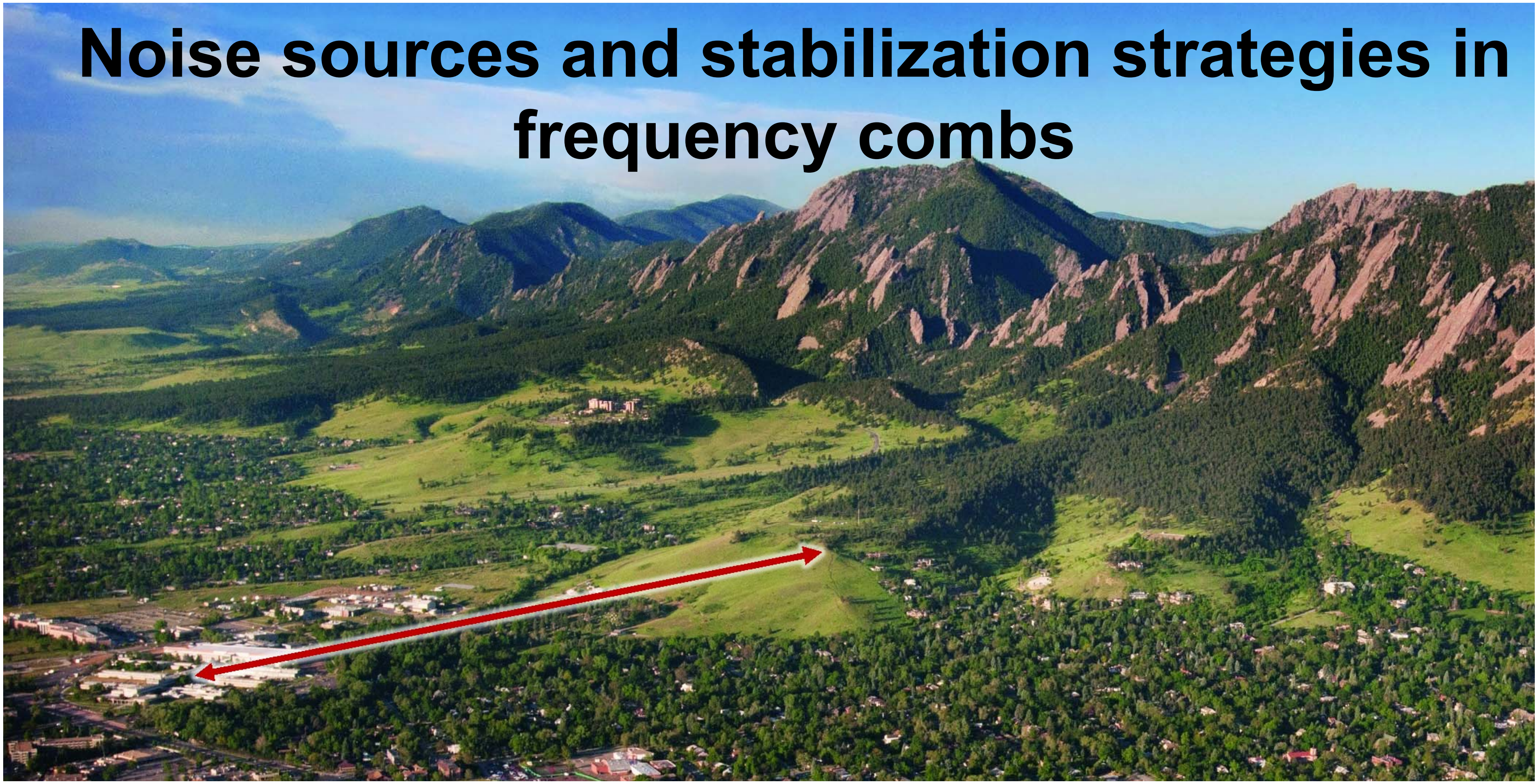
Noise sources and stabilization strategies in frequency combs



ICTP Winter College on Optics

Trieste, Italy

February 17, 2015

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Outline

- Motivation for frequency combs
- Frequency comb
- Noise in fiber-based frequency combs
  - Fixed point
- Making a quiet frequency comb
- Fiber frequency combs at NIST
  - Overview of different designs since 2003
  - Current “robust” NIST frequency comb
- Conclusion

People

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Mick Cermak
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Eleanor Waxman
Gabe Ycas

Other non-NIST collaborators:

Brian Washburn (Kansas State)
Jean Daniel Deschenes (U of Laval)
Greg Rieker (CU)

NIST collaborators:

Scott Diddams, Dave Leibrandt, Craig Nelson, Scott Papp, Frank Quinlan, Kevin Silverman, Jeff Shainline, Rich Mirin, …

Recent review articles

RSI Review article on current NIST comb design:

L.C. Sinclair, J.-D. Deschênes, L. Sonderhouse, W. C. Swann, I.H. Khader, E. Baumann, N. R. Newbury, and I. Coddington, **Invited Article: A Compact Optically-Coherent Fiber Frequency Comb,** Review of Scientific Instruments 86, 081301 (2015);

See also**:** http://www.nist.gov/pml/div686/grp07/fpga-based-digital-control-box-phase-stablization-frequency-comb.cfm

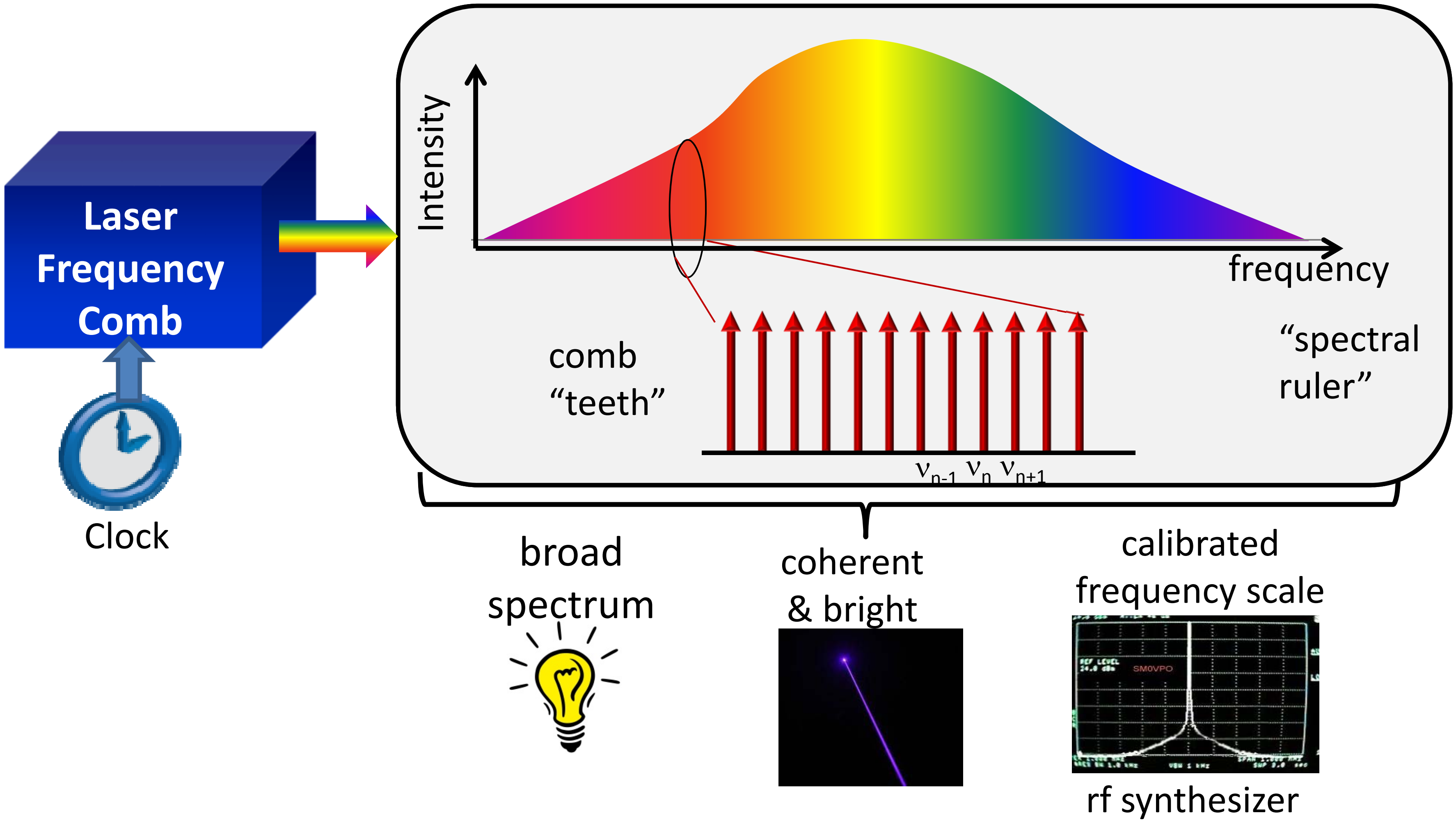
Nanophotonics upcoming review on fiber combs:

S. Droste, G. Ycas, B. R. Washburn, I. Coddington, NRN, **Optical Frequency Comb Generation based on Erbium Fiber Lasers**, Nanophotonics, to be published

Fiber frequency Comb noise

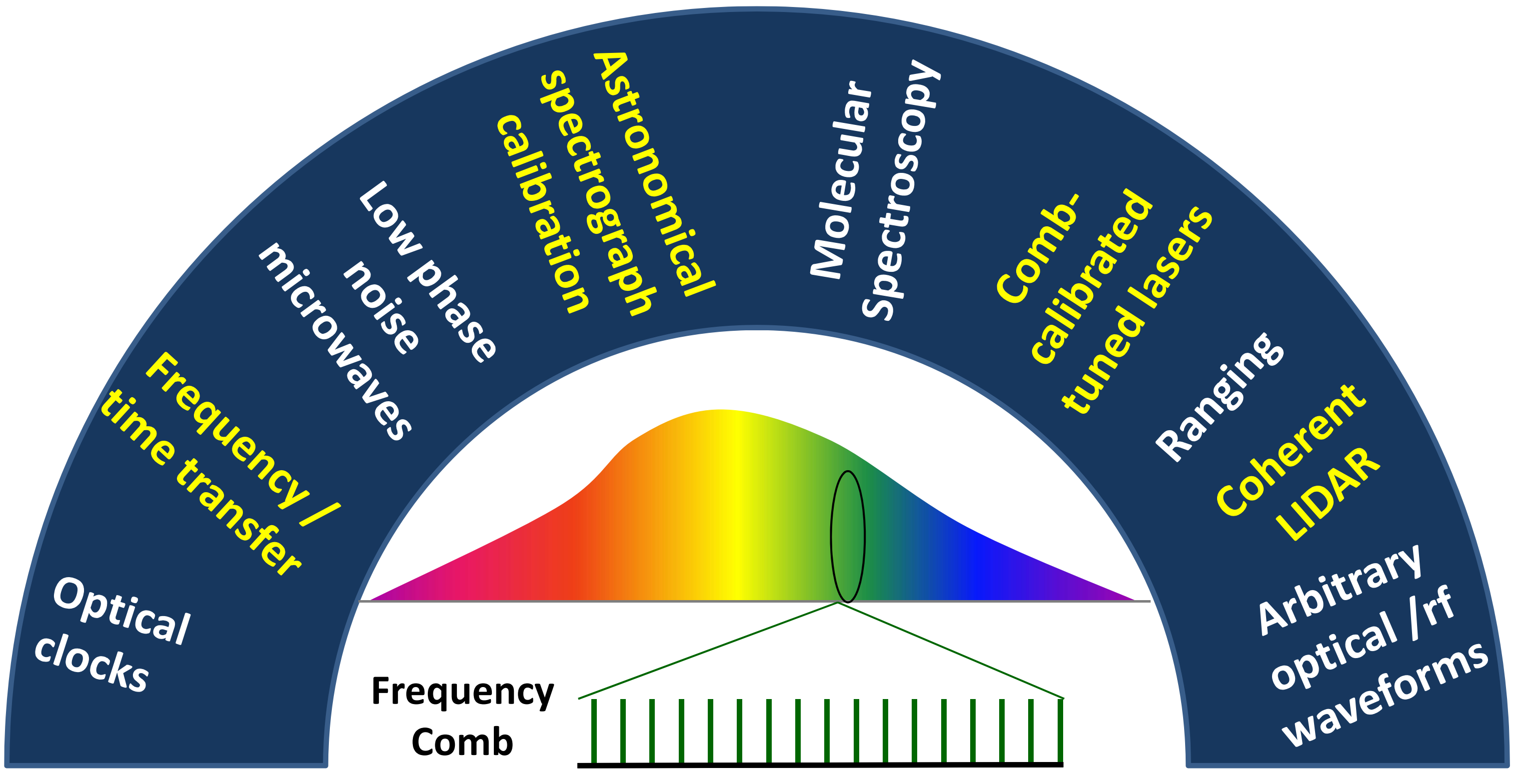
N. Newbury, W. Swann, J. Opt. Soc. Am. B, **Low-noise fiber-laser frequency combs,** 24, (2007)

Frequency Combs: Why are they special?



Newbury, Nat. Phot., 5, 186 (2011)
Diddams, JOSA B, 27, B51 (2010)

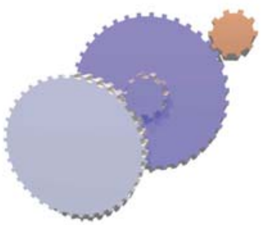
Applications of Frequency Combs

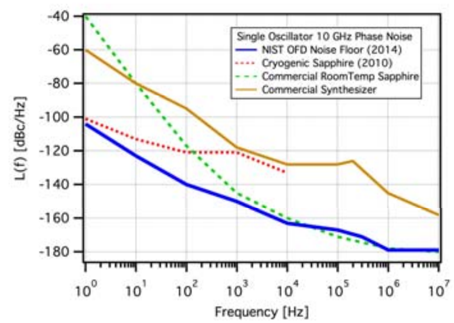


- Applied to laser-based metrology/sensing systems
  - As a spectral ruler
  - As a "time" ruler
  - As a frequency divider
  - As a calibrated broadband source

Example applications

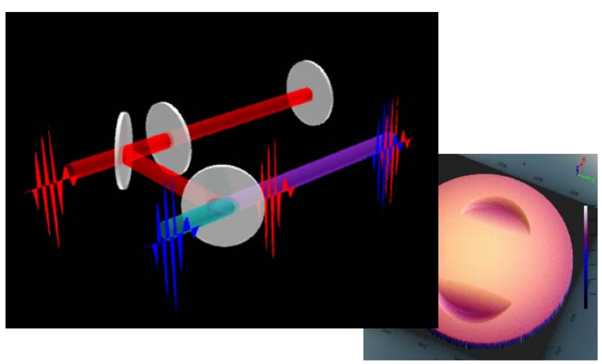
Precision microwave generation
(for RADAR)



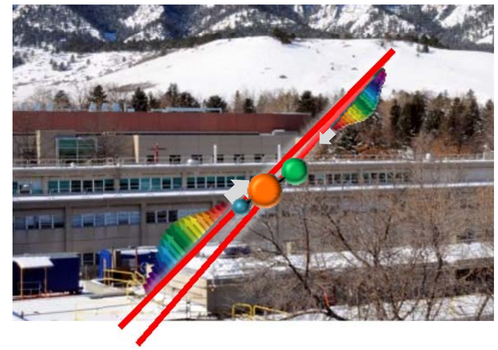


Precision spectroscopy
(for exoplanet searches)

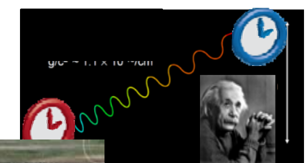
Precision Ranging

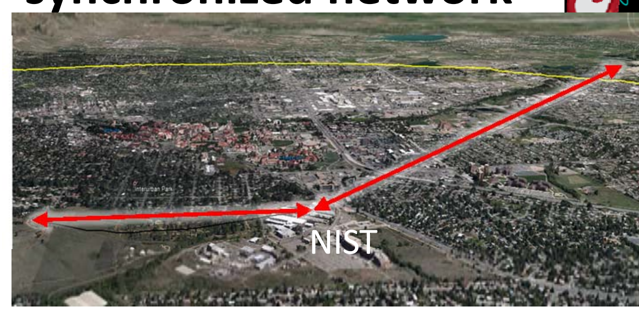


Precision molecular spectroscopy
(for greenhouse gases)



Precision timing across synchronized network



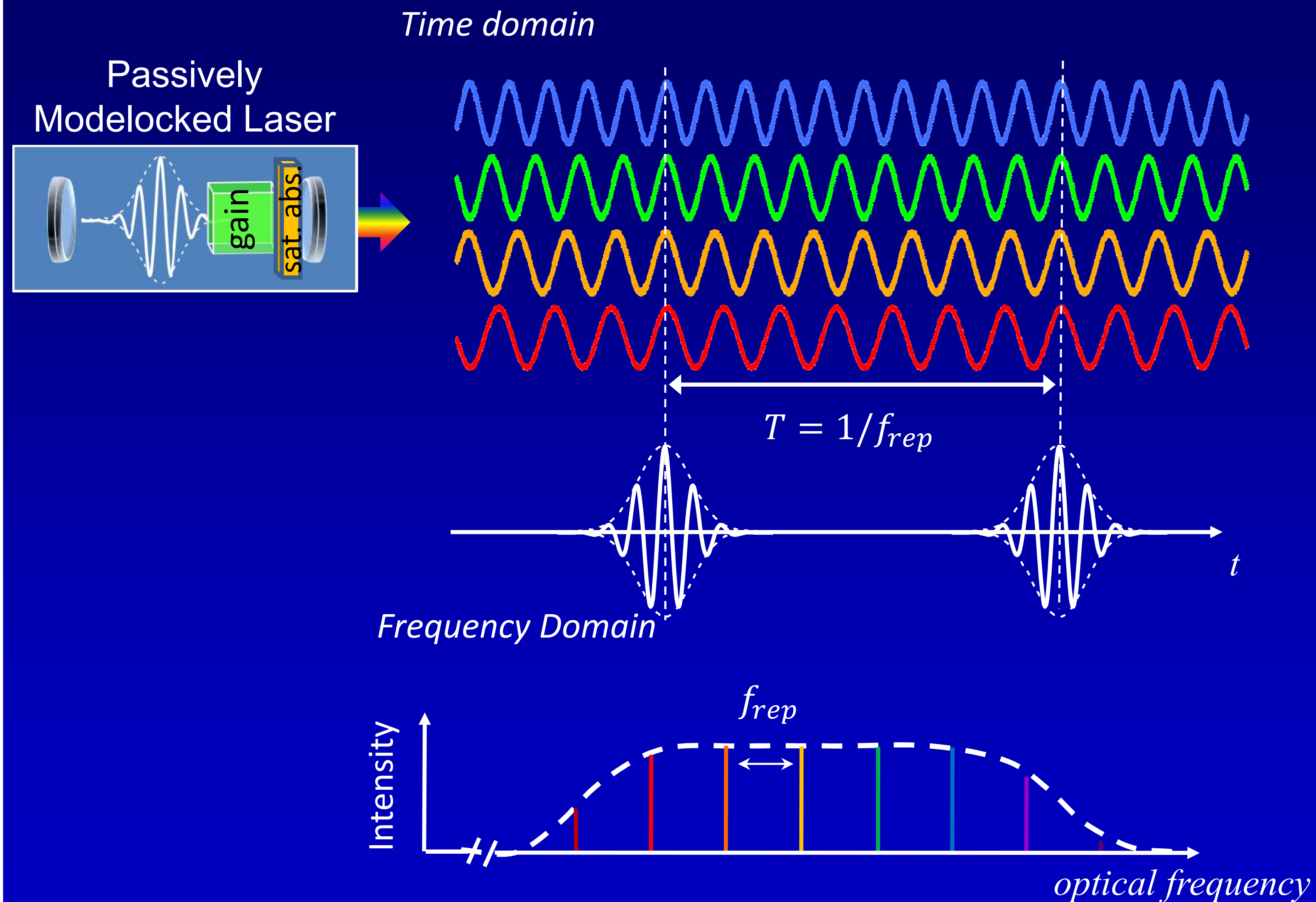


Others:
Advanced communications
Fundamental scientific tests
…

Outline

- Motivation for frequency combs
- Frequency comb
  - Basic picture
  - Types of Frequency combs
- Noise in fiber-based frequency combs
  - Fixed point
  - Noise sources
  - Actuators
- Making a quiet frequency comb
- Fiber frequency combs at NIST
  - Overview of different designs since 2003
  - Current “robust” NIST frequency comb
- Conclusion

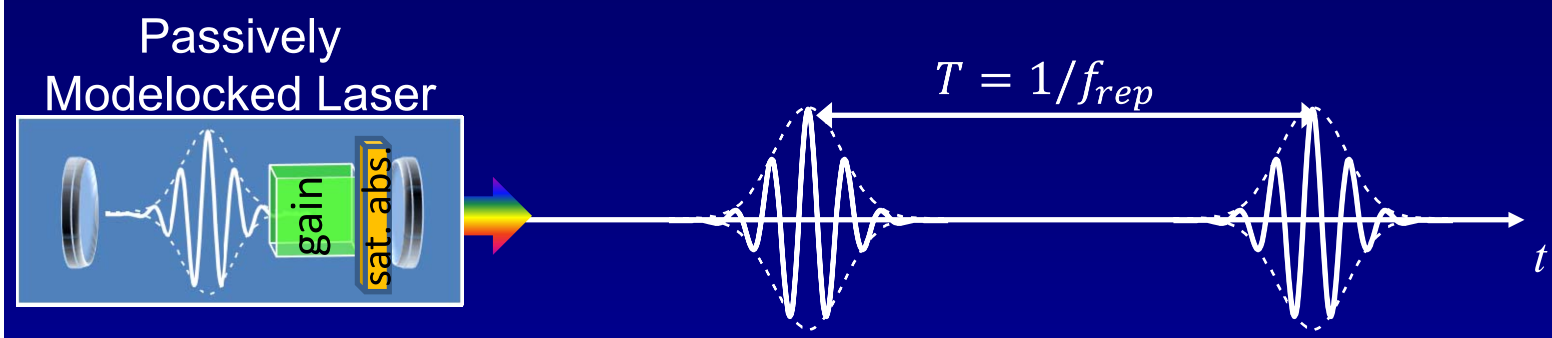
A Mode-Locked Laser



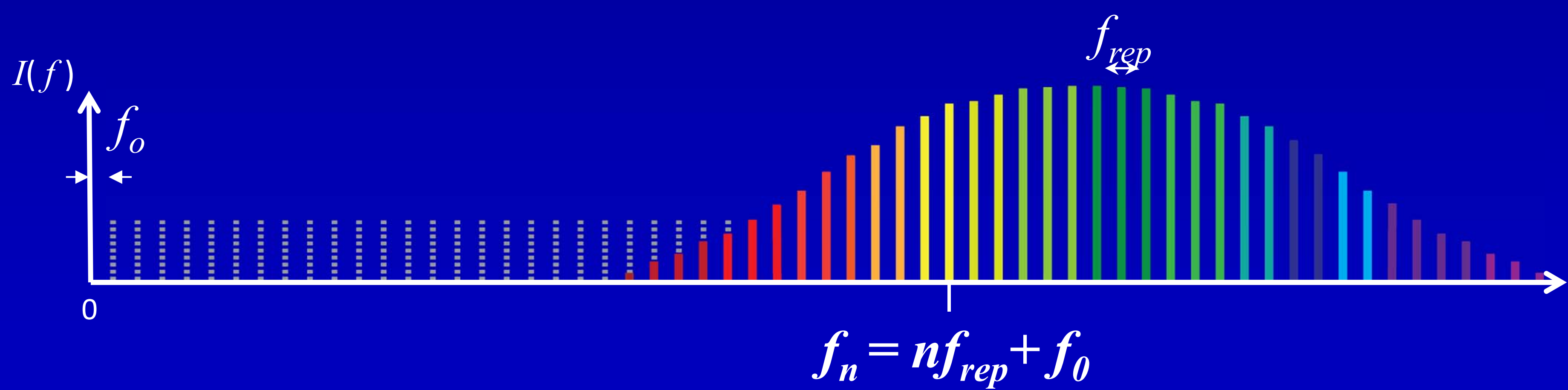
Outputs light at equally spaced modes of the laser

A Free-Running Mode-Locked Laser

Time domain

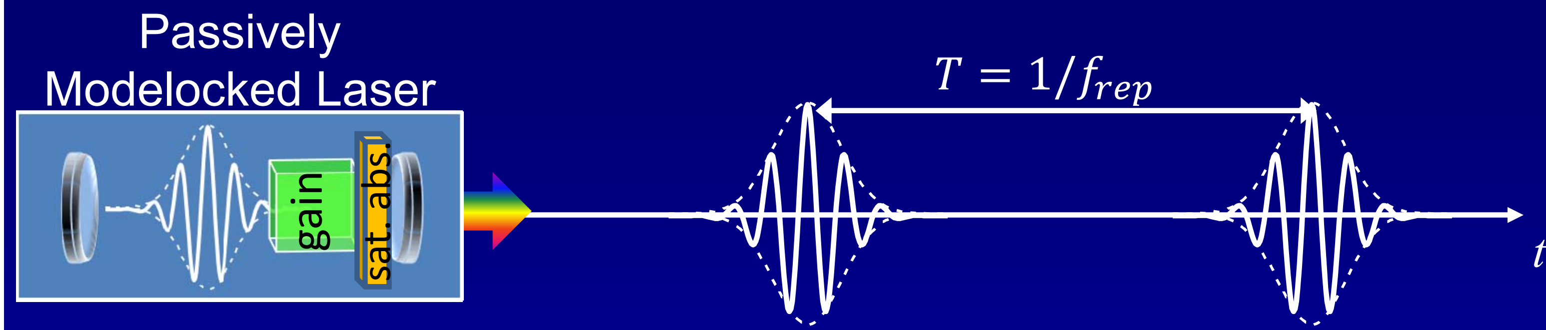


Frequency domain

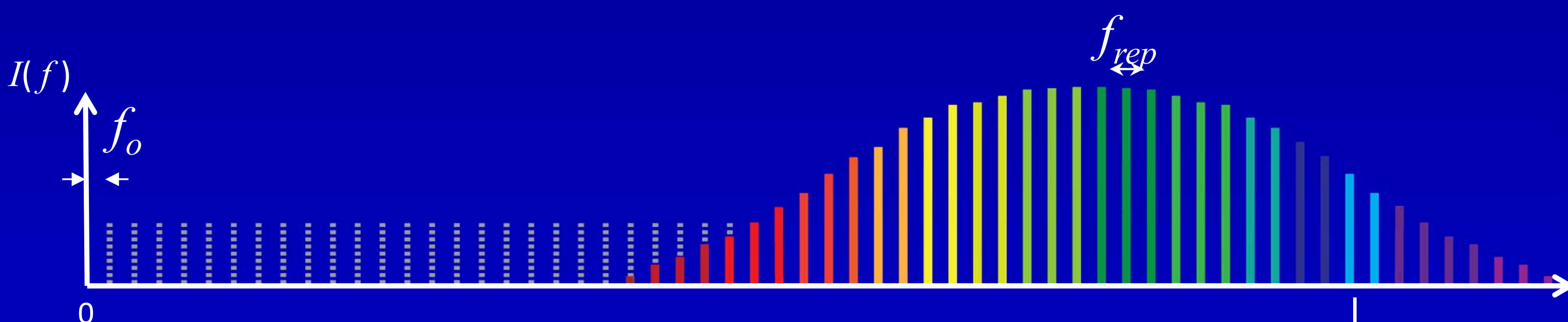


A Free-Running Mode-Locked Laser

Time domain



Frequency domain



$$f_n = nf_{rep} + f_0$$

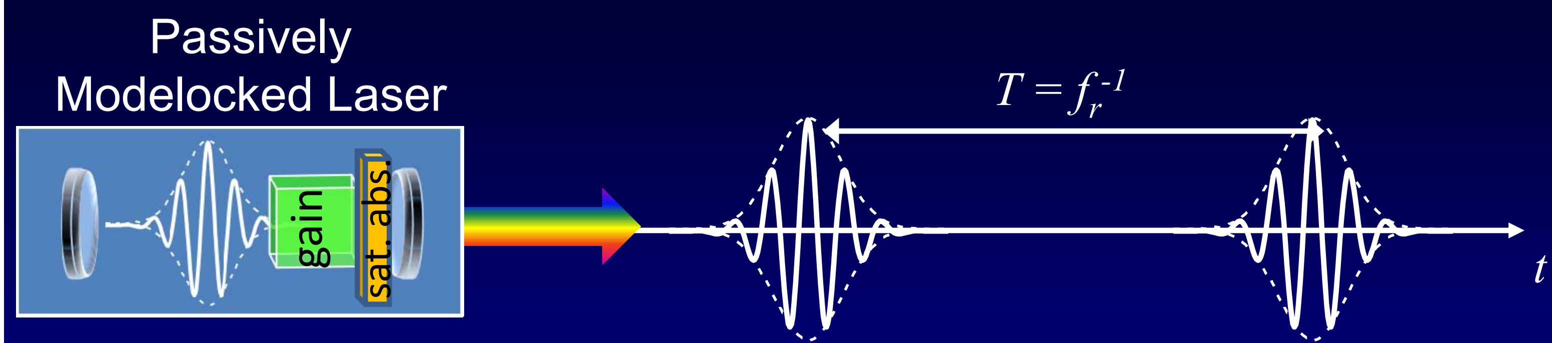
With noise, output moves around…

but basic comb structure is preserved.

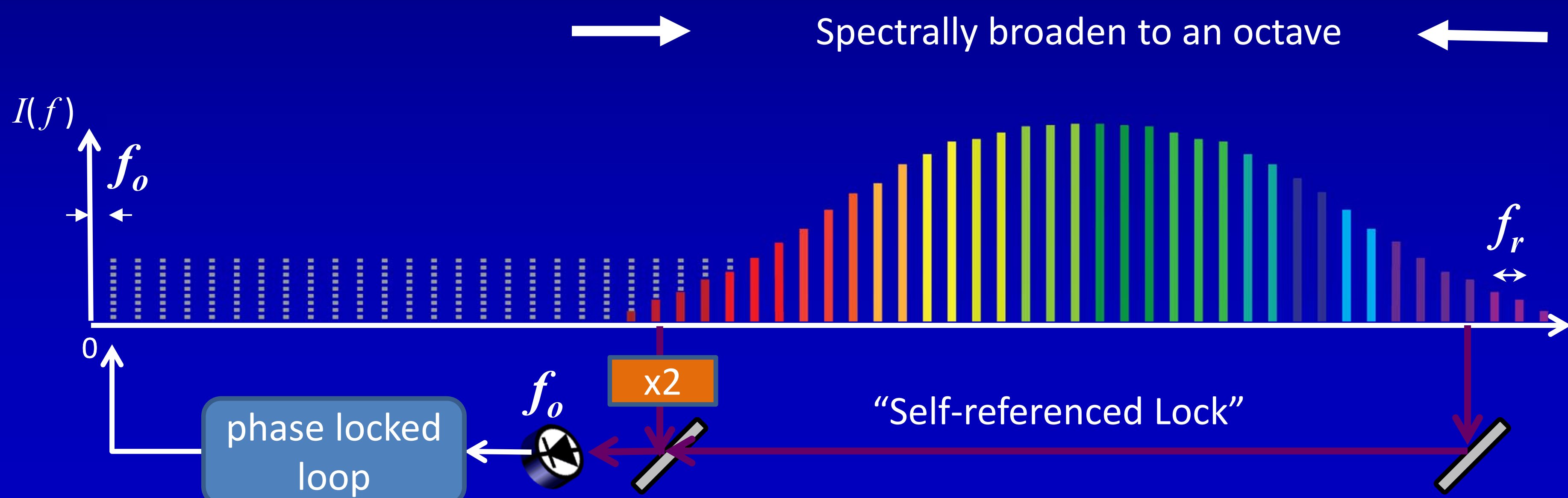
Comb can only “translate” and “breathe”

Offset Frequency Stabilization

Jones, et al. *Science* **288**, 635 (2000)



J. Hall
T. Hänsch

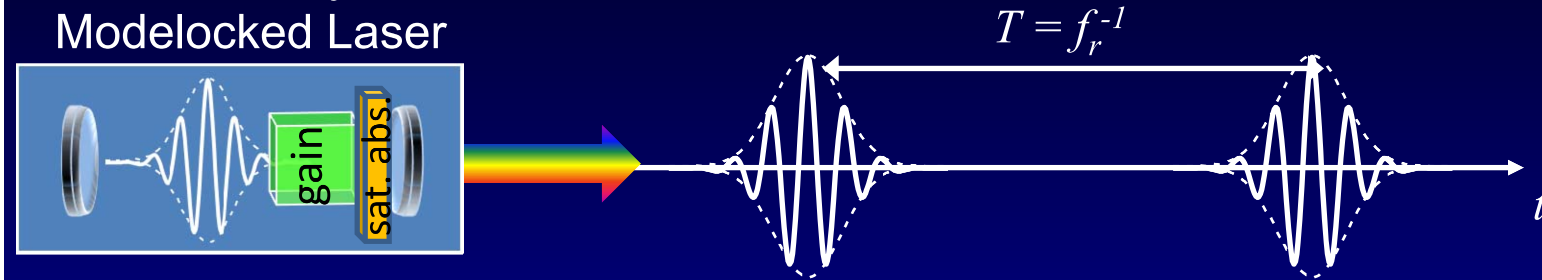


$$f_0 = 2(nf_{rep} + f_0) - 2nf_{rep} + f_0$$

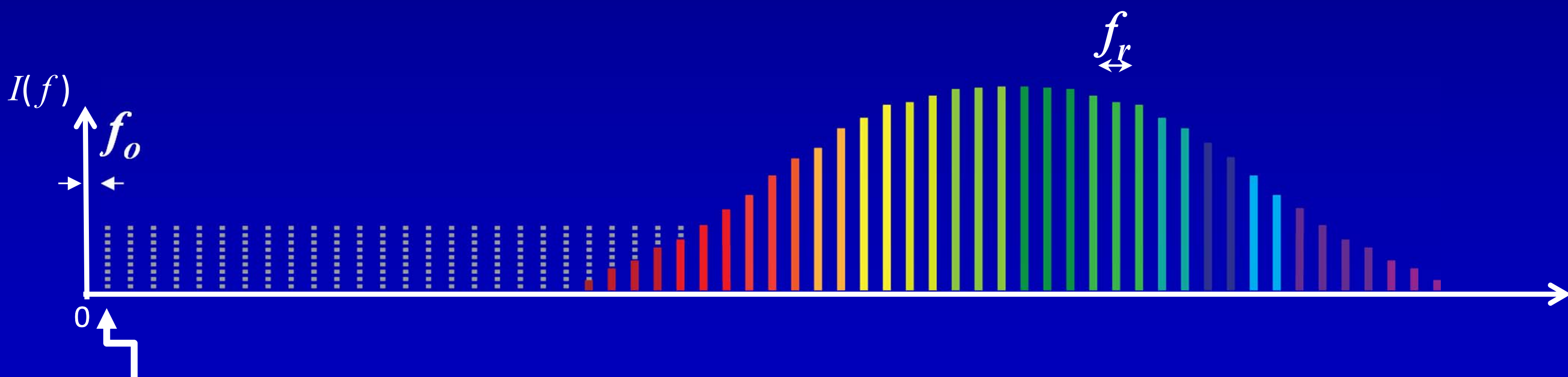
Stabilization of the Second Degree of Freedom

J. Hall
T. Hänsch

Passively
Modelocked Laser



A choice: Stabilize to an Optical or RF oscillator



Phase-lock (stabilize) offset frequency, f_o

Frequency Comb needs a Reference Oscillator

RF oscillator

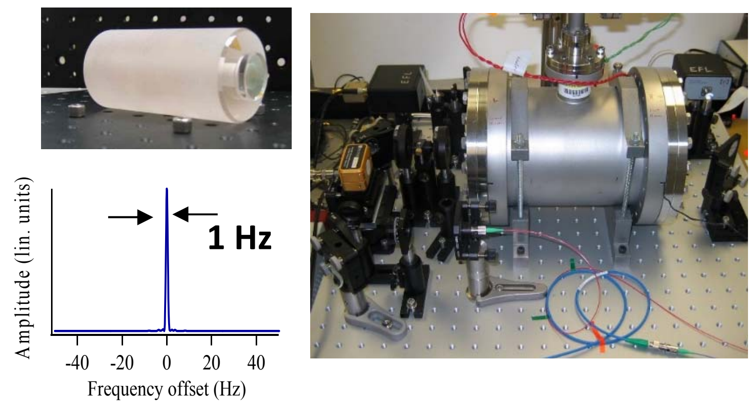
(Quartz / DRO / H-maser)

Signal @ 10 MHz – 10 GHz

Optical Oscillator

(cavity-stabilized Laser)

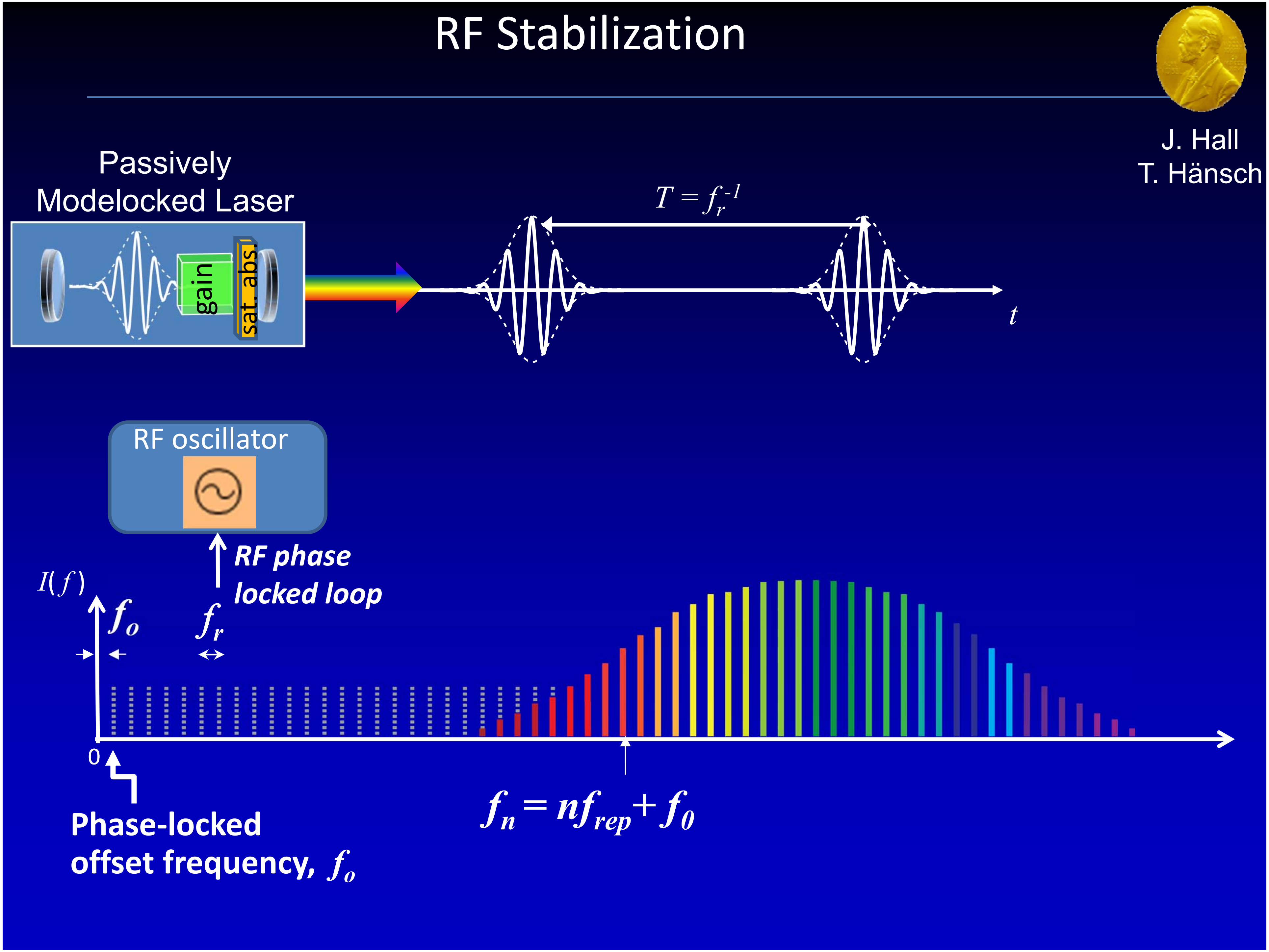
Signal @ 200 THz



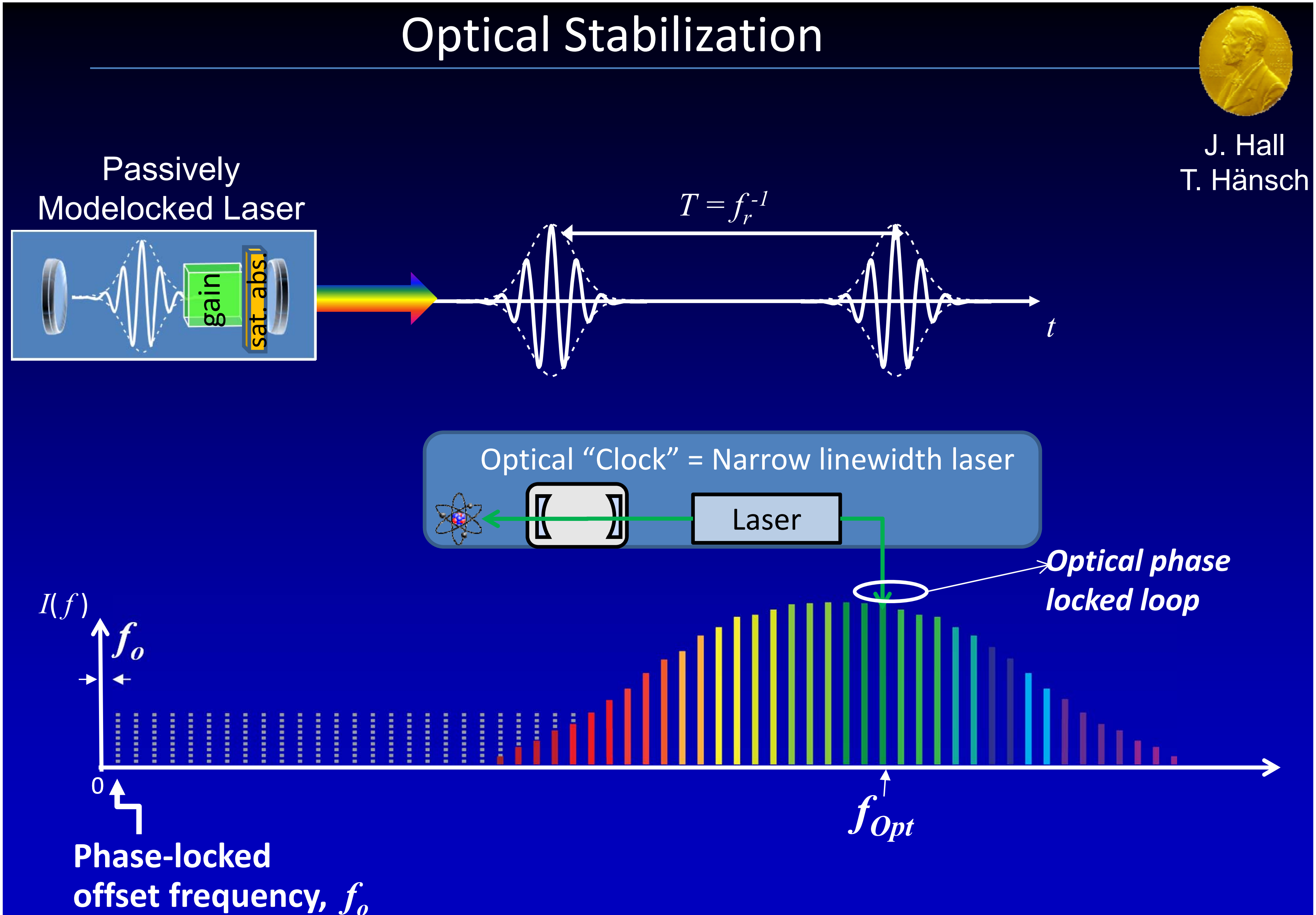
Pound-Drever-Hall Cavity Lock

- Quartz/DRO: small, compact, cheap
- RF comb stabilization easy
- No optical coherence in comb
- Broad optical teeth

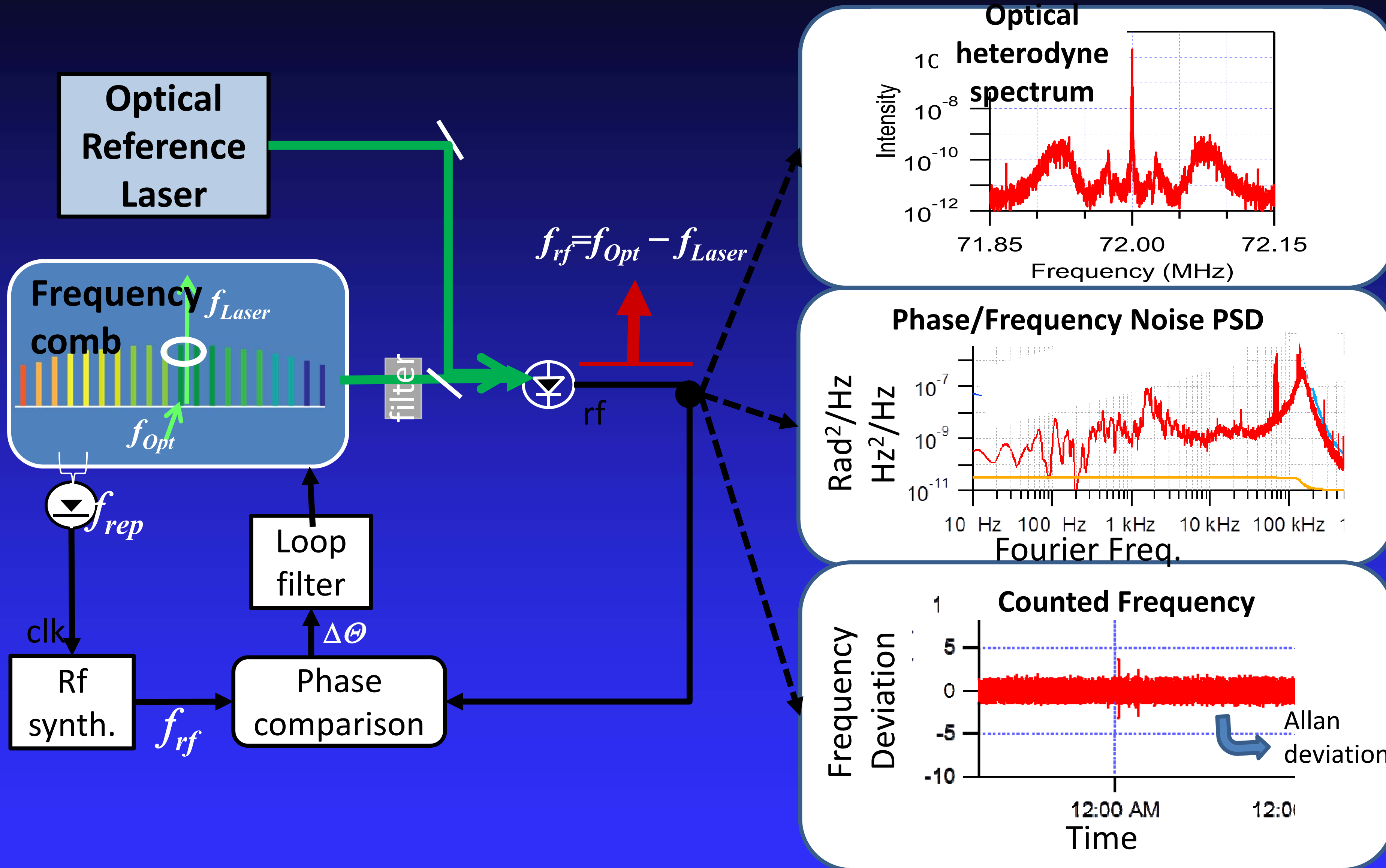
- Not small, not compact, not cheap
- Optical comb stabilization hard
- Optically coherent comb
- "Delta function teeth"


RF Stabilization
J. Hall
T. Hänsch
Passively
Modelocked Laser
gain
sat. abs.
T = f_r^-1
t
RF oscillator
RF phase
locked loop
I(f)
f_o
f_r
0
f_n = nf_rep + f_0
Phase-locked
offset frequency, f_o

Optical Stabilization

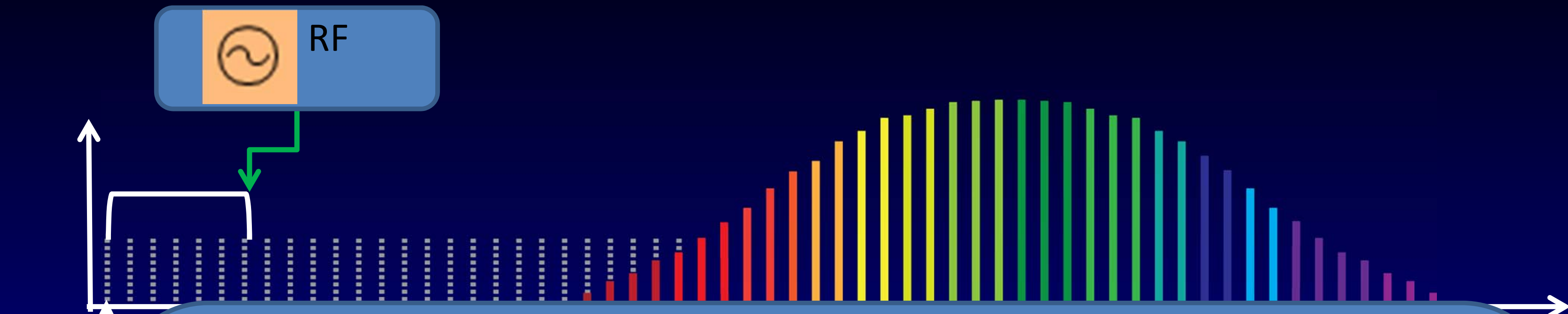


Optical Phase Locked Loop

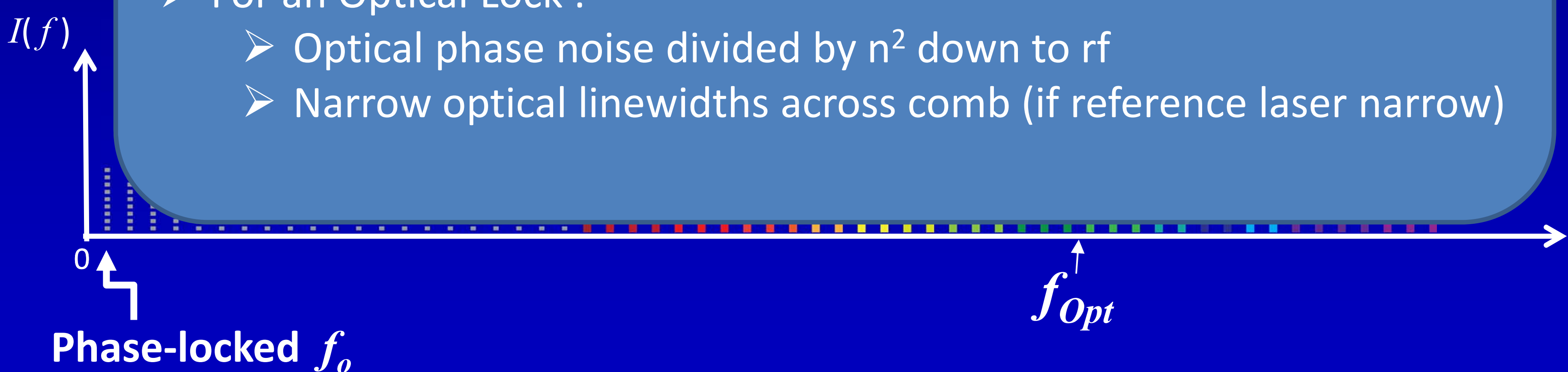


"in-loop" measures of comb phase coherence and frequency stability

RF vs Optical Stabilization: Lever Arm Difference

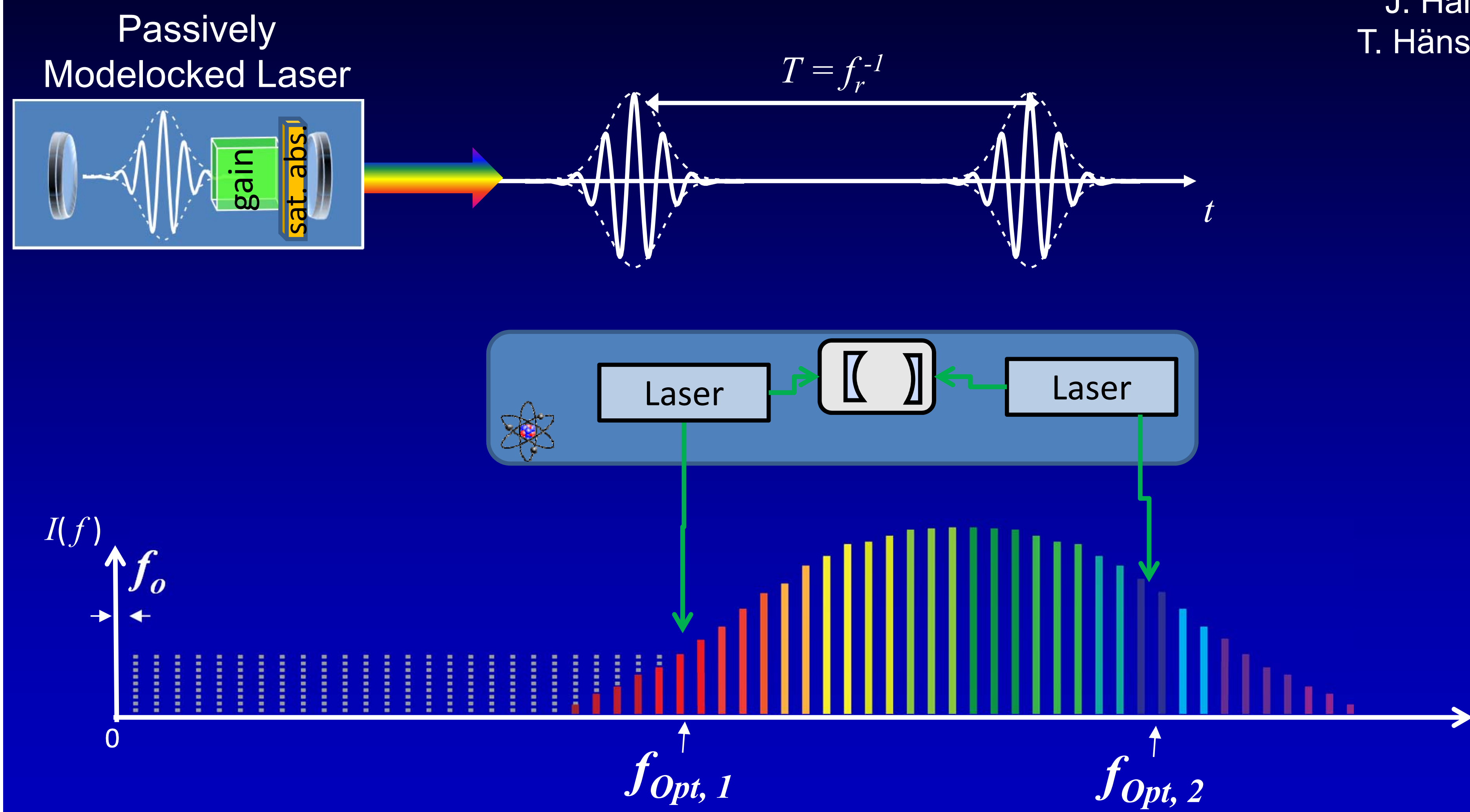


- For an RF lock:
  - RF phase noise is multiplied by n^2 up to optical
  - Broad optical linewidths
  - Optical teeth *central position* defined absolutely
- For an Optical Lock :
  - Optical phase noise divided by n^2 down to rf
  - Narrow optical linewidths across comb (if reference laser narrow)



Other Stabilization Options: double pinning

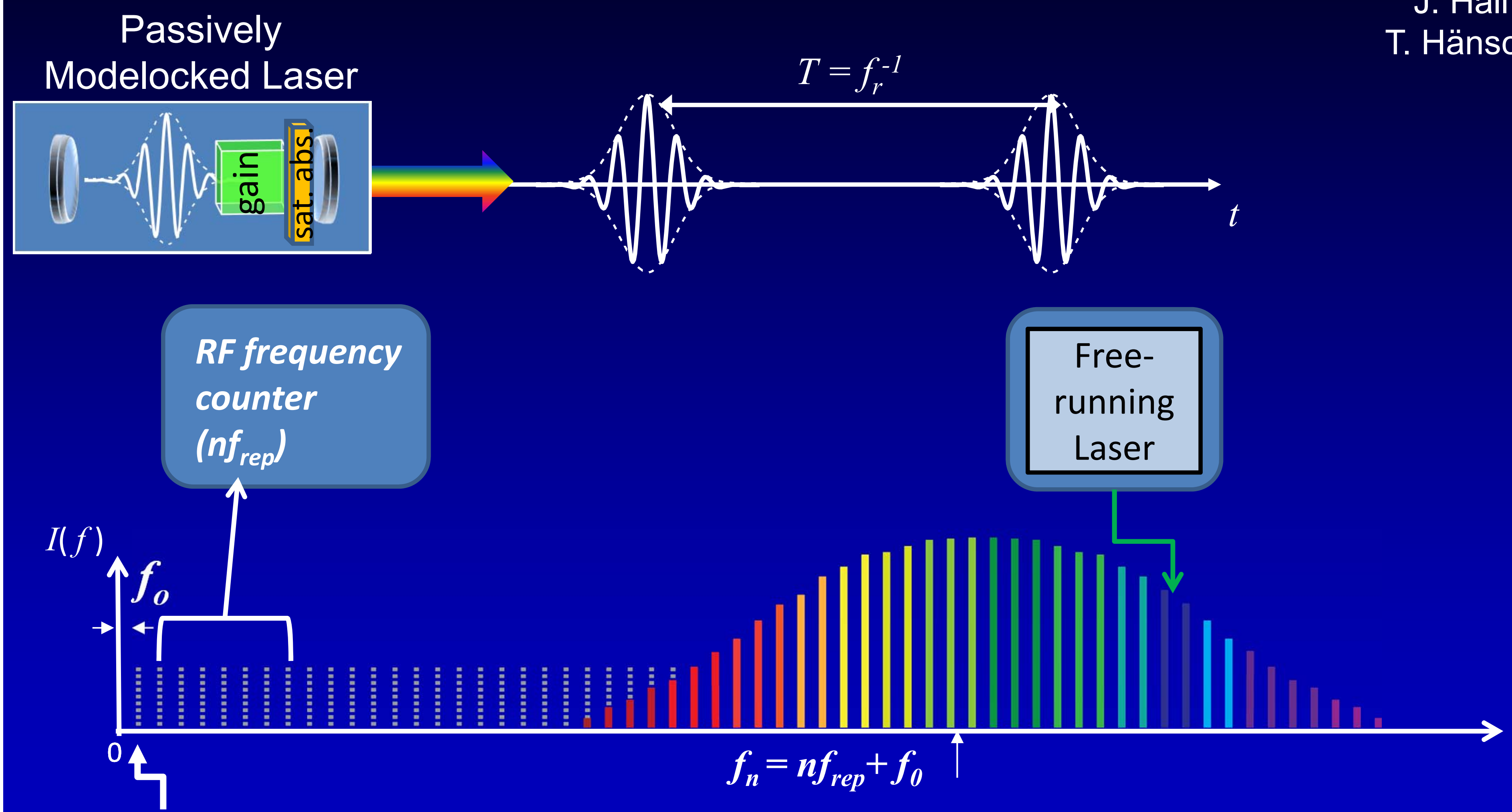
J. Hall
T. Hänsch



NO Offset frequency stabilization -> no need for octave supercontinuum
But no absolute frequency knowledge (unless cavity separately measured)

Other Stabilization Options: free running laser

J. Hall
T. Hänsch



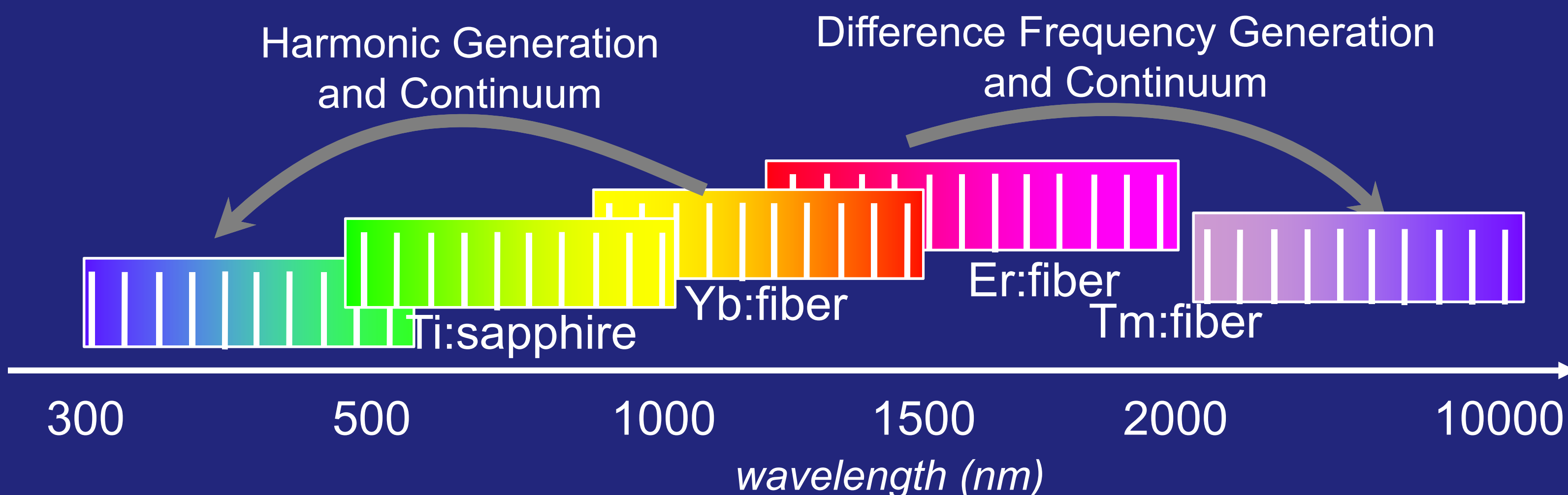
Phase-locked offset frequency, f_o

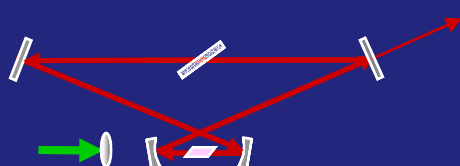
Avoids need for cavity-stabilized laser
Retains qbsolute frequency knowledge

Femtosecond Laser Frequency Combs

A unique source for sensing and spectroscopy

- an array of millions of phase-coherent CW oscillators
- large spectral coverage: 300 nm - 10 microns
- precisely known frequencies (~1 Hz resolution)
- high peak power for efficient nonlinear optics





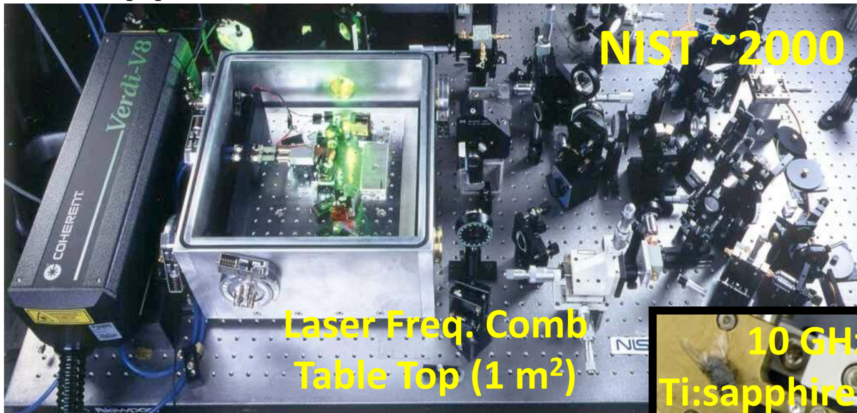
Ti:Sapphire laser

Er:fiber laser

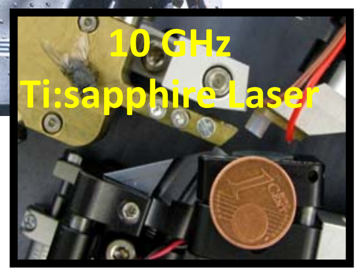
courtesy of S. Diddams et al.

Some Frequency Combs

Ti:Sapphire Combs

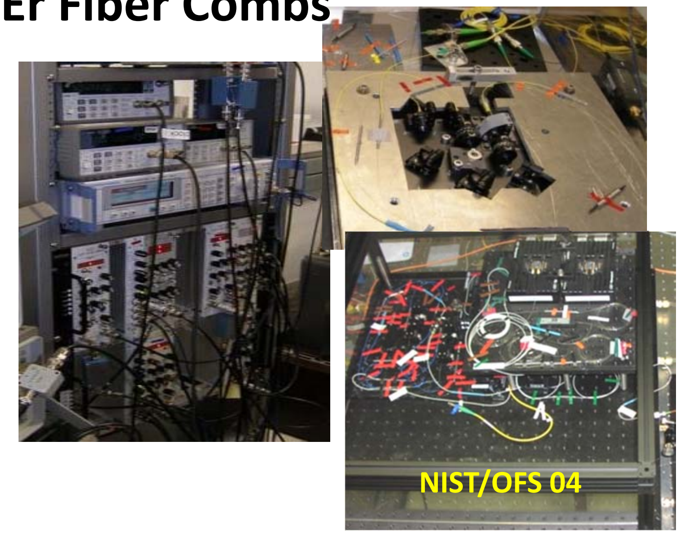


Courtesy S. Diddams

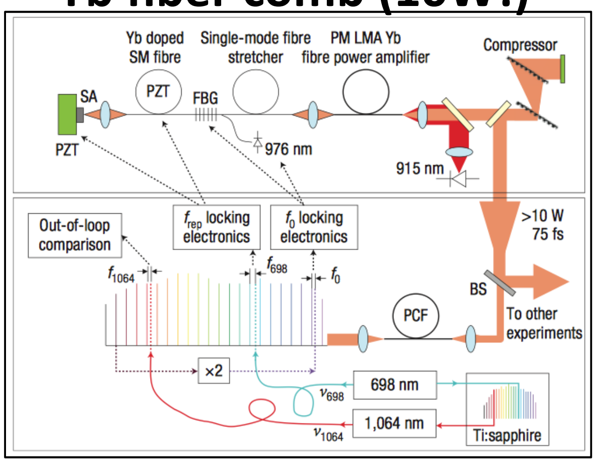


A. Bartels,, *Science* **326***,* 681 (2009).

Er Fiber Combs

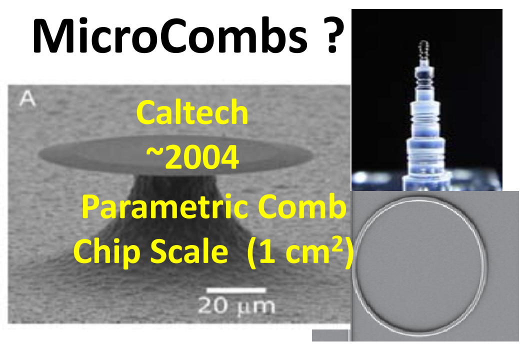


Yb fiber comb (10W!)



Schibli, et al. *Nature Photonics* 2, 355 - 359 (2008) (IMRA America & JILA)

MicroCombs ?



Del'Haye, Nature, 450, 1214, 2007; Levy, Nat. Phot. 4, 32 (2010), Papp, Diddams, *PR A* **84**, 053833 (2011), EPFL, OE waves, Cornell, CalTech, MPQ, NIST....

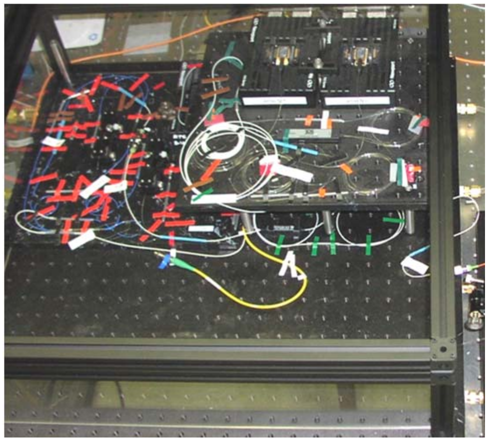
Many others
Er:Yb glass
Thulium Fiber combs
Cr:Forsterite

Most "universal" solution: Fiber Laser Based Combs

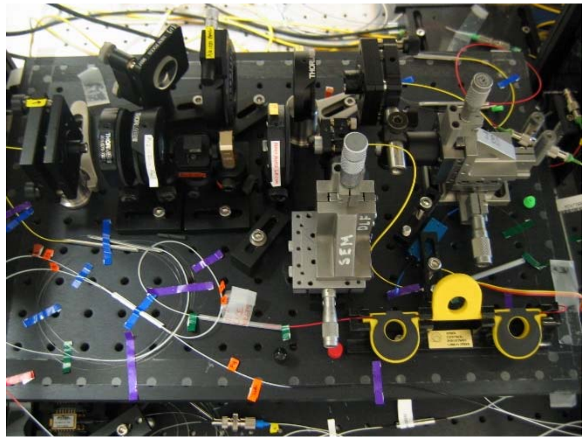
- Advantages of fiber frequency comb
  - Compact, inexpensive design
  - Potential for stable "hands-free" operation
  - Compatible with highly reliable telecommunication components
  - Covers the Infrared region of the spectrum
  - Under development at: Menlo, Toptica, MPQ, PTB, AIST, IMRA, OFS, U. Konstanz, Kansas State, Arizona, NIST, etc. etc.

- Rest of talk will focus on fiber frequency combs but many of the results/analysis are general and apply to other frequency combs as well .

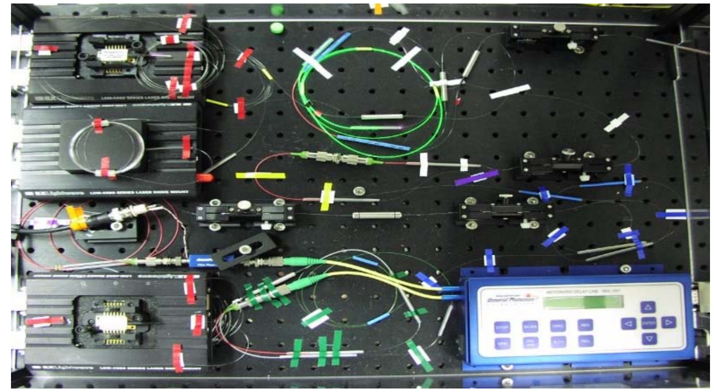
Some Different NIST Fiber Combs



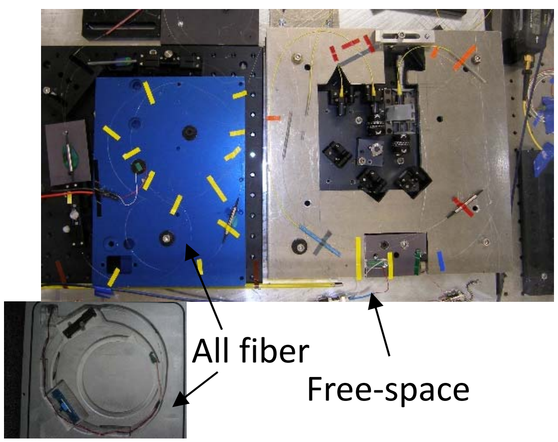
NIST/OFS Figure-8
Fiber Frequency Comb
Washburn et al., Opt. Lett. **29**, 250 (2004)



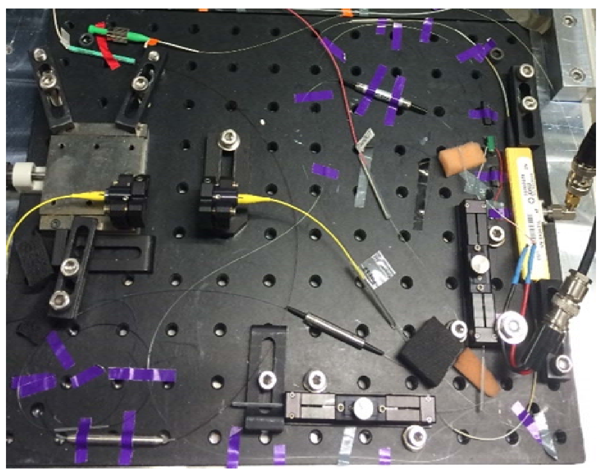
stretched-pulse ring laser
Fiber Frequency Comb
McFerran et al., Opt. Lett. 31, 1997 (2006)
Swann, Opt. Lett. **31**, 3046 (2006).



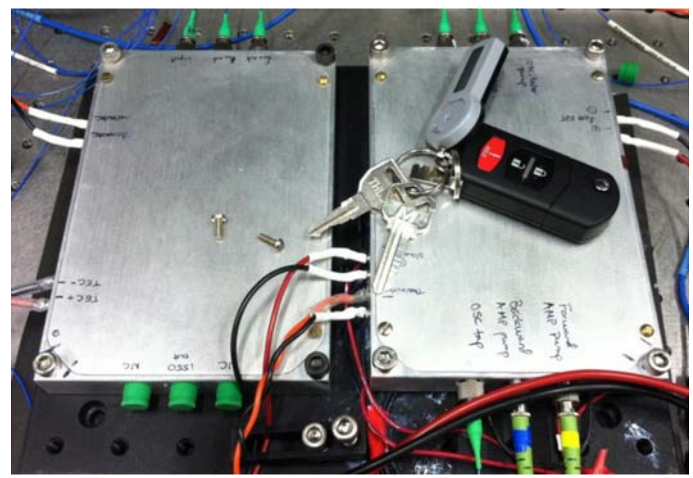
stretched-pulse ring laser with variable rep rate
Fiber Frequency Comb
Washburn et al, OE, 12, 4999 (2004)



Stretched-pulse ring lasers
Fiber Frequency Combs
Coddington et al, PRA, 81, 043817 (2010)

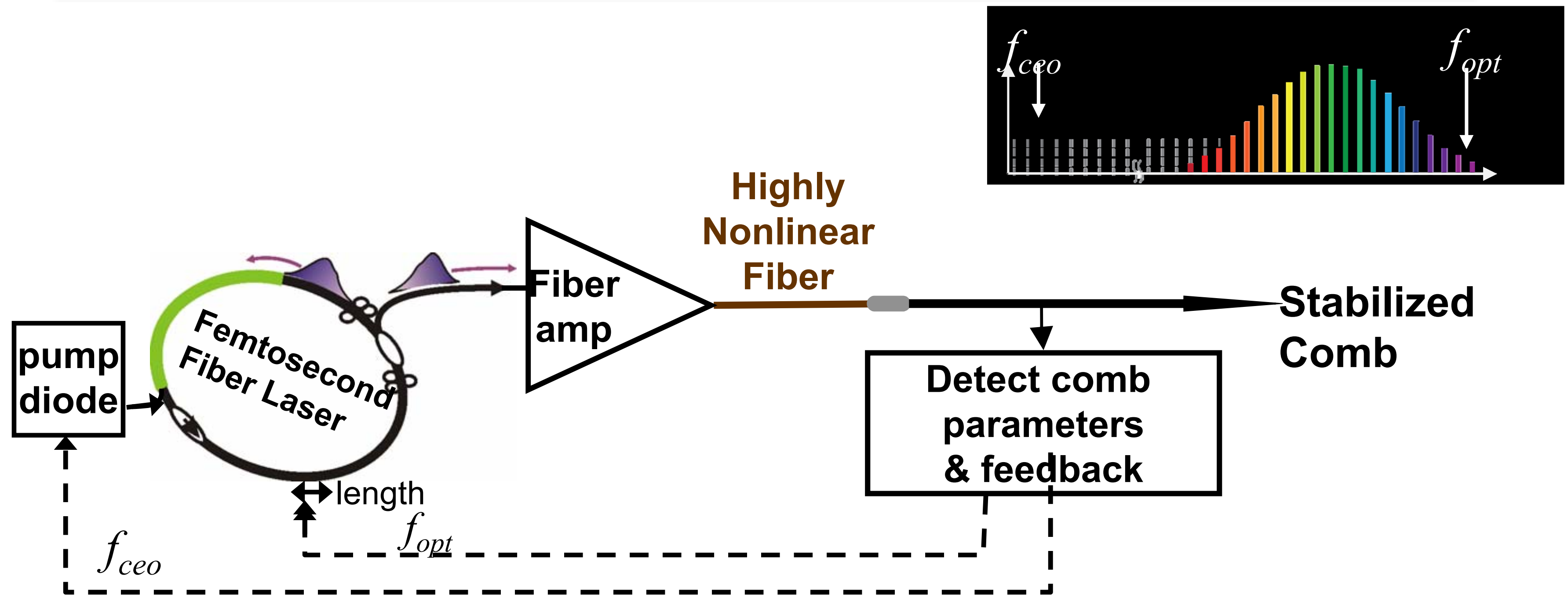


Ring laser with intracavity EOM
Swann et al. OE, 19, 243817(2011)



Linear SESAM Linear cavity Fiber Frequency Comb
Sinclair, OE, 22, 6996 (2014)
Sinclair, RSI, 86, 081301 (2015);

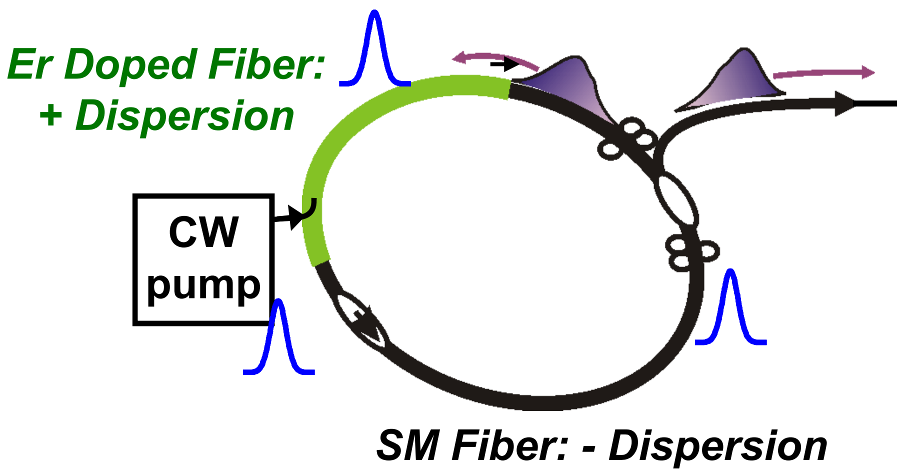
Fiber Laser
Frequency Comb

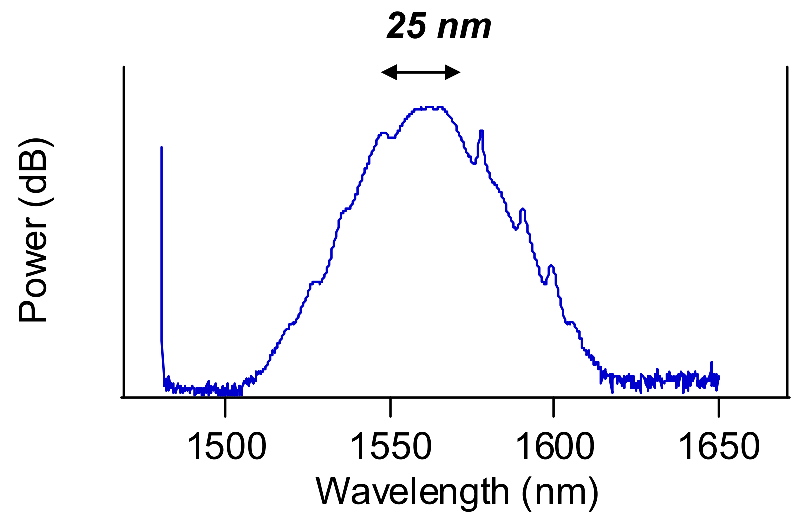


- Stabilize offset frequency by feeding back to pump power
- Stabilize f_{rep} (or optical tooth) by feeding back to cavity length

Ring Laser: “Soliton” vs. Stretched pulse mode

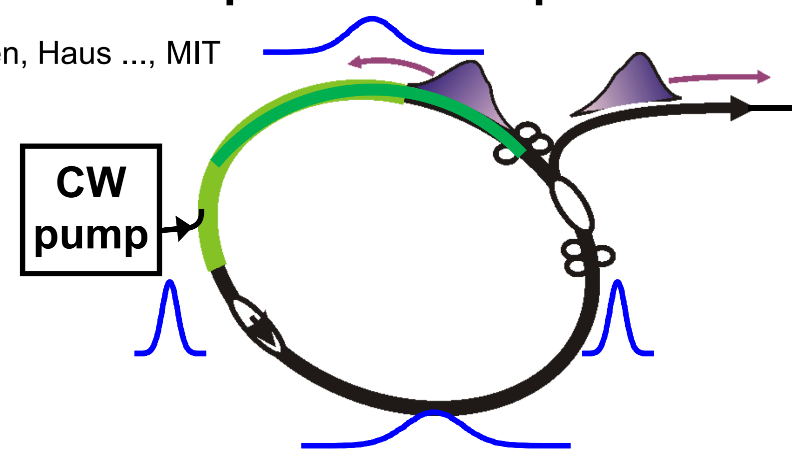
Soliton-mode: net dispersion < 0

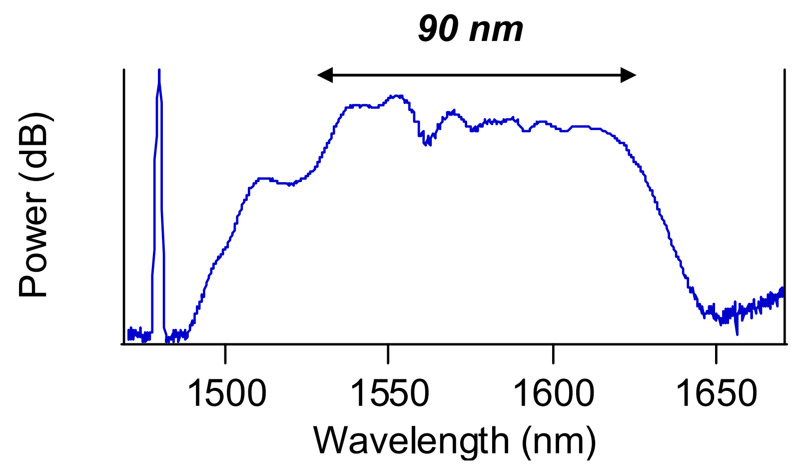




Stretched-pulse: net dispersion > 0

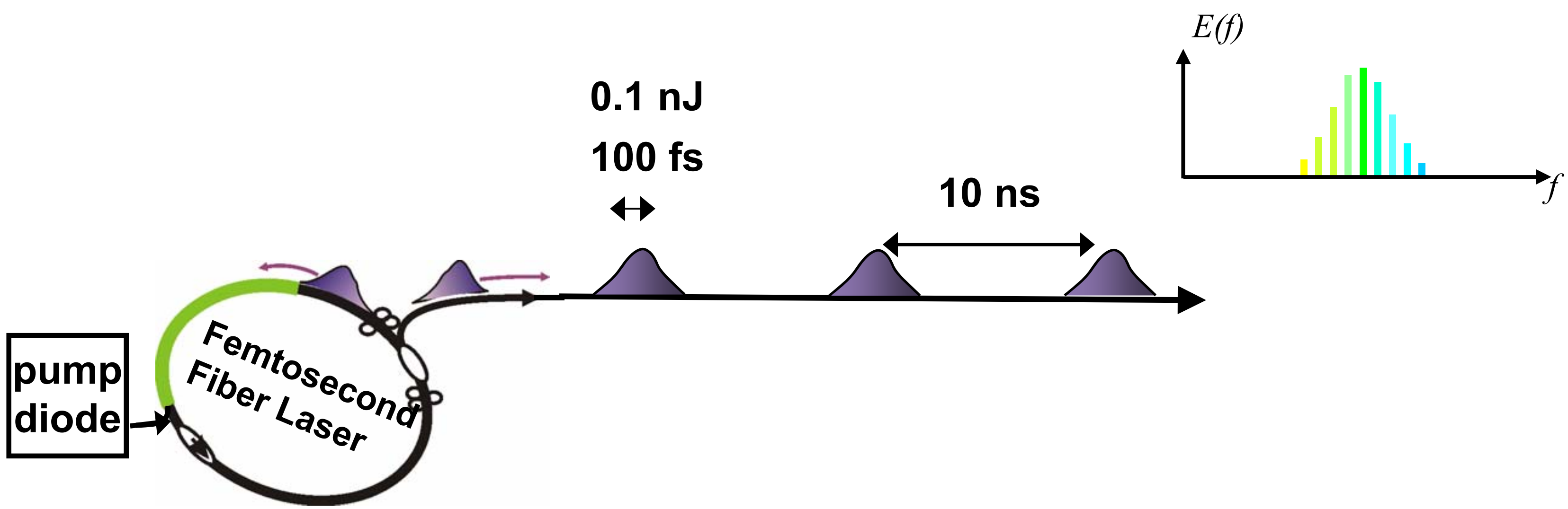
Ippen, Haus ..., MIT





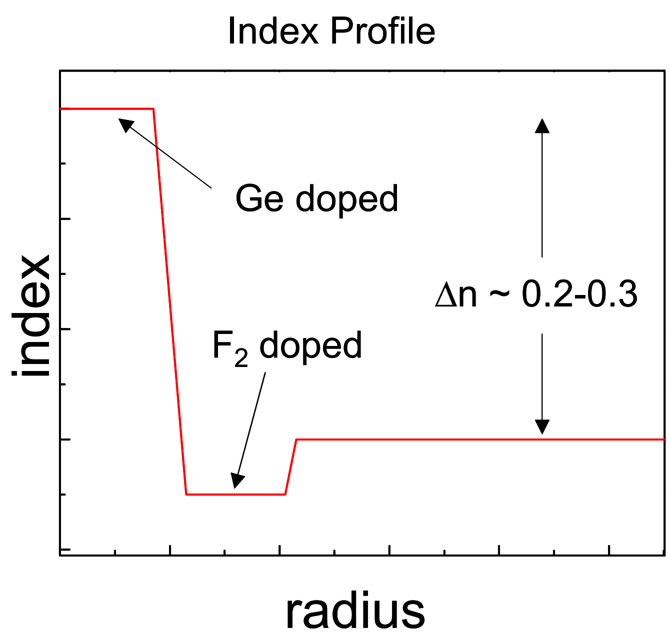
Either works for a frequency comb: low dispersion better for noise

Free-running Mode-locked laser

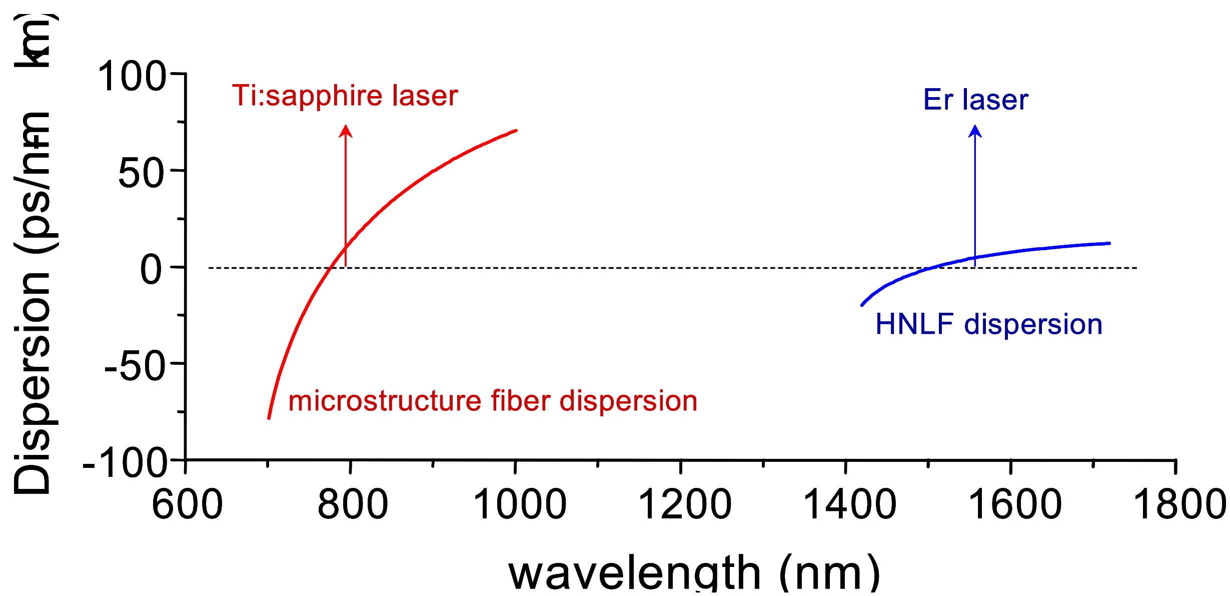


- A free-running frequency comb .
- Now need to broaden to octave-spanning supercontinuum

Highly Nonlinear Fiber (HNLF) for Er fiber combs

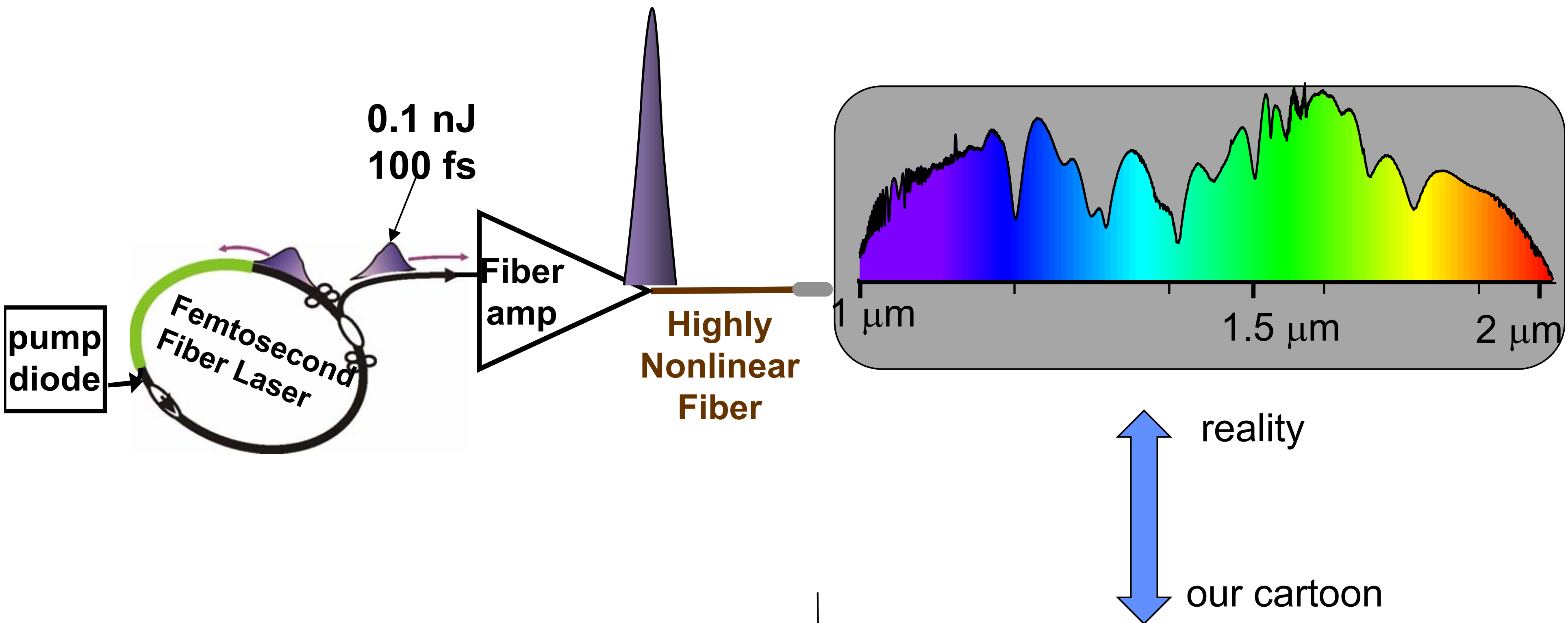


nonlinearity : 8 to 15 1/W-km
Effective Area : 13 μm²
loss : 0.7 to 1 dB/km
dispersion (1550 nm) :
-10 to +10 ps/nm-km
dispersion slope (1550 nm) :
0.024 ps/nm2-km
splice loss (to SMF) :0.18 dB
splice loss (to HNLF) :0.02 dB

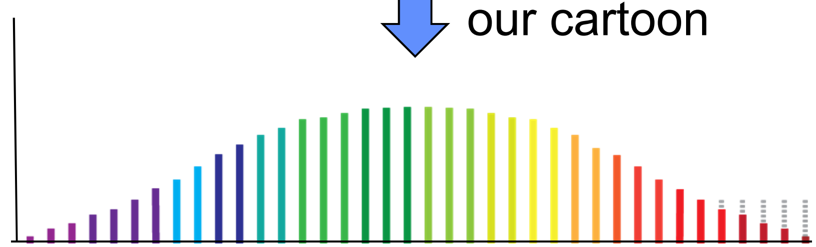


Fiber Laser Frequency Comb

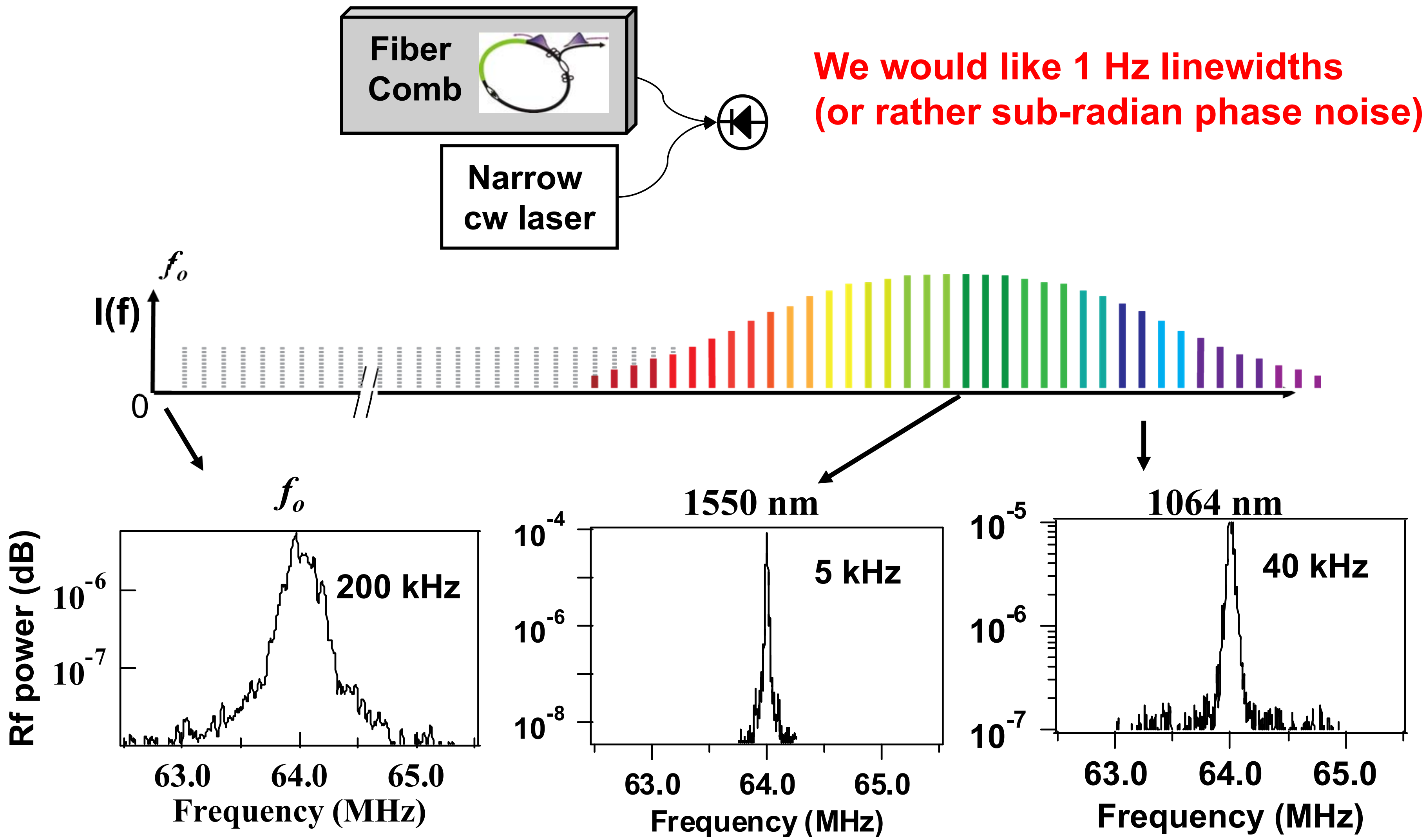
Octave Spanning Comb



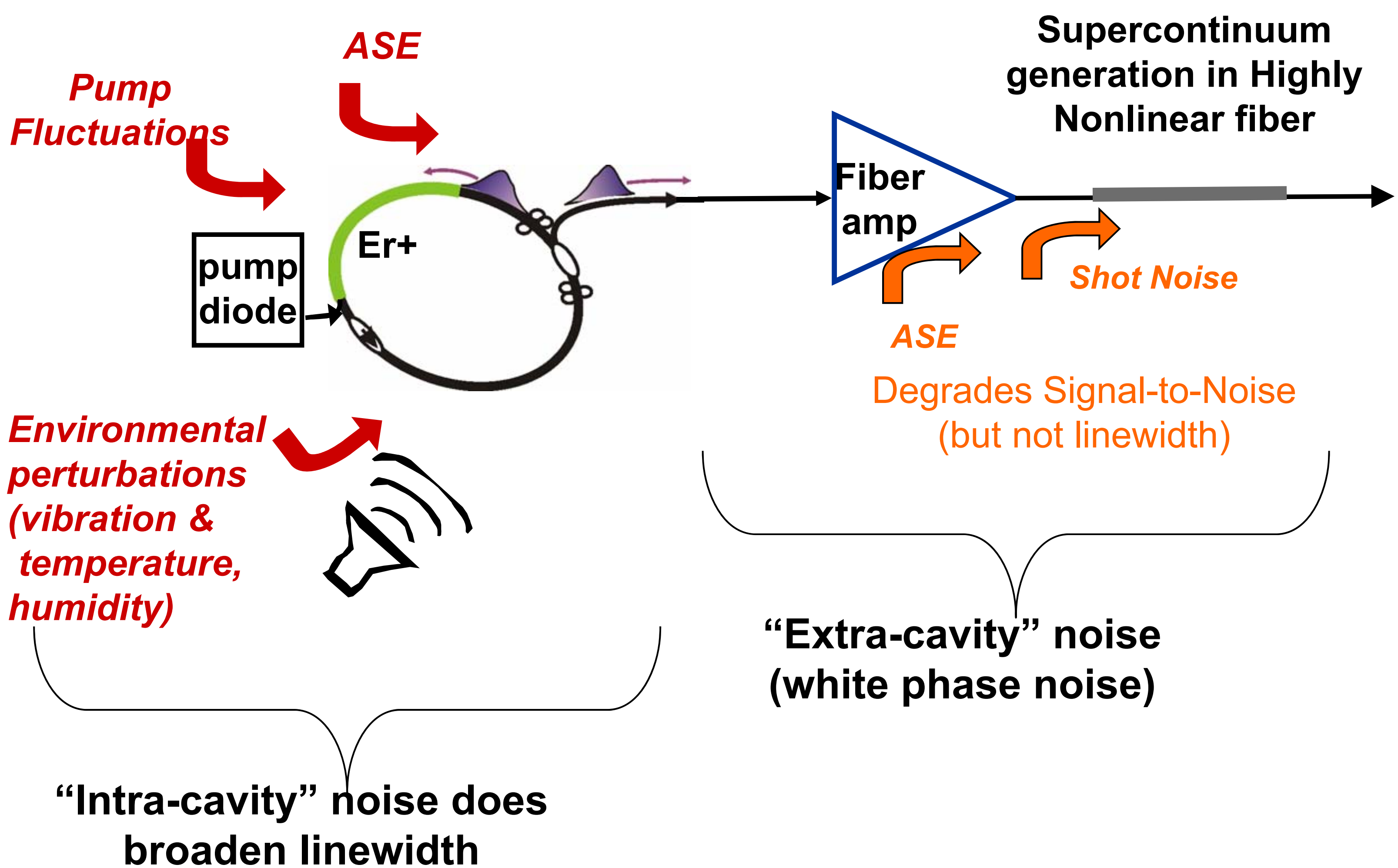
How noisy is the free-running comb?
What causes this noise?
How do we feedback against it?



Free-running Linewidths



Noise Sources



How to characterize the frequency comb response to noise (and actuators)?

NIST

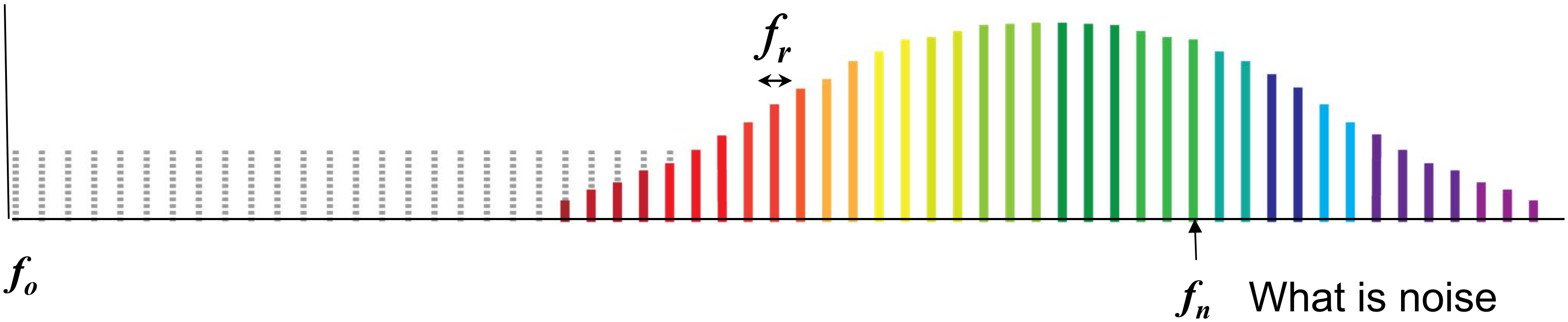
1. Use Fixed Point
   - $f_n = nf_r + f_{ceo}$ → tempting to characterize noise by effect on f_r and f_{ceo} → **Don't!**
   - All* noise/actuators change f_r
   - But differ in their "Fixed point"

2. Use Frequency noise PSD
   - Always characterize by frequency (or phase) noise power spectral density
   - Linewidth is a (misleading) convenience

(* except self phase modulation or external AOM)

Perturbation -> Comb Noise
Must be “accordion like”

From H. Telle and coworkers: H. R. Telle, B. Lipphart, and J. Stenger, APB, 74, 1 (2002)



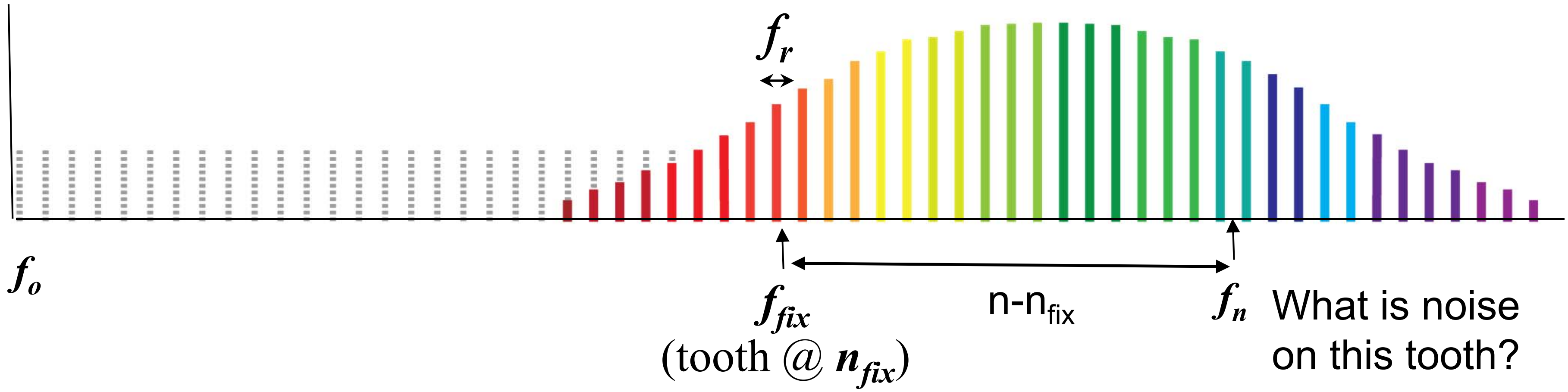
What is noise on this tooth?

$$\delta f_n = n\delta f_{rep} + \delta f_o$$

Correlated!!

"Fixed-Point" picture for Noise

From H. Telle and coworkers: H. R. Telle, B. Lipphart, and J. Stenger, APB, 74, 1 (2002)



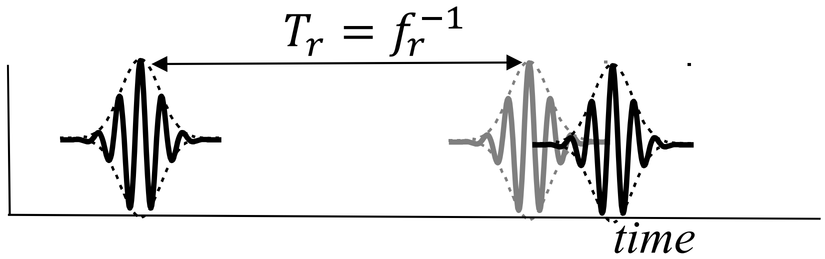
$$\delta f_n = (n - n_{fix})\delta f_{rep}$$

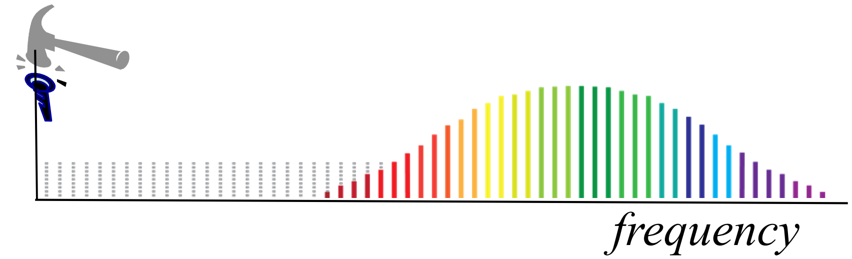
Any noise described by:

1. Fixed tooth that does not move
2. Repetition rate change about that point

Where is the fixed point?
Three important cases

Round trip & Carrier Phase shift together





How to characterize the frequency comb response to noise (and actuators)?

NIST

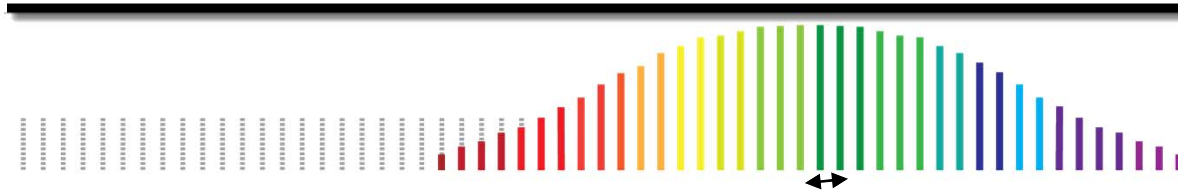
1. Use Fixed Point
   - $f_n = nf_r + f_{ceo}$ → tempting to characterize noise by effect on f_r and f_{ceo} → **Don't!**
   - All* noise/actuators change f_r
   - But differ in their "Fixed point"

2. Use Frequency noise PSD
   - Always characterize by frequency (or phase) noise power spectral density
   - Linewidth is a (misleading) convenience

(* except self phase modulation or external AOM)

Frequency Noise PSD

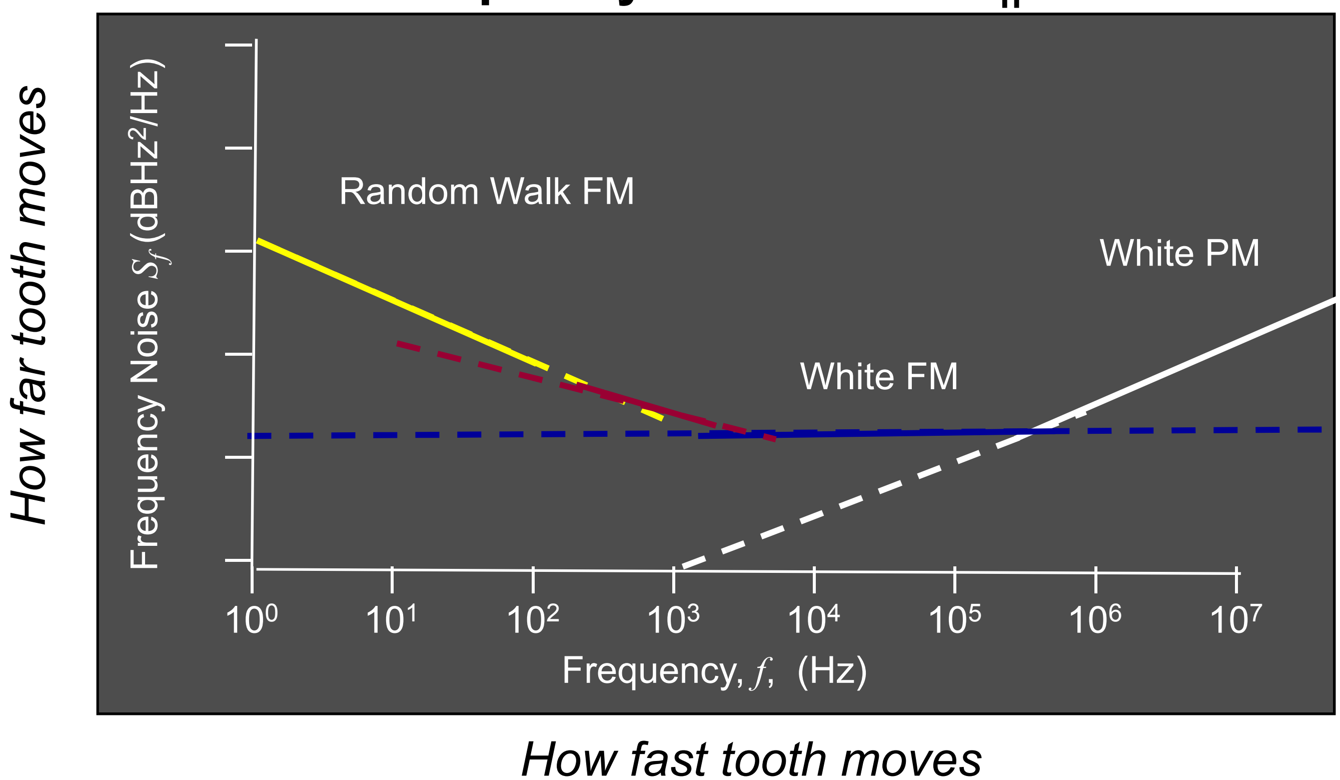
- Can use phase noise PSD to by just dividing by f^2



$< \delta f_n^2 >$

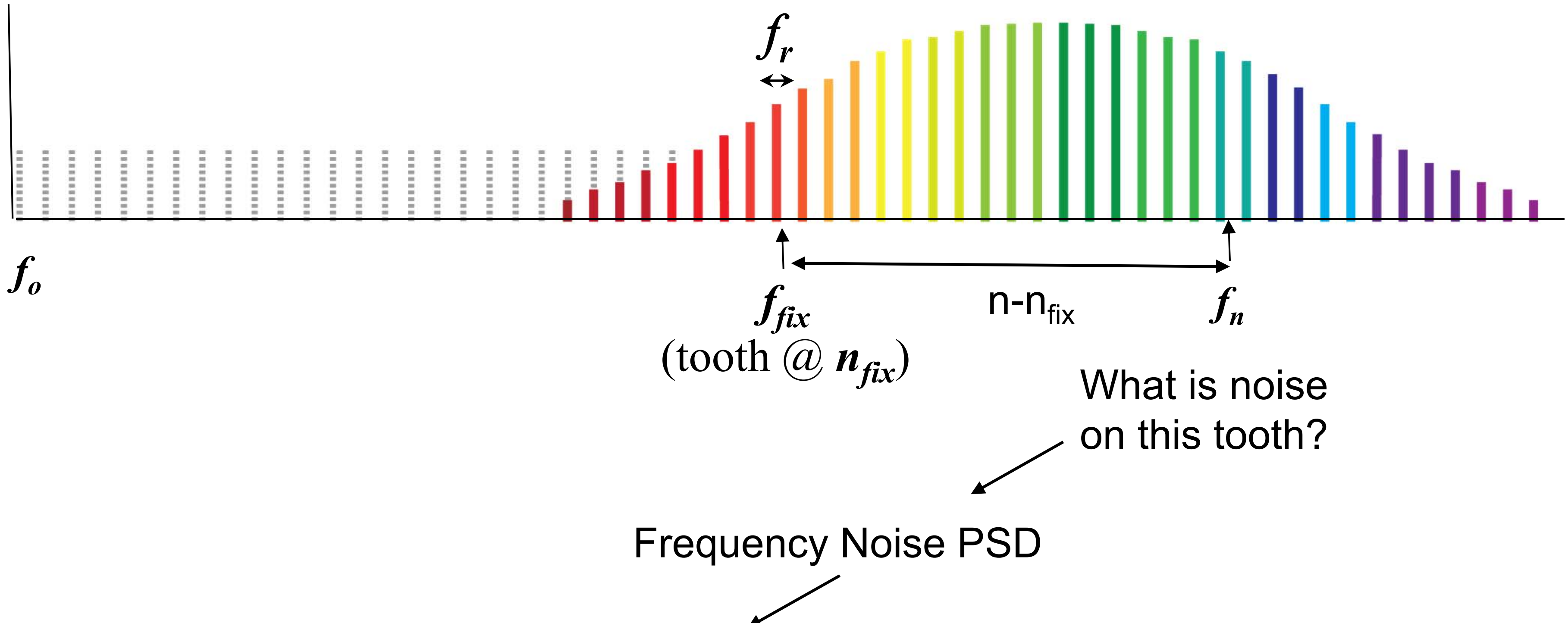
FFT

Frequency Noise PSD: S_n



“Fixed-Point” picture for Noise

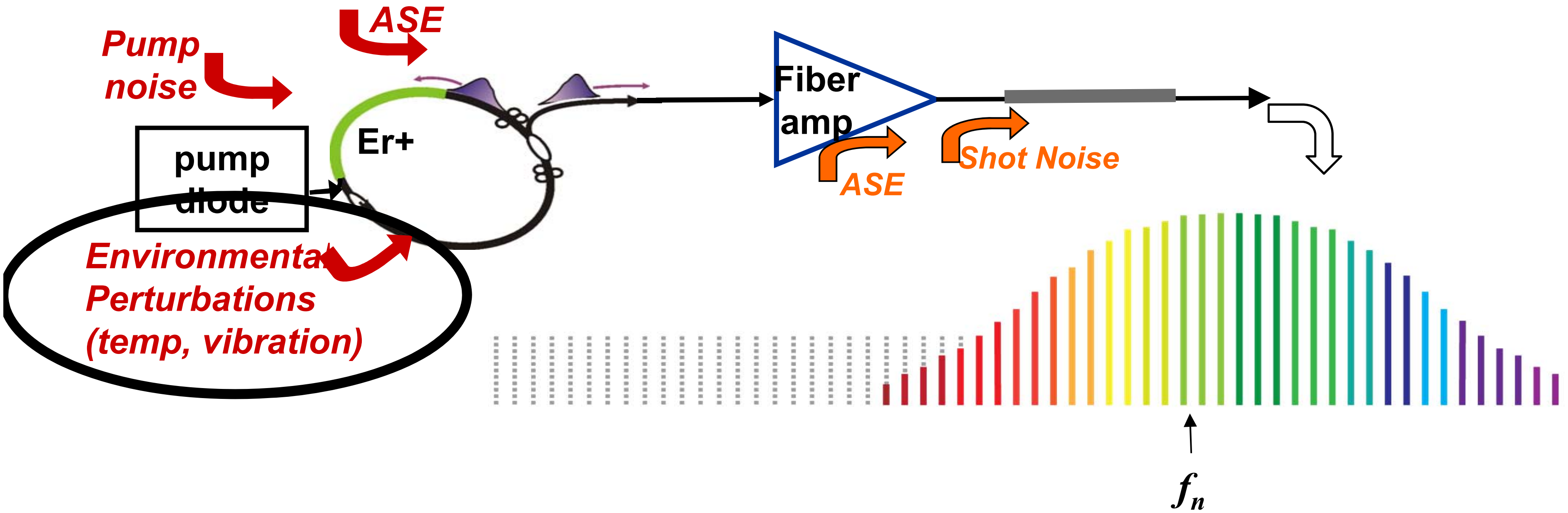
From H. Telle and coworkers: H. R. Telle, B. Lipphart, and J. Stenger, APB, 74, 1 (2002)



$$\widetilde{\langle \delta f_n^2 \rangle} = S_n = \left(n - n_{fix}\right)^2 S_{frep}$$

Noise on any tooth is just “scaled” repetition rate noise

Quantifying the Noise on the Comb
Summing Frequency Noise PSD



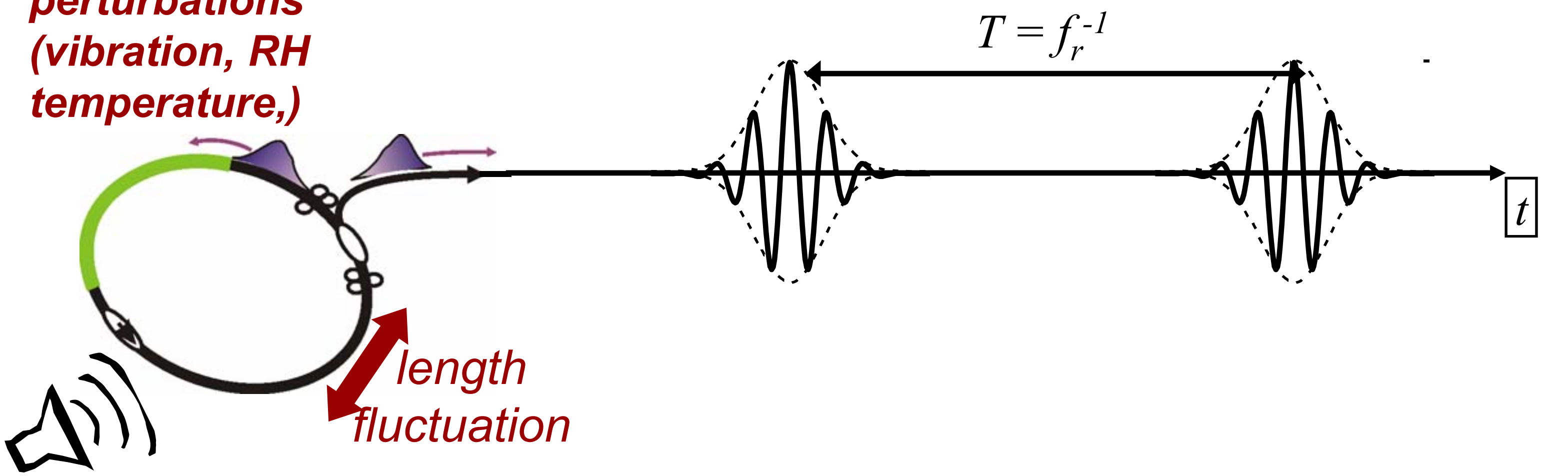
What is noise on the nth tooth? Sum of noise from each effect

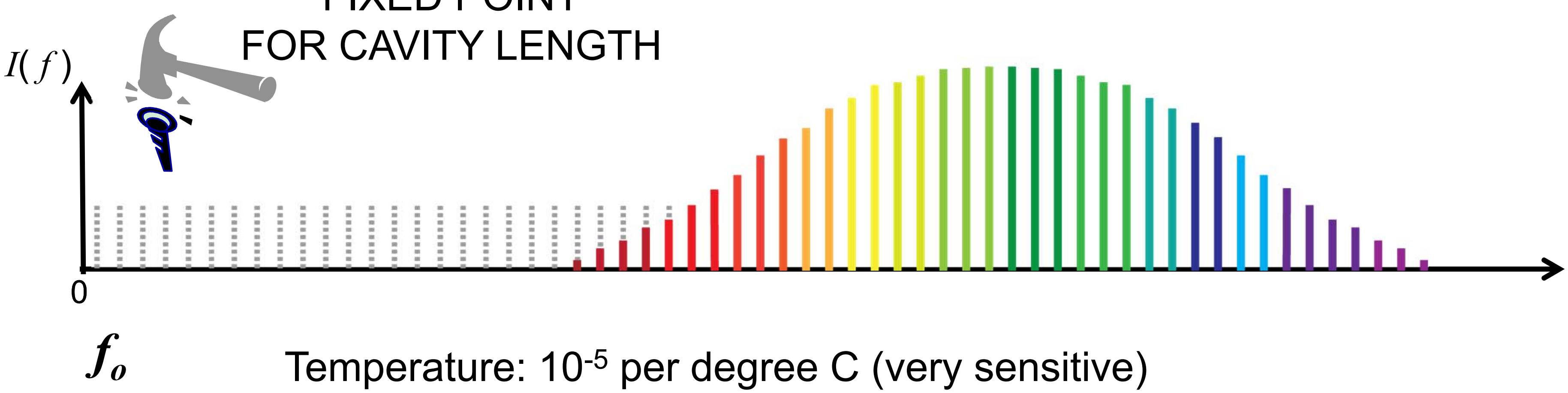
$$S_n = \left(n - n_{fix}^{temp}\right)^2 S_{temp} + \left(n - n_{fix}^{vib}\right)^2 S_{vib} + \left(n - n_{fix}^{ASE}\right)^2 S_{ASE} + \left(n - n_{fix}^{pump}\right)^2 S_{pump} + \ \dots$$

$\langle \delta f_n^2 \rangle$ = $\langle \delta f_n^2 \rangle$ from temperature + $\langle \delta f_n^2 \rangle$ from vibrations + $\langle \delta f_n^2 \rangle$ from amplified spontaneous emission + $\langle \delta f_n^2 \rangle$ from pump noise

Environmental Perturbations -> Cavity length

Environmental perturbations (vibration, RH temperature,)

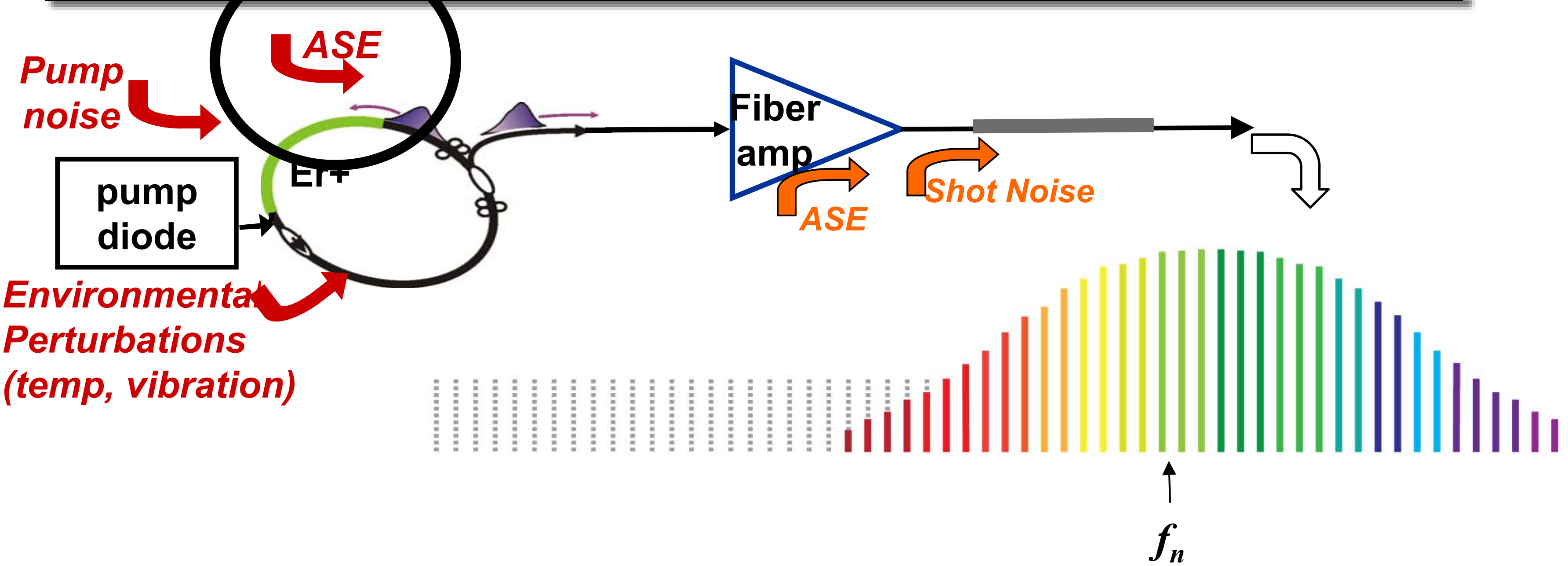




Temperature: 10^{-5} per degree C (very sensitive)
Vibration/Humidity: very sensitive
S ~1/f behavior

Quantifying the Noise on the Comb
Summing Frequency Noise PSD

NIST



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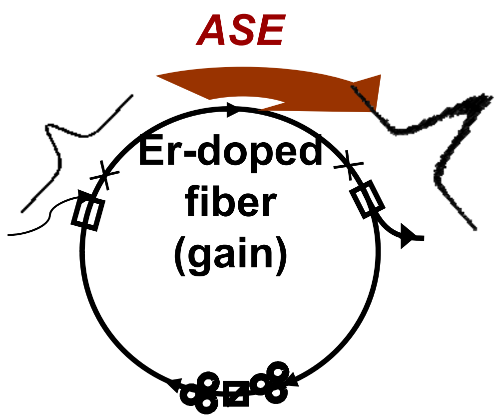
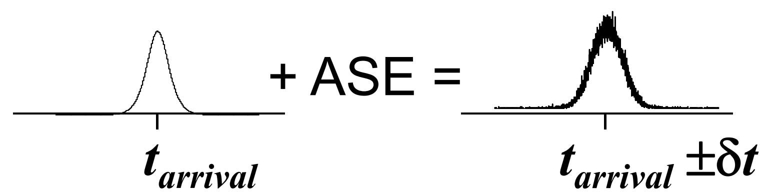
Effect of Amplified Spontaneous Emission Direct Timing Jitter

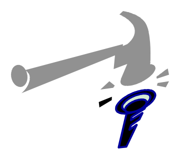
Often called Quantum Limit for mode-locked lasers

- H. A. Haus and A. Mecozzi, IEEE J. Quantum Electron. 29, 983 (1993).
- R. Paschotta, Appl Phys. B 79, 163 (2004).

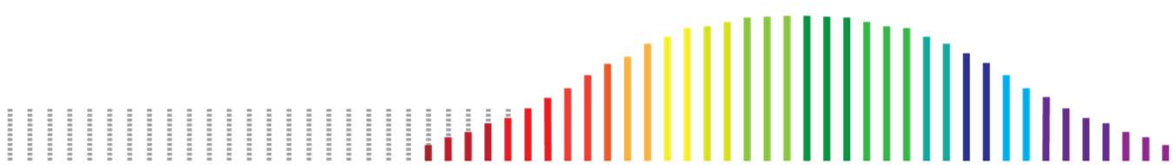




= **Round Trip Timing Shift**



Comb expands/contracts about center of spectrum

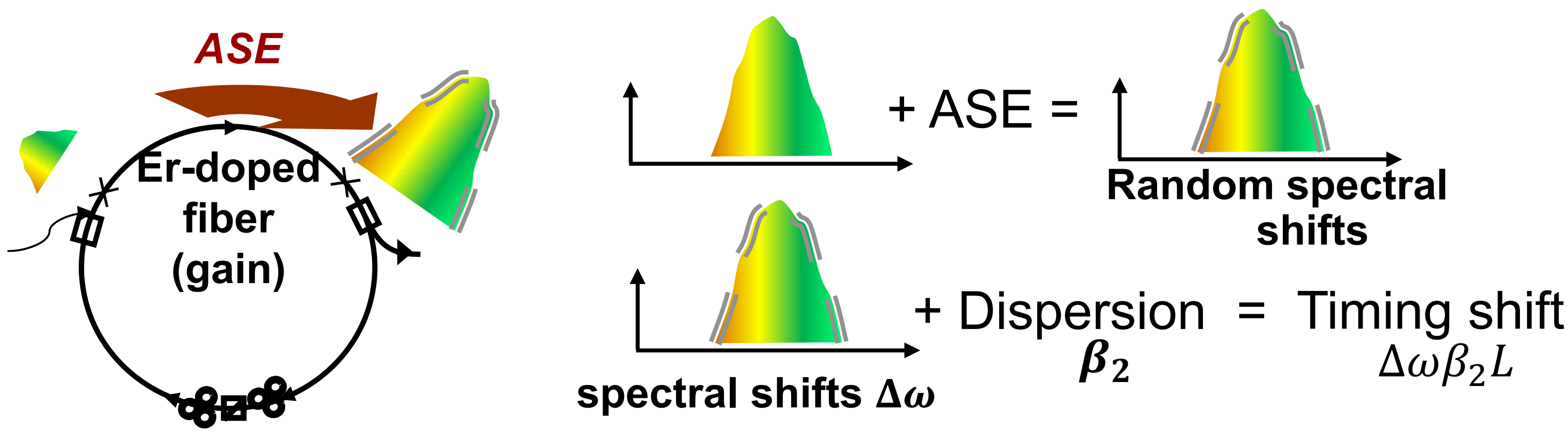


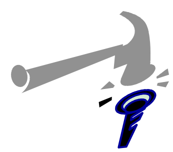
S_{ASE} ~ white noise (broadband)

* phase jitter gives S-T linewidth

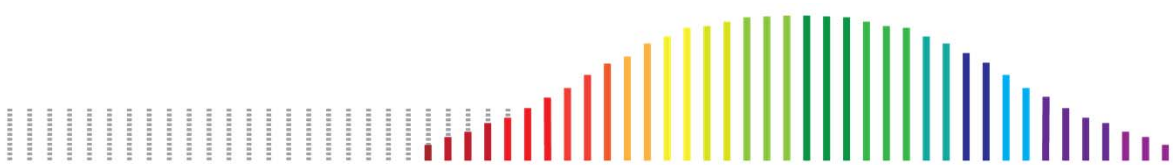
Effect of Amplified Spontaneous Emission Indirect Timing Jitter

- H. A. Haus and A. Mecozzi, IEEE J. Quantum Electron. 29, 983 (1993).
- R. Paschotta, Appl Phys. B 79, 163 (2004).



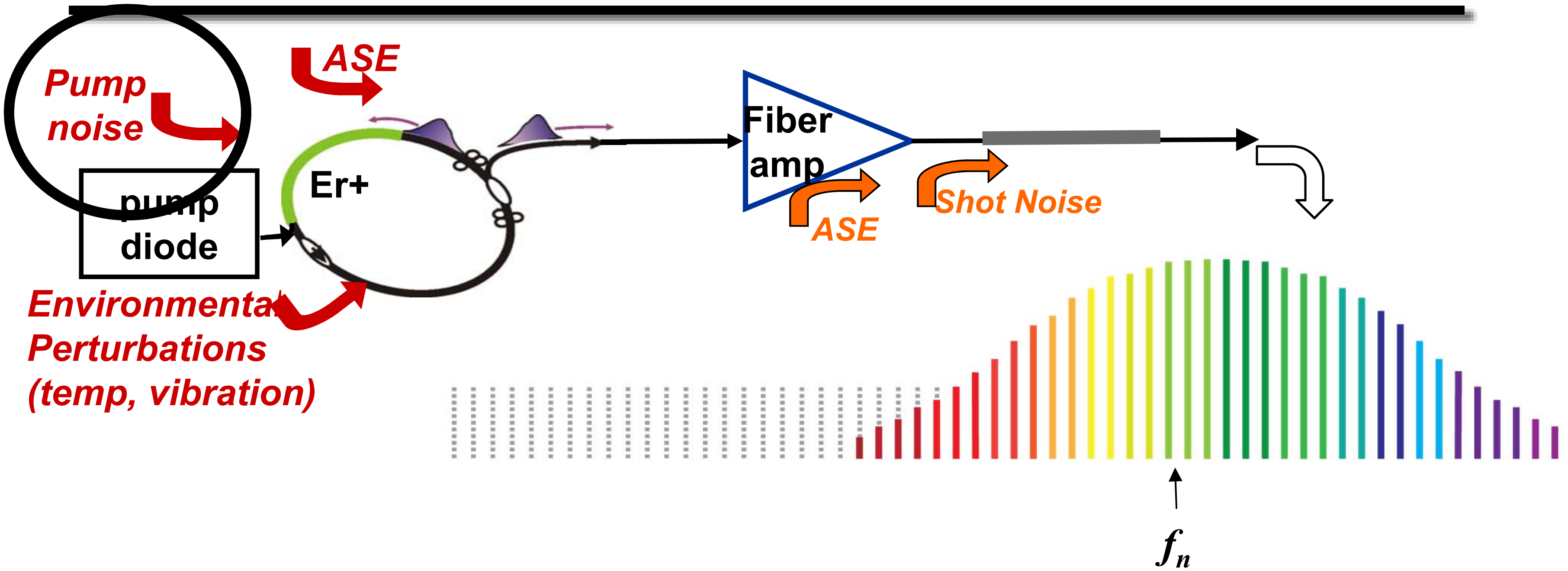


Comb expands/contracts about center of spectrum



This effect dominates ASE timing jitter at high cavity dispersion

Quantifying the Noise on the Comb
Summing Frequency Noise PSD



What is noise on the nth tooth? Sum of noise from each effect

$$S_n = \left(n - n_{fix}^{temp}\right)^2 S_{temp} + \left(n - n_{fix}^{vib}\right)^2 S_{vib} + \left(n - n_{fix}^{ASE}\right)^2 S_{ASE} + \left(n - n_{fix}^{pump}\right)^2 S_{pump} + \ldots$$

$\langle \delta f_n^2 \rangle$ = $\langle \delta f_n^2 \rangle$ from temperature + $\langle \delta f_n^2 \rangle$ from vibrations + $\langle \delta f_n^2 \rangle$ from amplified spontaneous emission + $\langle \delta f_n^2 \rangle$ from pump noise

How to solve for the Response of the Fiber-Laser Frequency Comb

NIST

Three Options

(1) √ Heuristic derivation

- Physical insight
- Ad hoc
- Numerical factors sometimes obscure
- Implementation:
  - L. Xu, et al. *Opt. Lett.*, vol. 21, 1996, Haverkampf, APB 78, 2004, etc.

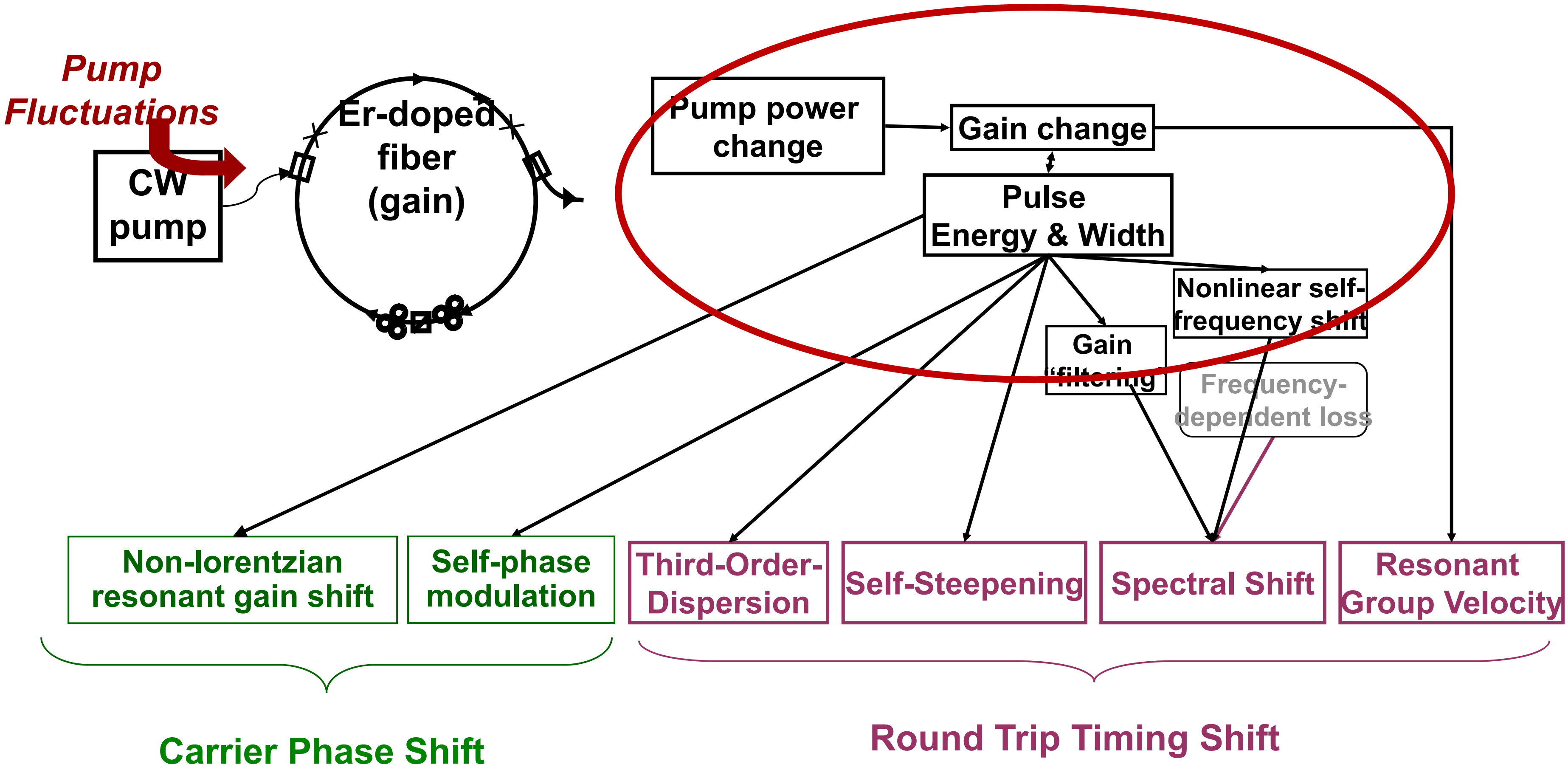
(2) √ Master Equation & Perturbation Theory

- Analytic, self-consistent treatment
- Rigorous bookkeeping
- Requires analytic perturbations (e.g. Lorentzian gain .)
- Master equation is an approximation
- Implementation:
  - Haus and Mecozzi, *JQE.*, vol. 29, 1993.
  - But add chirp, gain dynamics, all perturbations

(3) Numerical integration of Nonlinear Schrödinger Eq.

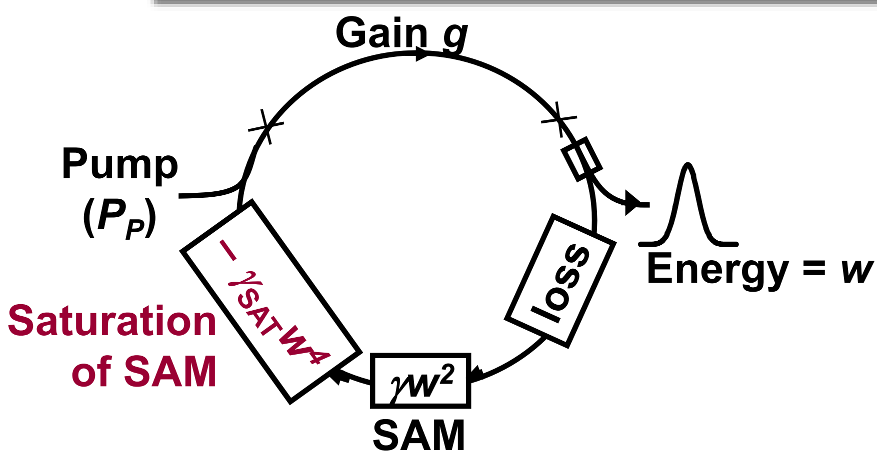
- Full solution of NLSE
- Include all effects
- Significant computation (pulse width vs round trip vs response time)
- Potential loss of physical insight
- Implementation:
  - Paschotta, *Appl. Phys. B*, vol. 79, 2004.

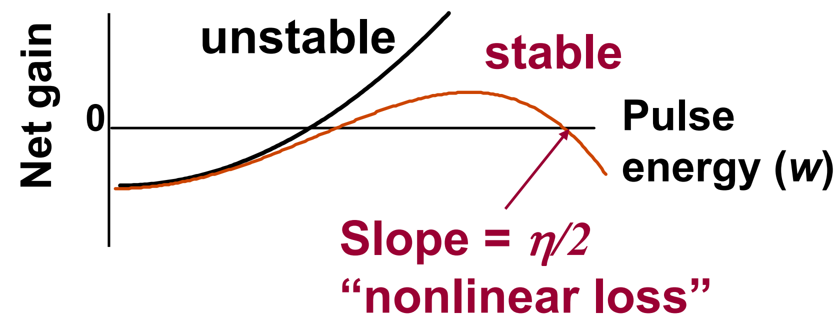
Effect of Pump Power Noise on Comb



N. R. Newbury and B. R. Washburn, JQE, **41**, 1388 (2005)

Response Bandwidth and Laser Stability
(Gain-Pulse Energy Coupling)





Coupled differential equations

***Energy* round trip** $$\partial_T \Delta w = -\frac{1}{T_r}\left[\eta \Delta w - 2\Delta g\, w\right]$$

***Gain* round trip** $$\partial_T \Delta g = -\frac{1}{T_g}\left[\Delta g + g_w \frac{\Delta w}{w} - g_P \frac{\Delta P_P}{P_P}\right]$$

Eigenvalues: Time constants

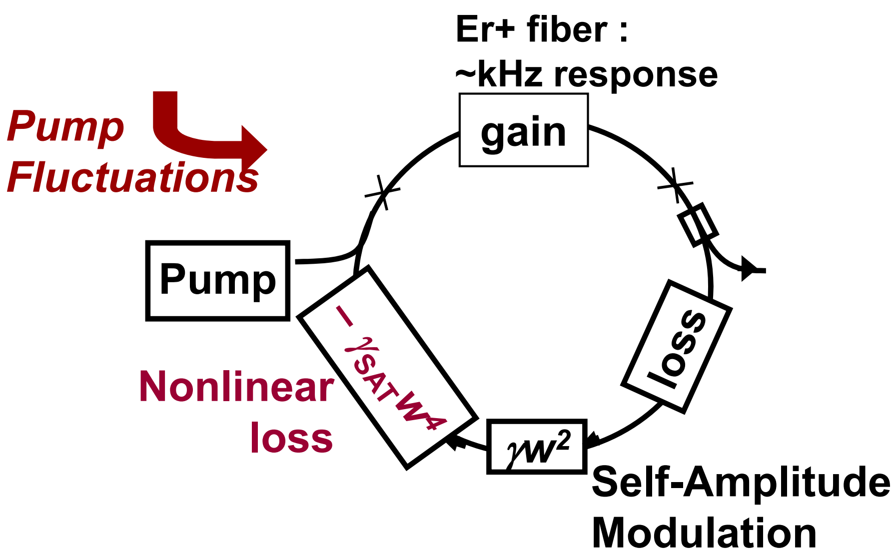
$$\nu_{3dB} = \left(1 + \frac{1}{\eta}\right)\nu_{3dB}^{Erbium}$$

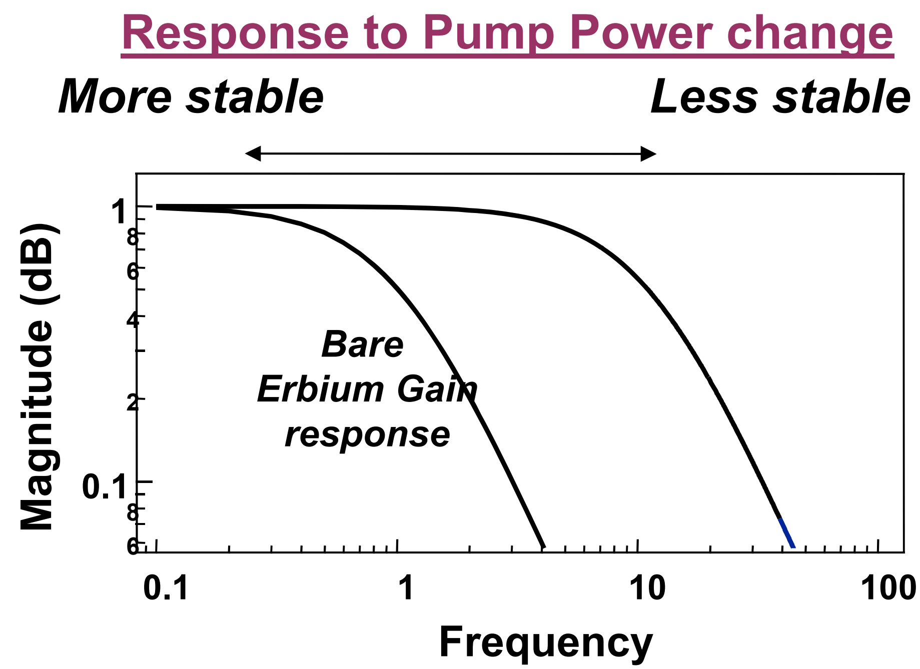
- **System is unstable without extra nonlinear loss**
  - ***Gain saturation too slow to counteract SAM***
- **Parameters support simple exponential decay**
  - **No relaxation oscillations**

(see Namiki et al, APL, 69,3969 (1996))

Dynamics Pump Power Noise on Comb
Responds as a Low-Pass Filter

NIST

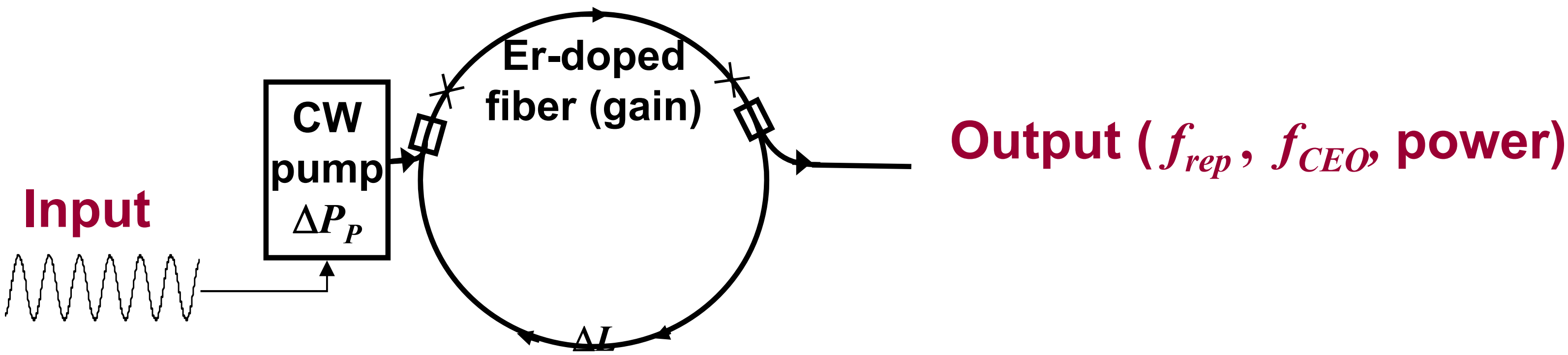


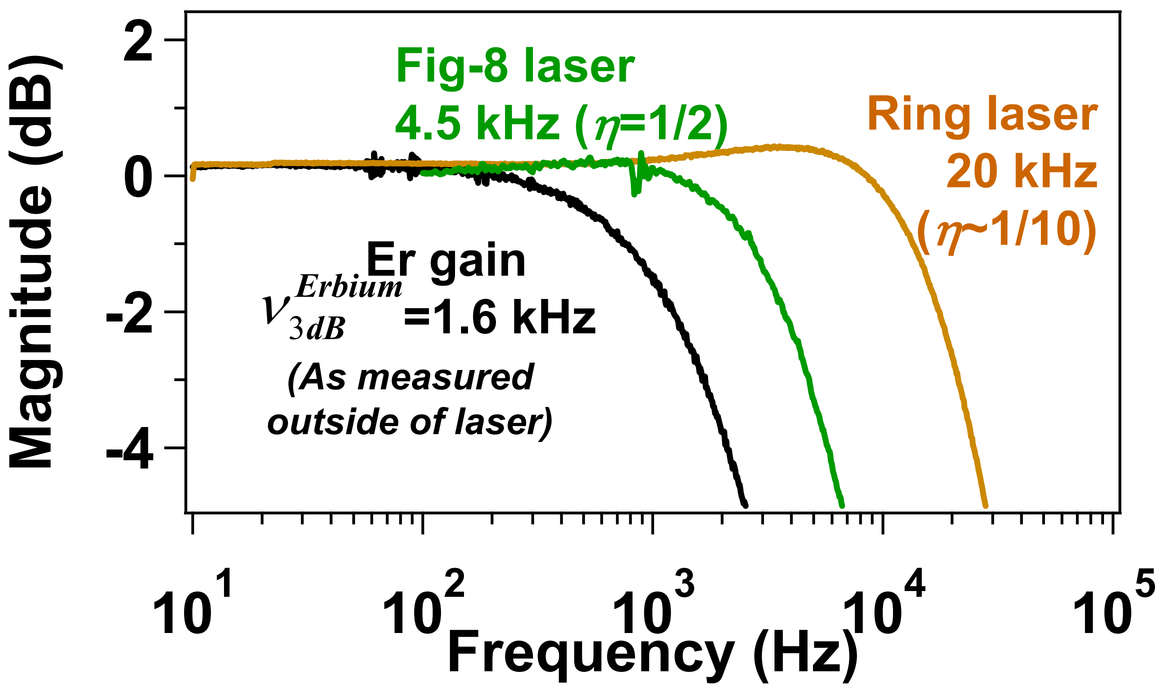


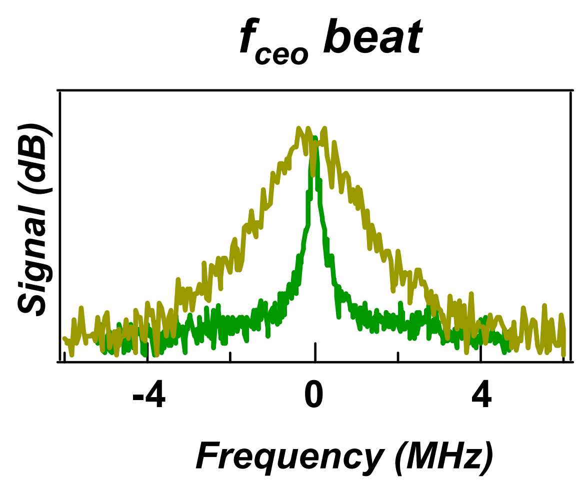
- *Overdamped system -> No Relaxation Oscillations!!*
- *Consequences:*
  - *Finite response to pump fluctuations*
  - *"Slows" laser response to pump power feedback*
  - *But can phase compensate for a simple rolloff with a capacitor!*

Namiki et al, APL, 69,3969 (1996), JOSAB 14, 2099 (1997);
J. McFerran et al, Opt. Lett. **31**, 1997 (2006) & APB, **86**, 219-227 (2007); Newbury and Washburn, JQE, 41, 1388 (2005)

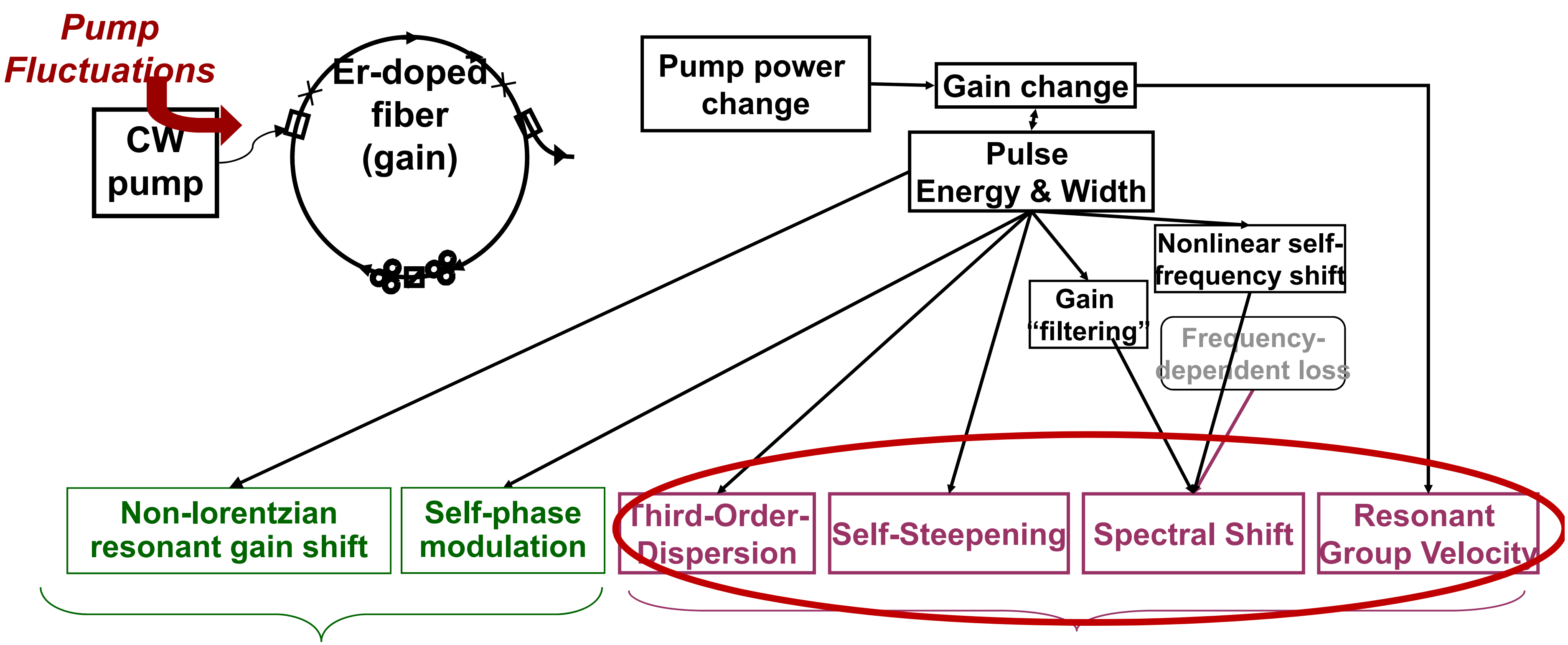
Response Bandwidth: Experiment







Effect of Pump Power Noise on Comb



Carrier Phase Shift

Fixed Point = - Infinity (overall shift of comb)

Round Trip Timing Shift

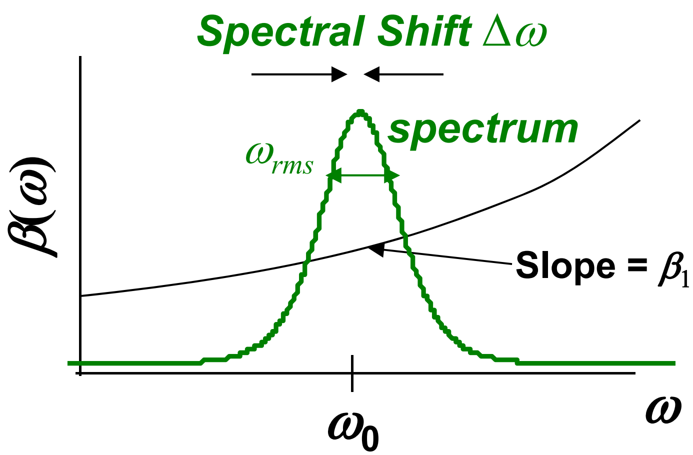
Fixed Point = Carrier Frequency

N. R. Newbury and B. R. Washburn, JQE, **41**, 1388 (2005)

Change in f_{rep}: Theory (Part I)

Spectral Shifts & Third-Order Dispersion Contributions

Effective Group Velocity depends on spectrum center and width

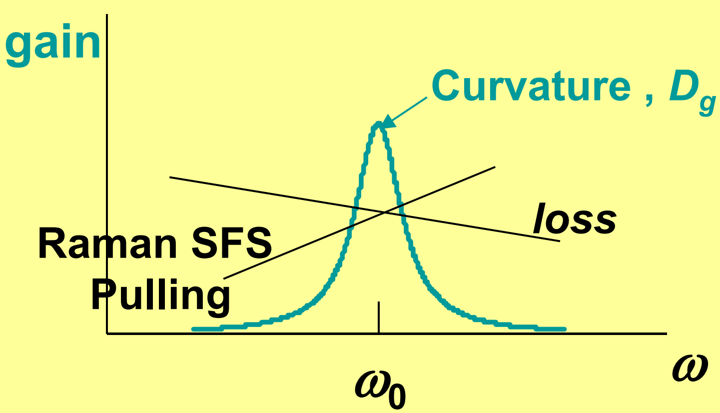


Round Trip Time Shift

$$\Delta T_r = \Delta\omega\beta_2 L + \frac{1}{2}\omega_{rms}^2\beta_3 L$$

Spectral Shifts ***Third-order dispersion***

Cause of Spectral Shifts :



1.) Gain pulls frequency toward gain peak

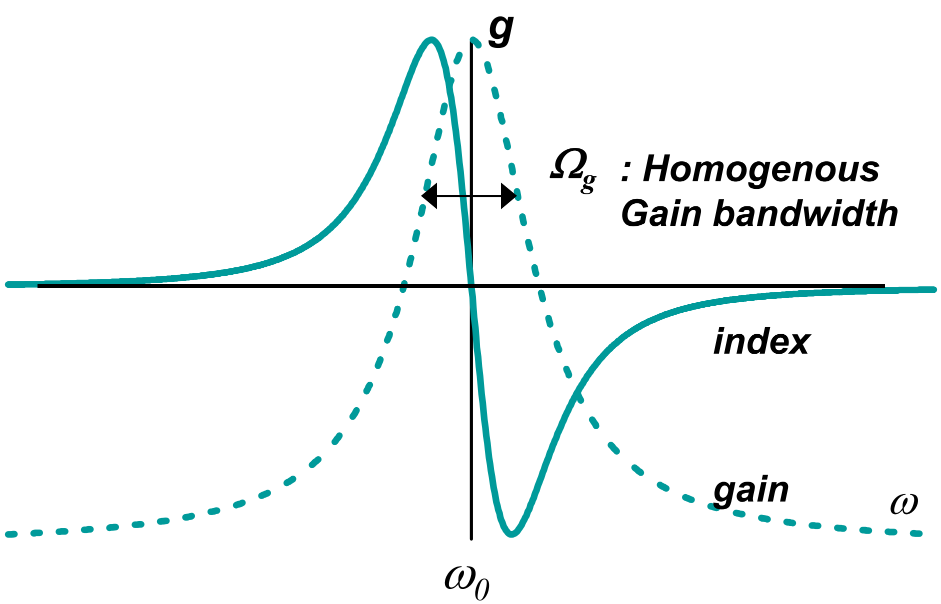
2.) Loss pushes frequency up or down

3.) Raman SFS pushes frequency down

$$\Delta\omega = \frac{-1}{2D_g}\left(l_{\omega,NL} + l_\omega\right)$$

Changes in f_{rep}: Theory (Part II) Resonant Gain Contribution

NIST

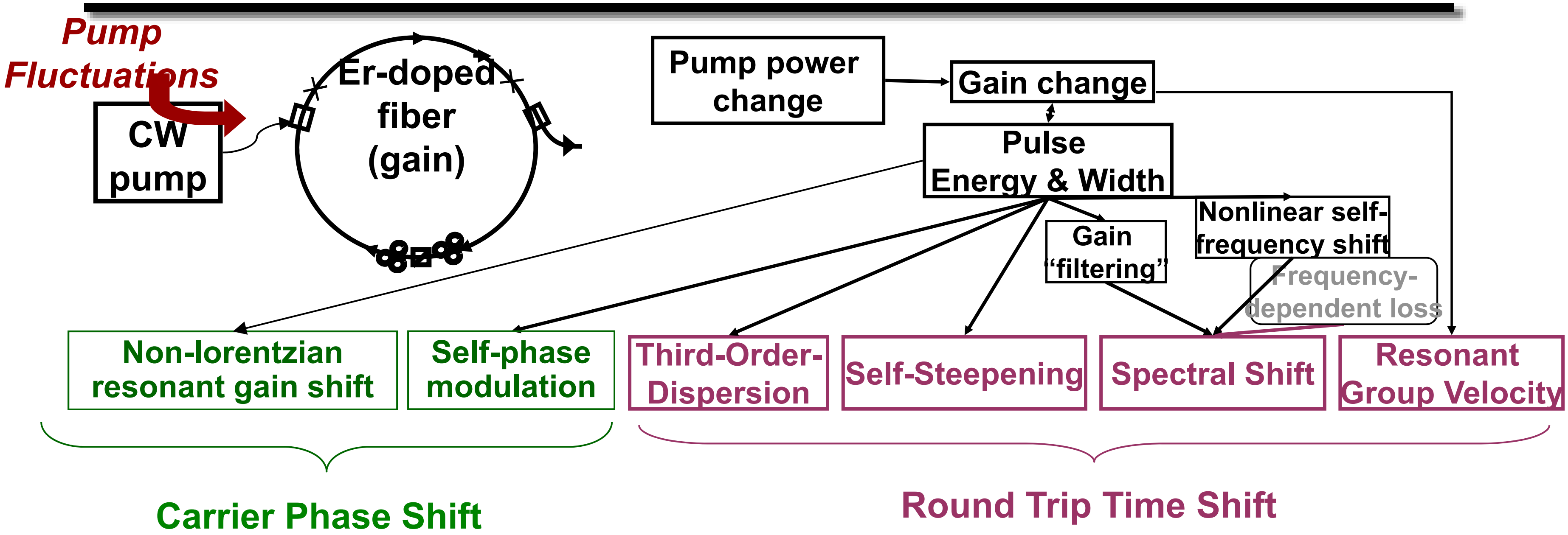


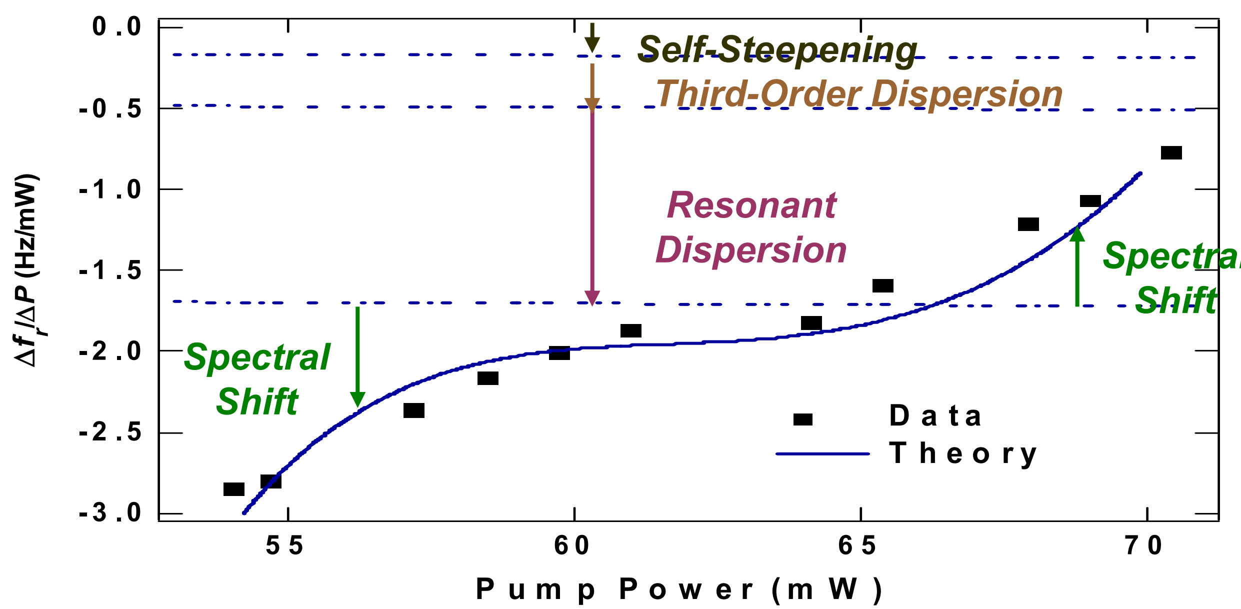
Round Trip Time Shift $\Delta T_r = \frac{\Delta g L}{\Omega_g} +$

Resonant gain dispersion

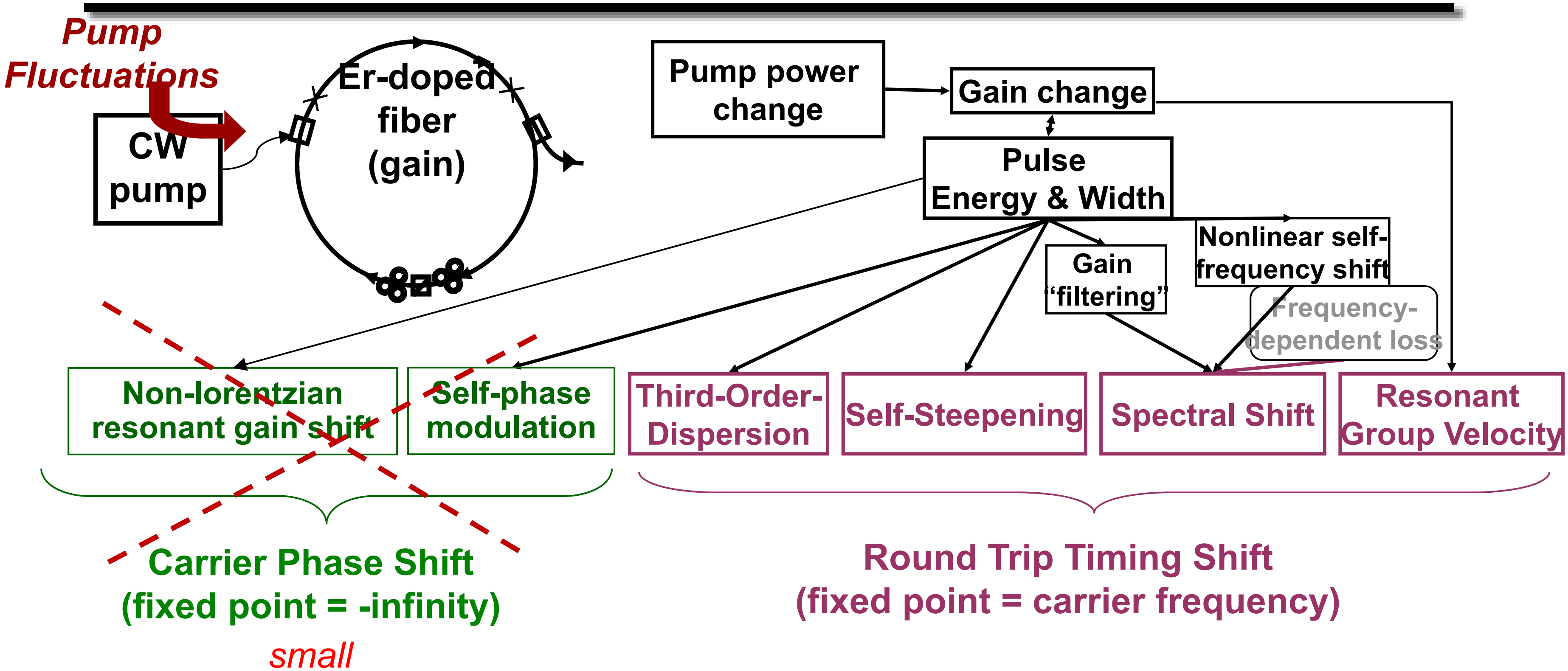
- **Group index of the Er gain fiber depends on the Er gain inversion**
- **For Lorentzian gain with gain bandwidth 5 nm, maximum shift:**
  - **10 ppm or 500 Hz out of 50 MHz rep. rate**

Effect of Pump Power Noise on Comb Summary





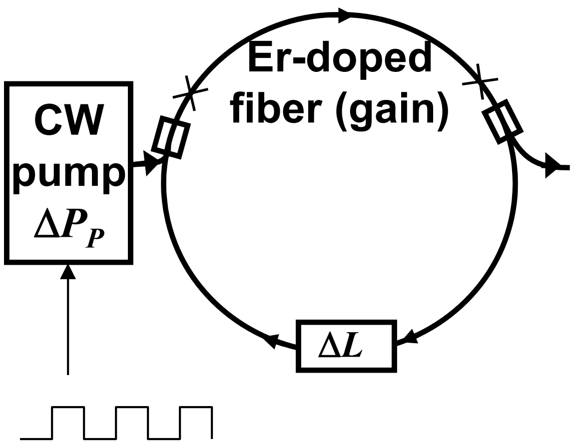
Effect of Pump Power Noise on Comb Summary

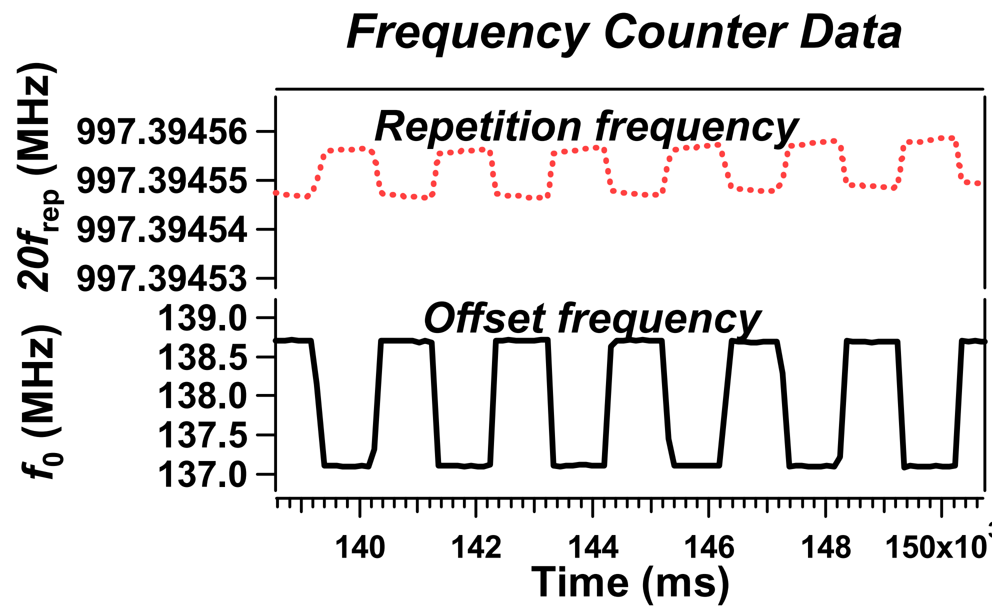


Usually **timing shift dominates**

Experimental Data for Comb Response to Pump Power

Not hard to measure the fixed point
Stimulate comb & measure response!





$$f_{fix} = 0 = n_{fix}\delta f_{rep} + \delta f_0$$

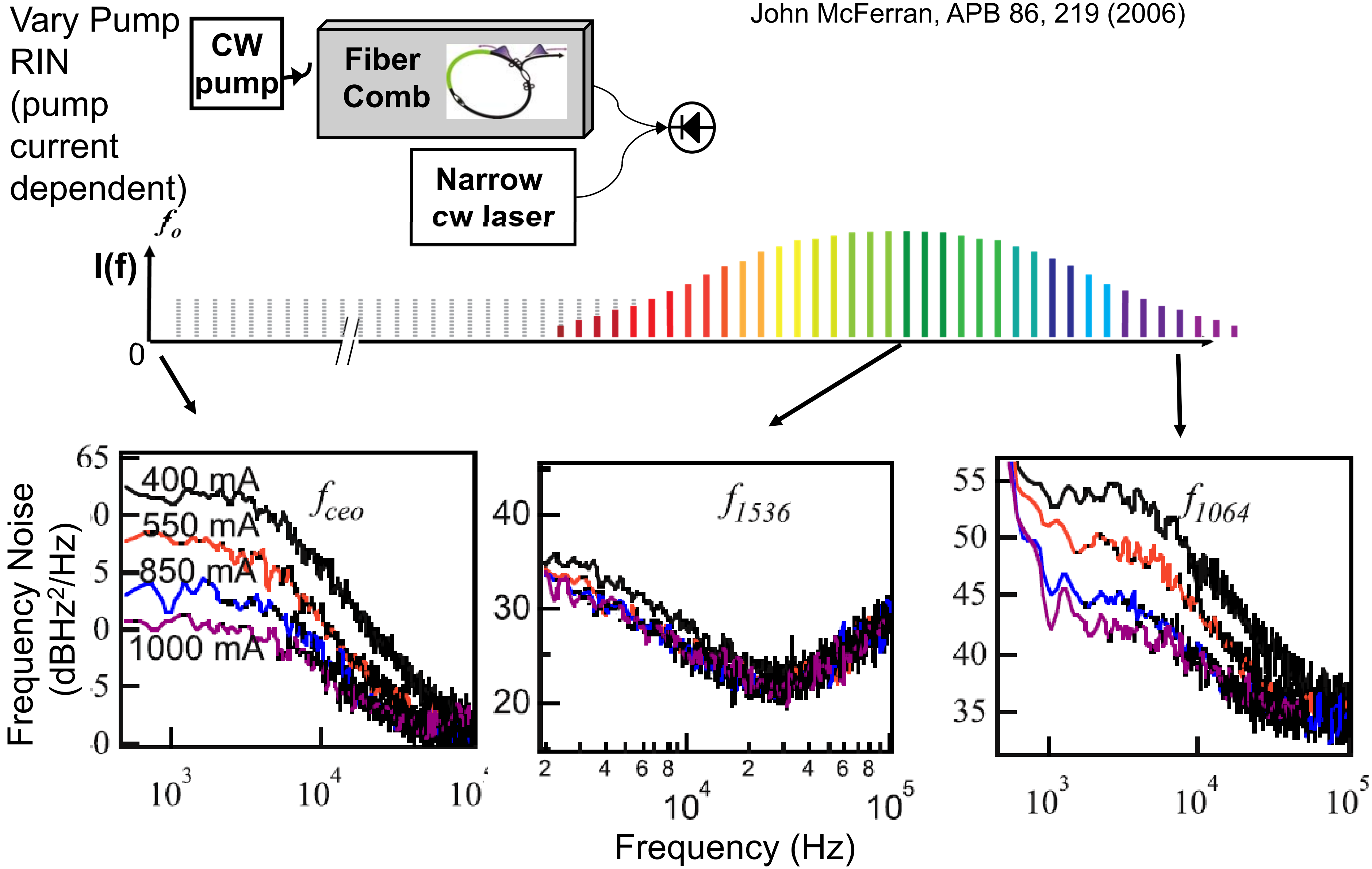
$$n_{fix} = -\frac{\delta f_0}{\delta f_{rep}}$$

Here fixed point = 150 THz fixed point

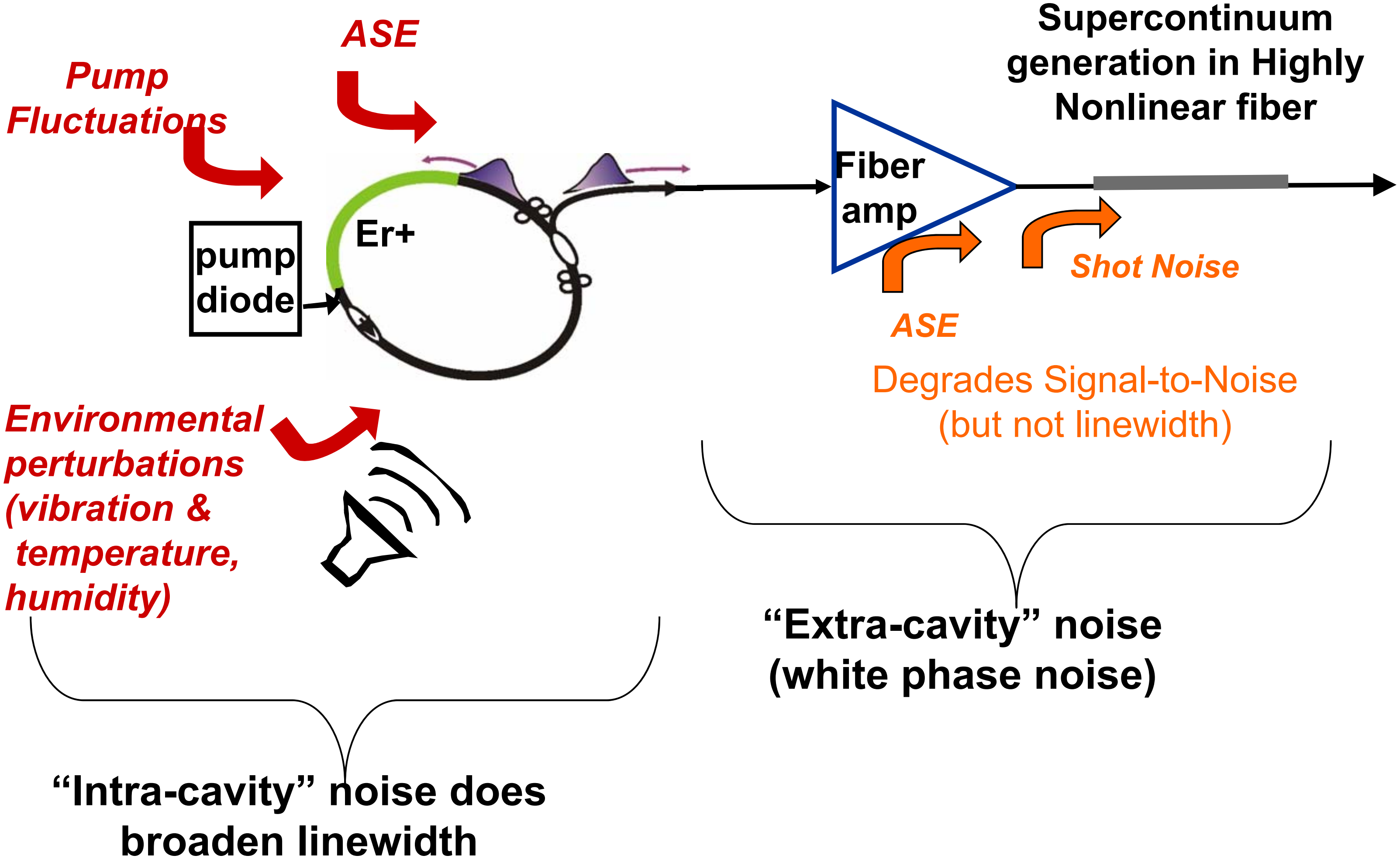
Frequency Noise PSDs vs Pump Noise

John McFerran, APB 86, 219 (2006)

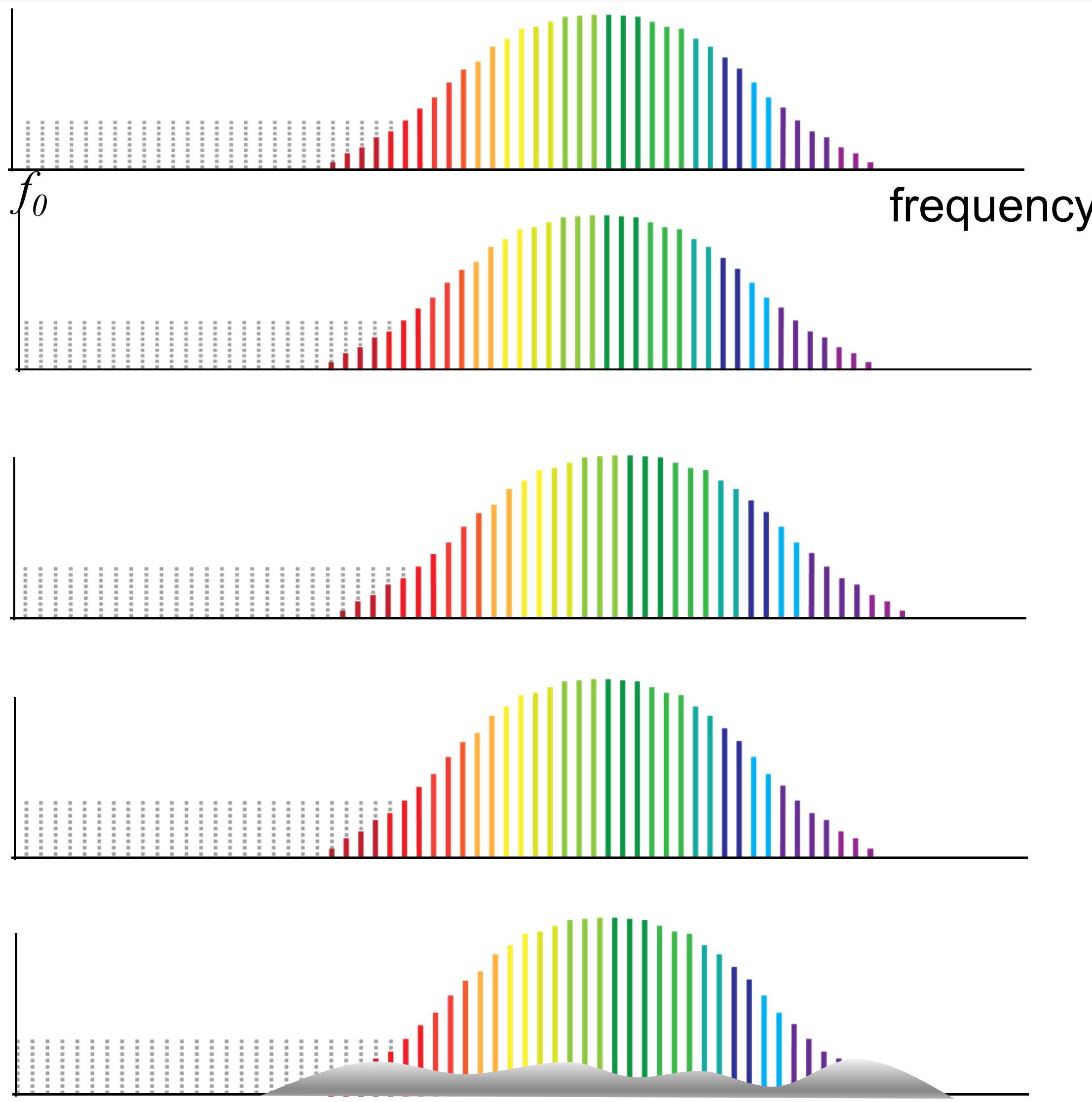
Vary Pump RIN (pump current dependent)



Noise Sources



Effect of Different Noise Source on Frequency Comb



Ideal Output

Environmental Effects PSD ~ 1/f

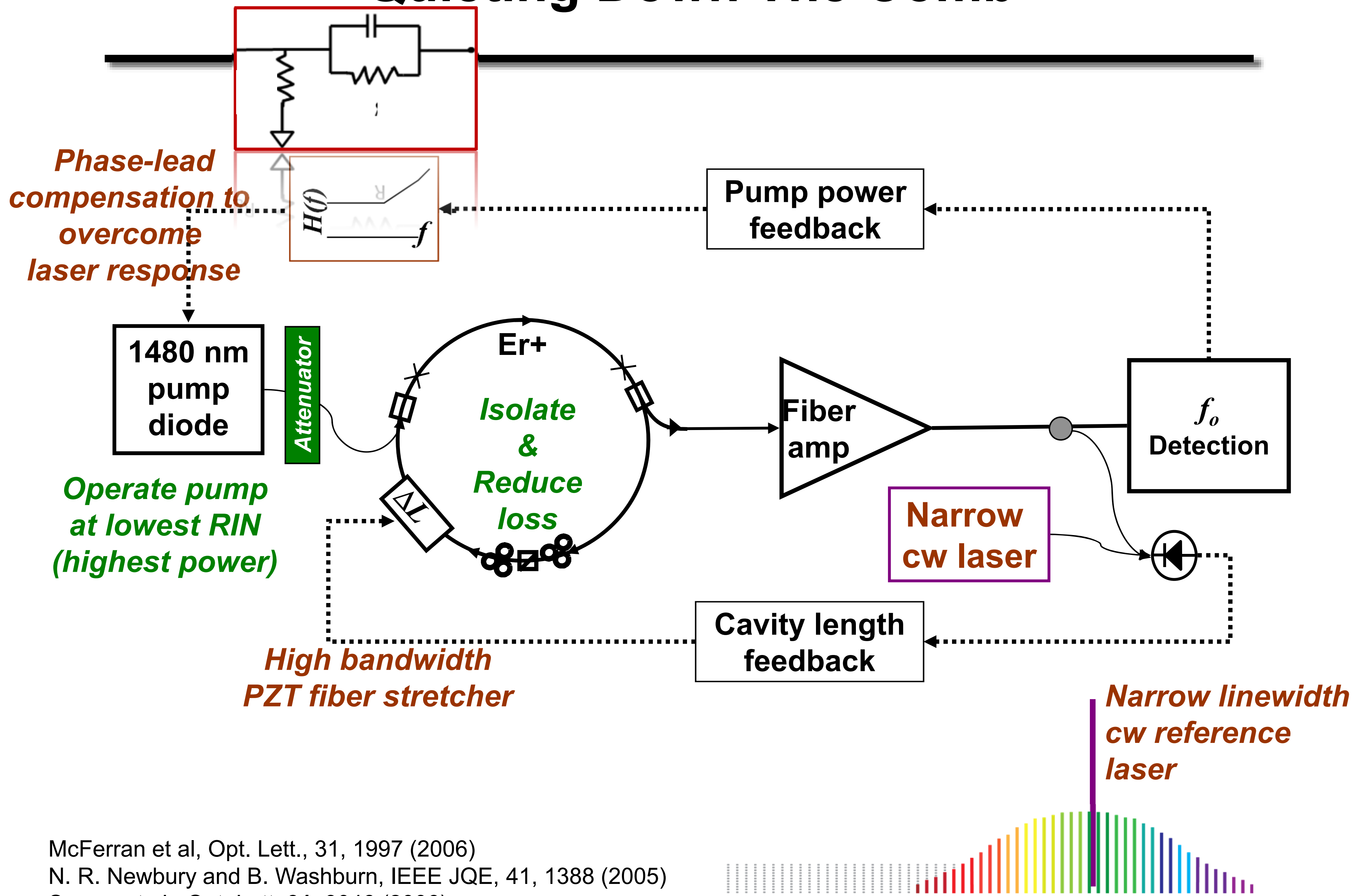
Pump Noise PSD ~ low pass filter

ASE-induced Quantum Noise PSD ~ white noise

“Extra-cavity noise” (ASE, shot noise)

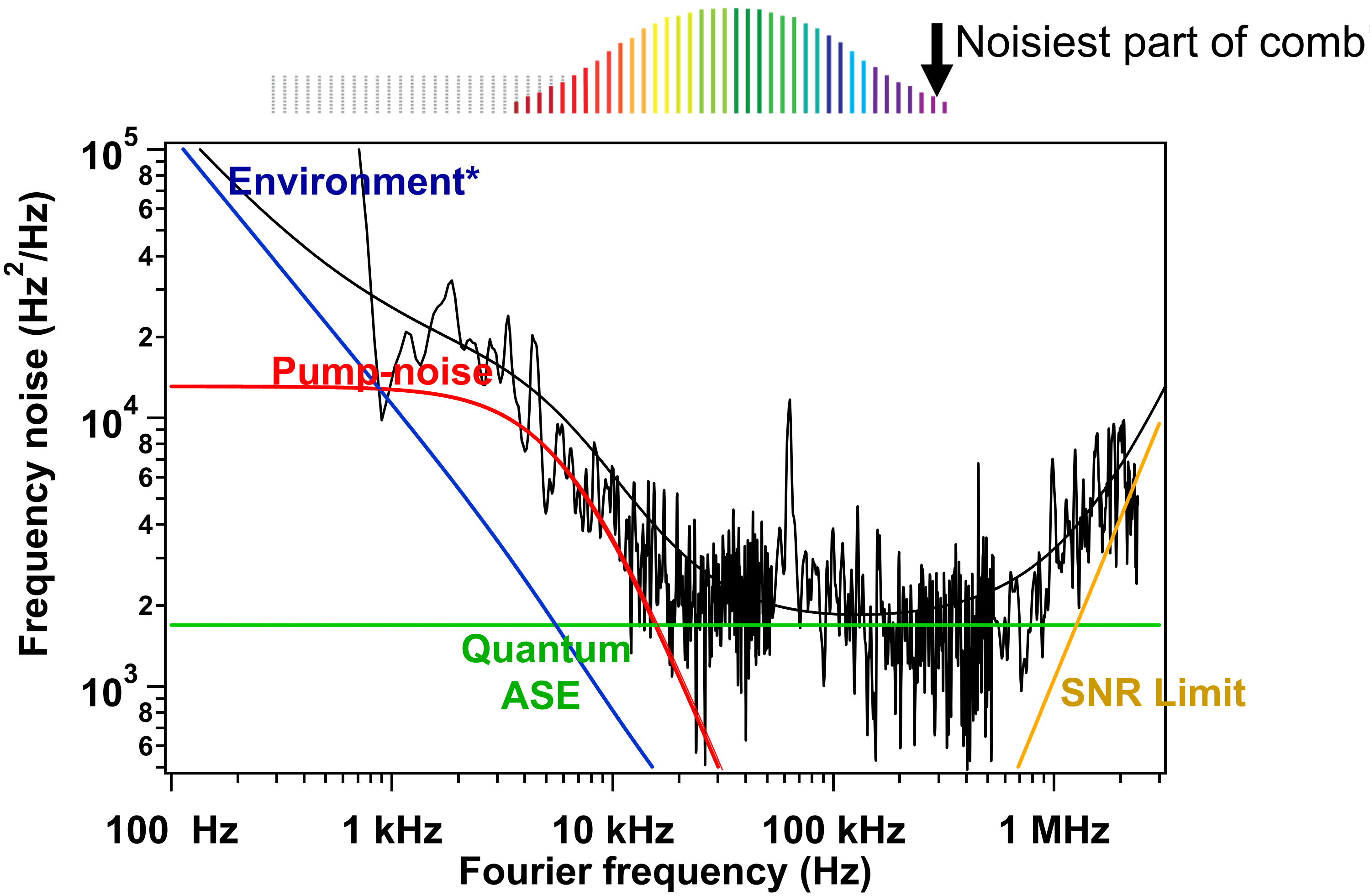
N. Newbury & W. Swann, JOSA B, 8, 1756-1770 (2007); fixed point: H. R. Telle, B. Lipphart, and J. Stenger, APB, 74, 1 (2002)

Quieting Down The Comb



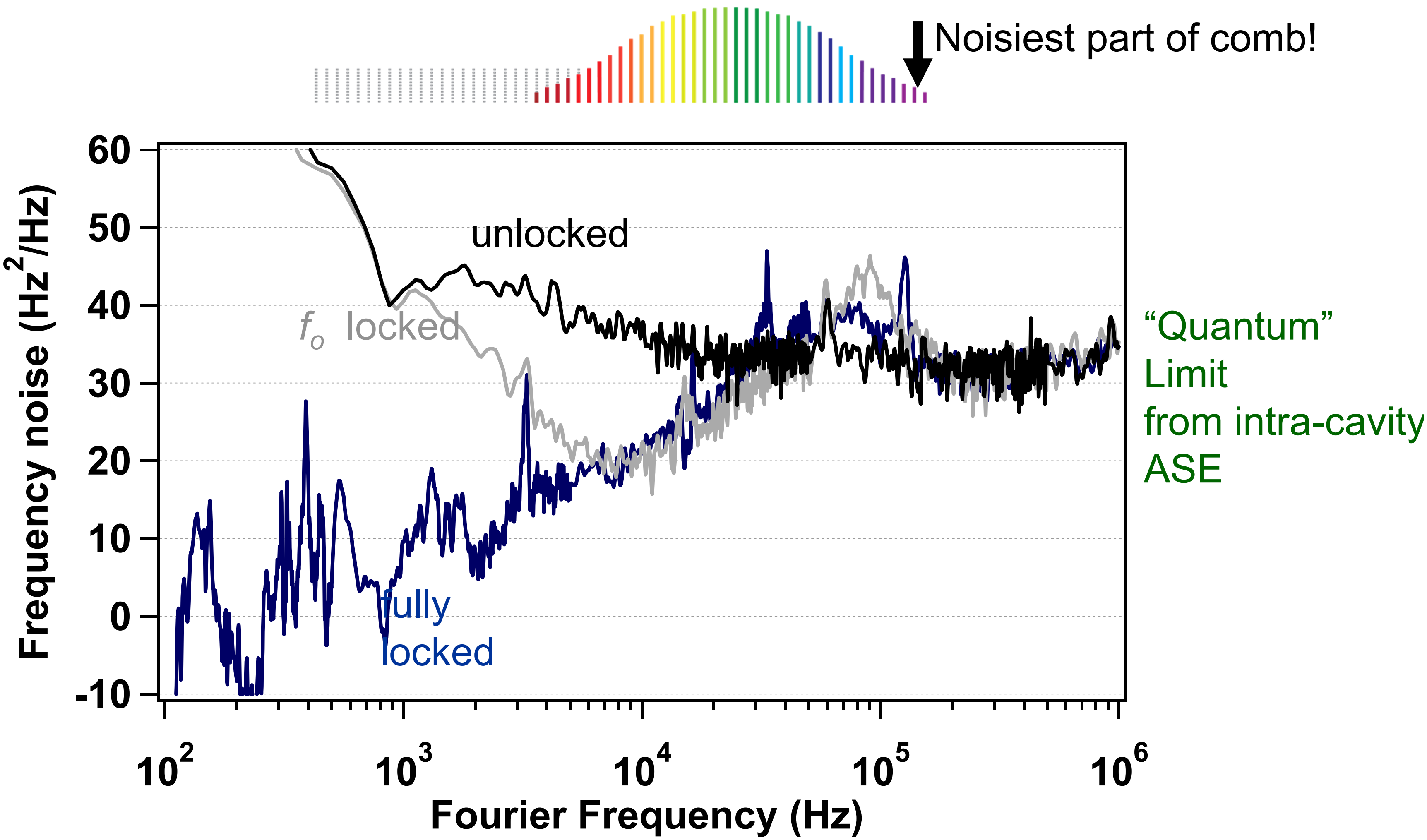
McFerran et al, Opt. Lett., 31, 1997 (2006)
N. R. Newbury and B. Washburn, IEEE JQE, 41, 1388 (2005)
Swann et al., Opt. Lett. **31**, 3046 (2006).

Free-running Frequency Noise at 1 μm (far edge of comb)



(Corresponding Linewidth is ~ 10's of kHz)

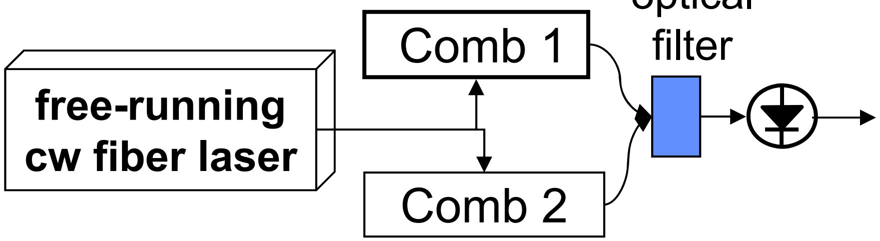
Phase-Locked Frequency Noise at 1 μm (far edge of comb)

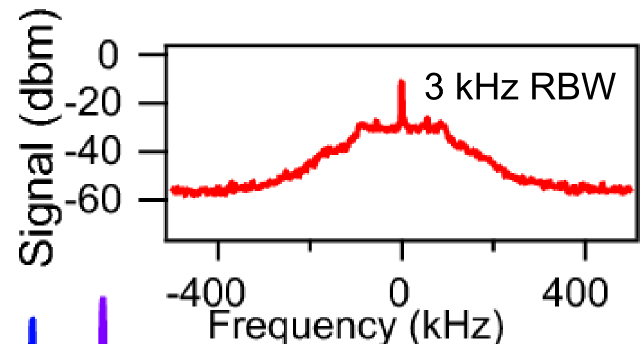


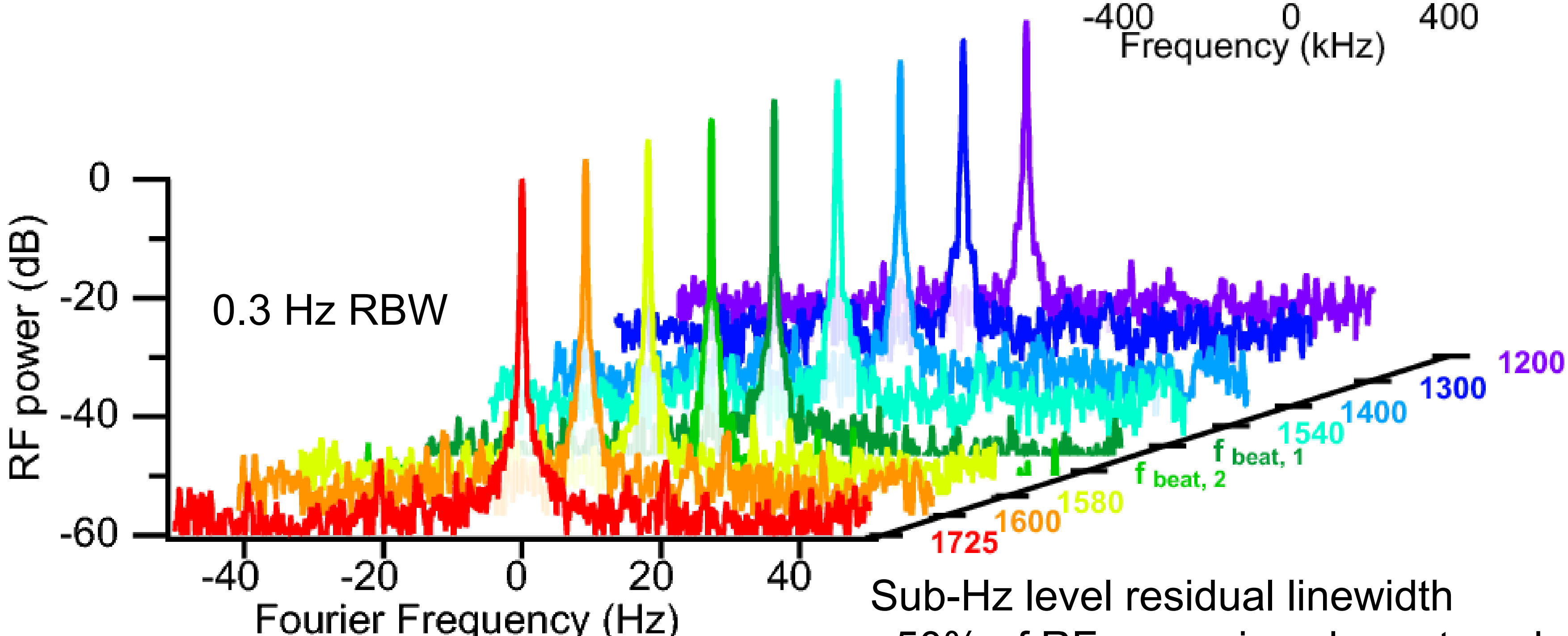
Unlocked phase noise ~ 200 radians
Locked phase noise ~ 0.6 radians

Optical Coherence Between Combs with IMRA America

Swann, I Hartl, M. Fermann, Opt. Lett. **31**, 3046 (2006).







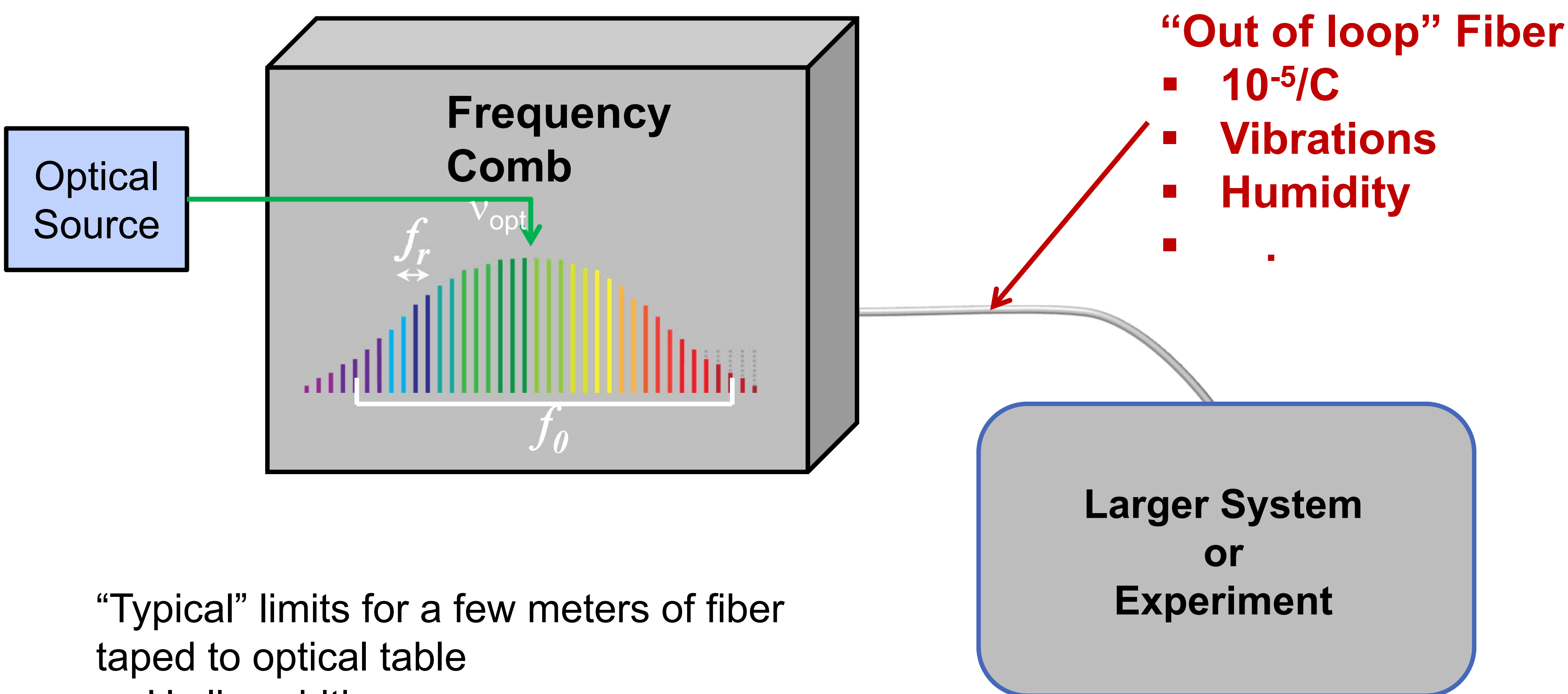
Sub-Hz level residual linewidth
~50% of RF power in coherent peak

Prescription for using a stabilized Frequency Comb

1. Measure the offset frequency
    - Hard to do - requires octave spanning continuum
2. Detect either an optical beat or high harmonic of the repetition rate (optical vs rf stabilization)
3. Understand and minimize noise
    - Check fixed point of pump power modulation if low dispersion cavity!
4. “Feedback” to actively cancel leftover noise
    - High bandwidth feedback
    - Two or more actuators (or signal processing on comb)
5. Design the rest of the experiment to not re-introduce noise we just cancelled
    - Minimize out-of-loop paths.

Limits to Comb Performance

For frequency stability or linewidth:
Limit is set by “out of loop fiber/free-space” and not comb



“Typical” limits for a few meters of fiber taped to optical table

- Hz linewidths
- ~10^{-16} stability @ 1 second

A Few General Rules of Thumb for Frequency combs

- Comb has no intrinsic accuracy -> needs an external reference
- "Flat" supercontinuum not achievable
  - Challenge for spectroscopy
  - Sometimes solved with multiple supercontinuum branches
- Hard to detect offset frequency (f_{ceo}) with enough SNR!
  - f-2f requires octave spanning continuum
  - 2f-3f requires less bandwidths but more power
- The "Fixed Point" picture is the best way to analyze the noise and the stabilization….
- Coherent narrow linewidth comb requires careful design & high bandwidth feedback.
- Frequency stability (Allan deviation) depends on more experiment than the comb
  - "Out-of-Loop" paths almost always dominate frequency stability