Optical Frequency Combs: Nonlinear Optics and the Meeting of the Ultrafast and Ultrastable

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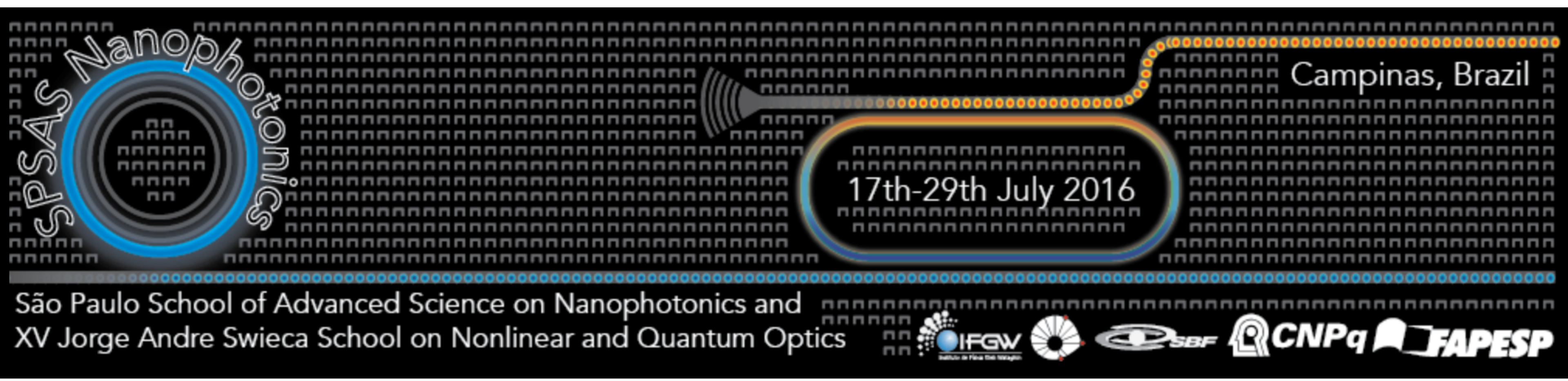


Outline

1. Background: Clocks and Precise Timing

2. Counting Cycles of Light
   - The optical frequency comb

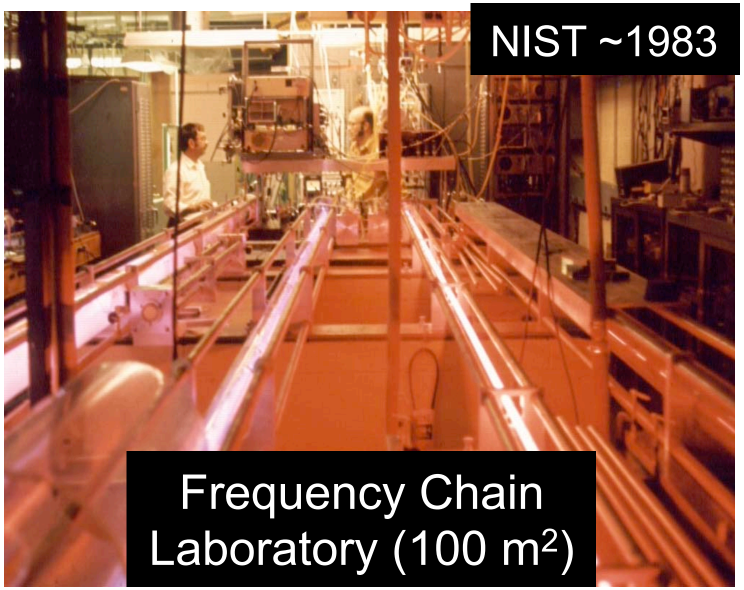
3. From Lab Scale to Chip Scale
   - Can we make a frequency comb on a chip?

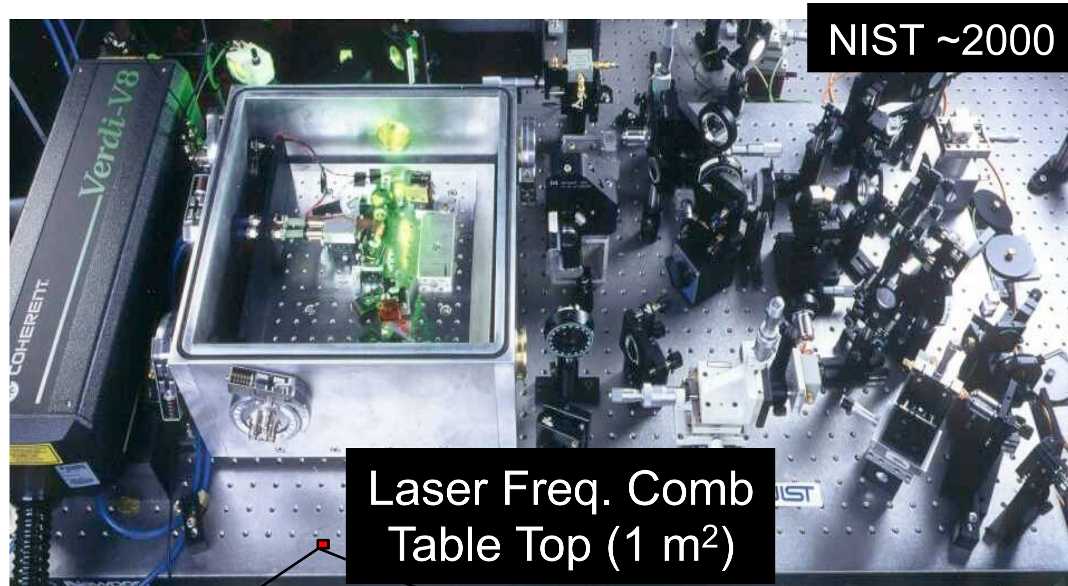
4. Applications and opportunities for frequency combs

Can we get the Technology out of the Lab?

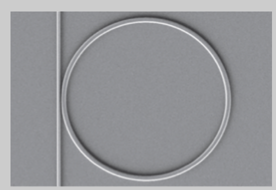
Atomic “wristwatch”
http://www.LeapSecond.com/

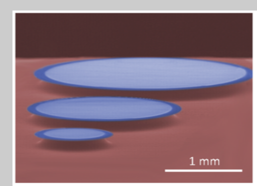
Moving from Lab Scale to Chip Scale





~10^4 size reduction





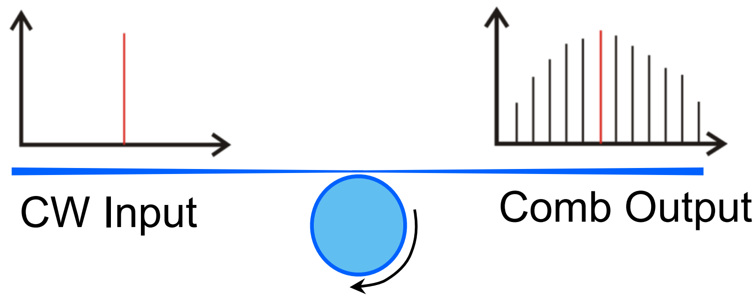
~1 cm^2

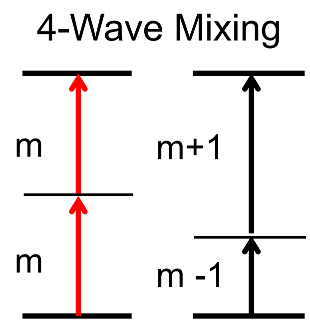
Future: Photonic Integrated Circuits

<u>Potential Impact:</u>

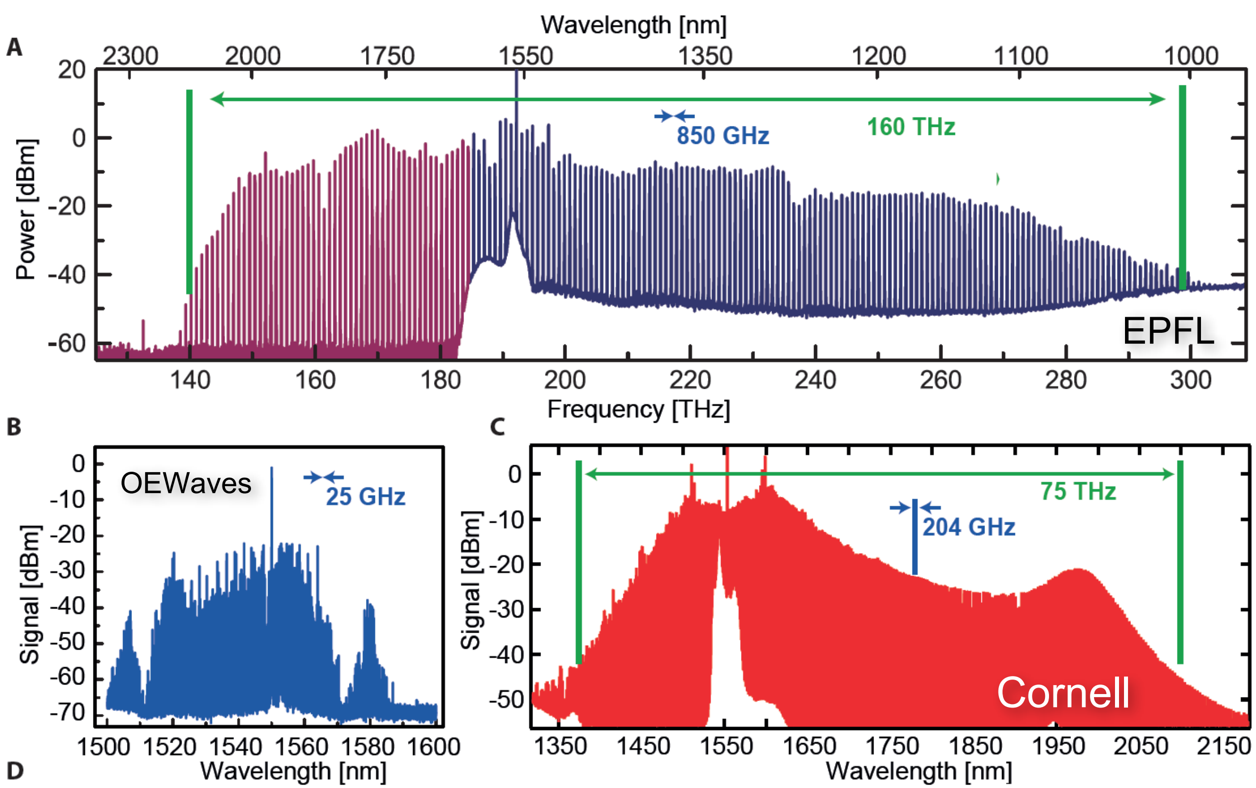
- Operation in any environment
- Chip scale clocks
- Inexpensive and mass produced
- Communication and navigation
- Sensing (environment, medical, manufacturing...)

A Tiny Revolution in Frequency Combs





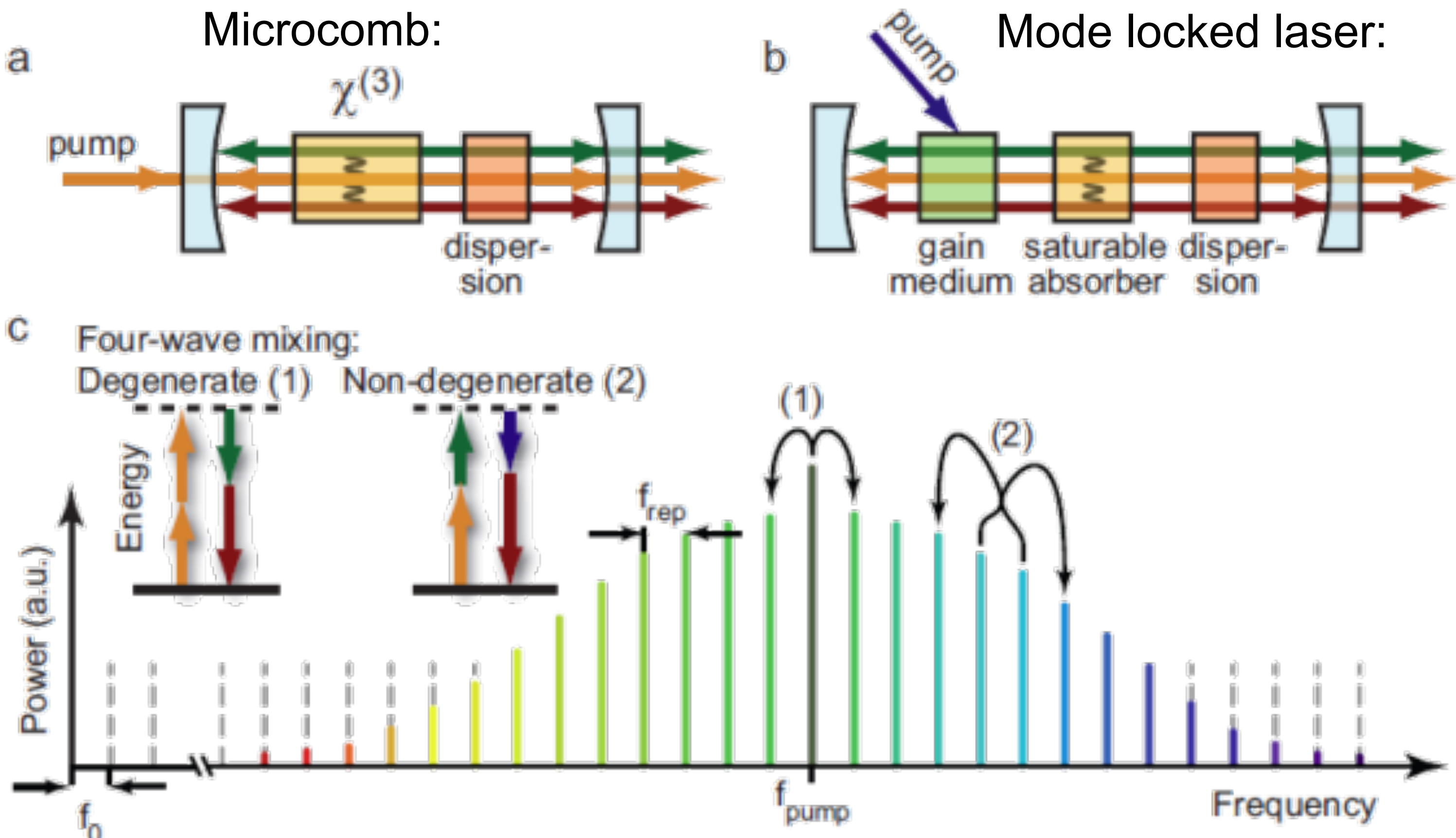
1. Energy conservation:
   $2\omega_P = \omega_S + \omega_I$
2. Momentum conservation:
   linear + nonlinear
3. Line spacing given by
   resonator size



- Combs that appear regularly-spaced are possible, but not all are useful for metrology
- Understanding (controlling?) noise processes is critical
- What is happening in the time domain?

Del'Haye, et al., Nature **450**, 1214 (2007)
Kippenberg, Holzwarth, Diddams Science **332** , 555 (2011).

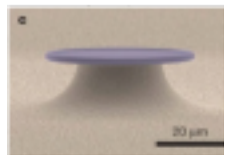
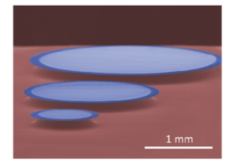
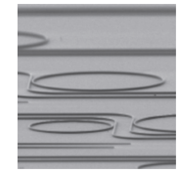
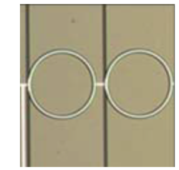
Comb Generation Principle



Microcomb:

- Parametric gain vs. stimulated emission
- Pump laser part of comb (offset tuning)
- No saturable absorber

Microresonator Gallery

Hydex	Si:Nitride	Silica toroid	Crystals	Silica wedge	Quartz	Diamond	Al:Nitride
							
RMIT	Cornell, Purdue, NIST G-burg, EPFL, UCLA	MPQ, EPFL, Caltech	OEWaves JPL EPFL	Caltech	NIST	Harvard	Yale

Key Properties

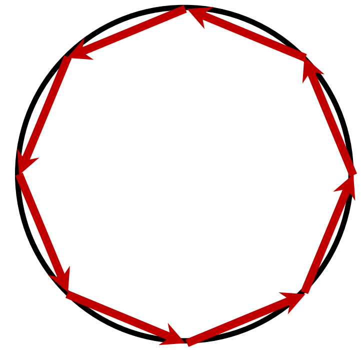
- High-Q cavity (>10^9)
- Small mode volume
- Mode-spacing given by perimeter
- Low & controllable dispersion
- Integrated chip-scale package

[1] L. Razzari, D. Duchesne, M. Ferrera, R. Morandotti, S. Chu, B. E. Little & D. J. Moss (Nature Photonics **4**, 41 – 45, 2010)
[2] J.S. Levy, A. Gondarenko, M.A. Foster, A.C. Turner-Foster, A.L. Gaeta & M. Lipson (Nature Photonics **4**, 37 – 40, 2010)
[3] P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, T. J. Kippenberg (Nature **450**, 1214-1217, 2007)
[4] A.A. Savchenkov, A.B. Matsko, V.S. Ilchenko, I.Solomatine, D. Seidel, and L. Maleki (Phys Rev Let. **101**, 093902, 2008)
[5] S.B. Papp and S.A. Diddams (PRA **84**, 053833, 2011)
[5] F. Ferdous, H. Miao, D. E. Leaird, K. Srinivasan, J. Wang, L. Chen, L. T. Varghese & A. M. Weiner (Nature Photonics **5**, 770, 2011)

Whispering Gallery Modes

Tian Tan Temple (Beijing) St. Pauls Cathedral (London)

whispering gallery



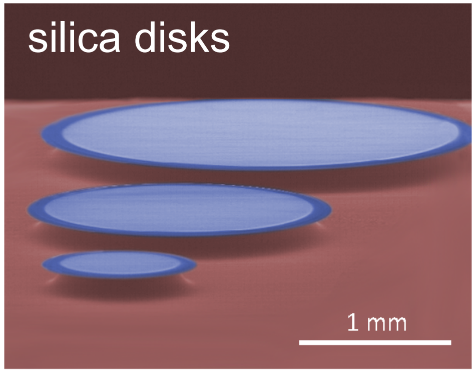
Sound waves travel along circular walls by continuous reflection

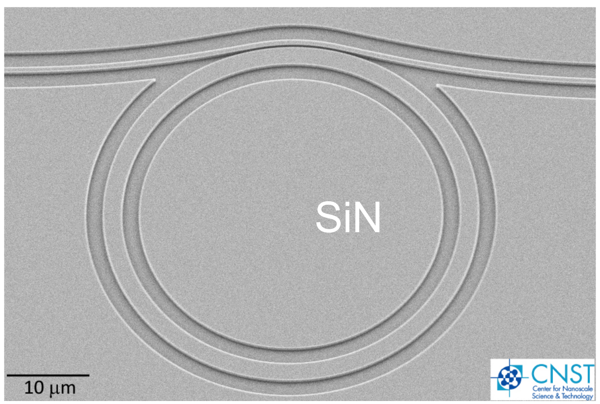
First explained by Lord Rayleigh in 1912

Rayleigh, L. "*The problem of the whispering gallery*" Scientific Papers, **5**, 617, 1912

Microresonator Research at NIST

Microresonators for Comb Generation

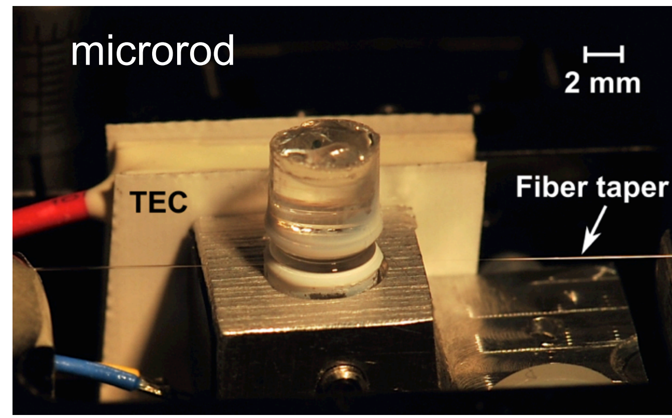


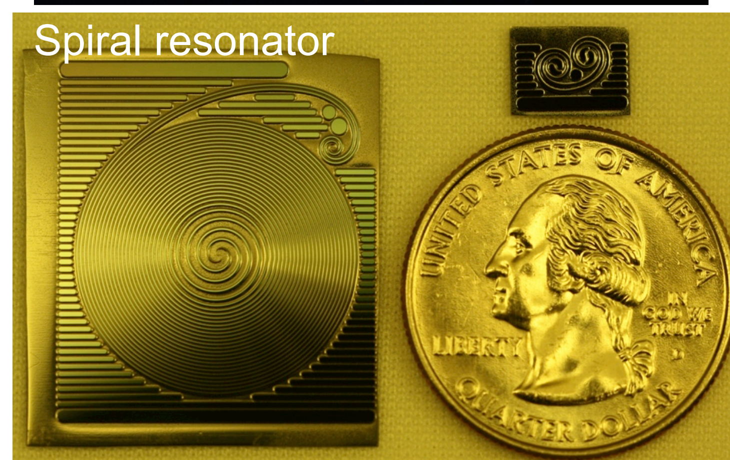


- → Q ~ 10^6 – 10^9
- → Large mode volume for low noise
- → Small mode volume for efficient nonlinear optics

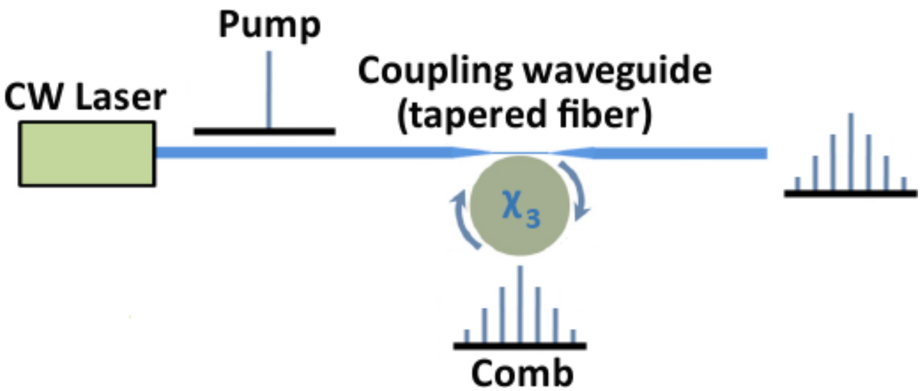
See the video on YouTube "Laser comb in a minute"
S. Papp, PRX (2013), P. Del'Haye, Appl. Phys. Lett. (2013)
F. Ferdous, Nat. Photon. (2011)
H. Lee, Nat. Photon. (2012), H. Lee Nat. Comm. (2013)

Microresonators for SBS and Laser Stabilization

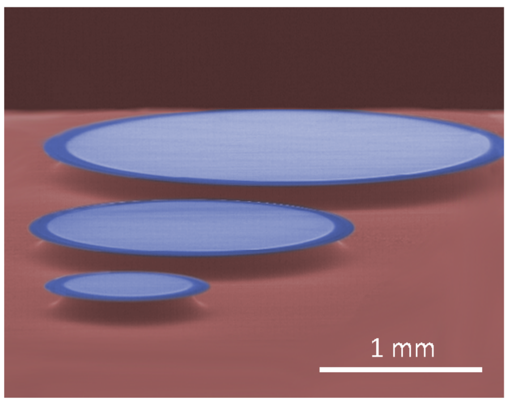


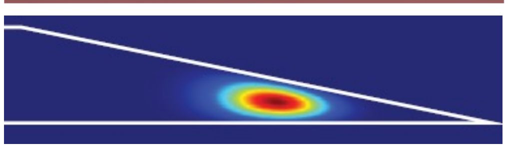


Kerr microcomb hardware



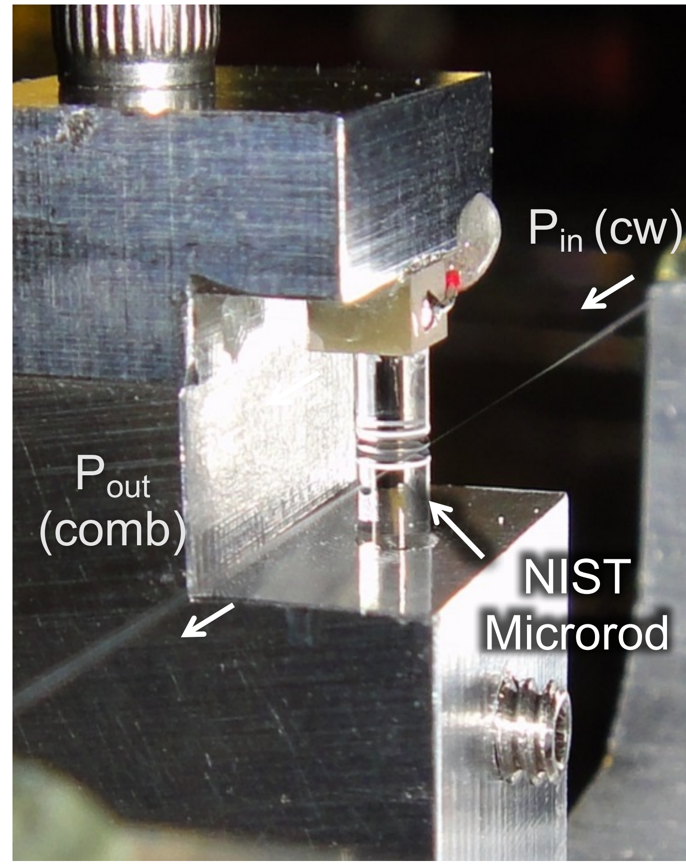
Caltech Disk Resonators





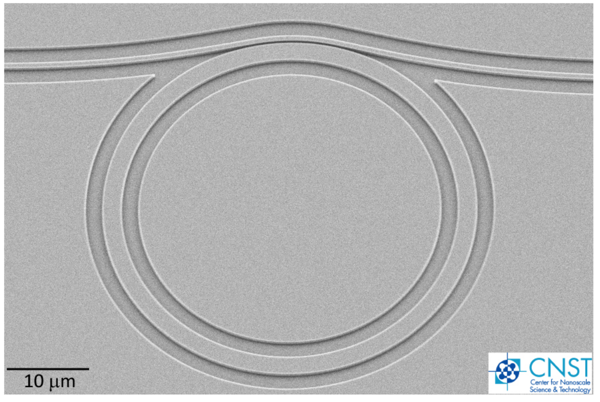
"Whispering gallery" mode

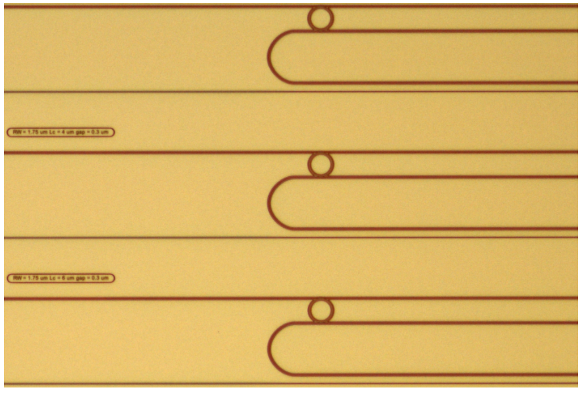
Tapered Fiber Coupling



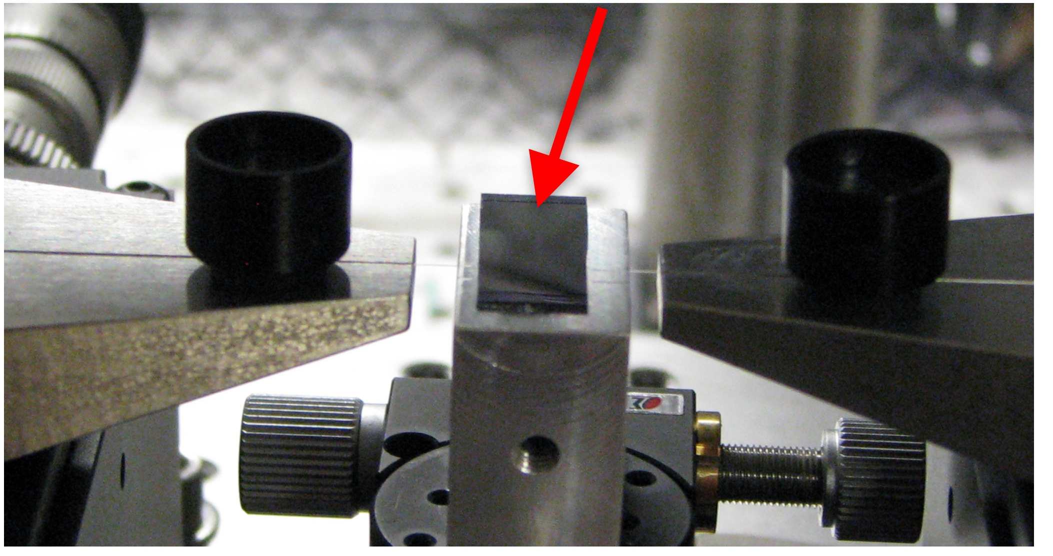
Kerr microcomb hardware

Si_3N_4 + lensed fibers



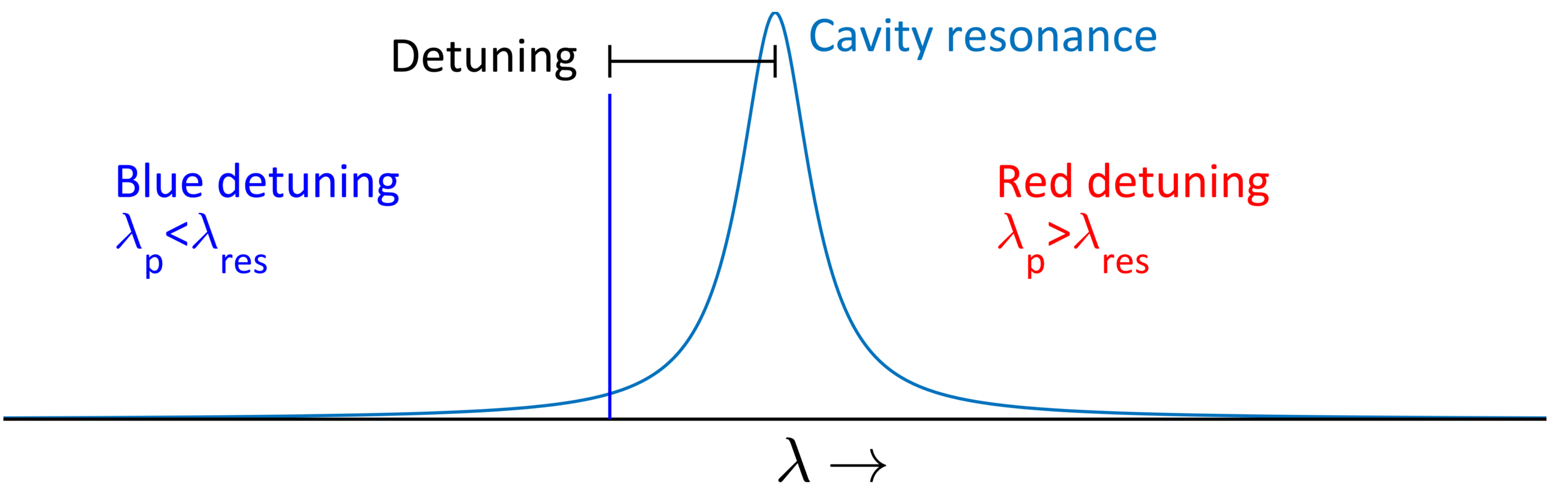


Chip



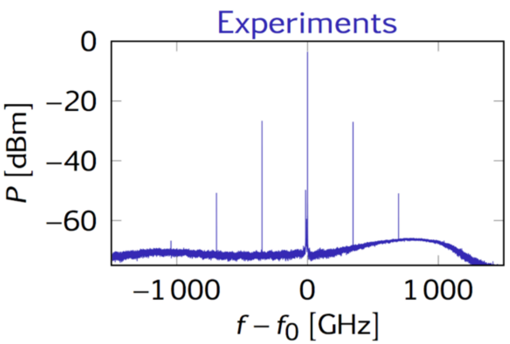
Microcomb Initiation

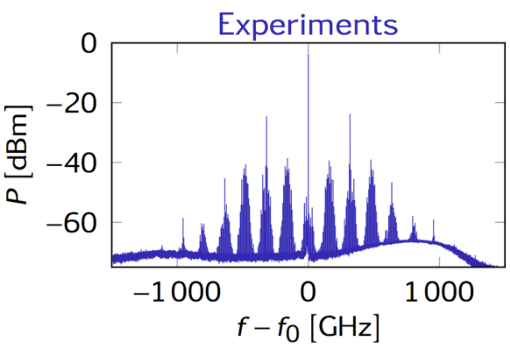
→ Initiate Kerr comb by tuning frequency of CW pump laser into a resonance of the microresonator

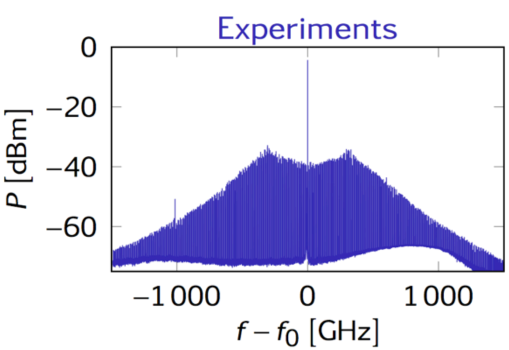


Kerr Nonlinear Microcavity Resonance

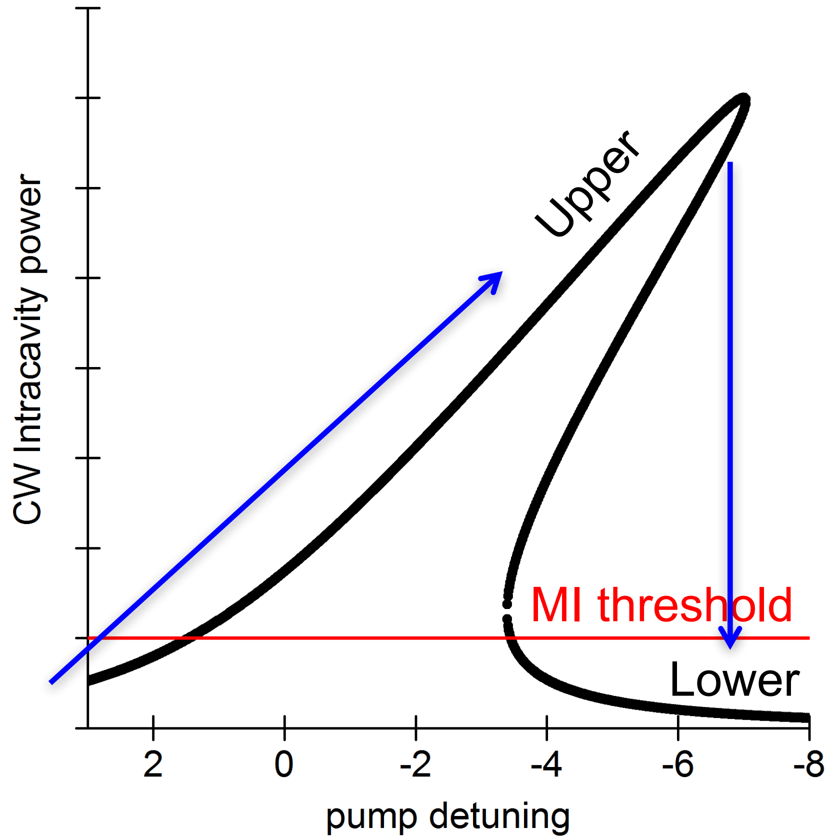
Upper branch:
Modulation instability



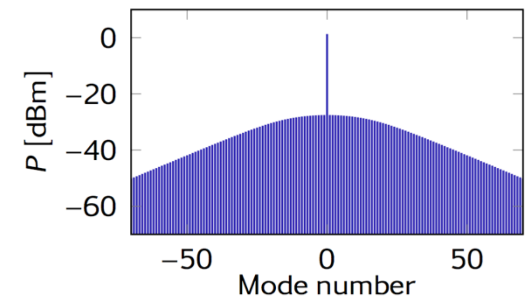


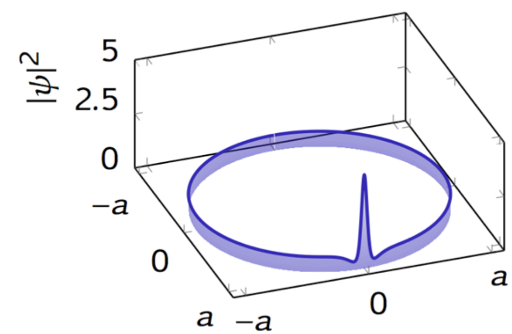


Resonance ”tilted” due to
Kerr phase shift: $n_2 I$

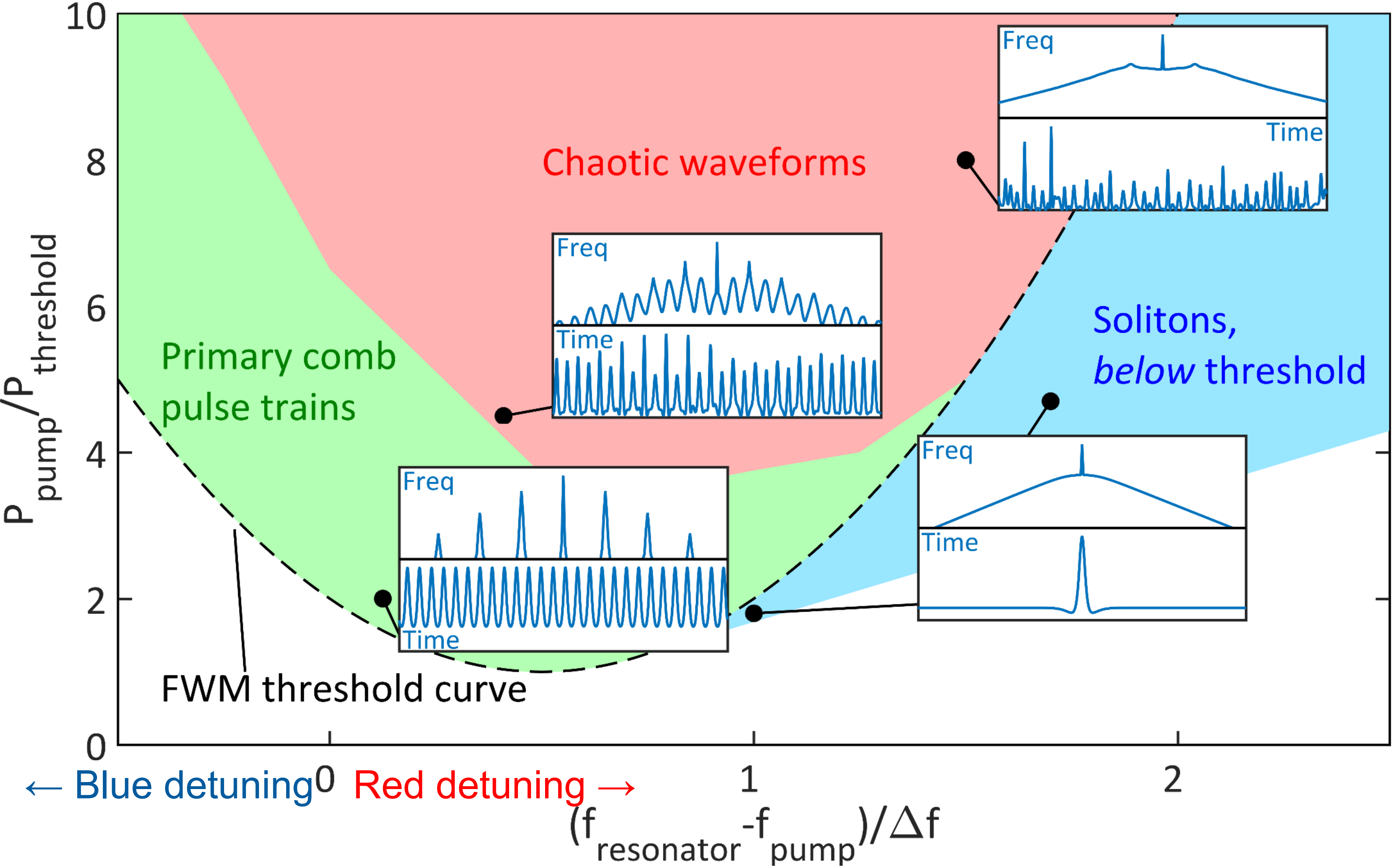


Lower branch:
Cavity soliton





Kerr microcomb 'phase space'



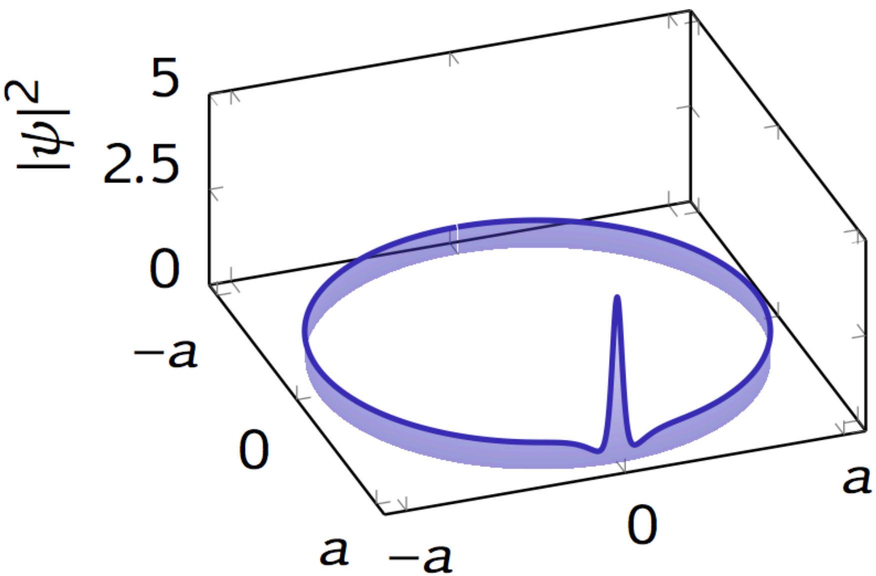
NIST

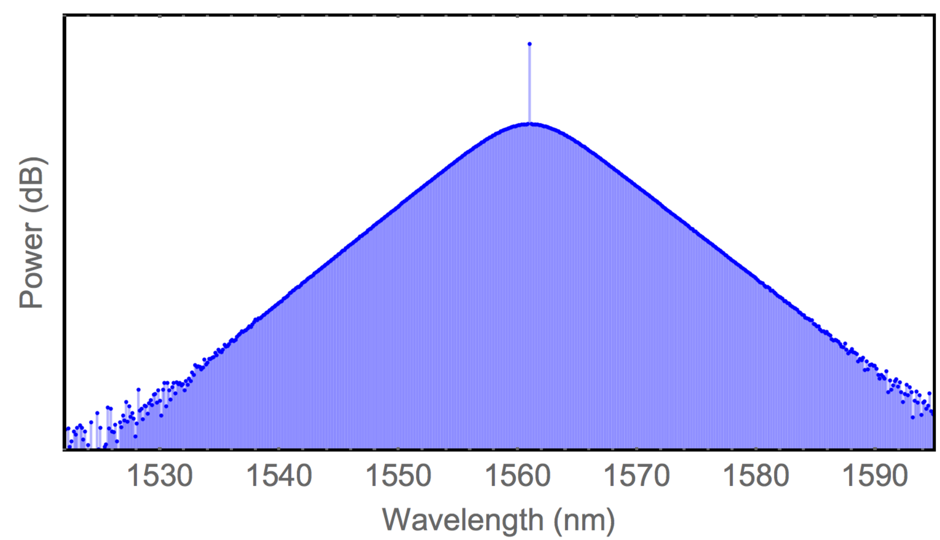
Kerr Solitons

Comb generation governed by **Kerr effect and dispersion**, described by **Lugiato-Lefever equation:**

	Loss and detuning		Kerr nonlinearity		Dispersion		Pump

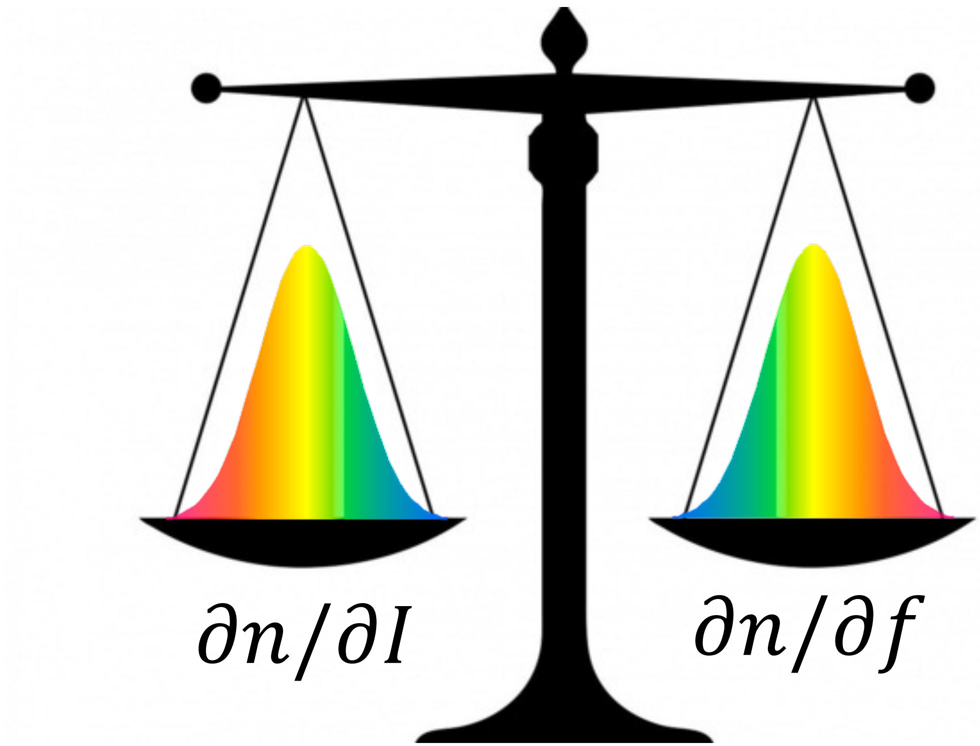
$$\frac{\partial\psi}{\partial\tau} = -(1+i\alpha)\psi + i|\psi|^2\psi - i\frac{\beta}{2}\frac{\partial^2\psi}{\partial\theta^2} + F$$

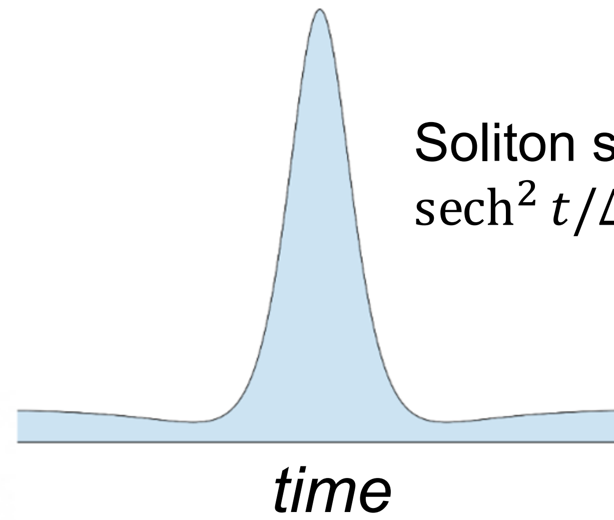




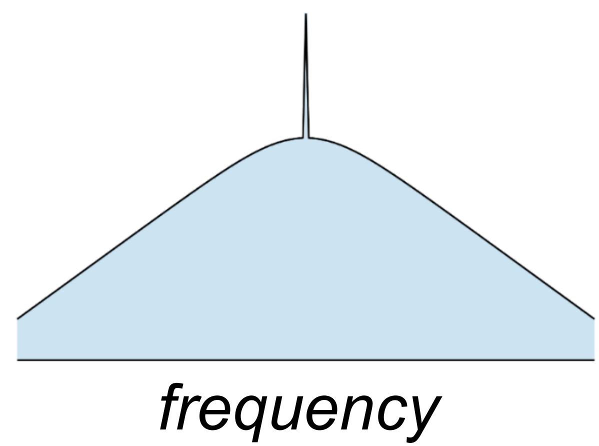
Solitons in microcombs

Soliton: pulse that is able to propagate with fixed width due to balance of nonlinearity and dispersion



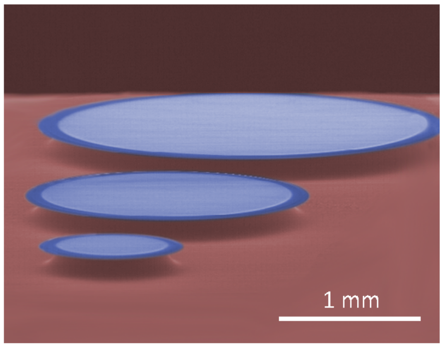


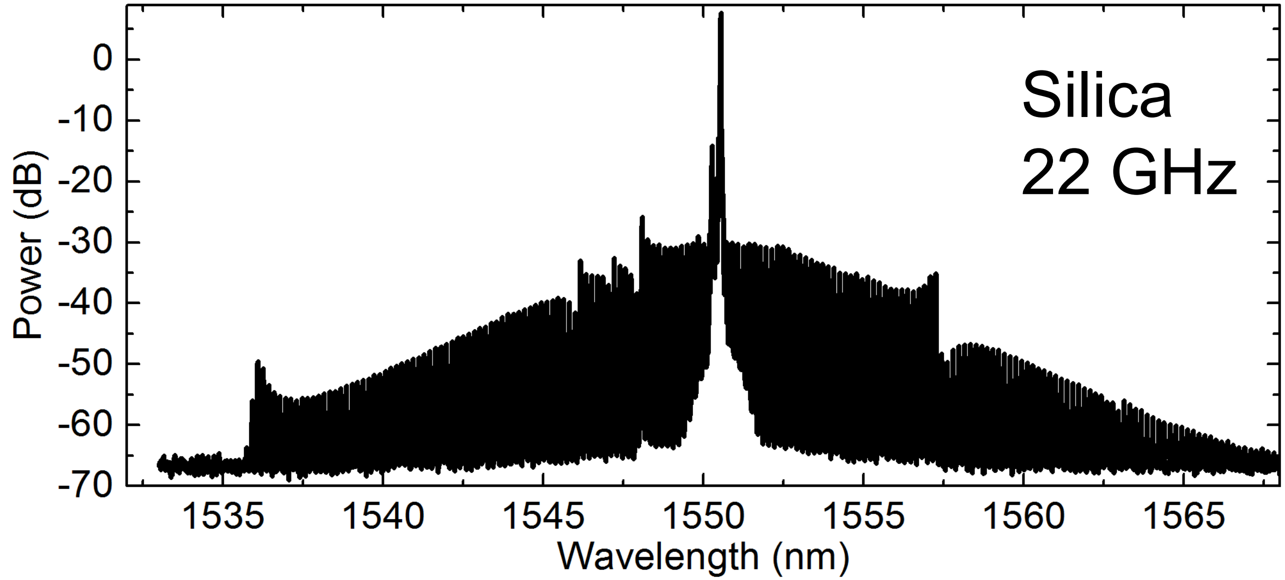
Soliton shape:
$\mathrm{sech}^2\, t/\Delta t$

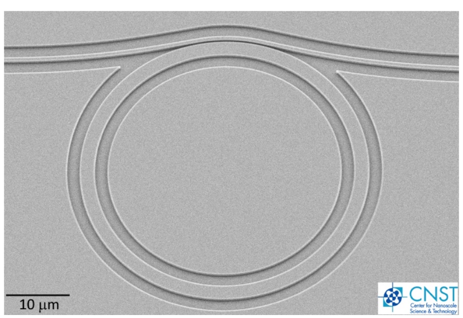


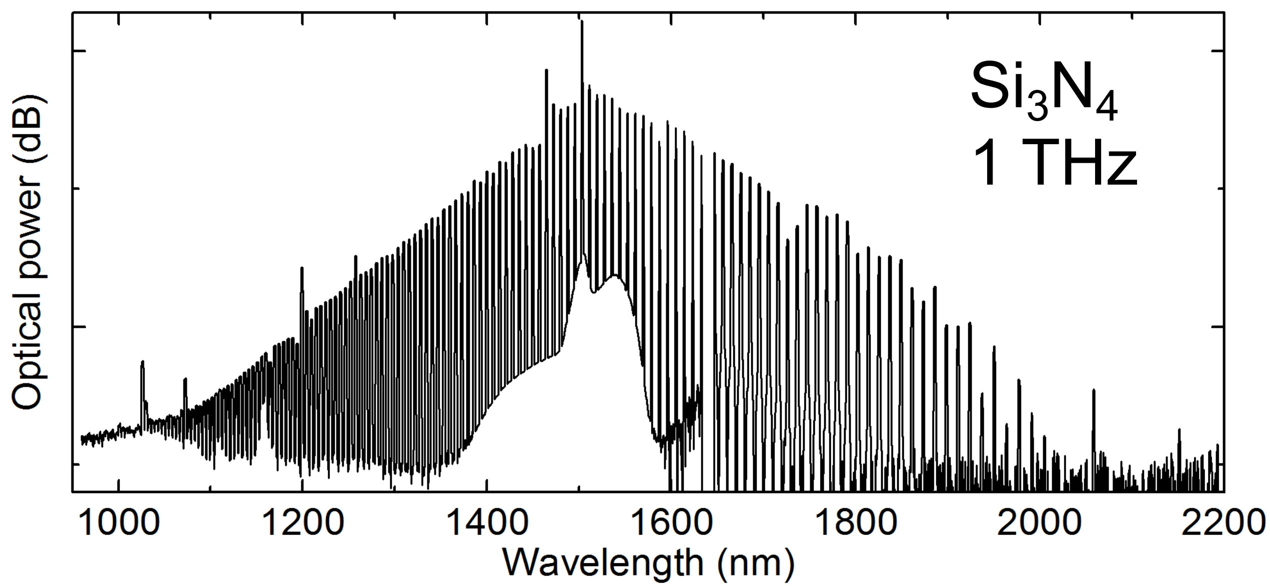
Soliton spectrum:
$\mathrm{sech}^2\, f/\Delta f$

Examples of Solitons





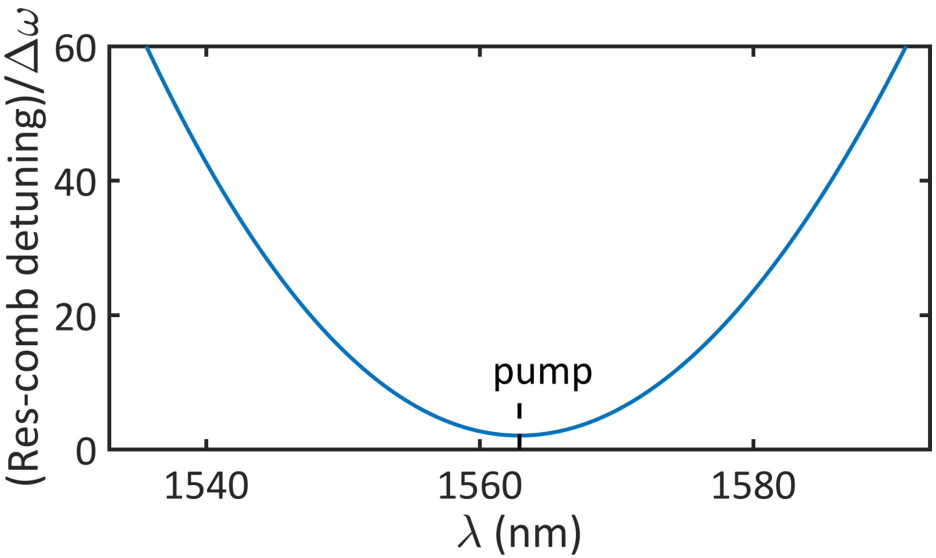




Comb-resonator detuning & mode crossings

- Resonator has dispersion, but comb has uniform spacing!
- Walk-off between resonator modes and comb modes decreases power in wings

- Perturb resonator mode-structure via coupling with different mode *family* in resonator



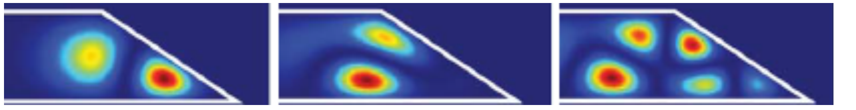
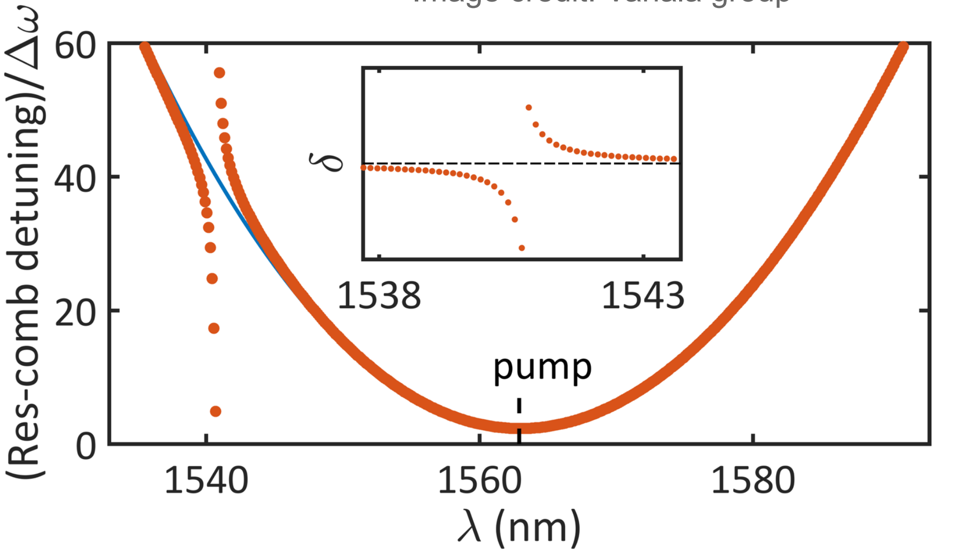


Image credit: Vahala group



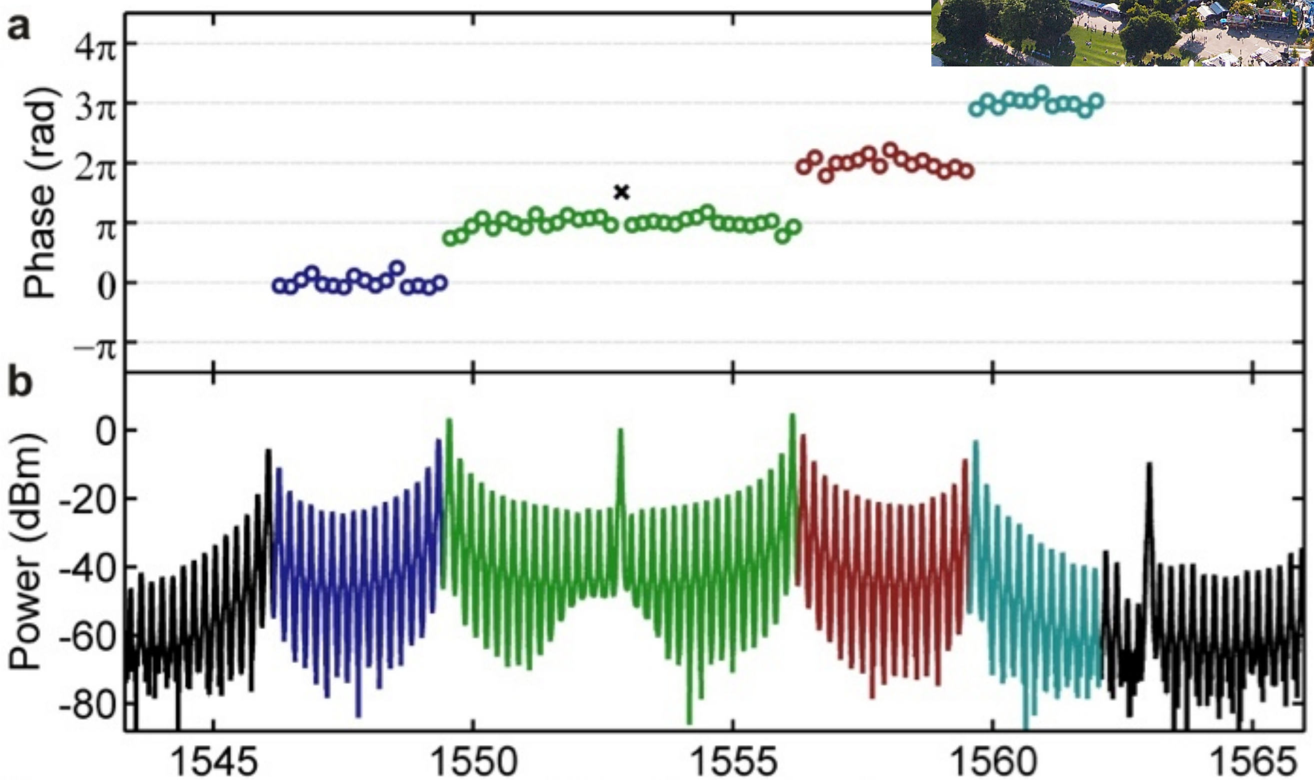
Comb generation locally enhanced/diminished in presence of mode crossing

Curious Phase-Locked Combs

- Sculpted spectral envelope
- π steps in the phase
- Stable, repeatable, stationary waveforms in time

Phase

Power

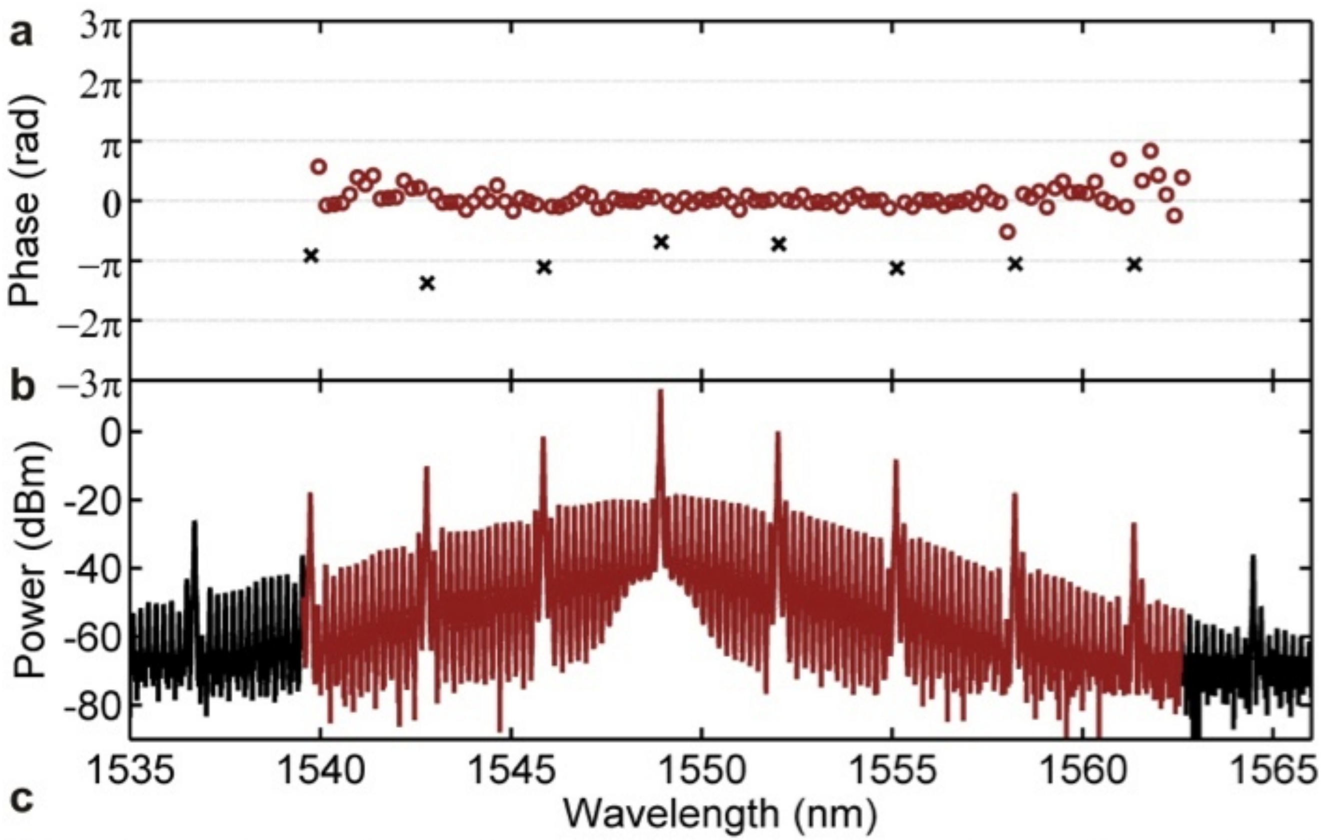


Pascal Del'Haye, Nat. Comm (2015)

Curious Phase-Locked Combs

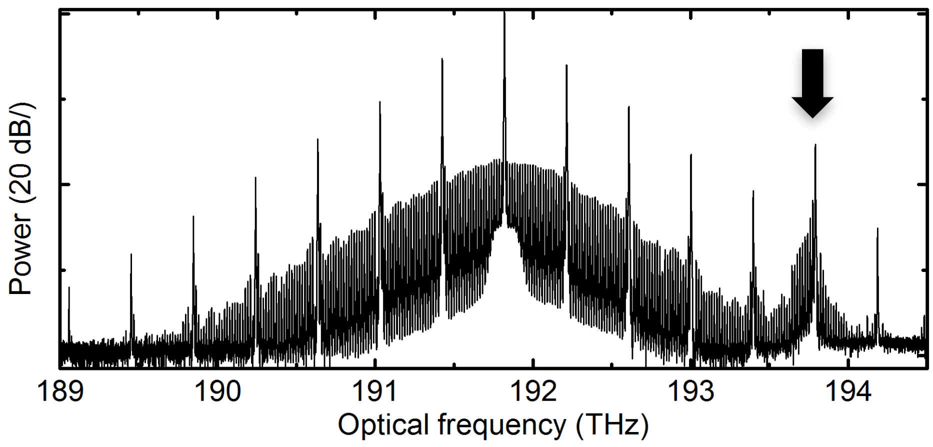
Phase

Power



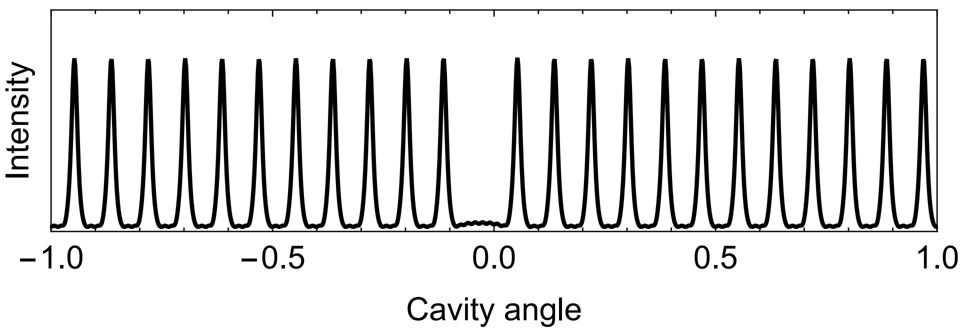
How can we understand these spectra ?

Kerr soliton crystals



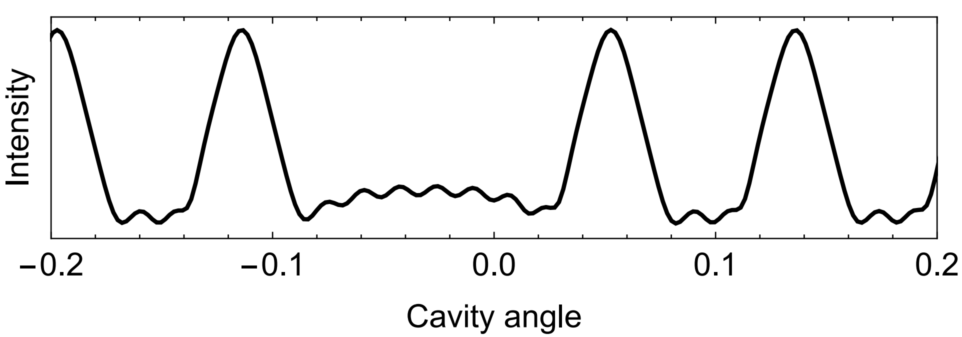
Spectrum:

- Intense comb every 24 modes
- $Sech^2$ profile
- High contrast



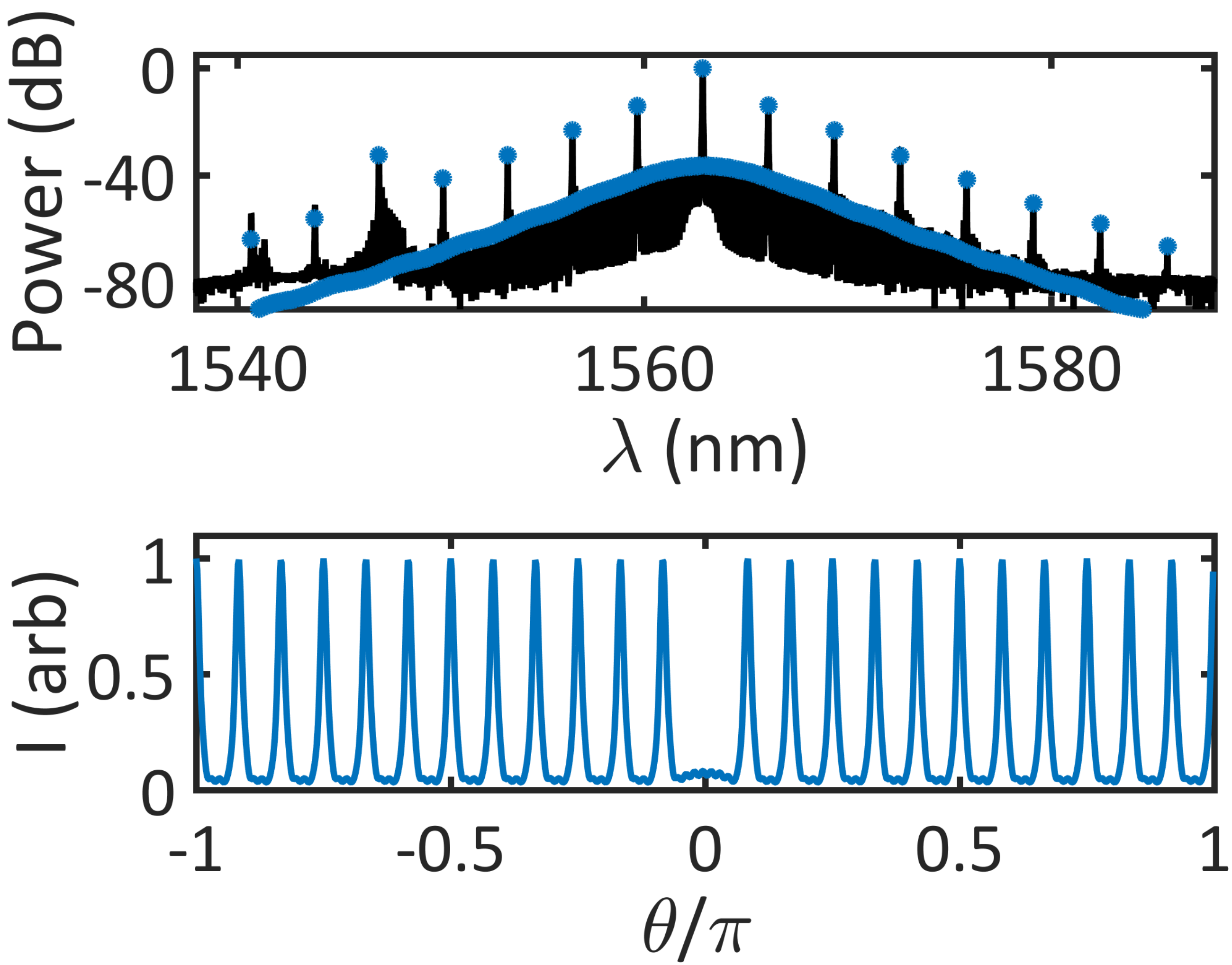
Origins of this spectrum:

- 23 pulses on a *perfect* 24x5 = 120 site lattice
- **Multi-soliton Kerr comb**
- **Not a stable LLE solution!**

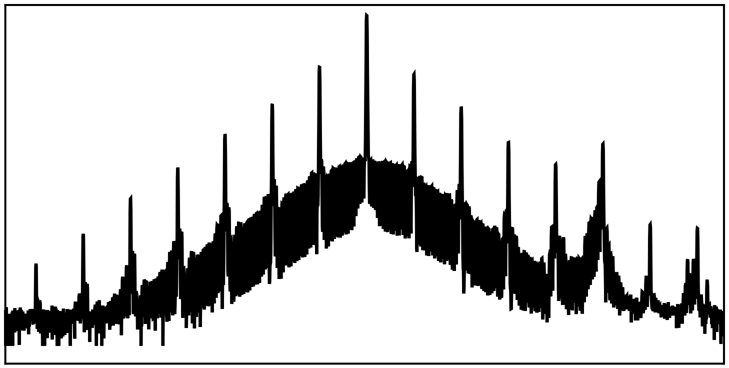


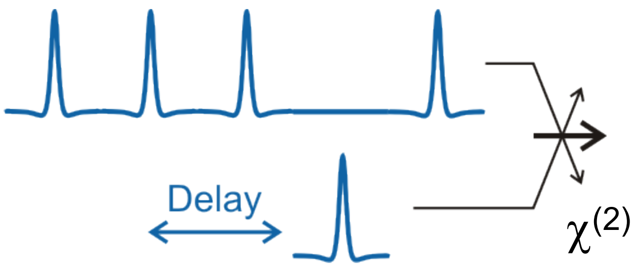
Lattice caused by **mode crossing defects**.

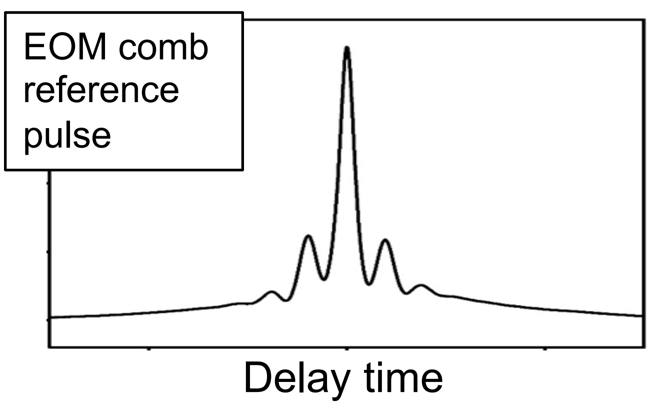
Model/Data agreement

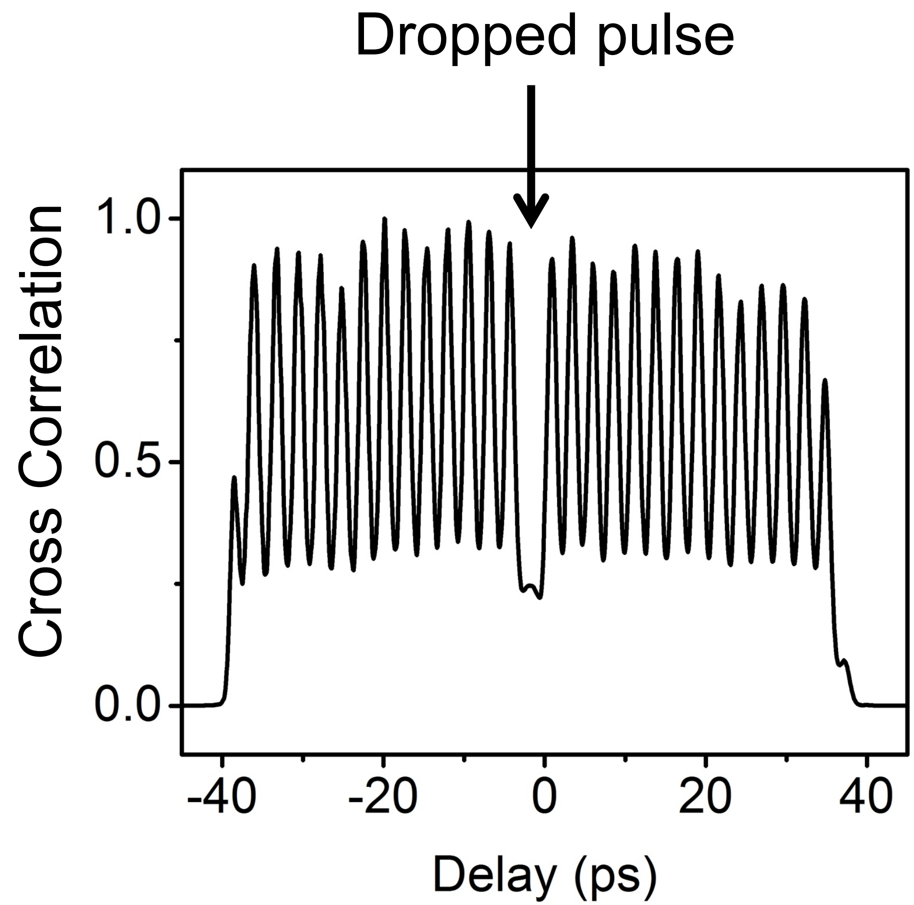


Cross-correlation crystal characterization

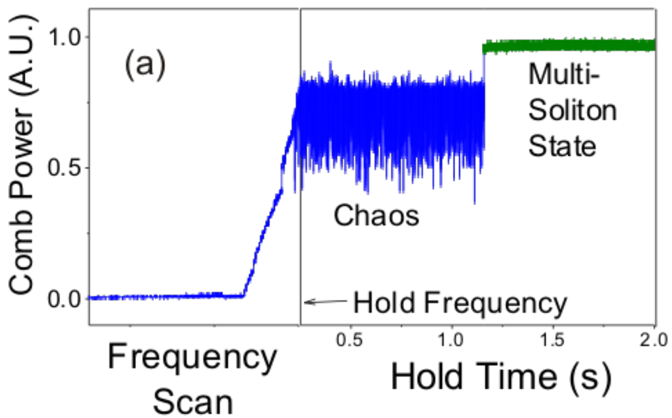




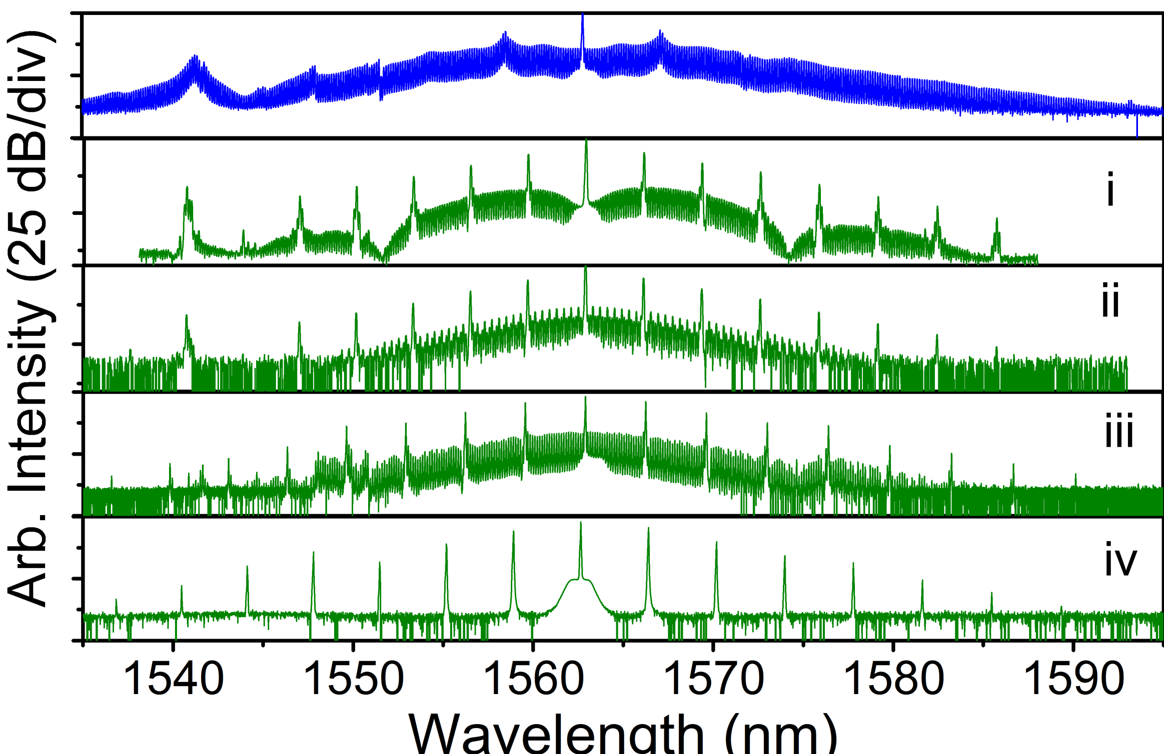


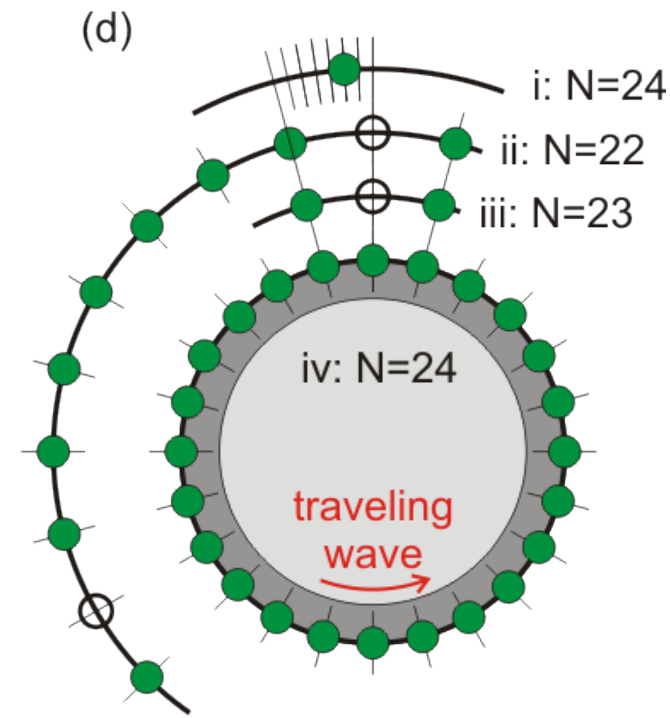


Multi-soliton crystals



- Multi-solitons accessed by slow laser ramp into resonance
- Stable configurations—not always uniformly distributed
- Low-noise, phase-locked spectra

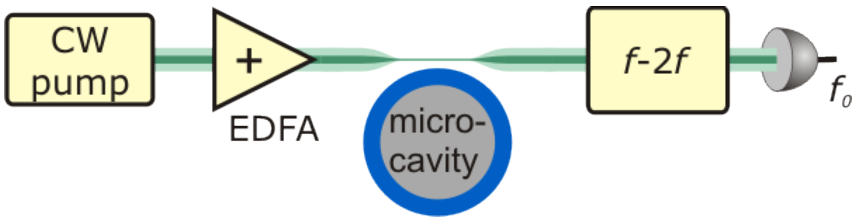




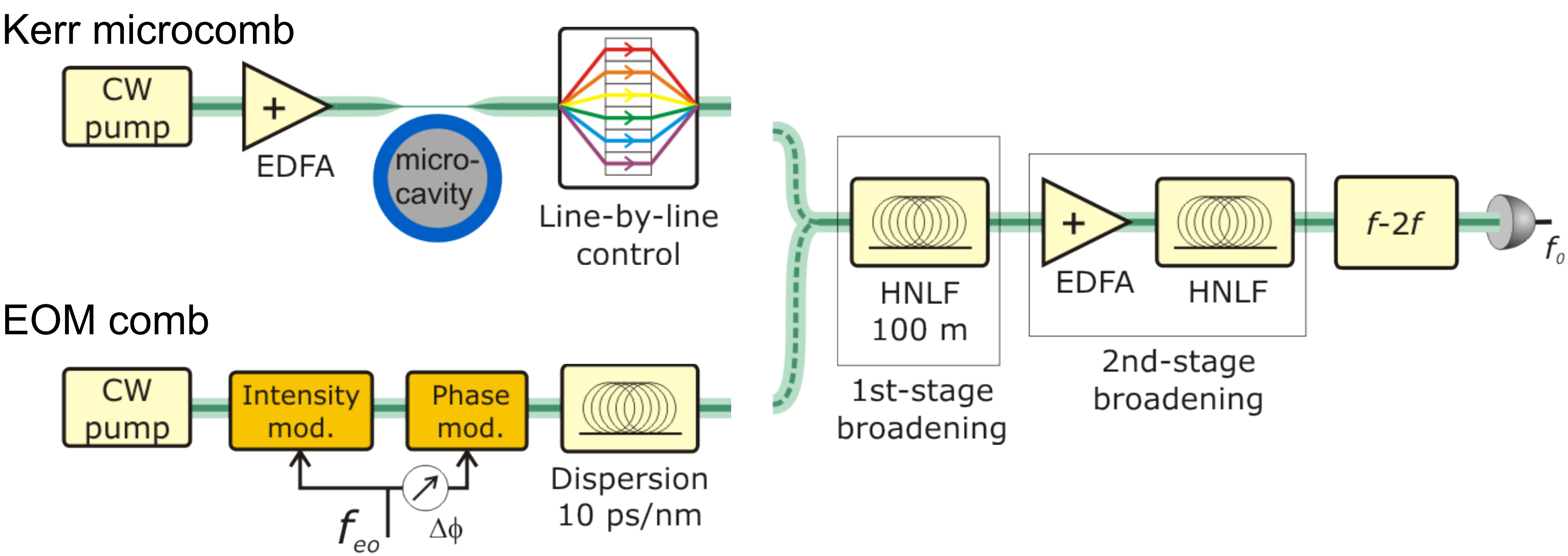
D. Cole, E. Lamb, S. Papp

Self-referencing a microcomb

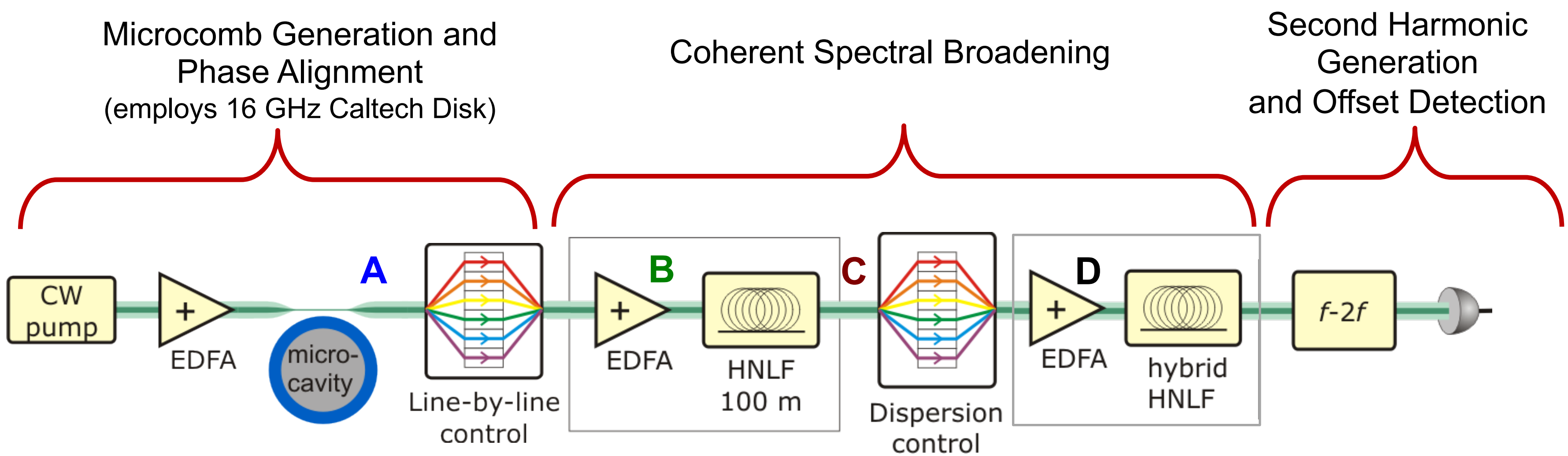
1. Octave spectra on-chip

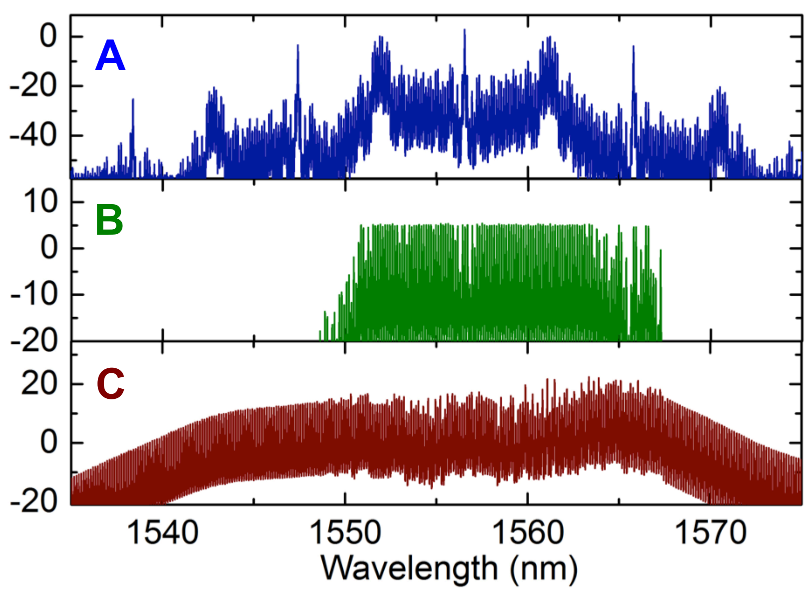


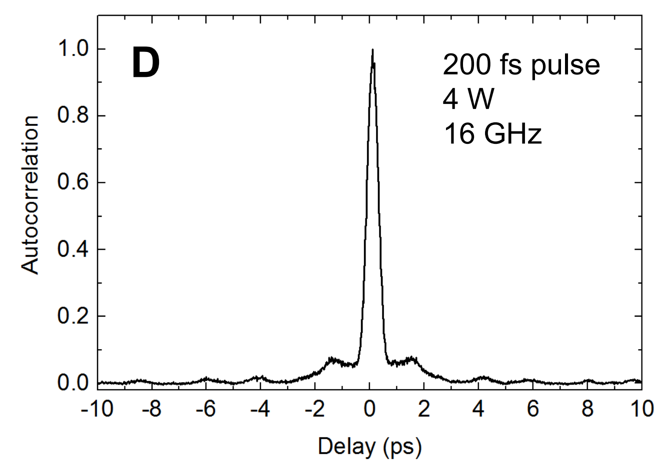
2. Spectral broadening outside resonator – ultrafast pulse broadening



Self-Referencing a Microcomb

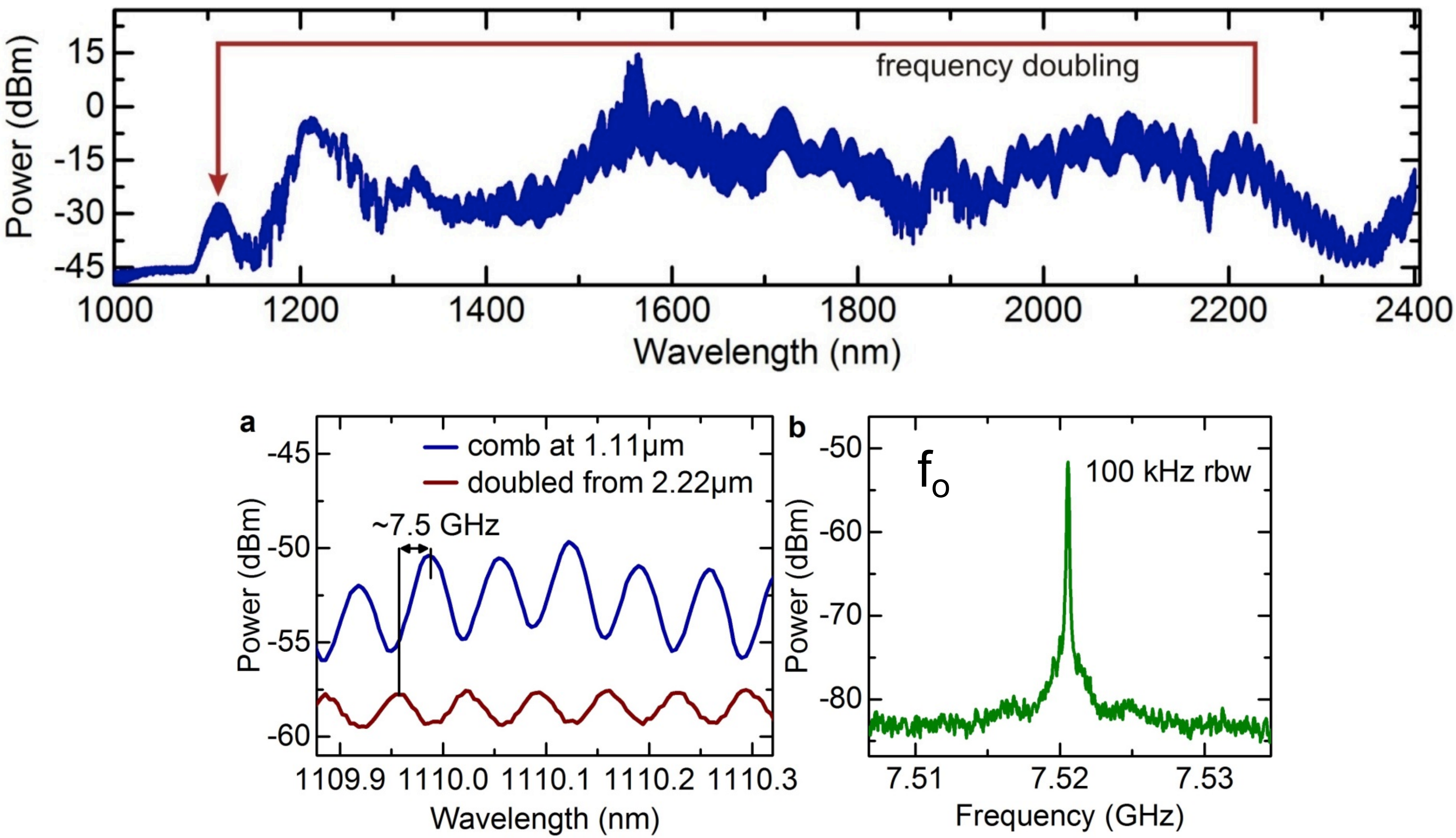






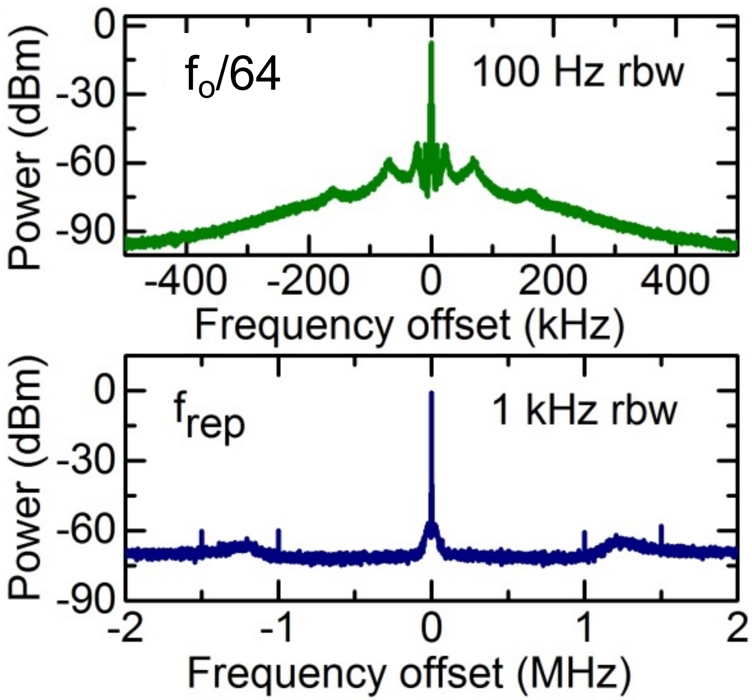
Pascal Del'Haye, Nature Photon (2016)

Self-Referencing a Microcomb



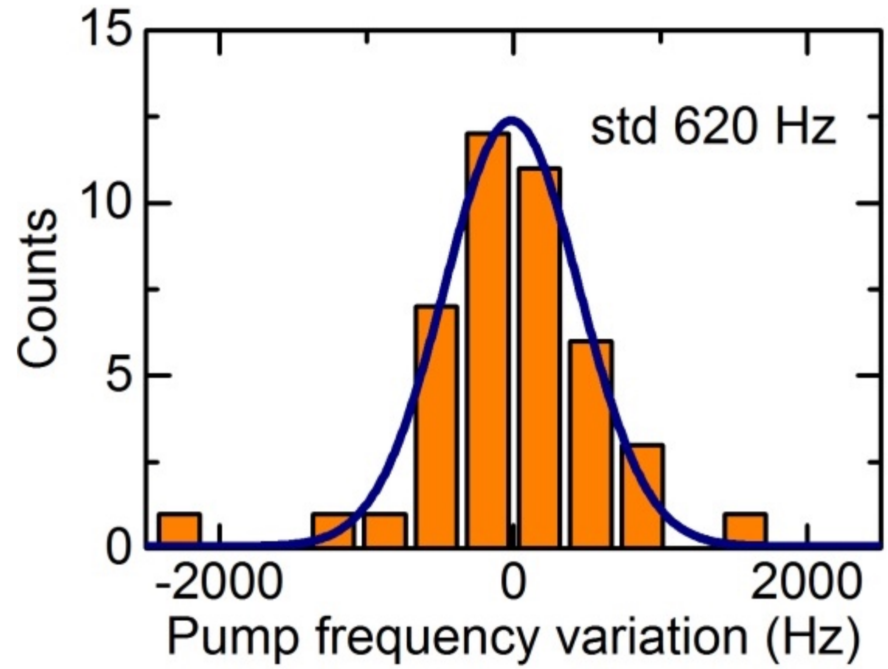
A frequency stabilized microcomb!

Phase-locked:
f_o (pump power)
f_{rep} (pump tuning)



Measure pump frequency:

$$\nu_{pump} = Nf_{rep} + f_o$$

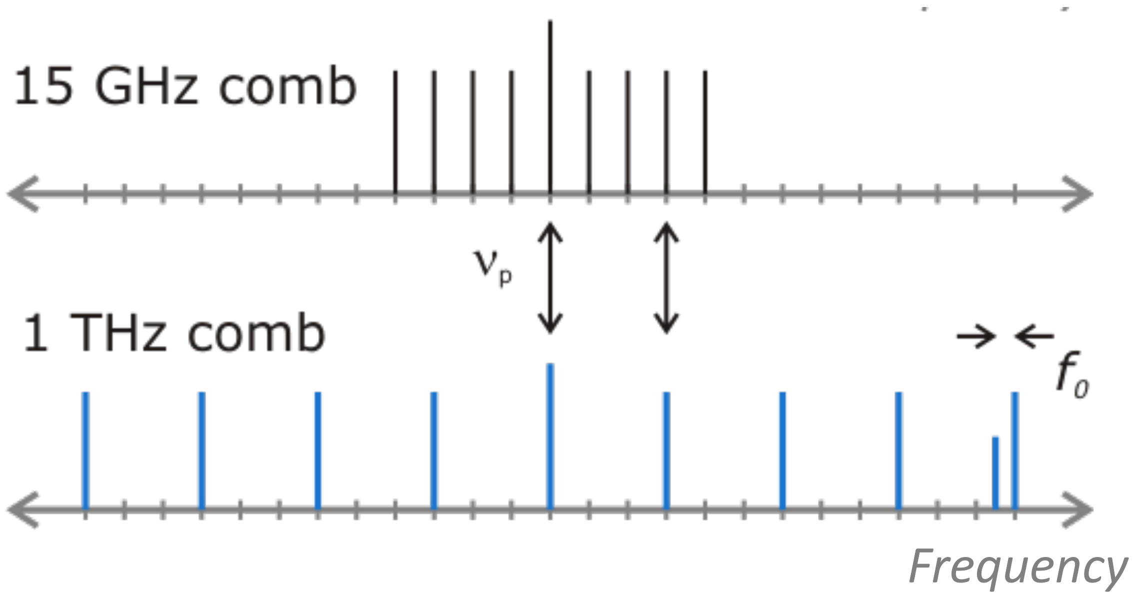


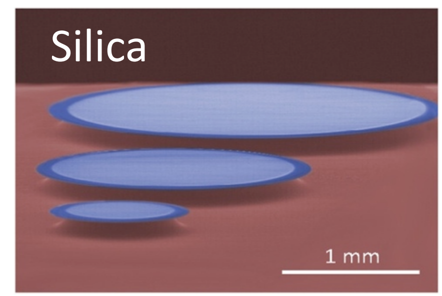
Fluctuations at level of H-maser

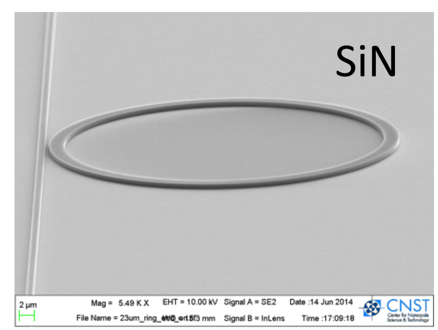
Pascal Del'Haye, Nature Photon (2016)

Self-referencing on a chip?

Goal: An octave-span, self-referenced microcomb on a chip
Challenges: Integration, power, frequency control & basic nonlinear optics
Approach: Dual reduction gear 200 THz → 1 THz → 15 GHz
Leverage: Photonic integration (pump laser, PPLN, photodiodes)



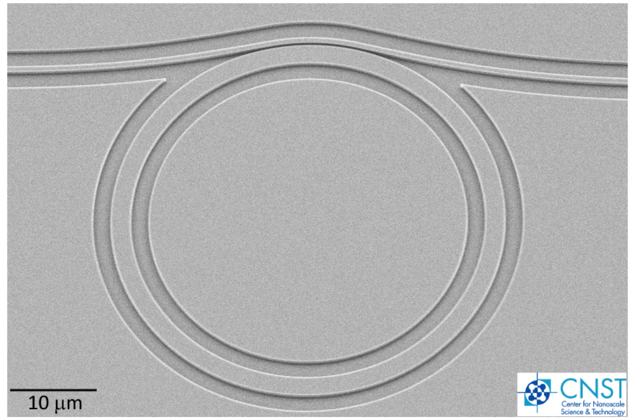




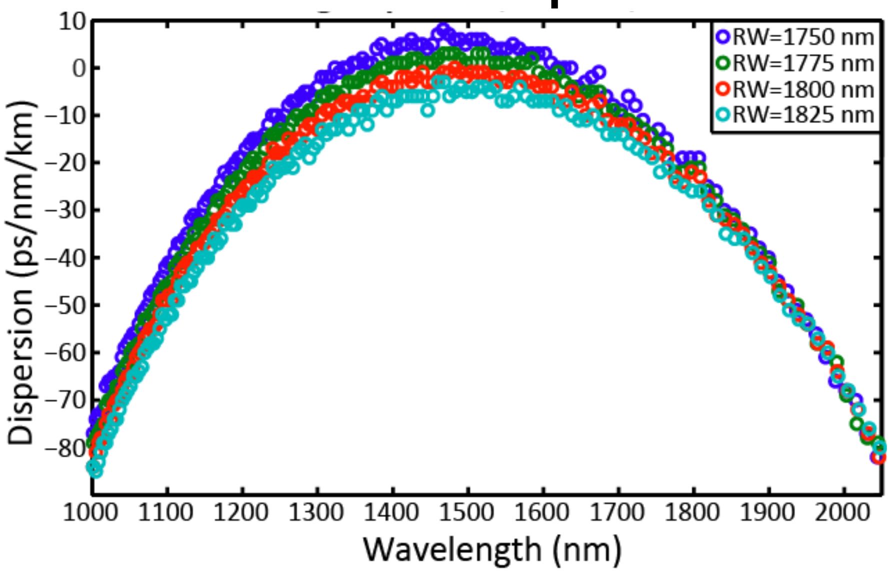
THz microcomb chip

Kartik Srinivasan
Qing Li
Daron Westly

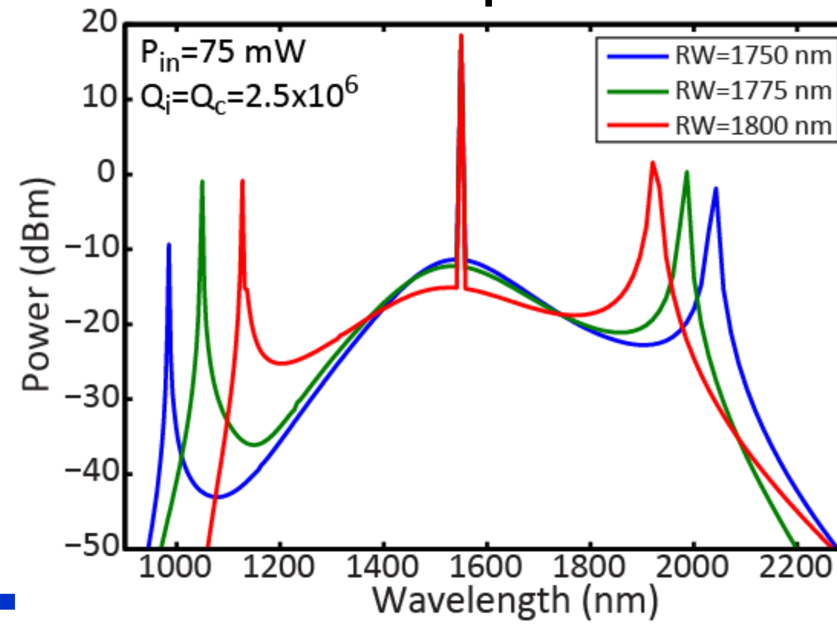
1 THz SiN resonator



Calculated Dispersion



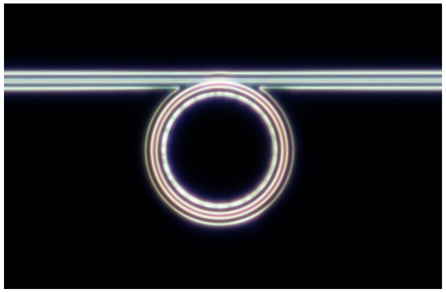
Modeled Spectrum

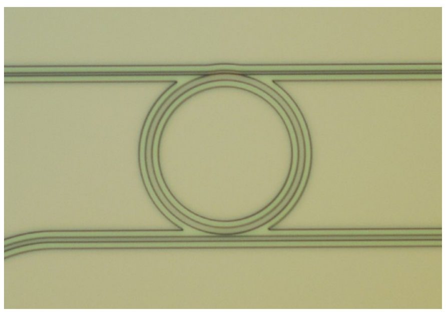


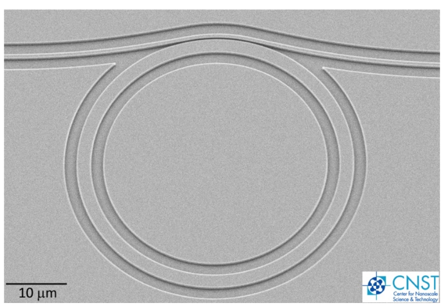
NIST

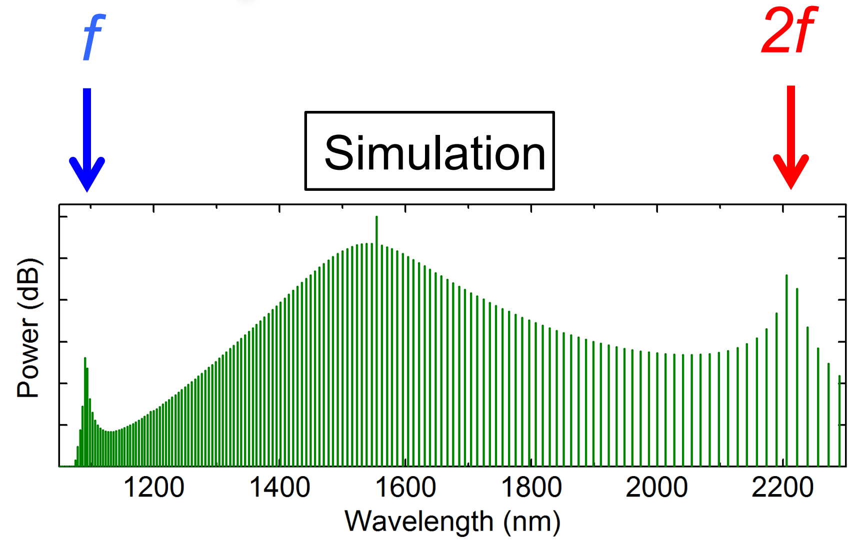
Octave Span & Dual Dispersive Waves

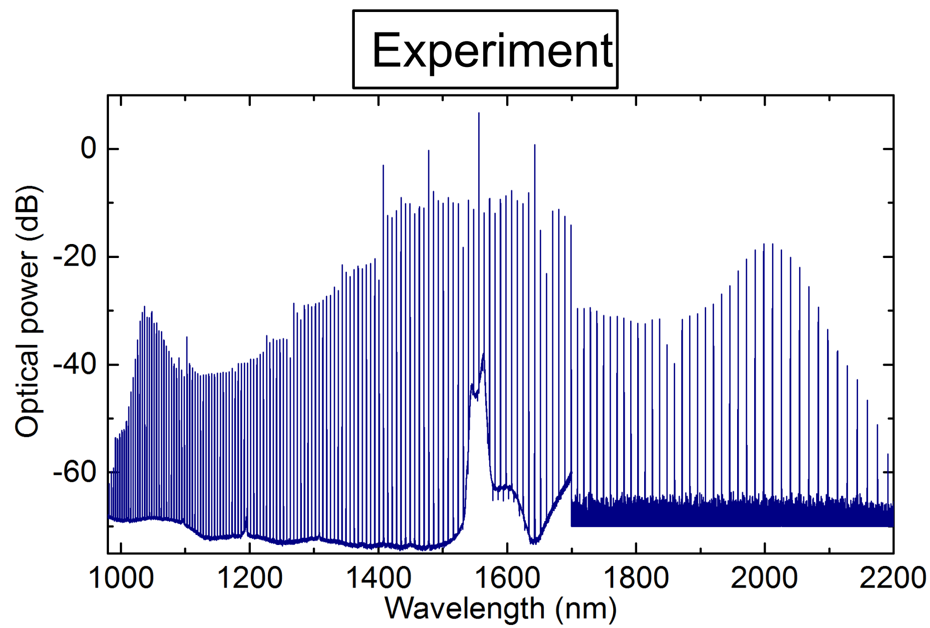
Goal: Octave bandwidth on chip







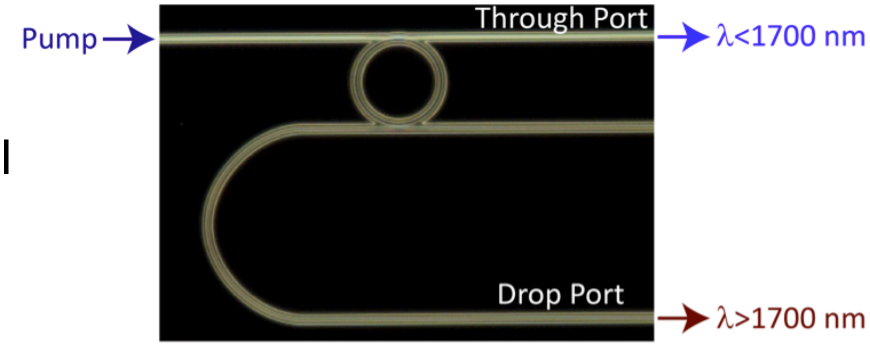




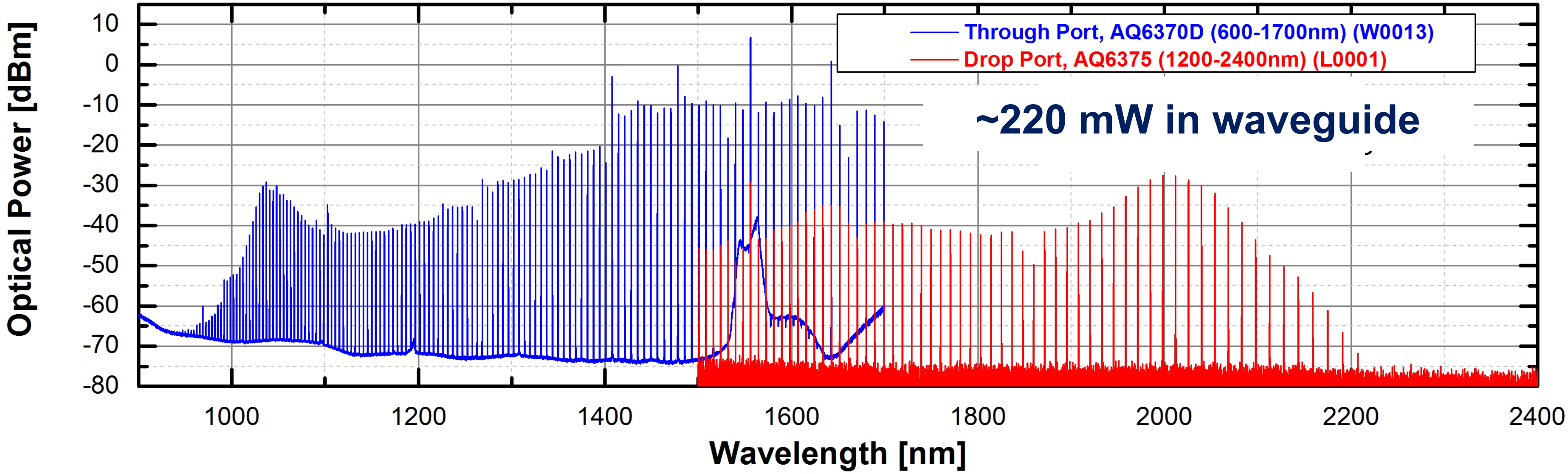
Q. Li OSA FiO postdeadline 2015

Octave Span & Dual Dispersive Waves

- dual dispersive waves via dispersion engineering
- "through" and "drop" ports provide optimal out-coupling of 1000 and 2000 nm



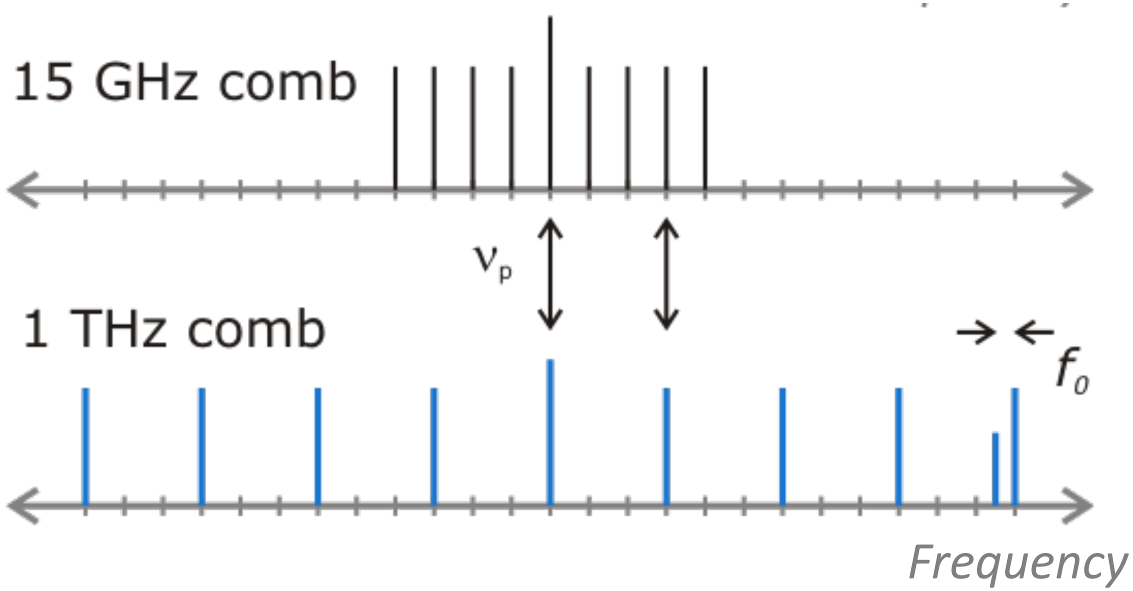
Travis Briles

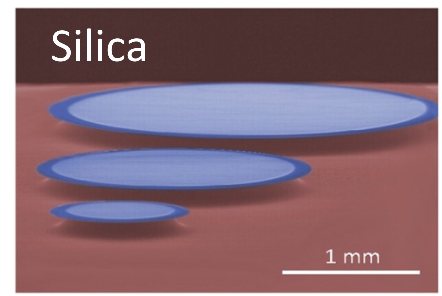


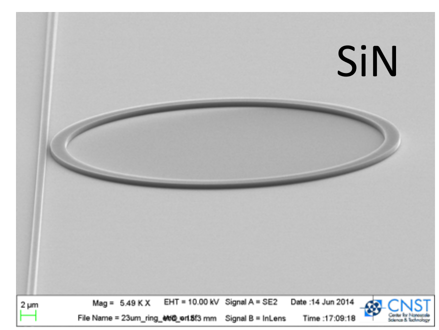
Spectra enable self-referencing!

Self-referencing on a chip?

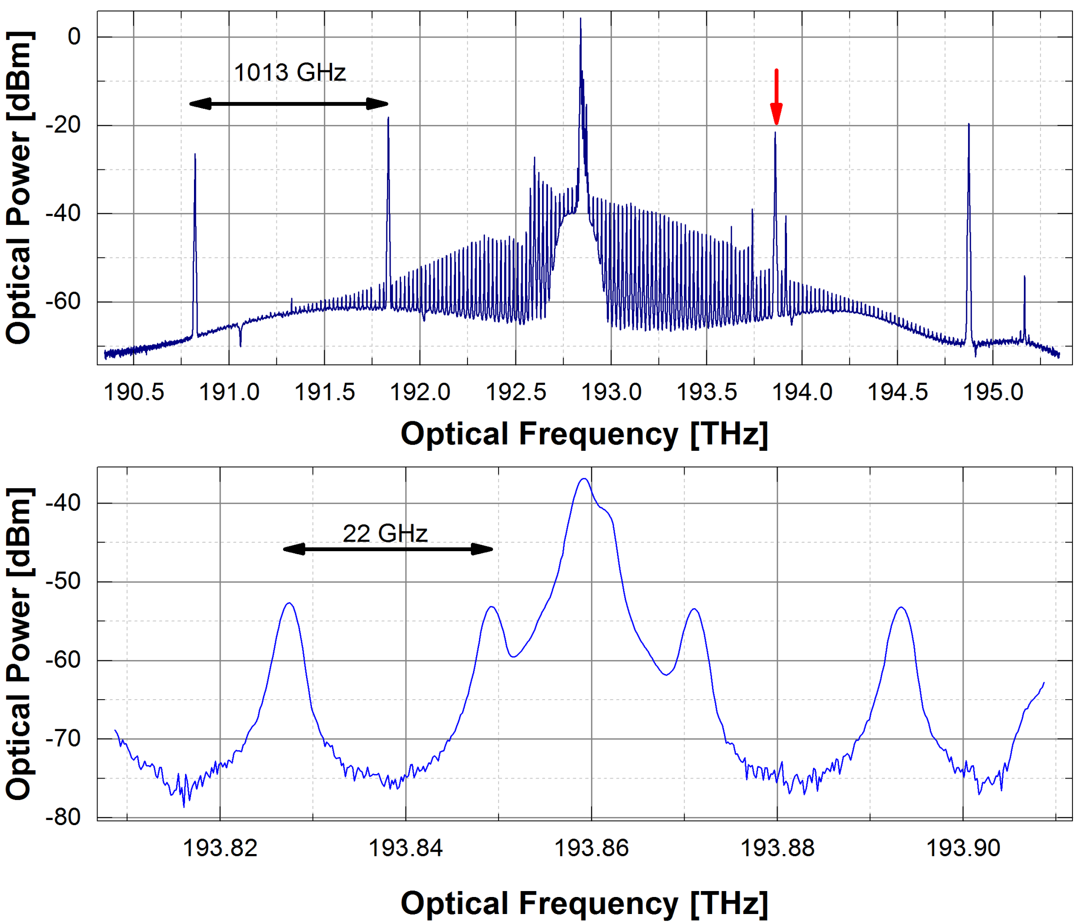
Goal: An octave-span, self-referenced microcomb on a chip
Challenges: Power, frequency control & basic nonlinear optics
Approach: Dual reduction gear 200 THz → 1 THz → 15 GHz
Leverage: Photonic integration (pump laser, PPLN, photodiodes)

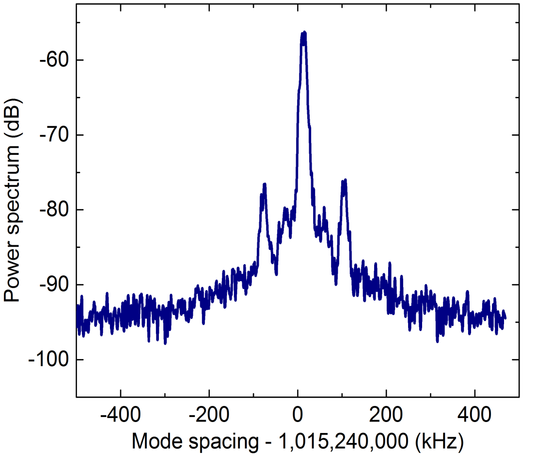






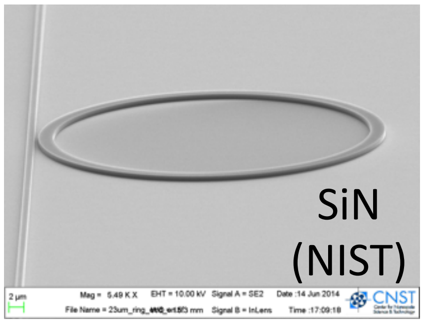
Counting the THz rep rate

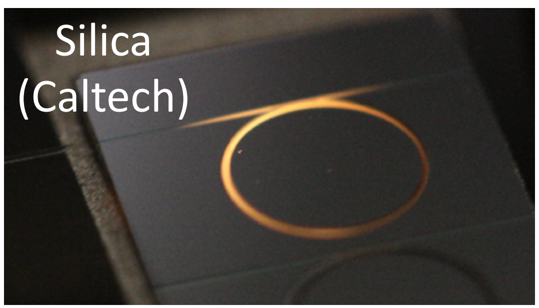




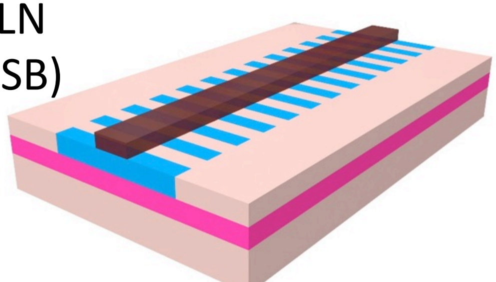
The future: Heterogeneous integration

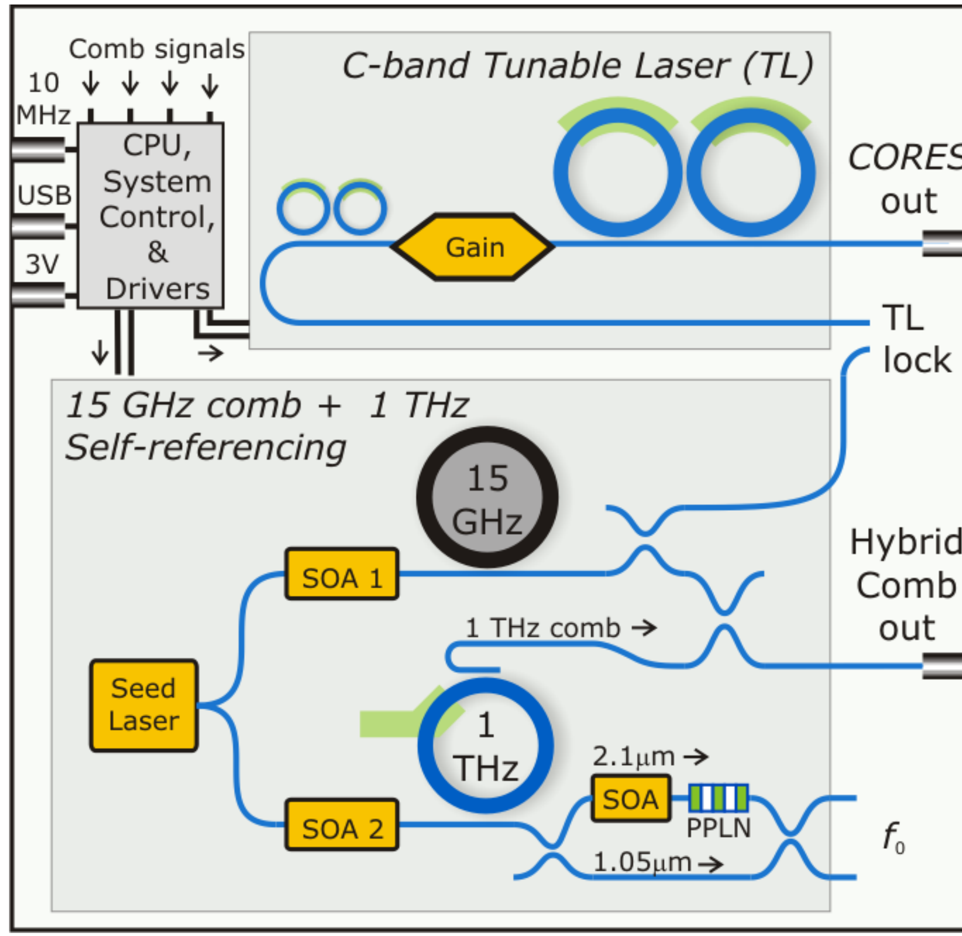
- Self-referenced comb on a silicon chip
- Included pump and tunable laser output





PPLN
(UCSB)





Bowers, IEEE FCS (2016)

Outline

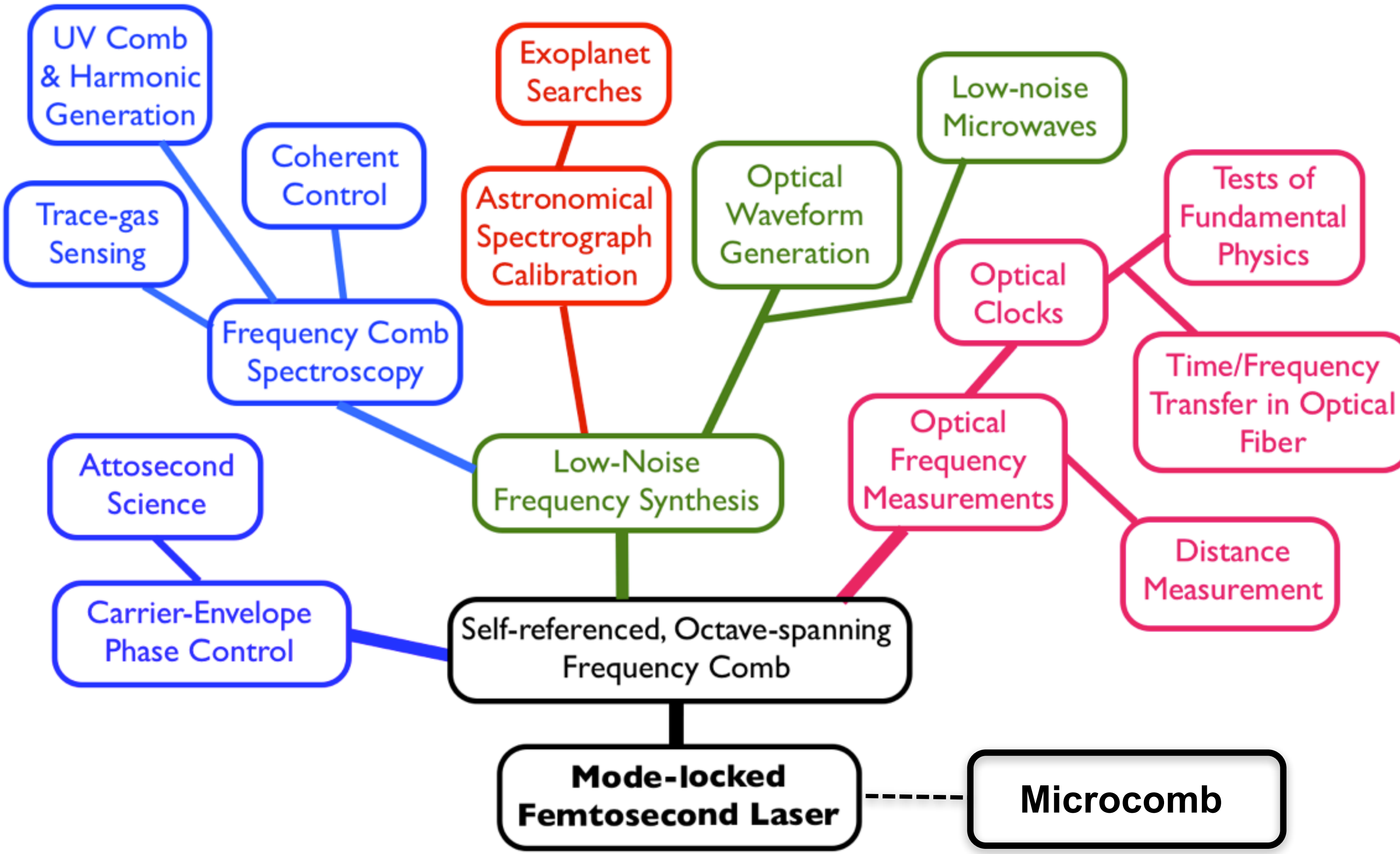
1. Background: Clocks and Precise Timing

2. Counting Cycles of Light
   - The optical frequency comb

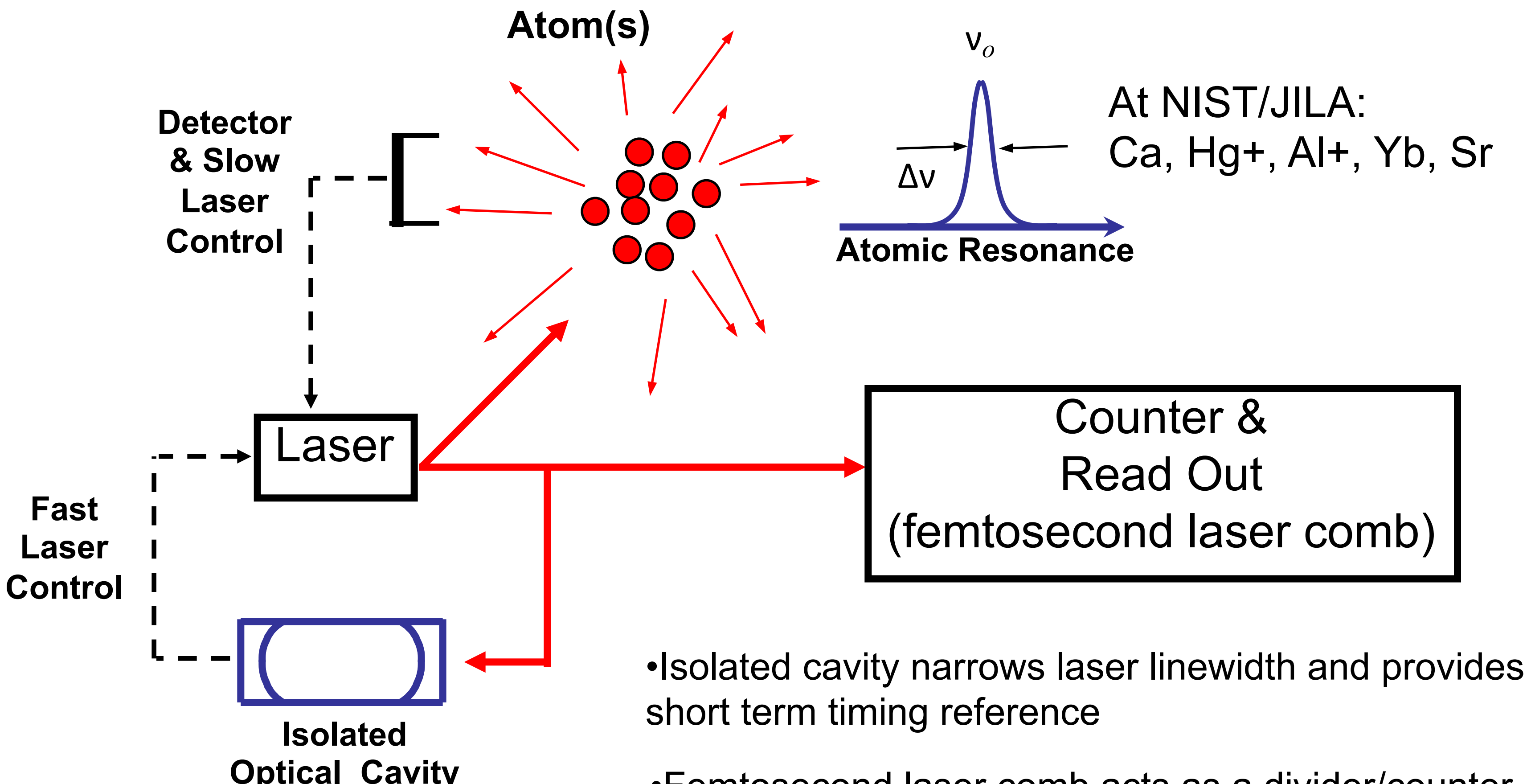
3. From Lab Scale to Chip Scale
   - Can we make a frequency comb on a chip?

4. Applications and opportunities for frequency combs

Frequency Comb Evolutionary Tree



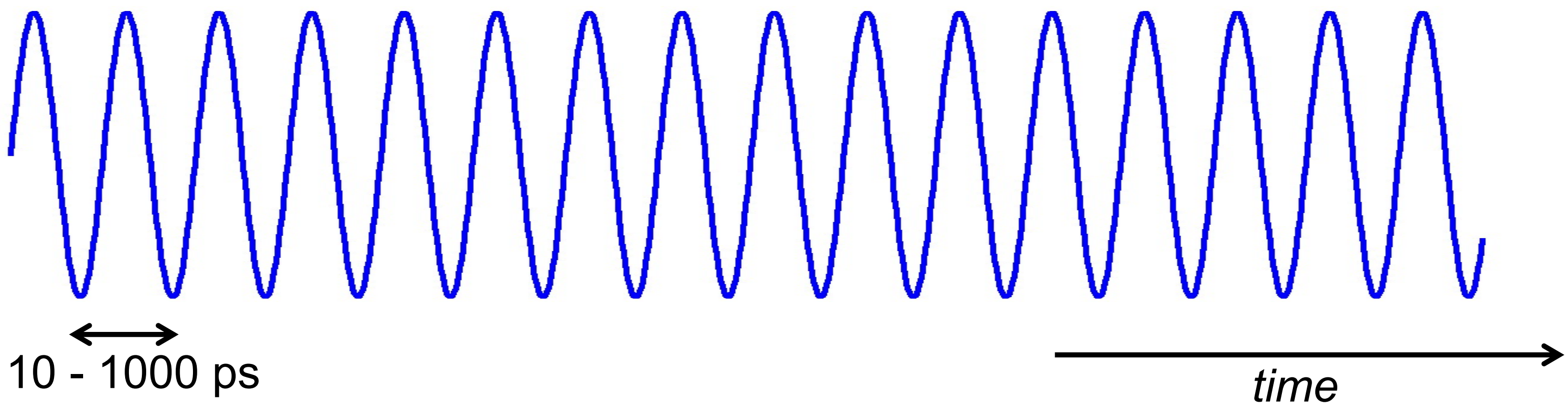
Optical Atomic Clocks



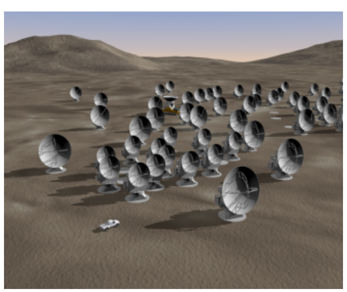
- Isolated cavity narrows laser linewidth and provides short term timing reference
- Femtosecond laser comb acts as a divider/counter
- Atoms provide long-term stability and accuracy— **now now at 10^{-18} level!**

Timekeeping: The short view

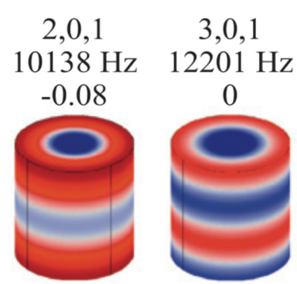
$$V(t) = A\sin[2\pi f_0 t + \phi(t)]$$



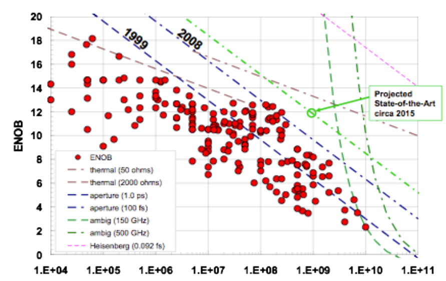
Timescale of interest: 10 ps - 1 second



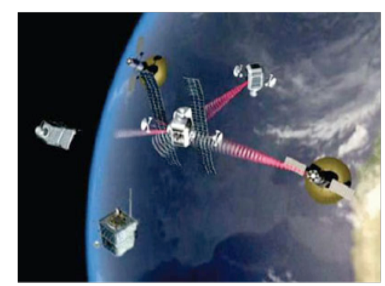
Astronomy & Timing Sync for Science



Optomechanics & Precision Measurements

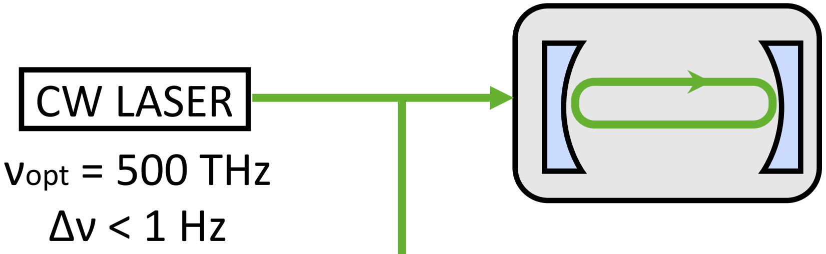


Communications & AD Conversion



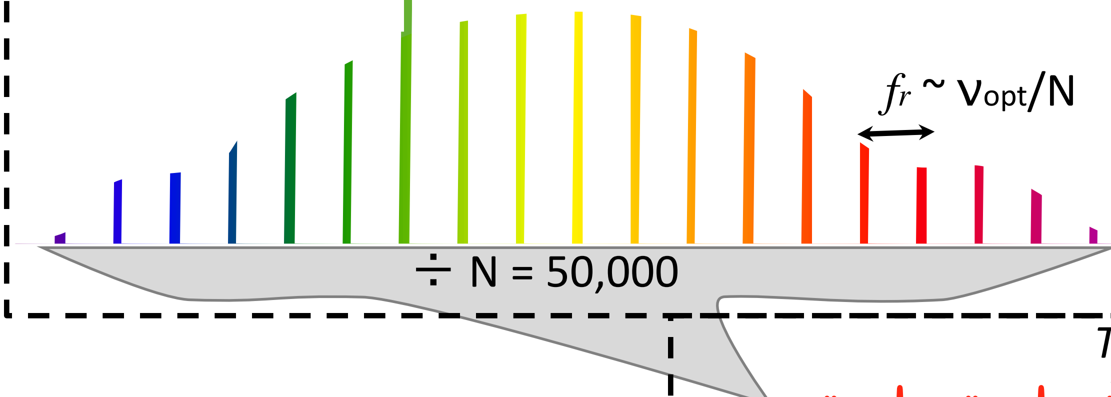
Radar & Navigation

Optical Frequency Division



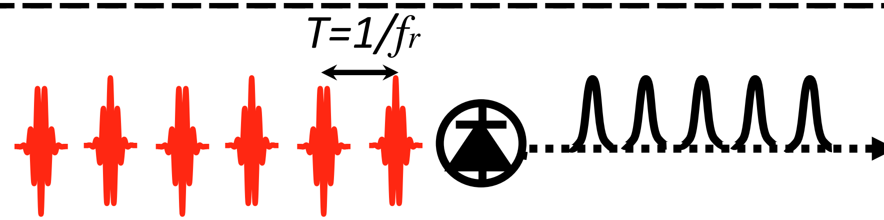
1. Ultrastable CW Laser Oscillator

- CW laser stabilized to well-isolated & vibrationally-insensitive optical cavity
- Optical cavity is the timing/frequency reference for entire system



2. Optical Frequency Divider

- Femtosecond laser frequency comb stabilized to CW laser
- Phase coherent division from optical to microwave
- Reduction of phase noise power by N^2



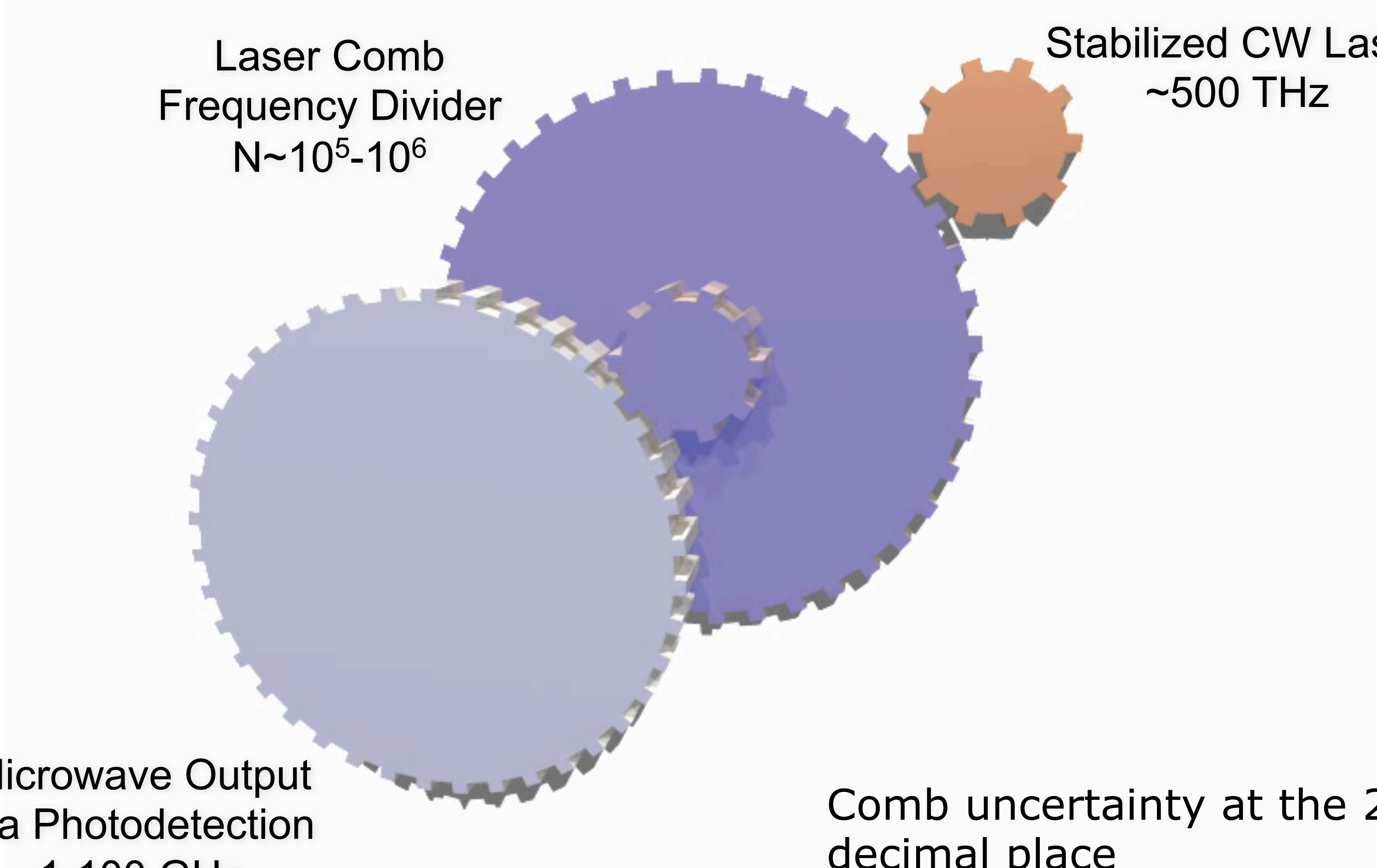
3. Opto-Electronic Conversion

- High-speed photodiode detects stable optical pulse train
- Provides electronic output
- Stringent demands on power handling and linearity

<u>microwave signal:</u>
any harmonic of f_r
$\Delta f/f < 10^{-15}$ @ 1s
$S_{\mu wave}(f) = S_{opt}(f)/N^2$

S. Diddams et al, IEEE JSTQE, **9**, 1072 (2003); A. Bartels, et al, *Opt. Lett.* **30**, 667 (2005); J. McFerran, et al. Electron. Lett. **41**, 36 (2005); T. Fortier, et al. *Nat. Photon.* **5**, 425 (2011).

Photonic Microwave Generation

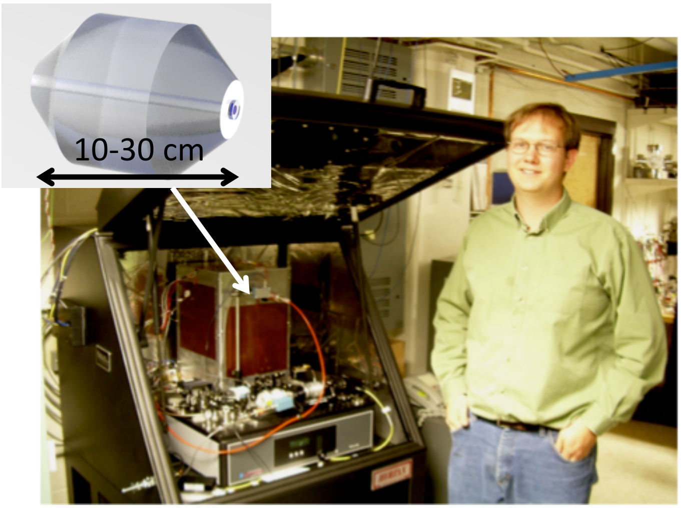


Comb uncertainty at the 20th decimal place

L.-S. Ma, et al., Science, **303**, 1843 (2004)

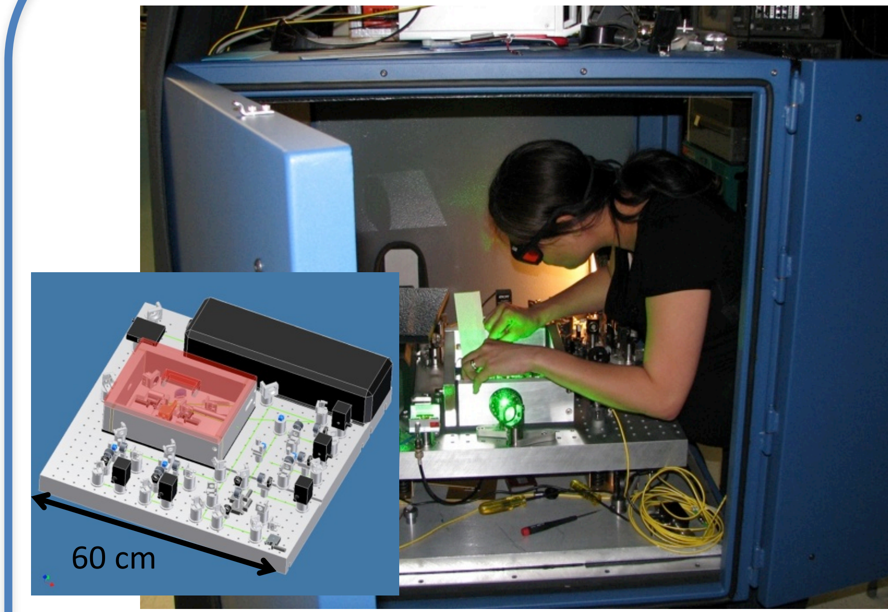
Main Components of Present System

Frequency Reference: Cavity-Stabilized Laser



- ULE fused silica Fabry-Perot etalon
- Housed in temp-controlled vacuum chamber
- Vibration (active) and acoustic isolation
- Cavity length is thermal noise limited to <1 femtometer (nuclear diameter)

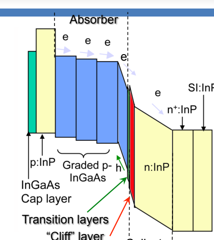
Optical Frequency Divider



- Self-referenced (octave spanning) femtosecond laser
- Demonstrated with both Ti:sapphire and Er:fiber systems
- Need very low intensity noise

Photodiode

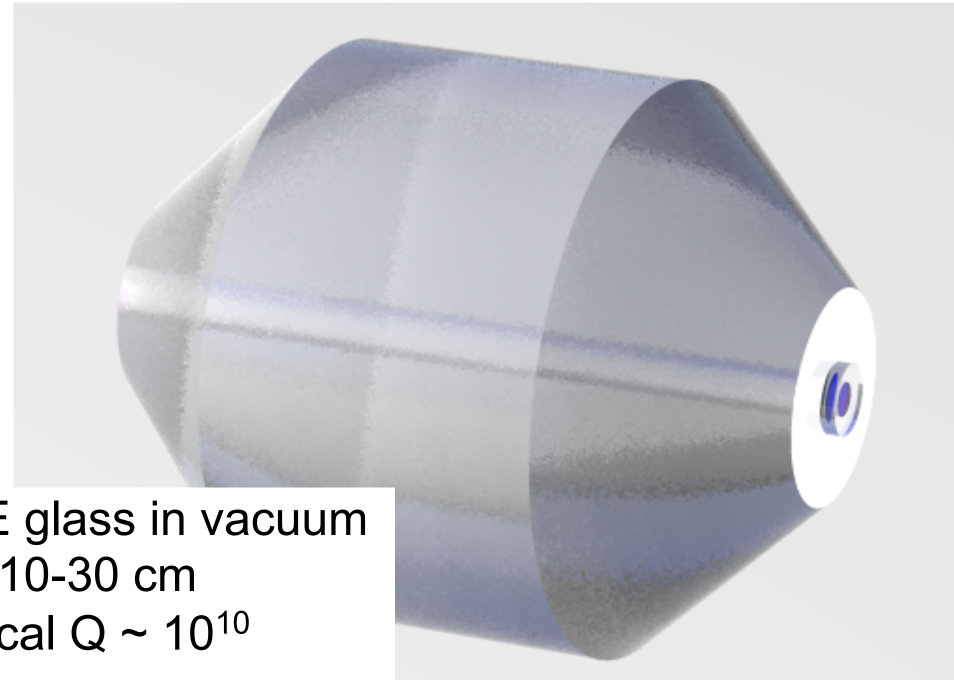
- 10-50 GHz bandwidth
- High linearity, high power handling



NIST

Thermal-noise-limited optical cavities

Hall, Bergquist, Ye, et al.

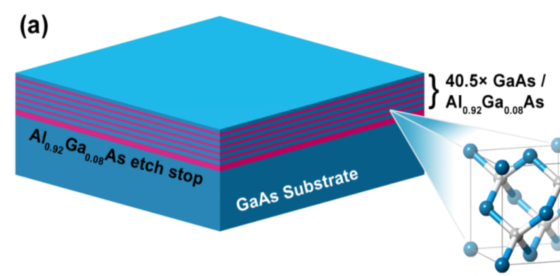


- Cavity length stable to <0.1 **femtometer**

- Limitation to length stability is thermal Brownian motion in mirror substrates

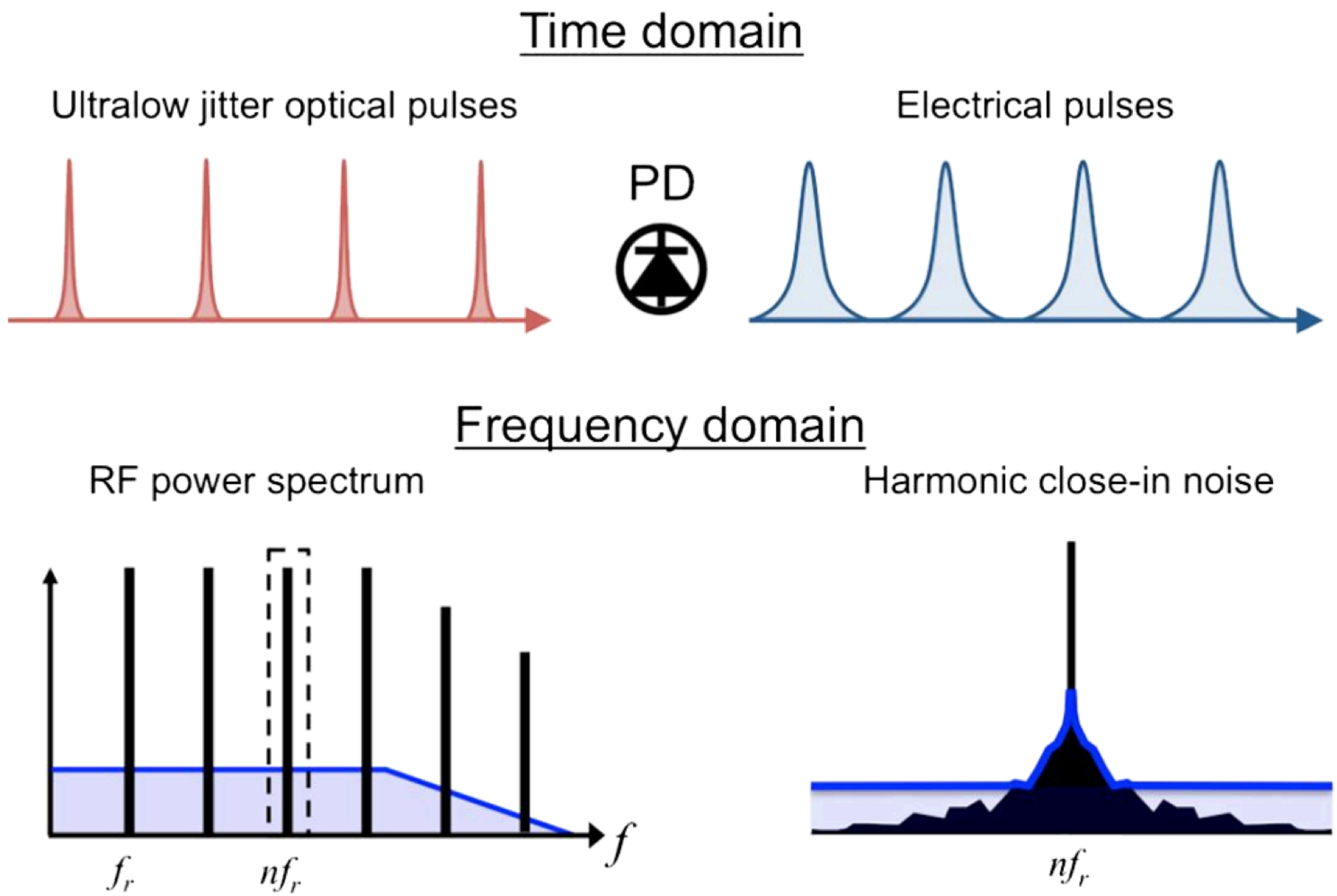
ULE glass in vacuum
L ~ 10-30 cm
optical Q ~ 10^{10}

→New developments: Single crystal silicon cavity & Crystalline Bragg reflectors provide reduced thermal-mechanical noise



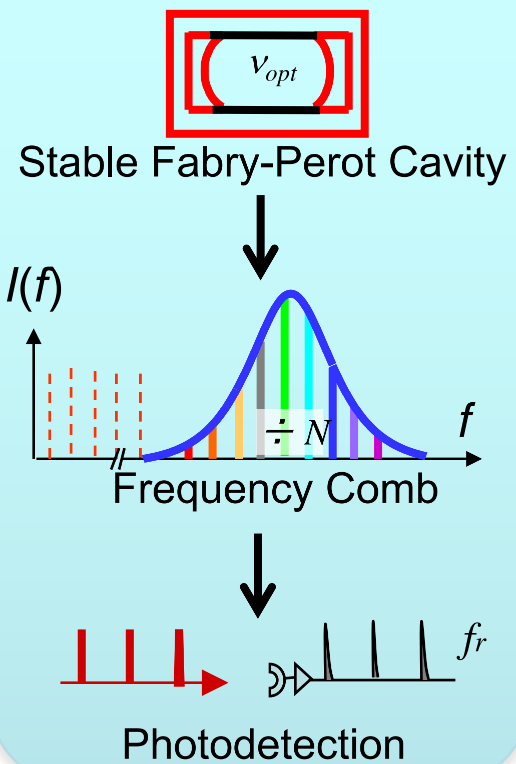
Cole et al, Nature Photon (2013).
Kessler et al. Nature Photon (2012).

Optical-to-microwave synthesis



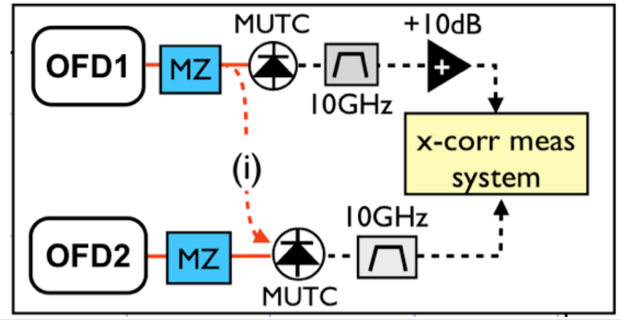
Optical-to-microwave synthesis

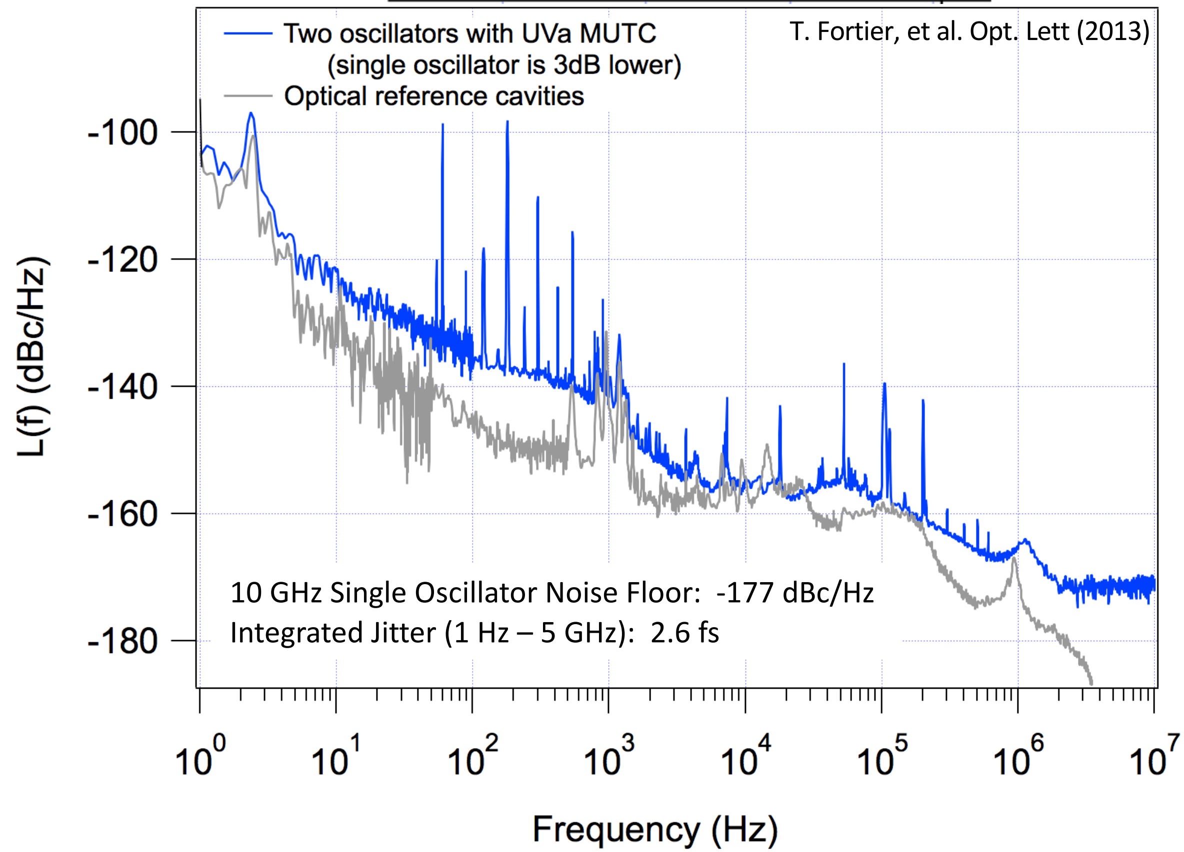
Optical
Frequency Division



$$f_r = \nu_{opt}/N$$

$$S_{\mu wave}(f) = S_{opt}(f)/N^2$$

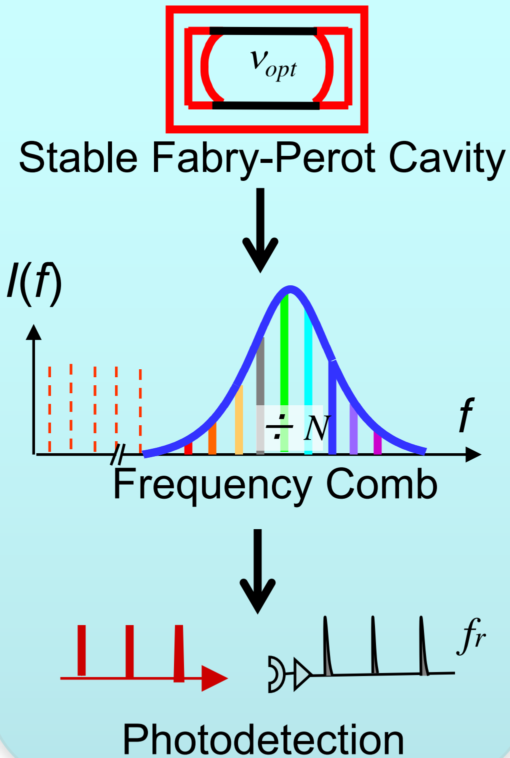




S. Diddams et al, IEEE JSTQE, **9**, 1072 (2003); A. Bartels, et al, *Opt. Lett.* **30**, 667 (2005);
J. McFerran, et al. Electron. Lett. **41**, 36 (2005); T. Fortier, et al. *Nat. Photon.* **5**, 425 (2011).

Optics beats electronics

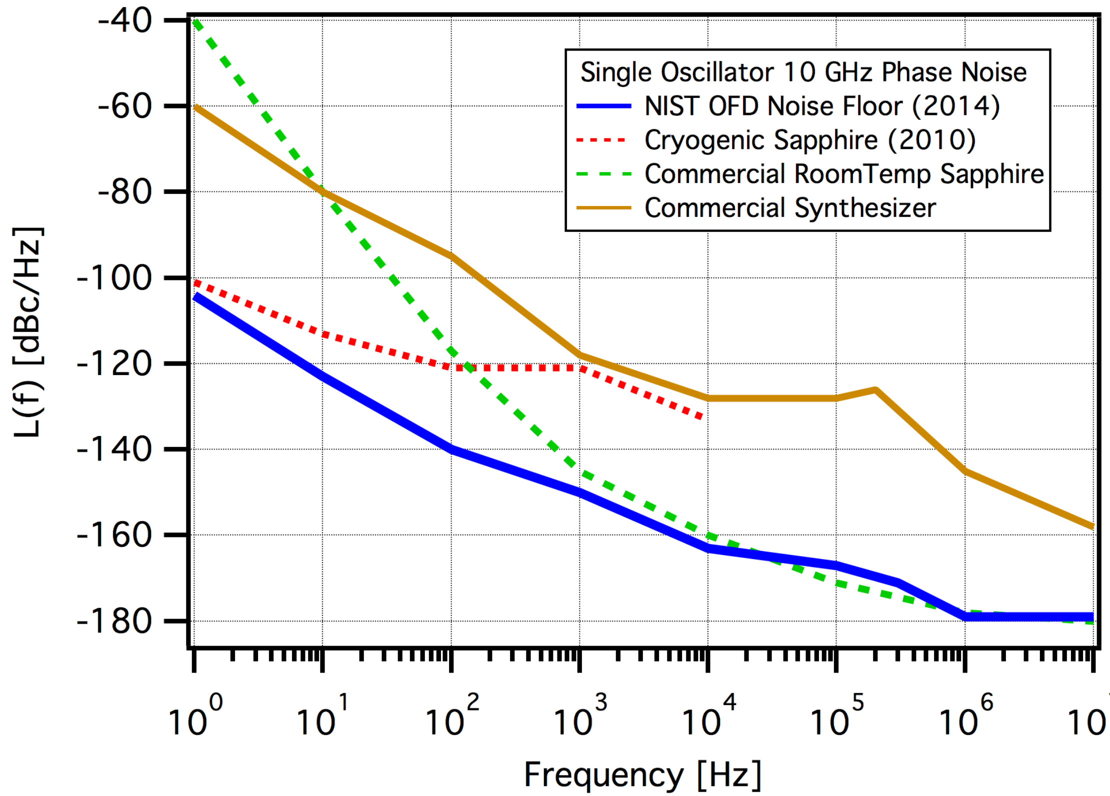
Optical Frequency Division



$$f_r = \nu_{opt}/N$$

$$S_{\mu wave}(f) = S_{opt}(f)/N^2$$

Integrated Jitter (1Hz – 5 GHz)	
OFD	2.6 fs
Sapphire dielectric	300 fs

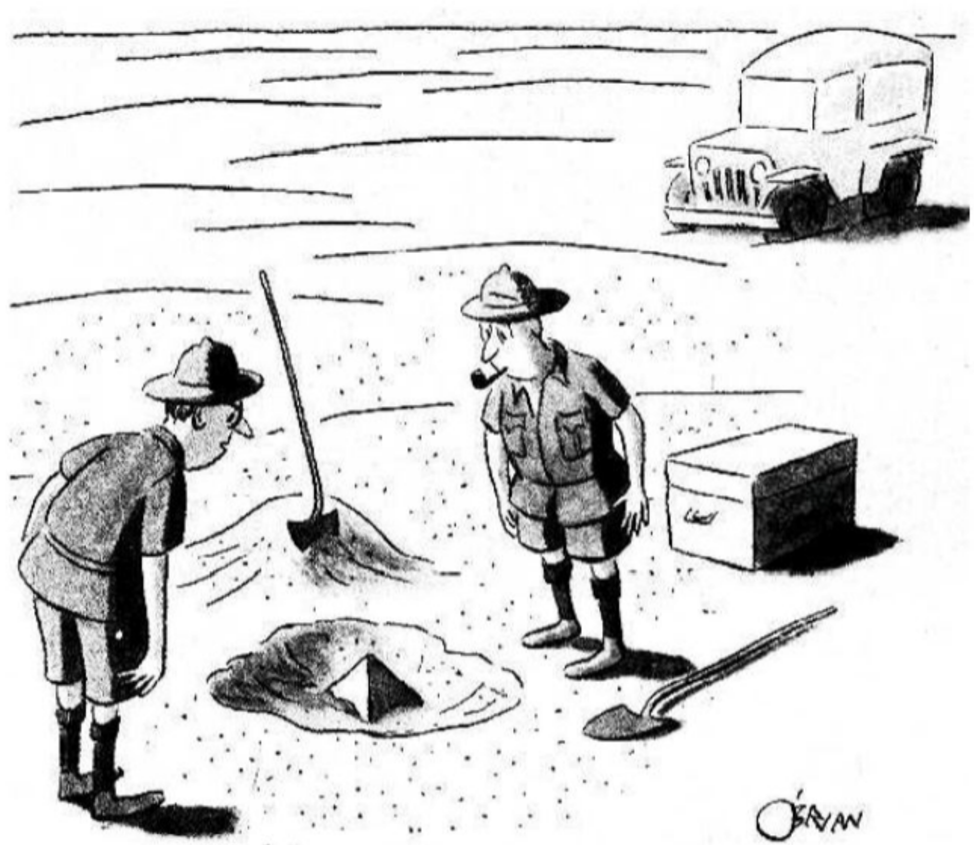


→ Have extended to frequencies from 10 MHz to 100 GHz

T. Fortier, et al. *Nat. Photon.* (2011), T. Fortier, et al. *Opt Lett* (2013), F. Quinlan, et al. *Opt. Lett* (2014)

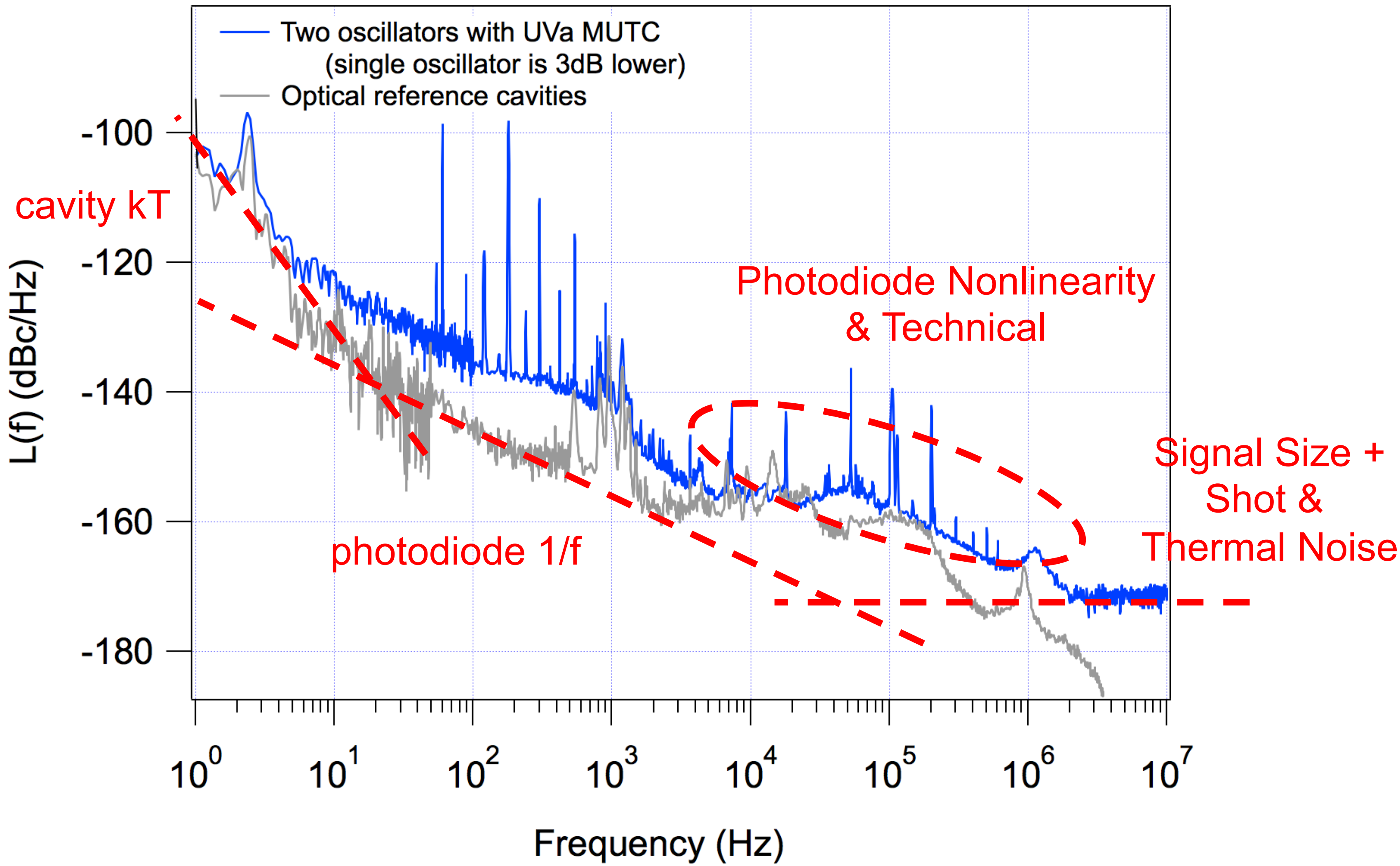
Why do we like looking at noise ?!

sometimes that is where the Physics is buried…



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

What are the limits?

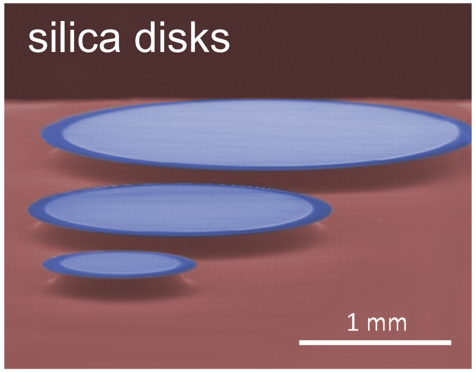


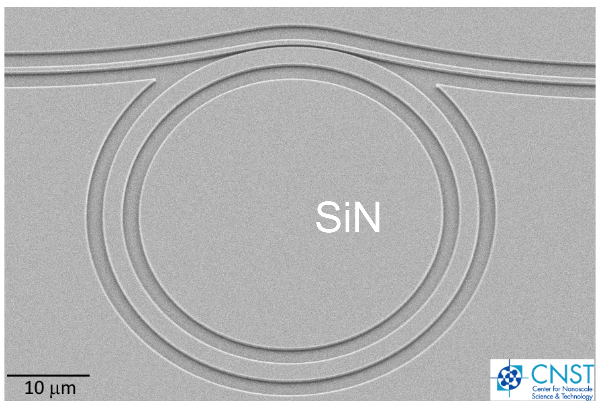
T. Fortier, et al. arXiv:1302.5927 and Opt. Lett (2013)

Microresonator Research at NIST

See the video on YouTube “Laser comb in a minute”
S. Papp, PRX (2013), P. Del’Haye, Appl. Phys. Lett. (2013)
F. Ferdous, Nat. Photon. (2011)
H. Lee, Nat. Photon. (2012), H. Lee Nat. Comm. (2013)

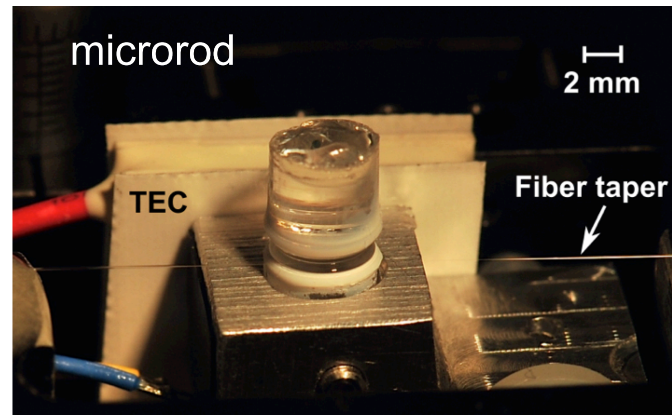
Microresonators for Comb Generation

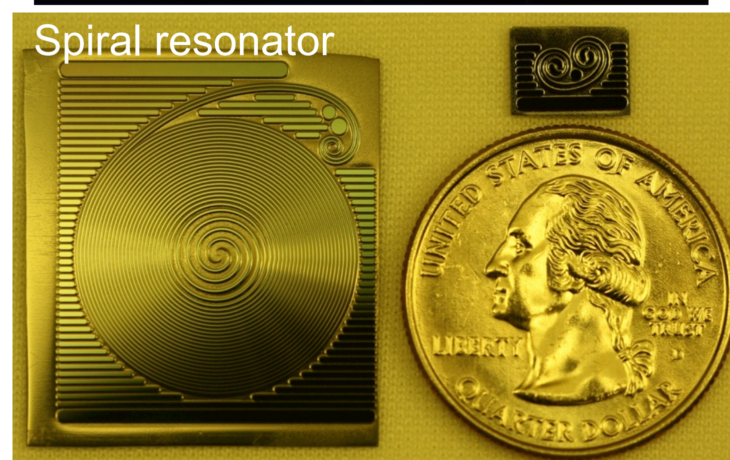




→ Q ~ 10^6 – 10^9
→ Large mode volume for low noise
→ Small mode volume for efficient nonlinear optics

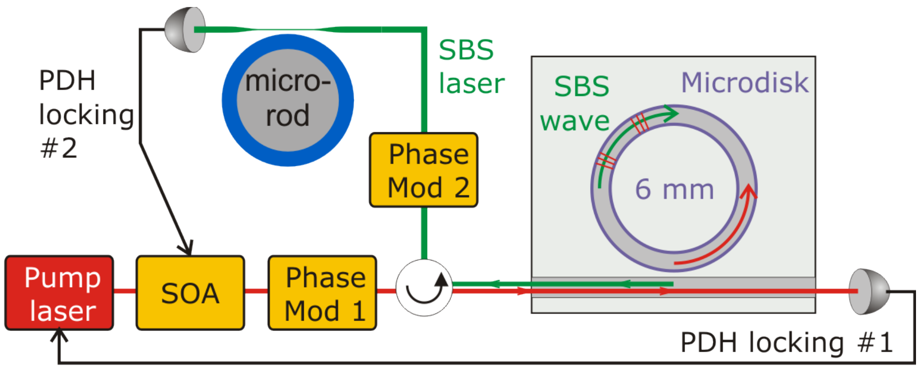
Microresonators for SBS and Laser Stabilization



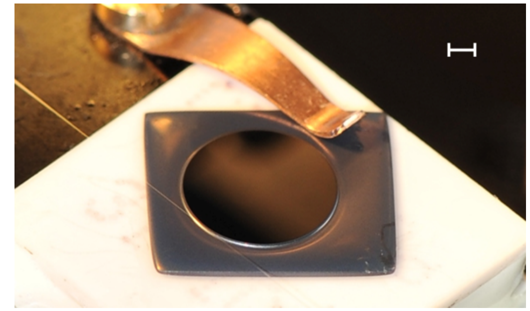


Devices: Vahala (Caltech), Srinivasan (NIST)

Hybrid microresonator systems

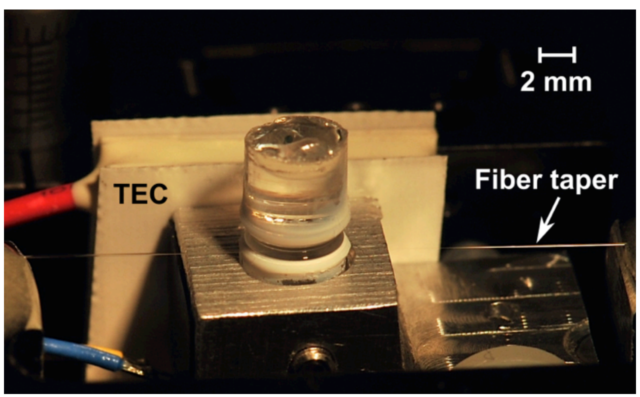


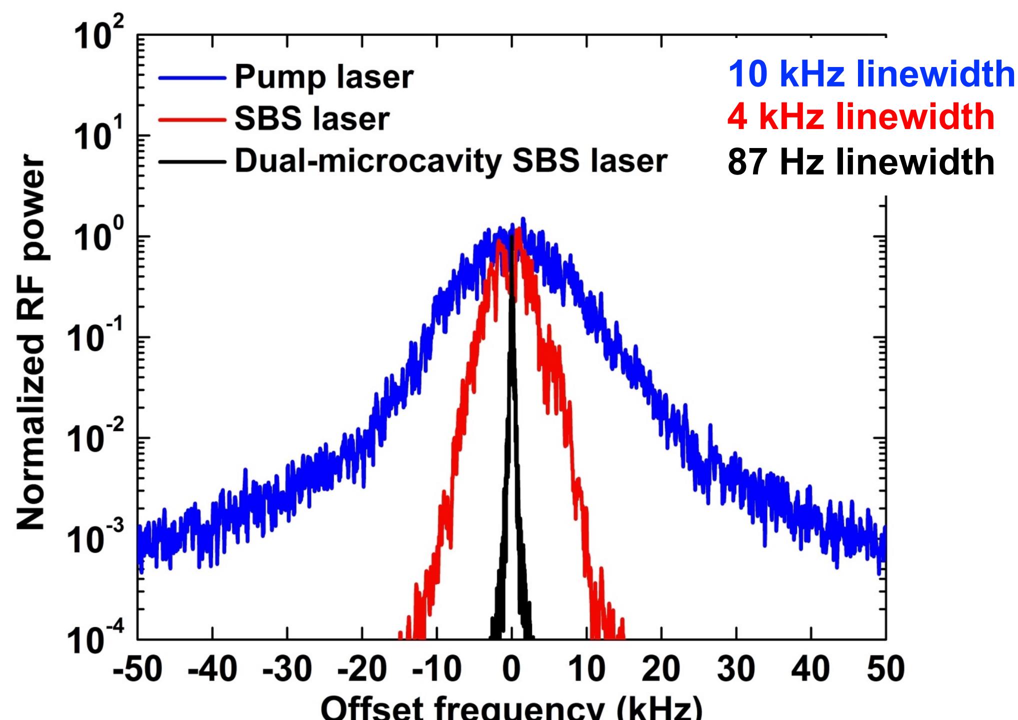
SBS disk



J. Li, K. Vahala

Microrod reference

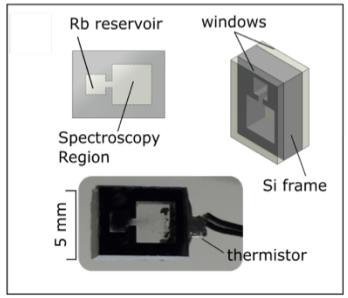




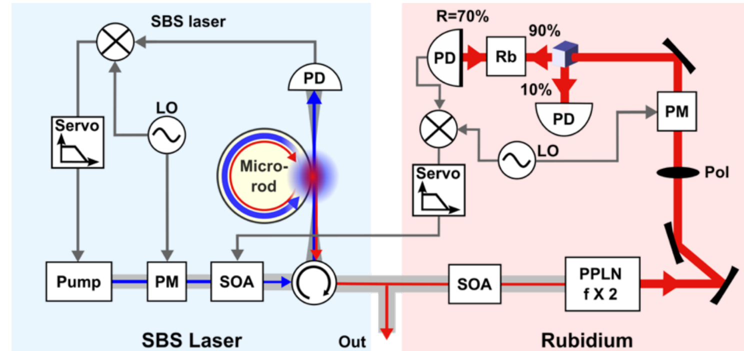
W. Loh, *Optica, PRA, arXiv*

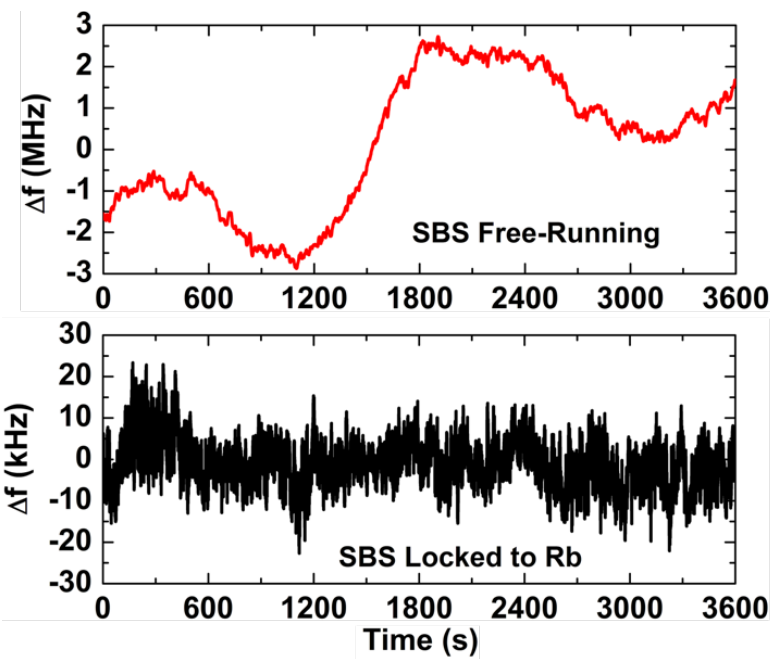
Rb-stabilized SBS Laser

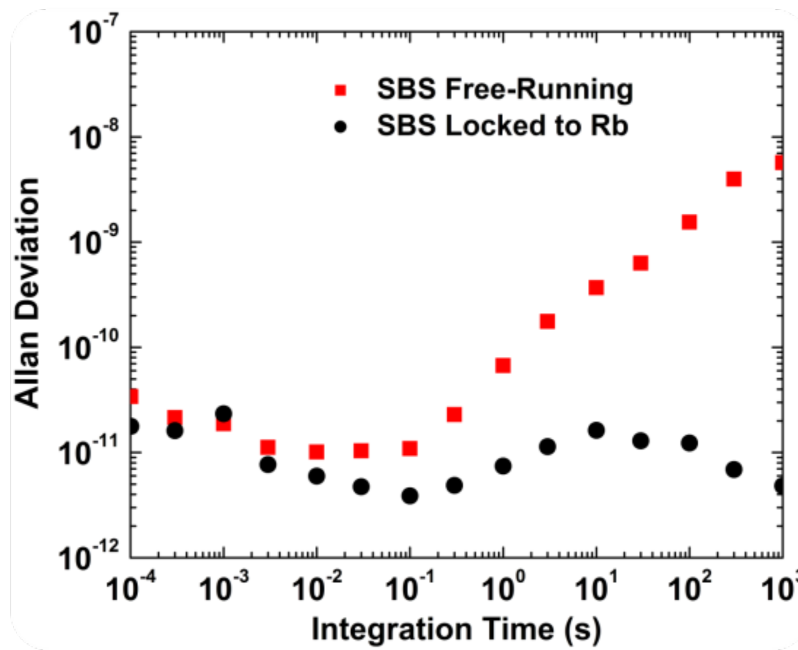
+



M. Hummon, J. Kitching

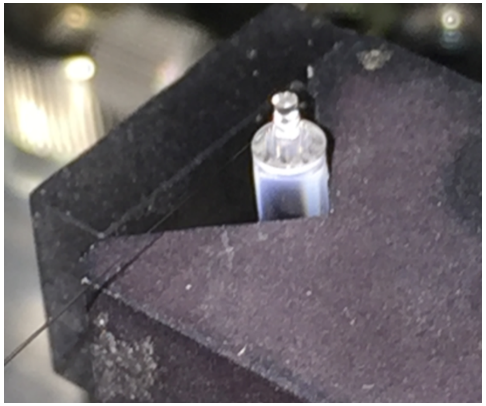


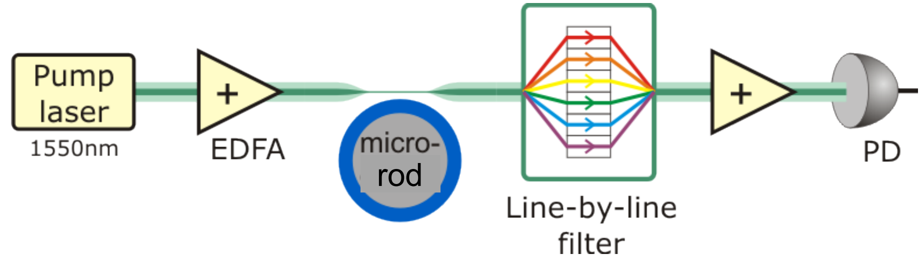


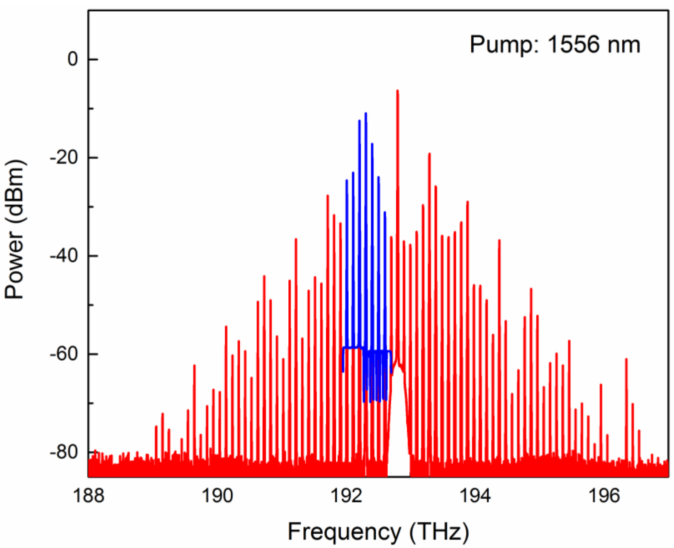


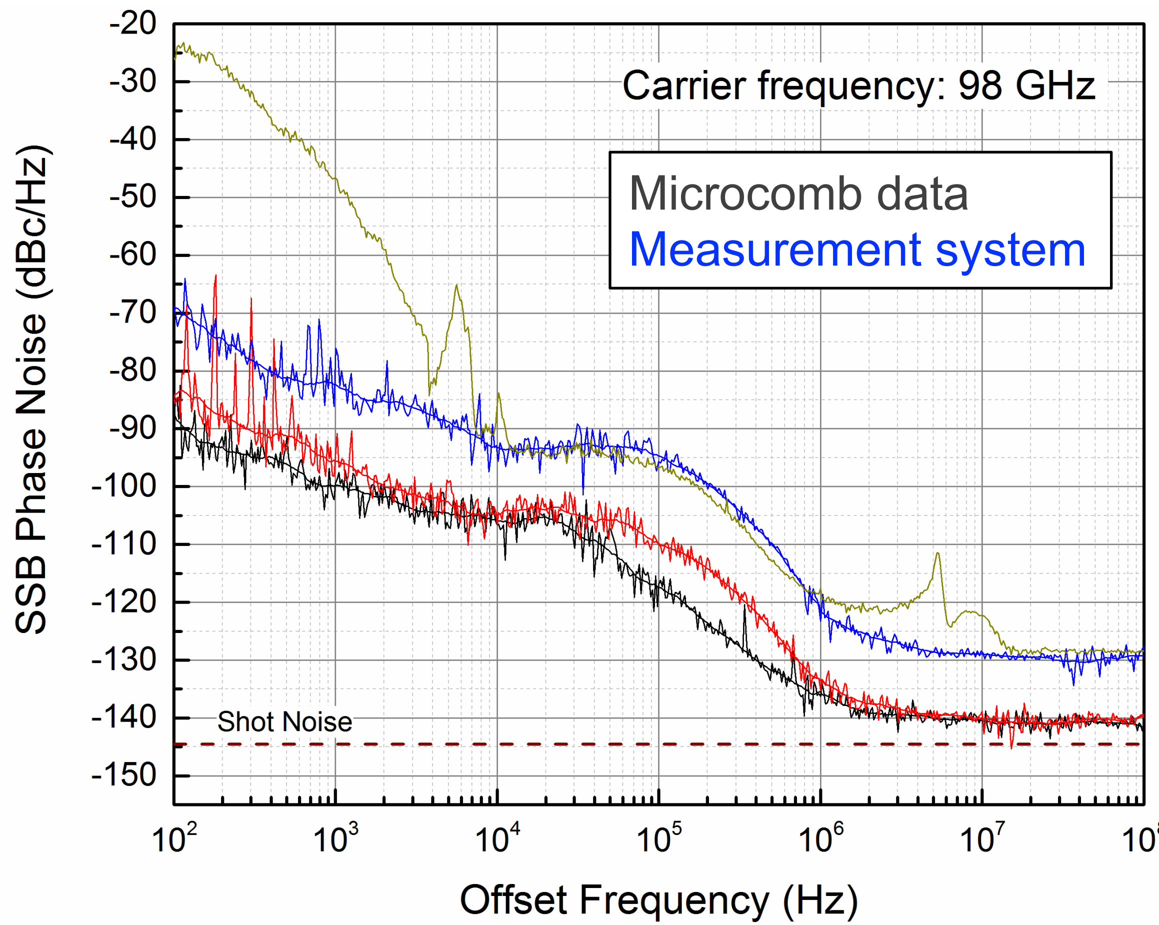
W. Loh & M. Hummon, Opt. Exp 2016

W-Band Phase Noise

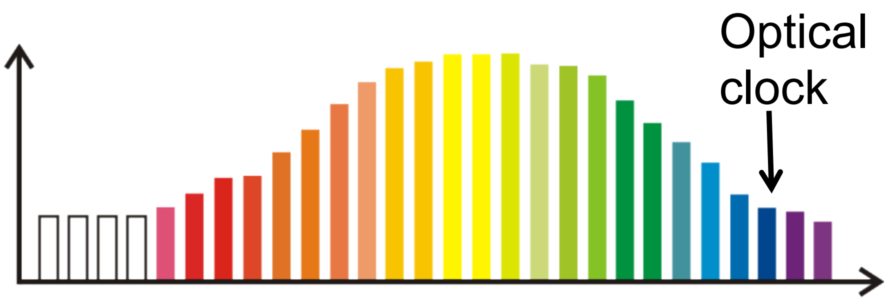




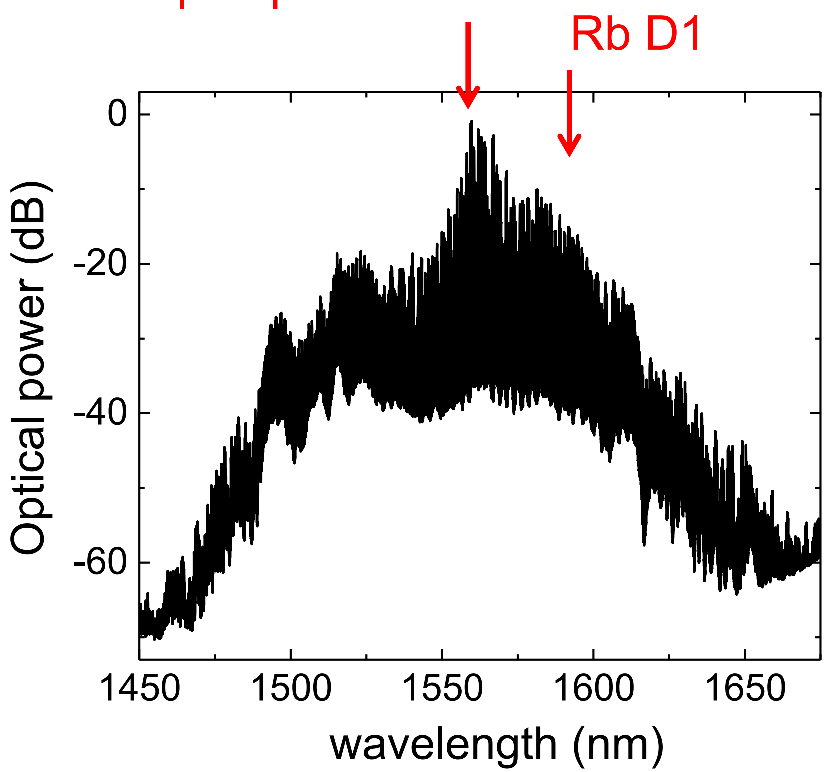


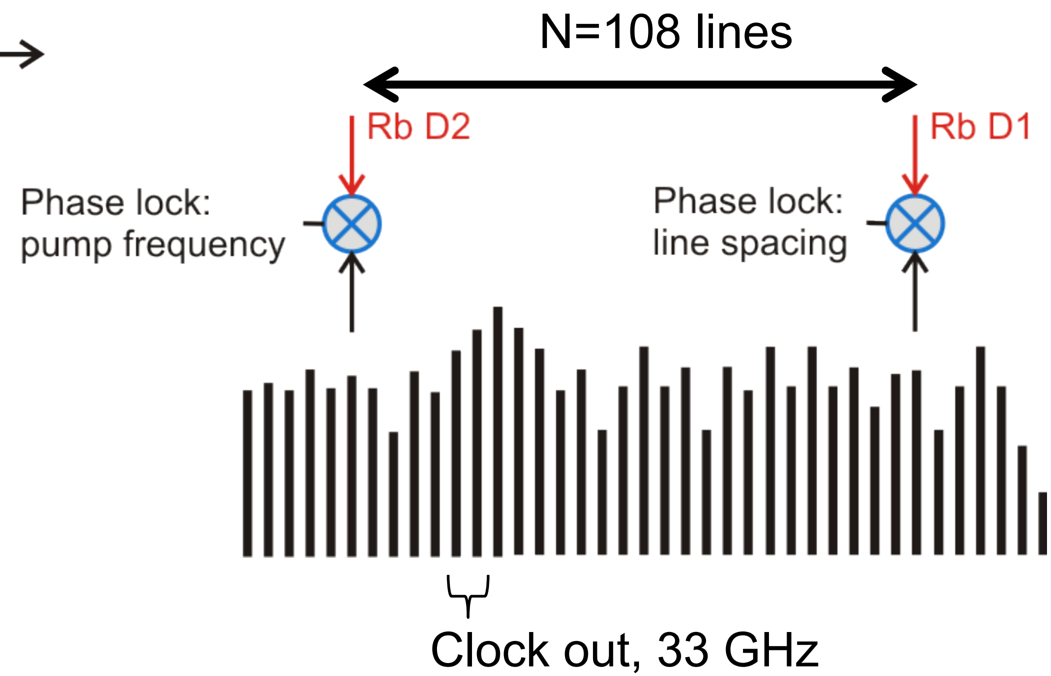


A microcomb optical clock



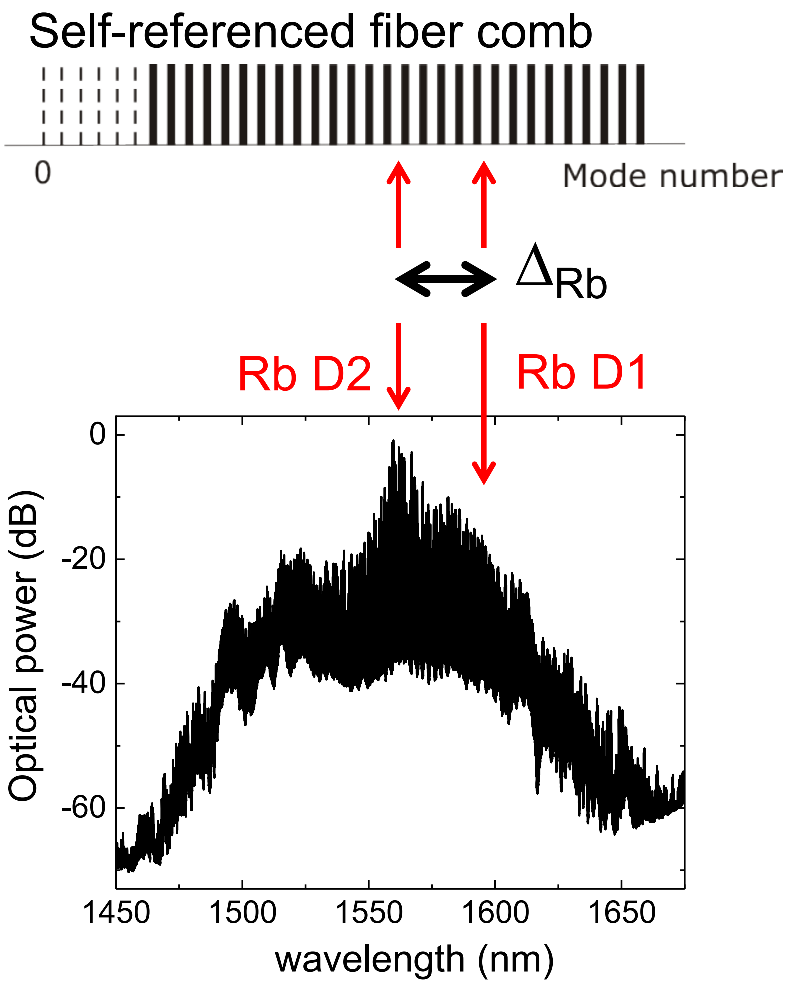
Control pump to Rb D2

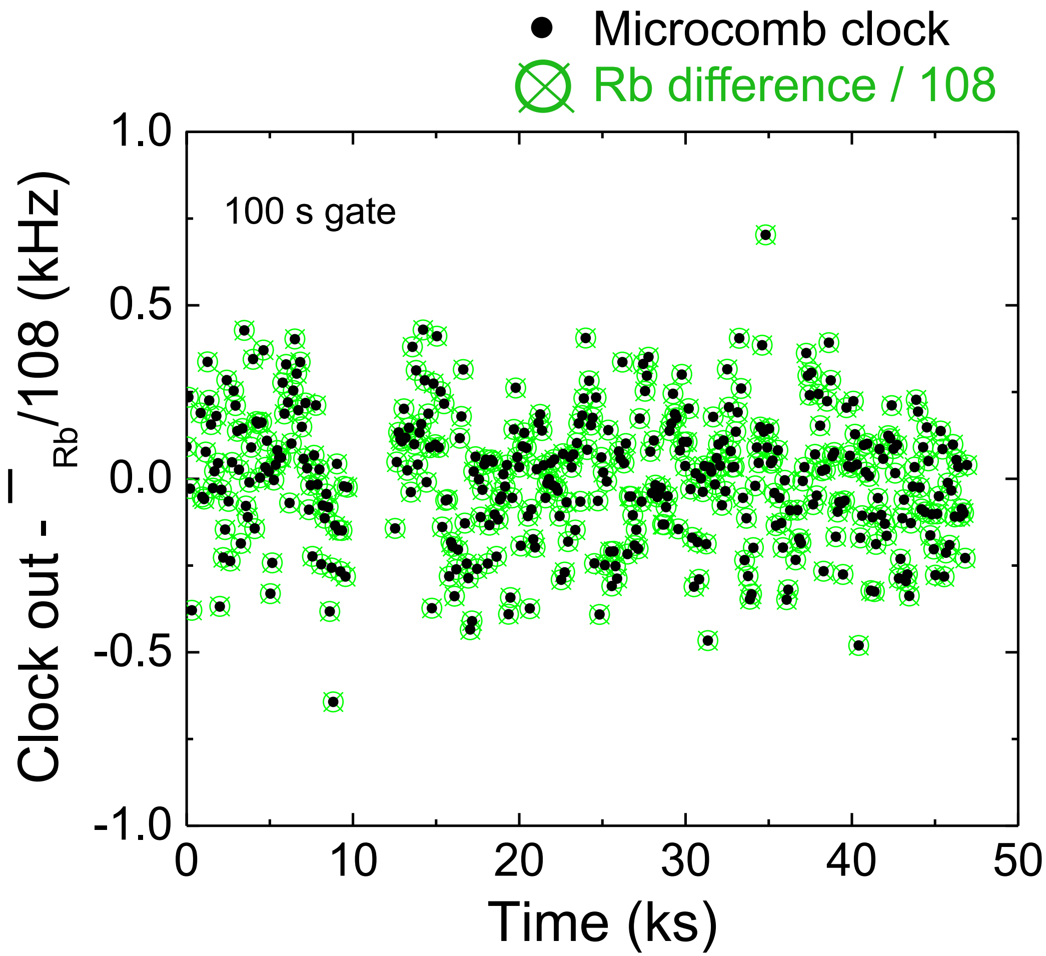




$$(\text{Clock noise})^2 = \frac{(\text{D2 noise})^2 + (\text{D1 noise})^2}{N^2}$$

A microcomb optical clock





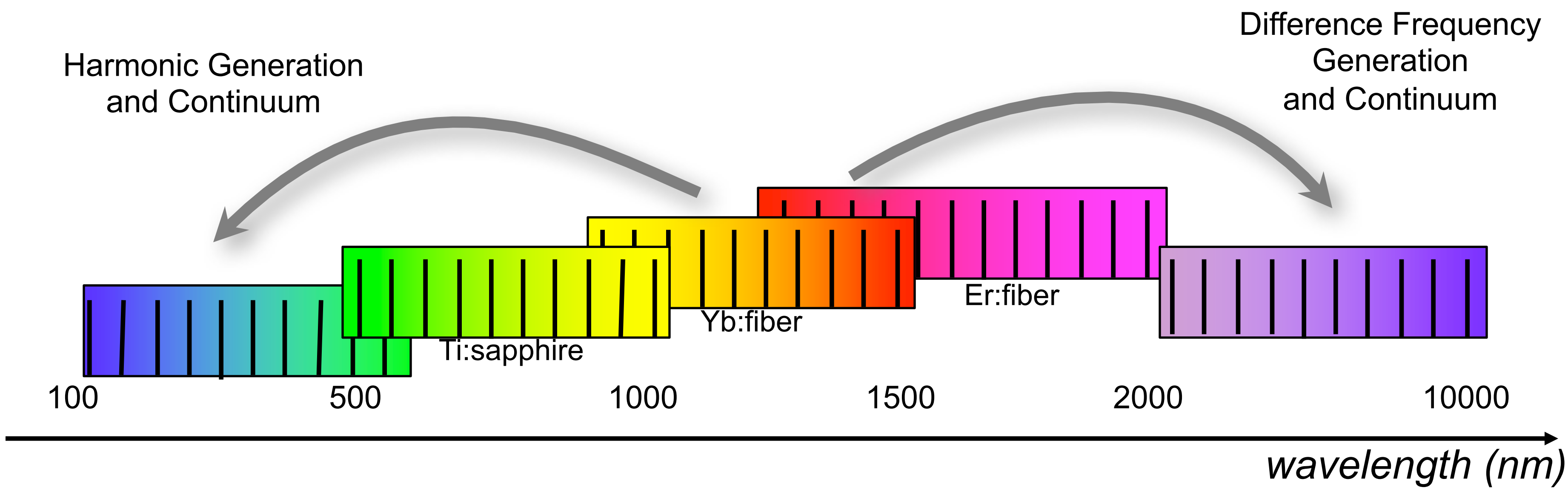
→ Instability: ~10^{-10} at 1 s
(Rb drift removed)

→ Residual noise: 10^{-14} at 1 s

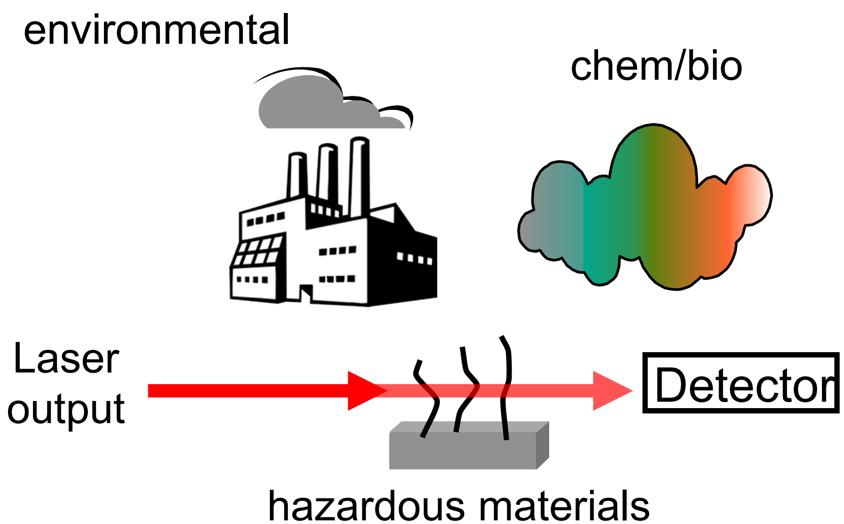
S. Papp, Optica 2014

Broadband Spectroscopy with Frequency Combs

- array of millions of phase-coherent CW oscillators
- large spectral coverage: <100 nm to >10 microns
- precisely known frequencies (~1 Hz resolution)
- simultaneously excitation of multiple transitions
- access to wavelengths otherwise difficult to produce
- coherent laser beam (cavity enhancement, standoff, etc.)



Trace Gas Detection via Broadband Frequency Comb Spectroscopy

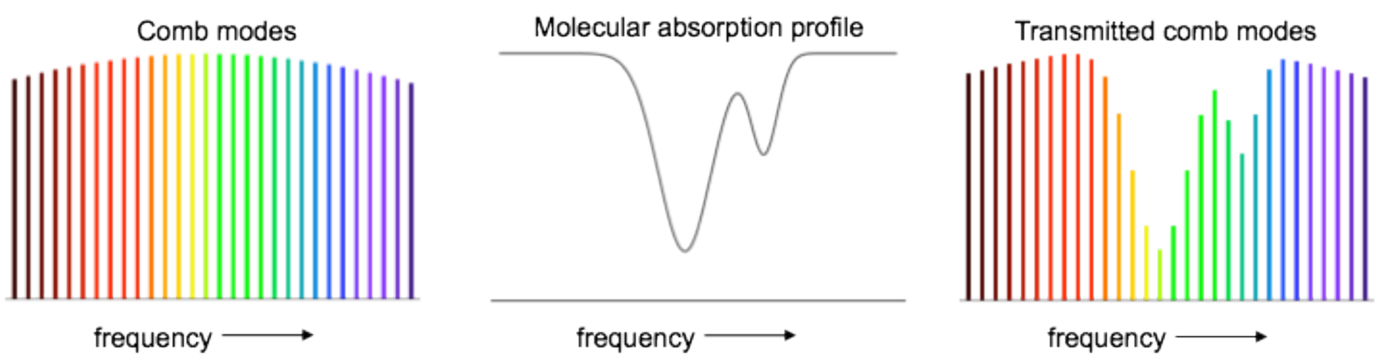


Typical Challenges:

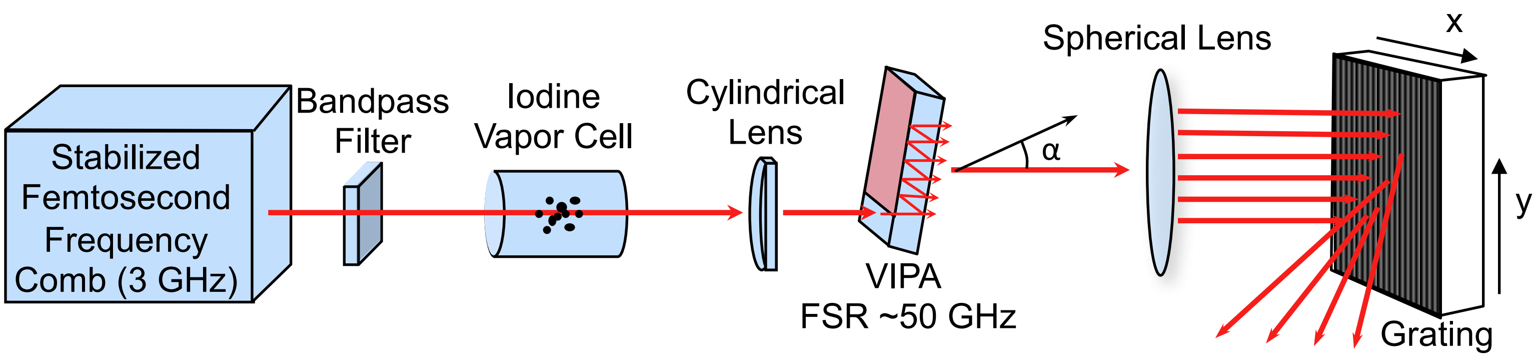
Sensitivity: Minimum detection limit given by measurement **SNR** and species

Quantification: Requires a model, fitting data including knowledge of the background

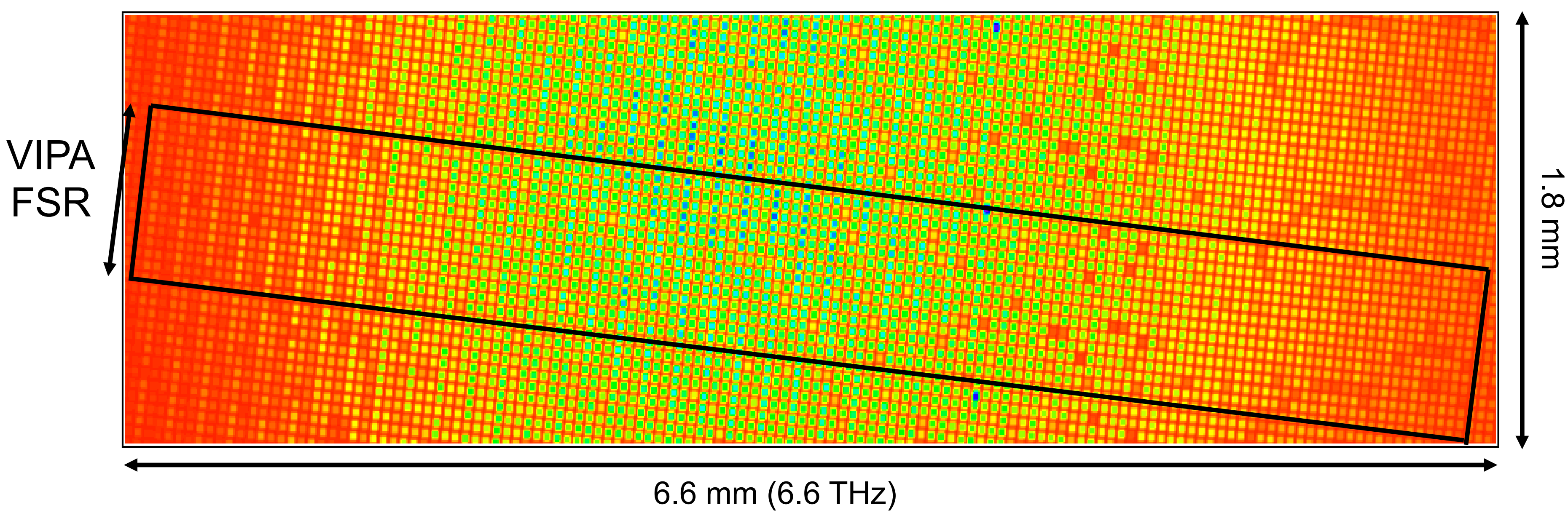
Discrimination: Broad bandwidth and high resolution combined with model



Molecular Fingerprinting with a Mode-Resolved Comb

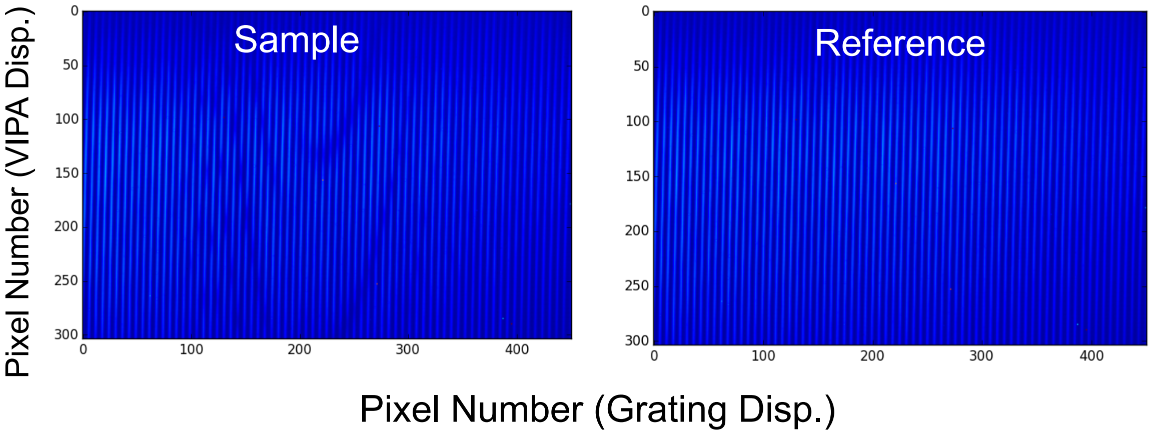


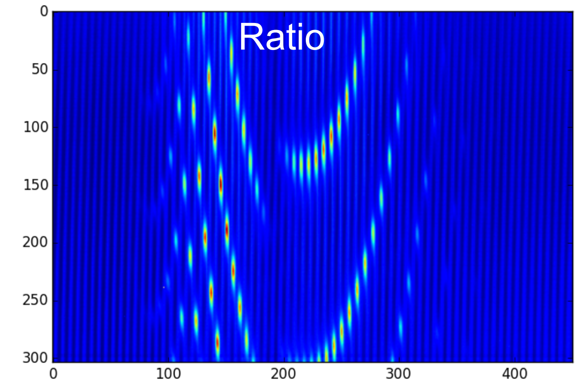
CCD Image



2200 modes = 6.6 THz @ 474 THz
5 ms acquisition time

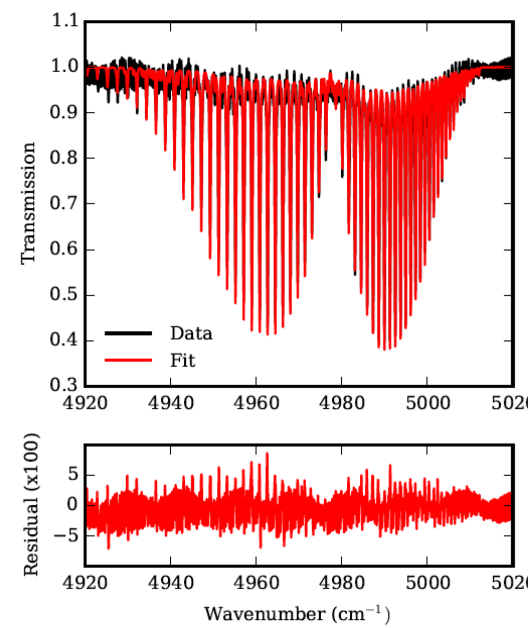
CO_2 Spectroscopy





13 cm cell, 840 mbar CO_2, 301K

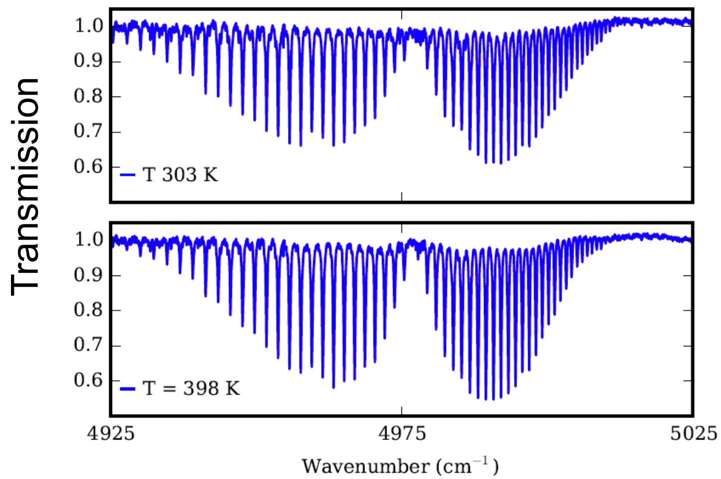
- Monitor change between sequential camera images
  - Sample and reference
  - Delta between two sample images
- **Resolution of <2 GHz achieved (~0.05cm^{-1})**
- **Simultaneous measurement of >100 cm^{-1} of bandwidth** (~2000 spectral elements)
- **1 ms integration time**
  (limited by light intensity)

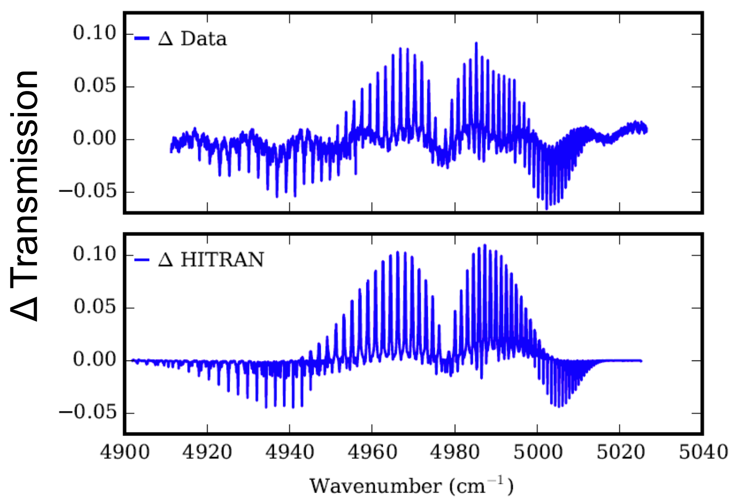


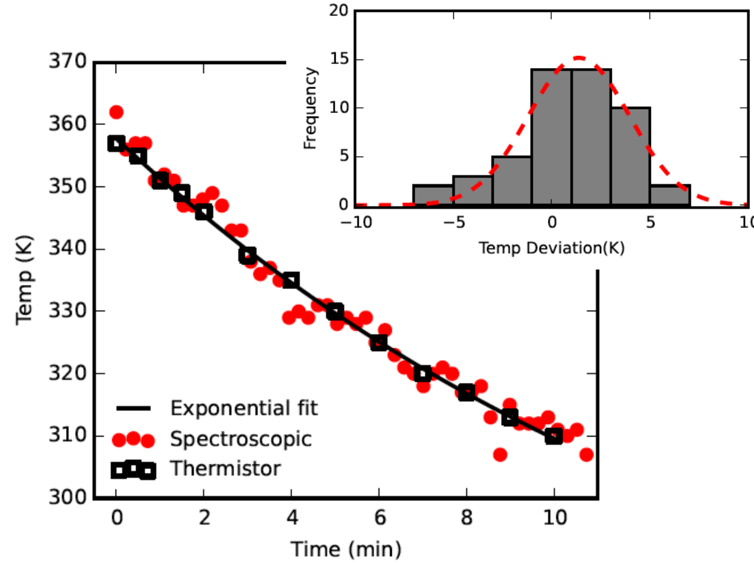
Klose, Appl Phys B (2016)

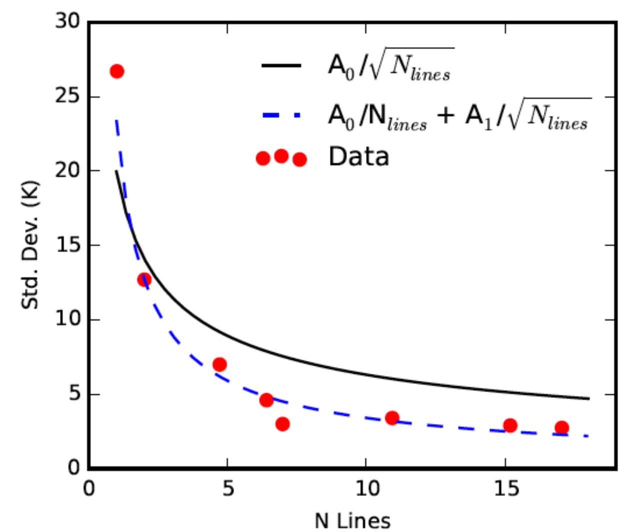
CO_2 Spectroscopy

- Measure difference in ro-vibrational level population as a function of temperature
- Rapid, spectroscopic in-situ measurement of gas temperature





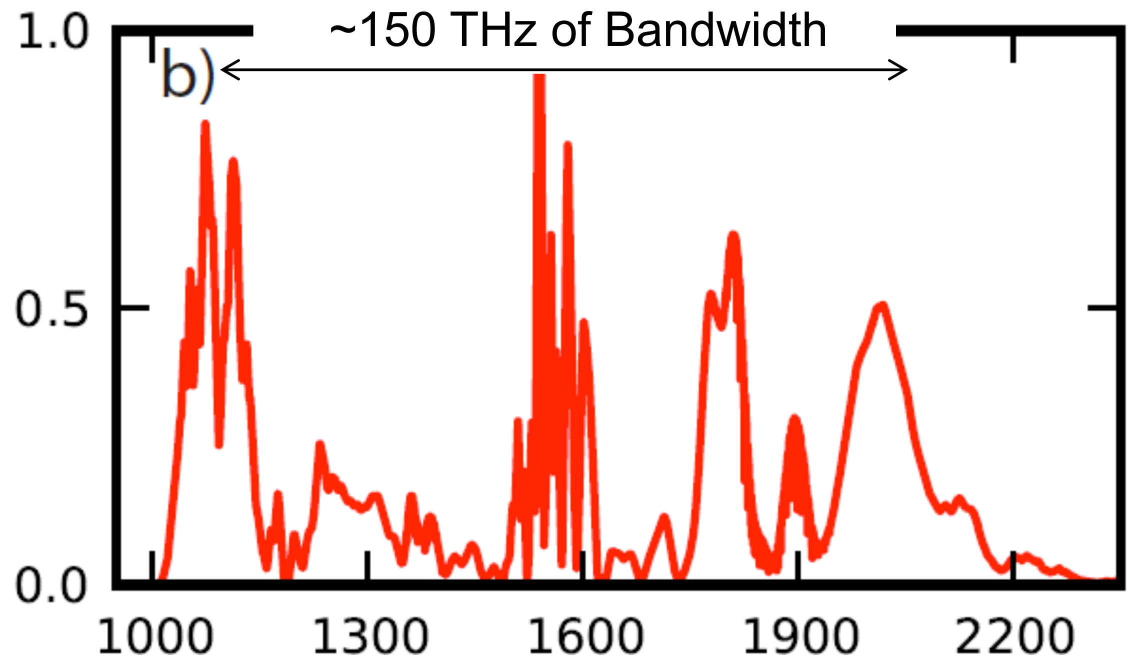


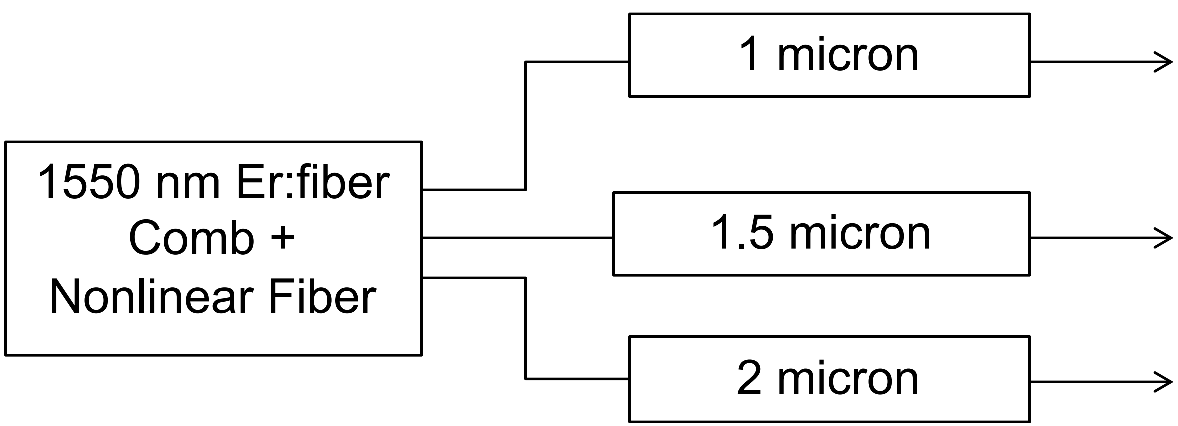


Klose, Appl Phys B (2016)

Spectral Extension to the MIR

Super Continuum
from Er:fiber Comb





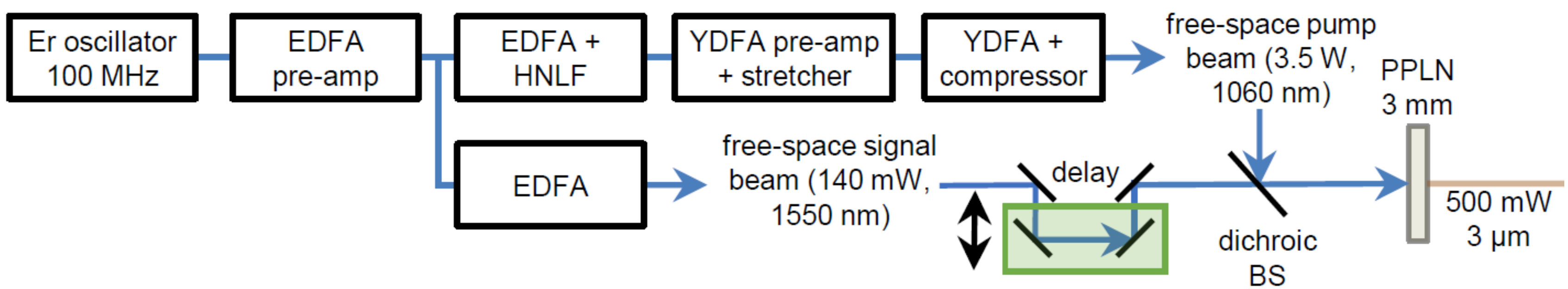
DFG Options

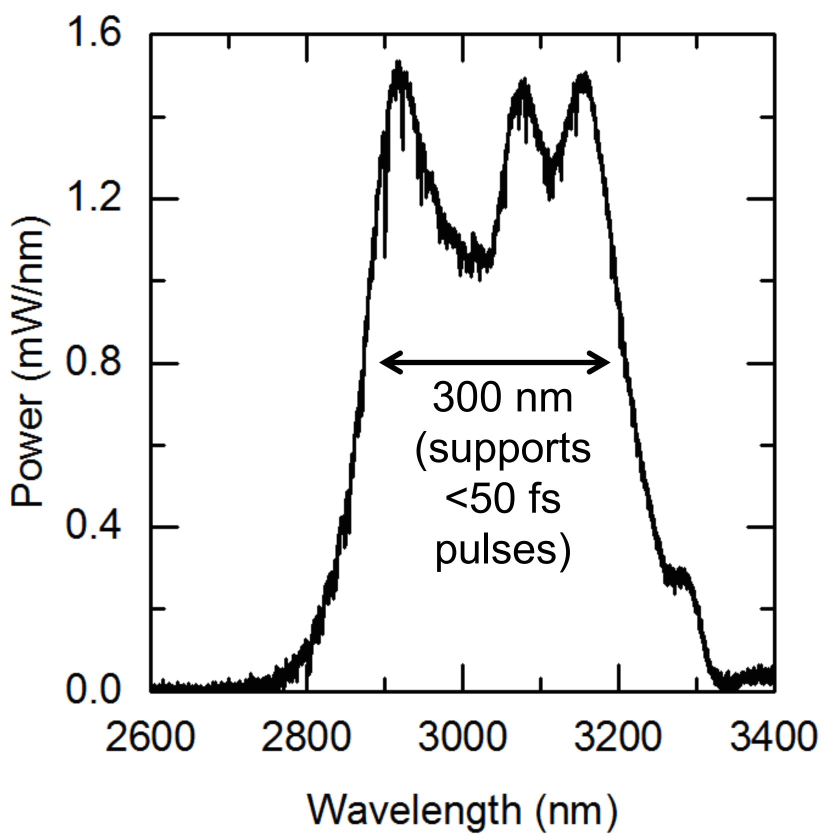
1 μm – 1.5 μm = 3 μm

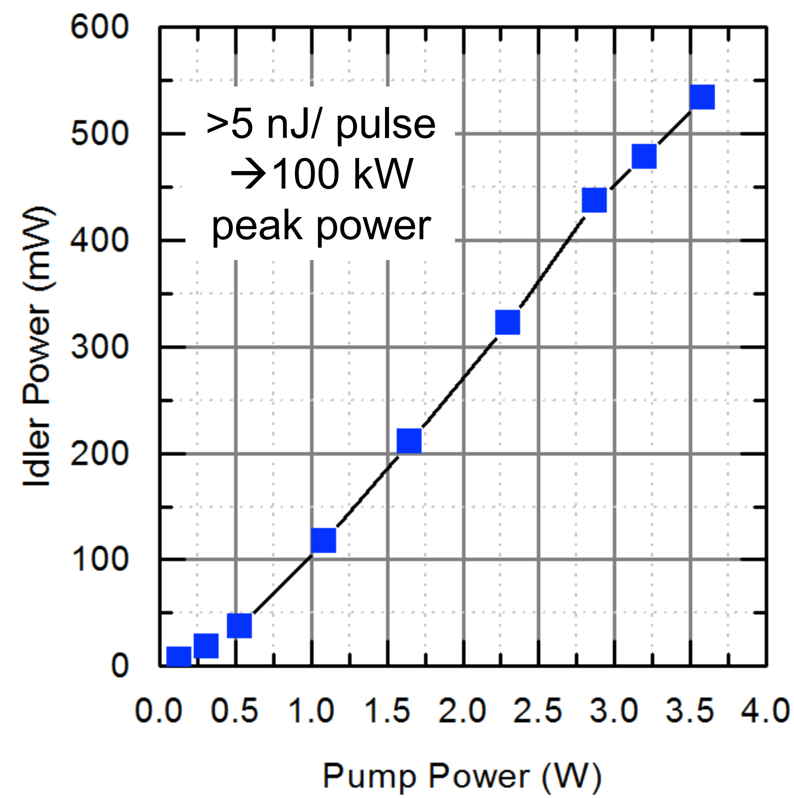
1.5 μm – 2 μm = 6.5 μm

Cruz, Opt Exp (2016)

MIR Diff. Freq. Spectrum



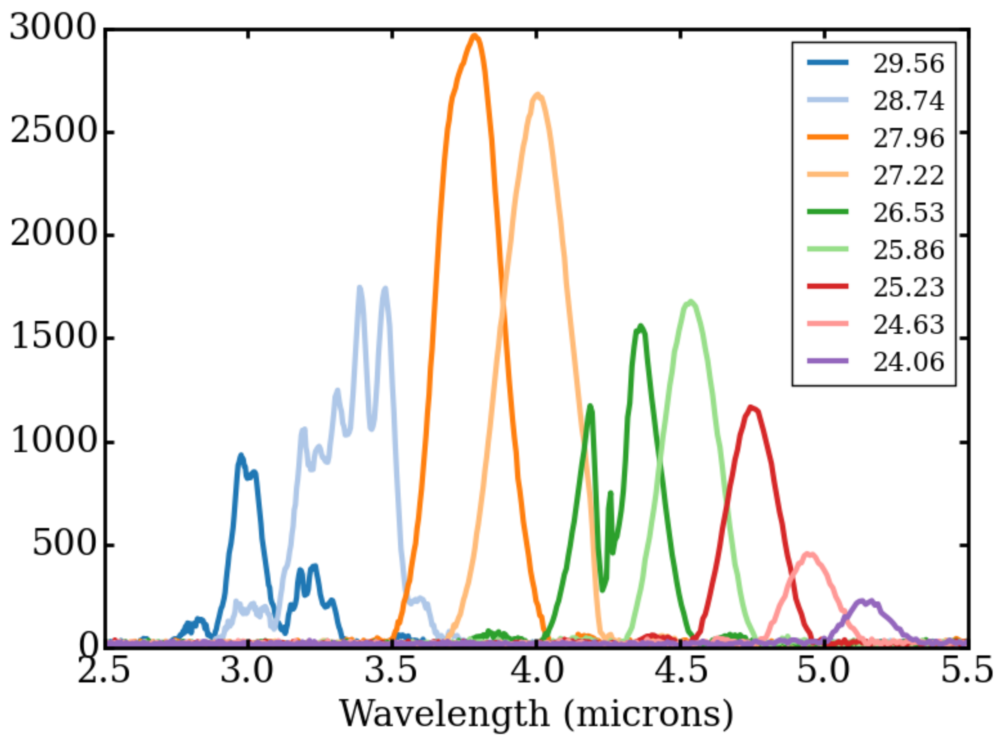




Cruz, Opt Exp (2016)

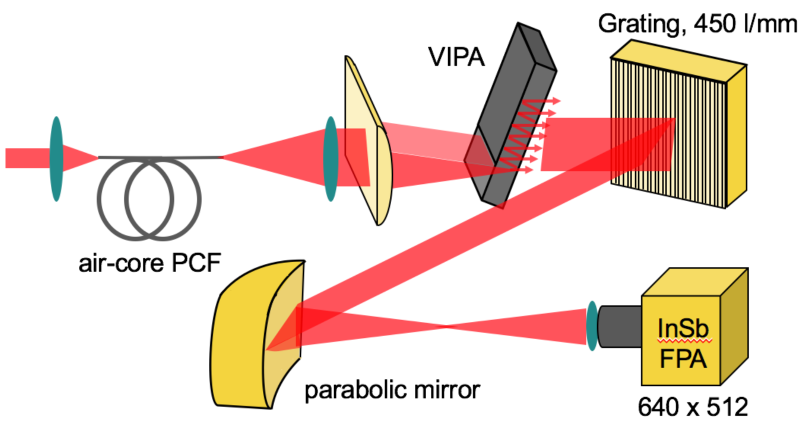
Broad bandwidth DFG

- Fixed strong pump at 1040 nm
- Tailor NIR spectrum 1300-1600 nm
- Use different PPLN periods to cover 3000-5000 nm
- Next: optimize + chirped & waveguide PPLN

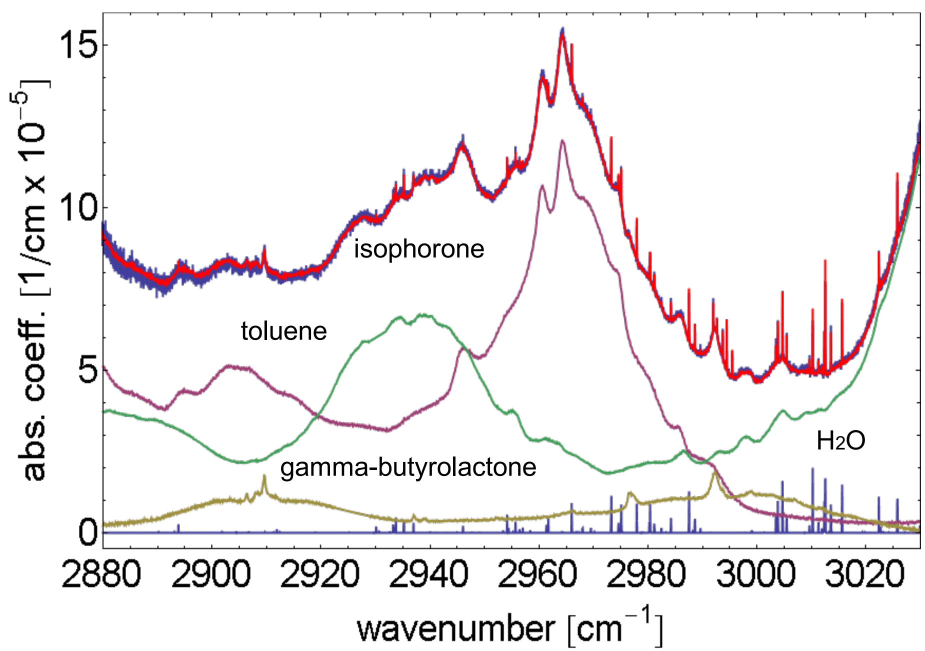


Mid IR Frequency comb spectroscopy

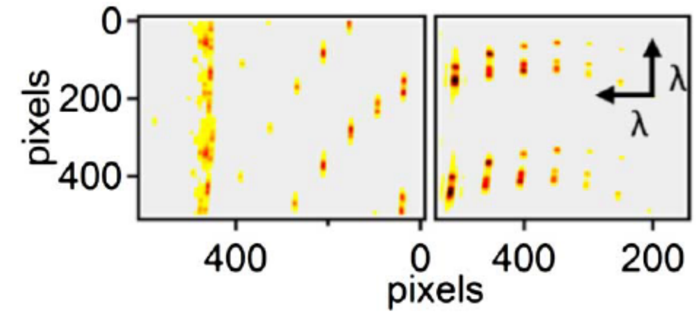
VIPA = Virtually **I**maged **P**hased **A**rray disperser

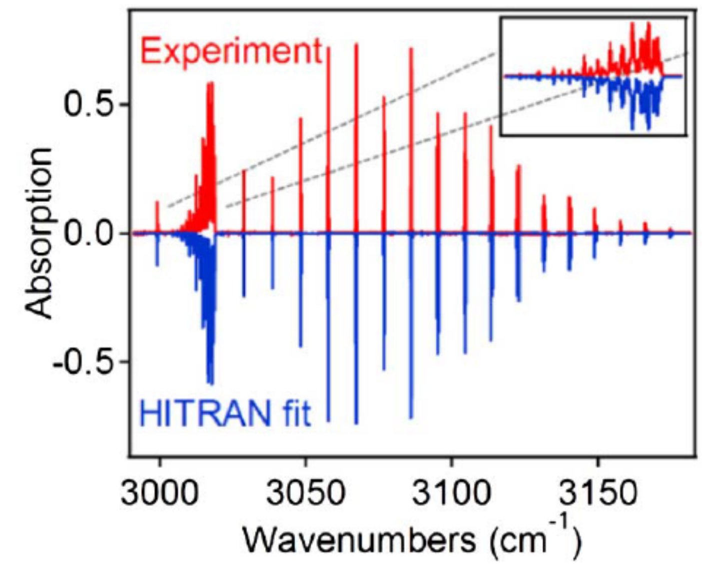


MID Infrared Molecular Fingerprinting



Green House Gas Quantification





M. Shirasaki. Opt. Lett. **2**1, 366 (1996).
S. Xiao, et al, Opt. Express **12**, 2895 (2004).
S. Diddams, et al, Nature **445**, 627 (2007).
T. Johnson, et al, Appl. Phys. B (2011)
L. Nugent-Glandorf, et al. Opt Lett. **37**, 3285 (2012)

From the *quantum* to the *cosmos*

Applications of precision spectroscopy in observational astronomy...

- Searches for variations in the fine structure constant

•J.K. Webb, et al. *Phys Rev Lett.*, **82**, 884 (1999). H. Chand, et al. *A&A* **417**, 853 (2004).

- Direct measurement of the cosmic acceleration

J. Liske., et al., arXiv:0802.1926v1 [astro-ph],

- Searches for terrestrial mass extrasolar planets

•R. P. Butler, et al., AJ, 646, 505 (2006). G. Rupprecht, et al., *Proc. SPIE*, **5492**, 148 (2004). ......??

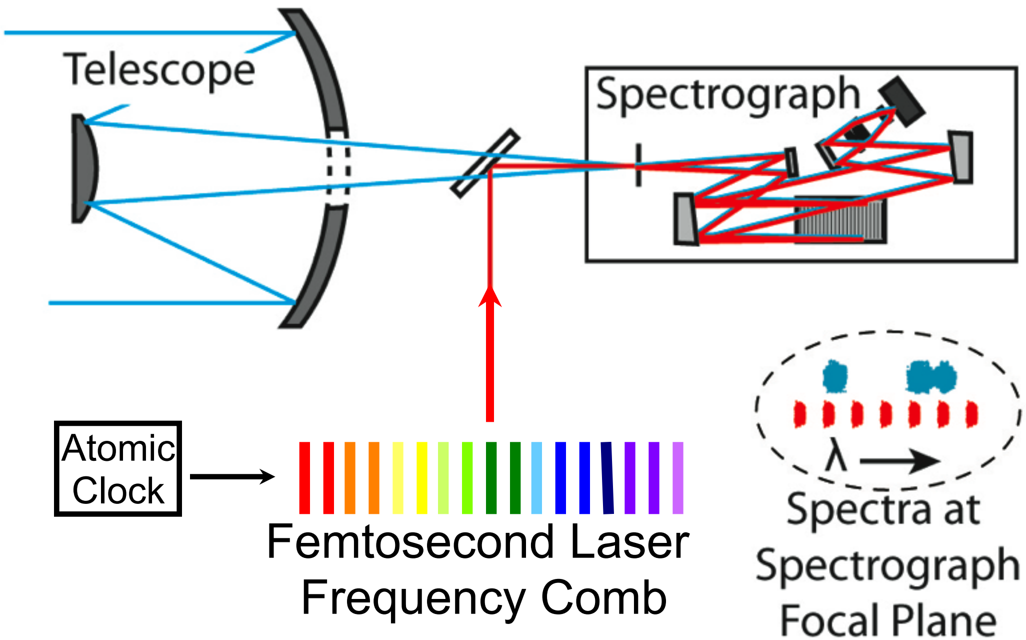
Present Spectral Precision: 3×10^{-8} (1 m/s radial velocity or ~1 MHz)

Most demanding applications need improvement by 100x

Can an optical frequency comb help?

Time & Frequency Division NIST

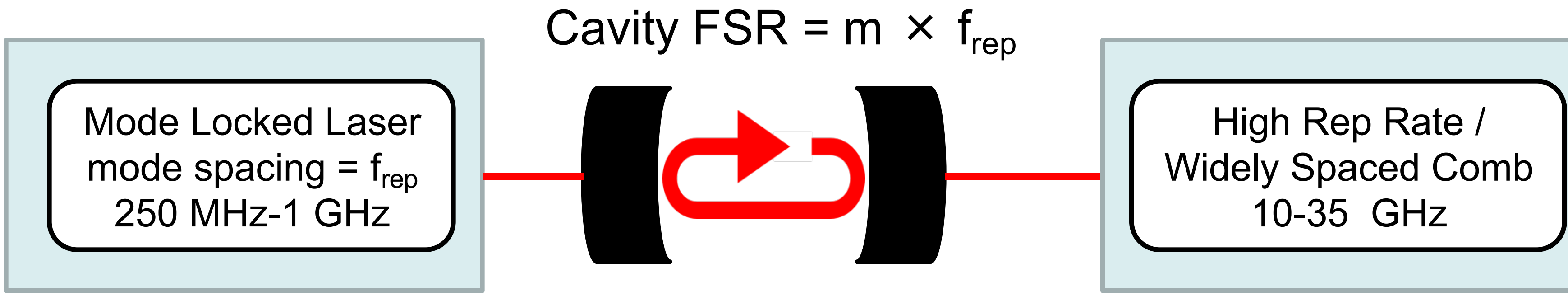
Frequency Combs for Astronomical Spectrograph Calibration

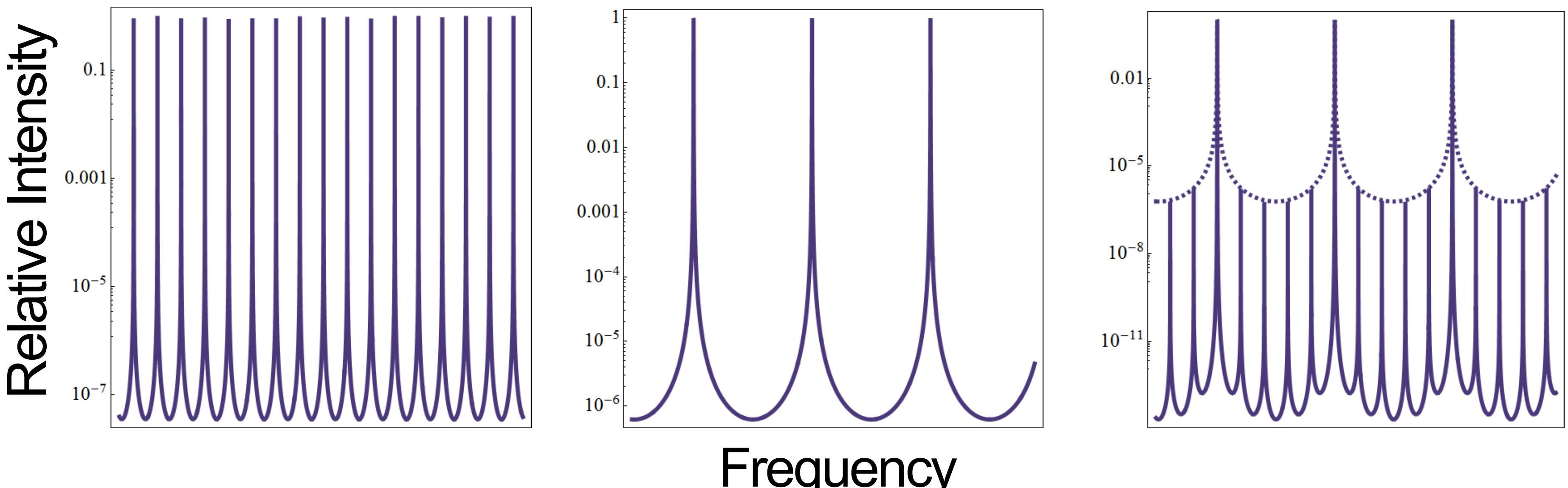


- ➡ Uniform grid of frequencies tied to atomic standards (stable over decades)
- ➡ Absolute uncertainty down to ~4×10^{-17} (limited by atomic reference)
- ➡ Broad spectral coverage (400-2000 nm)
- ➡ Power per mode in excess of 1 nW
- ➡ Need mode-spacing of 10's of GHz

M. Murphy et al., Mon. Not. Roy. Astr. Soc. **380**, 839 (2007)
P.O. Schmidt, et al., arXiv:0705.0763 v1 (2007)
S. Osterman, et al. Proc. SPIE **6693**, pp. 66931 (2007)
C.H. Li, et. al., Nature **452**, 610 (2008)
D. Braje, et al., Eur. Phys. Journ. D **48** 57 (2008)
T. Steinmetz, et al. Science **321**,1335 (2008)

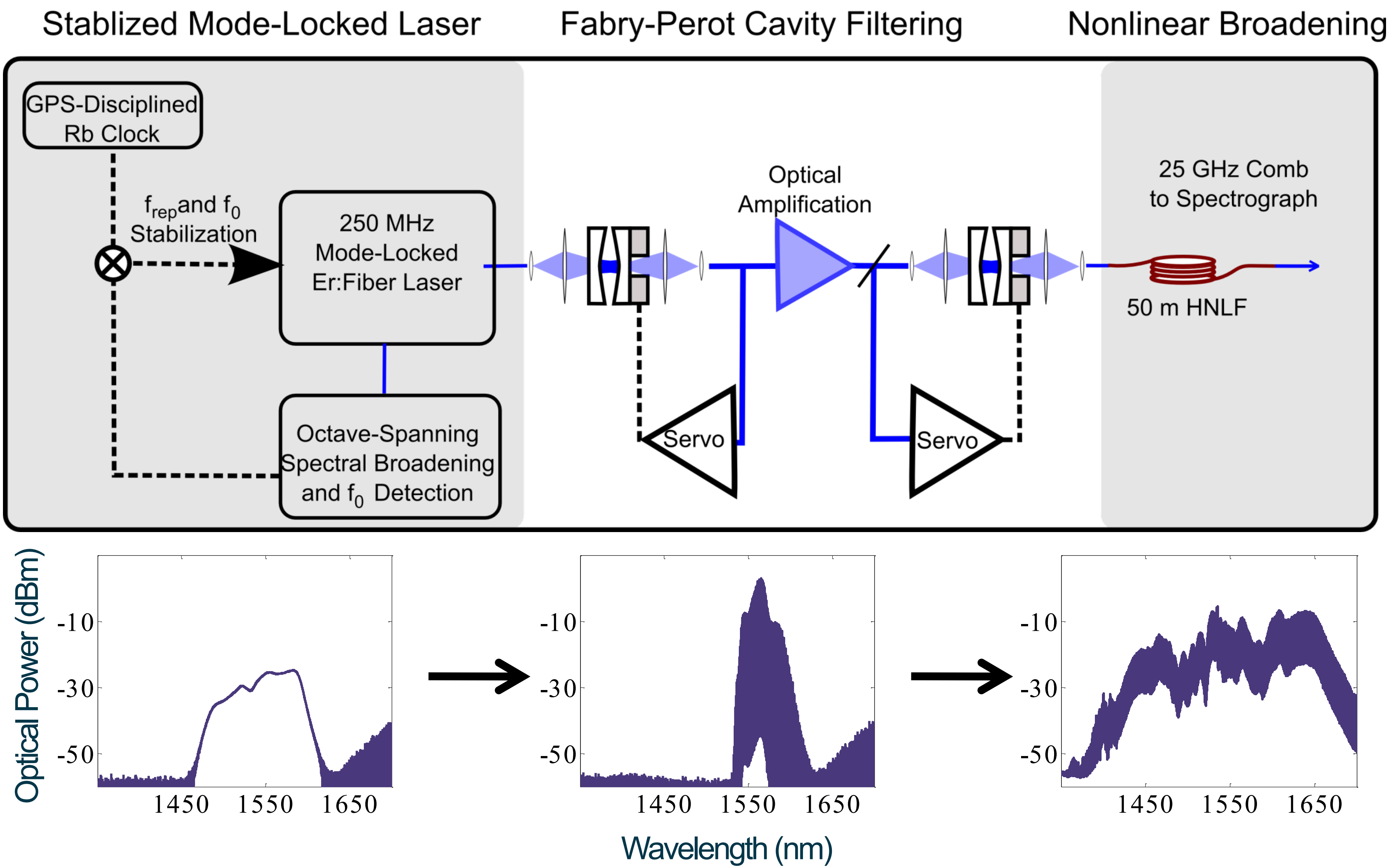
Fabry-Perot Cavity Filtering





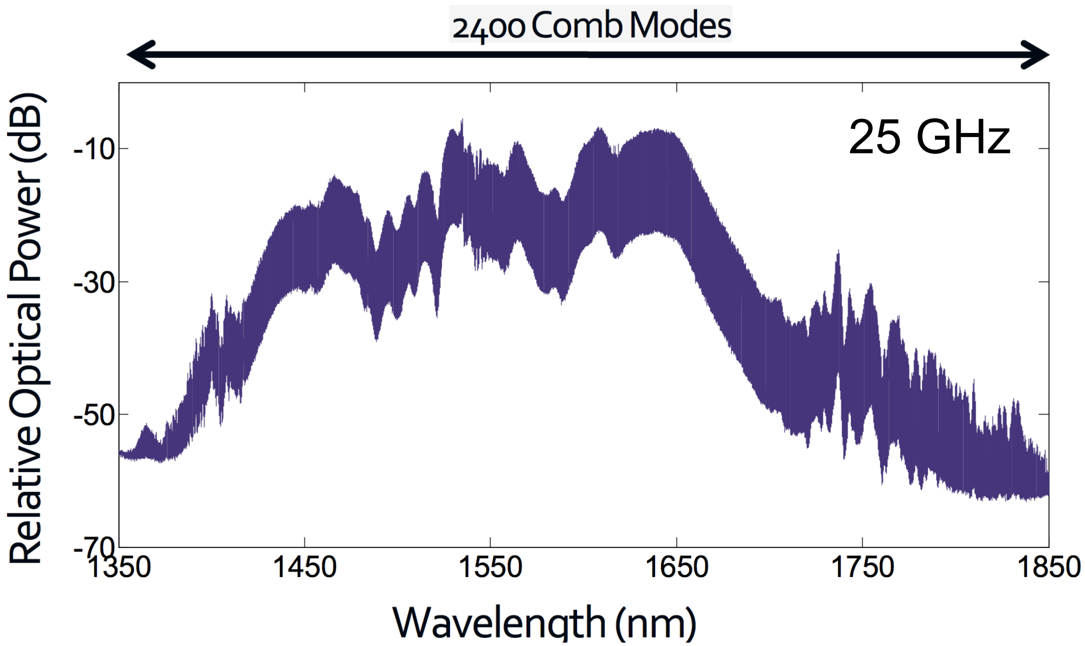
Sizer, IEEE Journ. Quant. Electron. (1989)
Osterman, Proc SPIE (2007)
Braje *et al*, Eur. Phys. D (2008)

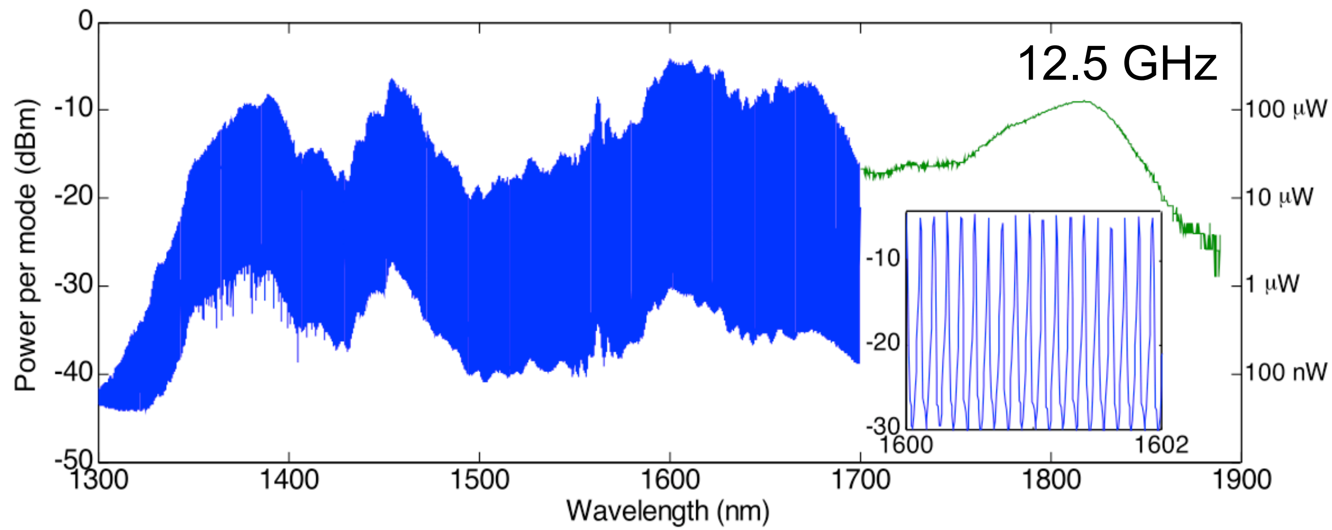
Cavity-Filtered H-Band Frequency Comb



Quinlan *et al*, Rev. Sci. Instr. (2010)
Ycas *et al*, Opt. Express (2012)

H-Band Optical Spectra

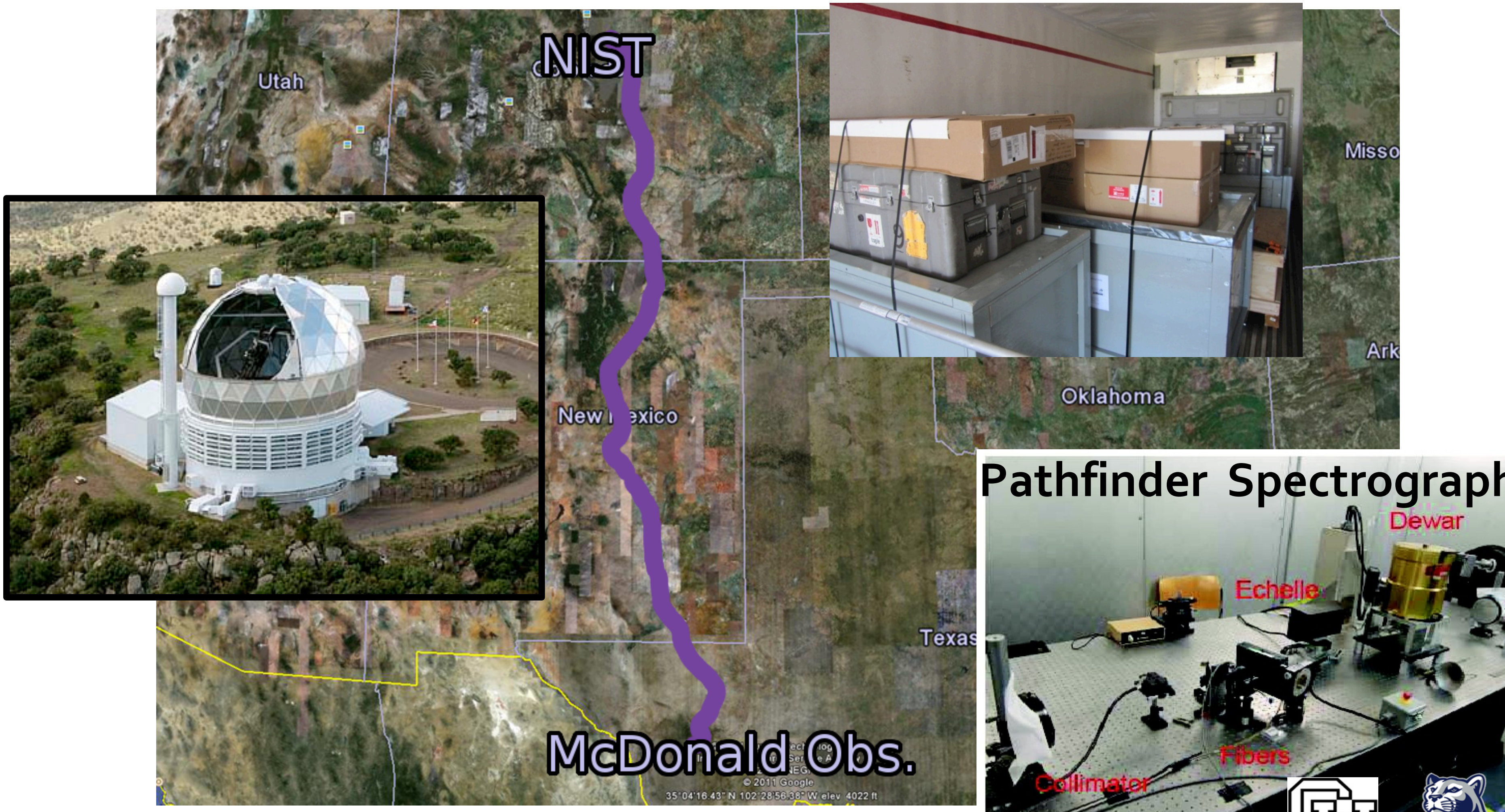




Quinlan *et al*, Rev. Sci. Instr. (2010)
Ycas *et al*, Opt. Express (2012)

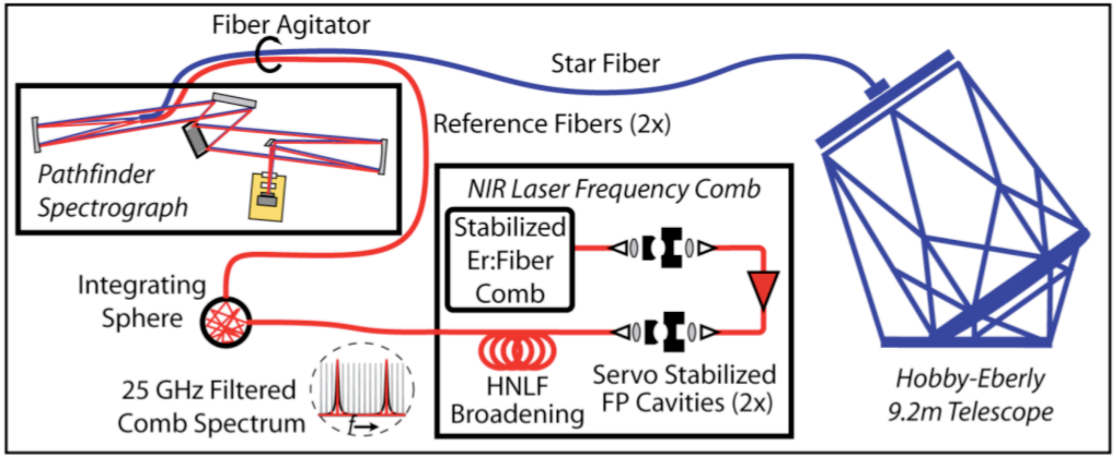
Out of the Lab and into the Field

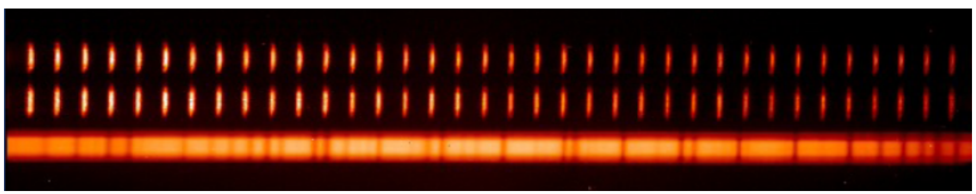
9.2m Hobby-Eberley Telescope, McDonald Observatory, Texas
Aug 4-12, 2010: Comb calibrates Penn State Univ. “Pathfinder” Spectrograph

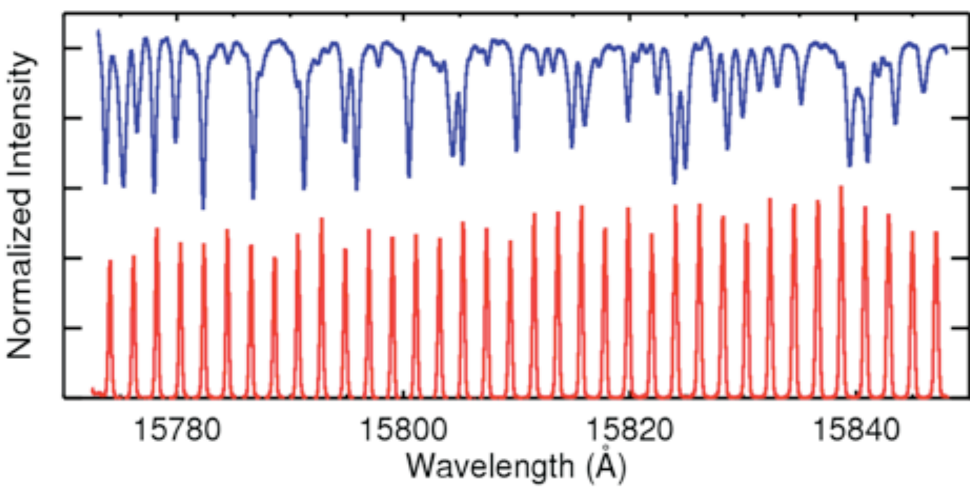


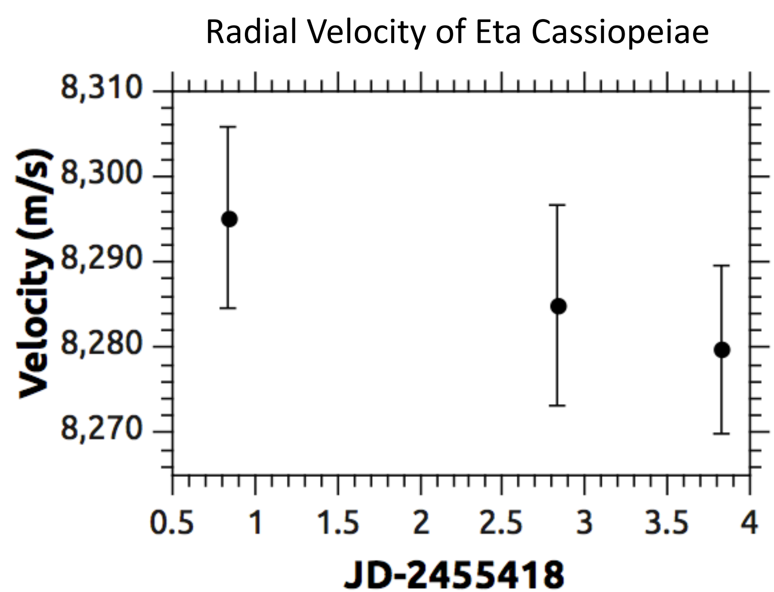
G.G. Ycas, et al. “Calibration of Stellar Spectra using a 25 GHz Laser Frequency Comb,” *Opt. Express* (2012).

Frequency Comb Calibration of Stellar RV's





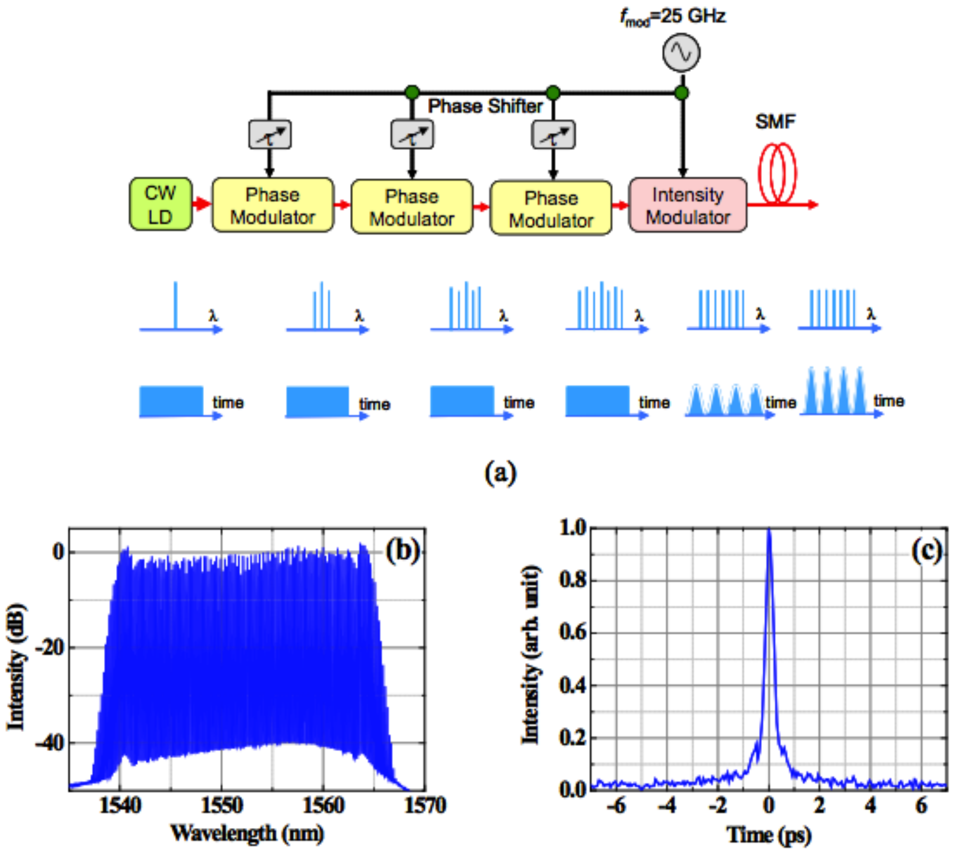




G. Ycas, et al, Optics Express **20**, 6631 (2012)

Electro-Optic Modulation Combs

Ishizawa, Opt Exp 2011
Weiner, JSTQE 2013



Advantages:

- No side modes
- Spacing tied to tunable microwave frequency (10-40 GHz)
- Easily referenced to microwave standard via GPS
- Short pulse also generated—amenable to nonlinear broadening
- Simple, robust implementation

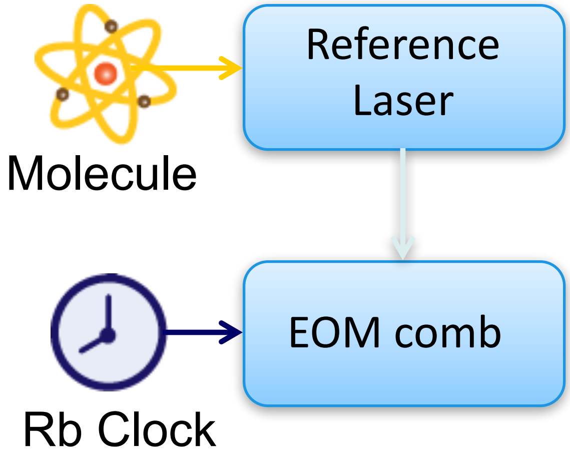
Disadvantages:

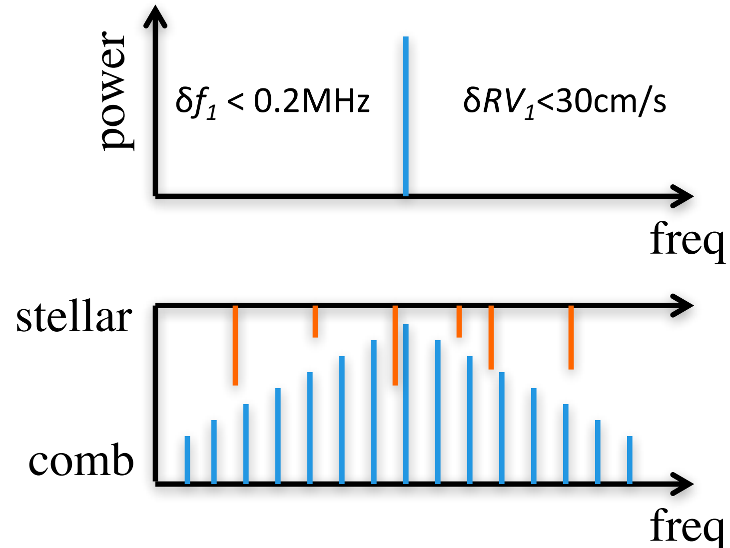
- CW seed laser is unstabilized; therefore, comb offset can drift (would have to be locked to something absolute)
- Spectral broadening is more difficult
- Noise of microwave source is multiplied up.

Line-Referenced Electro-Optic Modulation Comb

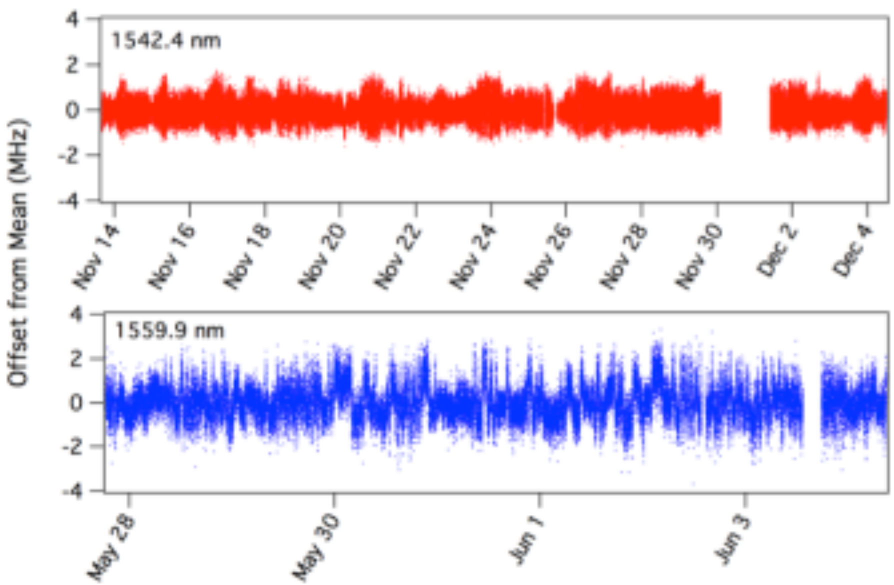
Jet Propulsion Laboratory
California Institute of Technology

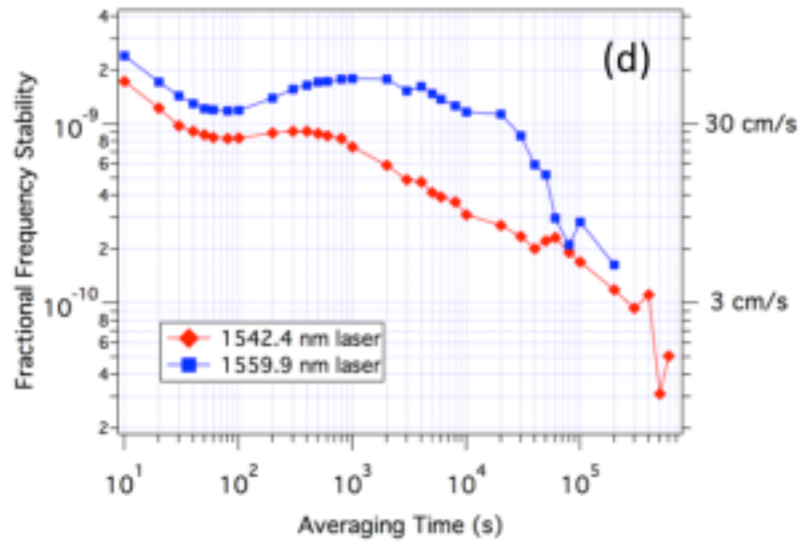
Xu Yi (Caltech), Nat. Comm (2016)





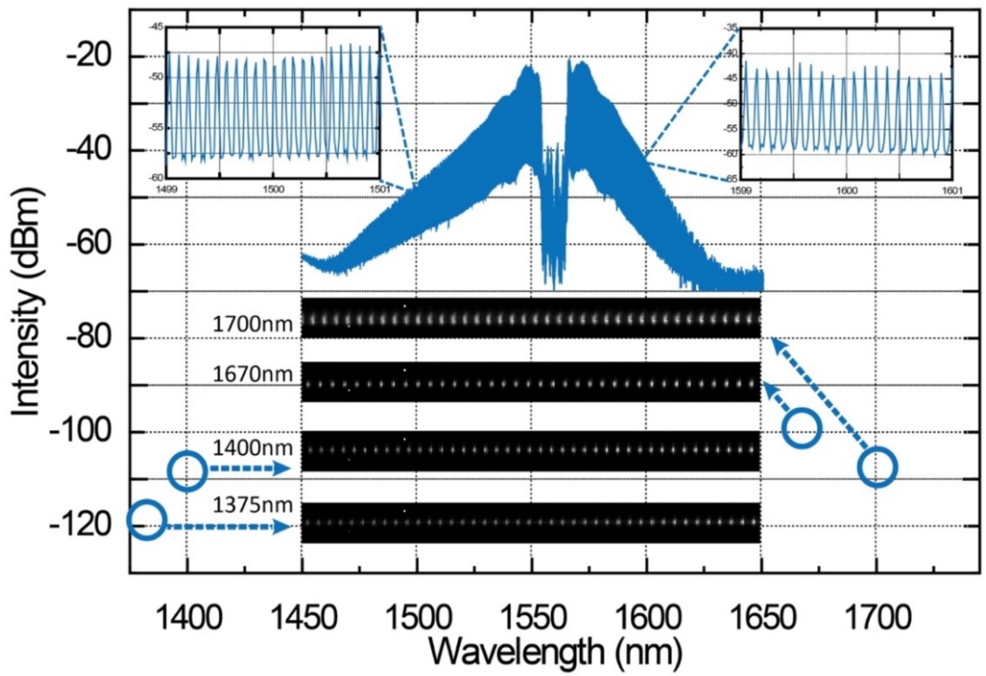
$$f_N = f_{ref} + N f_{rep}$$

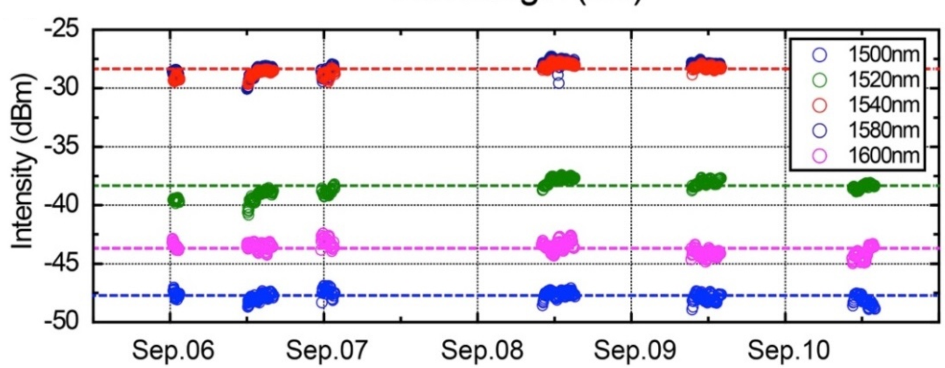




Rack-mounted comb at IRTF

Jet Propulsion Laboratory
California Institute of Technology

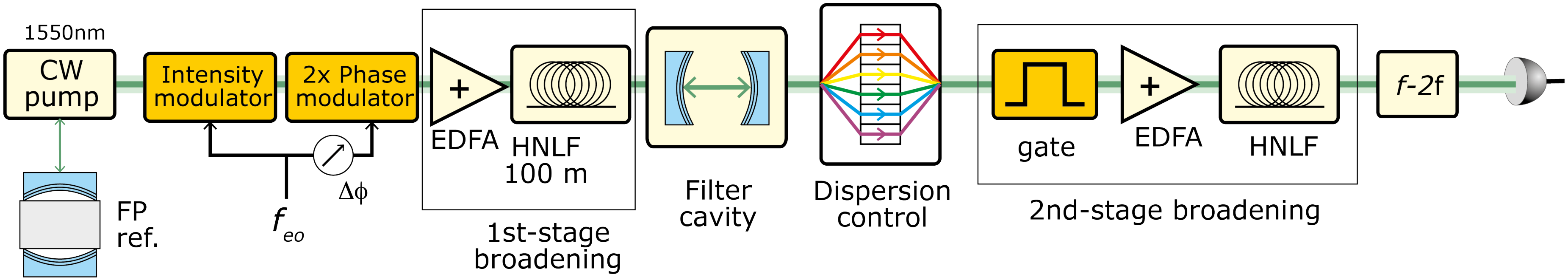


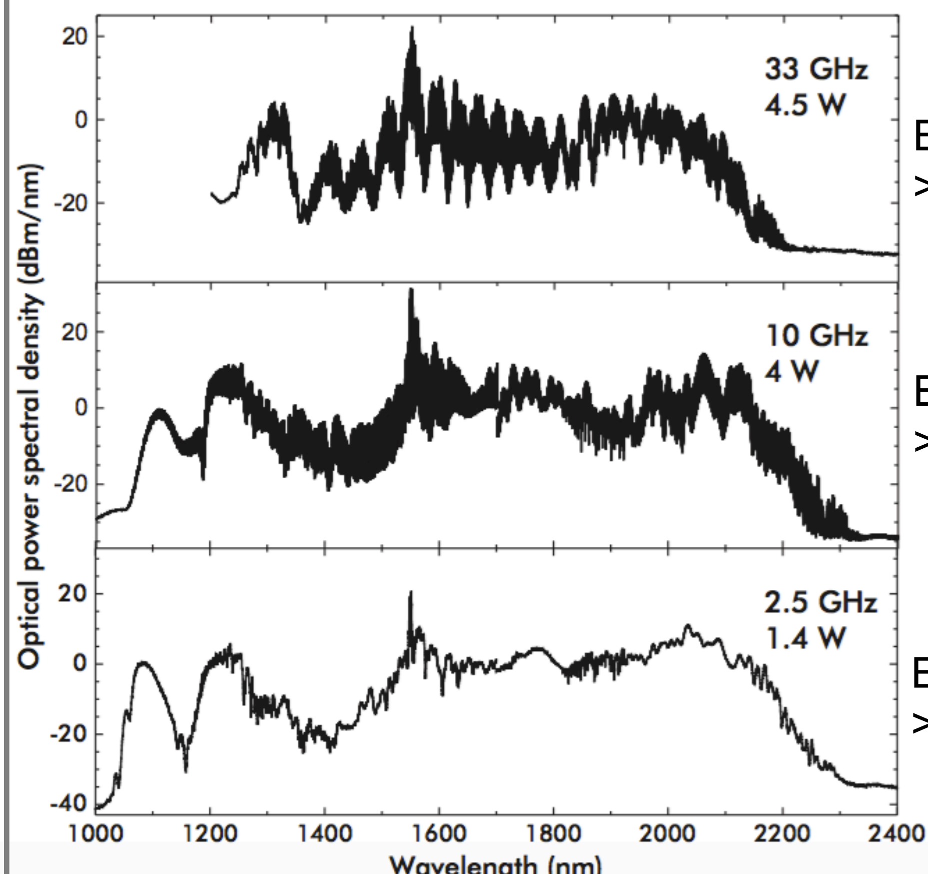


- **Hands-off operation.**
- **Comb in a rack**

Xu, et al. Nature Comm (2016)

Coherent Octave-Generation with EOM Comb





E_{pulse}= 120 pJ
> 2/3 octave

E_{pulse}= 450 pJ
> octave

E_{pulse}= 560 pJ
> octave

External broadening

Dual-stage pulse compression, amplification, and nonlinear broadening

+

Frequency noise control

Myslivets et al., Opt. Exp., **20**, 3331 (2012)
Ishizawa et al., Opt. Exp.,**19**, 22402 (2011)
Cole et al., arXiv:1310.4134 (2013)
Beha et. al. arXiv (2015)

Thank you!

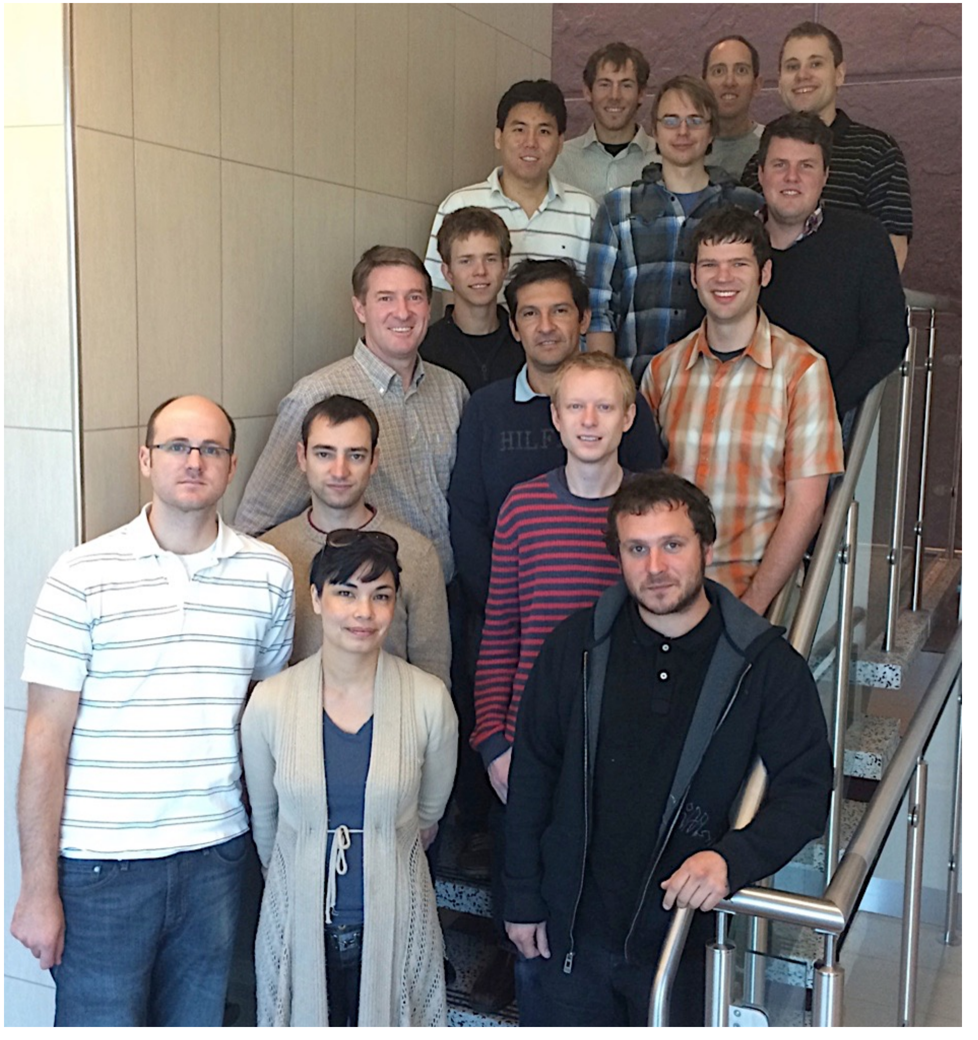
Staff: Tara Fortier, Scott Papp, Franklyn Quinlan

Students: Daniel Cole, Connor Fredrick, Holly Leopardi, Alex Lind, Dan Maser, Jordan Stone

Postdocs: Fred Baynes, Katja Beha, Travis Briles, Aurélien Coillet, Josue Davila-Rodriguez, Pascal Del'Haye, Tara Drake, Dan Hickstein, Andrew Klose, Erin Lamb, William Loh, Antoine Rolland, Daryl Spencer, Gabriel Ycas

Visitors: Yi-Chen Chuang, Flavio Cruz, Lorenzo Hernandez, Francisco Senna, Chaitanya Sudapalli

Collaborators: John Bowers (UCSB), Joe Campbell (Virginia), Kartik Srinivasan (NIST Gaithersburg), Kerry Vahala (Caltech)



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