A molecular fountain (and the time-variation of fundamental constants)

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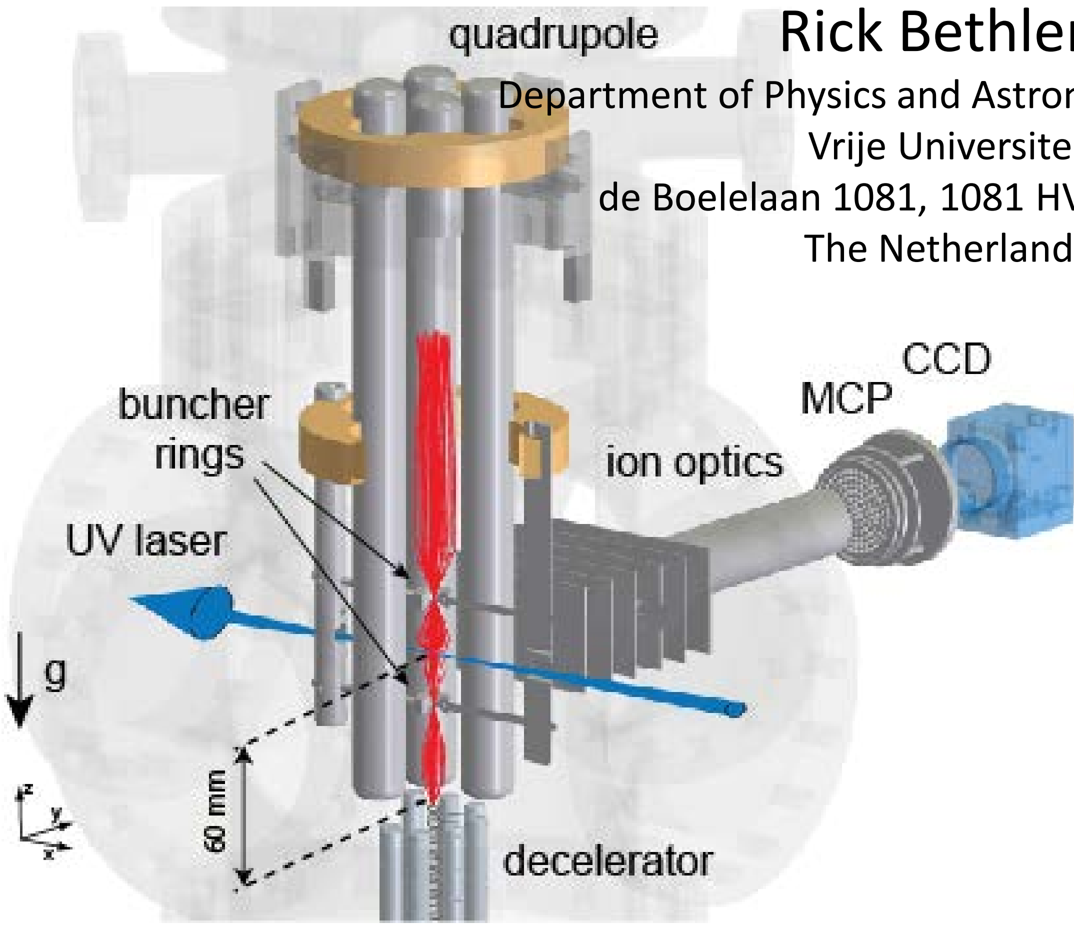

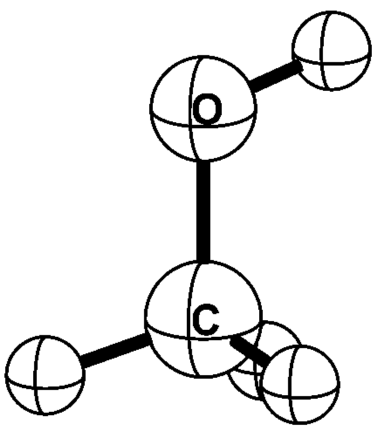

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Wishlist for a molecule

- ☐ Easy to produce in the gasphase
- ☐ Easy to detect (REMPI, LIF)
- ☐ Easy to manipulate (large Stark effect, closed transitions)
- ☐ Sensitive to new physics

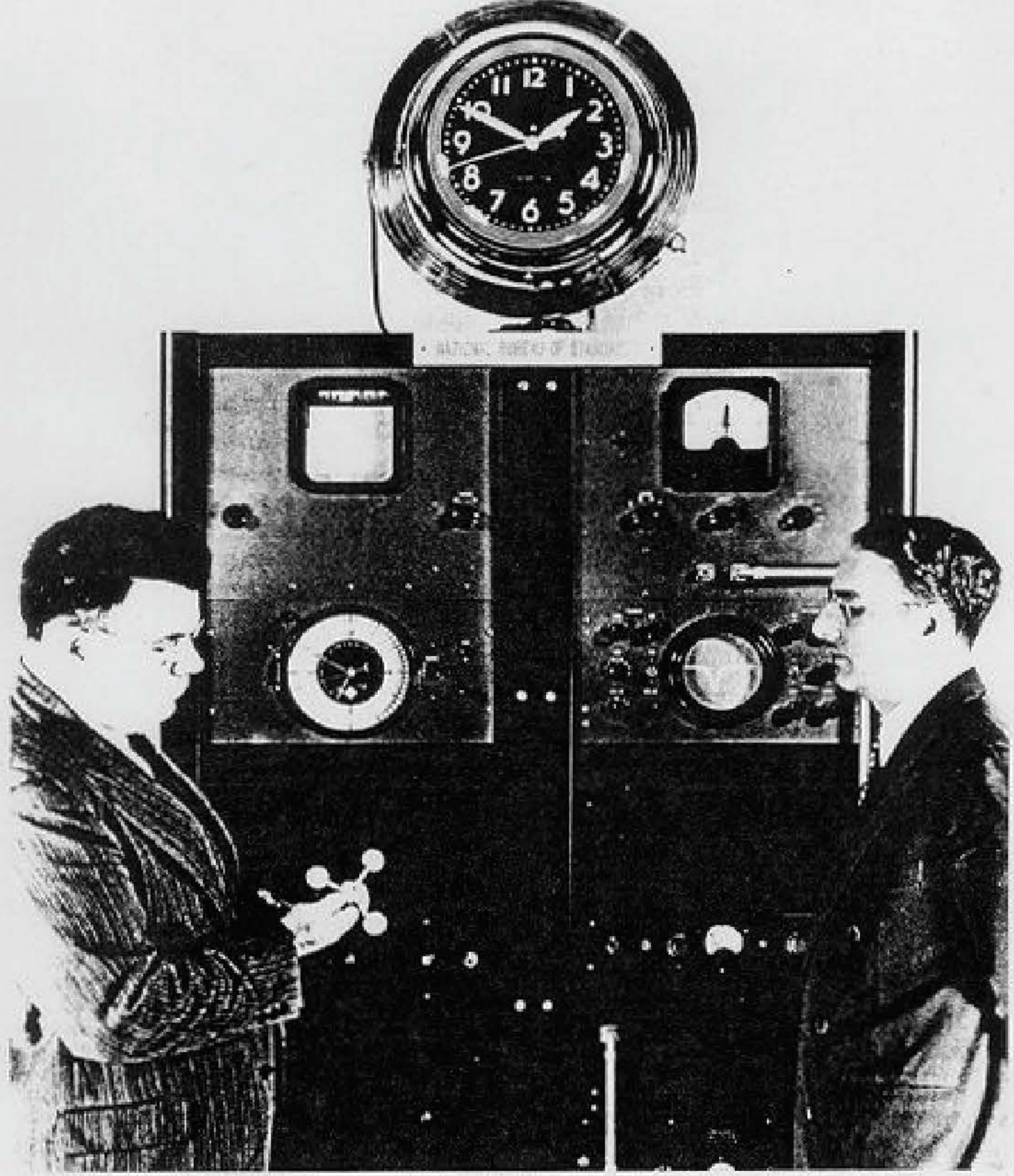
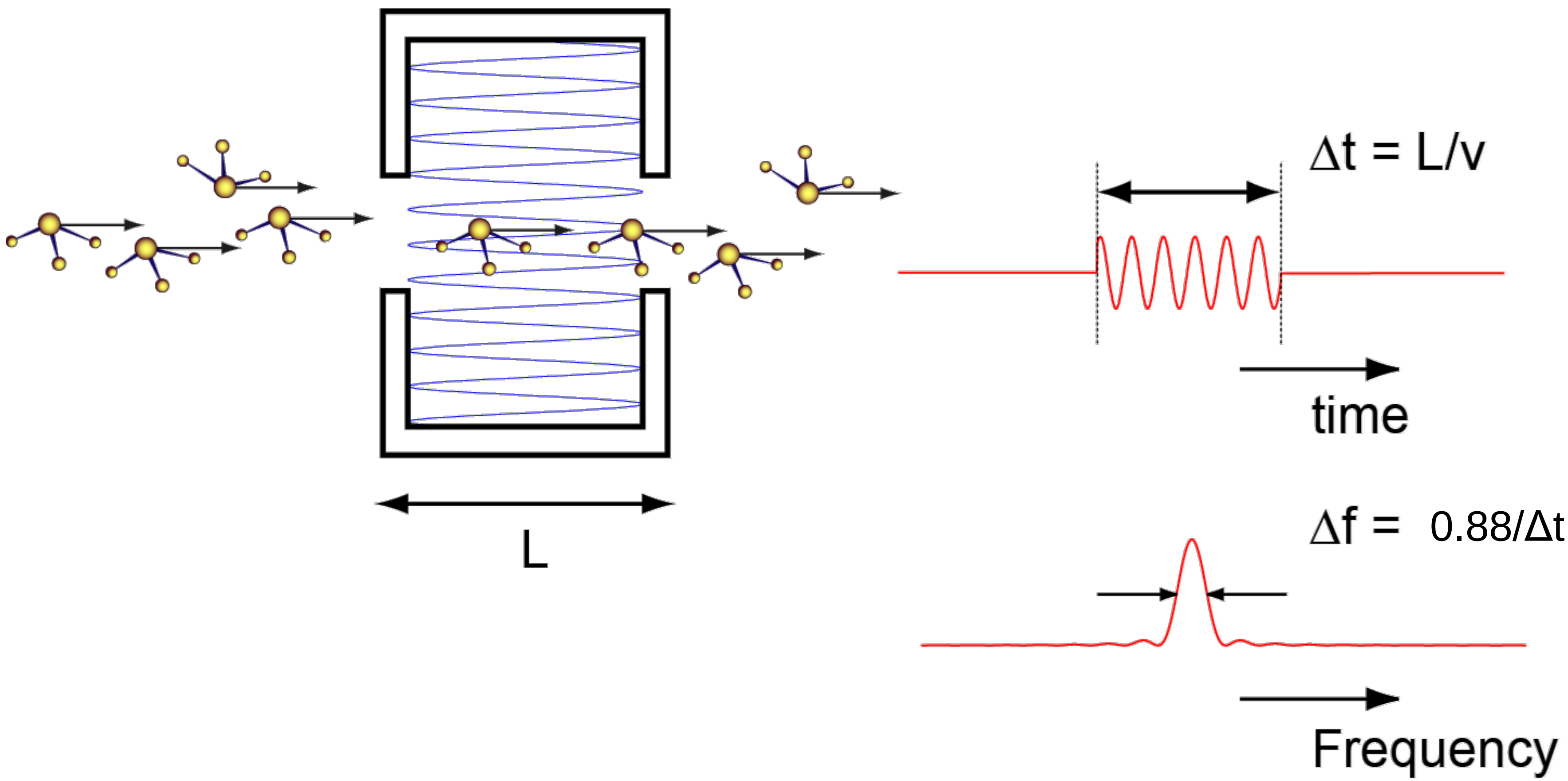


Figure 1: The World's first atomic clock; the ammonia absorption cell atomic clock at the National Bureau of Standards (now the National Institute of Standards and Technology) first operated in August 1948. Dr. Harold Lyons, inventor, is at the right; Dr. Edward U. Condon, Director of NBS, is at the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

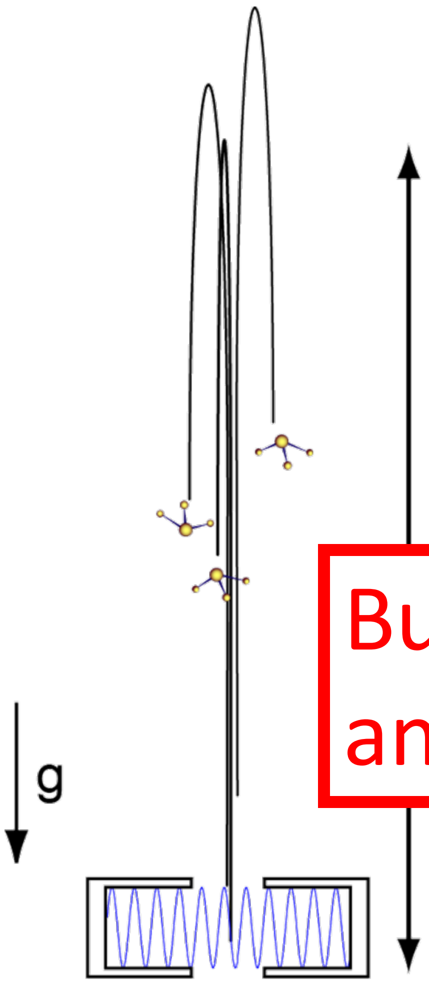
Why cold molecules?

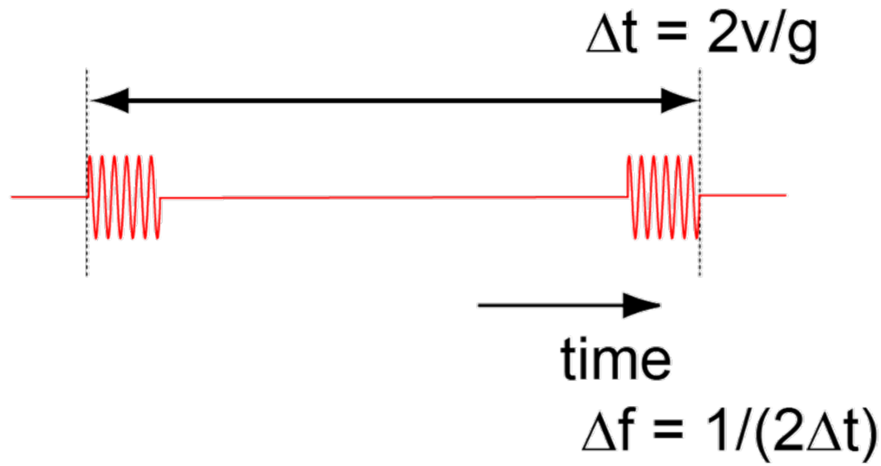


v = 500 m/s, L = 5 cm; Δt = 0.1 ms; Δf = 8.8 kHz

v = 50 m/s, L = 5 cm; Δt = 1 ms; Δf = 880 Hz

Ramsey scheme in a fountain:



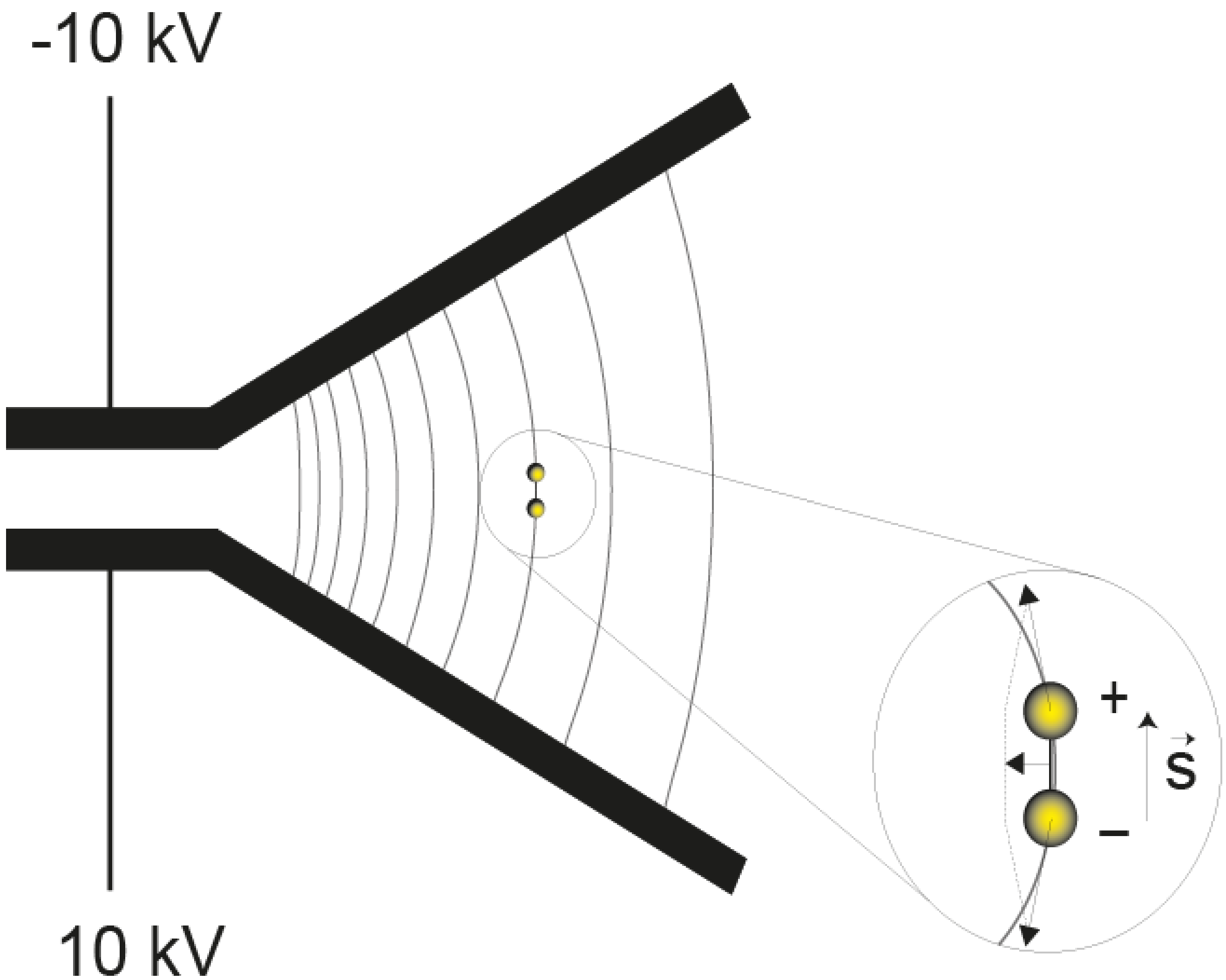


But we need (many) slow (< 3m/s) and cold (~1 μK) molecules!!

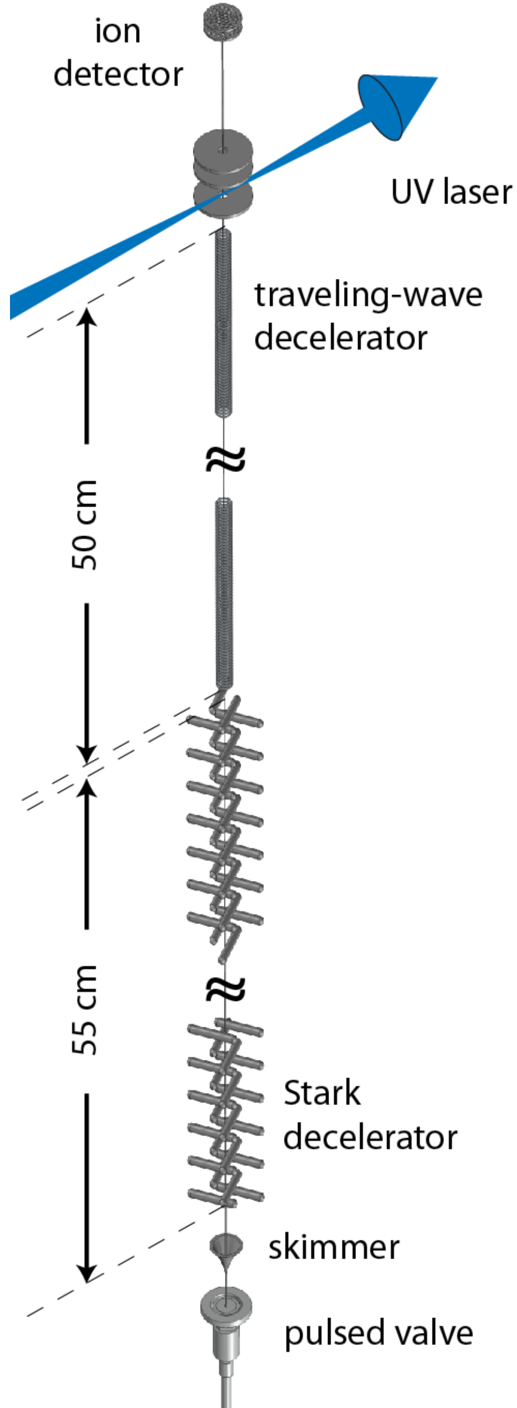
v = 3 m/s; L = 30 cm; Δt = 0.5 s; Δf = 1 Hz

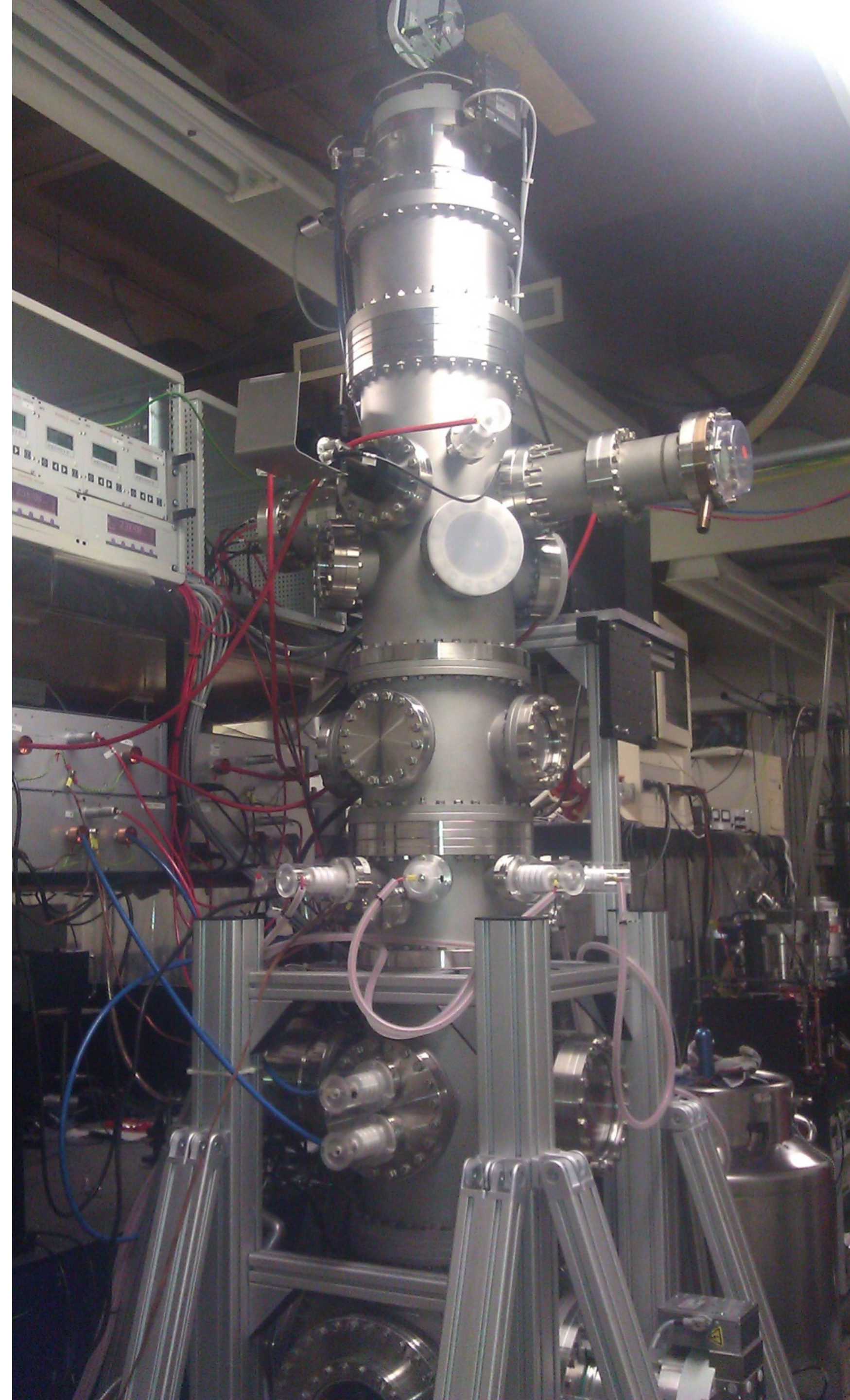
for ammonia f = 23.8 GHz; $\Delta f/f = 5.\ 10^{-11}$; accuracy 10^{-12} -10^{-15}

A dipole in an inhomogeneous E-field



Design of the fountain





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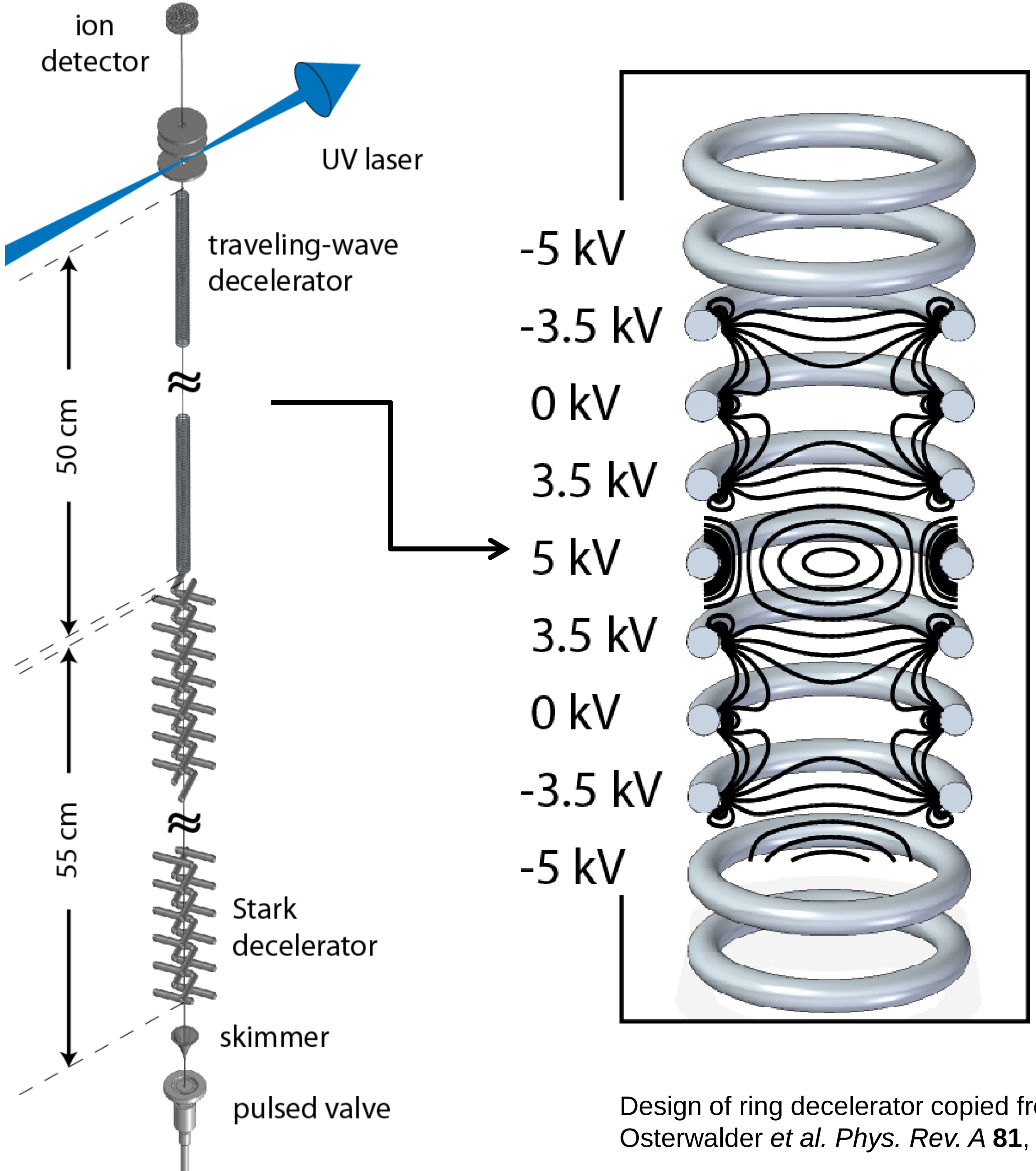
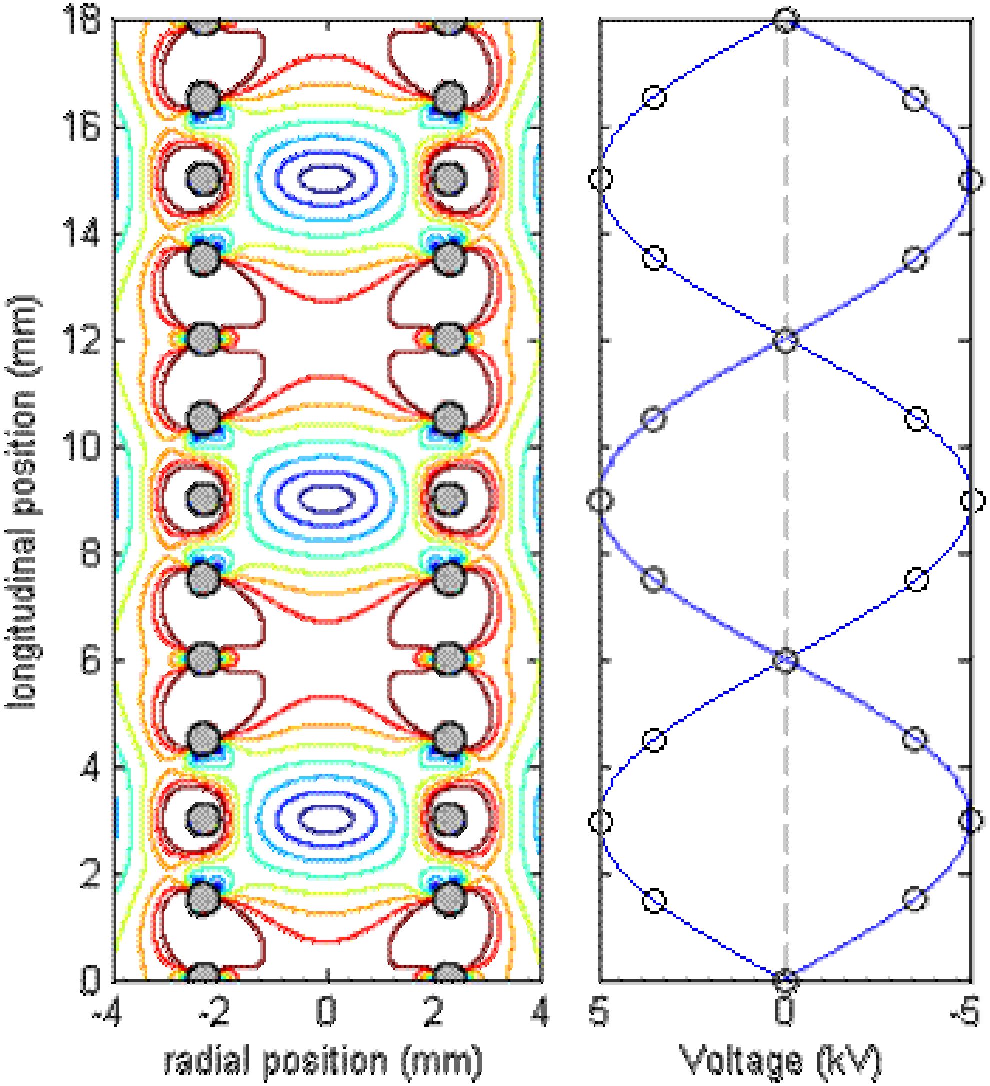
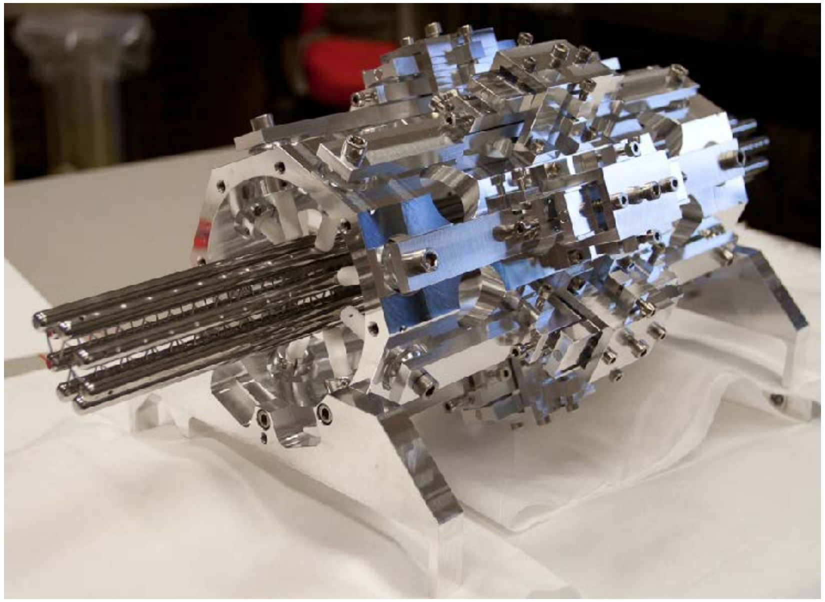


Design of ring decelerator copied from
Osterwalder *et al. Phys. Rev. A* **81**, 051401(R) (2010).

Operation principle of ring-type decelerator





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

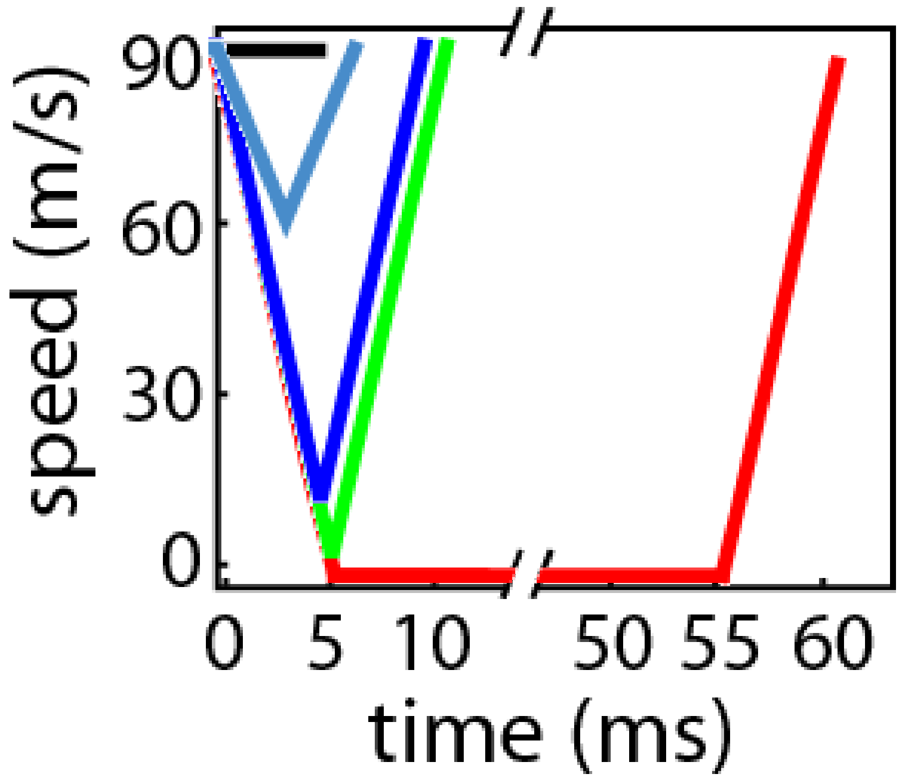
492mm long, consisting of 328 rings with 4 mm inner diameter; Periodicity 12 mm.

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

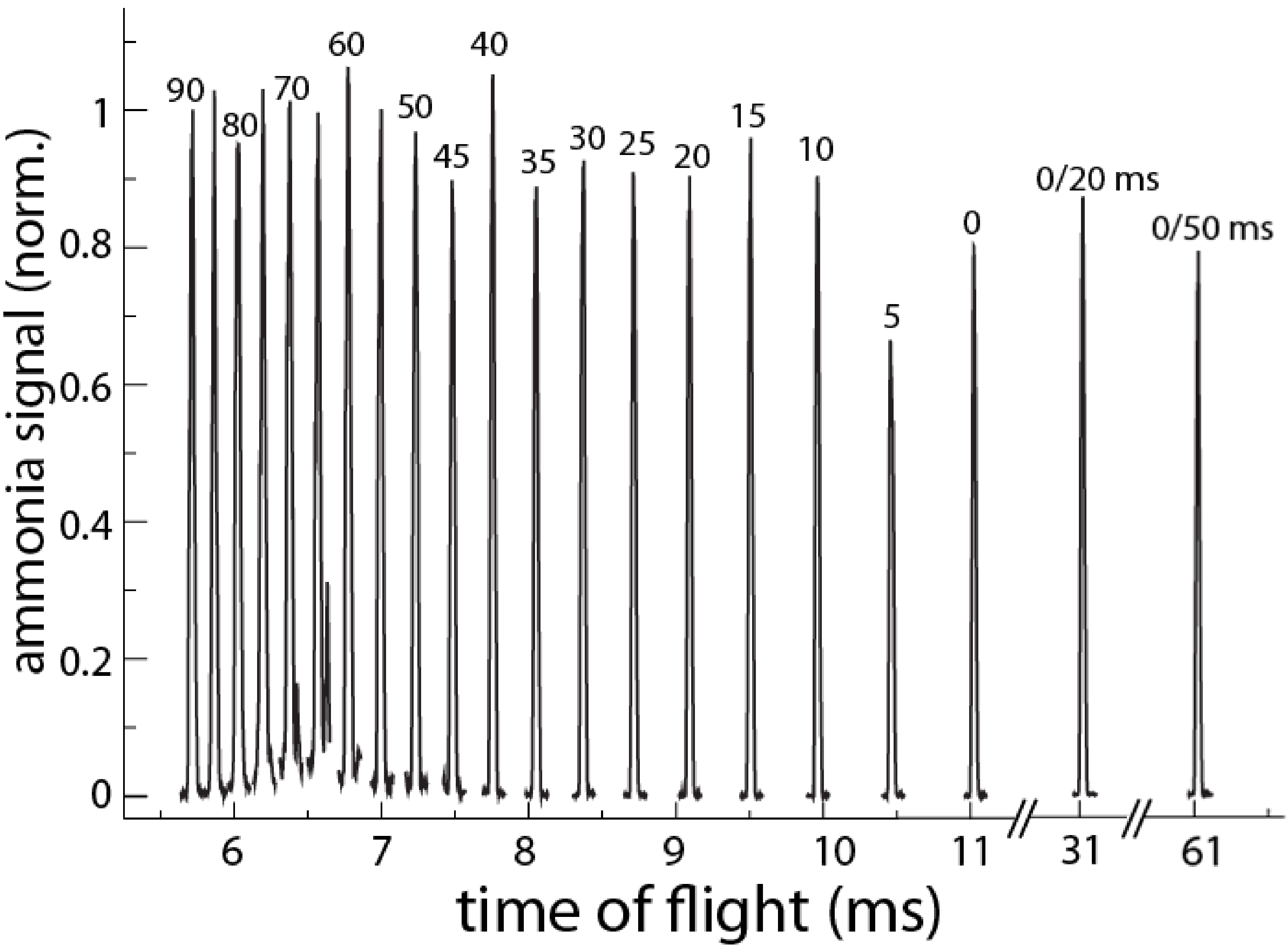
10 kV (peak to peak), frequency 0-15 kHz.

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

Guiding, Decelerating…

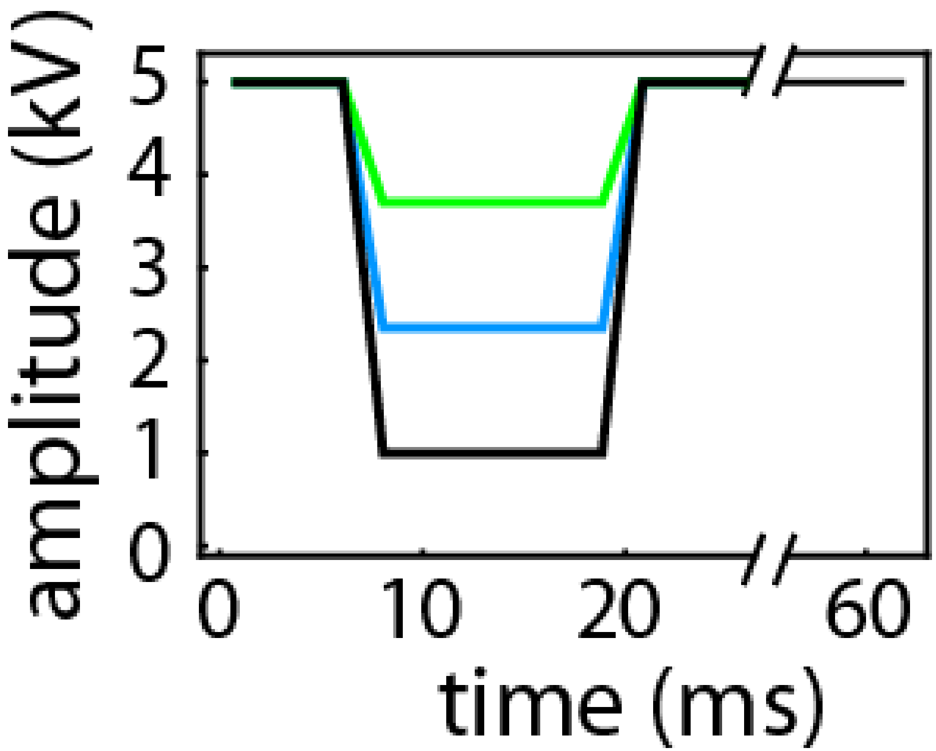


Guiding, Decelerating…



M. Quintero-Pérez *et al. PRL* **110**, 133003 (2013), JMS **300**, 112 (2014), P. Jansen *et al. PRA* **88**, 043424 (2013).

Adiabatic cooling



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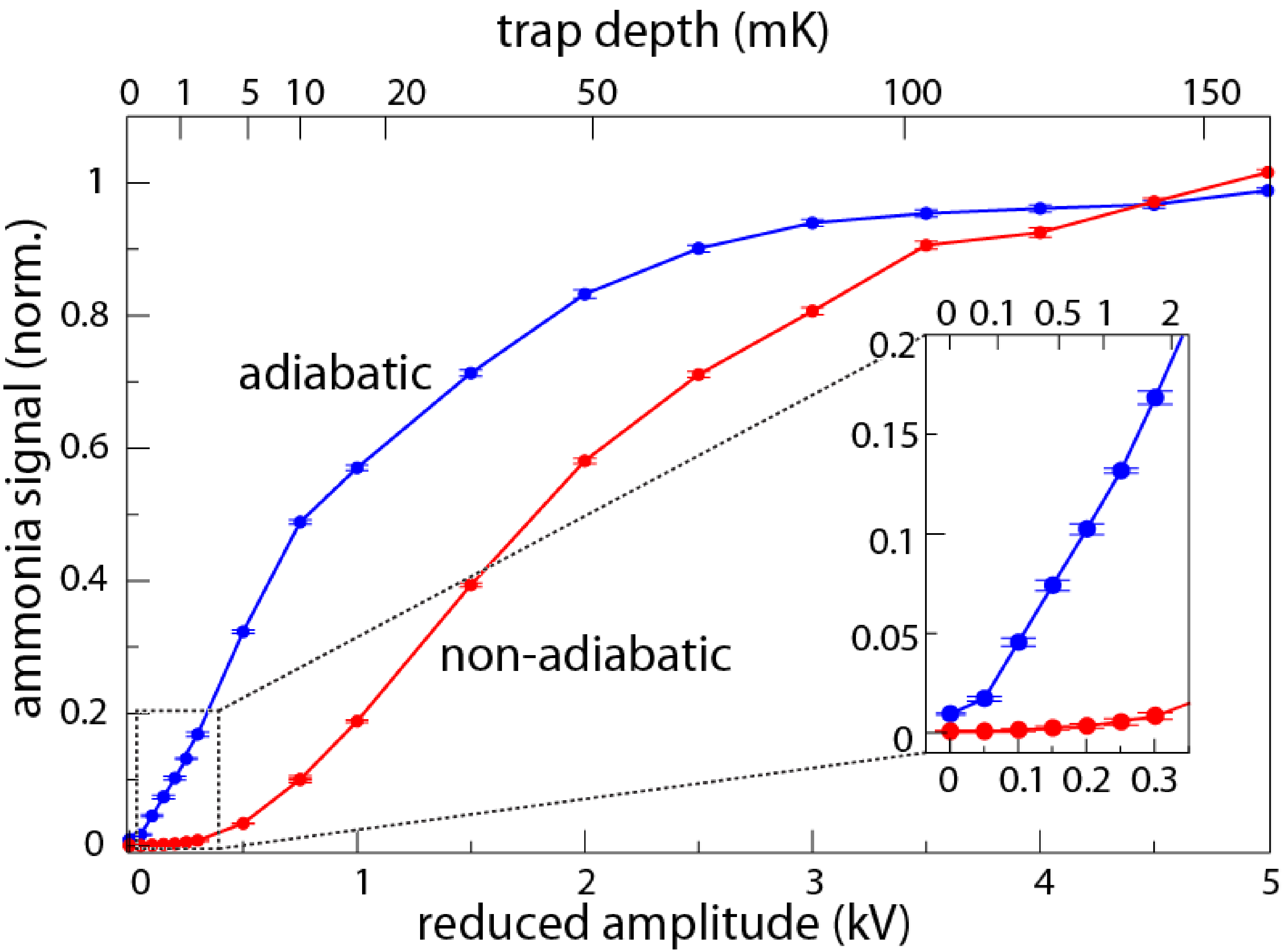
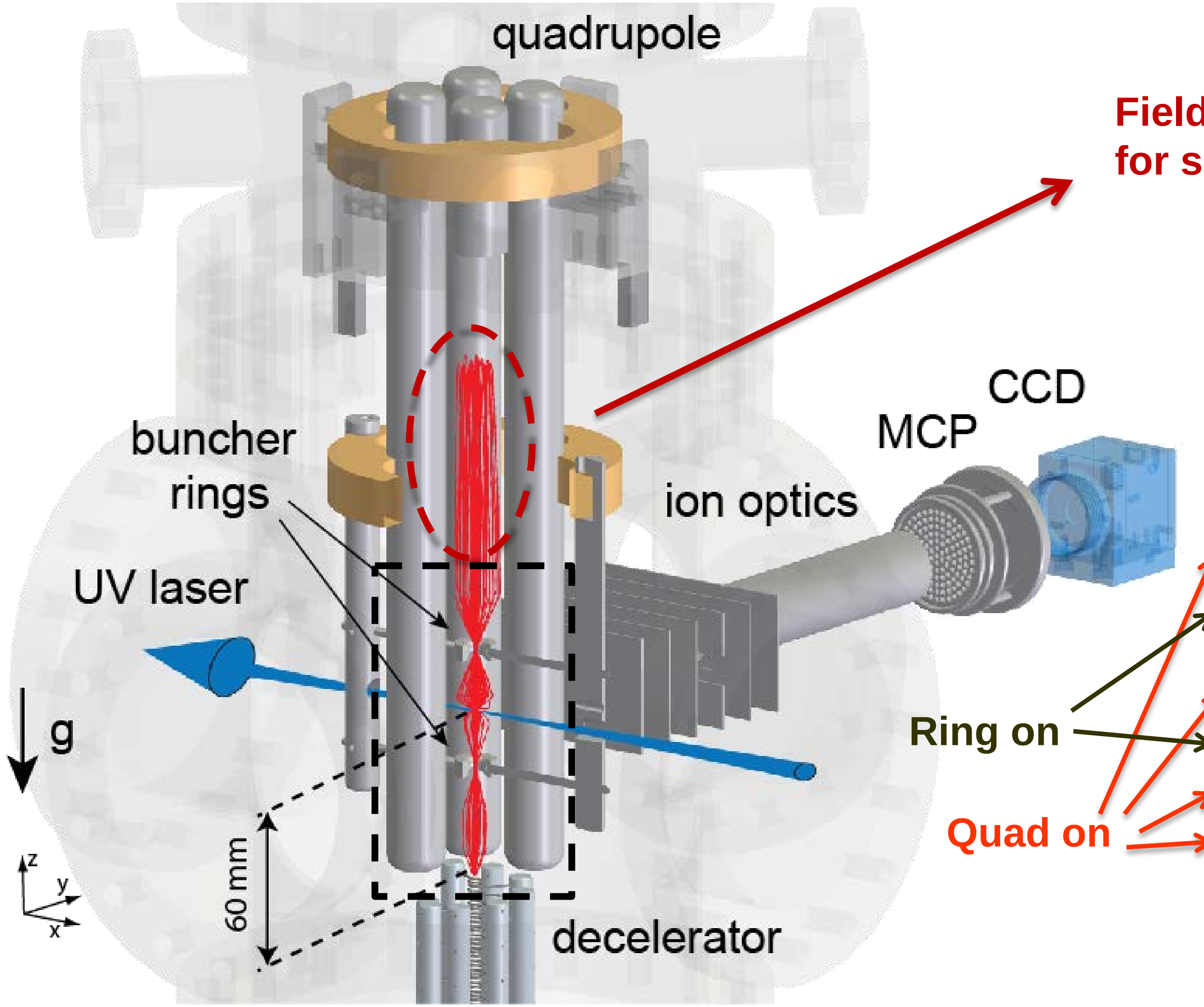
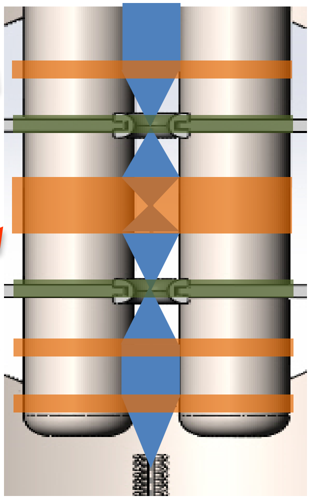


New lens system





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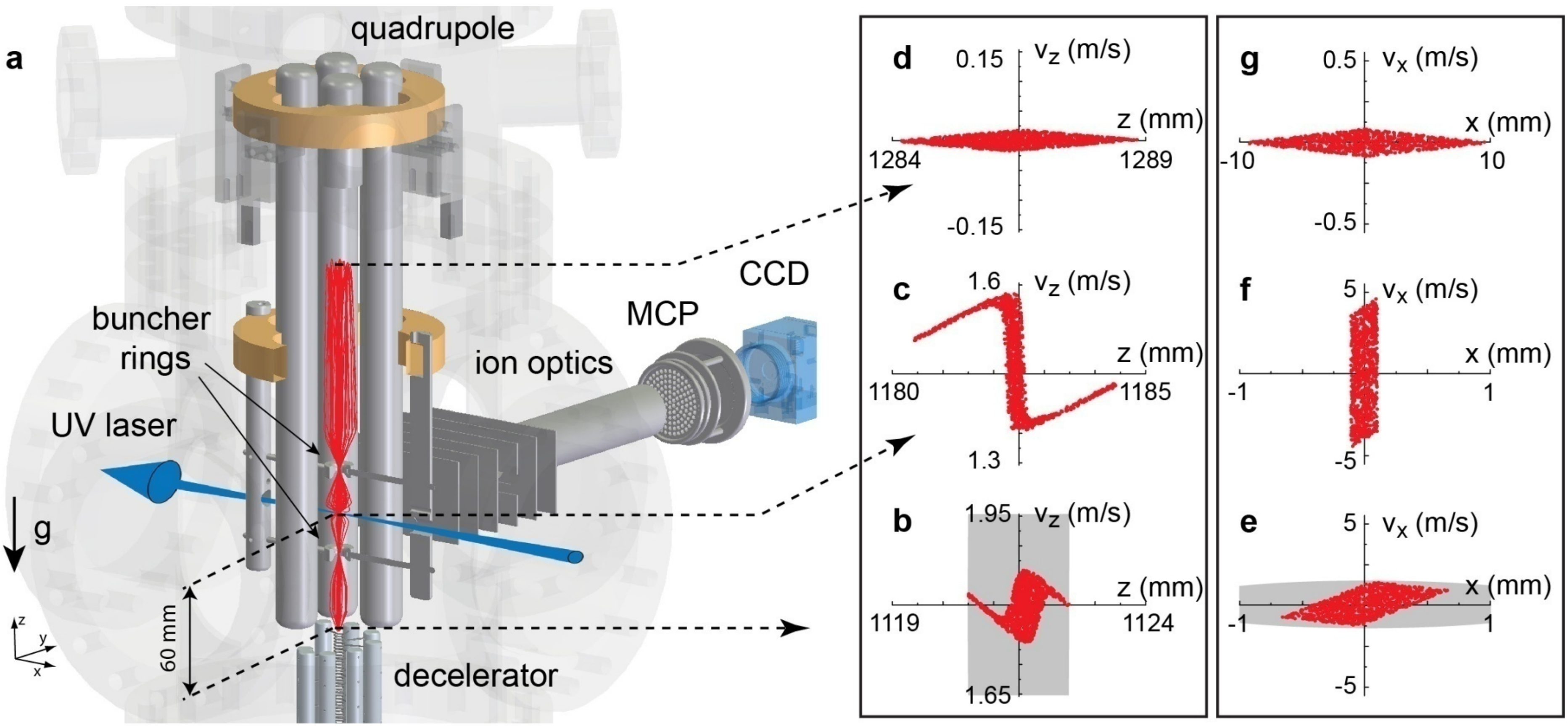
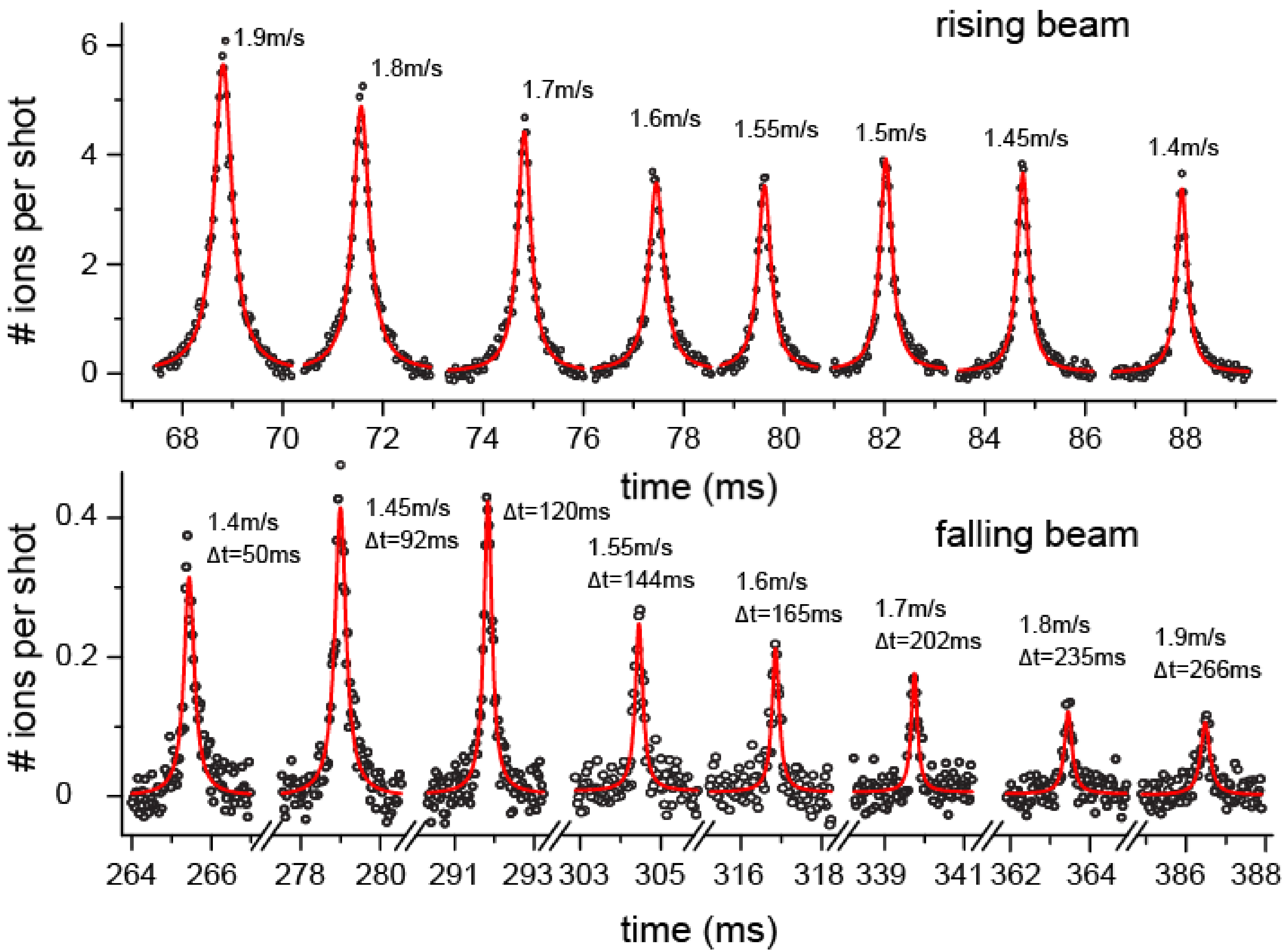


A molecular fountain



C. Cheng *et al. PRL* **117**, 253201 (2016).

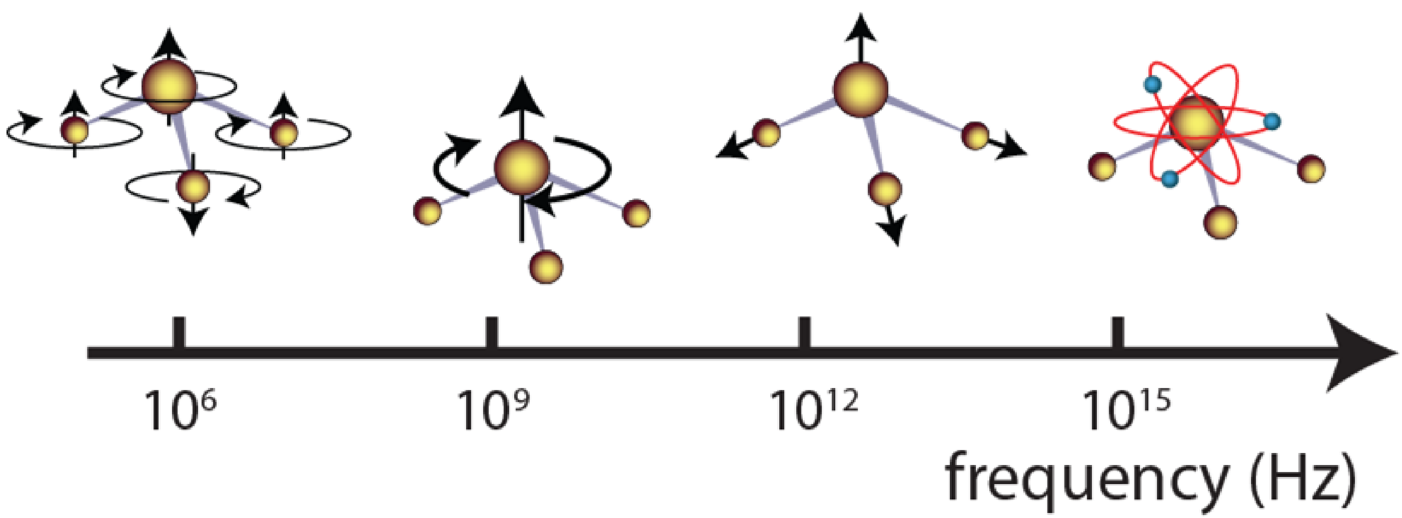
Molecular fountain

A molecular fountain based on a Stark decelerated molecular beam was made possible by three crucial improvements:

– A **traveling wave decelerator** that is virtually immune for losses at low velocity and can be used to cool the trapped molecules by adiabatic expansion; (**Phase-space density of slow beam > 10^{-11}**).
– A **compact lens system** that is easy to optimise.
– Elimination of background by detecting only slow molecules using a **VMI** ion lens system.

Future plans

– Measure the RF spectrum.
– Measure the inversion frequency.
– Measure 2-photon vibrational
transitions (2v1 +2v3) around 1.5 micron.
– Other molecules (BaF!?)



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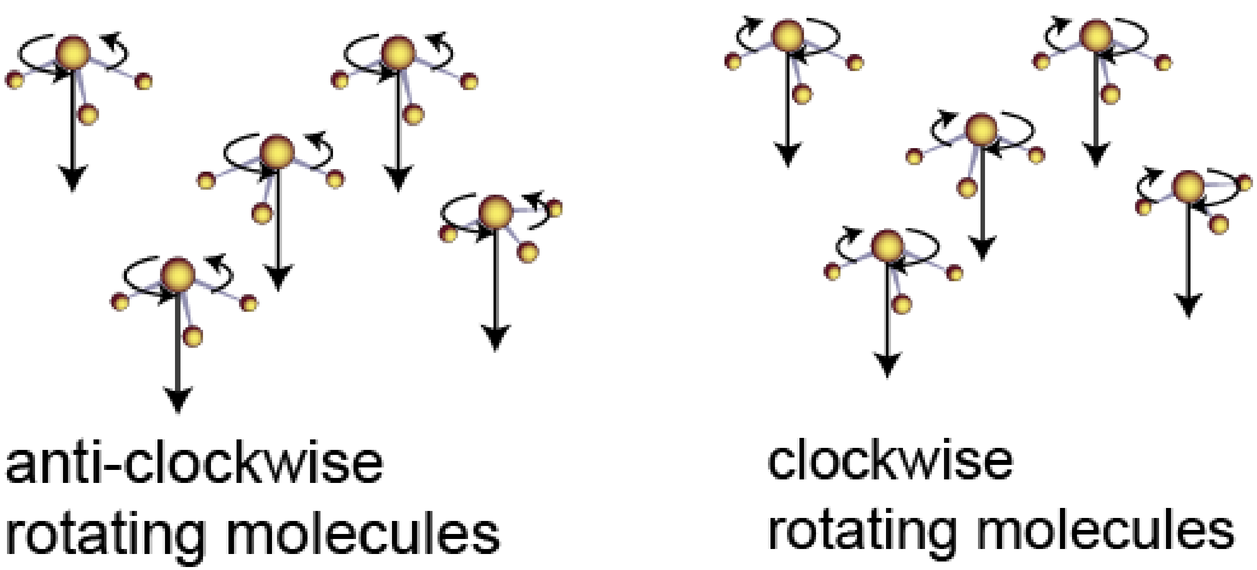
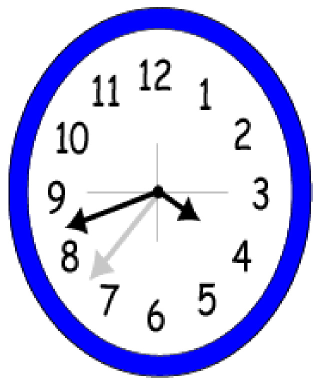
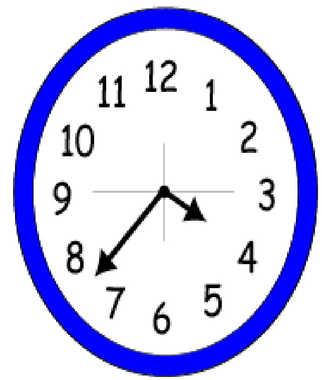
– Test Einstein's Equivalence Principle for rotating molecules.



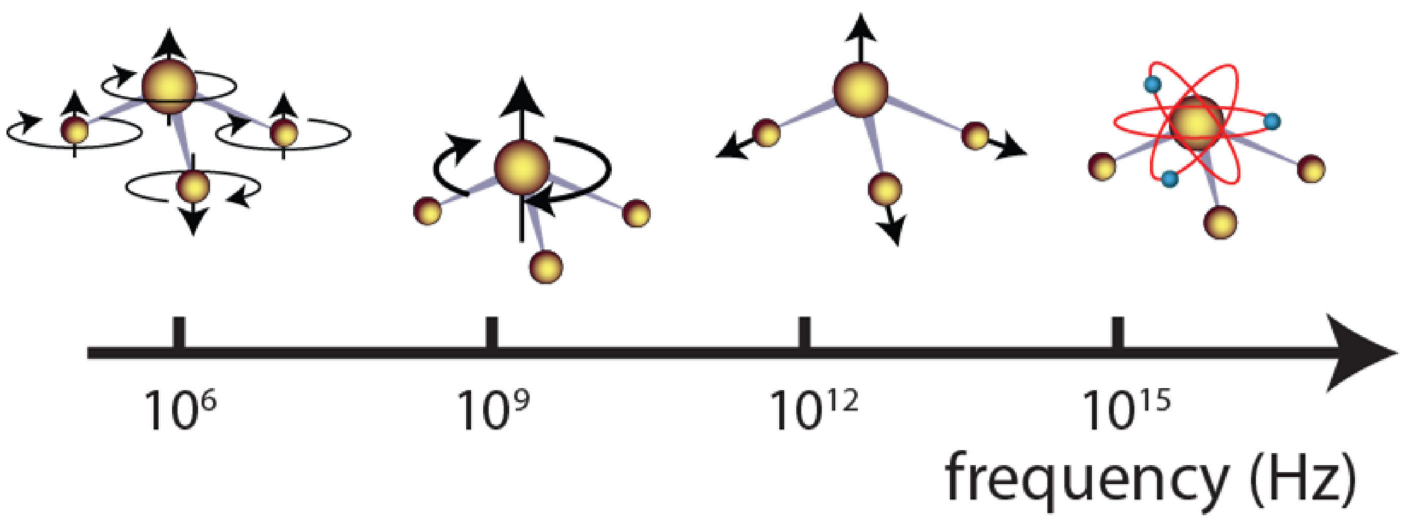
Time variation of fundamental constants



Clock based on rotation



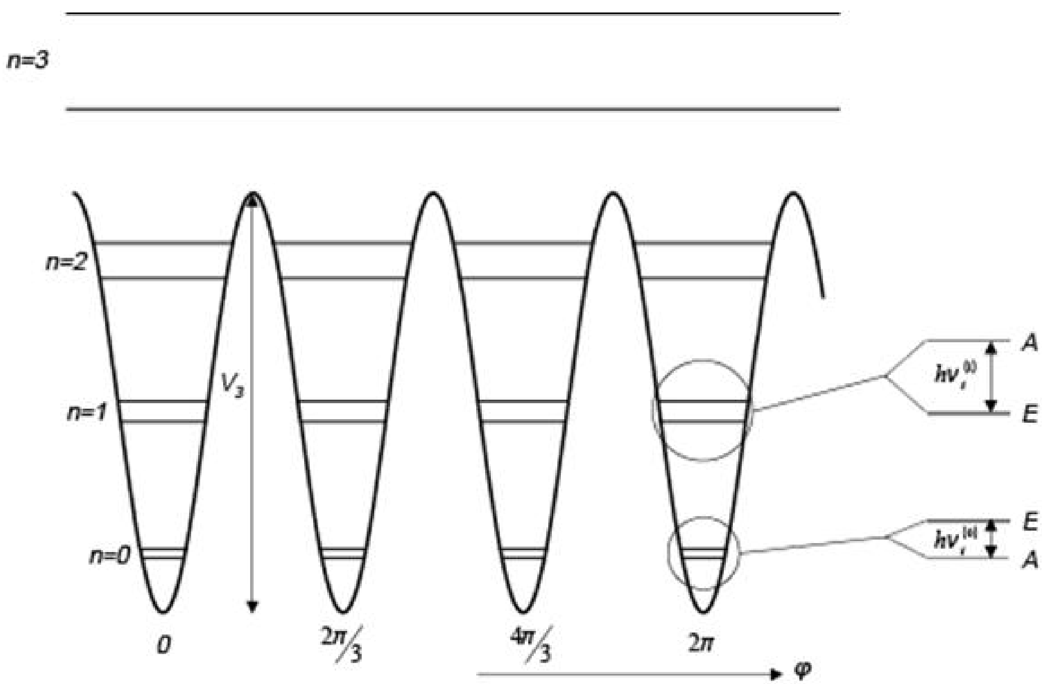
Clock based on vibration

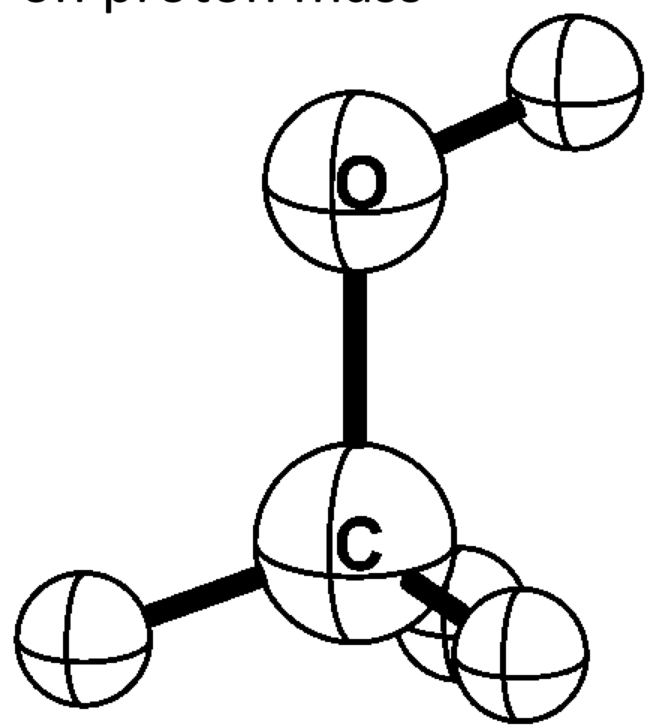


Hindered rotation in Methanol

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) (See also Levshakov, Kozlov, Reimers, *Astrophys. J.* **738**, 26 (2011)).

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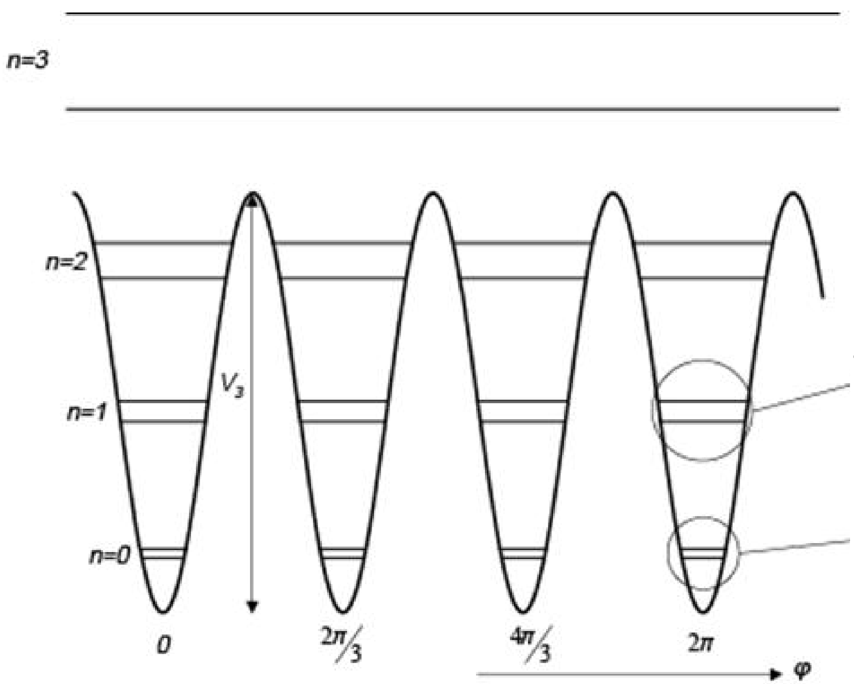
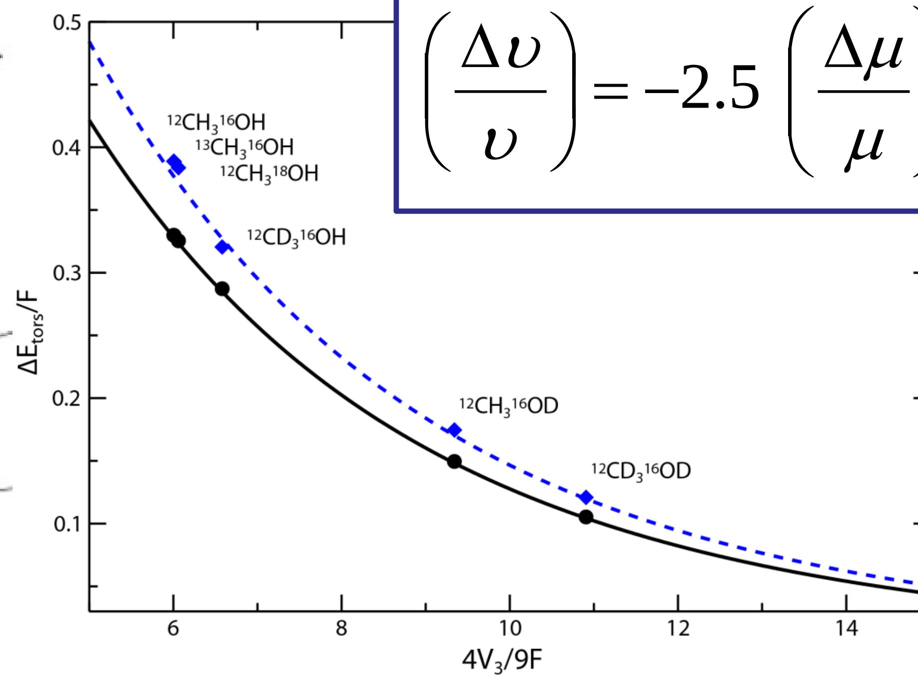
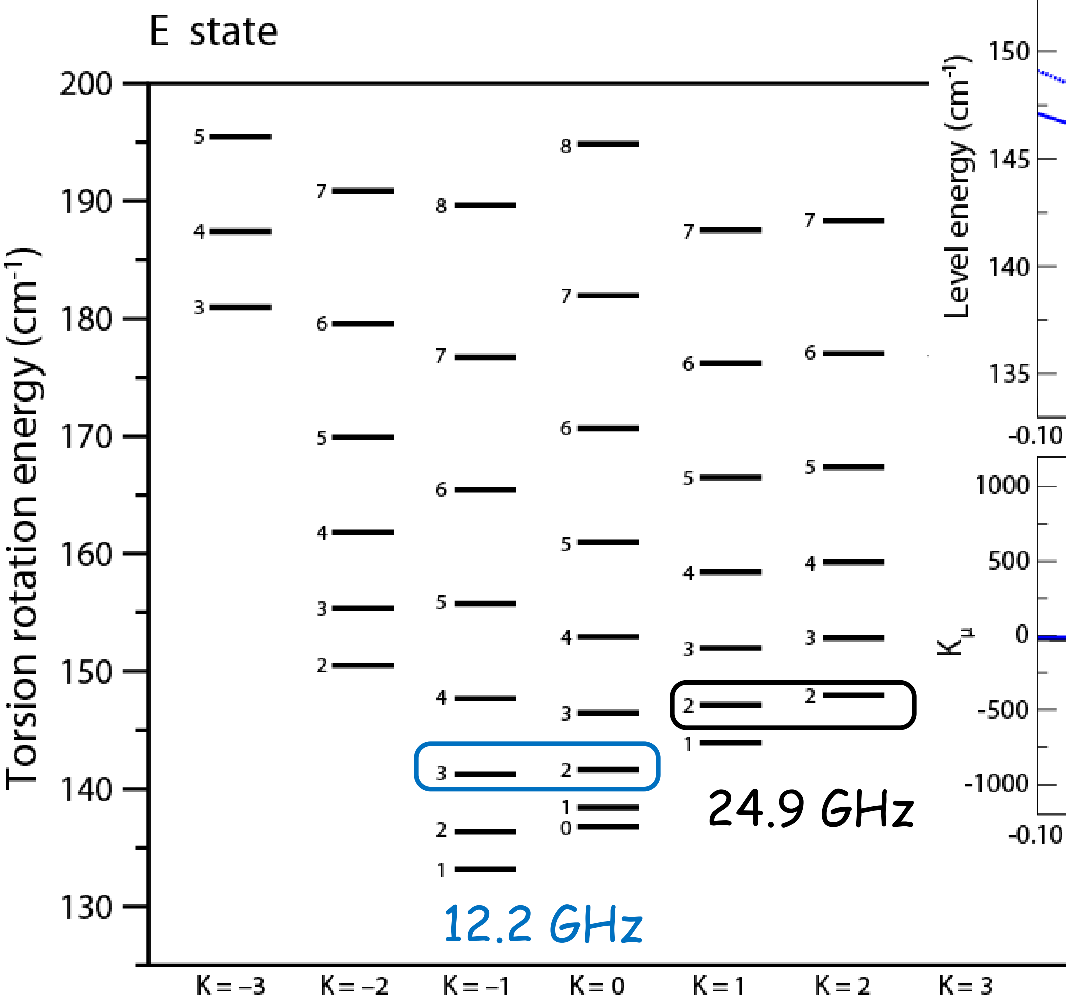


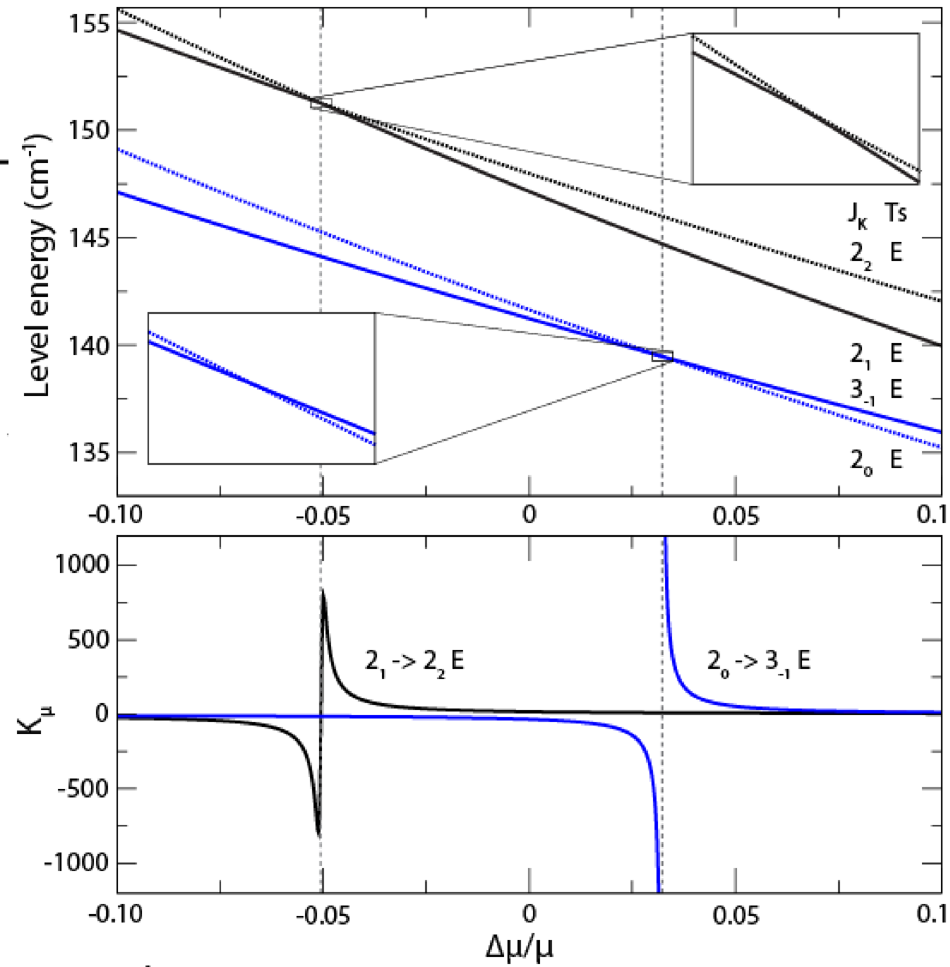


$$\left(\frac{\Delta\upsilon}{\upsilon}\right) = -2.5\left(\frac{\Delta\mu}{\mu}\right)$$

P. Jansen *et al. PRL* **106**, 100801 (2011) (See also Levshakov, Kozlov, Reimers, *Astrophys. J*. **738**, 26 (2011)).

Near degeneracies in level scheme

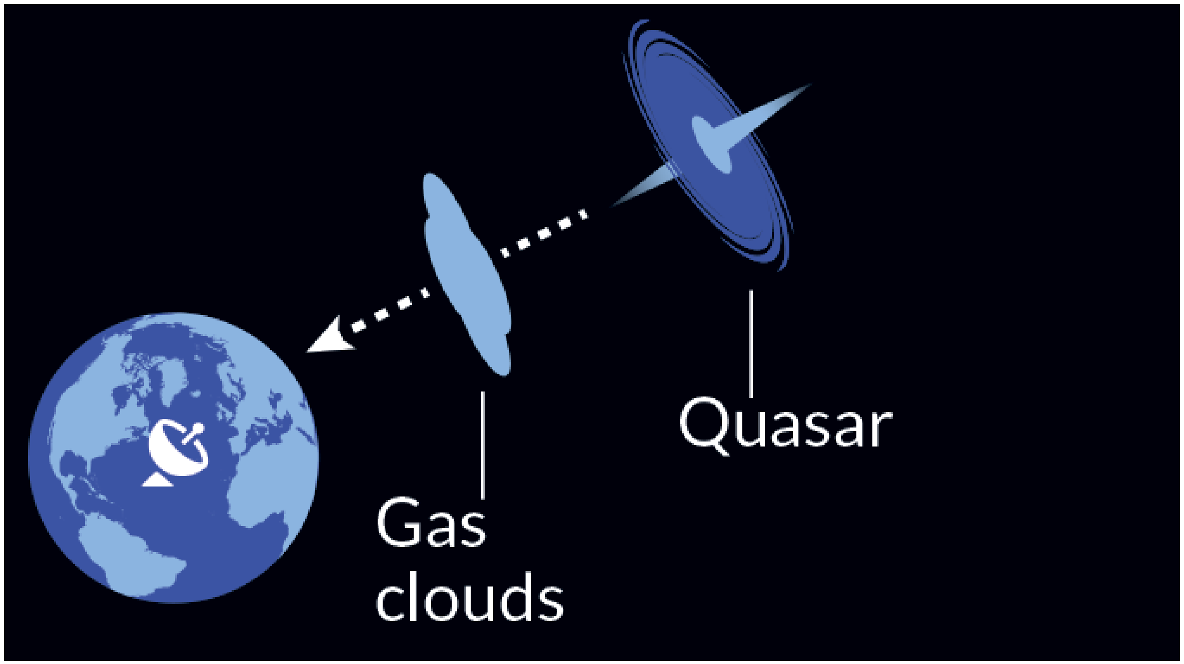




K_μ = -33 K_μ =+18

Effelsberg Radio Telescope

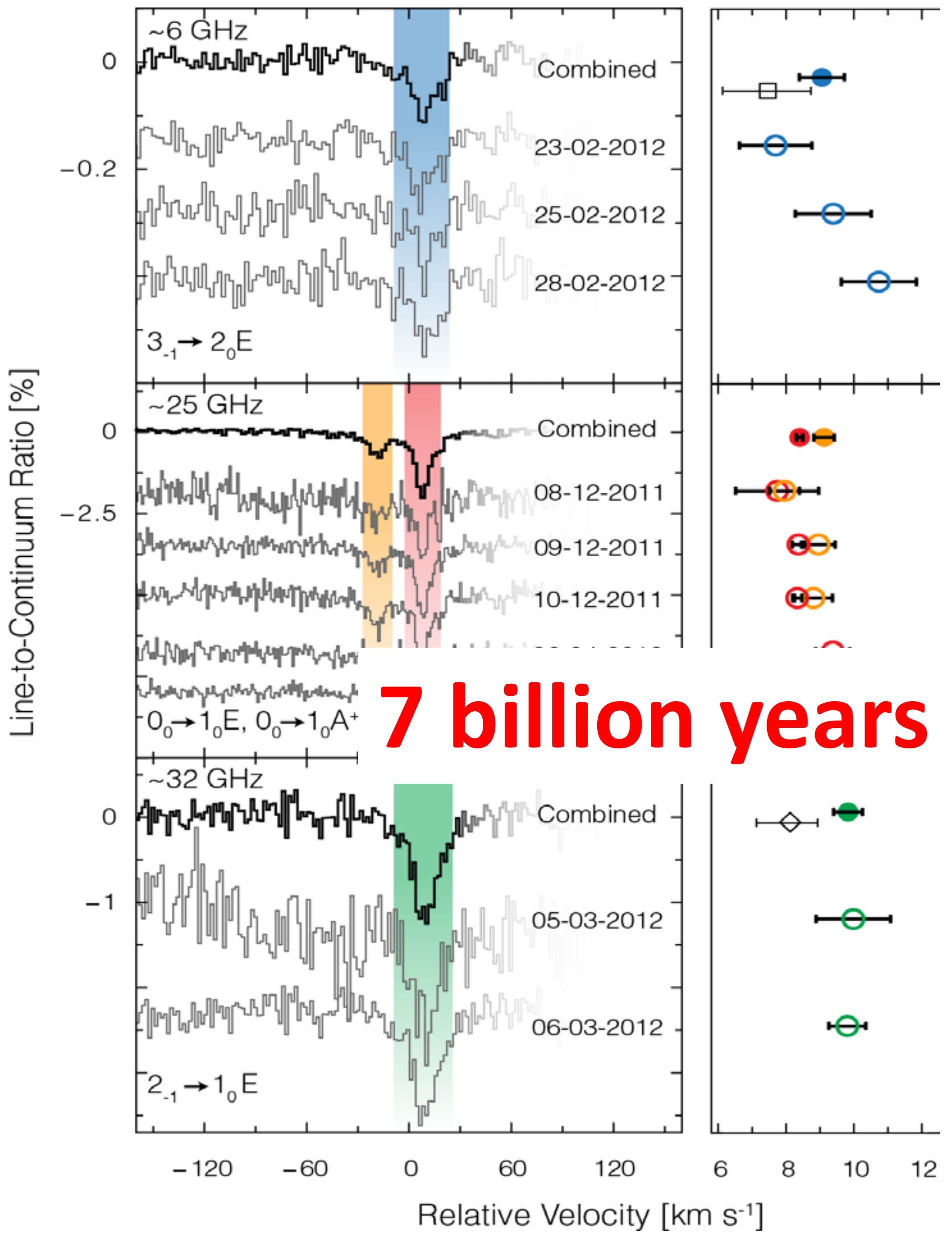
Methanol in line of sight of PKS-1830-211



– Very bright (radio-loud) quasar, pointing right at us
– Intervening cloud (at z=0.89) very rich of molecules
– cloud acts as gravitational lens

Methanol in PKS-1830-211

Intergalactic alcohol



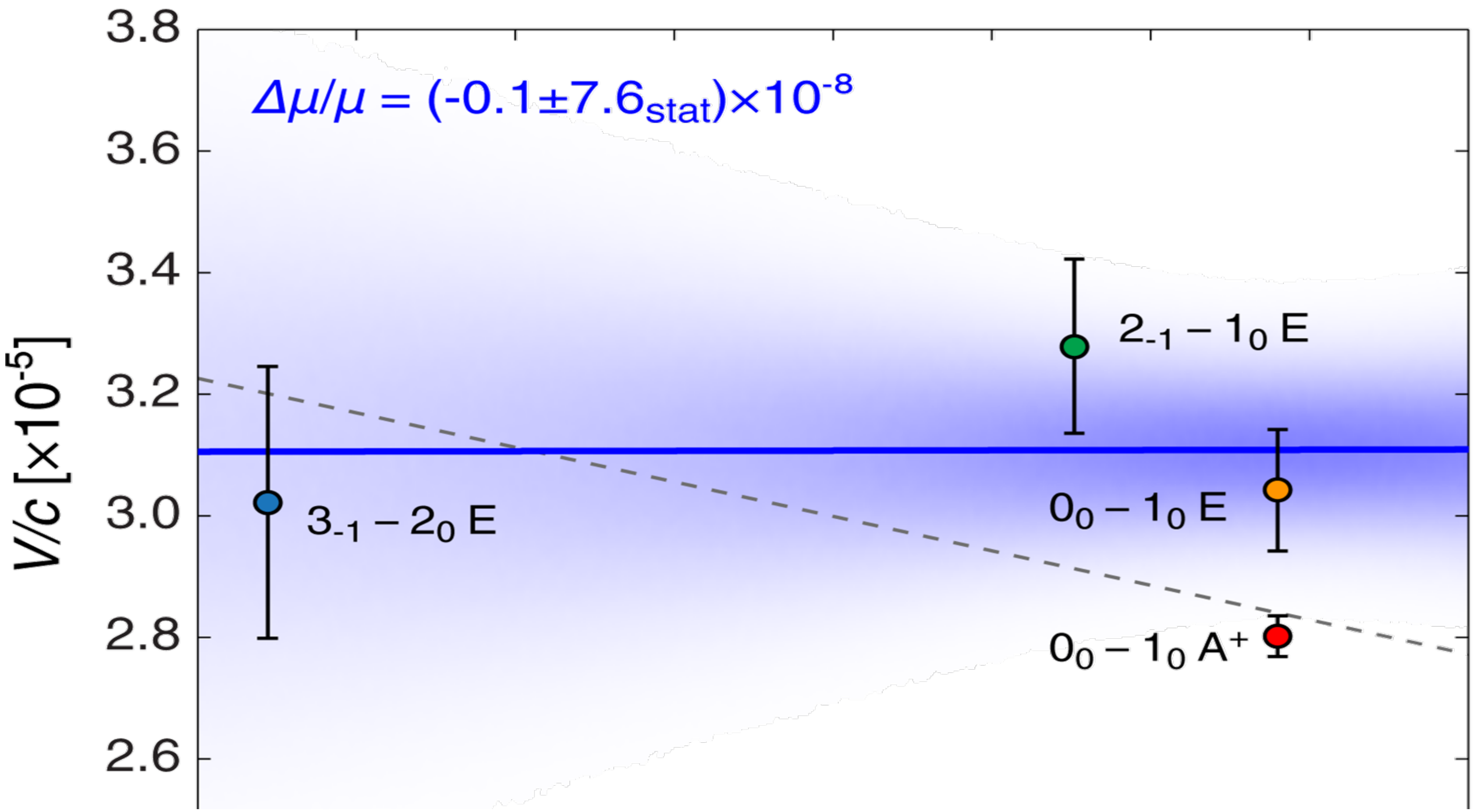
K=-33

K=-1

K=-7

7 billion years look-back time!!

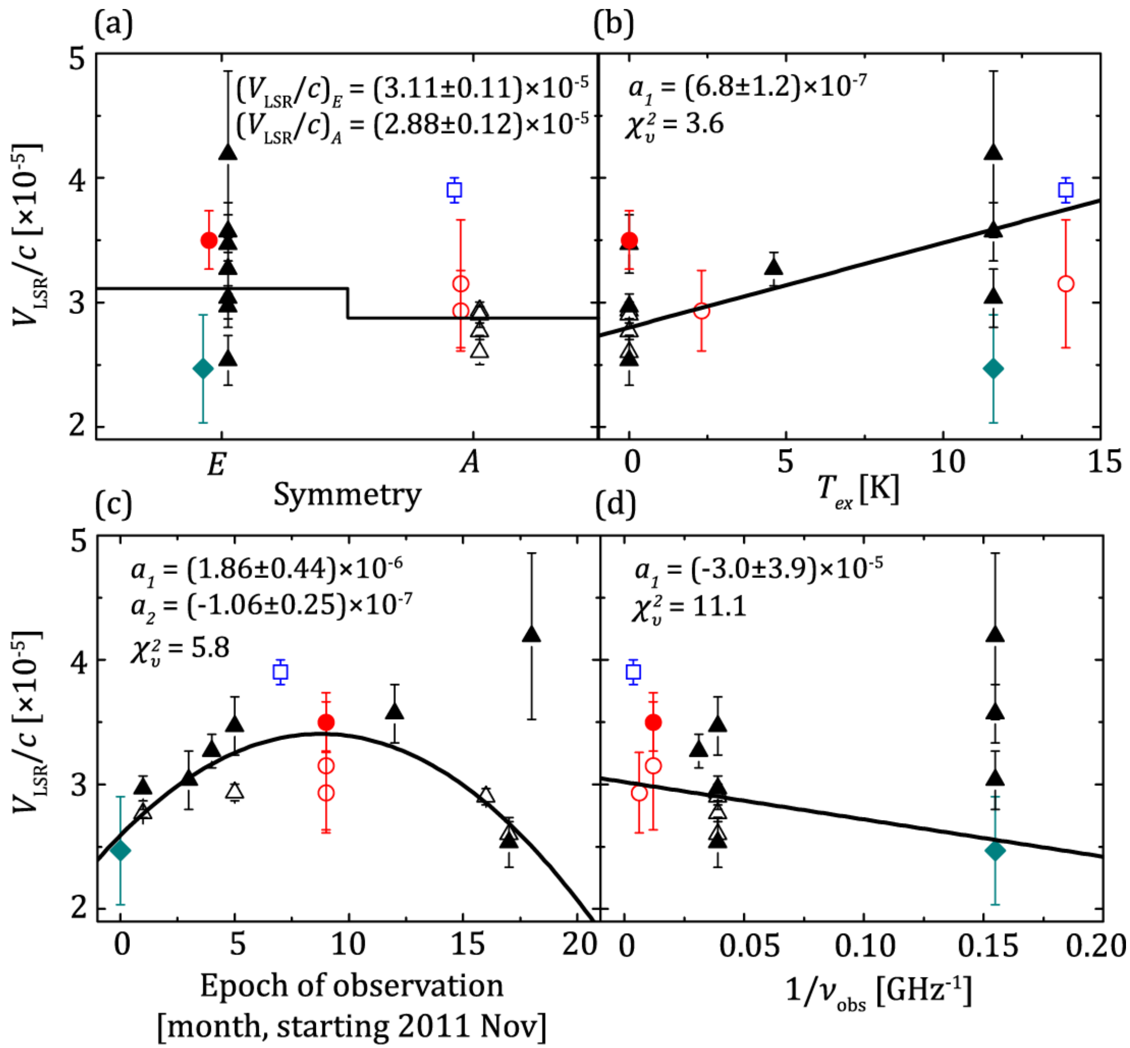
Constraint on time-variation of μ



Molecular mass has remained unchanged during the last 7 billion years; $\Delta\mu/\mu < 1 \times 10^{-17}$ yr^{-1}

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

Constraint on time-variation of μ

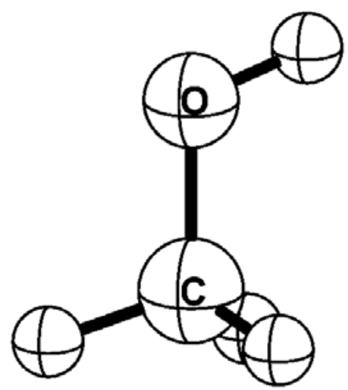


J. Bagdonaite *et al.* PRL **111**, 131101 (2013).

Constraining the time-variation of fundamental constants with methanol

-Most stringent on a possible time-variation of the proton to electron mass ratio; corresponding to $\Delta\mu/\mu < 1 \times 10^{-17}\ yr^{-1}$

-Astrophysical measurements limited by systematic effects; new measurements on the way using ALMA and the VLA measuring simultaneously.



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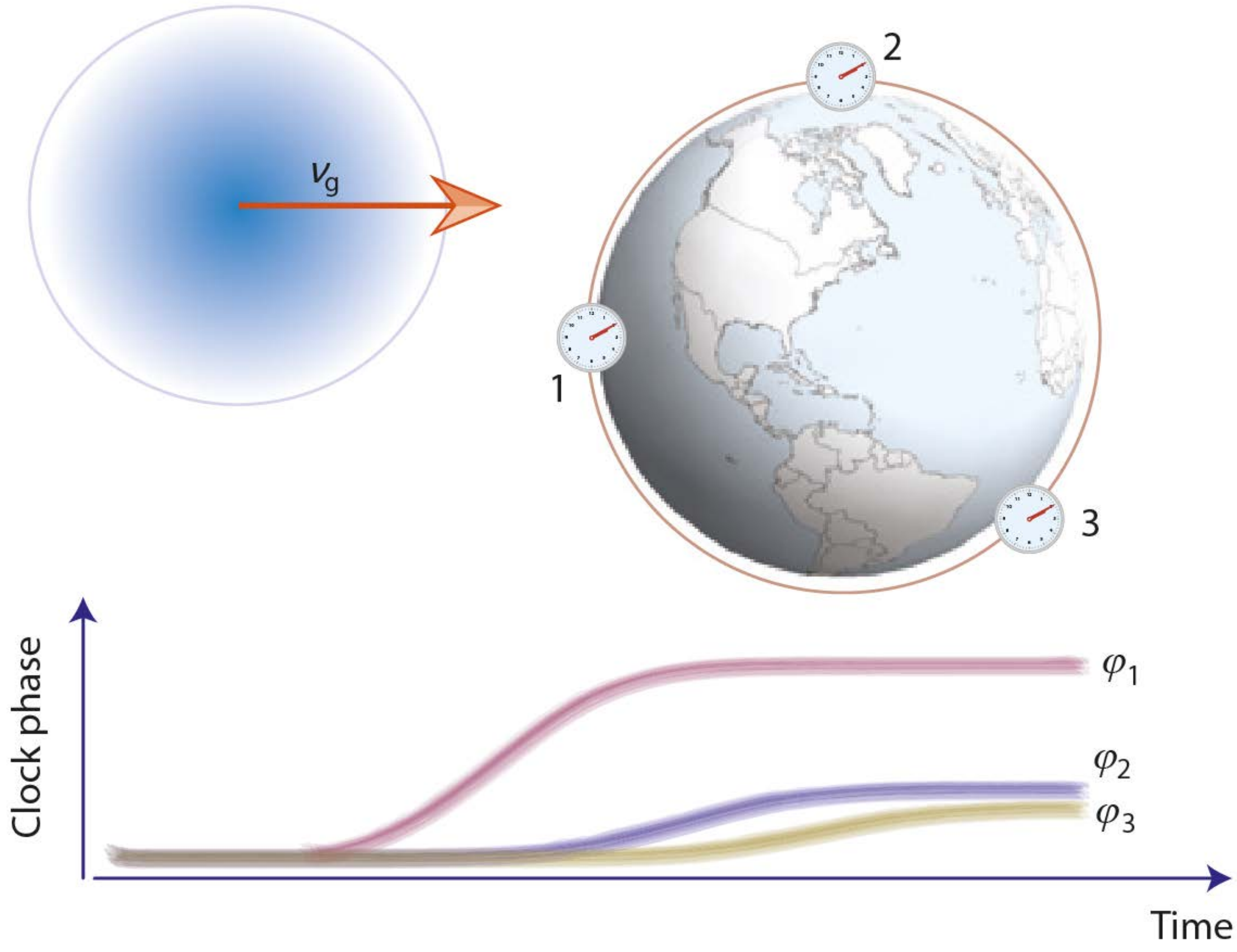
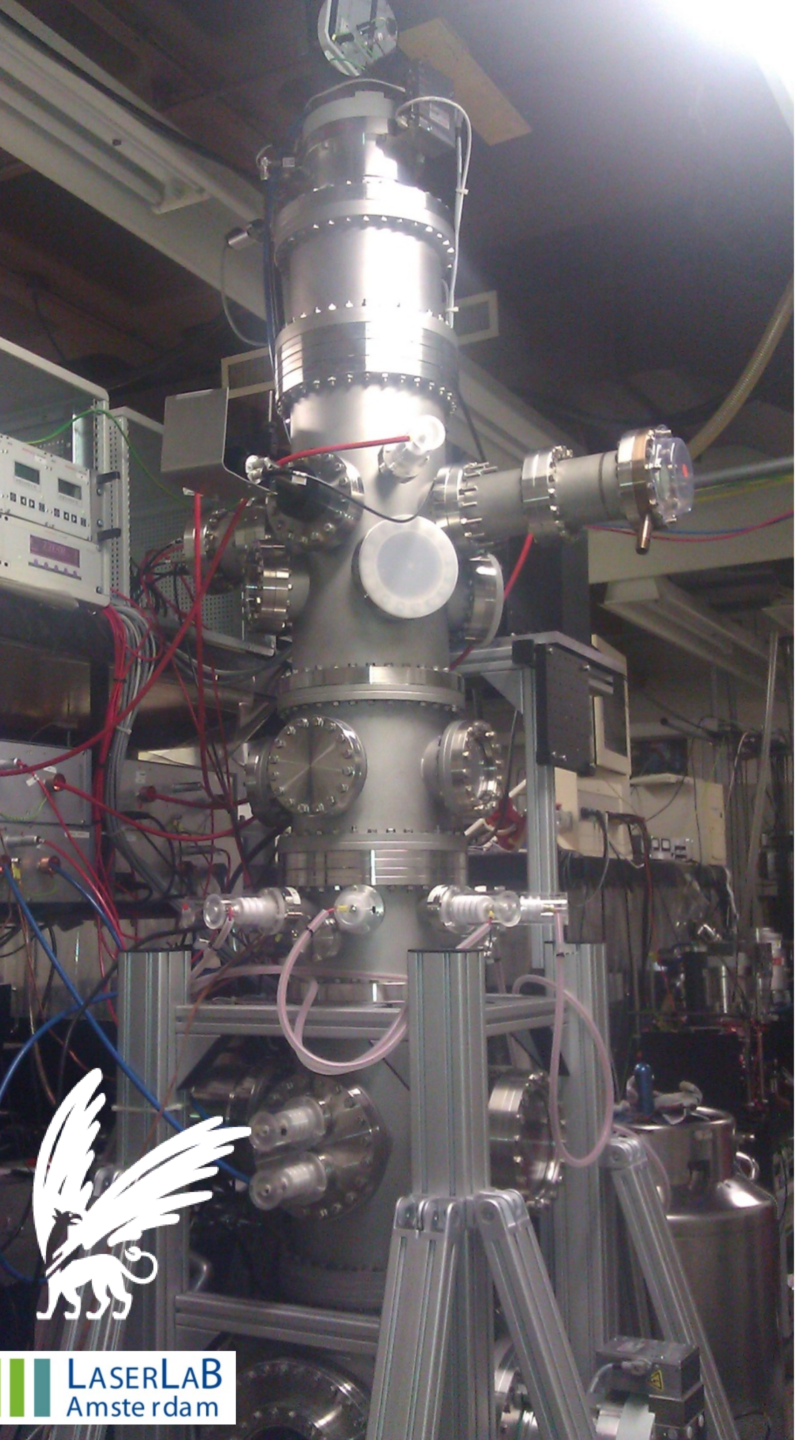
Dark matter causes a shift of μ



Derevianko and Pospelov, Nature Physics **10**, 933 (2015)



Molecular Fountain:
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Methanol:
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