New Opportunities for Fundamental Physics Research
with Radioactive Molecules, Online, July. 2, 2021

Measurement of the Variation of Electron-to-Proton Mass Ratio Using Ultracold Molecules Produced from Laser-Cooled Atoms

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Collaborator:
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Motivation: variation of fundamental constants over time

Various theories postulates oscillating scaler field to account for dark matter/dark energy

"Quintessence is a hypothetical form of dark energy, more precisely a scalar field, postulated as an explanation of the observation of an accelerating rate of expansion of the universe."

"Scalar field dark matter is a classical, minimally coupled, scalar field postulated to account for the inferred dark matter."

(In both theories, frequency is set by the mass of the particle: $\omega = \frac{mc^2}{\hbar}$)

Coupling to EM fields and/or ordinary matter can cause variation of fundamental constants over time

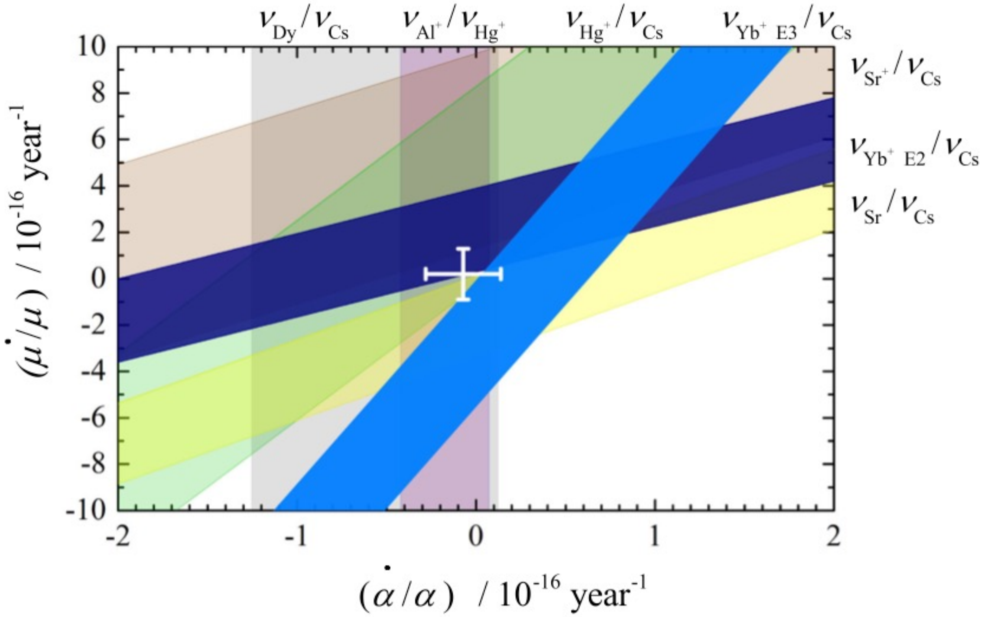
→Candidates for experimental tests:

$$\alpha,\ \mu = \frac{m_e}{M_p}, g-2, \ldots$$

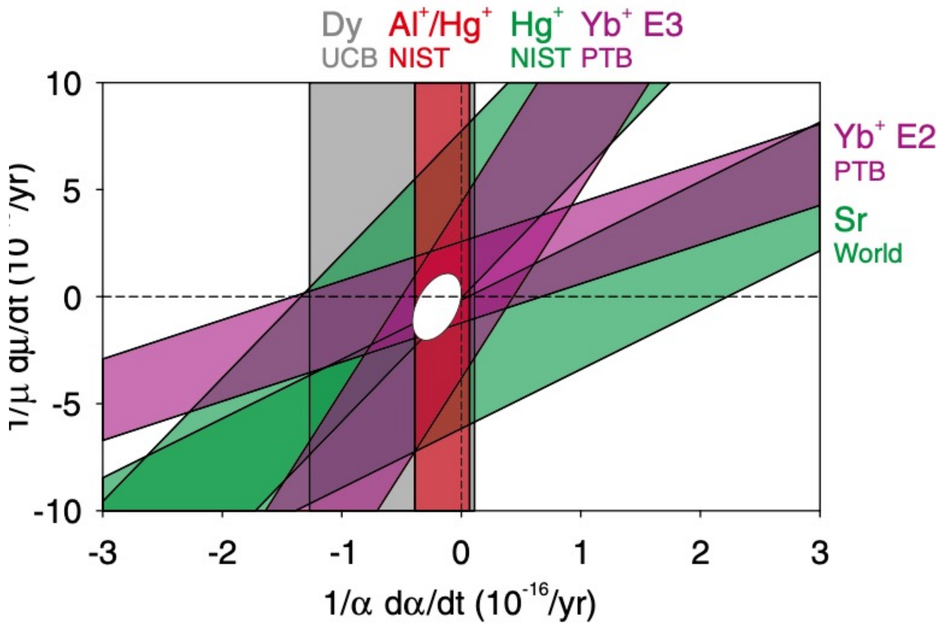
high precision atomic spectroscopy

optical lattice clock + Cs frequency standards

Sensitive to both α and $\mu = \frac{m_e}{M_p}$



R. M. Godun et al.,
PRL 113, 210801 (2014)

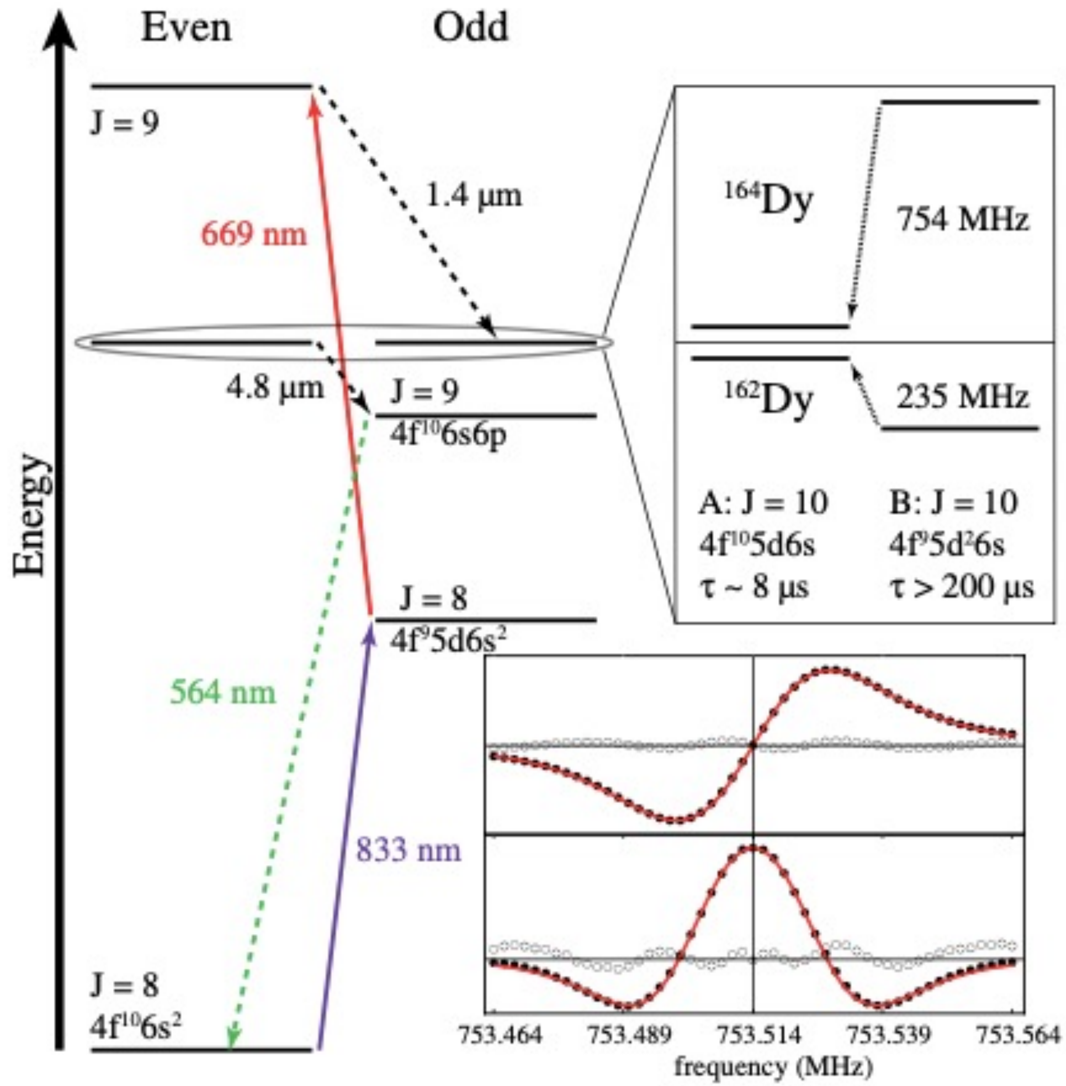


N. Huntemann et al
PRL 113, 210802 (2014)

PRL 111, 060801 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

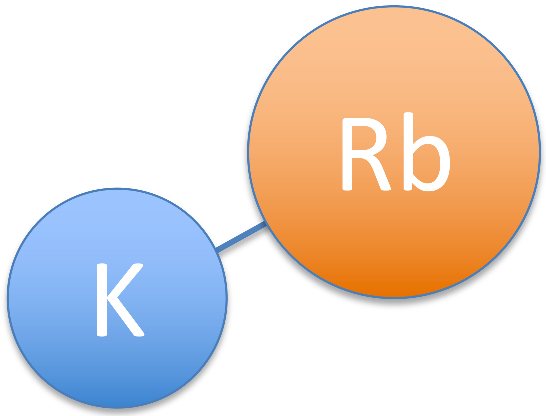
New Limits on Variation of the Fine-Structure Constant Using Atomic Dysprosium

N. Leefer,[1] C. T. M. Weber,[2] A. Cingöz,[3] J. R. Torgerson,[4] and D. Budker[1,5]



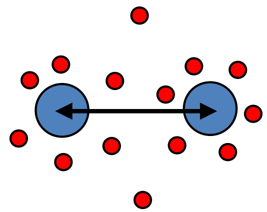
almost complete degeneracy of opposite-parity excited states

$$\dot{\alpha}/\alpha = (-5.8 \pm 6.9) \times 10^{-17}\ \mathrm{yr}^{-1}$$

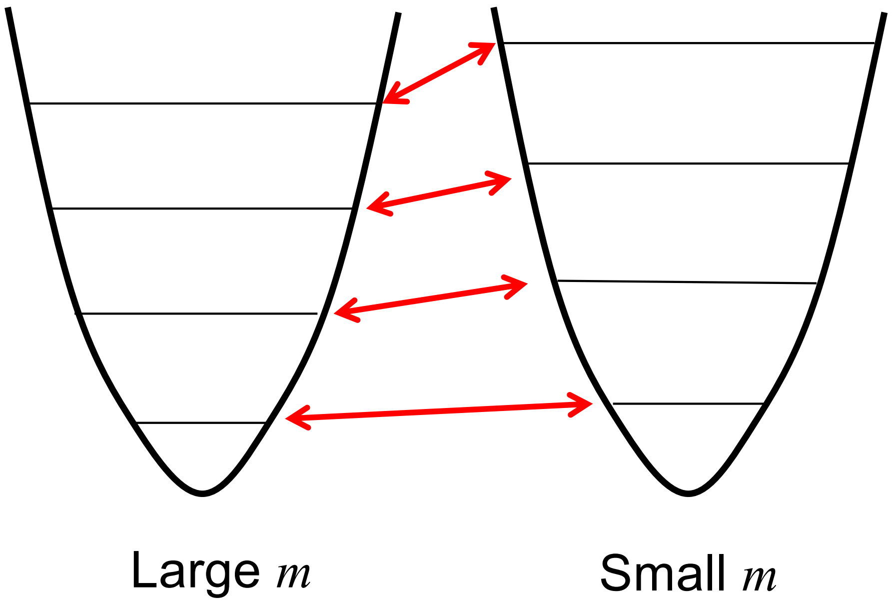


"Measurement of the variation of electron-to-proton mass ratio using ultracold molecules produced from laser-cooled atoms"
J. Kobayashi, A. Ogino and S. Inouye,
Nature Communications 10, 3771 (2019)

molecular spectra are sensitive to $\mu = \frac{m_e}{M_p}$



Molecular spectra are directly related to the inertial mass of nucleus.



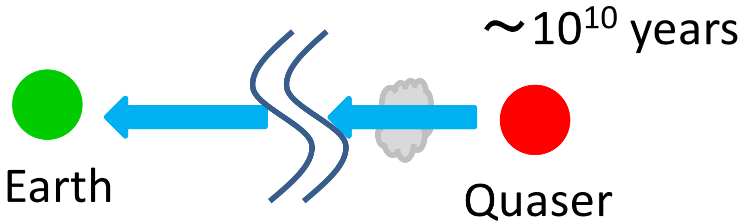
Relevant energy scales:

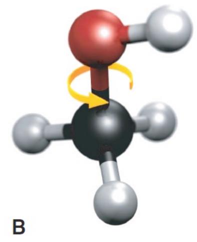
electronic $\propto \mu^0$

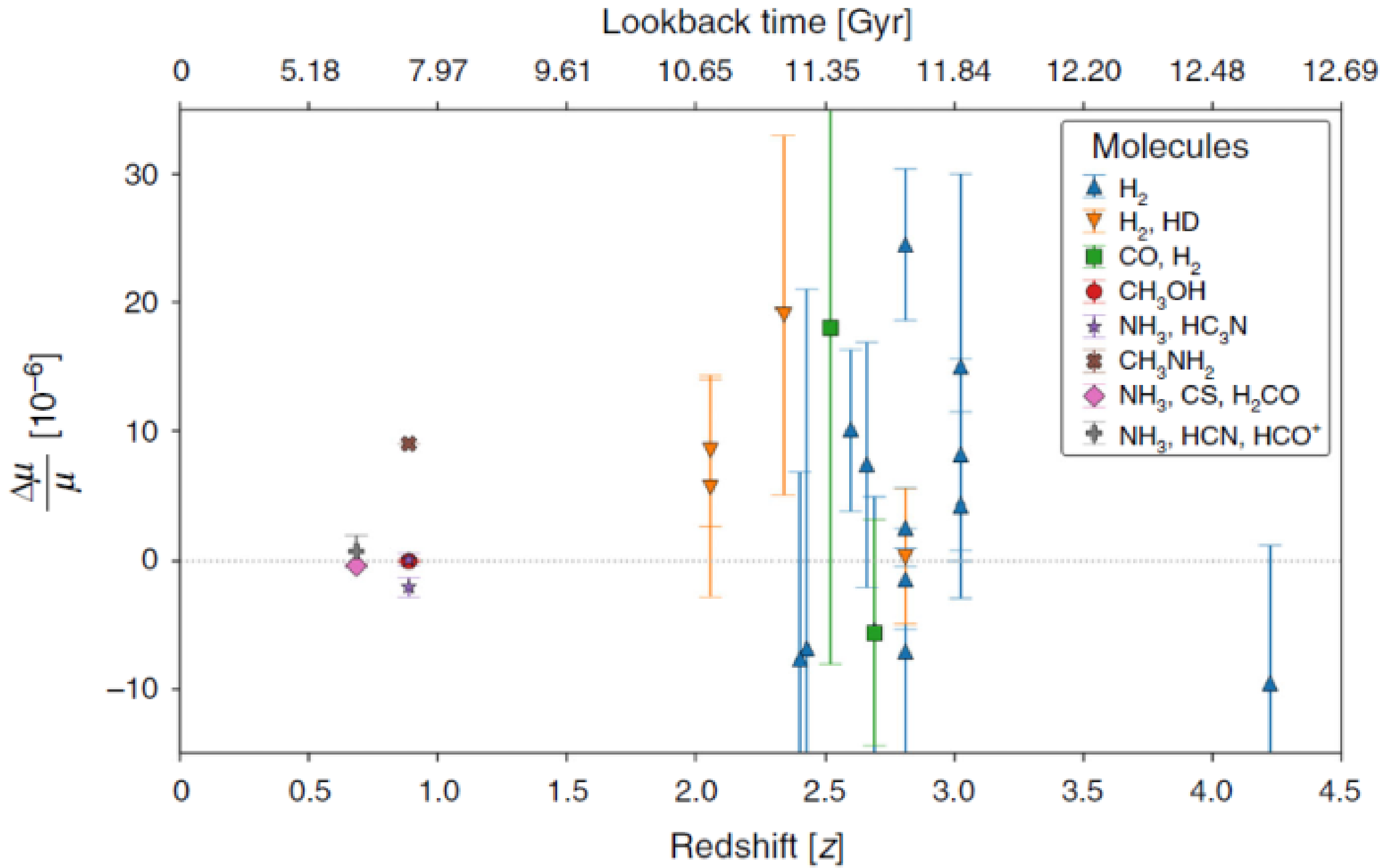
vibrational $\propto \frac{1}{\sqrt{\mu}}$

rotational $\propto \frac{1}{\mu}$

Radio-astronomical observations







S. Anna-Maree et al., *Aust. J. Chem.* (2019)

$$\frac{10^{-6}}{10^{10}\text{year}}$$

~10^{-16} /year

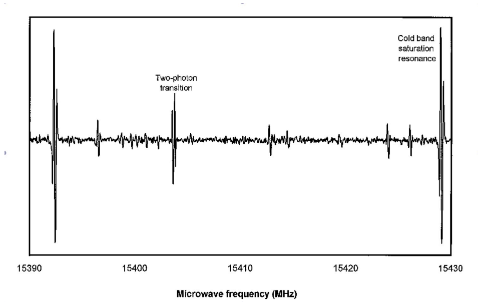
No definitive answer yet

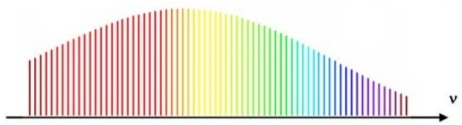
The limit of time variation of $m_e/M_p(\equiv\mu)$

Laboratory observations

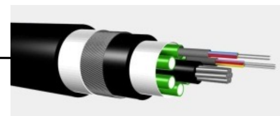
molecular spectroscopy of SF_6
A. Shelkovnikov et al, PRL 100, 150801 (2008)

$$\dot{\mu}/\mu = (3.8 \pm 5.6)\times 10^{-14} / year$$

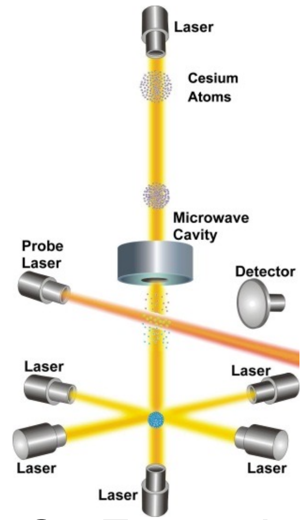




rovibrational transition in SF_6 + frequency comb

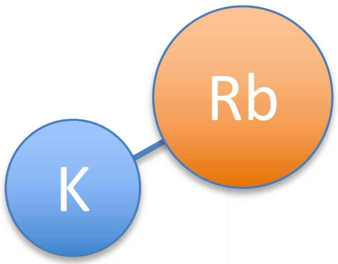


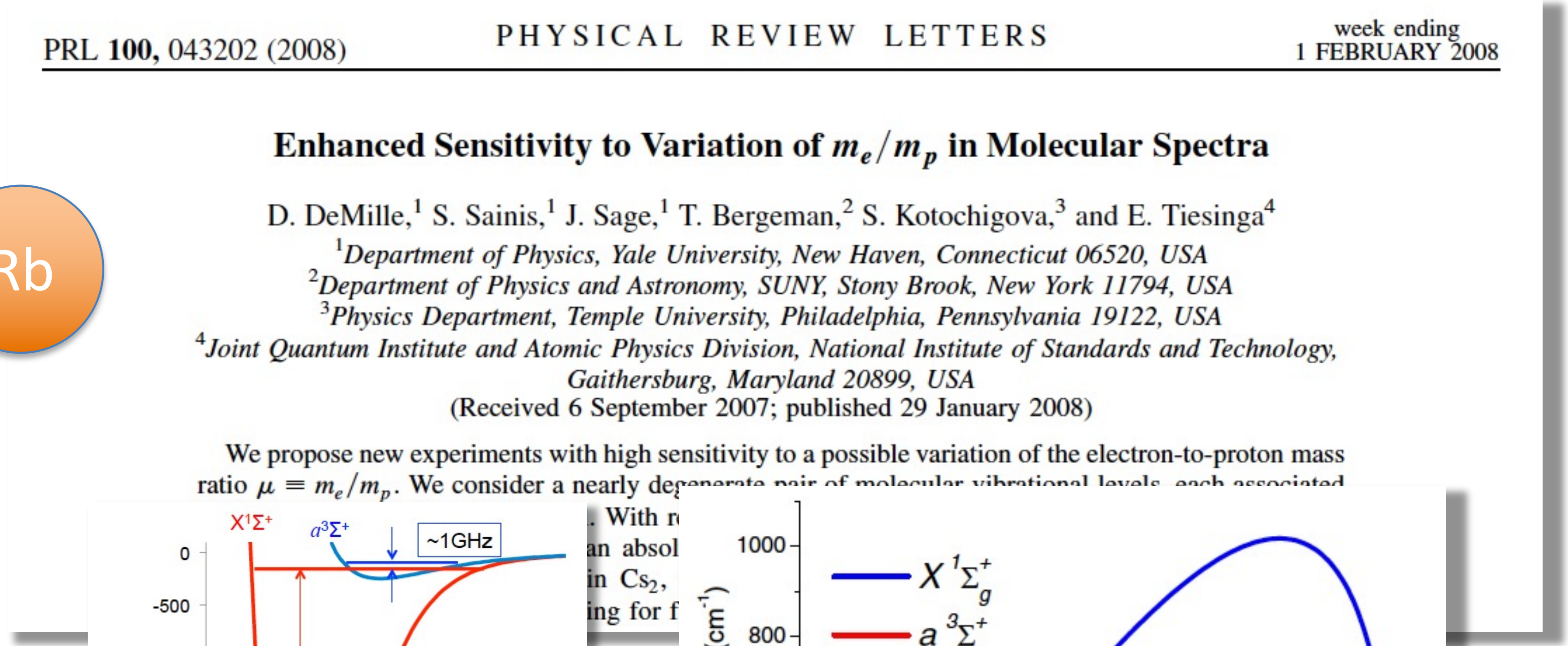
Optical Fiber link (~43km)



Cs Fountain

One can enhance the sensitivity to variation of μ
by using transitions between nearly degenerate levels with different symmetries
(i.e. like singlet and triplet potentials of bi-alkali molecules).




PRL 100, 043202 (2008) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2008

Enhanced Sensitivity to Variation of m_e/m_p in Molecular Spectra

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[2]*Department of Physics and Astronomy, SUNY, Stony Brook, New York 11794, USA*
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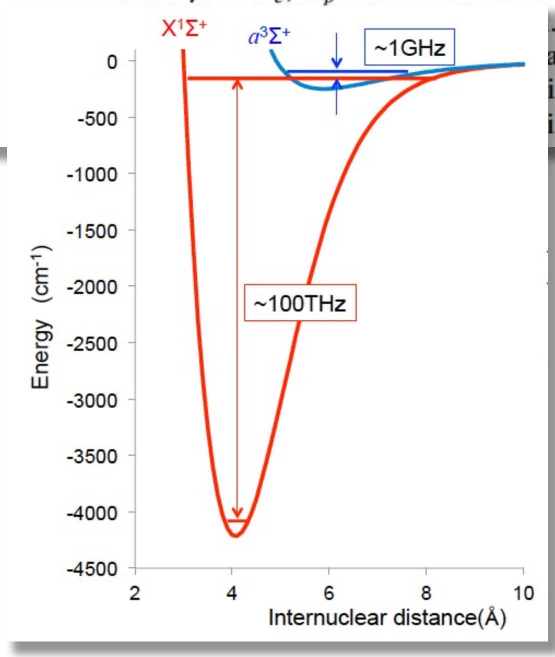
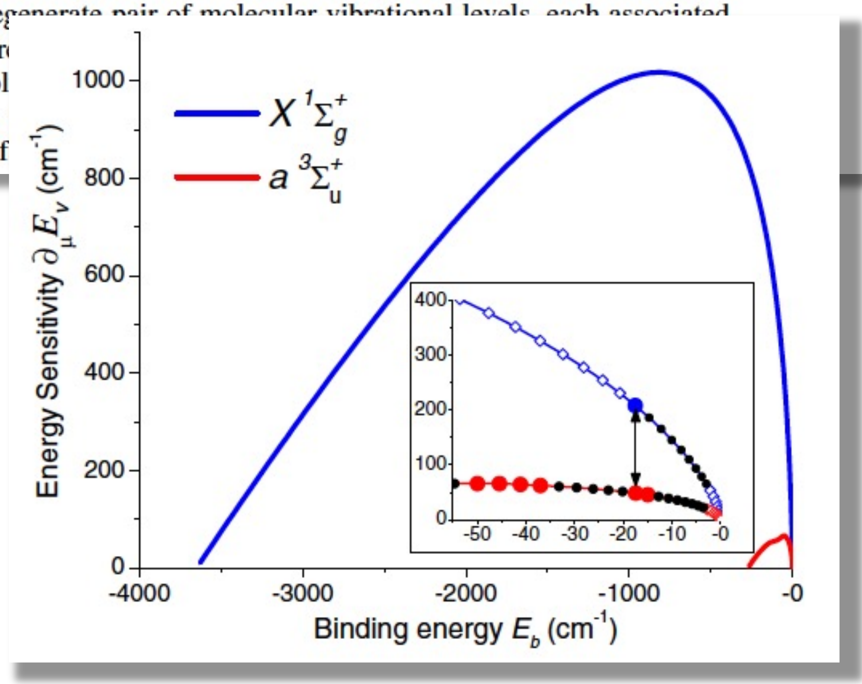
(Received 6 September 2007; published 29 January 2008)

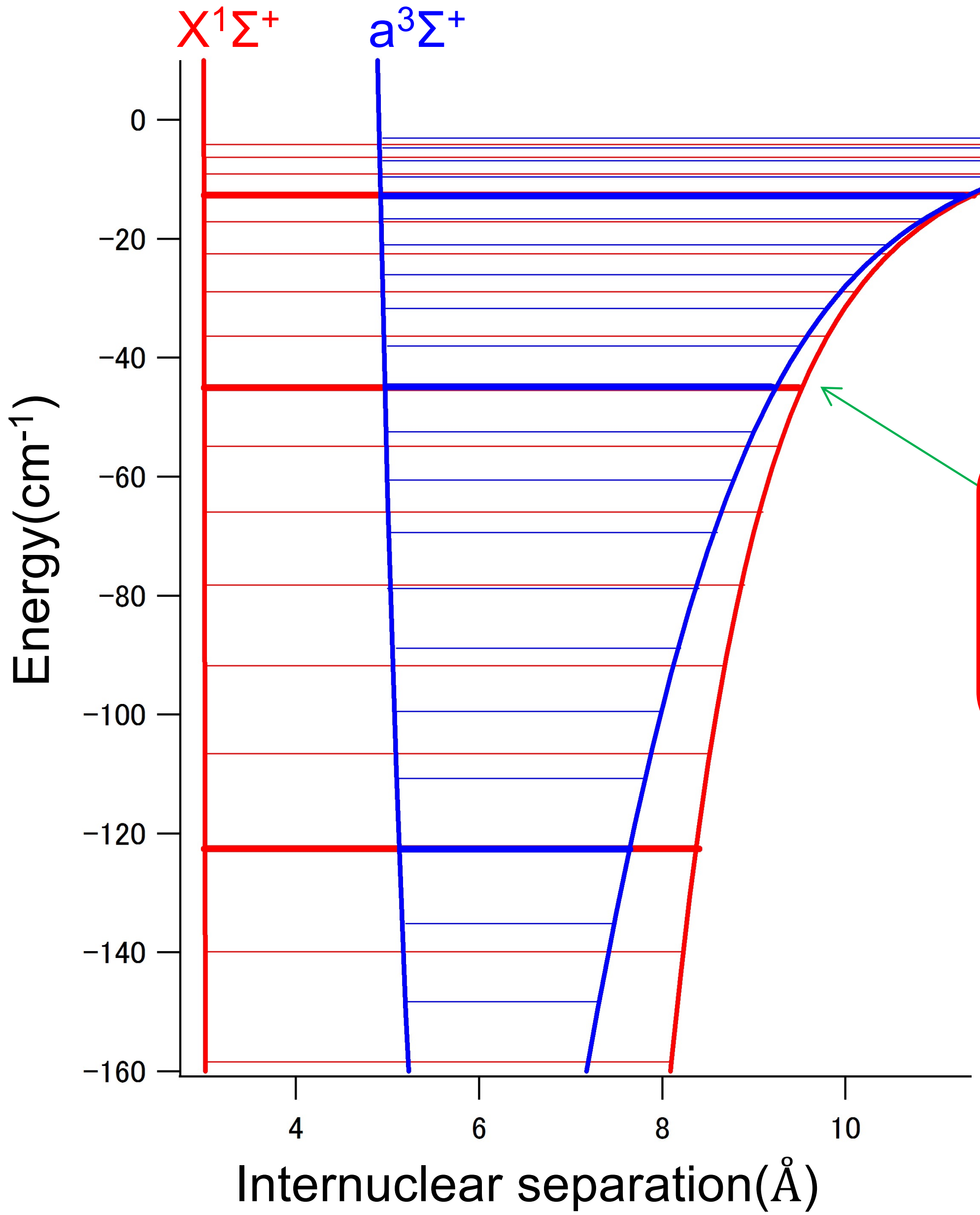
We propose new experiments with high sensitivity to a possible variation of the electron-to-proton mass ratio $\mu \equiv m_e/m_p$. We consider a nearly de... With r... an absol... in Cs_2, ...ing for f...





Candidates for “nearly degenerate levels” of $^{41}K^{87}Rb$

We need large sensitivity and non-vanishing mixing



Sensitivity $S \equiv \dfrac{\partial f}{\partial \mu/\mu}$

$v_X=91 \Leftrightarrow v_a=22$	$\Delta\omega$ ~2.4GHz S~3.5THz Mixing ~9%

We selected this transition

$v_X=86 \Leftrightarrow v_a=16$	$\Delta\omega$ ~1GHz S~9.5THz Mixing ~2%

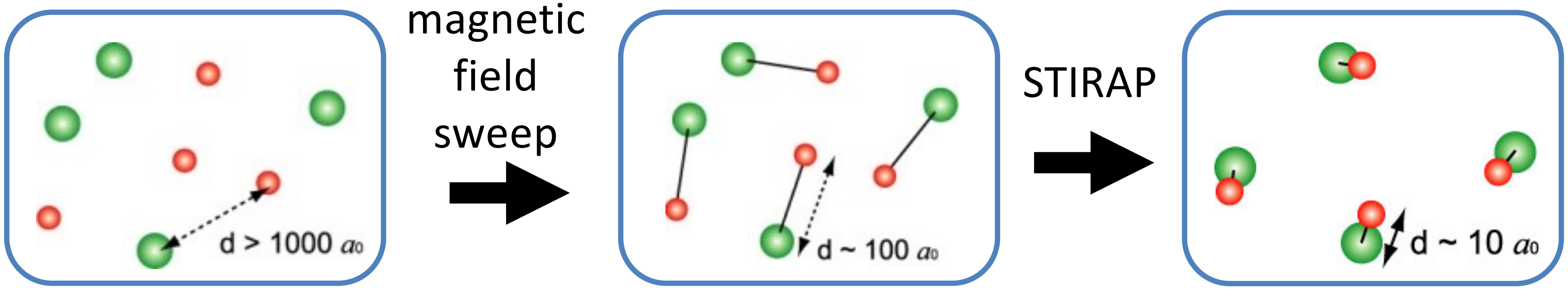
Enhancement: $\dfrac{S}{\Delta\omega} = -14890(60)$

“optical sensitivity using microwave transition”

“Indirect” method to produce ultracold molecules

Our initial plan

Dual BEC of ^{41}K and ^{87}Rb → magnetic field sweep → Feshbach molecules → STIRAP → tightly-bound molecules



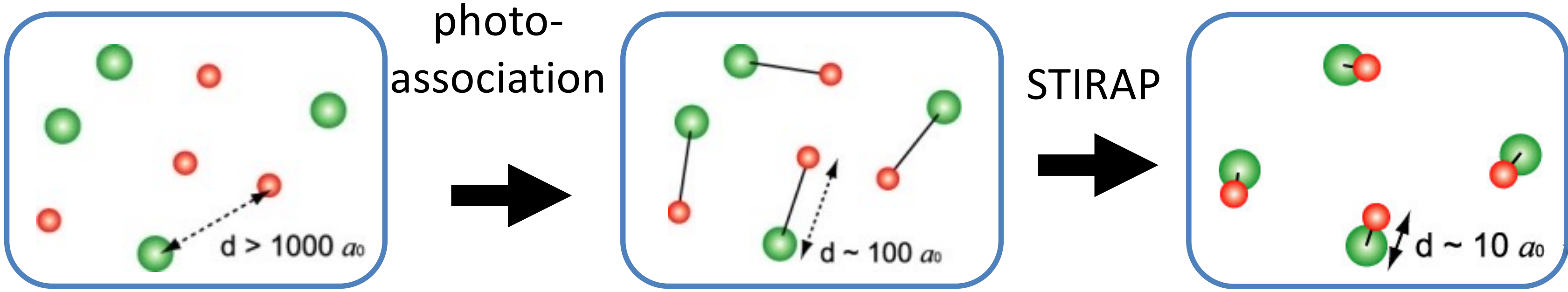
evaporation ~ 30 seconds

("BEC of molecules"?)

repetition rate ~ 0.01 Hz

What we did

Dual MOT → photo-association → photo-associated molecules → STIRAP → tightly-bound molecules

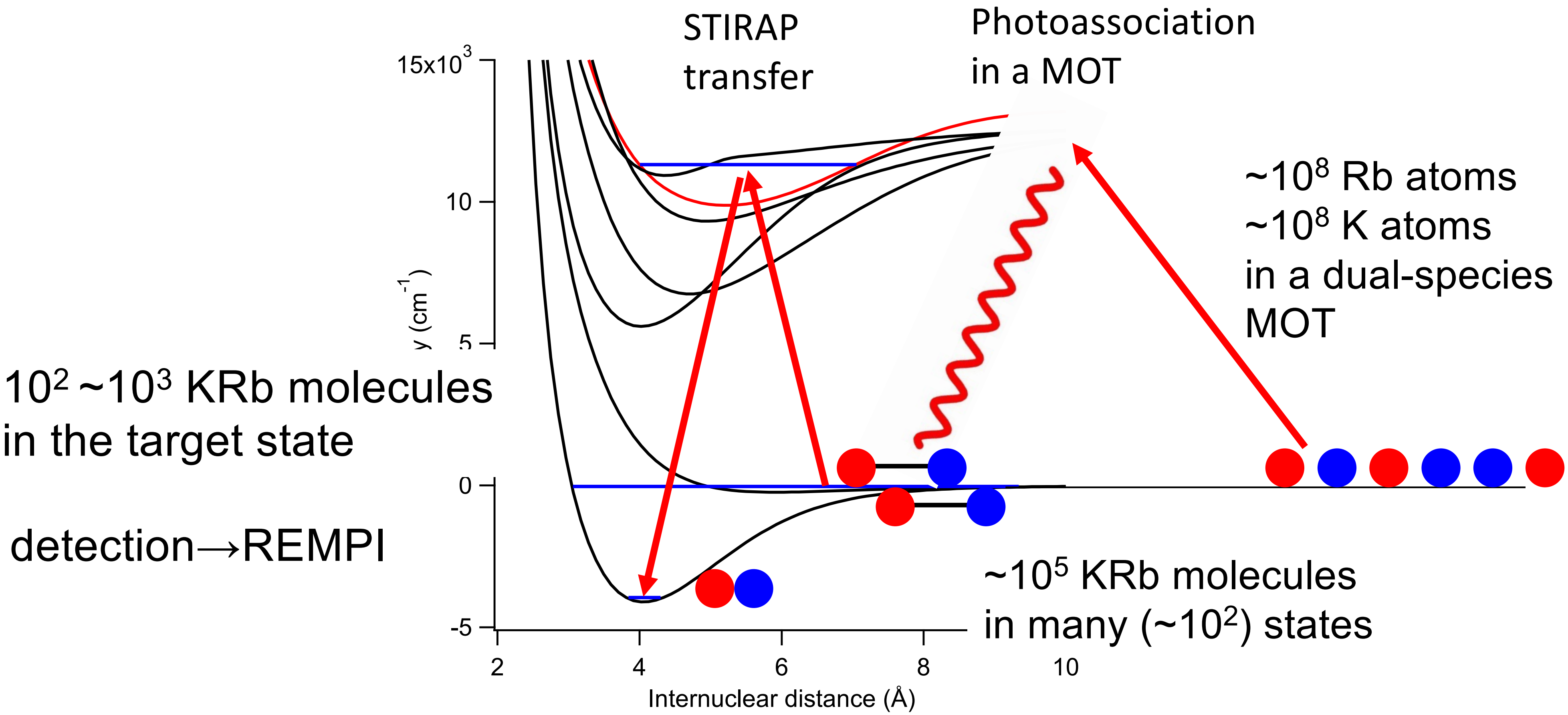


1000 times faster!

MOT loading : ~ 0.1 second

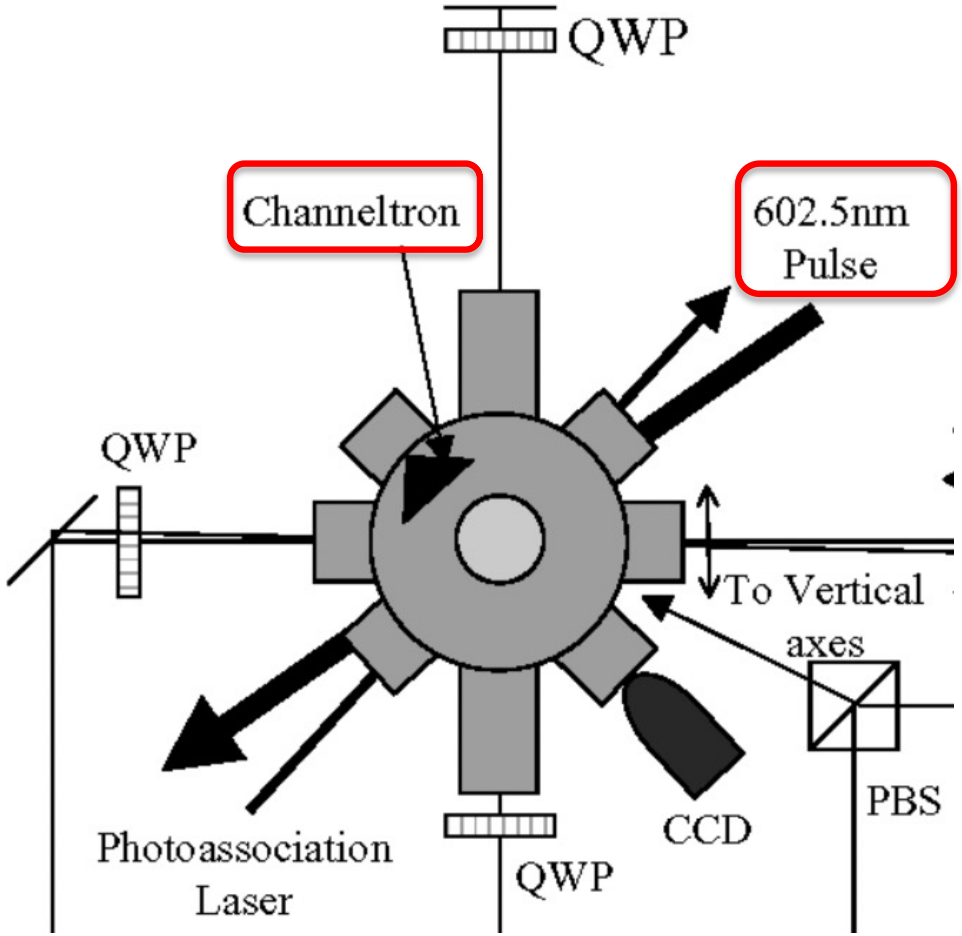
repetition rate: 10 Hz

Energy diagram



	PA+STIRAP	Feshbach + STIRAP
temperature	~100μK	~100nK
Number	$10^2 \sim 10^3$?	$10^5 \sim 10^6$?
Rate	~ 10 Hz	~0.01 Hz

Detection of small number of molecules: Resonance-enhanced multiphoton ionization (REMPI)

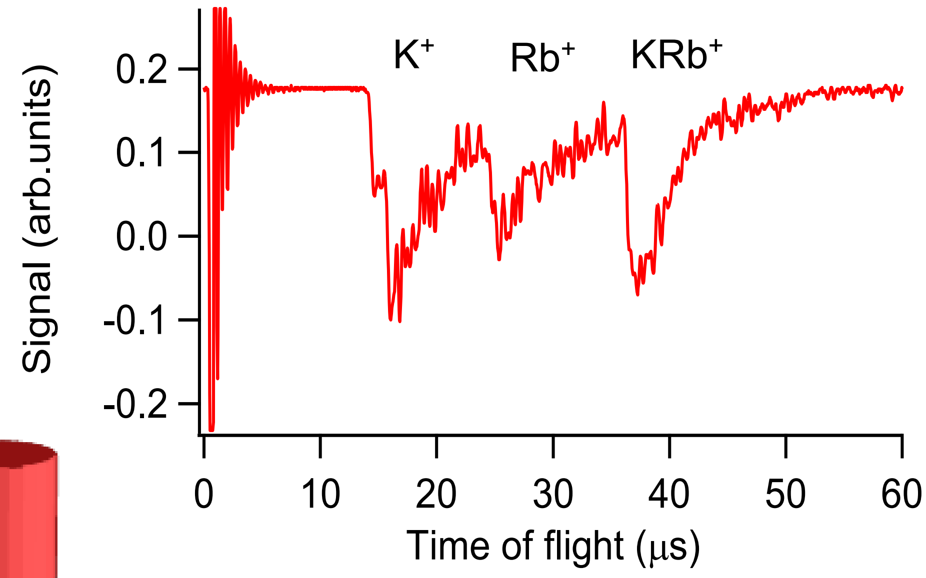


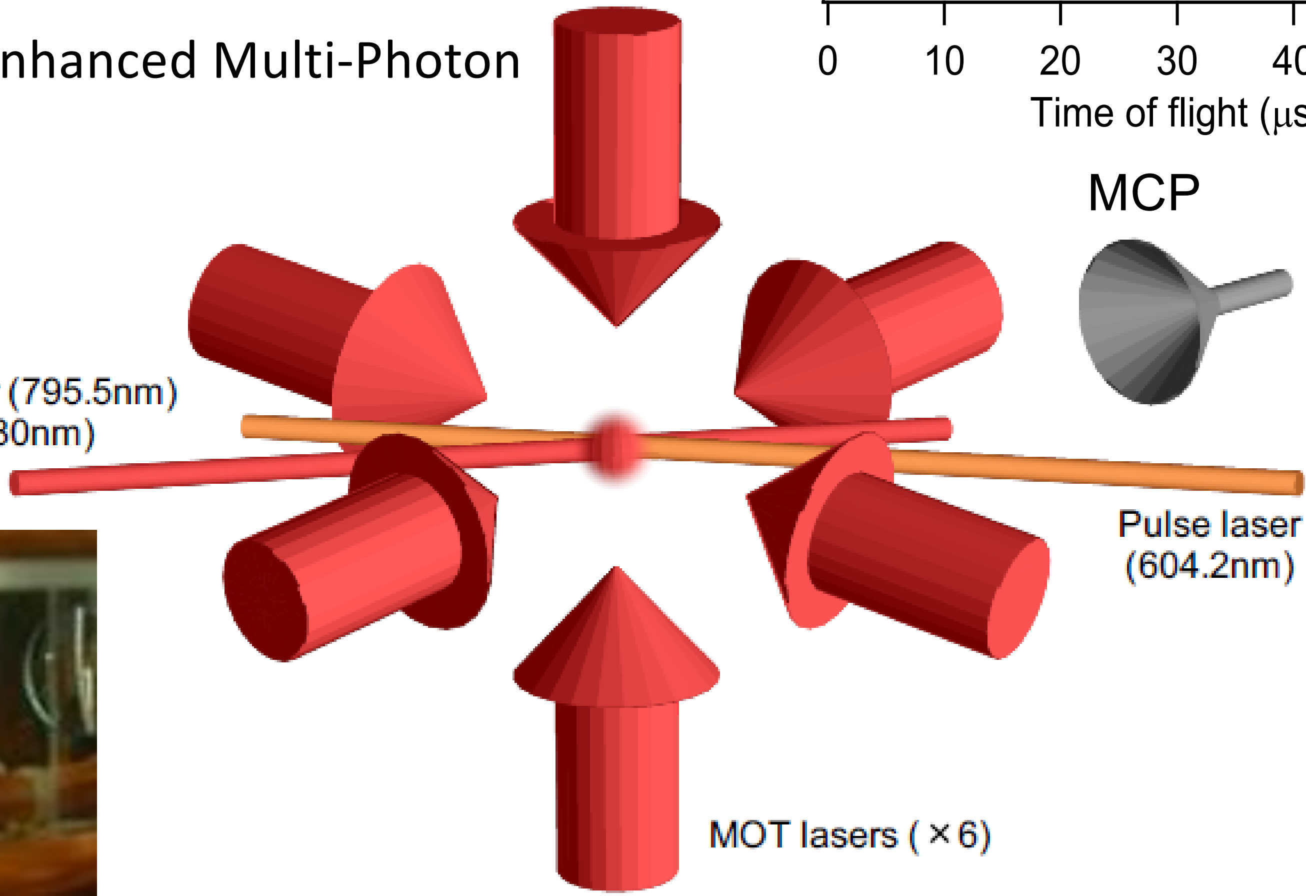
D. Wang et al., Eur. Phys. J. D 31, 165–177 (2004)

Experimental setup

- MOT
- Photoassociation
- STIRAP
- rf - spectroscopy
- Detect molecules with REMPI

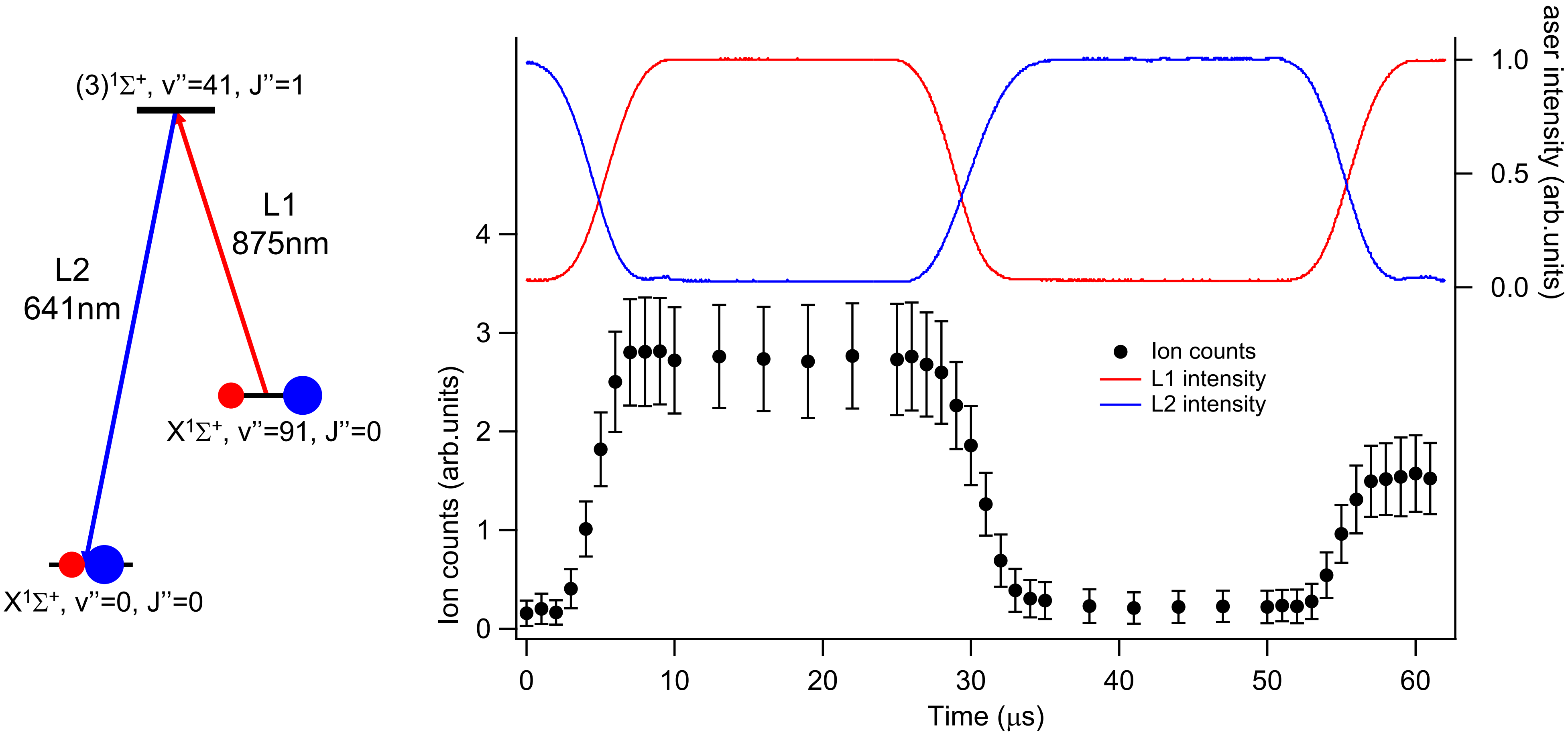
(Resonantly-Enhanced Multi-Photon Ionization)



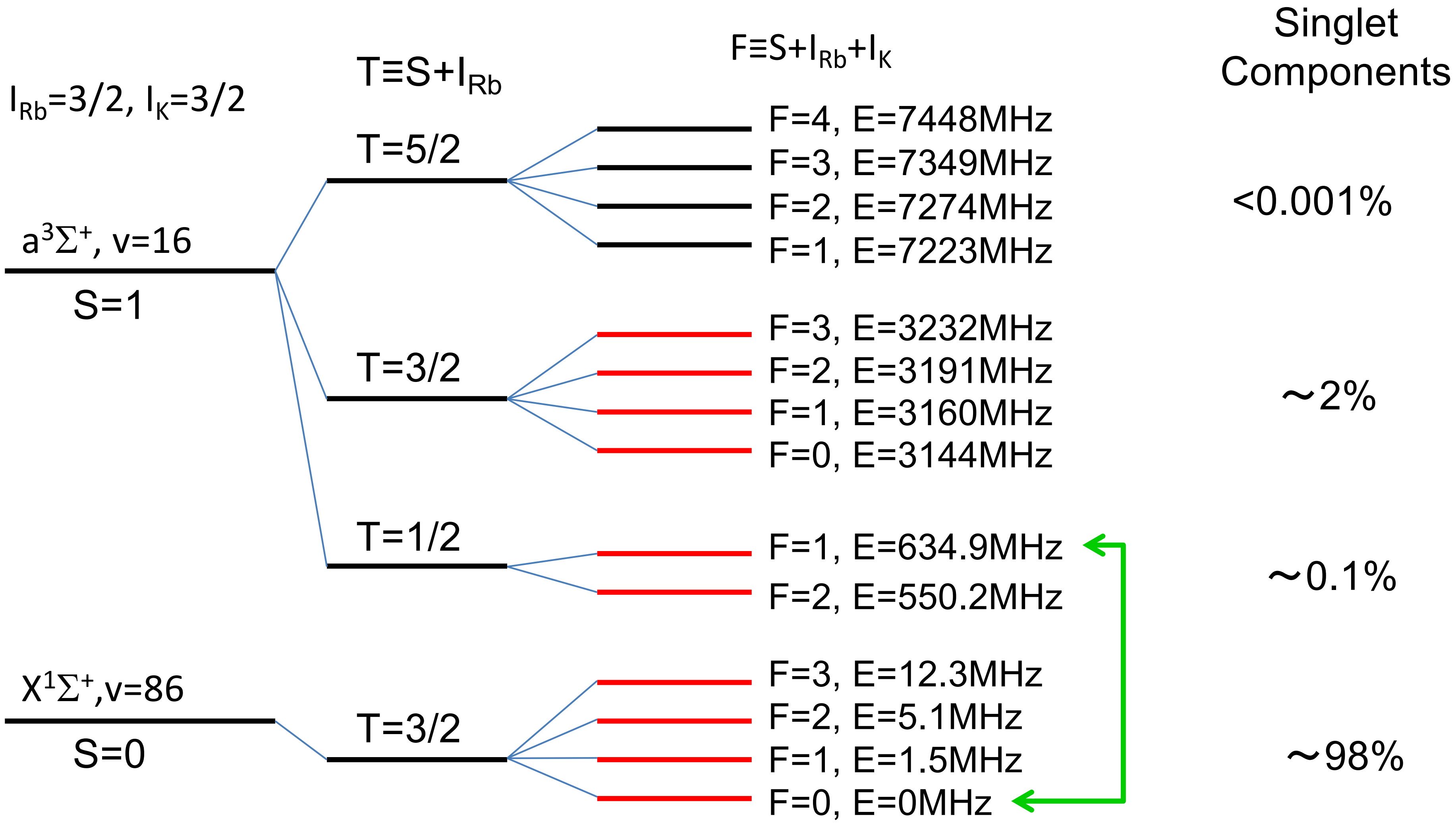


STIRAP

- Monitored the ion counts during multiple transfers
- Recovered 53% after the double STIRAP
- One-way transfer efficiency: 73%

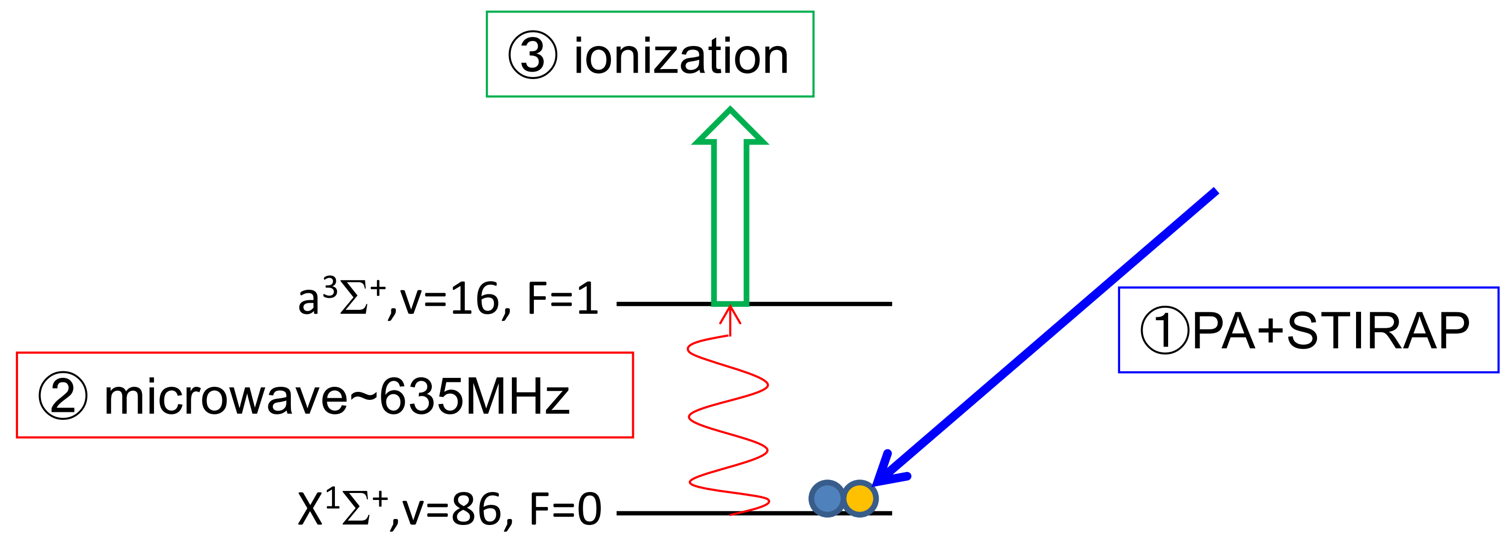


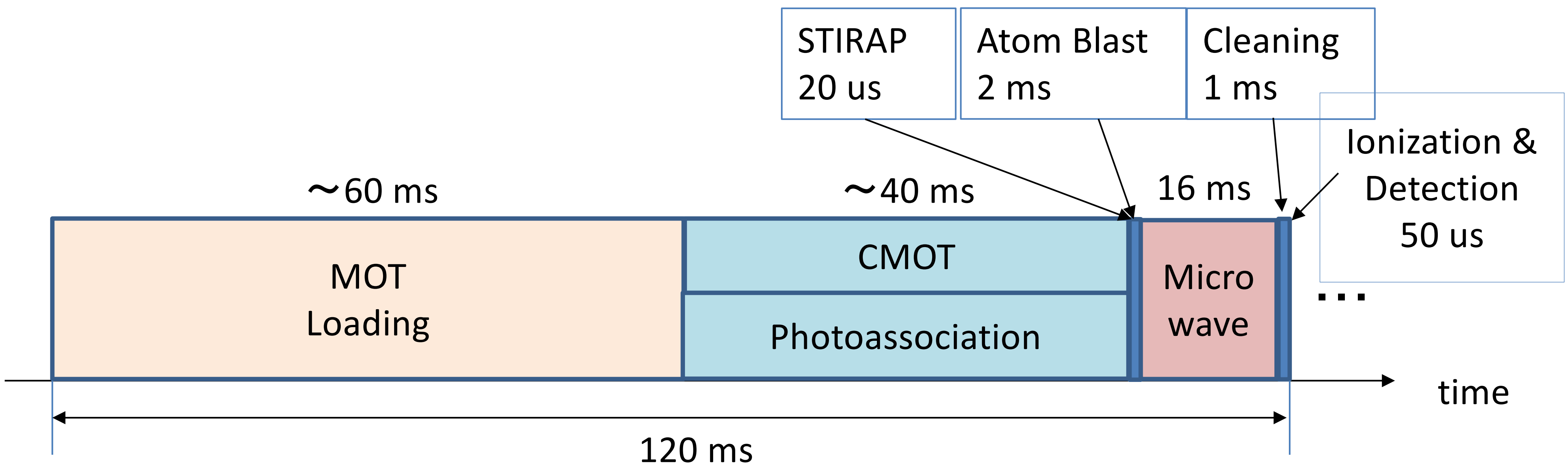
Hyperfine structure of $X^1\Sigma^+$ v=86 and $a^3\Sigma^+$v=16



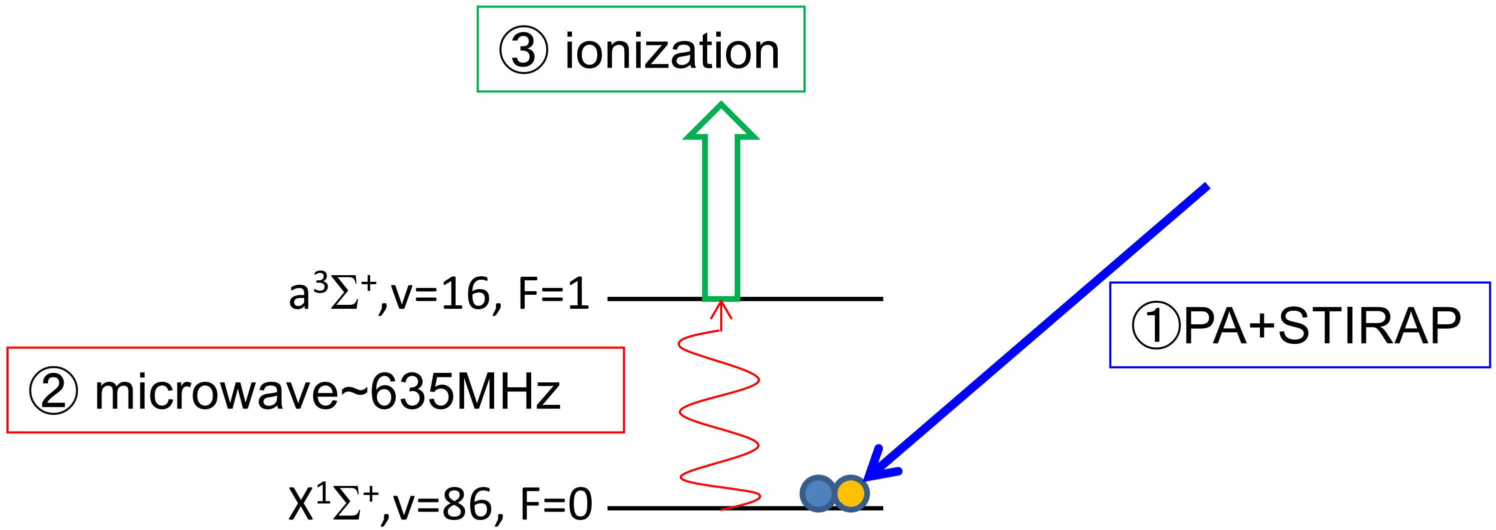
Use this microwave transition!

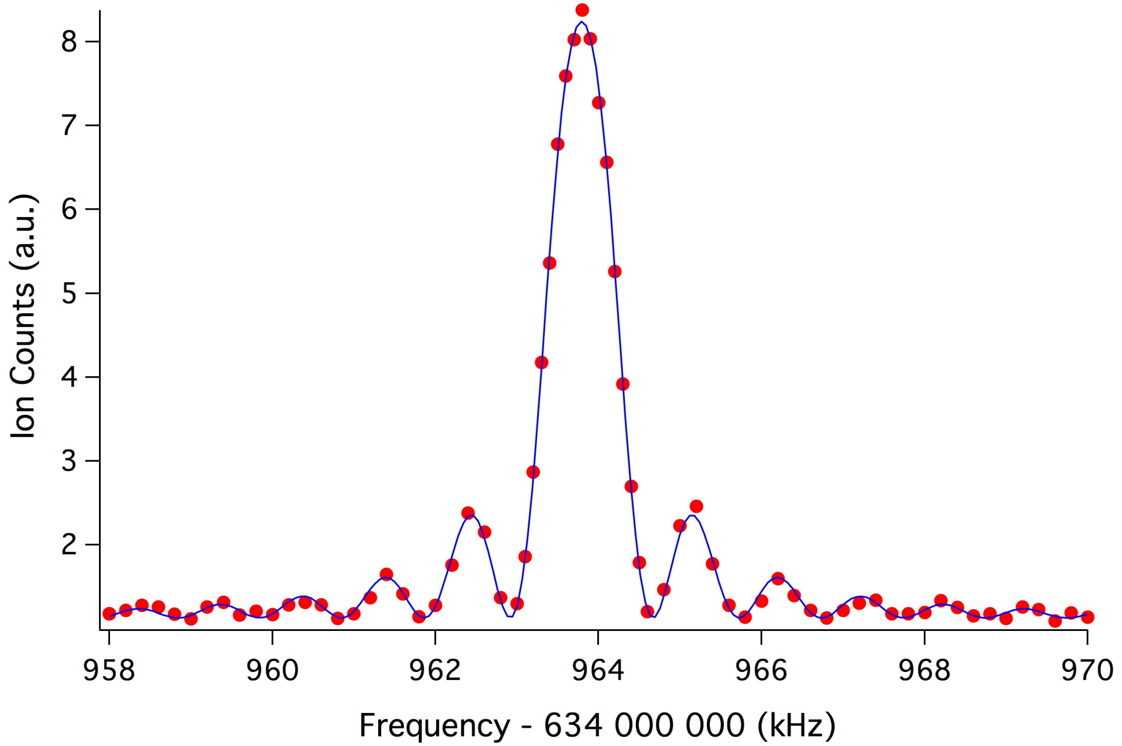
Microwave transition between $X^1\Sigma^+$,v=86,F=0→$a^3\Sigma^+$,v=16,F=1





Microwave transition between $X^1\Sigma^+$,v=86,F=0→$a^3\Sigma^+$,v=16,F=1



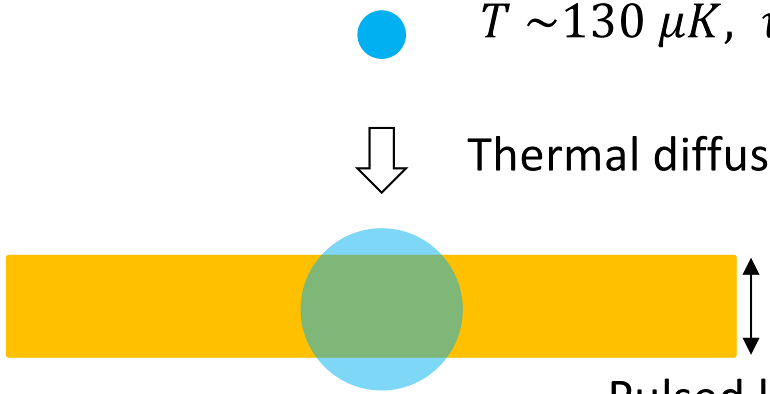


Thermal diffusion of molecular cloud

Photoassociated KRb

$T \sim 130\ \mu K,\ \bar{v} \sim 130\ mm/s$

Thermal diffusion

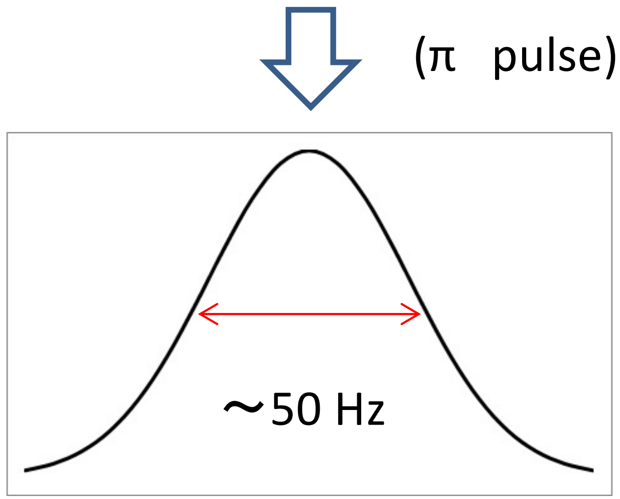


~4mm

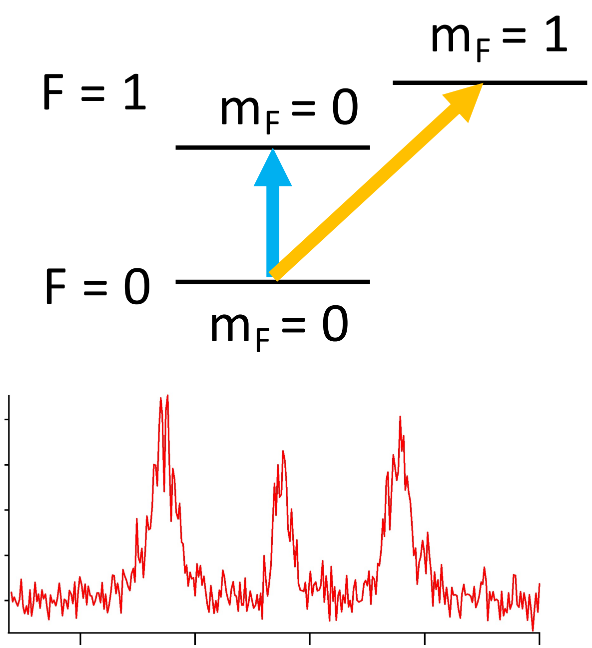
Pulsed laser

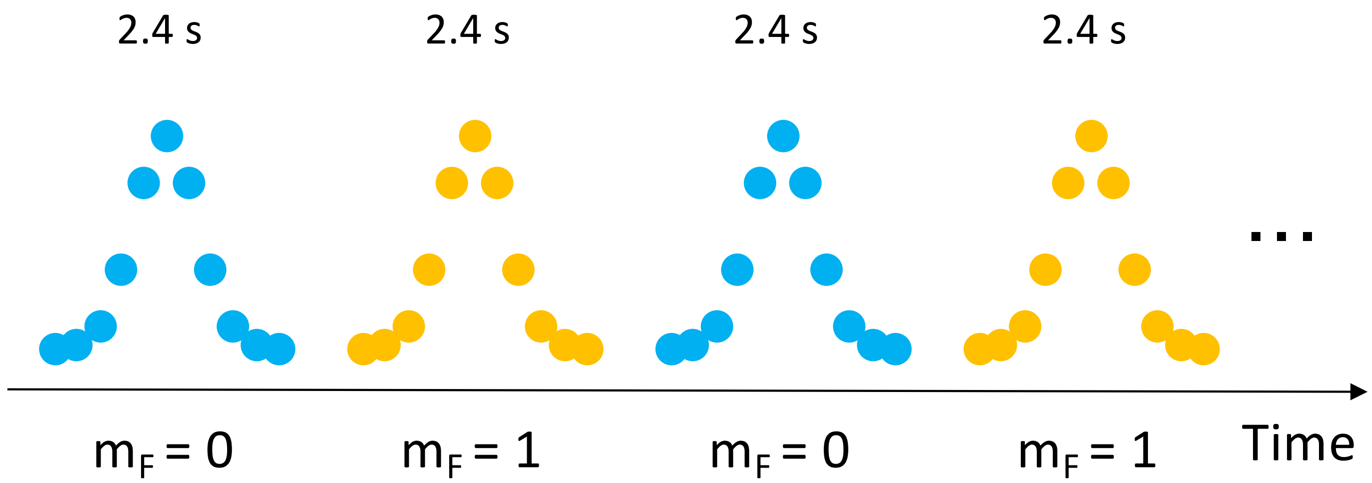
Measurement time ~16 ms

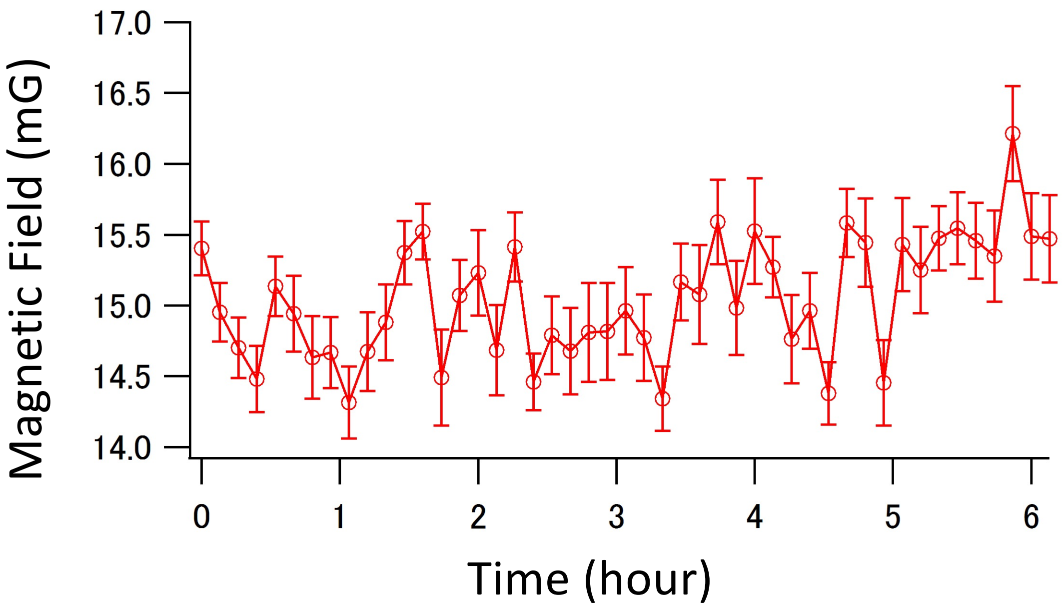
(π pulse)



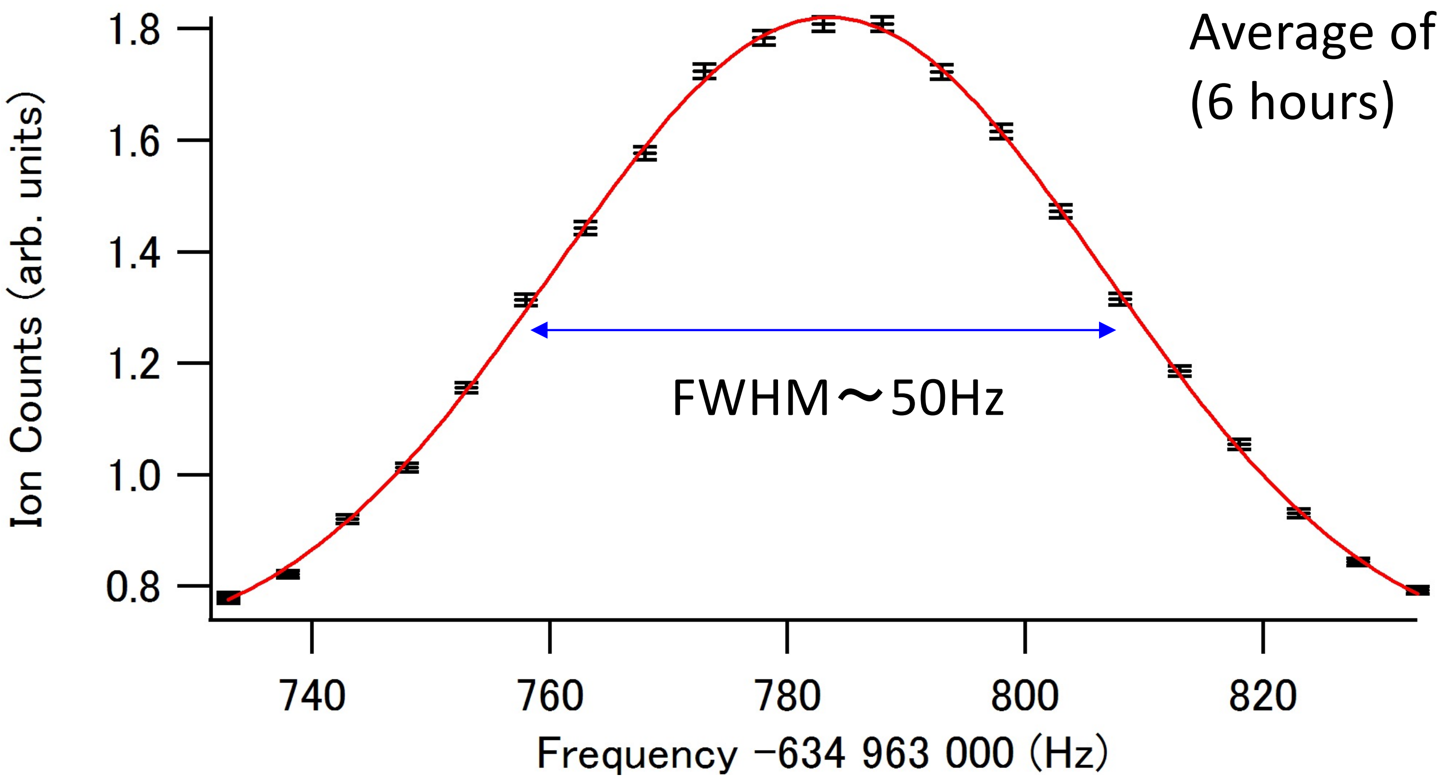
Calibration of the magnetic field







Obtained signal for $m_F = 0$



Average of 5000 sweeps (6 hours)

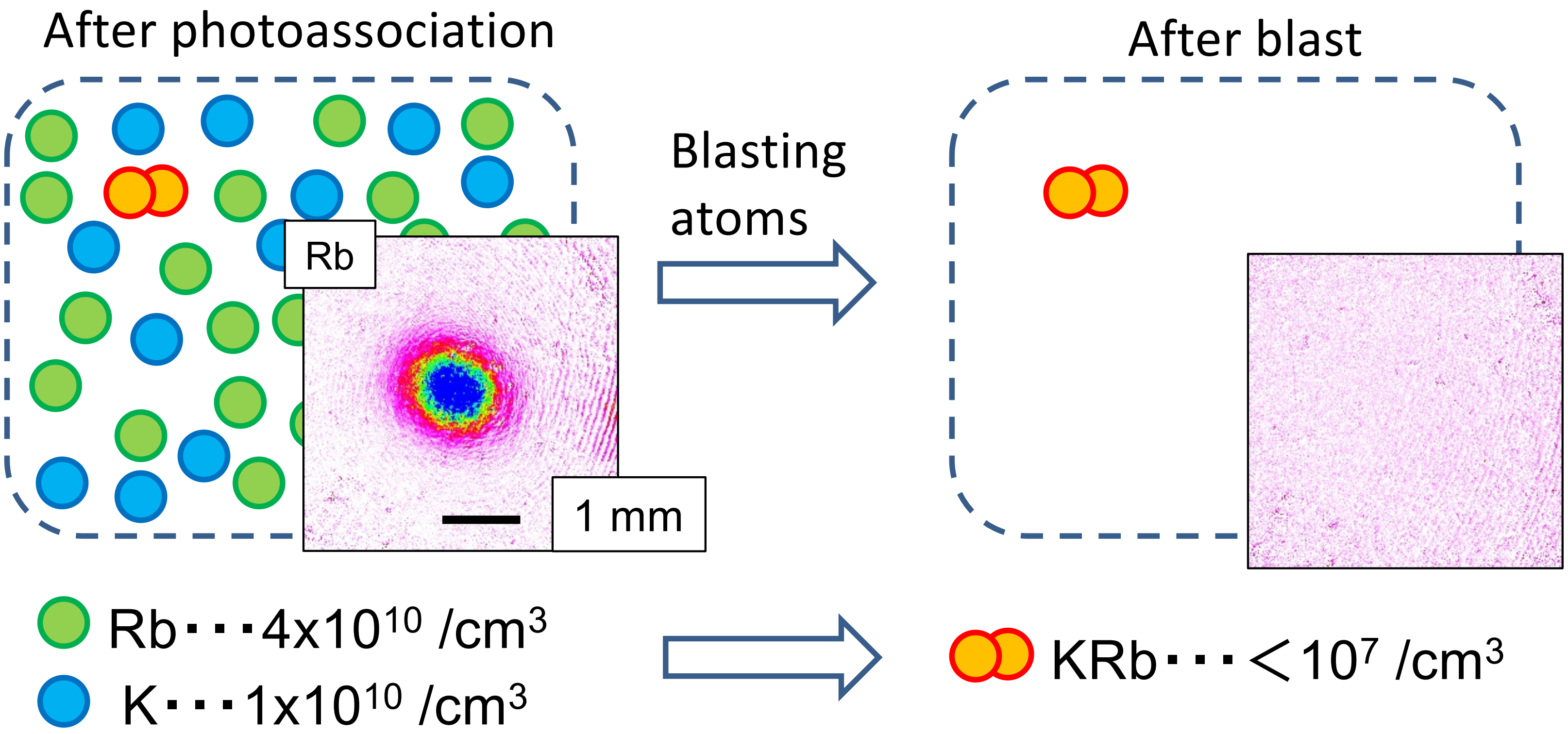
634 963 783.458±0.093 Hz

Zeeman shift compensation

634 963 781.564±0.094 Hz

S/N ~ 500 (c.f. Number of molecules used ~ 10^6)

Collisional shift



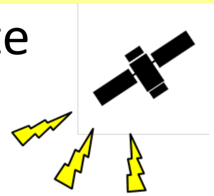
When we removed the blast, atomic density increased by more than factor of 100, but no shift observed

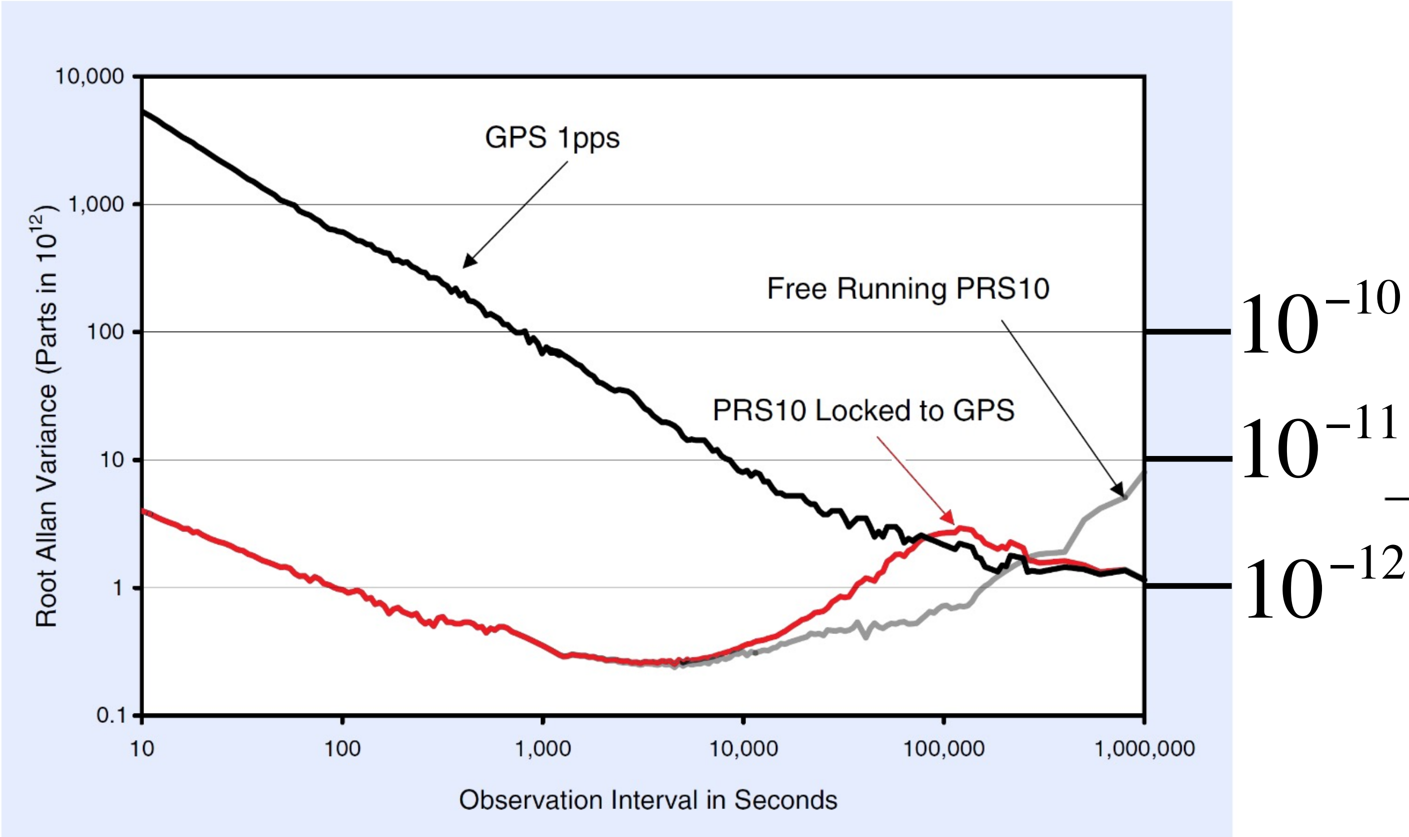
⇨ Collisional shift should be negligible

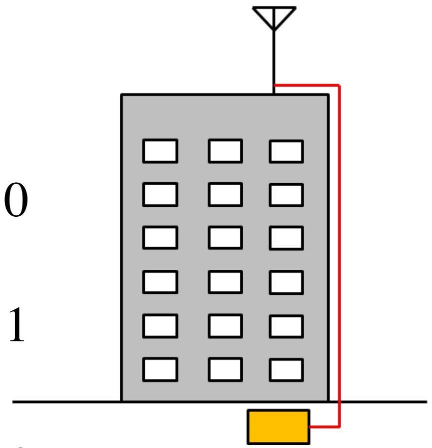
Reference Clock

SRS FS725 locked to GPS signal

GPS satellite







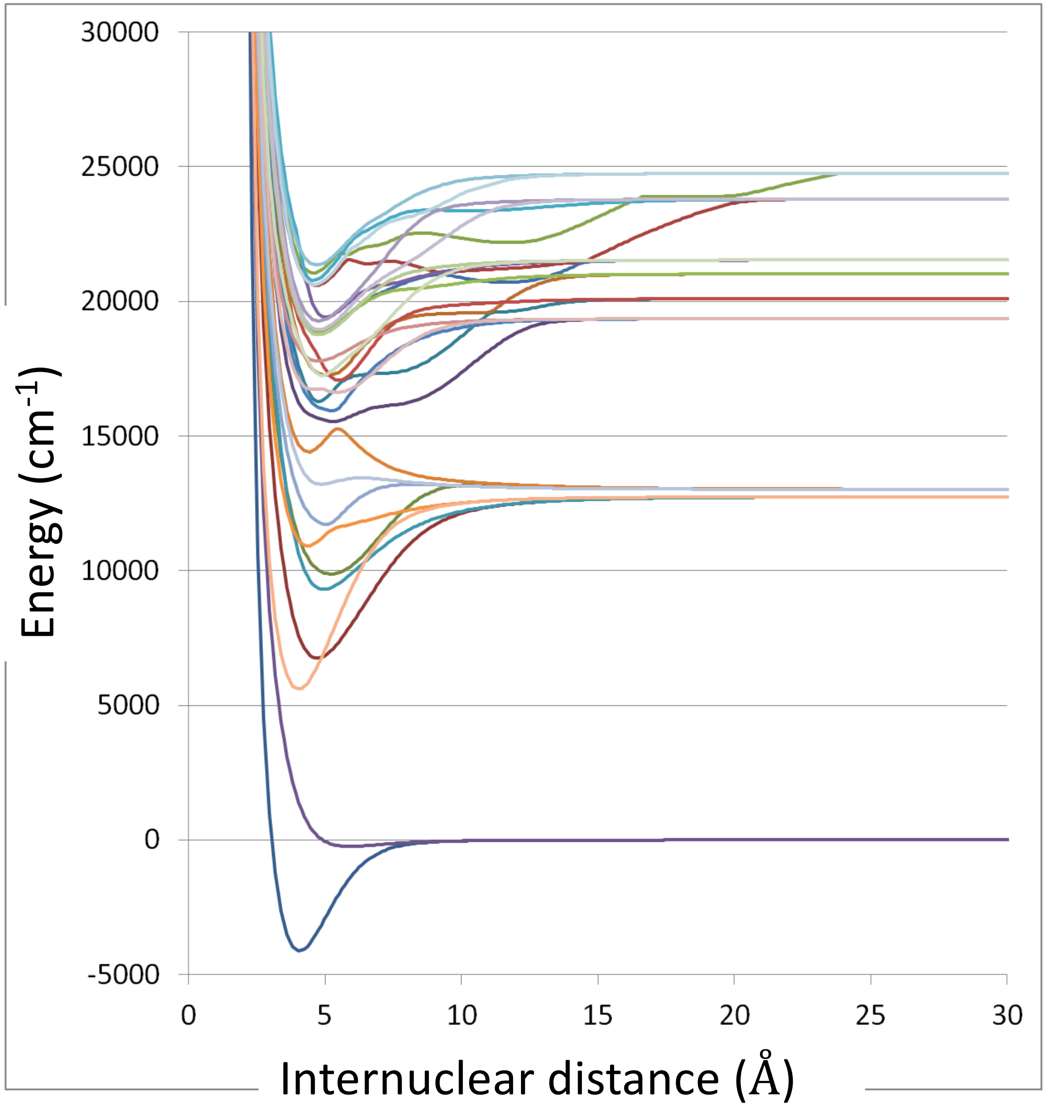
Laboratory

$$\frac{\delta f}{f} < 3\times 10^{-12}$$

$$\delta f_{\text{sys}} = \pm 1\ \text{mHz}$$

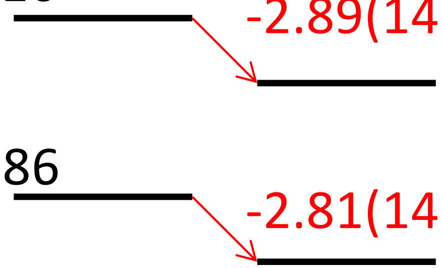
Black Body Radiation shift

Potential Energy curves for KRb



Ab-initio calculation of the transition dipole moment
[R.Beuc et al., J. Phys. B 39 S1191 (2006)]

BBR shift @ 300K



T=26.8 ±2.0 ℃

$$\Rightarrow \quad \delta f_{sys} = \pm 10 \text{ mHz}$$

Uncertainties (Error Budget)

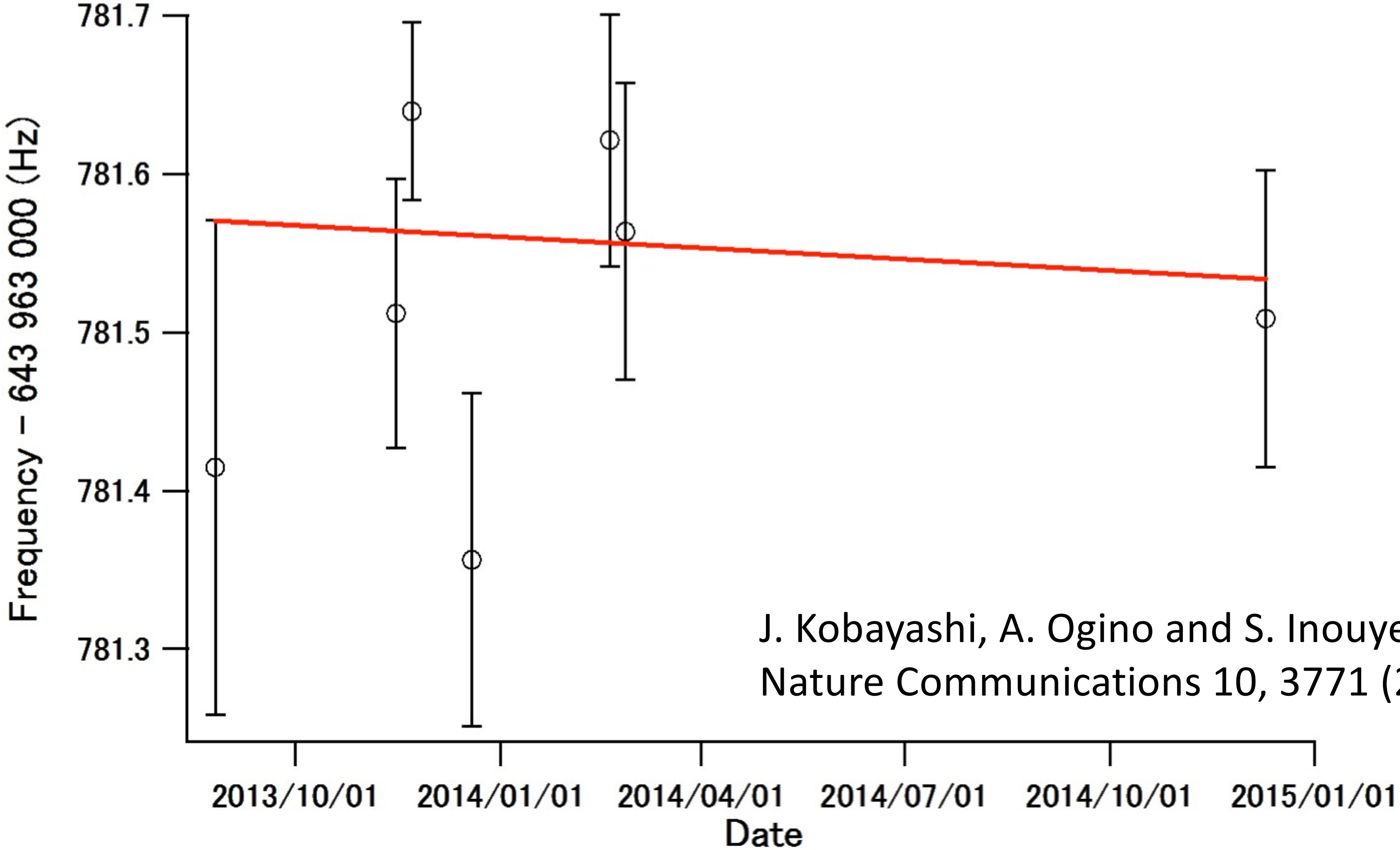
$^{41}K^{87}Rb$ ($X^1\Sigma^+$,v=86,N=0,T=3/2,F=0,m_F=0
→$a^3\Sigma^+$,v=16,N=0,T=1/2,F=1,m_F=0)

	Statistic	**Systematic**
S/N of the signal	93 mHz	-
Zeeman shift	15 mHz	1 mHz
Stark shift	-	1 mHz
Reference clock	-	< 1 mHz
BBR shift	-	10 mHz
Density shift		< 1 mHz
Total	**94 mHz**	**10 mHz**

$$\delta f_{\text{total}} = 95\ \text{mHz}$$

$$\frac{\delta\mu}{\mu} = 1.0 \times 10^{-14}$$

Final result



J. Kobayashi, A. Ogino and S. Inouye, Nature Communications 10, 3771 (2019)

$$\frac{1}{\mu}\frac{\partial\mu}{\partial t} = \left(0.30 \pm 1.00_{\mathrm{Stat}} \pm 0.16_{\mathrm{Sys}}\right) \times 10^{-14}\ /\ \mathrm{year}$$

Conclusion

- We measured the variation of electron-to-proton mass ratio using ultracold molecules produced from laser-cooled atoms

- Obtained result was $\frac{1}{\mu}\frac{d\mu}{dt} = \left(0.30 \pm 1.00_{St} \pm 0.16_{Sys}\right) \times 10^{-14}/\text{year}$, which was consistent with zero (Nat. Comm. 10, 3771 (2019))

Outlook

Dr. Kobayashi and the machine moved to Hokkaido (North of Japan). Current plan for the 2nd generation is:

- increase the observation time by trapping the molecules

- increase number of molecules by creating from a BEC trapped in a 3D optical lattice

- keep the repetition rate by creating BEC via direct laser cooling

A. Ogino Dr. J. Kobayashi