Probing time-variation of fundamental constants in cold and not so cold molecules.

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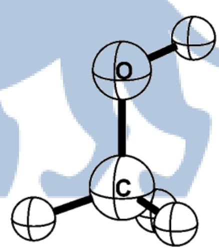

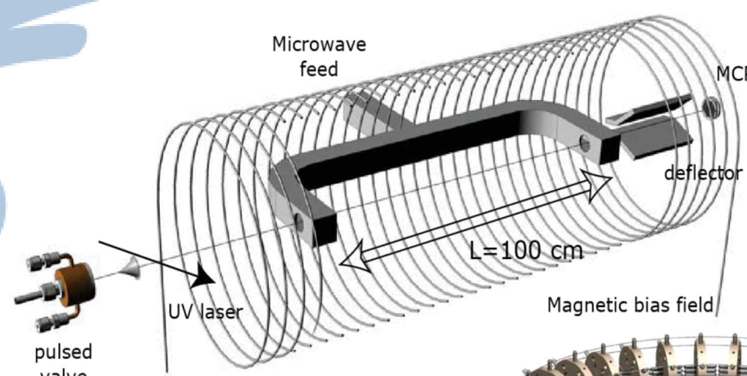

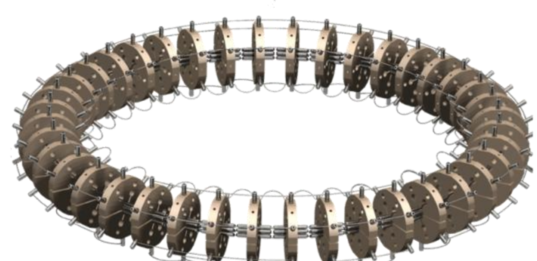

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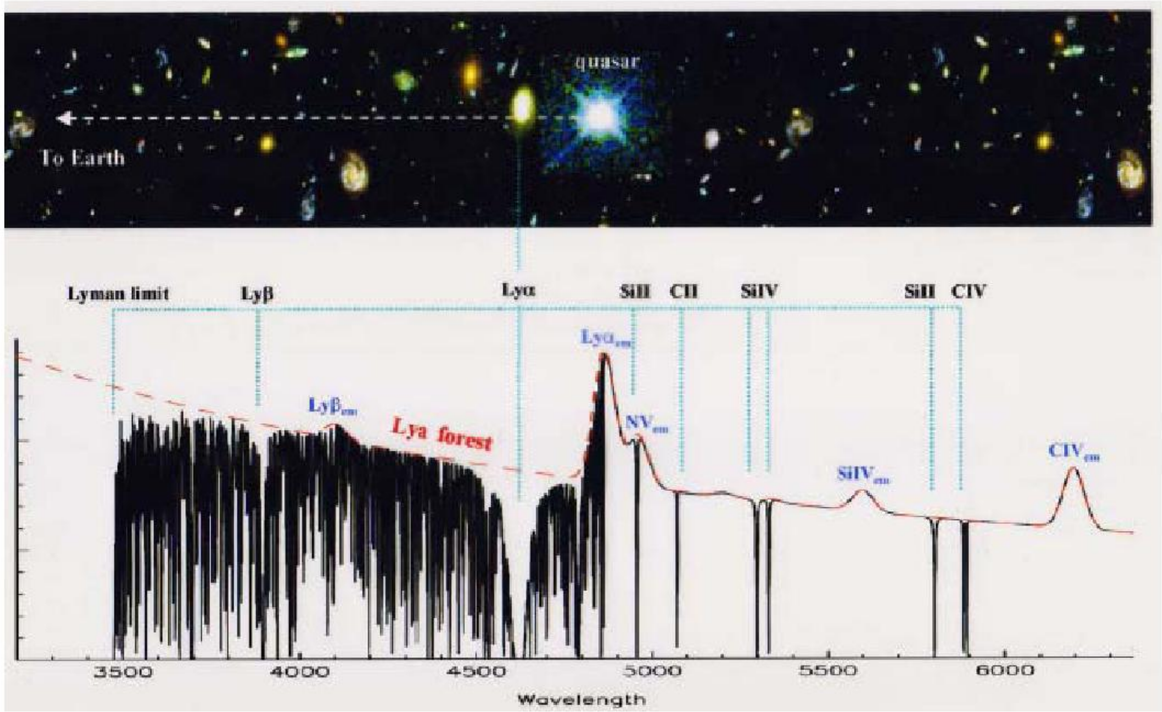
varying α and μ from astronomical data



$\Delta\alpha/\alpha$ = (-0.72 +/- 0.18) x 10^{-5}
over the last 12 Gyr [1]

If variation is linear:
0.6 x 10^{-15}/yr

$\Delta\mu/\mu$ = (2.4 +/- 0.6) x 10^{-5}
over the last 12 Gyr [2]

If variation is linear:
-2.0 x 10^{-15}/yr

[1] J.K. Webb et al., *Phys. Rev. Lett.* **87**, 091301 (2001).
[2] E. Reinhold et al., *Phys. Rev. Lett.* **96**,151101 (2006).

Ability to detect a time-variation of μ

fractional rate of change of μ

fractional precision of the experiment

$$\left(\frac{\partial \mu}{\partial t}\right) \Big/ \mu = \left(\frac{\Delta \upsilon}{\upsilon}\right) \Big/ K \cdot \Delta t$$

sensitivity of the transition

duration of the experiment

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Constraint from H_2 observations

$$\left(\frac{\partial\mu}{\partial t}\right)\Big/\mu = \left(\frac{\Delta\upsilon}{\upsilon}\right)\Big/ K\cdot\Delta t$$

$\sim 10^{-15}/yr$

$\sim 10^{-7}$

-0.05 - +0.01

$\sim 10^{10}$ yr

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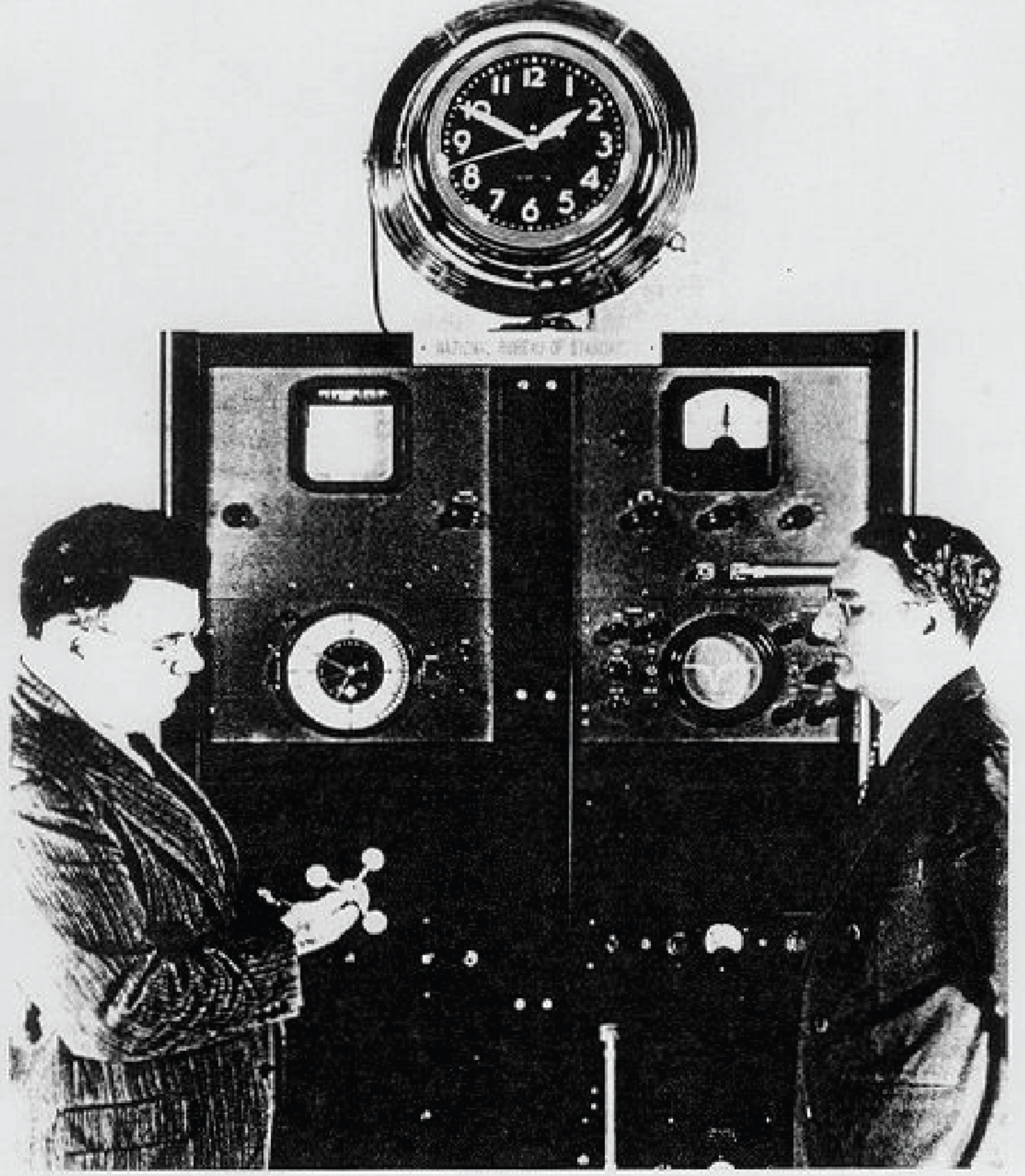
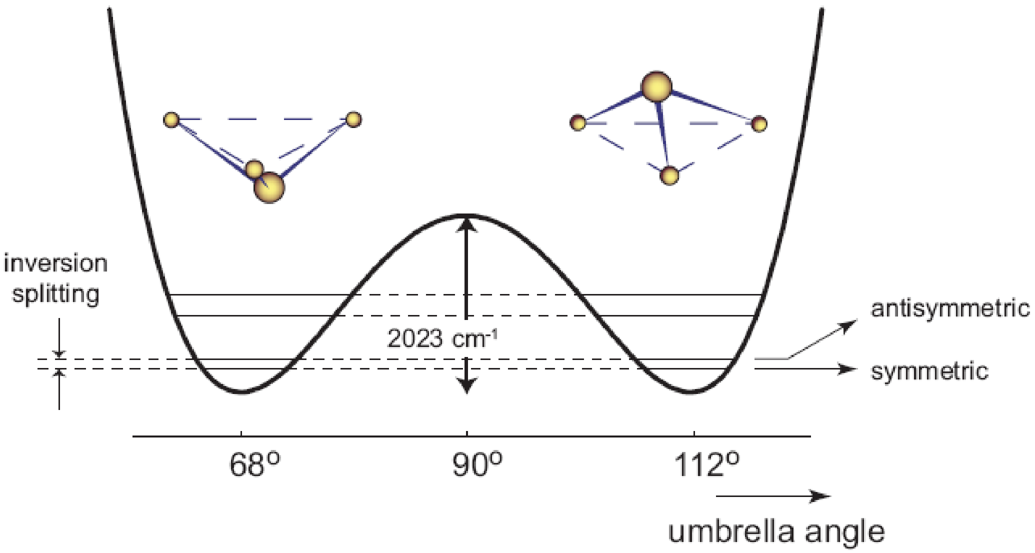
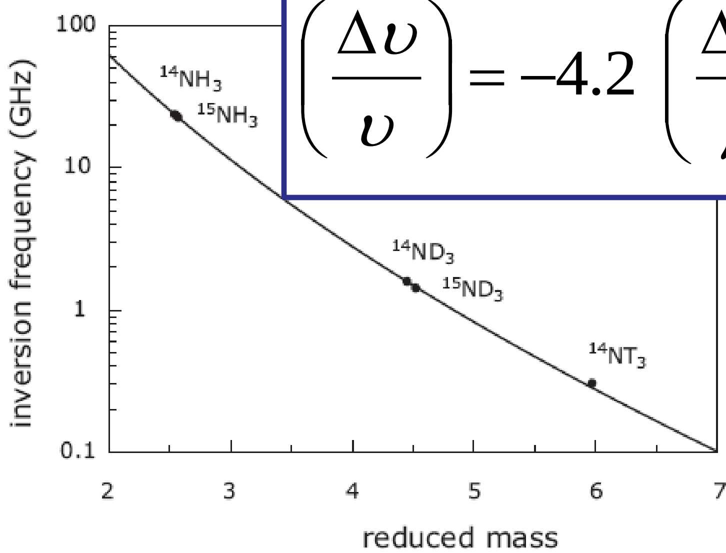


Figure 1: The World's first atomic clock; the ammonia absorption cell atomic clock at the National Bureau of Standards (now the National Institute of Standards and Technology) first operated in August 1948. Dr. Harold Lyons, inventor, is at the right; Dr. Edward U. Condon, Director of NBS, is at the left. The ammonia absorption cell is the coil of waveguide surrounding the clock face.

Inversion splitting in Ammonia

- Ammonia has a double-well potential, giving rise to inversion doubling
- Inversion frequency strongly depends on proton mass





$$\left(\frac{\Delta\upsilon}{\upsilon}\right) = -4.2\left(\frac{\Delta\mu}{\mu}\right)$$

J. van Veldhoven *et al.* EPJD **31**, 337 (2004).

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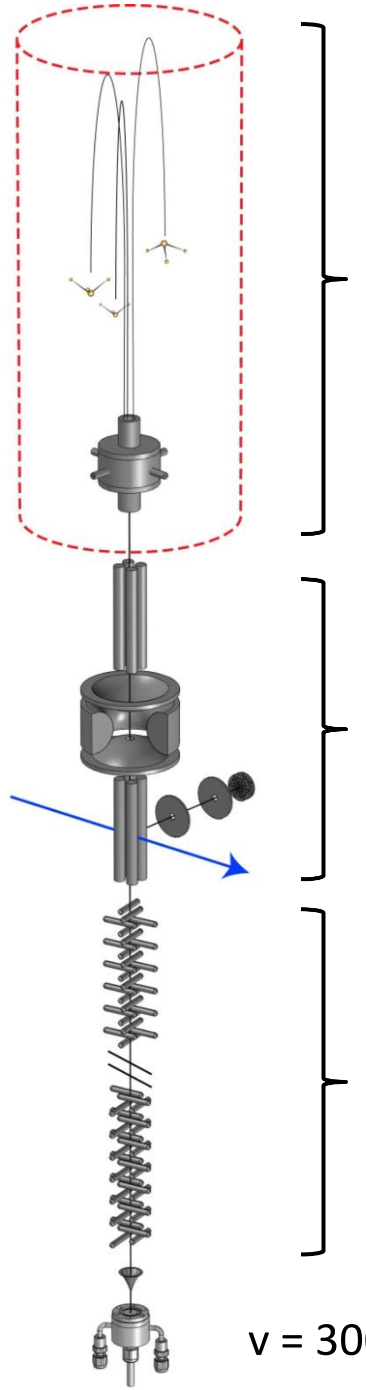
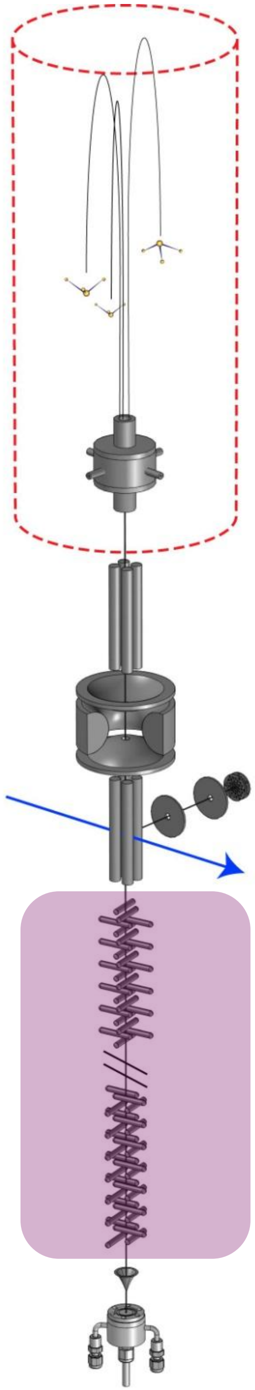
Design of the fountain



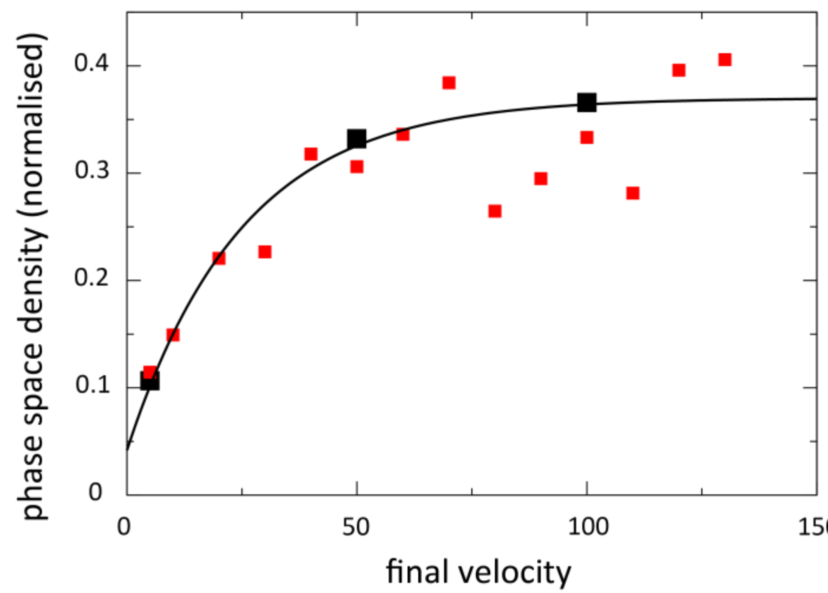
Design of the fountain



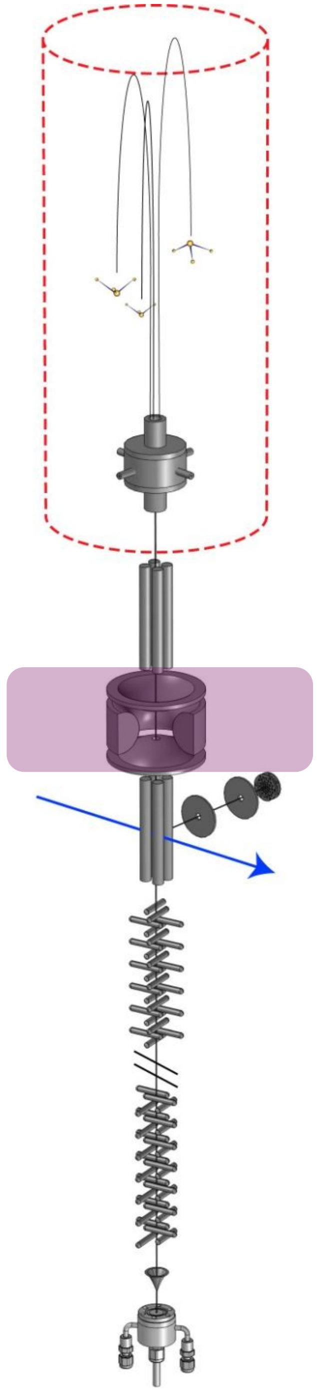
PROBLEMS:

Decelerator: Poor efficiency at low velocities

- Coupling between longitudinal and transverse motion.
- Over-focusing in last stages.



Design of the fountain



PROBLEMS:

Decelerator: Poor efficiency at low velocities

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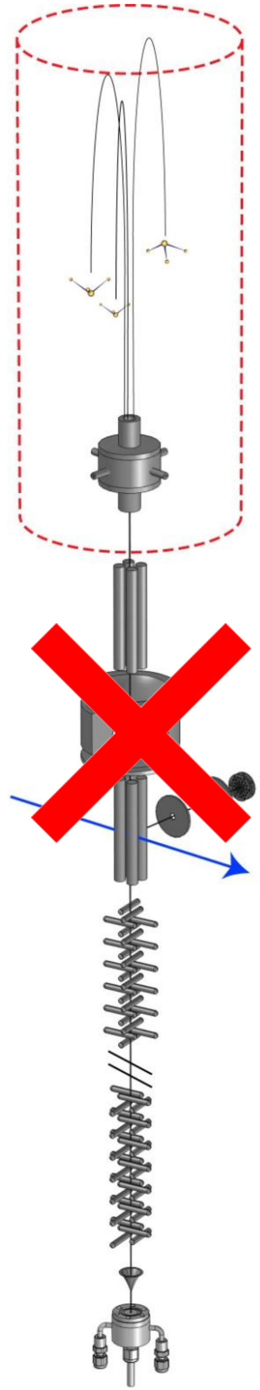
Buncher: No longitudinal focusing observed

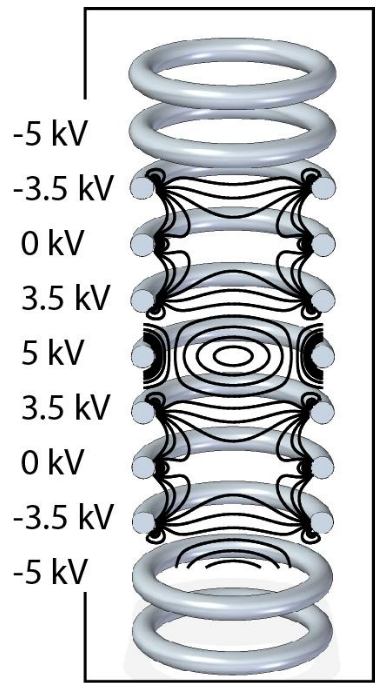
- The buncher is most effective for $v \leq 8$ m/s; while the lowest velocity observed after the buncher is 12 m/s.
- Bunching depends very critically on the timing of the applied voltages.

Design of the fountain



Solution (?):

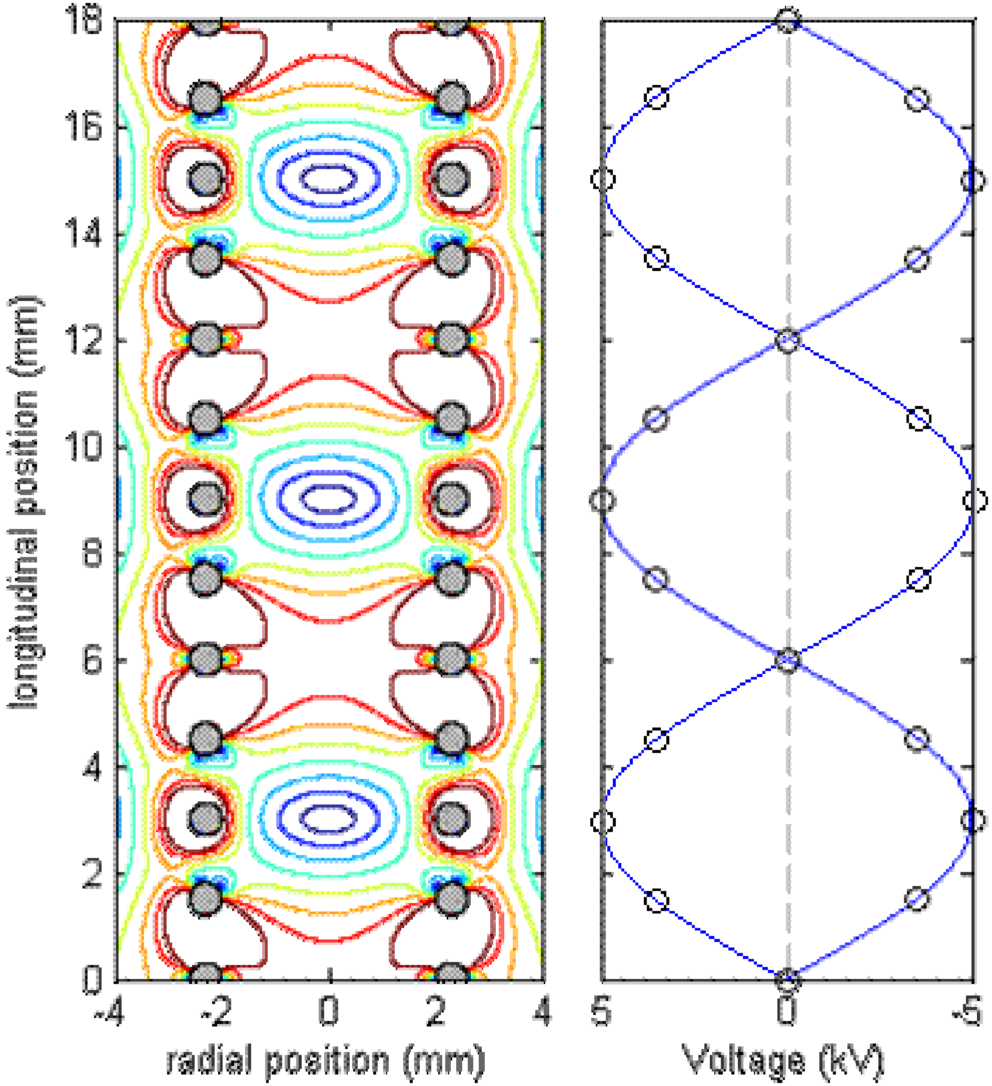
Replace focusing section by a ring-type decelerator



Improve deceleration efficiency:
Use ring-type decelerator to decelerate from ~100m/s to 3m/s.

More robust cooling:
Performing adiabatic cooling by slowly lowering the voltages applied to the ring-type decelerator.

Operation principle of ring-type decelerator



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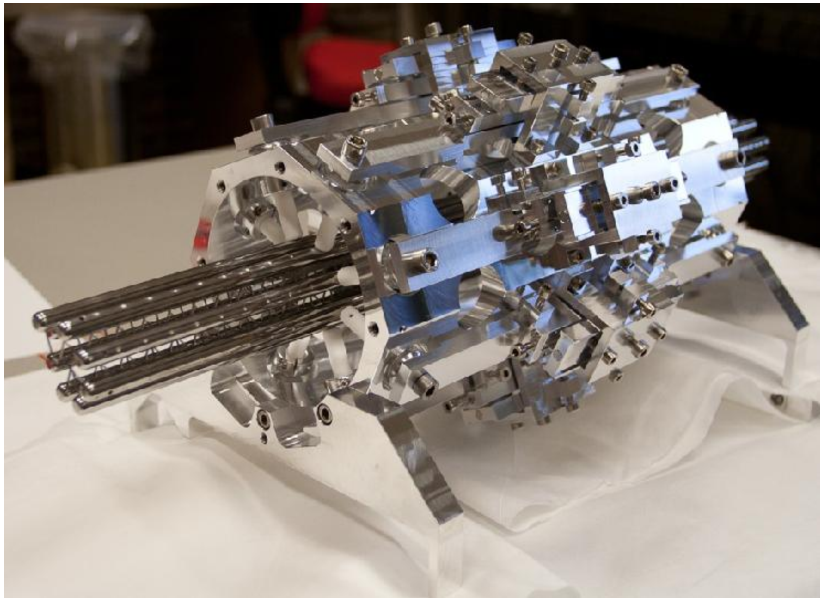
The ring decelerator



Ring decelerator constructed at KVI Groningen similar to the design that was used by Osterwalder et al. [1]

492mm long, consisting of 328 rings with 4 mm inner diameter; Periodicity 12 mm.

Amplifiers (8 x TREK 5/80-H-CE)

10 kV (peak to peak), frequency 0-15 kHz.

[1] Osterwalder *et al. Phys. Rev. A* **81**, 051401(R) (2010).

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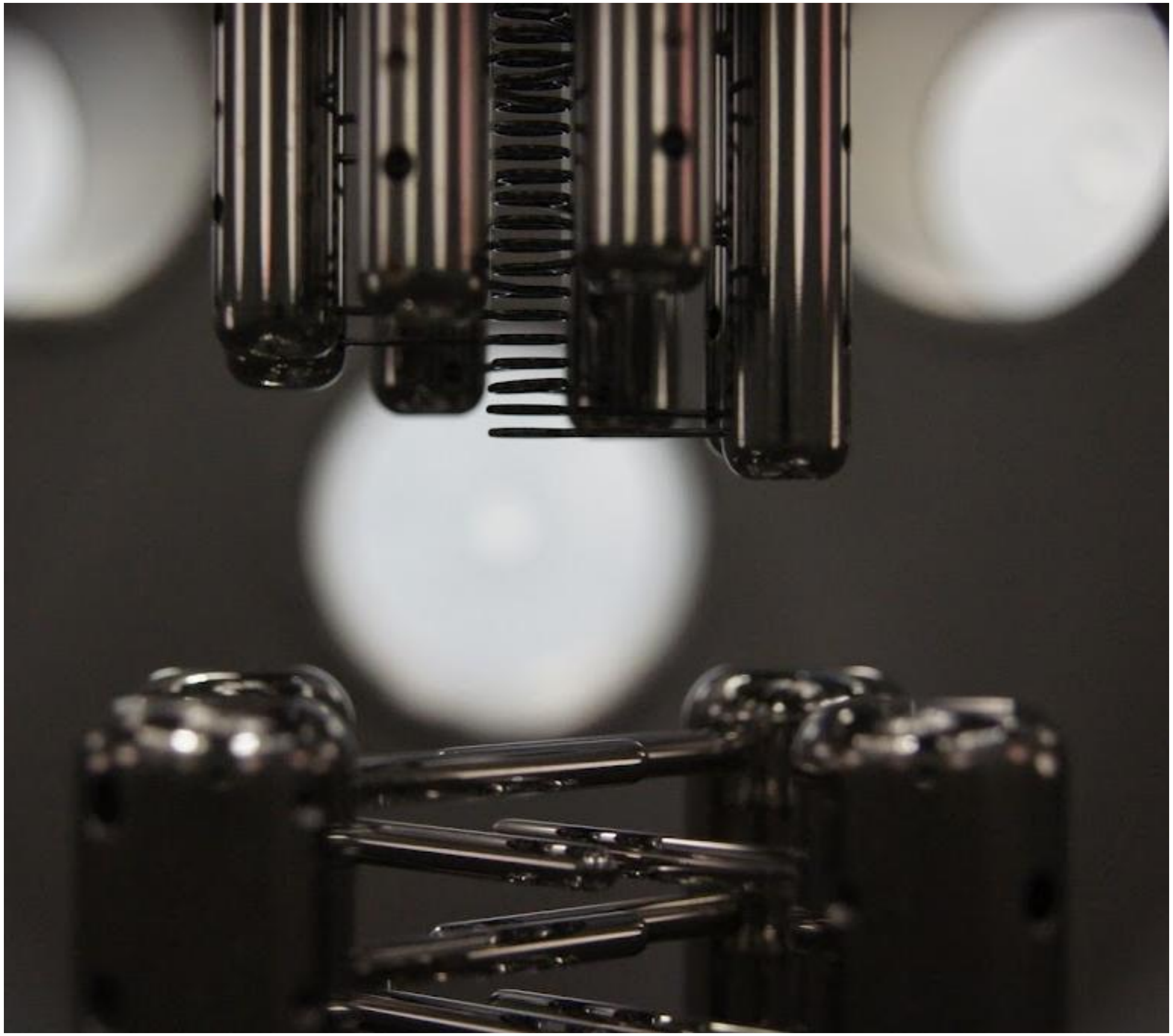
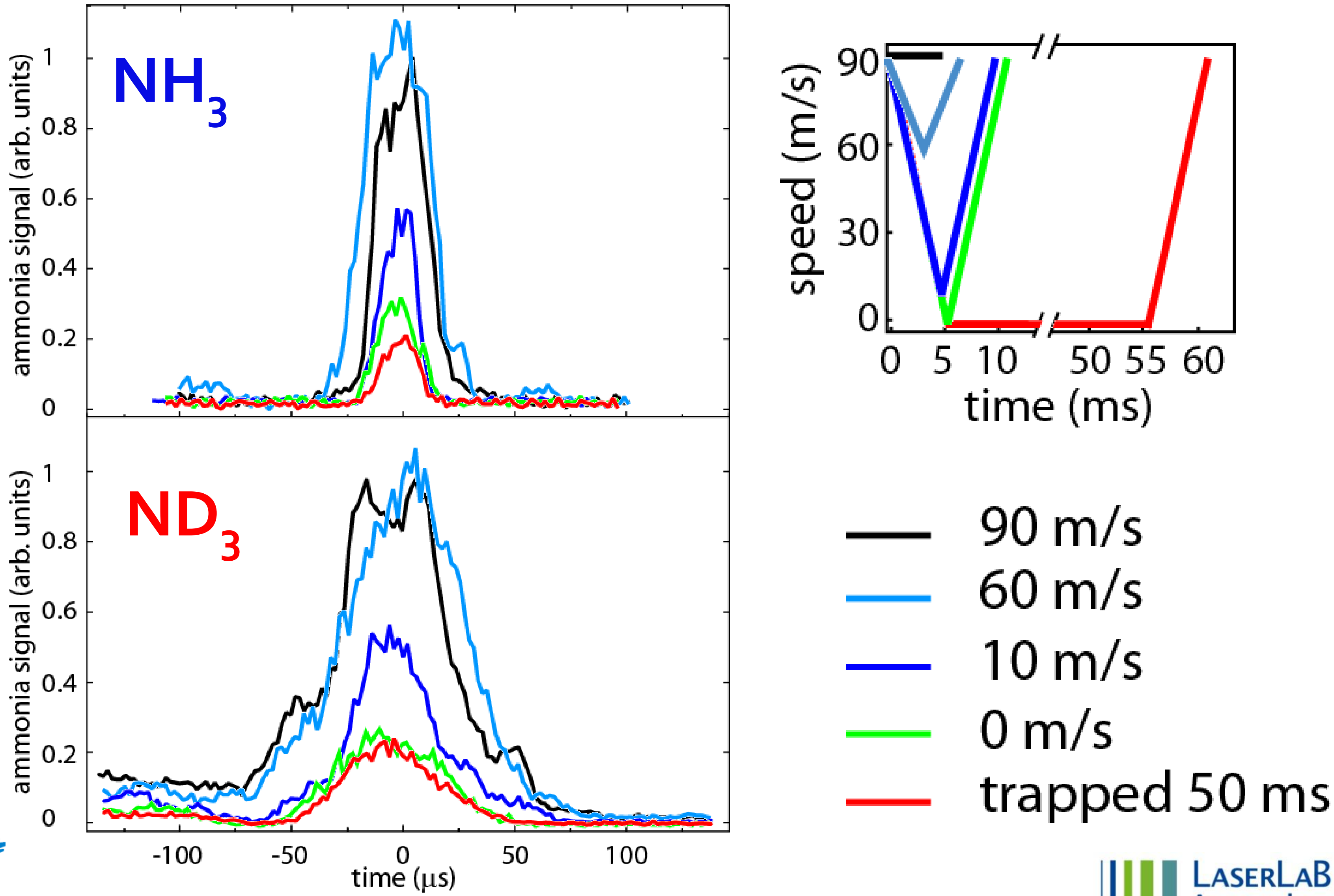
Where two worlds meet

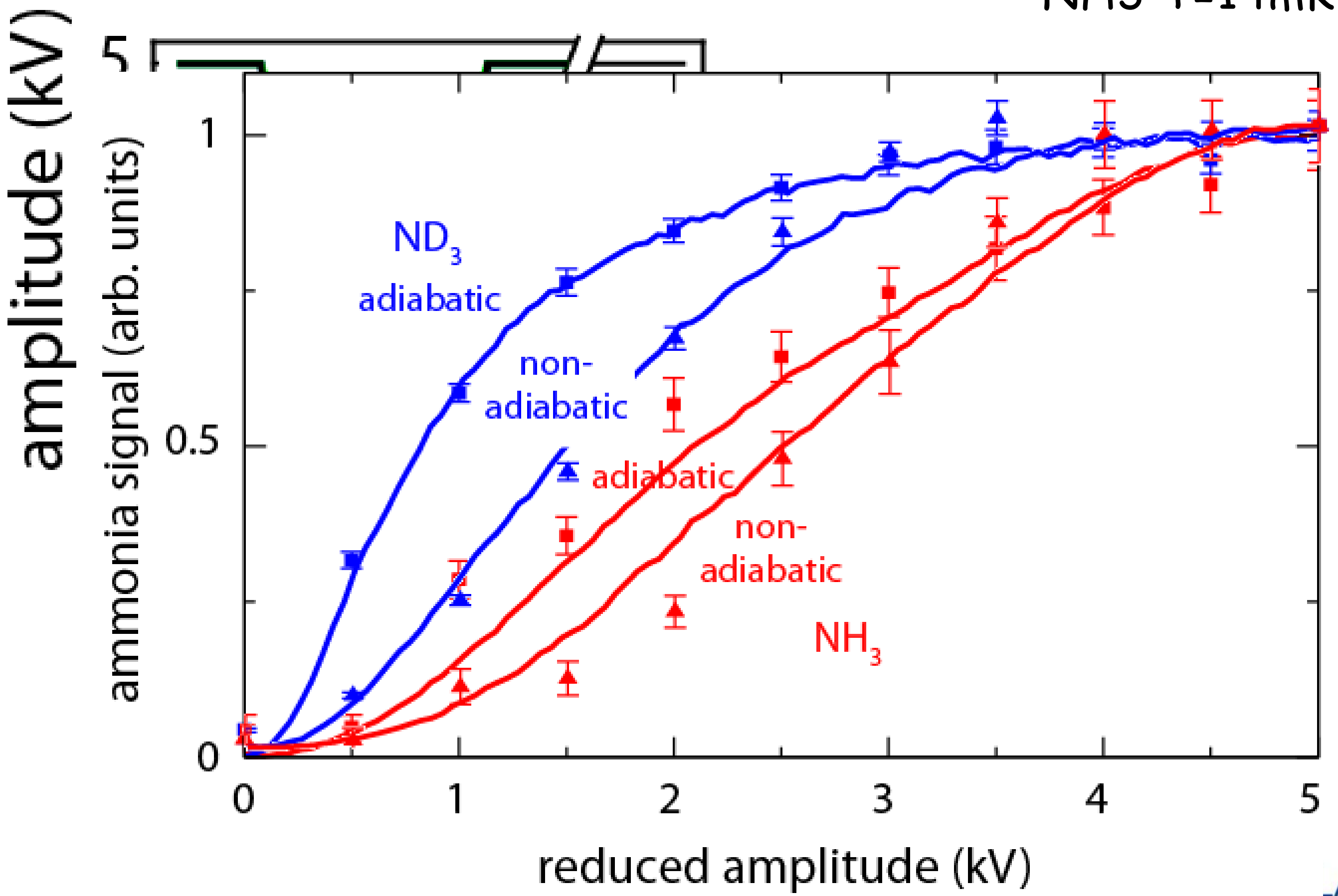


Guiding, Decelerating…



Adiabatic cooling

ND3 T=30mK
NH3 T=14mK



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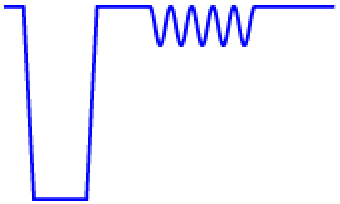
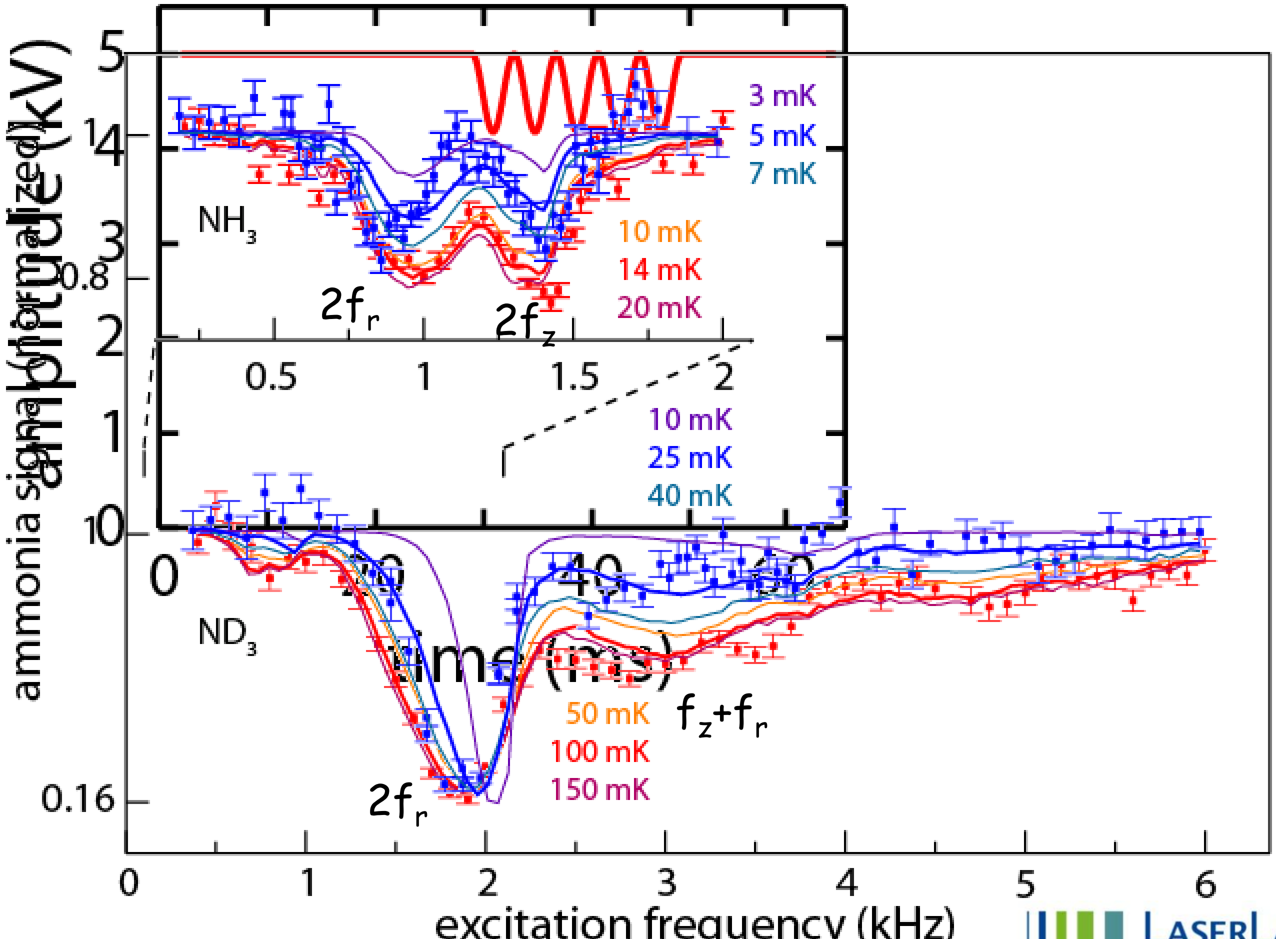
Exciting the trap motion





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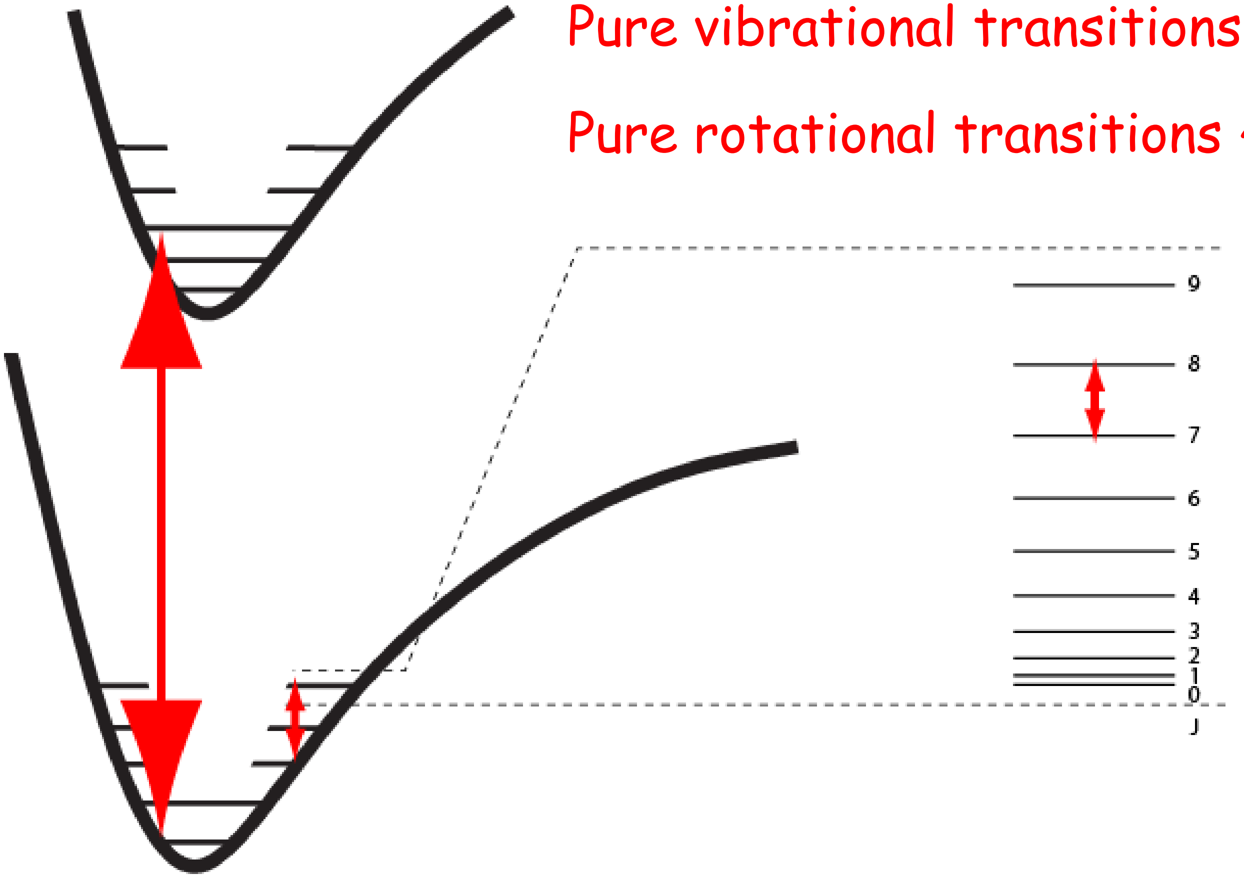
Dependence of molecular spectra on μ and α

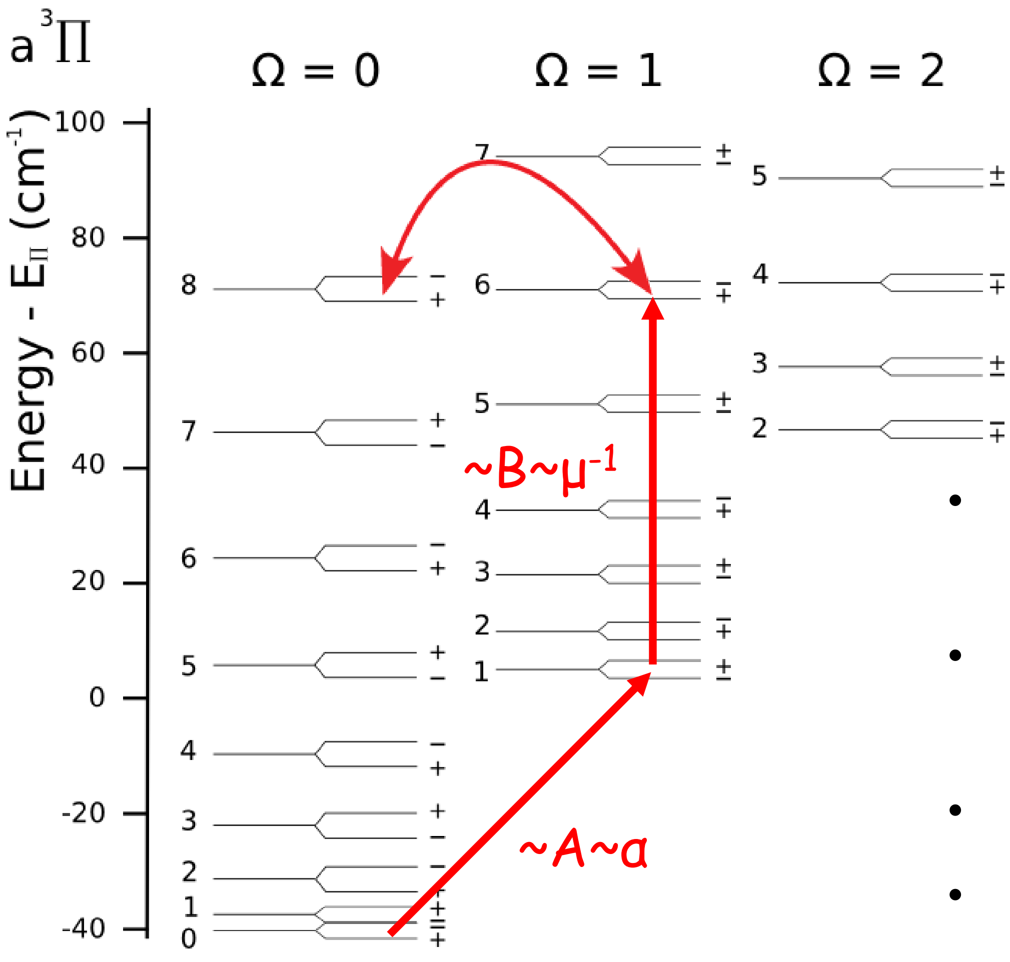
Electronic transitions ~ Ry ~α^2; K_μ =0

Pure vibrational transitions ~ω_e~$\mu^{-\frac{1}{2}}$; K_μ =$-\frac{1}{2}$

Pure rotational transitions ~B~μ^{-1} ; K_μ =-1



Energy levels of CO in $a^3\Pi$ state



Enhancement: $K_\mu \sim A/2v$

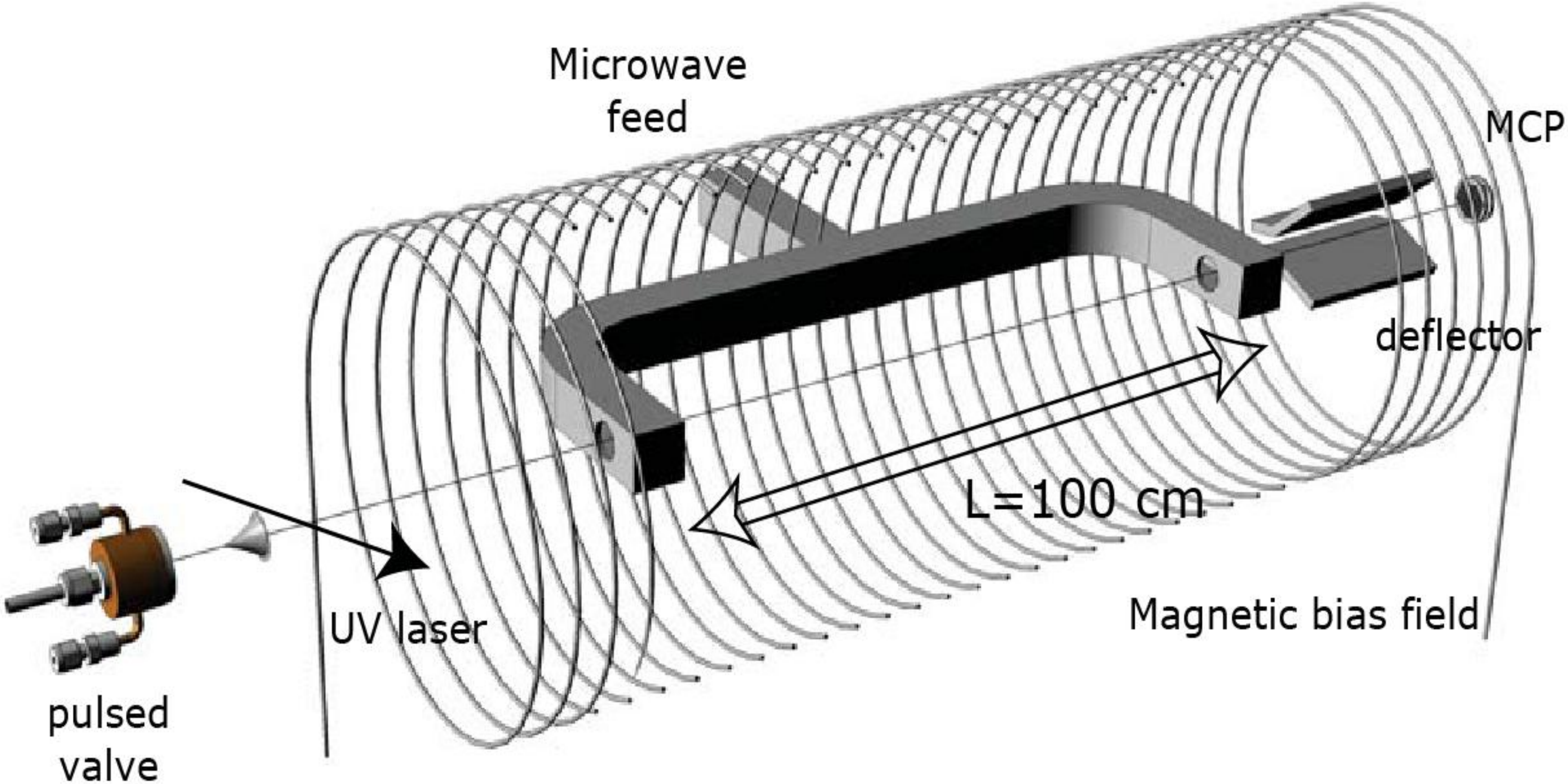
- $a^3\pi$ is the first excited state of CO at 6eV.
- Decay to the groundstate is spin-forbidden.
- Lifetime 3-200ms.
- Can be directly excited from the groundstate using light around 206nm.

K-coefficients of 2-photon transitions in CO

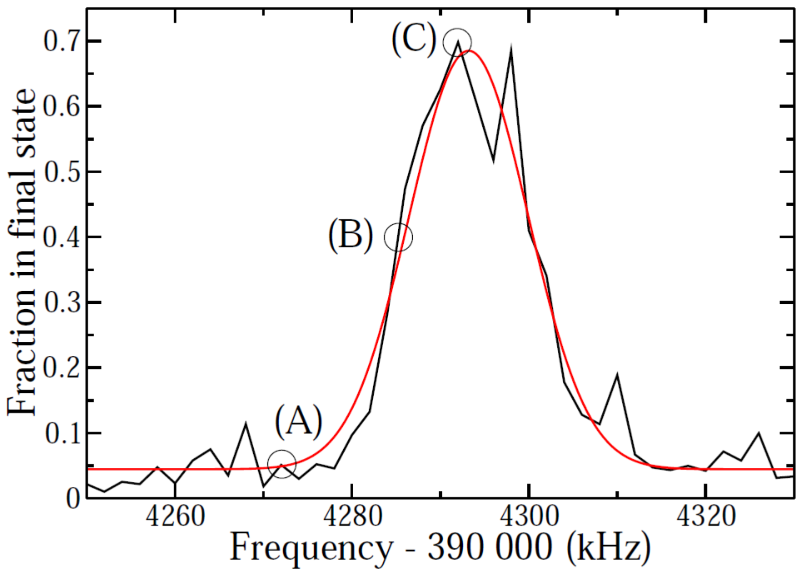
Isotopologue	Transition	Measured (MHz)	Meas . -Calc. (MHz)	K_μ
$^{12}C^{16}O$	$J = 6, \Omega = 1, + \to J = 4, \Omega = 2, +$	19270.1	3.5	27.8
	$J = 6, \Omega = 1, - \to J = 4, \Omega = 2, -$	16057.7	4.7	33.7
	$J = 6, \Omega = 1, + \to J = 8, \Omega = 0, +$	−1628.3	−3.3	−334
	$J = 6, \Omega = 1, - \to J = 8, \Omega = 0, -$	−19406.7	4.5	−27.3
$^{13}C^{16}O$	$J = 6, \Omega = 1, +, F = 3.5 \to J = 4, \Omega = 2, +, F = 6.5$	43005.8	0.1	12.9
	$J = 6, \Omega = 1, -, F = 3.5 \to J = 4, \Omega = 2, -, F = 6.5$	39988.0	0.7	12.2
	$J = 6, \Omega = 1, +, F = 5.5 \to J = 8, \Omega = 0, +, F = 8.5$	22329.6	6.0	23.5
	$J = 6, \Omega = 1, -, F = 5.5 \to J = 8, \Omega = 0, -, F = 8.5$	4003.4	5.0	128
$^{13}C^{18}O$	$J = 6, \Omega = 1, +, F = 3.5 \to J = 4, \Omega = 2, +, F = 6.5$	69062.0	−7.1	7.22
	$J = 6, \Omega = 1, -, F = 3.5 \to J = 4, \Omega = 2, -, F = 6.5$	66277.5	−3.6	7.60

A.J. de Nijs *et al. Phys. Rev. A* **84**, 052509 (2011).

Setup to measure 2-photon transitions

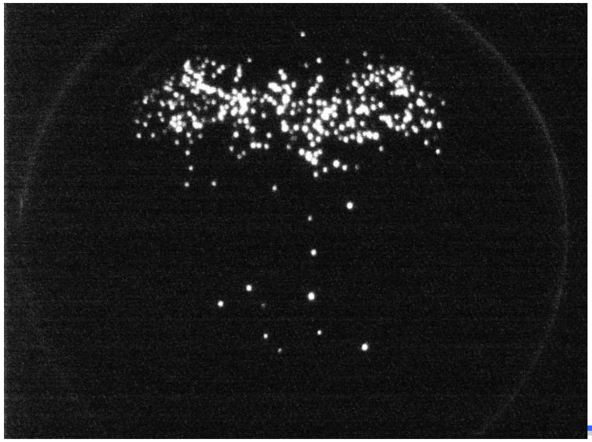


Microwave measurements

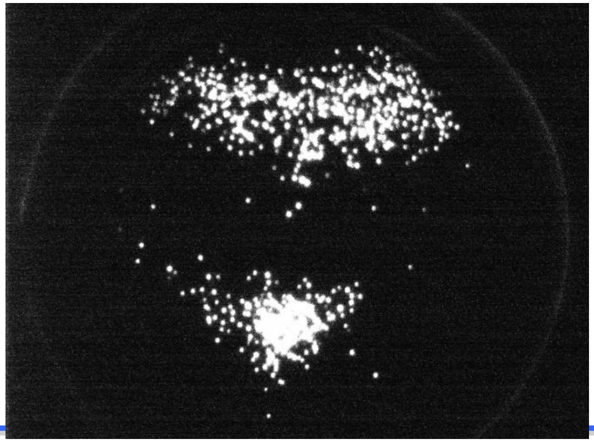


- MW-frequency scanned
- Fraction of molecules in final state calculated
- ~250 molecules per shot
- Shot-to-shot noise cancels

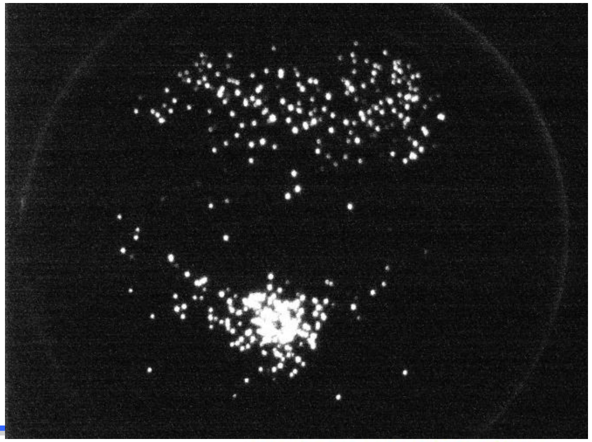
(A)



(B)



(C)



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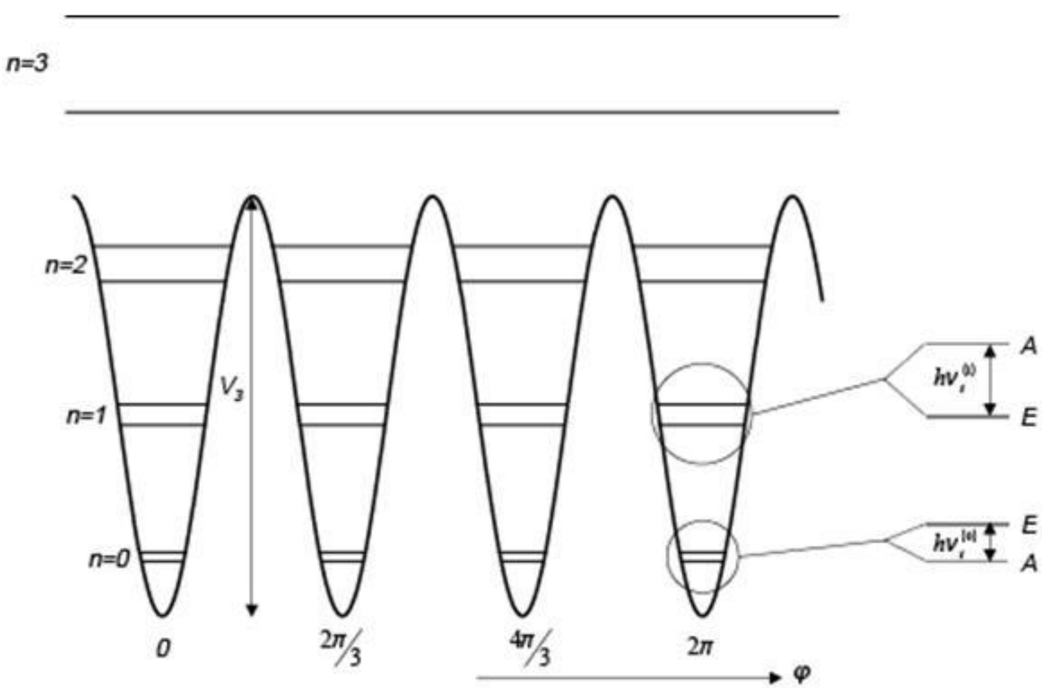
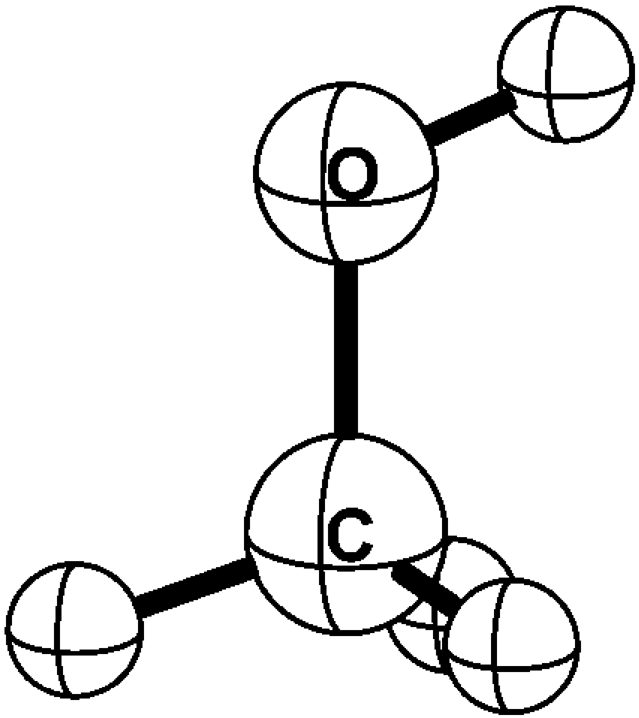
Hindered rotation in Methanol

- The internal rotation is hindered by a barrier, leading to a splitting between levels of A and E symmetry.
- The torsional splittings strongly depends on proton mass





P. Jansen *et al.* *PRL* **106**, 100801 (2011).

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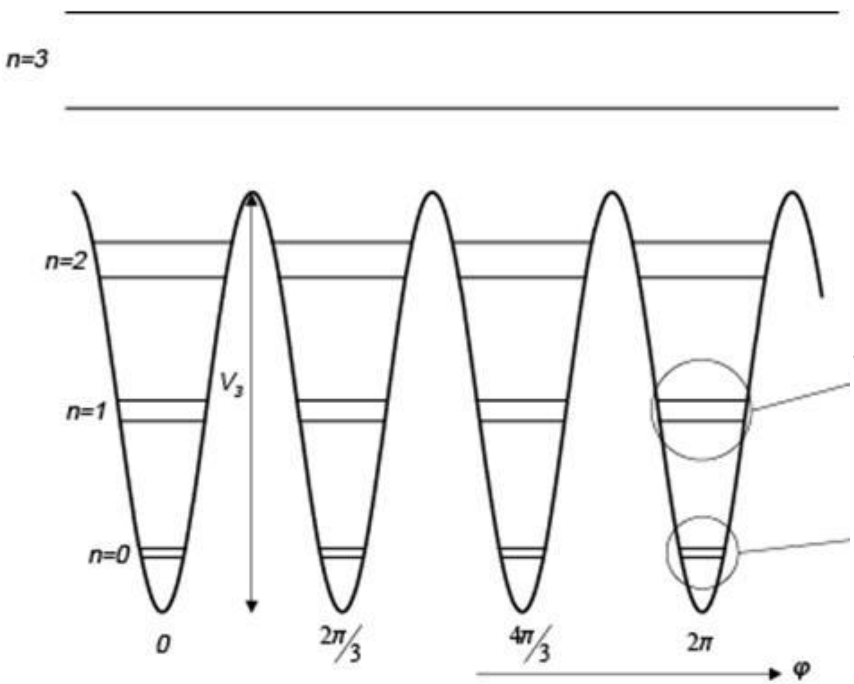

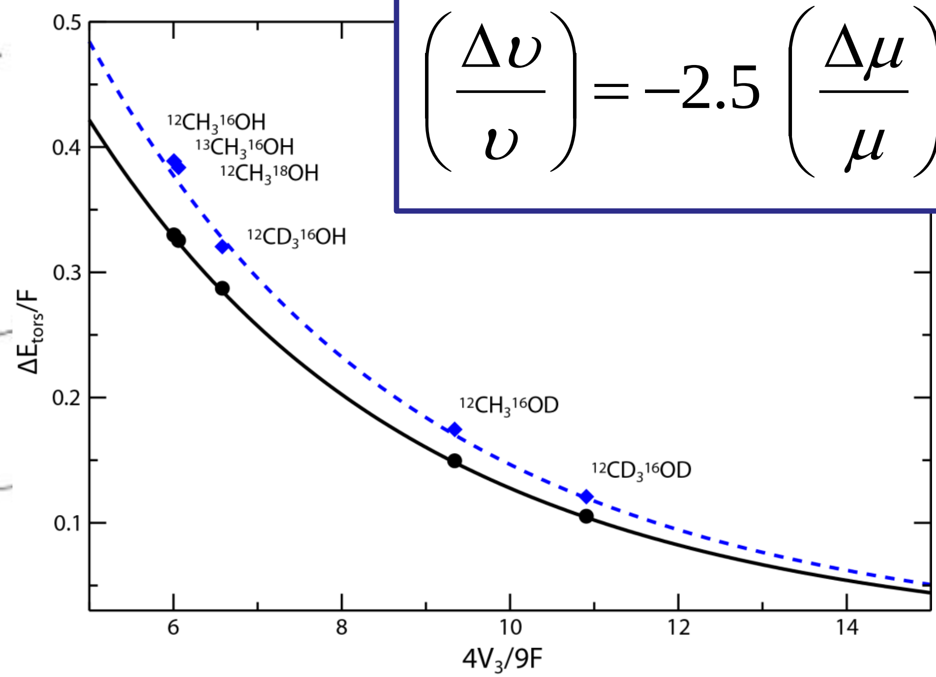

$$\left(\frac{\Delta\upsilon}{\upsilon}\right) = -2.5\left(\frac{\Delta\mu}{\mu}\right)$$

P. Jansen *et al. PRL* **106**, 100801 (2011).

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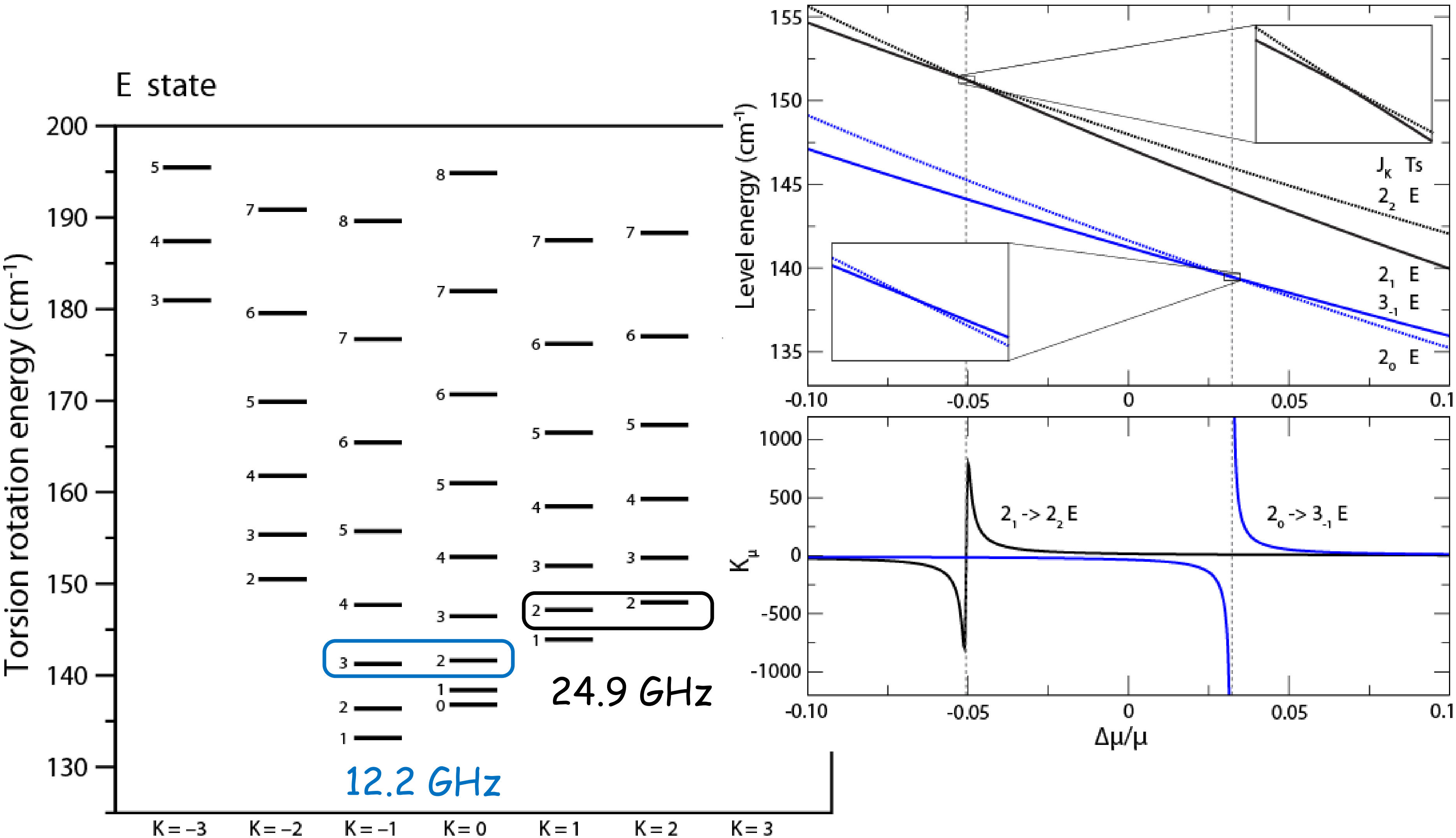
Near degeneracies in level scheme

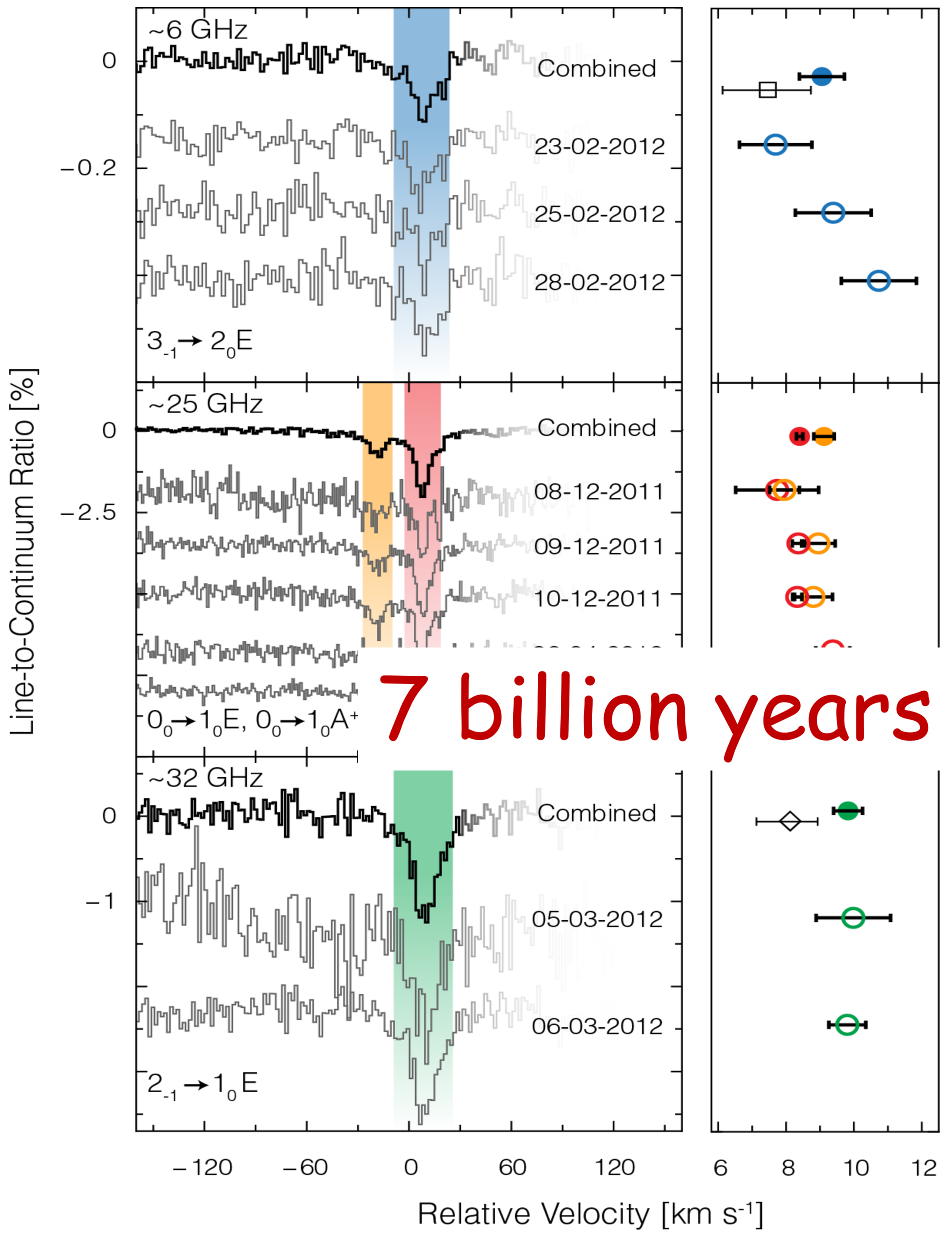


$K_\mu = -33$ $K_\mu = +18$

Effelsberg Radio Telescope

Intergalactic alcohol

Methanol in PKS-1830-211



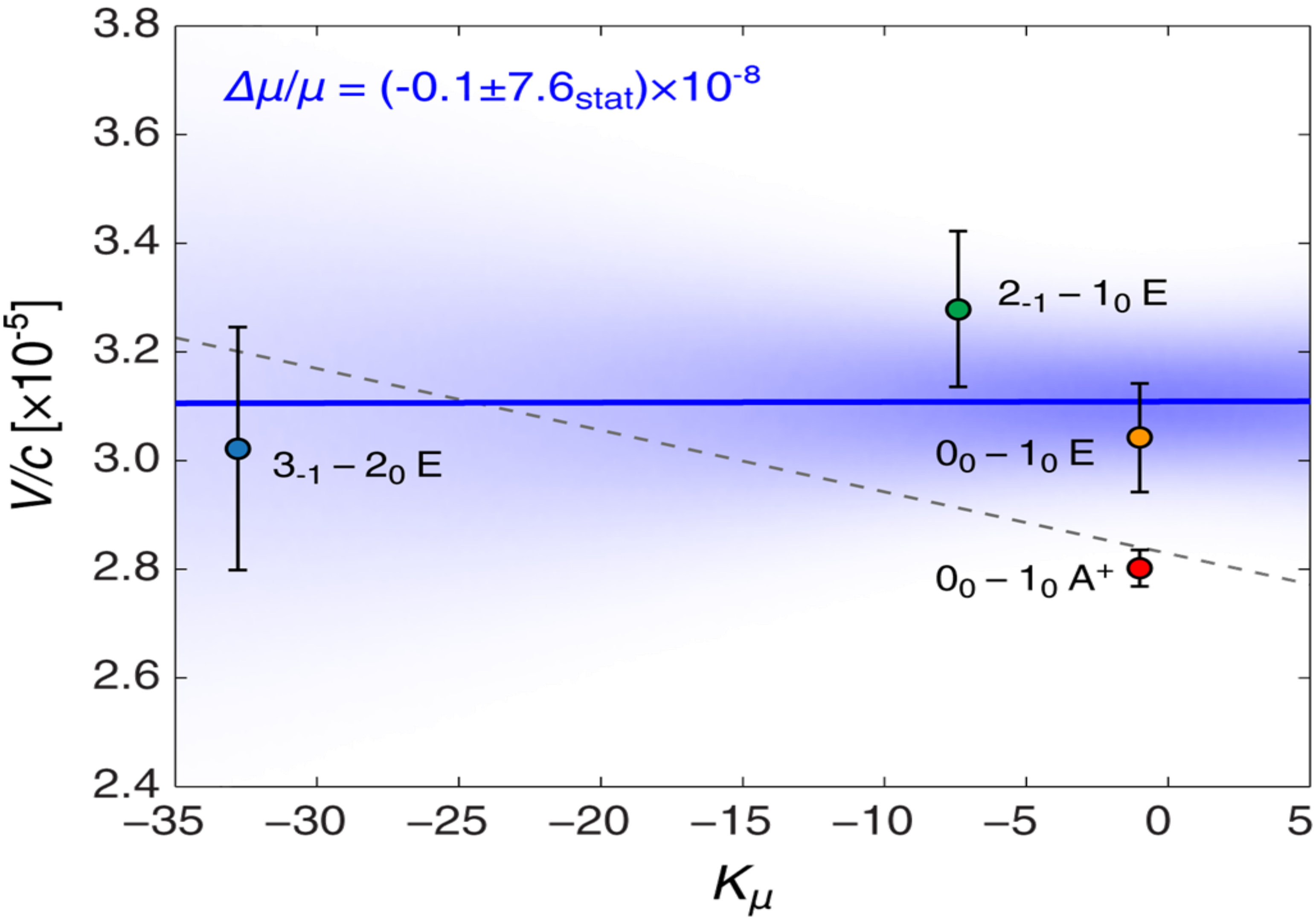
K=-33

K=-1

K=-7

7 billion years look-back time!!

Constraint on time-variation of μ



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

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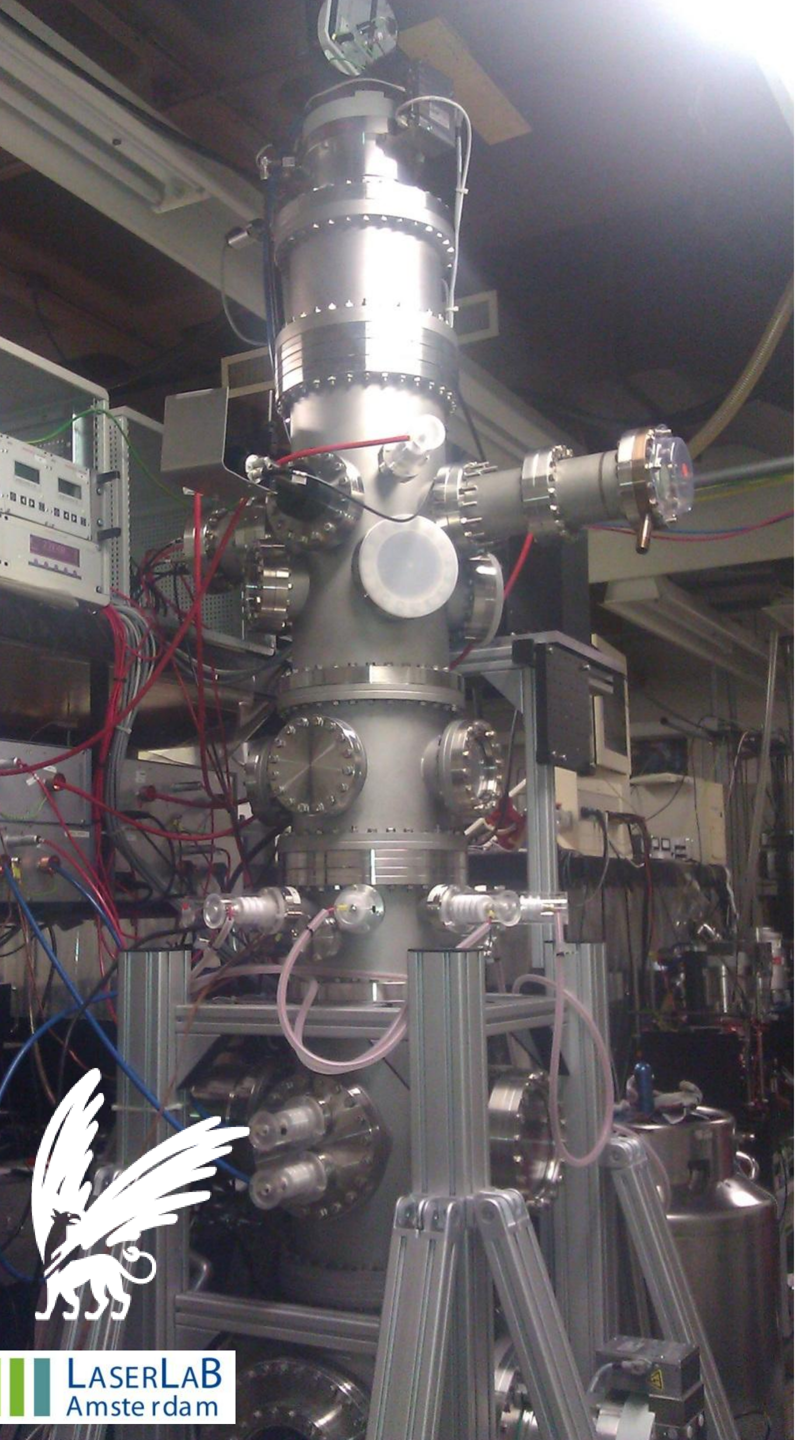

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