Searching for chameleon-like scalar fields

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Local Test

Whether the scalar field models – candidates to dark energy carrier – have chameleon-type interaction with ordinary matter ?

$$\alpha \quad \& \quad \mu = m_e / m_p$$

chameleon-like scalar field models

Khoury, Weltman 2004

Brax et al. 2004 ; Feldman et al. 2006; Avelino 2008 ; Upadhye et al. 2010

dependence of masses and coupling constants on environmental matter density

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

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

Olive & Pospelov 2008

Optical vs Radio

Spectral resolution, FWHM

$\sim$ 5 km/s → **$\delta \sim 5 \times 10^{-6}$**

$\sim$ 30 m/s → **$\delta \sim 10^{-9}$**

Ammonia Method to probe μ

$E_{vib} \sim \mu^{0.5}$

$E_{rot} \sim \mu$

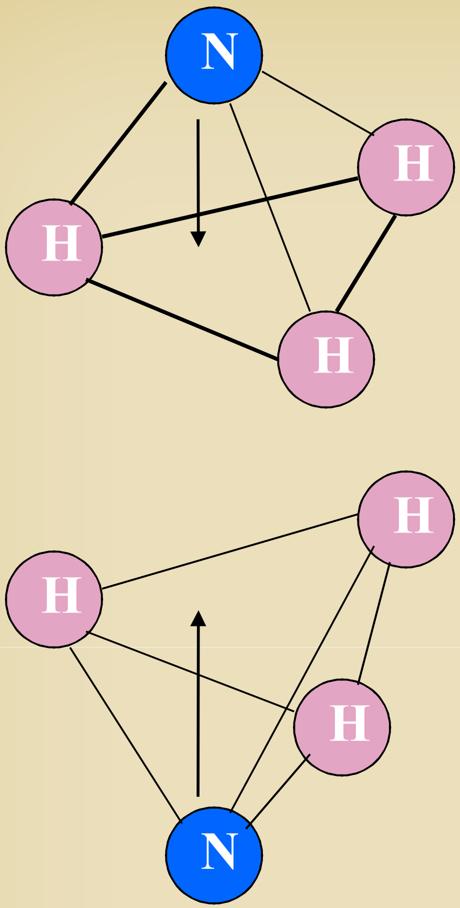
$E_{inv} \sim \mu^{4.5}$

$$\Delta\omega/\omega = \begin{cases} 0.5\,\Delta\mu/\mu \\ 1.0\,\Delta\mu/\mu \\ 4.5\,\Delta\mu/\mu \end{cases}$$

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

ND_3 van Veldhoven et al. 2004

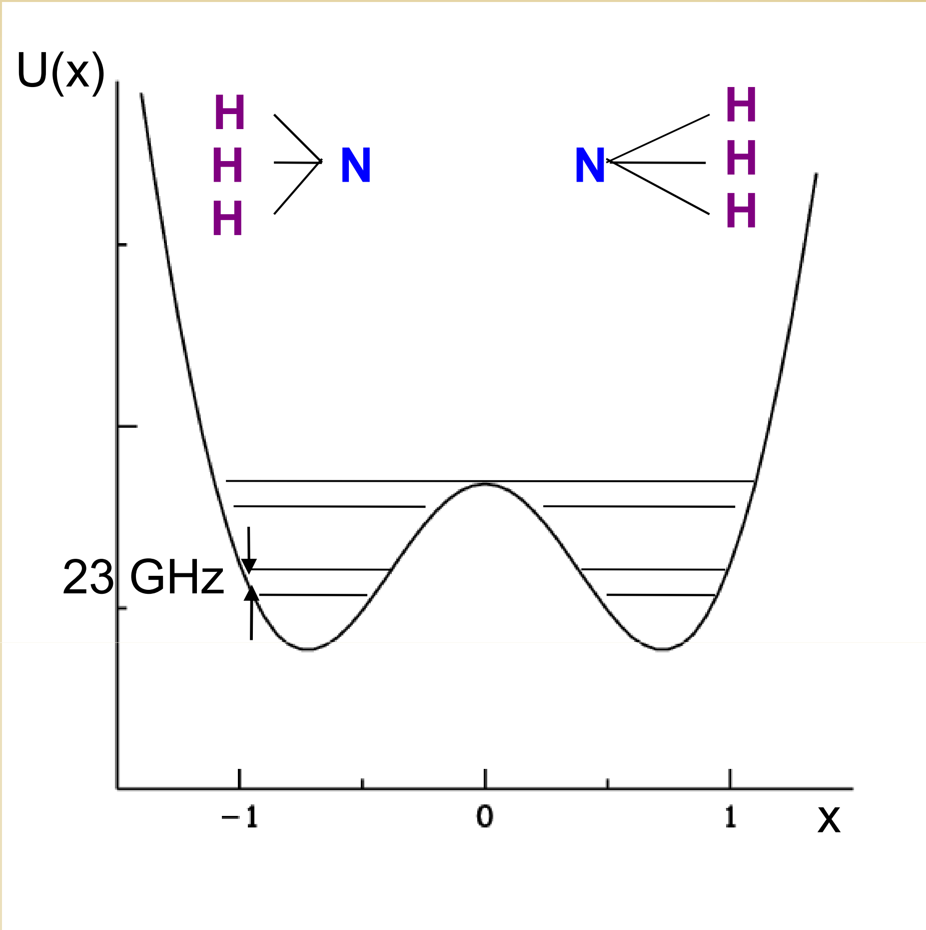
NH_3 Flambaum & Kozlov 2007



Quantum mechanical tunneling

$$\omega \sim \exp(-S)$$

$$S \sim \mu^{1/2}$$



Double-well potential of the inversion vibrational mode of NH_3

By comparing the observed inversion frequency of ammonia with rotational frequency of another molecule arising co-spatially with ammonia, a limit on spatial variation in mass-ratio can be obtained

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

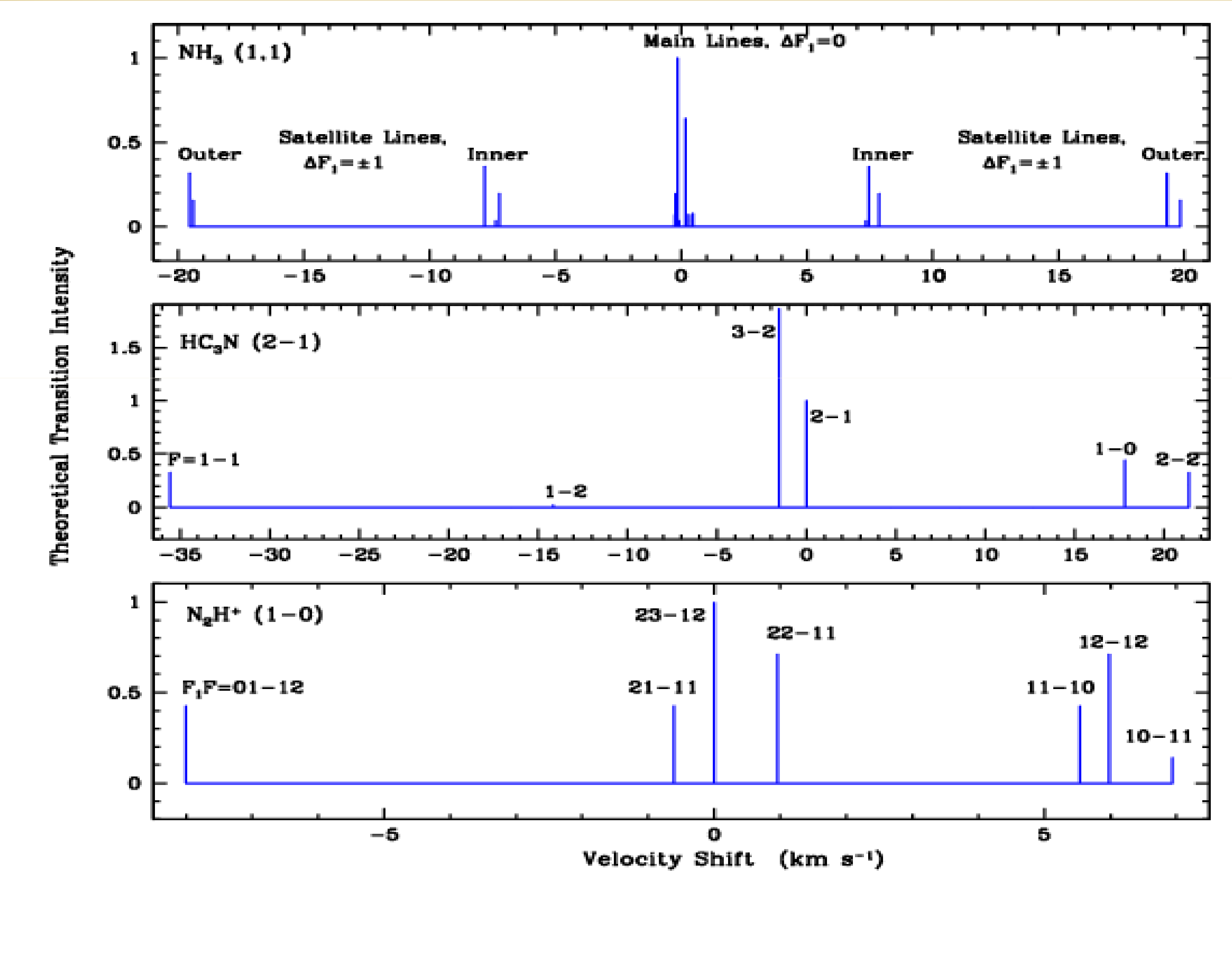
$$\Delta V = \Delta V_{\mu} + \Delta V_{n}$$

Doppler noise

$$\overline{\Delta V_{n}} = 0$$

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

Hyperfine splittings in NH_3, HC_3N, & N_2H^+



23 GHz

$\varepsilon_v = 0.6$ m/s

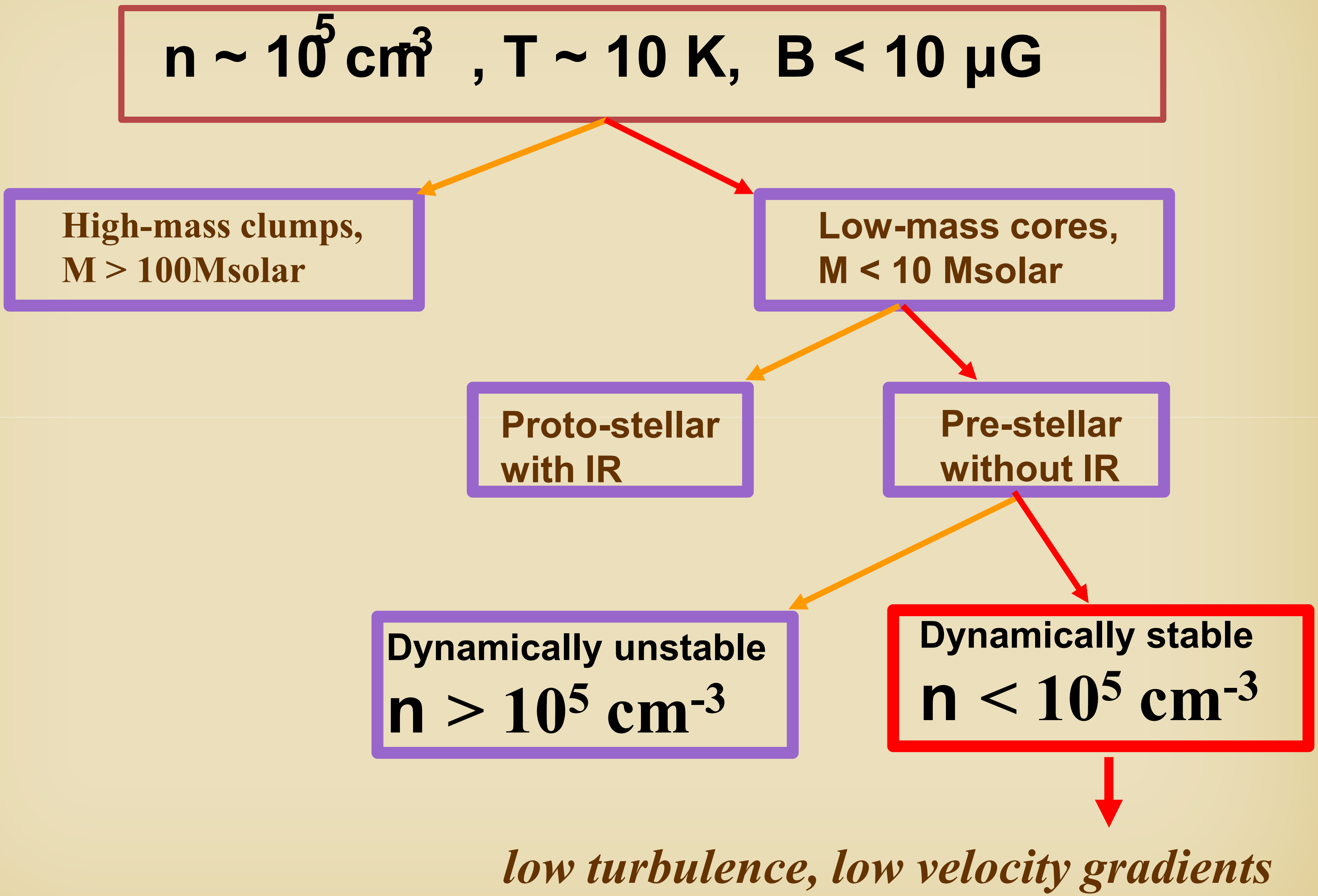
18 GHz

$\varepsilon_v = 2.8$ m/s

93 GHz

$\varepsilon_v = 14$ m/s

Dense molecular clouds



First Results (A&A, 512, 44-62, 2010)

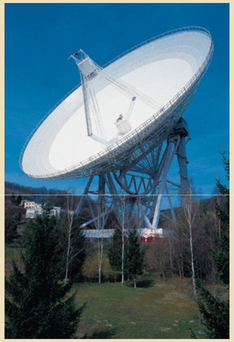
Nov 24-28, 2008

32m MEDICINA (Bologna) Italy

NH_3 & HC_3N

Feb 20-22, 2009

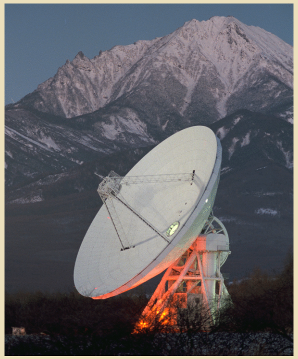
100m EFFELSBERG (Bonn) Germany



NH_3 & HC_3N

Apr 8-10, 2009

45m NOBEYAMA (NRAO) Japan



NH_3 & N_2H^+

Collaboration

Paolo Molaro
Christian Henkel
Alexander Lapinov
Takeshi Sakai
Michael Kozlov
Irina Agafonova
Dieter Reimers

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

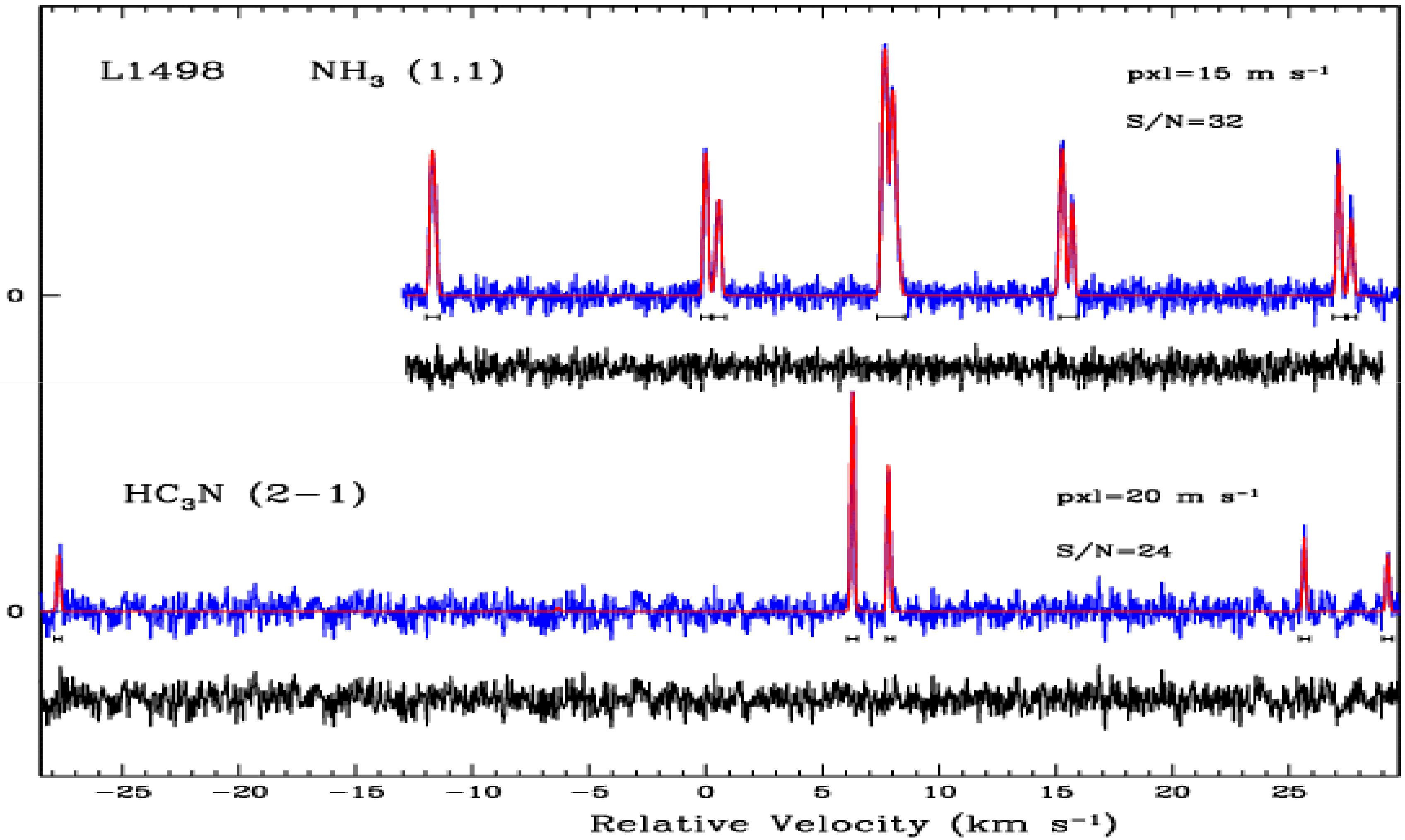
45-m Nobeyama Telescope:

HEMT receiver (NH_3), and SIS (Superconductor-Insulator-Superconductor) receiver (N_2H^+)

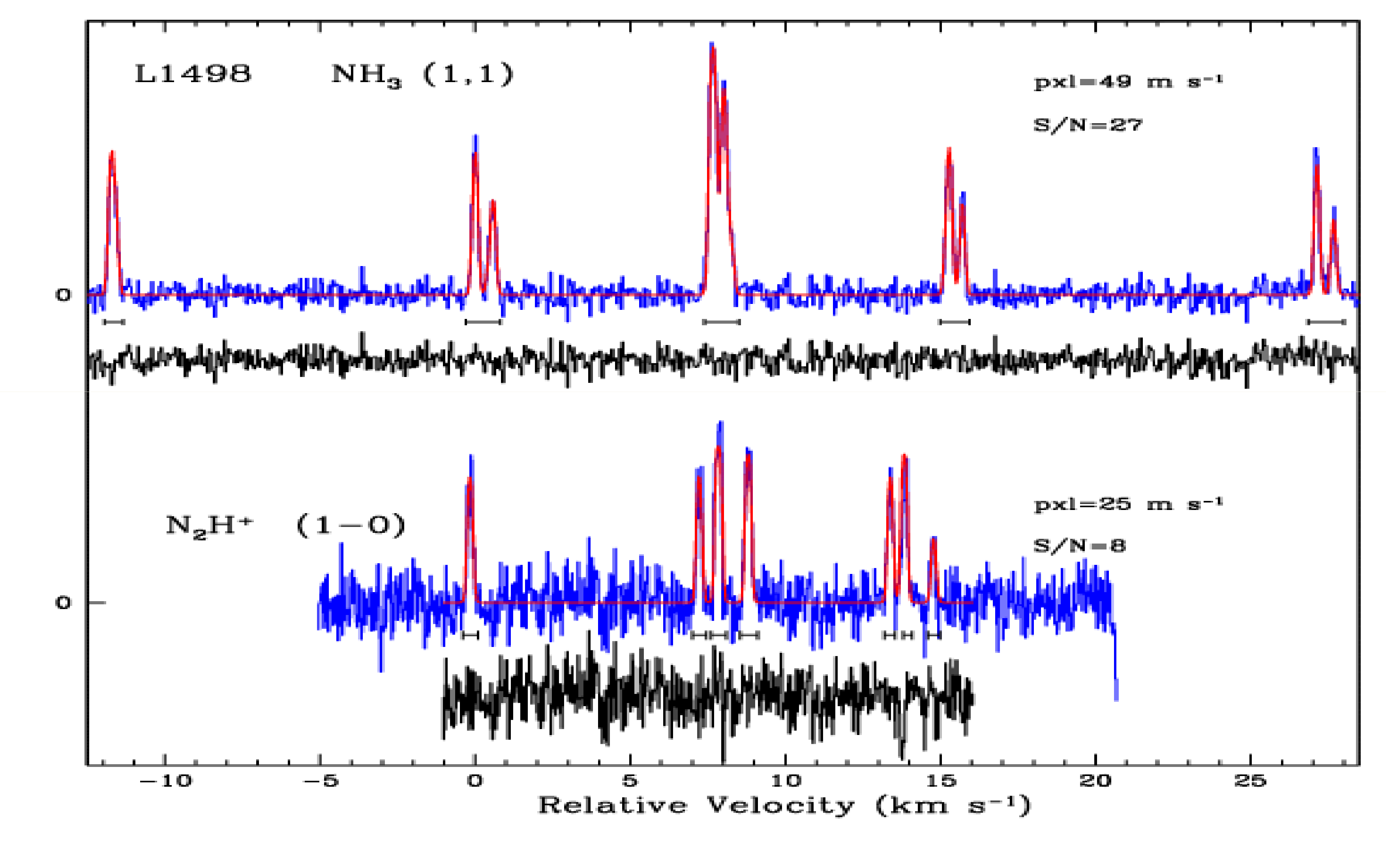
Spectral res. = 49 m/s (NH_3), 25 m/s (N_2H^+)
beam size at 23 GHz, FWHM = 73 arcsec
position switching mode

Independent Doppler tracking of the observed molecular lines

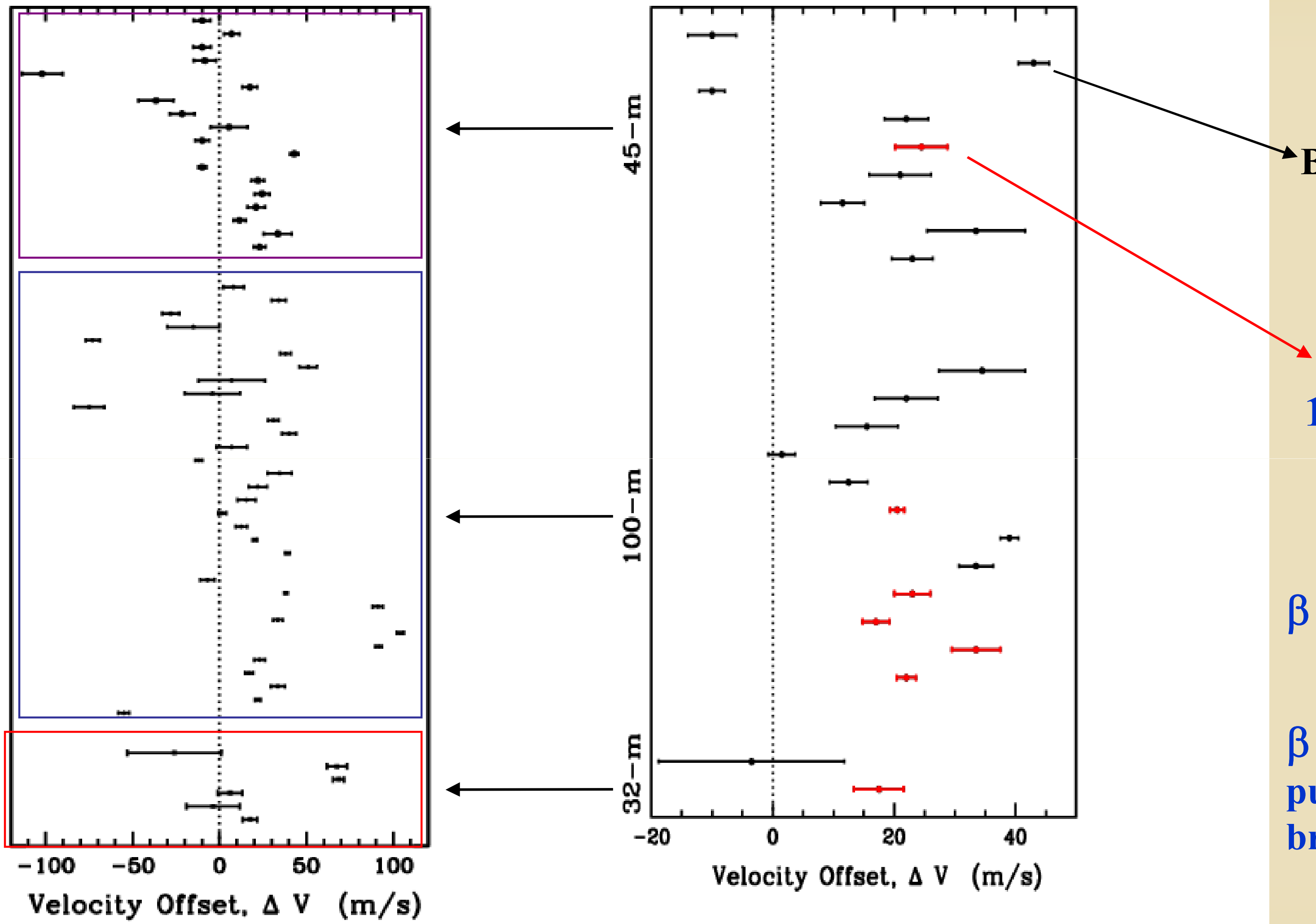
Effelsberg 100-m



Nobeyama 45-m



total n=55 **co-spatially distributed**



Black: $1 \leq \beta < 1.2$

Red: $1.2 \leq \beta < 1.7$

$$\beta = \frac{b(NH3)}{b(HC3N)}$$

$\beta = 1.7$ for pure thermal broadening

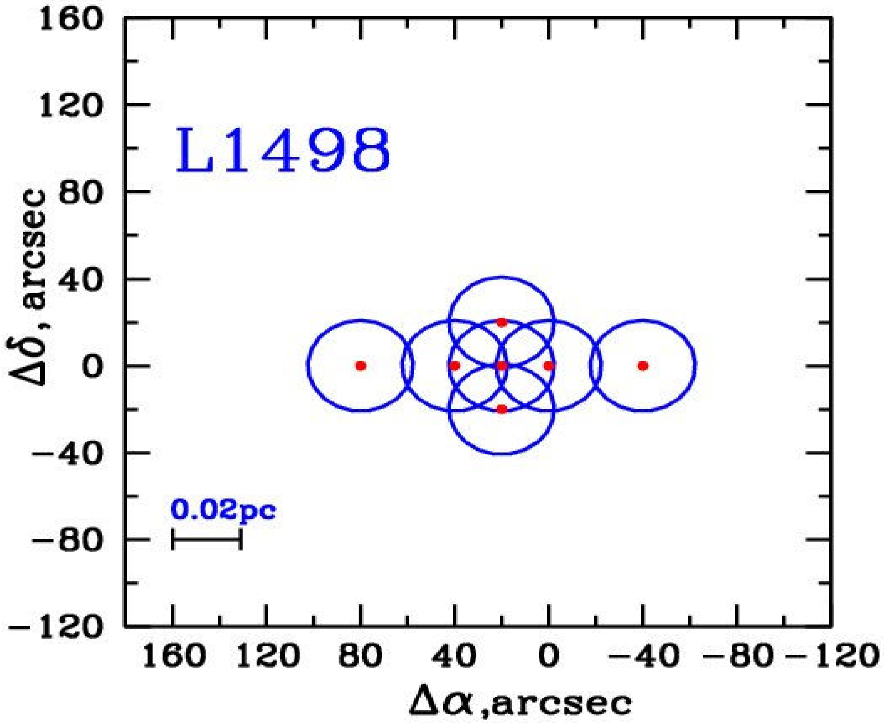
Effelsberg:

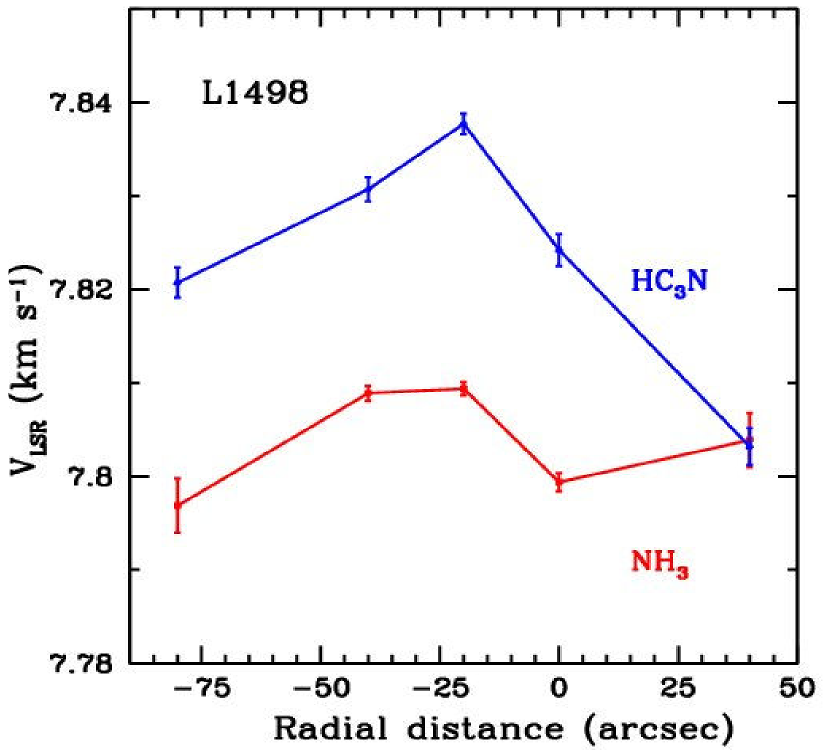
$$\Delta V = 26 \pm 4 \pm 3 \text{ m/s}$$

$$\Delta\mu/\mu = 26 \pm 4 \pm 3 \text{ ppb} \;!$$

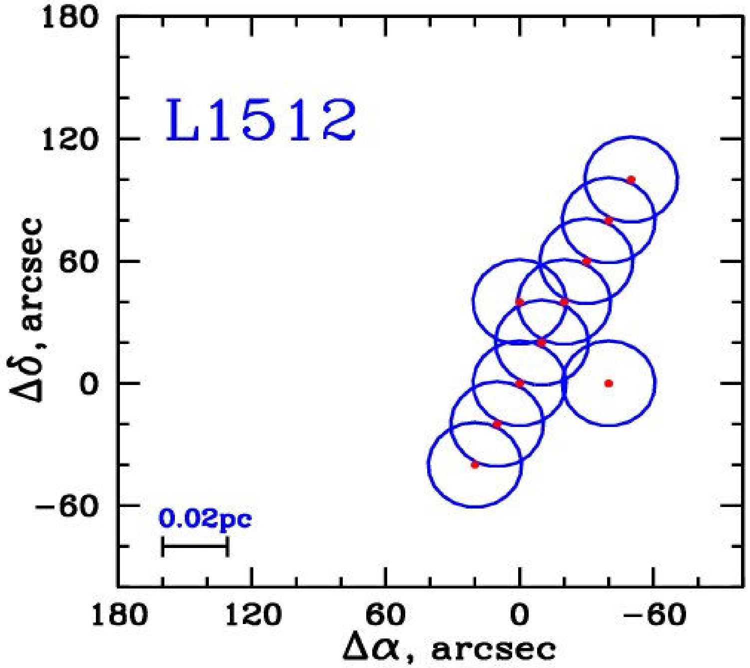
$1 \text{ ppb} = 10^{-9}$

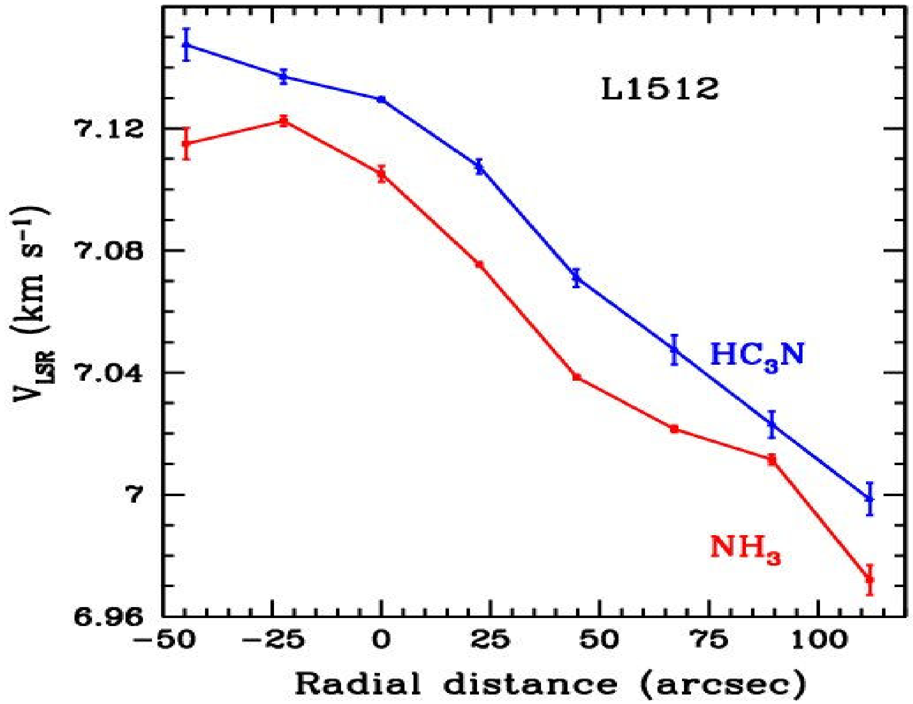
New observations, Jan 2010





A&A, in press, astro-ph/1008.1160

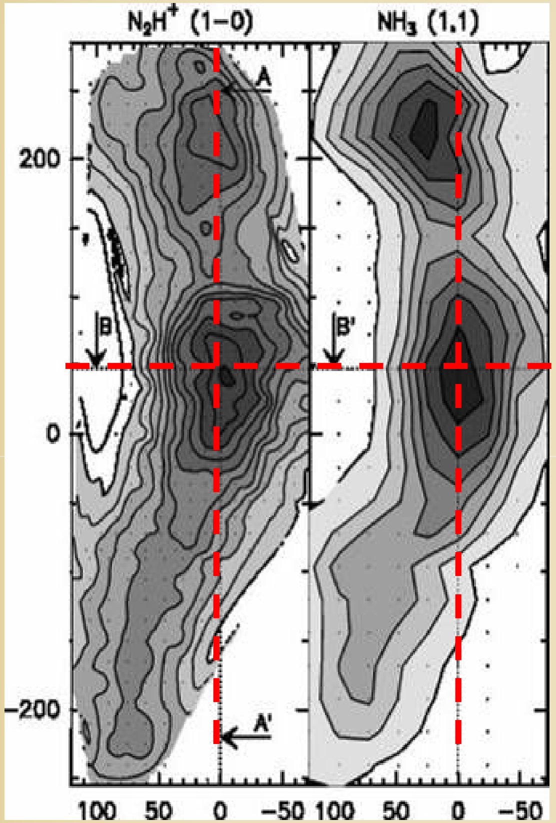


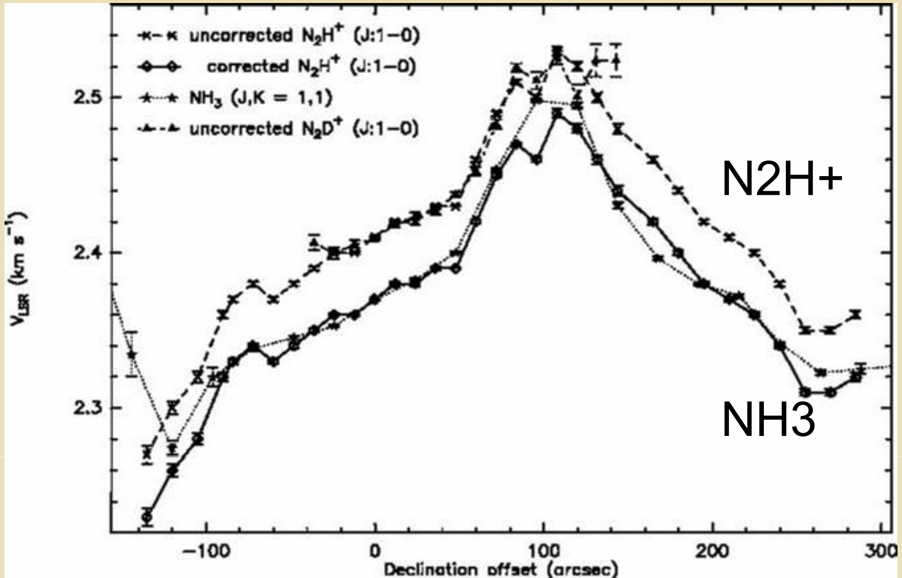


Pagani et al., 2009, A&A 494, 719

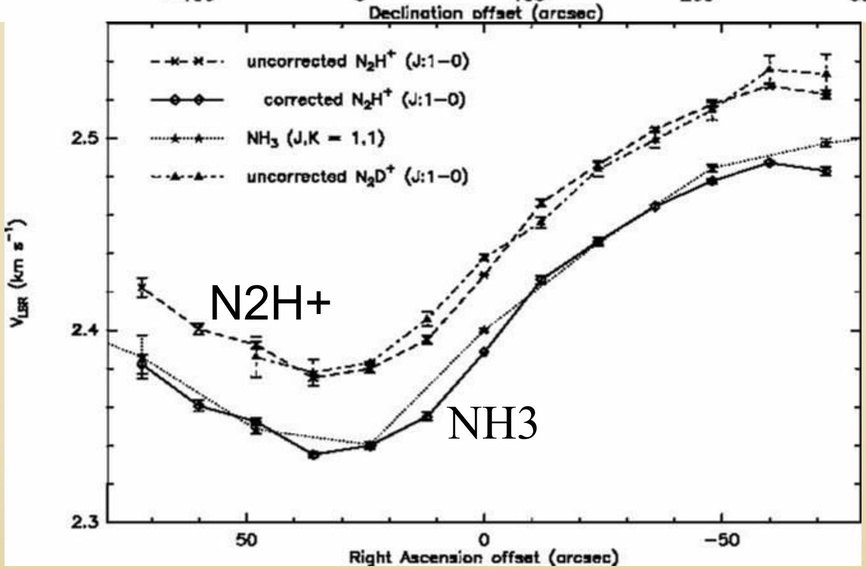
N2H+ : IRAM 30-m

NH3 : GBT 100-m





A-A' cut



B-B' cut

L183

low Doppler noise

Current results (Effelsberg):

$\Delta V = 27 \pm 1 \pm 3$ m/s (L1498+L1512)

$\Delta\mu/\mu = 26 \pm 1 \pm 3$ ppb

Jan, 2010

Previous results:

$\Delta V = 26 \pm 4 \pm 3$ m/s

$\Delta\mu/\mu = 26 \pm 4 \pm 3$ ppb

Feb, 2009

Systematics:

turbulence

at $T_{kin} = 10$ K :

$\sigma_{th}(NH_3) = 70$ m/s

$\sigma_{th}(HC_3N) = 40$ m/s

L1512:

$\sigma_v(NH_3) = 78 \pm 1$ m/s

$\sigma_v\,(HC_3N) = 59 \pm 2$ m/s

→ $\sigma_{turb} \sim 30$ m/s

sub-sonic

sound speed $V_s = (kT_{kin}/m_0)^{1/2} = 190$ m/s

Thermal-dominated broadening

Stark effect induced by static electric fields

Townes & Schawlow 1955, Microwave Spectroscopy

$$\delta V_{St}/c = (2K^2)/(3J(J+1))(DF/h\nu_{inv})^2$$

K – angular momentum projection

D – electric dipole momentum, = 1.42Debye

F – electric field strength

K = J transitions – max offset

$$\delta V_{St} = 1\ m/s \quad \Longleftrightarrow \quad F = 2\ V/cm$$

↓

accelerates electrons to ultra-relativistic energies ~ 10^{10} eV

Stark effect induced by black body radiation

Farley & Wing 1981, PhysRevA, 23, 2397

$$\delta V_{St} /c = (32\pi^4/9c^3h^3)(K^2D^2/J(J+1))(kT)^2$$

even at T ~ 300 K, $\delta V_{St} /c \sim 10^{-13}$

Zeeman effect induced by static magnetic fields

molecular cores, $B \sim 10^{-5}$ G

Earth's surface, $B \sim 0.5$ G

Lab magnetic shields reduce B to a mG level

$g_p = 5.6 >> g_N = 0.4$ → magnetic interaction dominated by 3 protons

$$\delta\omega_{inv} = \mu_n g_p I_z B$$

μ_n – nuclear magneton
I_z – proton spin

max offset when all 3 protons aligned, $I_z = 3/2$

with $\mu_n = 5.05 \times 10^{-24}$ erg/G, and $B = 10^{-3}$ G, we have

$\delta\omega_{inv} \sim 6$ Hz vs detected 2 kHz

Conclusions

1) Velocity offset $\Delta V \sim 30$ m/s
reproduced at different facilities

2) No known systematic at 30 m/s level

3) Verification of $\Delta\mu/\mu \sim 30$ ppb
new targets needed

NH_2D, ND_2H (Kozlov et al. 2010, J.Phys.B, 43, 074003)

H_3O^+ (Kozlov & Levshakov 2010, in prep.)