9th Symposium on Frequency Standards and Metrology

Low-noise optical frequency divider for precision measurement

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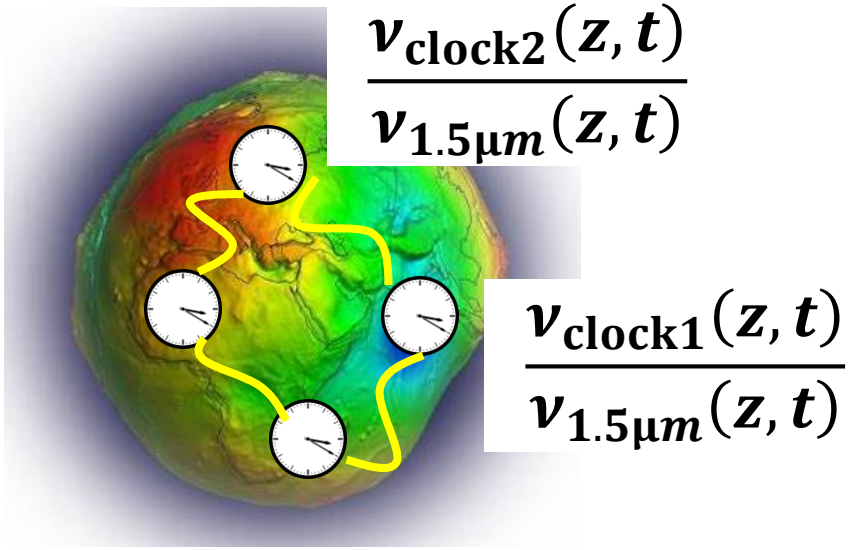
Motivation

- **Redefinition of the second** $R = \frac{\nu_{\mathrm{clock1}}}{\nu_{\mathrm{clock2}}}, \quad \frac{\delta R}{R} < 5 \times 10^{-18}$
- **Precision measurement**
  - Test the constancy of α
  - Dark matter detection
  - Geodesy

$$\frac{\nu_{\mathrm{clock1}}(t)}{\nu_{\mathrm{clock2}}(t)}, \quad K_1 - K_2$$

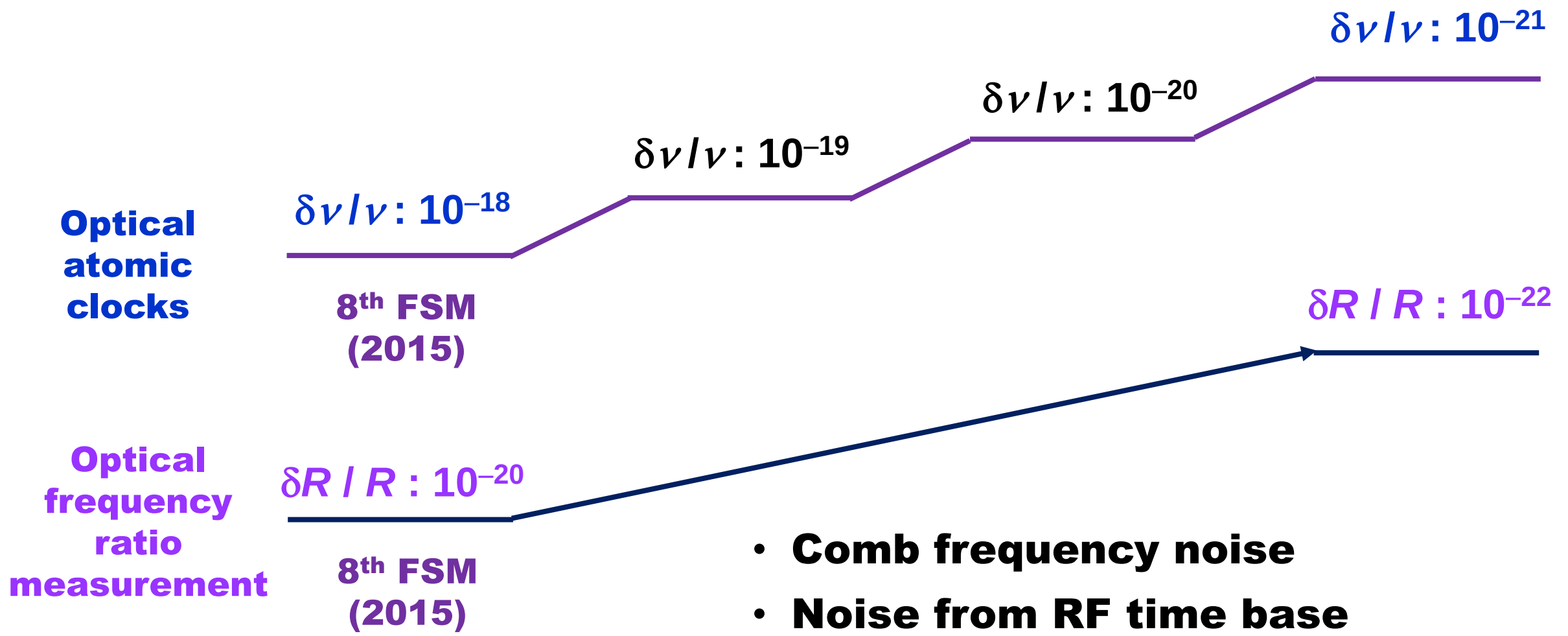


- **Precision spectroscopy (CaH^+, ^{229}Th...)**

$$R = \frac{\nu_{\mathrm{probe}}}{\nu_{\mathrm{clock1}}}$$

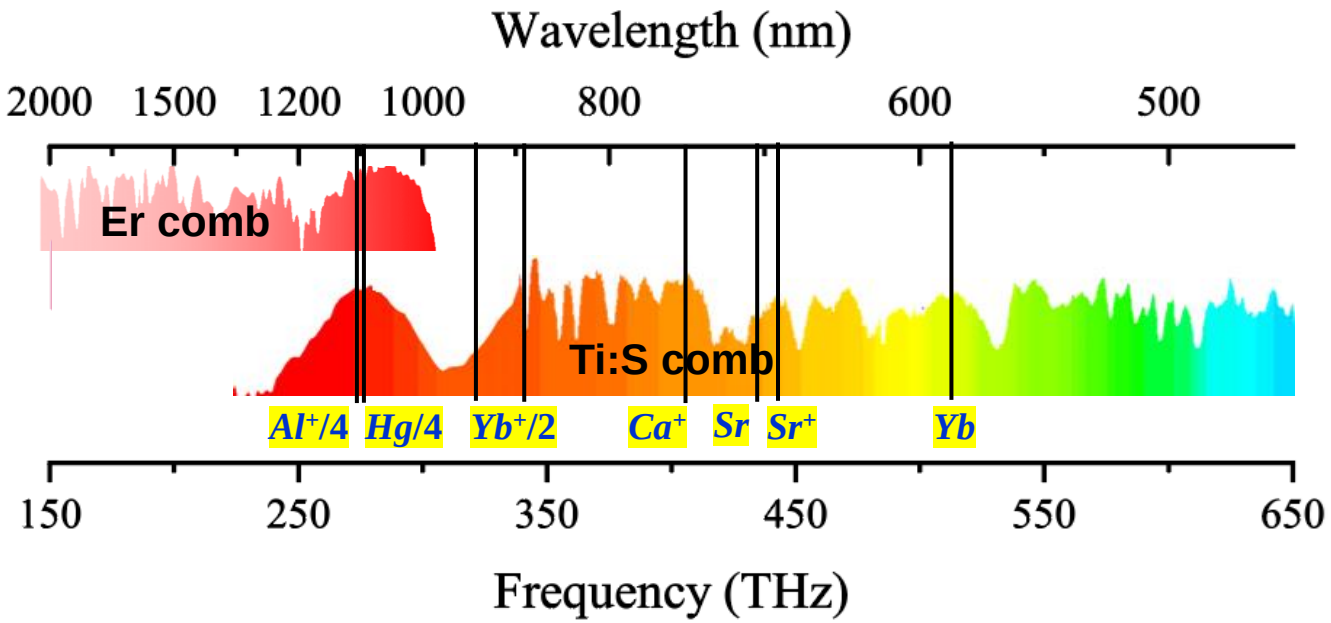
An accurate ratio measurement relies on optical clocks and measurement device!

Precision ratio measurement supports applications of optical atomic clocks

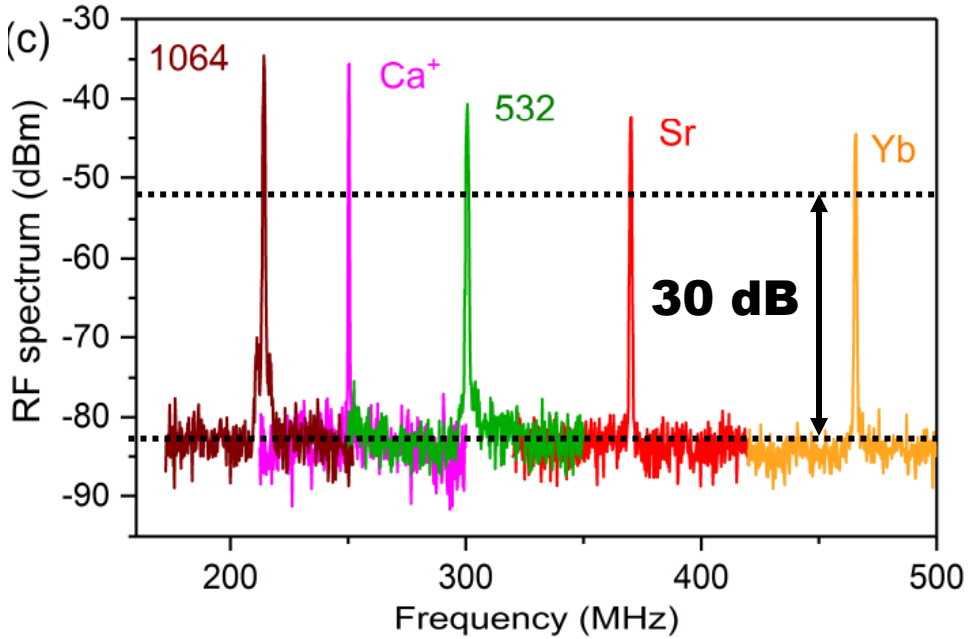


- Comb frequency noise
- Noise from RF time base
- Noise due to light path fluctuation

Ti:Sapphire optical frequency comb



Beat notes between a Ti:S comb and optical clocks or lasers (RBW=300 kHz)

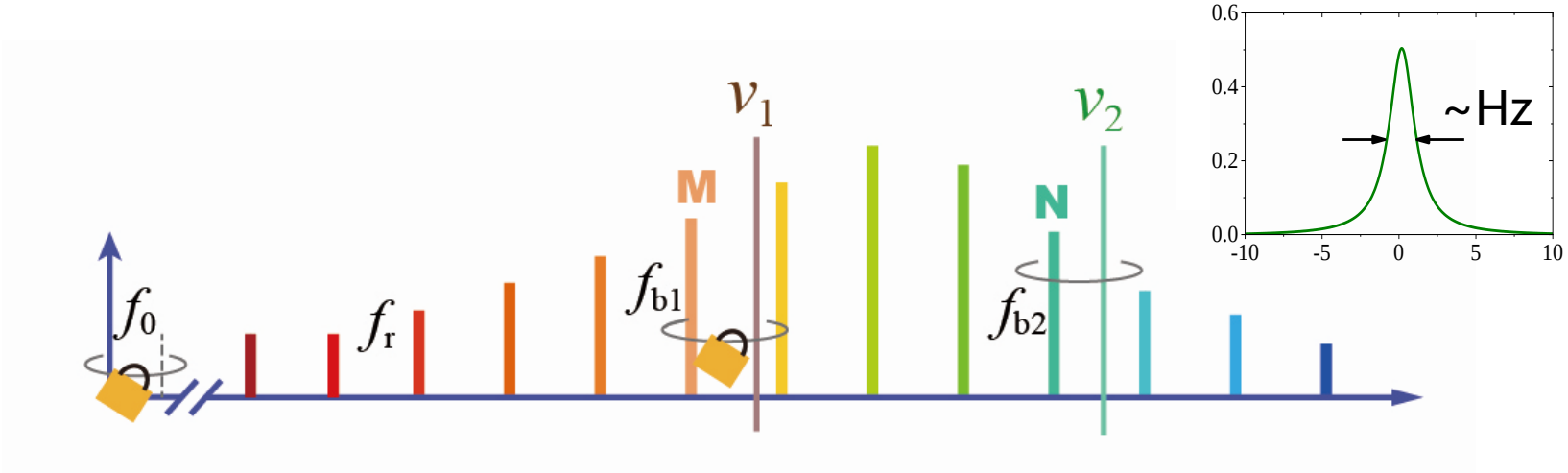


- **Low frequency noise** (mm-scale solid state gain medium)
- **Broadened spectrum covers most of optical clocks**

  (no amplifiers, less frequency doublers…)

Reduce comb & RF time-base frequency noise

- **Comb phase-locked to an ultra-stable laser or an optical clock**



Synchronous counting

$$\frac{\nu_1}{\nu_2} = \frac{f_0 + M \cdot f_r + f_{b1}}{f_0 + N \cdot f_r + f_{b2}}$$

A×f_{time} B×f_{time} D×f_{time}

A×f_{time} B×f_{time} C×f_{time}

	1 s instability	uncertainty	
BIPM, ECNU, NIST	2.3×10^{-17}	1.4×10^{-19}	Science, 303, 5665 (2004)
RIKEN	5×10^{-18}	/	Appl. Phys. Exp., 10, 6 (2017)
NIST	3×10^{-18}	1.7×10^{-20}	Optica, 4, 879-855 (2017)
Menlo	5×10^{-18}	5.3×10^{-21}	Nat. Photonics 14, 44–49 (2020)

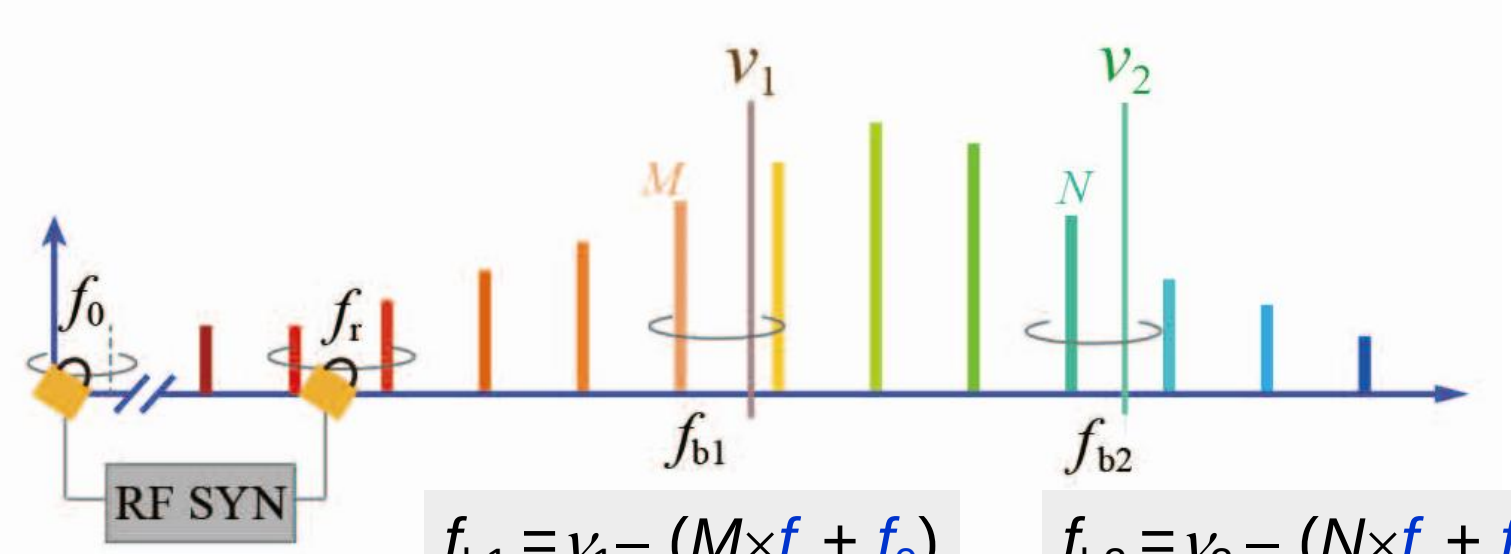
× **High servo bandwidth**

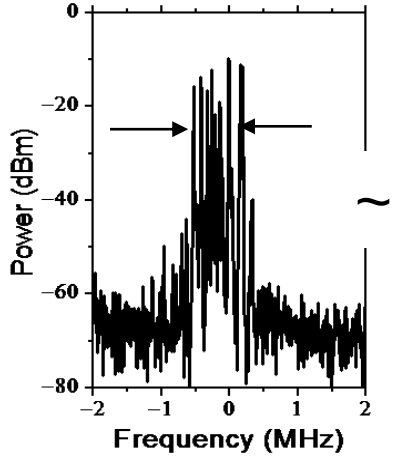
× **Easily lose lock**

Immune to comb frequency noise

- **comb stabilized to a H maser or a Rb clock**

  (extend continuous operation time, less cycle slips)





~ kHz-MHz

$$f_{b1} = \nu_1 - (M \times f_r + f_0) \qquad f_{b2} = \nu_2 - (N \times f_r + f_0)$$

Transfer oscillator scheme [1] → Comb noise free

$$f_b \sim \frac{\nu_1}{M} - \frac{\nu_2}{N}$$

Extra RF time base induces noise

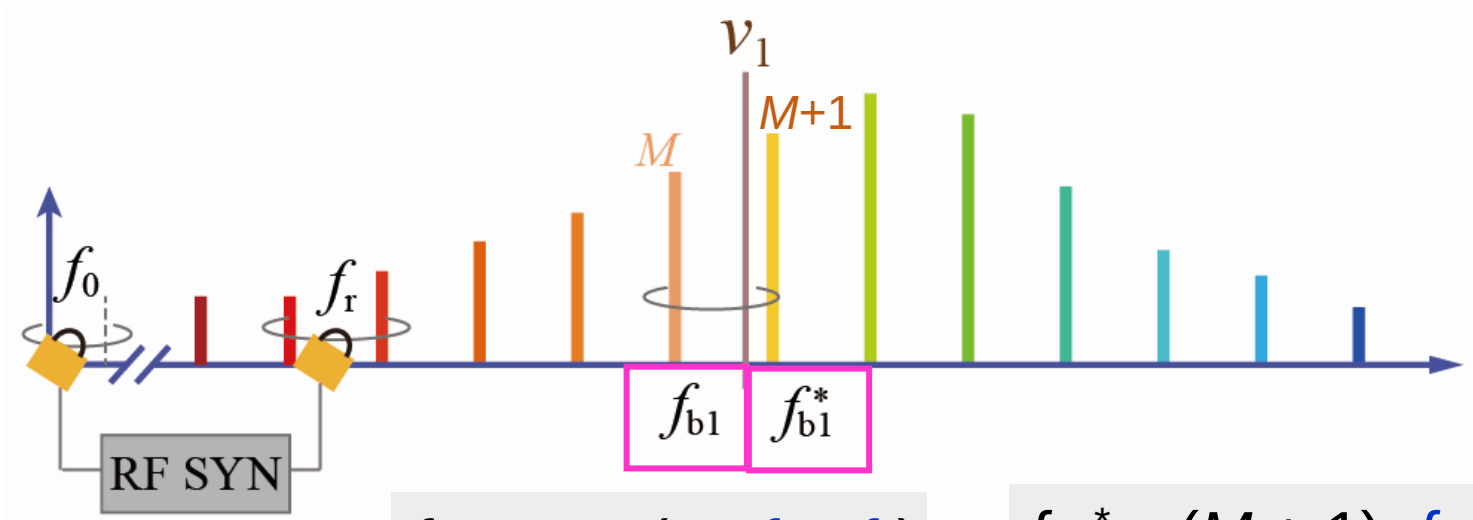
- **Count $f_b \rightarrow \nu_1 / \nu_2$**
- **Lock $f_b \rightarrow$ PLL ν_2 to ν_1**

[1] Telle, et. al. Appl. Phys. B **74**, 1 (2002)

Optically-referenced RF time base

- **comb stabilized to a H maser or a Rb clock**

  (extend continuous operation time, less cycle slips)



$$f_b \sim \frac{\nu_1}{M} - \frac{\nu_2}{N} = \frac{\nu_1}{K'}$$

$$\nu_2 = \nu_1 N\left(\frac{1}{M} - \frac{1}{K'}\right) = \frac{\nu_1}{R}$$

***R* can be preset & sweep**

$$f_{b1} = \nu_1 - (M \times f_r + f_0)$$

$$f_{b1}^* = (M+1) \times f_r + f_0 - \nu_2$$

Transfer oscillator scheme →

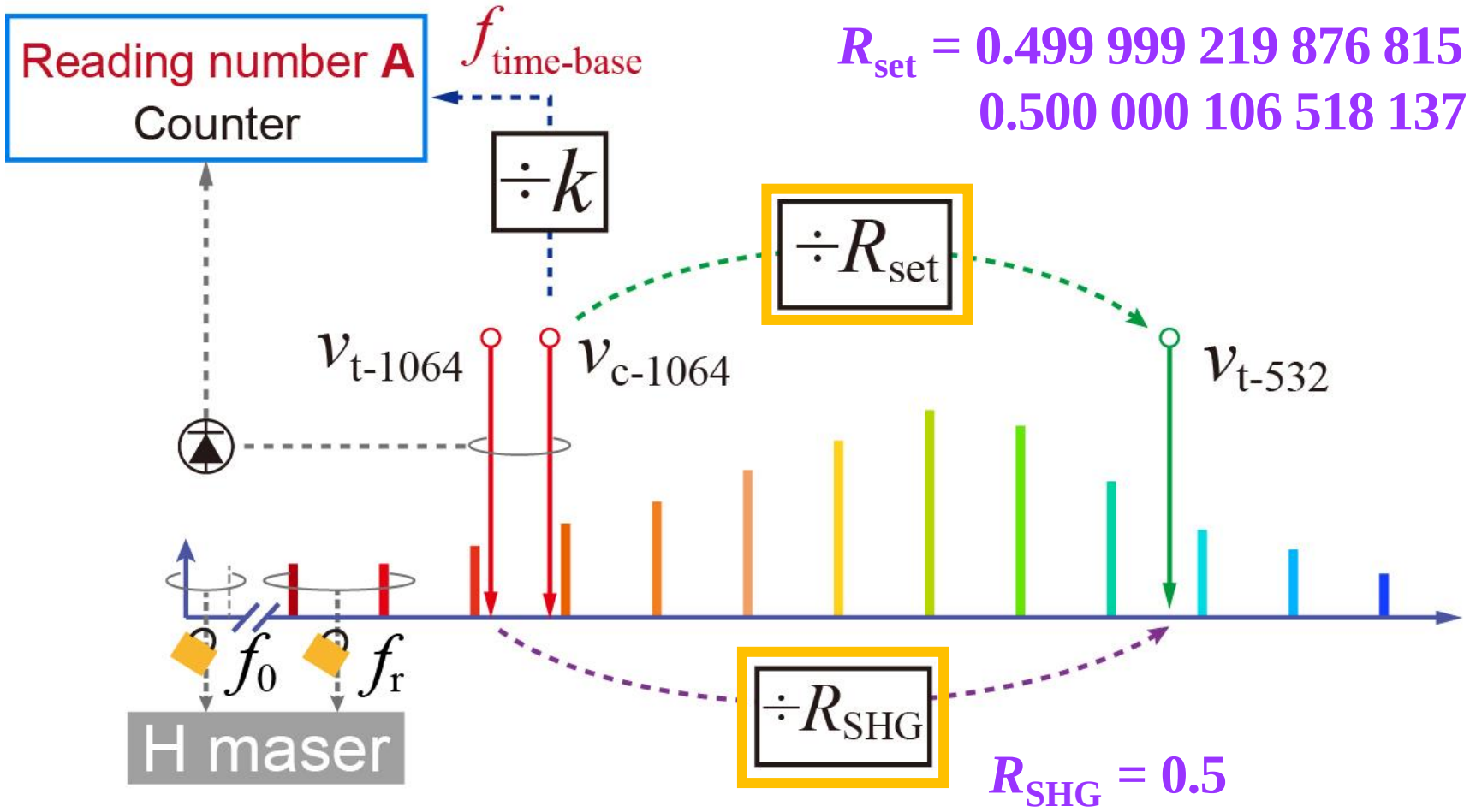
Comb noise free

$$\delta \sim \frac{\nu_1}{M} - \frac{\nu_1}{M+1} \sim \frac{\nu_1}{k}$$

Only related to ν_1

Yao et. al. Nat. Sci. Rev. 3, 463 (2016)

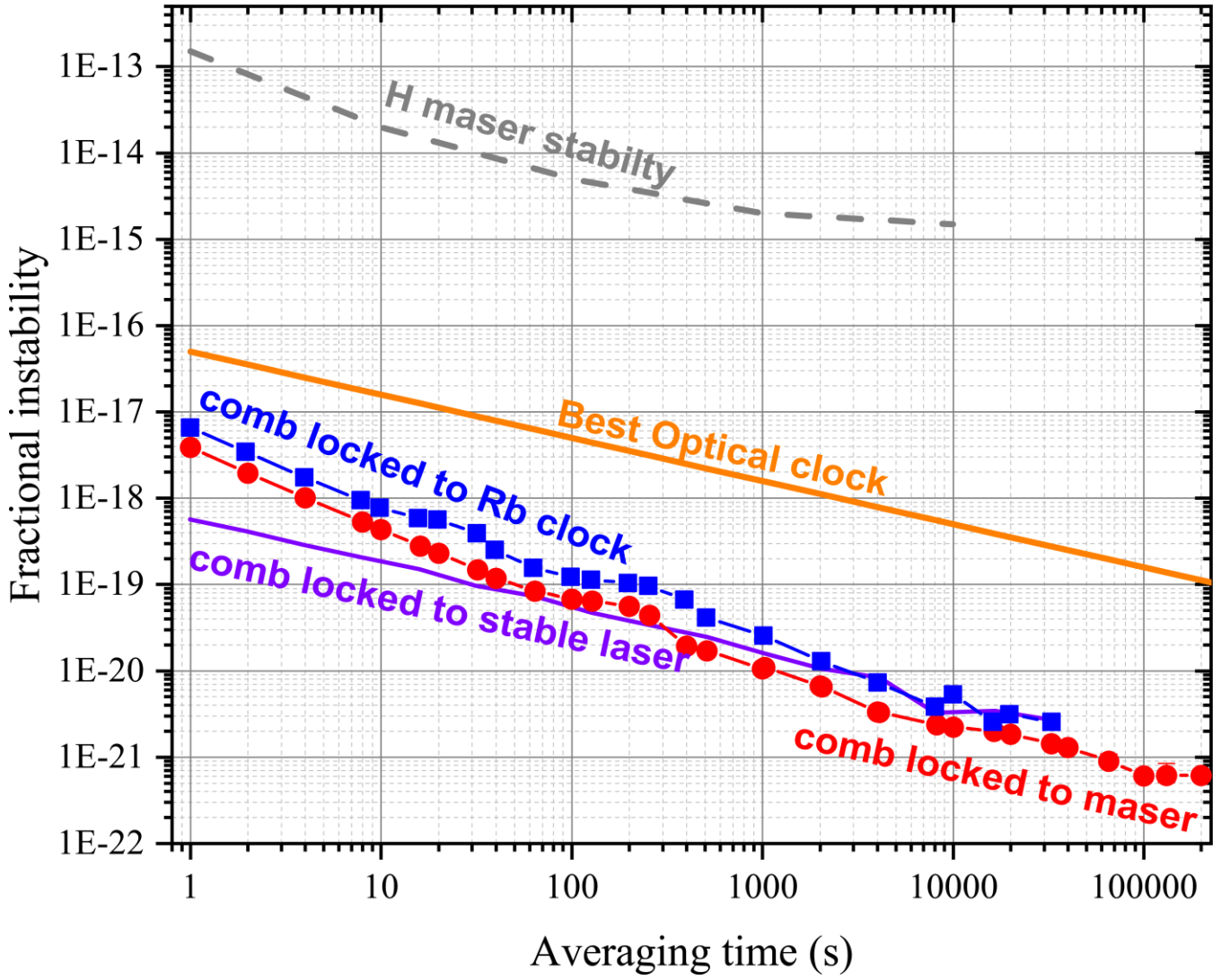
Division noise characterization



R_{set} = 0.499 999 219 876 815 223 597 90
0.500 000 106 518 137 671 678 87

- Noise due to light path fluctuation: common path, air sealed box

Division noise characterization



- **Comb frequency noise immunity factor: 10^3– 10^6**

	Instability of comb line @ 1 s	Instability of *R* @1 s
Rb[1]	1×10^{-11}	8×10^{-18}
H[2]	1×10^{-13}	4×10^{-18}
Laser[3]	1×10^{-15}	6×10^{-19}

Applicable to chip-based combs

- **independent on comb *f* stability**

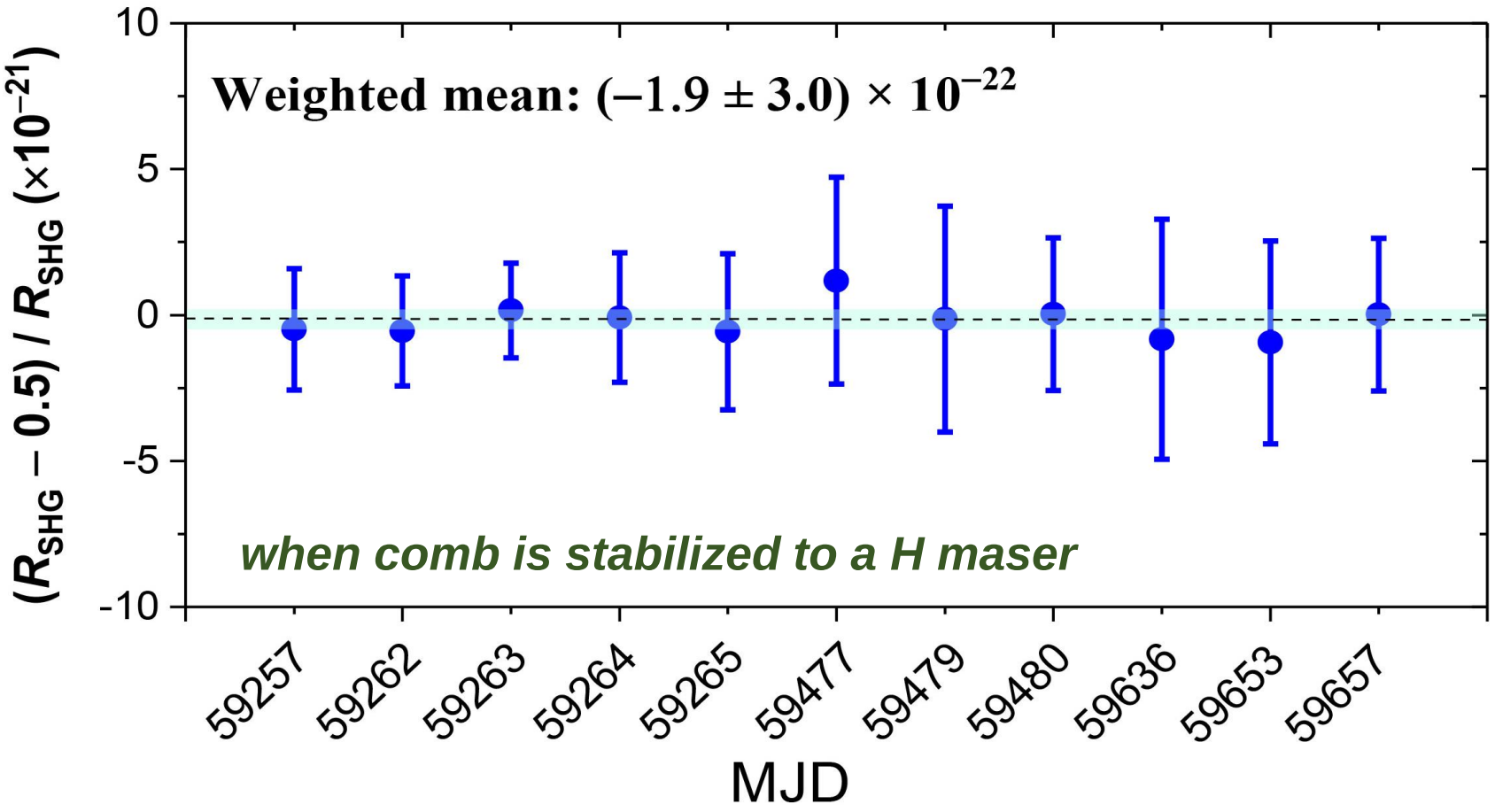
multi-channel division (f_0, f_b)

[1] Yao et. al. Photon. Res. 9, 98 (2021)

[2] Shi et. al. APL Photonics (2023)

[3] Yao et. al. Nat. Sci. Rev. 3, 463 (2016)

10^{-22} uncertainty in frequency division

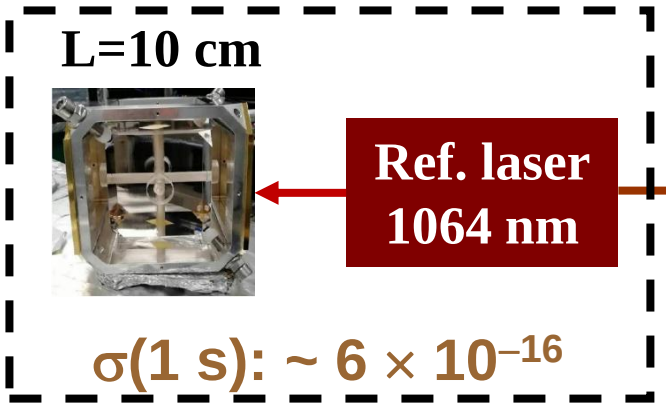


Dataset with effective time >20 h in a day:

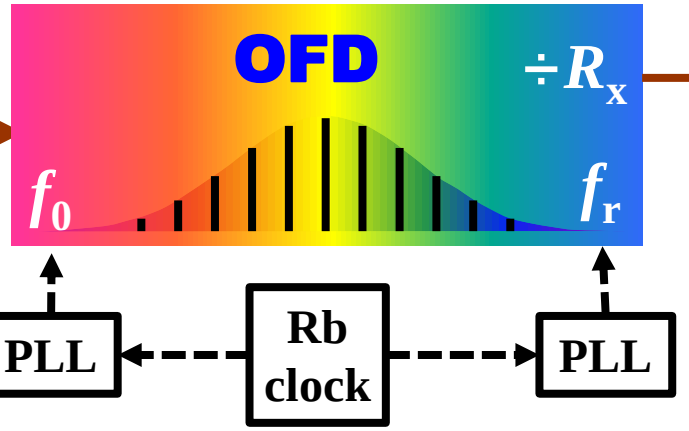
→ eliminate daily *T* and *P* variation-induced offset

Coherence transfer

Portable ultra-stable laser



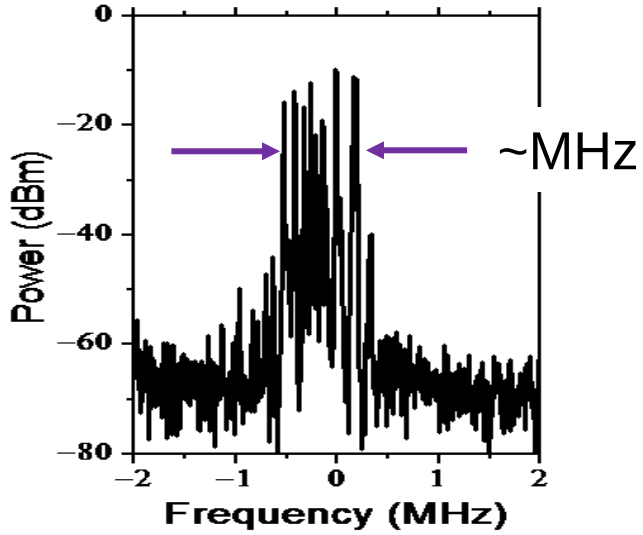
ν_{ref}



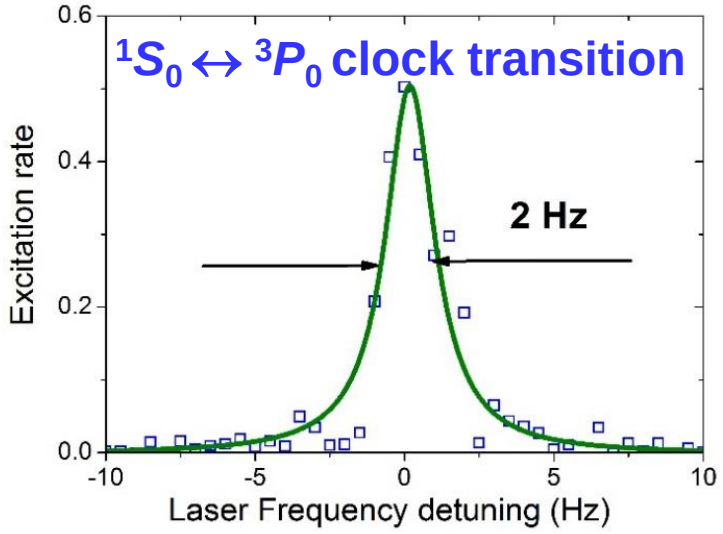
Servo bandwidth: MHz (without pre-stabilization)

Target laser 578 nm

$= \nu_{ref} / R_x$

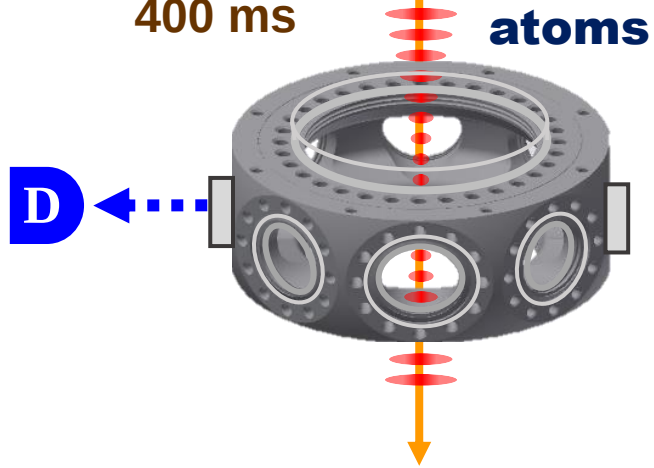


Comb frequency jitter



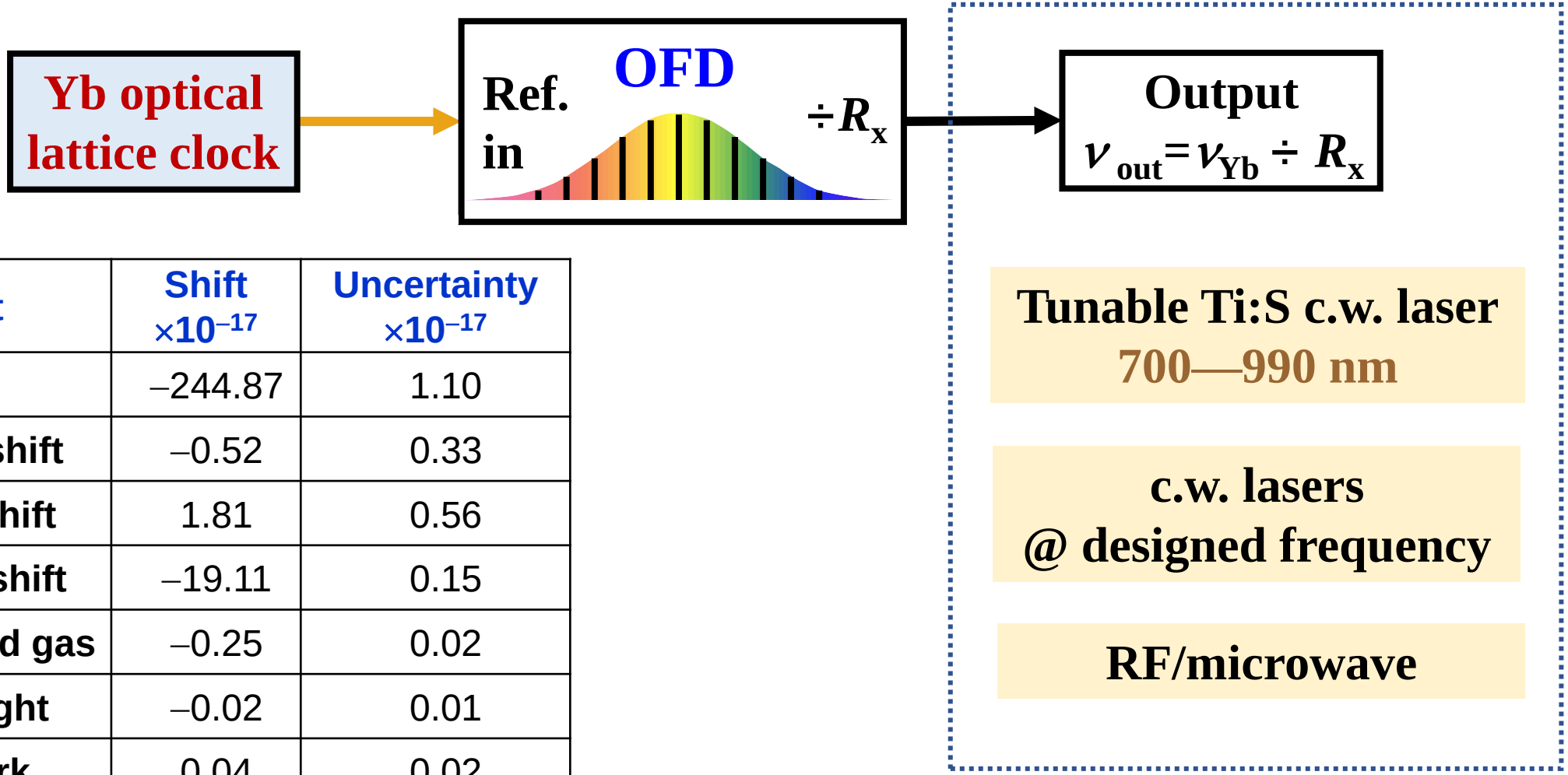
Probe time 400 ms

Yb atoms



Yao et. al. Photon. Res. 9, 98 (2021)

Synthesizer referenced to Yb optical clock



Effect	Shift $\times 10^{-17}$	Uncertainty $\times 10^{-17}$
BBR	–244.87	1.10
Density shift	–0.52	0.33
Lattice shift	1.81	0.56
Zeeman shift	–19.11	0.15
background gas	–0.25	0.02
Probe light	–0.02	0.01
DC Stark	0.04	0.02
Servo error	0	<0.10
Total	**–262.92**	**1.3**

Yao *et. al.* Appl. Phys. Lett. **3**, 463 (2016)

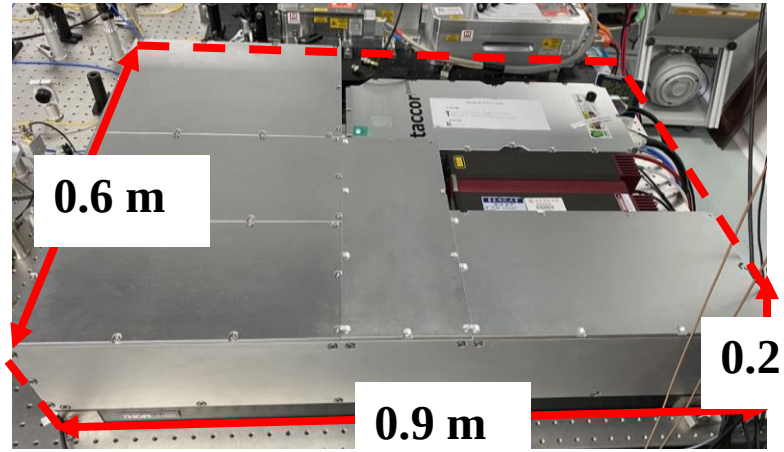
OFD for clock comparison

ν_{Sr} (NIM)

R ?

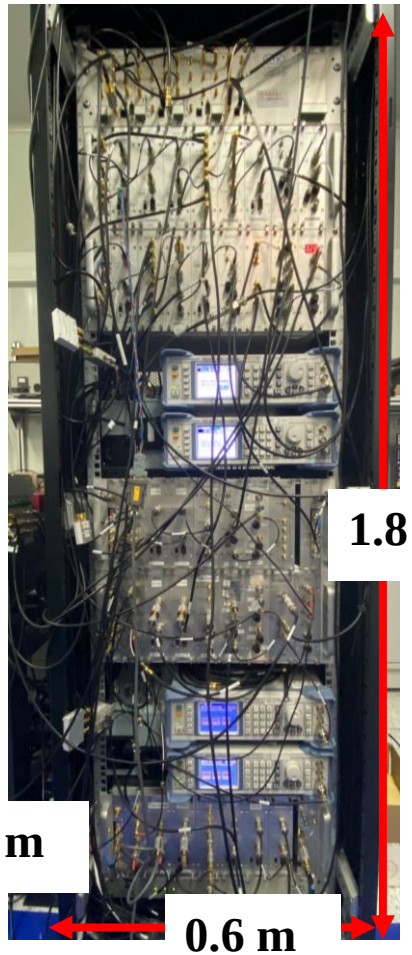
ν_{Ca+} (APM)

Differential spectroscopy

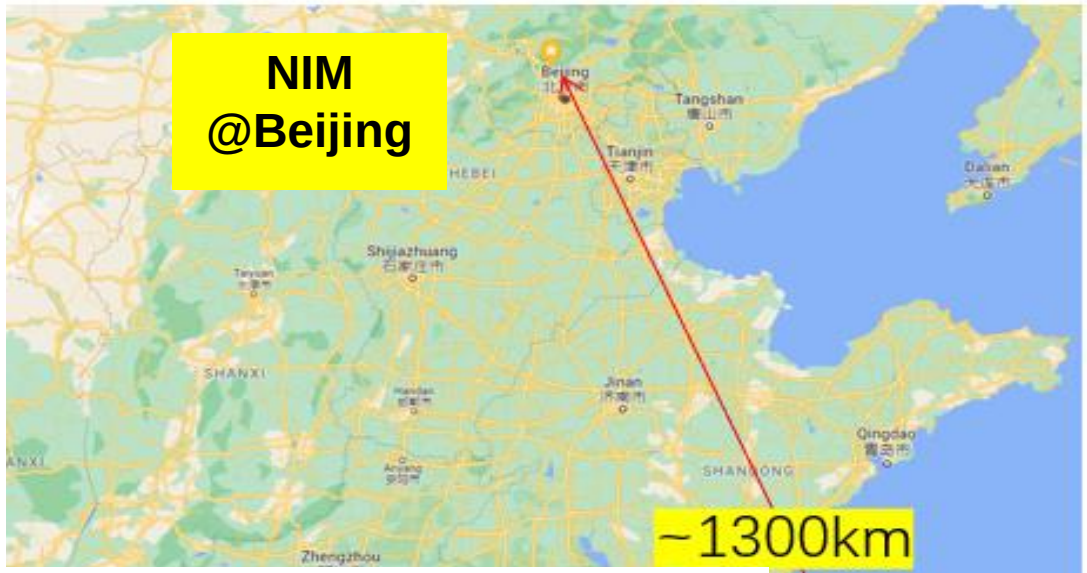


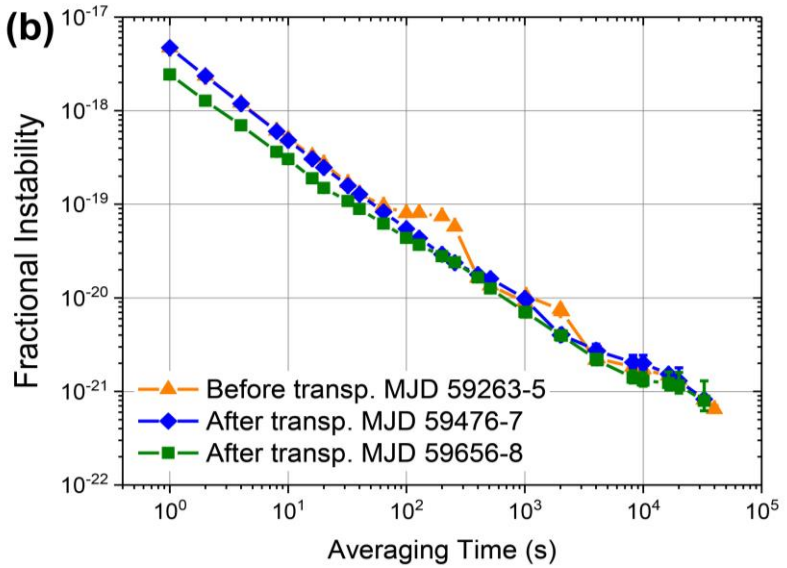
Optics

Input: 698 nm, 578nm, 729 nm…

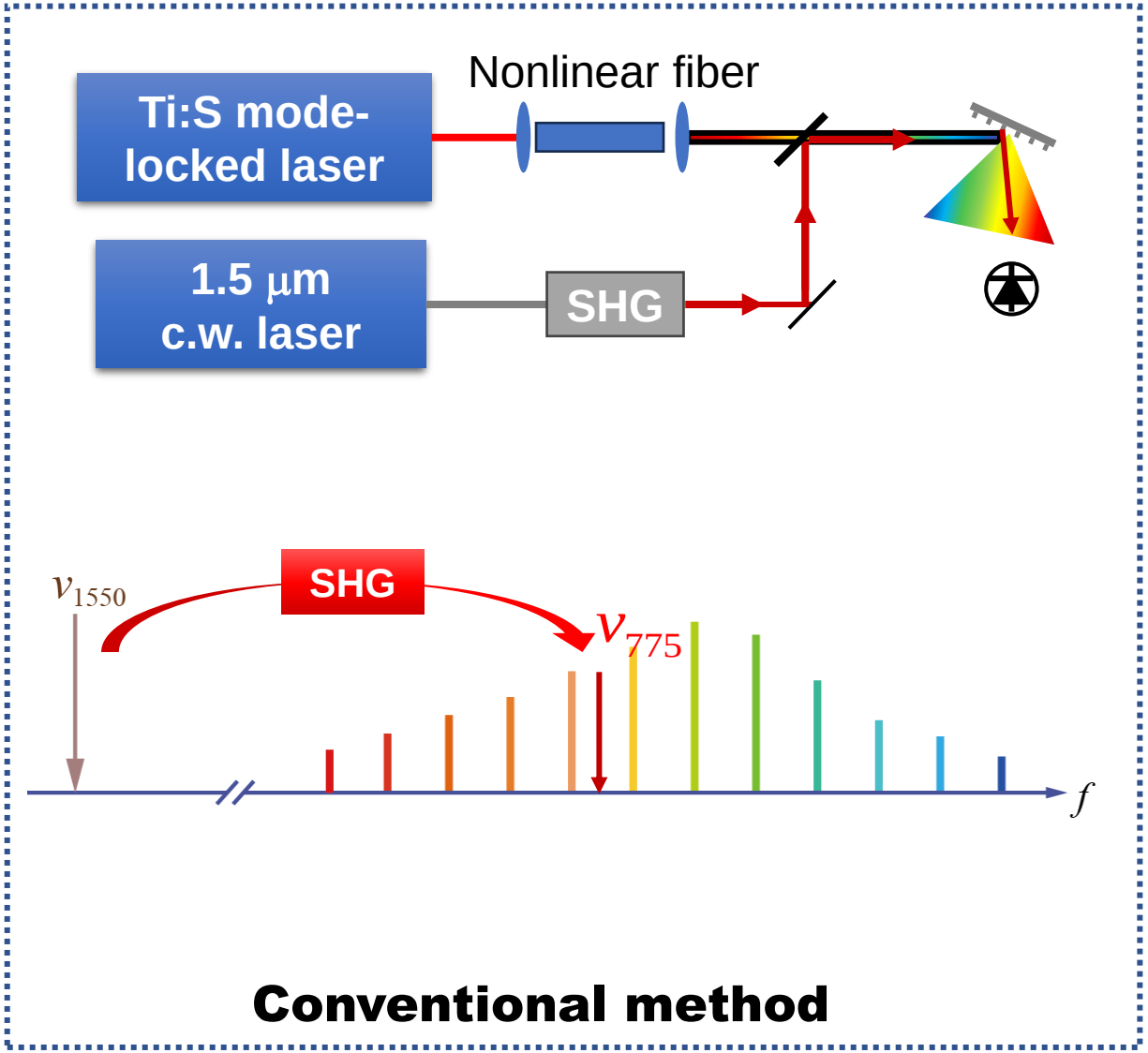


Electronics for 4-channel OFD

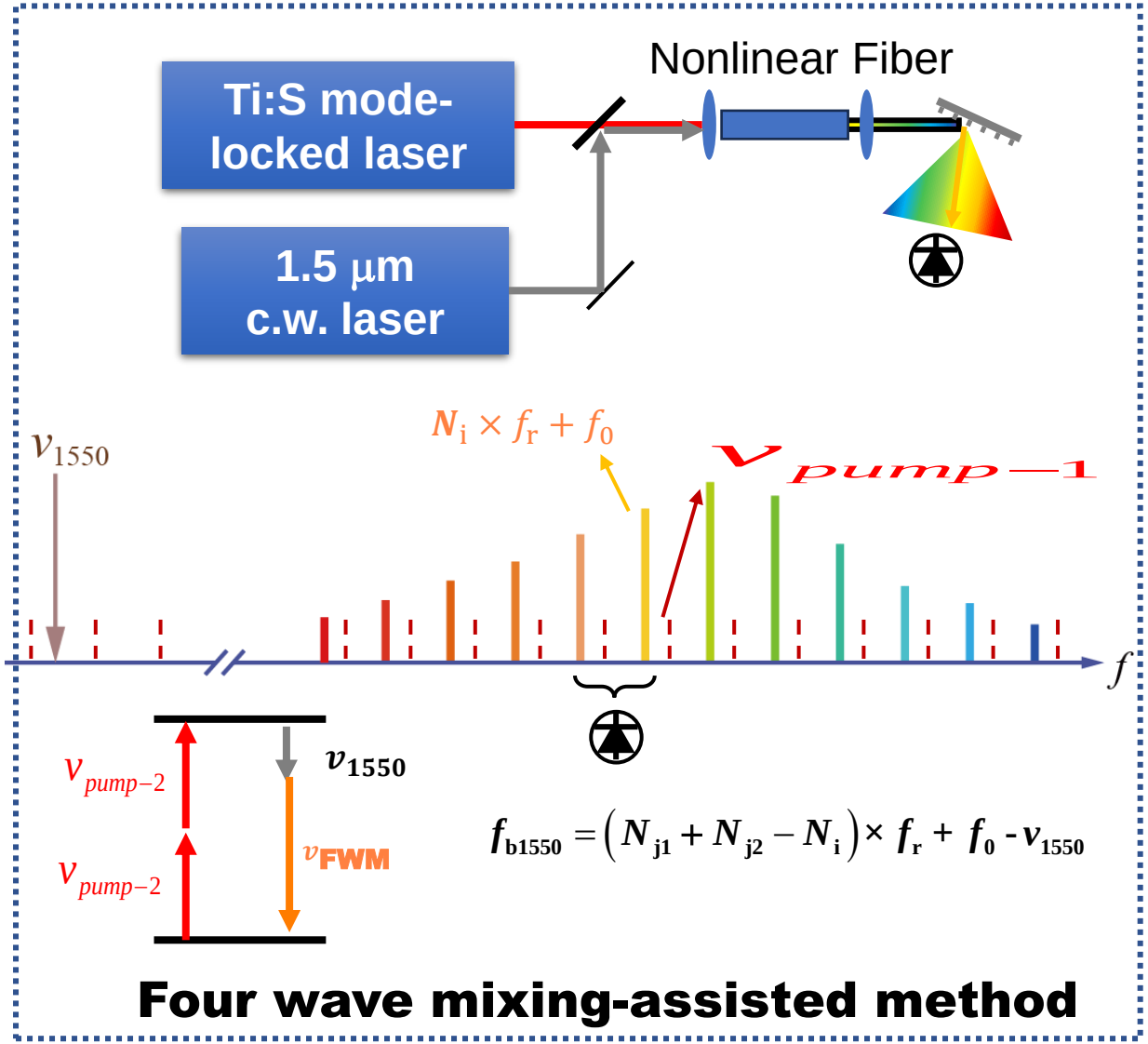




Beat note between Ti:S comb & 1.5 μm light

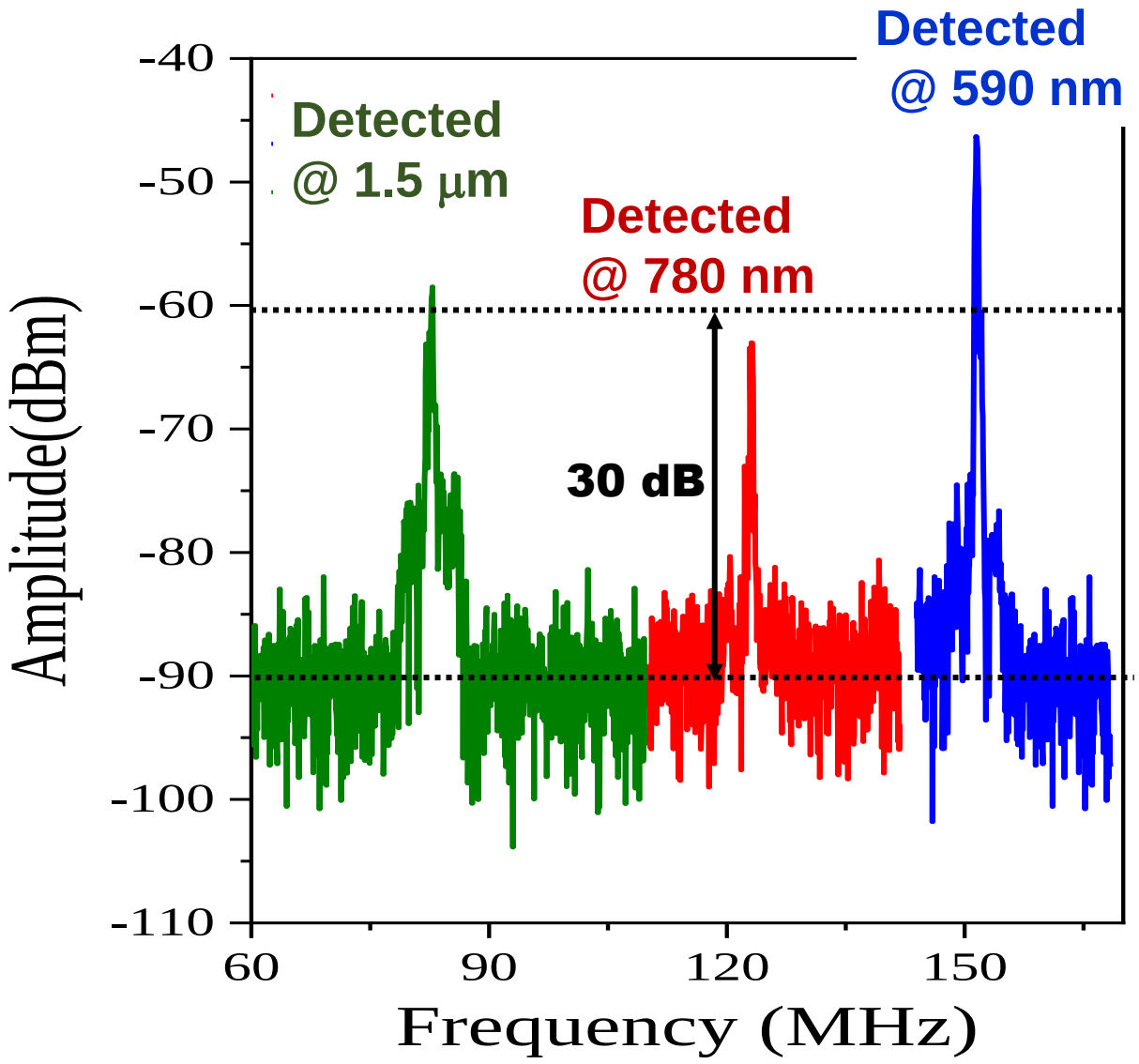


Conventional method



Four wave mixing-assisted method

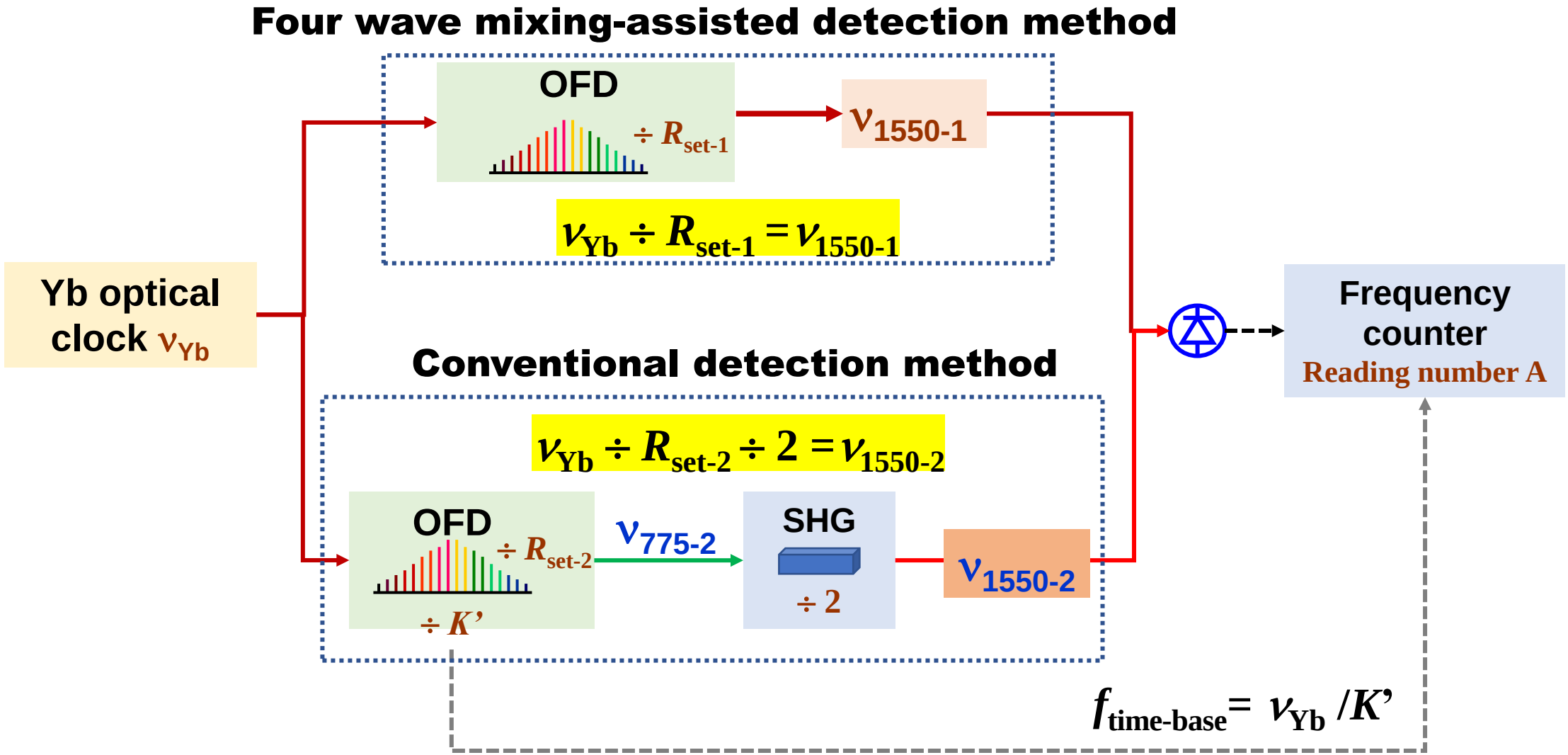
Beat note between Ti:S comb & 1.5 μm light



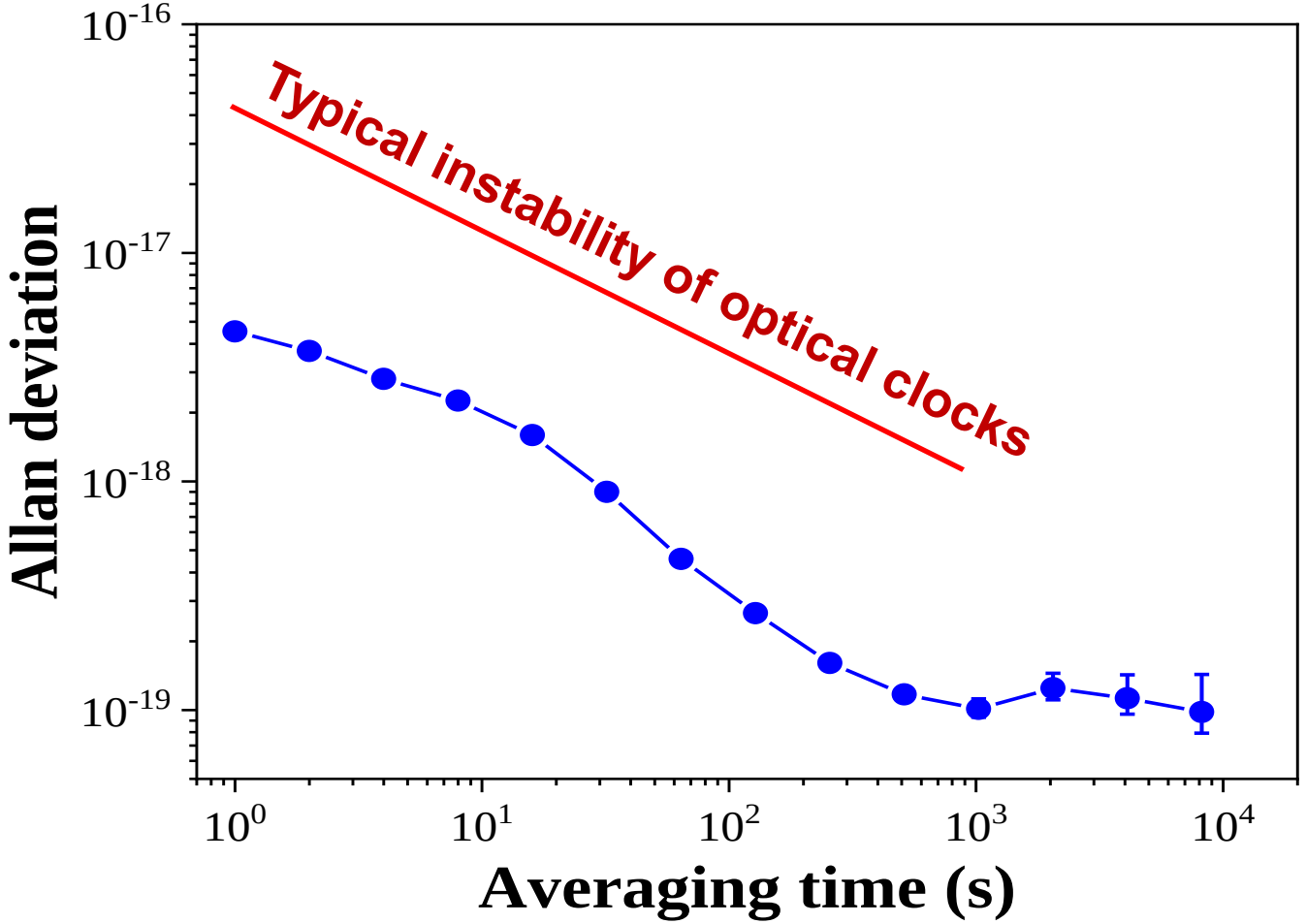
Four wave mixing-assisted detection method

- No SHG to double 1.5 μm laser frequency
- Low 1.5 μm laser power: ~10 mW → 45 dB SNR f_b
- Detection at convenient wavelength and bandwidth

Division from Yb optical clock to 1.5 um



Division from Yb optical clock to 1.5 um



- Instability: 5×10^{-18}@1s,
  1×10^{-19}@1000s
- Uncertainty：2.2×10^{-19}
- Limited by 30 cm-long uncompensated light path fluctuation

Yao et. al. submitted

Summary & outlook

Low-noise optical frequency divider

- Division noise: (0.6–8)$\times 10^{-18}$@1s, 6×10^{-22}@10^5 s
- Division uncertainty: 3×10^{-22}
- Coherence transfer: resolve Hz-linewidth spectrum of Yb clock transition even when comb frequency jitter is 1 MHz
- Coherent linking Ti:S comb with 1.5 μm laser using FWM-assisted detection

Outlook:

- Frequency comparison between optical clocks
- Precision measurement & precision spectroscopy
- Optical frequency synthesis with chip-based combs

Acknowledgement

Group members:

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Collaborators:

NIM: Yige Lin, Zhanjun Fang, Fang Fang…

APM: Kelin Gao, Hua Guan, Yao Huang, Baolong Lv, Linxiang He…

Special thanks to

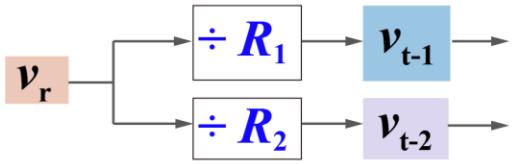
Andrew Ludlow, Chris Oates, Jun Ye, Scot Diddams, Tara Fortier, Chin-wen Chou, Albrecht Bartels…

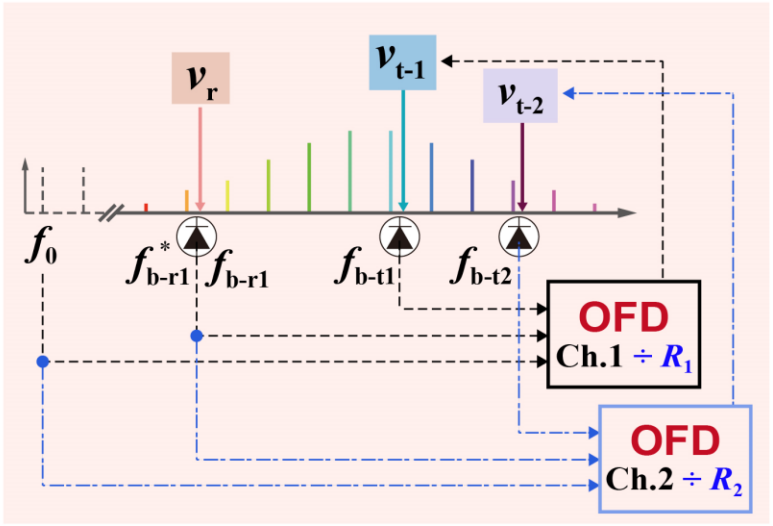
Thank you for your attention!

Multi-channel division

➢ Single reference

(a)

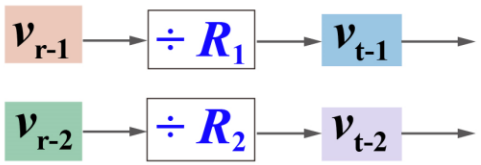


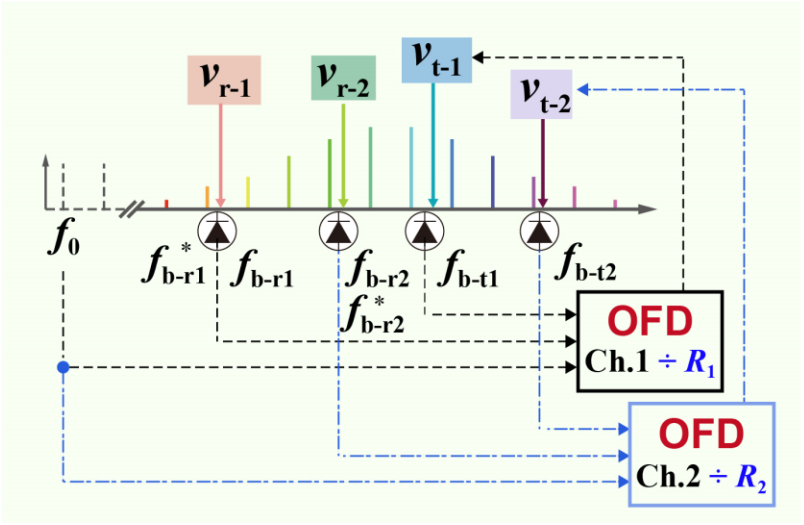


➢ Independent references

(b)

Parallel





(c)

Series