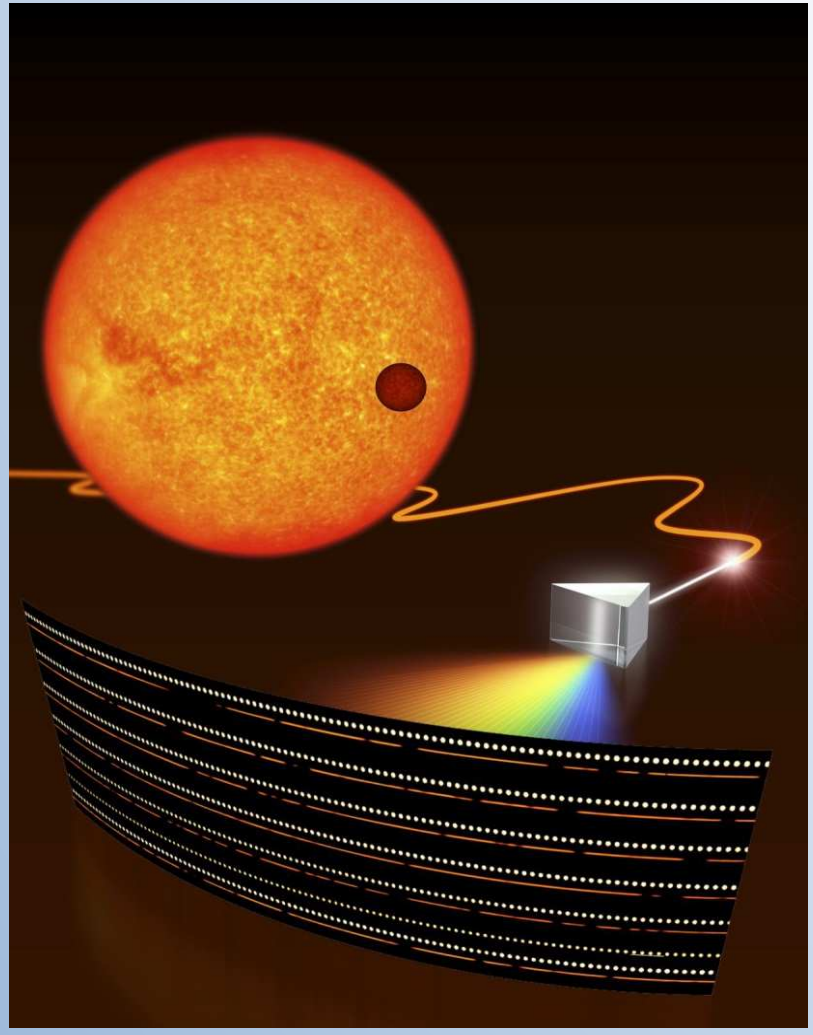
Technology and Applications of Frequency Comb Lasers



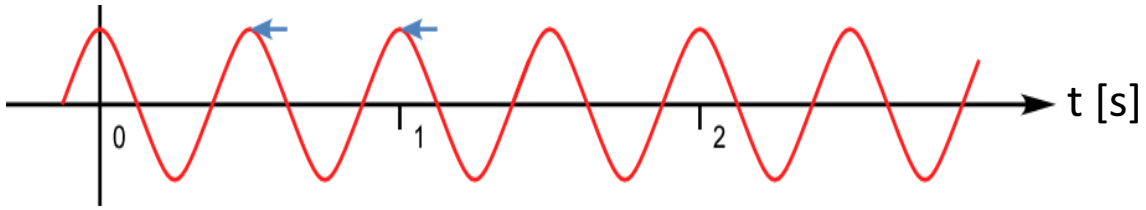
Matthias Lezius
Menlo Systems GmbH
Martinsried
www.menlosystems.com

Presentation at
Max-Planck-Institut für Astronomie
Heidelberg am 6.2.2015

Some basic physics…

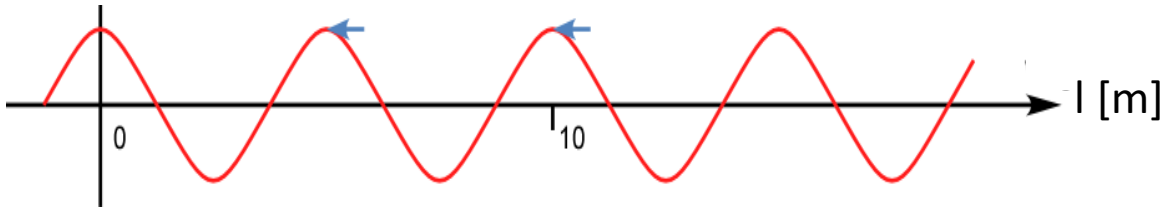
What is frequency?

Frequency is a measure of how often something (e.g. maxima of a electromagnetic wave) occurs in a certain time.



What is wavelength?

Wavelength is the spatial distance between two identical features of a (electromagnetic) wave.



Some basic physics…

Speed of light = constant = wavelength * frequency

Speed of light has been defined as c = 299 792 458 m/s

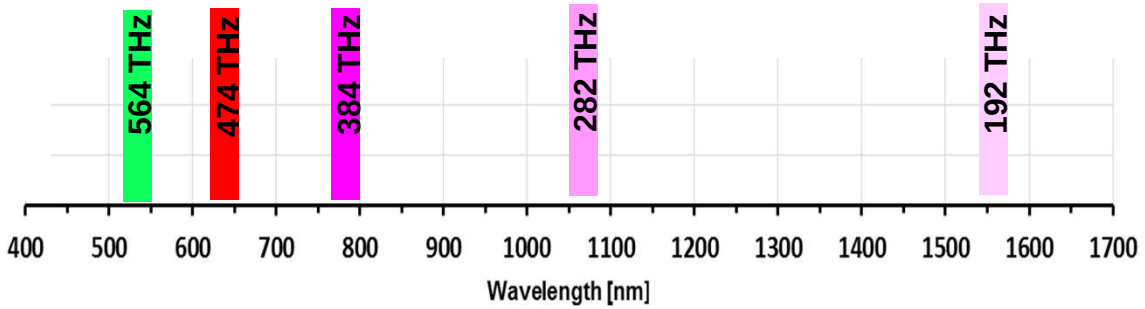
"Never measure anything but frequency!" (Arthur L. Schawlow, Nobel Price laureate 1981)

A simple idea: count the frequency of light

Is counting oscillations of light waves possible ?

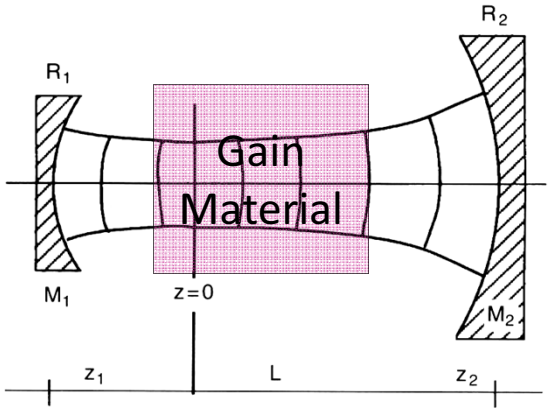
Use a rf counter?

532 nm or 564 THz, 564 000 000 000 000 oscillations per second.
Too much for rf counters!



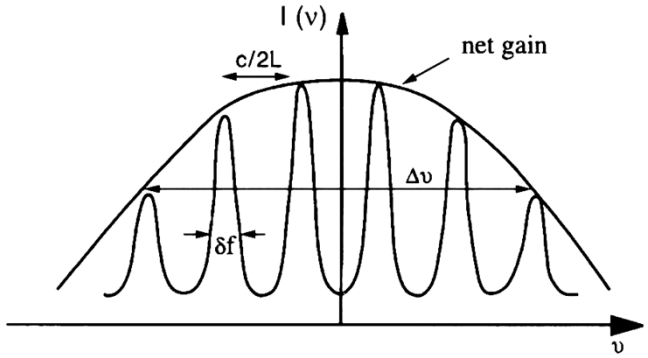
Solution to the problem requires some basic knowledge in laser physics…

Femtosecond Laser Basics I



The electromagnetic field between two mirrors can only exist as a standing wave.

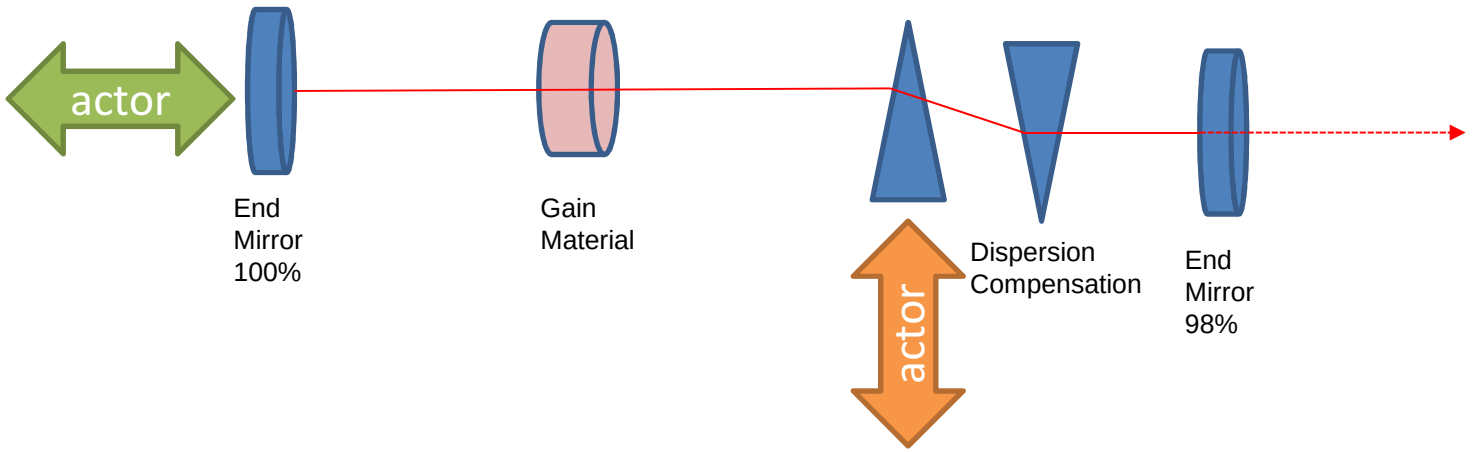
- Cavity modes $L = m \lambda/2$
- Round trip time $T = 2L/c$



A single pulse of a femtosecond laser provides a comb-like spectrum !

For a short laser pulse the phase of these frequencies need to be controlled by dispersion

Femtosecond Laser Basics II

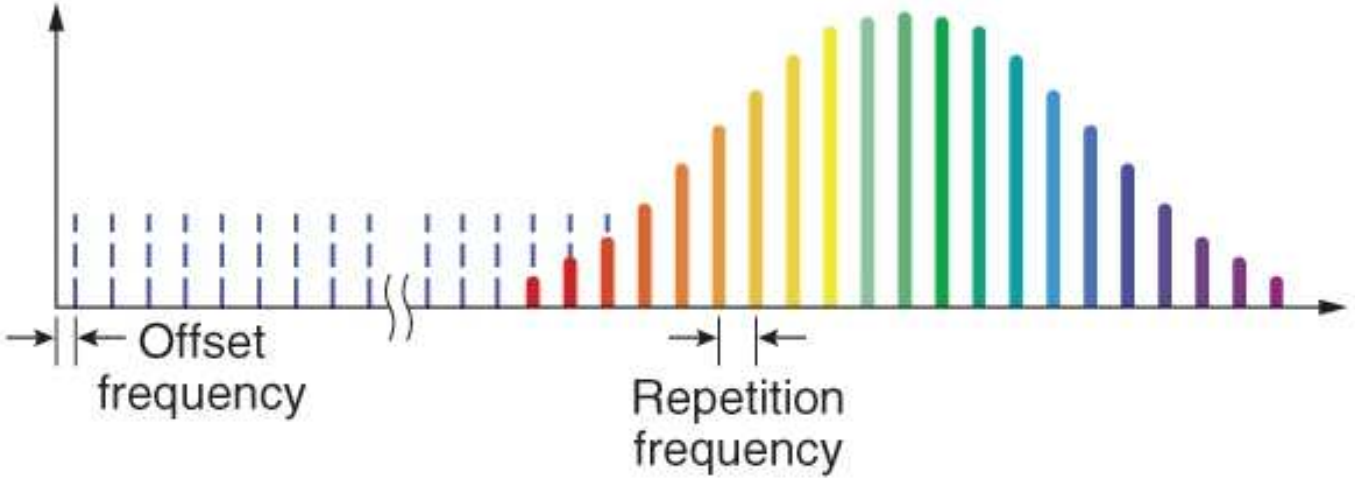


For frequency stabilization of cavity lines two actors are needed:

1) **Cavity length control**
2) **Cavity dispersion control**

<u>This is basically what you need for the optical frequency comb!</u>

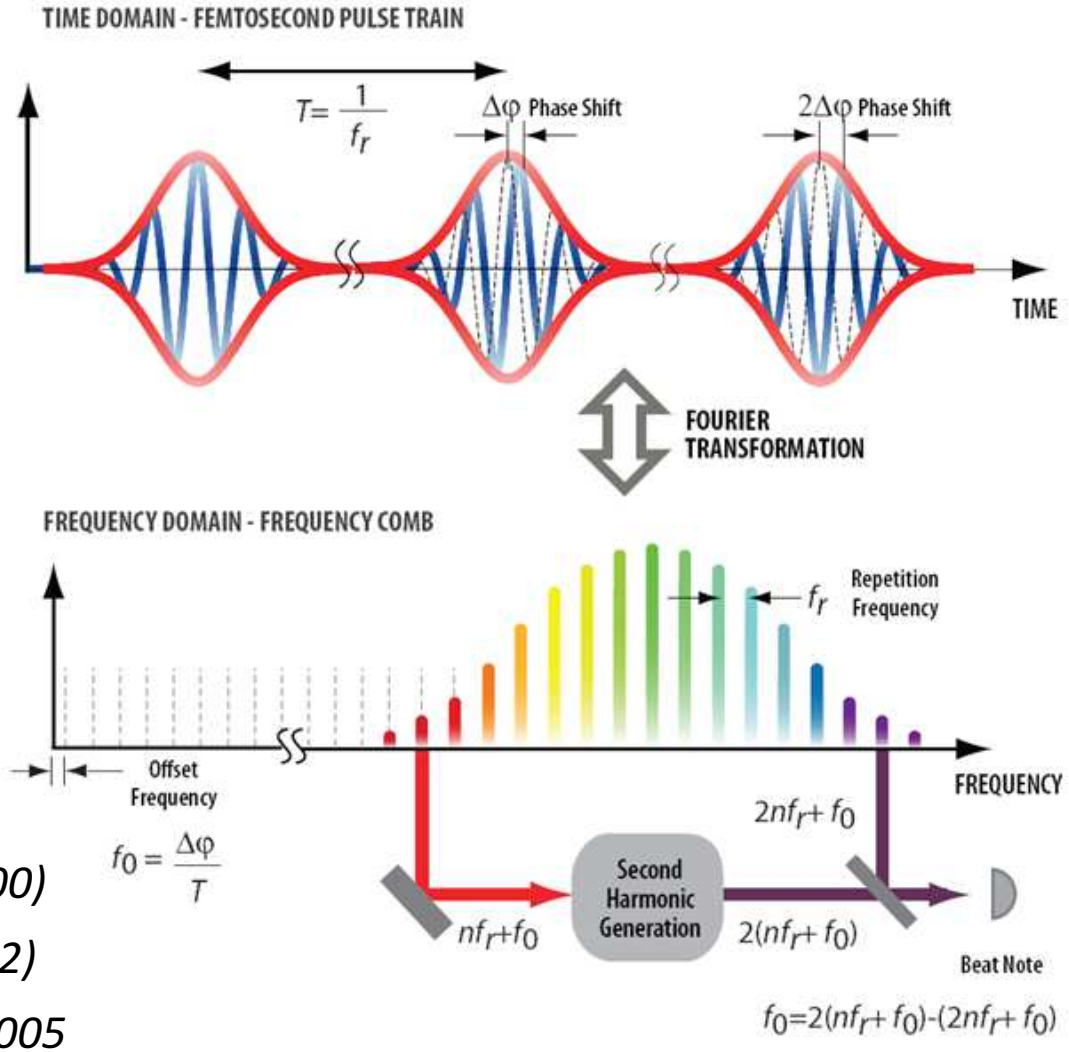
Frequency Ruler



$$f = n f_{rep} + f_o$$

How to measure the Offset Frequency

The CE-Phase is the Offset Frequency *and* it is controlled by intracavity dispersion



Jones, et al. Science, vol. 288 (2000)

Udem et al. Nature, vol. 416 (2002)

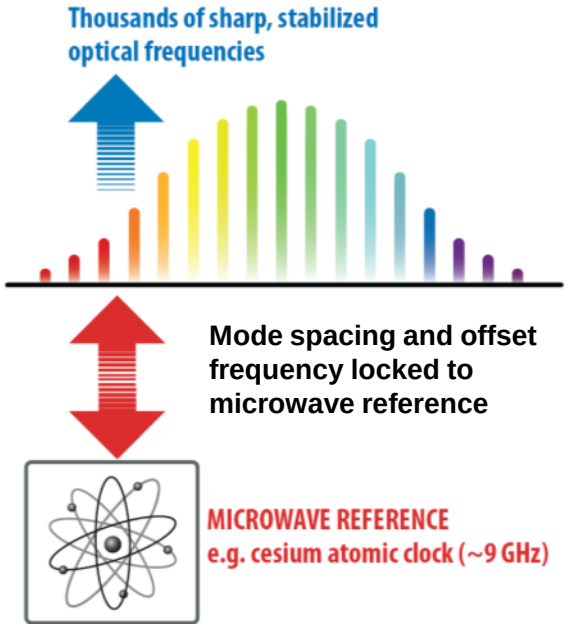
J. Hall & T. Hänsch Nobel Prize 2005

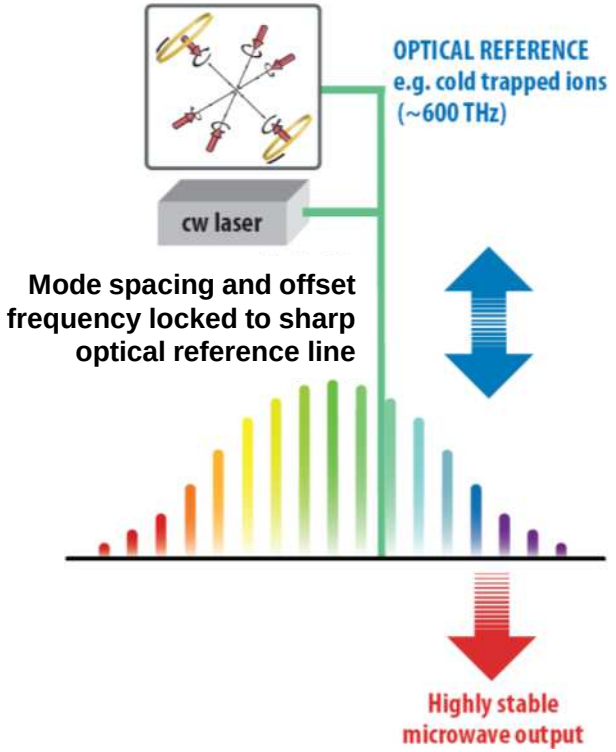
OPTICAL ⇔ RF ⇔ OPTICAL

Frequency Comb is a gear between the optical and the radio frequencies !

It links microwave to optical frequency domain.

This link can be used in both directions





Commercialization: FC1500-250

Frequency Comb is the core product of Menlo Systems GmbH

- Turn key
- Easy to operate
- Covers visible to MIR
- Compact
- Robust
- Reliable
- Installation in < 1 day

You need a Frequency Comb if you want to…

… work at highest accuracy and precision…

- Measure and calibrate cw lasers
- control and stabilize cw lasers
- calibrate precision spectrographs
- optical fourier transform spectroscopy
- generate stable radio frequencies
- for massive parallel spectroscopy
- for precision dimensional metrology and ranging

Typical customers are from

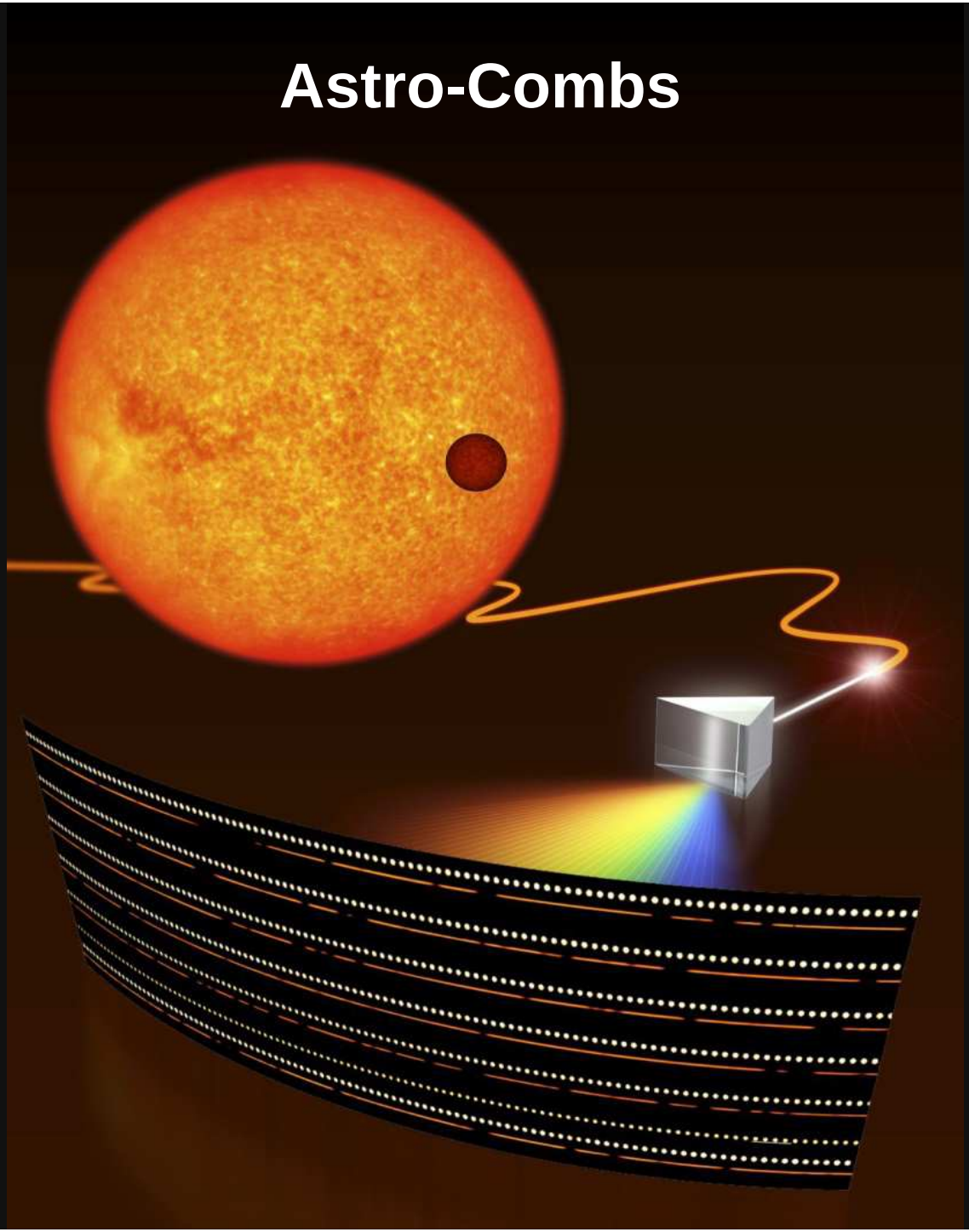
- cold atom physics (> 180 groups)
- quantum optics (plenty)
- time and frequency generation (NMIs + research institutions, universities)
- optical clock experiments (> 40 experiments)
- astrophysics labs (several)

Laser Applications

Menlo offers solutions for many fields

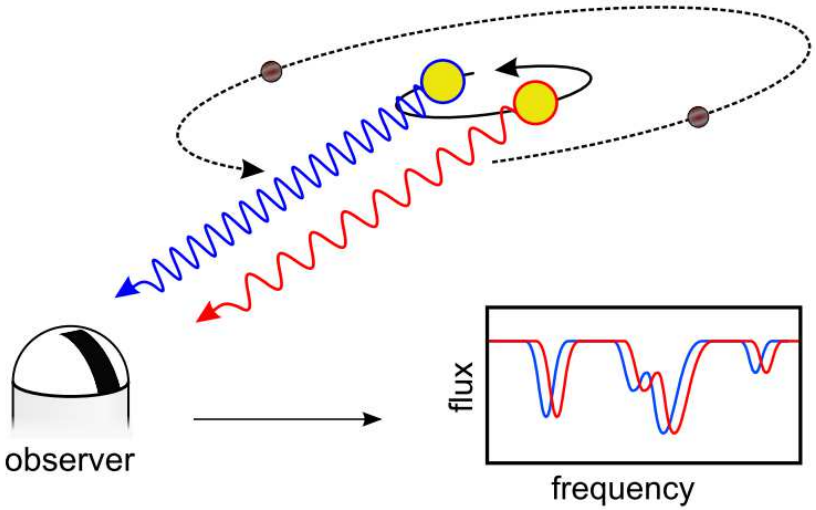
- dimensional metrology
- precision measurements & control
- detection and analysis
- optical clocks
- calibration of lasers & spectrometers
- synchronization and timing
- frequency distribution
- amplifier seeding
- high resolution and THz spectroscopy
- quality inspection
- medical & ophthalmology
- micromachining
- 2 photon polymerization and 3d printing

Astro-Combs



Astronomic applications

- **Hunt for Earth-like exoplanets**



Dopplershift:

$$\frac{\Delta f}{f} = -\frac{\Delta v_r}{c}$$

Δv_r for an exo-Earth with 1 yr period: **9 cm/s**

@ $600\,THz$:

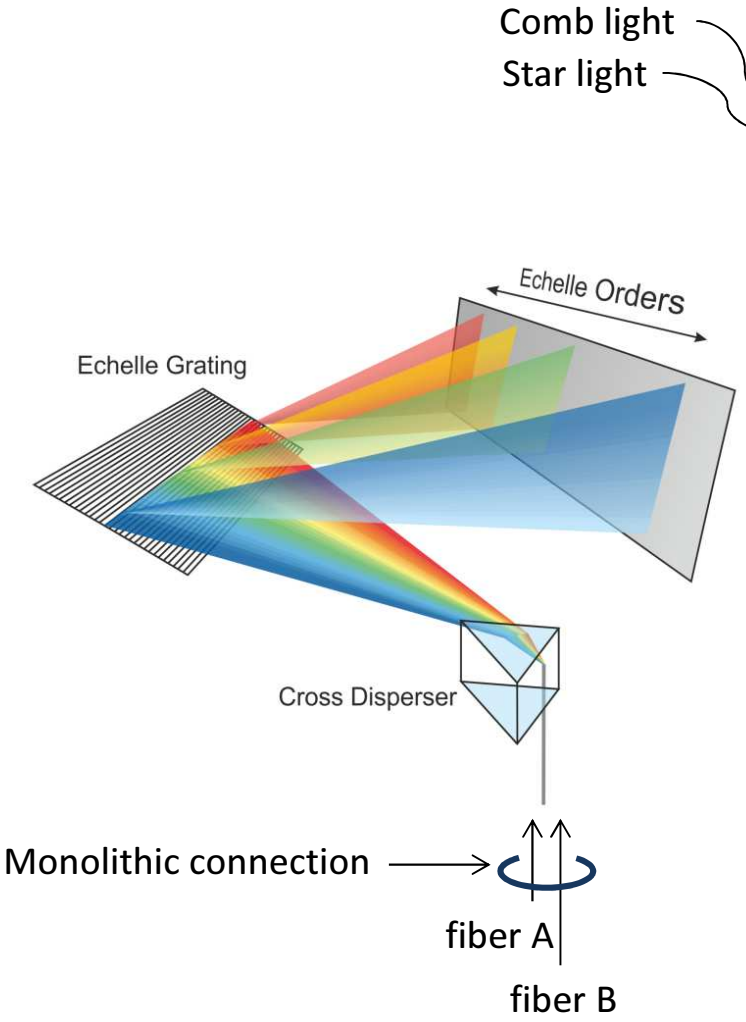
$1\,cm\,s^{-1} \triangleq 20\,kHz$

$\triangleq 3 \text{ x } 10^{-11}$

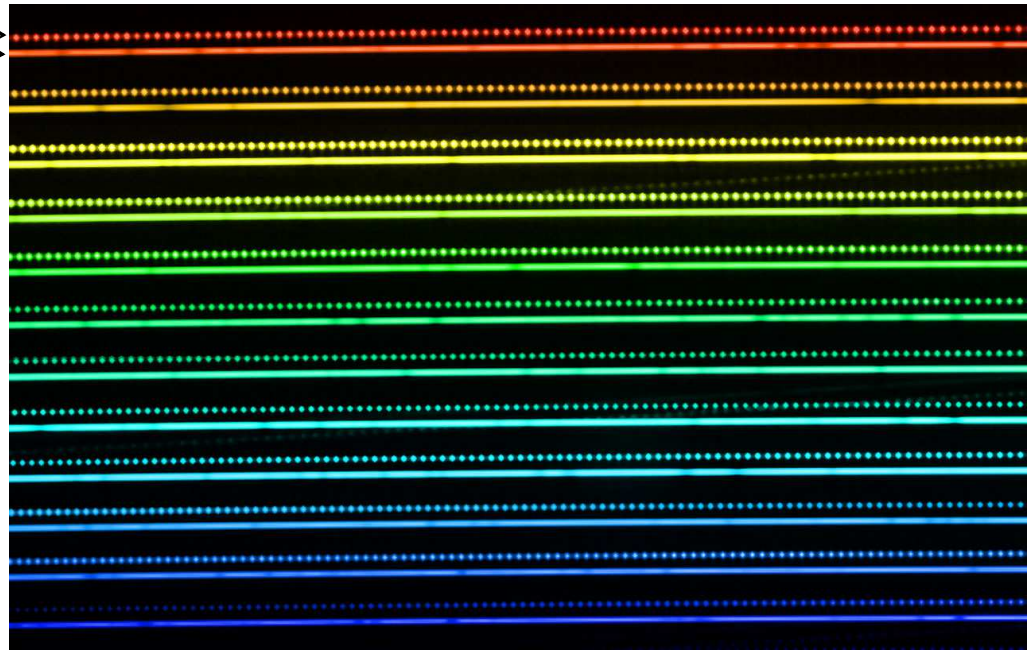
$\triangleq 1/75000$ px

- **Direct measurement of the cosmic expansion**
- **Study the variation of fundamental constants**

Echelle spectrograph calibration



Star light and comb light on HARPS CCD:

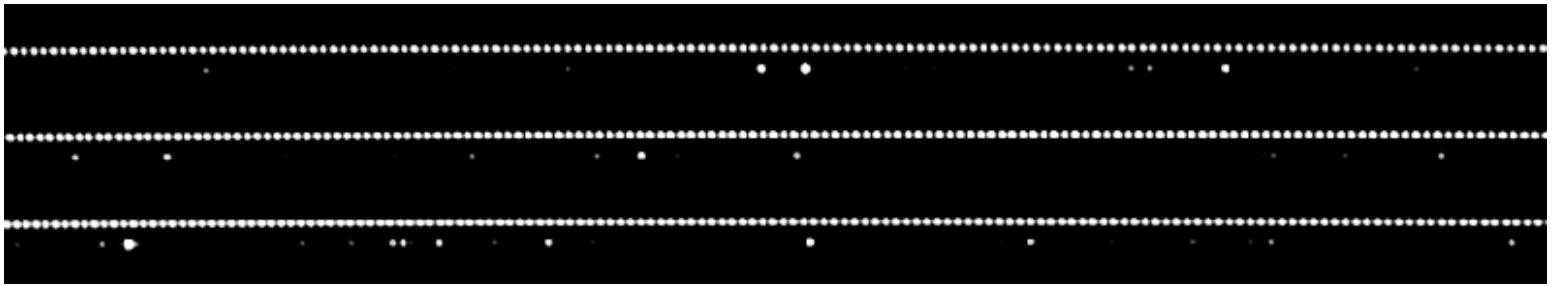


Source of image: ESO press release
The color range is for illustrative purposes only.

Comb compared to Thorium-Argon calibration

Menlo

ThAr and comb spectrum on HARPS spectrograph



	Thorium-Argon	Frequency comb
Line spacing	- irregular	+ perfectly regular, adjustable
Line intensities	- irregular	+ Low fluctuations line-to-line, Spectral envelope programmable
Line positions	- fixed	+ tunable
Absolute frequency	- Known to ~ 10 m/s	+ Given by atomic clock
Short-term repeatability	- Some 10 cm/s	+ 2.5 cm/s demonstrated, 1 cm/s appears feasible
Long-term repeatability	- Drifts through aging of lamp (~m/s)	+ No drift

Astro-combs need > 10 GHz mode spacing

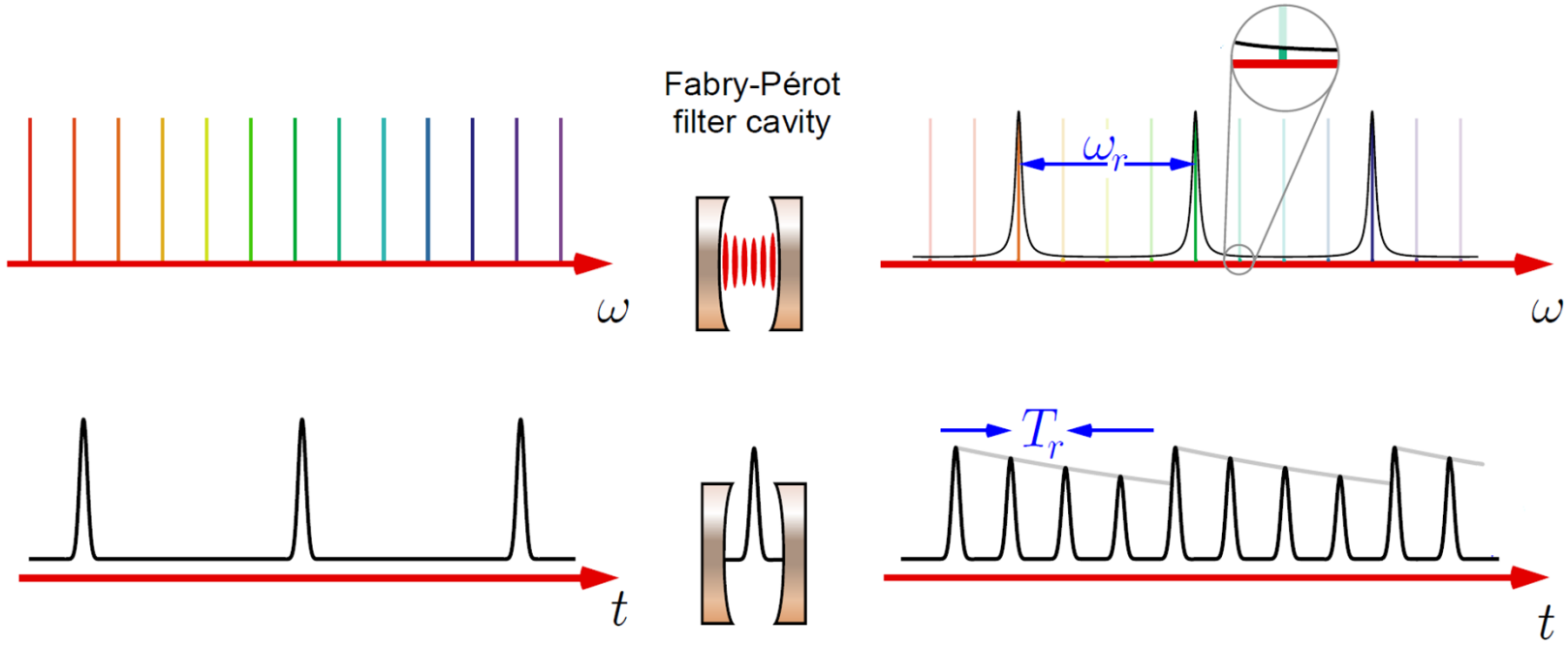
Optimum mode spacing for spectrograph calibration:

3x Resolution of spectrograph

➡ Typical mode spacings: 10 – 30 GHz

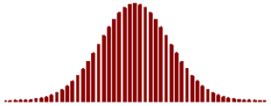
Mode spacing for HARPS: 18 GHz

➡ Increase of mode spacing by Fabry-Perot filters

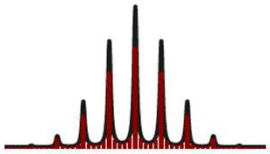


Concept of HARPS comb

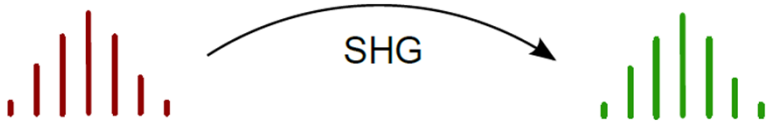
IR fiber comb



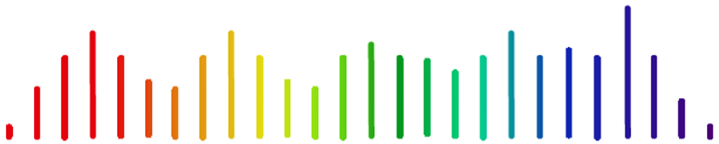
Mode filtering



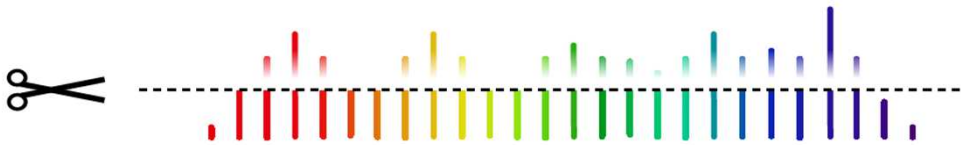
Second-harmonic generation (SHG)



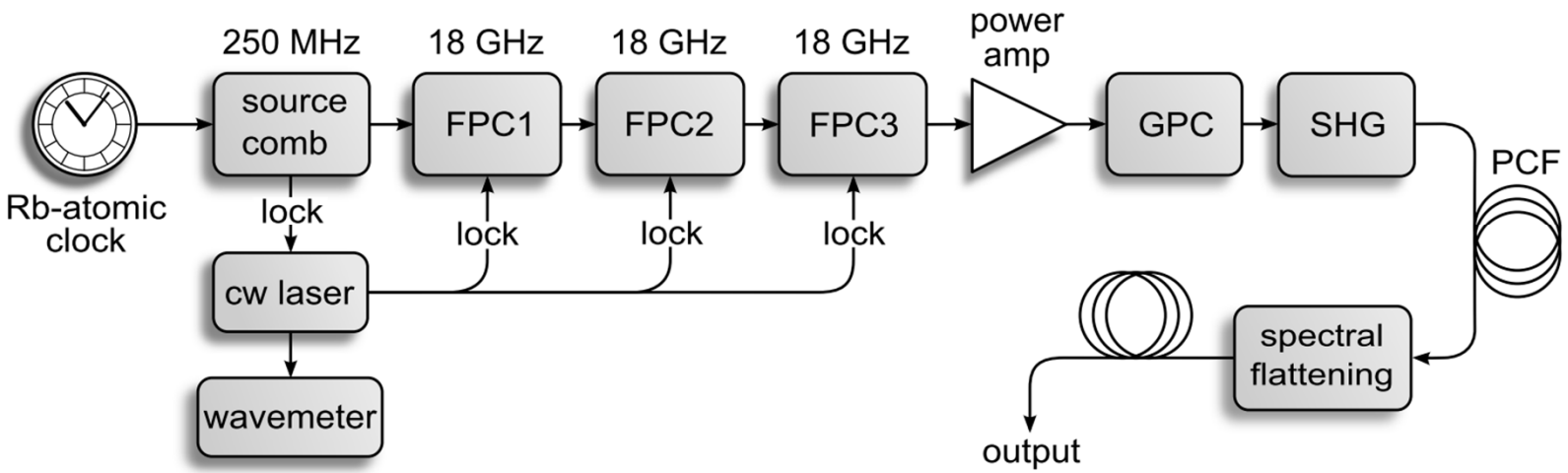
Spectral broadening



Spectral flattening



Configuration of an Astrocomb



Abbreviations:

Cw laser: continuous wave fiber laser

FPC: Fabry-Pérot cavity

GPC: combined grating and prism compressor

SHG: Second-harmonic generation

PCF: tapered photonic crystal fiber

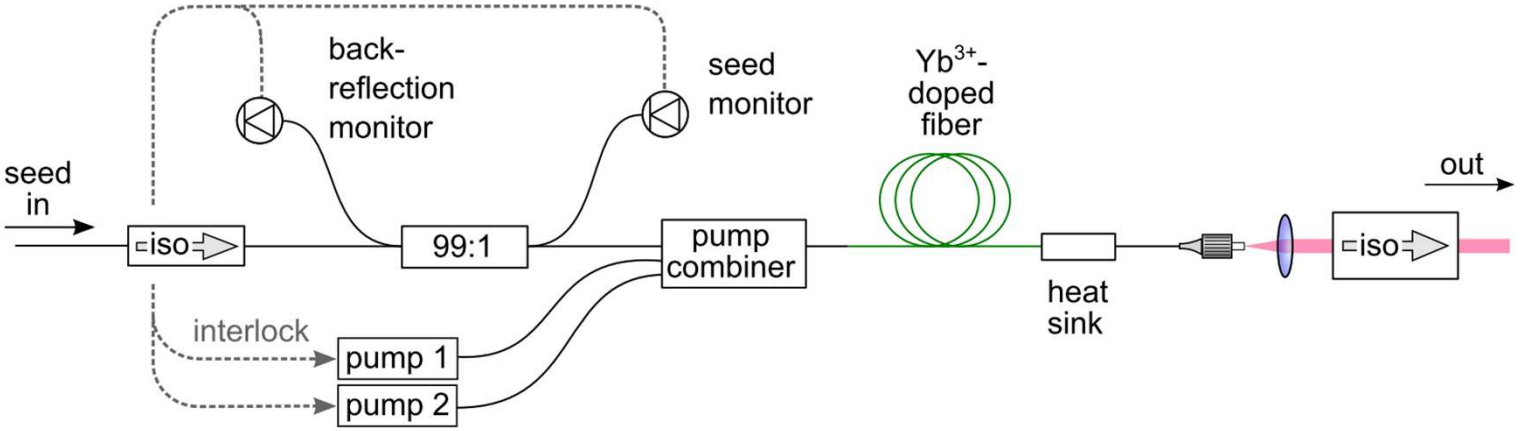
Typical Astrocomb System

2 Boxes like this ↑

By December 2014 four units have been shipped

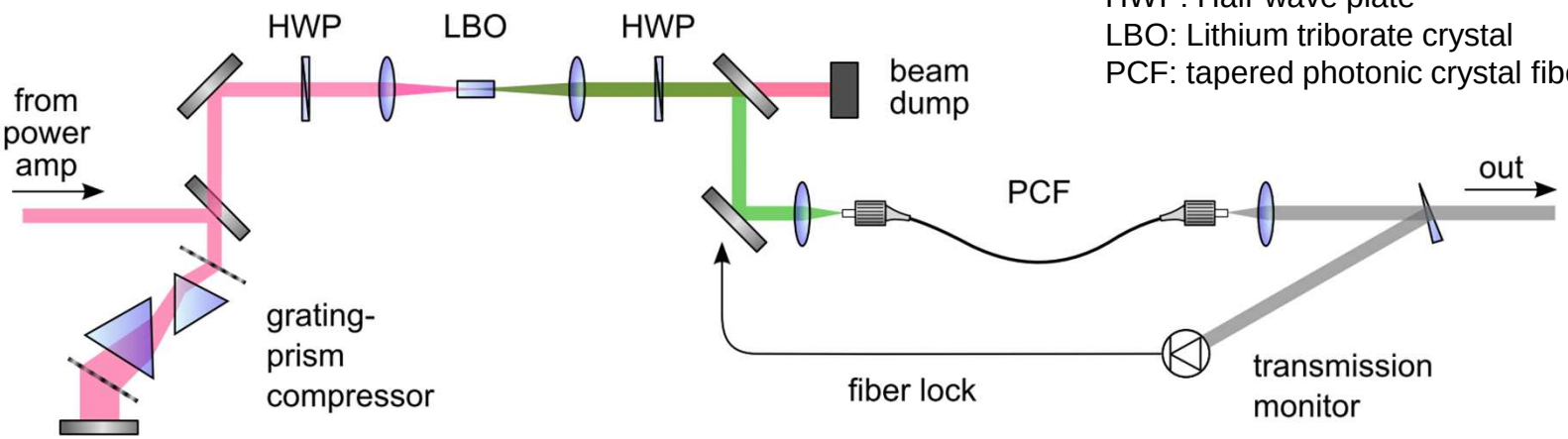
Nonlinear frequency conversion

Power amplifier:

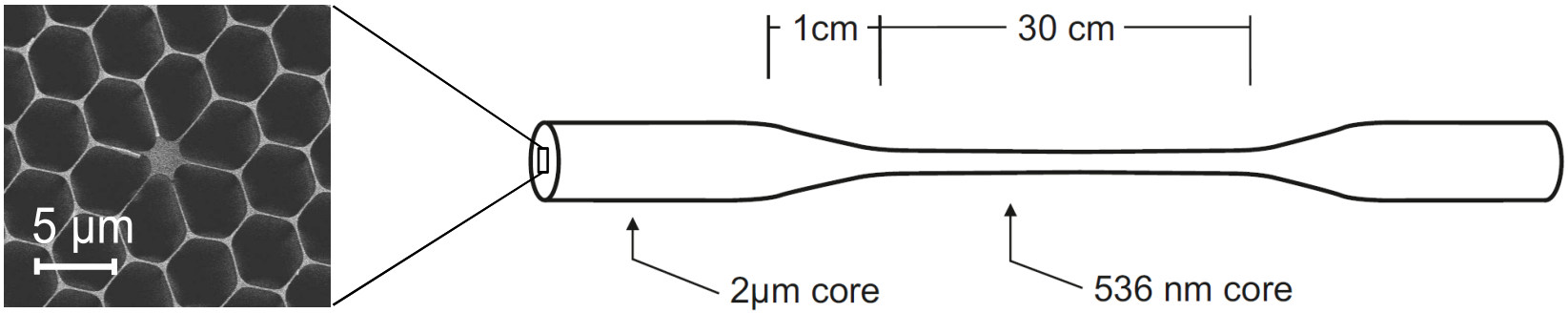


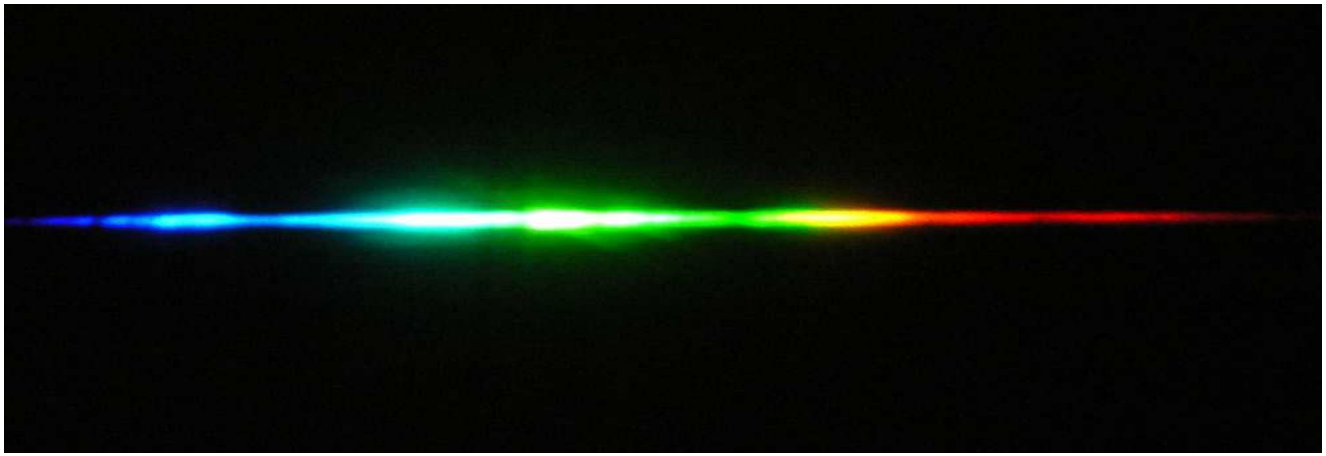
Frequency conversion:

HWP: Half-wave plate
LBO: Lithium triborate crystal
PCF: tapered photonic crystal fiber

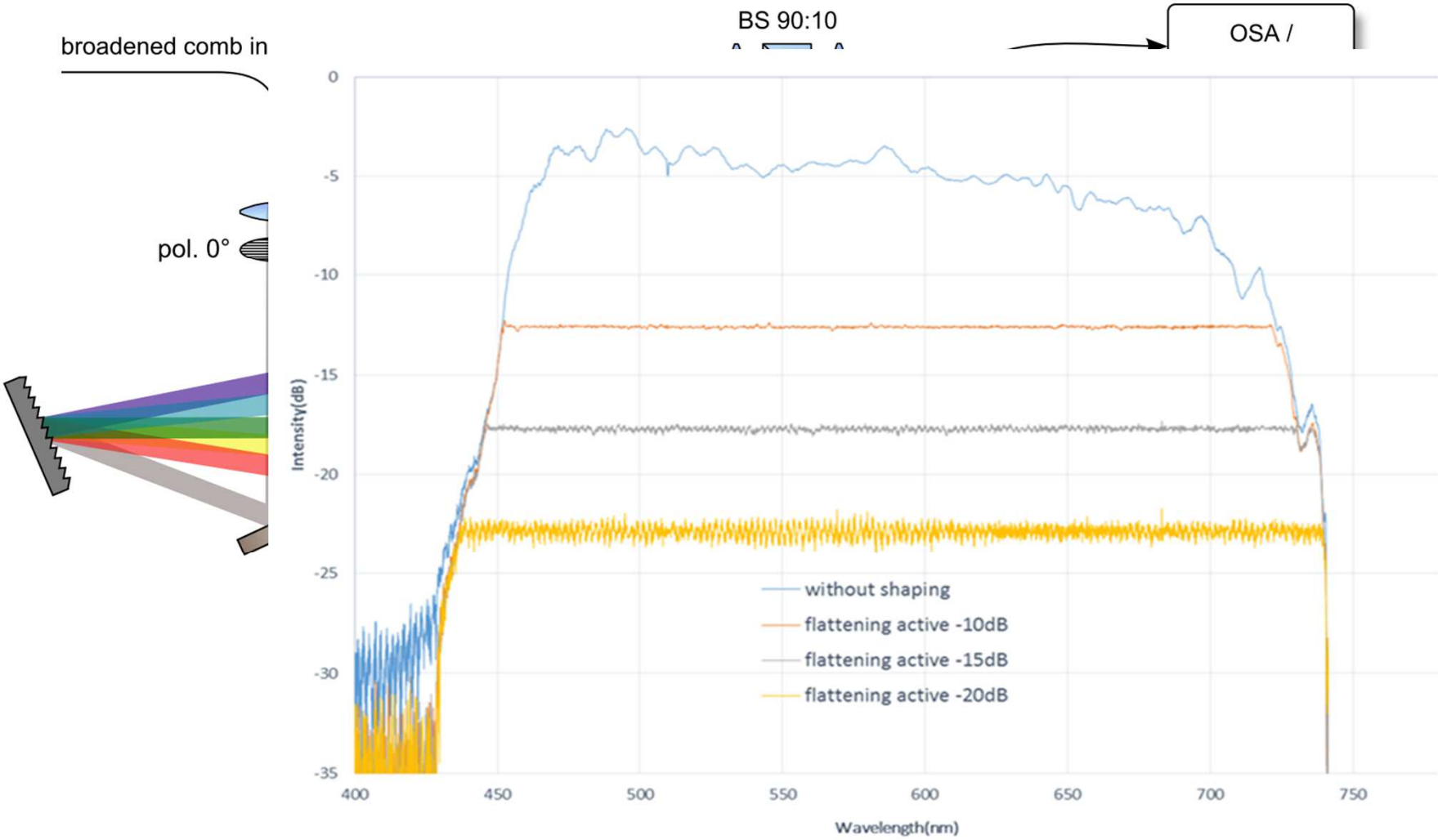


Spectral broadening



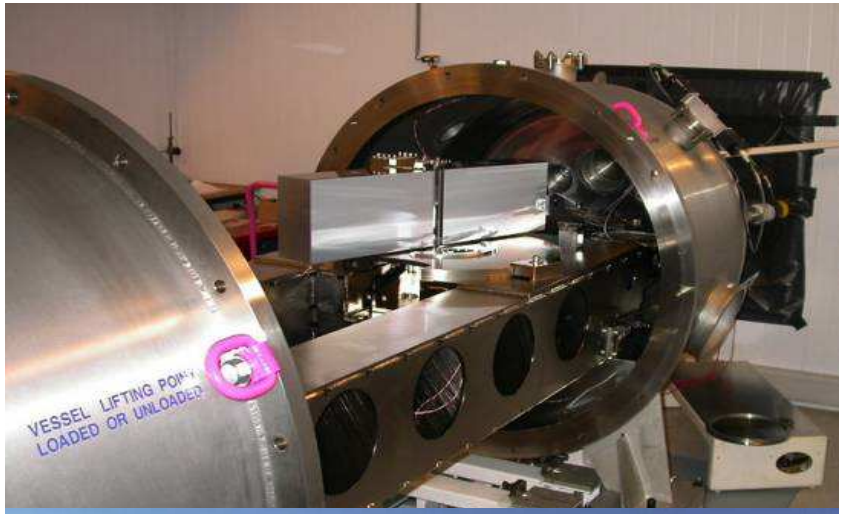


Flattening of broadened spectrum



Calibration of HARPS spectrograph in La Silla, Chile

Test campaigns on HARPS



January 2009

March 2010

Nov. & Dec. 2010

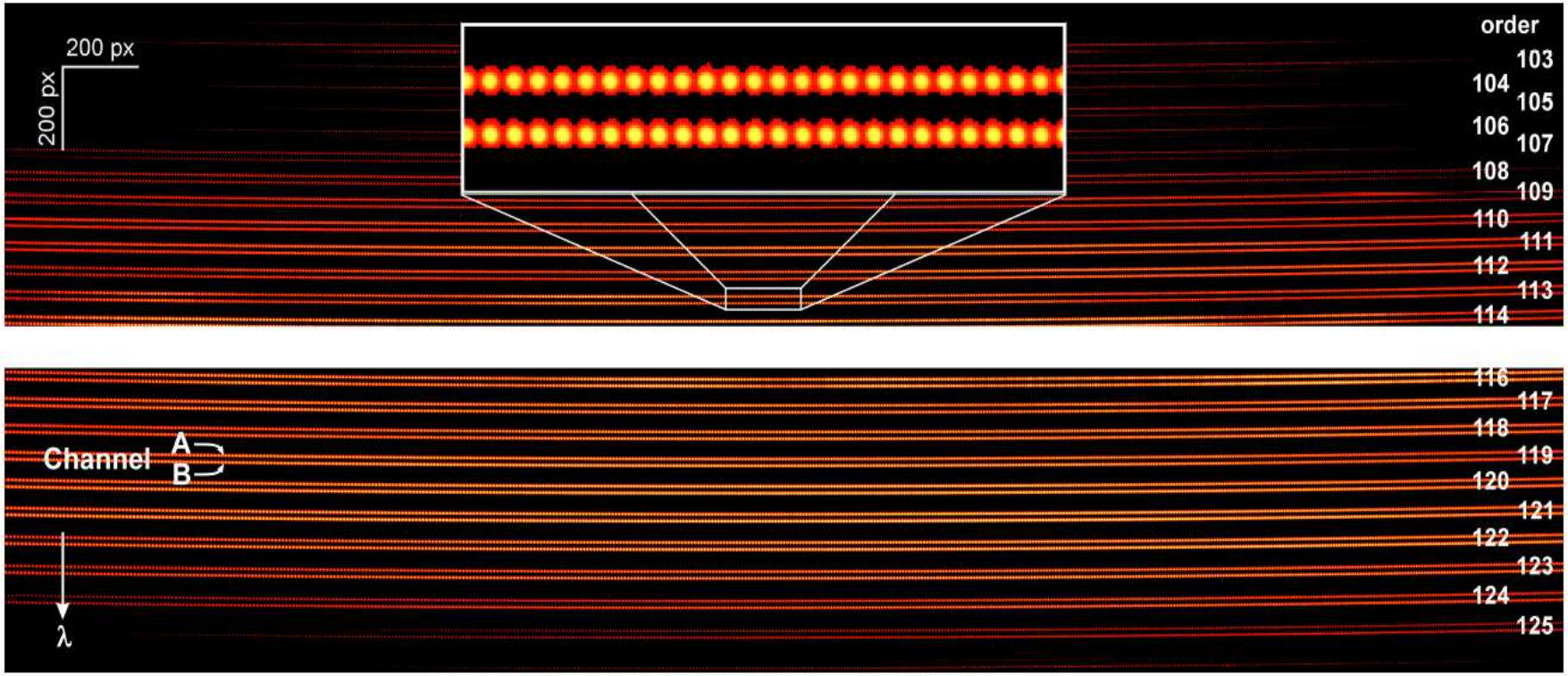
January 2011

February 2012

November 2014

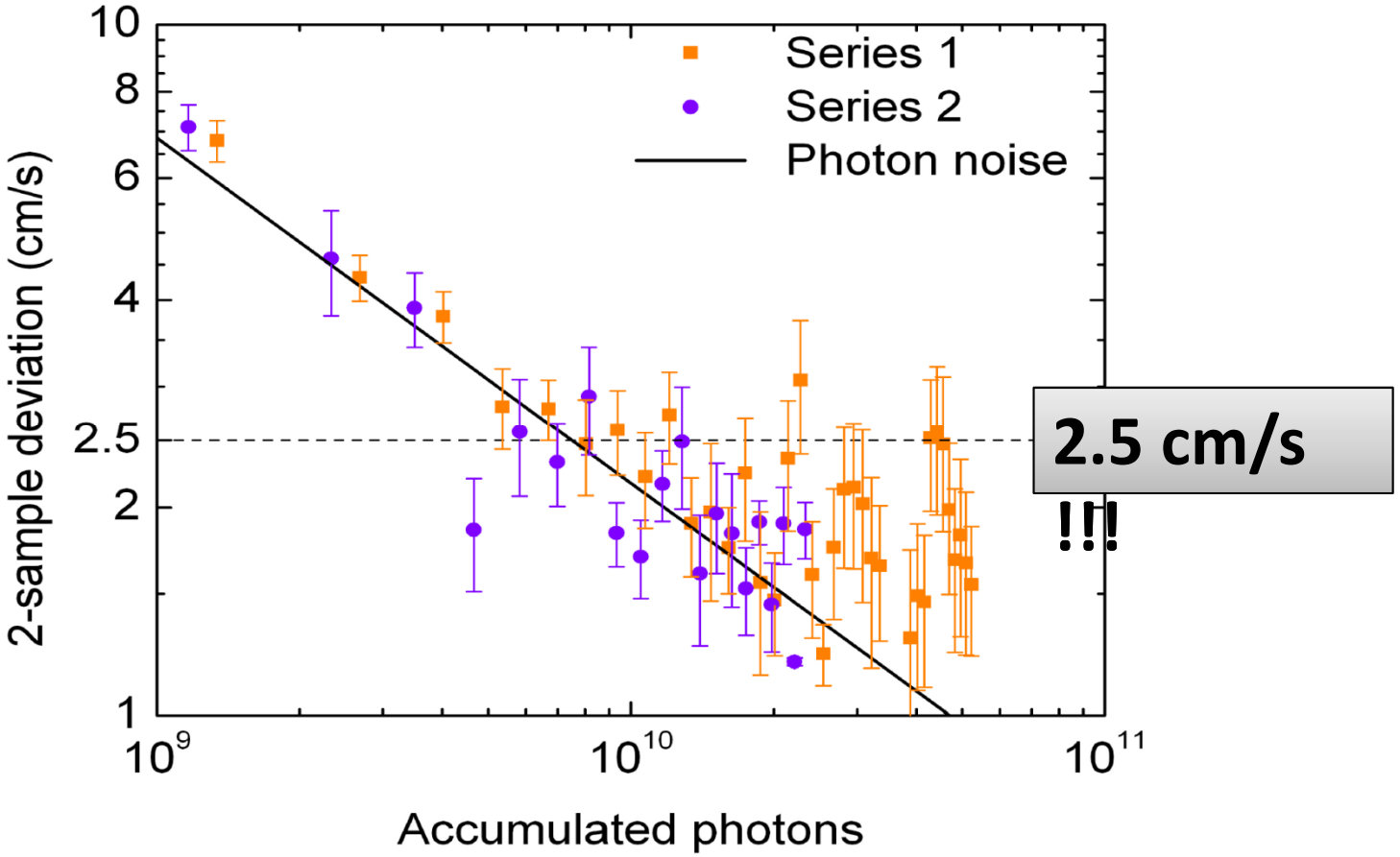
Eng mated
syst ration

Calibration Tests



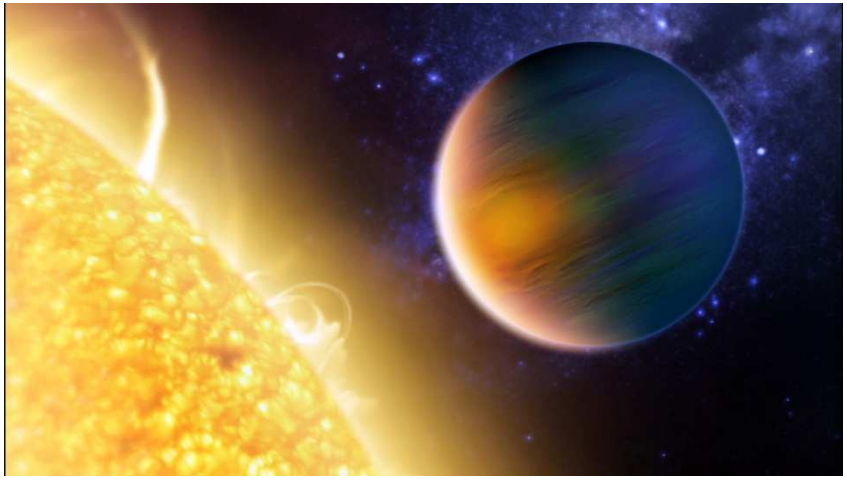
2-sample deviation

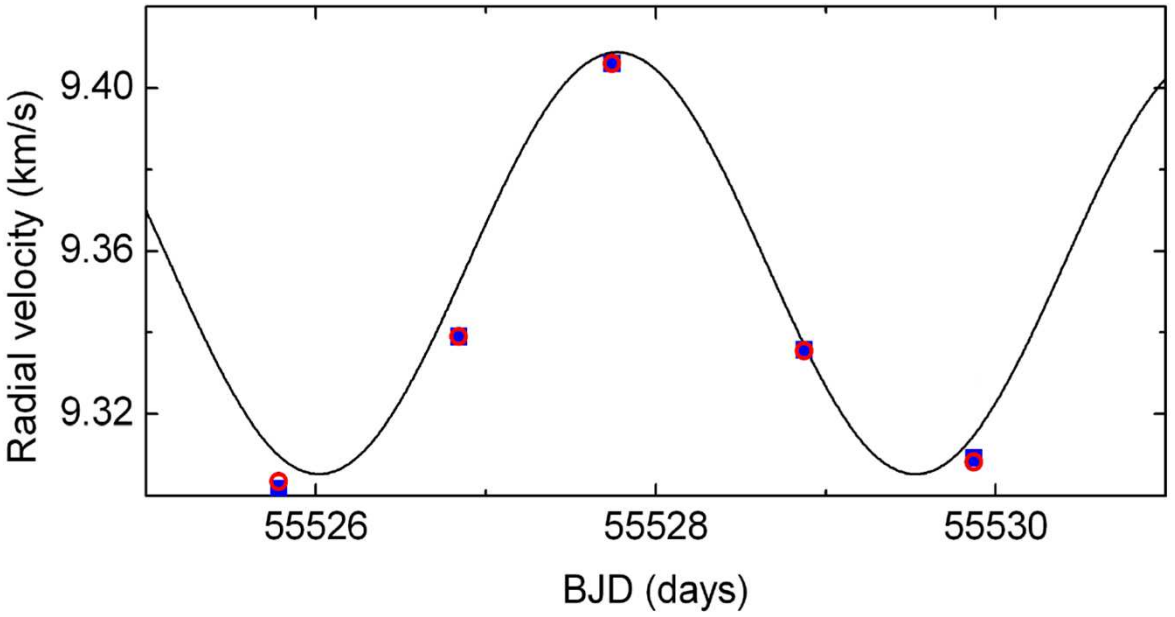
averaging over several exposures



Exoplanet HD 75289 b

Menlo





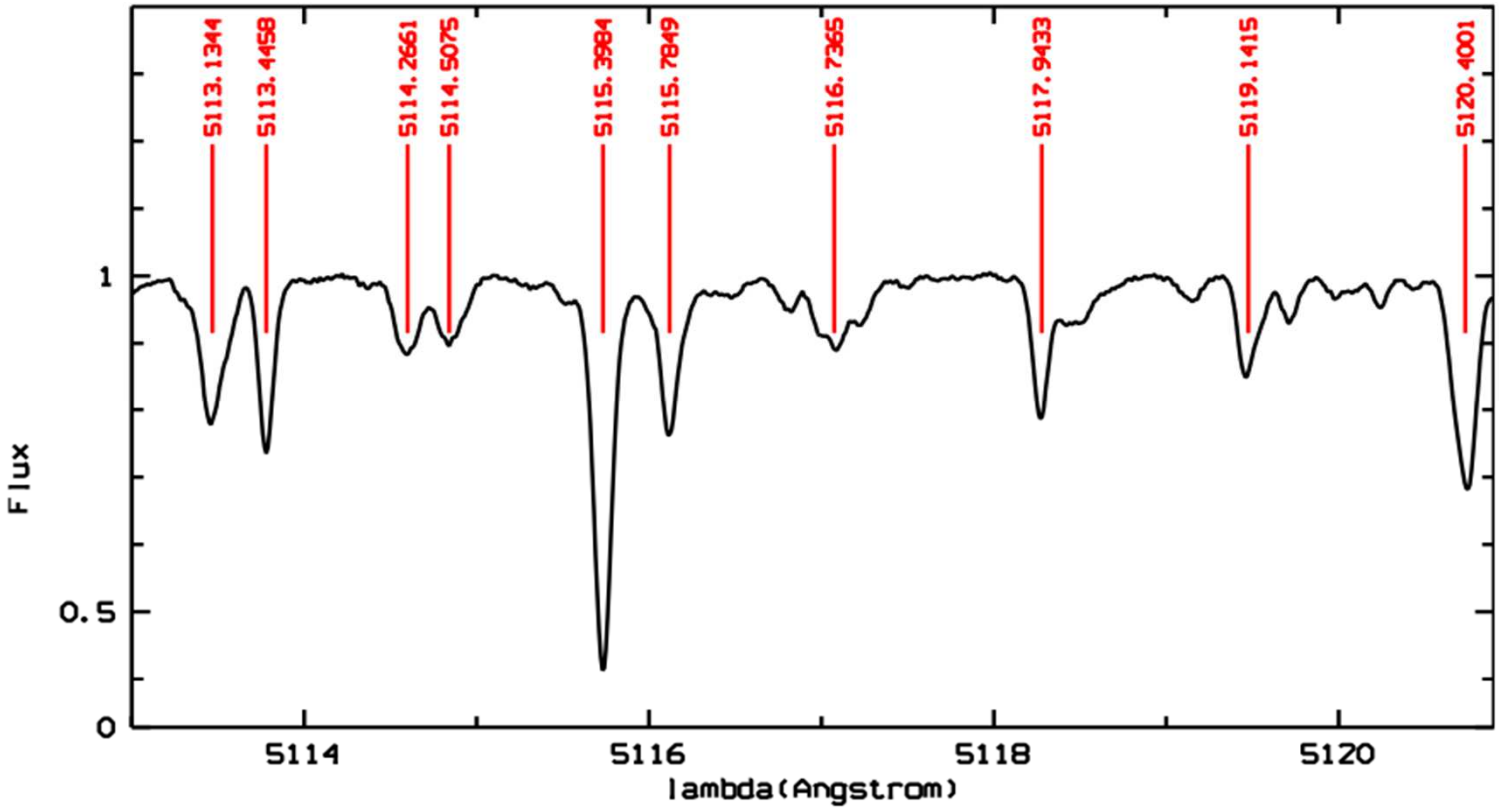
Installation at the German Vacuum Tower Telescope (VTT) in Tenerife, Canary Islands

October 2011 / May 2012

Comb calibrated solar atlas

A comb-calibrated solar atlas

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



VTT telescope, Tenerife

Installation on the VTT site

Tilo Steinmetz and Rafal Probst installing on site

Astro-Comb installations

2014	HARPS, Chile
2014	Wendelstein, Germany
2014	LAMOST, China
2015	ESPRESSO, Chile

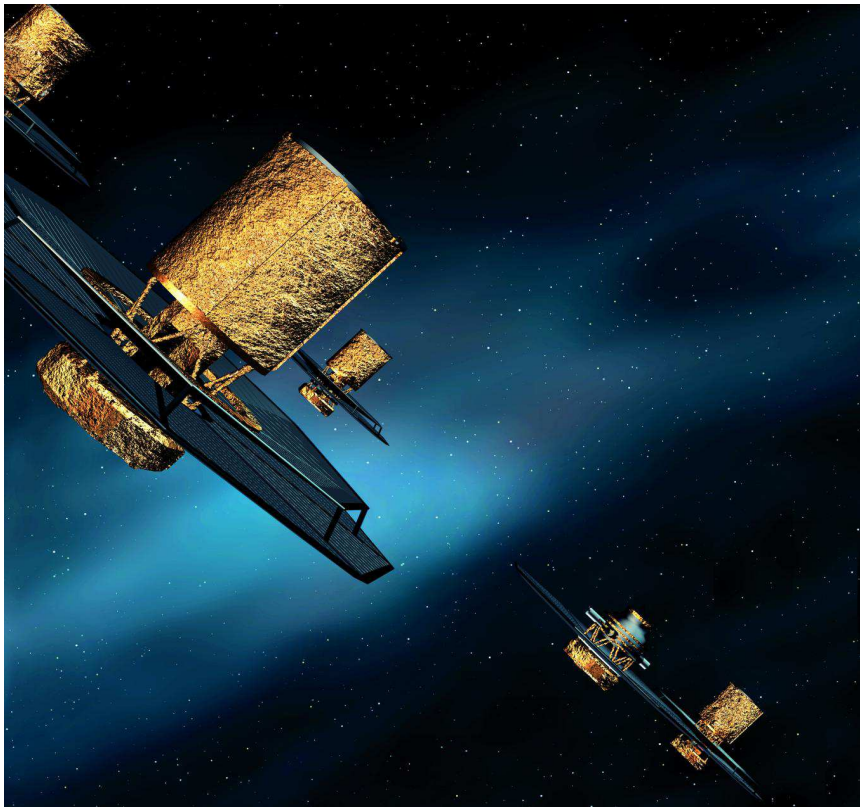
Comb based ranging

Comb based Formation Flights: IRASSI

Menlo

Future mission study for 5 free flying satellite based telescopes

Telescopes	5
Baselines	10
Baseline distance	7 – 1000 m
MIR Wavelength	50 – 300 µm
Bildfeld (Einzelteleskop)	6 arcsec
Winkelauflösung (@ 300 µm)	0.1 arcsec
Genauigkeit Teleskop-Pointing (APE)	0.3 arcsec
Ranging precision	1 µm

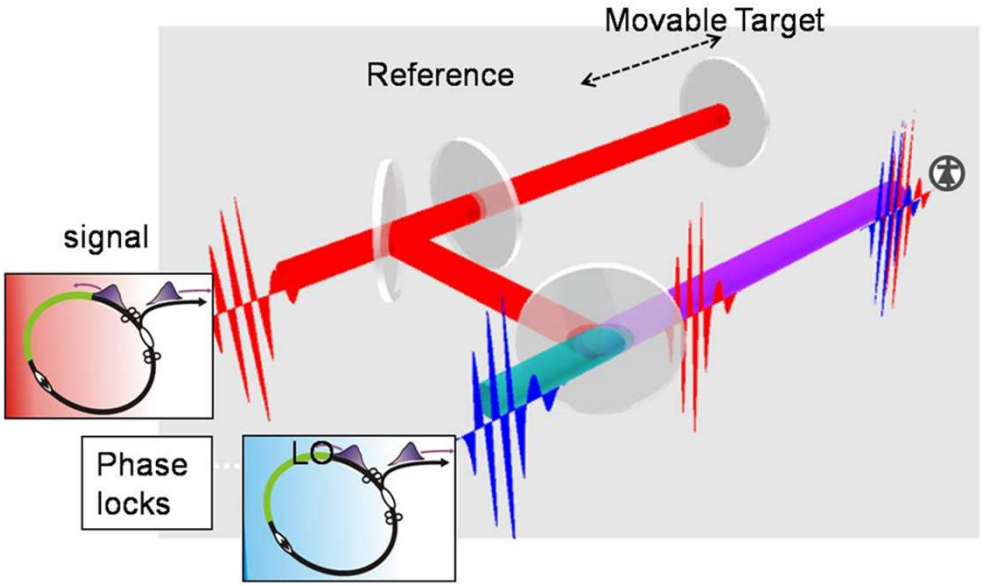


Infrared telescope formation DARWIN (credit ESA)

Goal: Solve MIR interferometric ranging problem for a a DARWIN-type mission with comb based technology

(Menlo, MPIA, UniBWM, TUBs, financed by DLR)

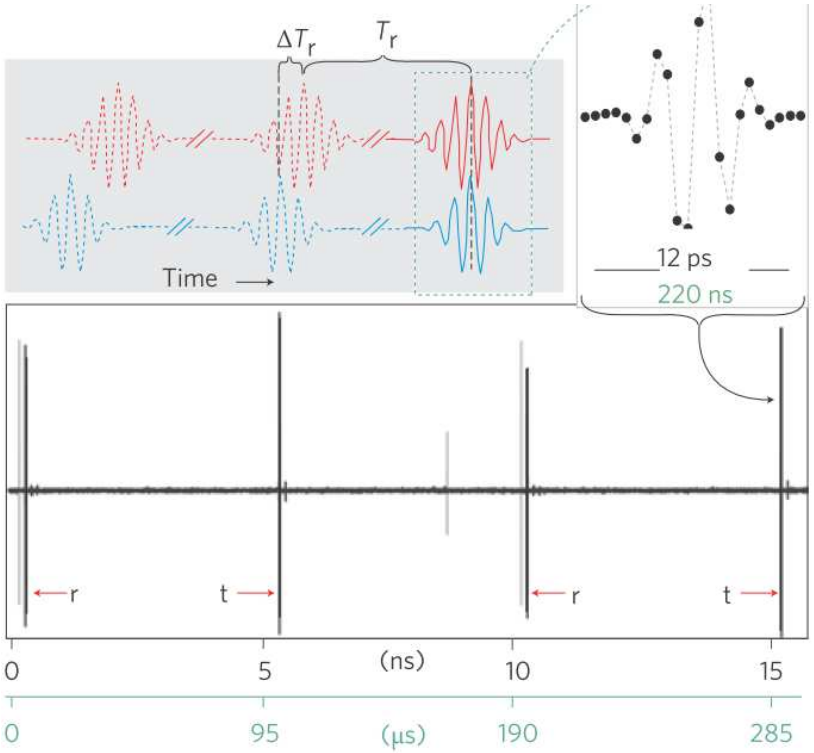
Dual Comb based Ranging



Interferometric range detection
via RF time dependent signals
from heterodyning between
2 combs at different repetition rate

(Newbury & coworkers 2009)

Time Of Flight + Interferometric measurement resolves the ambiguity compared to pure interferometric ranging




Thank you for your attention