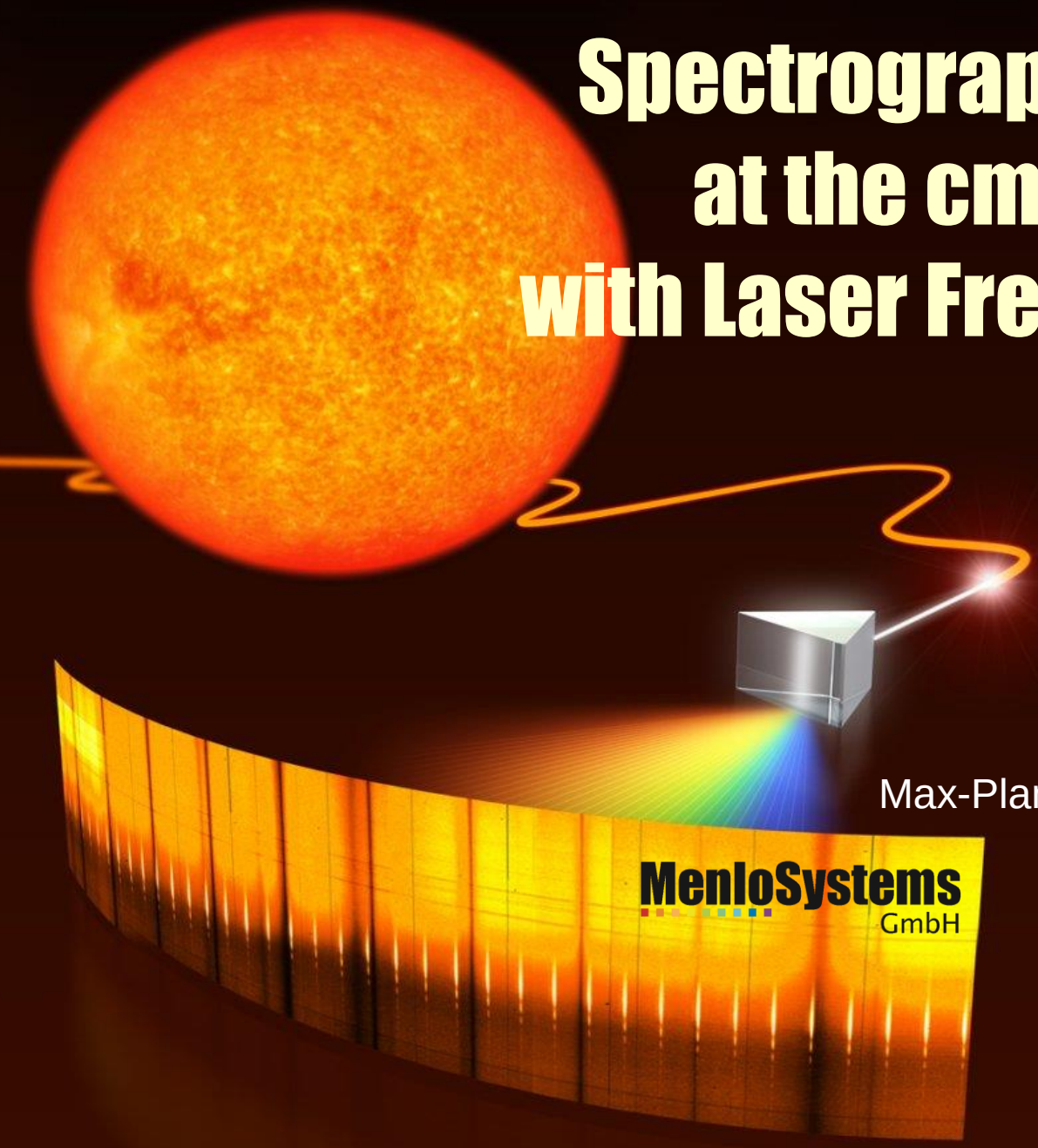
Spectrograph Calibration at the cm/sec Level with Laser Frequency Combs



Ronald Holzwarth

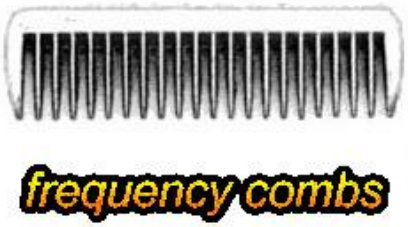
Menlo Systems GmbH
Martinsried, Germany

And

Max-Planck-Institute for Quantum Optics
Garching, Germany

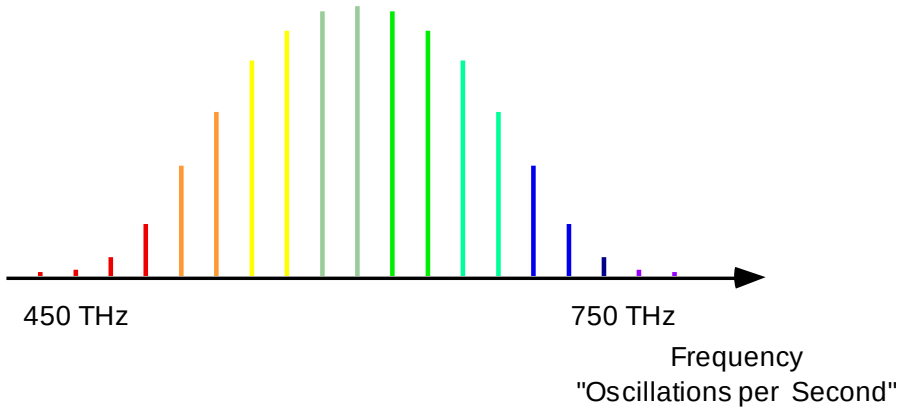
Photonics for Planets
Firenze
November 6th, 2014

Calibration with Frequency Combs

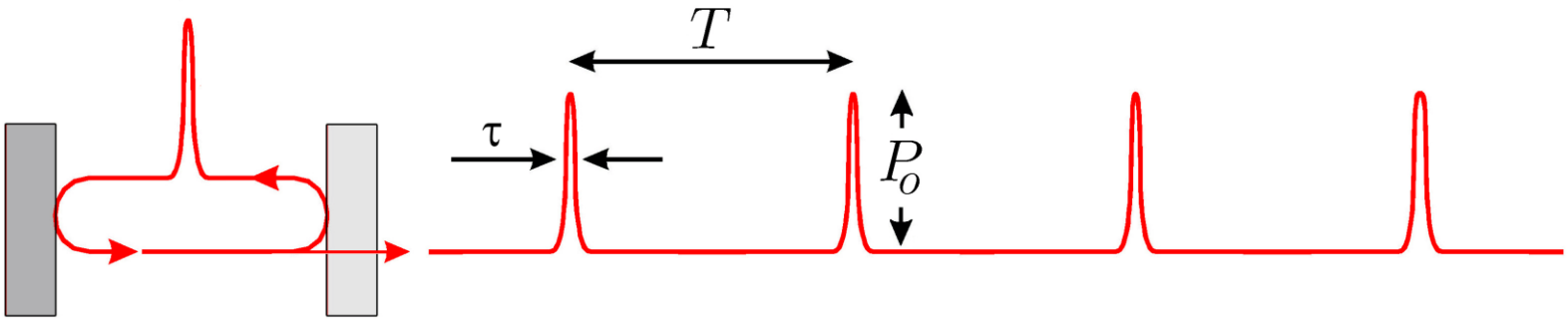


1. **Astro Combs for the visible spectral range**

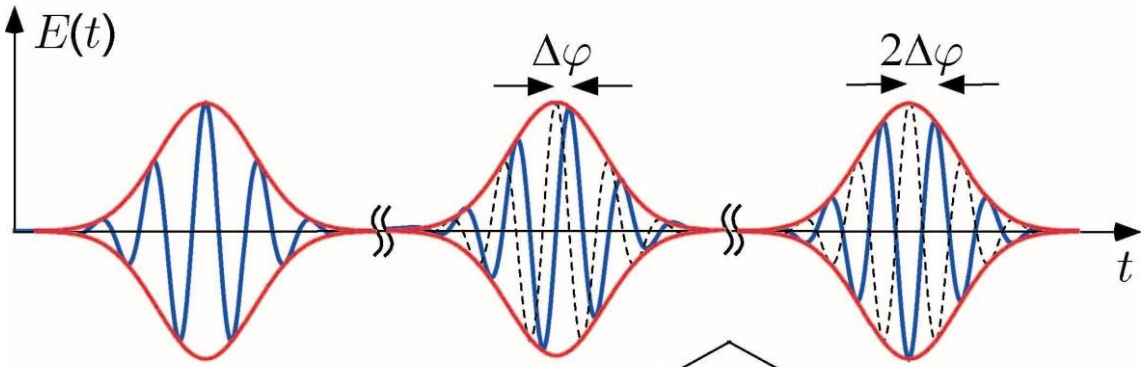
2. HARPS Measurements



Pulsed Laser = Comb Generator

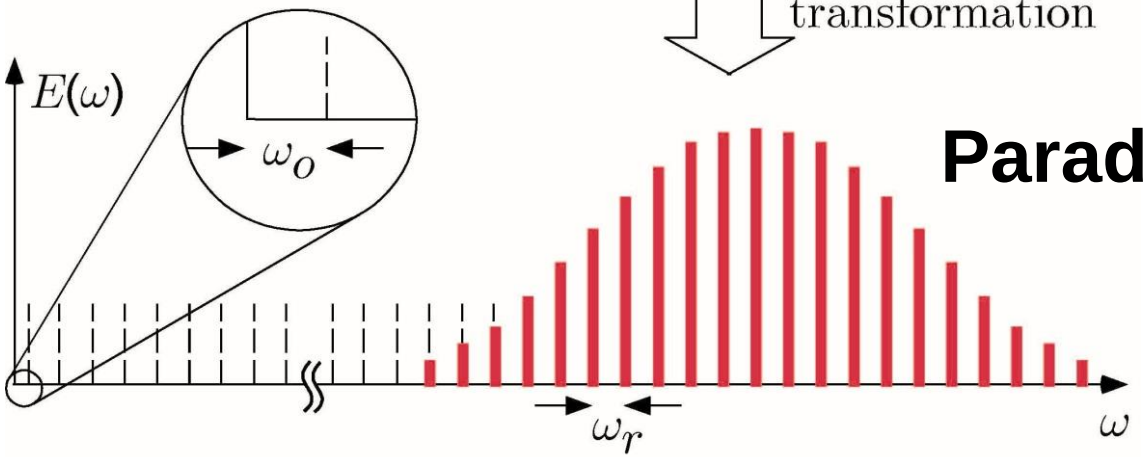


Frequency Combs



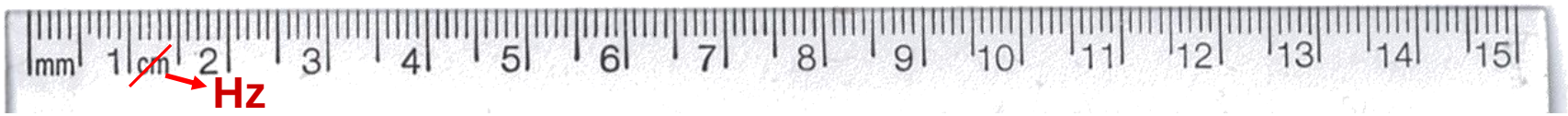
Ted Hänsch 1978 - 1998

Fourier transformation



Paradigm shift!

$\omega_{opt}=N\ \omega_{rep} + \omega_0$



Astronomical Precision Spectroscopy

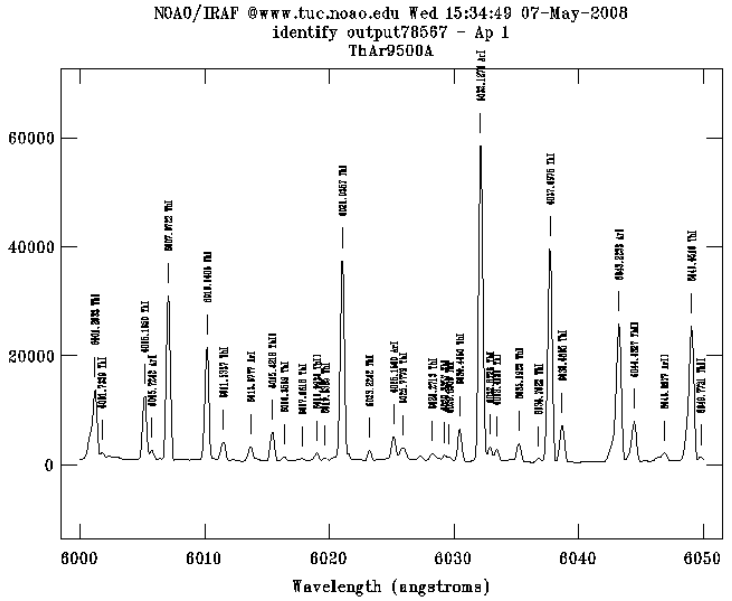
	Required precision		
• **Detection of extra solar Earths**	$2x10^{-10}$	~5 cm/s	~100 kHz
• **Acceleration of cosmic expansion**	$4x10^{-11}$	~1 cm/s	~20 kHz

- **Calibration must be reproducible over years / decades!**

Calibration Sources

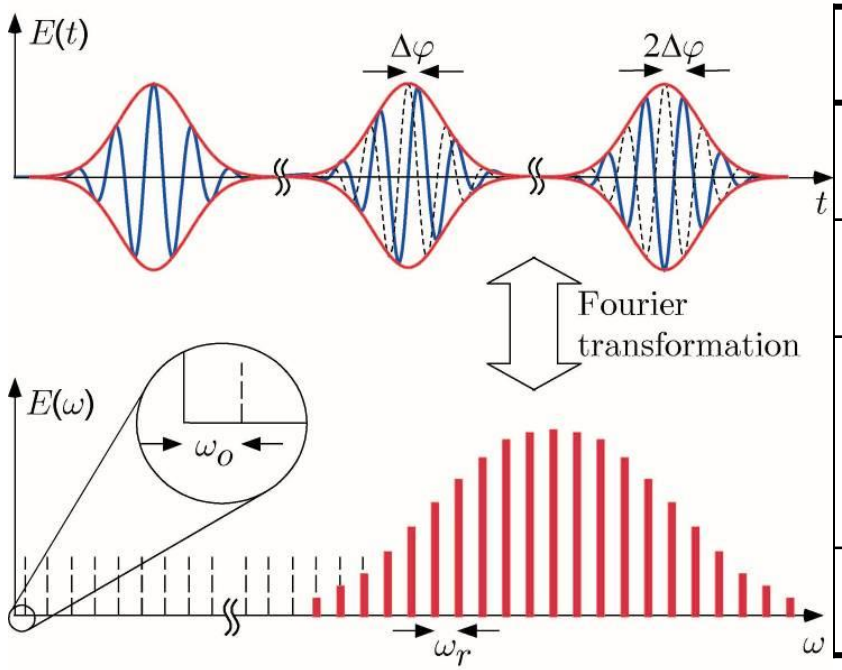
- **Traditional calibration sources (e.g. Th-Ar spectral lamps) achieve presently ~2x10^{-9}, but have major drawbacks:**

Th-Ar lamp
Lines differ in intensity and spacing
Fixed line positions
Ar ions are sensible to lamp pressure changes.
Lamp ages
Accuracy limited to ~10^{-9}



Calibration Sources

- **A specifically designed frequency comb overcomes all these problems and has the potential for mm/sec precision!**



Frequency comb
Uniform mode spacing and intensity
Tunable line positions
Reference to atomic clock: does not change with time
Accuracy limited to ~10^{-15}

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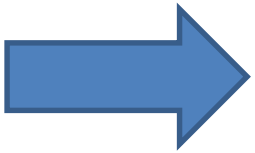
Comb vs. Th Ar

Th-Ar lamp ☹	Frequency comb ☺
Lines differ in intensity and spacing	Uniform mode spacing and intensity
Fixed line positions	Tunable line positions
Ar ions are sensible to lamp pressure changes.	Reference to atomic clock: does not change with time
Lamp ages	
Accuracy limited to ~10^{-9}	Accuracy limited to ~10^{-15}

Frequency Comb Specs

Fs Lasers as comb generators
100 MHz to 1 GHz mode spacing
Most spectrographs: R = 20 000 to 100 000 or 5 GHz to 20 GHz



needs filtering

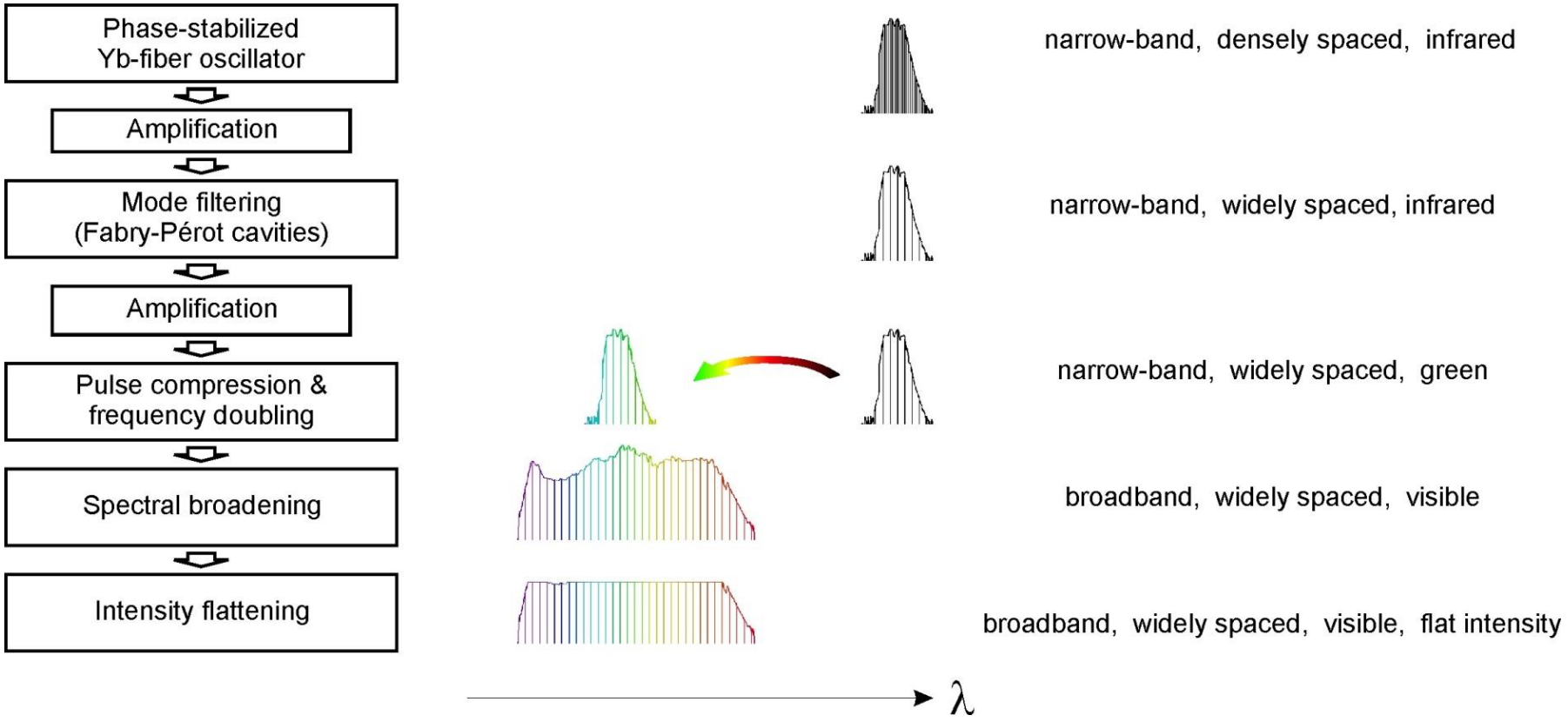
Comb Accuracy:
relativ: 10^{-12} to 10^{-15} from commercial clocks
absolut: 500 Hz to 0.5 Hz at 500THz (green)
In RV: 200 µm/sec to 200 nm/sec

1 m/s ~ 2 MHz ~ 0.002pm

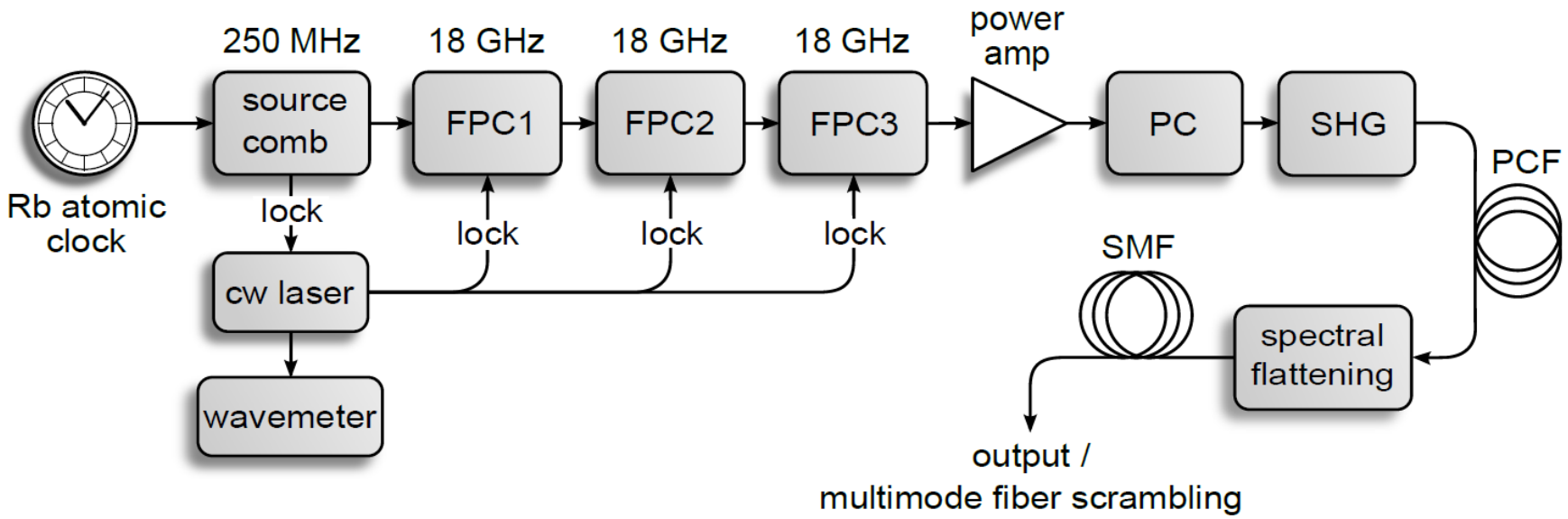
$$v = \frac{\Delta f}{f} c = \Delta f \cdot \lambda$$

Limitation: Delivery fiber, Spectrograph

Astro Comb System Overview



Astro Comb System Layout



Abbreviations:

cw laser: continuous wave fiber laser

FPC: Fabry-Pérot cavity

PC: pulse compressor

SHG: Second-harmonic generation

PCF: tapered photonic crystal fiber

One button control:

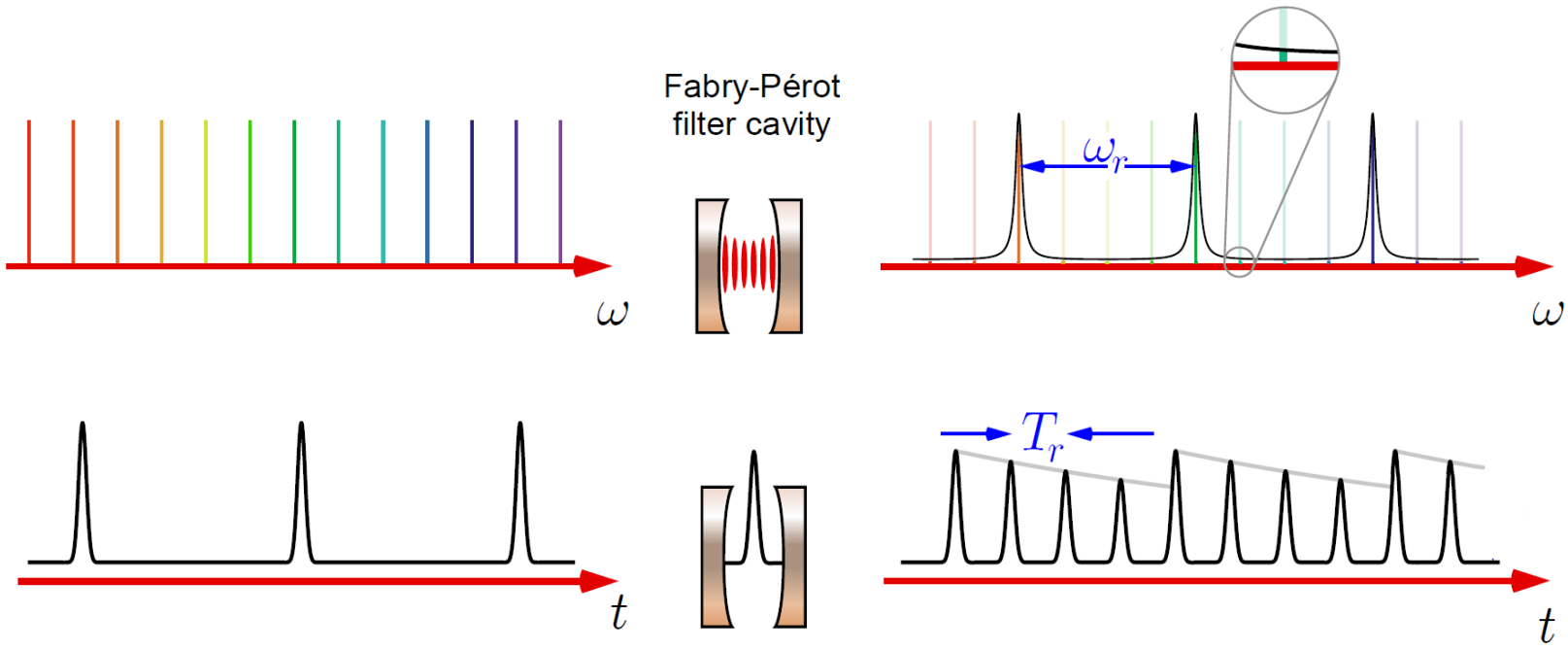
The complete system can be launched upon a single mouse click, locks are established automatically

Mode Filtering

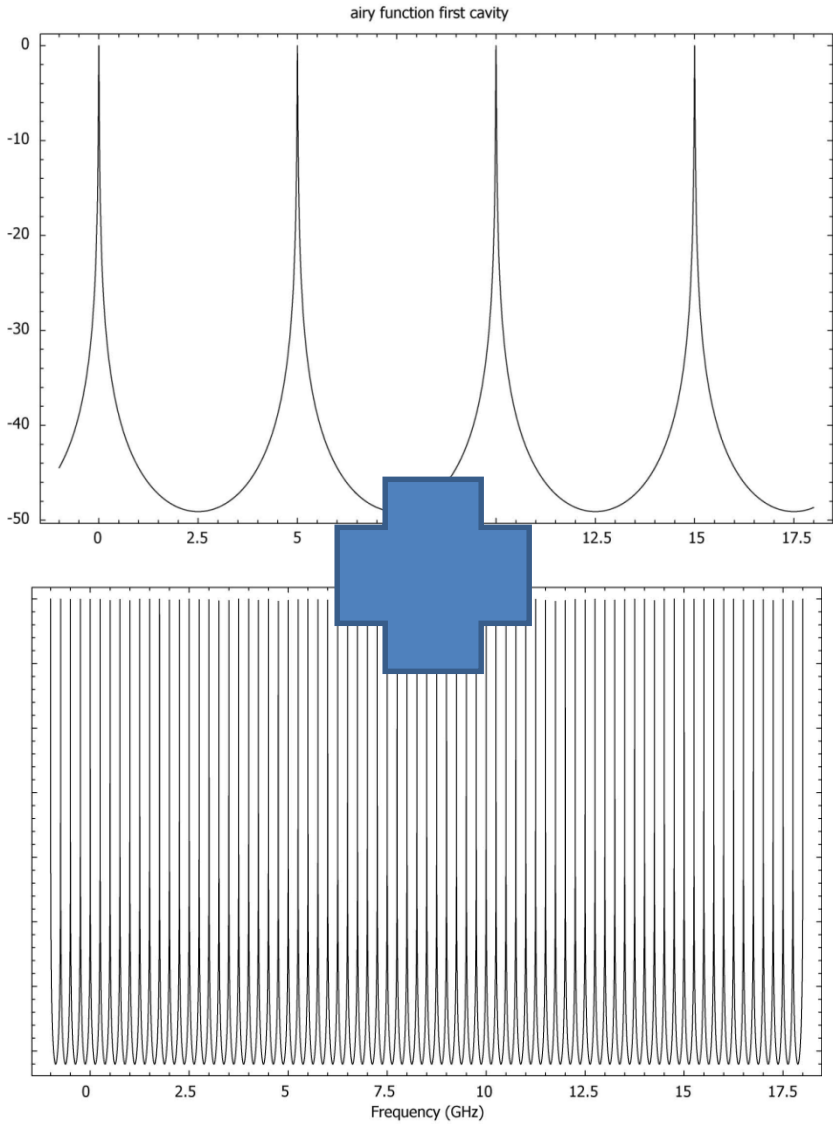
Optimum mode spacing for spectrograph calibration:

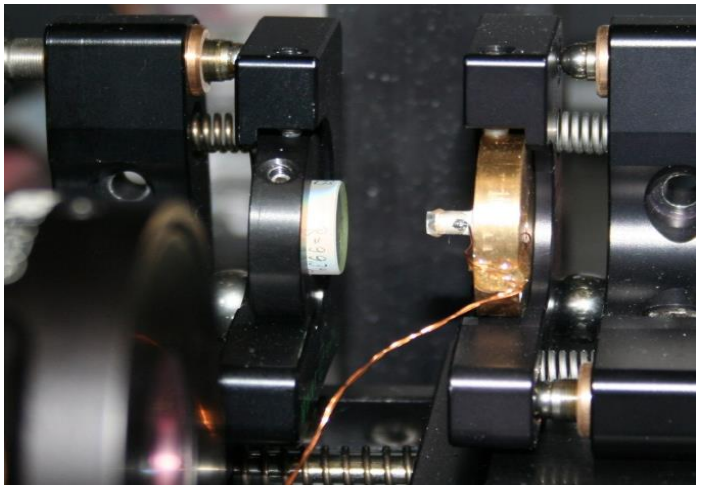
3x Resolution of spectrograph

- Typical mode spacings: 10 – 30 GHz
  Mode spacing for HARPS: 18 GHz
- Increase of mode spacing by mode filtering:



Filtering the Comb





18 GHz

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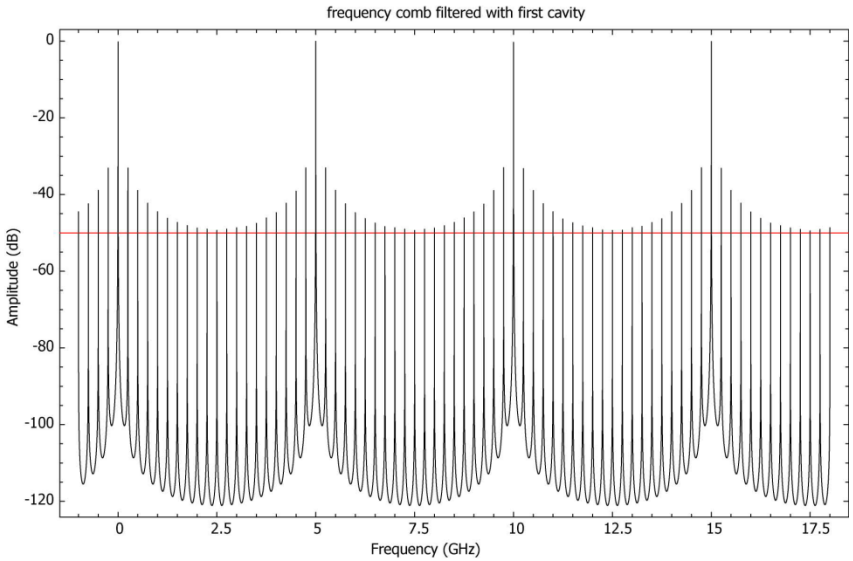
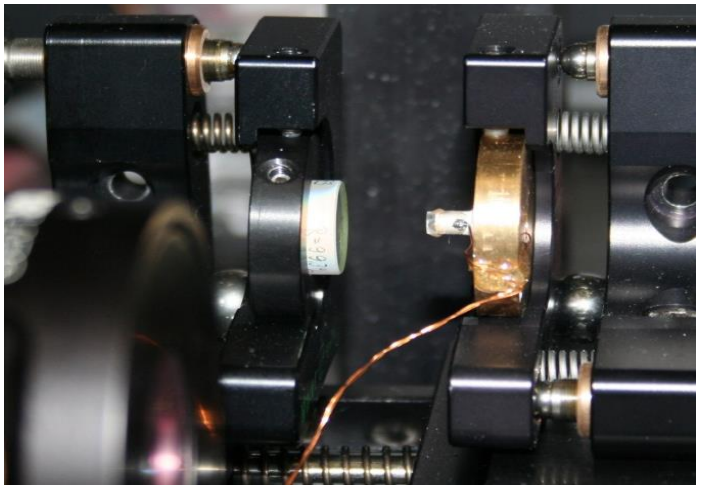
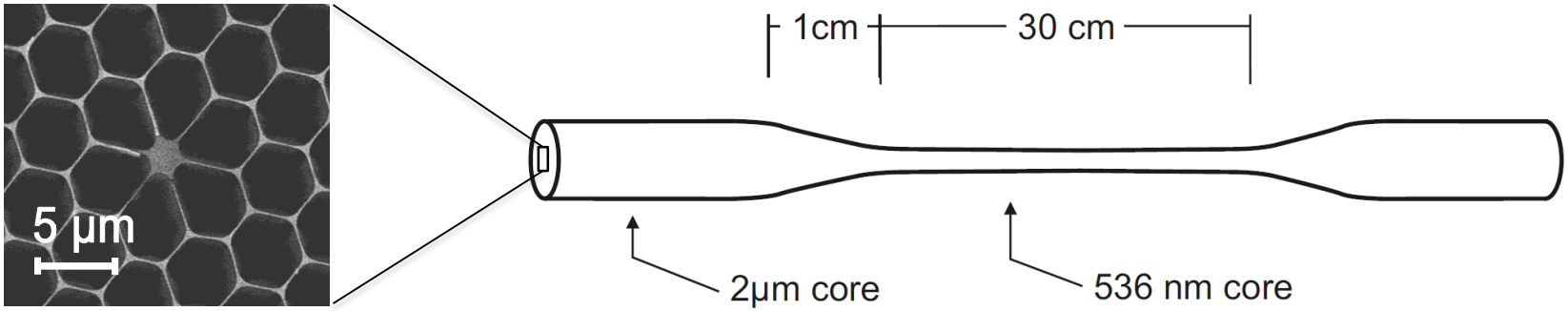
Filtering the Comb

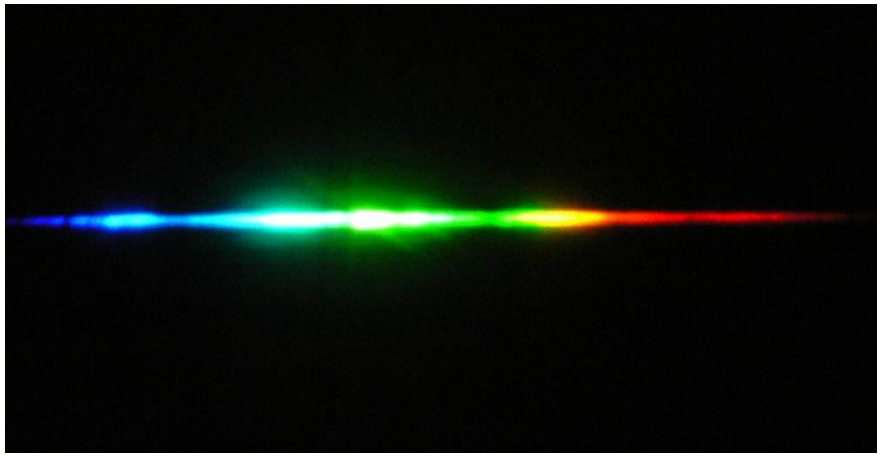




18 GHz

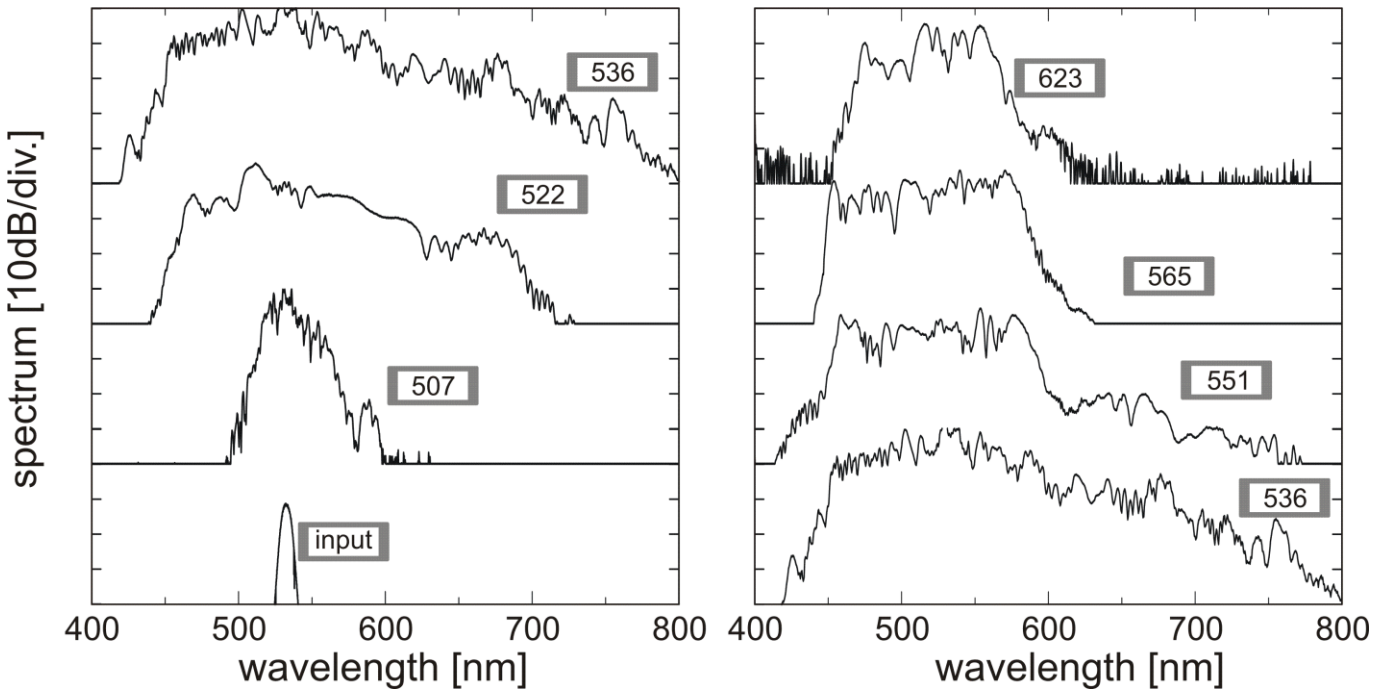
Spectral Broadening

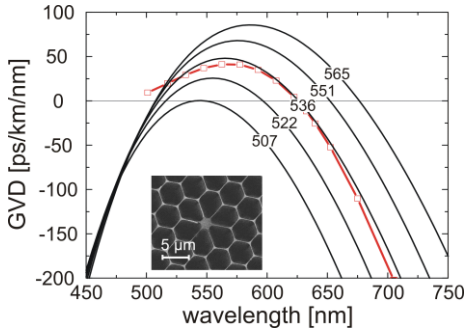




In collaboration with
P. Russell et al., MPL, Erlangen

Spectral broadening





S. Stark et al., OPTICS EXPRESS , Vol. 19, No. 17, P. 15691 (2011)

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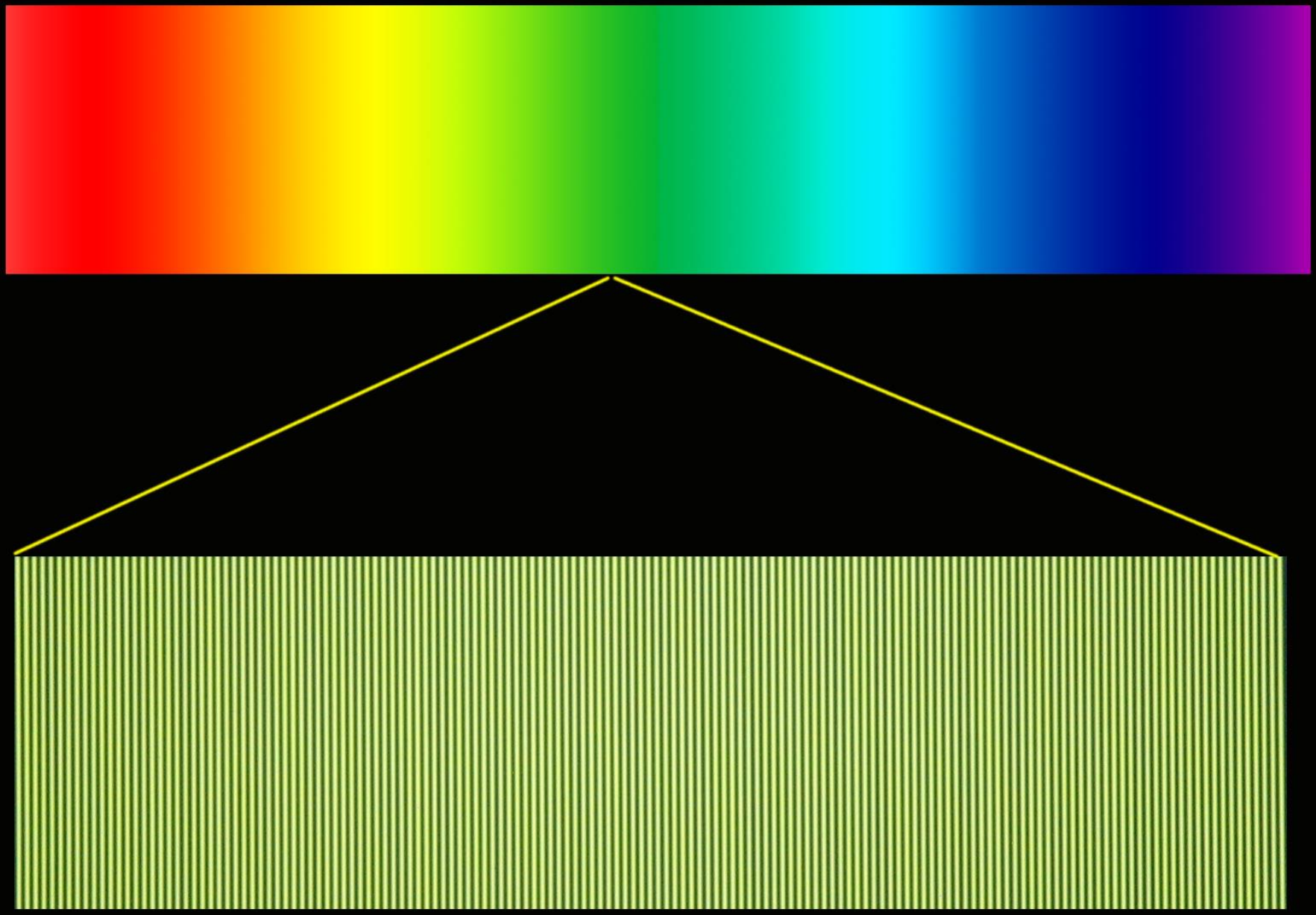
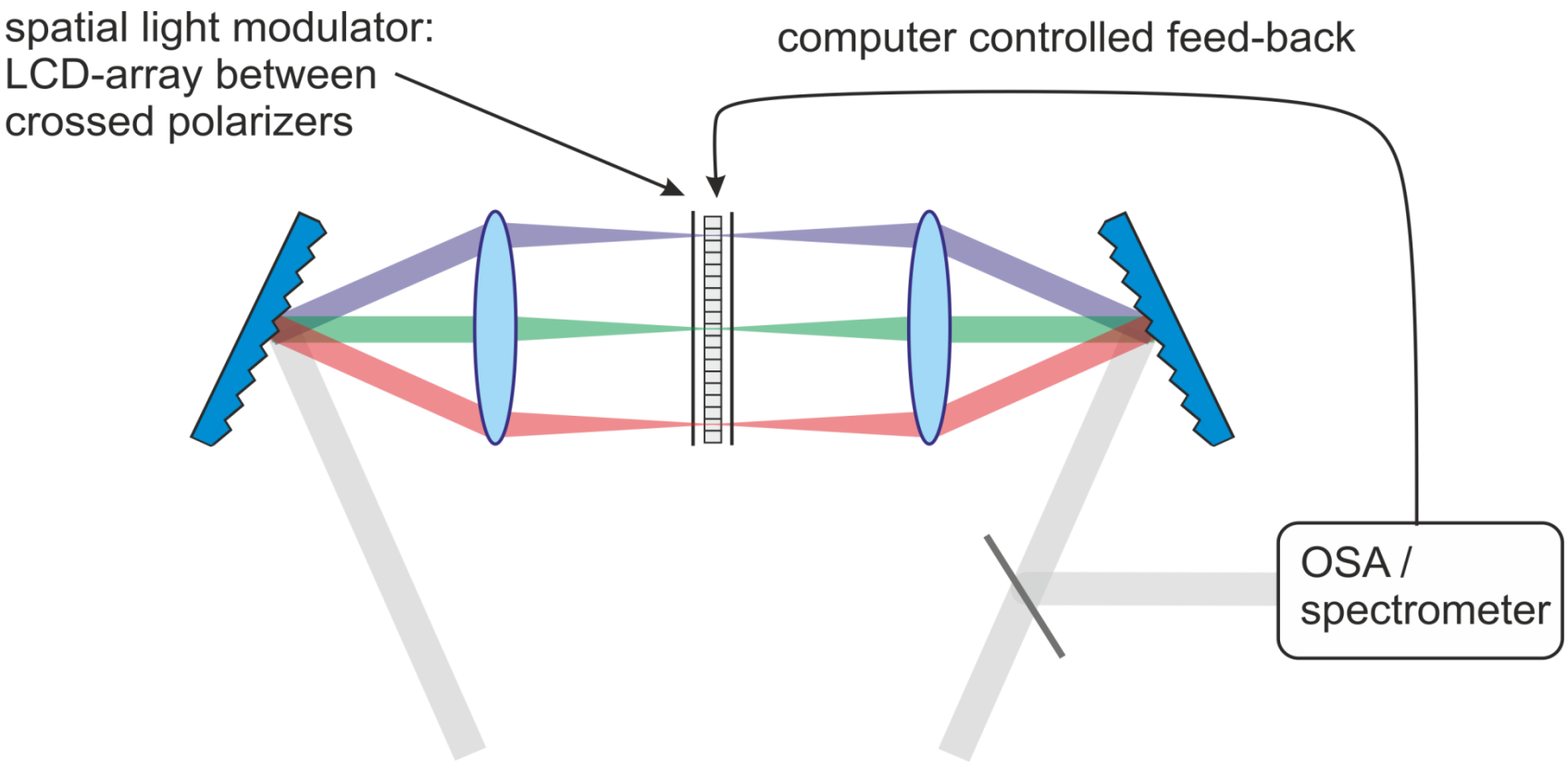
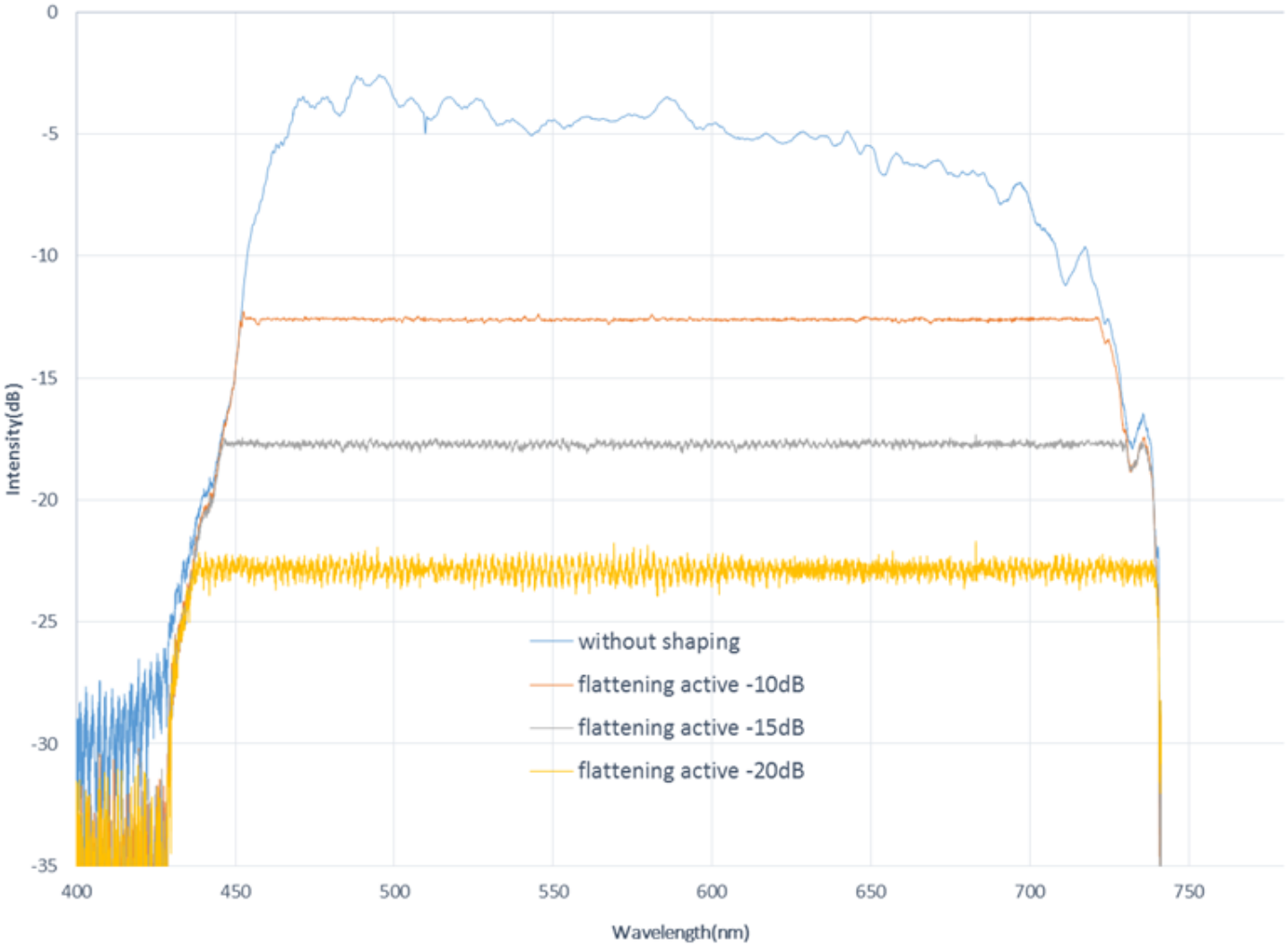


Spectral Flatening



Optical Spectrum

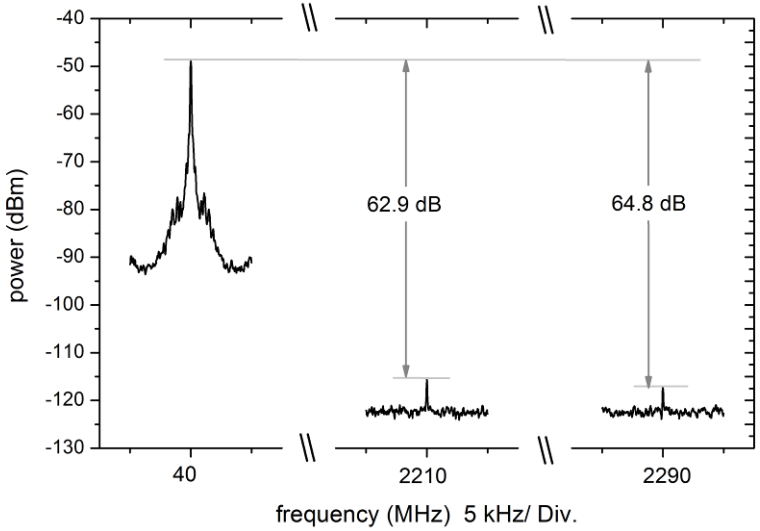


Side mode supression

Beat measurement with 3 cavities:

- broadened comb ($\Delta\lambda \approx 200$ nm)
- f_{rep}=18 GHz

- Sidemode reamplification by 40 dB



beat note:
cw vs. astro-comb
(frequency doubled)

wavelength of cw:
532.4 nm

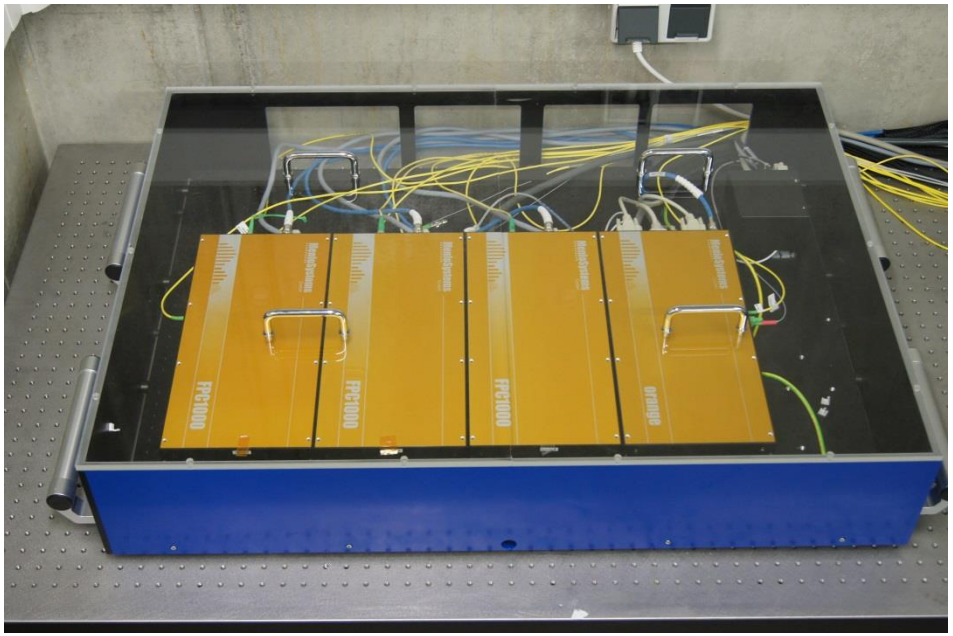
res. bandwidth:
91 Hz

average:
100 scans

46 dB suppression after broadening in PCF

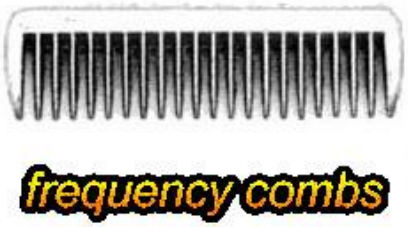
→ maximum drift < 1 cm/s

Astro Comb Hardware



Currently: final acceptance testing for 3 units

Calibration with Frequency Combs



1. Astro Combs for the visible spectral range

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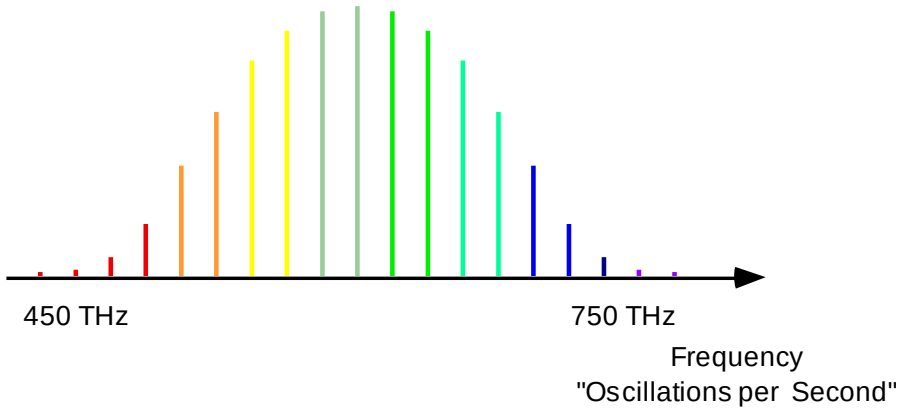

HARPS at La Silla

MPQ

ESO

OBSERVATOIRE DE GENÈVE
FONDÉ EN 1772

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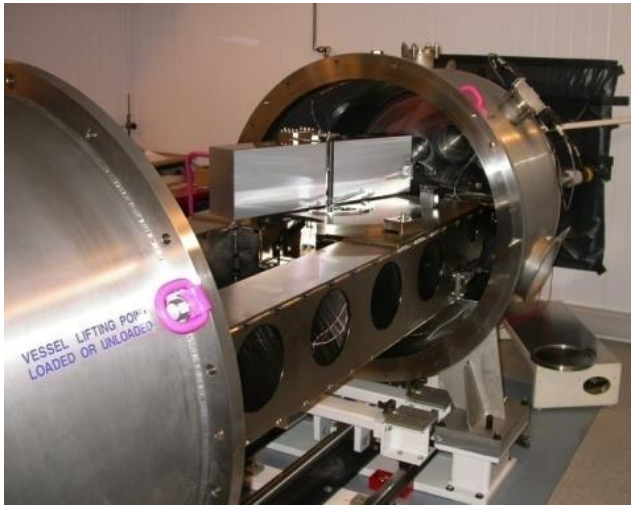
GmbH

HARPS at the 3.6m La Silla Telescope

HARPS = High Accuracy Radial velocity Planetary Search

- Cross dispersed Echelle
  - Grating 200 x 800 mm

- Wavelength Range: 378 -691 nm (68 orders)
- Resolution: 120 000 (5 GHz @ 520 nm)
- Fibre fed (2 fibres)
- In vacuum, mK temp. stability
- Detectors: mosaic of 2 CCDs (2k x 4k)
  - 15 um pixel size
  - Actively cooled by cryostat



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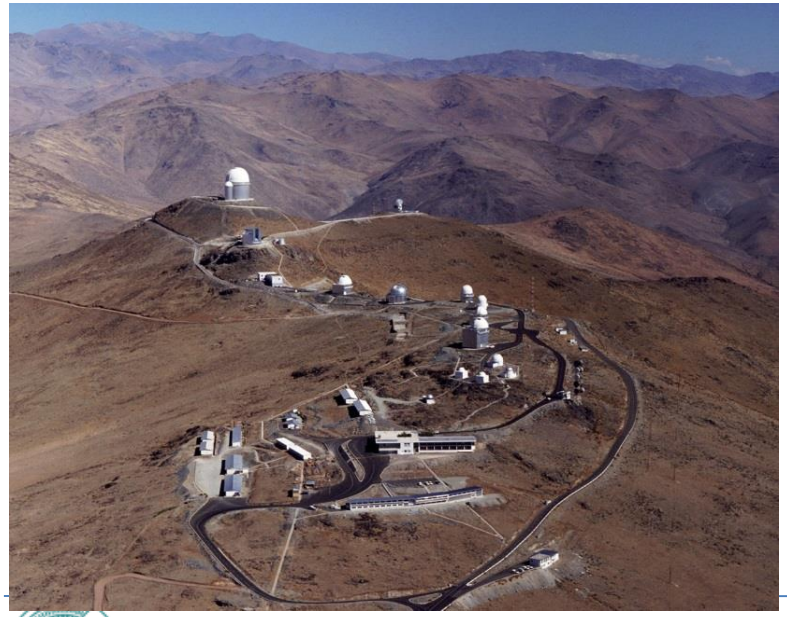
HARPS Comb Campaigns



January 2009

March 2010

Nov. & Dec. 2010

January 2011

February 2012

November 2014

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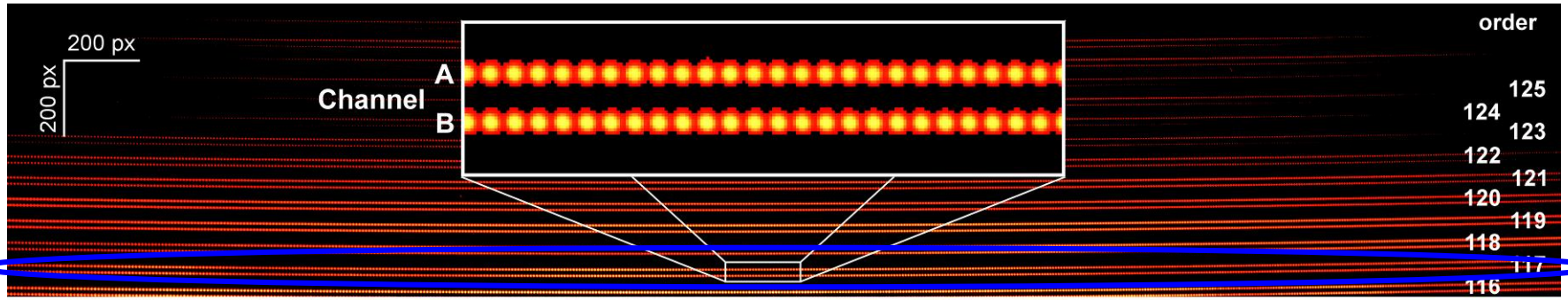
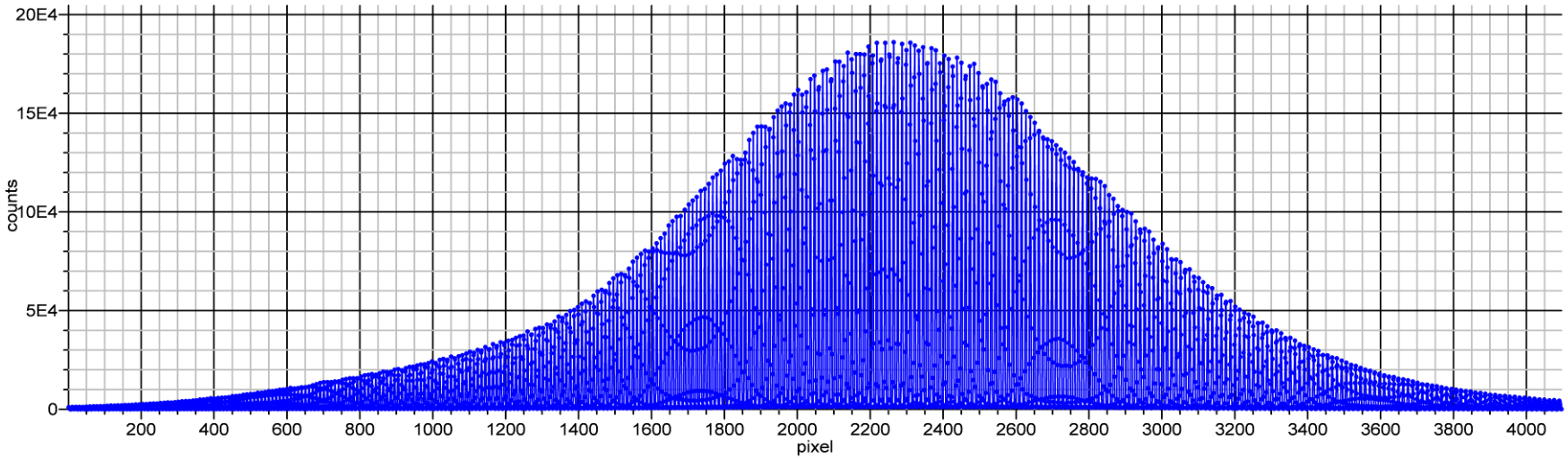
Comb Spectrum on the CCD





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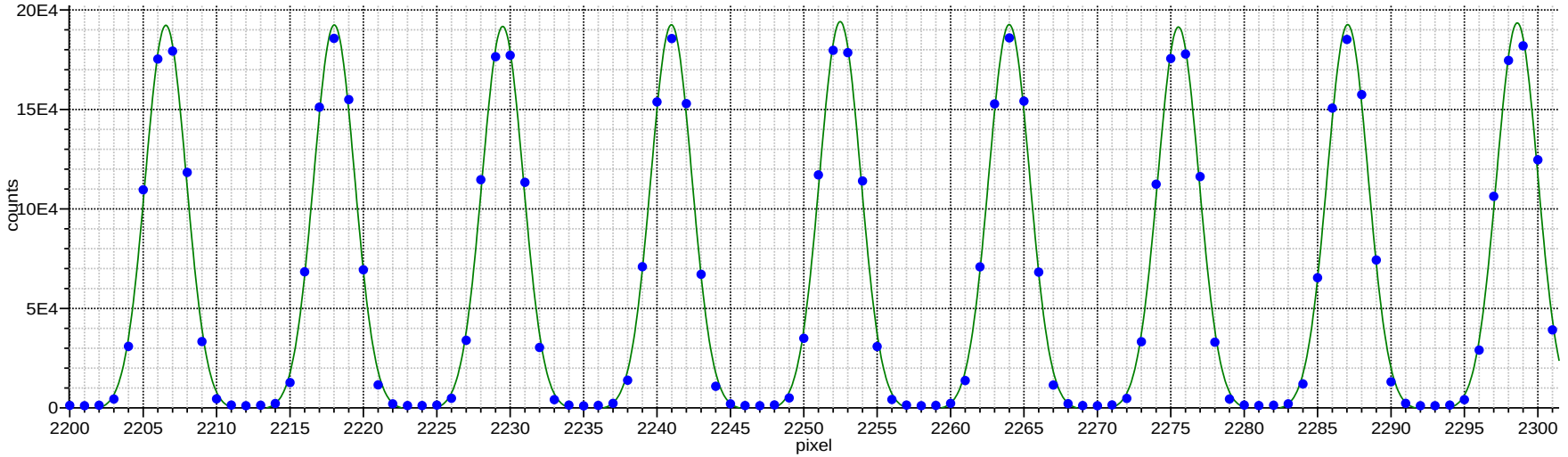
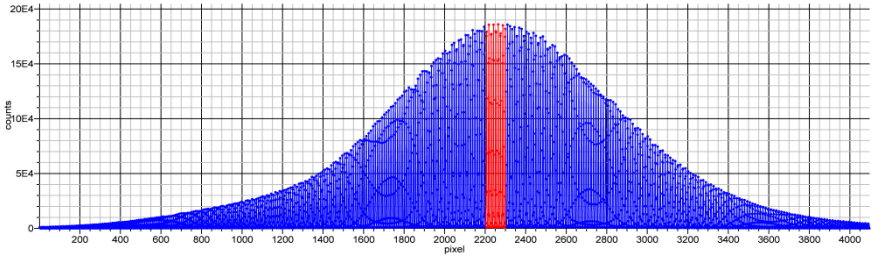
Fitting the lines



Fit functions:
350 – 450 individual Gaussians



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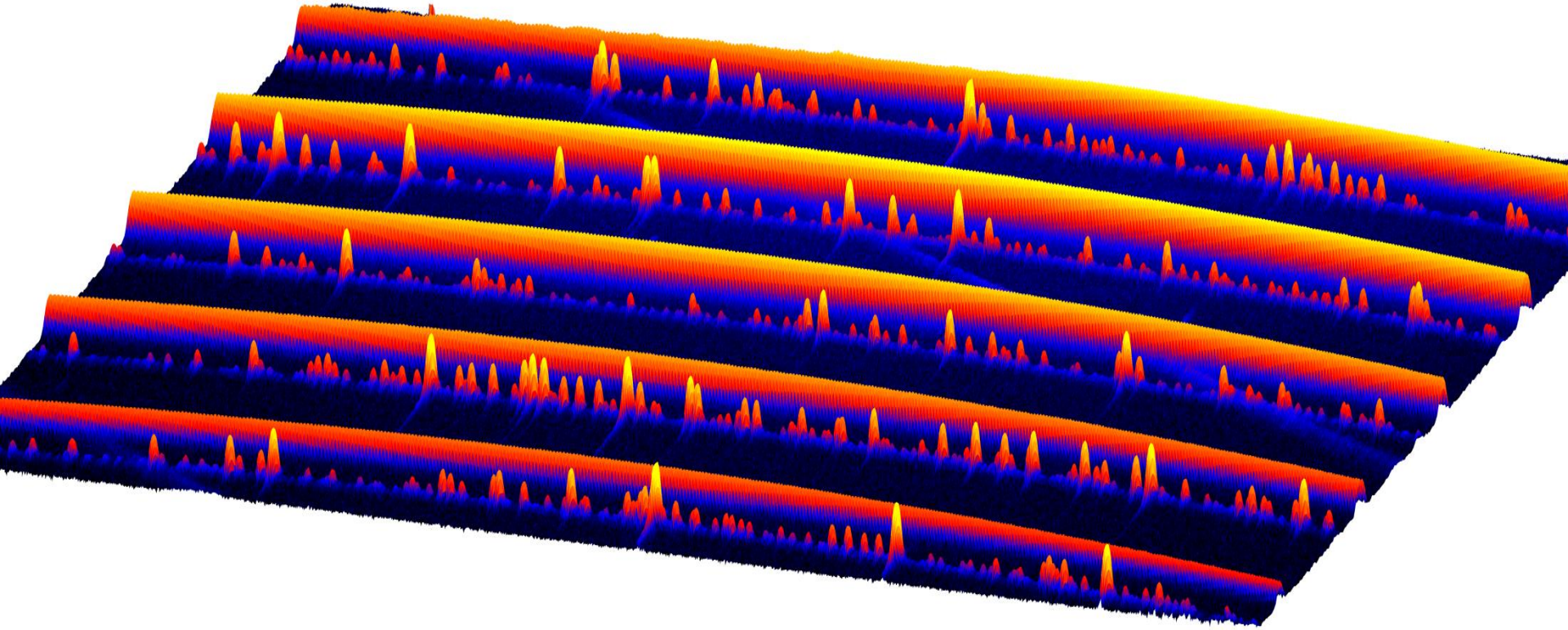
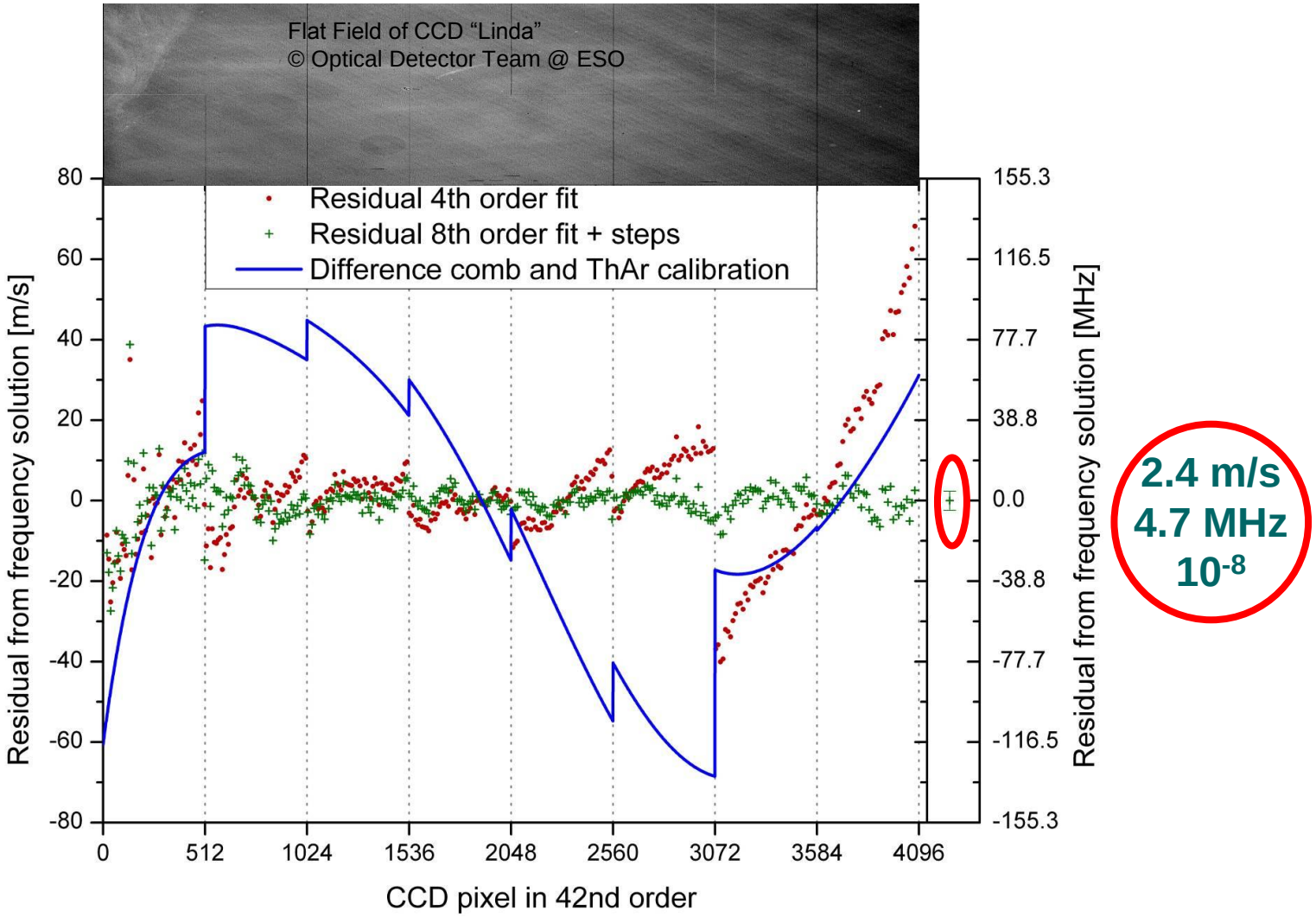
Comb and Th Ar on CCD

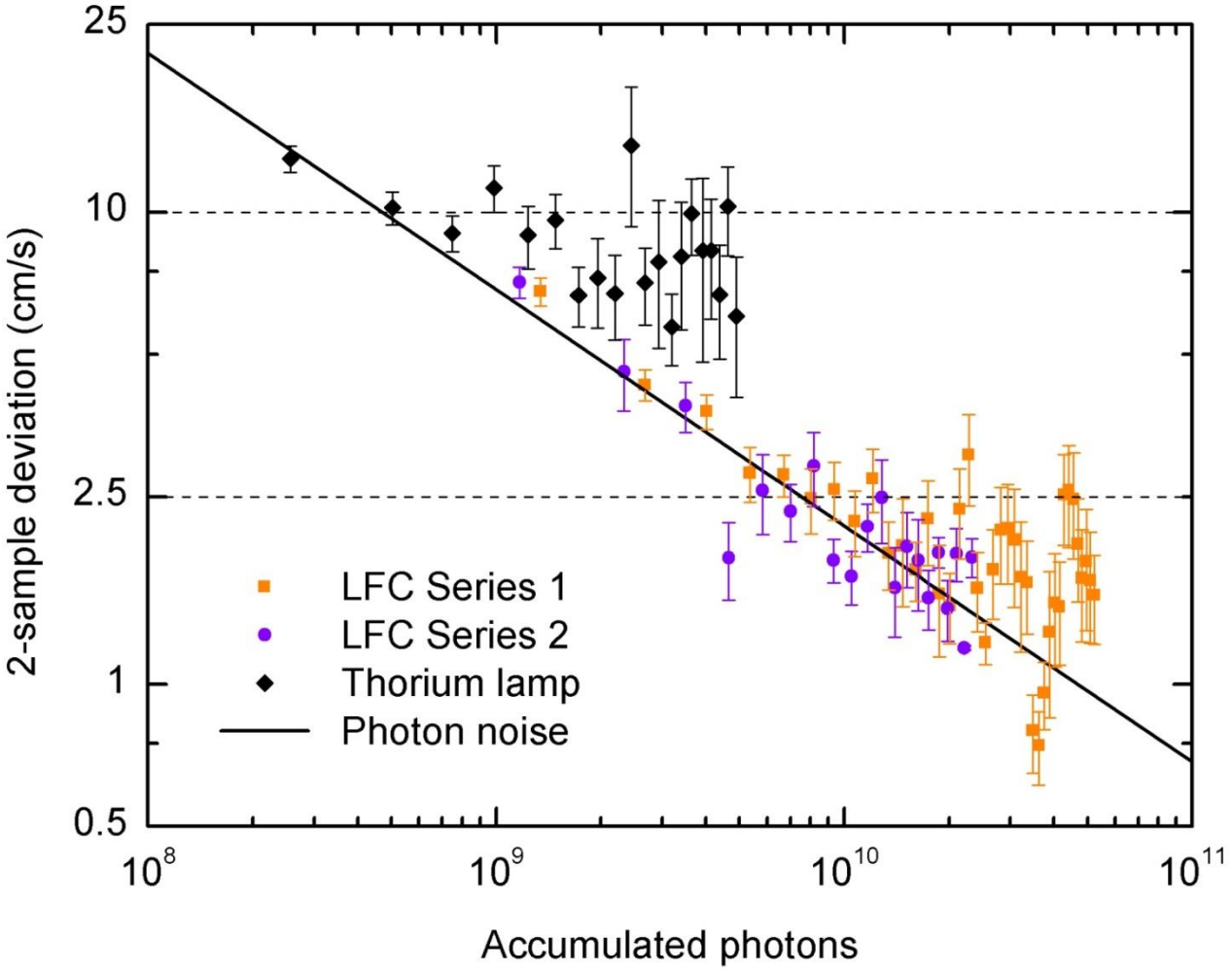


Absolute calibration



Wilken et al. MNRAS 405, L16 (2010)

Limit of Repeatability



T. Wilken et al., Nature 485 p. 611 31 May 2012

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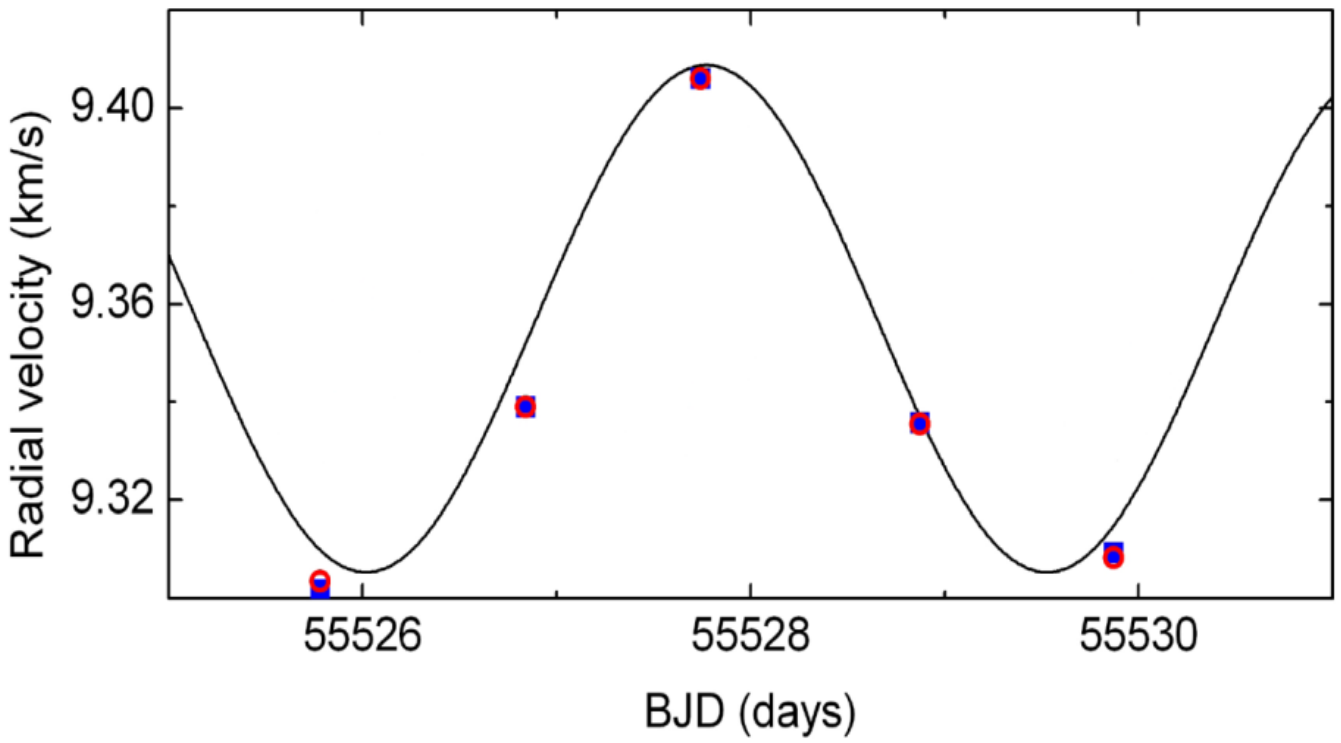
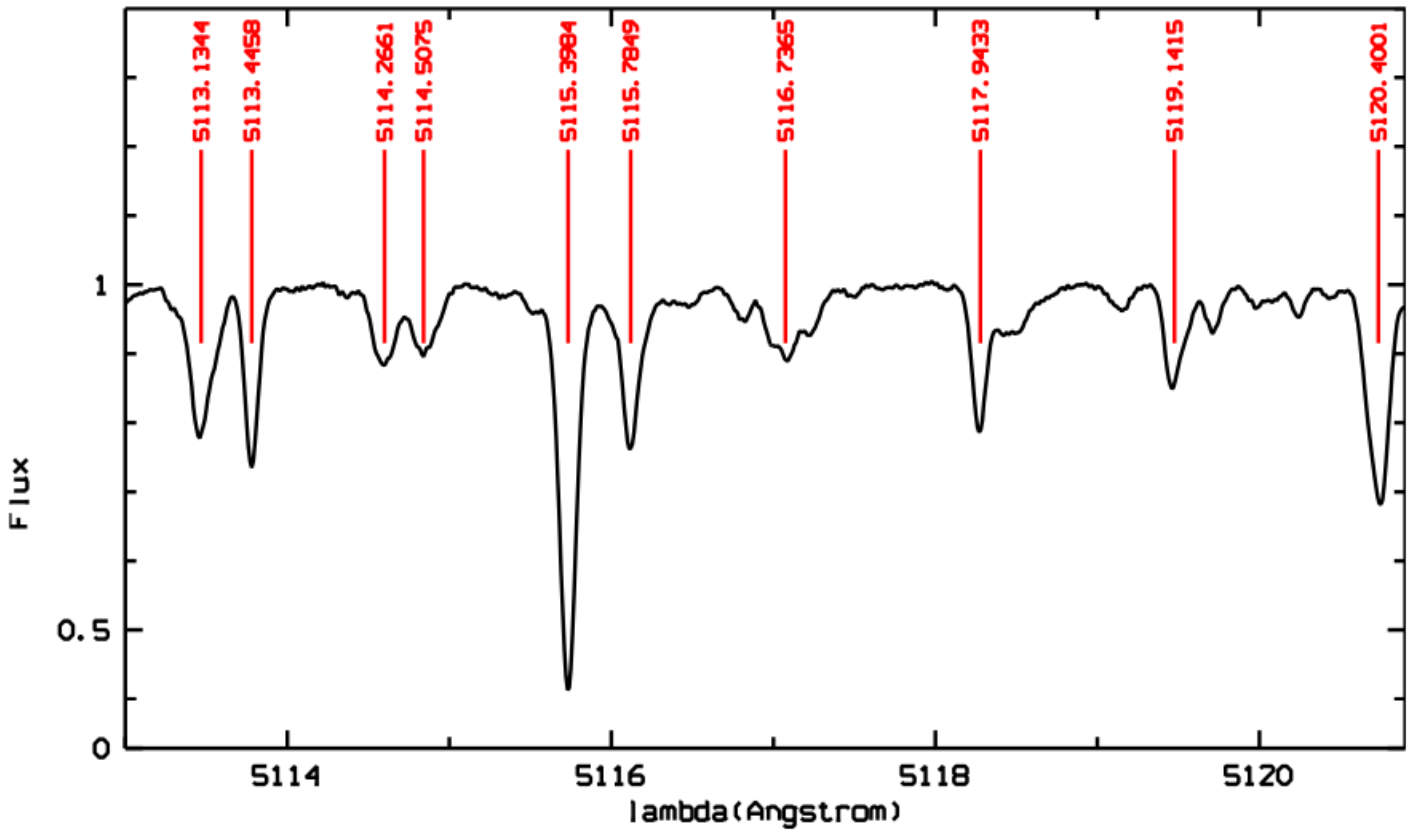
Exoplanet with Comb



Demo of comb-assisted exoplanet detection (HD 75289 b)
Wilken et al. Nature 485, 611 (2012)

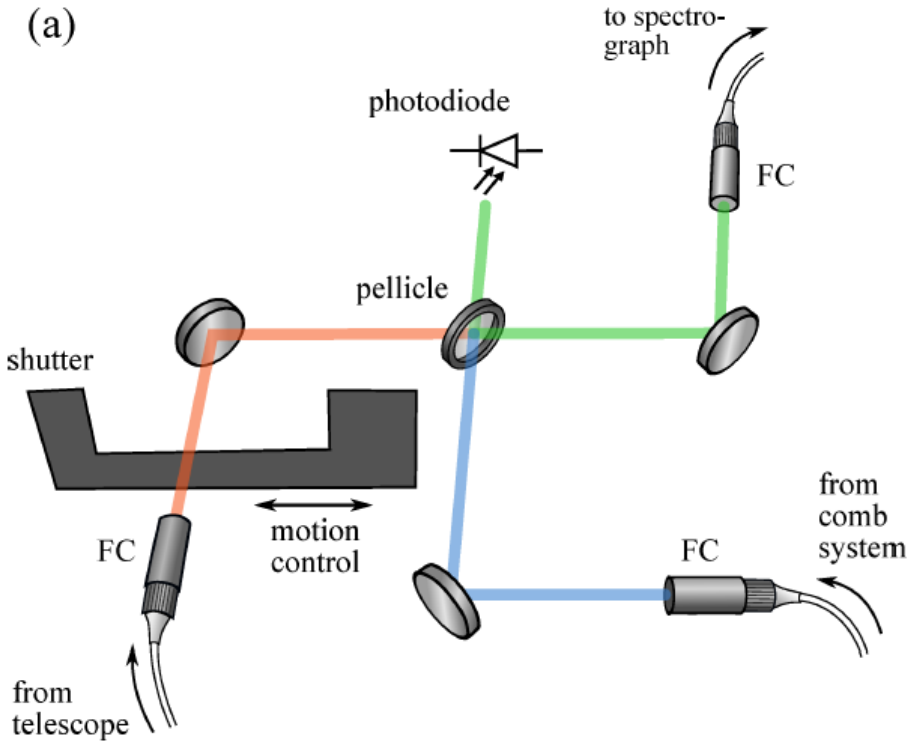
Solar Atlas

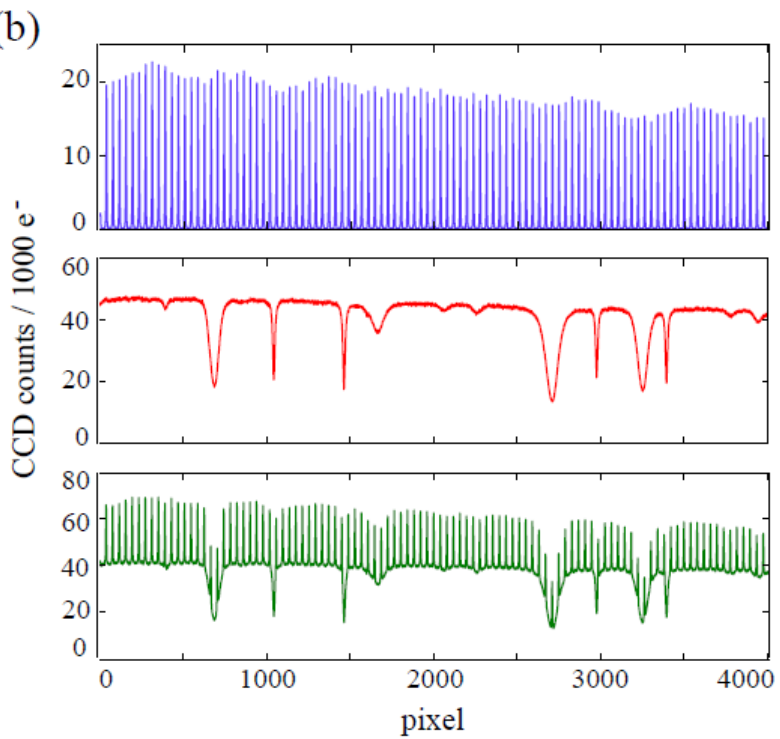


A comb-calibrated solar atlas

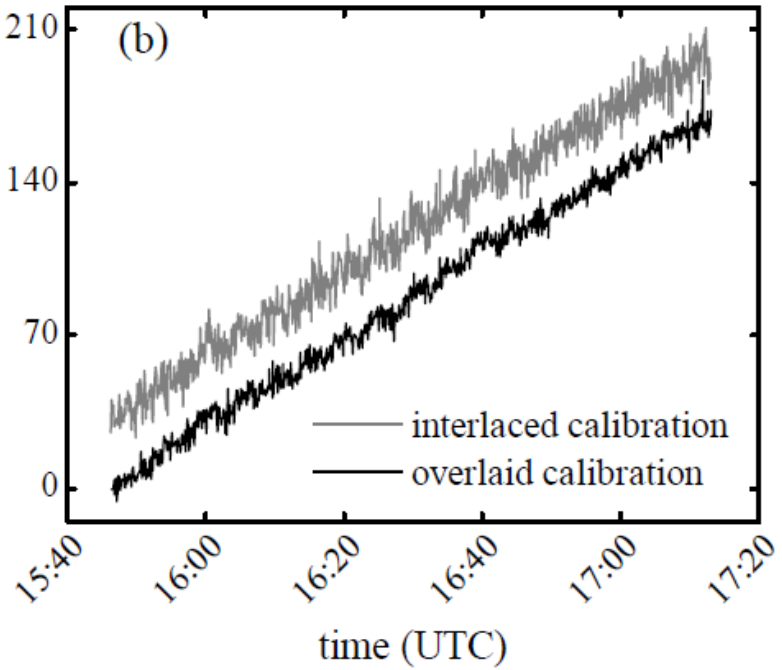
Molaro et al. A&A 560, A61 (2013)

Single Mode Fiber Experiments

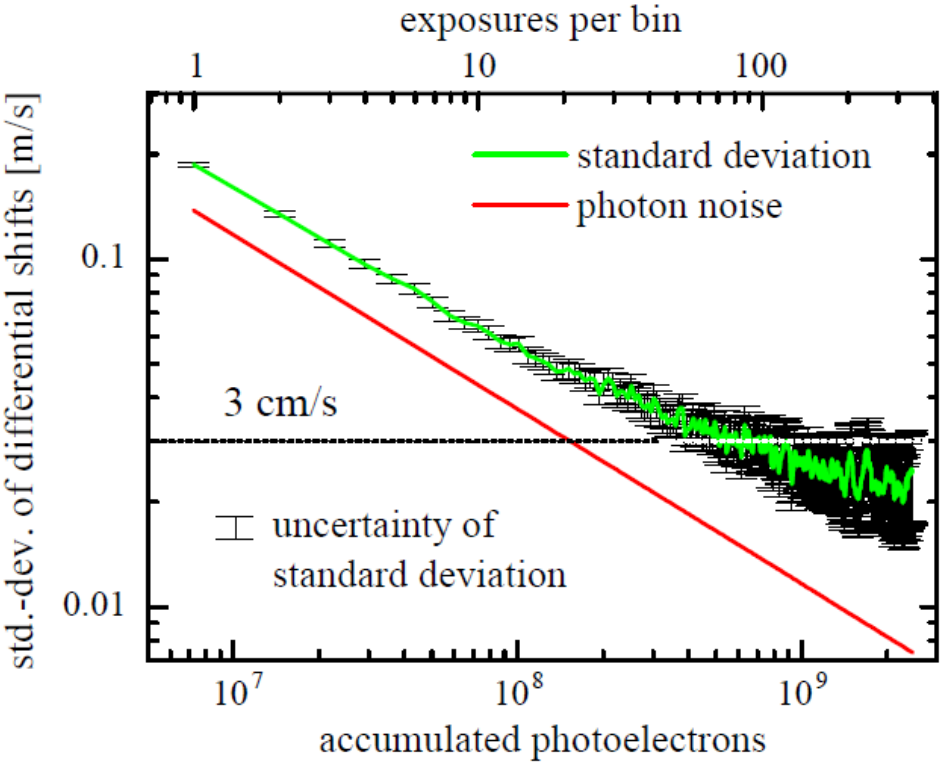




Solar single mode fiber results



Average shift of 3 Fe I lines



Submitted for publication

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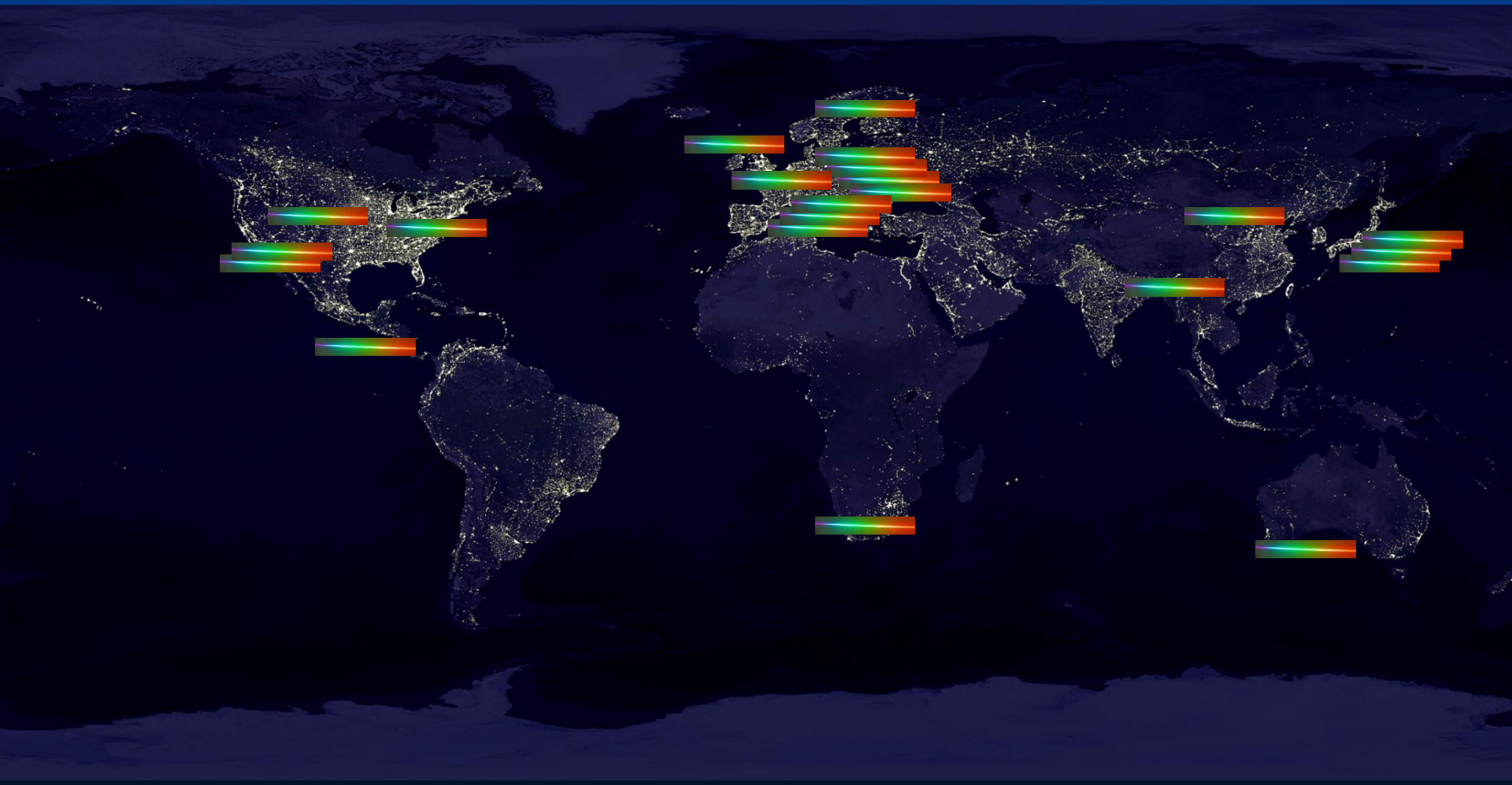
W. Schmidt
T. Kentischer
H. Dörr



Menlo Systems WE TURN THE LIGHTS ON