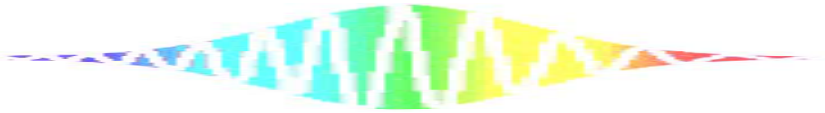


State of progress in THz and broadband spectrum manipulation group

Takeshi Yasui
(Tokushima University)

Minoshima ERATO　2nd group meeting in 2014
（Dec. 22, 2014@AIST）

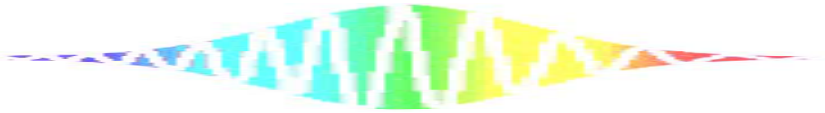
Research topics

(1) Intelligent THz instrumentation and application

- Adaptive sampling dual THz comb spectroscopy (M2)
- Broadband THz synthesizer (M2)
- THz-comb-referenced spectrum analyzer (M2)
- THz digital holography (B4, just start)
- THz ghost imaging (M1, not start)

(2) Novel optical comb measurement and application

- Full-field confocal optical-comb microscopy (M2)
- Discrete Fourier transform infrared spectroscopy (Hsieh) (in collaboration with AIST)
- CARS gas analysis (Harsono, not start)
- Sensing comb for photoacoustic imaging (M1, just start)



(1) Adaptive sampling dual THz comb spectroscopy

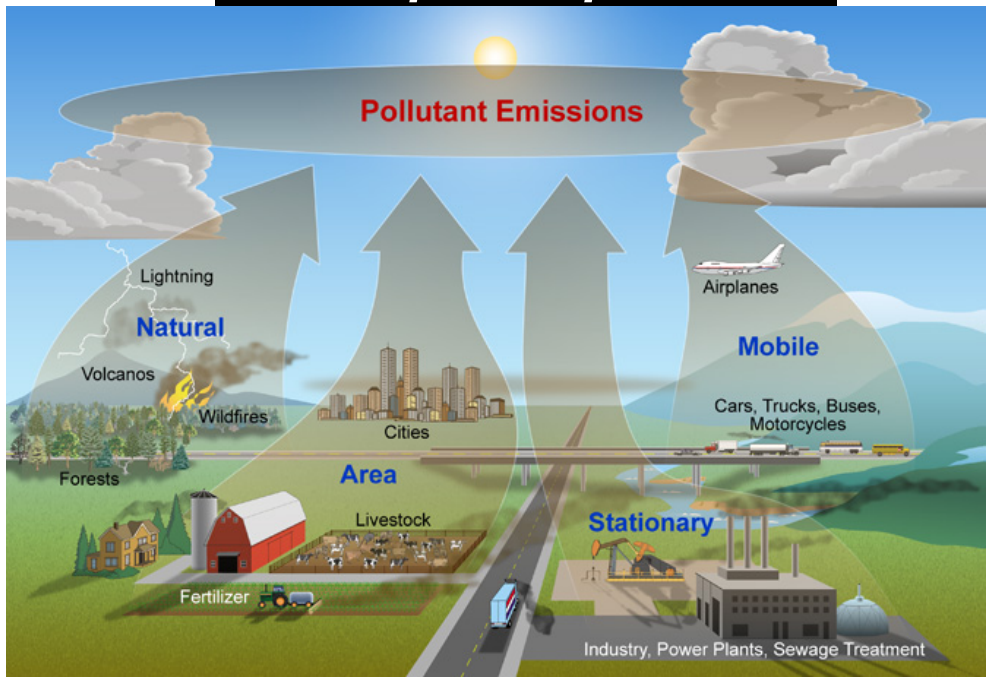
THz gas spectroscopy

(1) Rotational transitions of polar molecules

- ✓ Rich spectral fingerprints
- ✓ High selectivity and high sensitivity
- ✓ High discrimination at low pressure due to narrow Doppler linewidth (~1MHz)

☞**Multiple gas analysis**

Atmospheric pollution



Ref)http://www.nature.nps.gov/air/aqbasics/sources.cfm

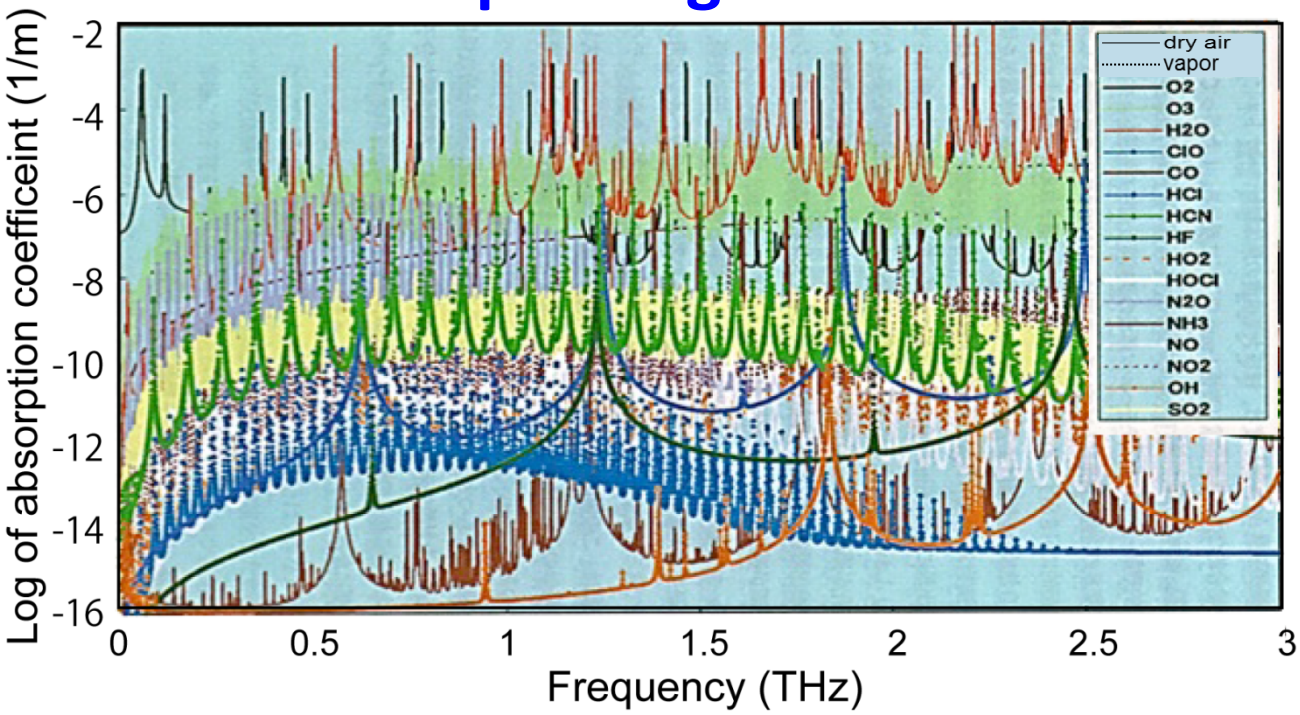
(2) Less scattering

- ✓ λ_{THz} >> particle diameter

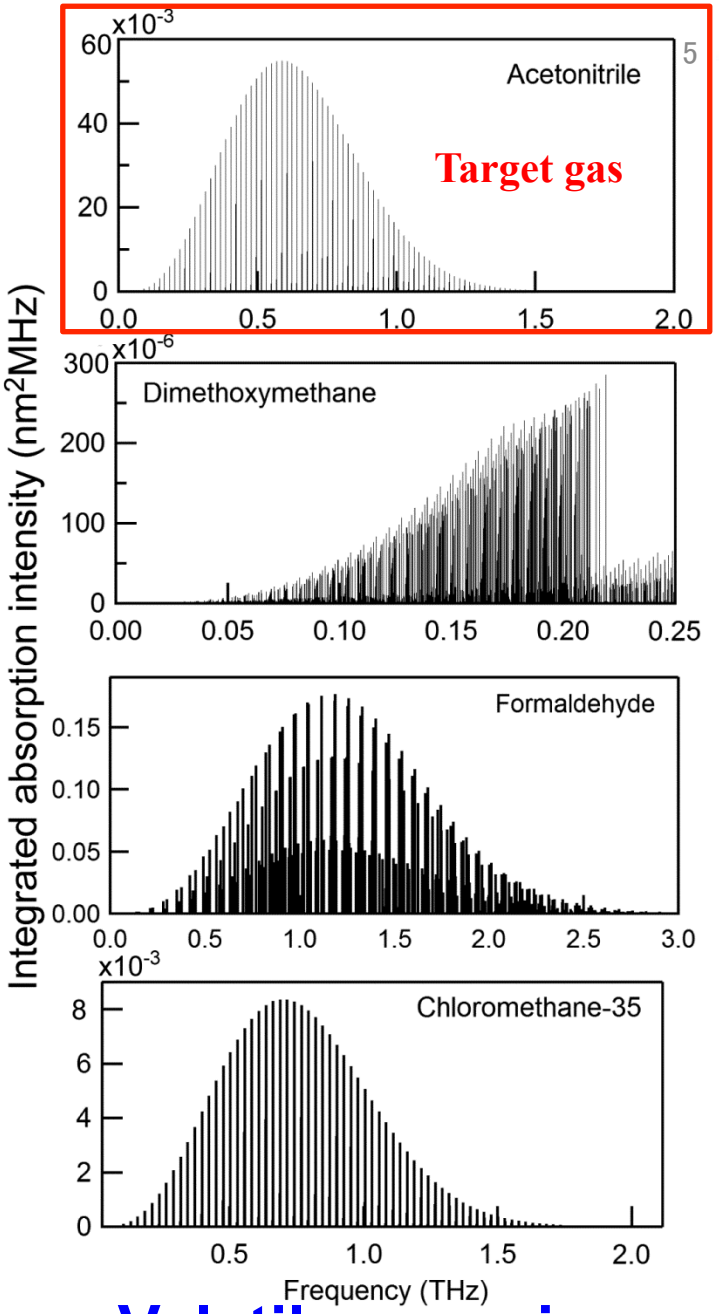
☞**Possible to analyze gas mixed with aerosols (fog, cloud, smoke, soot, etc)**

THz spectral fingerprints

Atmospheric gas molecule

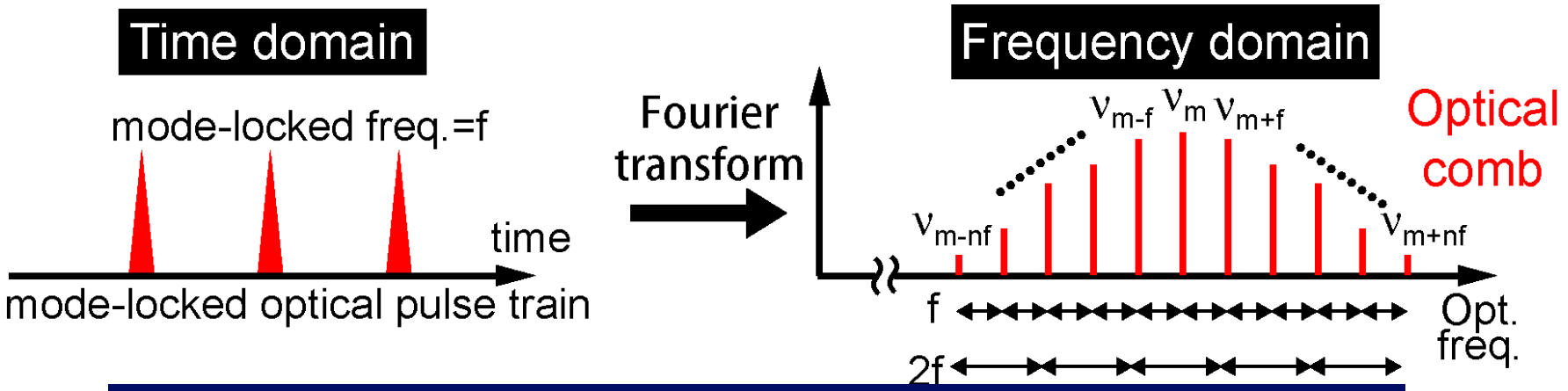


To discriminate the target gas correctly, high resolution, high accuracy, and broadband spectrum are required!!

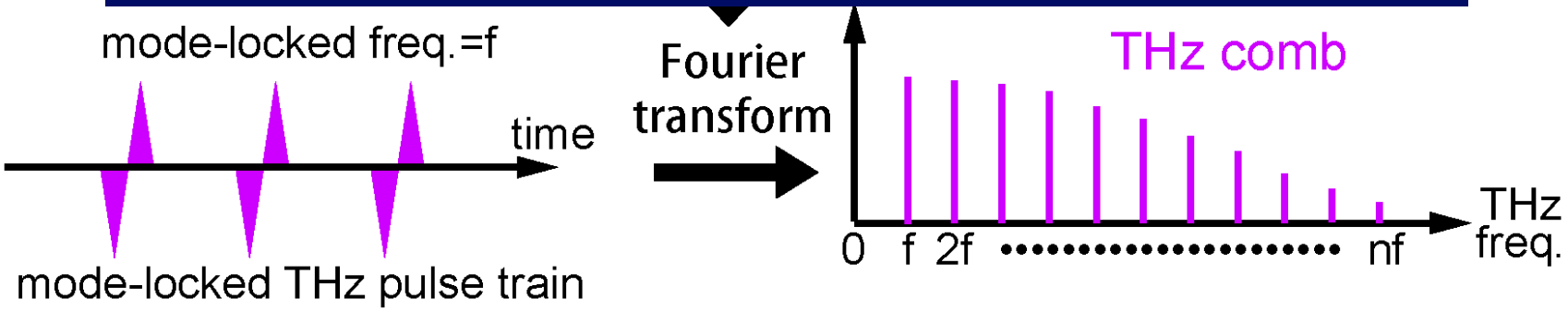


Volatile organic compound (VOC) gas

Optical comb and THz comb



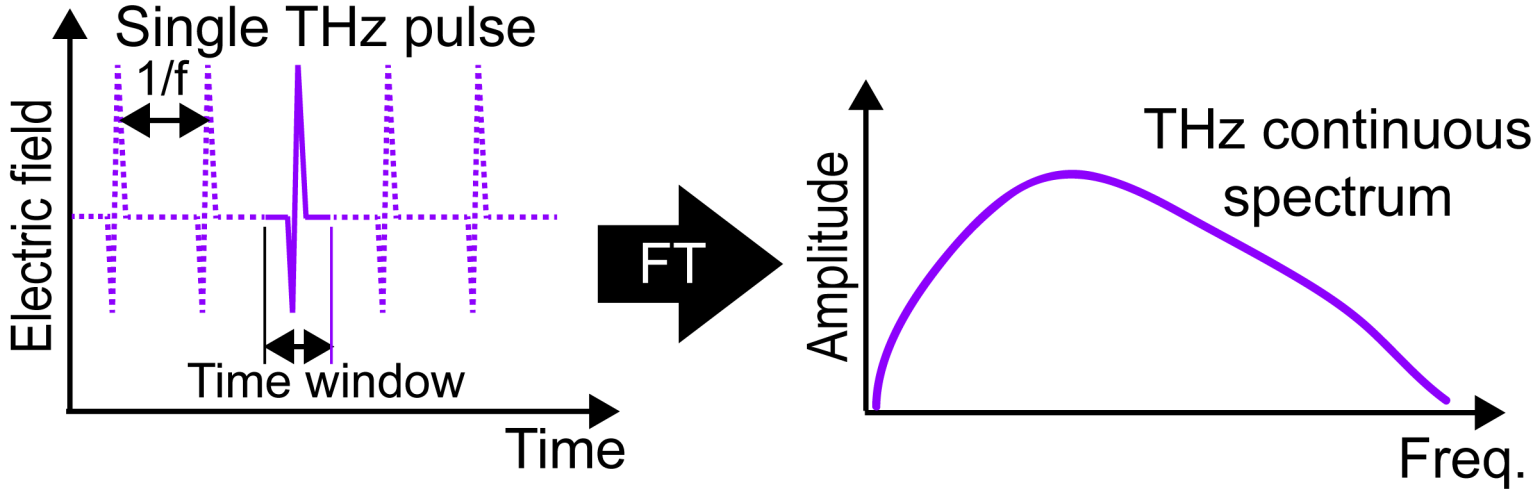
Precise frequency marker for broadband THz spectrum



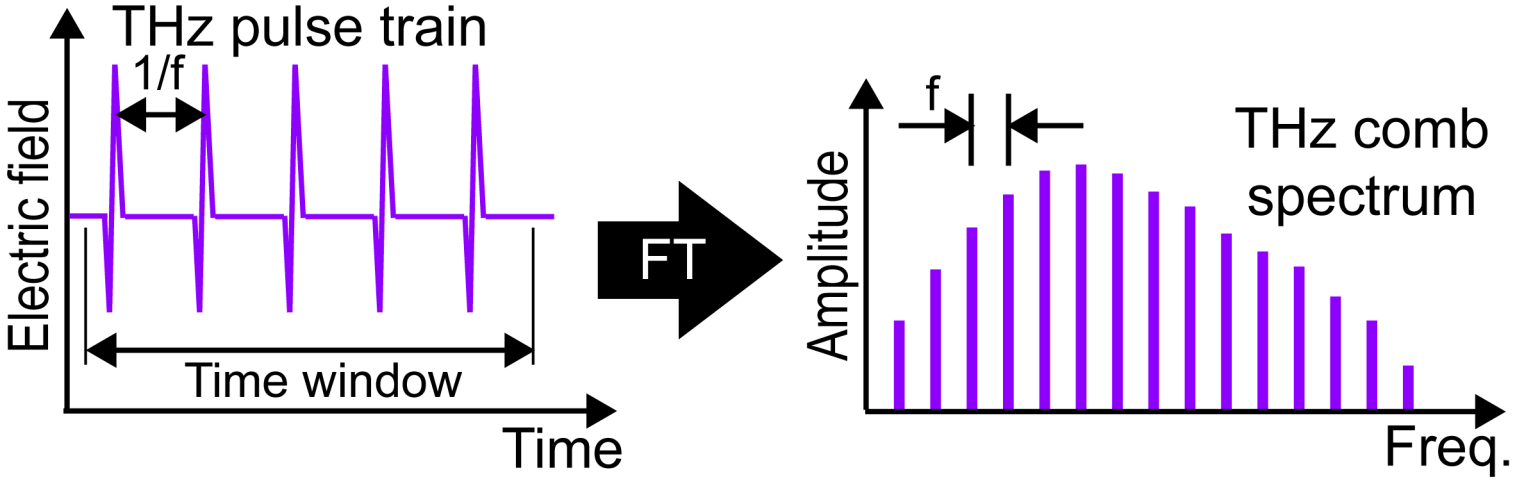
Simple, broadband selectivity, high spectral purity, and absolute frequency calibration

How to measure mode-resolved THz comb spectrum

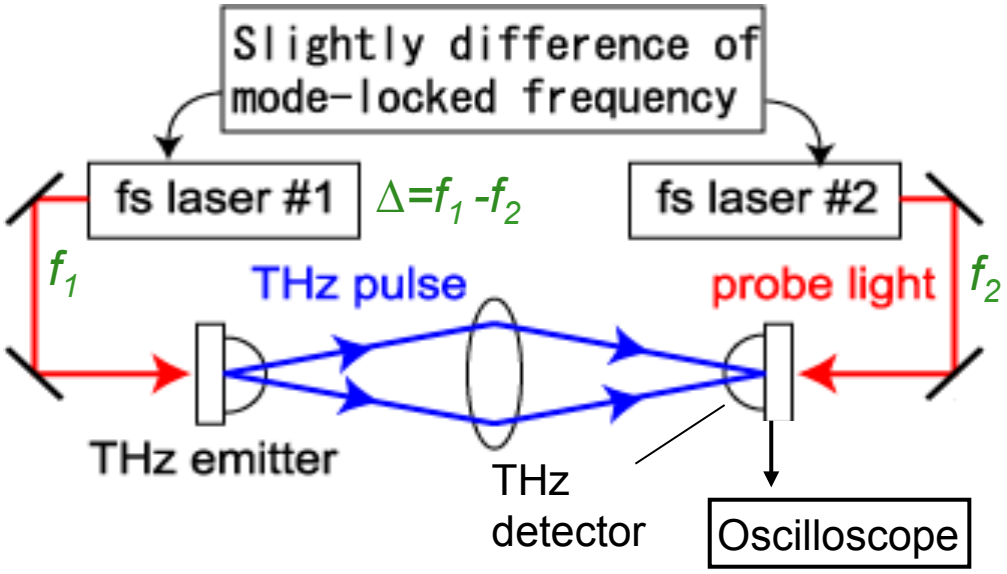
Traditional THz-TDS equipped with mechanical time-delay scanning



Time-window-extended THz-TDS



Asynchronous-optical-sampling THz-TDS (ASOPS-THz-TDS)

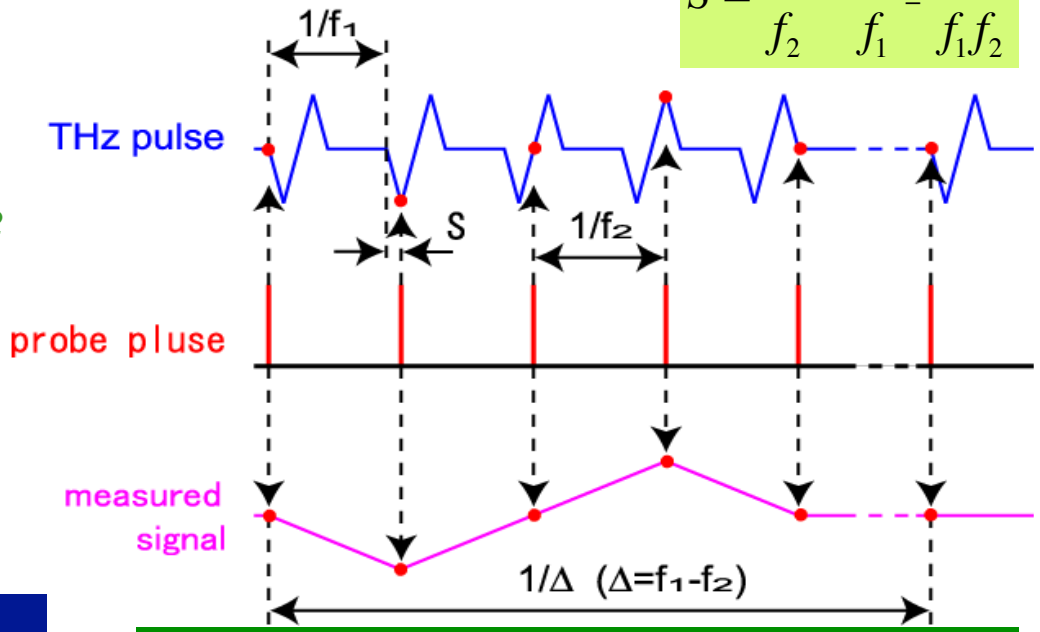


ref) T. Yasui, Appl. Phys. Lett. 87, 061101 (2005).

- **No need for mechanical time-delay scanning**
- **No limitation for size of time window**

Overlap timing between THz and probe pulses is automatically shifted every pulse

$$S = \frac{1}{f_2} - \frac{1}{f_1} = \frac{\Delta}{f_1 f_2}$$



Time scale of ps THz pulse is linearly expanded to μs order

Temporal magnification factor (TMF) = $f_1/\Delta f$

Use of **free-running**, dual fs lasers in dual THz comb spectroscopy

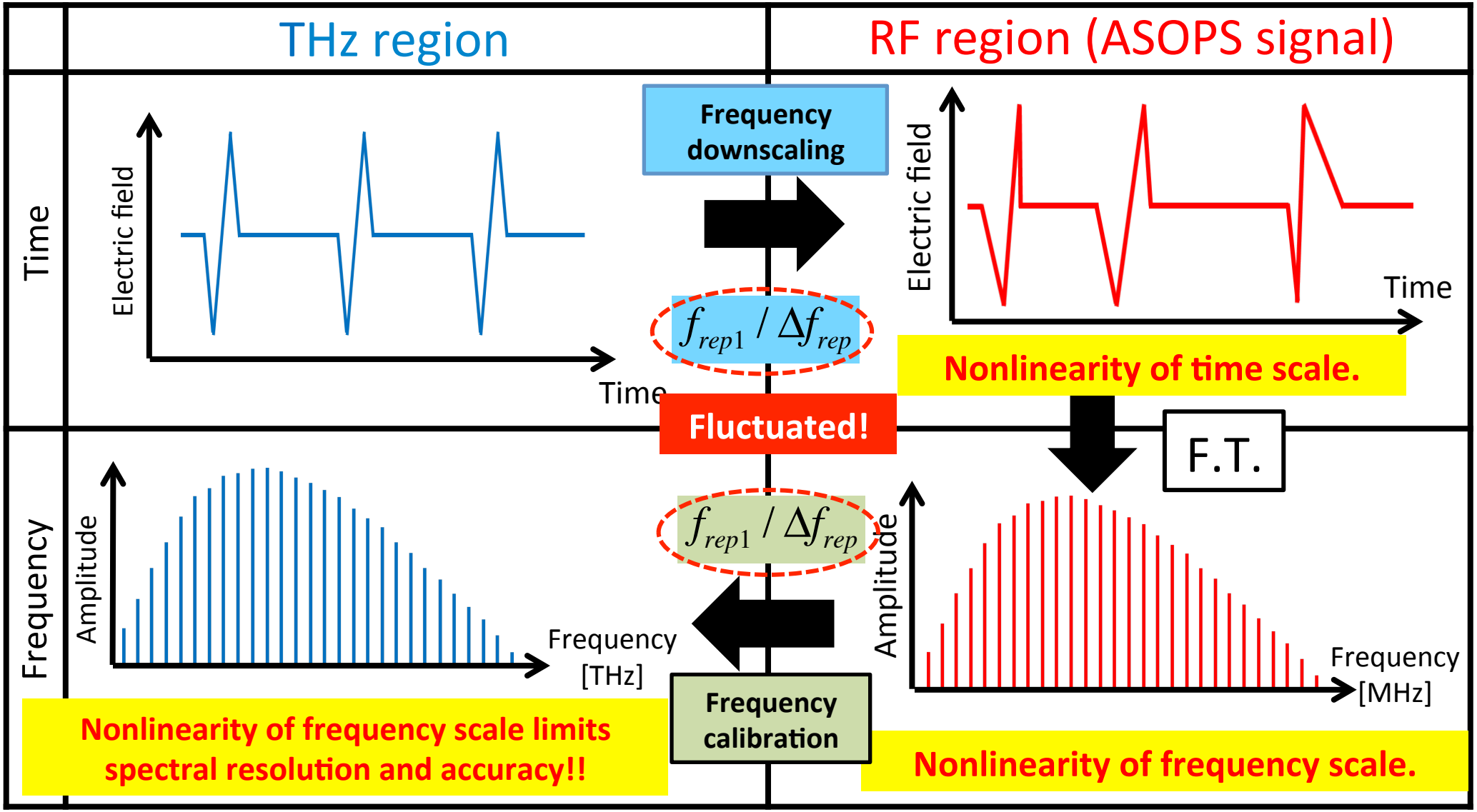
↓

Expand the application fields of dual THz comb spectroscopy

↓

However, timing jitter between free-running dual fs lasers distorts the linearity of time and frequency scales due to fluctuation of TMF!

Influence of timing jitter in ASOPS

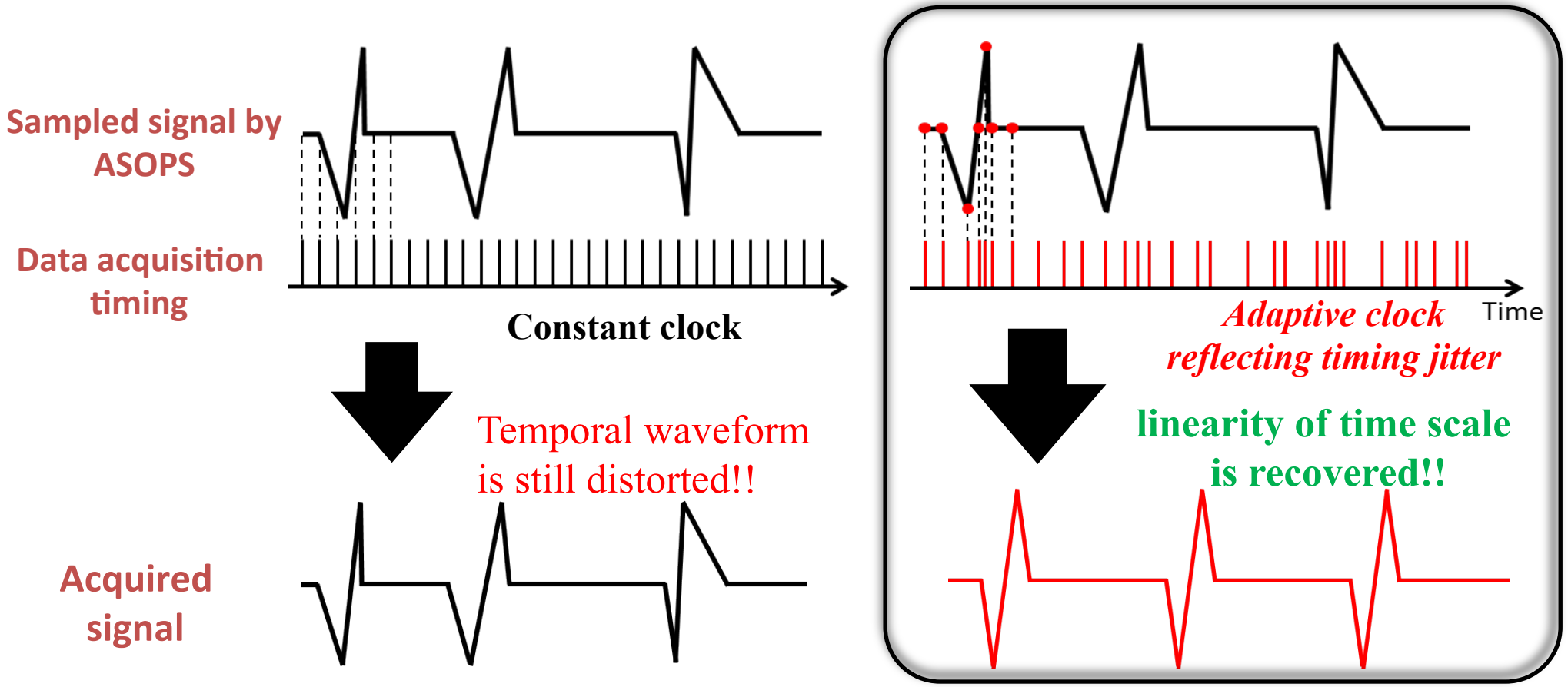


Adaptive sampling method

Ref) T. Ideguchi, Nat. Comm., **5**, 3375 (2014).

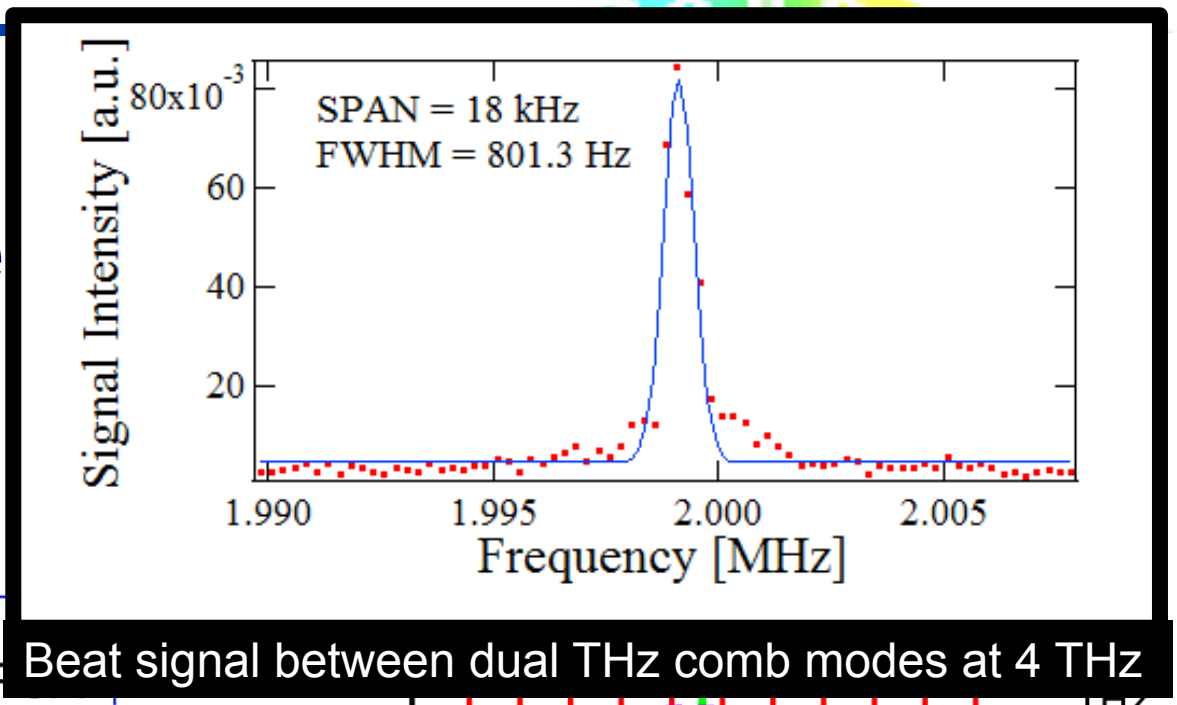
Conventional method (constant sampling)

Proposed method (Adaptive sampling)

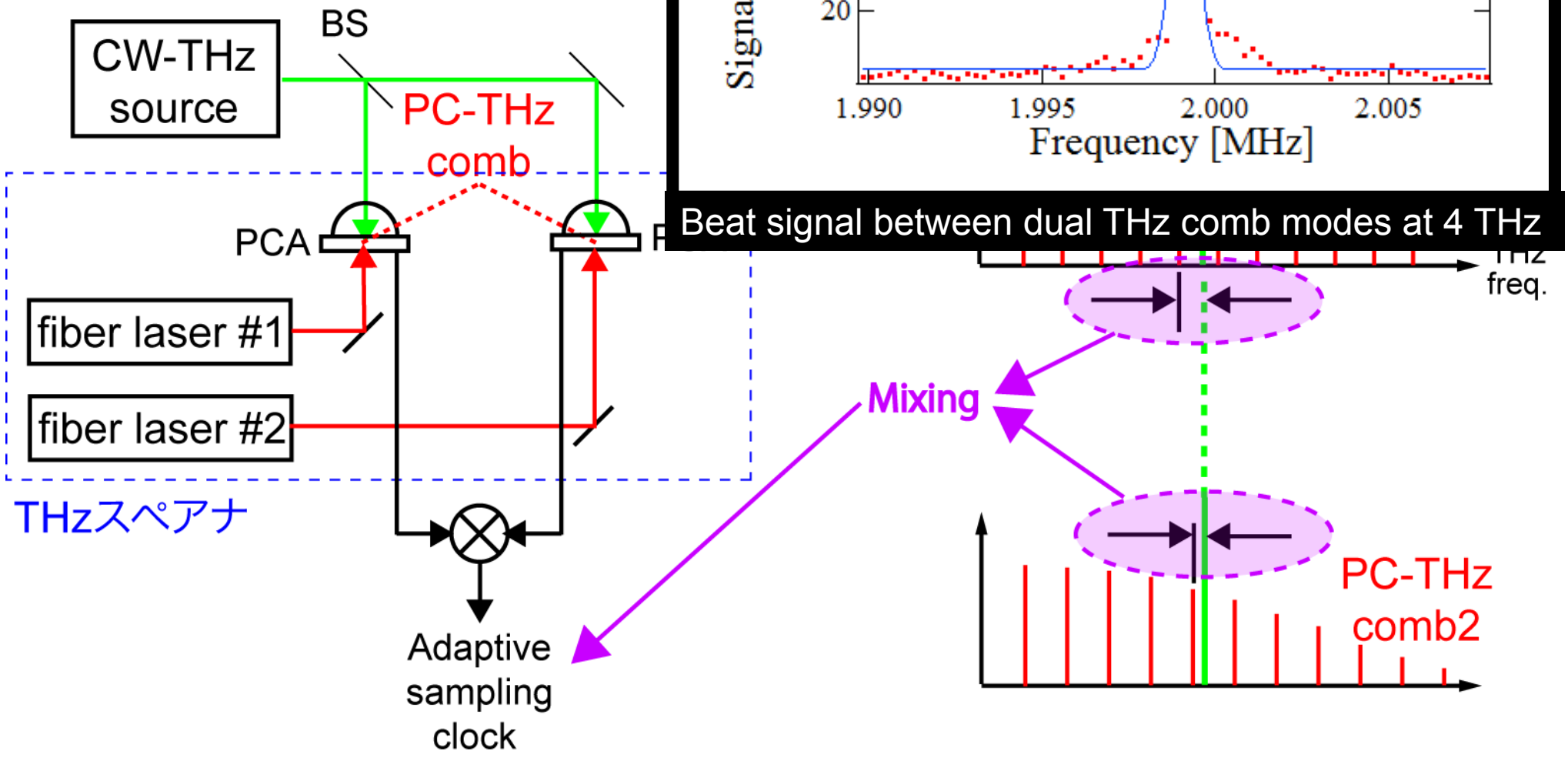


Adaptive clock can be generated by beat signal between dual THz comb modes!!

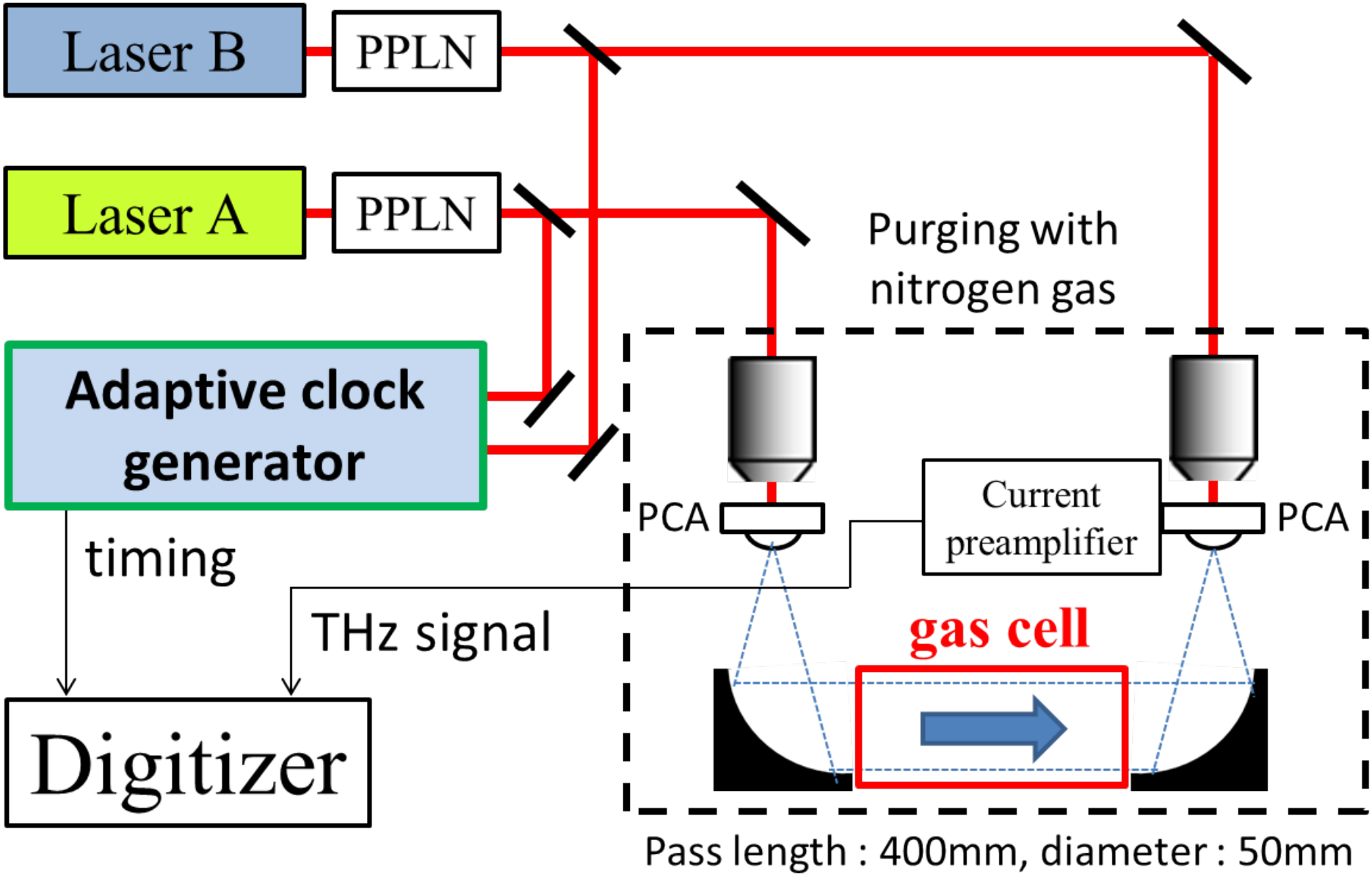
Generation of THz
THz-comb-refere



Beat signal between dual THz comb modes at 4 THz



Setup for dual THz comb spectroscopy



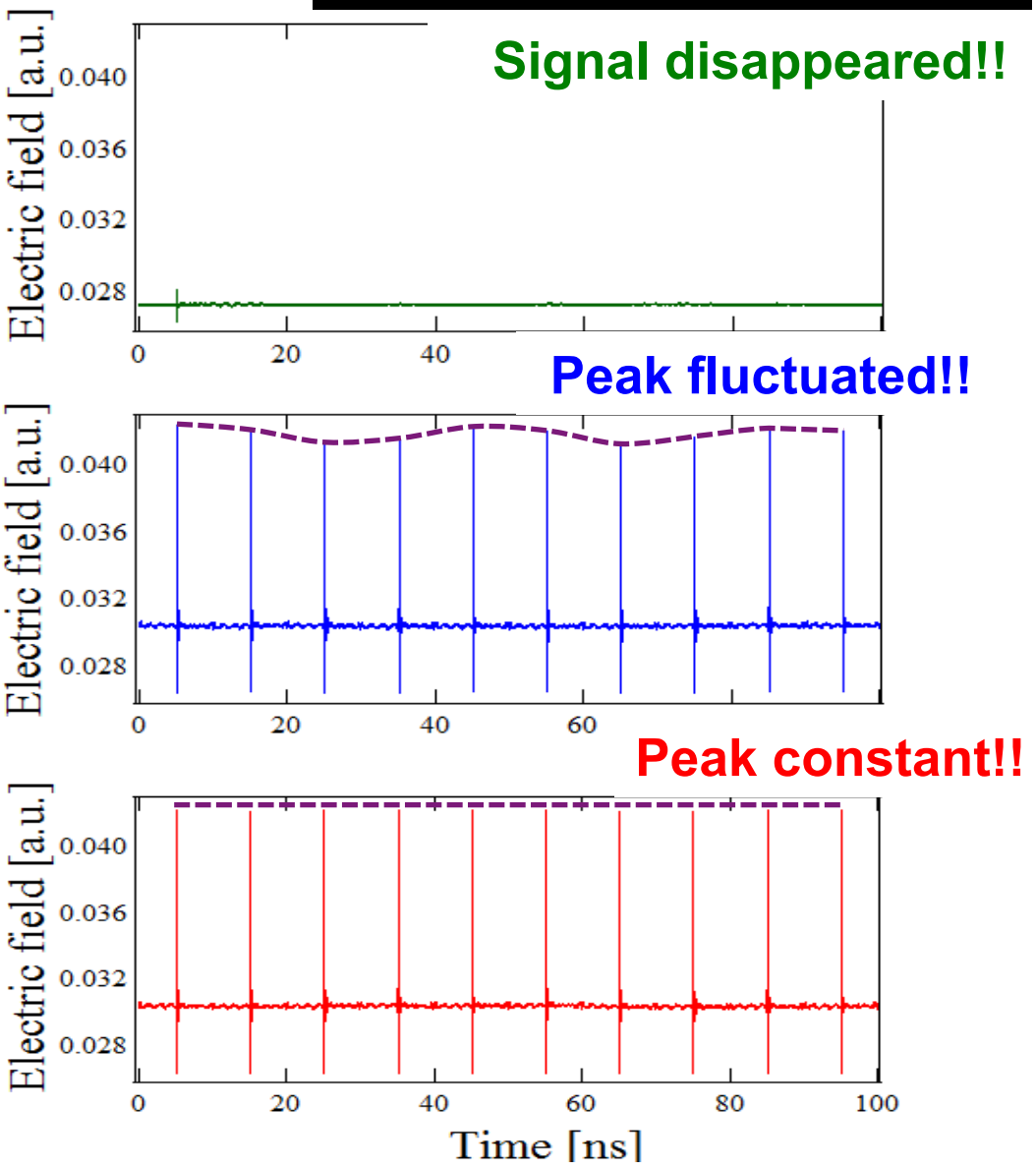
Integrated temporal waveform of THz pulses

Integration number=10000

Constant clock
with free-running lasers

Constant clock
with stabilized lasers

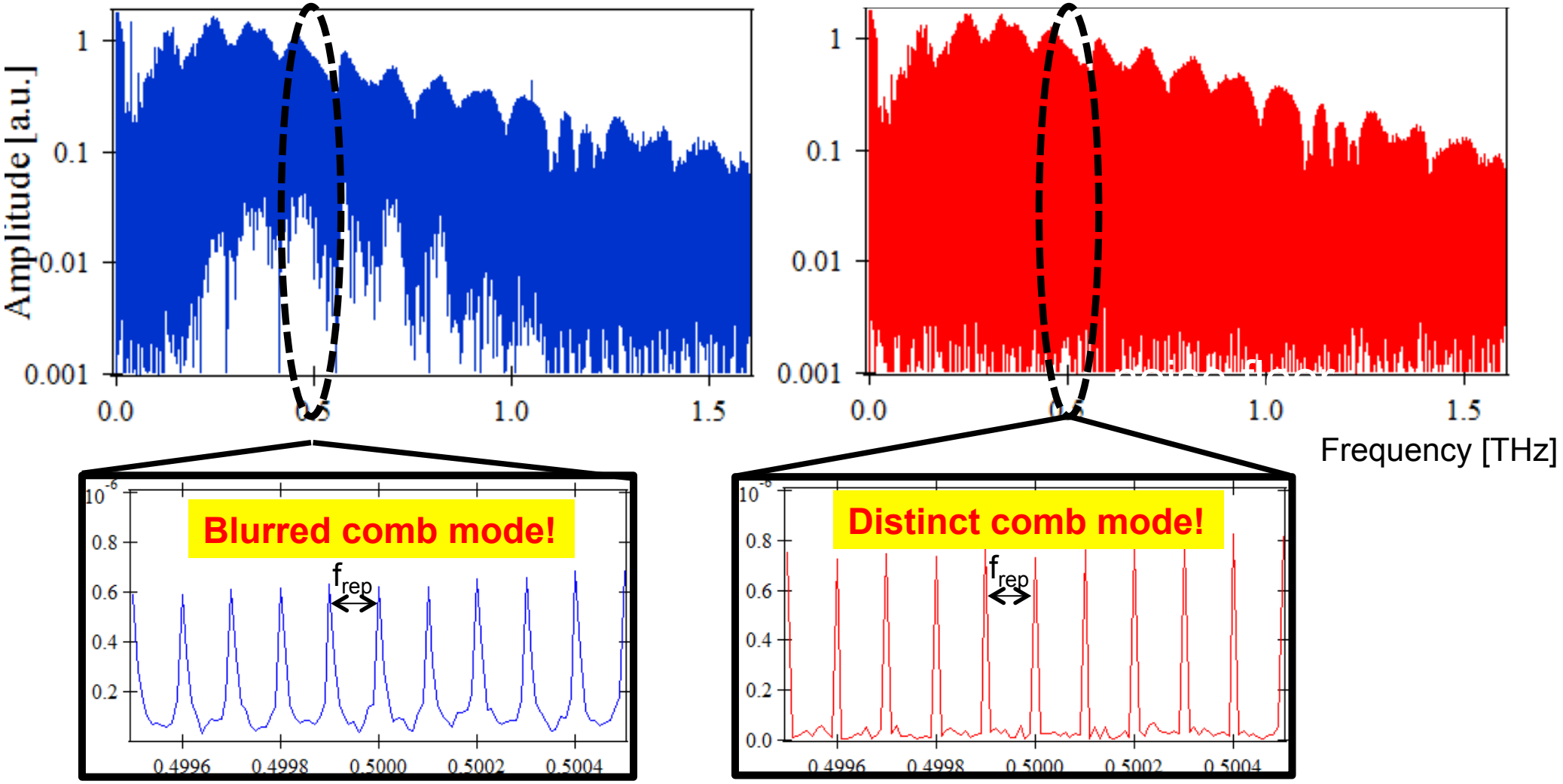
Adaptive clock
with free-running lasers



Mode-resolved THz comb spectrum

Constant clock with stabilized lasers

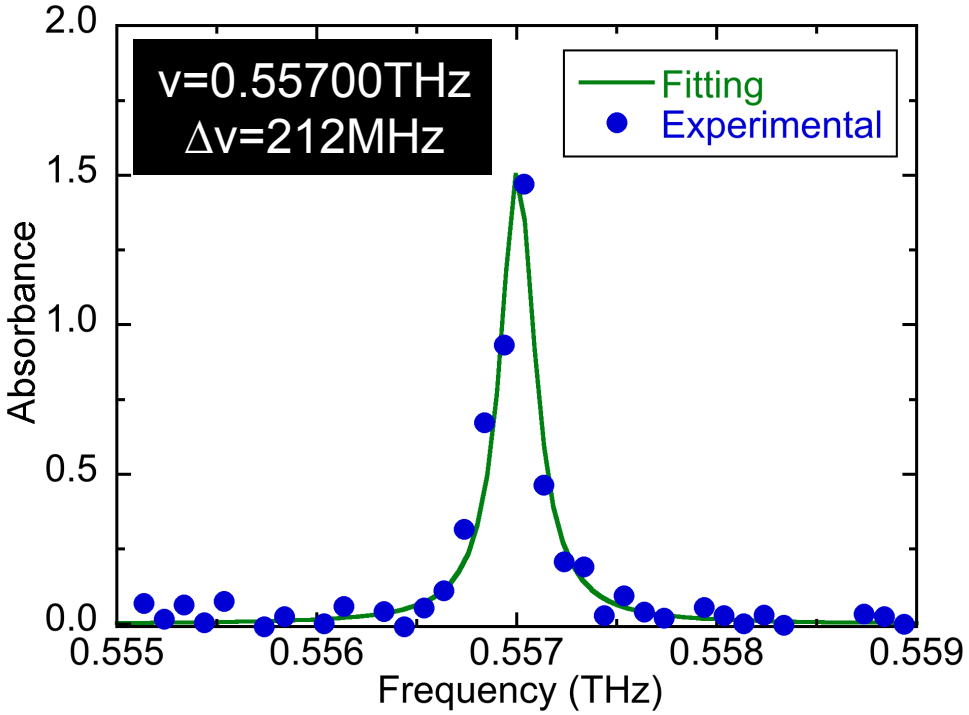
Adaptive clock with free-running lasers



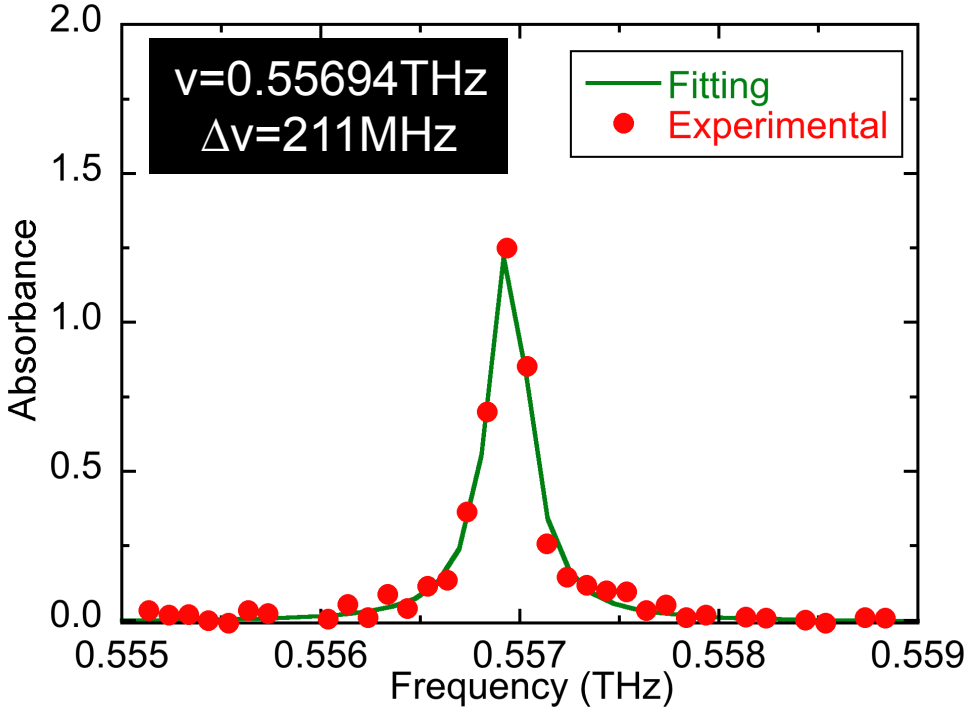
Water vapor at low pressure

Rotational transition $I_{10} \leftarrow I_{01}$ @ 0.556936THz
Pressure broadening linewidth = 200MHz

Constant clock with stabilized lasers



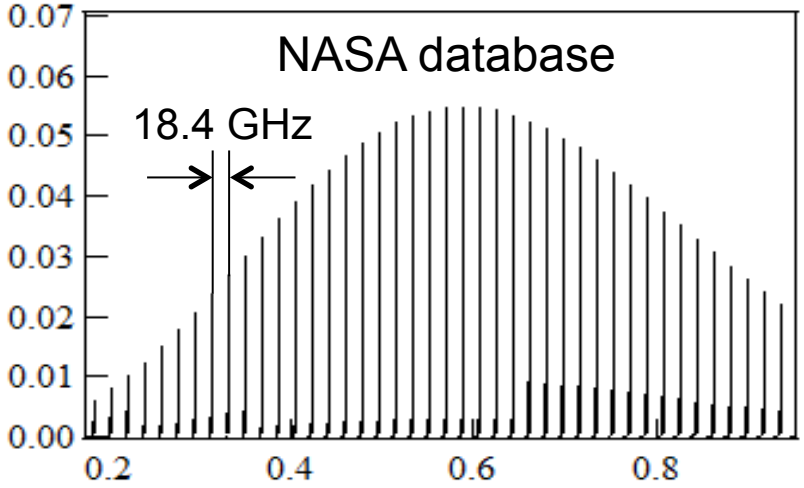
Adaptive clock with free-running lasers



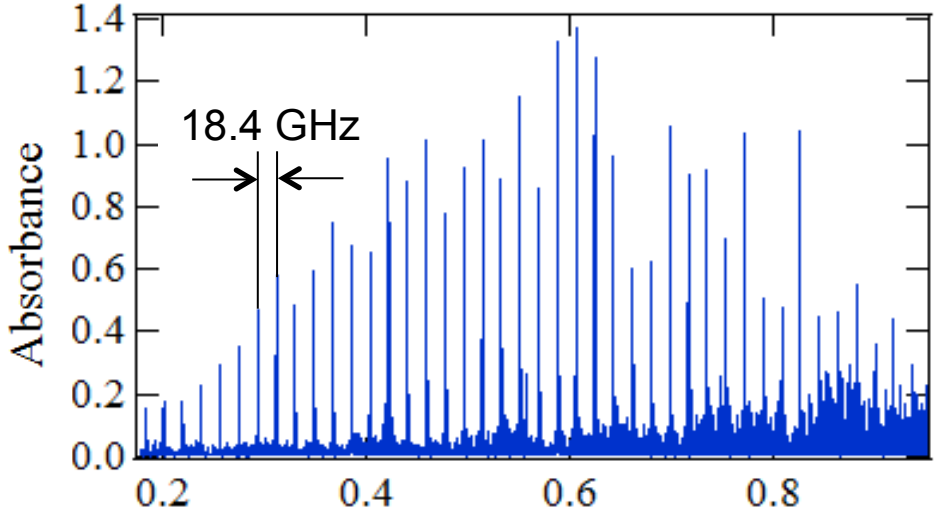
Acetonitrile gas at low pressure(1kPa)

Acetonitrile (CH_3CN)

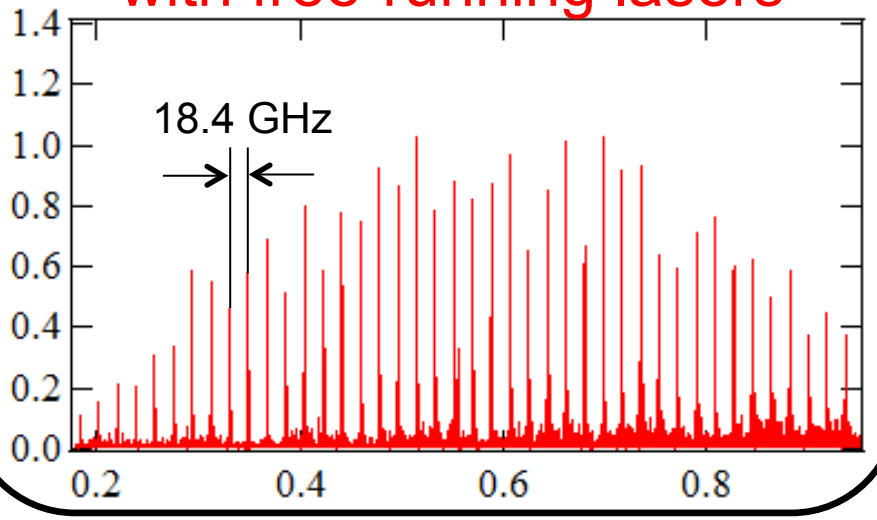
- One of VOCs
- Very abundant species in interstellar medium



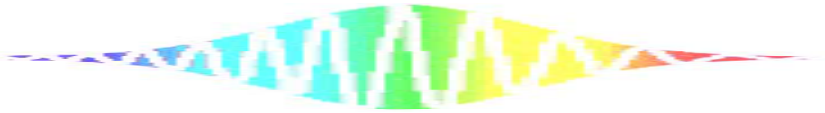
Constant clock
With stabilized lasers



Adaptive clock
with free-running lasers

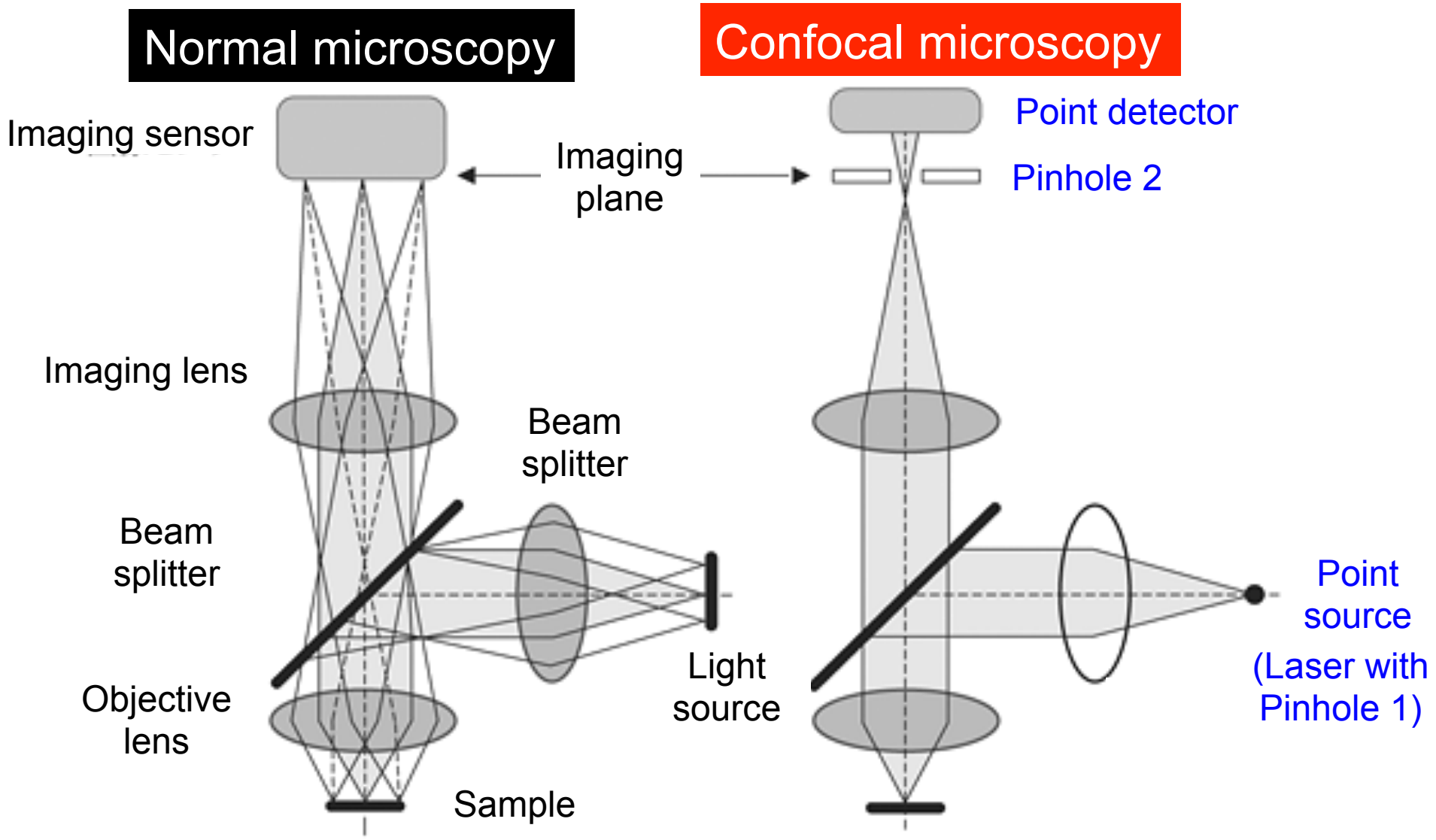


Frequency [THz]



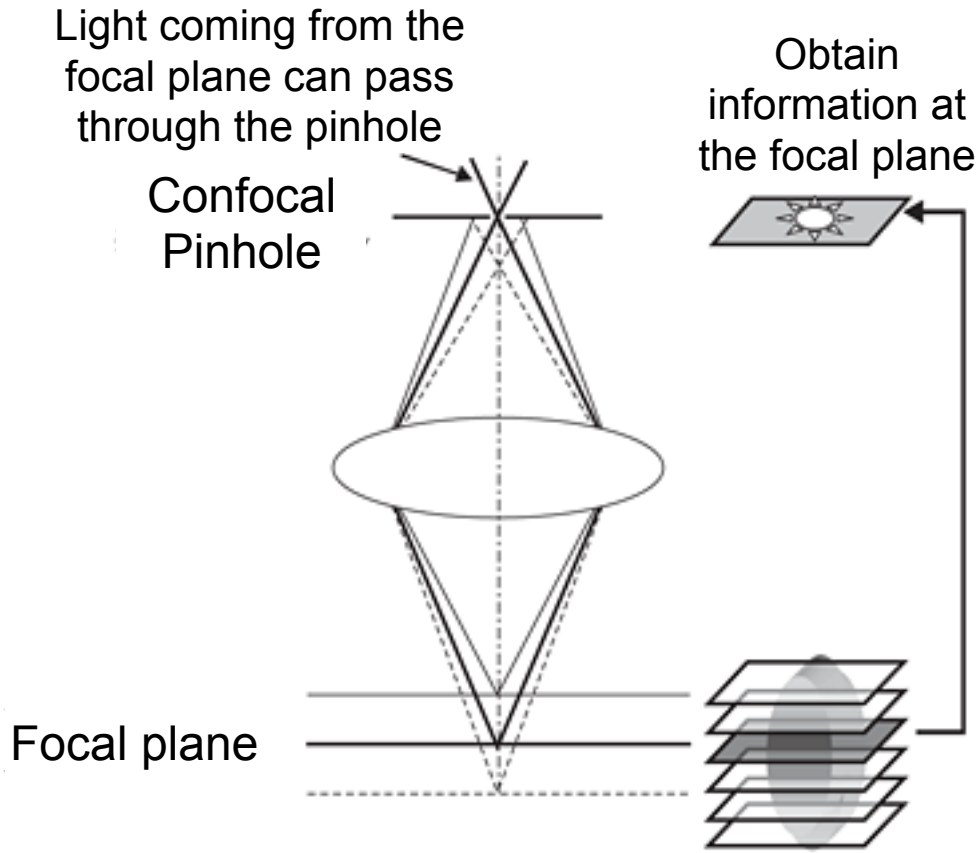
(2) Full-field confocal optical-comb microscopy

Optical microscopy



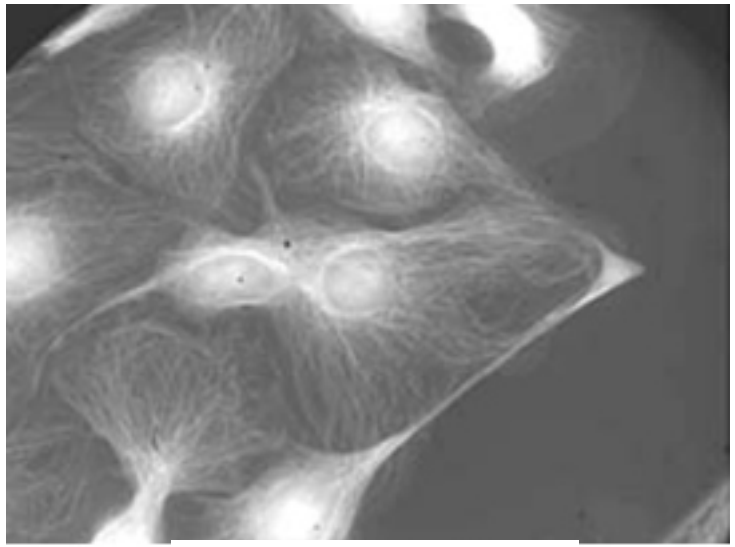
http://bioimaging.jp/learn/023/

Confocal optical microscopy

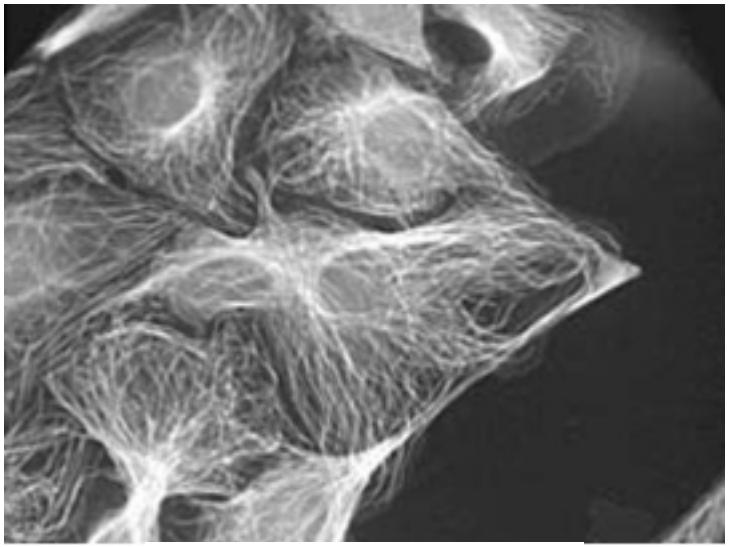


Detect signal at focal plane
- No stray light
- Depth resolution
- Applicable for thick sample

http://bioimaging.jp/learn/023/

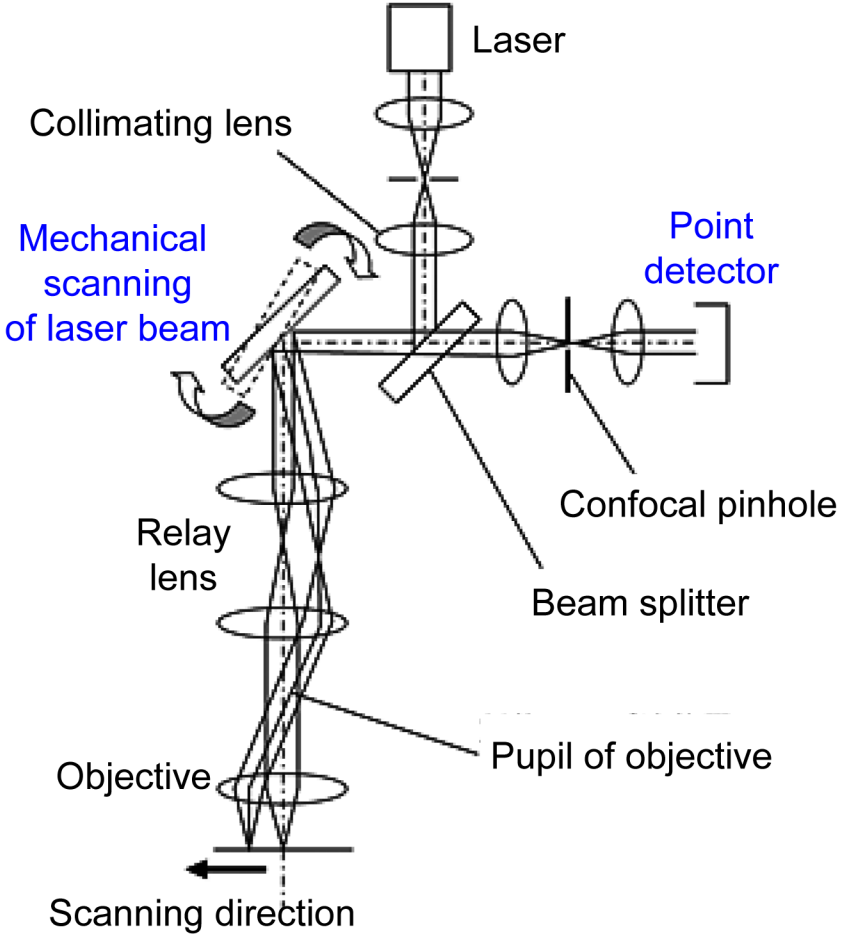


Normal microscopy



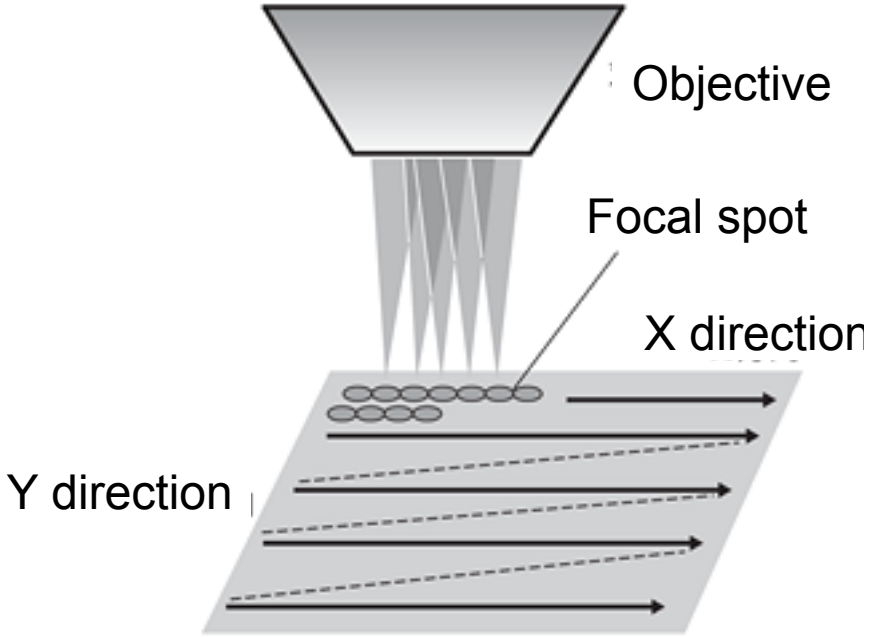
Confocal microscopy

Confocal laser microscopy



Optical configuration

http://bioimaging.jp/learn/023/index_2.html



Raster scanning of a focused laser spot

http://bioimaging.jp/learn/023/

Faster image acquisition ! Higher spatial resolution!

Fast confocal microscopy

Conventional

Serial imaging based on mechanical scanning

Optical comb

Proposal

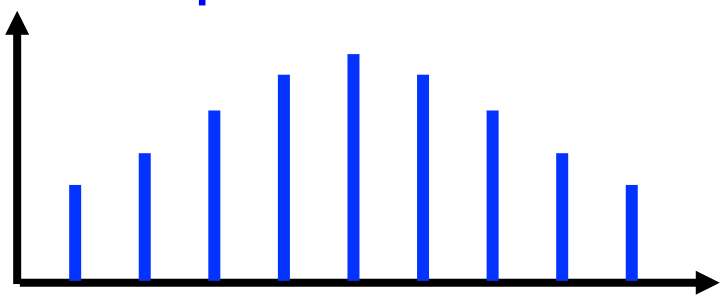
One-shot imaging based on parallel data acquisition

Dimension-converting comb

Temporal
Spatial
Polarization
etc

Conversion to wavelength

Optical comb



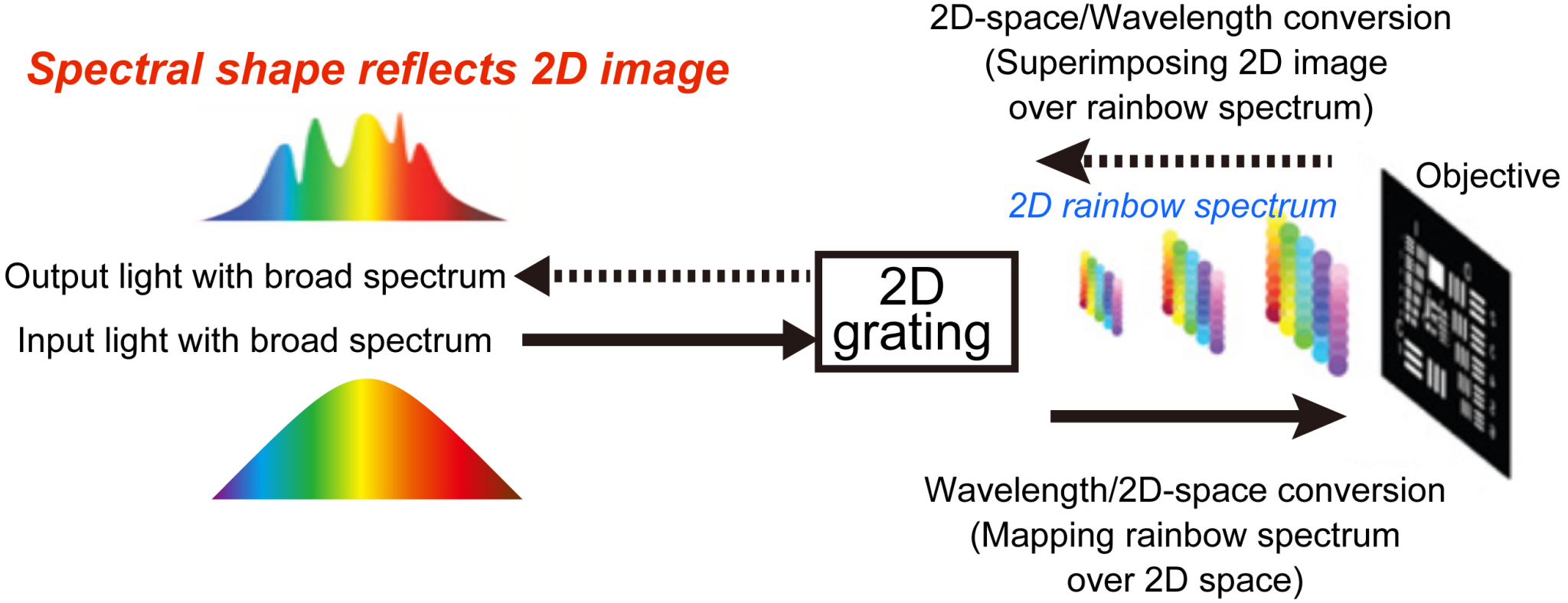
Information is superimposed on each comb mode

Dual comb spectroscopy

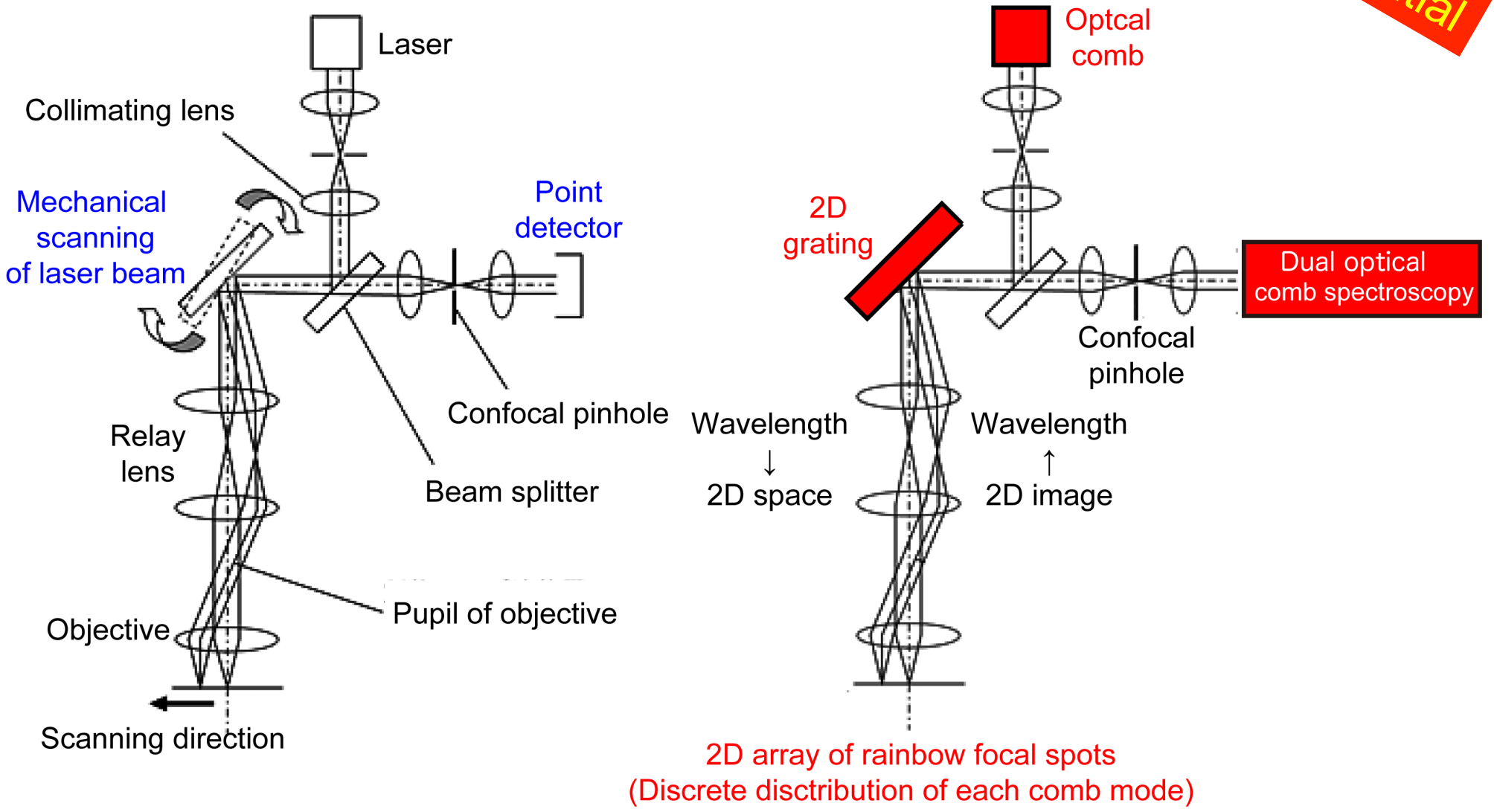
Number of comb mode
☞Tremendous channel number
Linewidth of comb mode
☞Infinitesimal sampling interval

Mode-resolved comb spectrum

Single-shot imaging based on bidirectional conversion between wavelength and 2D space

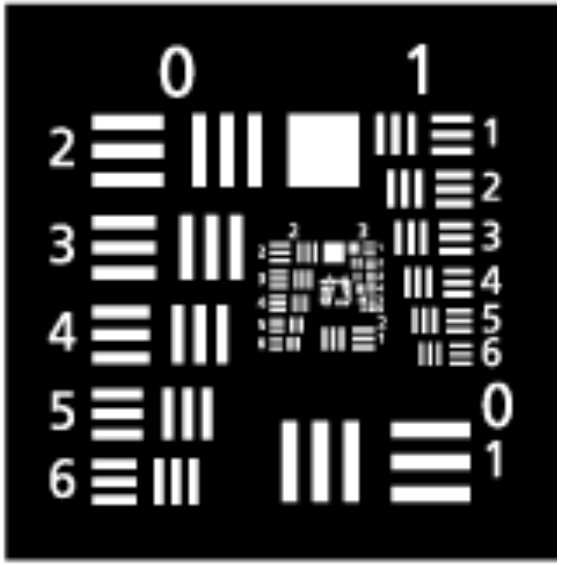


Optical-comb confocal microscopy



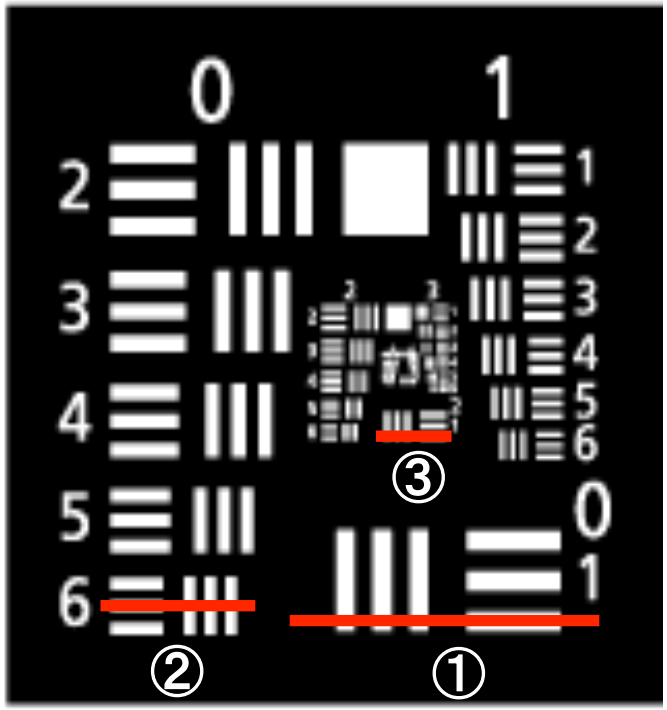
No mechanical scanning, single-shot imaging, super resolution

Optical setup for line imaging with OSA



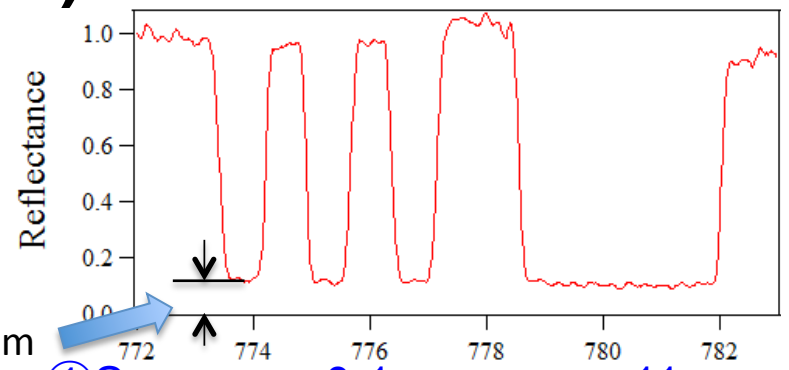
Sample : Test Target
(1951USAF negative)

Results (1)



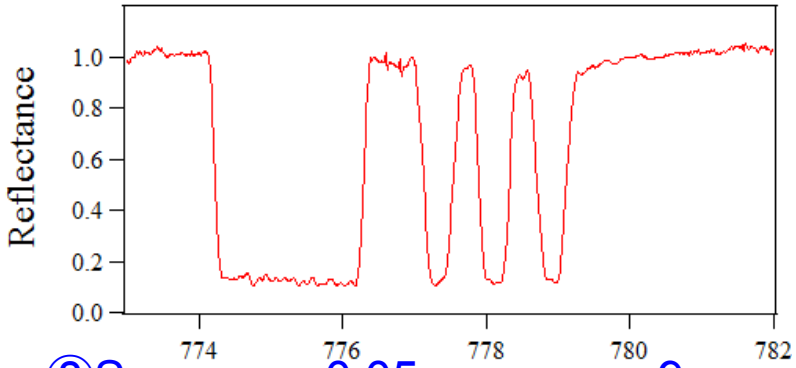
要素番号	0	1	2
1	① 1.00	2.00	4.00 ③
2	1.12	2.24	4.49
3	1.26	2.52	5.04
4	1.41	2.83	5.66
5	1.59	3.17	6.35
6	② 1.78	3.56	7.13

Can not resolved

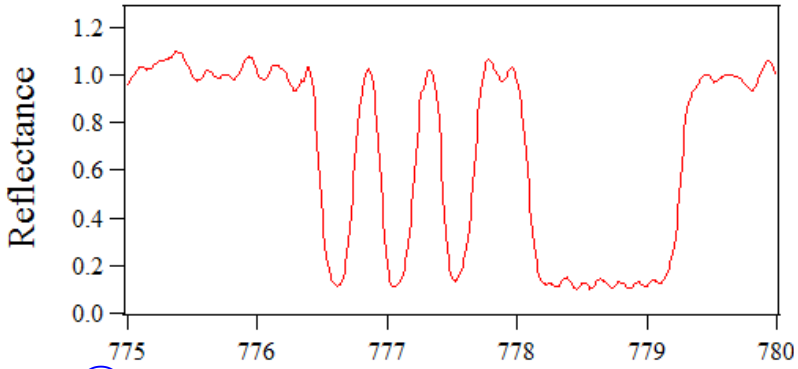


Reflection from glass

①Spec. res=0.1 nm, span=11 nm

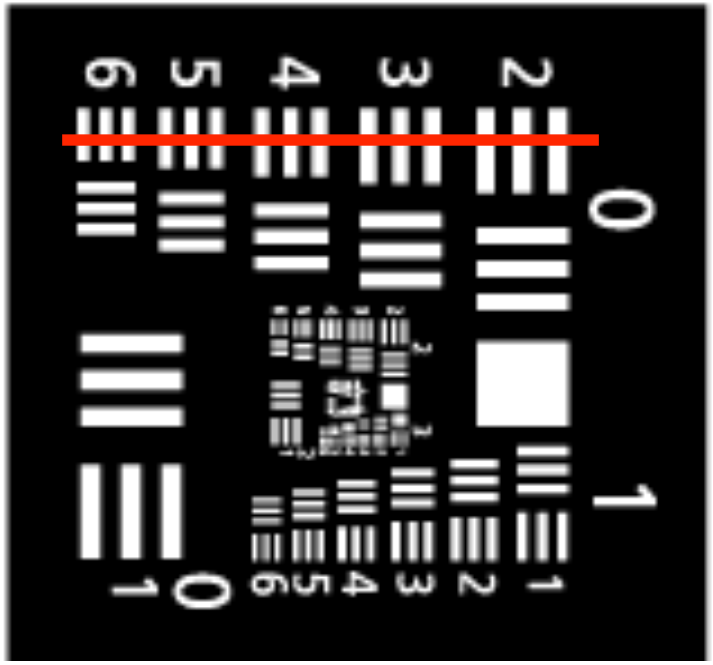


②Spec. res=0.05 nm, span=9 nm



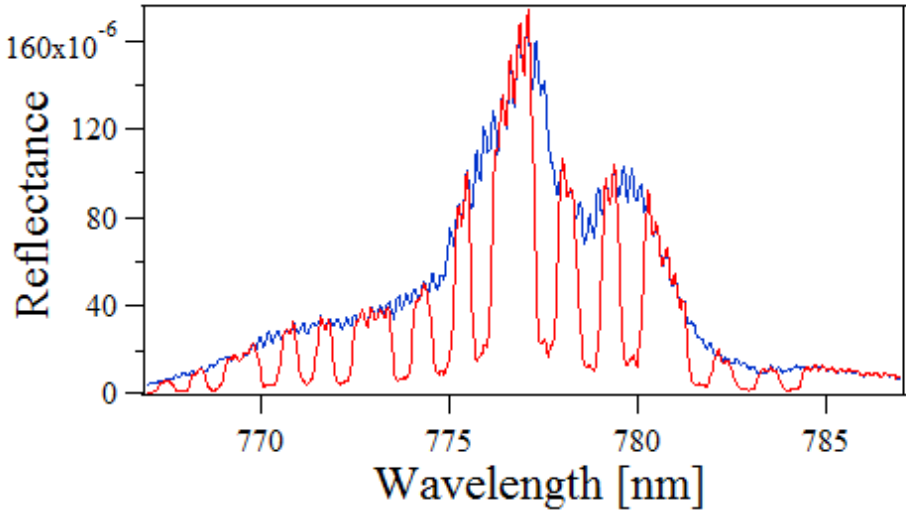
③Spec. res=0.05 nm, span=5 nm

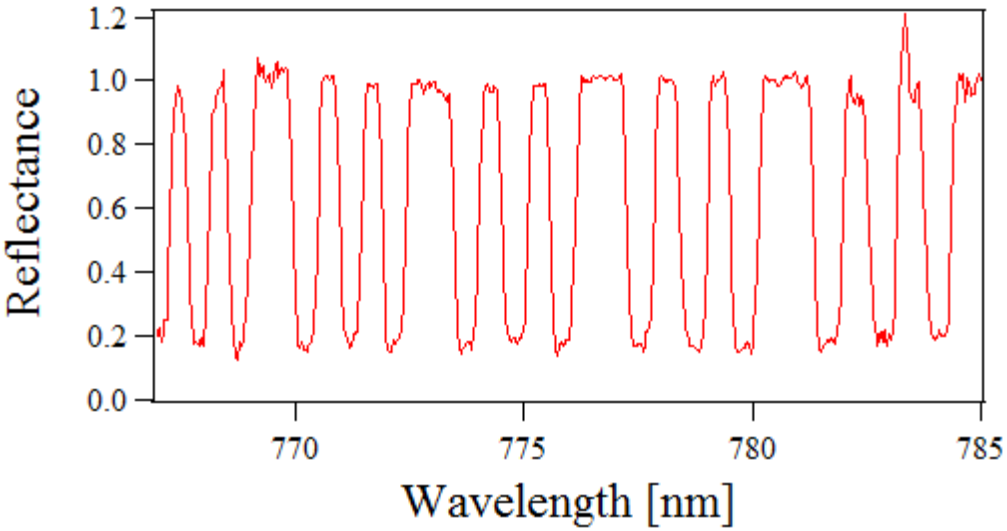
Results (2)

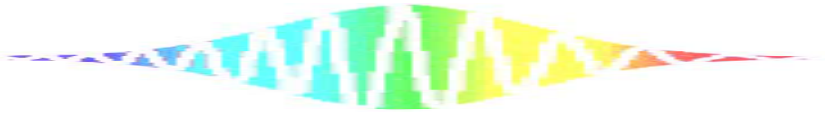


1 mmあたりのラインペアの数 (IP/mm)

	グルー			
要素番号	0	1	2	3
1	1.00	2.00	4.00	8.00
2	1.12	2.24	4.49	8.98
3	1.26	2.52	5.04	10.10
4	1.41	2.83	5.66	11.30
5	1.59	3.17	6.35	12.70
6	1.78	3.56	7.13	14.30





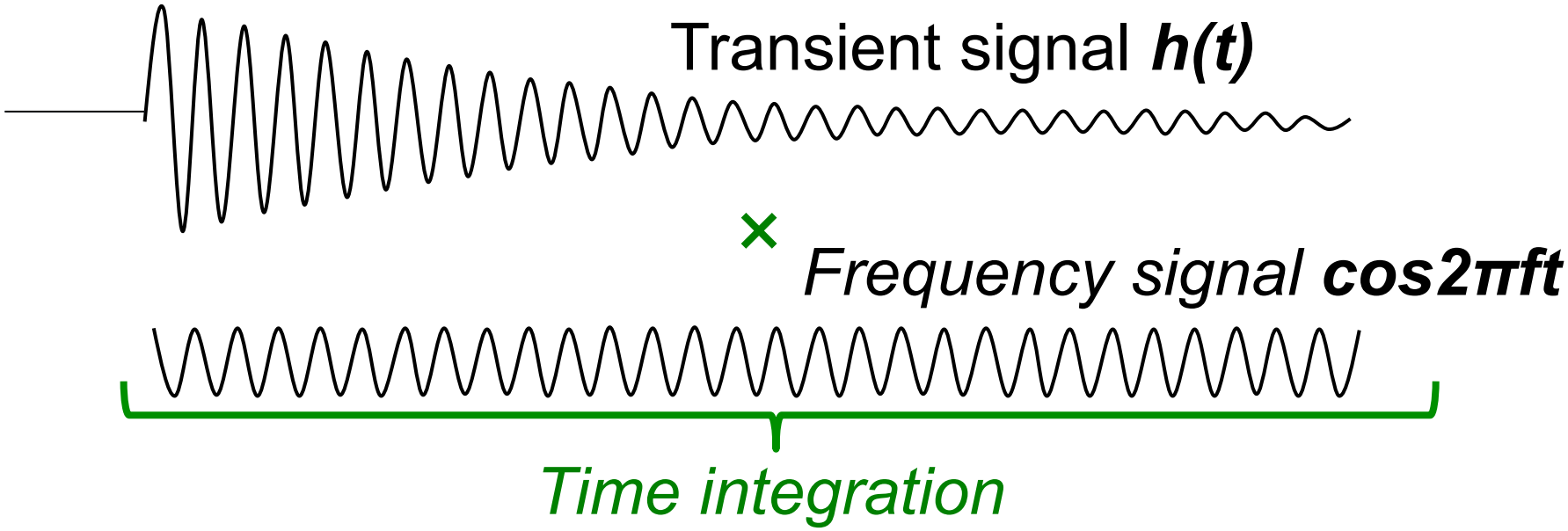


(3) Discrete Fourier transform infrared spectroscopy (in collaboration with AIST)

Fourier transform of transient signal ***h(t)***

Formula of FT

$$H(f) = \int_{-\infty}^{+\infty} h(t) \bullet \exp(-2\pi i f t) dt$$



Actual spectral resolution is determined by observed time window.

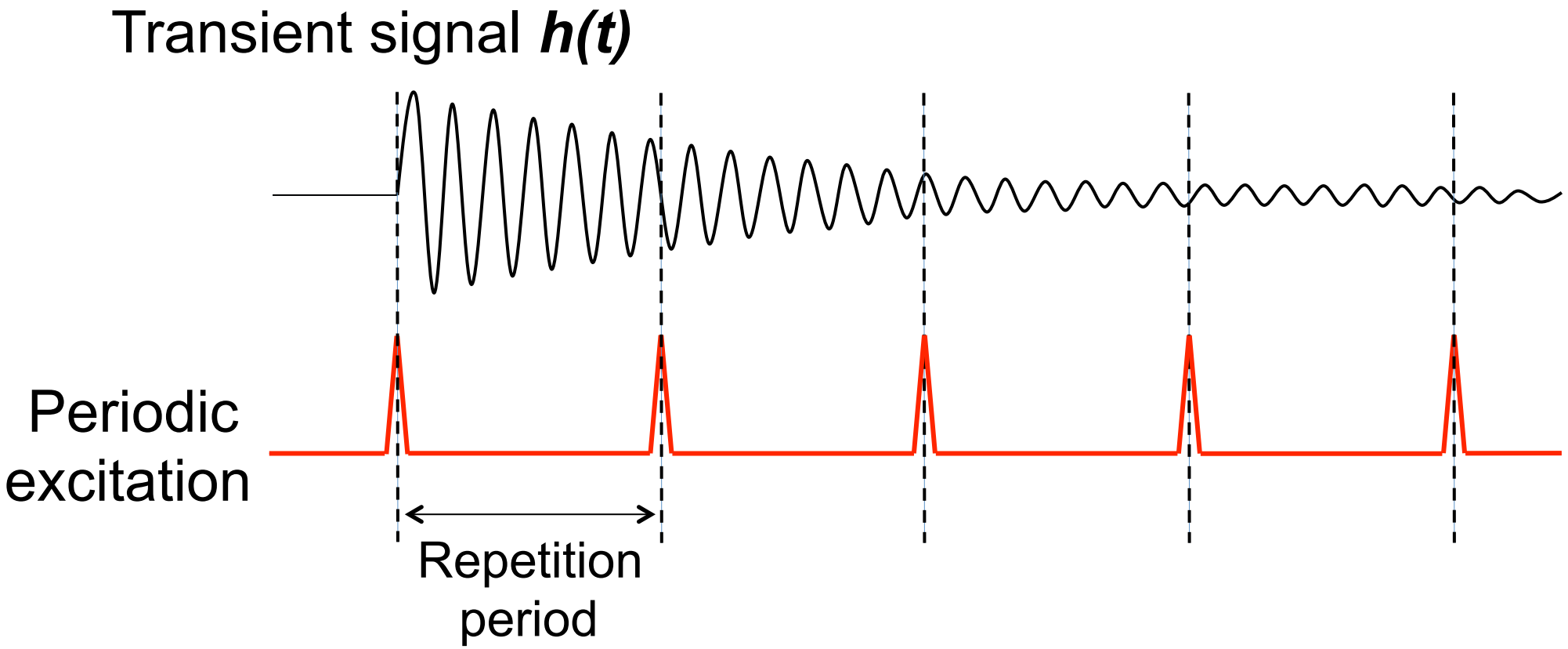
Pulse train of THz electric field

Upper limit of time window
= repetition period of THz pulse

FT of transient signals induced by THz pulse train

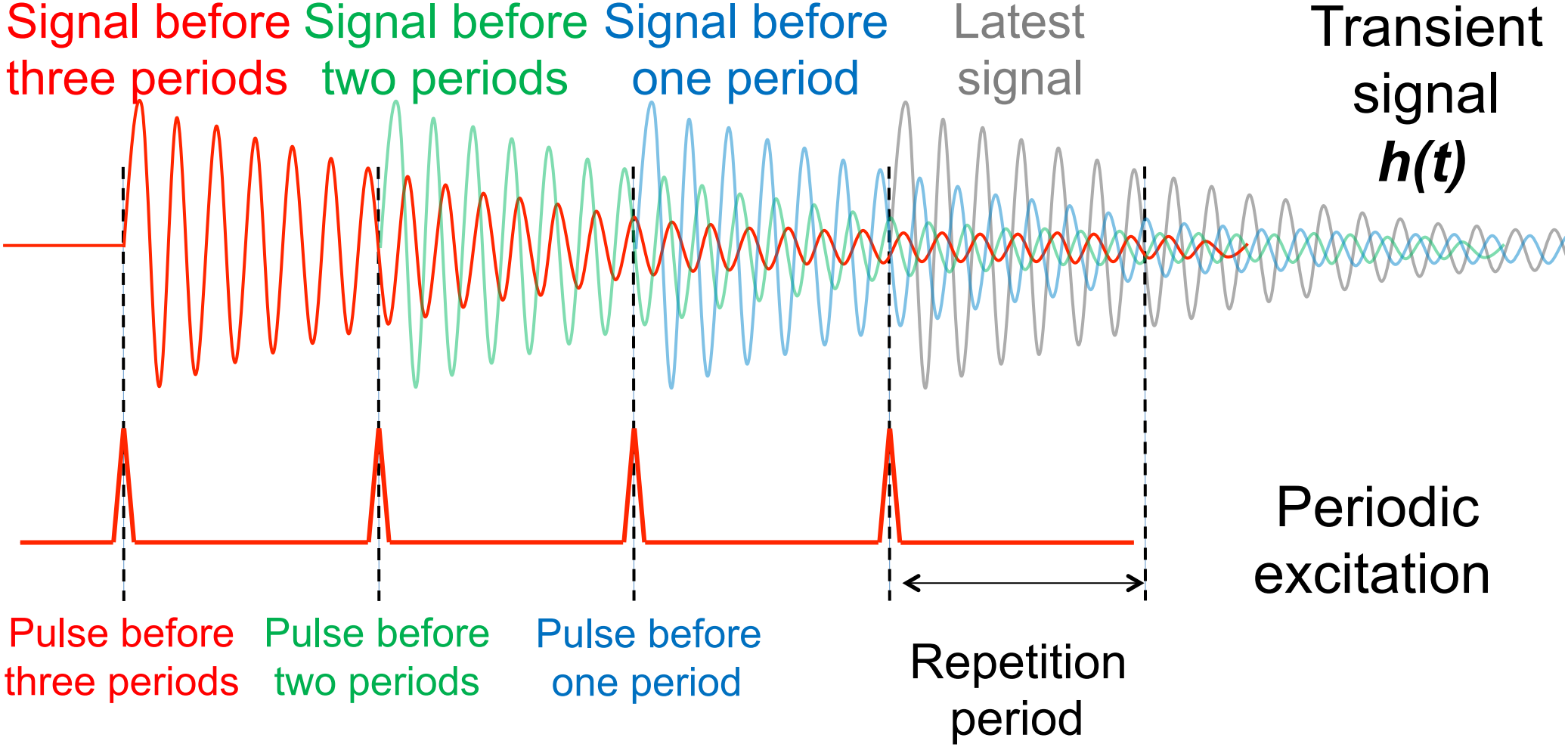
Relaxation time of transient signal > Repetition period of THz pulse train

e.g. FID signal



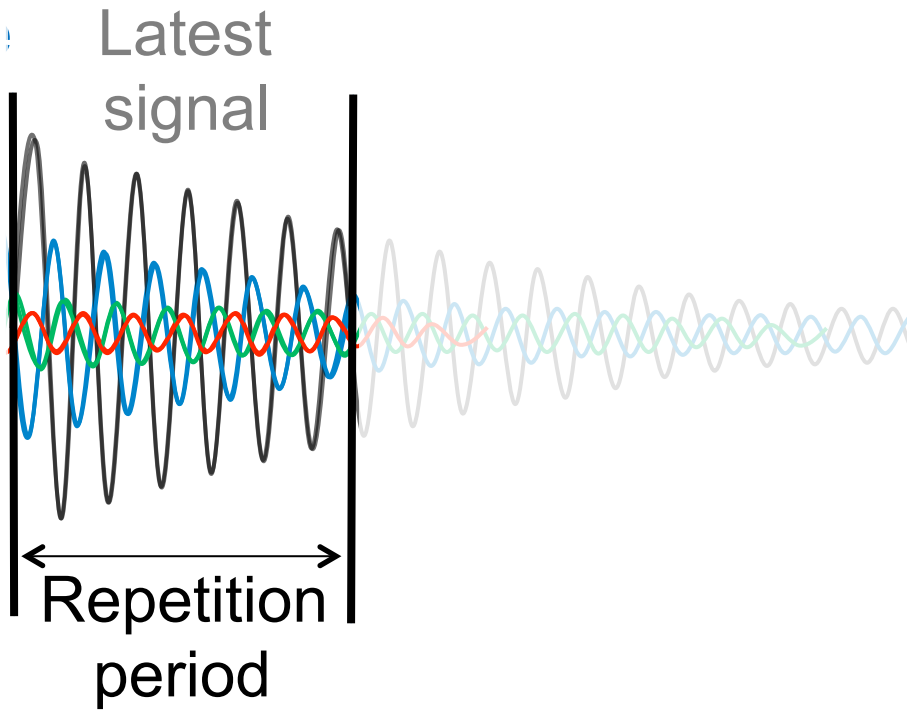
FT of transient signals induced by THz pulse train

Relaxation time of transient signal > Repetition period of THz pulse train



FT of transient signals induced by THz pulse train

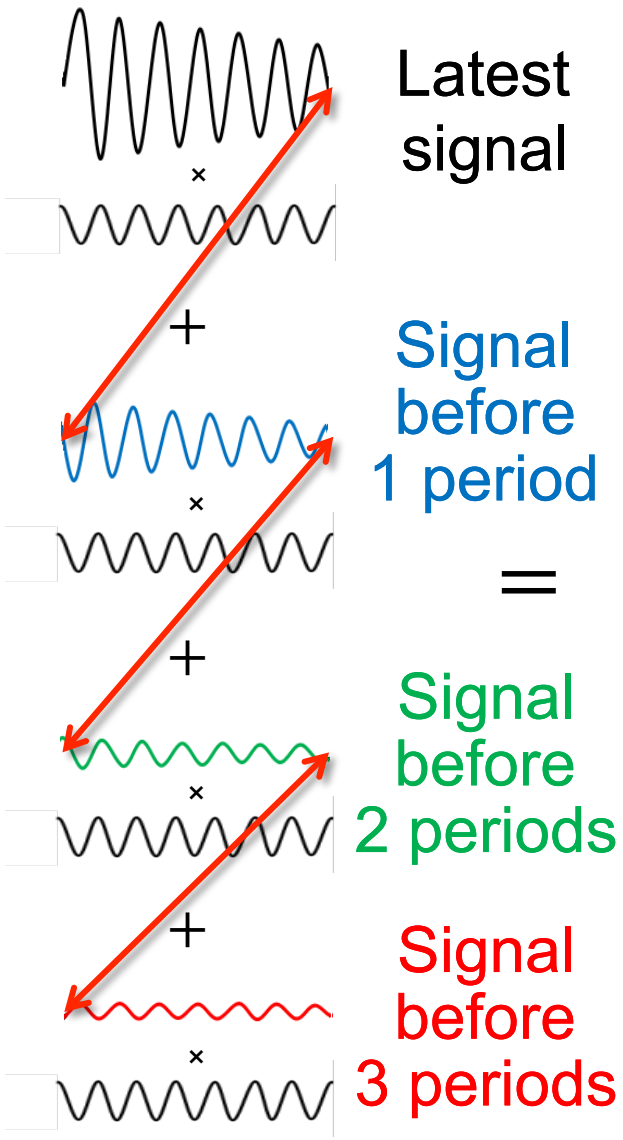
Relaxation time of transient signal > Repetition period of THz pulse train



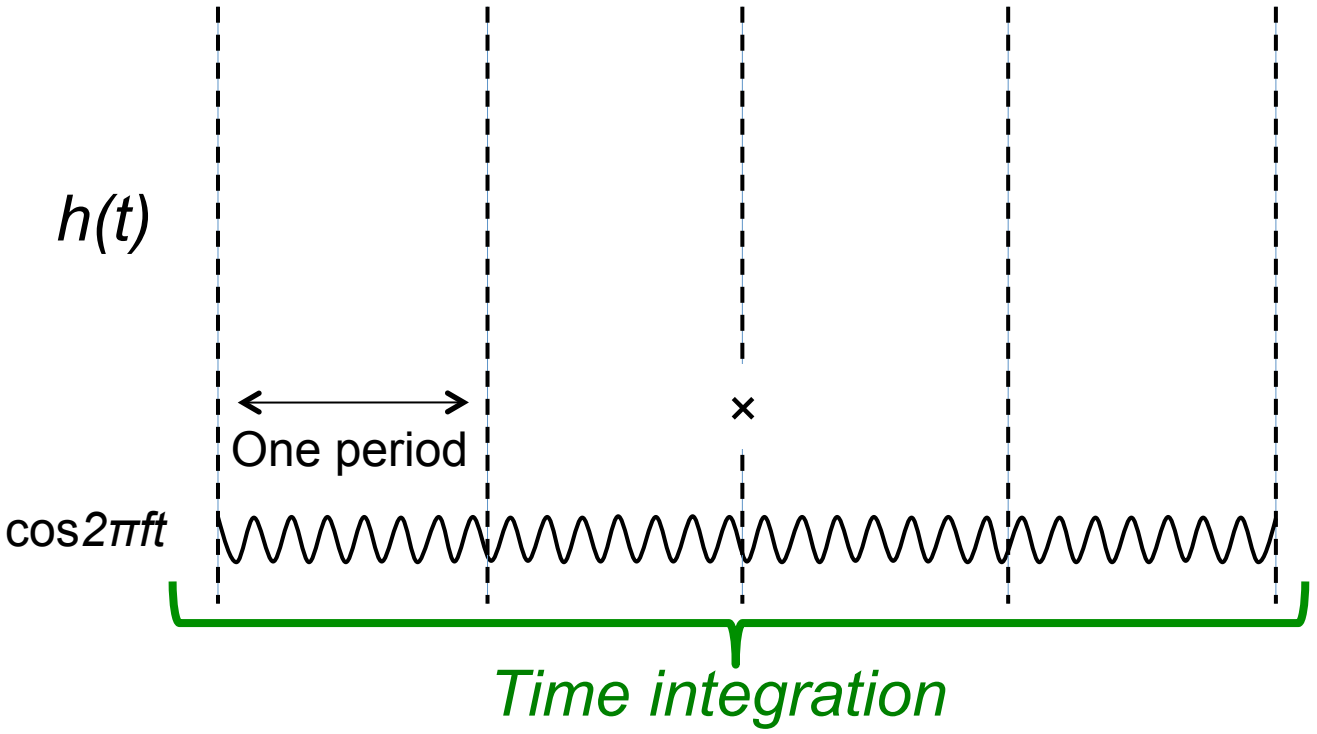
Focus on pieces of different transient signals included in the same one period

Observed time window = One repetition period

ls induced by THz pulse train



Each piece can be temporally connected!



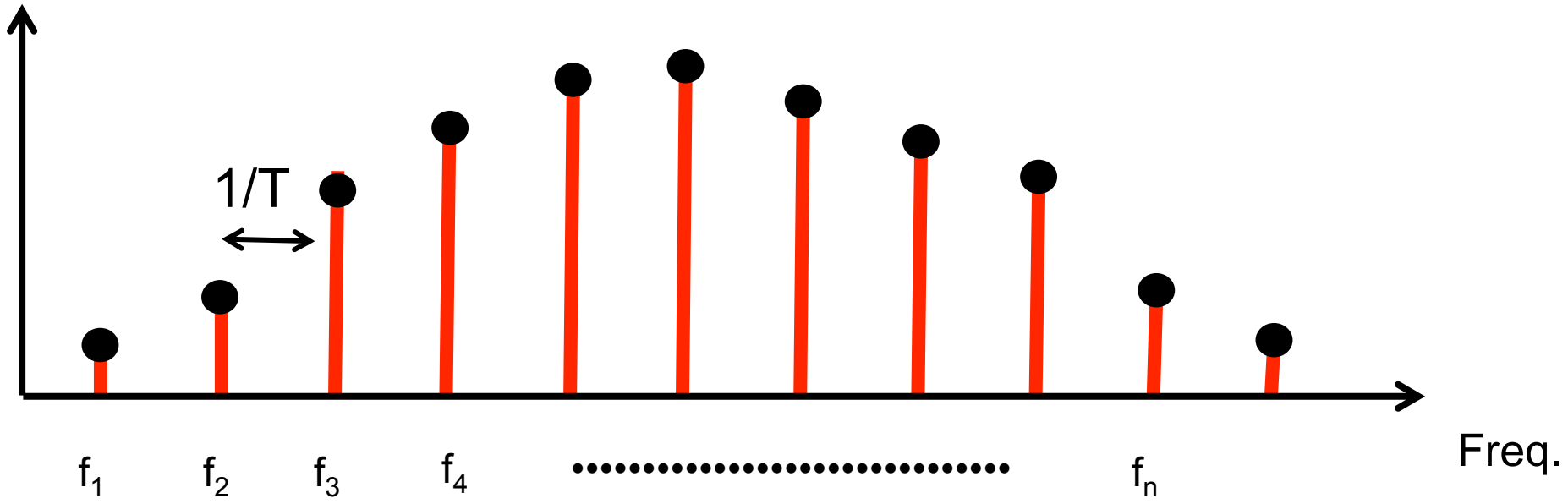
Equivalent to integration of $h(t) \cdot \cos 2\pi ft$ within infinite time window!

Discrete Fourier transform spectrum

Frequency of each plot

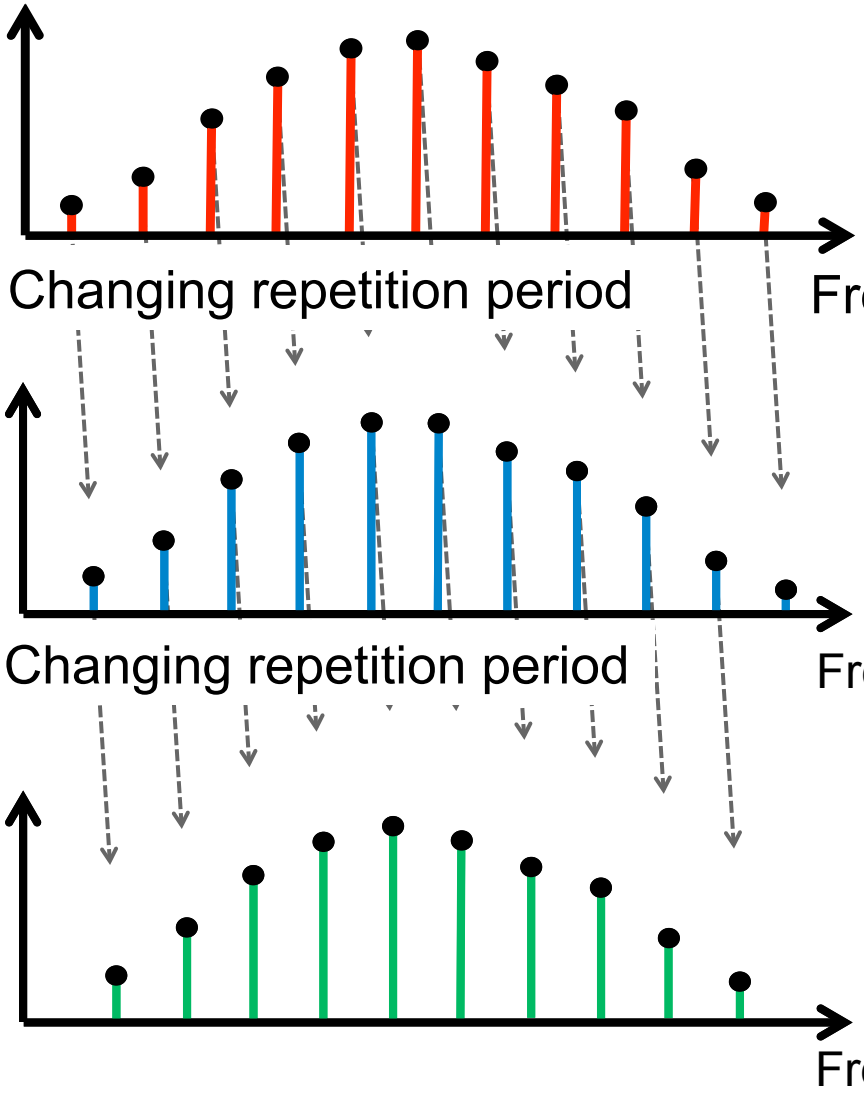
$$f_n = \frac{n}{T}$$

n: number of data plot
T: repetition period



Each plot has infinite spectral resolution due to infinite time window.
However, discrete distribution limits spectral resolution to plot interval.

Sweeping of discrete FT spectrum

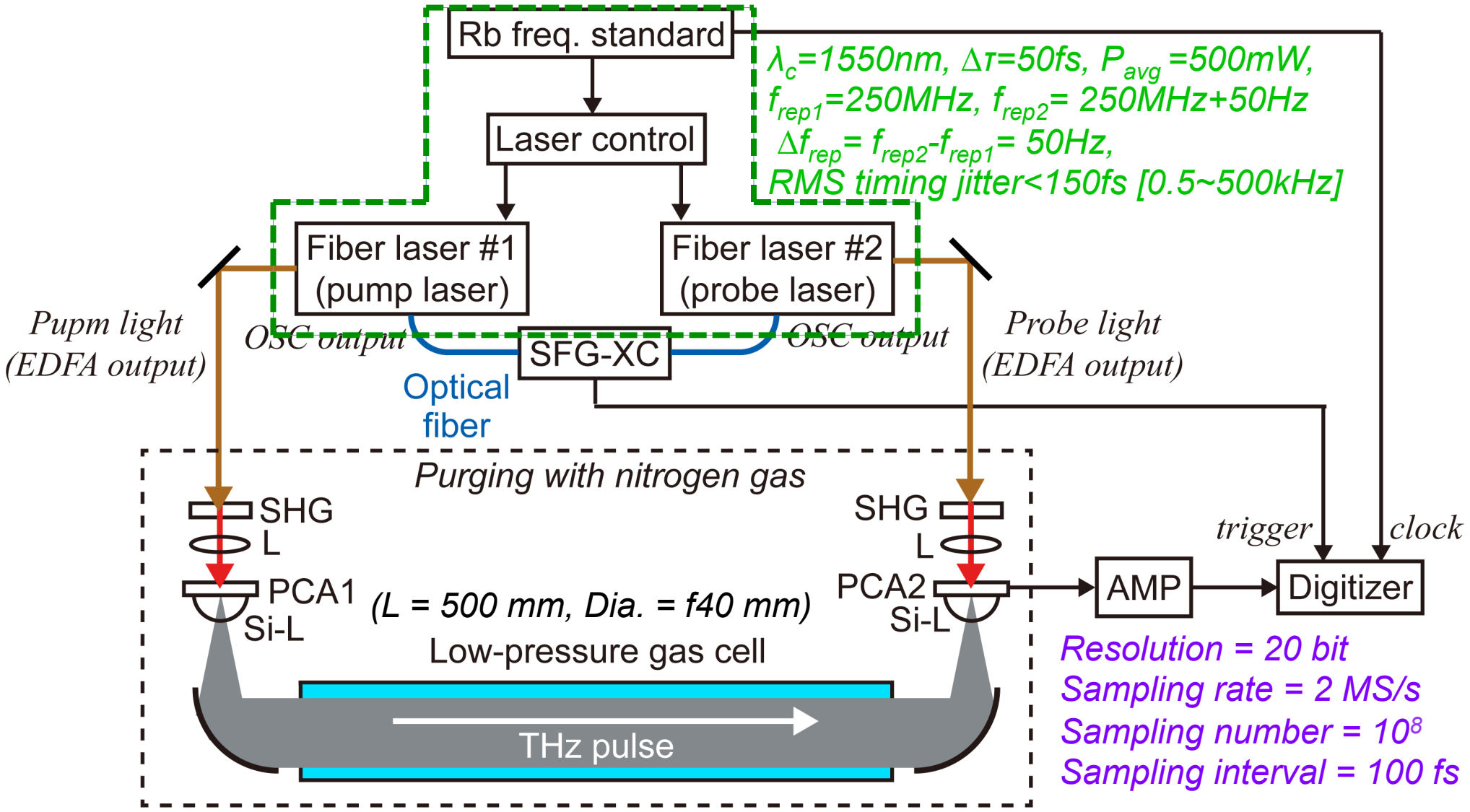


Spectral overlapping

Spectrally interleaving spectrum

Gaps between data plots can be filled in

Experimental setup

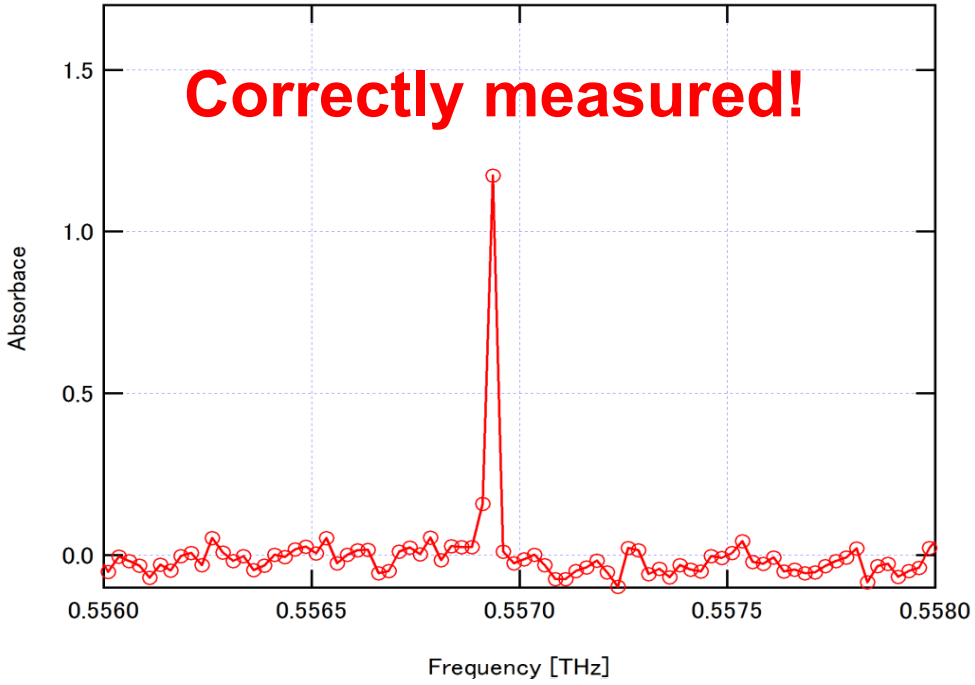


Relation between time window and repetition period

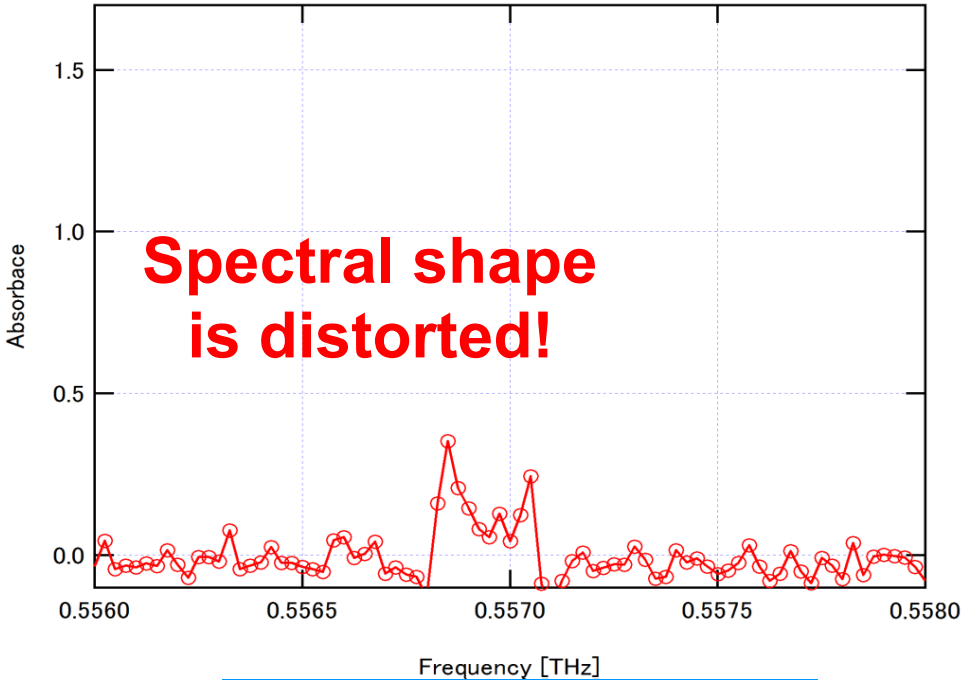
(Relaxation time > repetition period)

Rotational transition of H_2O at 0.557 THz (H_2O@6 Pa & N_2@140 Pa)
Expected pressure broadening linewidth = 10.6 MHz
Relaxation time of absorption = 94ns (25 periods)

Time window = 1 period

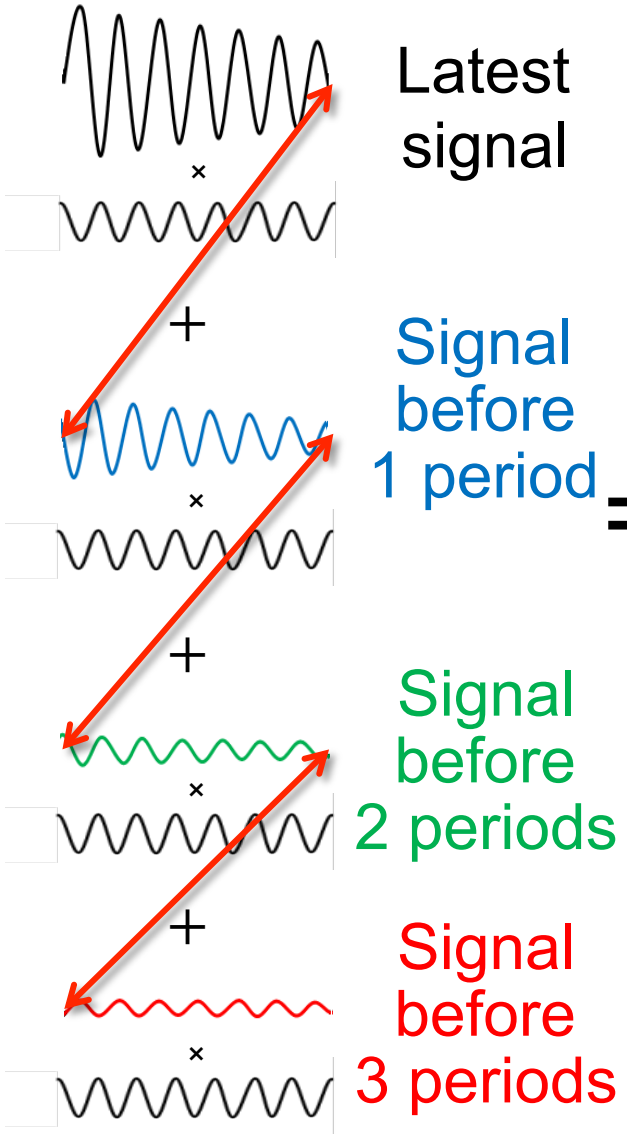


Time window = 0.9995 period

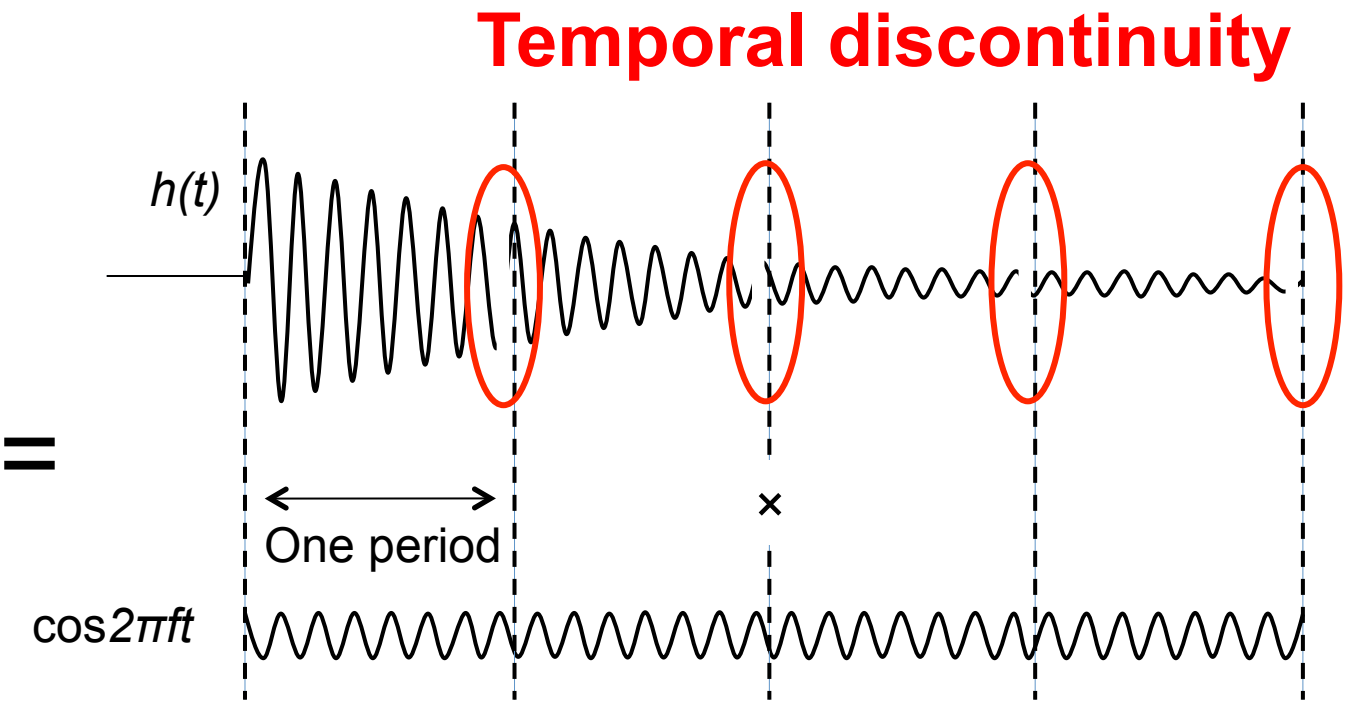


Relation between time window and repetition period

(Relaxation time > repetition period)



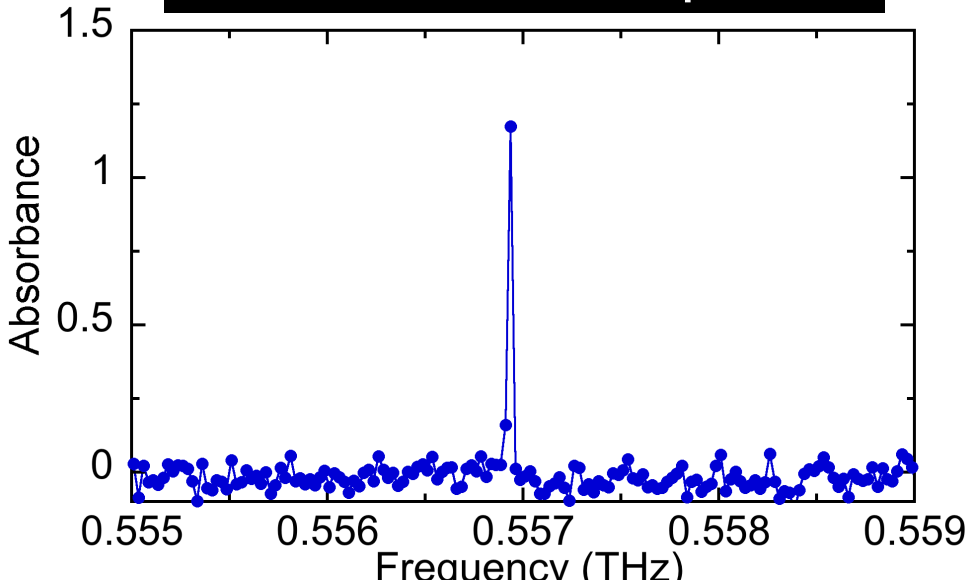
=



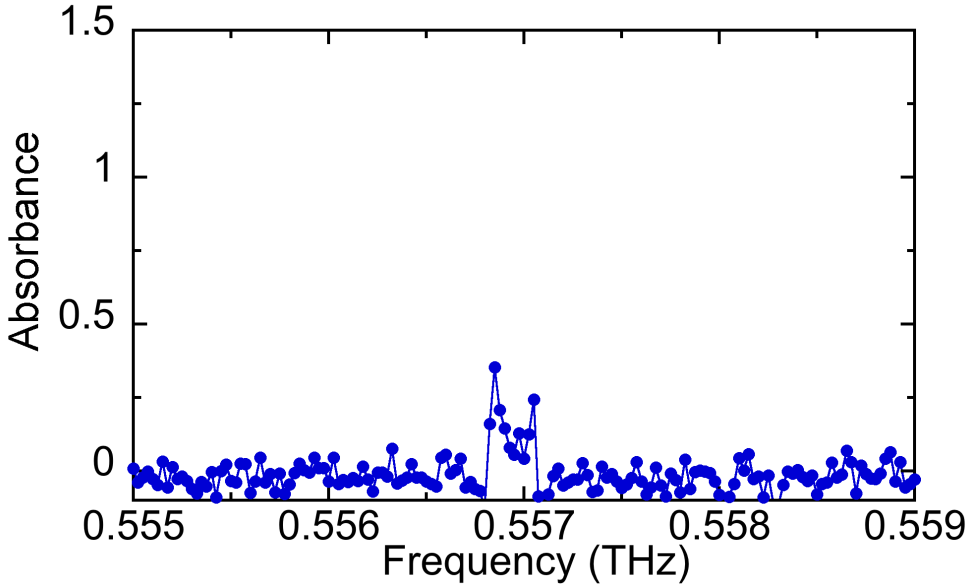
Each piece of different transient signals can not be connected!

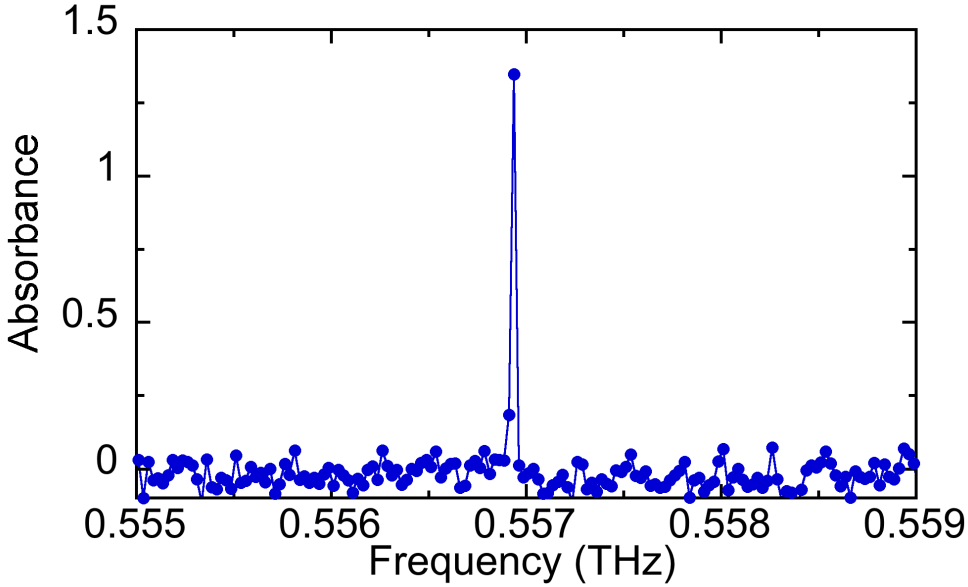
Relation between time window and repetition period

Time window = 1 period



Time window = 0.9995 period





Time window = 1 period

Data for 0.9995period

+

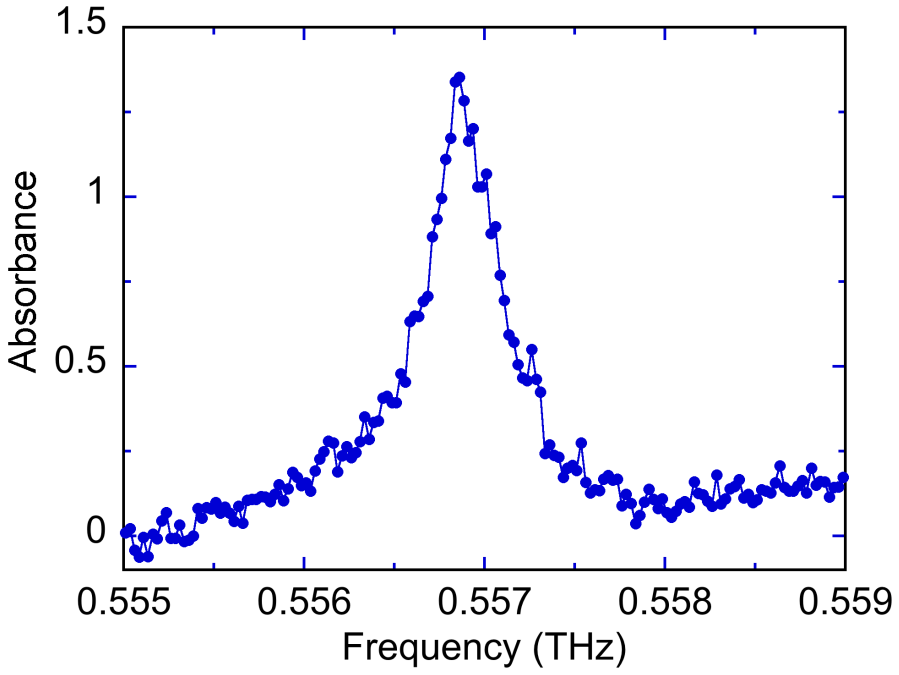
Null for 0.005period

Relation between time window and repetition period

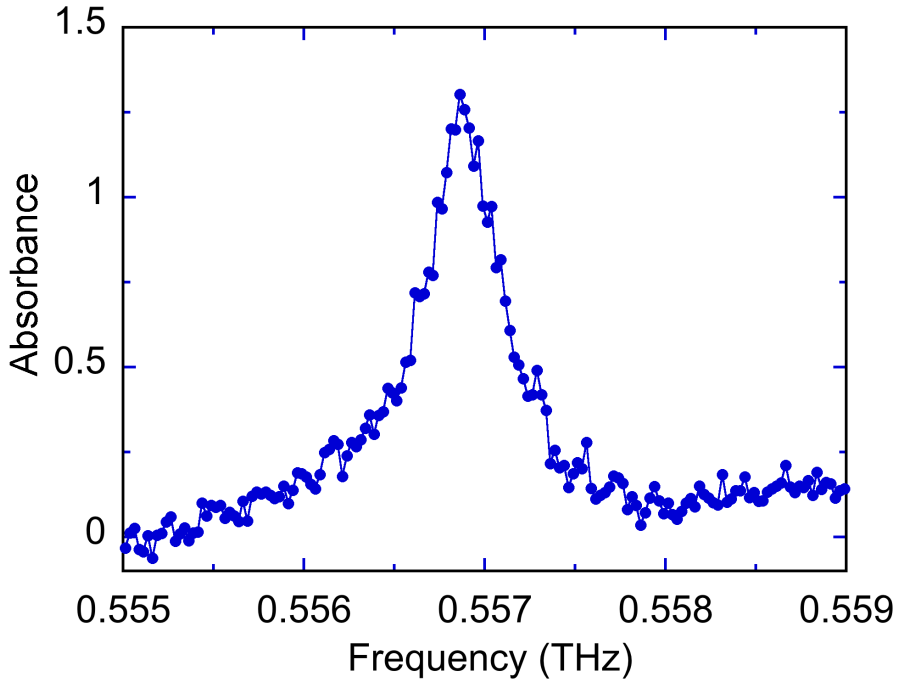
(Relaxation time < repetition period)

Rotational transition of H_2O at 0.557 THz (H_2O@1kPa&N_2@3.5kPa)
Expected pressure broadening linewidth = 500 MHz
Relaxation time of absorption = 2 ns (0.5periods)

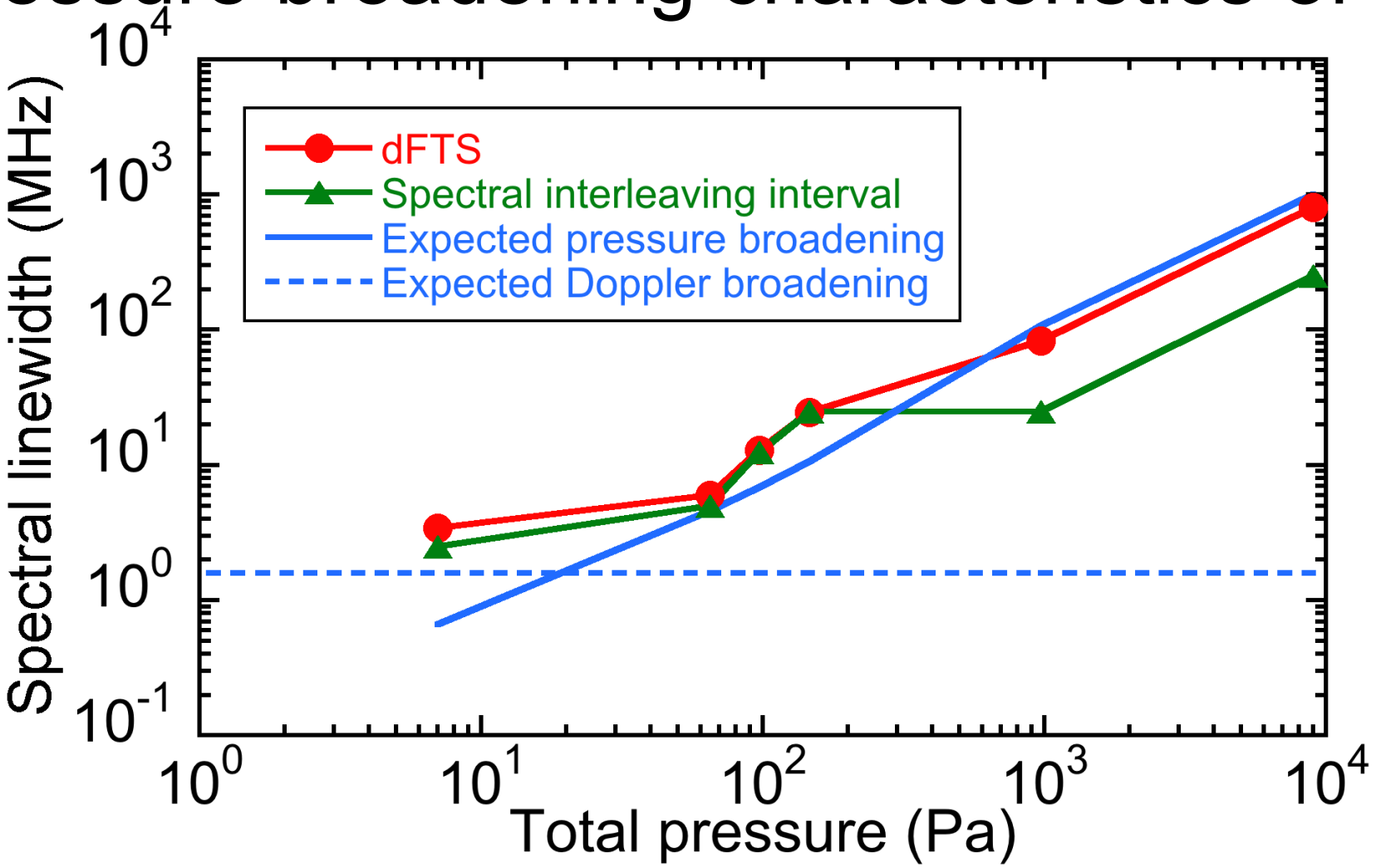
Time window = 1 period



Time window = 0.9995 period



Pressure broadening characteristics of H_2O

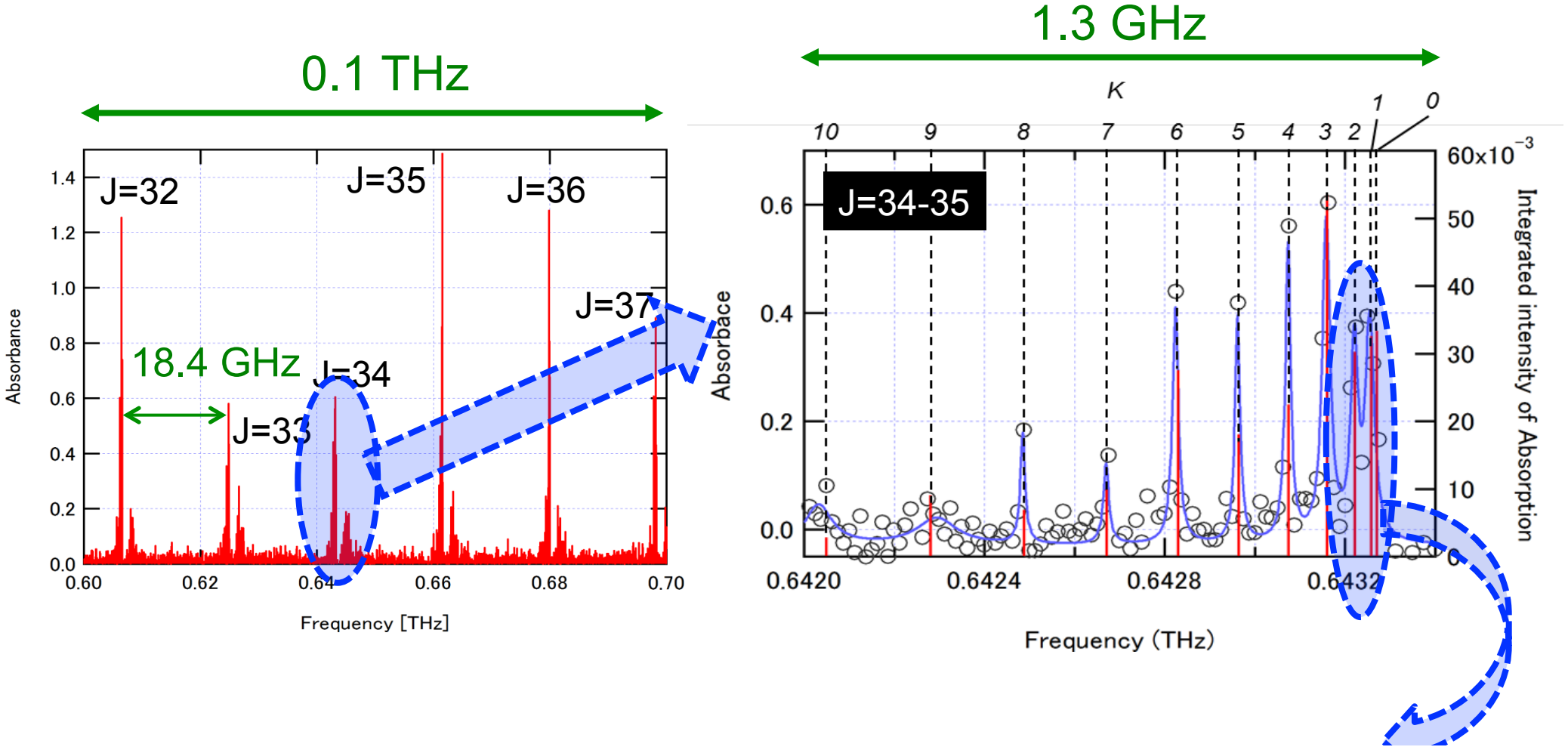


Spectral interleaving interval limits spectral resolution independent of time window size

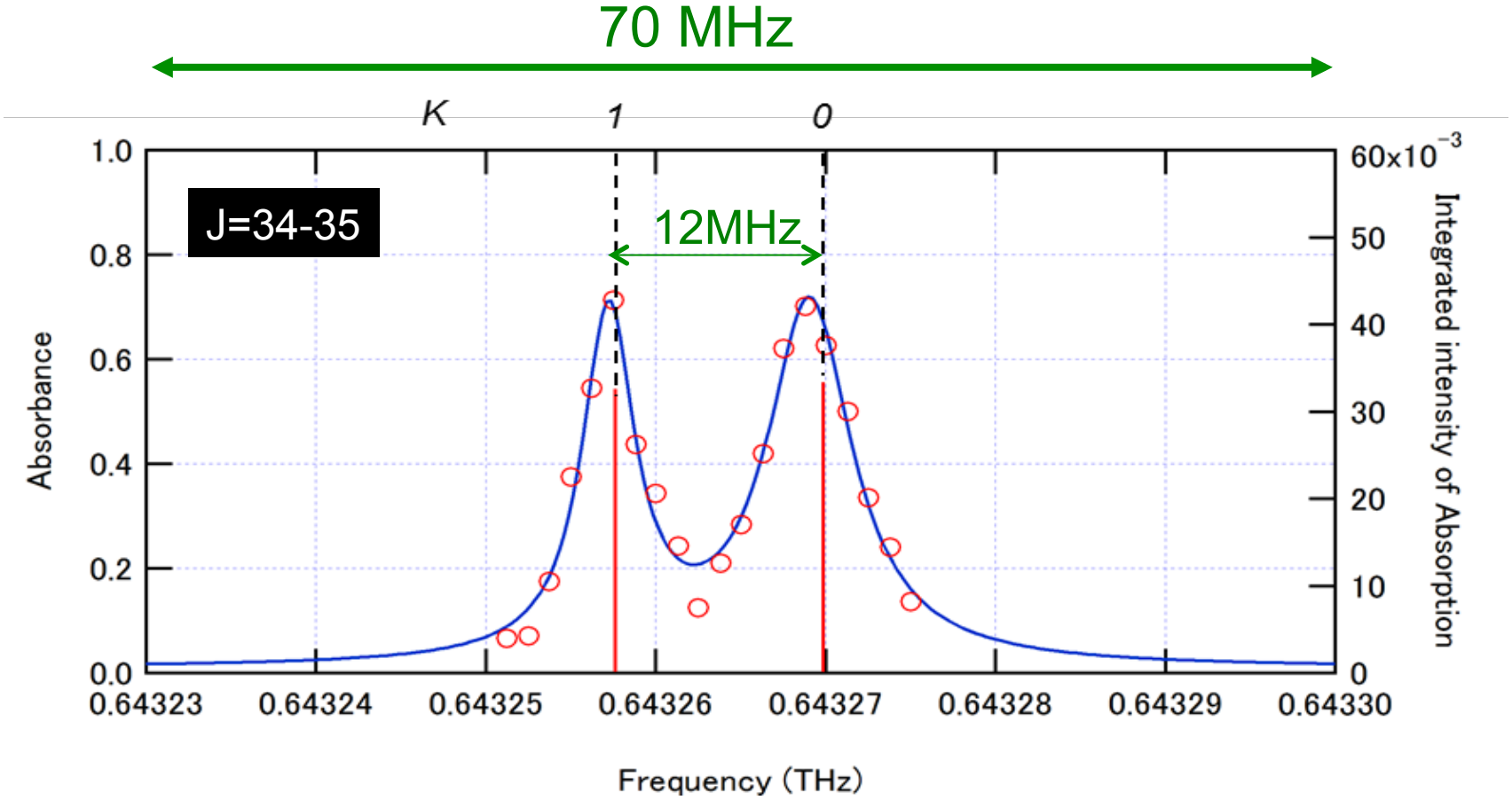
Spectroscopy of multiple absorption lines

Sample gas : CH_3CN@30Pa

Symmetric top molecule with rotational constant B of 9.2GHz

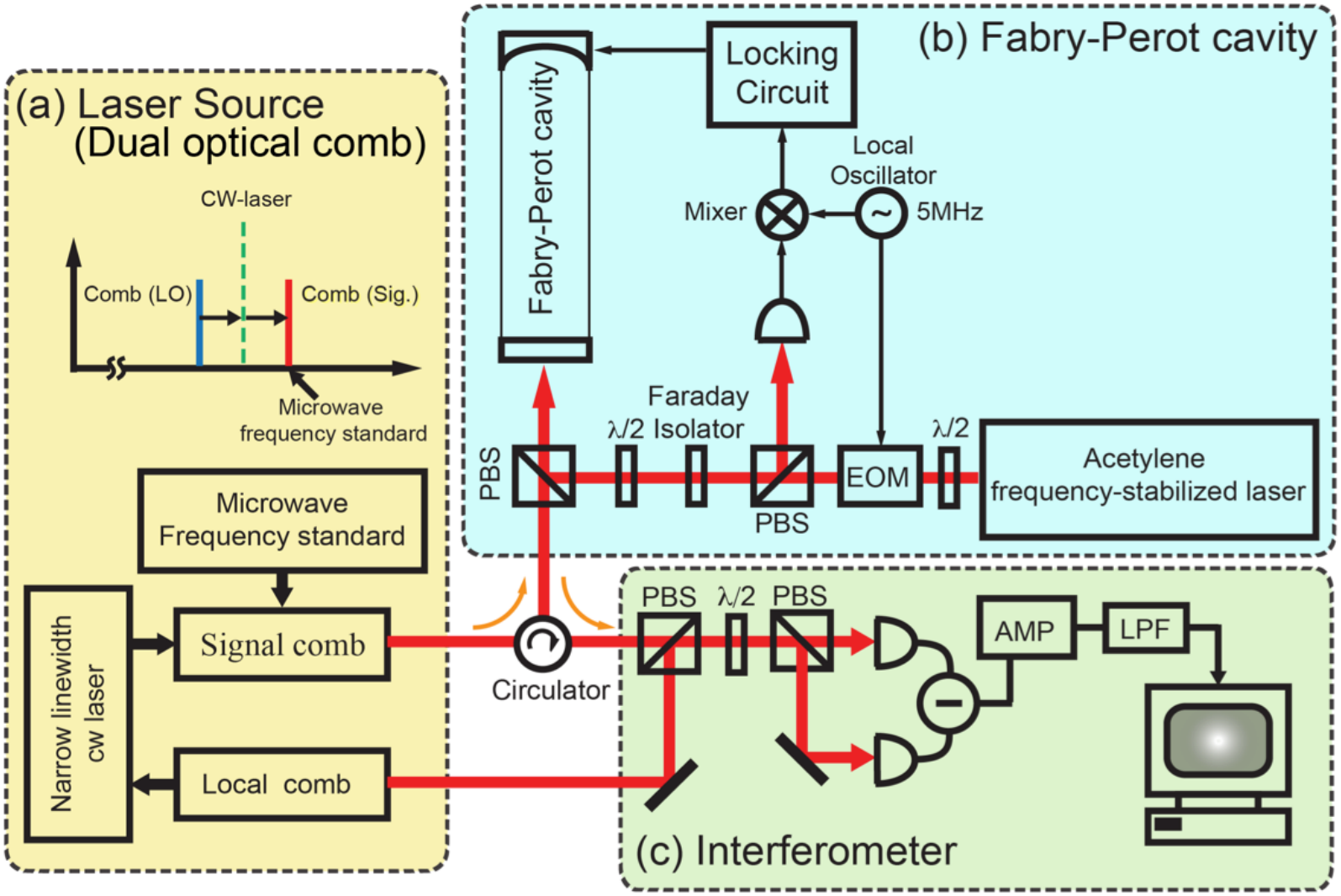


Spectroscopy of multiple absorption lines



K	Literature value (THz)	Experimental value (THz)	Discrepancy (MHz)
1	0.643 257 622 0	0.643 257 498 7	0.12
0	0.643 269 866 7	0.643 268 764 0	1.10

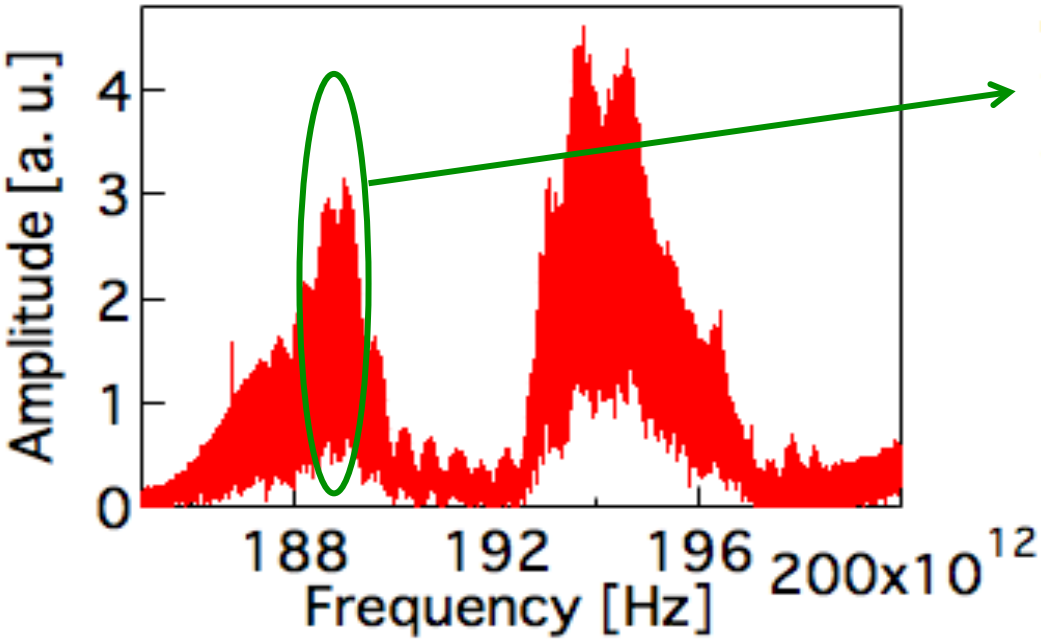
Experimental setup

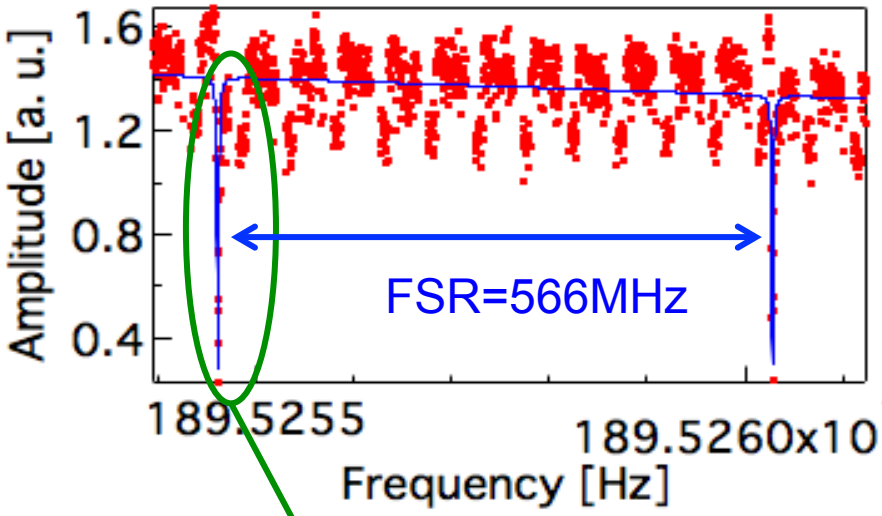


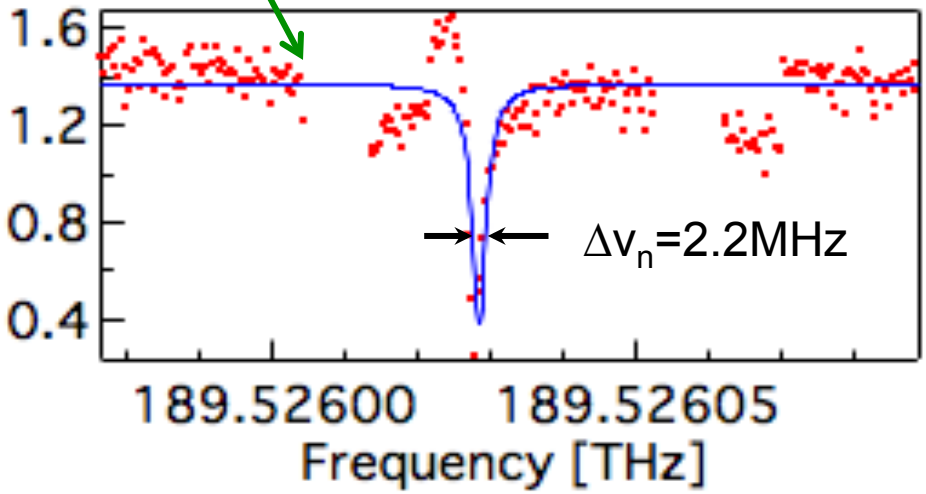
f_{rep_LO}=48,350,631Hz
f_{rep_S}= 48,350,676Hz
$\Delta f_{rep} = f_{rep\_S} - f_{rep\_LO}$= 45Hz

Result

- $f_{rep,\ S}$=48.350676MHz➔48.350685MHz, 100 times sweep
- Δf=*44.99513*Hz







The resonance mode in Fabry-Perot cavity

Summary

(1) Intelligent THz instrumentation and application

- Adaptive sampling dual THz comb spectroscopy (CLEO, to be submitted in this year)
- THz-comb-referenced spectrum analyzer (CLEO)

(2) Novel optical comb measurement and application

- Full-field confocal optical-comb microscopy (Patent preparation)
- Discrete Fourier transform infrared spectroscopy (CLEO)