Optical frequency combs for stable radiation in the microwave, terahertz and optical domains

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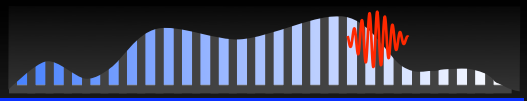
Time and Frequency Division,
National Institute of Standards and Technology
Boulder, CO



stabilized frequency combs from mode-locked femtosecond lasers provide new opportunities for….

- § optical frequency metrology
- § optical clocks
- § measuring distance
- § time & frequency transfer
- § laboratory tests of fundamental physics
- § carrier-envelope phase control (key technology for attosecond science)
- § femtosecond pulse synthesis & arbitrary optical waveform generation
- § generation of ultralow noise microwaves
- § new spectroscopic techniques
- § harmonic generation
- § coherent control
- § spread-spectrum secure communications
- § part of a Nobel Prize!

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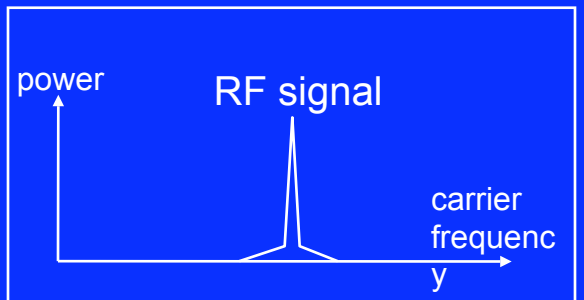
Jan Hall

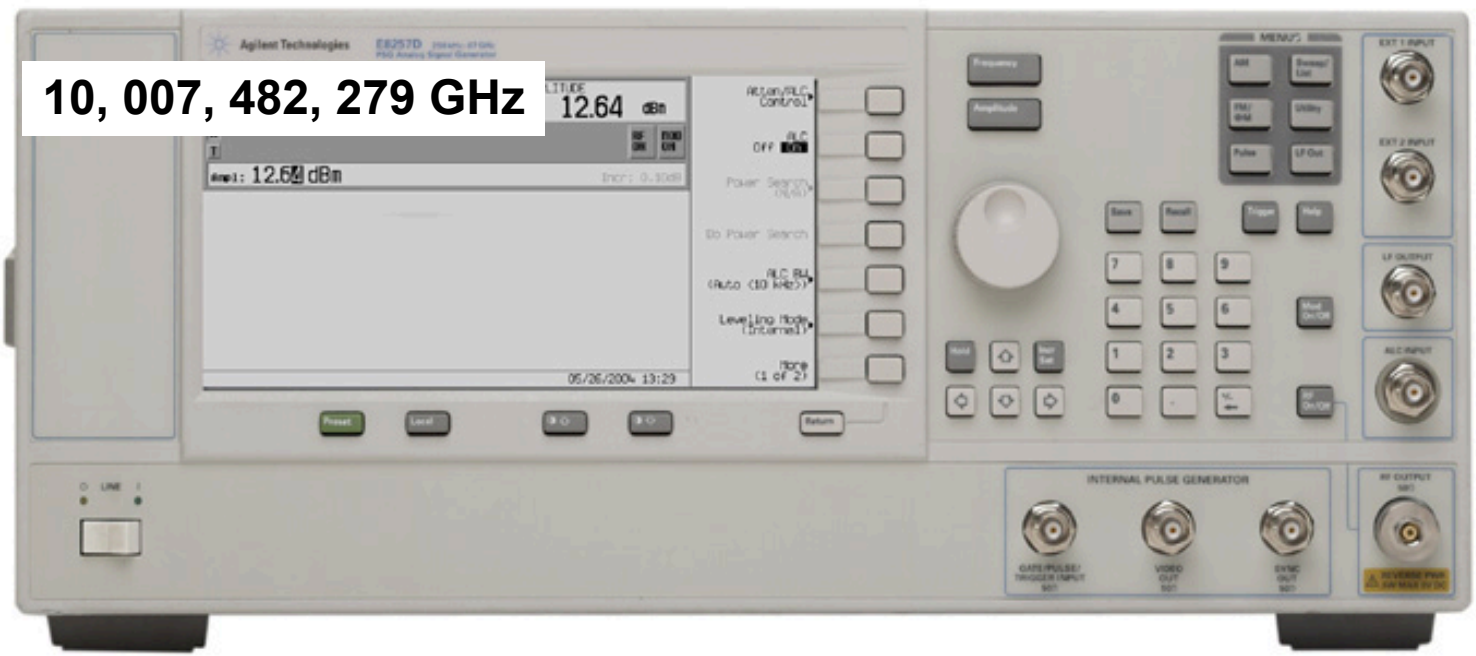
Ted Hänsch

microwave frequency synthesizers



specifications

250 kHz – 20 GHz +
low phase noise



Agilent E8257D frequency synthesizer

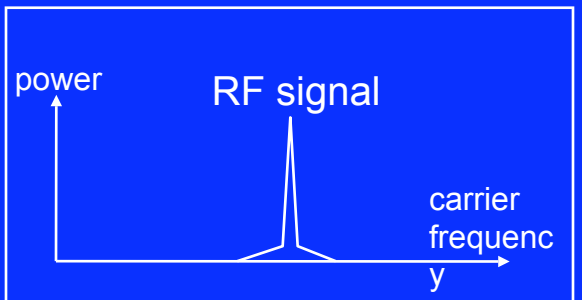
microwave frequency synthesizers

user defined:

(a) frequency
(b) amplitude
(c) noise (to some extent)

uses:

(i) references
(ii) comparisons
(iii) microwave electronics



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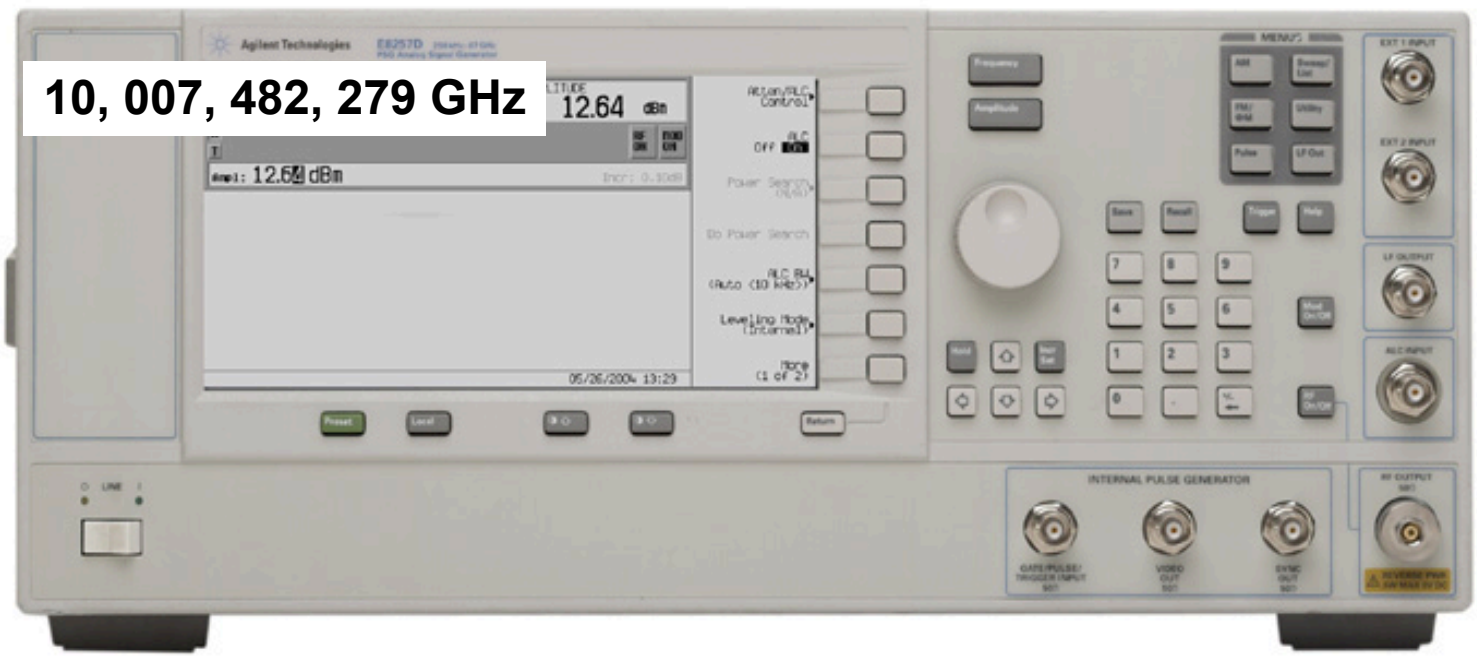

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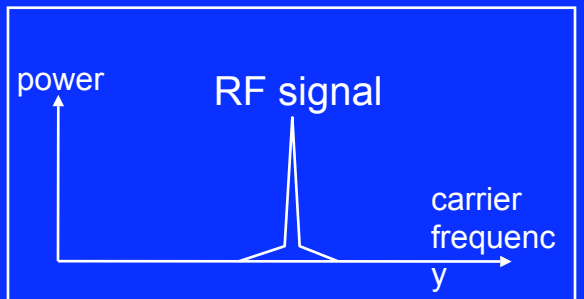

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commercial optical frequency synthesizer

idea: optical frequency synthesizer

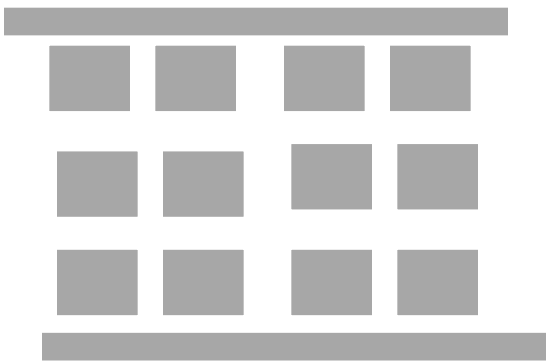
FREQUENCY:

352, 567, 323, 826, 841 Hz

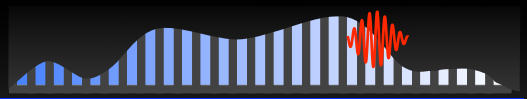
POWER: 2 nW

NOISE: -100 dBc/Hz at 1 Hz

port 1 **port 2**



commercial optical frequency synthesizer



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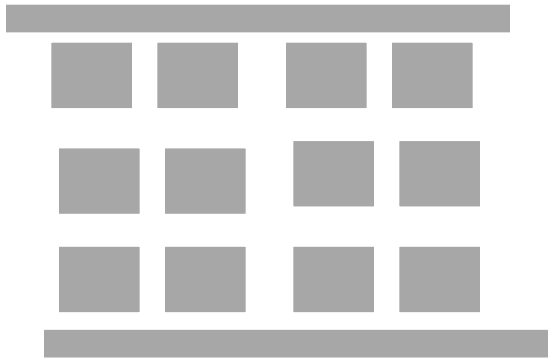

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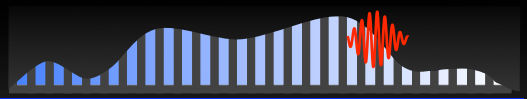
850 nm (352 THz)



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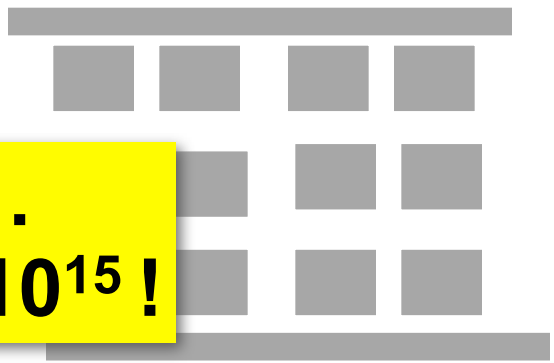
1 part in 10^{15} !



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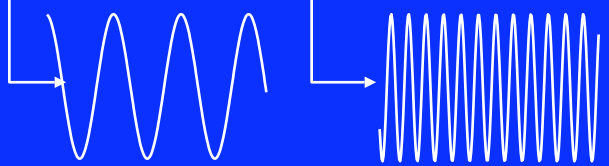

850 nm (352 THz)

commercial optical frequency synthesizer

microwave or optical reference

atoms or molecules ⟷ **stable cavity**

your are only as good as your reference

idea: optical frequency synthesizer

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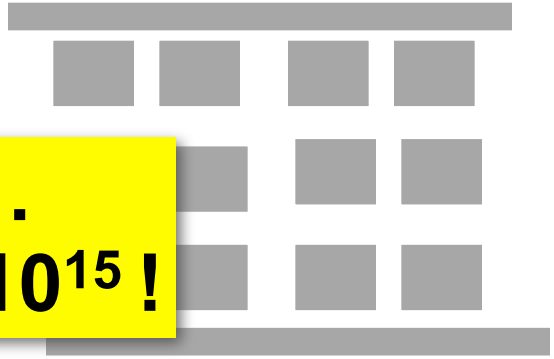

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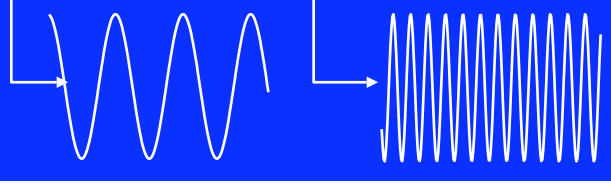


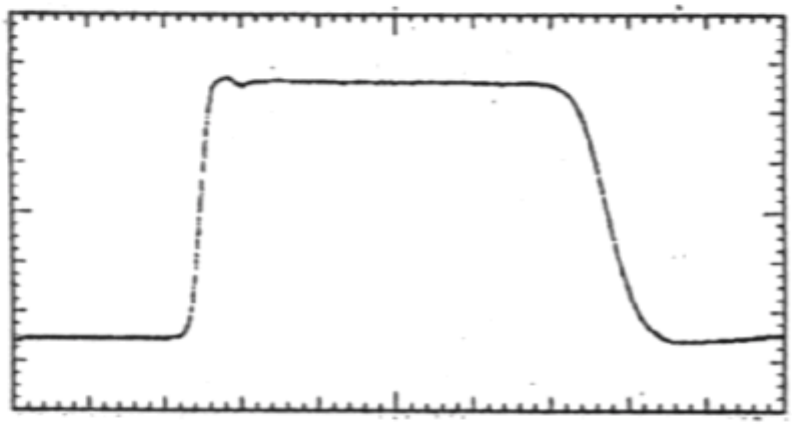
850 nm (352 THz)

microwave pulse generators

Picosecond Pulse Labs 2600C

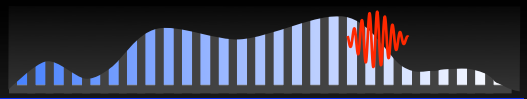
specifications

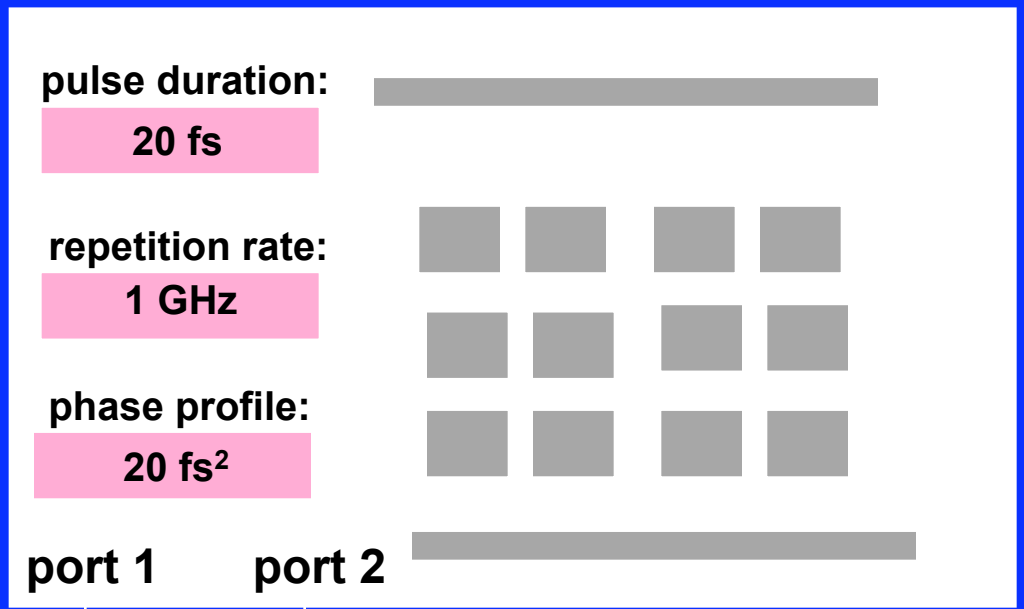
rise time 250 ps
dynamic range 70 dB
pulse duration 1 ns to 100 nsec
repetition rate 1 Hz – 100 kHz

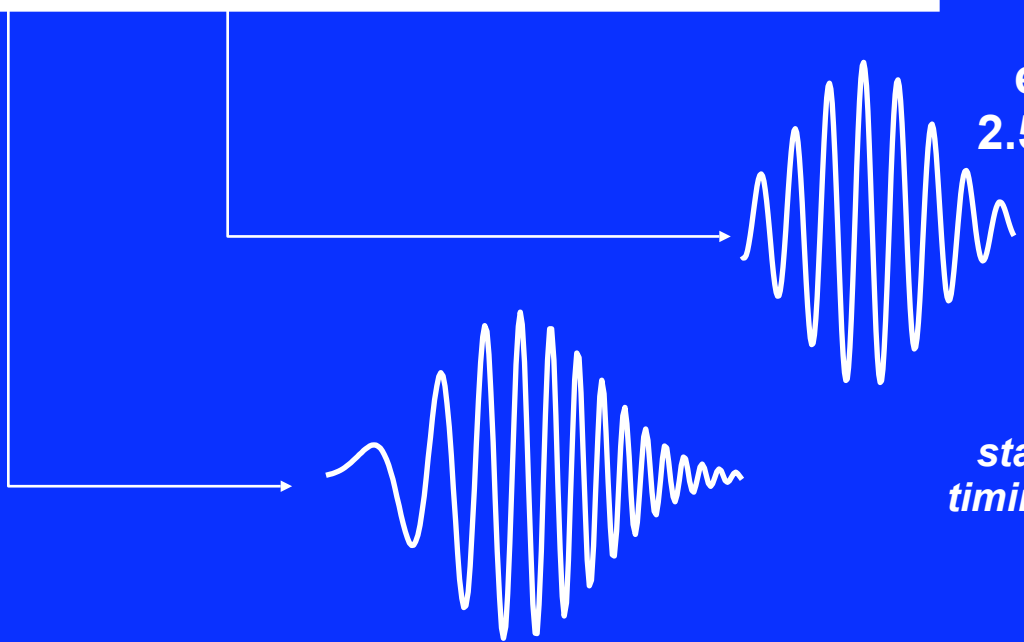


10 V/div and 1 ns/div
Positive Pulse

optical pulse generators?



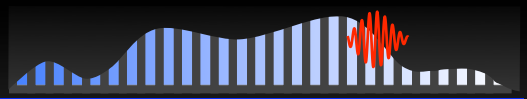




each cycle:
2.5 fs (800 nm)

stabilized combs have subfs timing jitter from pulse-to-pulse

optical pulse generators?



pulse duration:

20 fs

repetition rate:

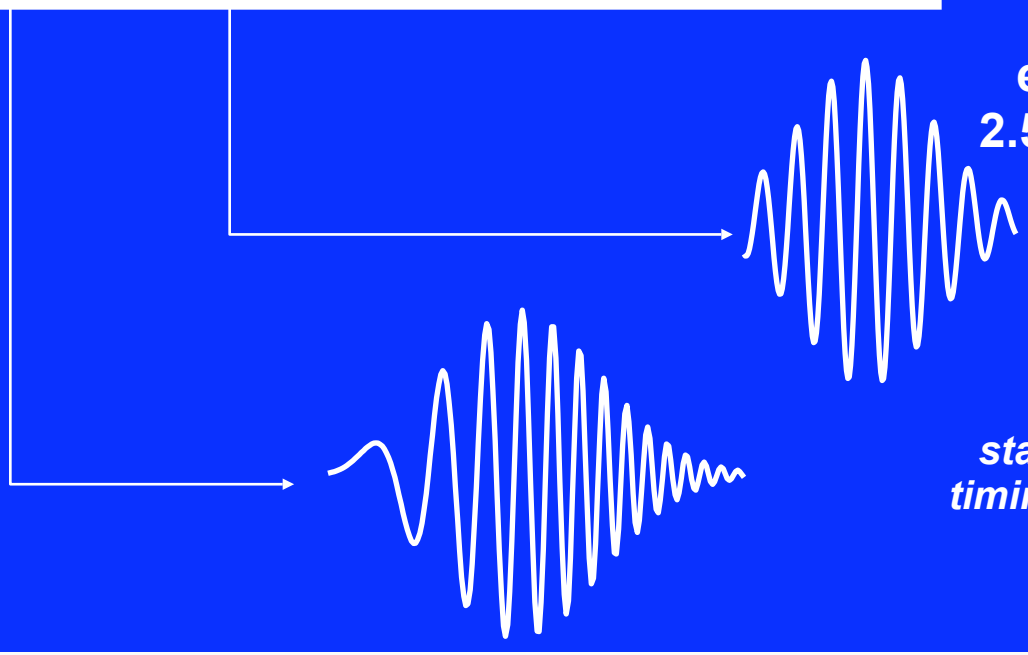
1 GHz

phase profile:

20 fs²

port 1 **port 2**

SUB FEMTOSECOND phase stability !



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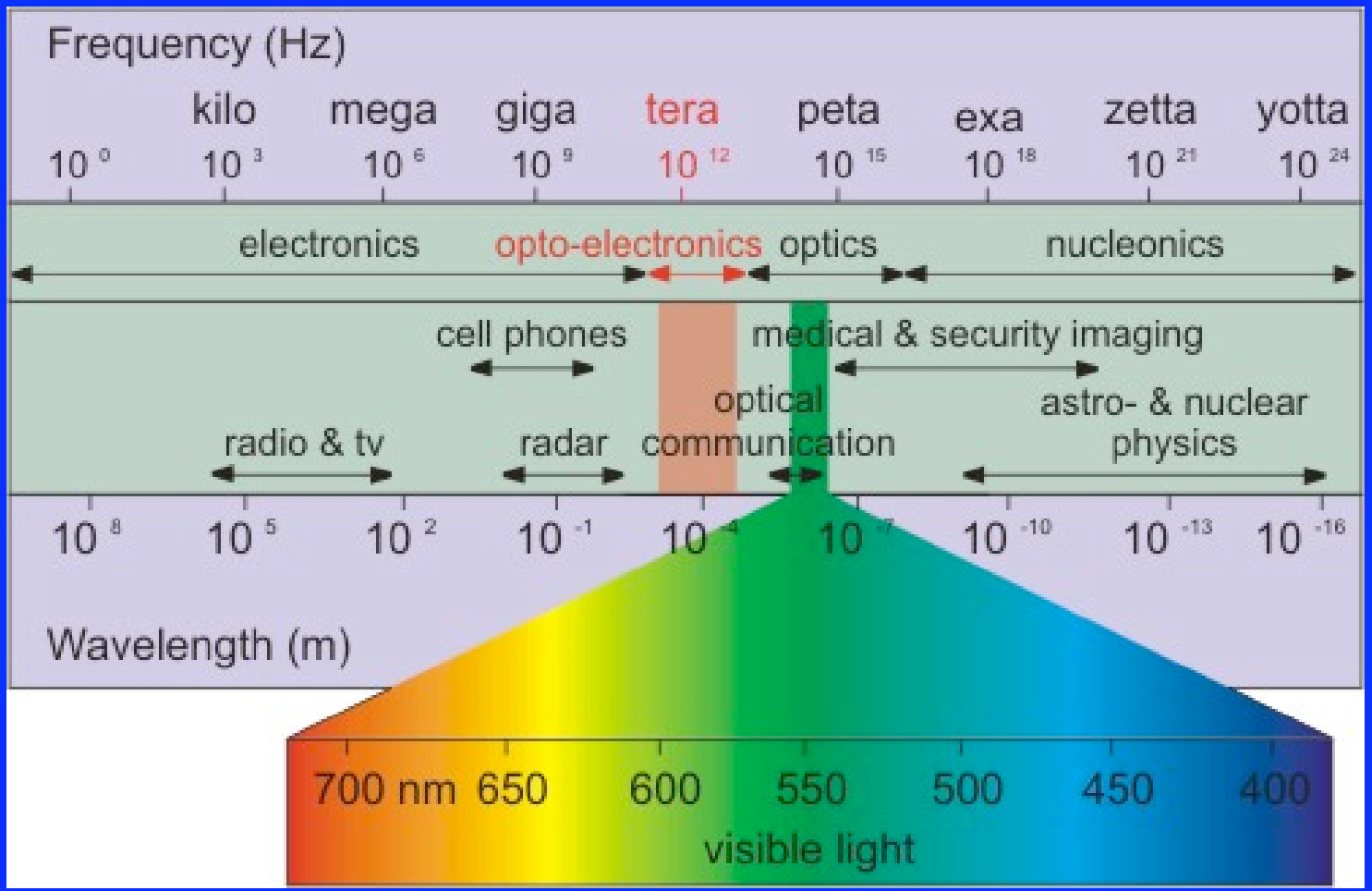
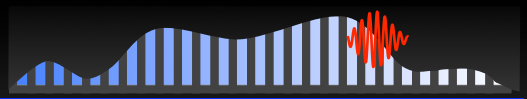
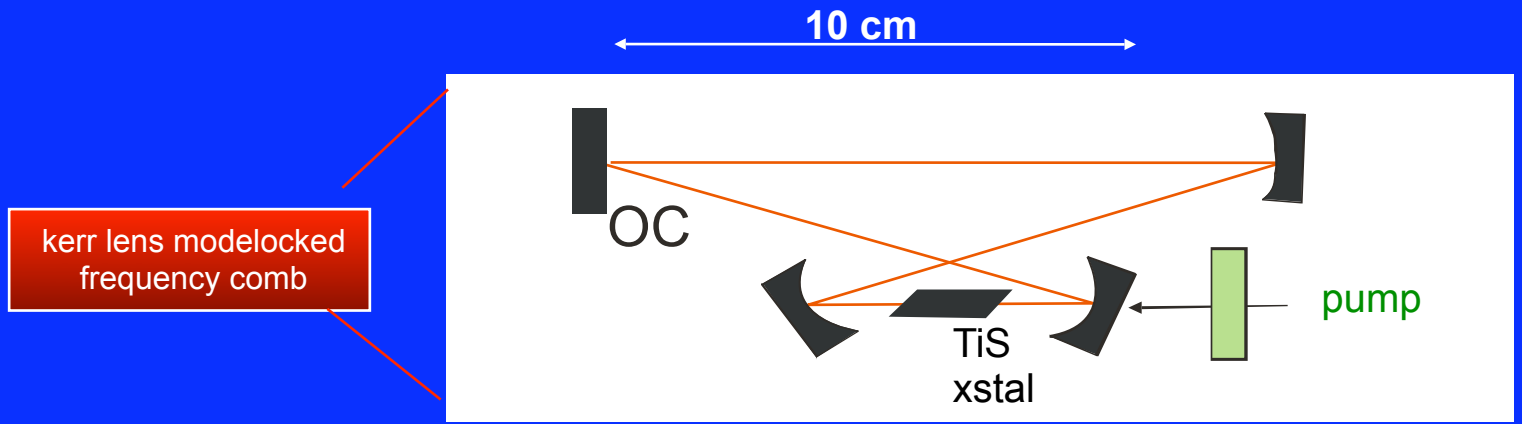
frequency combs are extending our ideas about user-defined frequency sources, *from the microwave to the optical*

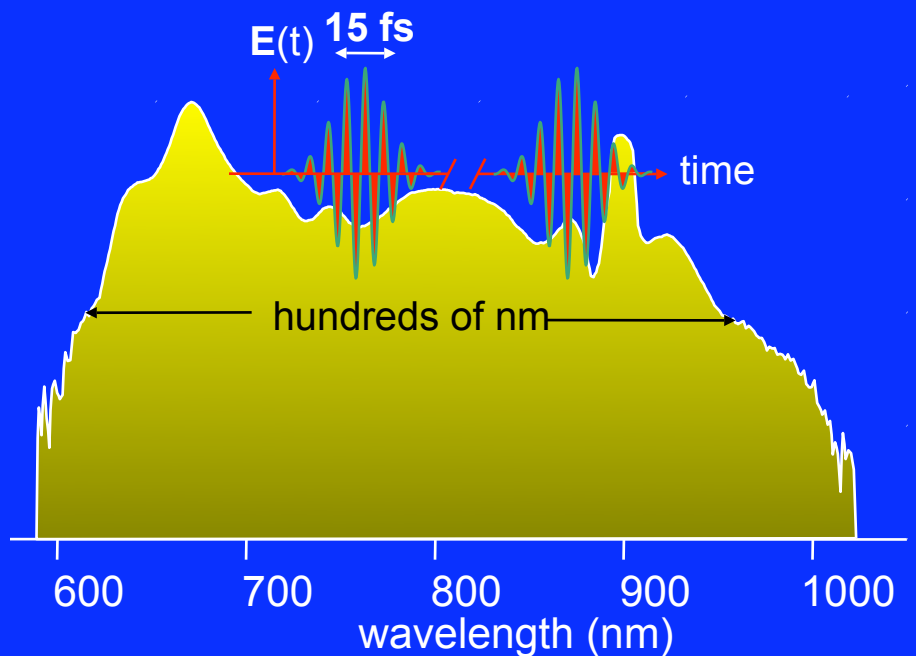


optical spectrum is discrete, appearing every frep





600 mW modelocked power
1 GHz repetition rate pulses
8.5 W pump beam at 532 nm



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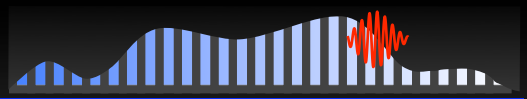

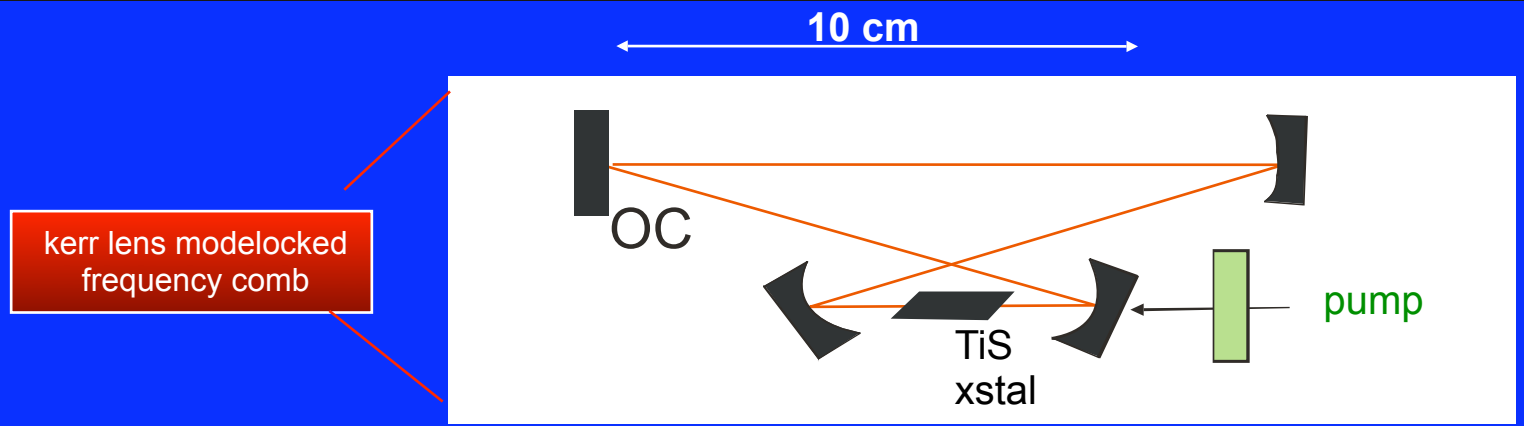

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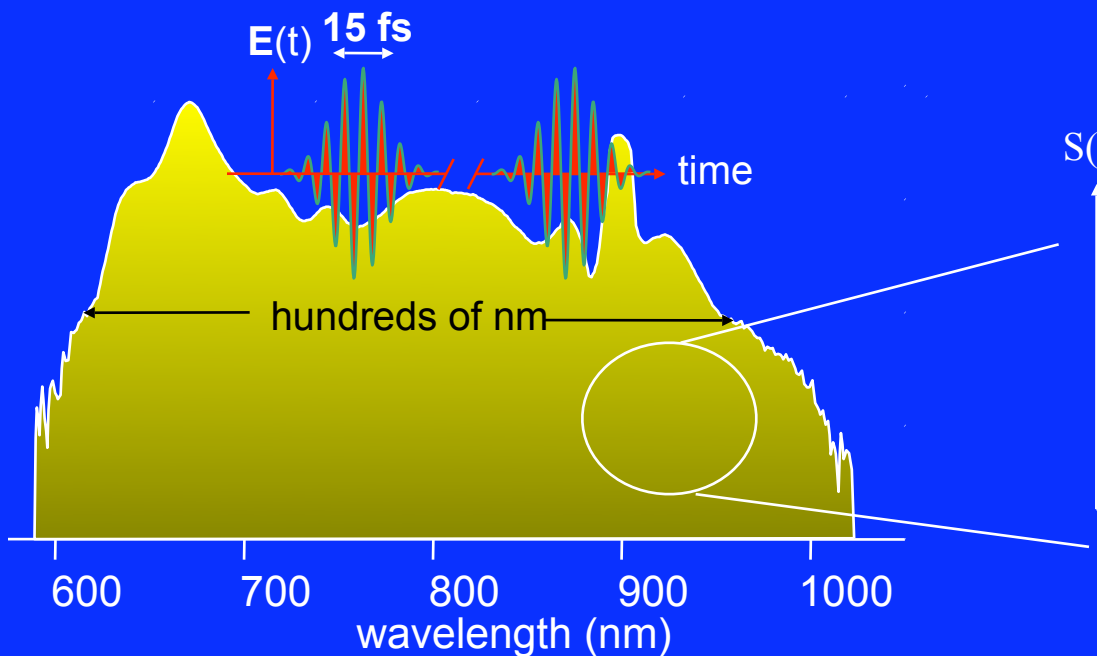

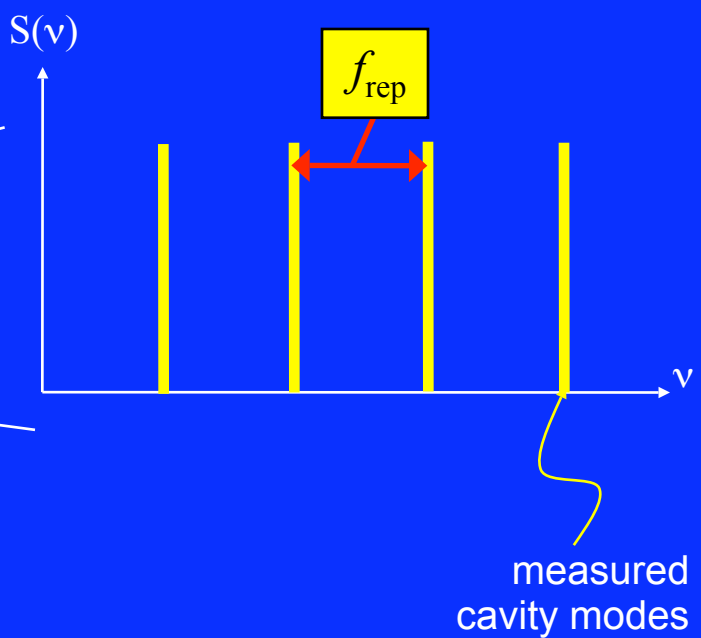

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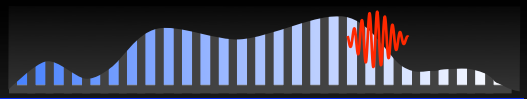

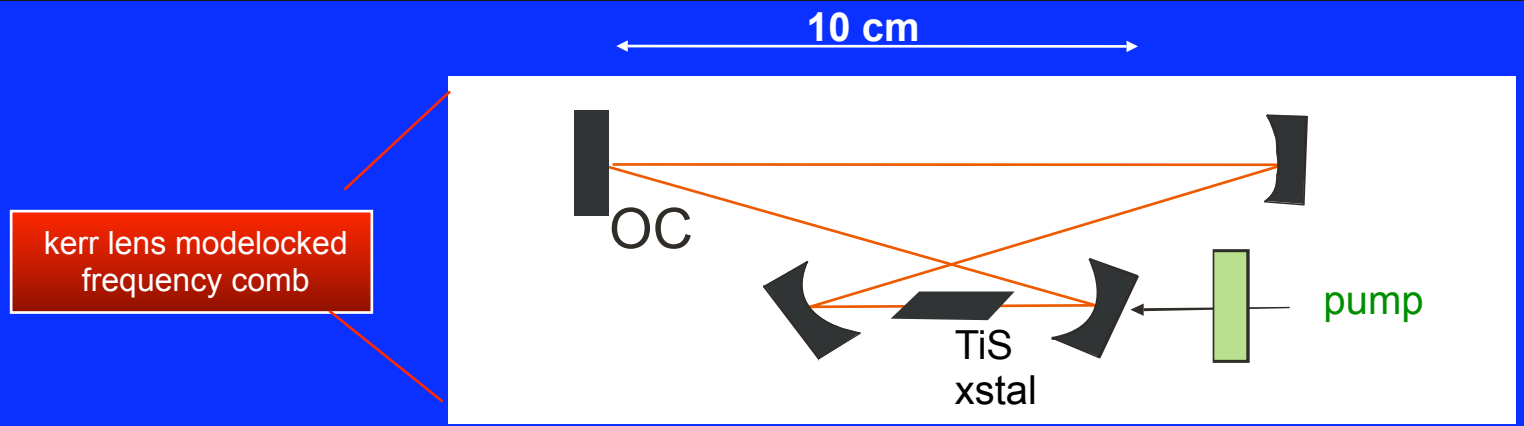

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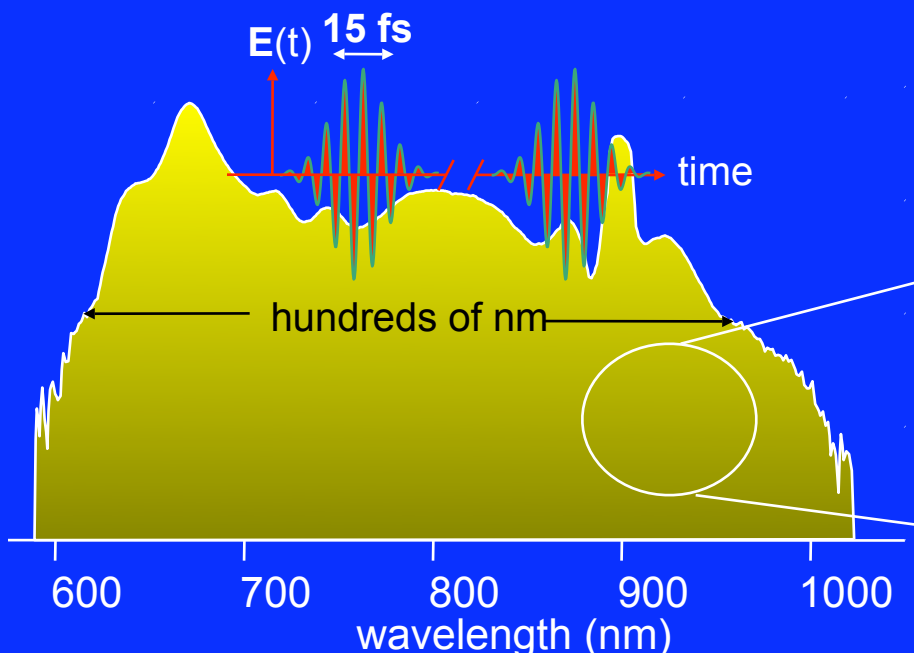

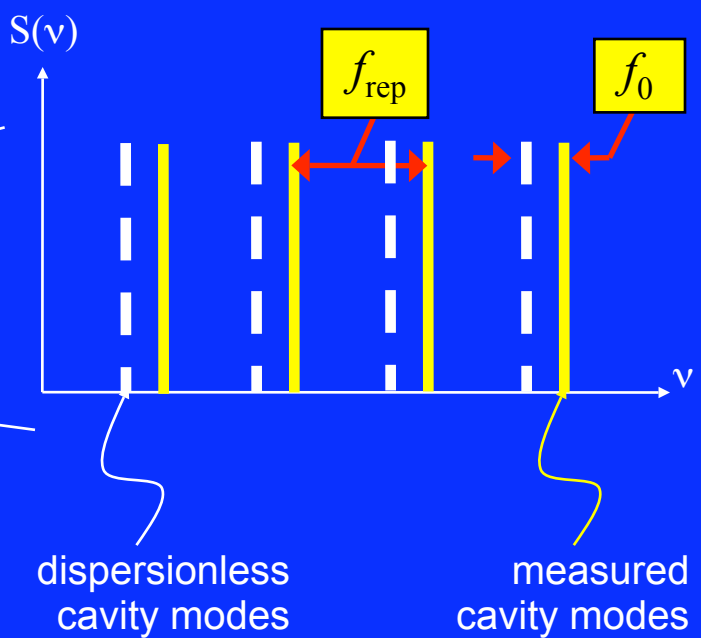

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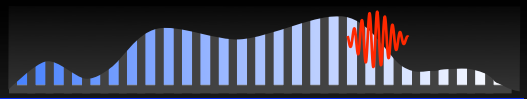

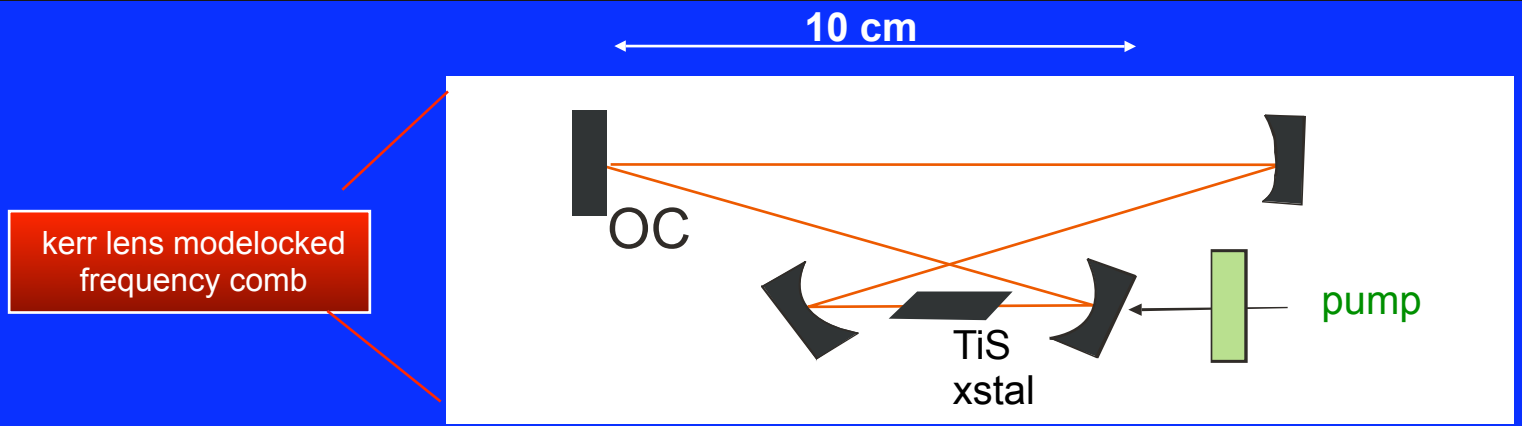

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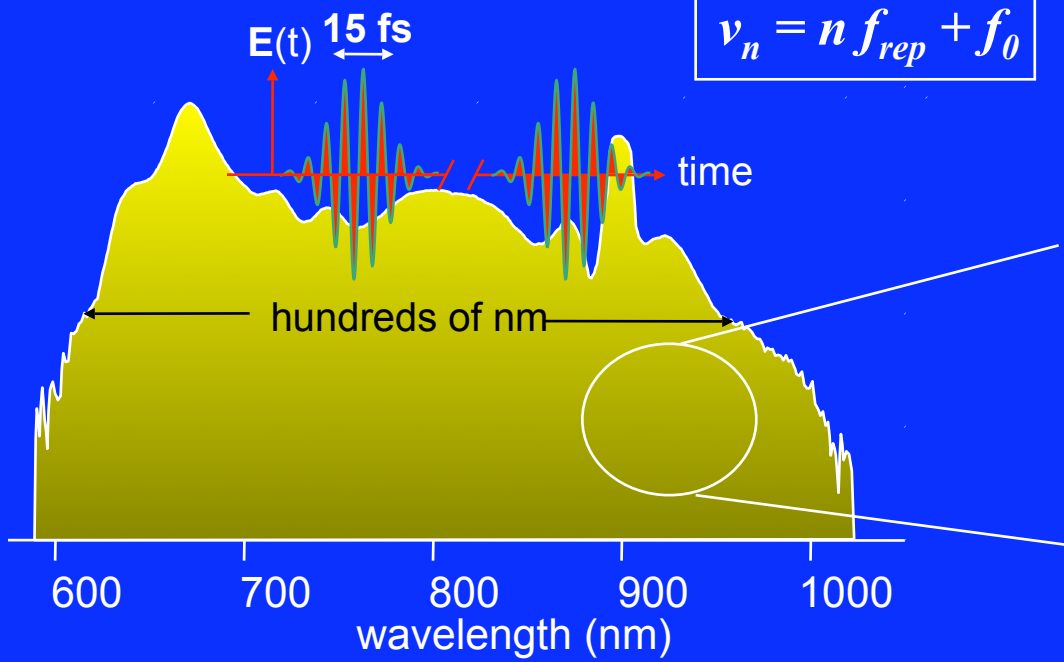
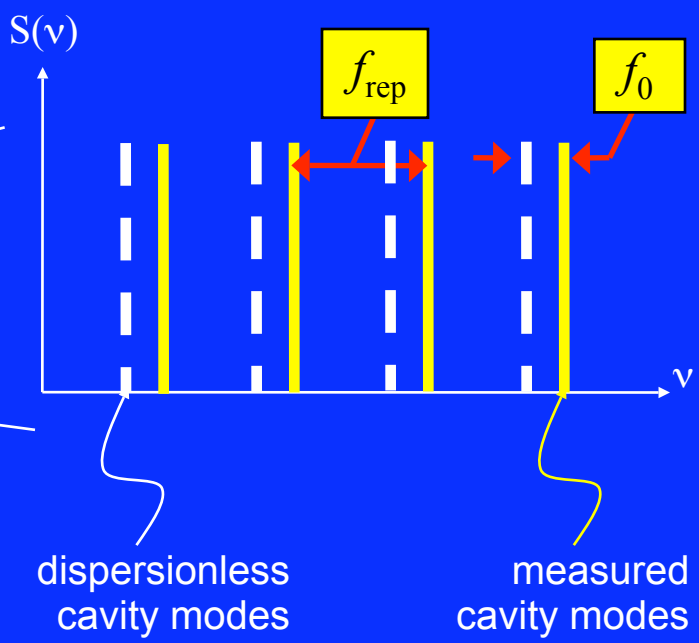
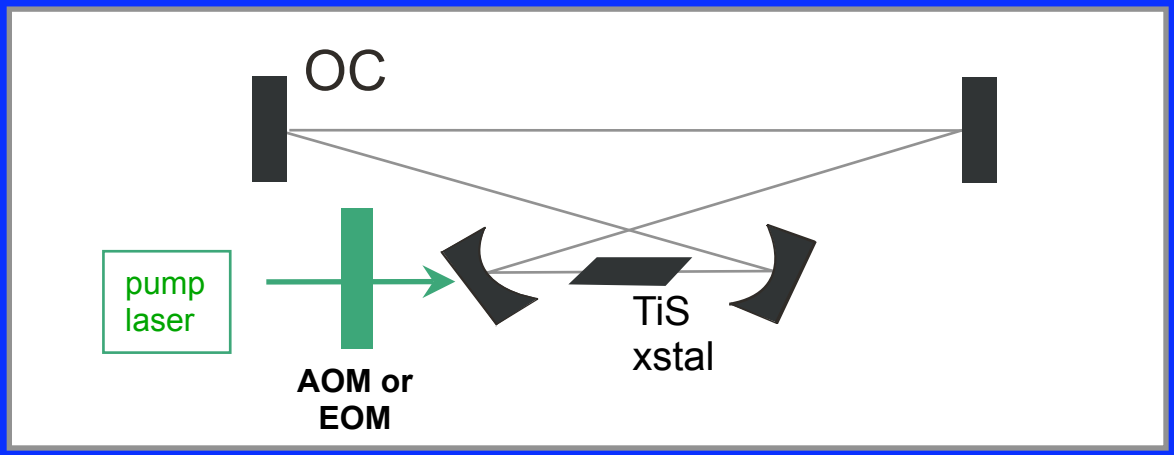
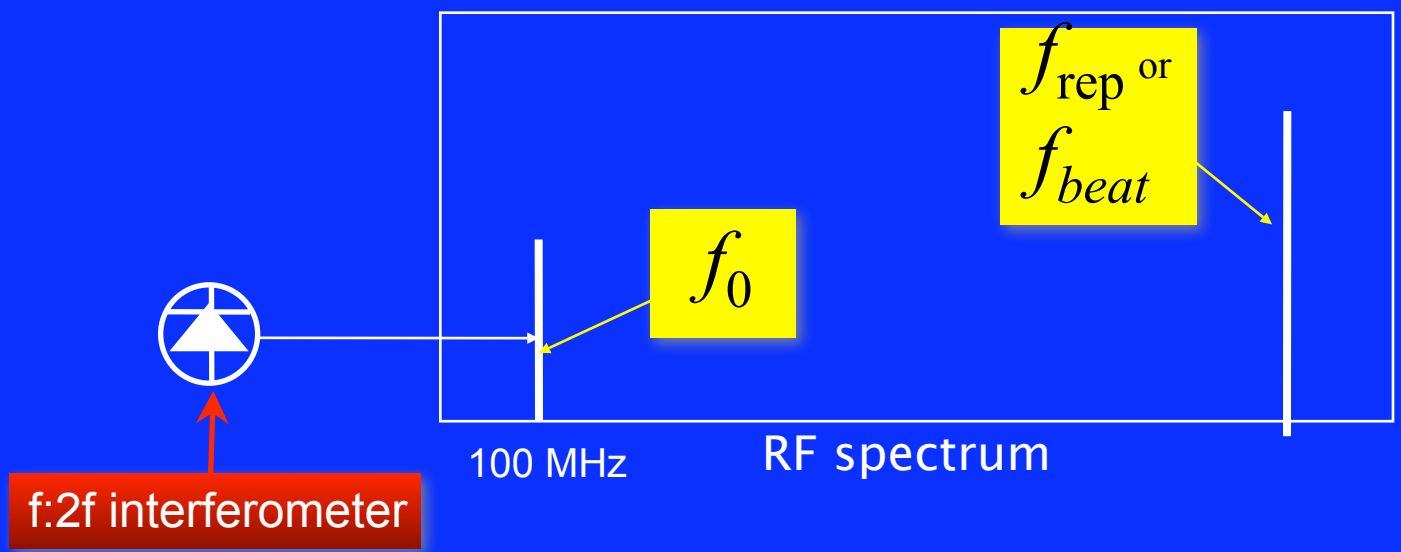




stabilization of optical frequency comb

- offset controlled by modulating pump
- rep. rate or beatnote (with CW laser) controlled with cavity mirror





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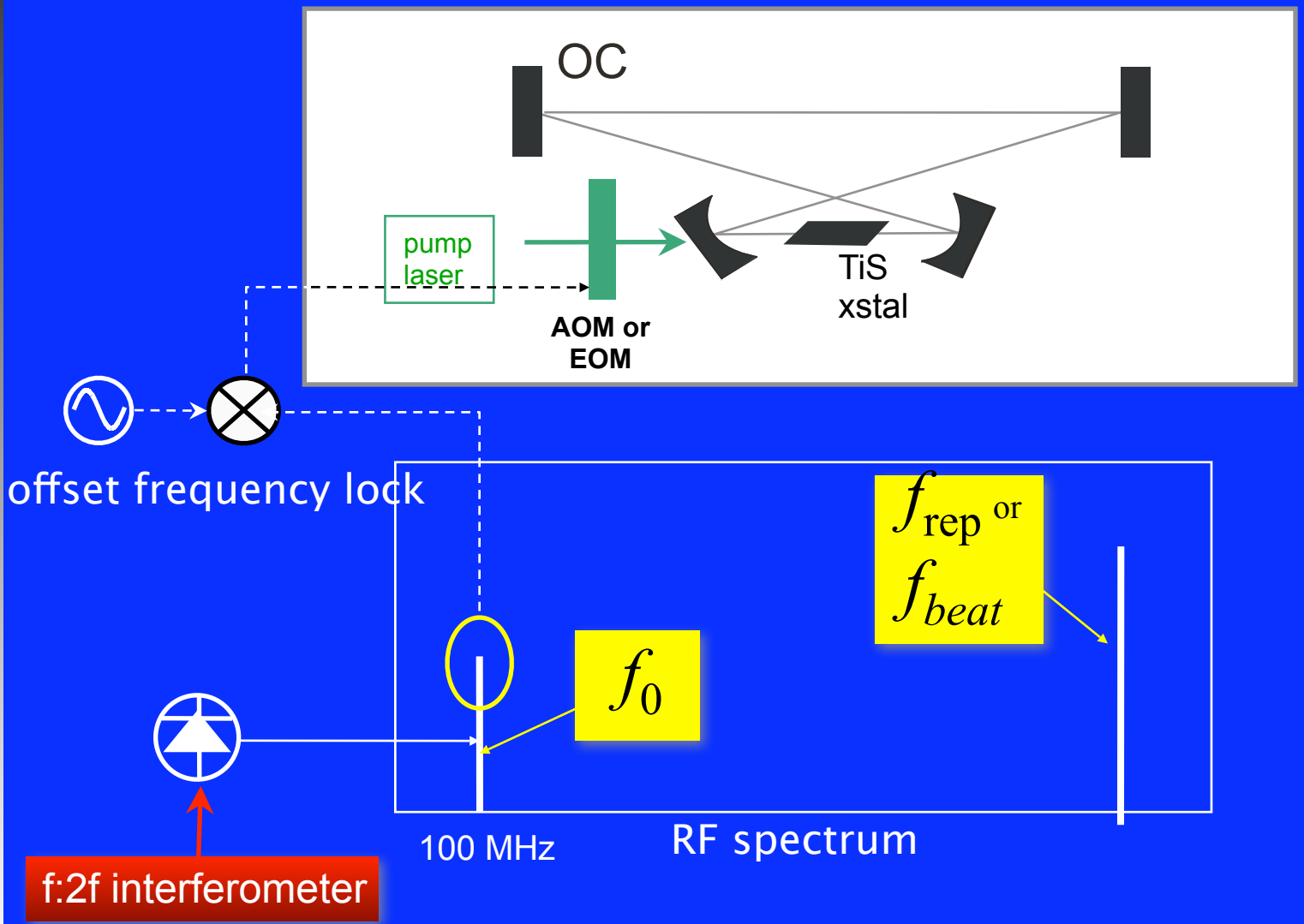

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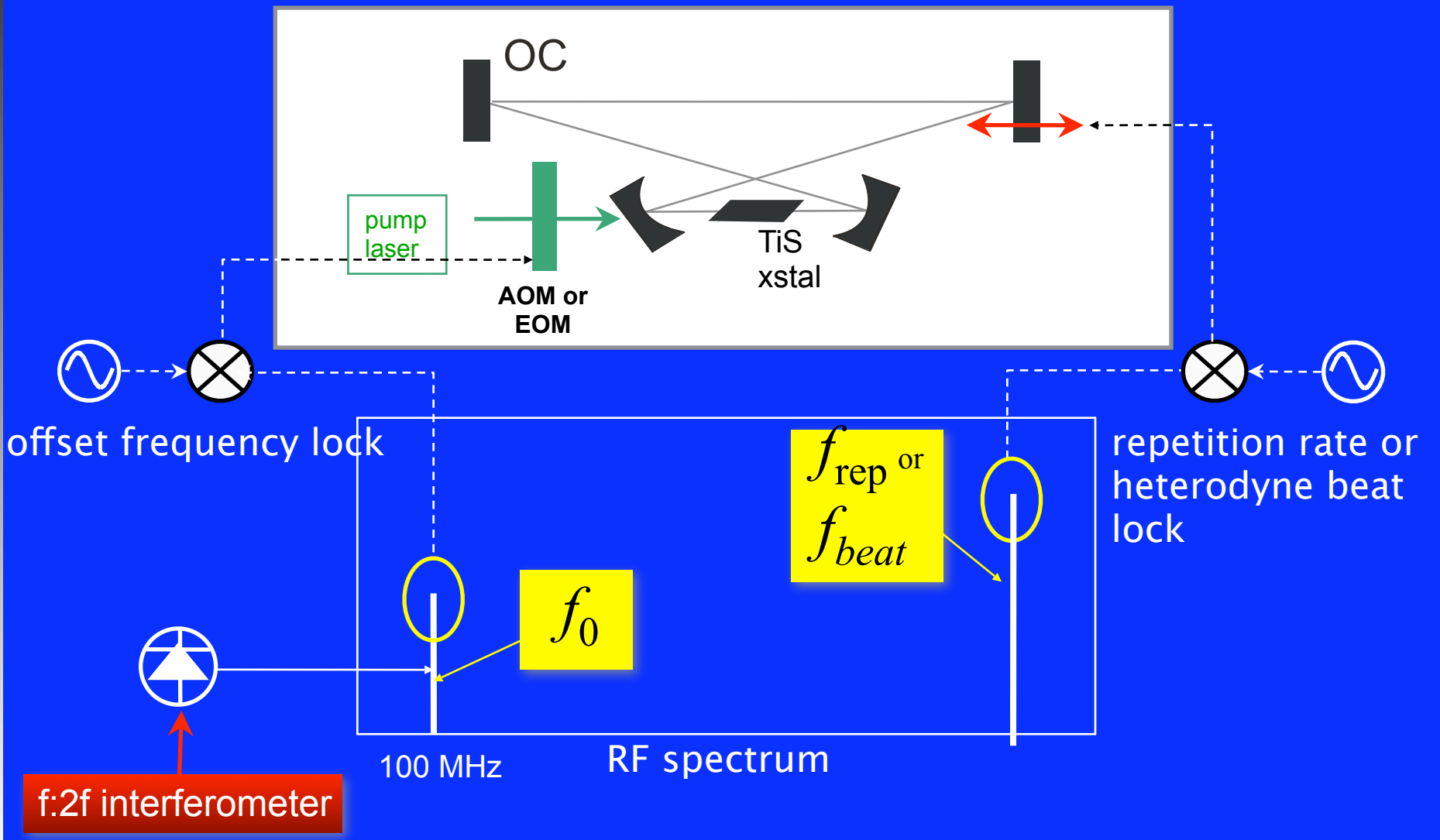
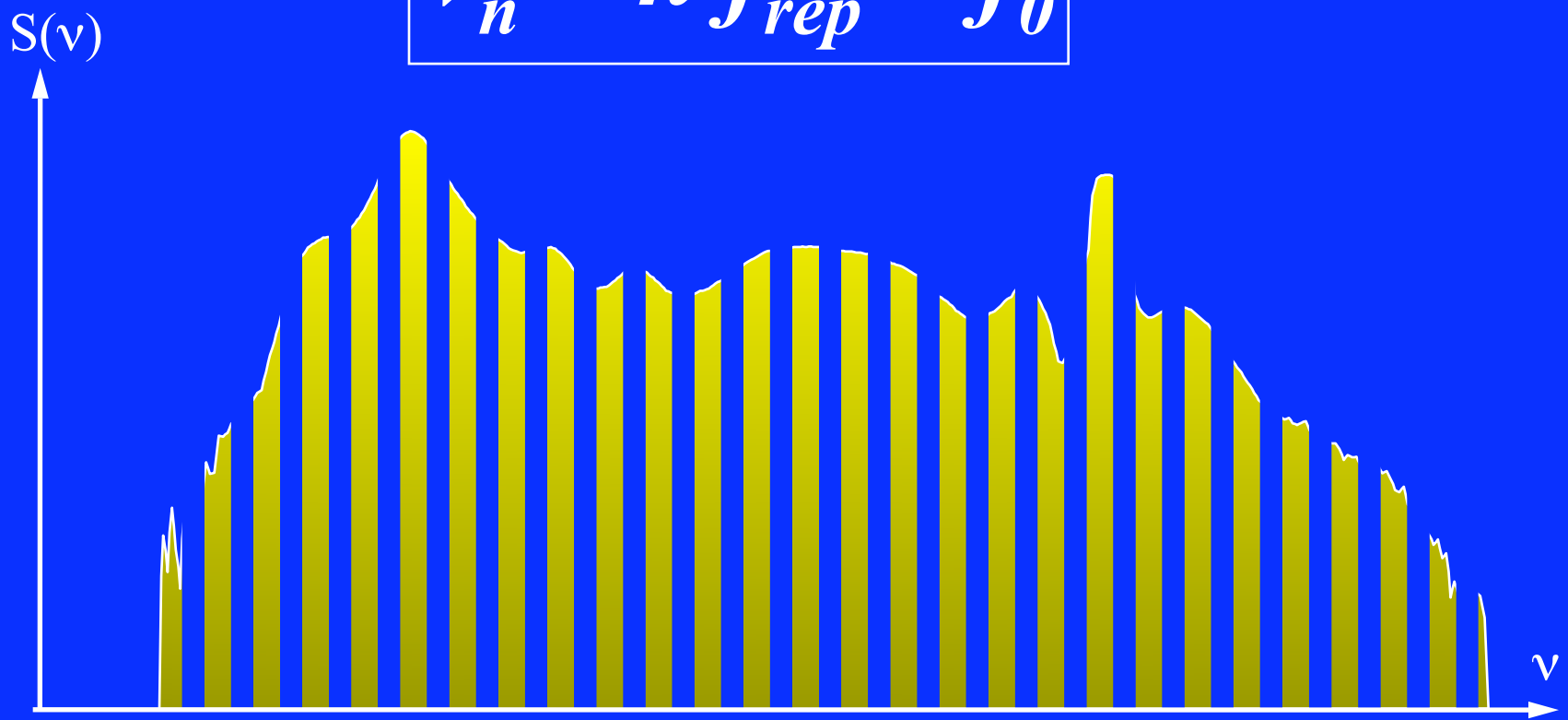


comb equation predicts optical frequencies

$$\nu_n = n f_{rep} + f_0$$



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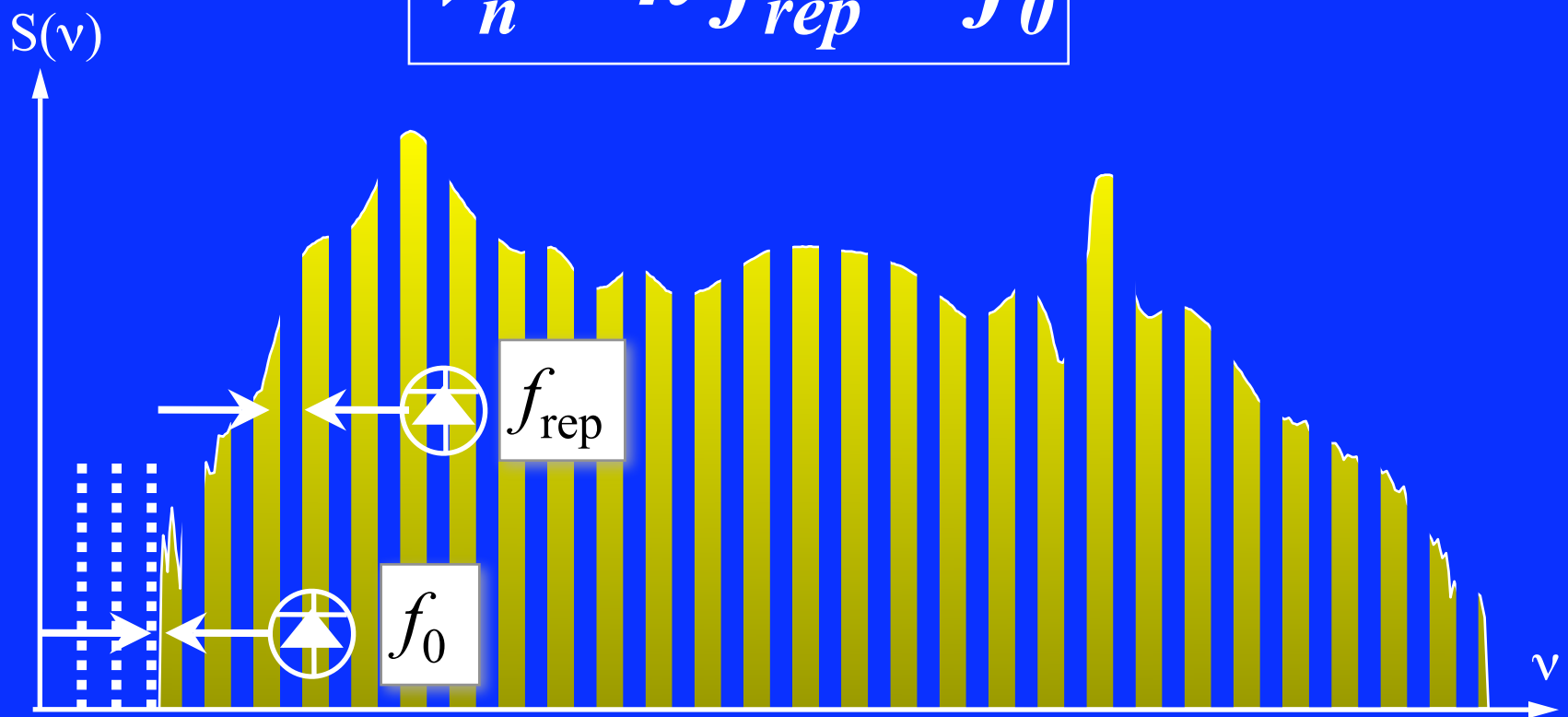

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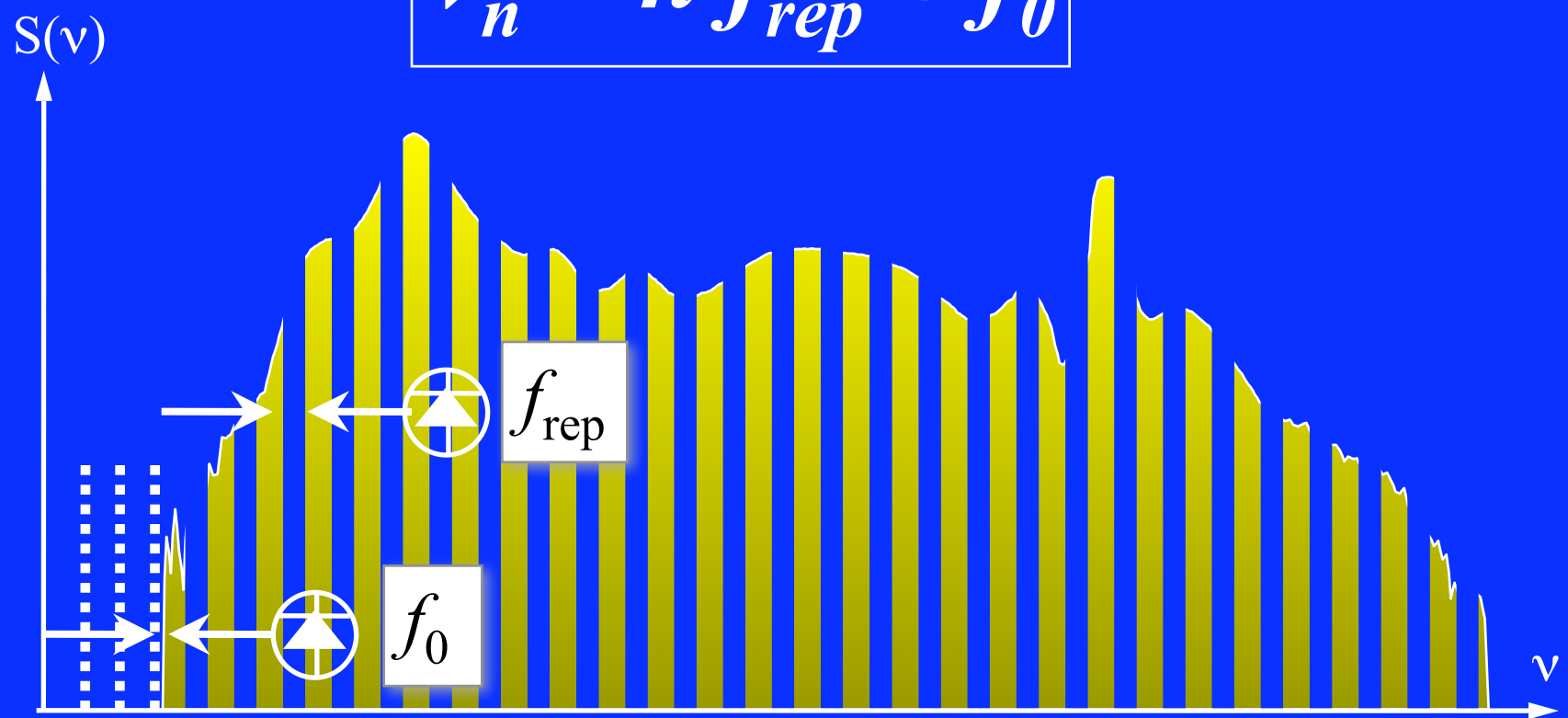
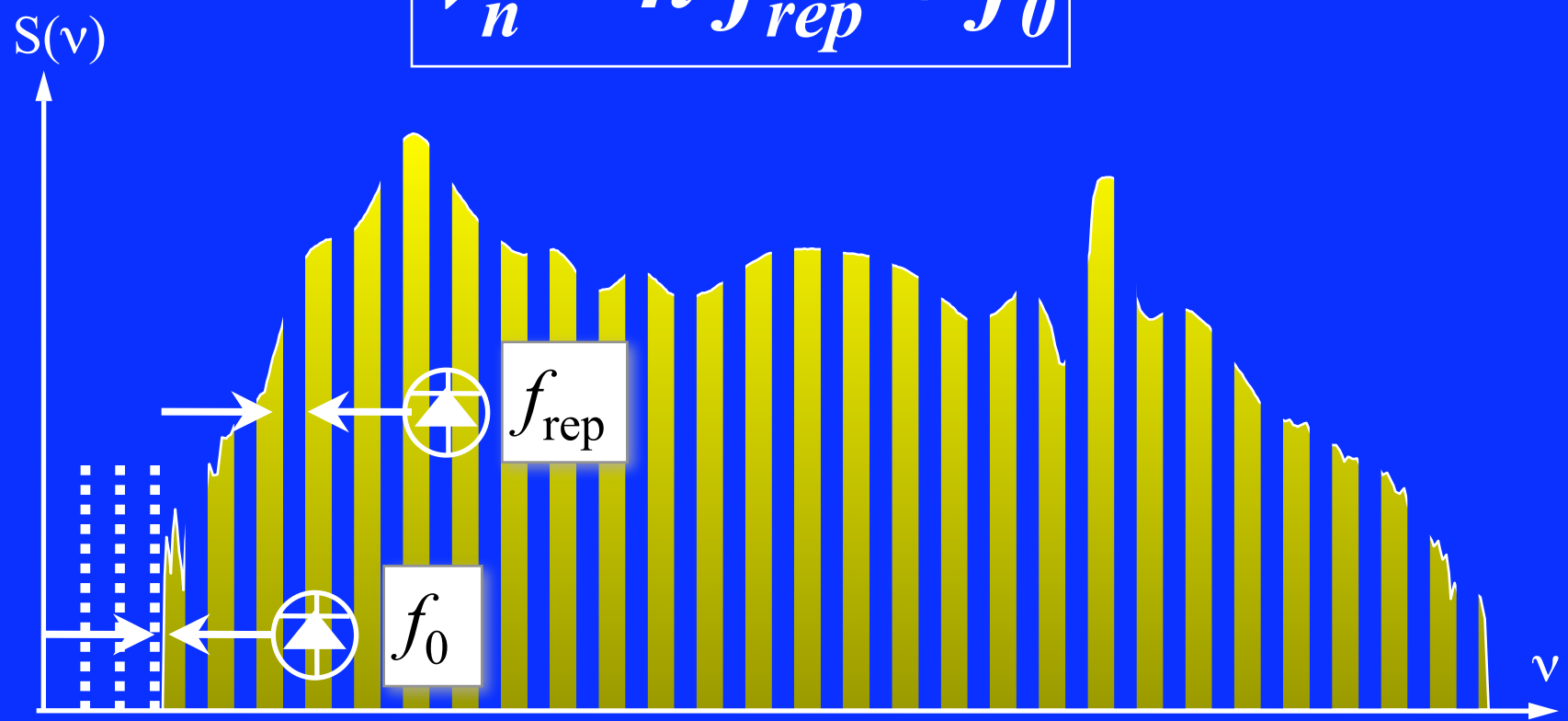


meaning that if I measure:

$f_0 = 120$ MHz

$f_{rep} = 1000$ MHz

$$\nu_n = n f_{rep} + f_0$$



meaning that if I measure:

$f_0 = 120$ MHz

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then I know *all* the optical frequencies:

the n=500,000 mode has a freq. of:

$\nu_n = n f_{rep} + f_0 =$ **5e5(1GHz) + 120 MHz**

= 500,000,120,000,000 Hz

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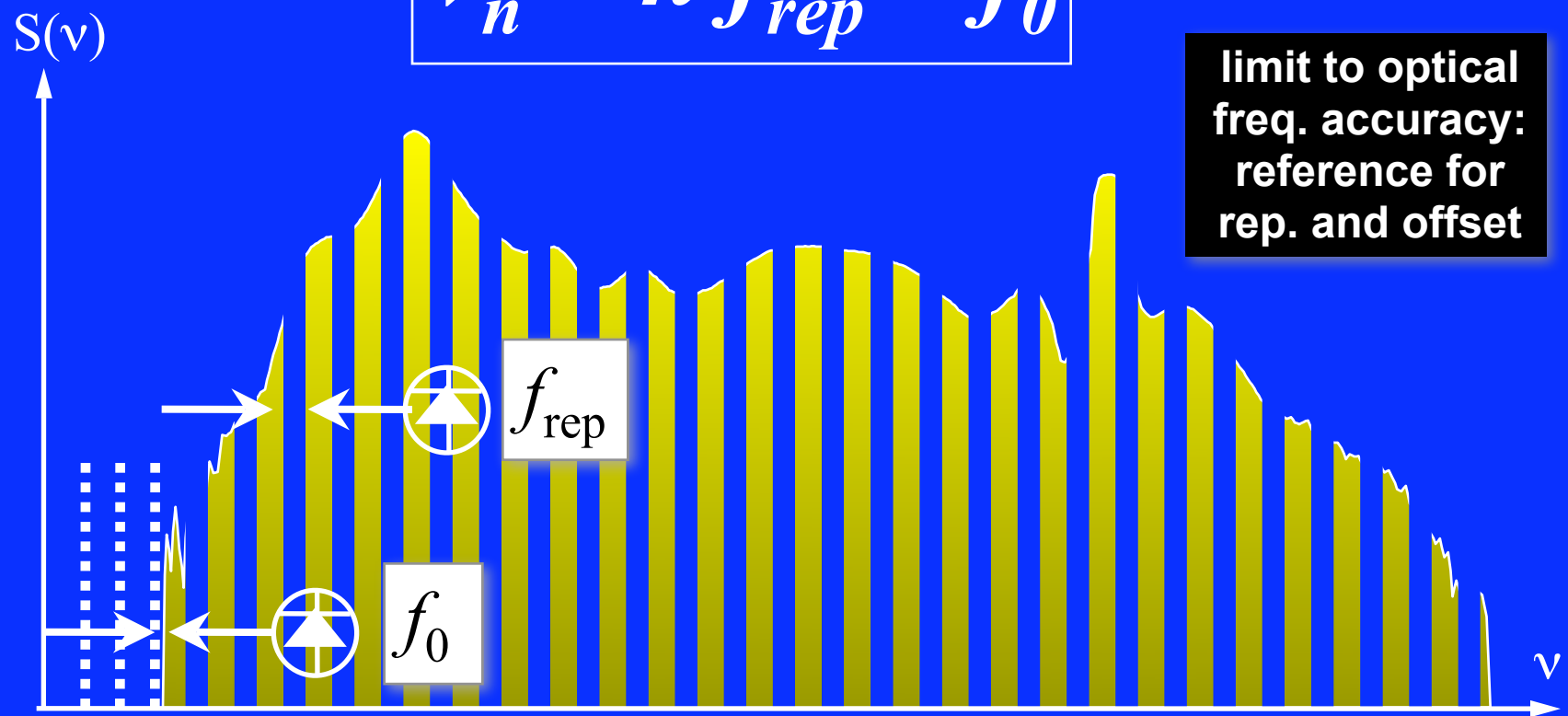

limit to optical freq. accuracy: reference for rep. and offset

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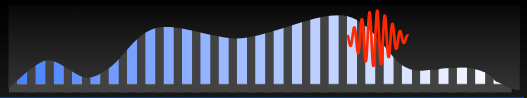
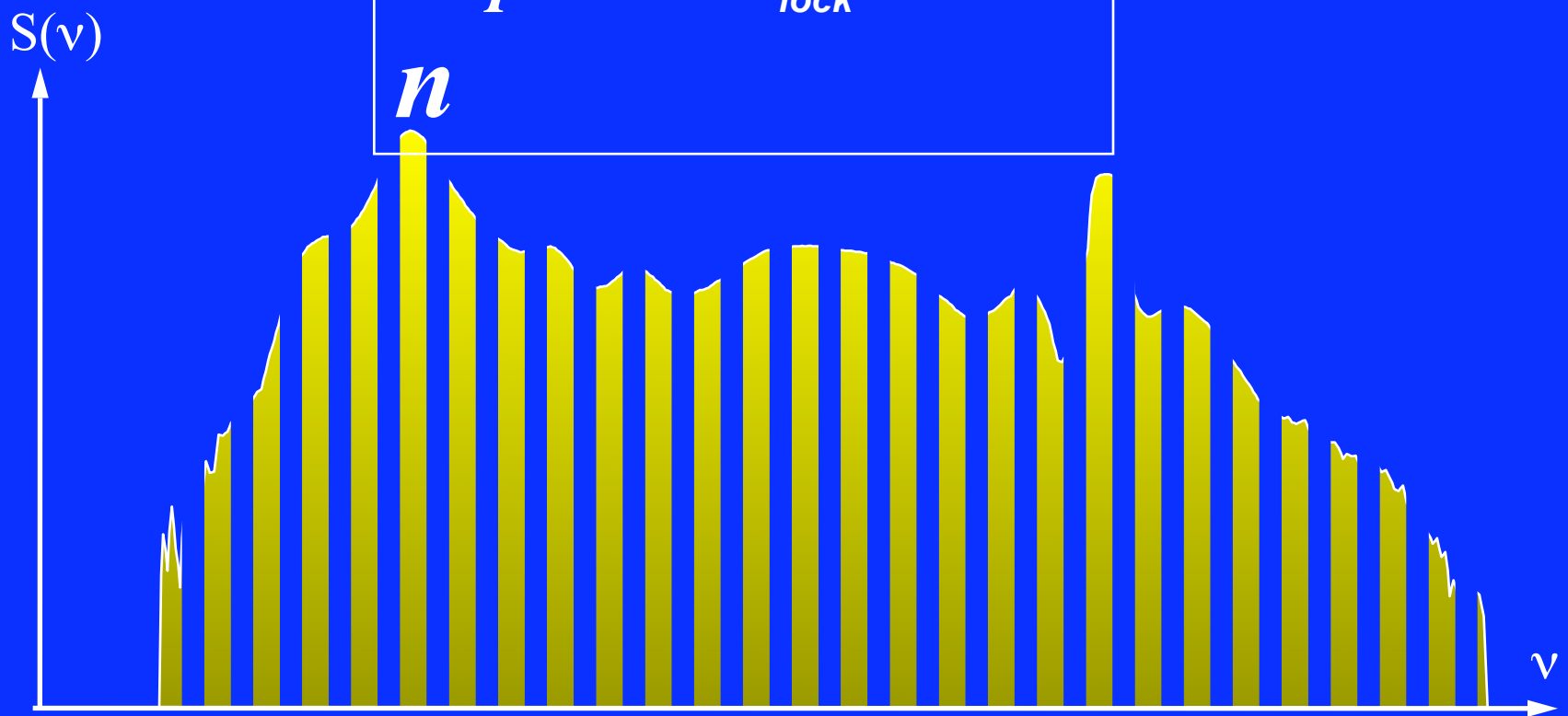


…on the other hand…

…we can extract microwave signals from stabilized combs.

comb equation predicts optical frequencies

$$f_{rep} = (\nu_{n\,lock} + f_0)/n$$



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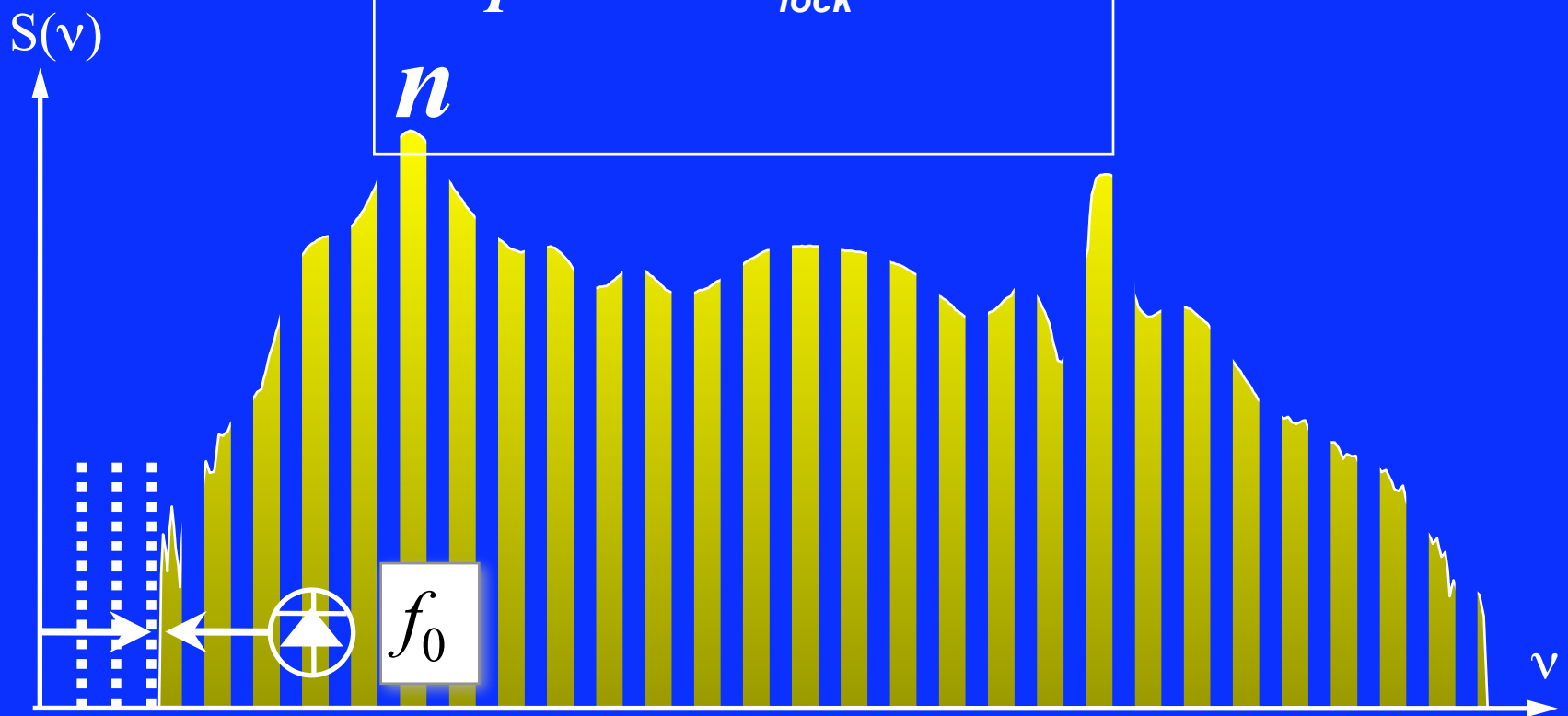

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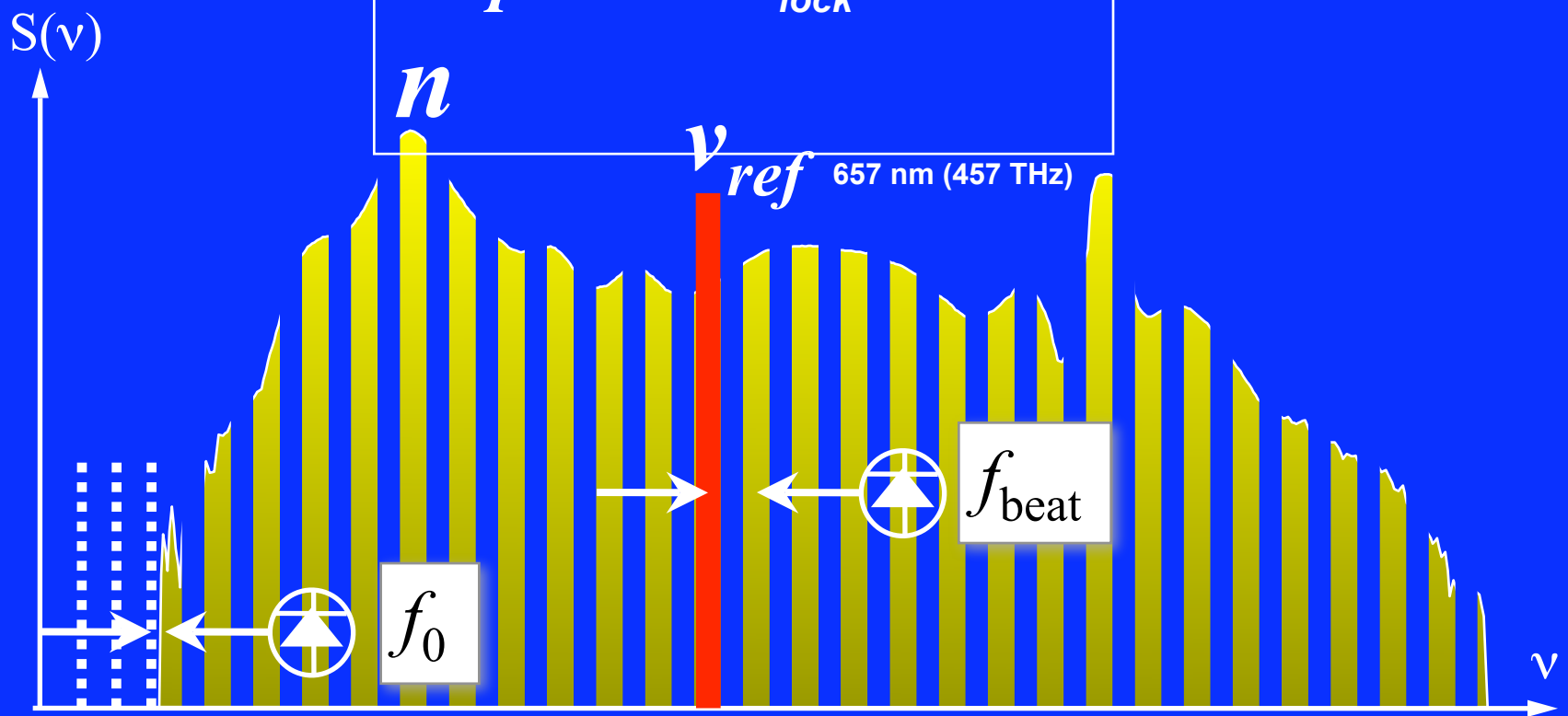
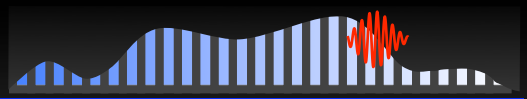
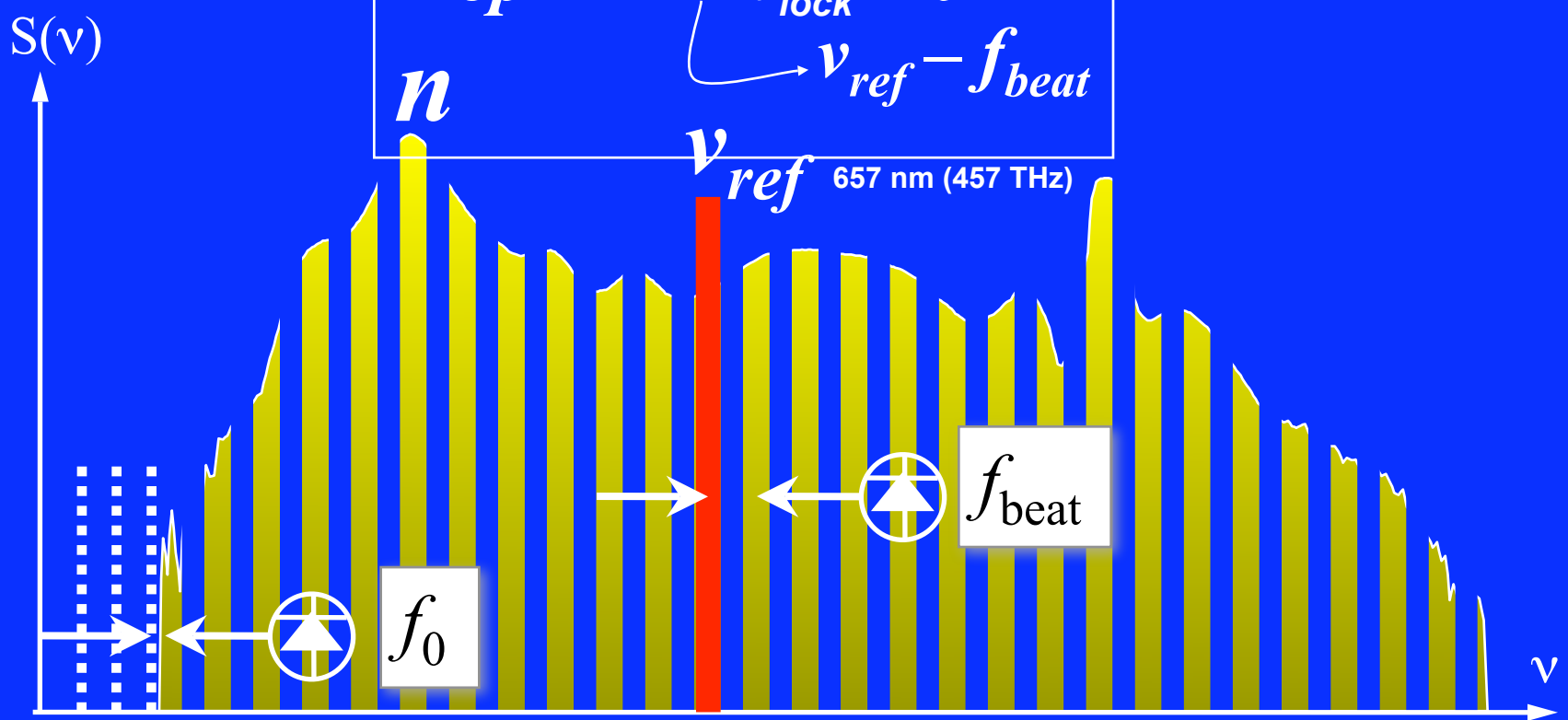


comb equation predicts optical frequencies



$$f_{rep} = (\nu_{n_{lock}} + f_0)/n \qquad \nu_{ref} - f_{beat}$$



$$f_{rep} = (\nu_{n_{lock}} + f_0)/n$$

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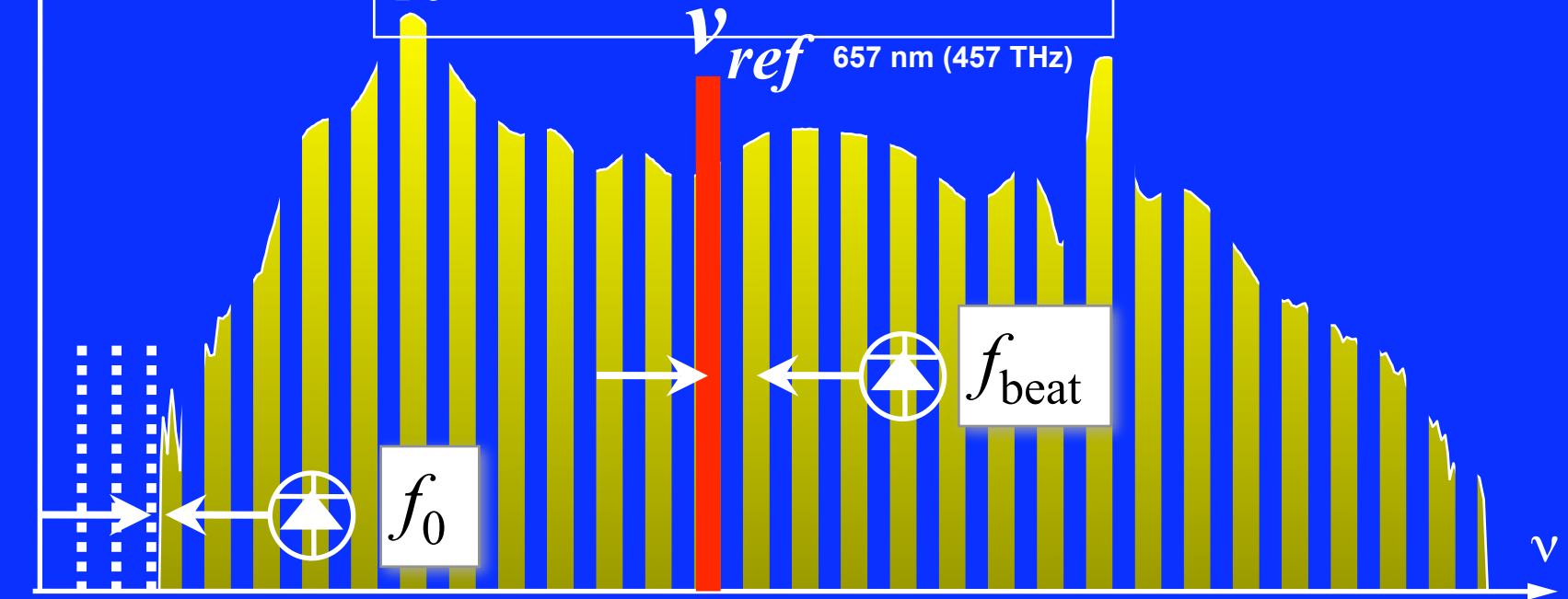


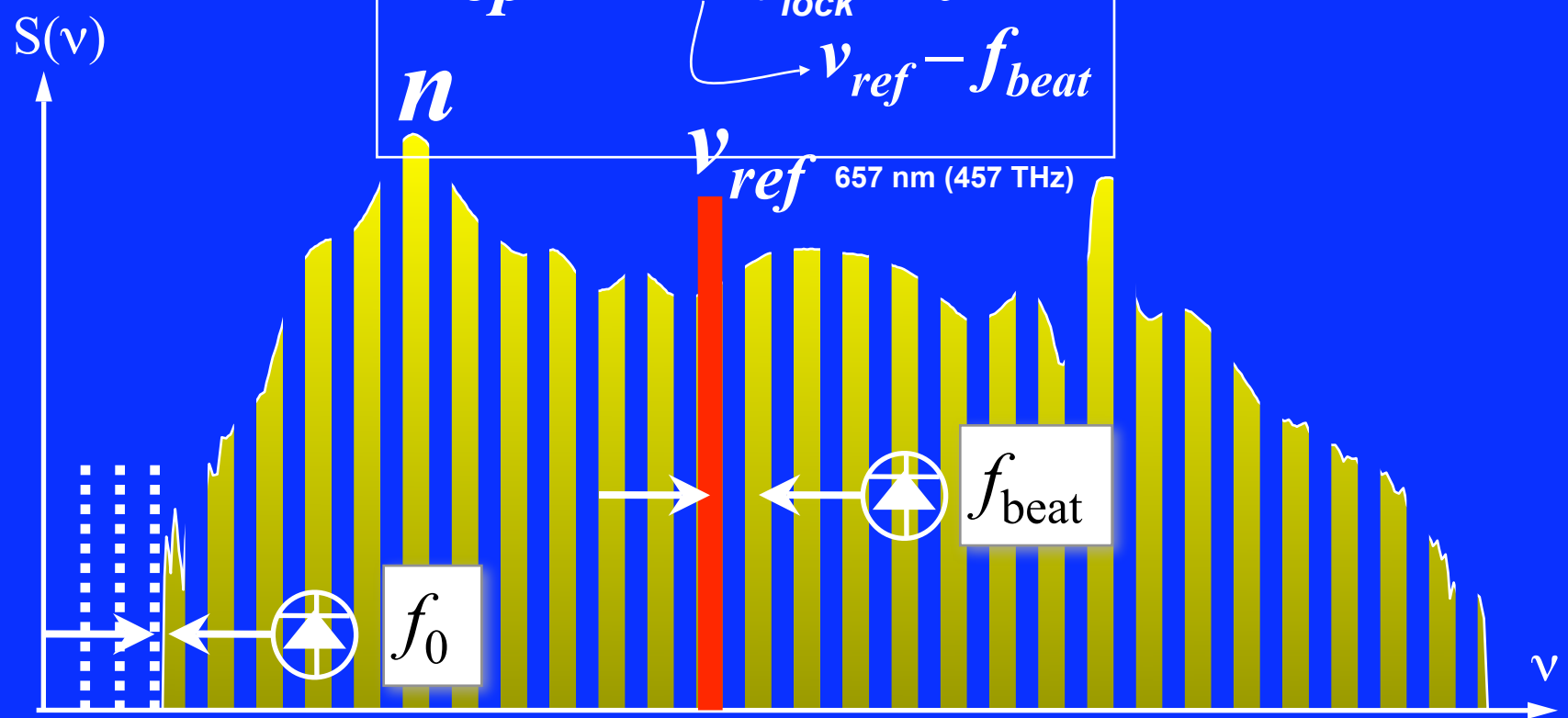
meaning that if I measure:

$f_0 = 120$ MHz

$f_{beat} = 300$ MHz

comb equation predicts optical frequencies

$$f_{rep} = (\nu_n + f_0)/n \qquad \nu_n \text{ lock} \rightarrow \nu_{ref} - f_{beat}$$



meaning that if I measure:

$f_0 = 120$ MHz

$f_{beat} = 300$ MHz

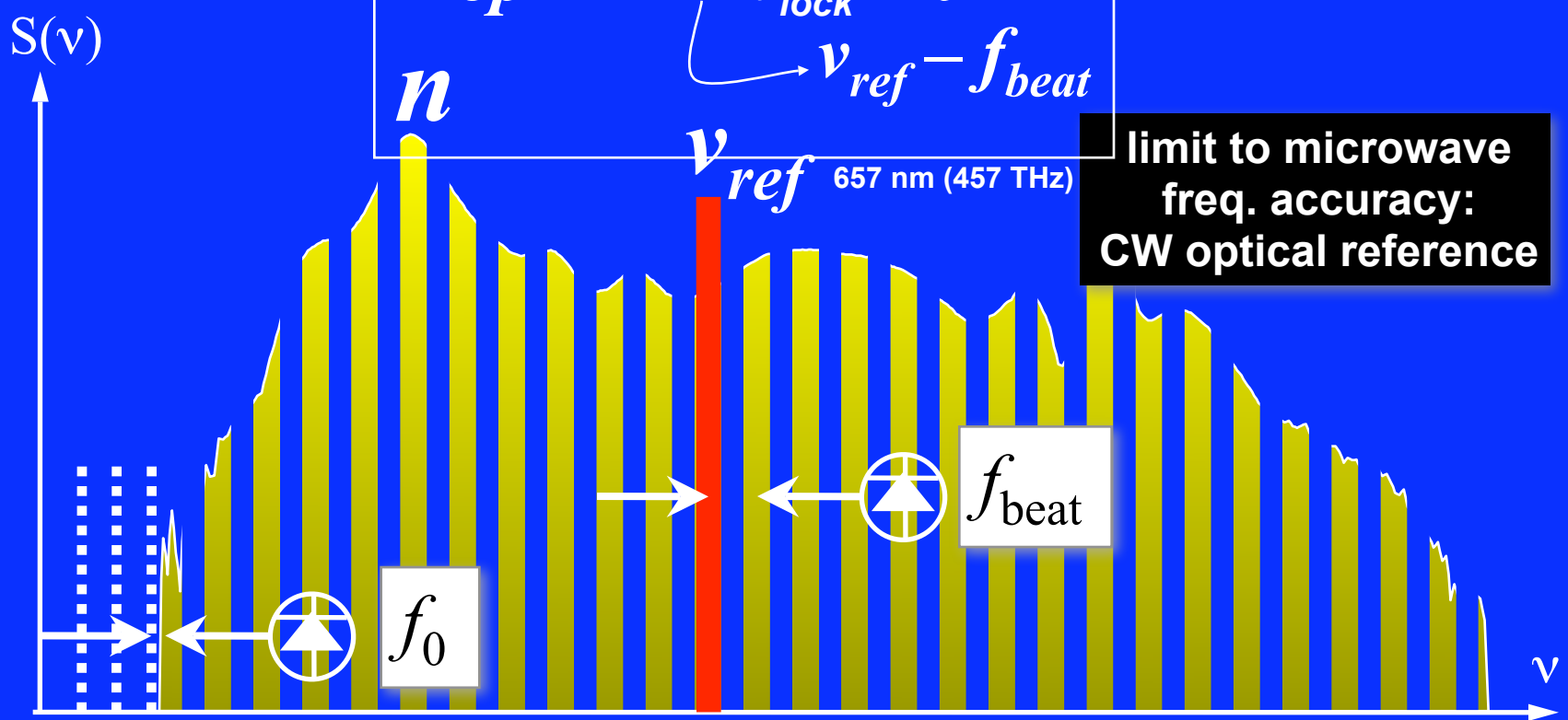
then I know *all* the microwave frequencies:

the n=500,000 divided mode is:

f_{rep} = (457e12 – 300 MHz – 120 MHz)/n

= 914 MHz (this moves with CW reference say, 1 Hz per second)

$$f_{rep} = (\nu_n + f_0)/n \qquad \nu_n \text{ lock} \rightarrow \nu_{ref} - f_{beat}$$



limit to microwave freq. accuracy: CW optical reference

meaning that if I measure:

$f_0 = 120$ MHz

$f_{beat} = 300$ MHz

then I know *all* the microwave frequencies:

the n=500,000 divided mode is:

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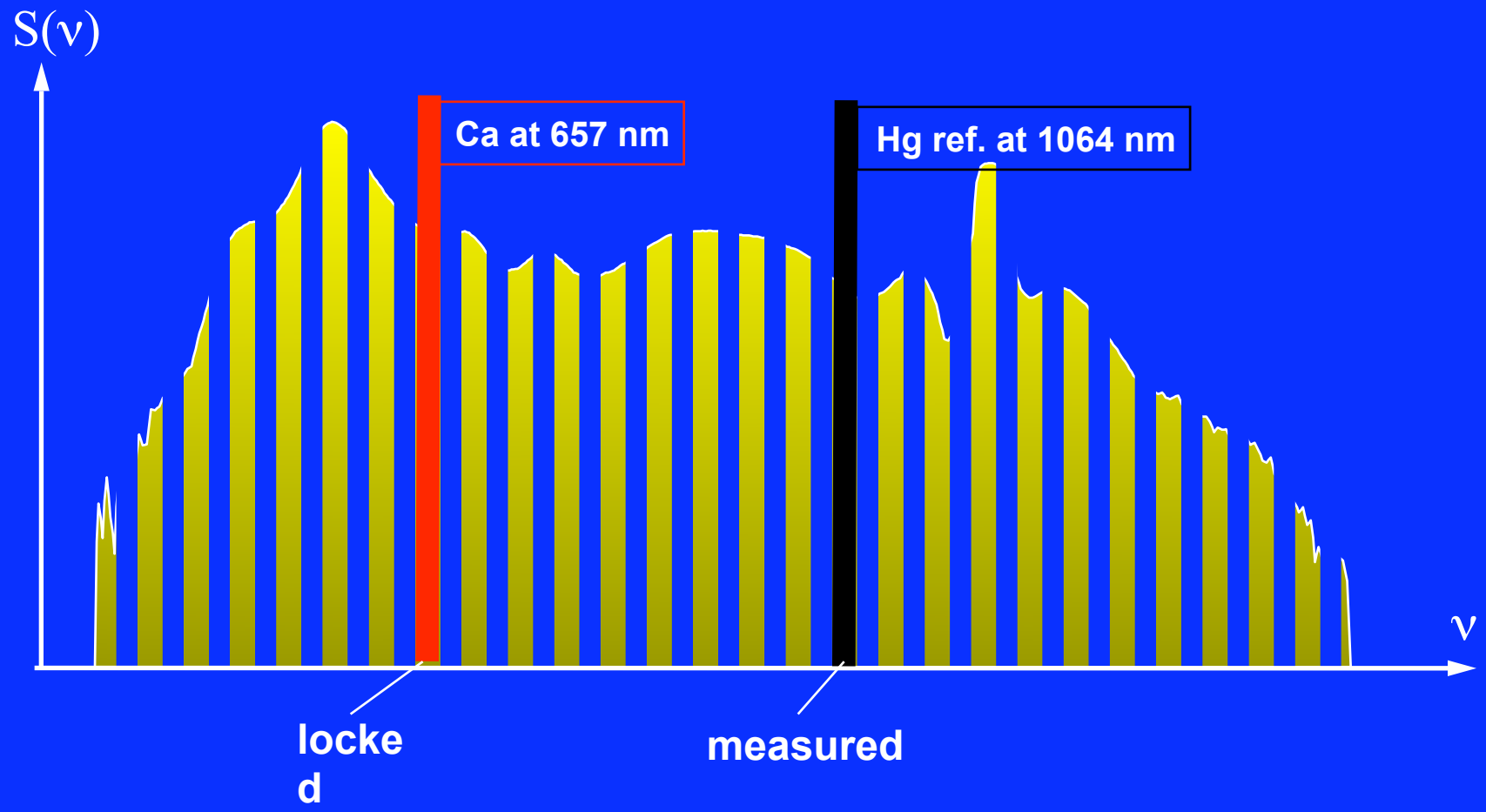
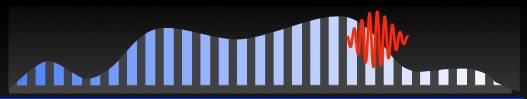
comb equation predicts optical frequencies

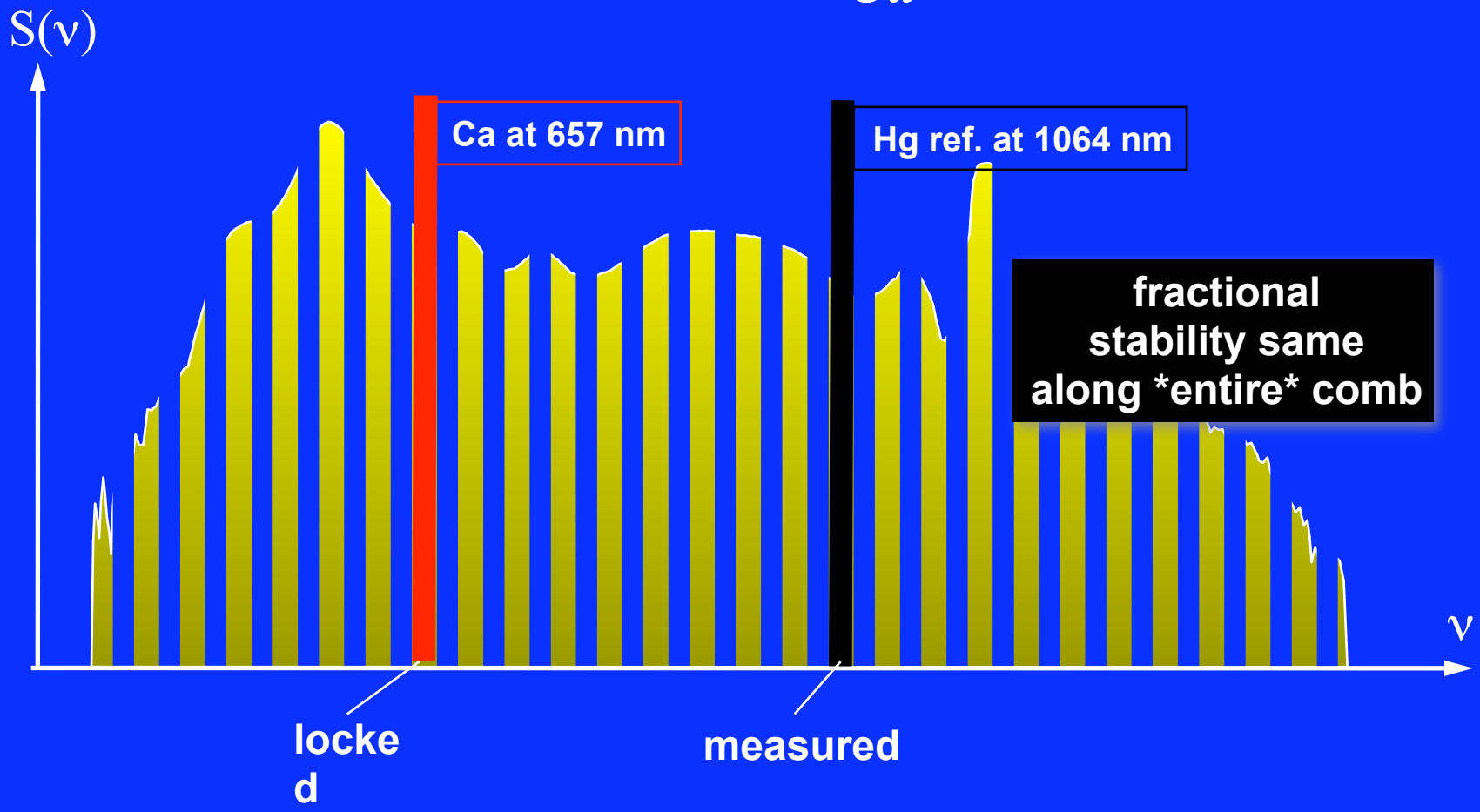
combs stability $\frac{\delta \nu_0}{\nu_0}$



comb equation predicts optical frequencies



combs stability $\frac{\delta \nu_0}{\nu_0} \approx \frac{\delta \nu_{Ca}}{\nu_{Ca}}$ optical reference stability



comb equation predicts optical frequencies

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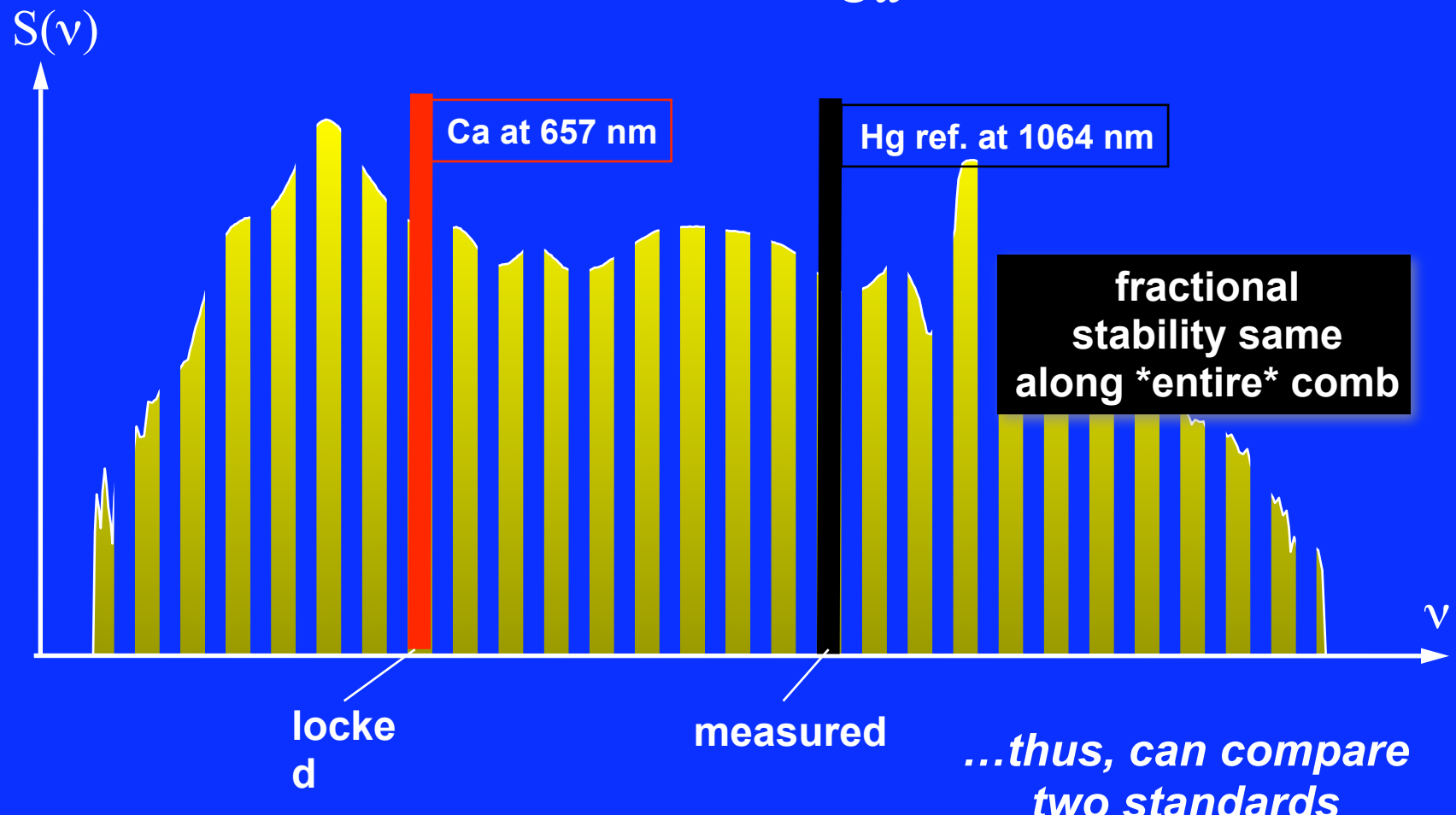
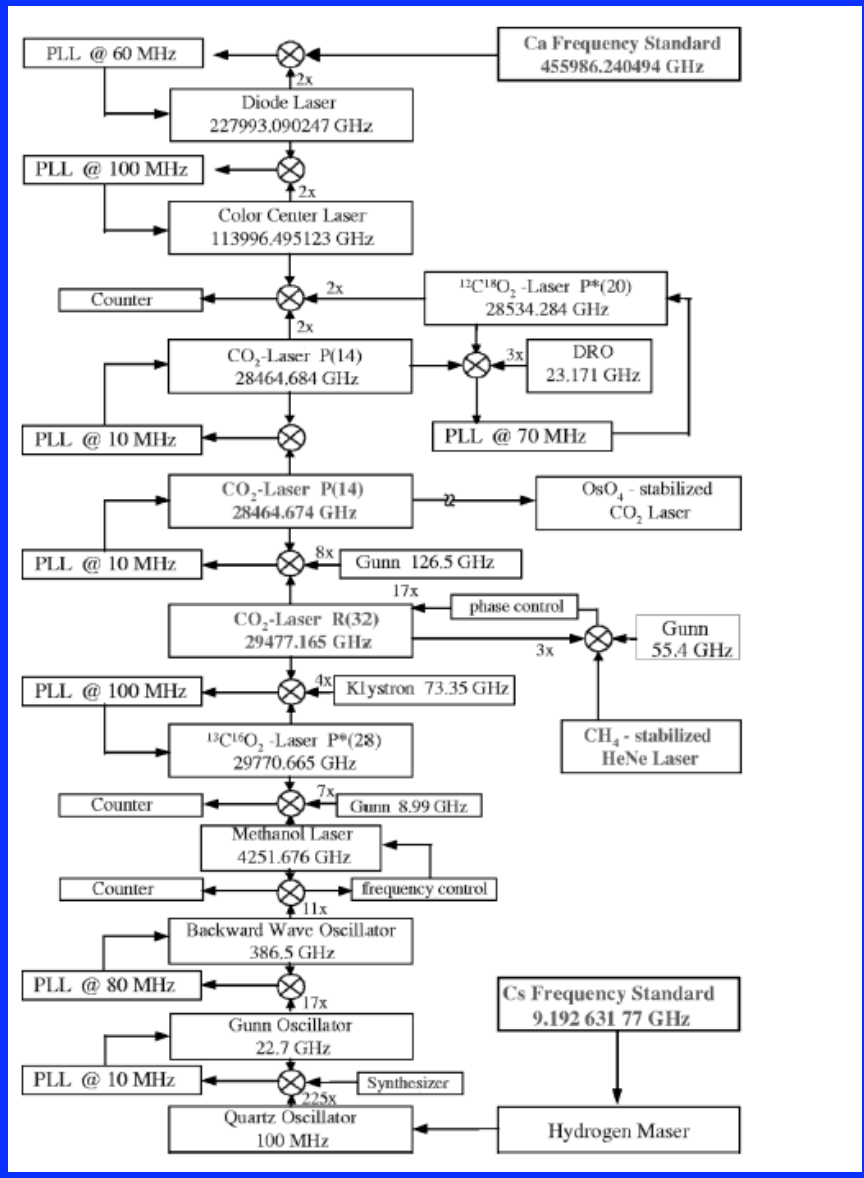
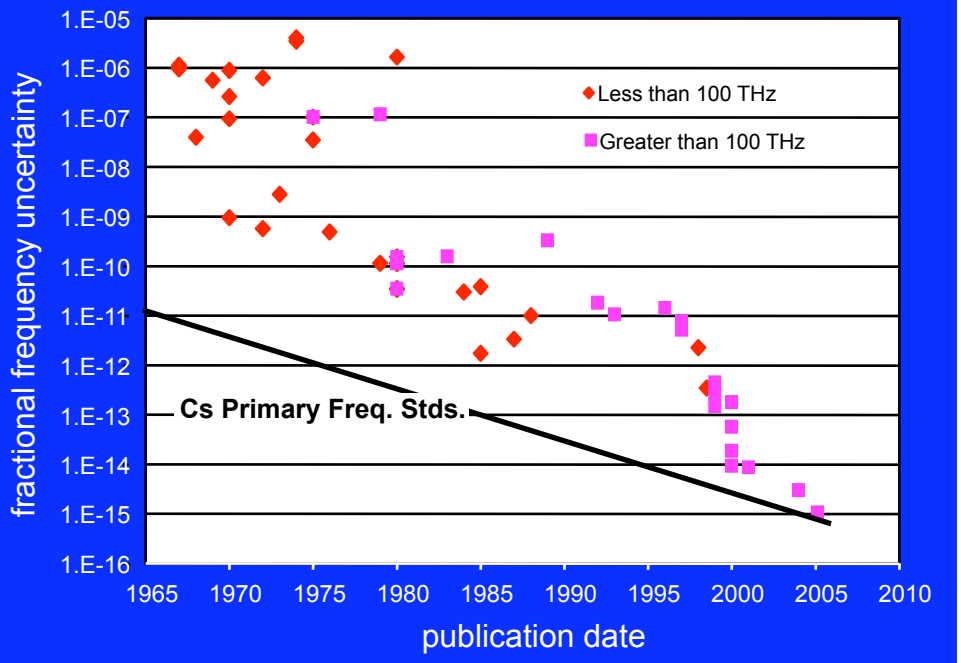


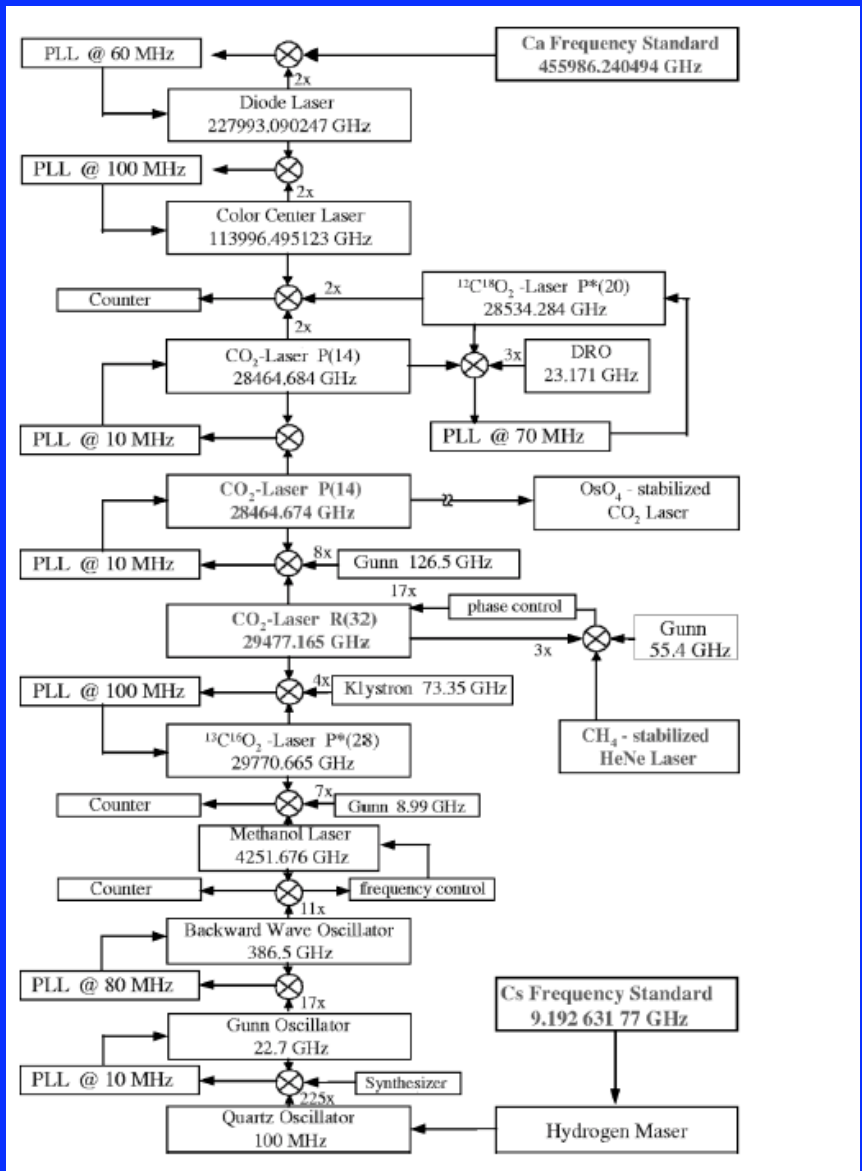
frequency measurements: simplified with combs



stabilized frequency comb

frequency measurements of laser-based frequency standards





stabilized frequency comb

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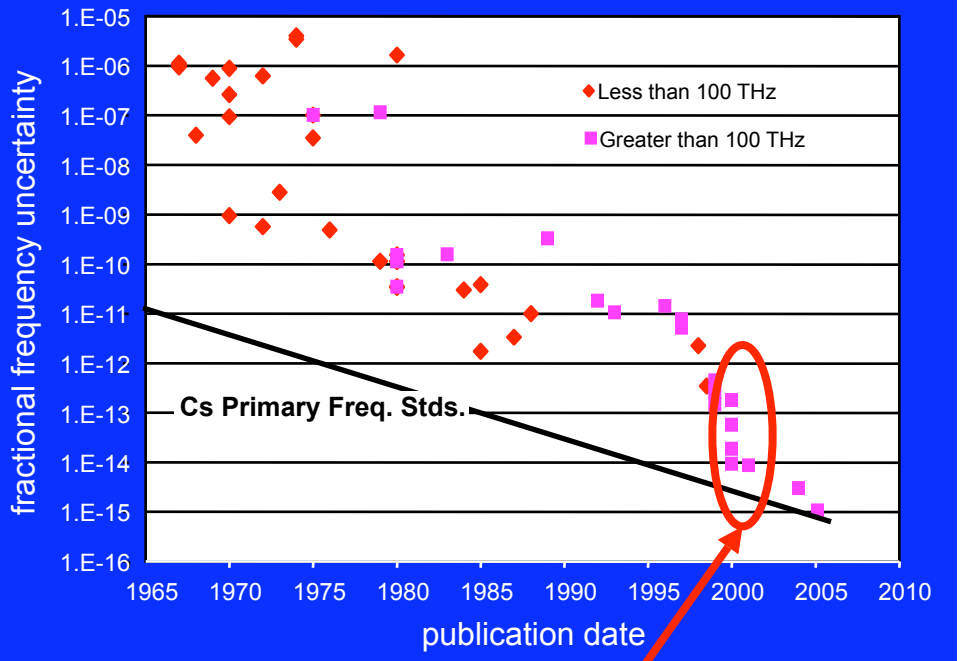
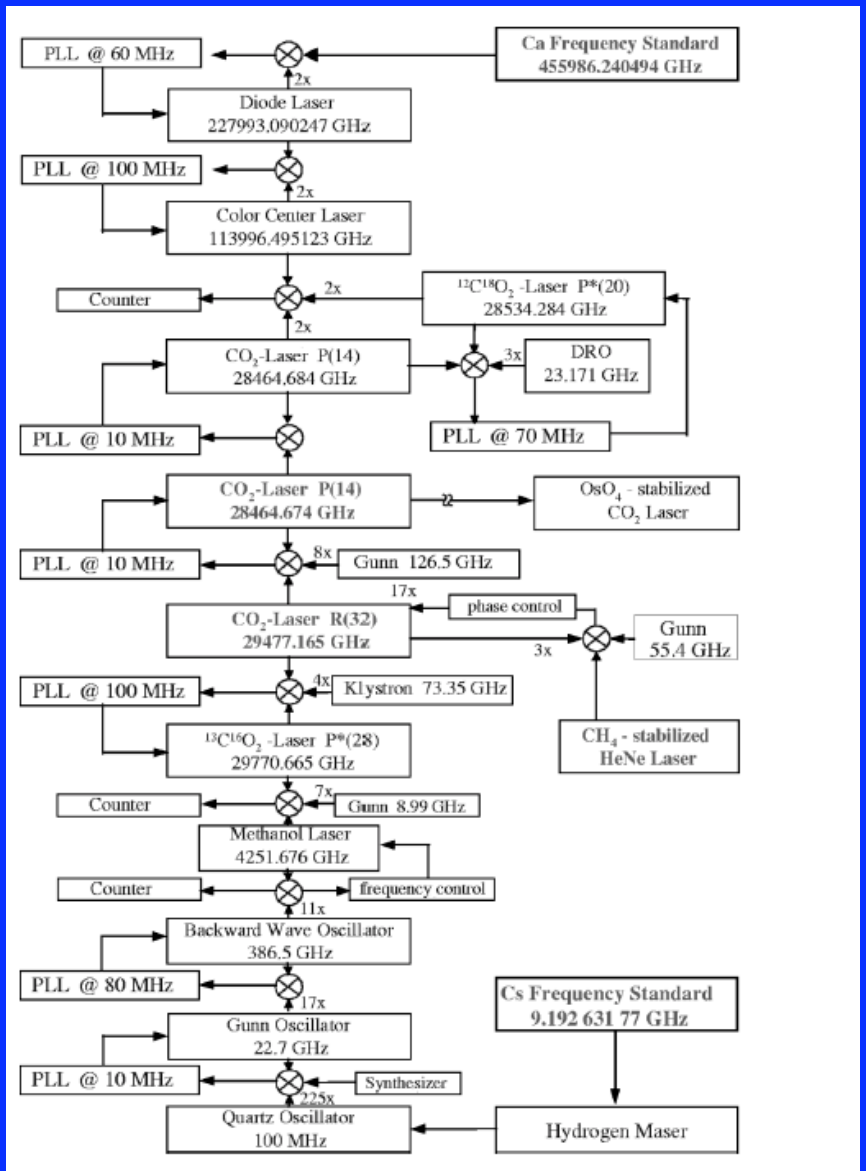
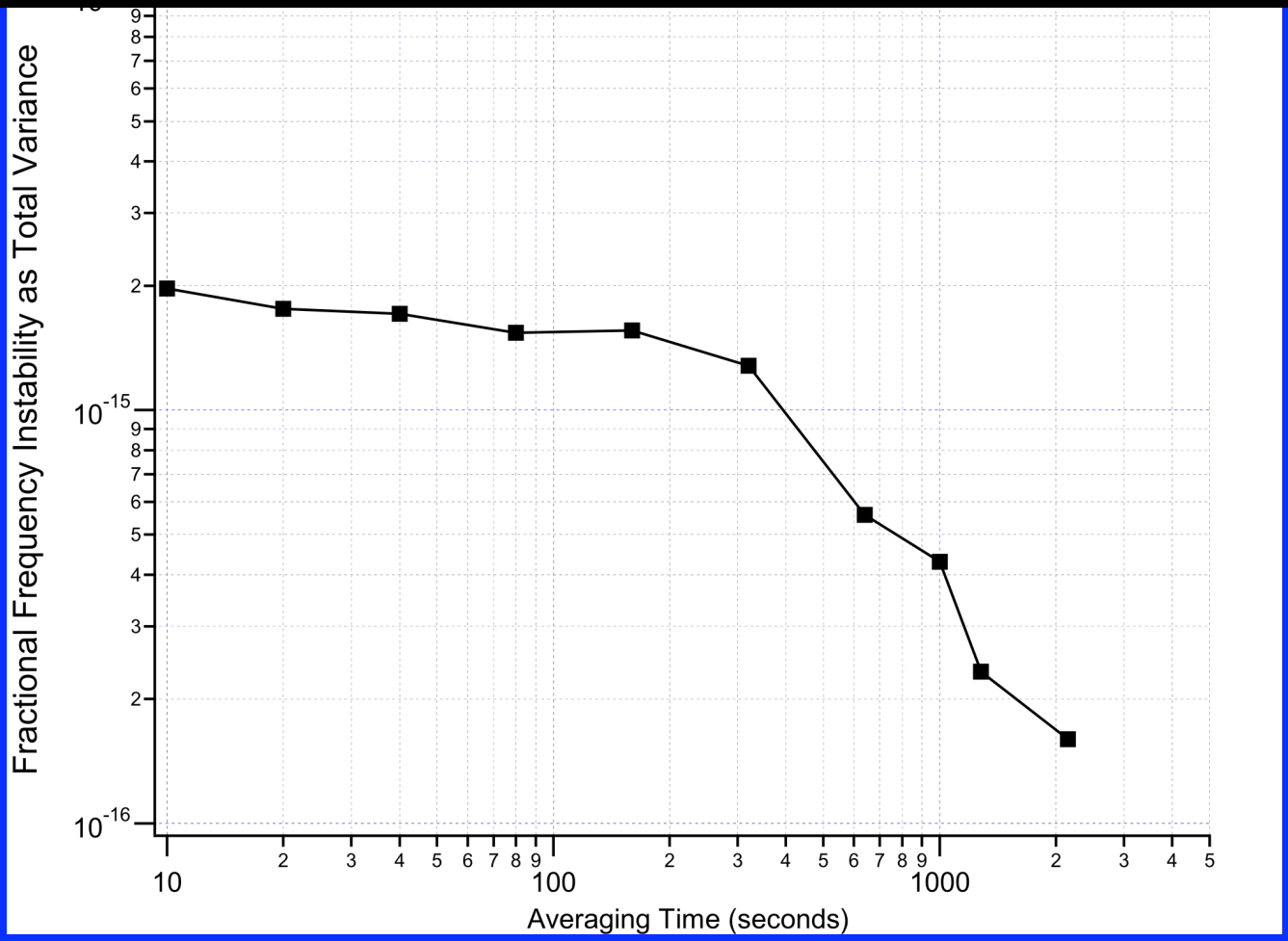


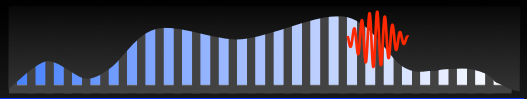
optical frequency metrology now routinely (as of year 2000) involves frequency combs for measurements



neutral Ca atoms: 457 THz (657 nm)
Hg+: 563 THz (532 nm)

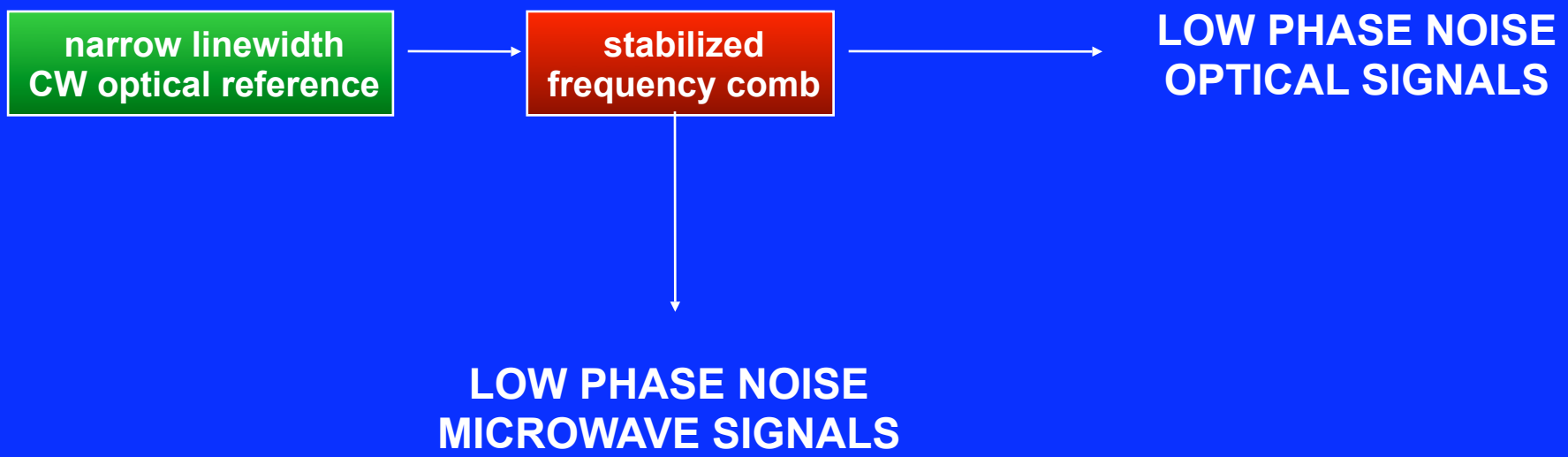
frequency comb as gearwork for optical-atomic clocks



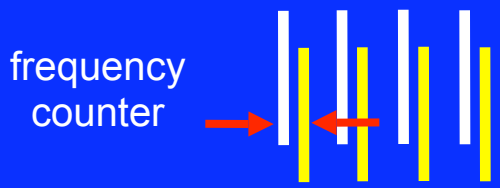


much of the work with combs relies on low phase noise

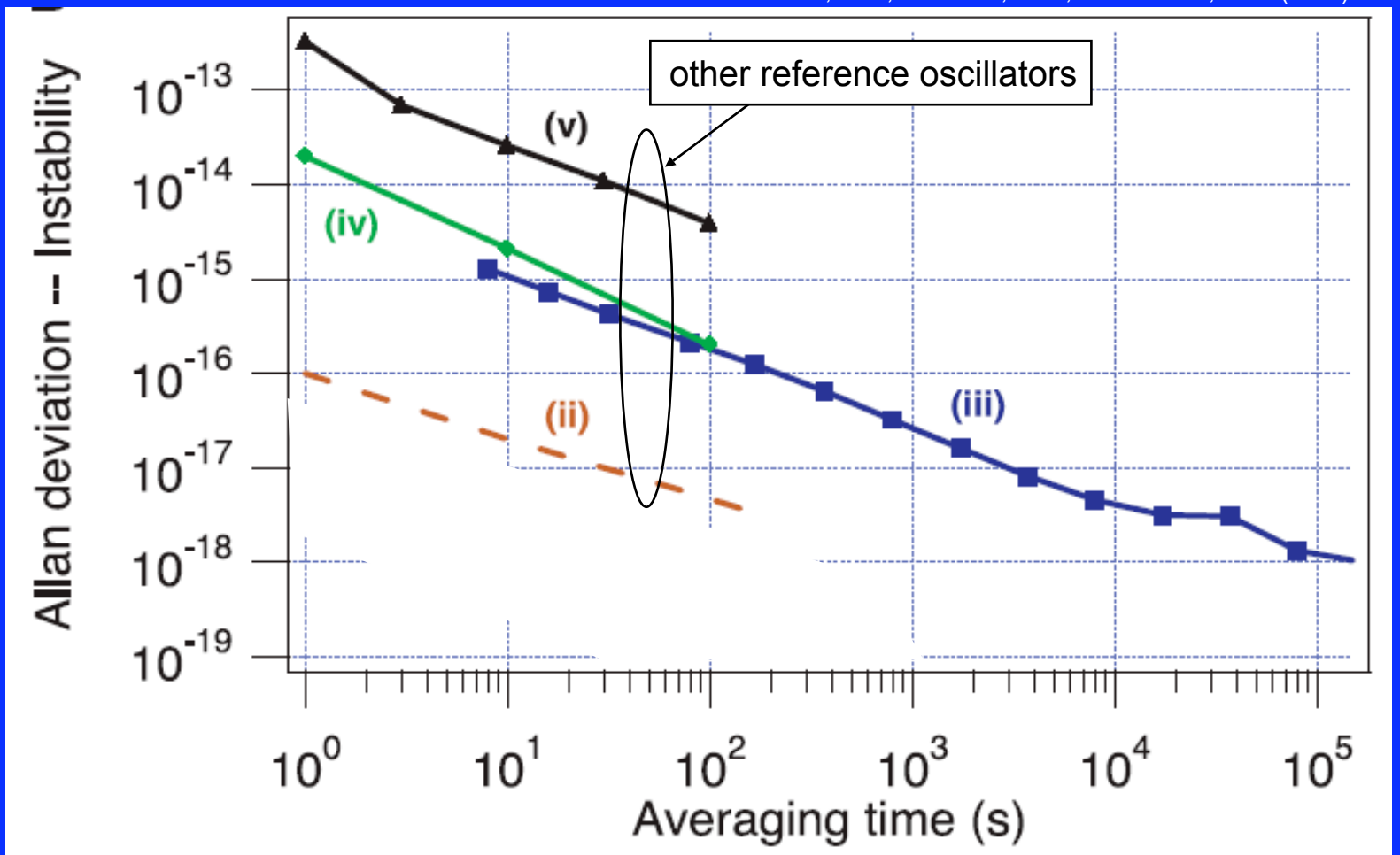
at NIST, we are interested in performance in both regimes



first step: establish frequency stability of comb



L.-S. Ma, Z. Bi, A. Bartels, *et al.*, Science **303**, 1843 (2004).



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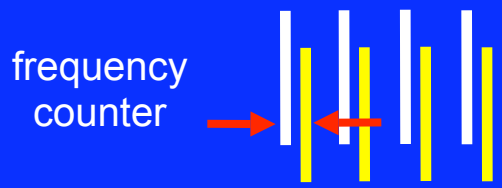

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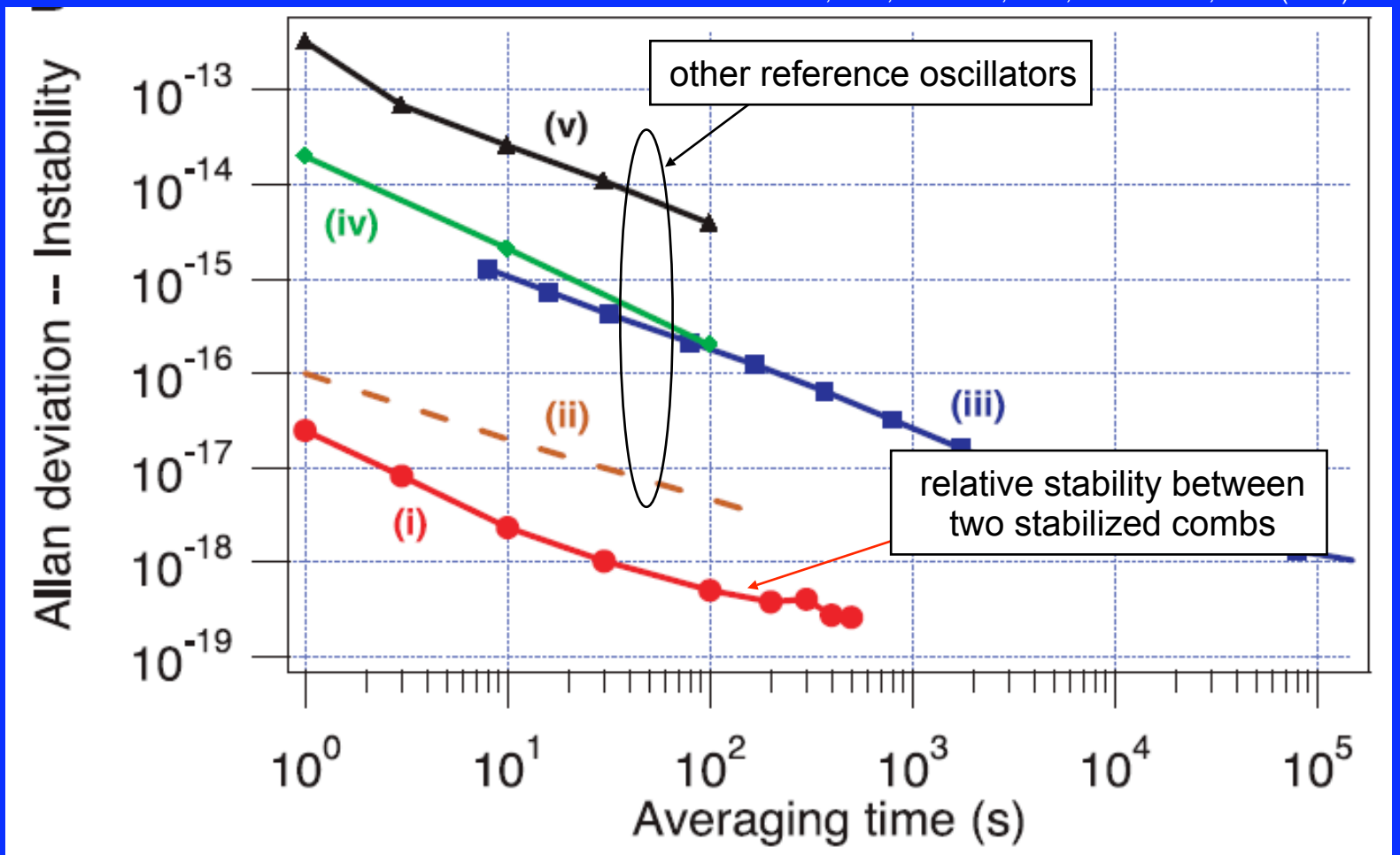

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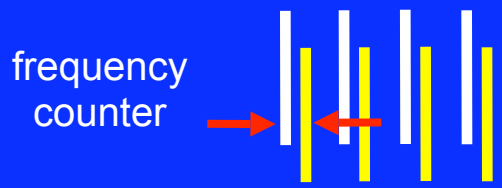

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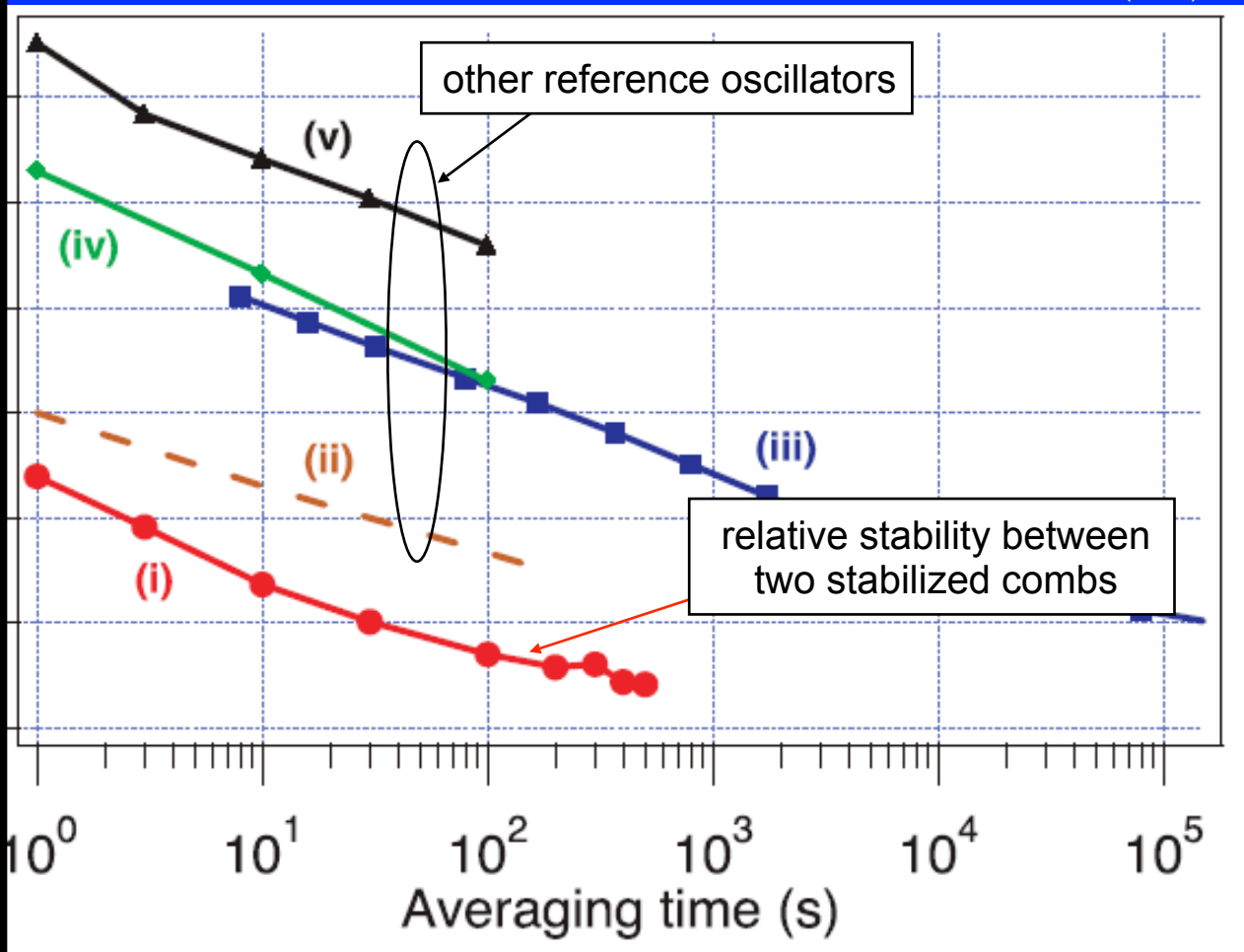
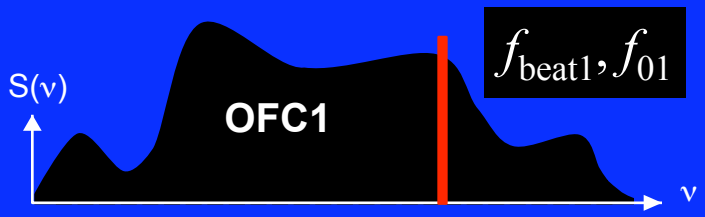
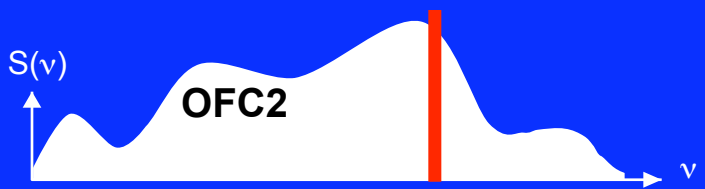


methods for measuring optical coherence

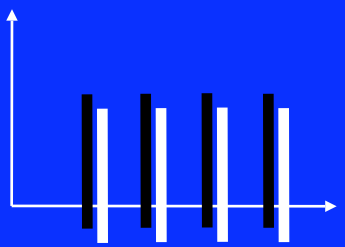




f_{beat2}, f_{02}

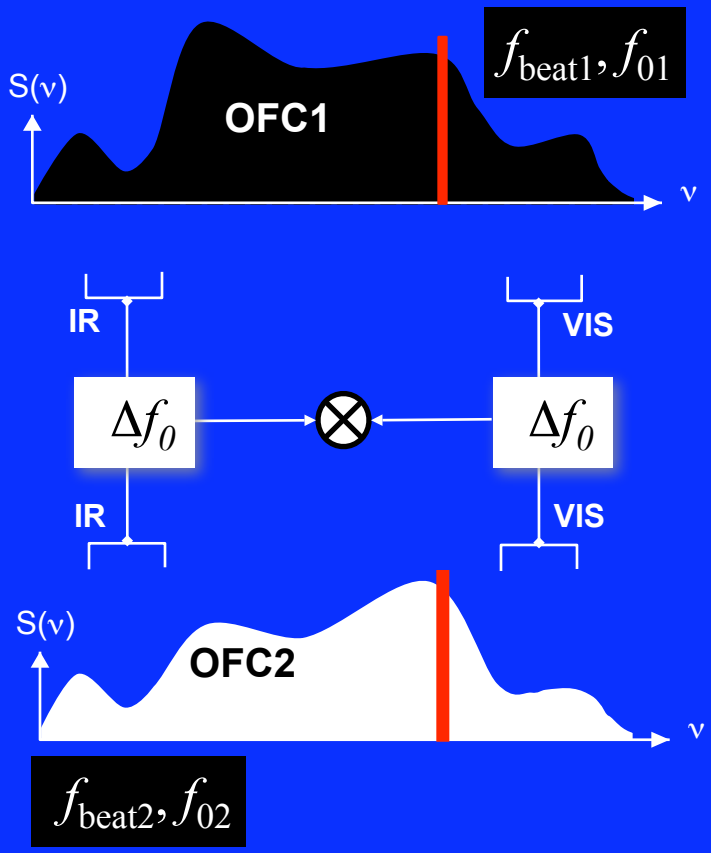
relative phase noise measurement

to compare different spectral regions,
…can extract RF parameter from each region



$f_{01} - f_{02} = \Delta f_0$

methods for measuring optical coherence



relative phase noise measurement

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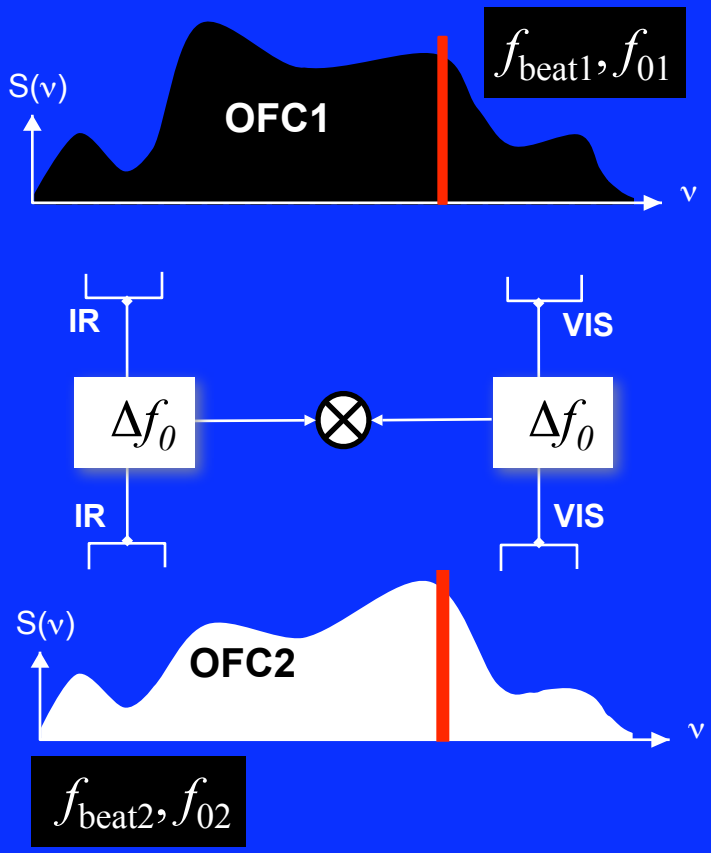

relative phase noise measurement

to compare different spectral regions,
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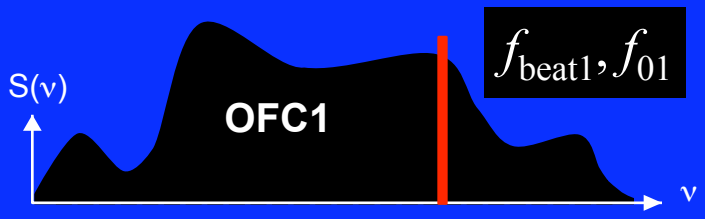
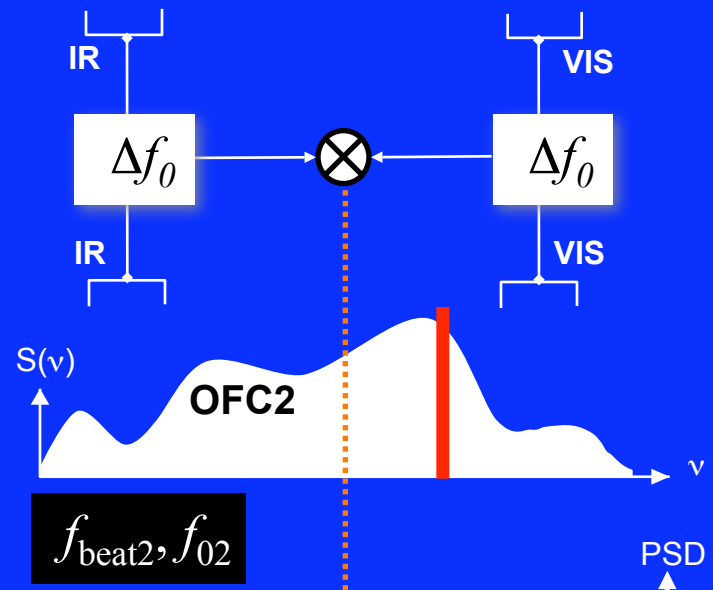
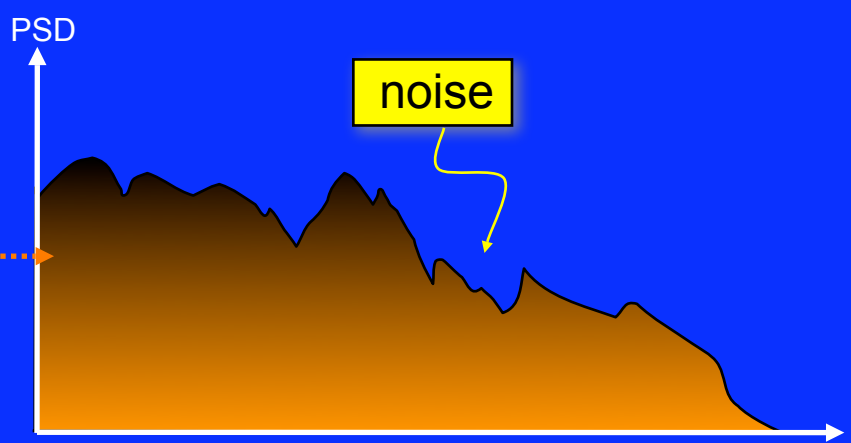
with this technique we can:
§ downconvert optical noise into RF parameter
§ compare noise at different spectral regions

…that is, look at dynamics of comb…

methods for measuring optical coherence







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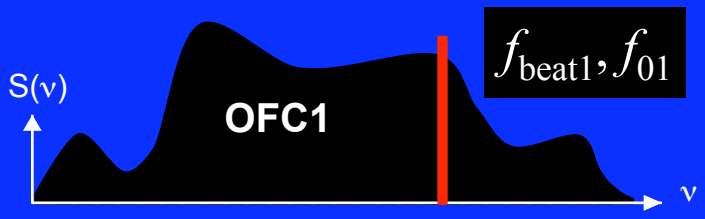

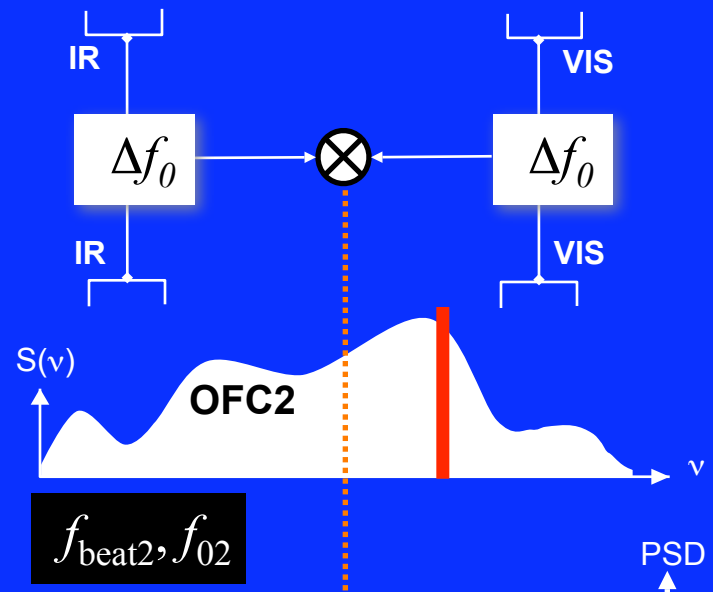

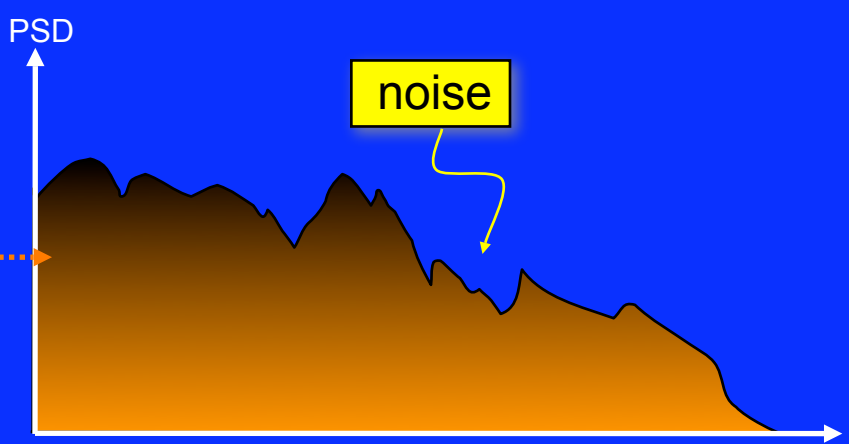

relative phase noise measurement

to compare different spectral regions,
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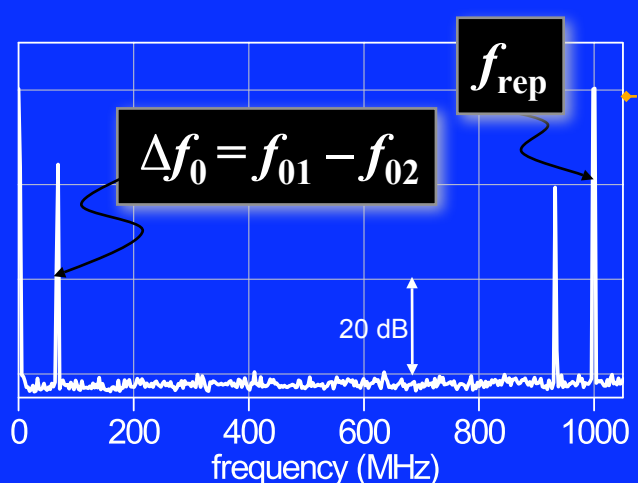
with this technique we can:
§ downconvert optical noise into RF parameter
§ compare noise at different spectral regions

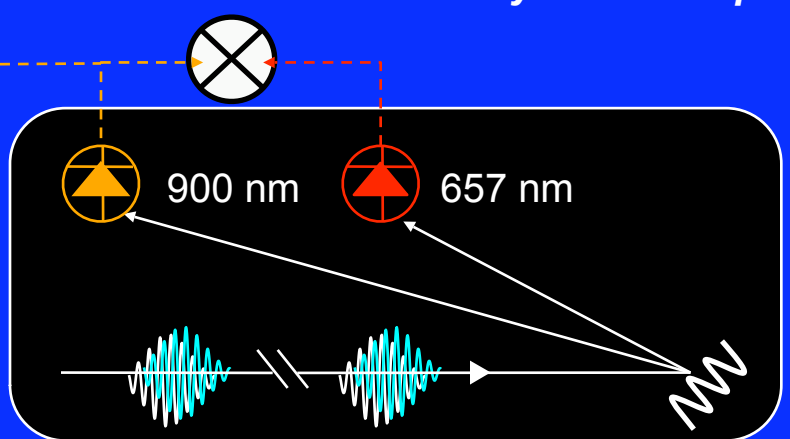
…that is, look at dynamics of comb…

§ how does the phase noise vary across comb?
§ can the comb equation predict the measured noise?

relative noise between lock point and region 230 nm away



240 nm away from lock point!



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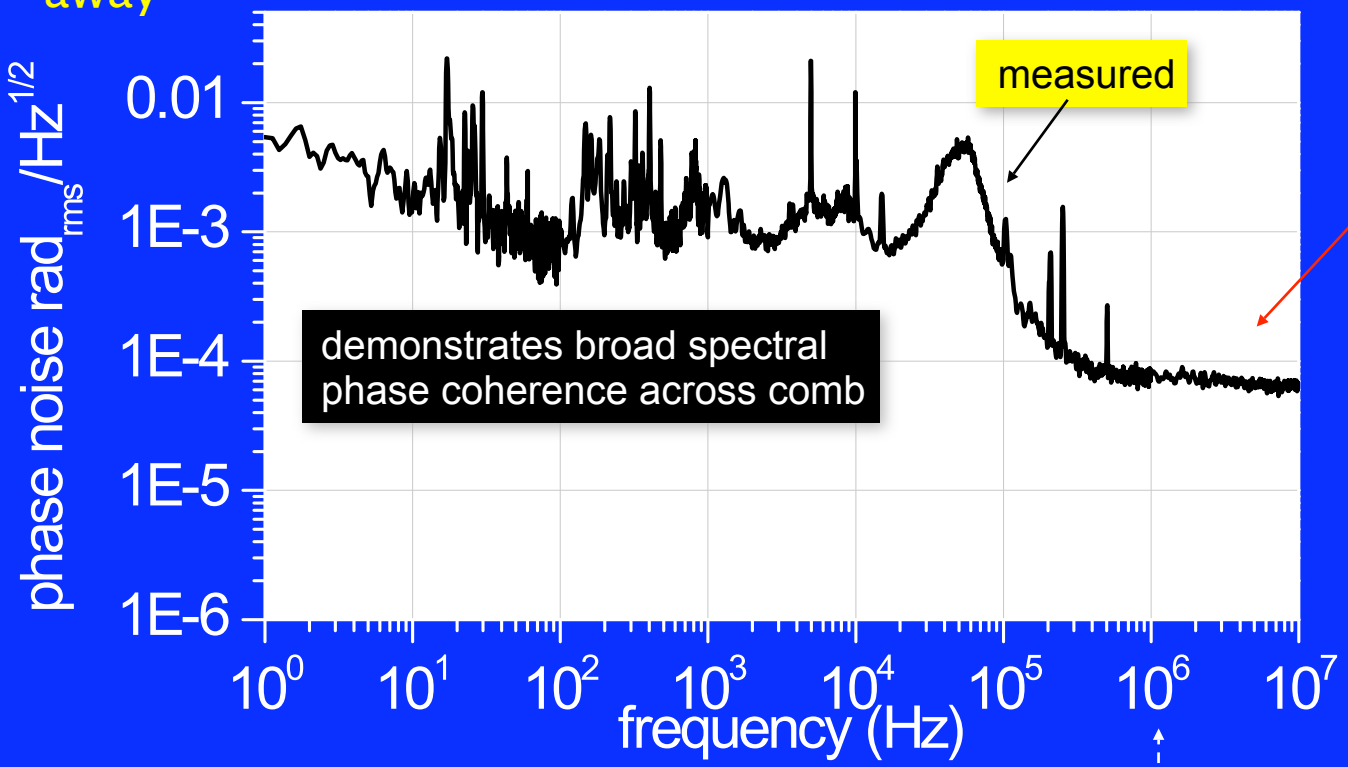
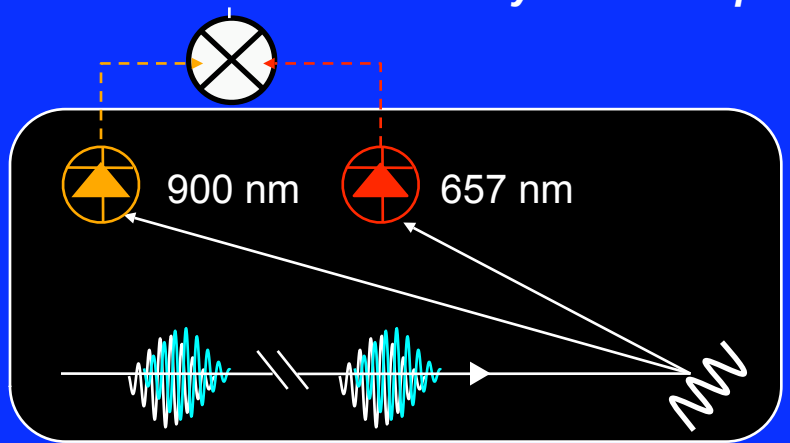


limited by measurement noise floor

240 nm away from lock point!



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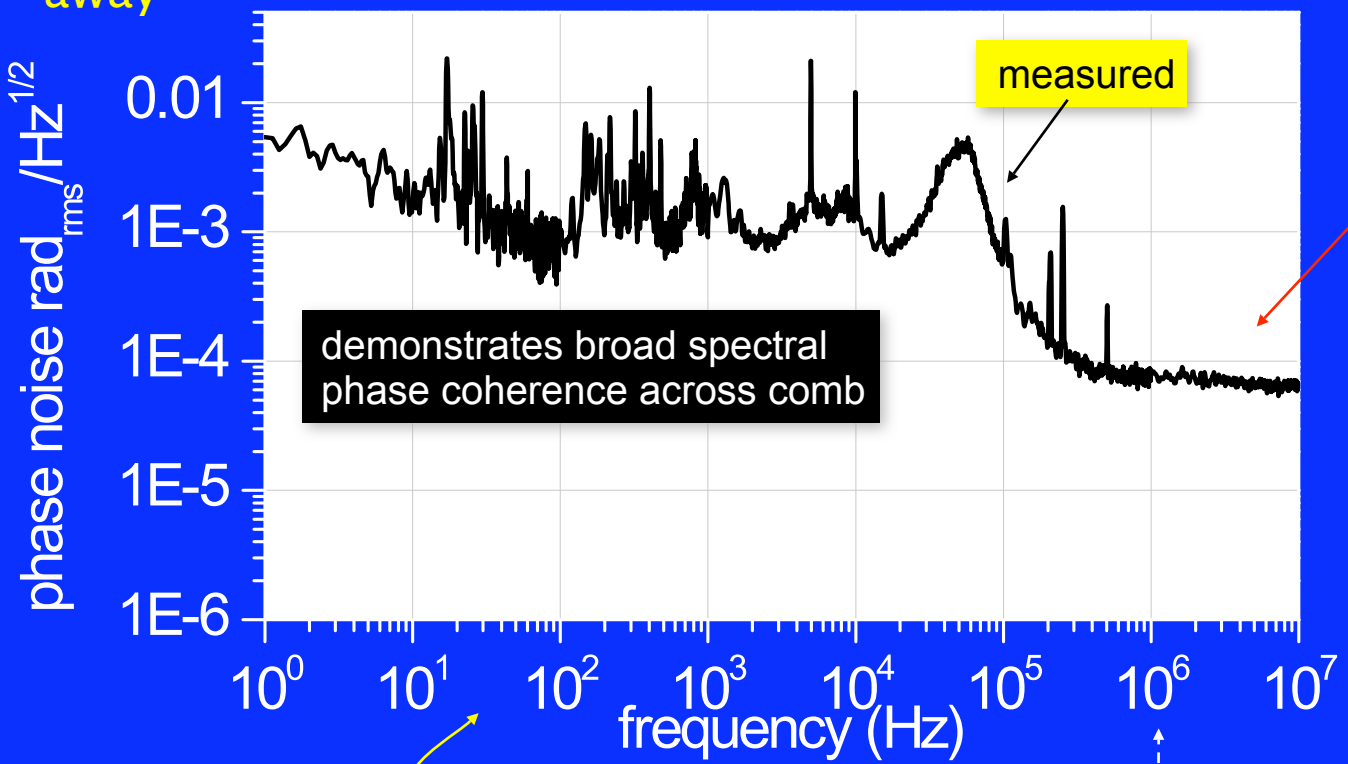
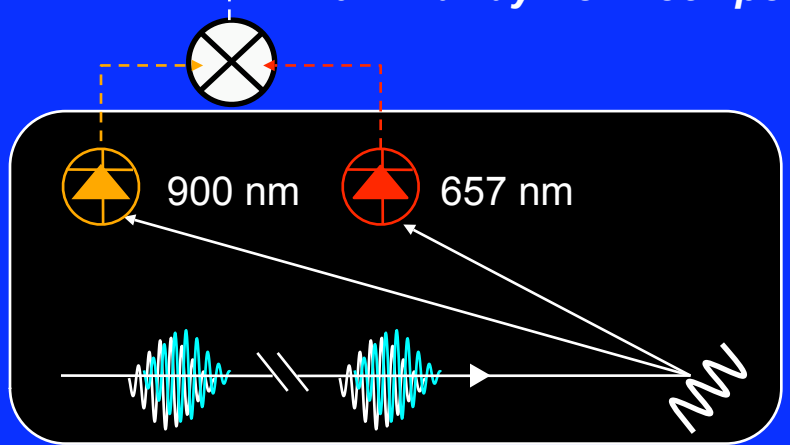


low level noise milliradian/Hz$^{1/2}$ on optical signal

sub-fs timing jitter

240 nm away from lock point!



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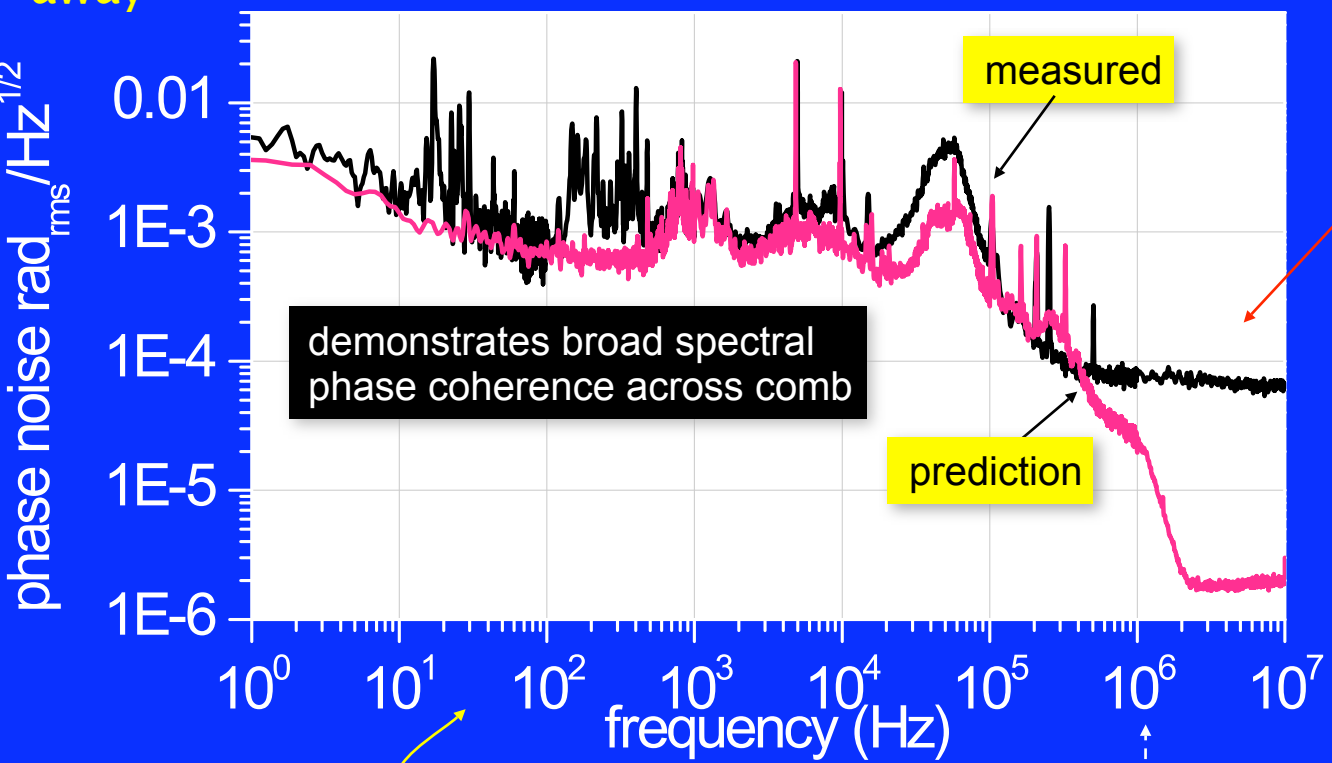

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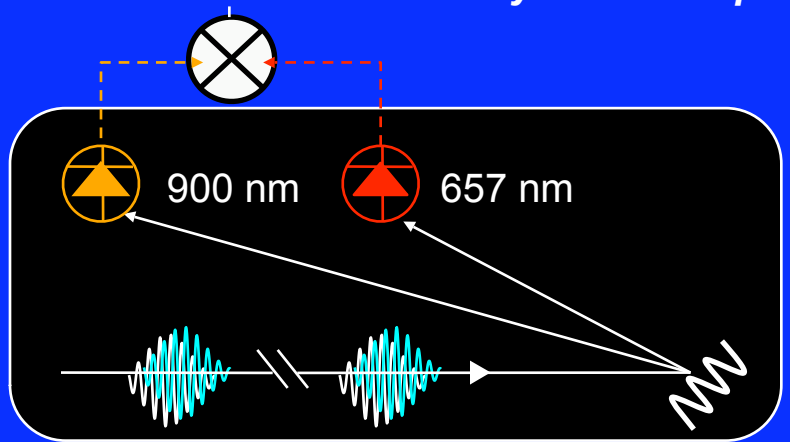

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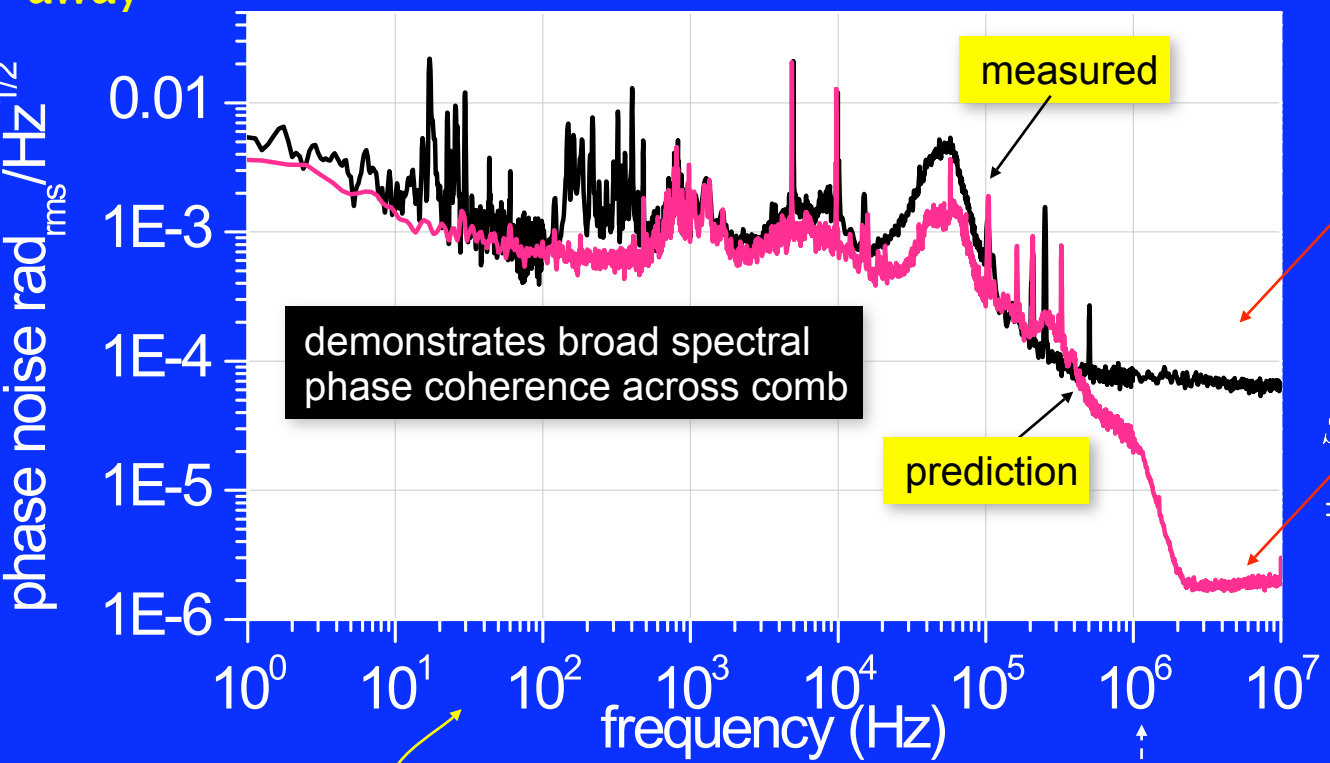


limited by measurement noise floor

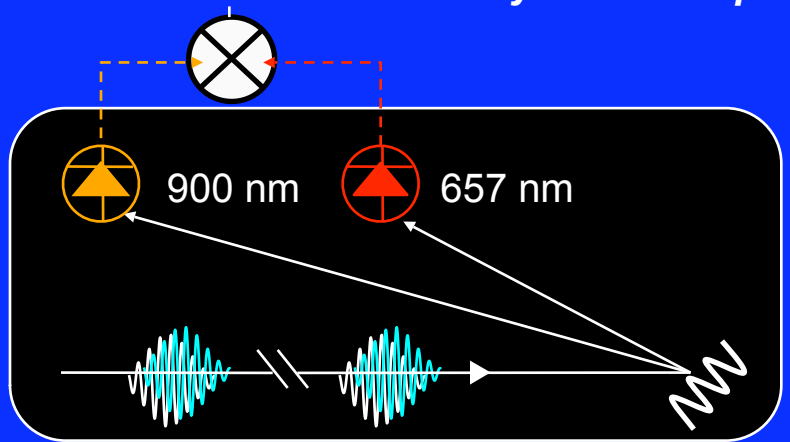
using comb equation, we predict:

$$S_{\Phi,m,n}(f) = (r^m - r^n)^2 \sum S_i(f)$$

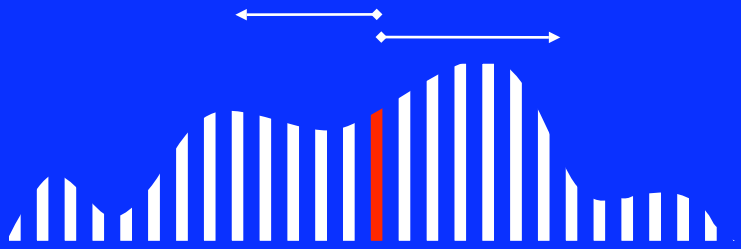
low level noise milliradian/Hz$^{1/2}$ on optical signal

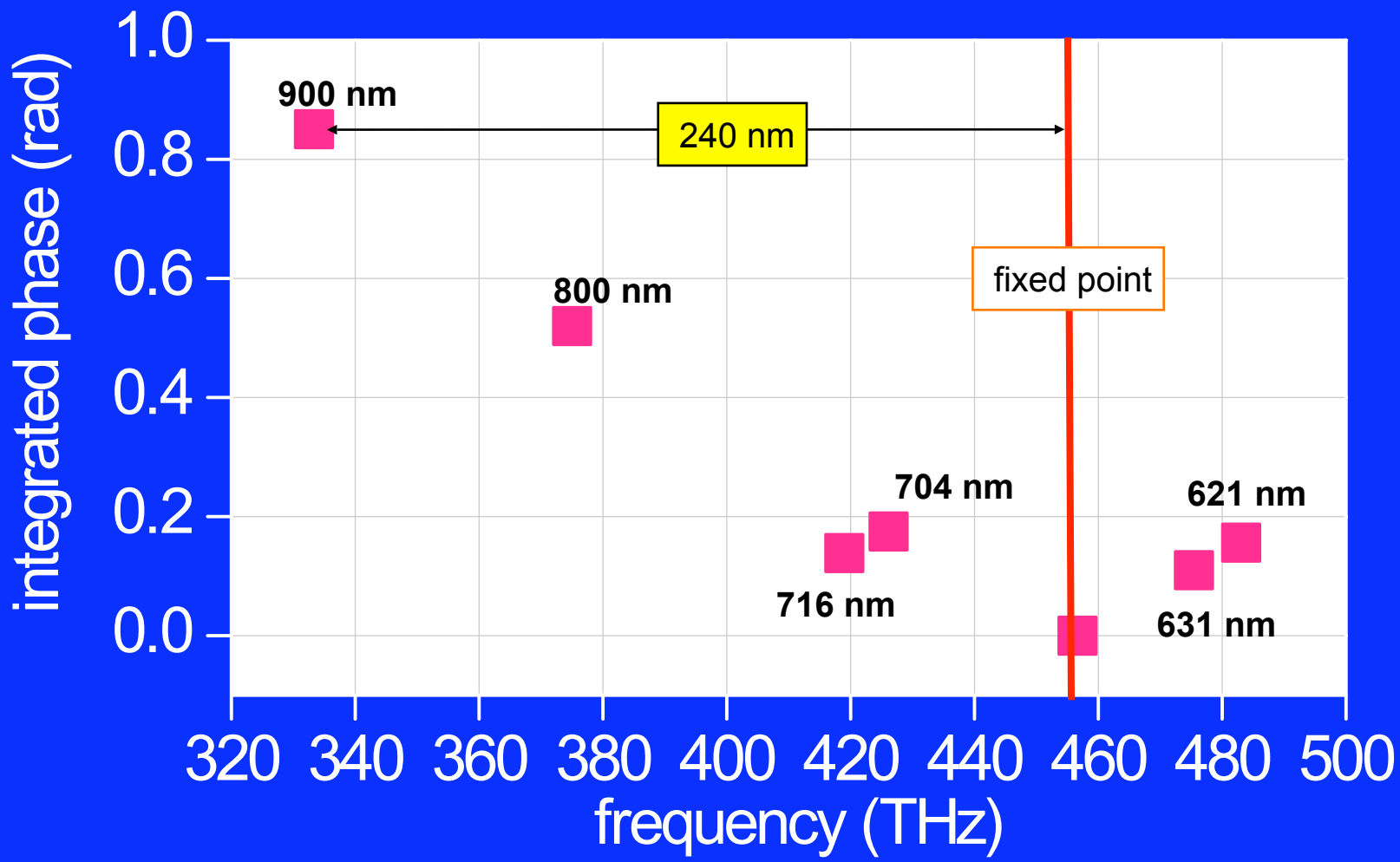
sub-fs timing jitter

240 nm away from lock point!



scaling of phase away from locked point





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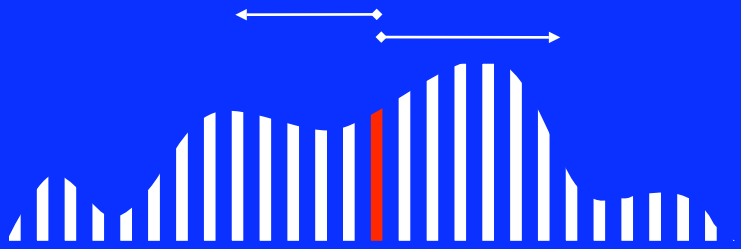

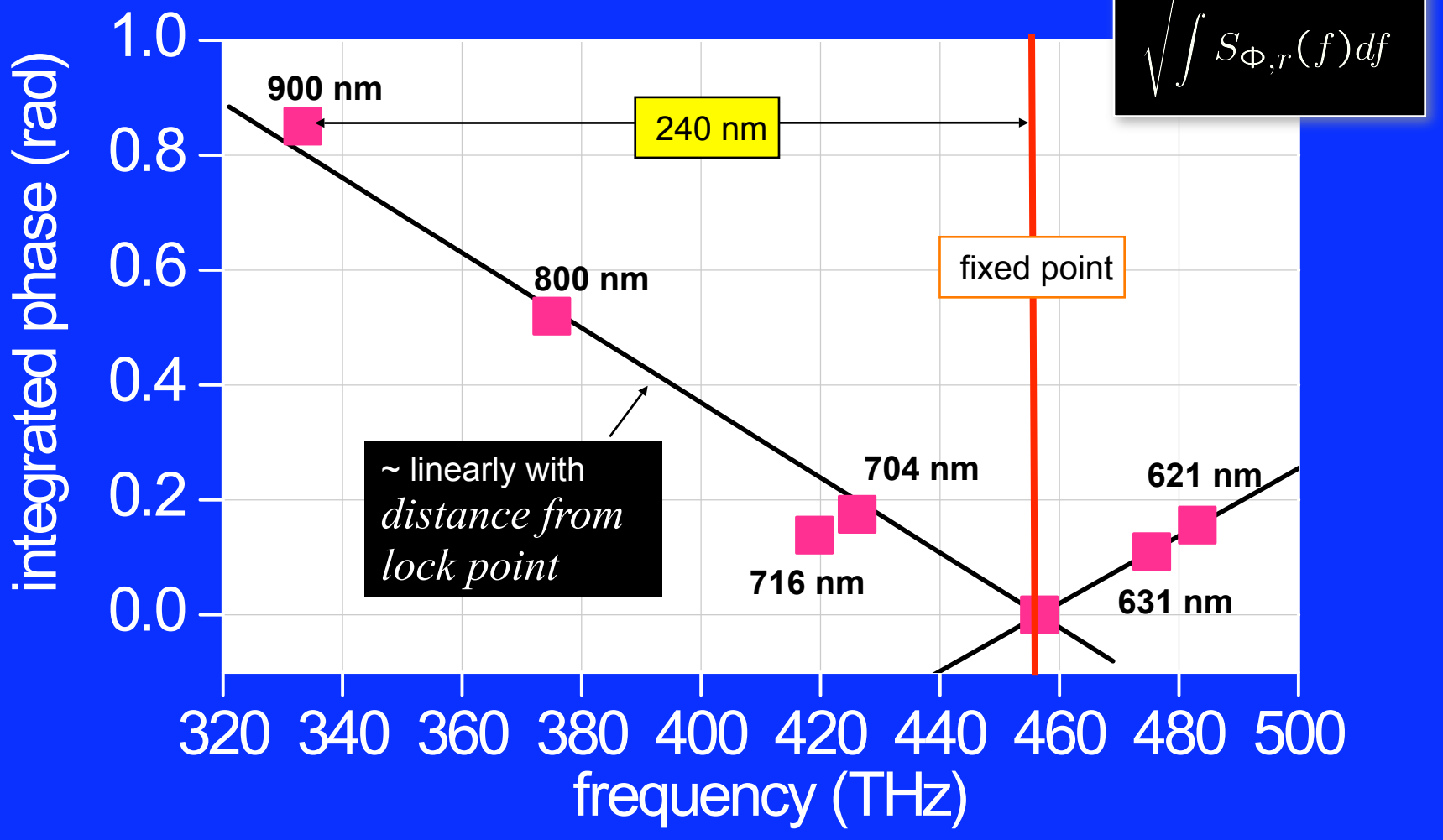

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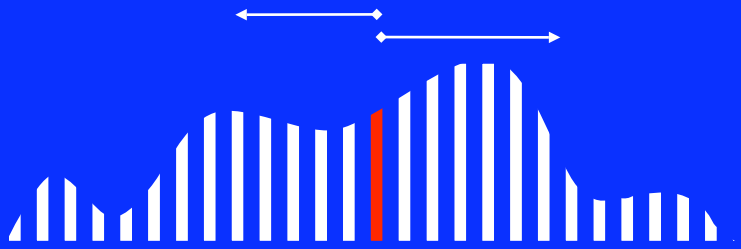


§ first demonstration scaling of phase noise across comb

§ comb equation can predict phase dynamics

§ shows substantial coherence across comb

$$\sqrt{\int S_{\Phi,r}(f)\,df}$$

integrated phase (rad)

1.0
0.8
0.6
0.4
0.2
0.0

900 nm
240 nm
800 nm
fixed point
704 nm
621 nm
716 nm
631 nm

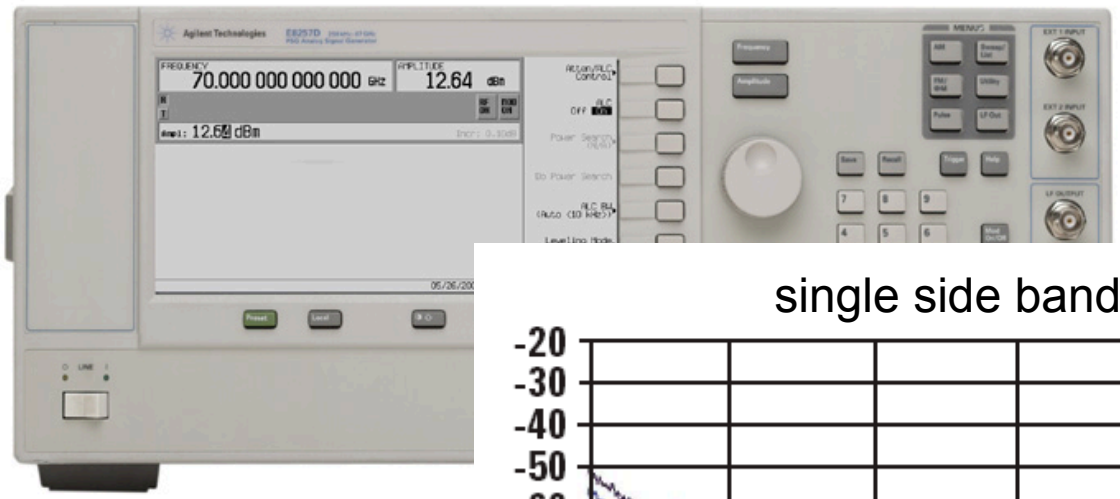
~ linearly with *distance from lock point*

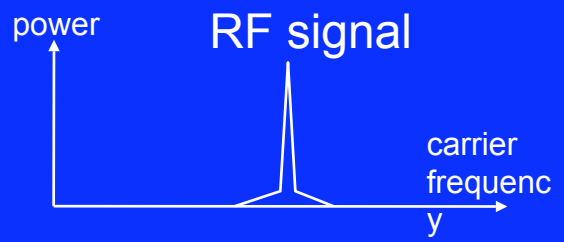
320 340 360 380 400 420 440 460 480 500

frequency (THz)

microwave frequency synthesizers

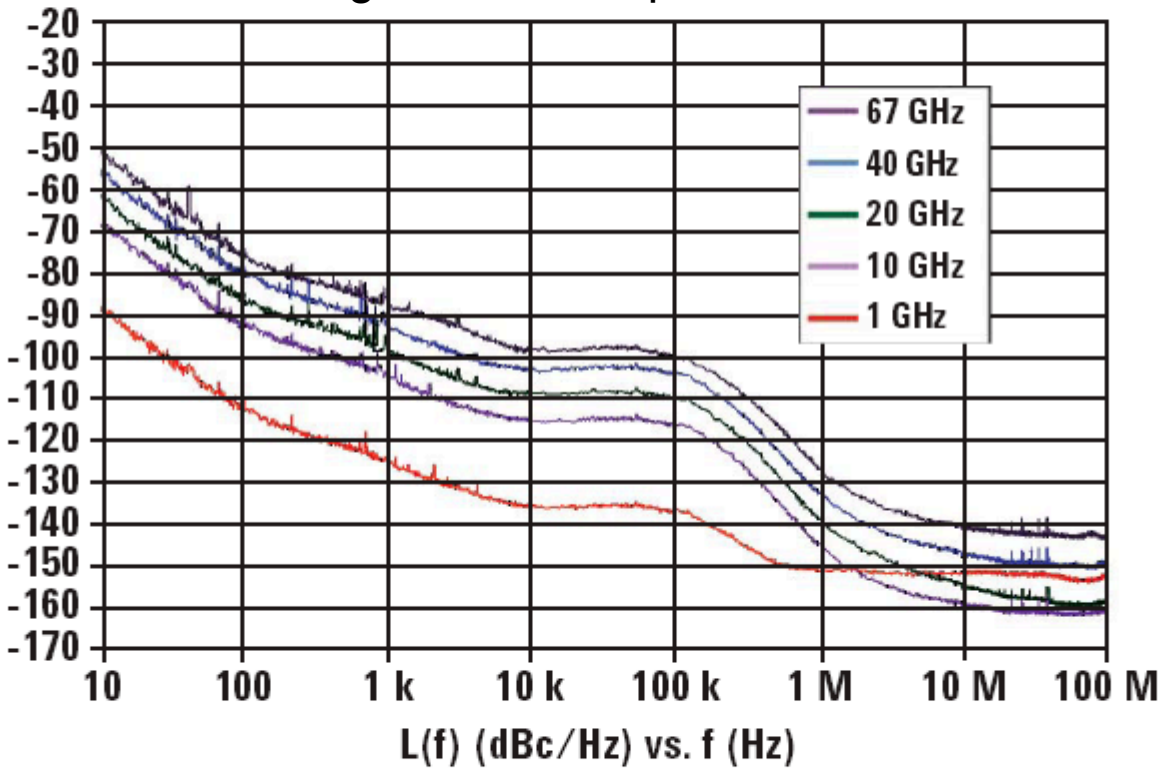
Agilent E8257D frequency synthesizer





plotted without spurs

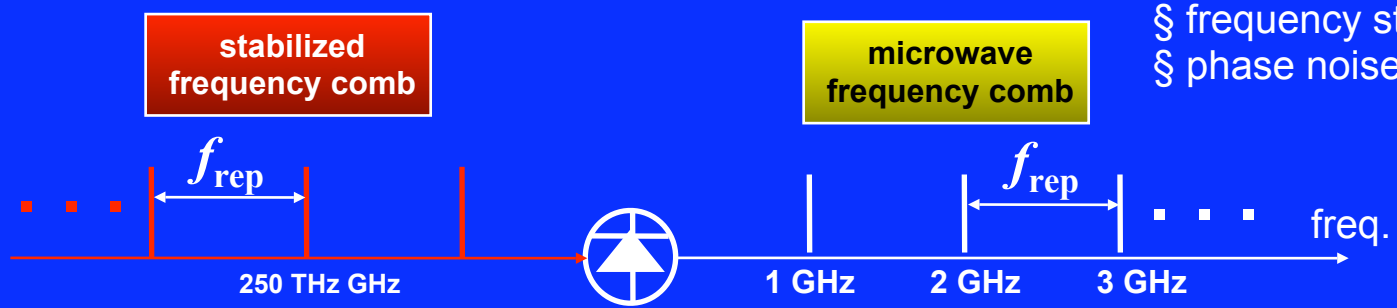
single side band phase noise

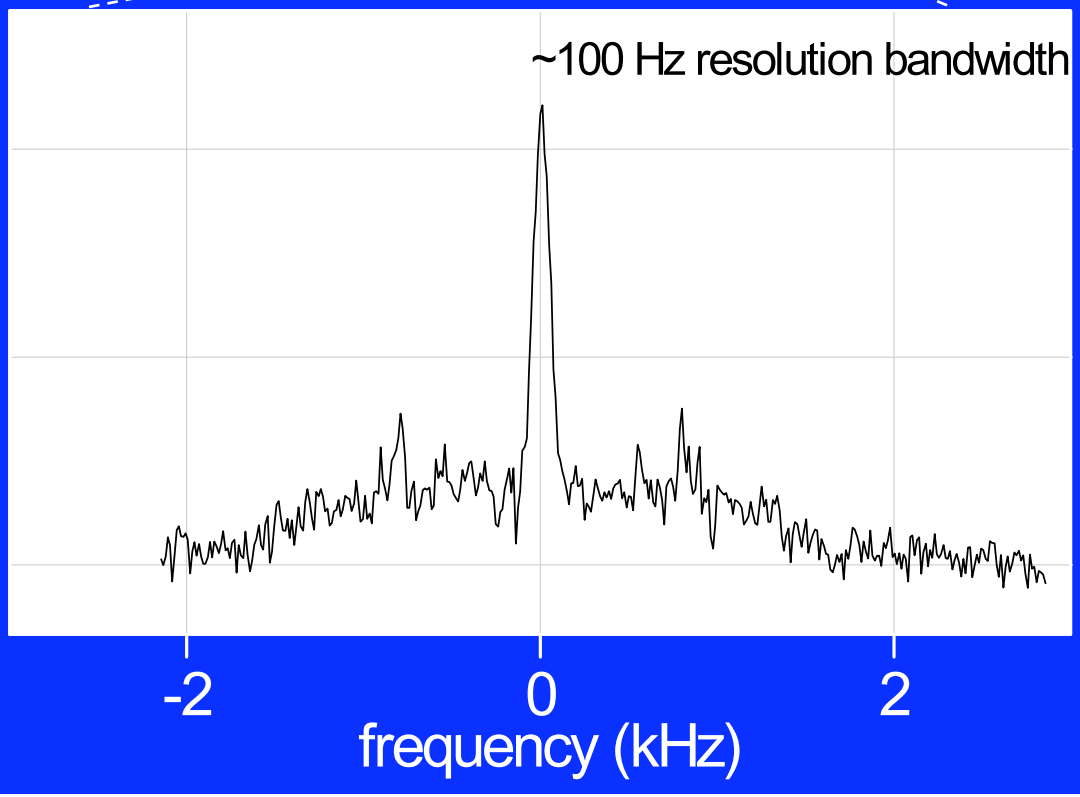


specifications

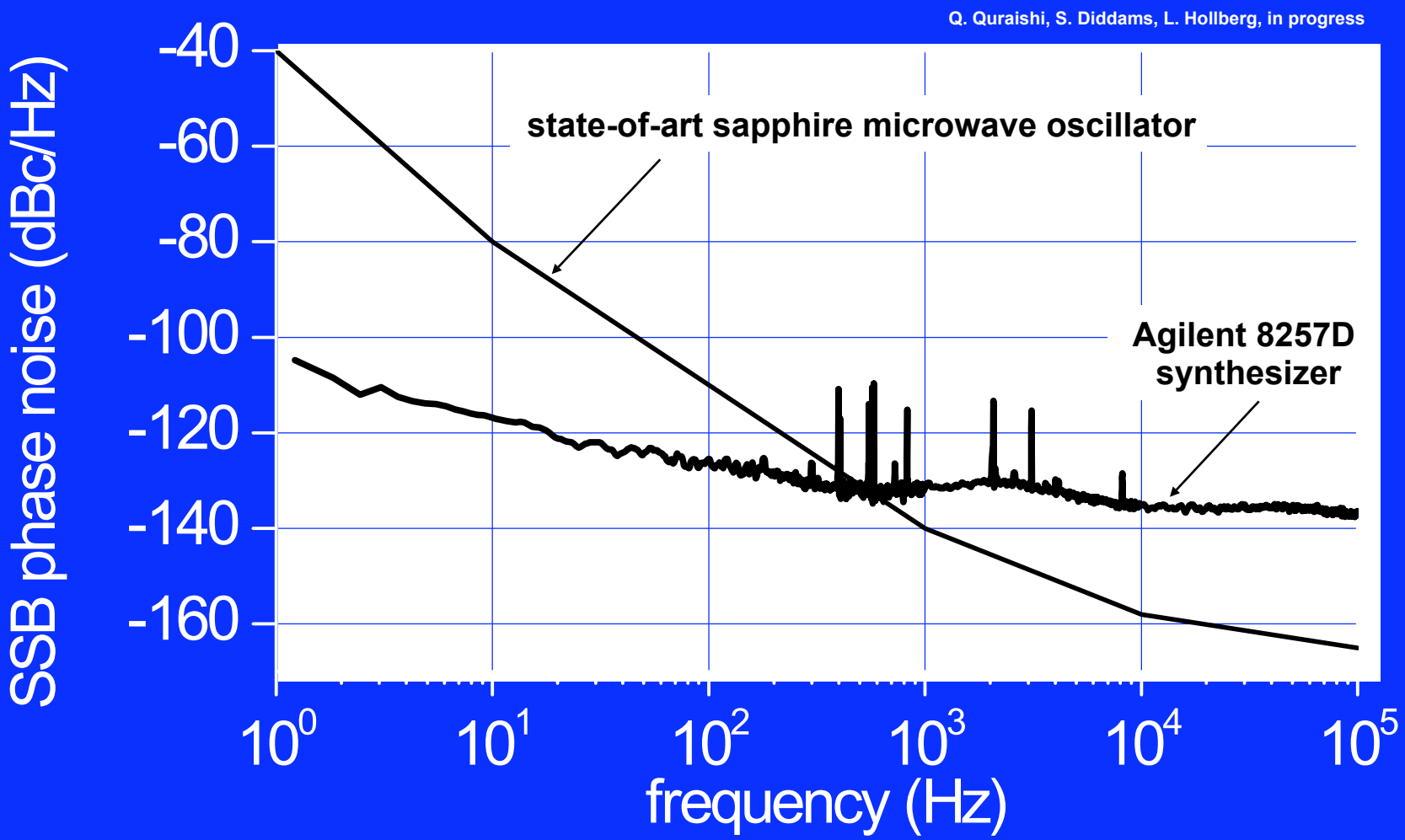
250 kHz – 20 GHz +
low phase noise

microwave signals from optical frequency combs





microwave noise from combs very good



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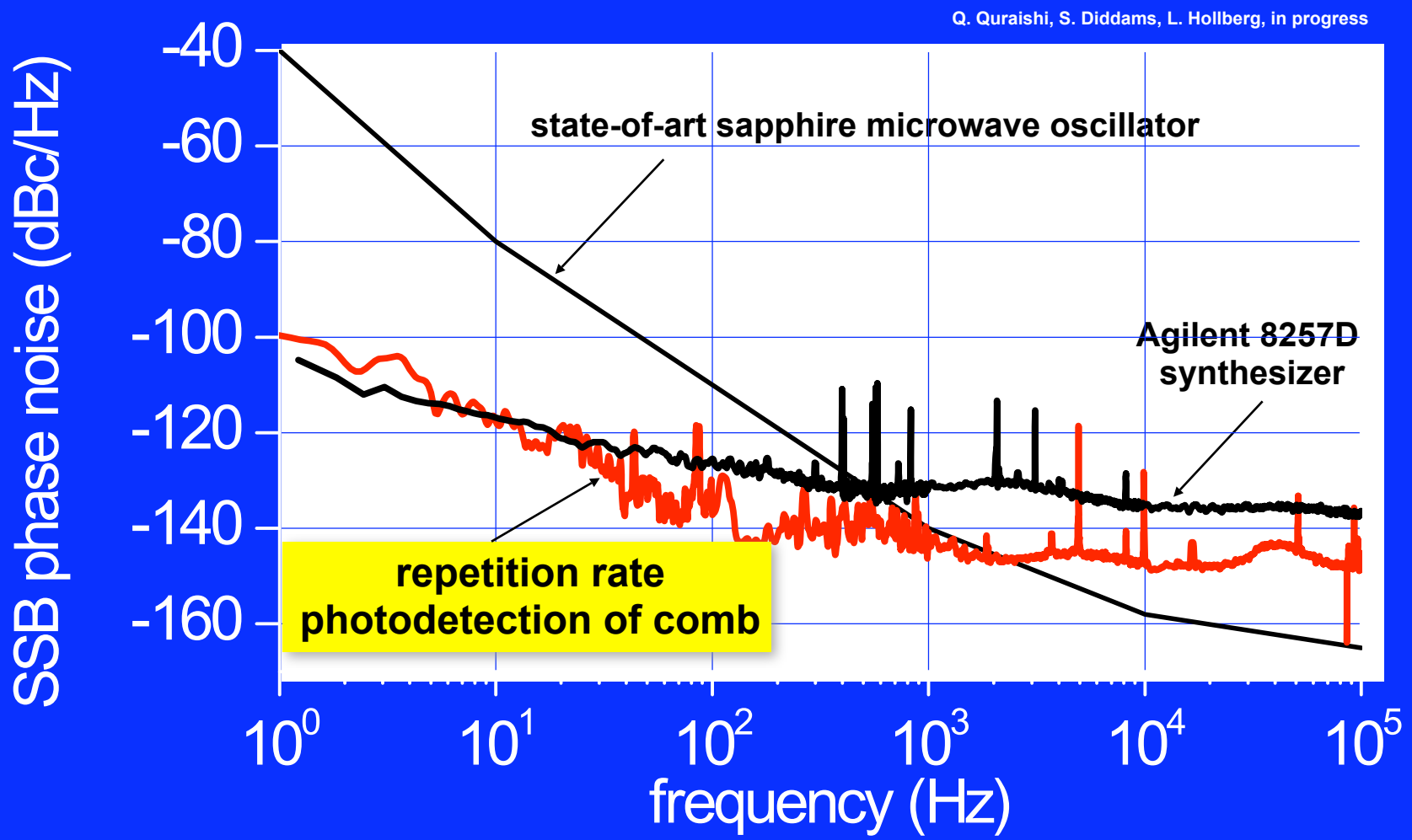

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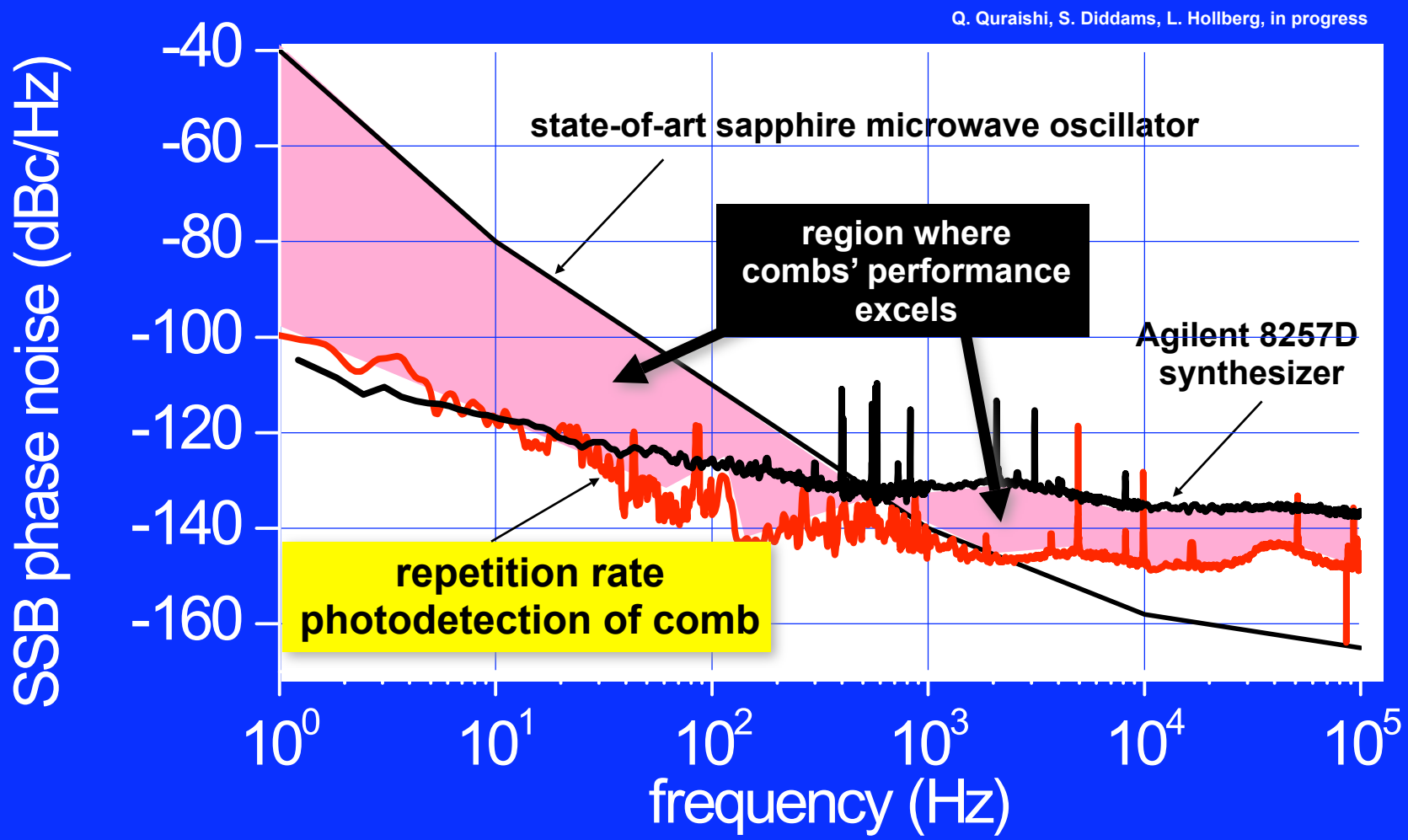
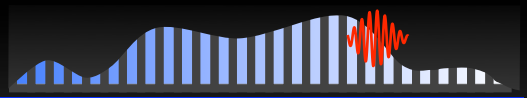
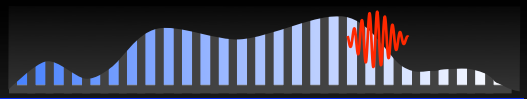


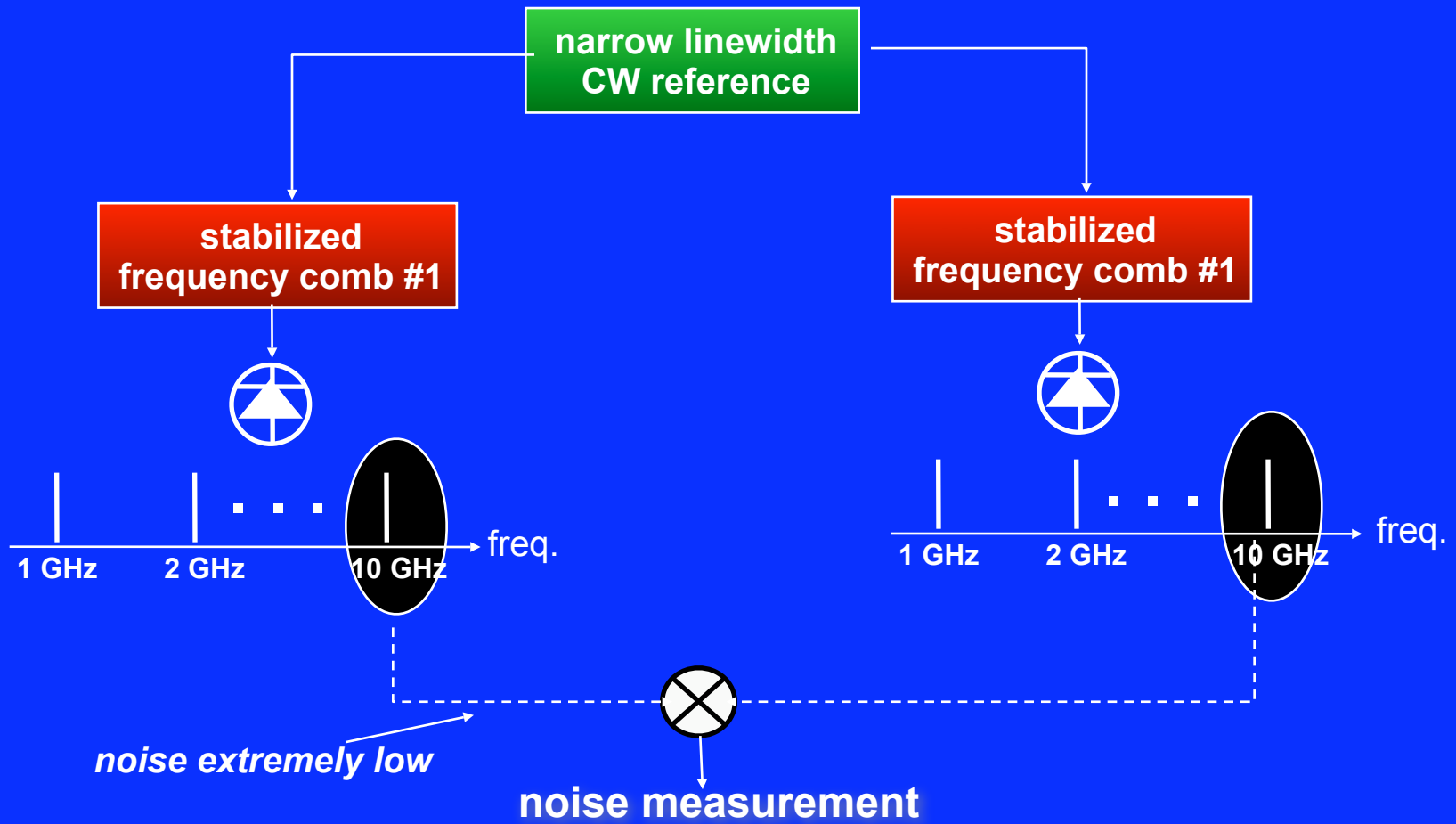


if noise is low than other microwave sources…

how was the measurement done?

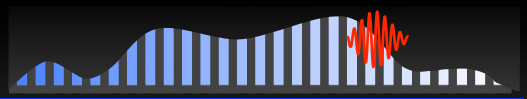
measuring microwave noise of combs



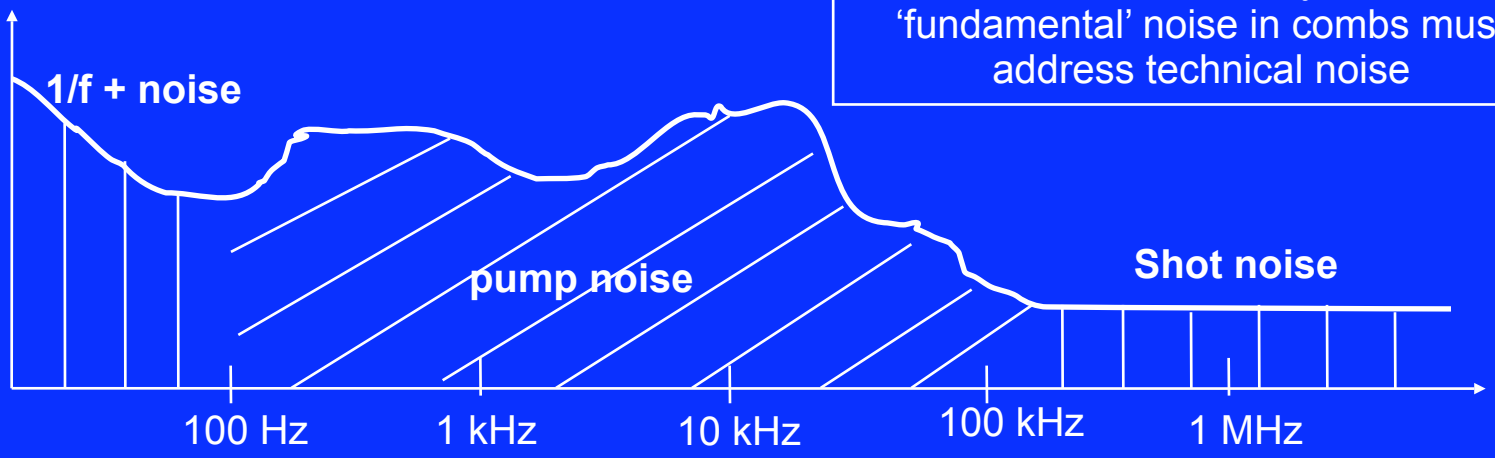


microwave noise from each comb so low that we can only measure it by comparing to another comb.

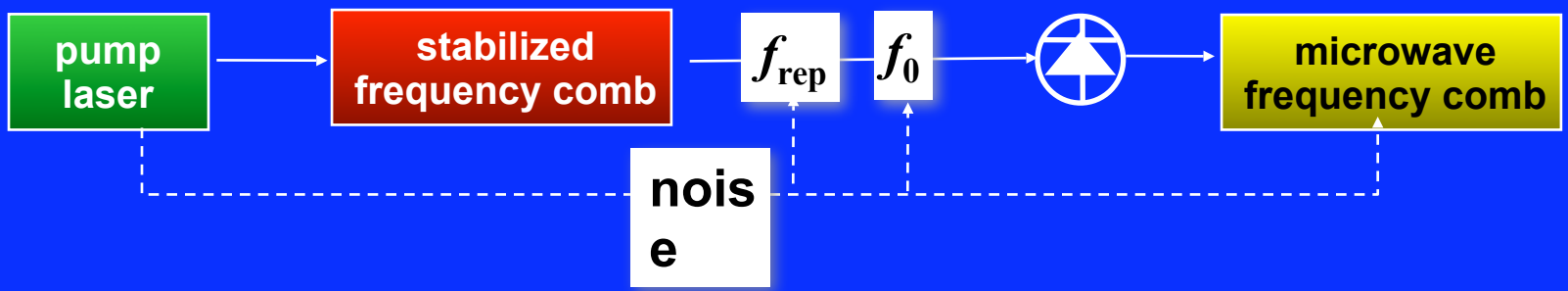
details about current limitations to microwave from combs

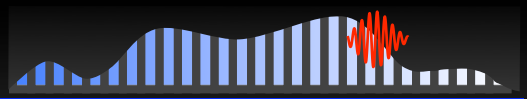


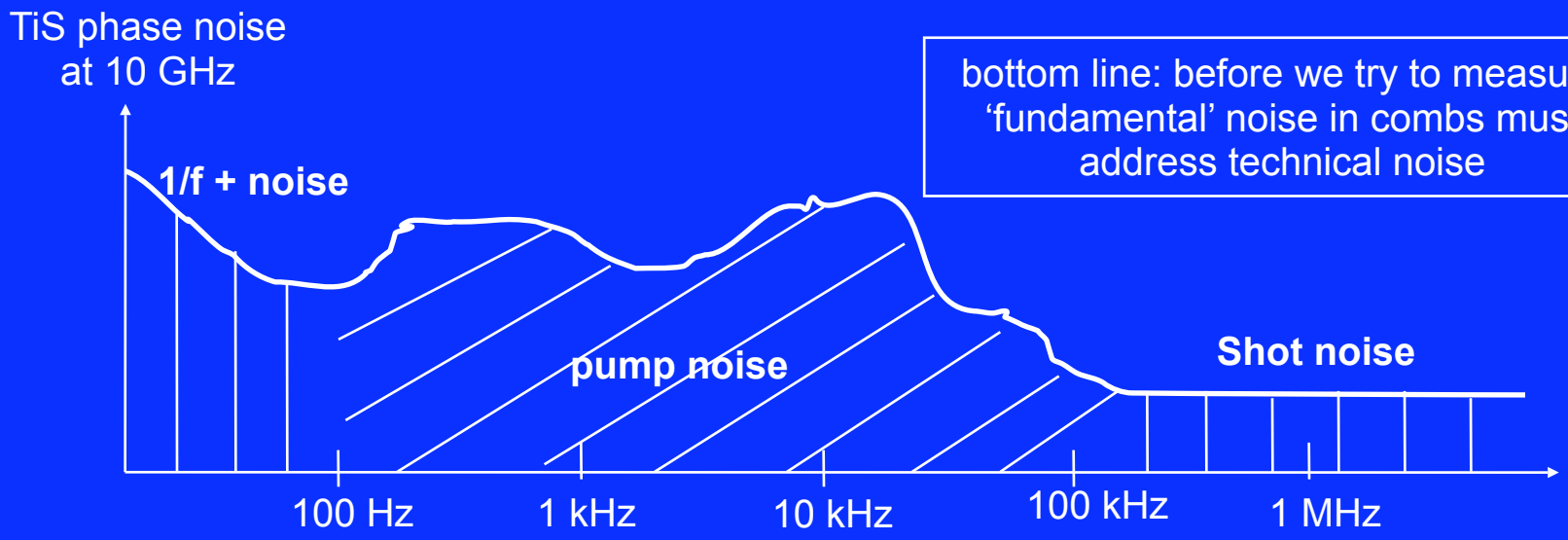
TiS phase noise
at 10 GHz



bottom line: before we try to measure 'fundamental' noise in combs must address technical noise

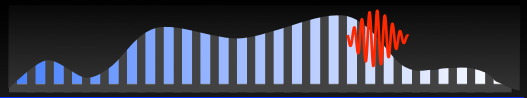






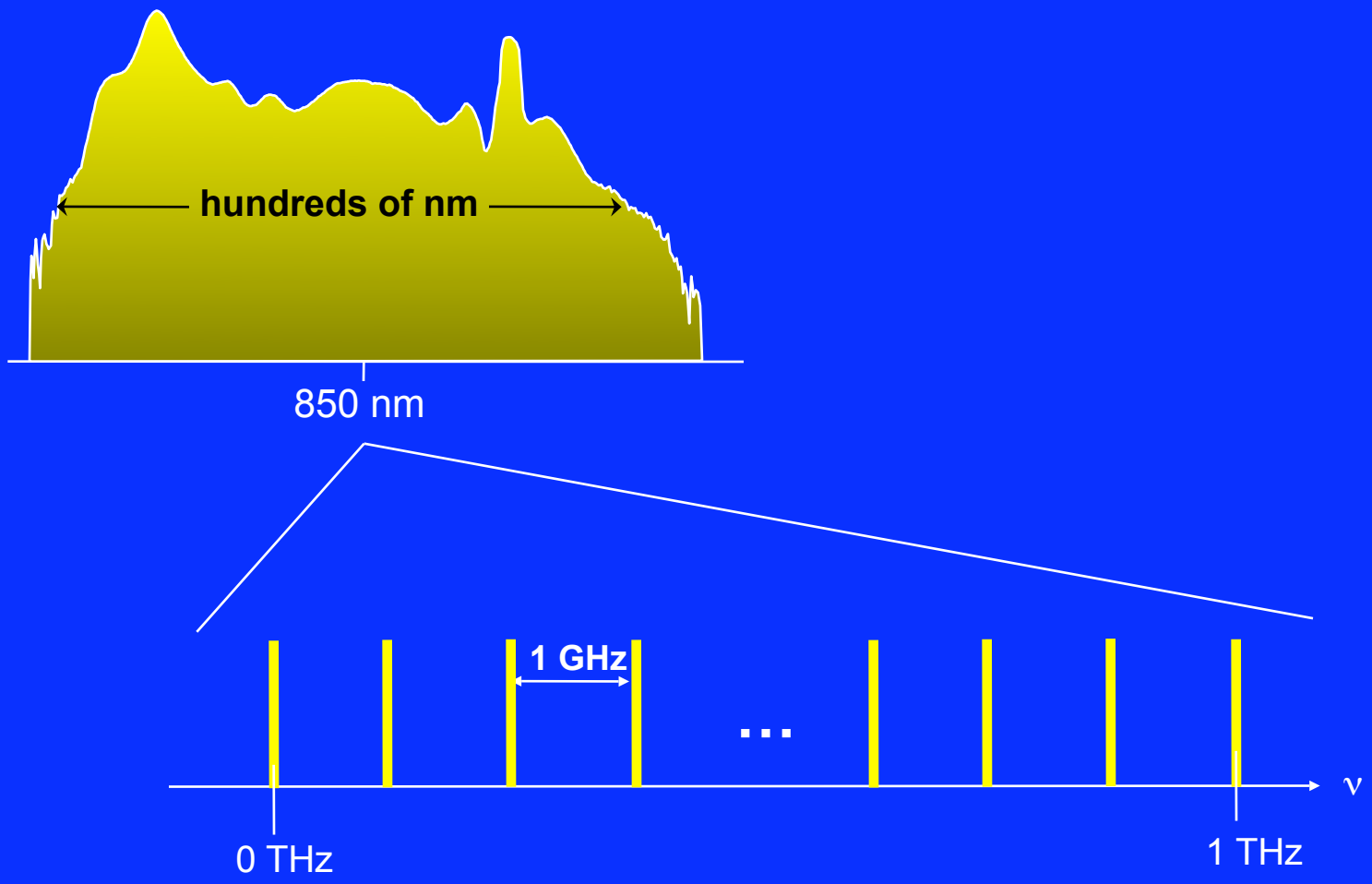
bottom line: before we try to measure 'fundamental' noise in combs must address technical noise

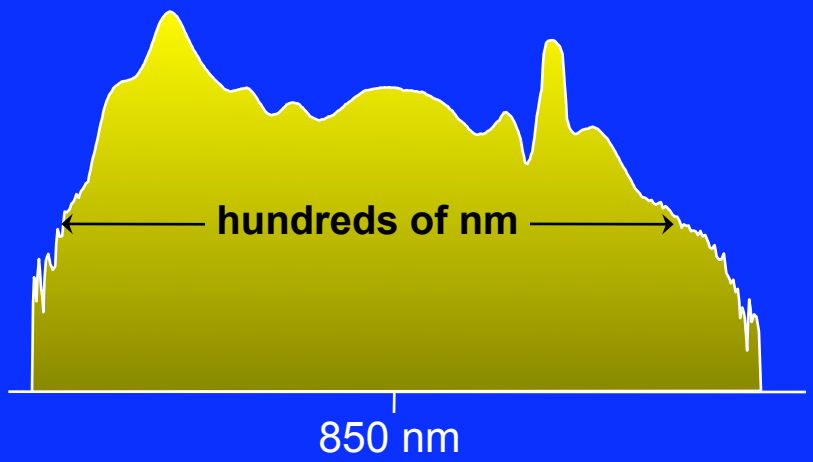
so far, technical noise constitutes our most immediate challenge

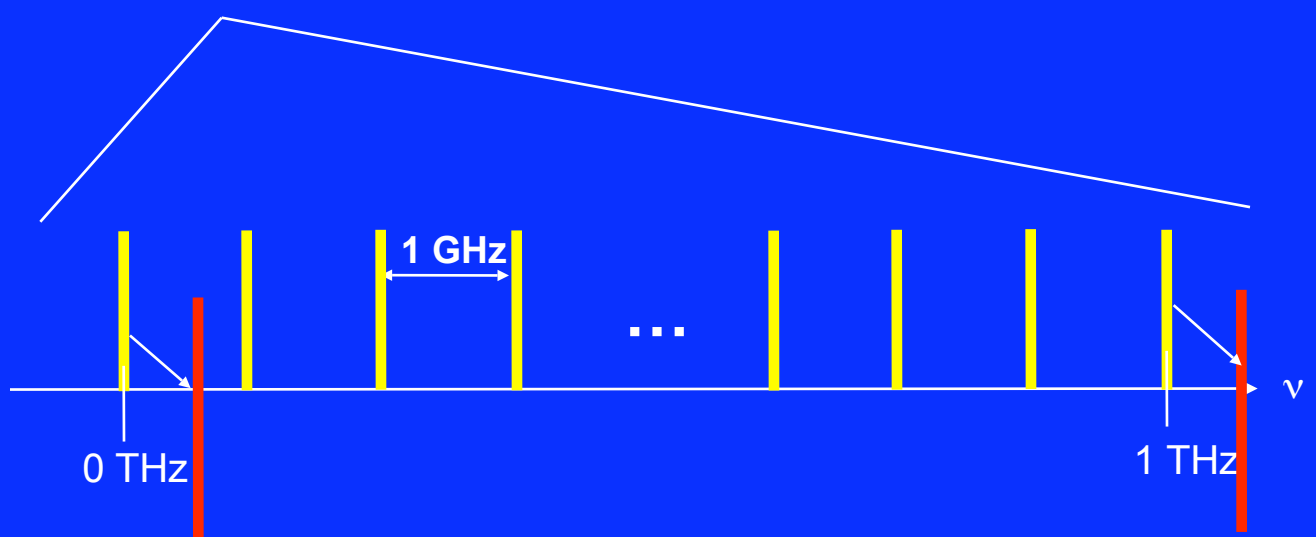


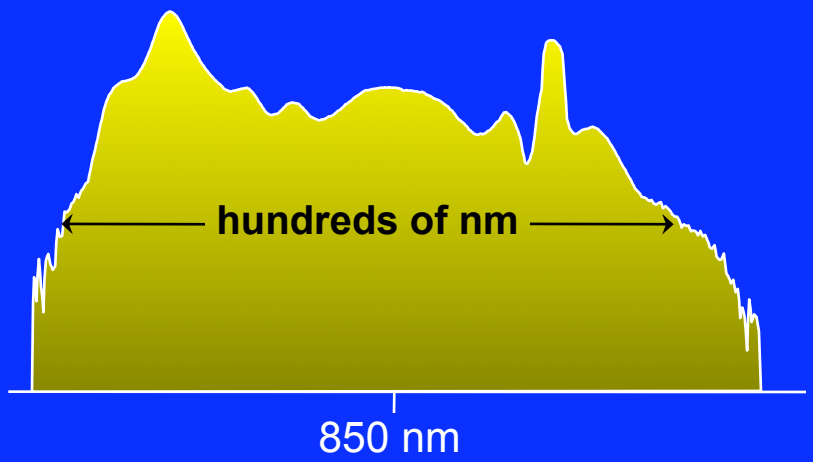
final example of comb application:

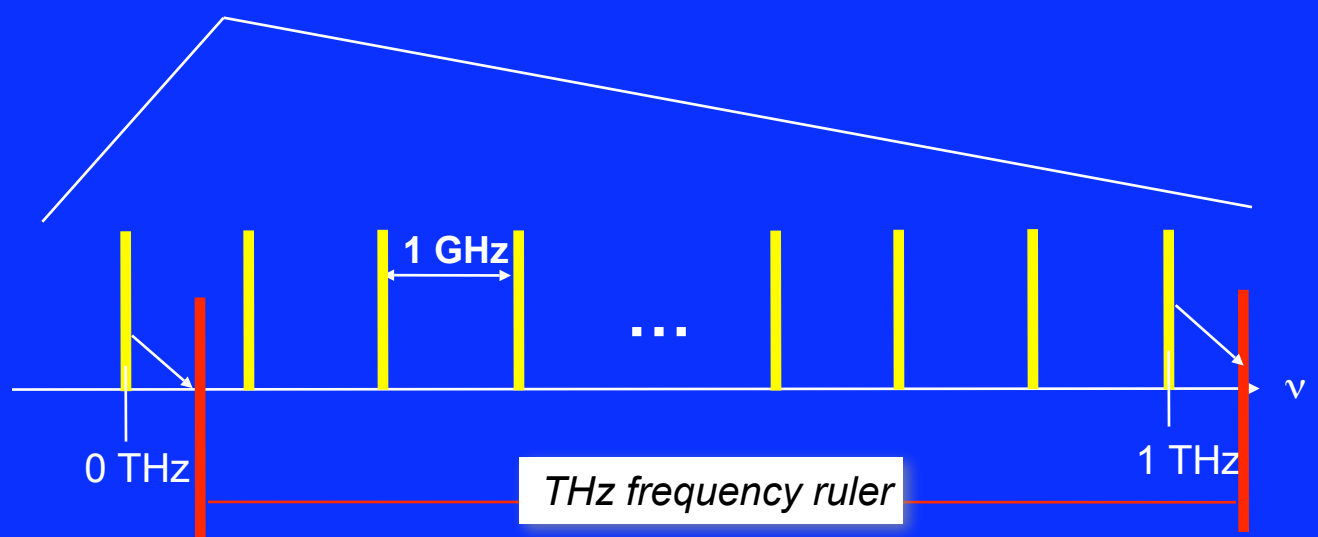
transfer the coherence of comb to terahertz domain


hundreds of nm
850 nm
1 GHz
...
ν
0 THz
1 THz


hundreds of nm
850 nm


1 GHz
...
ν
0 THz
1 THz

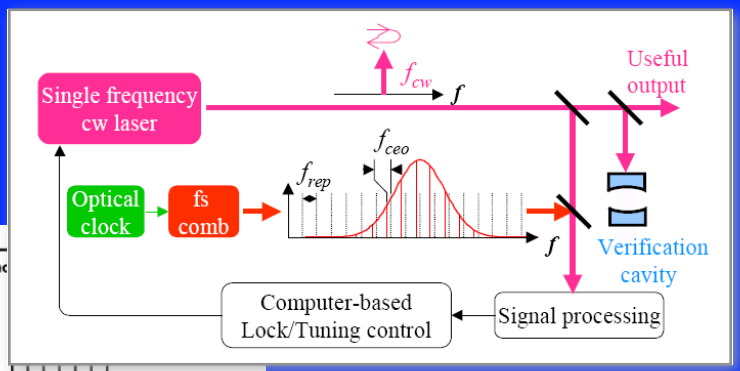

hundreds of nm
850 nm


1 GHz
...
ν
0 THz
1 THz
THz frequency ruler

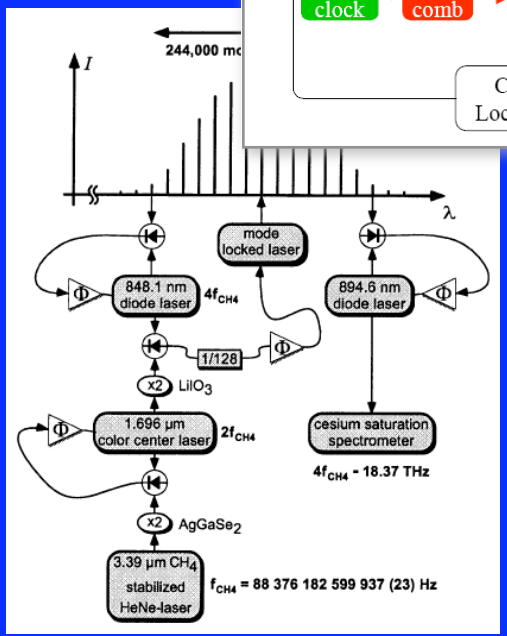
combs for referenced terahertz radiation

§ diode lasers referenced to optical frequency combs

1 THz ~ 0.3 μm



J. D. Jost, J. L. Hall and J. Ye
Opt. Exp. 10, 515 (2002).



Th. Udem, J. Reichert, R. Holzworth and
T. W. Hänsch, Phys. Rev. Lett. 82, 3568 (1999)

combs for referenced terahertz radiation

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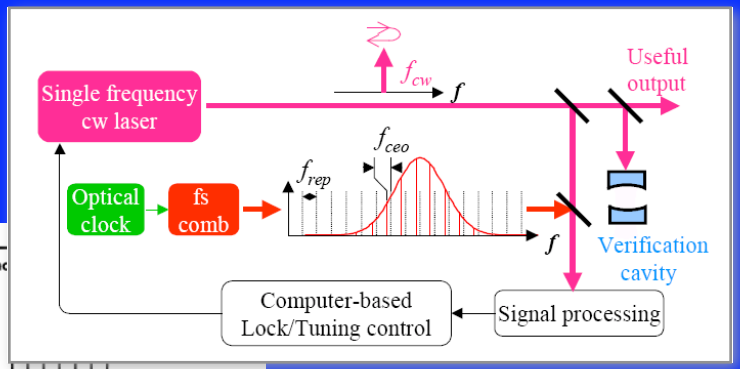

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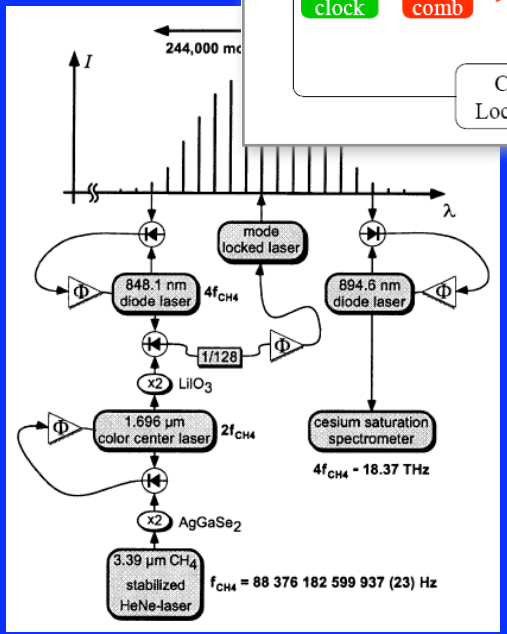

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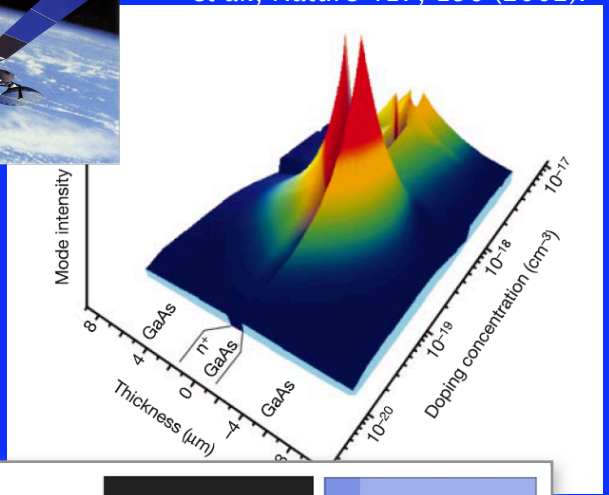
§ THz generation and spectroscopy

0.1 – 10 THz 1 THz ~ 0.3 µm

R. Köhler, A. Tredicucci, F. Beltram, et al., Nature 417, 156 (2002).



B. Ferguson and X. Zhang Nature Mat. **1**, 26 (2002)

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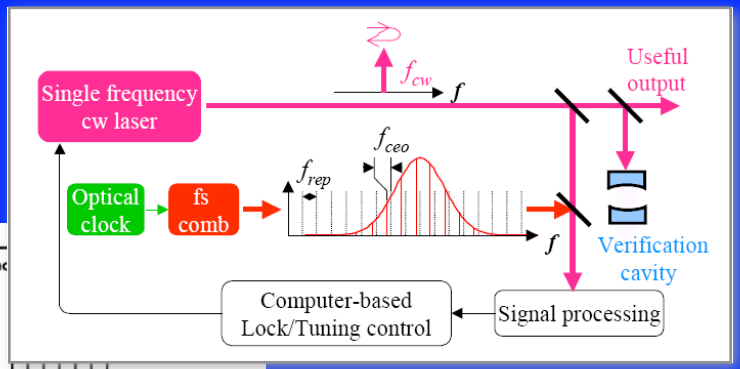

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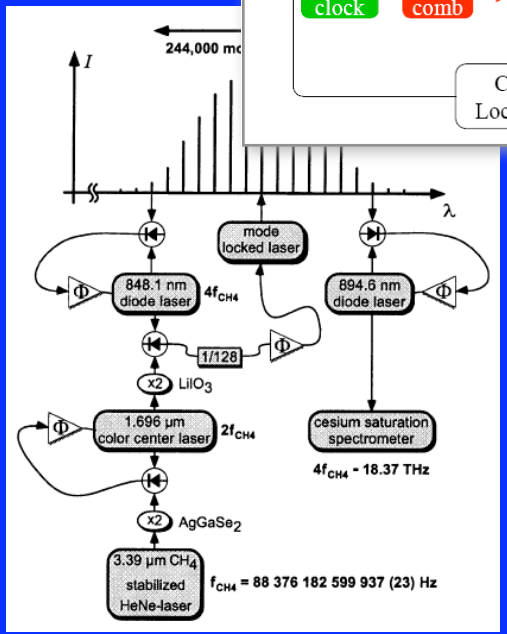

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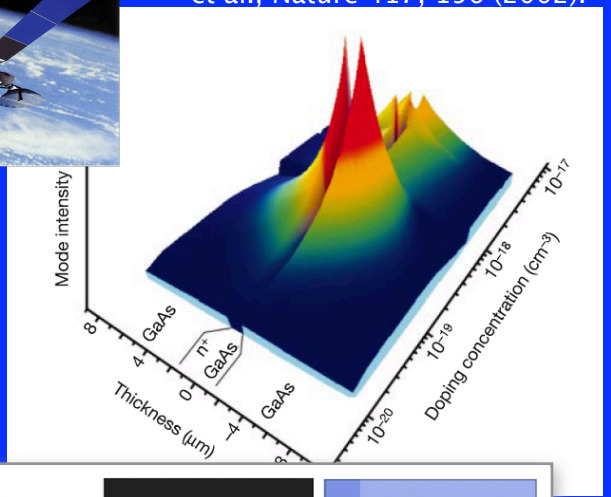
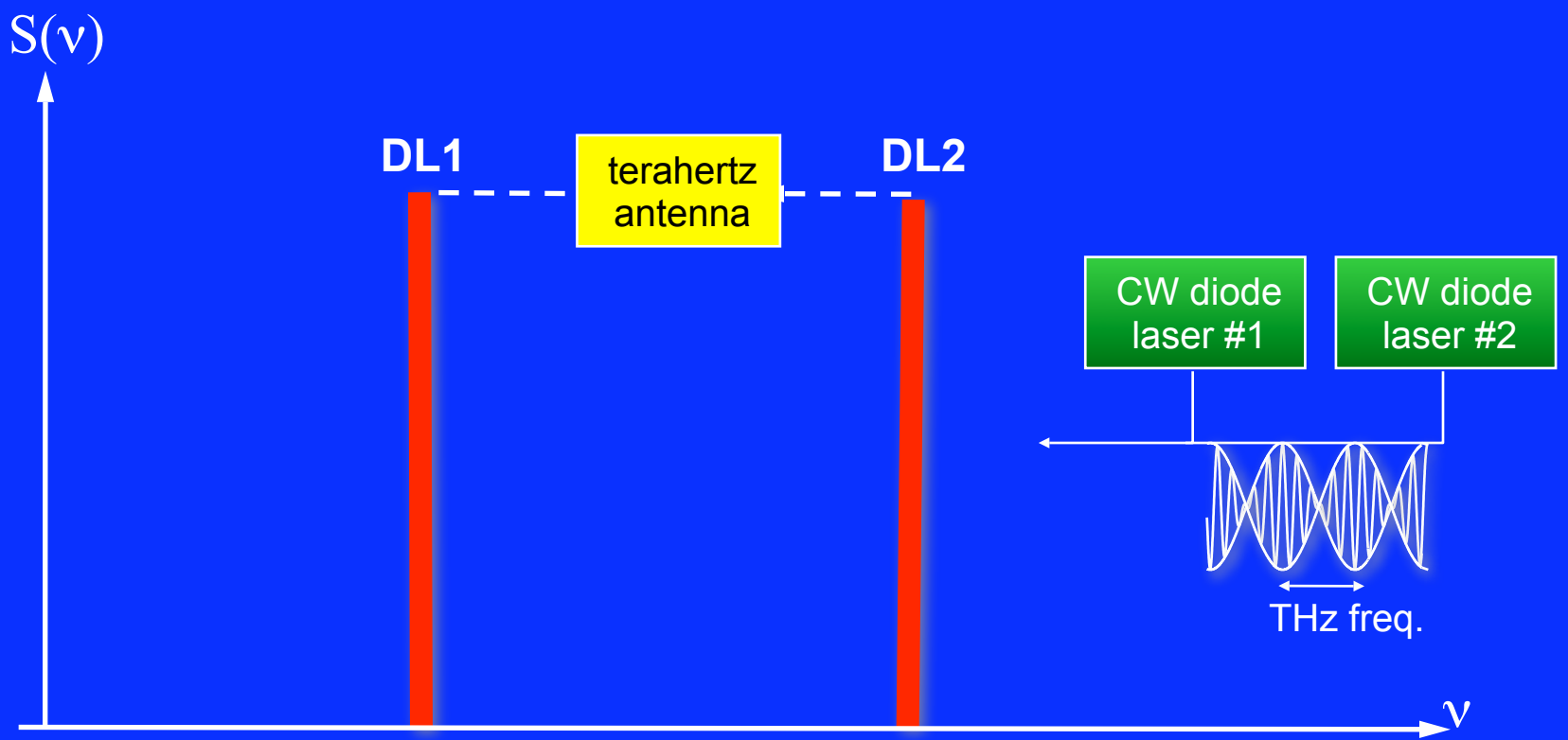
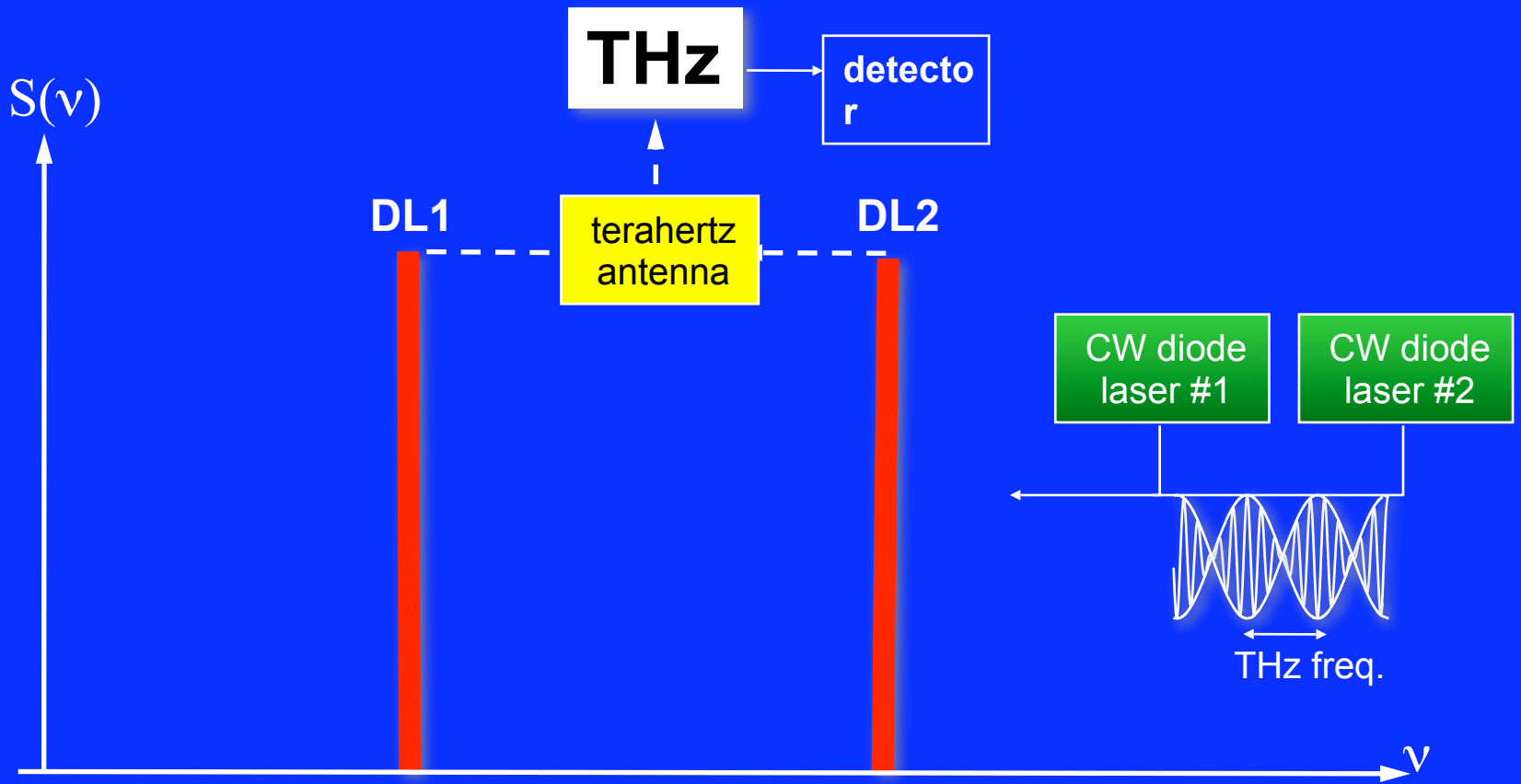


B. Ferguson and X. Zhang Nature Mat. **1**, 26 (2002)

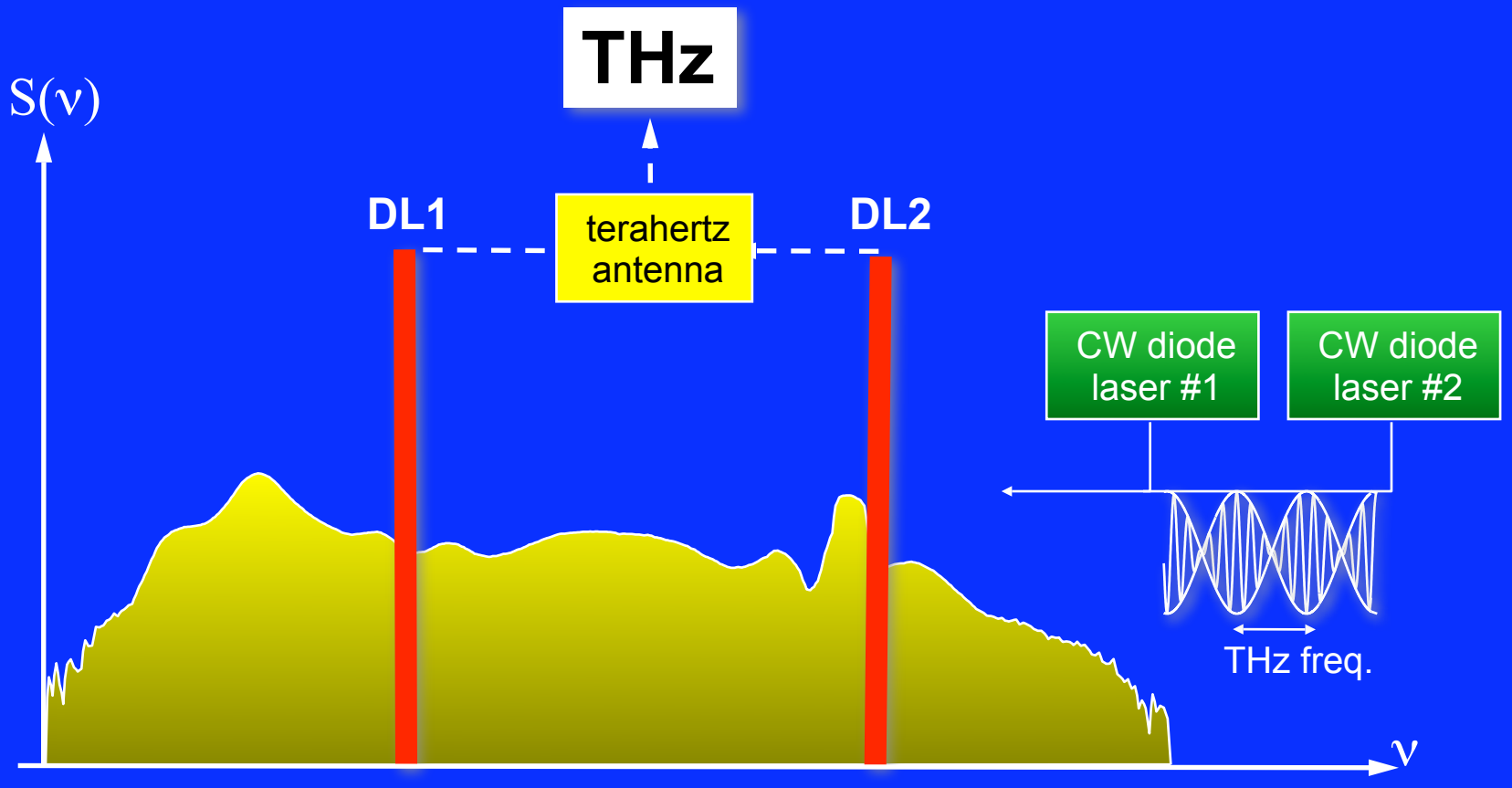
combine powerful ideas of stabilized optical frequency combs with THz domain


S(ν)
DL1
terahertz antenna
DL2
CW diode laser #1
CW diode laser #2
THz freq.
ν


THz
detecto
r
S(ν)
DL1
terahertz
antenna
DL2
CW diode
laser #1
CW diode
laser #2
THz freq.
ν

comb allows us to:

§ broad tune THz
§ know THz freq. precisely while tuning



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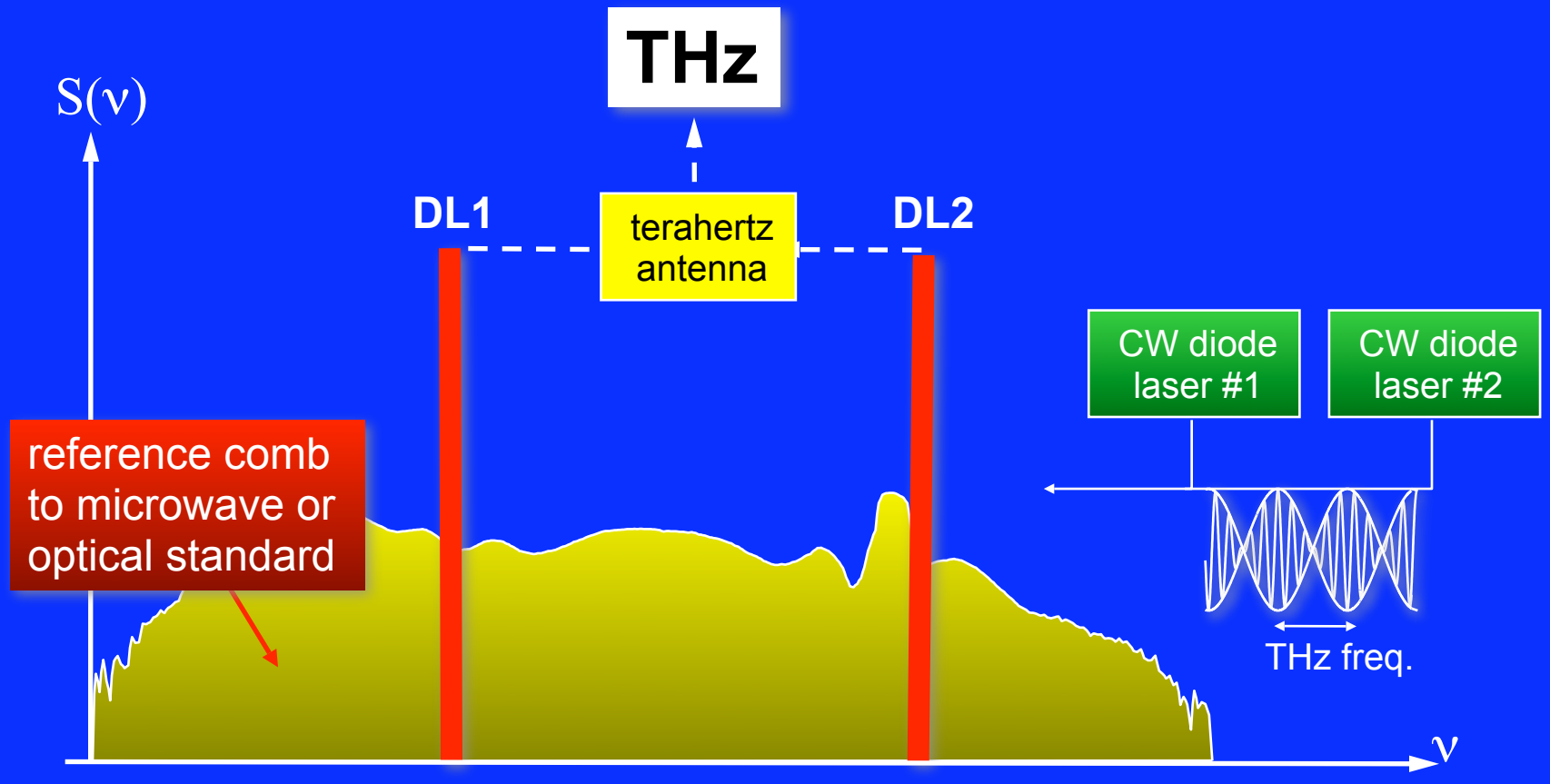

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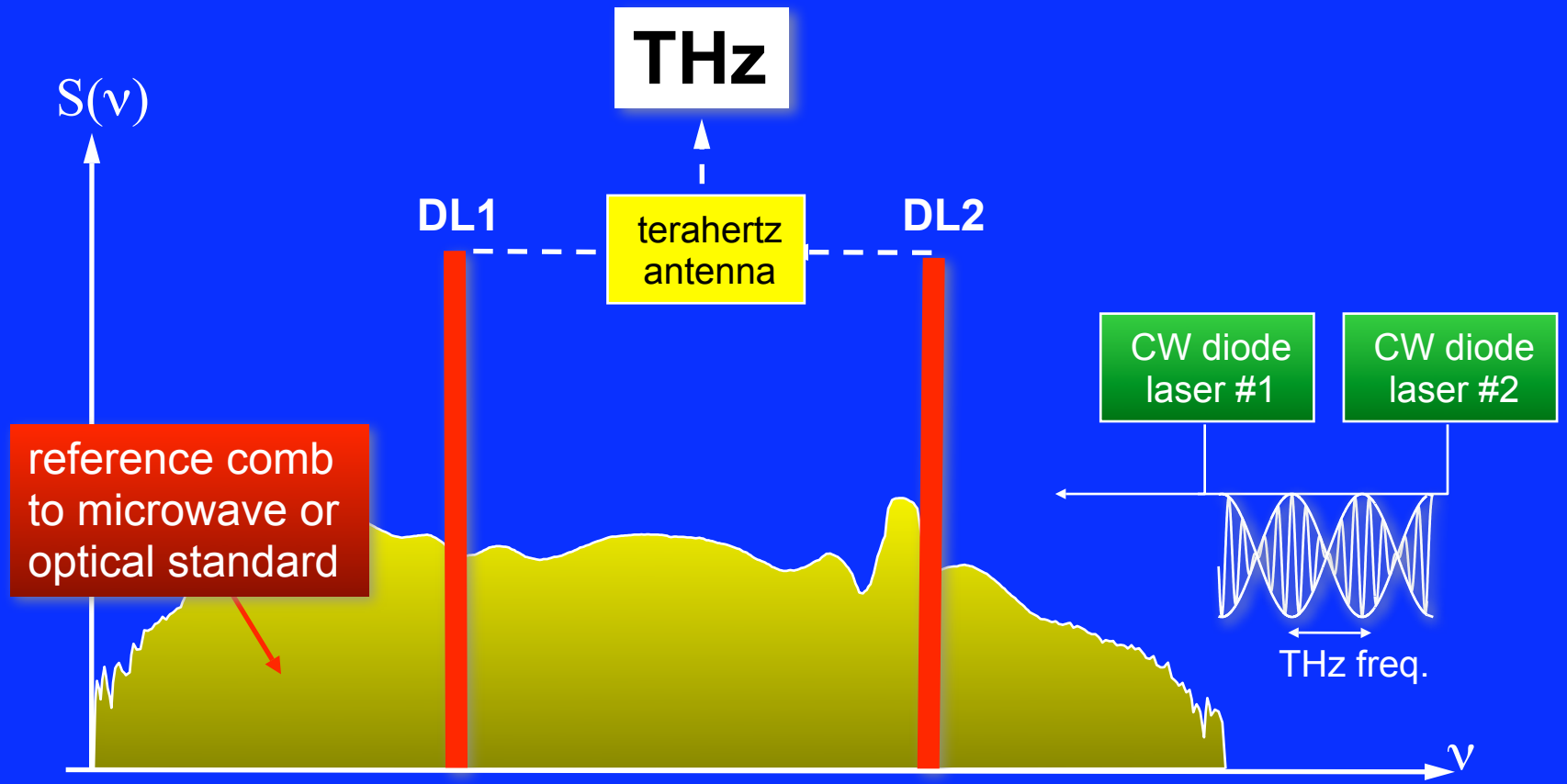
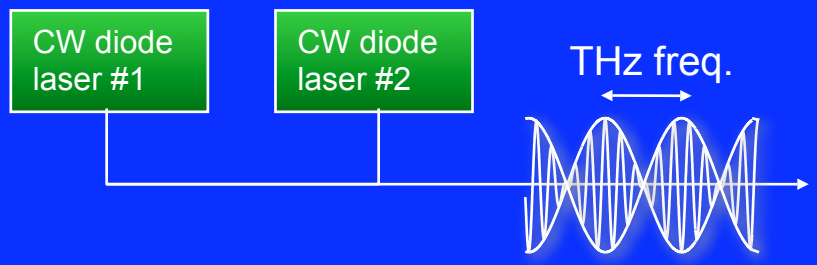


potential applications:

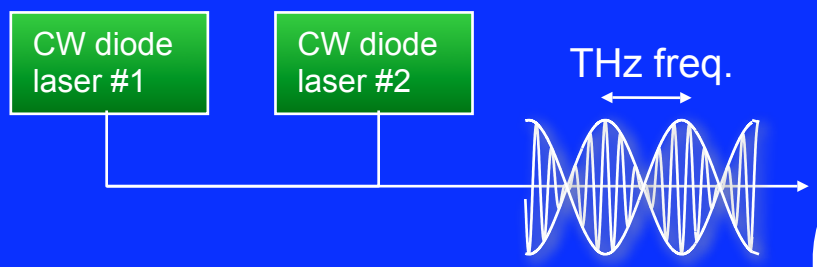
§ THz frequency standards
§ precision molecular spectroscopy
§ commercial applications in defense and space industries
§ studies of semiconductor dynamics

CW THz source: heterodyne photomixer



spiral antennas radiate at detuning between lasers

CW THz source: heterodyne photomixer



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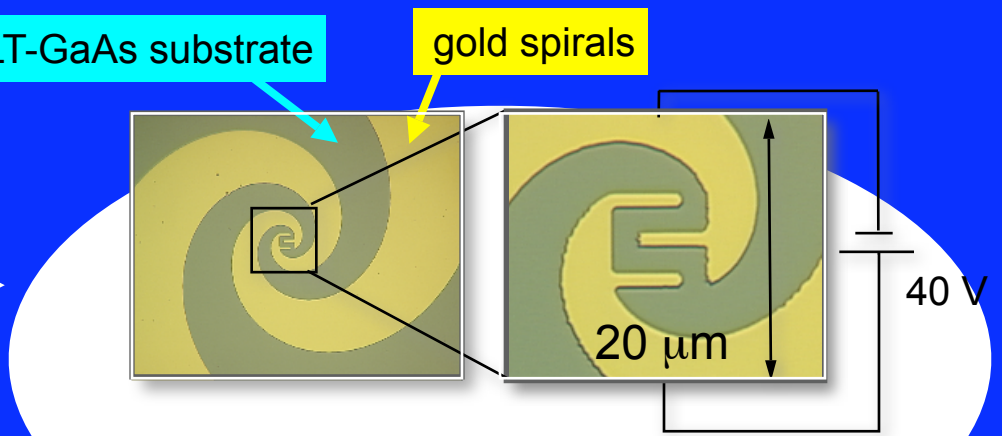
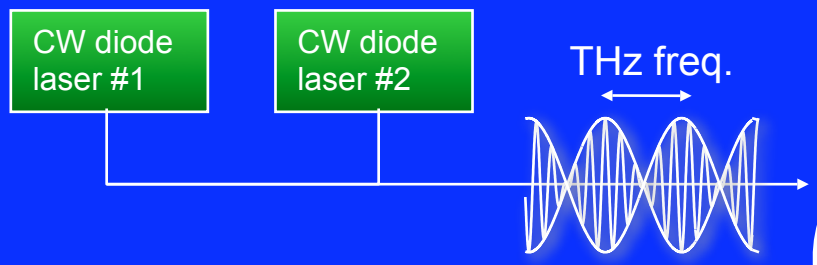


photoconductive antenna on LT-GaAs

$$E_{\mathrm{THz}} \sim \frac{\partial I_{\mathrm{photo}}}{\partial t}$$

Vershese et al. IEEE Trans. on Micro. Theory and Tech. **45** 1307 (1997).
Smith et al. IEEE J. of Quantum Electron. **24** 255 (1988).

CW THz source: heterodyne photomixer



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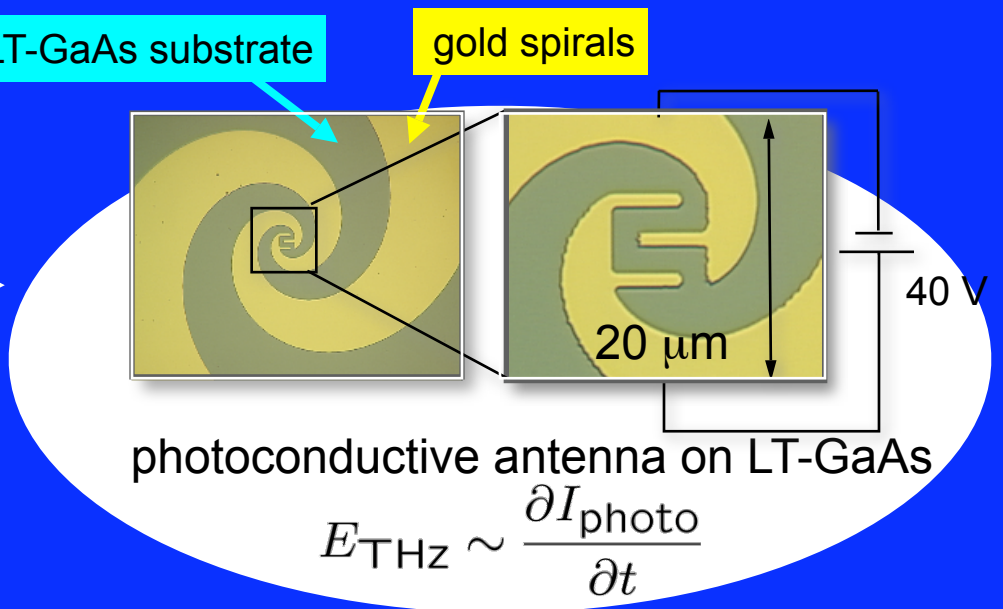

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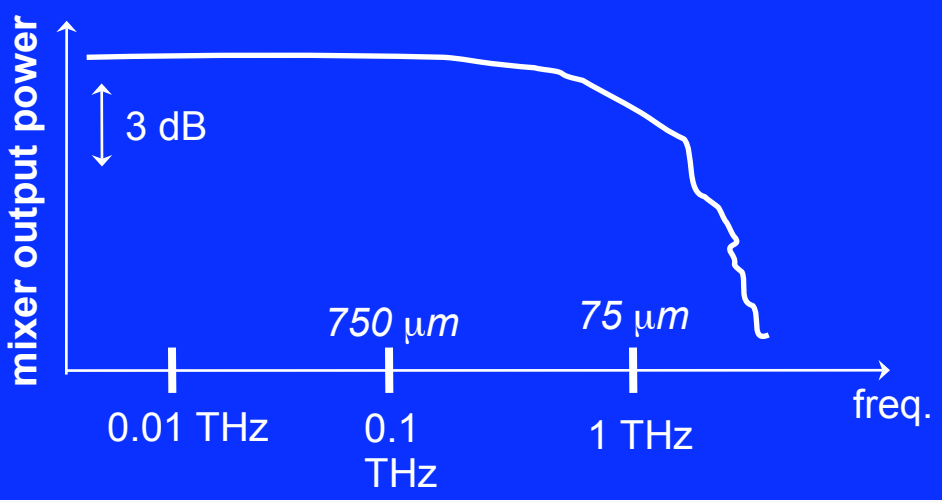
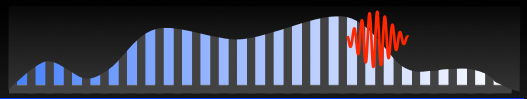
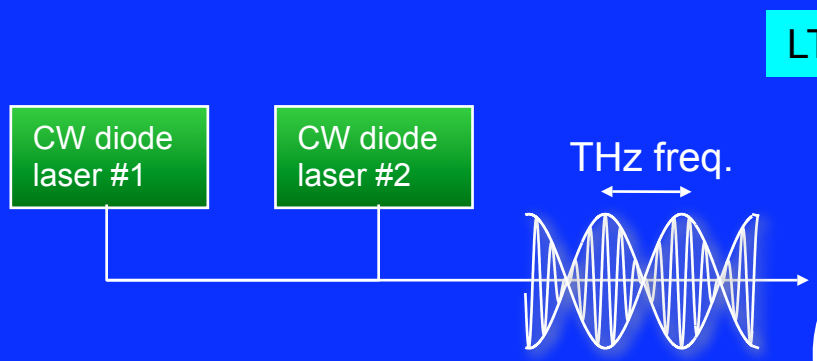


CW THz source: heterodyne photomixer





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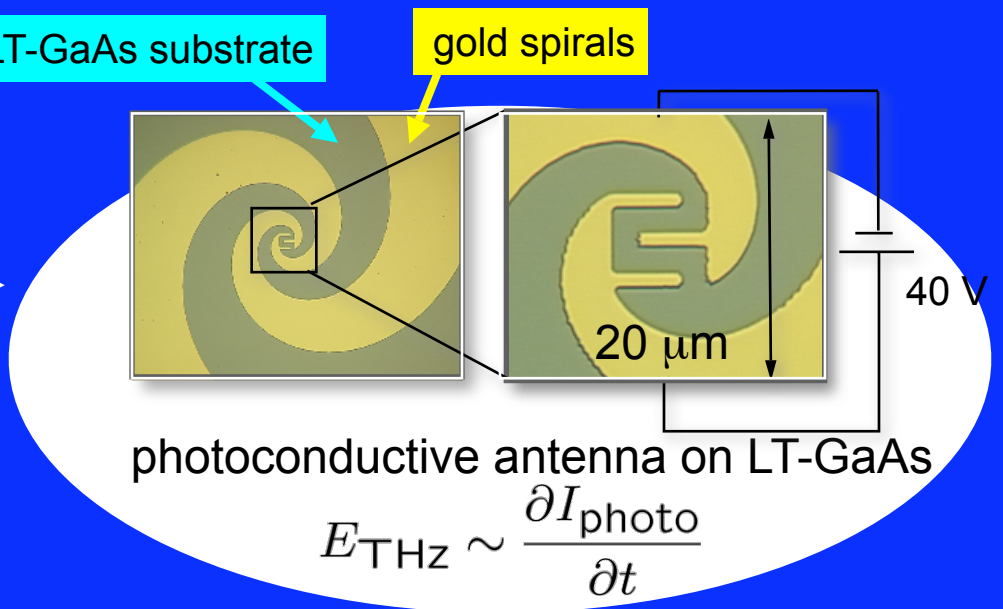
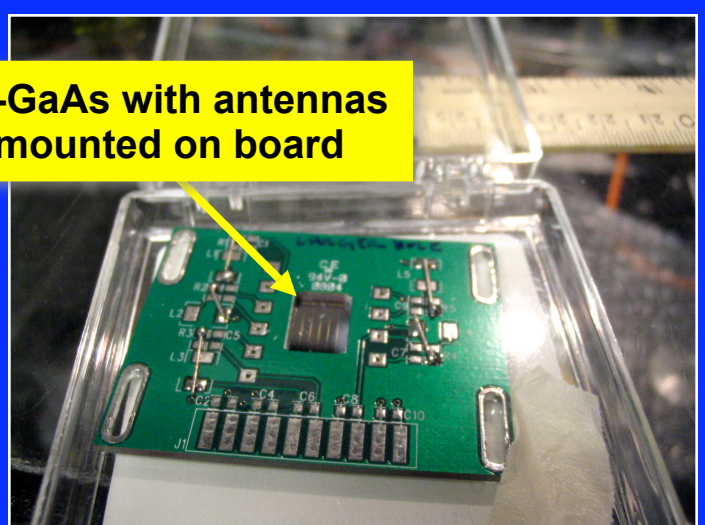
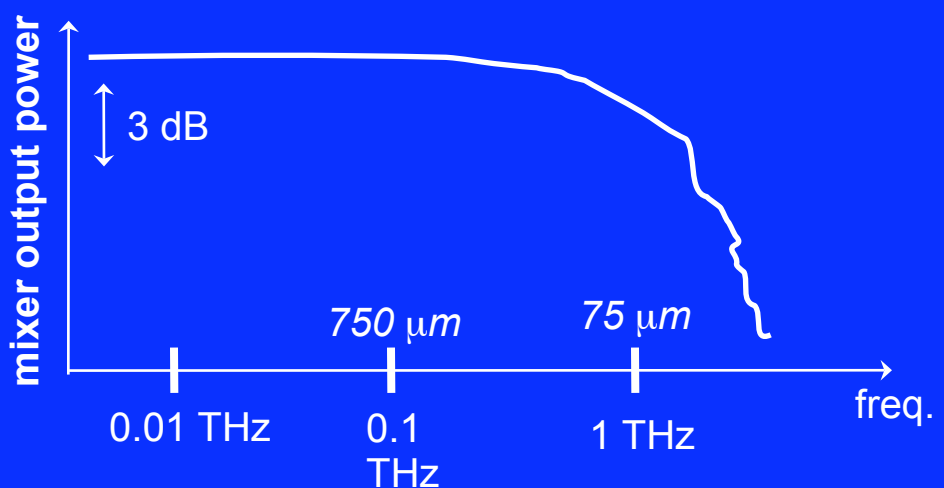


Vershese et al. IEEE Trans. on Micro. Theory and Tech. **45** 1307 (1997).
Smith et al. IEEE J. of Quantum Electron. **24** 255 (1988).

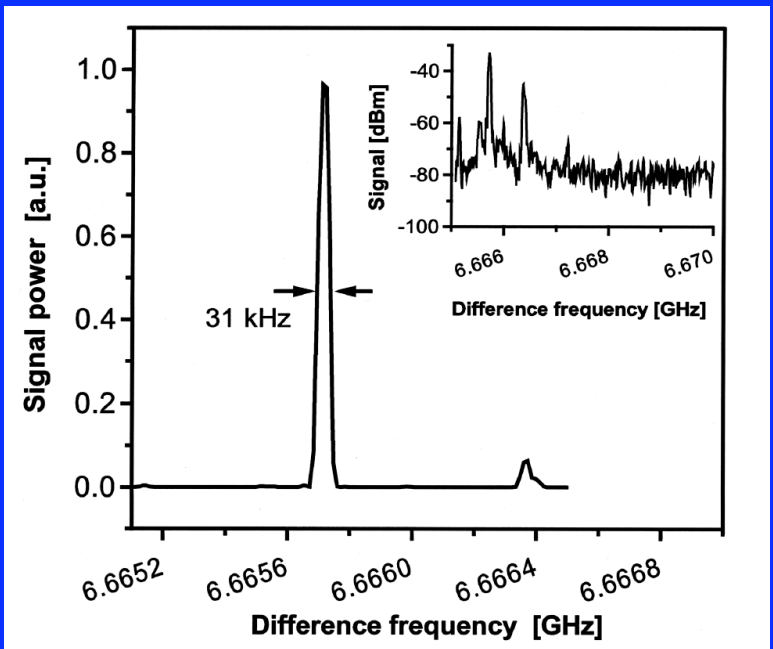




linewidth comparison of our results to others

quantum cascade laser

§ tunability: 10 GHz
§ cryogenic temperatures
§ linewidth ~30 kHz



A. Barkan *et al*., Opt. Lett. **29** 575 (2004).

quantum cascade laser

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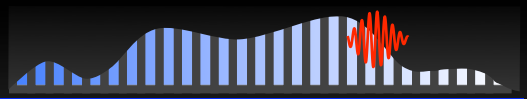

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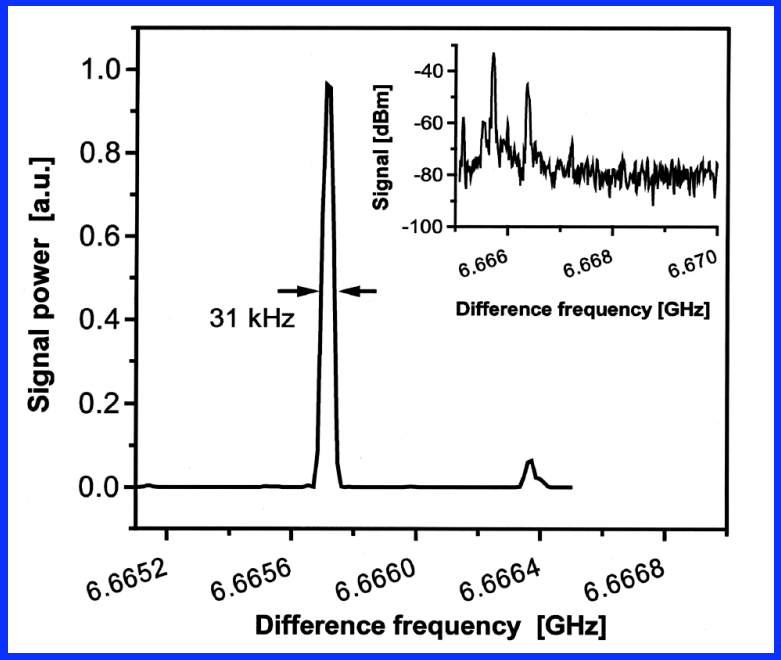
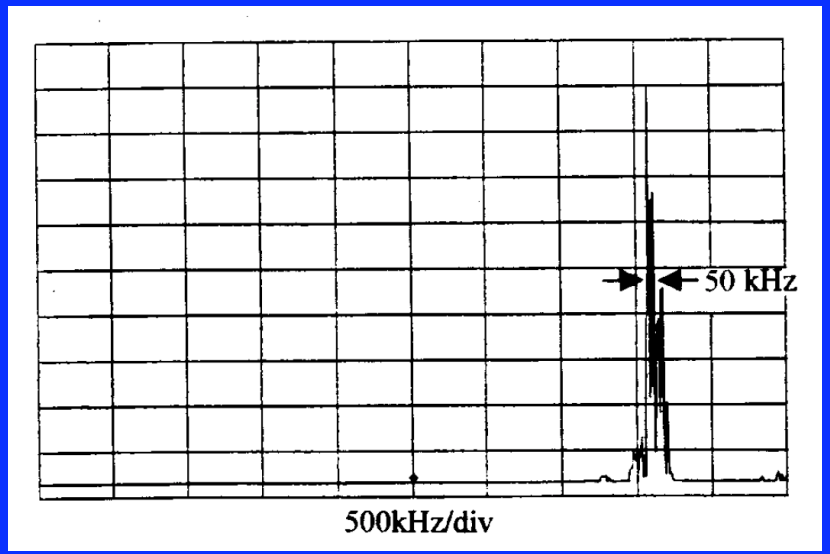


A. Barkan *et al.*, Opt. Lett. **29** 575 (2004).

quantum cascade laser

two CW lasers referenced to optical cavity

§ tunability: THz
§ more work required to know THz frequency
§ locked linewidth ~50 kHz, but can be made narrower

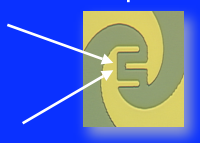


P. Chen *et al.*, App. Phys. Lett. **71** 1601 (1997).

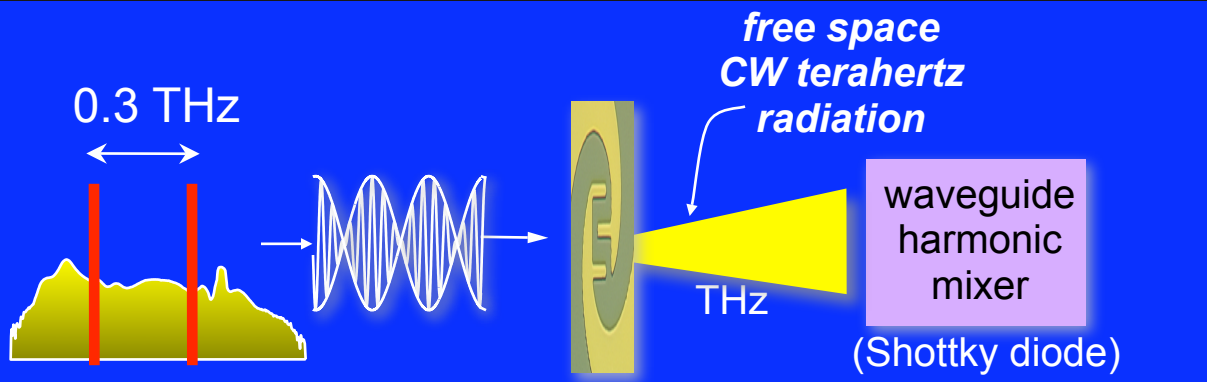
optical cavity

laser #1

laser #2



THz freq. down-conversion: waveguide harmonic mixer



Waltmann, L. W. Hollberg, K. A. McIntosh
and E. R. Brown, Proc. SPIE **2842**, 55 (1996).

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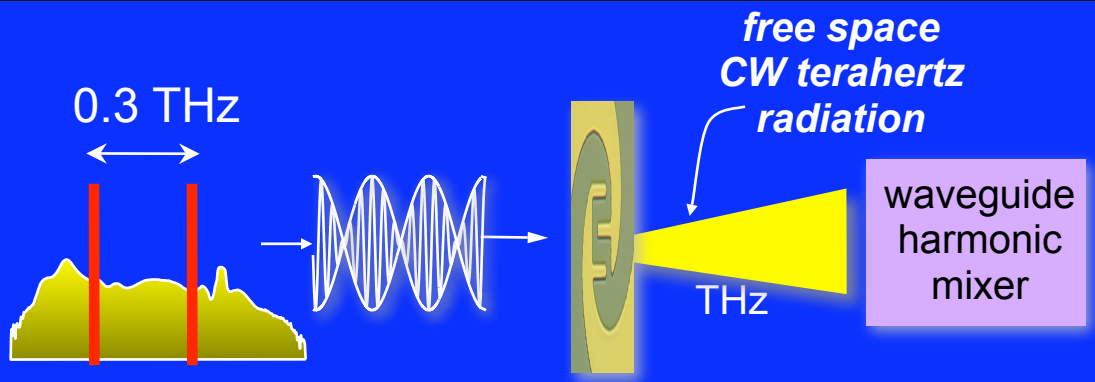

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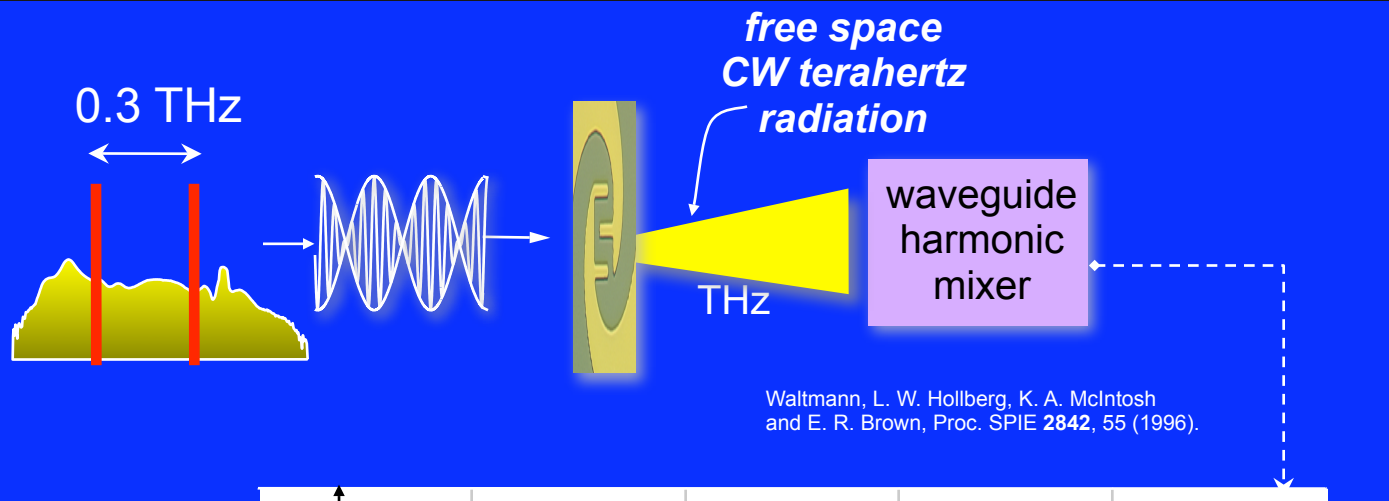

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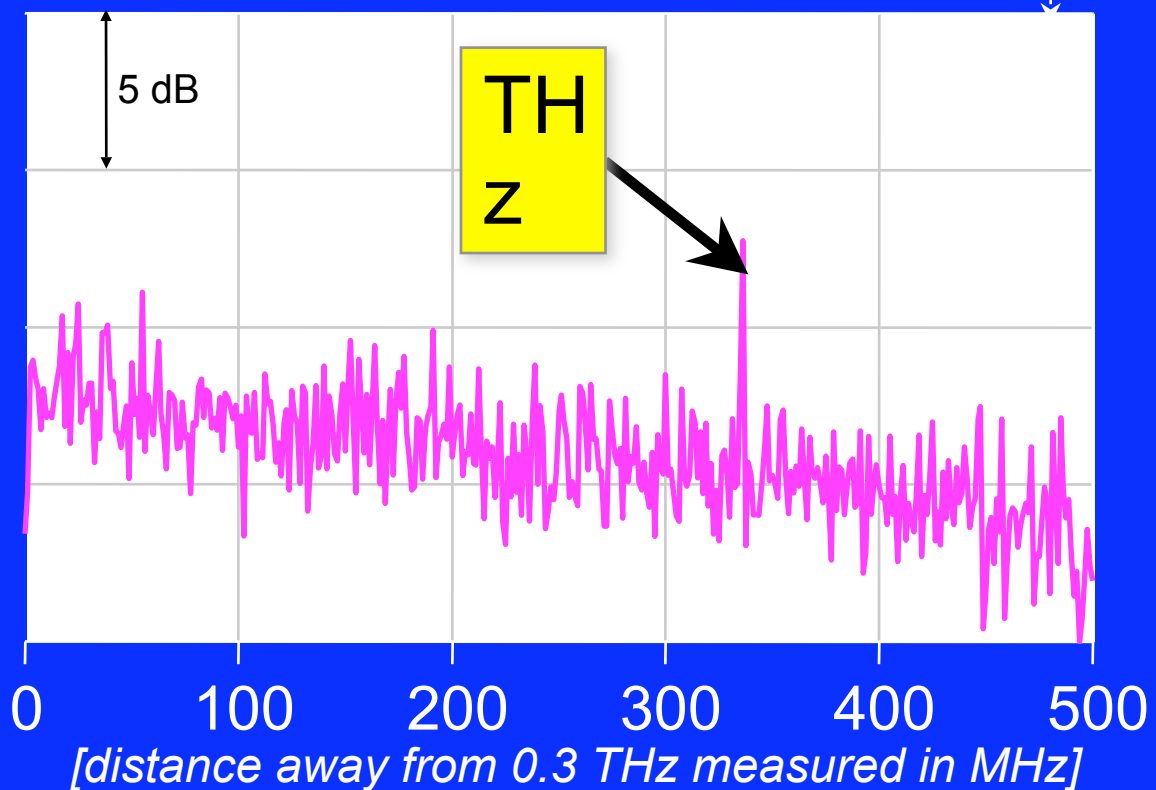

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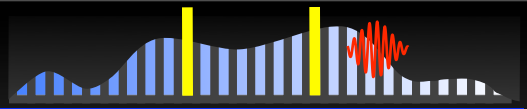

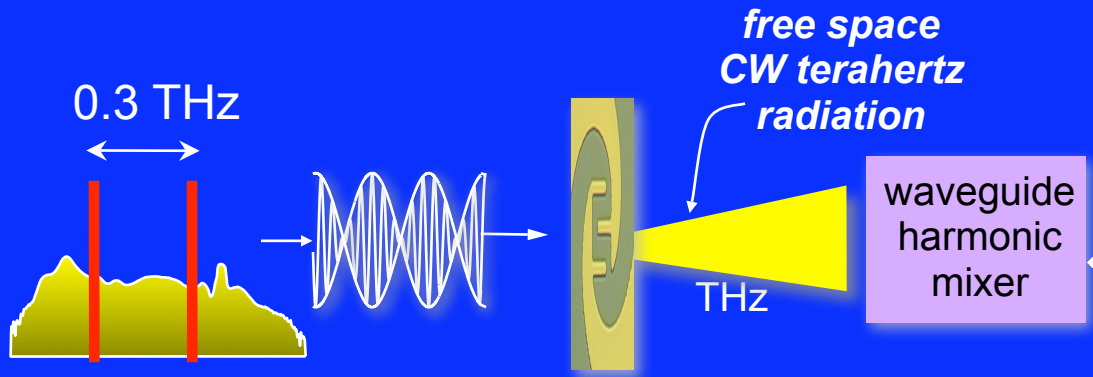

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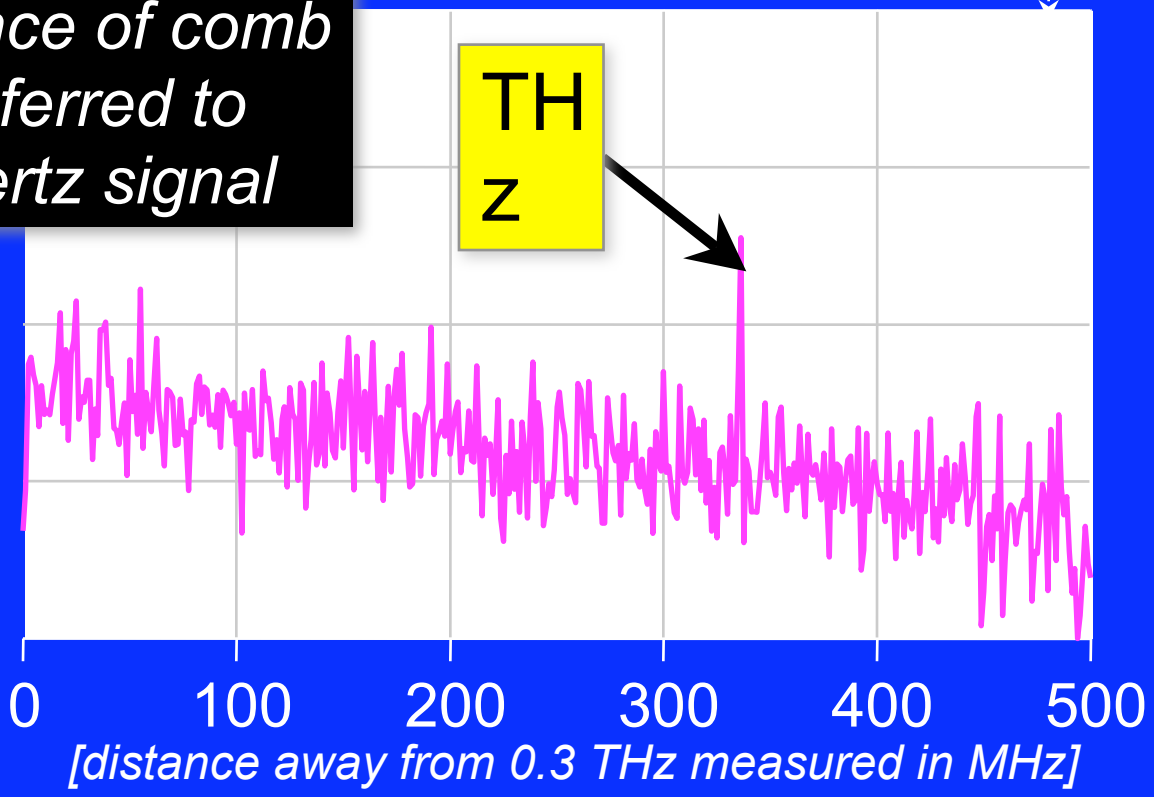
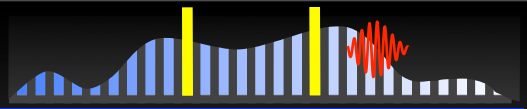
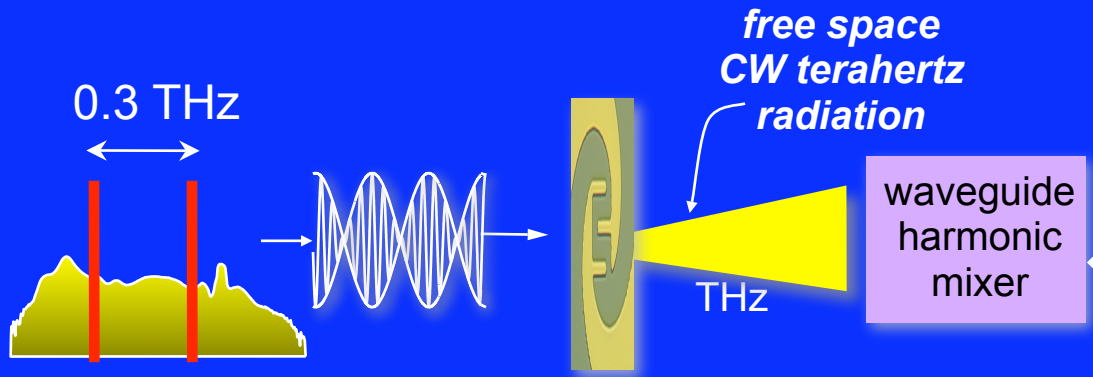
coherence of comb transferred to terahertz signal



THz freq. down-conversion: waveguide harmonic mixer





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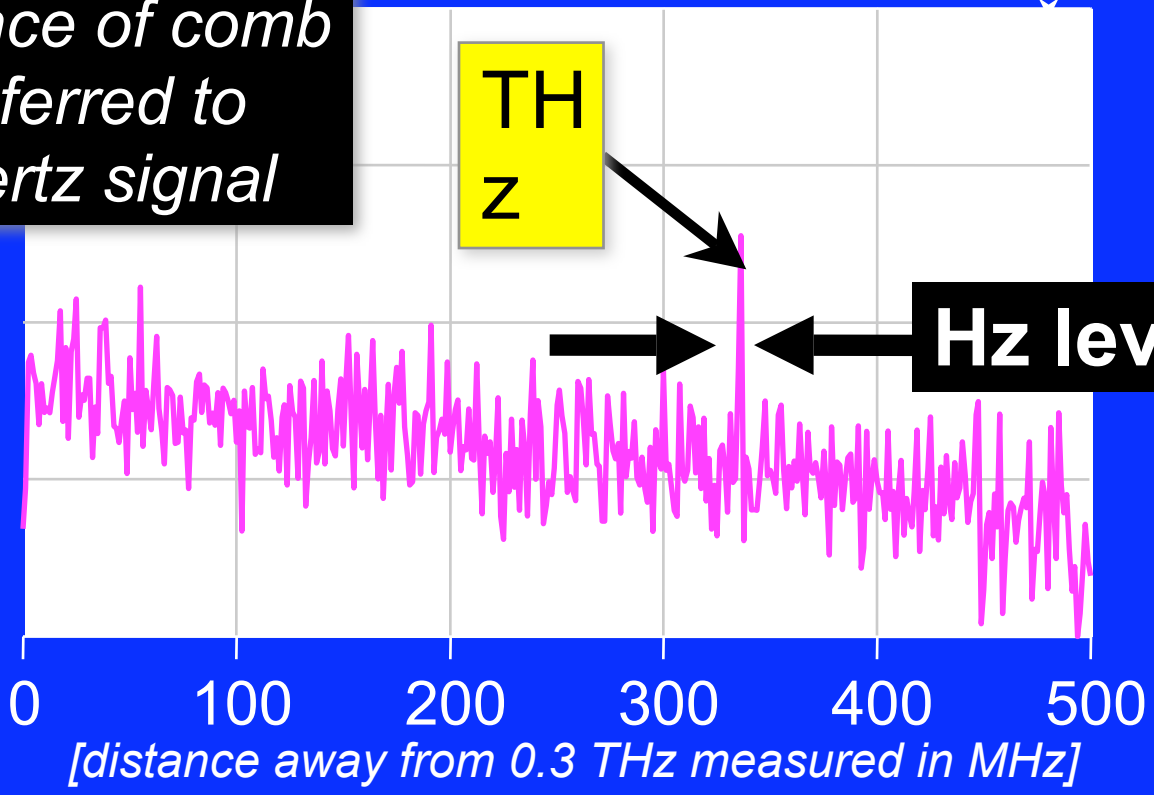

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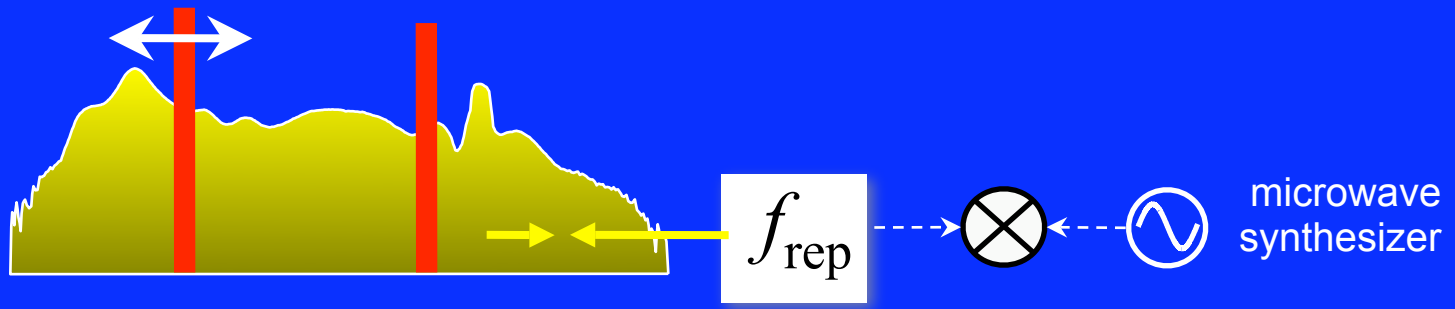
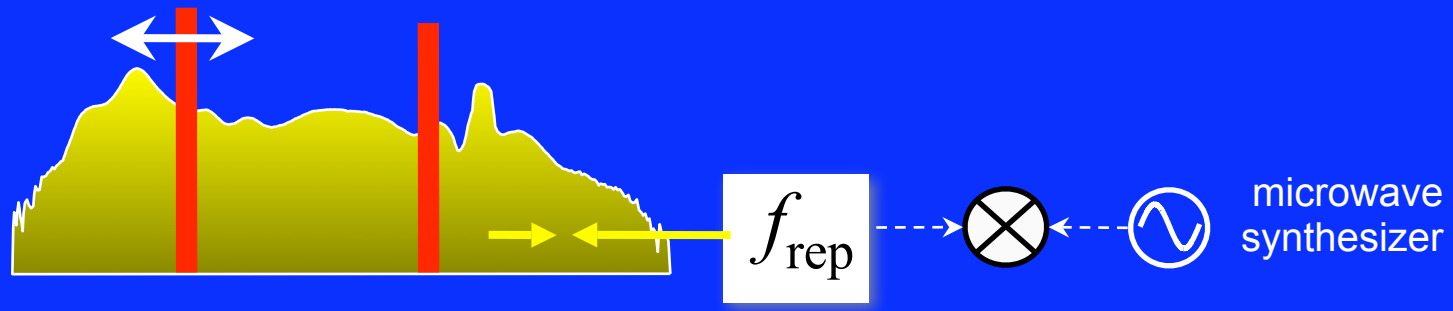
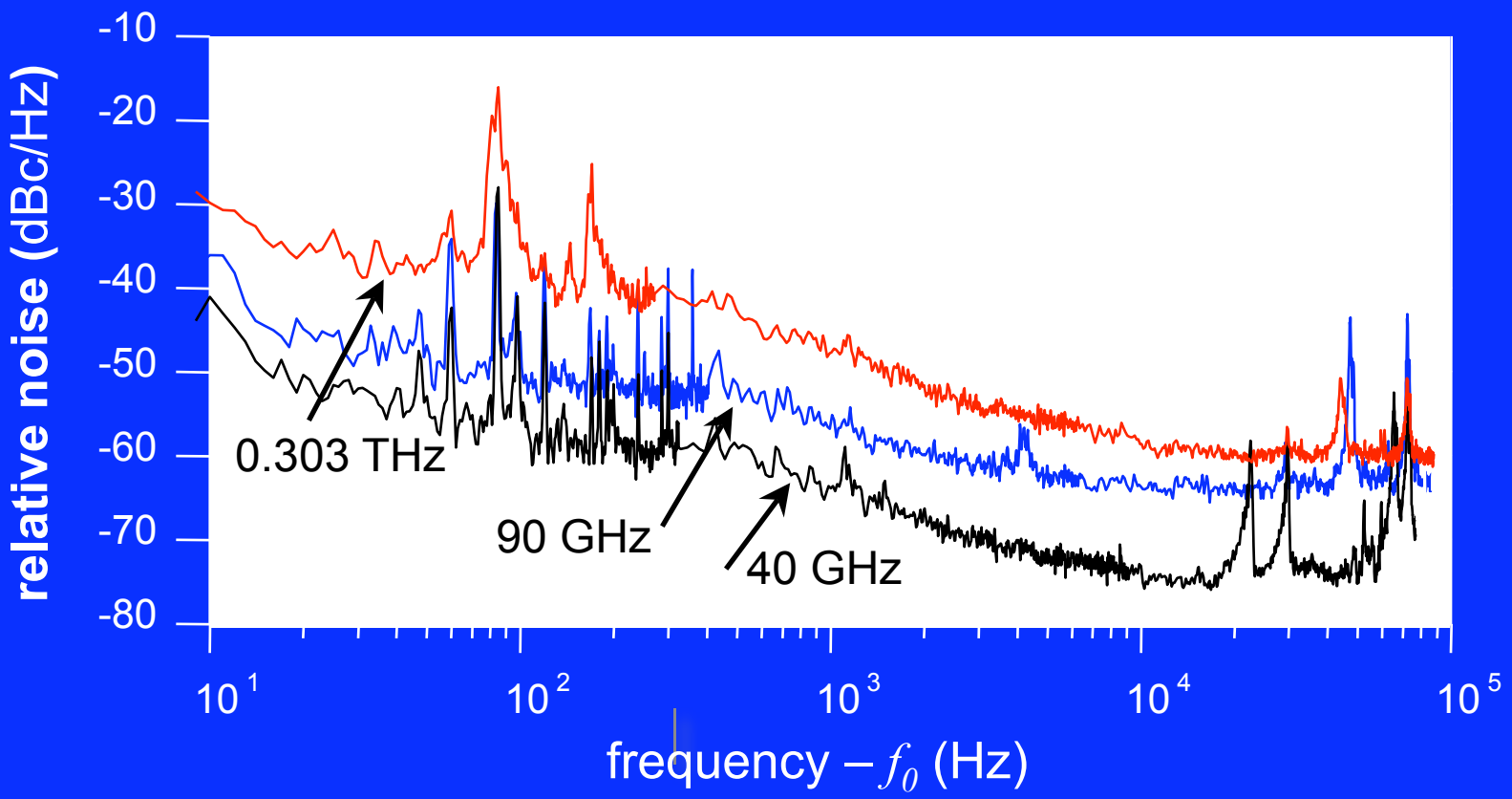
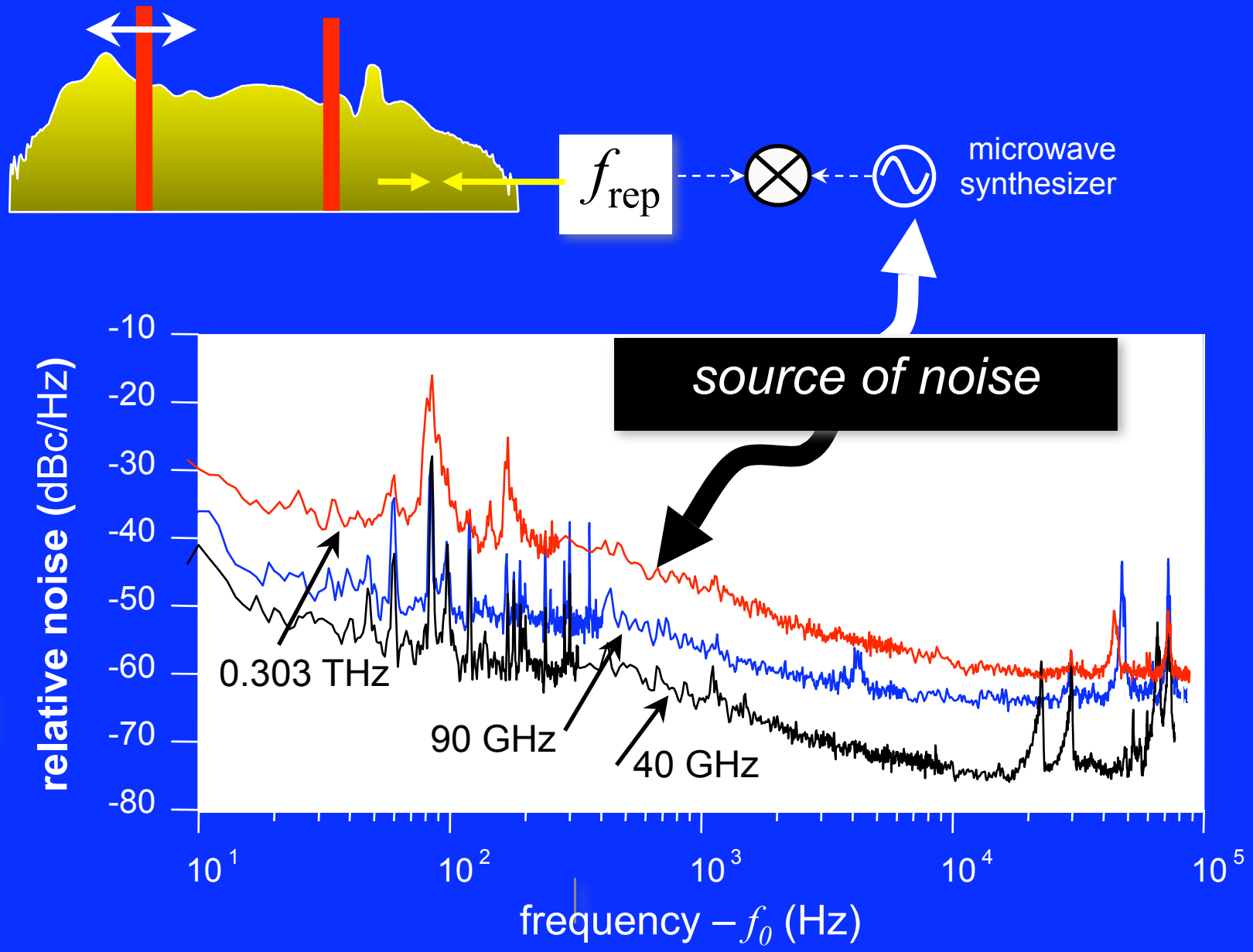


coherence of comb transferred to terahertz



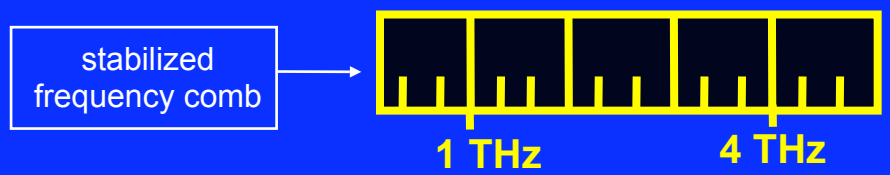


coherence of comb transferred to terahertz



(a) demonstrated that stabilized optical frequency combs may be successfully integrated into THz spectrometers.

resulting in: excellent linewidth and broad tunability

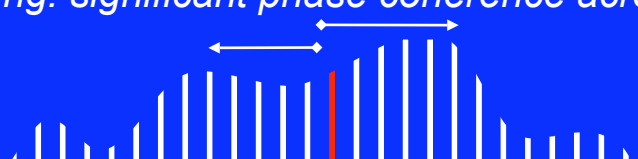


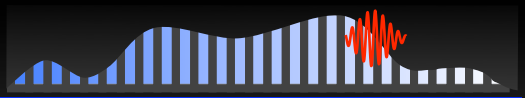
(b) demonstrated improved optical phase noise performance of TiS

resulting in: potential for enhance microwave phase noise performance

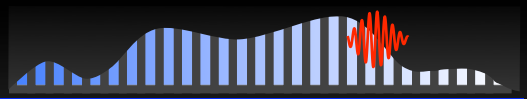
(c) showed optical coherence properties of comb

demonstrating: significant phase coherence across 100s of nm across

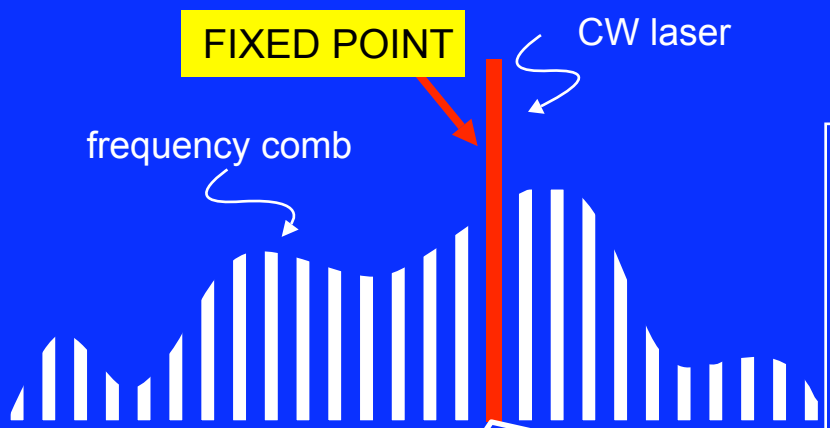




frequency combs locked to optical references



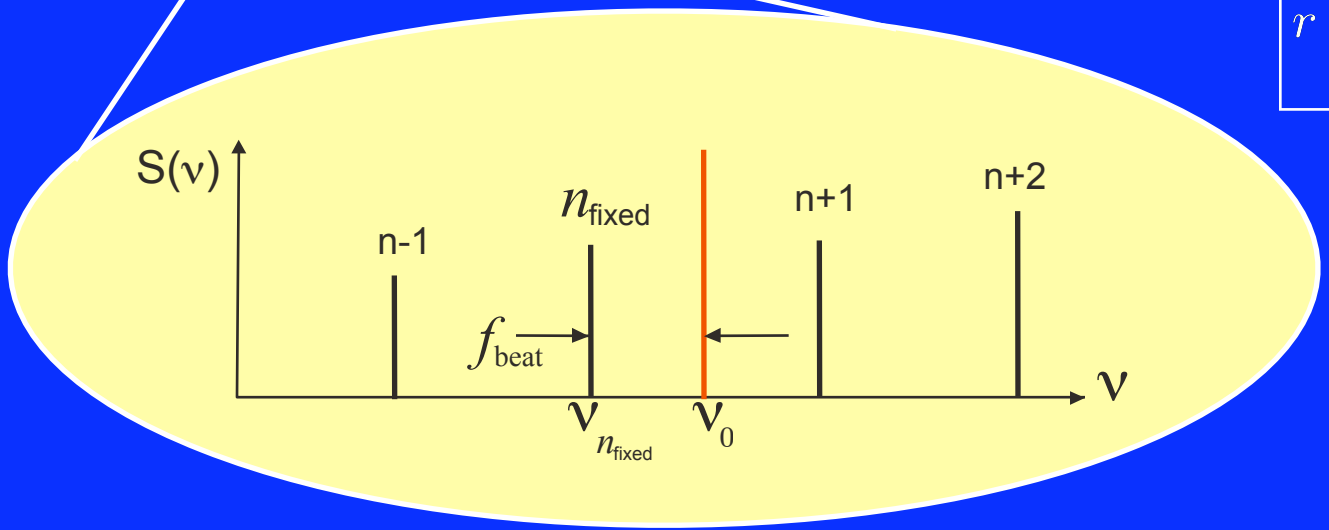
$$f_{rep} = \frac{\nu_0 + f_{beat} - f_0}{n_{fixed}}$$



OFC modes redefined in terms of fixed point

$$\begin{aligned} \nu_n &= n f_{rep} + f_0 \\ &= n\frac{\nu_0 + f_{beat} - f_0}{n_{fixed}} + f_0 \\ &= r(\nu_0 + f_{beat}) + (1-r) f_0 \end{aligned}$$

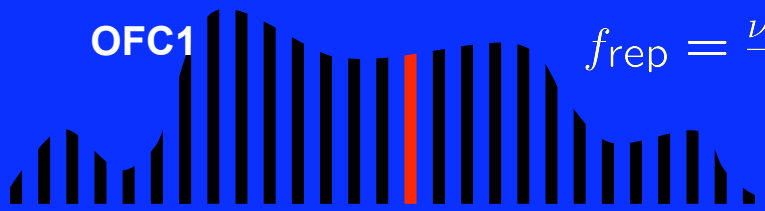
$$r = \frac{n}{n_{fixed}}$$



§ f_0 independently stabilized

deriving prediction for phase noise across comb

§ rewrite comb equation in terms of phase-locked parameters



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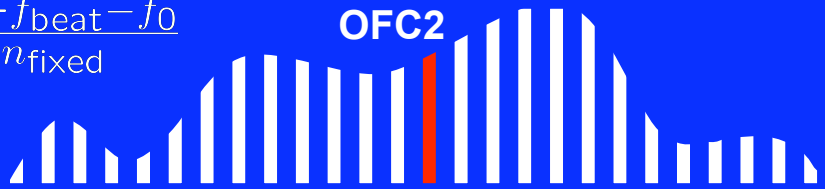

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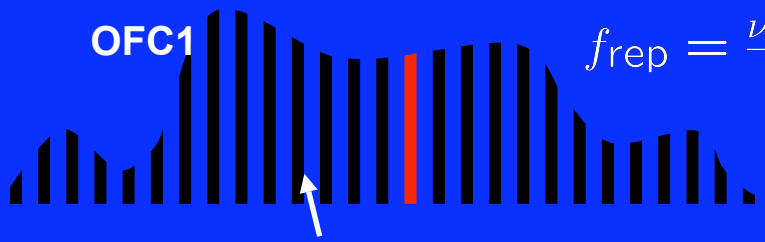
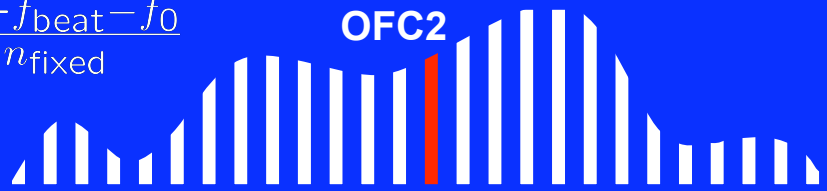


$$f_{\mathrm{rep}} = \frac{\nu_0 + f_{\mathrm{beat}} - f_0}{n_{\mathrm{fixed}}}$$



$$\nu_n = r^n(\nu_0 + f_{\mathrm{beat1}}) + (1 - r)f_{01} \qquad r_n = \frac{n}{n_{\mathrm{fixed}}}$$

deriving prediction for phase noise across comb

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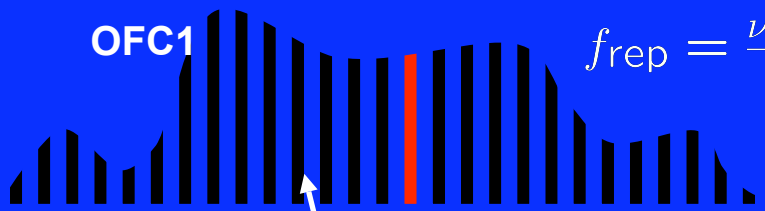

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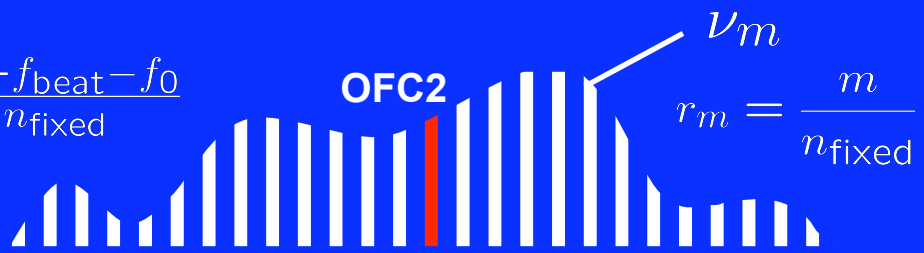

$$r_m = \frac{m}{n_{\mathrm{fixed}}}$$

$$\nu_n = r^n(\nu_0 + f_{\mathrm{beat1}}) + (1 - r)f_{01} \qquad r_n = \frac{n}{n_{\mathrm{fixed}}}$$

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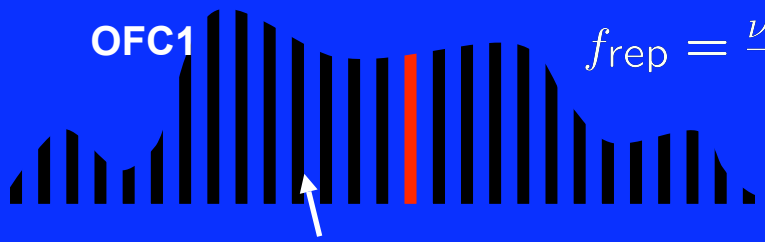

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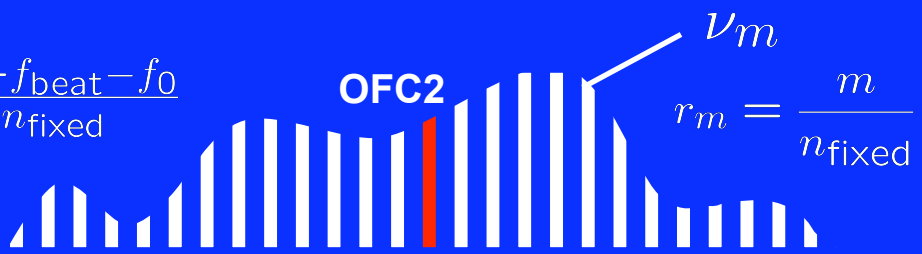


$$r_m = \frac{m}{n_{fixed}}$$

$$\nu_n = r^n(\nu_0 + f_{beat1}) + (1 - r)f_{01} \qquad r_n = \frac{n}{n_{fixed}}$$

§ relative noise between these two, using ν_n equation is:

projected phase noise

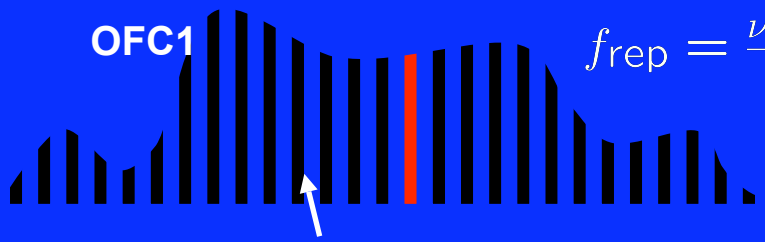
phase noise of each locked parameter

$$S_{\Phi,m,n}(f) = (r^m - r^n)^2 \sum_i S_{\phi,i(f)} \quad \frac{\text{rad}^2}{\text{Hz}}$$

(we neglect cross terms)

deriving prediction for phase noise across comb

§ rewrite comb equation in terms of phase-locked parameters



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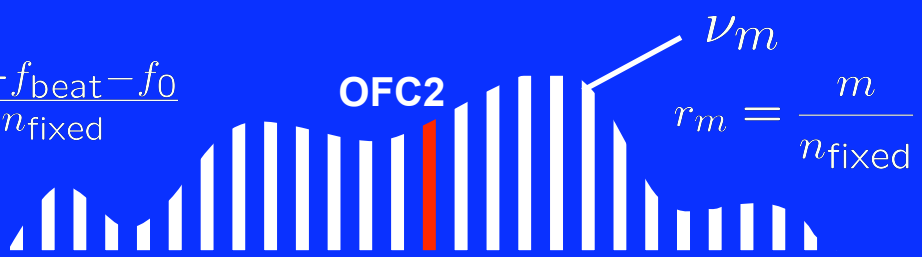

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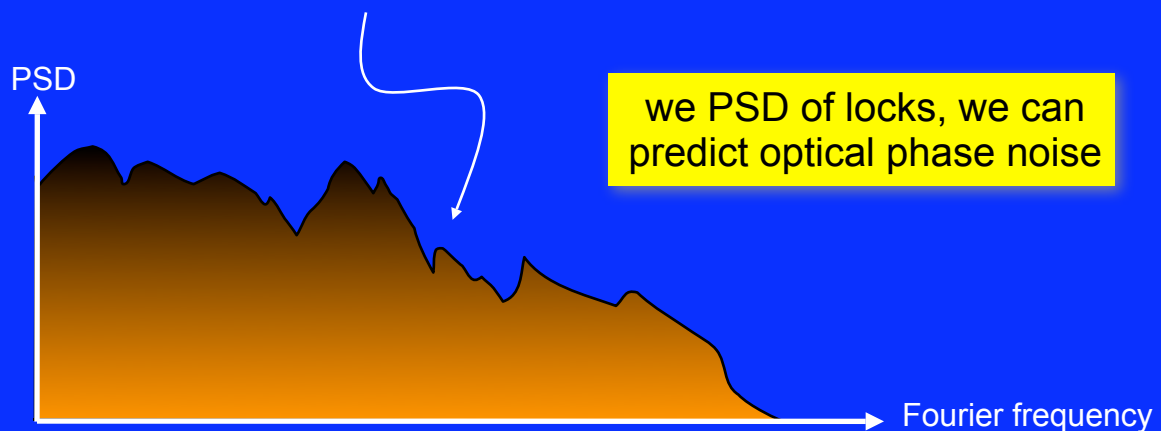
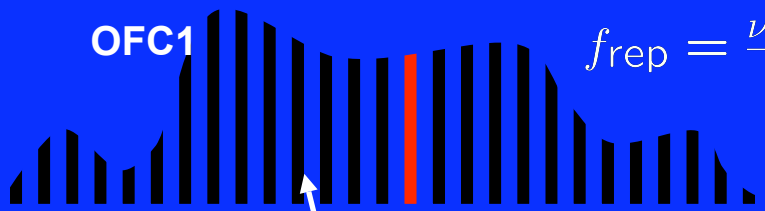


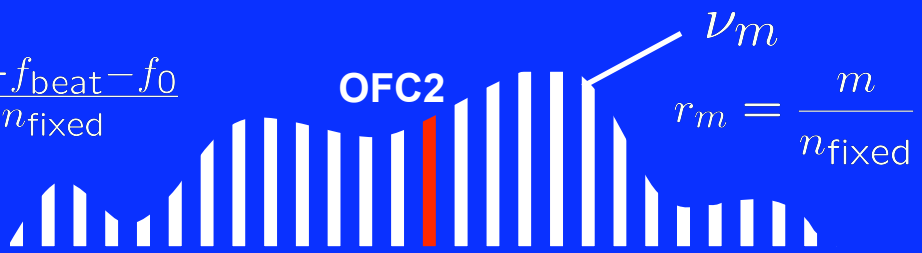
we PSD of locks, we can predict optical phase noise

deriving prediction for phase noise across comb

§ rewrite comb equation in terms of phase-locked parameters



$$f_{rep} = \frac{\nu_0 + f_{beat} - f_0}{n_{fixed}}$$



$$\nu_m \qquad r_m = \frac{m}{n_{fixed}}$$

$$\nu_n = r^n(\nu_0 + f_{beat1}) + (1 - r)f_{01} \qquad r_n = \frac{n}{n_{fixed}}$$

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phase noise of each locked parameter

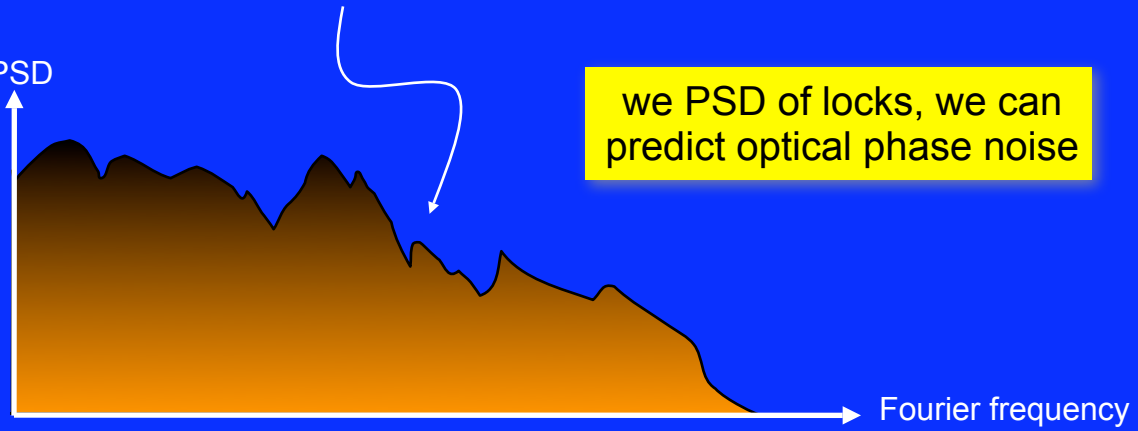
projected phase noise

$$S_{\Phi,m,n}(f) = (r^m - r^n)^2 \sum_i S_{\phi,i(f)} \quad \frac{\text{rad}^2}{\text{Hz}}$$

(we neglect cross terms)

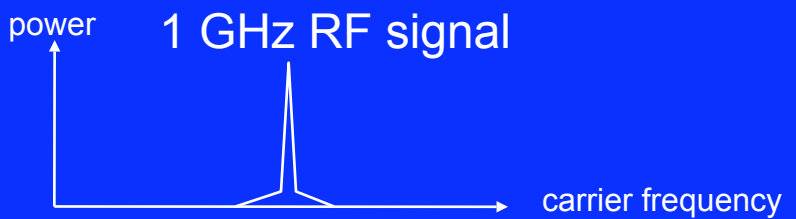
phase = $\sqrt{\int S_{\Phi,m,n}(f)df}$

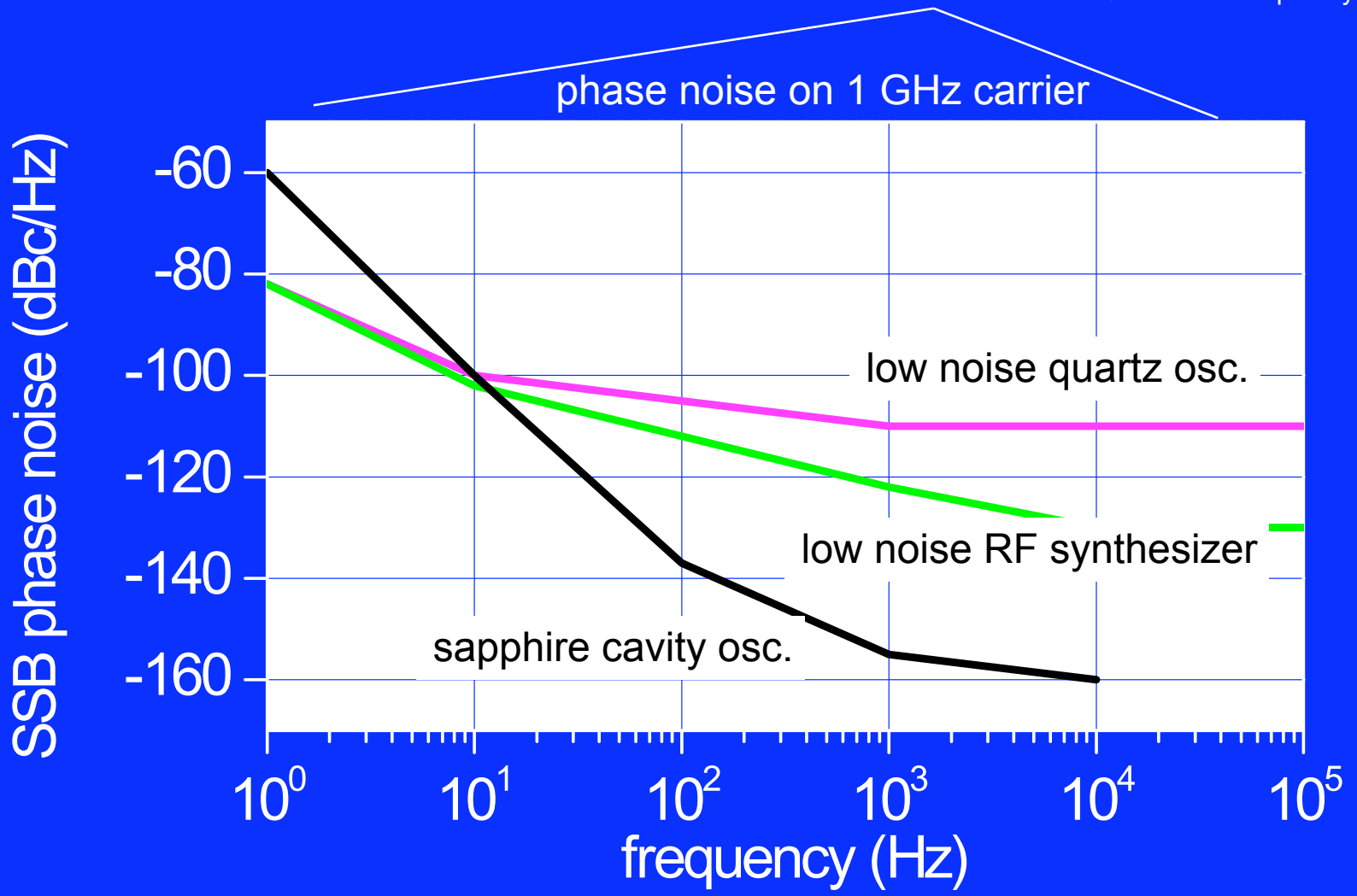
~ linearly with r

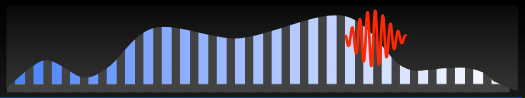


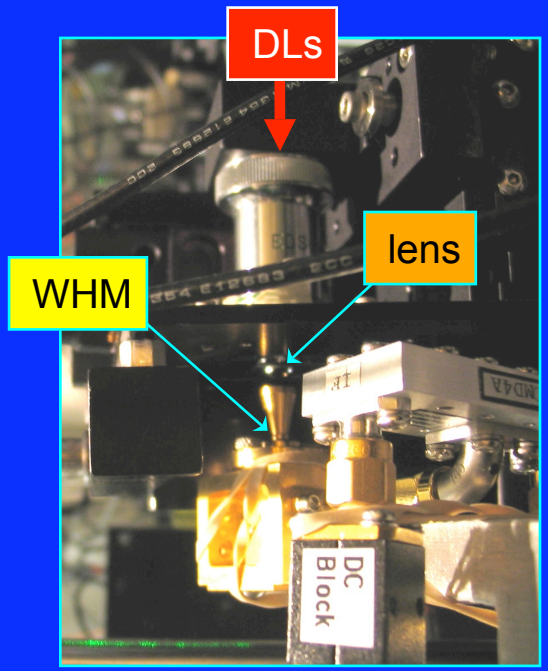
we PSD of locks, we can predict optical phase noise

low noise microwave frequency sources








DLs
lens
WHM
DC Block