Comb photon and intriguing features in Comb laser-atom interaction

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Department of Physics, National Central University, Taiwan

2021 workshop on quantum technology

I am a comb laser or "clock" expert, not "quantum optics"

However, it might be a good chance to sell my unique comb laser to people in the field of "quantum optics"

Quantum state of light

Photon-atom interaction

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Outline

1. **What is comb laser?**
   → From the perspective of spectroscopist
   → From the perspective of "quantum optics" people

2. **40-femtosecond pulse train simultaneously resolves Rb and Cs spectra with 3-kHz resolution**
   1. Spectral line narrowing
   2. Multi-pathway AC stark shift
   3. Quantum interfered spectra

3. **Application: a novel comb laser without need of expensive cesium clock**

What is comb laser (I):

from the perspective of “laser spectroscopy”

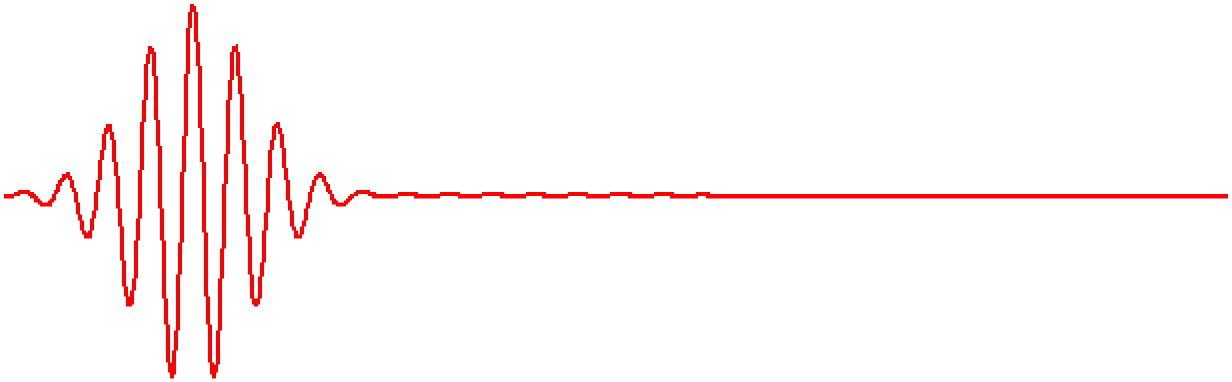
Viewpoint of time domain:

- High peak power (compared to CW laser)
- Femtosecond time scale

Good for controlling extremely nonlinear optics

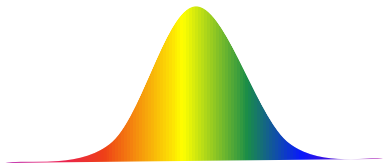
- Fixed carrier-envelope phase

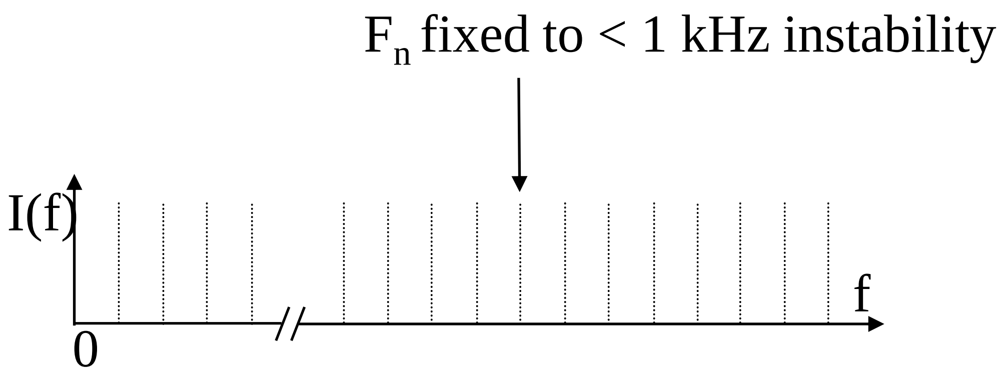
Good for selecting atomic quantum states



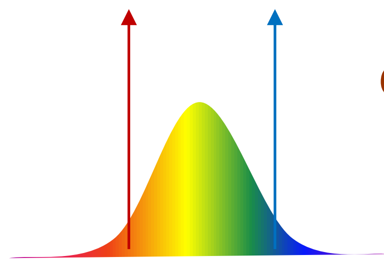
Viewpoint of frequency domain:

- Wide-band





- High-resolution



Coherent–state photons
with different colors

- High coherence

In this talk, we demonstrate:

<u>“wide-band (40 nm) & high resolution (5 kHz) laser spectroscopy”</u>

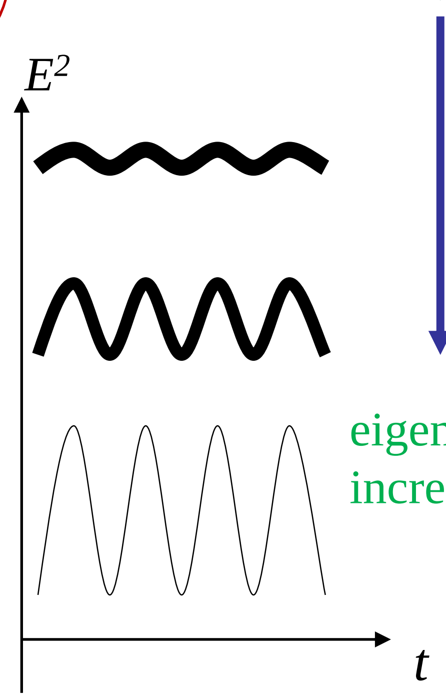
What is comb laser (II):

from the perspective of “quantum optics”

Cohere state is a superposition of Folk states photons

Photon number state

$$\left|\alpha\right\rangle_t = e^{-\left|\alpha\right|^2/2} \sum_{n=0}^{\infty} \frac{(\alpha e^{-i\omega t})^n}{\sqrt{n!}} e^{-i\omega t/2} \left|n\right\rangle$$



Coherent state photon reach the minimum criteria of uncertainty principle

$$\Delta q \times \Delta p = \frac{1}{2}\hbar$$

$p \sim H \sim \frac{\partial E}{\partial t}$ ~ phase of E

q ~ amplitude of E

over-complete

$g^{(2)}(\tau) = 1$

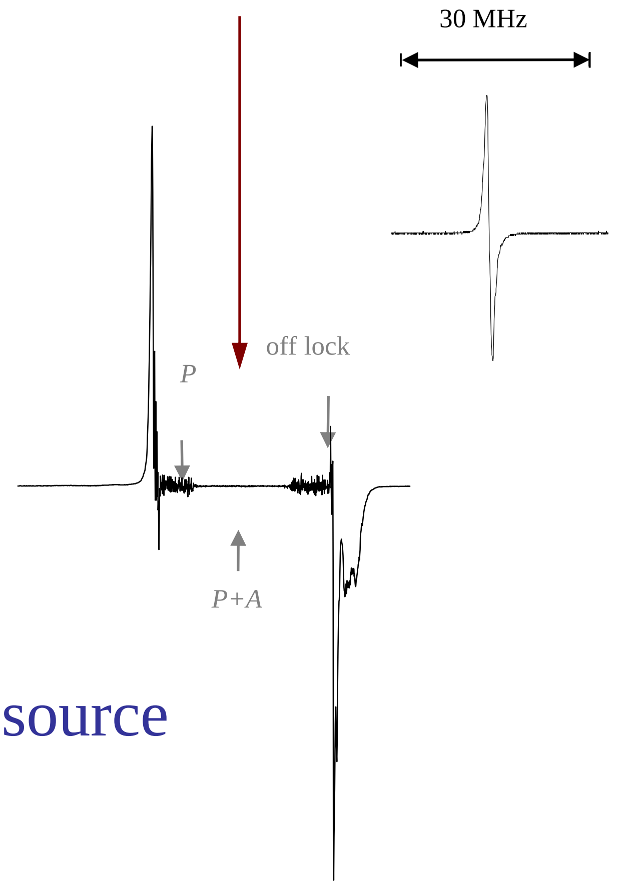
$\left\langle \alpha \middle| \alpha' \right\rangle \neq 0$

Frequency-stabilized laser provide “Coherent state” photon

frequency instability 40 Hz
*Over 3.2*10^{14} Hz duty cycle*

cesium 6S-8S
dipole not-allowed transition

Opt. lett. **32**, 563 (2007)



electronics for
feedback control

Coherent-state light source

Comb laser is a superposition of N ($N=10^5$-10^6) frequency-stabilized lasers

$$\left|\alpha_{\omega 1}\right\rangle_t \left(= e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{-i\omega_1 t})^n}{\sqrt{n!}} e^{-i\omega_1 t/2}\left|n\right\rangle\right)$$

$$+\left|\alpha_{\omega 2}\right\rangle_t \left(= e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{-i\omega_2 t})^n}{\sqrt{n!}} e^{-i\omega_2 t/2}\left|n\right\rangle\right)$$

●
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$$+\left|\alpha_{\omega N}\right\rangle_t \left(= e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{-i\omega_N t})}{\sqrt{n!}}\right.$$

They all have the same phase (mode locked)

$$\Delta q \times \Delta p = \frac{1}{2}\hbar$$

$$p \sim H \sim \frac{\partial E}{\partial t} \sim \text{phase of } E$$

q ~ amplitude of E

Superposition of all coherence-state light with wide-band mode locked carrier frequencies (femtosecond pulse train)

Via Spontaneous down conversion

Still keep the anti-bunching property

COMMUNICATIONS PHYSICS

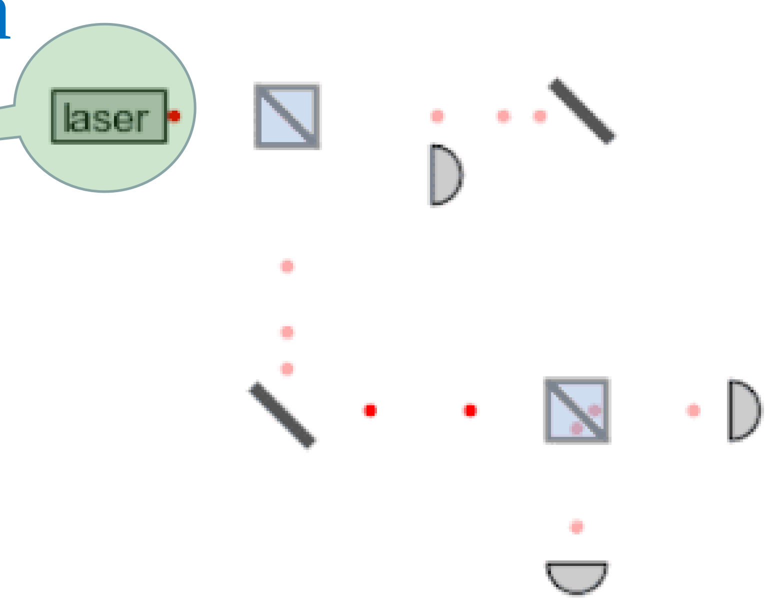
Commun. Phys. 1, 51 (2018)

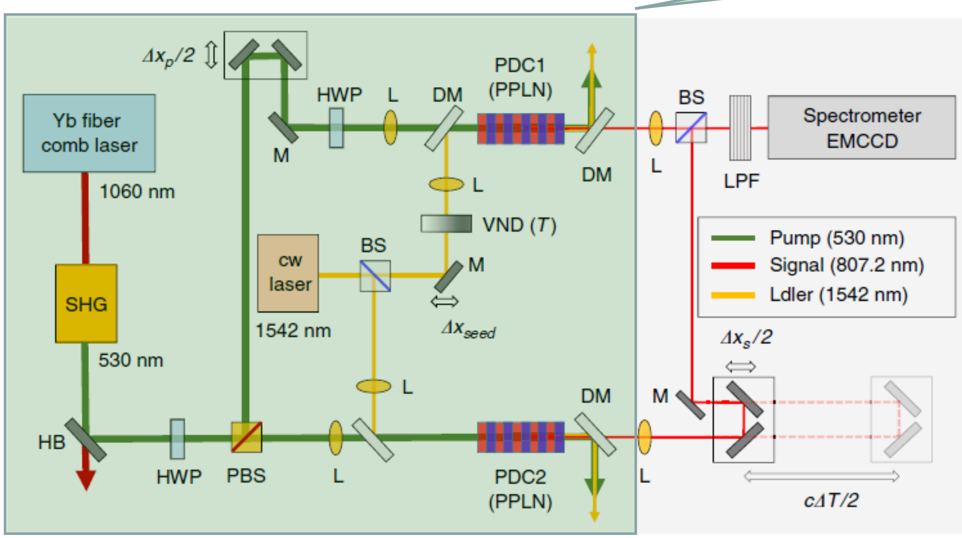
Frequency comb single-photon interferometry

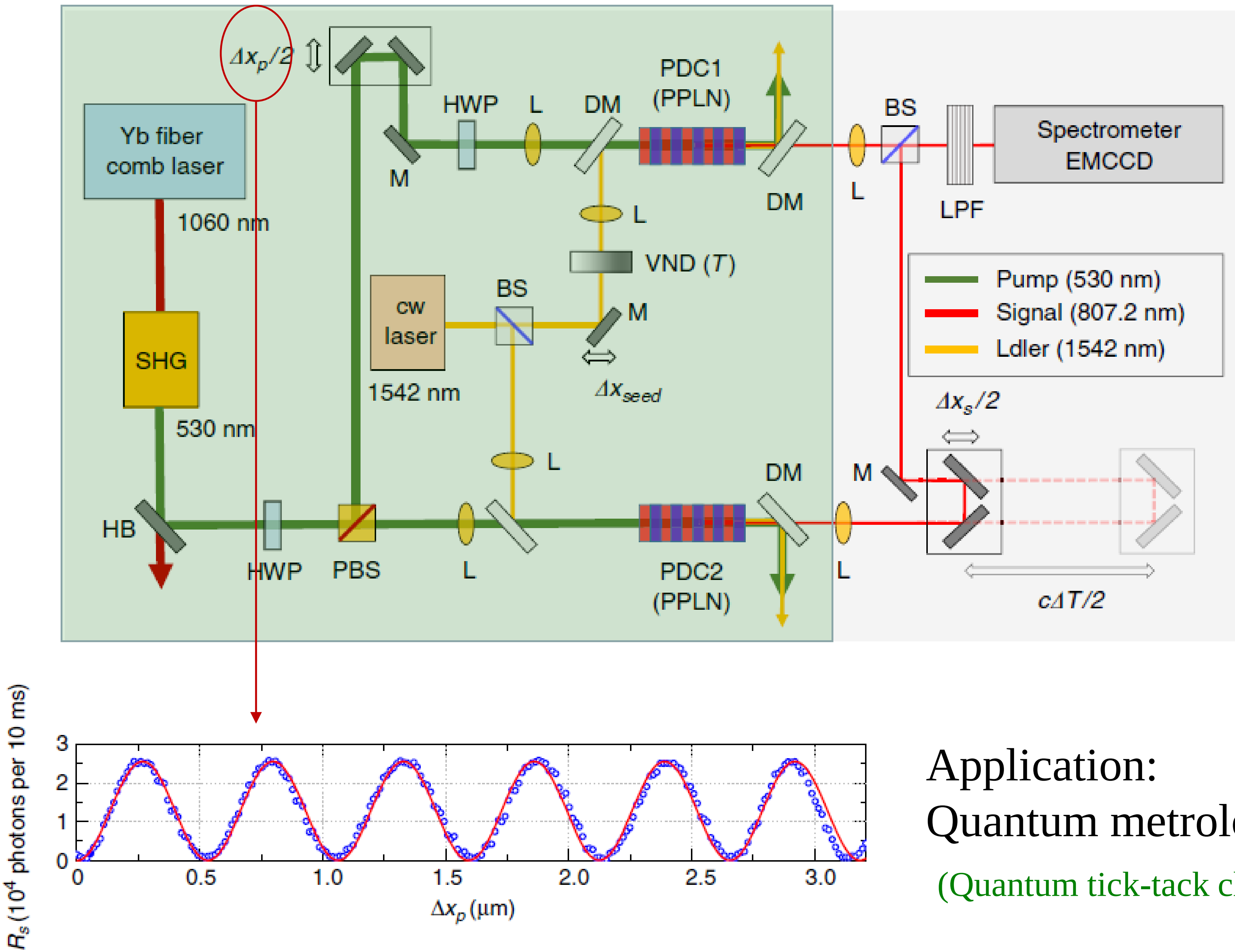
Sun Kyung Lee[1], Noh Soo Han[1], Tai Hyun Yoon[1,2] & Minhaeng Cho[1,3]

Use comb laser as a light source for "which-way interferometer" experiment

Comb laser +down conversion







Application: Quantum metrology

(Quantum tick-tack clock)

Their very recent report by using comb laser:

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Quantitative complementarity of wave-particle duality

Tai Hyun Yoon[1,2]* and Minhaeng Cho[1,3]*

Yoon and Cho, *Sci. Adv.* 2021; **7** : eabi9268 18 August 2021

Quantum interference in

comb laser-atom interaction

Tz-Wei Liu

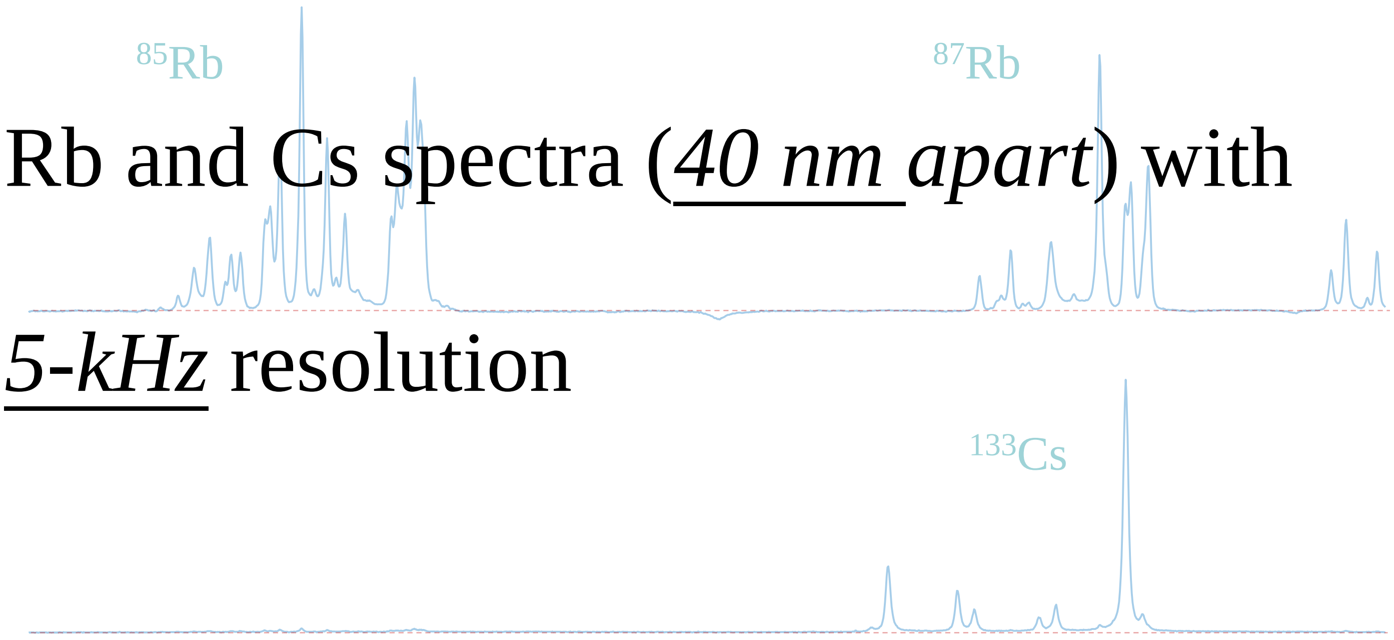
He is currently looking for a teaching job

40×10^{-15} second pulse laser

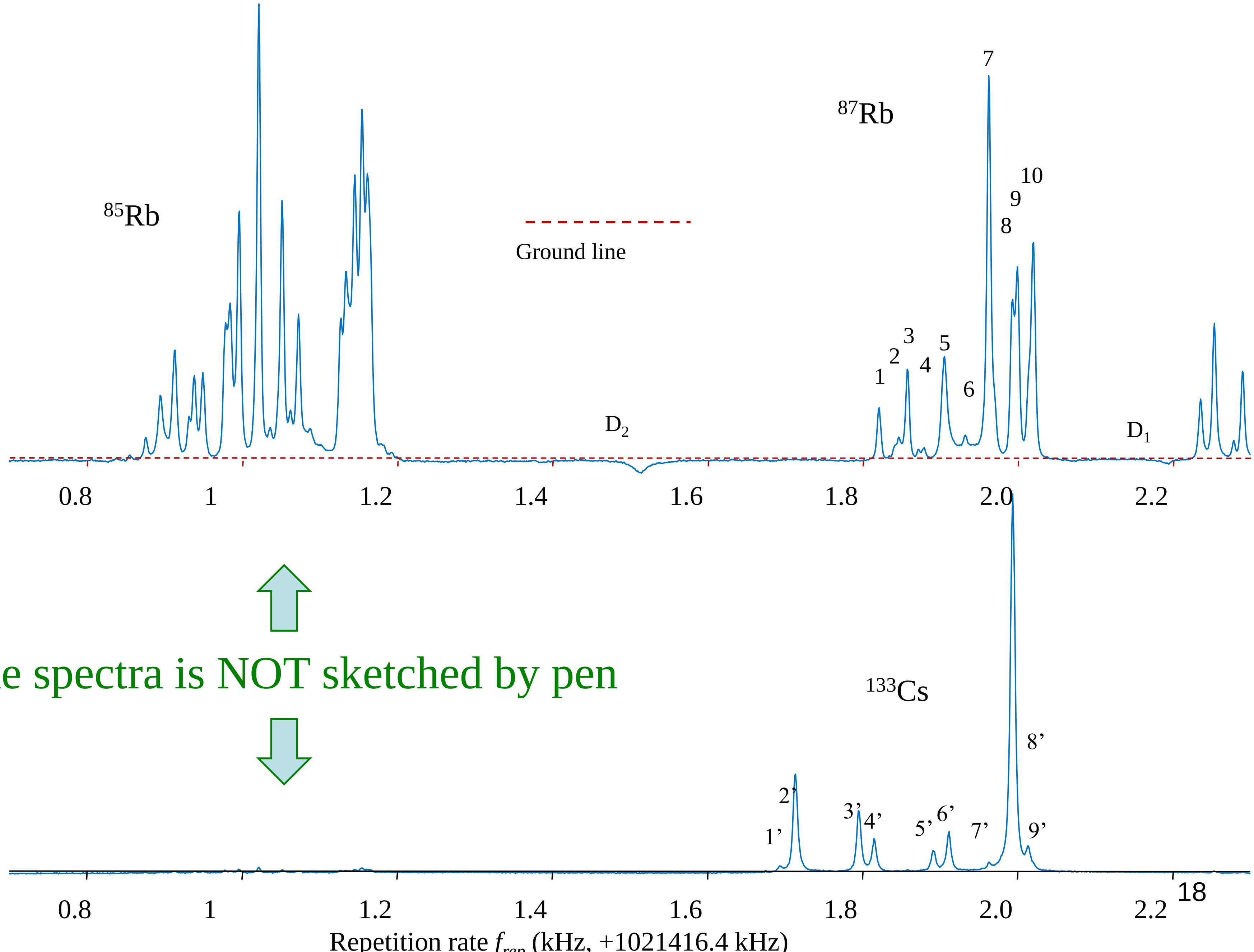
Simultaneously resolves

Rb and Cs spectra (*40 nm apart*) with

5-kHz resolution

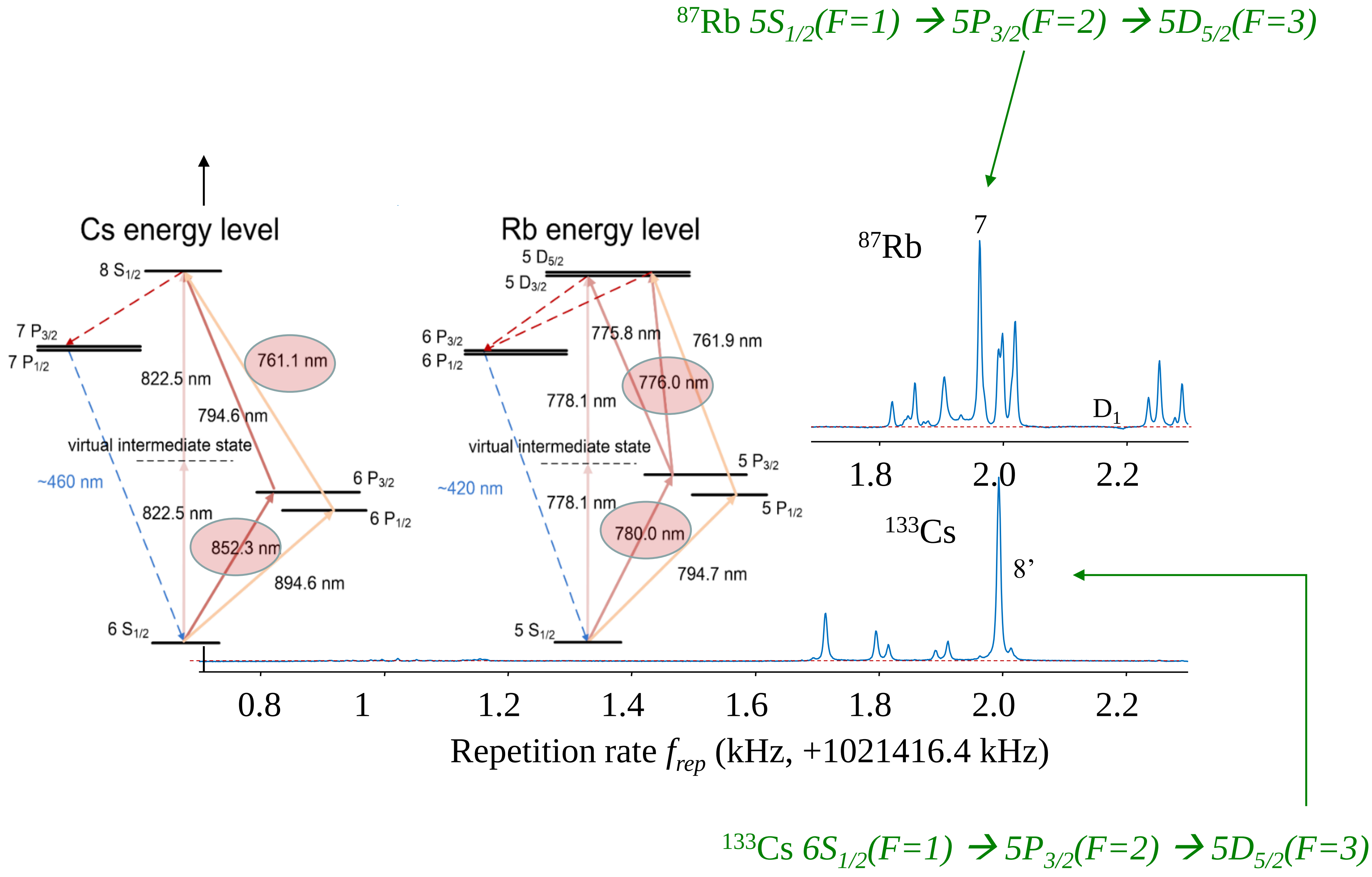


Direct frequency comb spectroscopy in record resolution

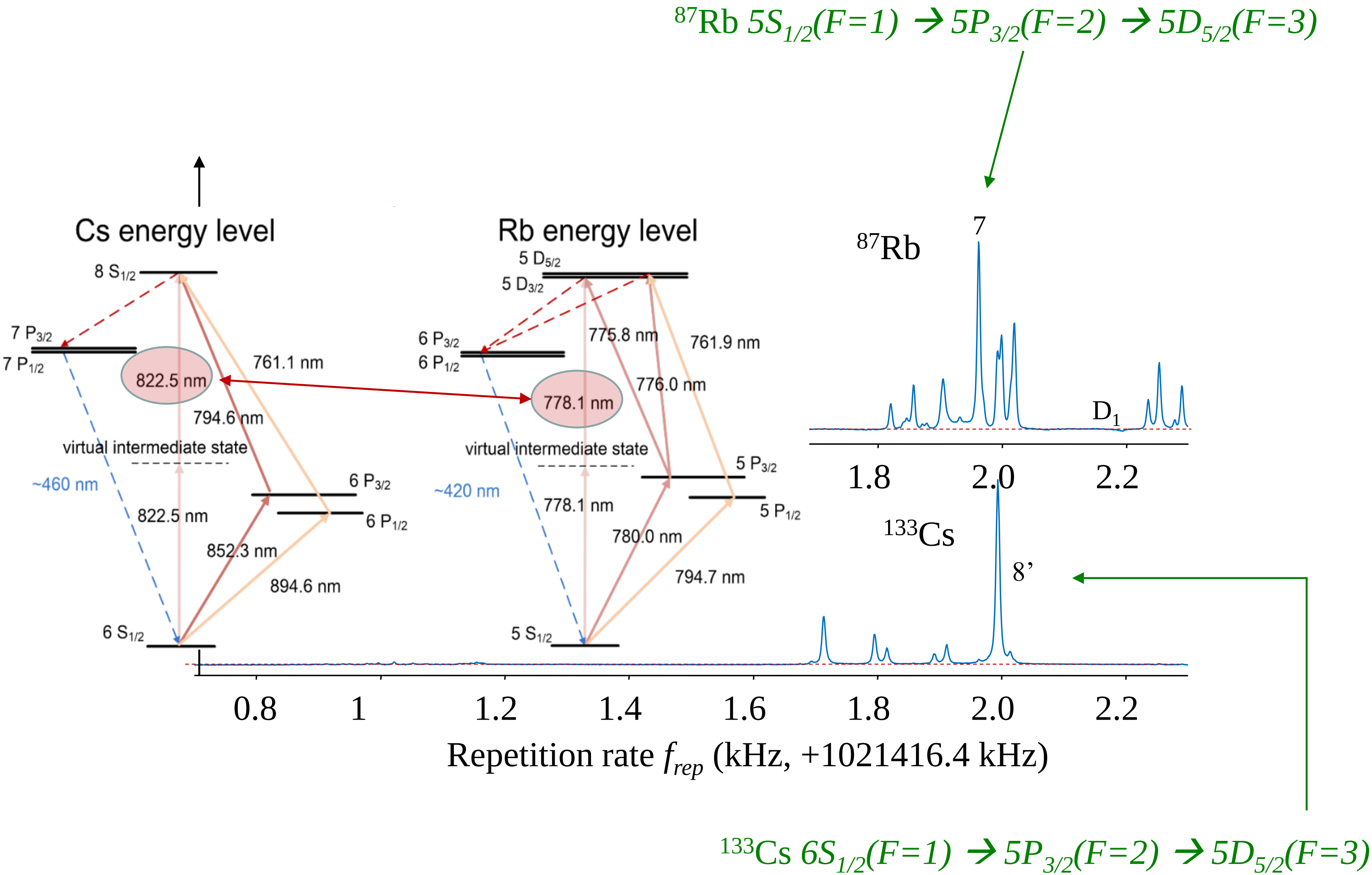


The spectra is NOT sketched by pen

Two clock transitions



The two clocks separates for 40 nm, resolved simultaneously



Some intriguing spectral features (I)

Line narrowing

Doppler-free two-color spectroscopy of the $6_2S_{1/2}$–$8_2S_{1/2}$ cesium transition using semiconductor diode lasers

C. Fort[1], M. Inguscio[1], P. Raspollini[1], F. Baldes[2], A. Sasso[2]

Appl. Phys. B 61, 467–472 (1995)

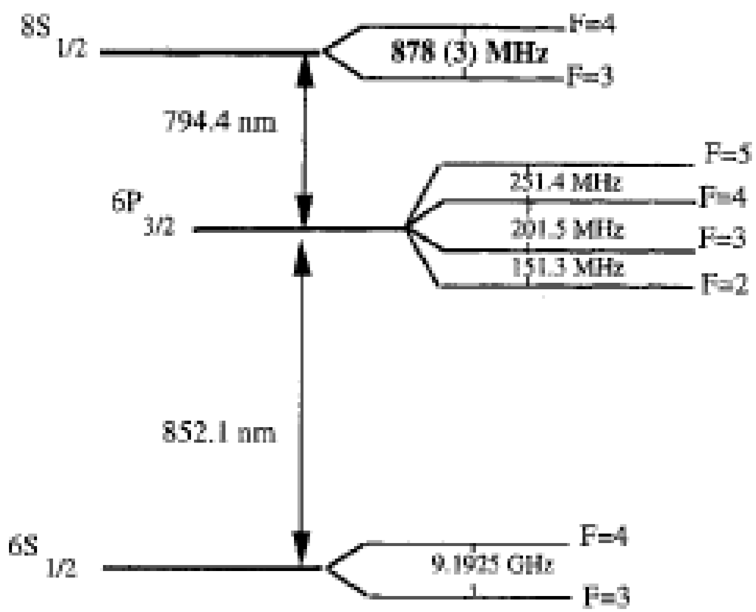


Fig. 4. Energy-level diagram of the relevant cesium states and the relative transitions involved in this experiment

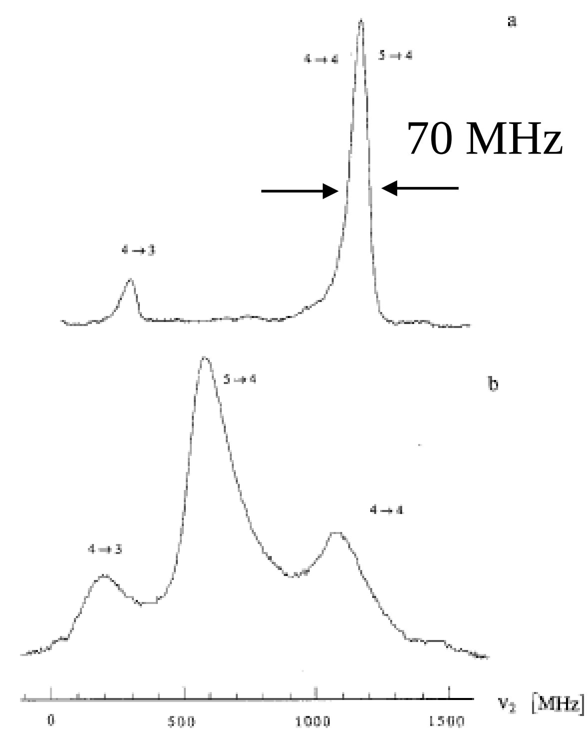


Fig. 6a,b. Two-color transition with DL1 locked onto the $F = 4$–$F = 5$ cross-over resonance. The hyperfine structure of the final state 8S is partially resolved with the counterpropagating scheme **(a)** while it is fully resolved with copropagating laser beams **(b)**

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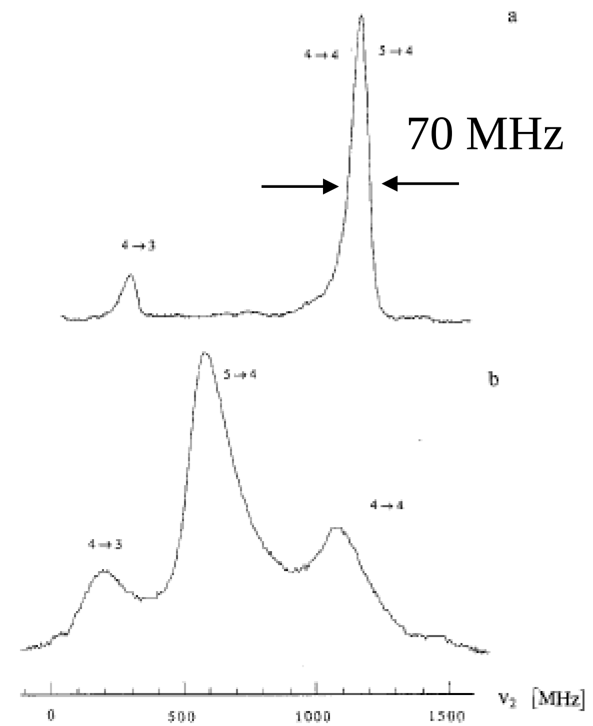

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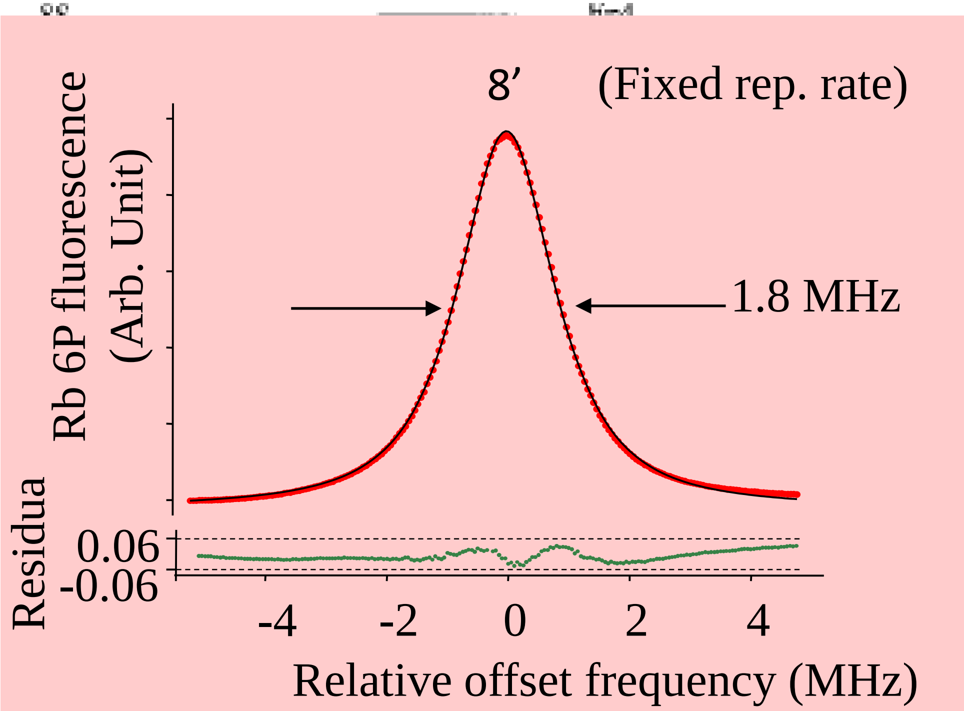
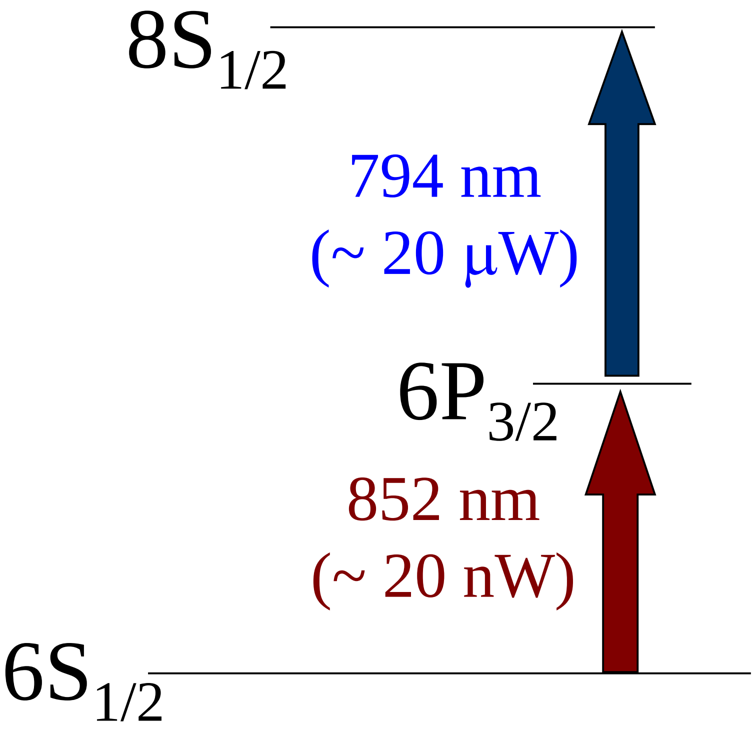




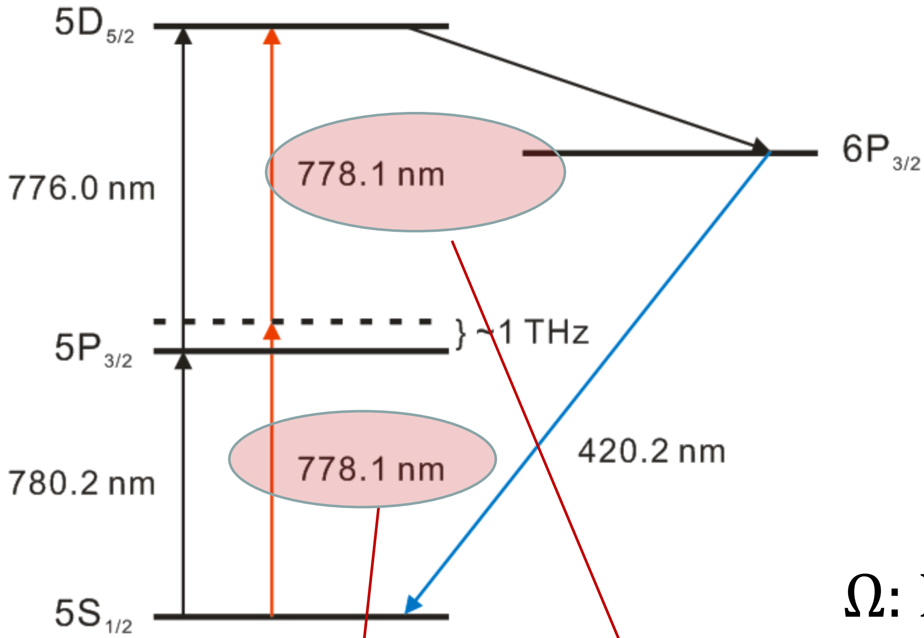
The intermediate state is **transparent?**

Some intriguing spectral features (II)

Multi-pathway AC stark shift

CW-clocks

^{85}Rb



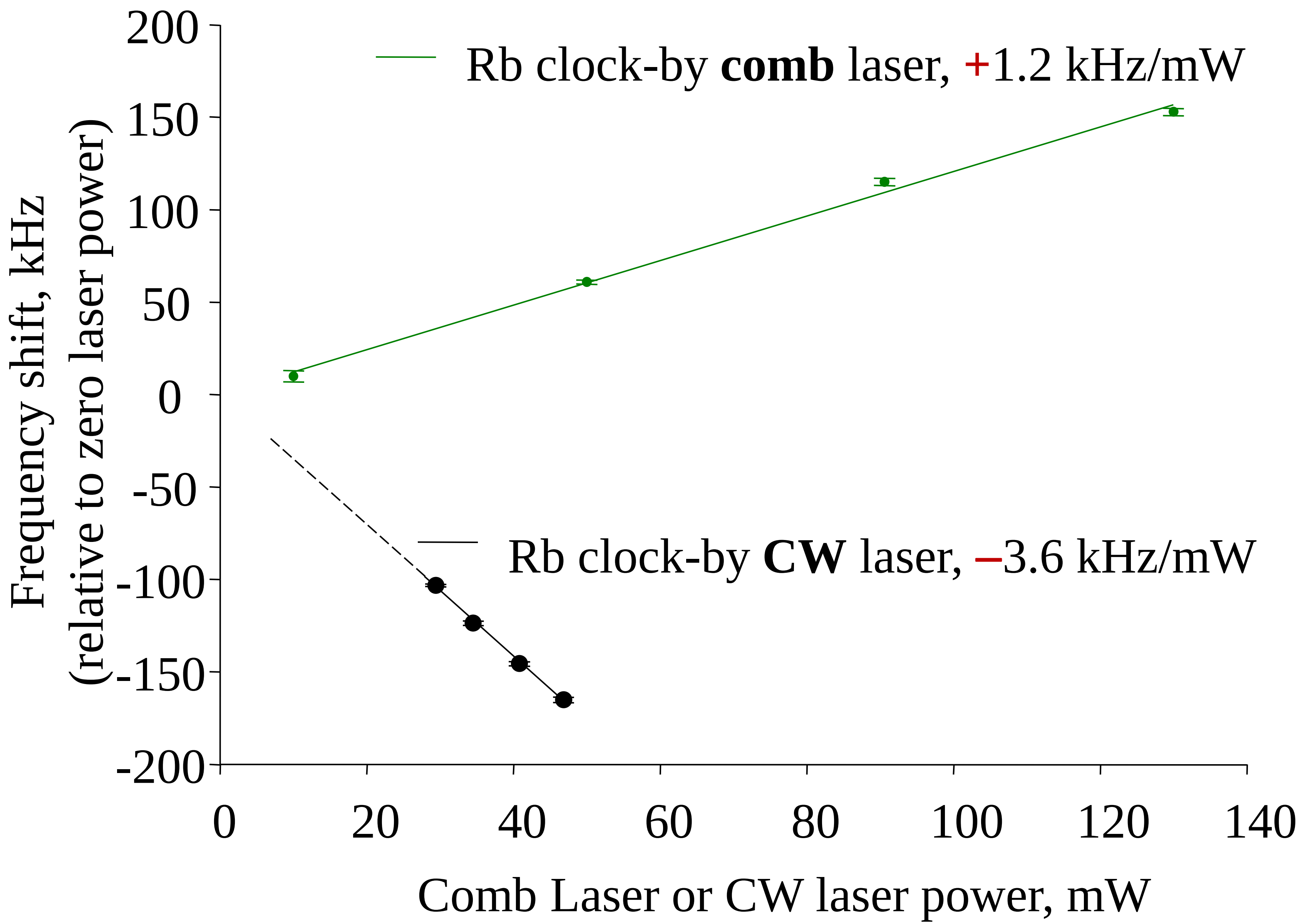
Ω: Rabi frequency

S_i: frequency shift

$$S_{fg}=S_f-S_g=-\sum_m\left(\frac{\Omega_{mg}^2}{\omega_L-\omega_{mg}}+\frac{\Omega_{fm}^2}{\omega_{fm}-\omega_L}\right)$$

Single pathway: Ladder direct two-photon yields red shift

Most concerned issue in clock !!

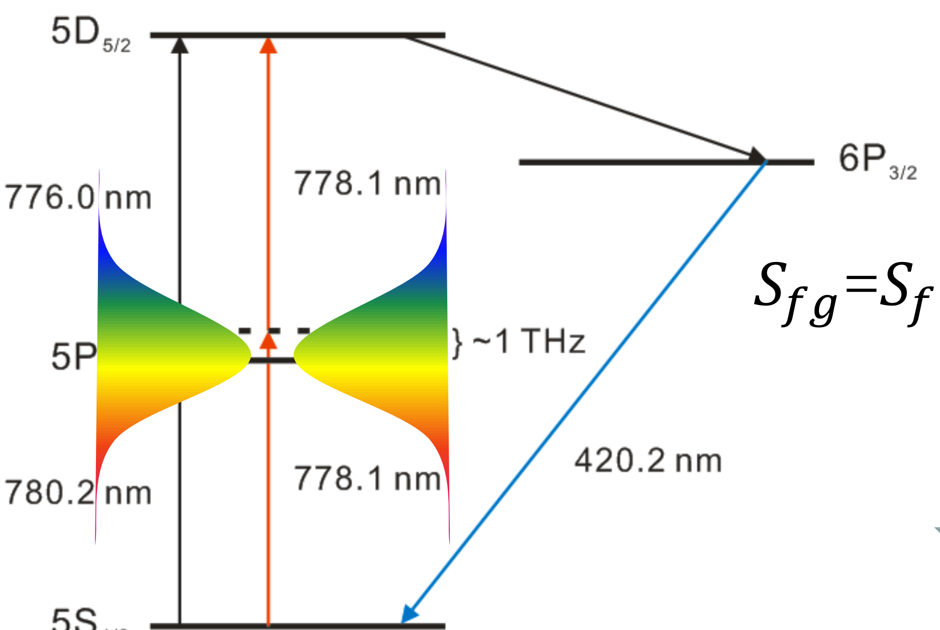


Rb clock-by **comb** laser, +1.2 kHz/mW
Rb clock-by **CW** laser, –3.6 kHz/mW
Frequency shift, kHz
(relative to zero laser power)
200
150
100
50
0
-50
-100
-150
-200
0
20
40
60
80
100
120
140
Comb Laser or CW laser power, mW

CW-clocks

Multi-paths induced AC stark shift

^{85}Rb



$$S_{fg}=S_f\text{-}S_g=-\sum_{m}\left(\frac{\Omega_{mg}^2}{\omega_L-\omega_{mg}}+\frac{\Omega_{fm}^2}{\omega_{fm}-\omega_L}\right)$$

$$S_{fg}=S_f\text{-}S_g=-\sum all\ comb\ modes\sum_{m}\left(\frac{\Omega_{mg}^2}{\omega_L-\omega_{mg}}+\frac{\Omega_{fm}^2}{\omega_{fm}-\omega_L}\right)$$

Question: Would it be possible to quantum controlling the AC stark shift to be zero by pulse shaping?

陽明交通大學

寺西慶哲 教授

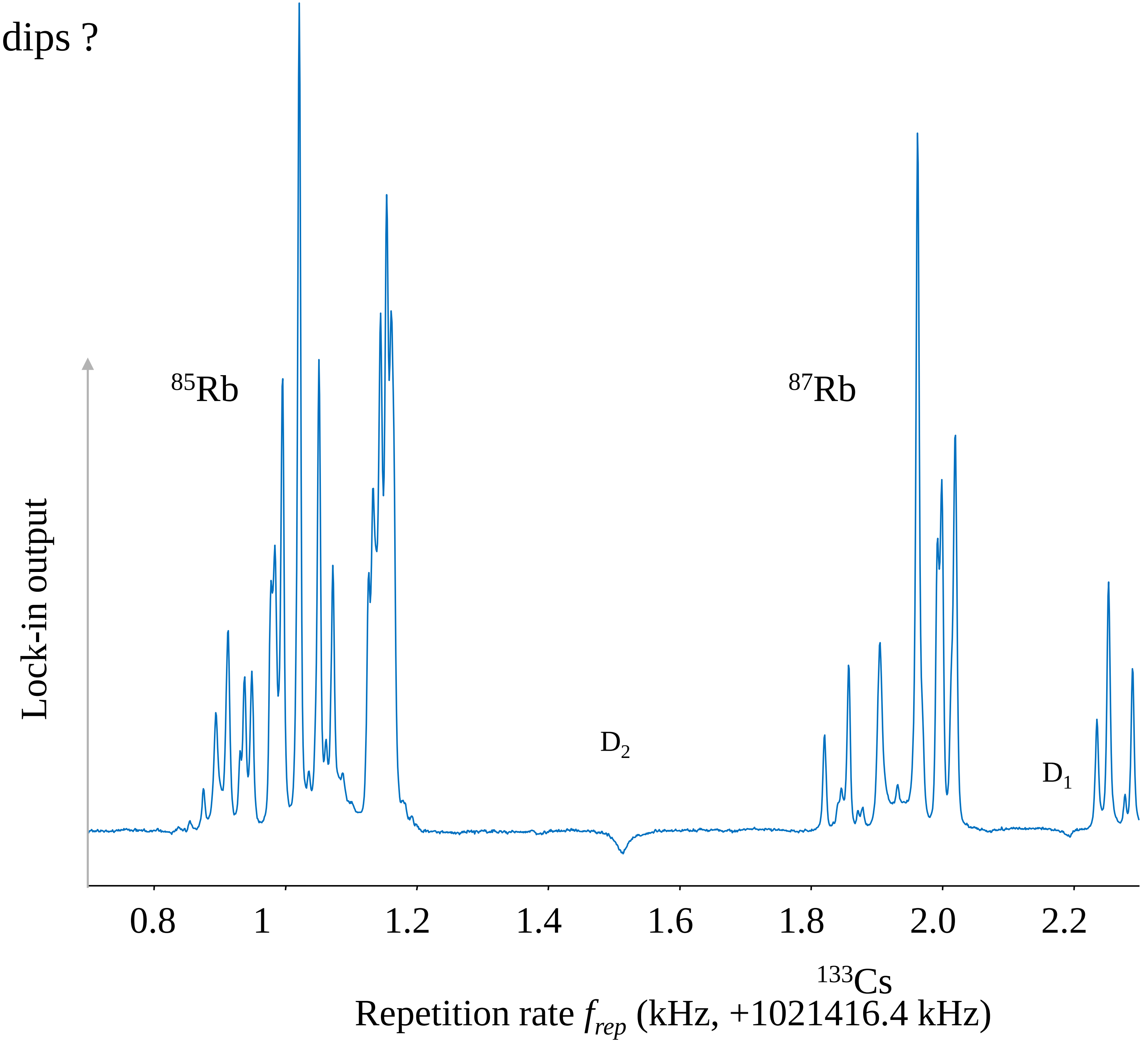
• 物理研究所

Most concerned issue in clock !!

Some intriguing spectral features (III)

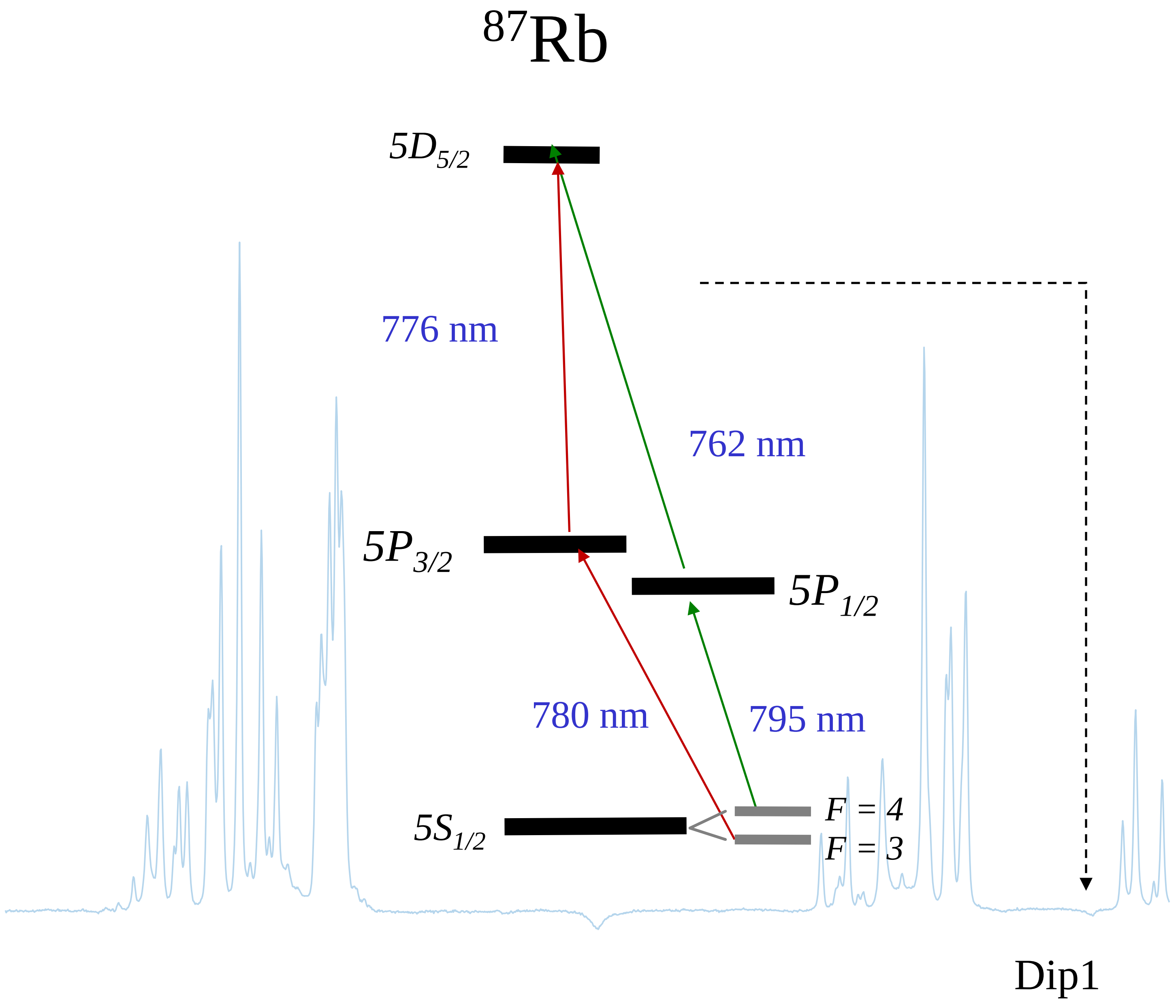
Quantum interference by different comb modes

Why dips ?



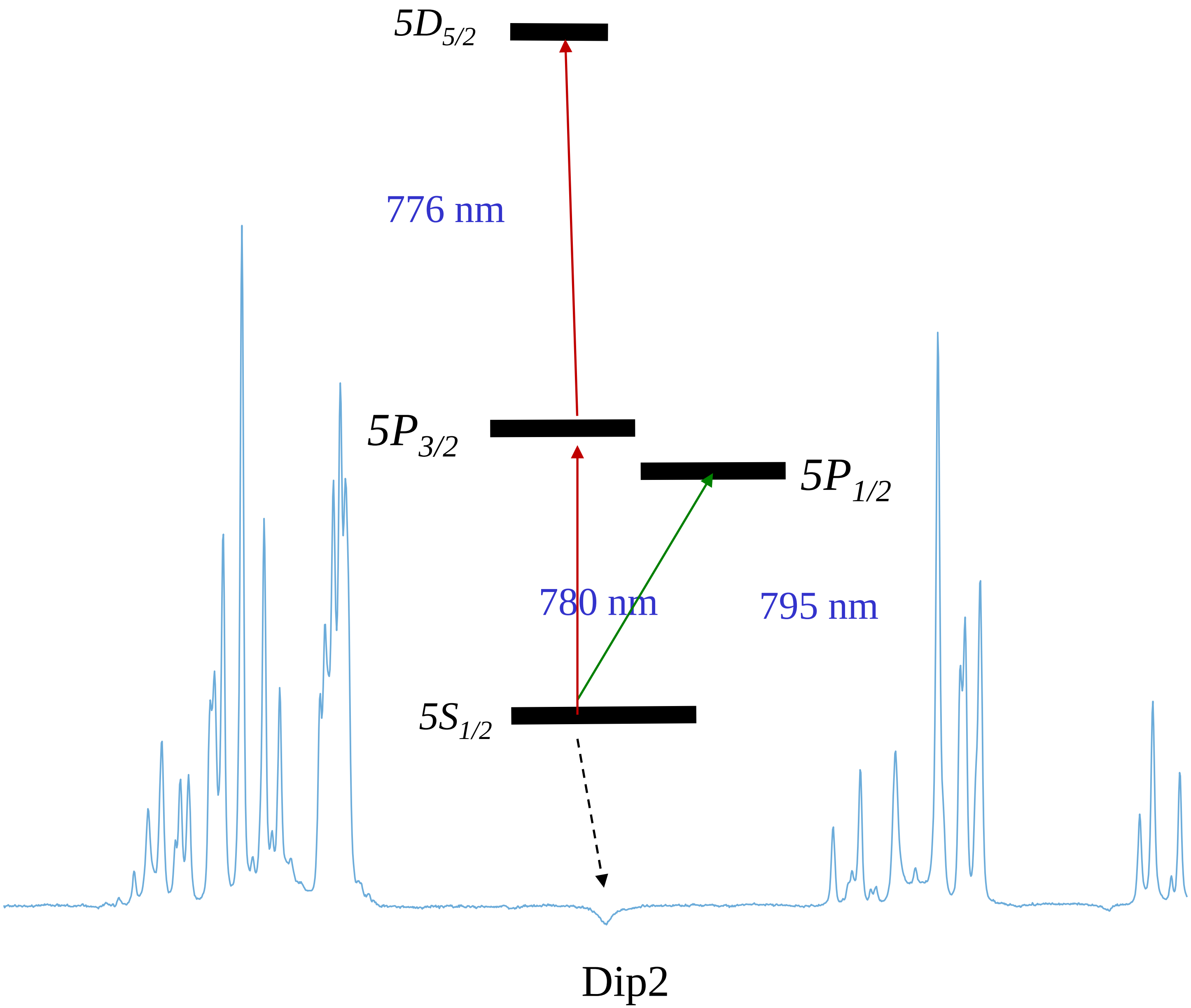
Lock-in output
^{85}Rb
^{87}Rb
D_2
D_1
0.8
1
1.2
1.4
1.6
1.8
2.0
2.2
^{133}Cs
Repetition rate f_{rep} (kHz, +1021416.4 kHz)

Two-pathway quantum interference



V type EIT interference

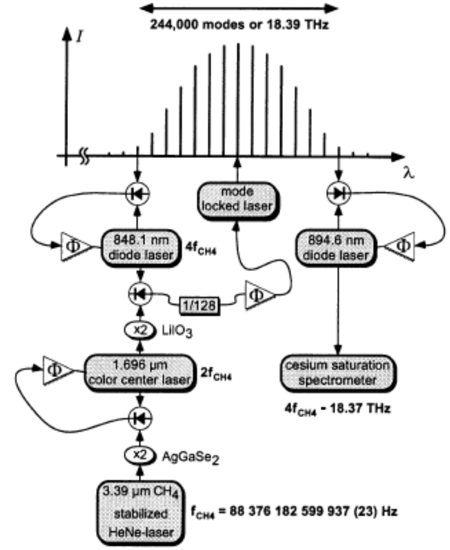
^{87}Rb



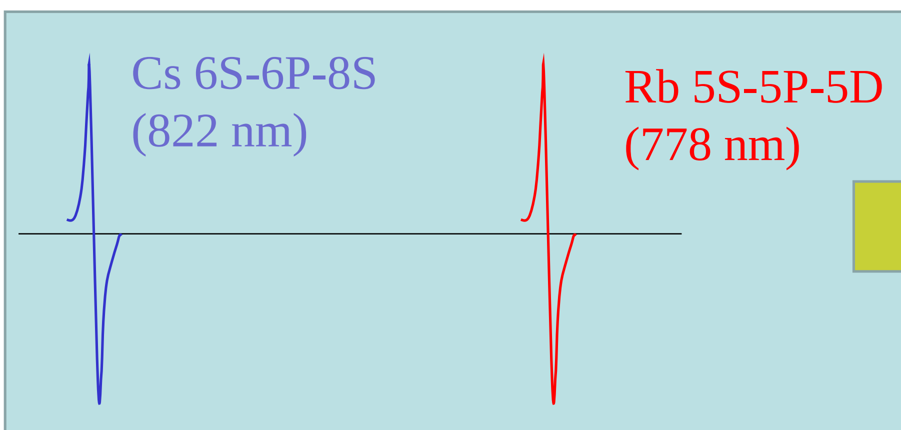
Application:

Direct comb clocks

Ted Hansch

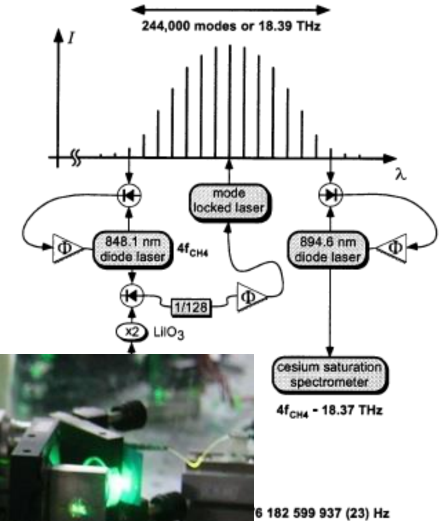


They all need a Cs clock to lock rep. rate!!

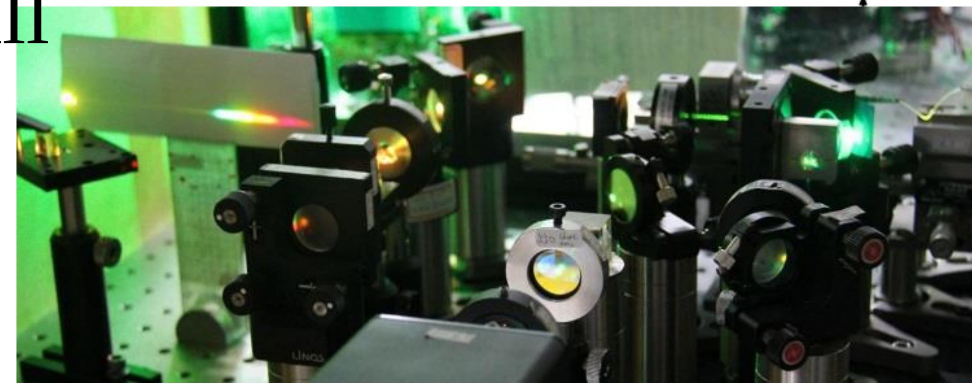


We locked two parameters directly with two spectra (without Cs clock)

Ted Hansch



Jan Hall



They all need a Cs clock to lock rep. rate!!

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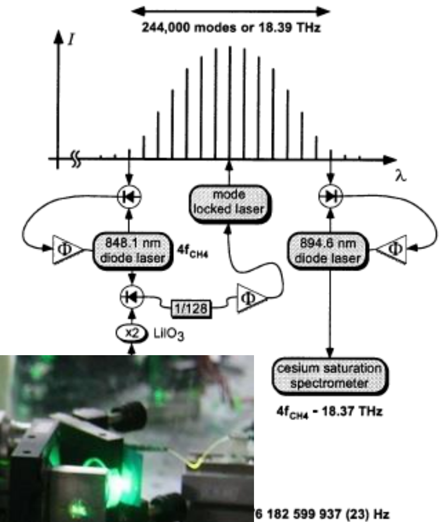
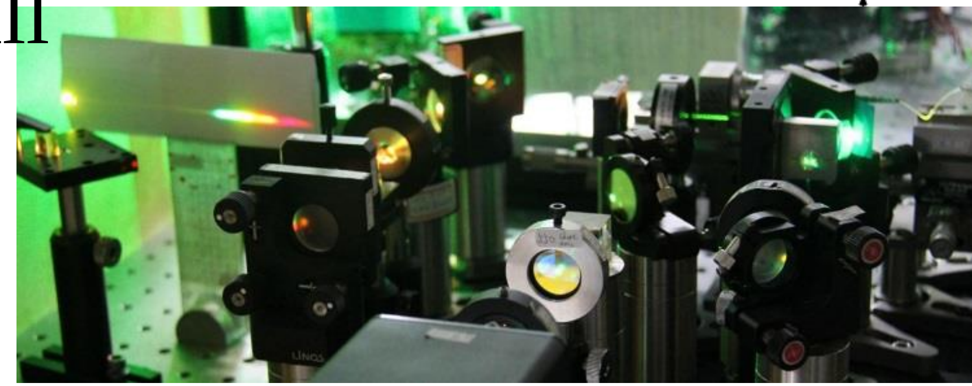


Jan Hall



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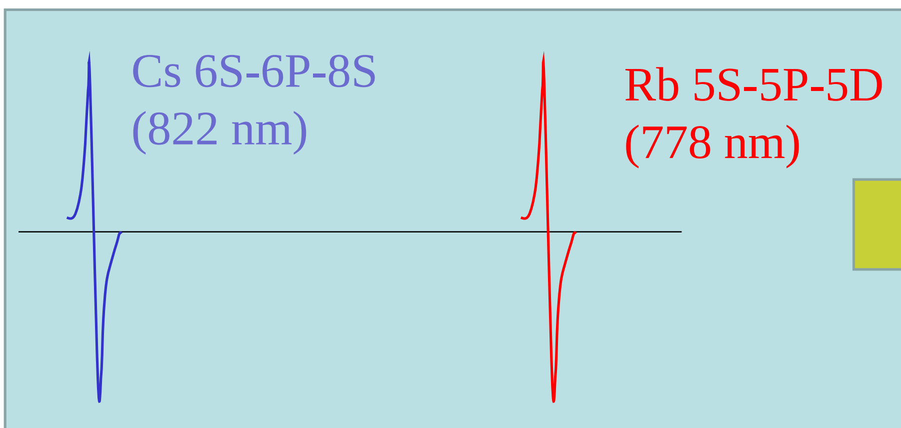
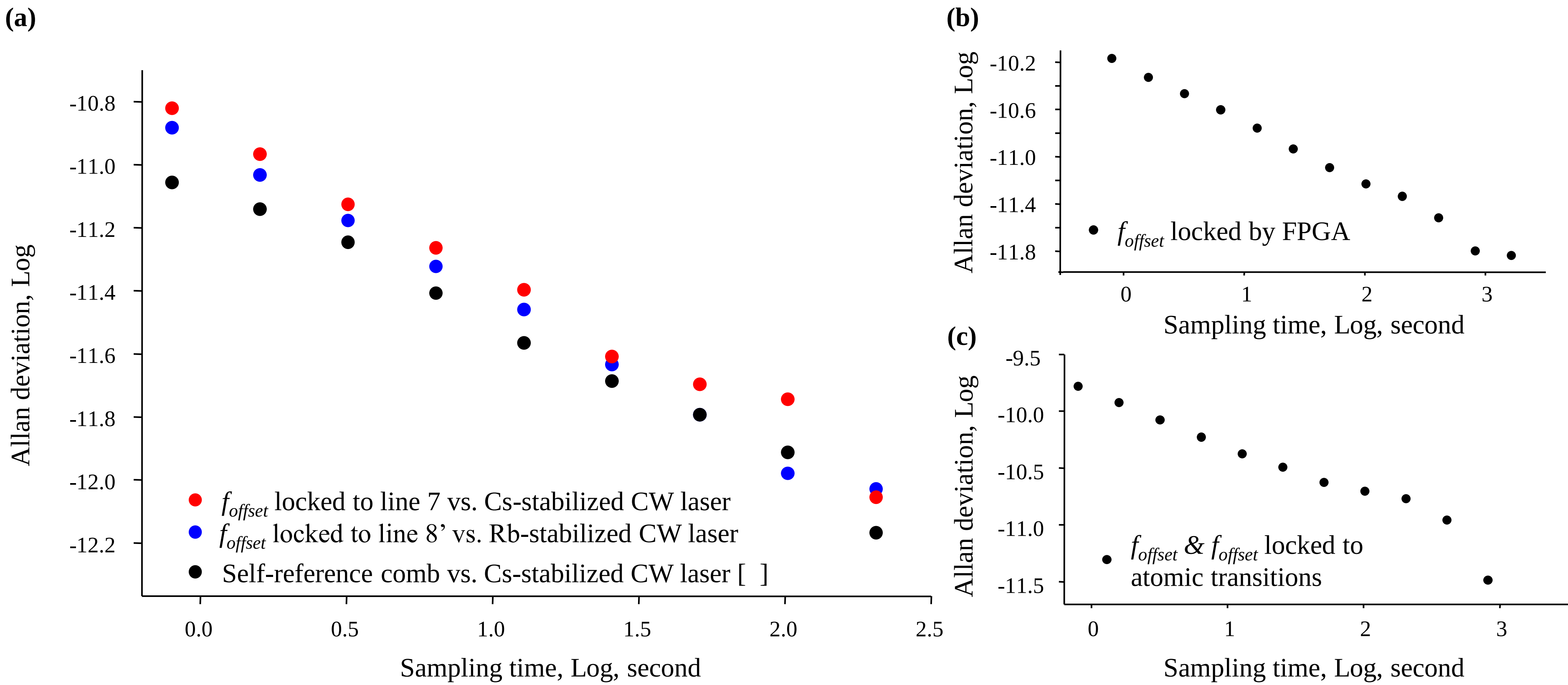


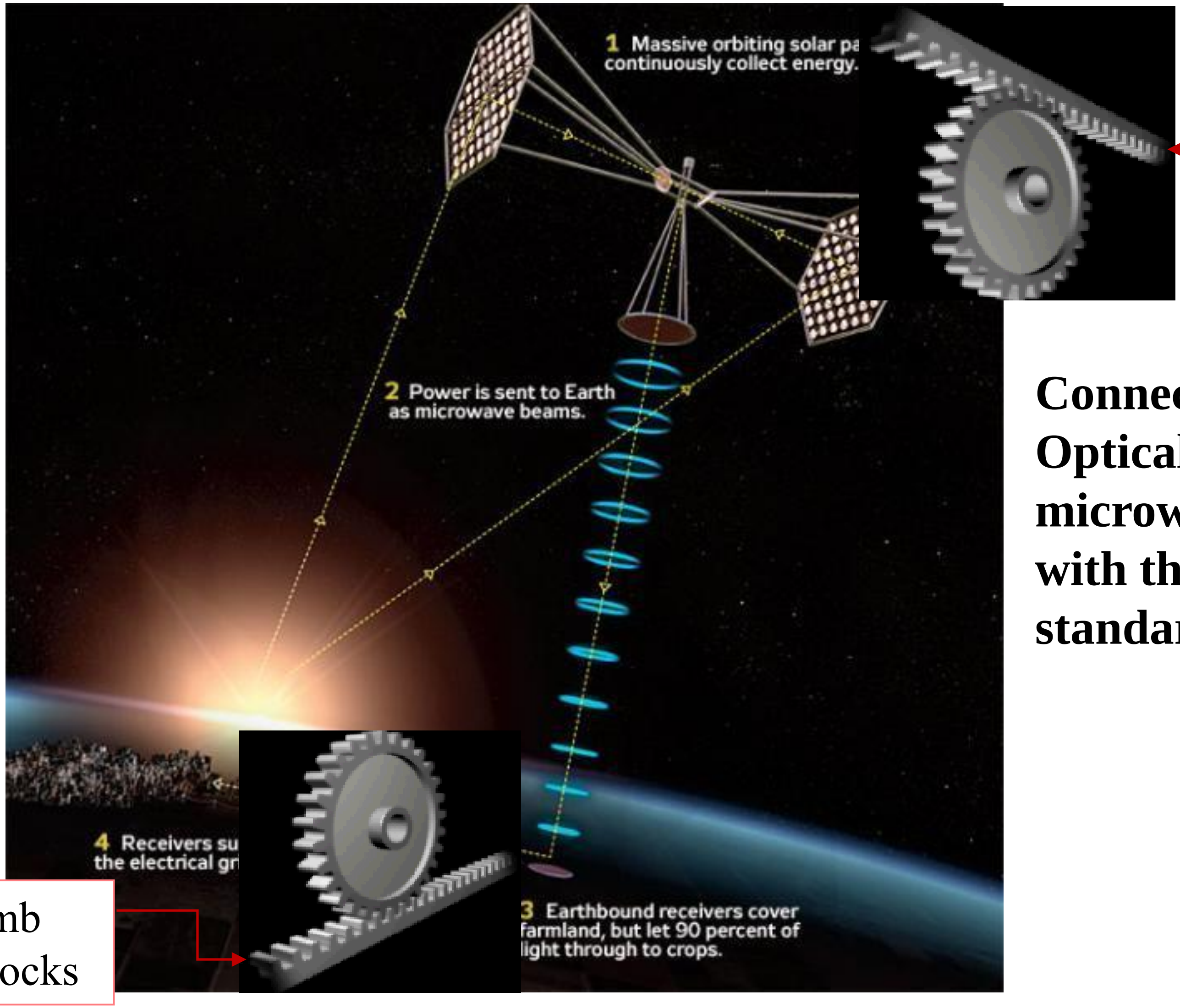
We locked two parameters directly with two spectra (without Cs clock)

Now we need merely one 6-cm Cs/Rb mixed cell to build up comb clocks



Future direction (1)

Comb laser in artificial satellite



Connects both Optical and microwave clocks with the ground standards

Ground comb laser and clocks

Future direction (2)

You can entangle comb photon

PRL 107, 030505 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Parallel Generation of Quadripartite Cluster Entanglement in the Optical Frequency Comb

Matthew Pysher,[1] Yoshichika Miwa,[2] Reihaneh Shahrokhshahi,[1] Russell Bloomer,[1] and Olivier Pfister[1,*]

You can squeeze comb photon

PRL 108, 083601 (2012) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2012

Generation and Characterization of Multimode Quantum Frequency Combs

Olivier Pinel,[1] Pu Jian,[1] Renné Medeiros de Araújo,[1] Jinxia Feng,[1,2] Benoît Chalopin,[1,3]
Claude Fabre,[1,*] and Nicolas Treps[1]

You can apply comb photon on quantum computation

Selected for a Viewpoint in *Physics*
PRL 101, 130501 (2008) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2008

One-Way Quantum Computing in the Optical Frequency Comb

Nicolas C. Menicucci,[1,2] Steven T. Flammia,[3] and Olivier Pfister[4]

You can use comb laser to entangle atomic Qubits

Selected for a Viewpoint in *Physics*
PRL **104**, 140501 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Entanglement of Atomic Qubits Using an Optical Frequency Comb

D. Hayes,* D. N. Matsukevich, P. Maunz, D. Hucul, Q. Quraishi, S. Olmschenk, W. Campbell, J. Mizrahi, C. Senko, and C. Monroe

Acknowledgement:

Telecommun. Labs. (中華電信研究所)

Ministry of Science and Technology (科技部)

partner in next step:

陽明交通大學

寺西慶哲 教授

- 物理研究所

中央研究院

張銘顯 研究員

原子分子研究所

中央大學

陳彥宏 教授

- 光電研究所

中央大學

李依珊 教授

- 電機研究所