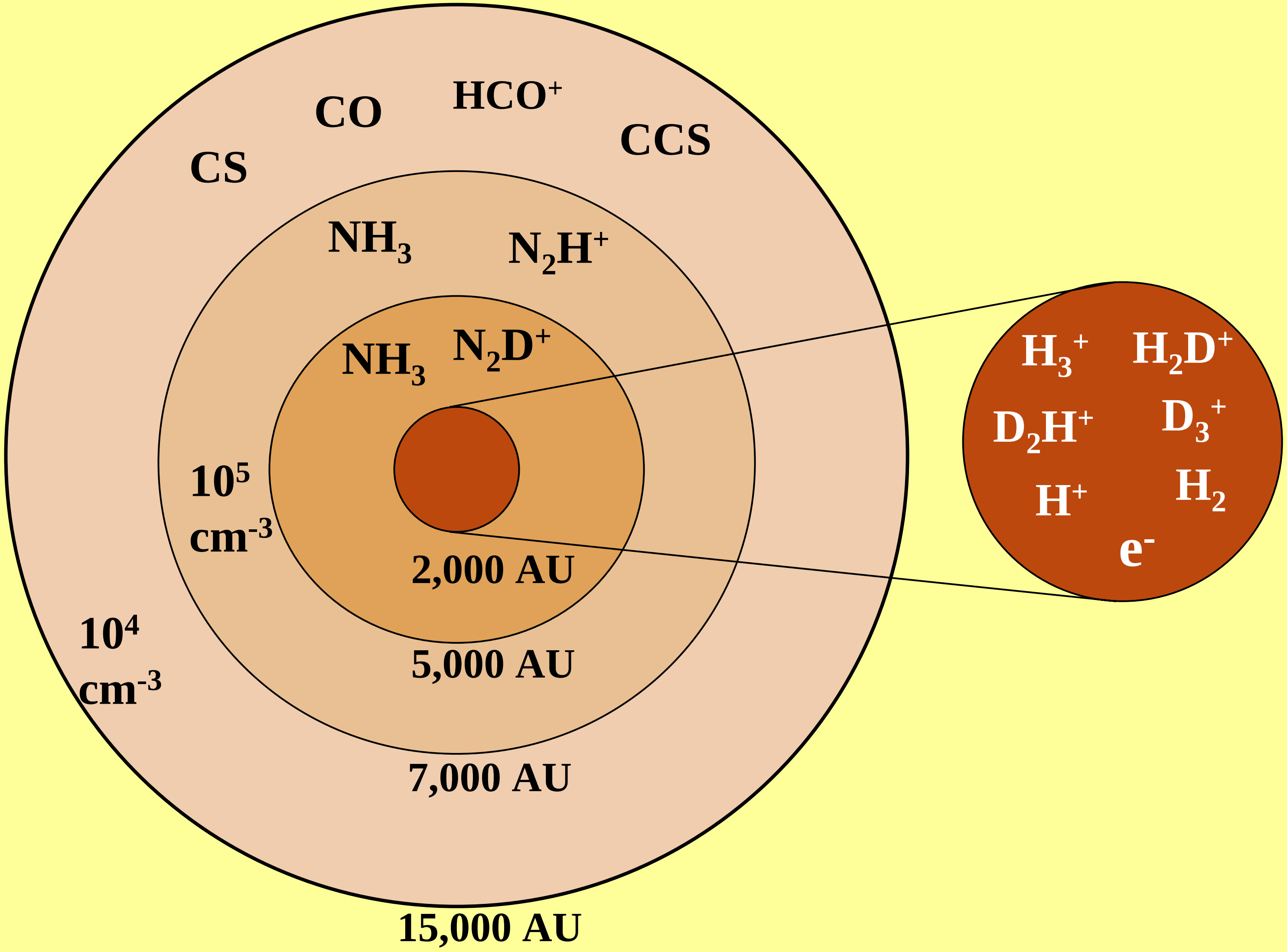
Dynamically stable against grav contraction

$n_H \leq 10^5$ cm^{-3}

Unstable

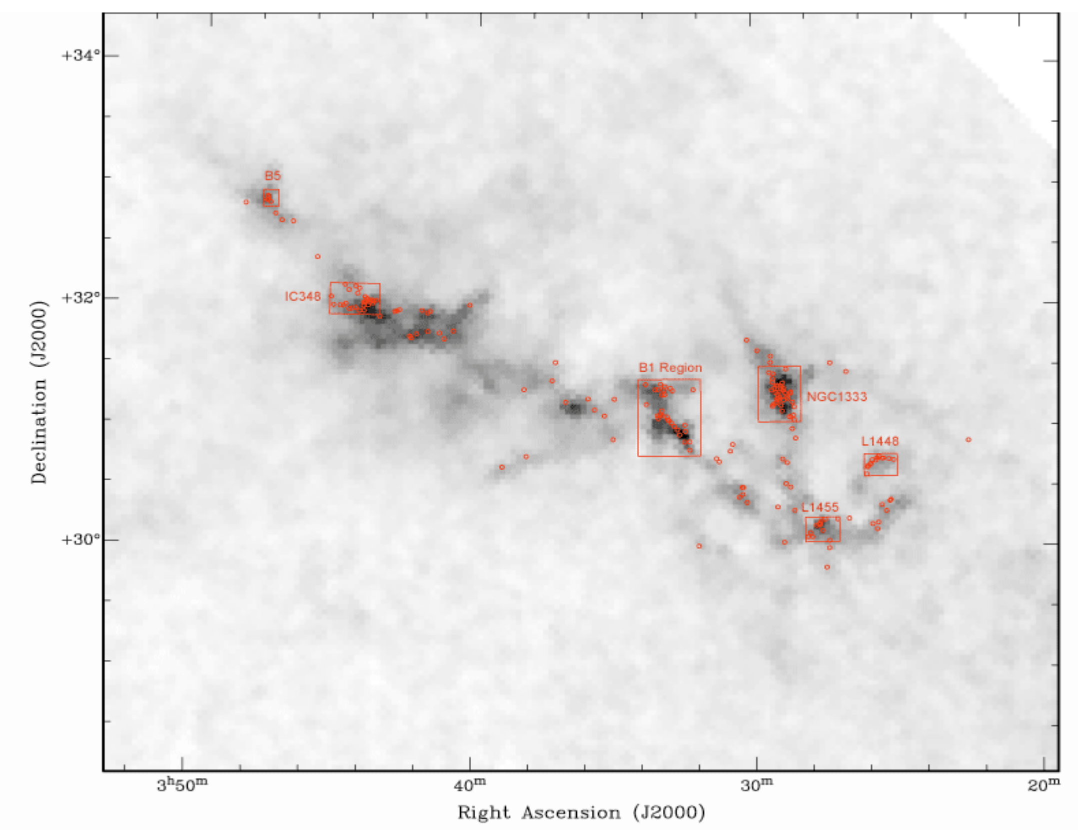
$n_H > 10^5$ cm^{-3}

Molecular differentiation within a low-mass core



Preliminary obtained results

(Levshakov, Molaro, Kozlov 2008, astro-ph/0808.0583)



Perseus molecular cloud

$D \approx 260\ pc$

$6 \times 2\,^{o}$ or $27 \times 9\ pc$

$M \sim 10^{4}\ M_{solar}$

$n_{\mathrm{H}} \sim 100\ \ cm^{-3}$

Perseus molecular cores

Rosolowsky et al. 2008 | **ammonia spectral atlas of 193 molecular cores in the Perseus cloud**

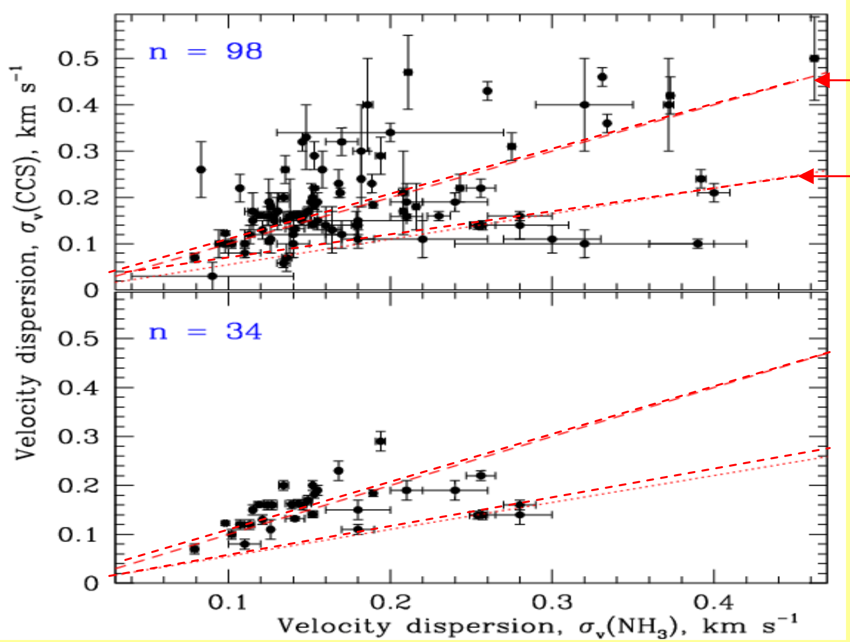
Observations: **100-m Green Bank Telescope (GBT)**

GBT beam size at 23 GHz is FWHM = 31arcsec (0.04 pc)

→ **Spectral resolution = 24 m/s (!)**

Single-pointing, simultaneous observations of NH_3 and CCS lines

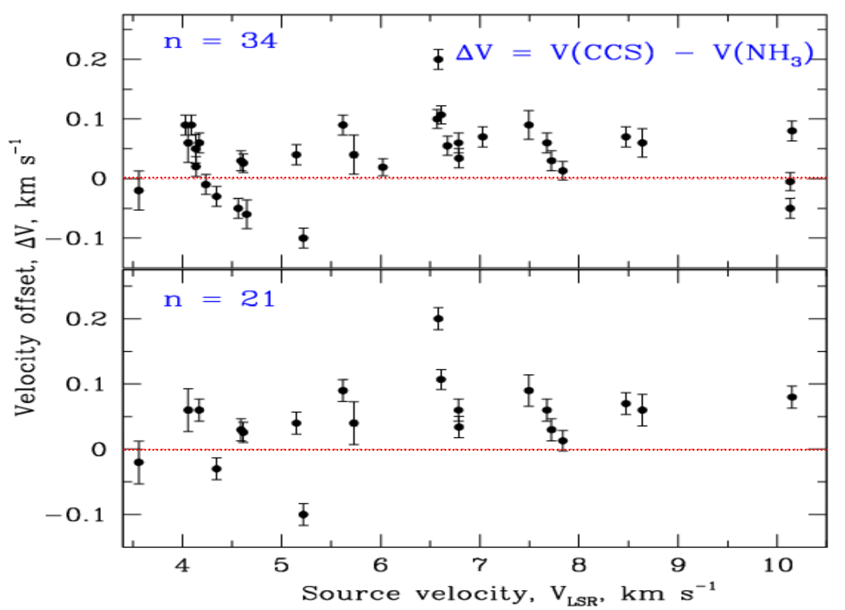
CCS vs NH_3



pure turbulent broadening, $\sigma(CCS) = \sigma(NH_3)$

pure thermal, $\sigma(CCS) = 0.55\sigma(NH_3)$

symmetric profiles



$$\Delta V_{n=98} = 44 \pm 13 \text{ m/s}$$

$$\Delta V_{n=34} = 39 \pm 10 \text{ m/s}$$

$$\Delta V_{n=21} = 52 \pm 7 \text{ m/s}$$ ⟶

$$\Delta\mu/\mu = (5.2 \pm 0.7)\times10^{-8}$$

Pipe Nebula

Rathborne et al. 2008 | **46 molecular cores in Pipe Nebula**

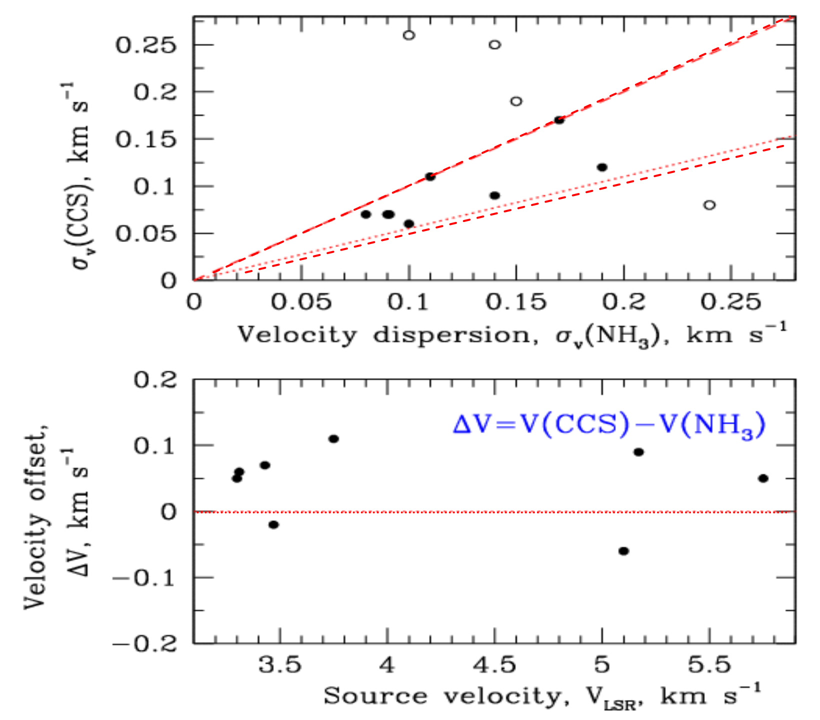
Observations: **100-m Green Bank Telescope (GBT)**

GBT beam size at 23 GHz is FWHM = 30arcsec (0.02 pc)

Spectral resolution = 23 m/s (!)

Single-pointing, simultaneous observations of
NH_3 and CCS lines

CCS vs NH_3



$$\Delta V_{n=8} = 69 \pm 11 \text{ m/s}$$

New results

(Astron.Astrophys., astro-ph/0911.3732)

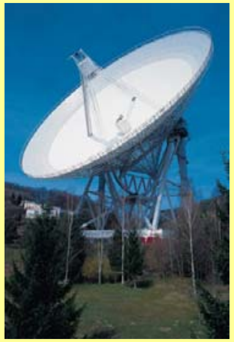
Nov 24-28, 2008

32m MEDICINA (Bologna) Italy

NH_3 & HC_3N

Feb 20-22, 2009

100m EFFELSBERG (Bonn) Germany



NH_3 & HC_3N

Apr 8-10, 2009

45m NOBEYAMA (NRAO) Japan

NH_3 & N_2H^+

Collaboration with

Alexander Lapinov

Christian Henkel

Takeshi Sakai

Paolo Molaro

Dieter Reimers

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41 cold and compact molecular cores in the Taurus giant molecular complex

55 molecular pairs in total

Observations:

32-m Medicina Telescope: two digital spectrometers ARCOS (ARcetri COrrelation Spectrometer) and MSpec0 (high resolution digital spectrometer)

Spectral res. = 62 m/s (NH_3), 80 m/s (HC_3N) ARCOS
Spectral res. = 25 m/s (NH_3), 32 m/s (HC_3N) MSpec0
beam size at 23 GHz, FWHM = 1.6 arcmin
position switching mode

100-m Effelsberg Telescope: K-band HEMT (High Electron Mobility Transistor) receiver, backend FFTS (Fast Fourier Transform Spectrometer)

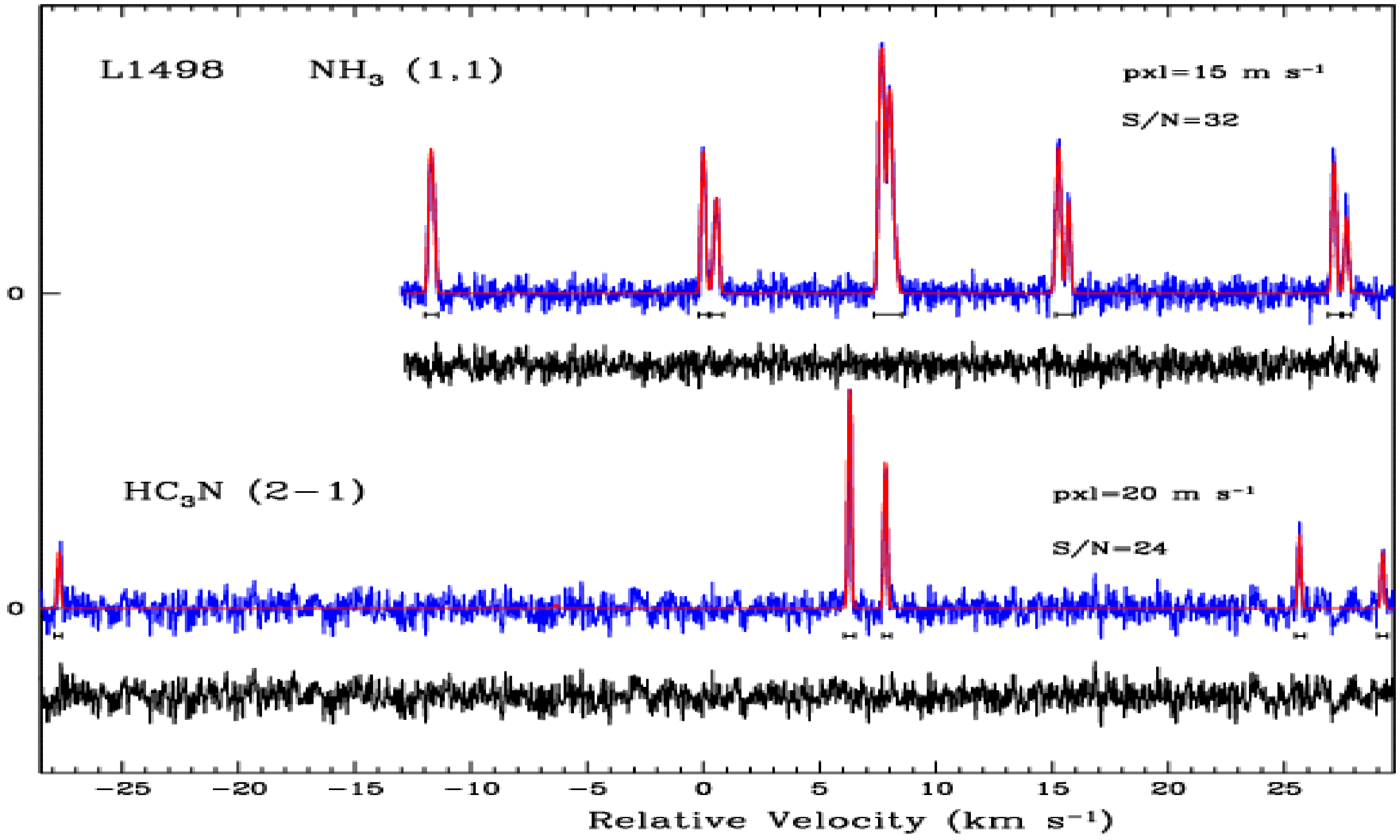
Spectral res. = 30 m/s (NH_3), 40 m/s (HC_3N)
beam size at 23 GHz, FWHM = 40 arcsec
frequency switching mode

45-m Nobeyama Telescope: HEMT receiver (NH_3), and SIS (Superconductor-Insulator-Superconductor) receiver (N_2H^+)

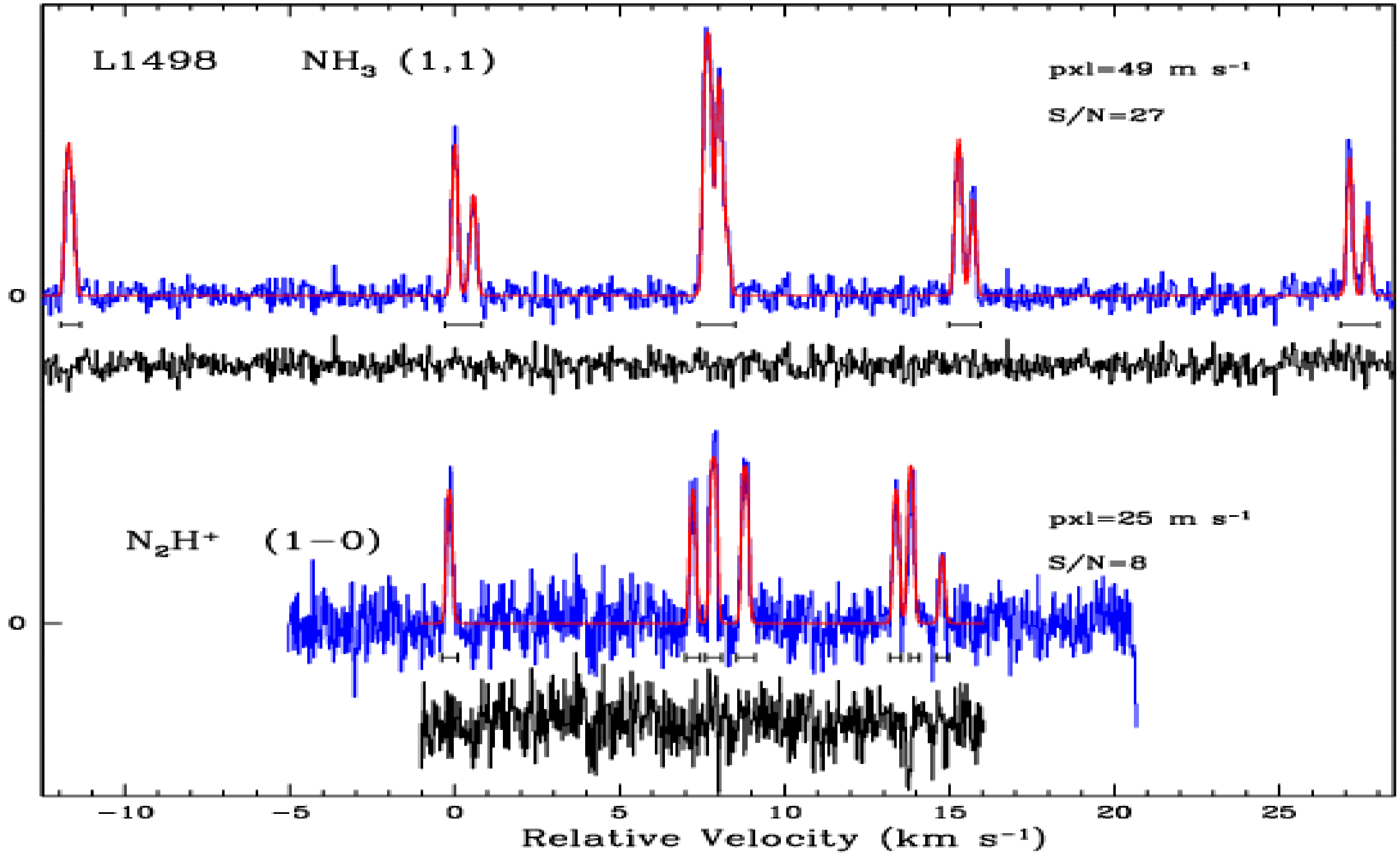
Spectral res. = 49 m/s (NH_3), 25 m/s (N_2H^+)
beam size at 23 GHz, FWHM = 73 arcsec
position switching mode

Independent Doppler tracking of the observed molecular lines

Effelsberg 100-m

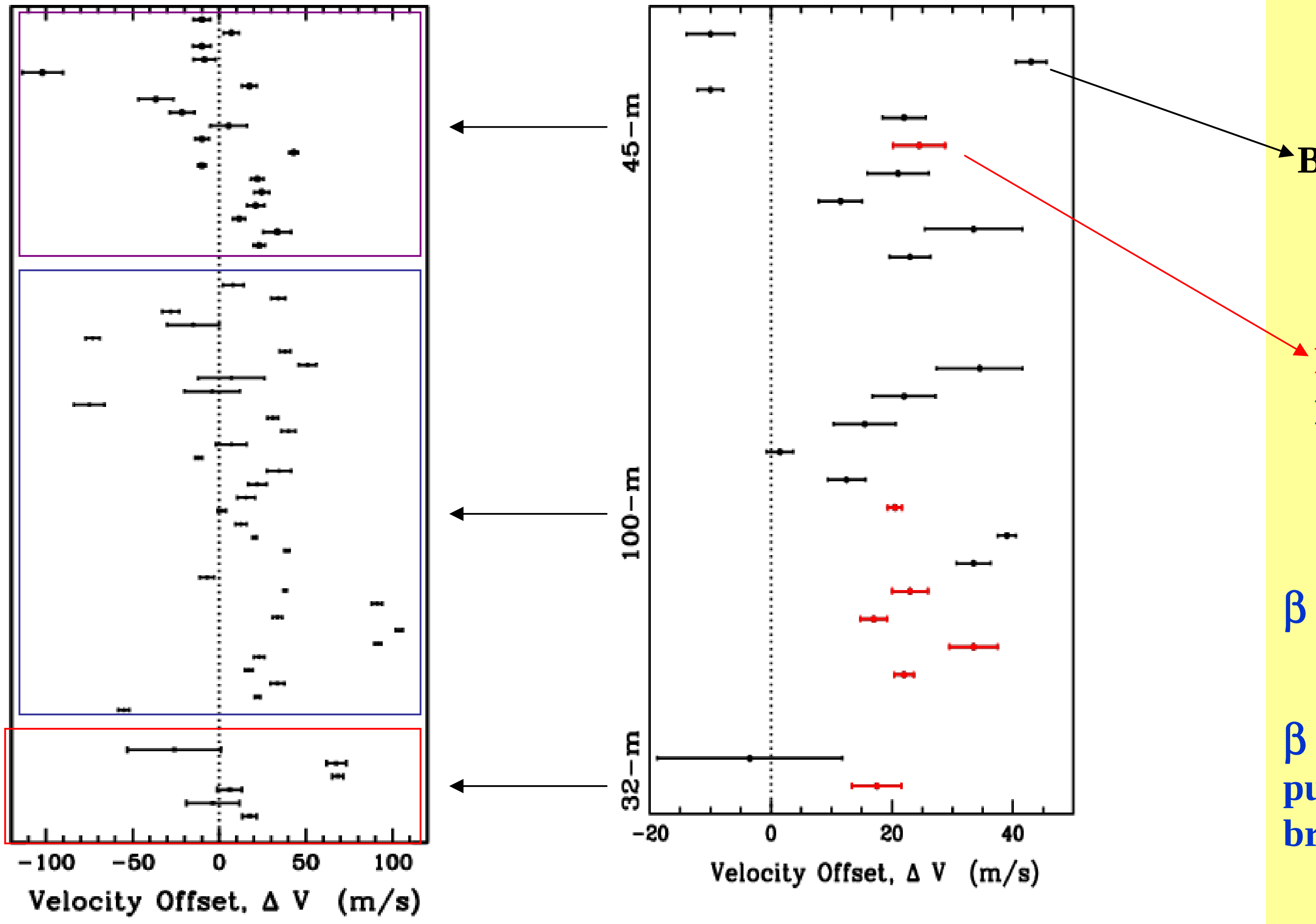


Nobeyama 45-m



total n=55

co-spatially distributed



Black:
$1 \leq \beta < 1.2$

Red:
$1.2 \leq \beta < 1.7$

$$\beta = \frac{b(NH_3)}{b(HC_3N)}$$

$\beta = 1.7$ for pure thermal broadening

Results

total sample, n=55	**mean ΔV = 14.1 ± 4.0 m/s** **scale = 29.6 m/s (standard deviation)** **median ΔV = 17 m/s**
co-spatially distributed, **n=23 (red & black points)**	**mean ΔV = 21.5 ± 2.8 m/s** **scale = 13.4 m/s** **median ΔV = 22 m/s**
thermally dominated, **n=7 (red points)**	**mean ΔV = 21.2 ± 1.8 m/s** **scale = 3.4 m/s** **median ΔV = 22 m/s**
effelsberg, n=12 **NH_3 & HC_3N**	**mean ΔV = 23.2 ± 3.8 m/s** **scale = 13.3 m/s** **median ΔV = 22 m/s**
nobeyama, n=9 **NH_3 & N_2H^+**	**mean ΔV = 22.9 ± 4.2 m/s** **scale = 12.7 m/s** **median ΔV = 22 m/s**

Poor accuracy in lab frequencies - main source of uncertainties

$NH_3 \longrightarrow \varepsilon_{sys} = 0.6$ m/s

$HC_3N \longrightarrow \varepsilon_{sys} = 2.8$ m/s

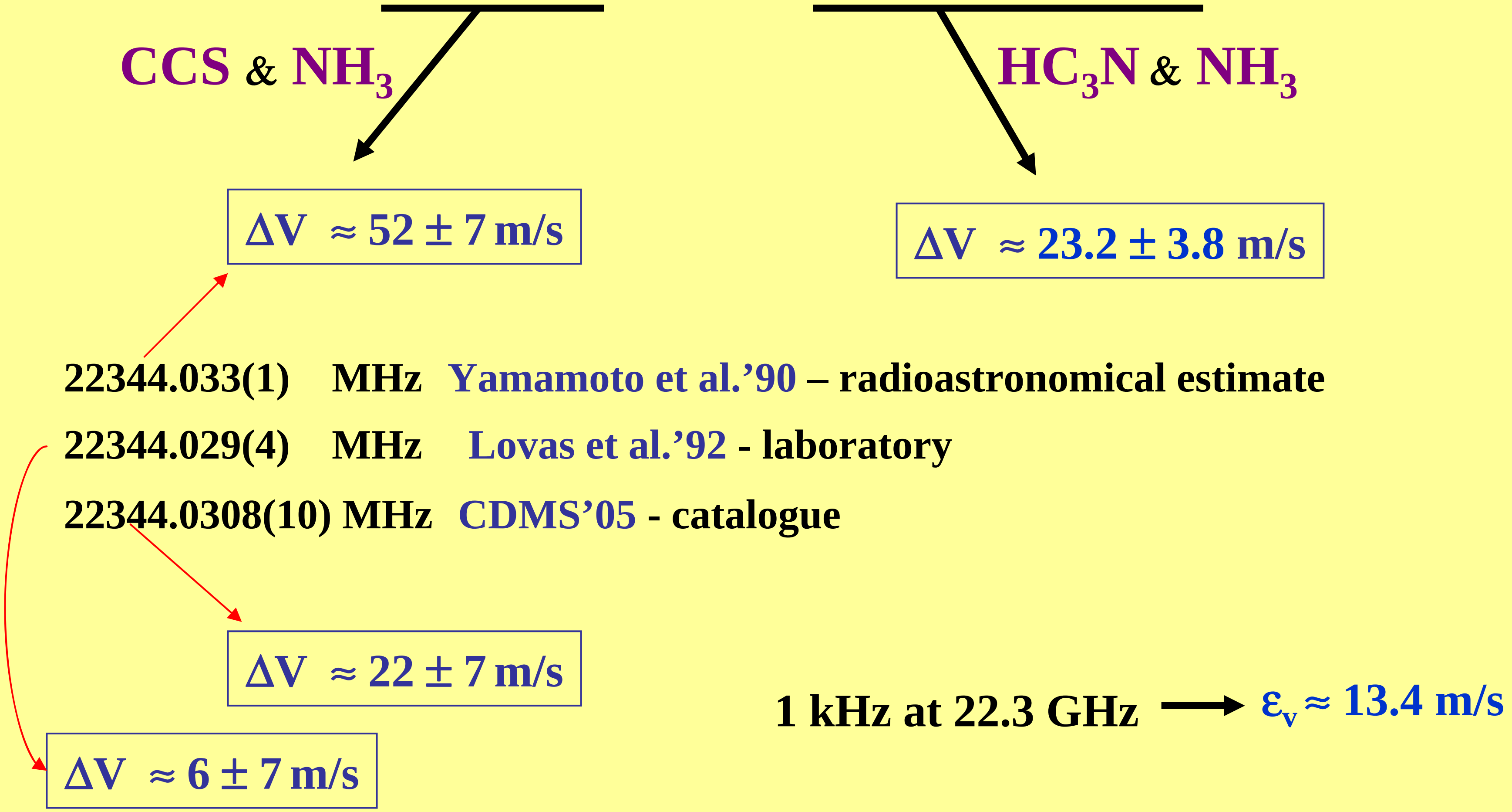
$N_2H^+ \longrightarrow \varepsilon_{sys} = 14$ m/s

Effelsberg:

$$\Delta V = 23.2 \pm 3.8_{stat} \pm 2.8_{sys} \ \ \mathrm{m/s}$$

$$\Delta\mu/\mu = (2.2 \pm 0.4_{stat} \pm 0.3_{sys}) \times 10^{-8}$$

GBT vs Effelsberg



CCS & NH_3

HC_3N & NH_3

$\Delta V \approx 52 \pm 7$ m/s

$\Delta V \approx 23.2 \pm 3.8$ m/s

22344.033(1) MHz Yamamoto et al.’90 **– radioastronomical estimate**

22344.029(4) MHz Lovas et al.’92 **- laboratory**

22344.0308(10) MHz CDMS’05 **- catalogue**

$\Delta V \approx 22 \pm 7$ m/s

$\Delta V \approx 6 \pm 7$ m/s

1 kHz at 22.3 GHz → $\varepsilon_v \approx 13.4$ m/s

new precise lab freqencies badly needed !

$\varepsilon_{lab} \approx 1$ m/s

Constraint on α-variation

fine-structure transition of carbon **[CI] 609 μm**

low-lying rotational lines of **^{13}CO J=1-0 (2.7 mm), J=2-1 (1.4 mm)**

$\boxed{F = \alpha^2/\mu}$ $\boxed{\Delta F/F = 2\Delta\alpha/\alpha - \Delta\mu/\mu = \Delta v/c}$ $\Delta v = v_{rot} - v_{fs}$

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observations of cold molecular clouds	TMC-1	Schilke et al.'95	FWHM = 200-400 m/s
	L 183	Stark et al.'96	
	Ori A,B	Ikeda et al.'02	FWHM = 100 m/s

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sample size n=13

mean $\Delta V = 0 \pm 60$ m/s

scale = 215 m/s (standard deviation)

median $\Delta V = 0$ m/s

$\boxed{|\Delta F/F| < 0.3 \text{ ppm}}$ $\boxed{|\Delta\alpha/\alpha| < 0.15 \text{ ppm}}$

Conclusions (Part II)

- velocity offset $\Delta V = 23 \pm 4_{stat} \pm 3_{sys}$ m/s → reproduced at different facilities

- no known systematic at the level of 20 m/s

  ↓

  $\Delta\mu/\mu = (2.2 \pm 0.4_{stat} \pm 0.3_{sys})\times 10^{-8}$ ← verification – other molecules new targets

- conservative upper limits at z=0 :
  $|\Delta\mu/\mu| \leq 3\times 10^{-8}$ & $|\Delta\alpha/\alpha| < 1.5\times 10^{-7}$

- at high-z, $\rho_{ISM}(z=0) \approx \rho_{ISM}(z>0)$ → expected $\Delta\mu/\mu \sim 10^{-8}$ if no temporal dependence of $\mu(t)$ is present