Combing Through Space:
Precision Optical Frequencies for Astronomy

D. Braje, M. Kirchner, T. Fortier and S. Diddams
National Institute of Standards and Technology, Boulder Colorado

S. Osterman and C. Froning
Center for Astrophysics and Space Astronomy
University of Colorado, Boulder, Colorado

A. Bartels and D. Heinecke
Center for Applied Photonics
University of Konstanz, Konstanz Germany

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$$ from NIST, Univ of Colorado, and DARPA

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Precision spectroscopy has been a critical tool for discovery in both the **quantum** and the **cosmos**

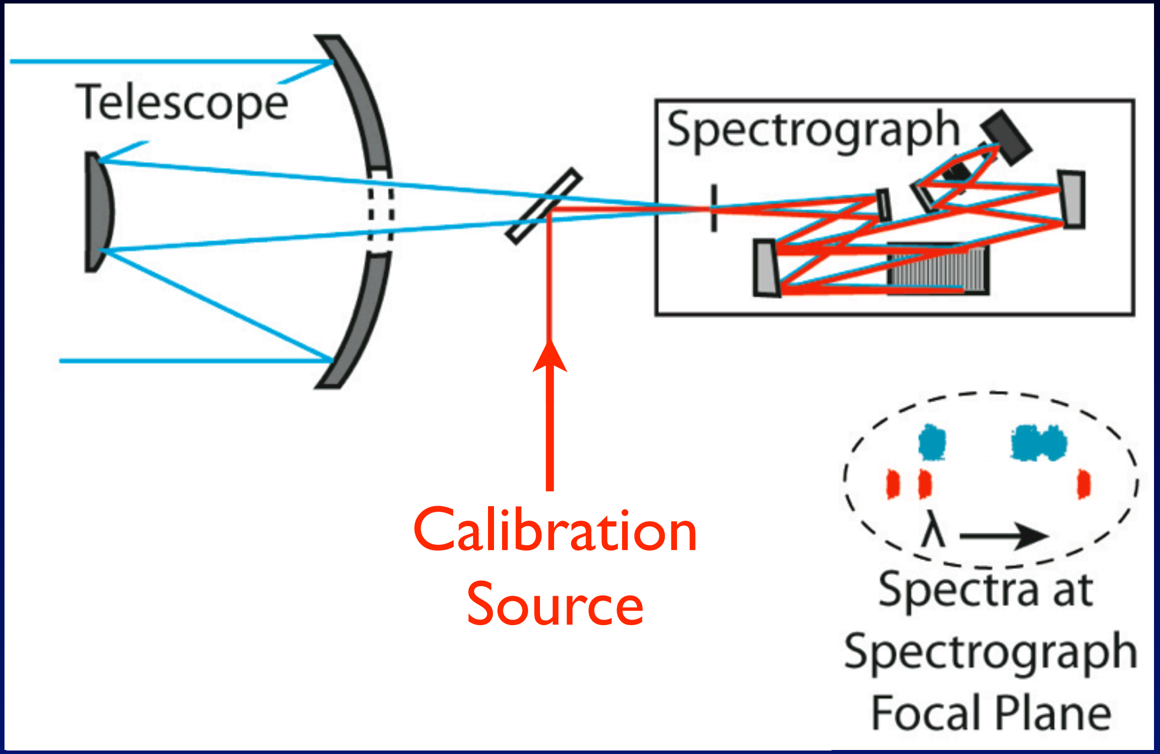
Applications of precision spectroscopy in observational astronomy...

- 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

Challenges of High-Tech "Classical" Spectroscopy



Present Centroiding: 10^{-3}

Goal: improve to 10^{-5} !!

➡ Extreme demands on mechanical and optical system design

➡ Requires a better calibration source (10^{-11})

Current Calibration Technology: Discharge Lamps and Absorption Cells

Advantage: Simplicity, mature technology

Disadvantages: limited throughput, limited spectral range and density, uncertainty in line shape and identification, variable line intensity, aging.....

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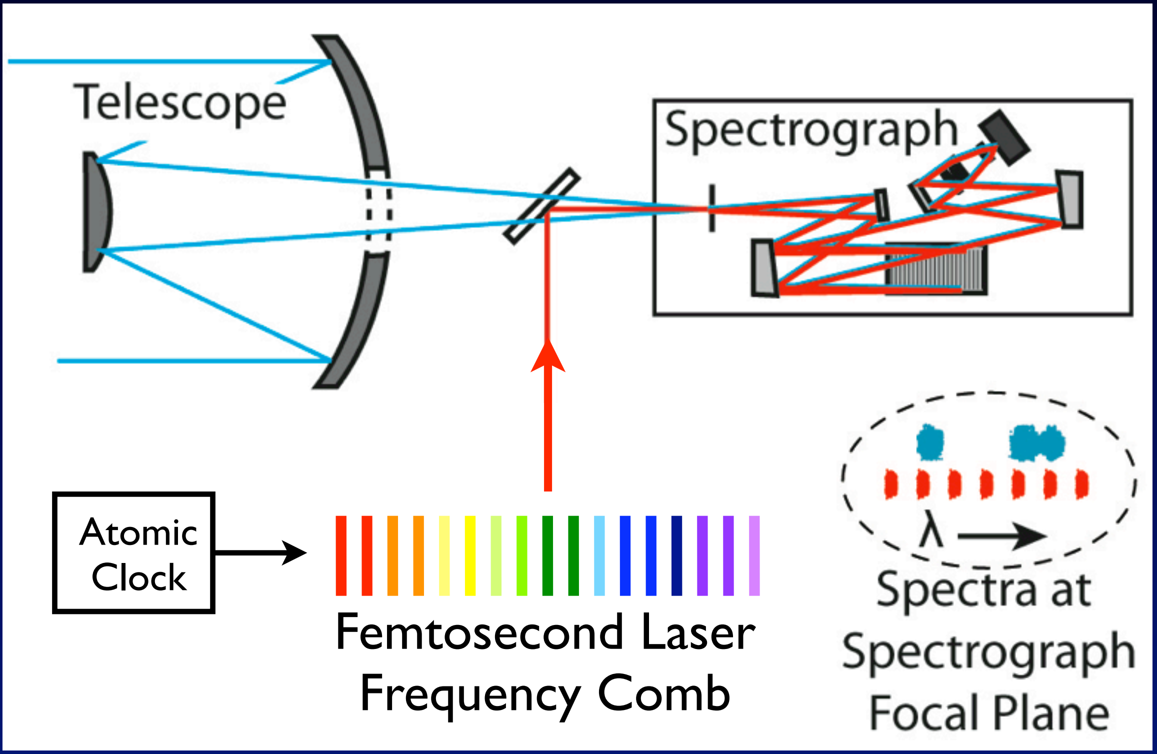
Frequency Combs for Spectrograph Calibration



➡ Uniform grid of frequencies tied to atomic standards (stable over decades)

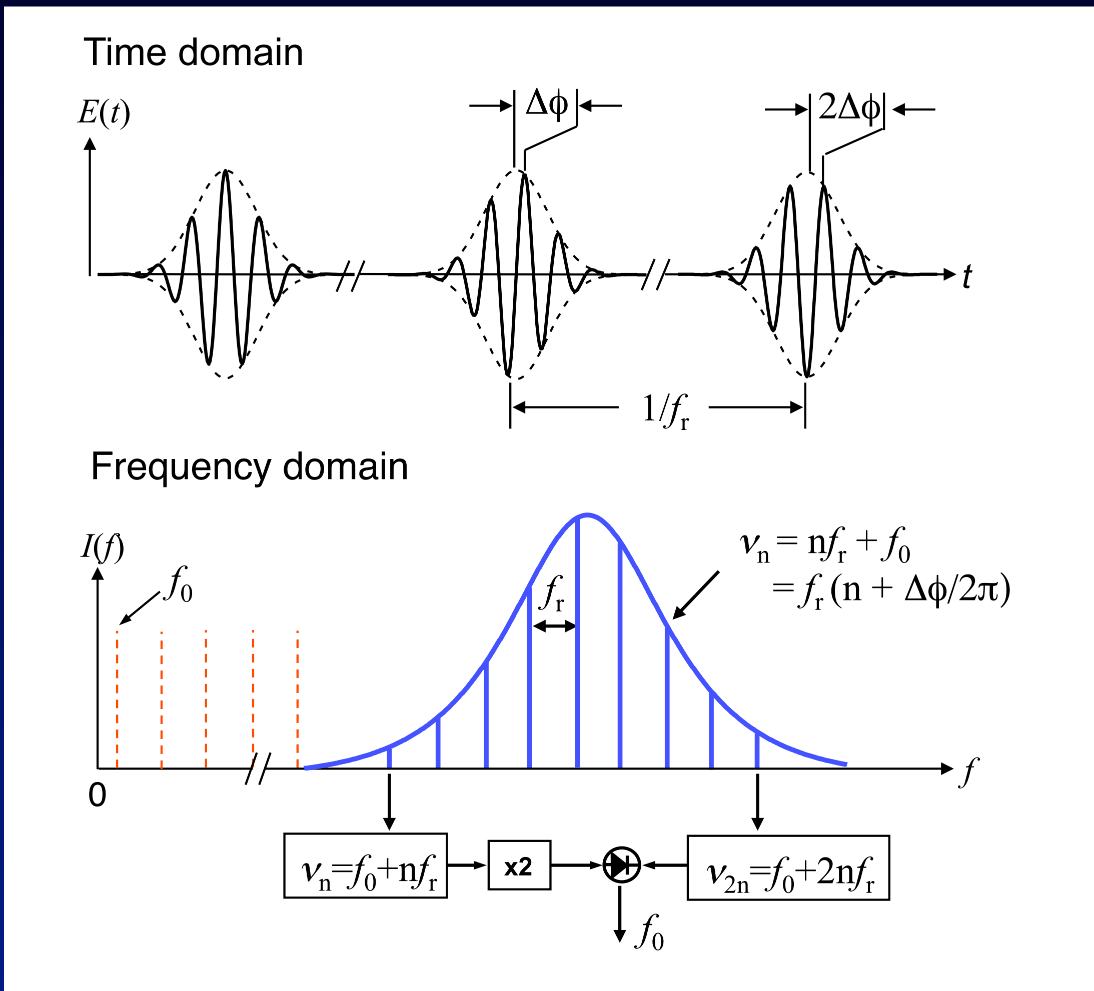
➡ Absolute uncertainty down to ~4×10^{-17} (limited by atomic reference)

➡ Broad spectral coverage (400-2000 nm)

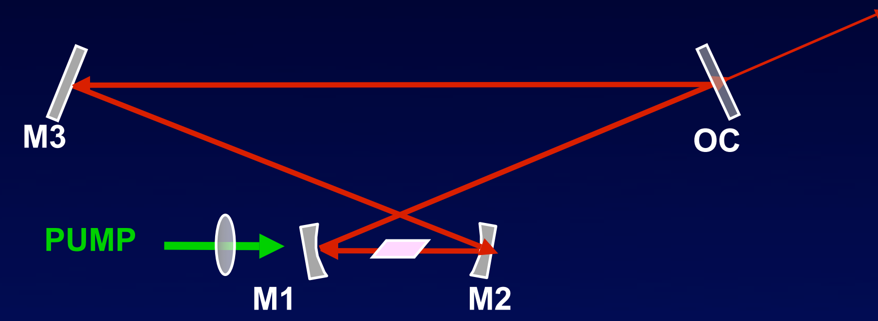
➡ Power per mode in excess of 1 nW

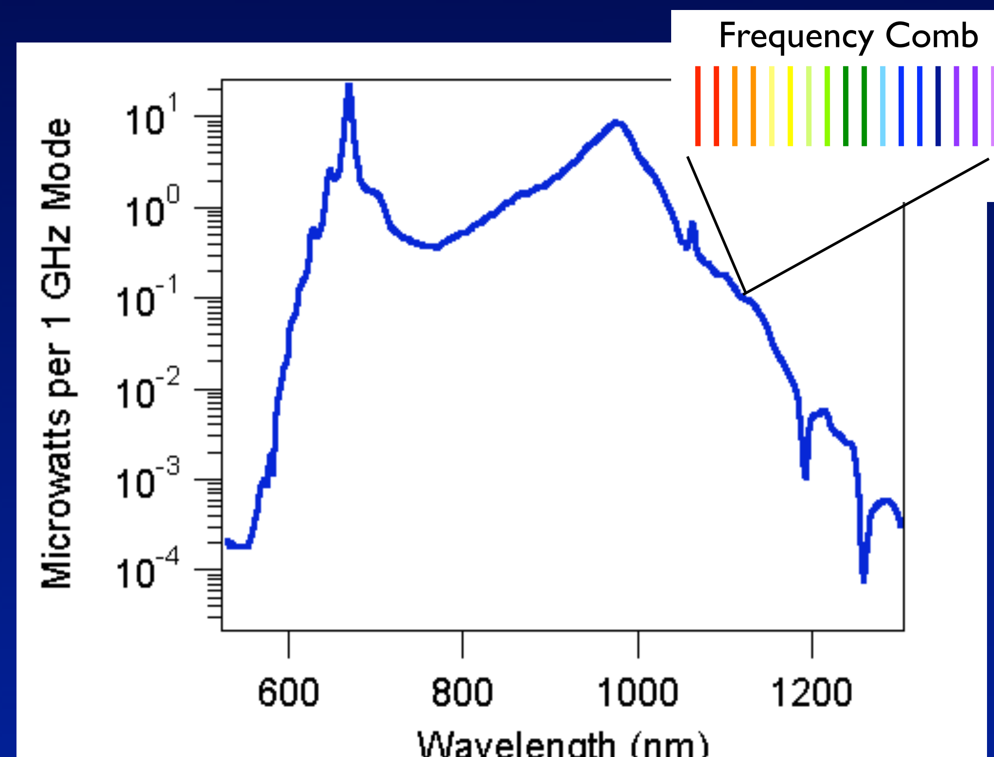
M. Murphy et al., Mon. Not. Roy. Astr. Soc. **380**, 839 (2007)
P.O. Schmidt, et al., arXiv:0705.0763 v1 (2007)
S. Osterman, et al. Proc. SPIE **6693**, pp. 66931 (2007)
C.H. Li, et. al., Nature **452**, 610 (2008)
D. Braje, et al., Eur. Phys. Journ. D **48** 57 (2008)

Femtosecond Laser Frequency Combs



A. Bartels, H Kurz, *Opt. Lett.* 27, 1839 (2002)
T. Fortier, A. Bartels, S. Diddams, *Opt. Lett.* 31, 1011 (2006)





Stabilized Comb = 10^6 Modes
⇒ with Hz-level linewidths
⇒ residual frequency noise at
1×10^{-19} level

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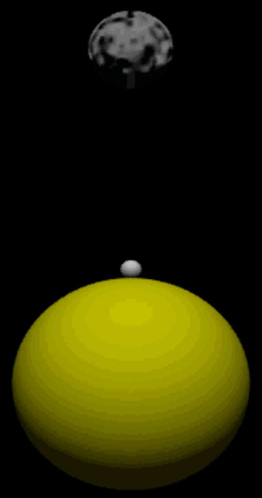
Requirements for Spectrograph Calibration

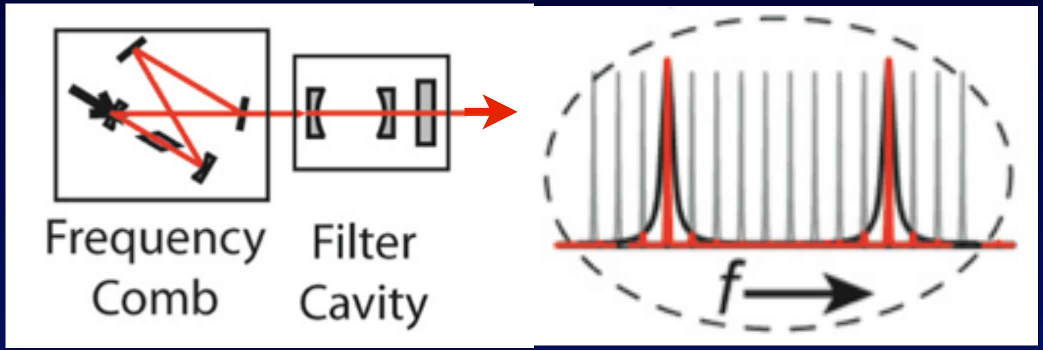


Desired Parameters

- ➡ Mode Spacing: 10-50 GHz
- ➡ Coverage: 300-1100 nm (or 1000-2000 nm)
- ➡ Power: 10^{-15} W/mode (ideally flat spectrum)
- ➡ 10^{-11} accuracy over years

Approaches to High Rep Rate Combs

1. Cavity Filtering



D. Braje, et al., Eur. Phys. Journ. D **48** 57 (2008)
C.H. Li, et. al., Nature 452, 610 (2008)

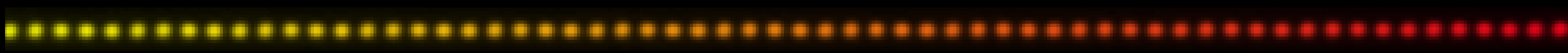
- 10-15% fractional bandwidth with single cavity
- Multiple cavities likely required
- Need 25-50 dB side mode suppression
- Residual side modes can lead to asymmetry

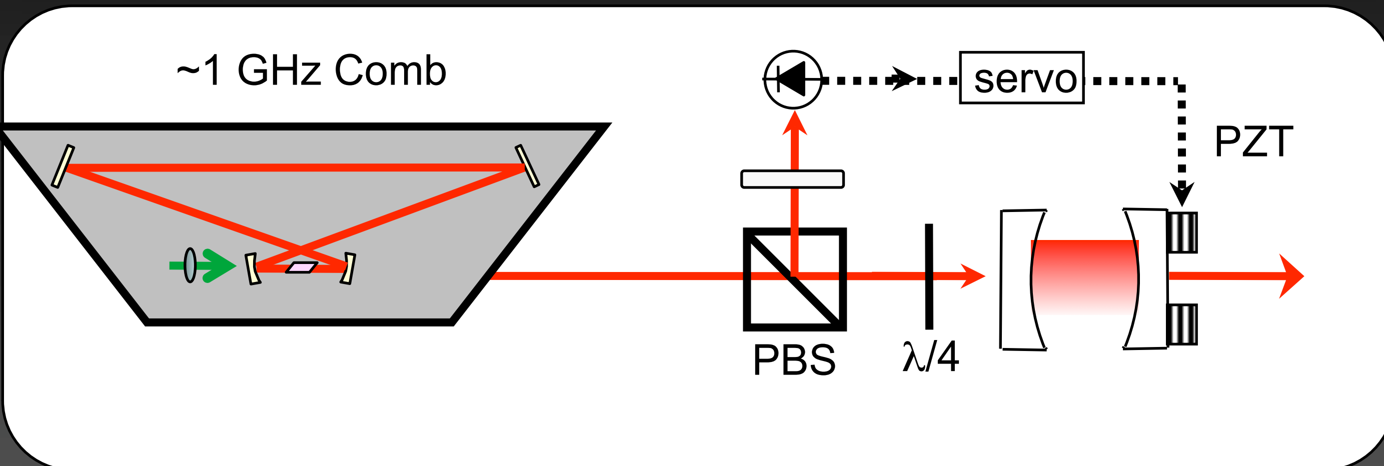
2. Direct Generation

Mode-locked lasers >100 GHz, but .....

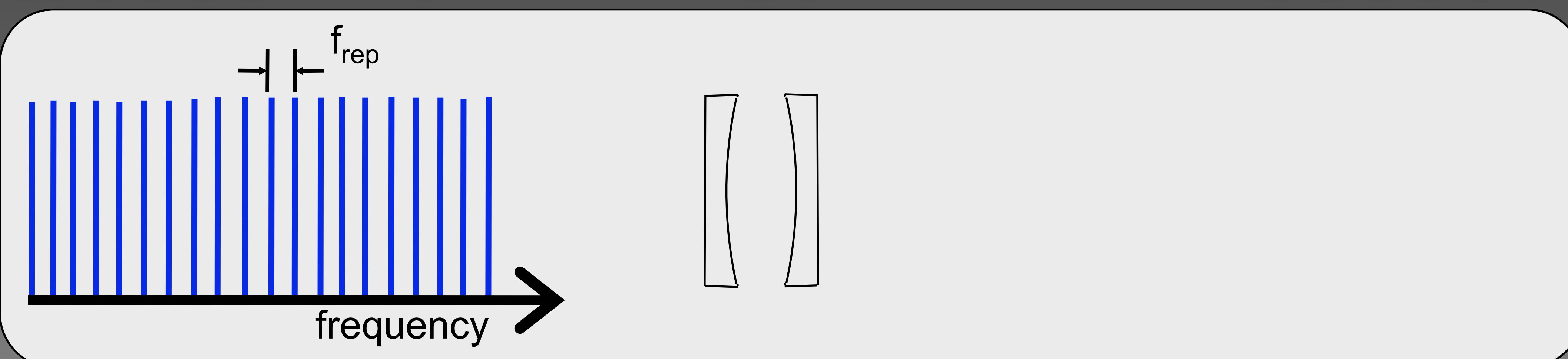
- typically picosecond pulses with low energies
- difficult to make low noise, broad bandwidth combs

Cavity-filtered comb





$$\frac{E_{out}(\omega)}{E_{in}(\omega)} = \frac{1 - R(\omega)}{1 - R(\omega)e^{i[2n(\omega)\omega L/c + 2\phi_R]}}$$



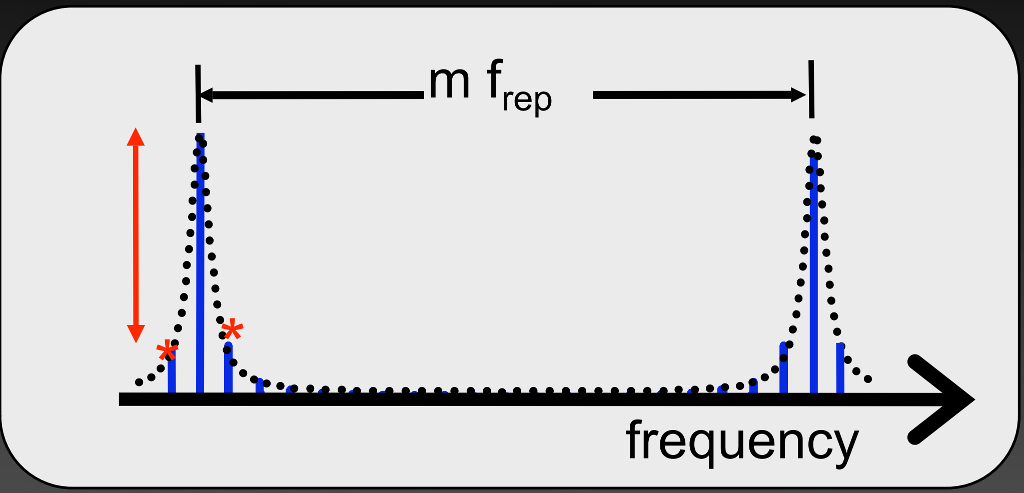
$$FSR \approx \frac{c}{2nL}$$

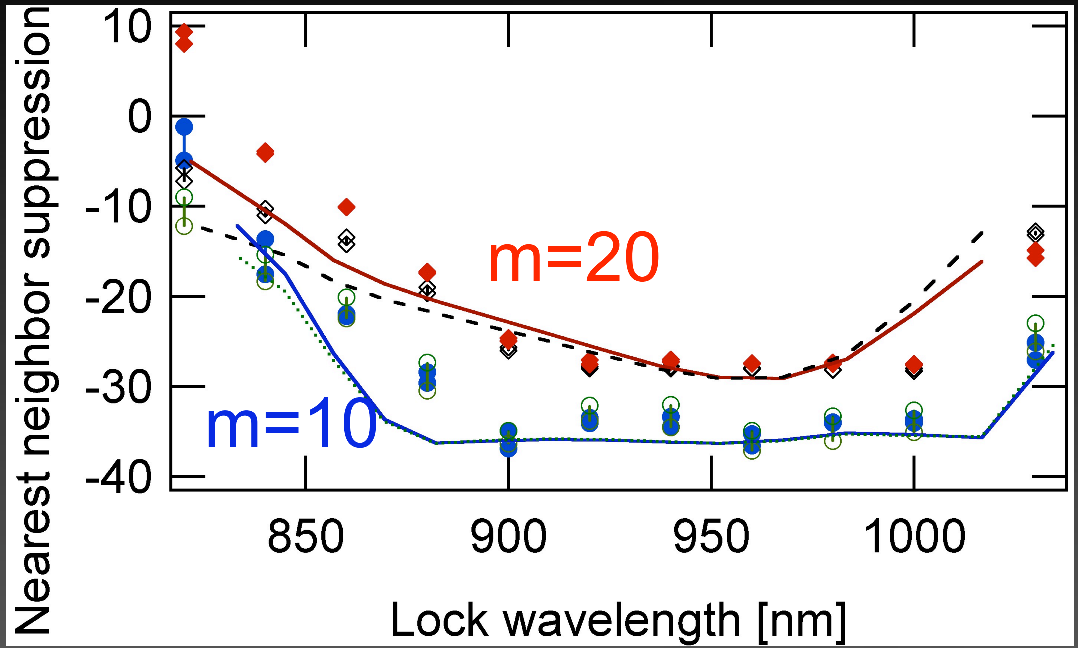
$$\nu_{FW} \approx \frac{c}{2\pi nL}(1 - R)/\sqrt{R}$$

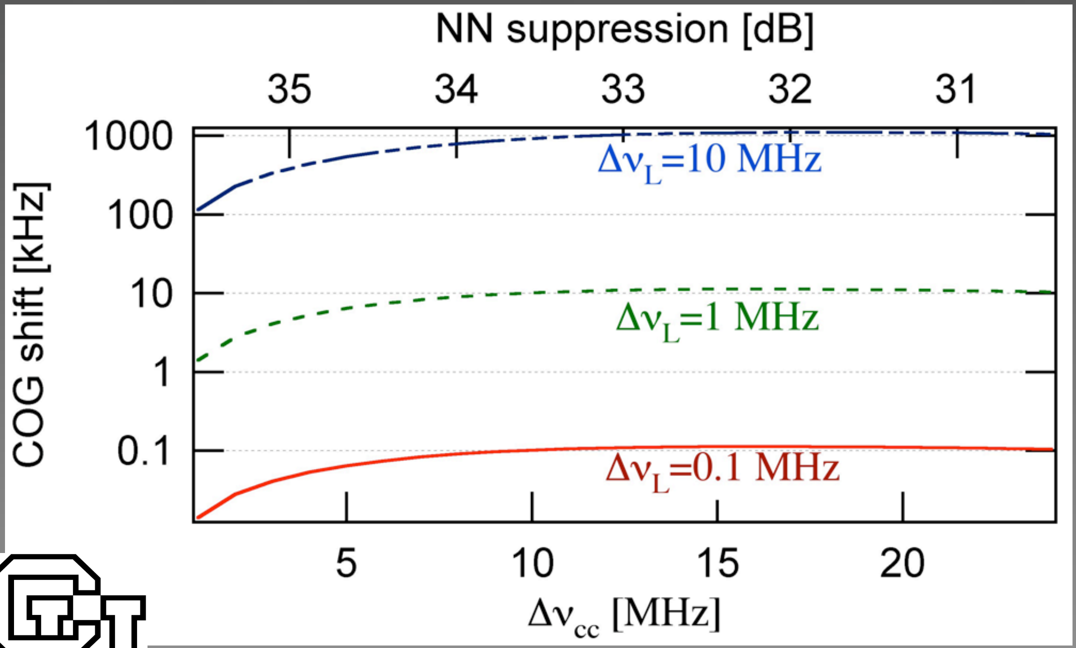
Th. Udem, et al., *Phys. Rev. Lett.* **82**, 3568 (1999)
D. Braje, et al., *Eur. Phys. Journ. D* **48**, 57 (2008)

Side mode suppression + comb linewidth

D. Braje, et al., *Eur. Phys. Journ. D* **48,** 57 (2008)







Unsuppressed side modes

+

Asymmetric suppression

+

Excessive comb linewidth

Can lead to biases >> 10 kHz

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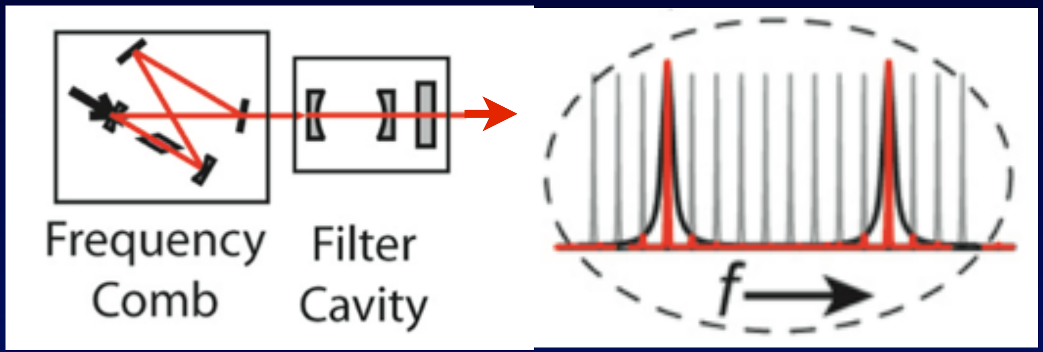

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C.H. Li, et. al., Nature 452, 610 (2008)

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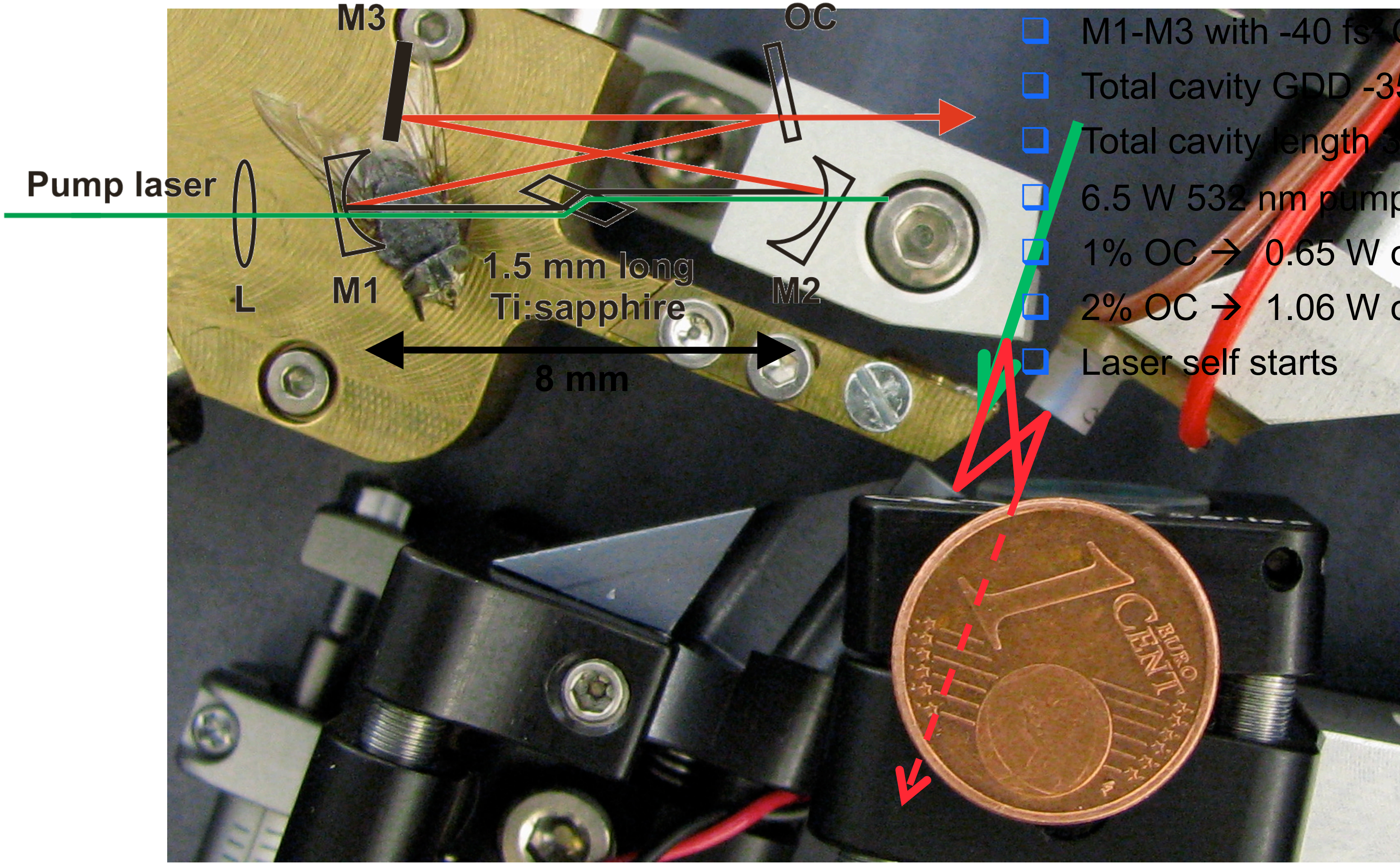
10 GHz femtosecond Ti:sapphire ring laser

A. Bartels, Univ. Konstanz and GigaOptics



- M1-M3 with $-40\ fs^2$ GDD
- Total cavity GDD $-35\ fs^2$
- Total cavity length 30 mm
- 6.5 W 532 nm pump power
- 1% OC → 0.65 W output
- 2% OC → 1.06 W output
- Laser self starts

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GIGAOPTICS femtosecond technologies

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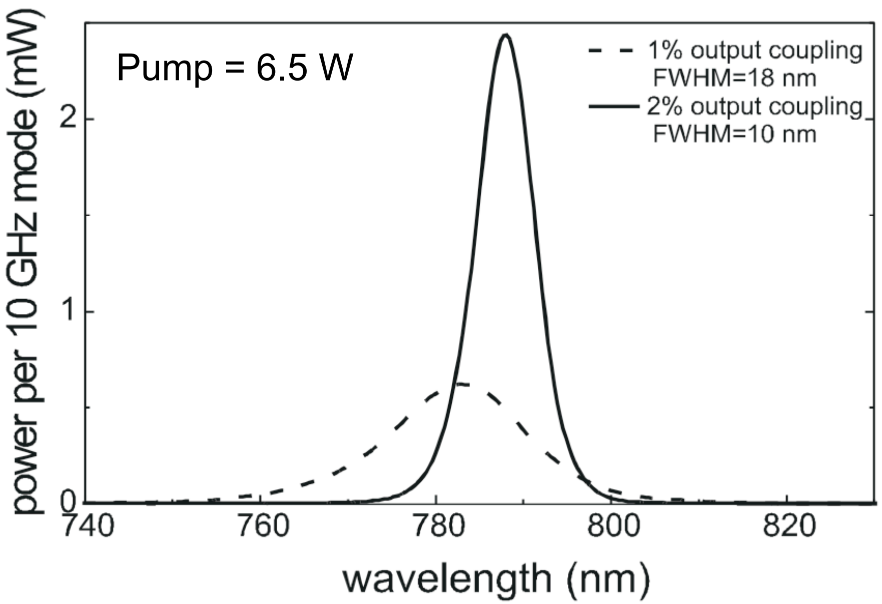
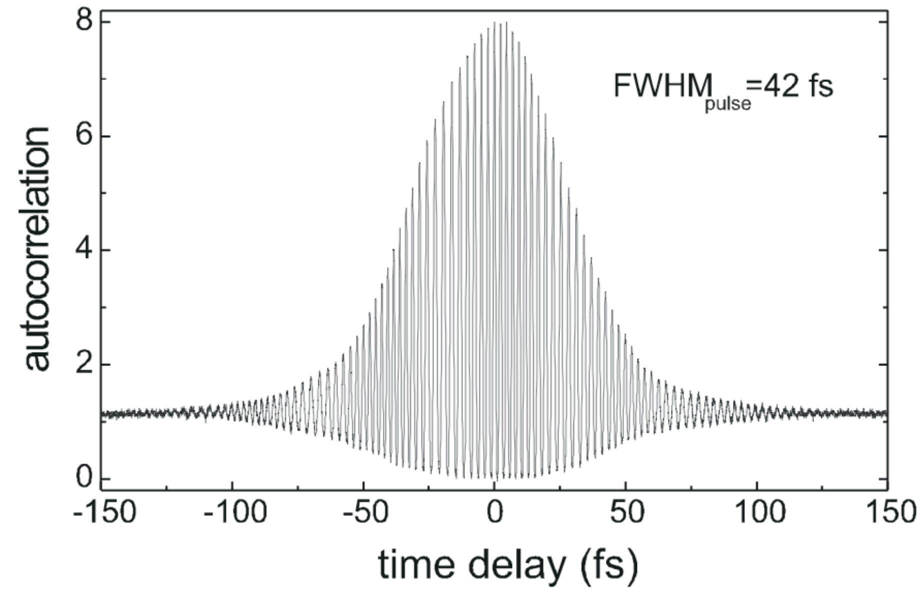
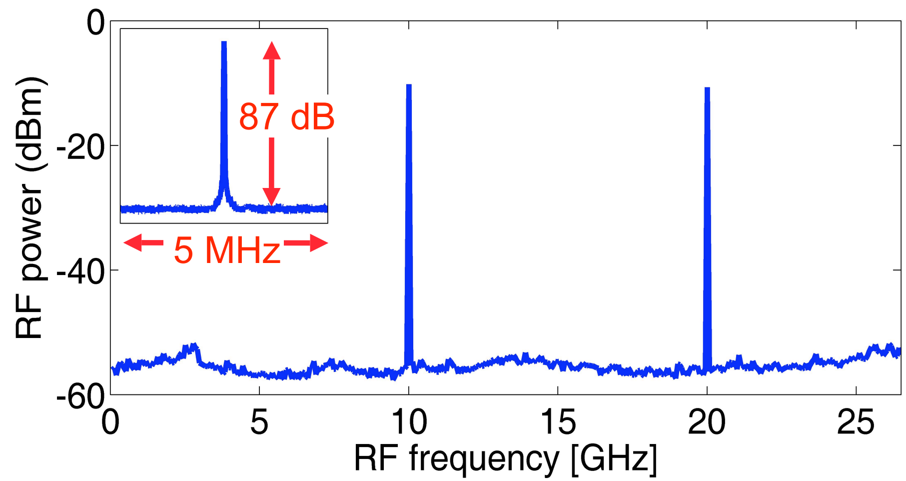
10 GHz laser output

Combination of shortest pulse, highest rep rate, and highest average power





- Shortest pulse: 42 fs
- 500+ modes with power >1 mW
- Clean microwave spectrum: No super modes or Q-switching



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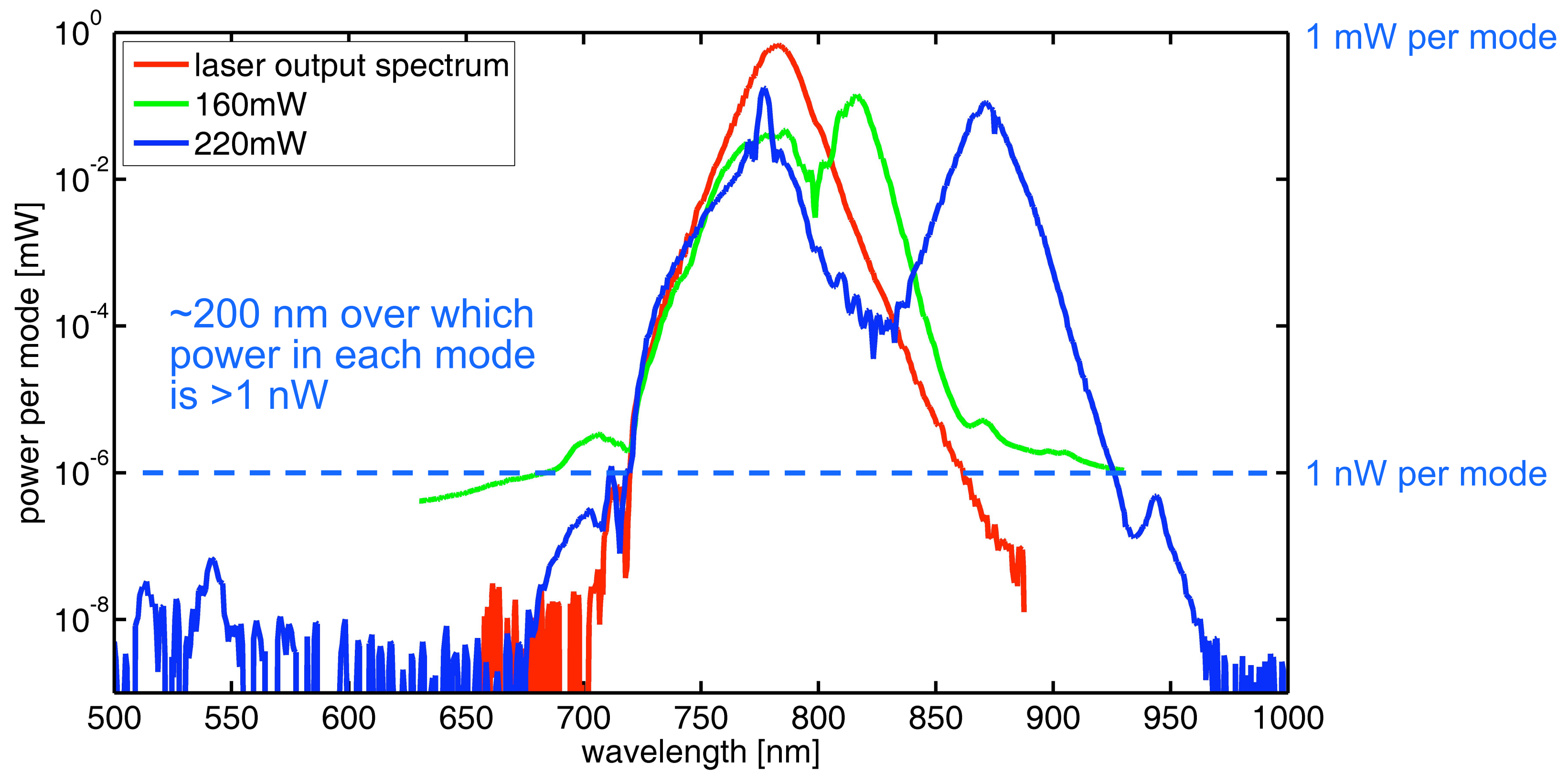
Continuum Generation



For octave spanning spectrum: Need **~2x more power** in this fiber, or a fiber with **~2x larger nonlinearity**

nanowatt powers are sufficient for frequency metrology; astronomical applications require femtowatts

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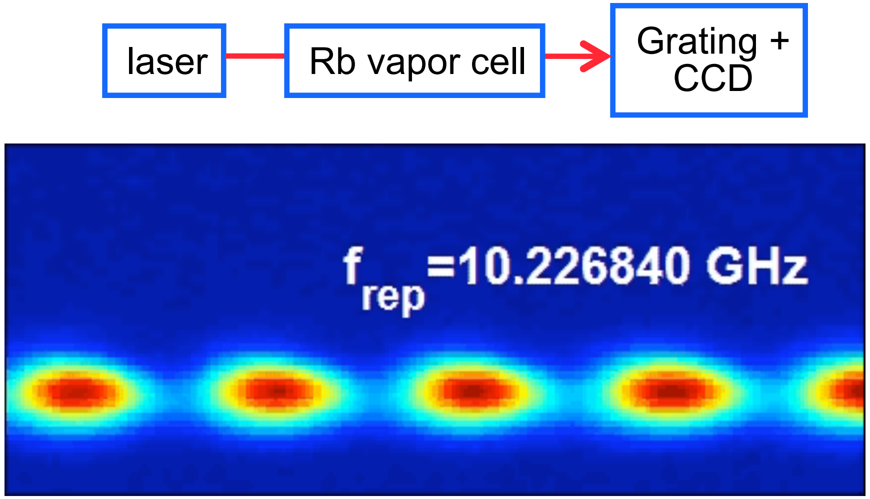
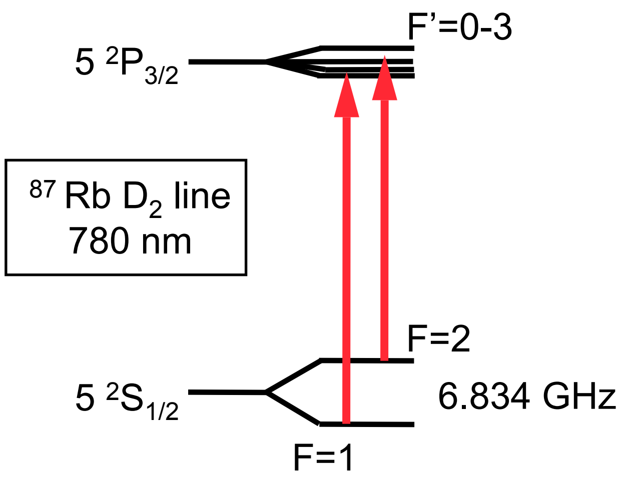
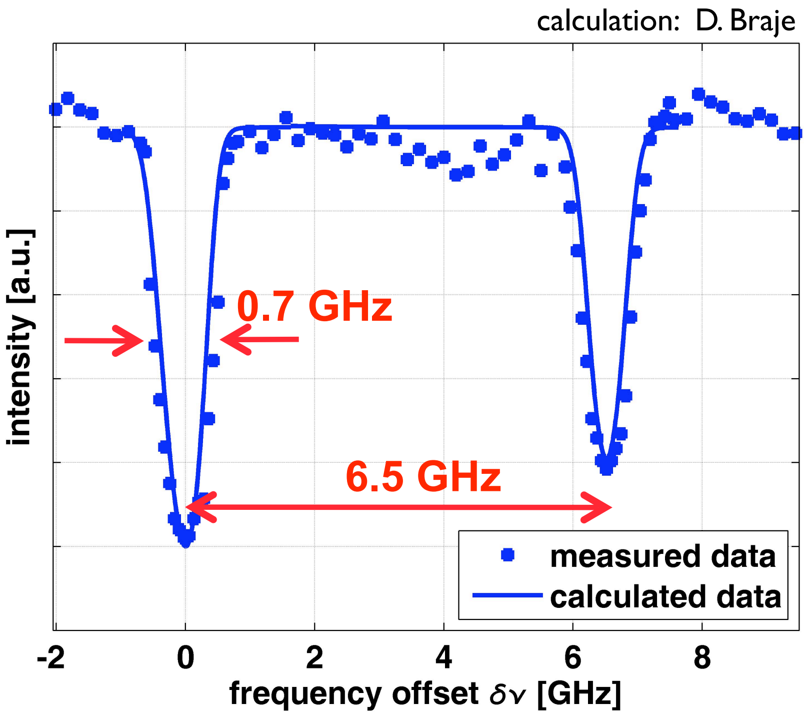
Mode-resolved Spectroscopy



- Doppler limited spectroscopy.
- Enables determination of mode index and f_o
- With f_{rep} locked, we determine optical frequencies of modes to ~50 MHz
- Nonlinear spectroscopy with single mode should be possible → 100 kHz precision





Combs in Space??

Several aspects of high resolution astronomical spectroscopy would benefit from space-born or lunar observatories

➡ atmospheric absorption and blurring
➡ wind loading and vibrations
➡ thermal stability
➡ pointing stability

Frequency comb technology has progressed to the point where deployment in space appears feasible

SWAP of Er and Yb-based combs could be
10 liters, 10 W, 10 kg

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