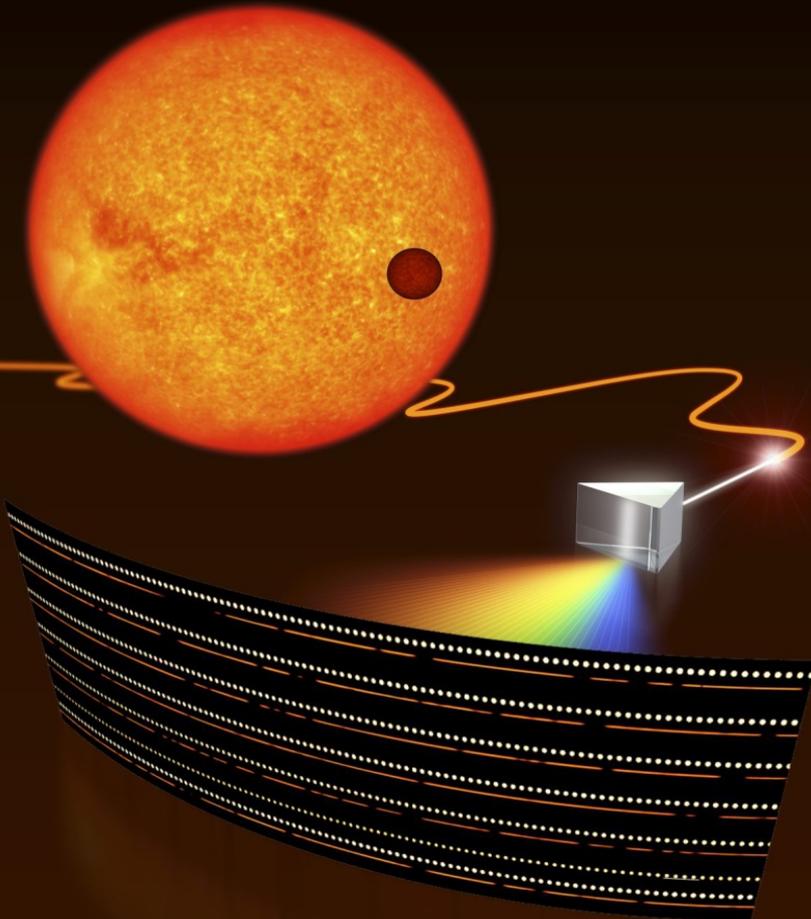


# Frequency Combs for Astronomical Applications



Yuanjie Wu

Menlo Systems GmbH  
Martinsried, Germany

ESO Calibration Workshop  
17. 01. 2017



Tobias Wilken  
Thomas Udem  
Theodor W. Hänsch



Gaspare Lo Curto  
Gerardo Avila  
Florian Kerber  
Antonio Manescau  
Luca Pasquini  
Eszter Pozna



Ronald Holzwarth  
Tilo Steinmetz  
Rafael A. Probst  
Yuanjie Wu  
Olaf Mandel  
Sebastian Stark



Massimiliano Esposito  
Jonay I. González Hernández  
Rafael Rebolo-López



Frank Grupp  
Hanna Kellermann  
Anna Brucalassi



Bruno L. Canto Martins  
José Renan de Medeiros  
Izan C. Leão

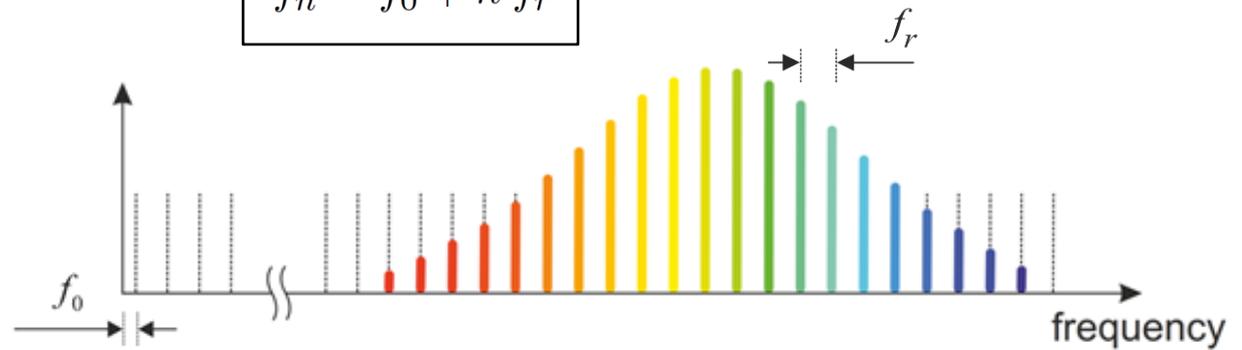
# **Basic concepts**

frequency combs as calibration source

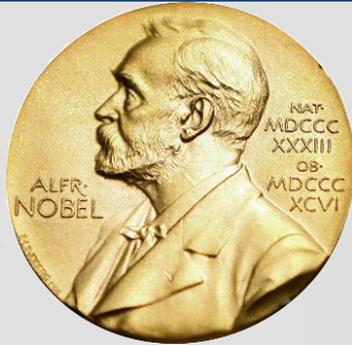
# Laser frequency combs (LFCs)

FREQUENCY DOMAIN:  
FREQUENCY COMB

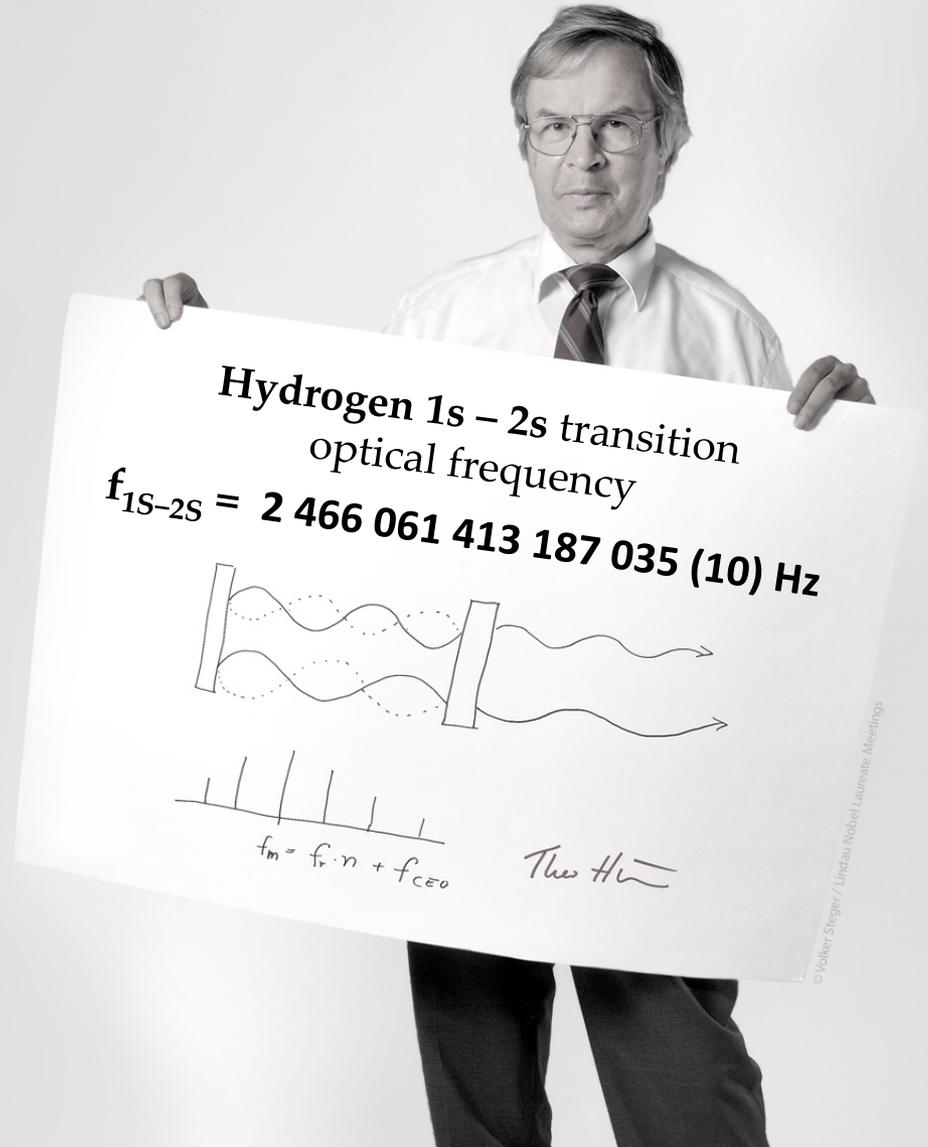
$$f_n = f_0 + n f_r$$



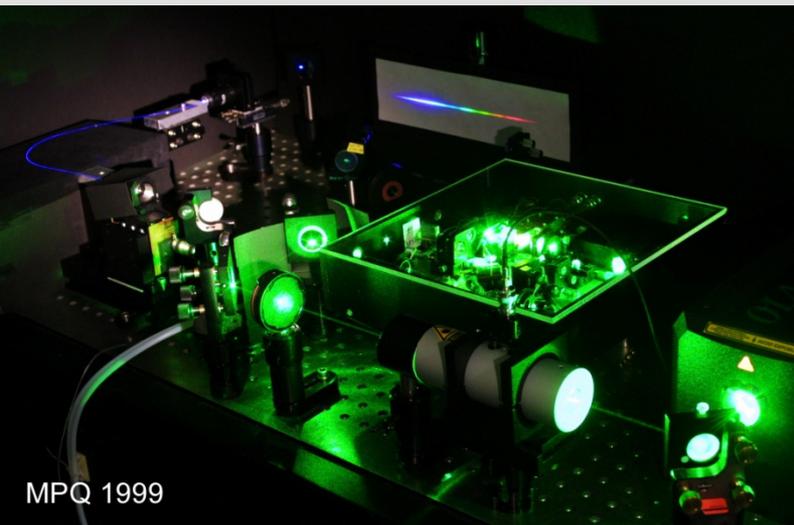
# Physics Nobel Prize of 2005



T. W. Hänsch J. L. Hall R. Glauber

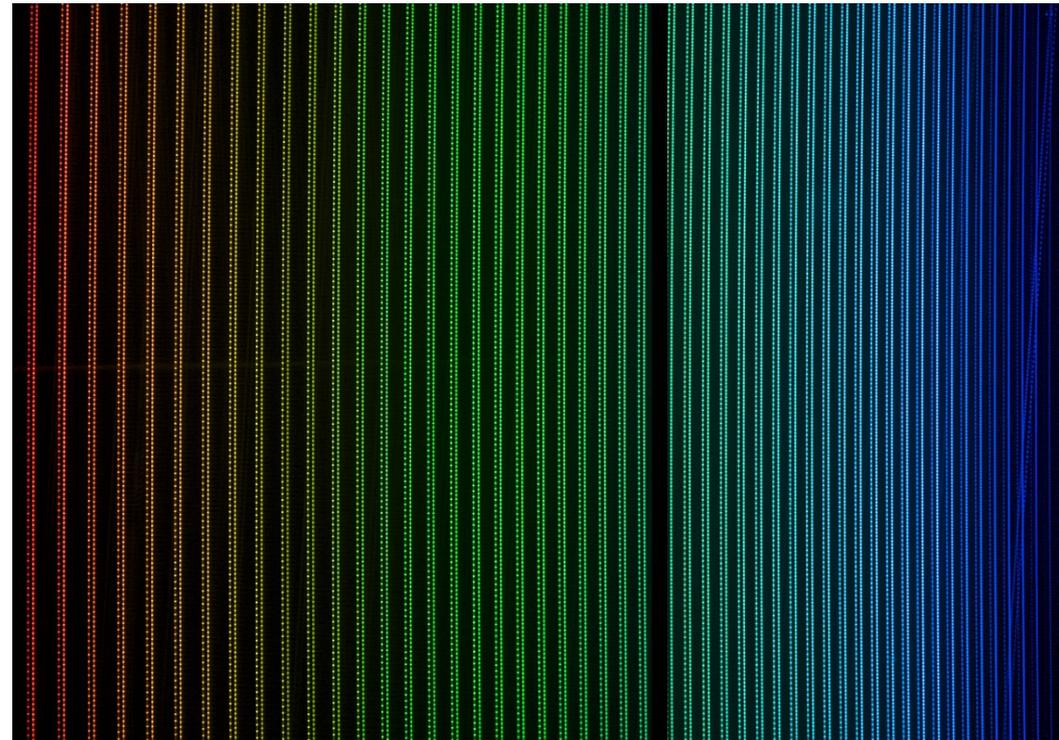
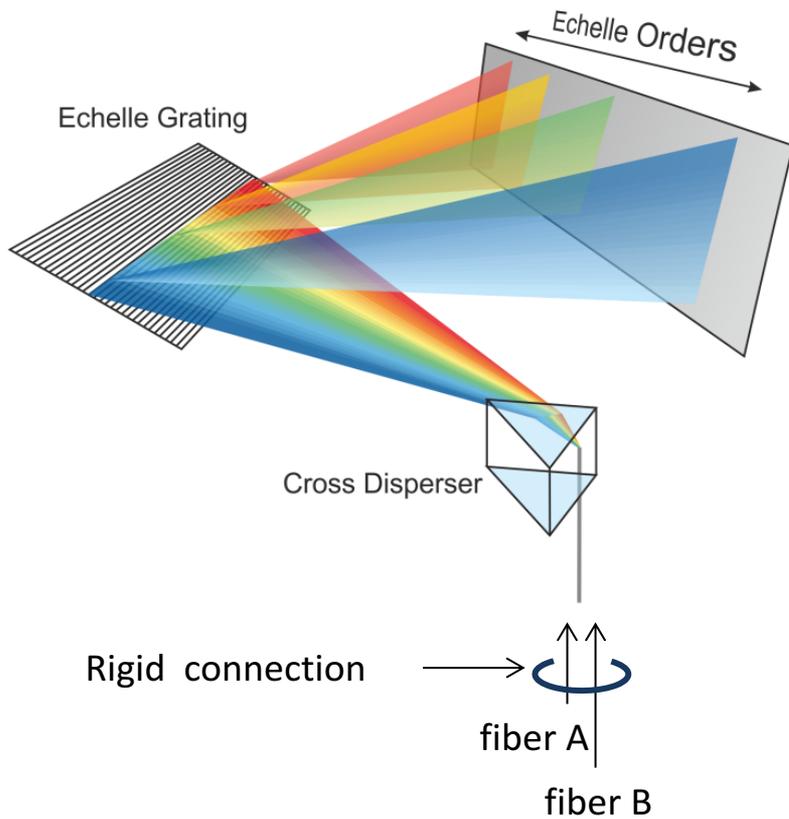


© Volker Steger / Lindau Nobel Laureate Meetings



# Echelle spectrograph calibration

Echelle orders on spectrograph CCD:



Source of image: ESO press release

fiber A fiber B

Comparison between ThAr and comb spectrum :



	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 $\sim 10$ m/s	+ Given by atomic clock
Short-term repeatability	- Some 10 cm/s	+ 1 cm/s demonstrated @ HARPS
Long-term repeatability	- Drifts through aging of lamp ( $\sim$ m/s)	+ No drift

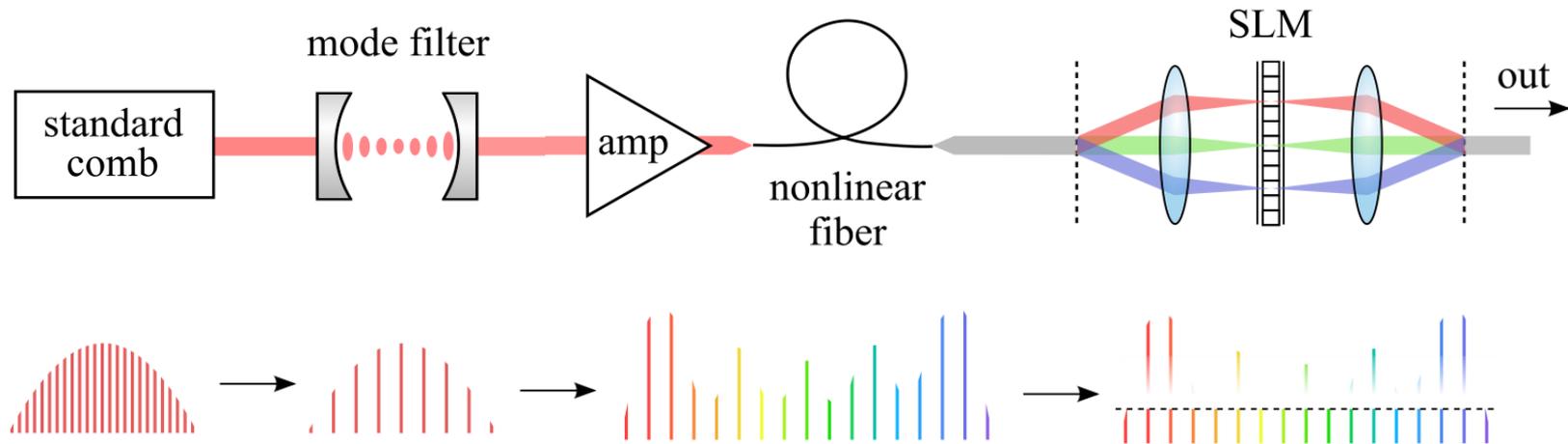
# **The astro-comb system**

# Requirements for astro-combs

Optimum mode spacing for spectrograph calibration:  
3x Resolution of spectrograph

- **Typical mode spacings: 10 – 30 GHz**  
Mode spacing for ESPRESSO & HARPS: 18 GHz
- **Visible, broadband, balanced spectrum**
- Long term fail-safe & **maintenance-free operation**

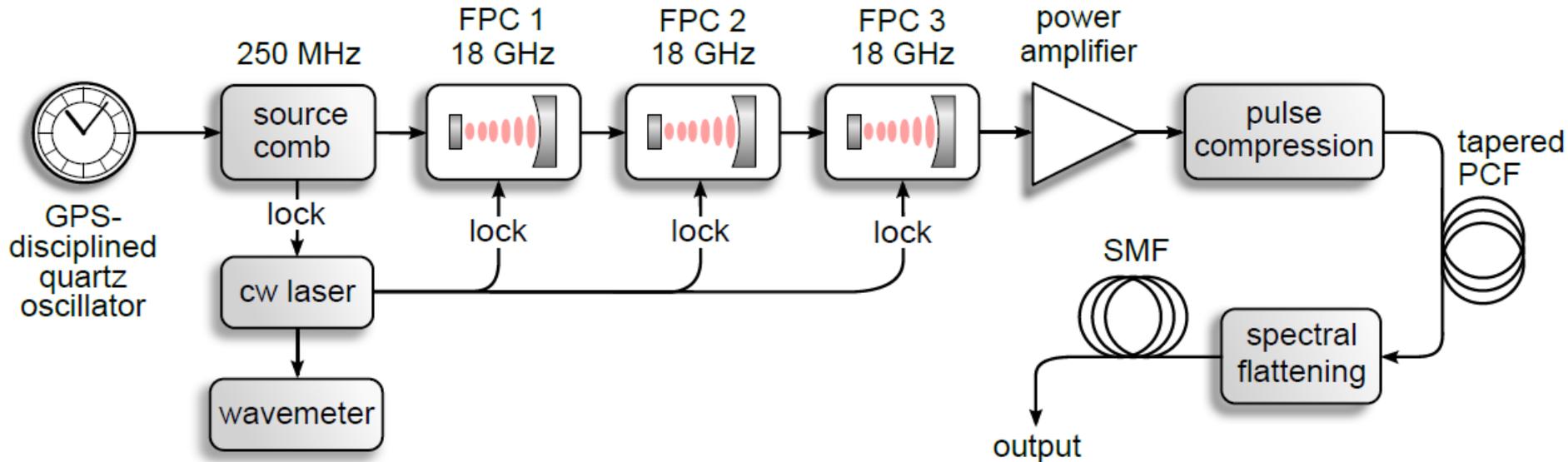
→ **Concept:**



SLM: spatial light modulator

# Configuration of ESRPESSO LFC

Menlo



## Abbreviations:

cw laser: continuous wave fiber laser

FPC: Fabry-Pérot cavity

PCF: tapered photonic crystal fiber

## One button control:

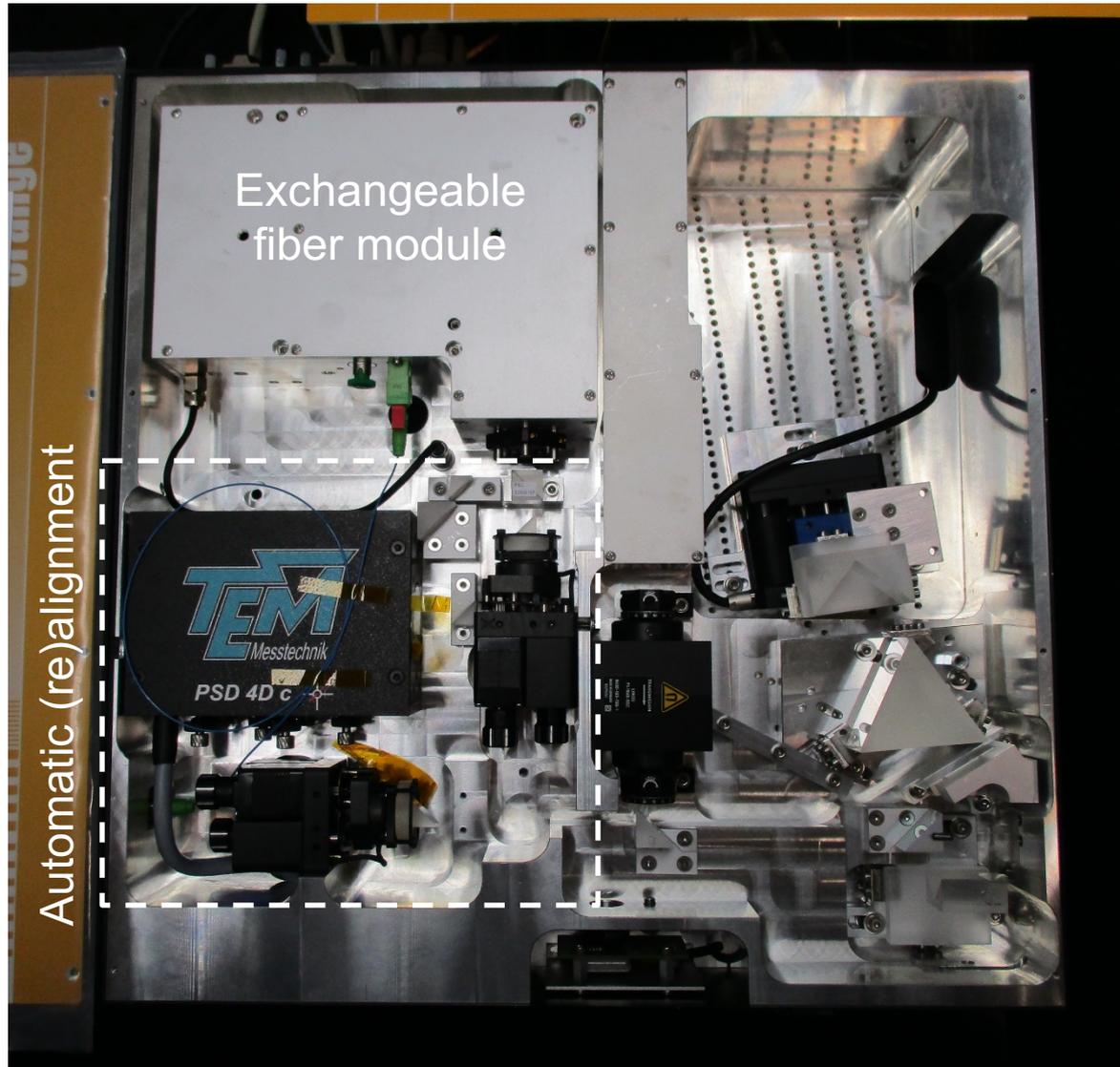
The complete system can be launched upon a single mouse click, locks are established automatically

**Cavity finesse:** 2300

**Side-mode suppression:** >46 dB (limited by measurement)

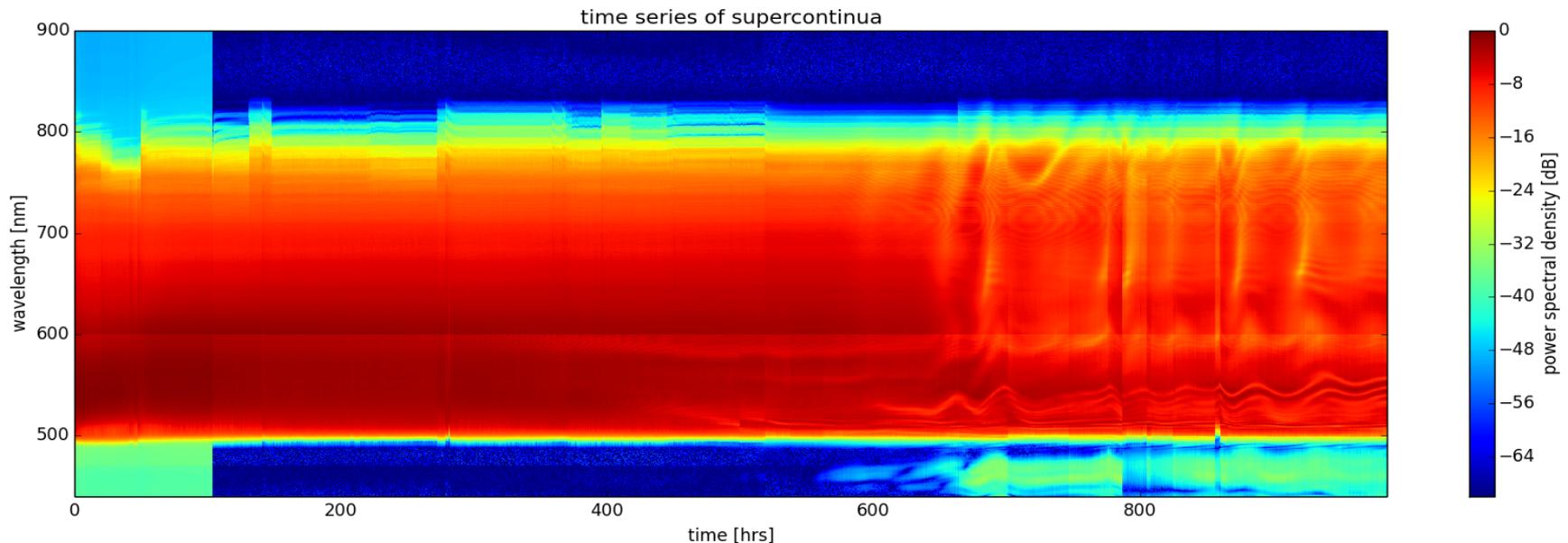
**Accuracy:** < 4 mm/s

# Spectral broadening unit

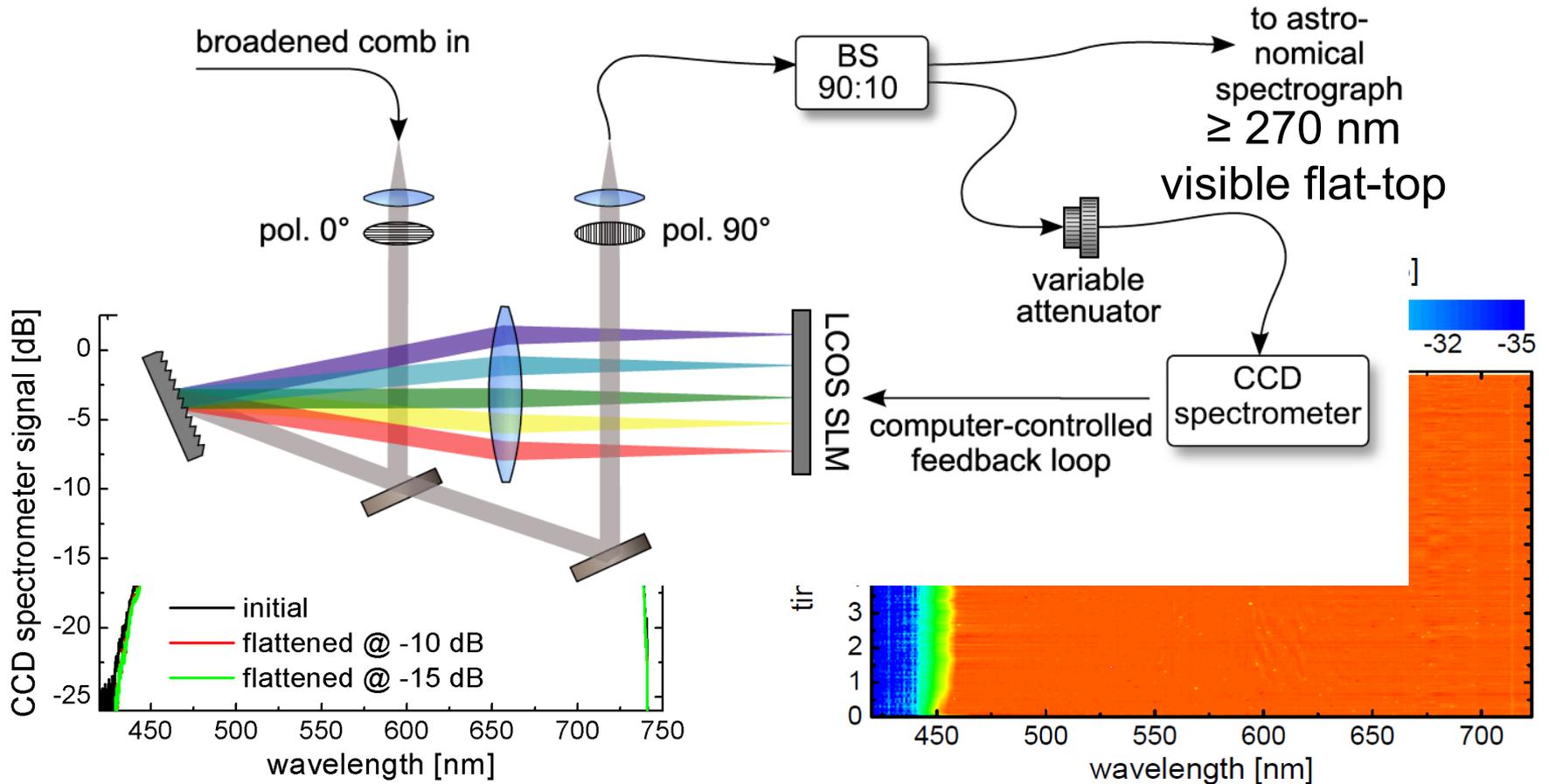


Broadening fibers are subject to long term changes:  
Probable origins: color center formation, grating formation  
-> Trade-off between bandwidth and lifetime

Continuous >900 h fiber lifetime in ESPRESSO LFC, spectrum down to 500 nm  
-> coverage of red arm for ESPRESSO



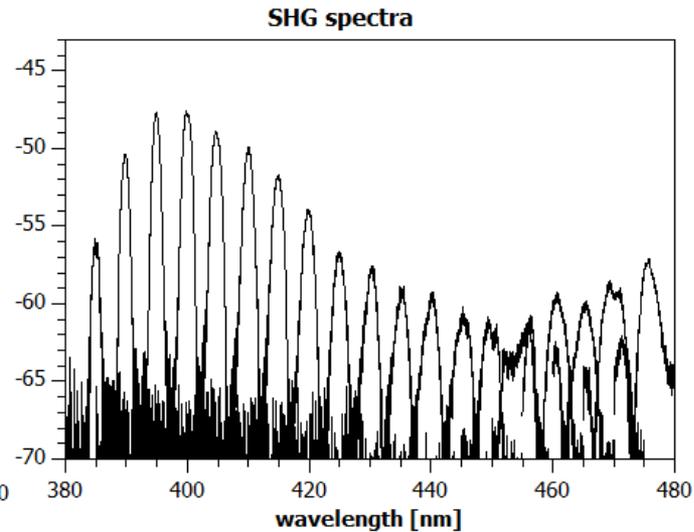
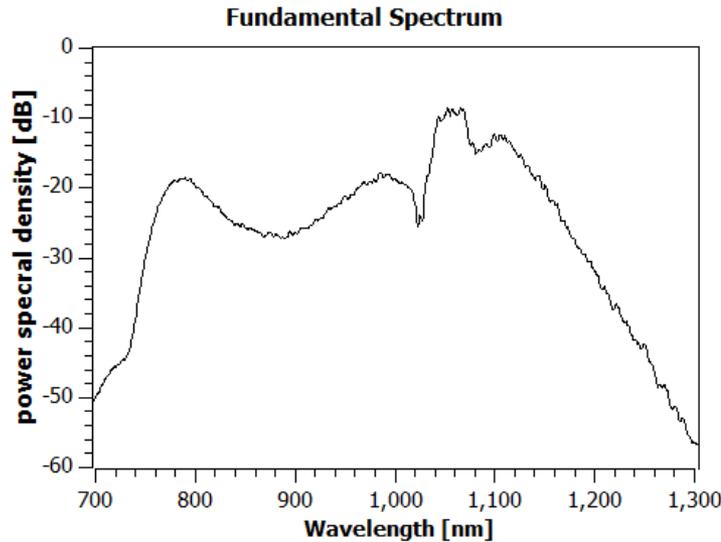
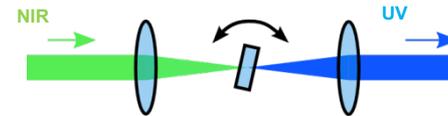
# Broadband, flat spectra



# Future coverage of ESPRESSO's blue arm by broadband SHG techniques

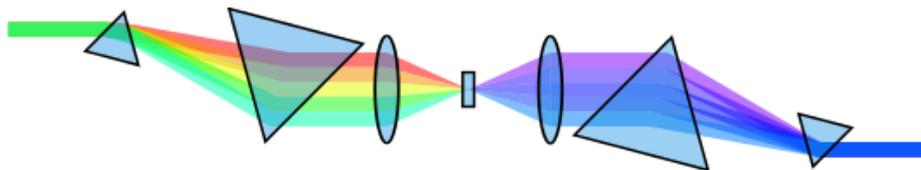
## Second-harmonic generation (SHG) by scanning the angle of nonlinear crystal

Scan may be possible at rates of 100 – 1000 Hz  
Feasibility study by Menlo Systems:



Galvanometer scanner

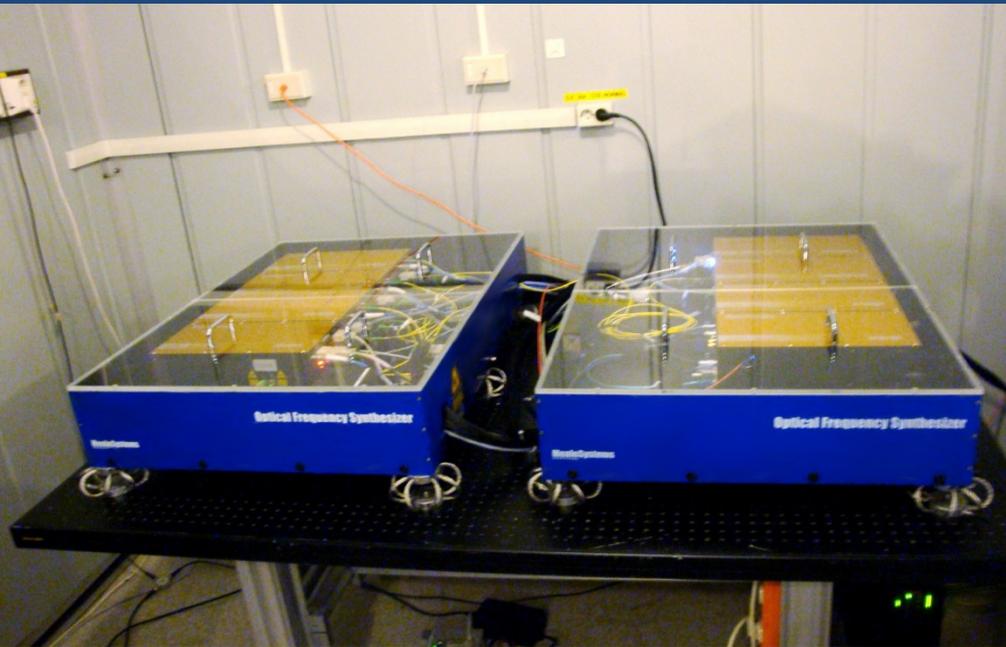
## Alternative method: Achromatic SHG



All-optical but very challenging

# Astro-comb (after installation at HARPS)

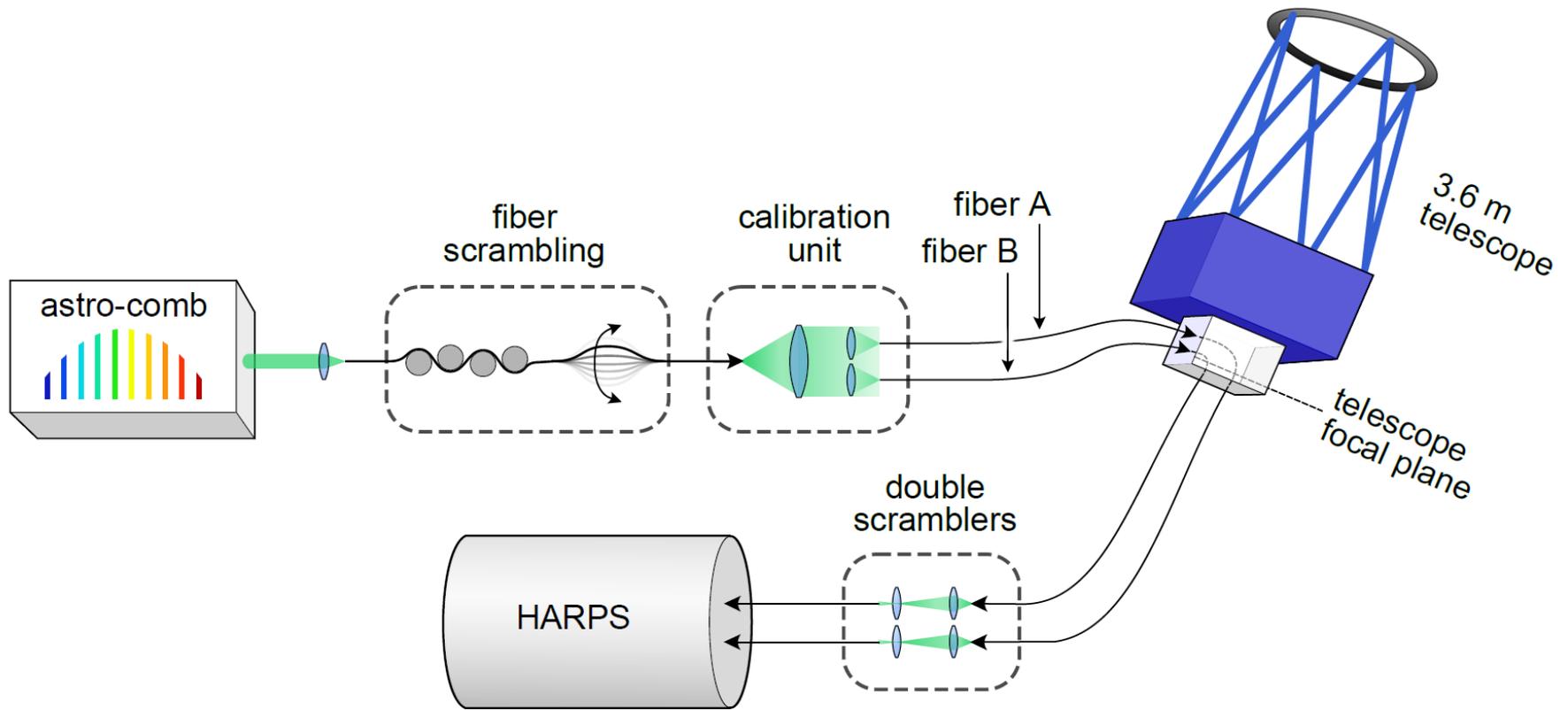
**Menlo**



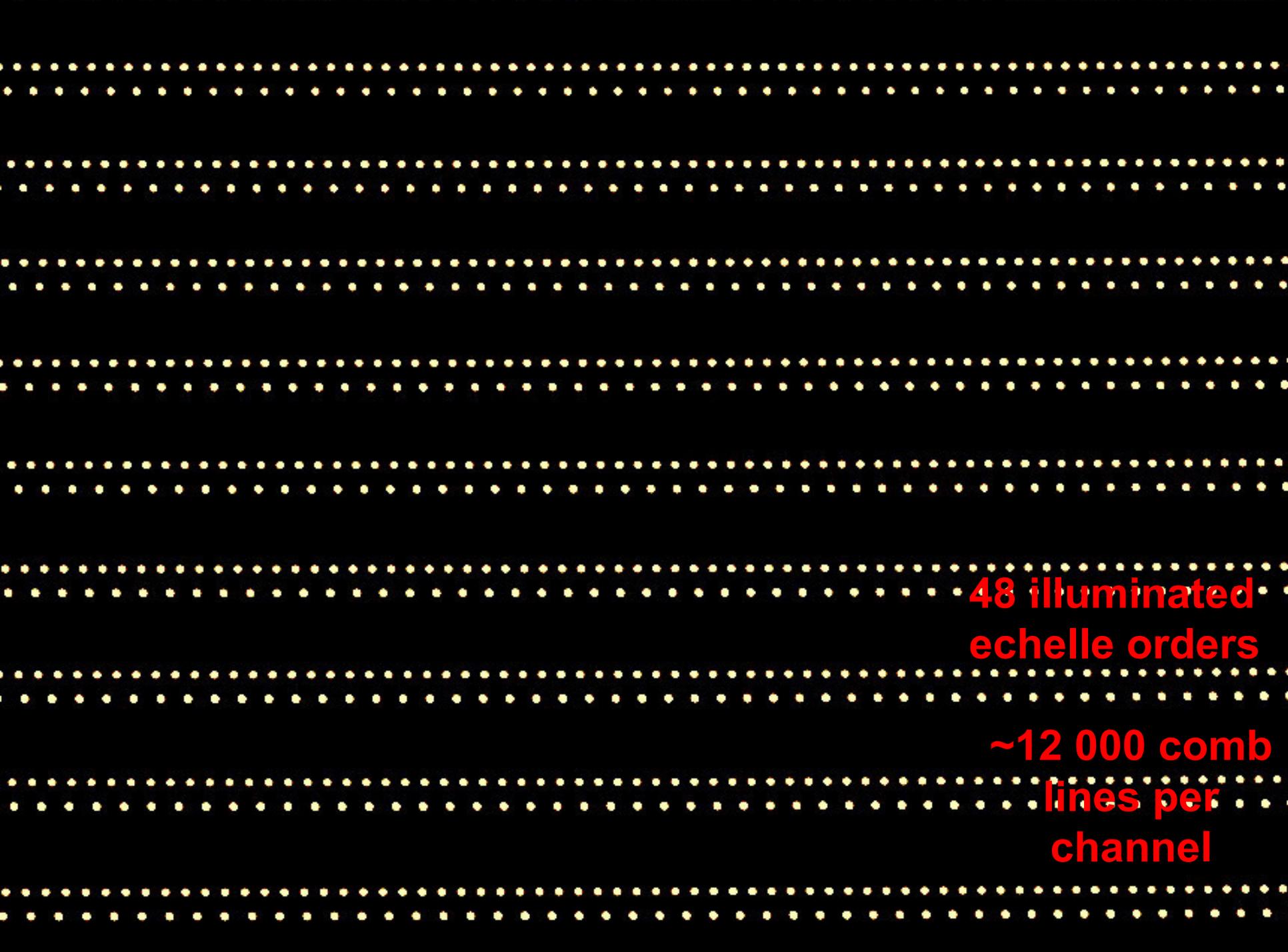
# **Demonstrating the astro-comb in the field**

*HARPS results April 2015*

# Coupling scheme



**Scrambled fiber:** plastic fiber, 980  $\mu\text{m}$  core  
(yielded better results than silica fiber with 200  $\mu\text{m}$  octagonal core)



**48 illuminated  
echelle orders**

**~12 000 comb  
lines per  
channel**

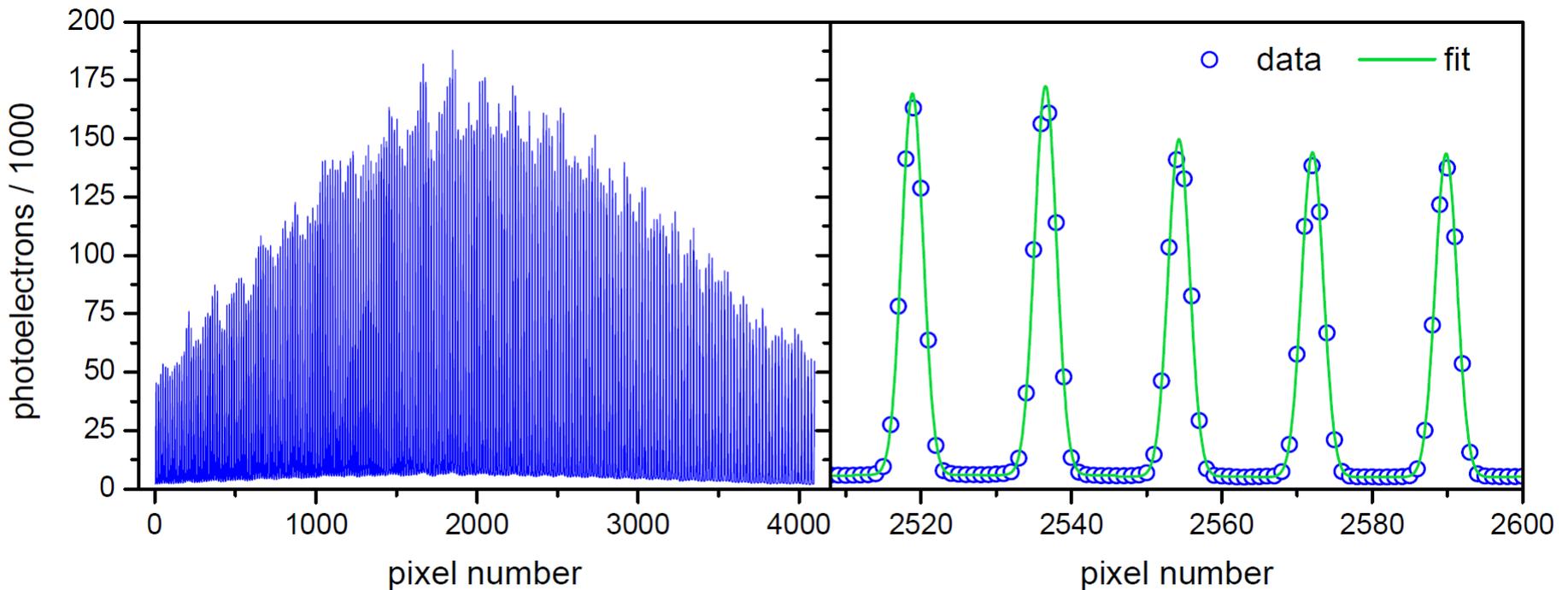
## HARPS pipeline:

Produces 1D data  
for every order



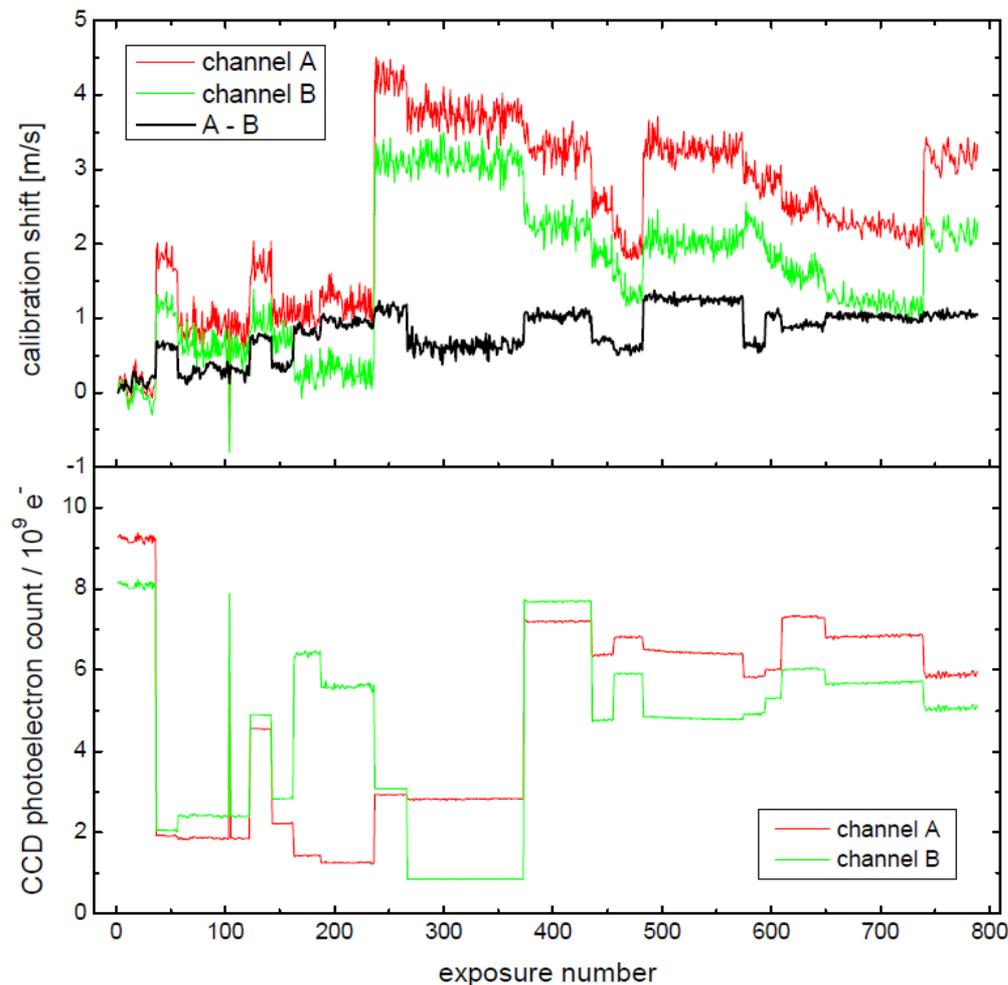
## Gaussian fit:

Determines line centers  
Uncertainty: Photon noise



# 18 GHz vs. 18 GHz comb

all exposures in 2015

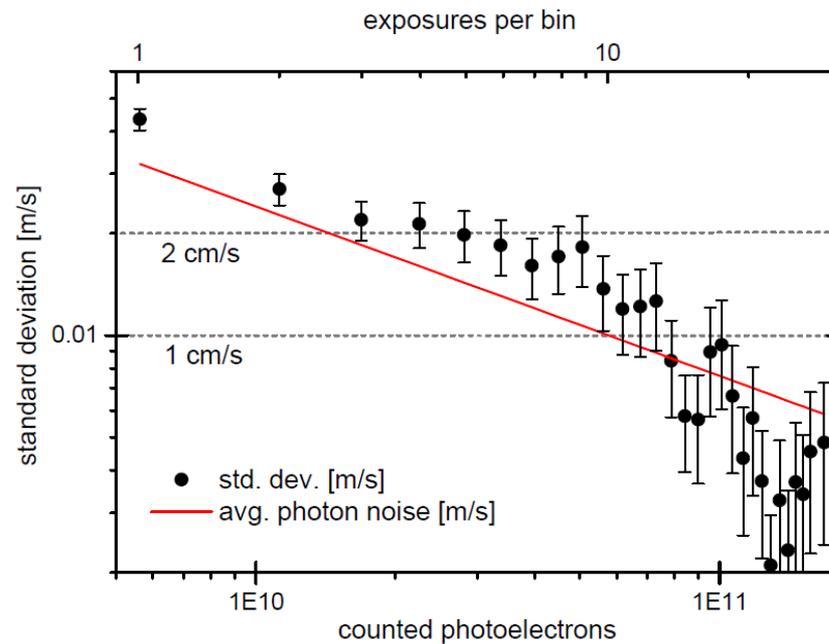
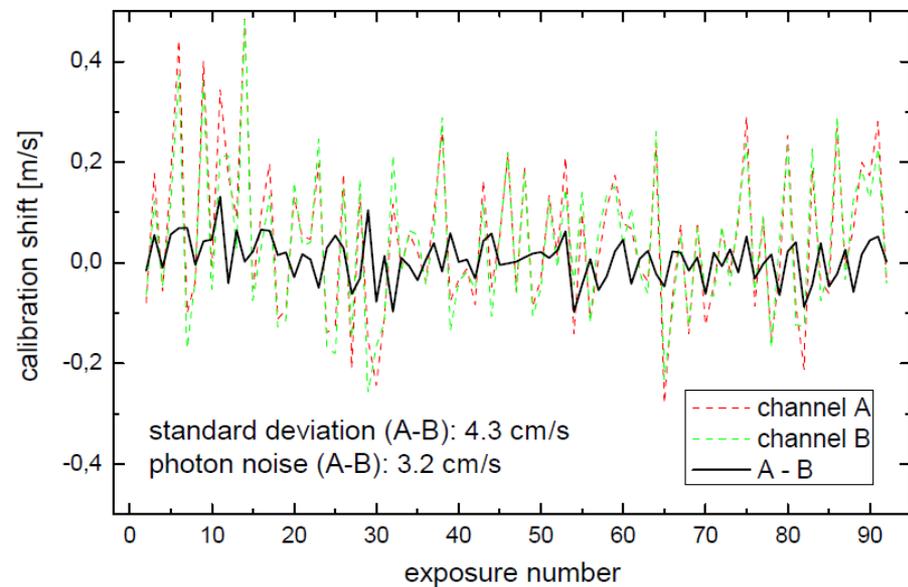


Standard deviation A-B: 32 cm/s.  
Average photon noise: 4 cm/s.

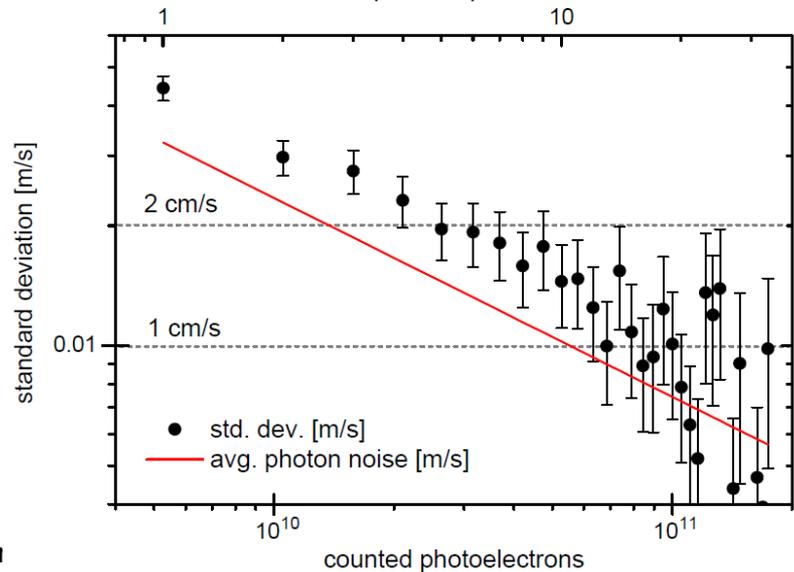
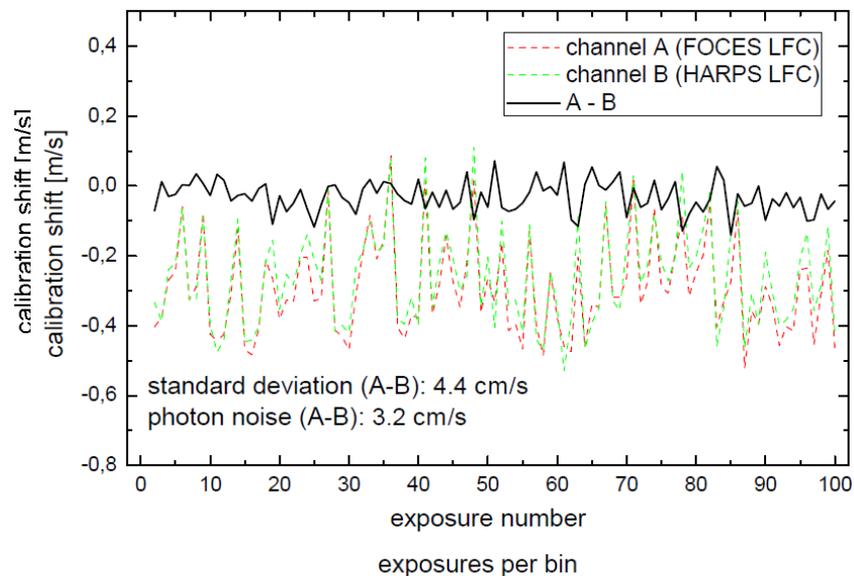
## Altered fiber illumination

- changes spatial mode occupation in fibers  
→ shifts line centers
- changes light flux  
→ induces charge transfer inefficiency in CCD

# 18 GHz vs. 18 GHz comb

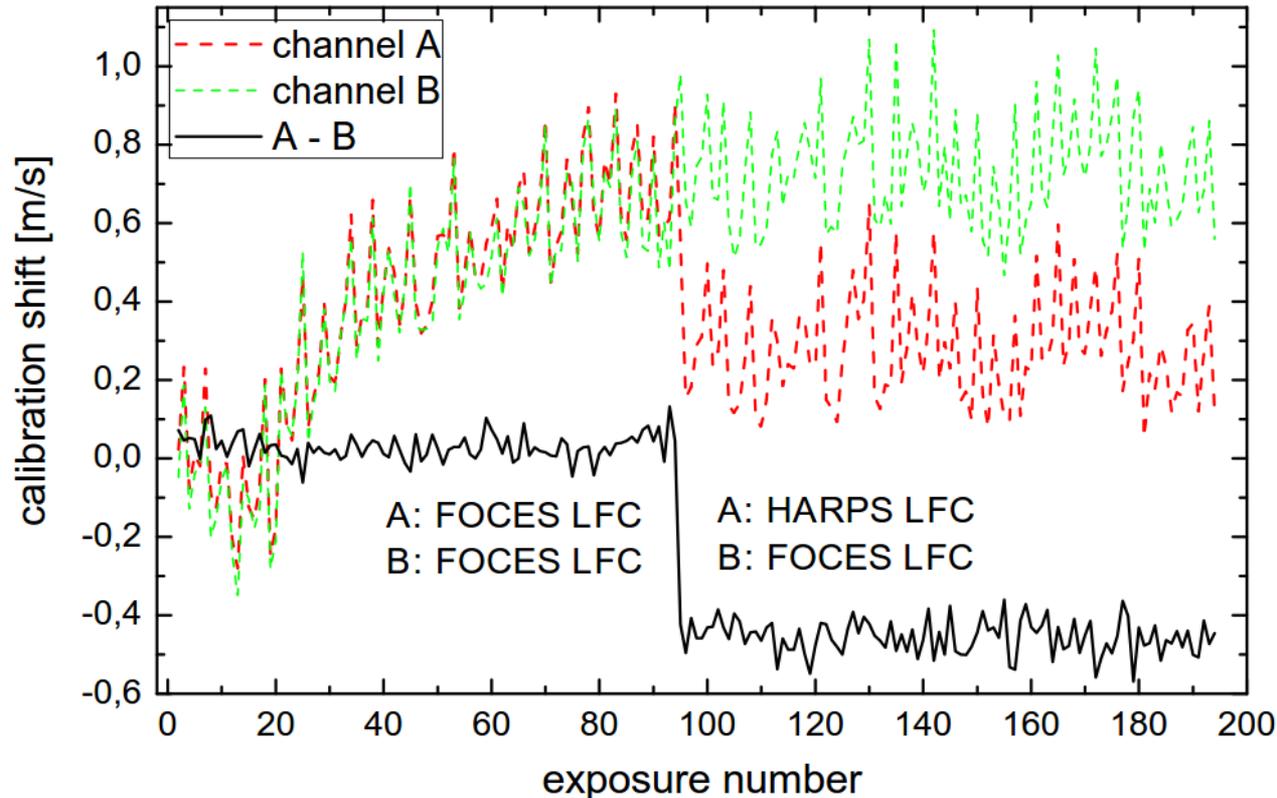


# 18 GHz vs. 25 GHz comb



# Absolute consistency

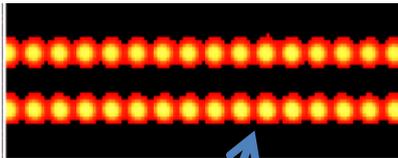
(calibration reproducibility)



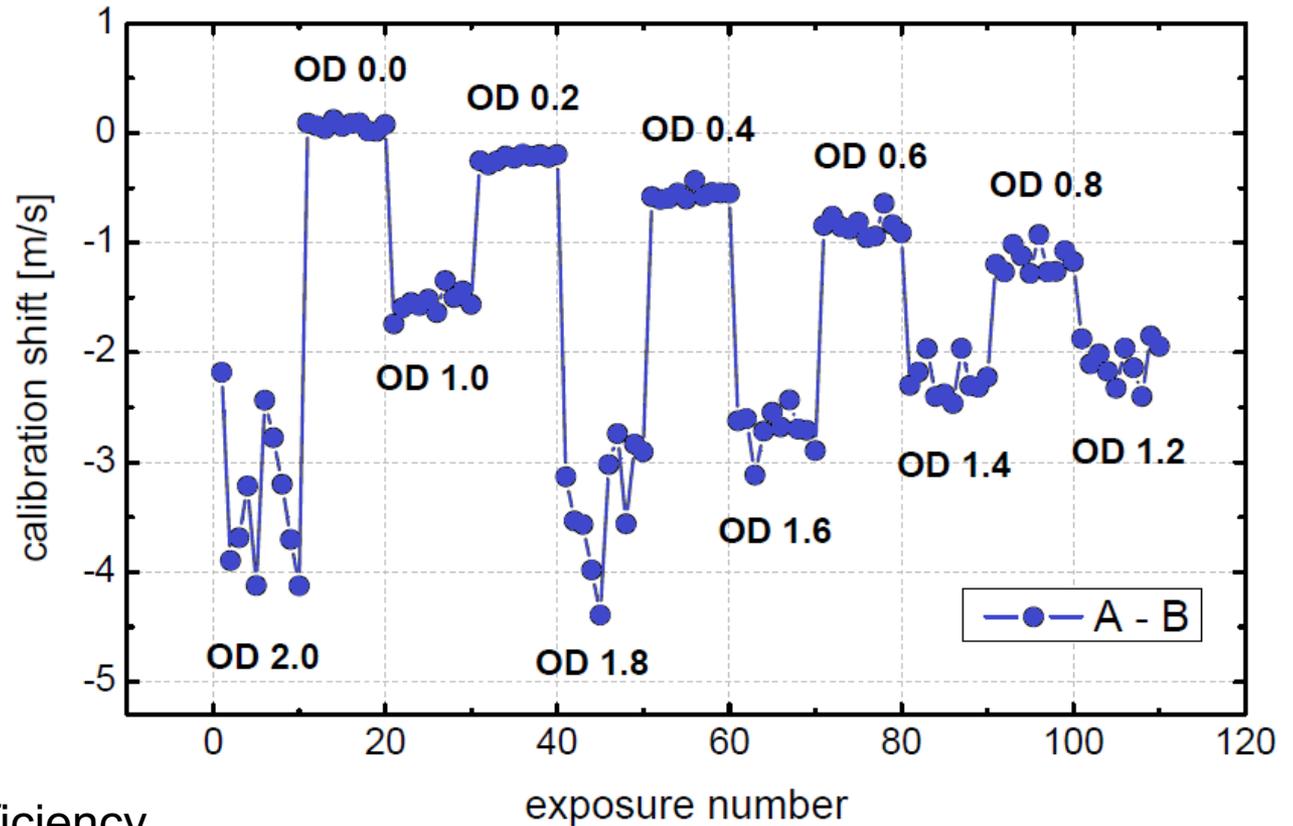
Up to exposure 94, the 25 GHz LFC is used to calibrate both channels.

When replacing the 25 GHz LFC with the 18 GHz LFC on channel A, the calibration is shifted by 0.49 m/s.

# Intensity dependent shift



Fiber B  
Attenuated  
(NG filter)



## Caused by:

- Charge transfer inefficiency
- Pipeline

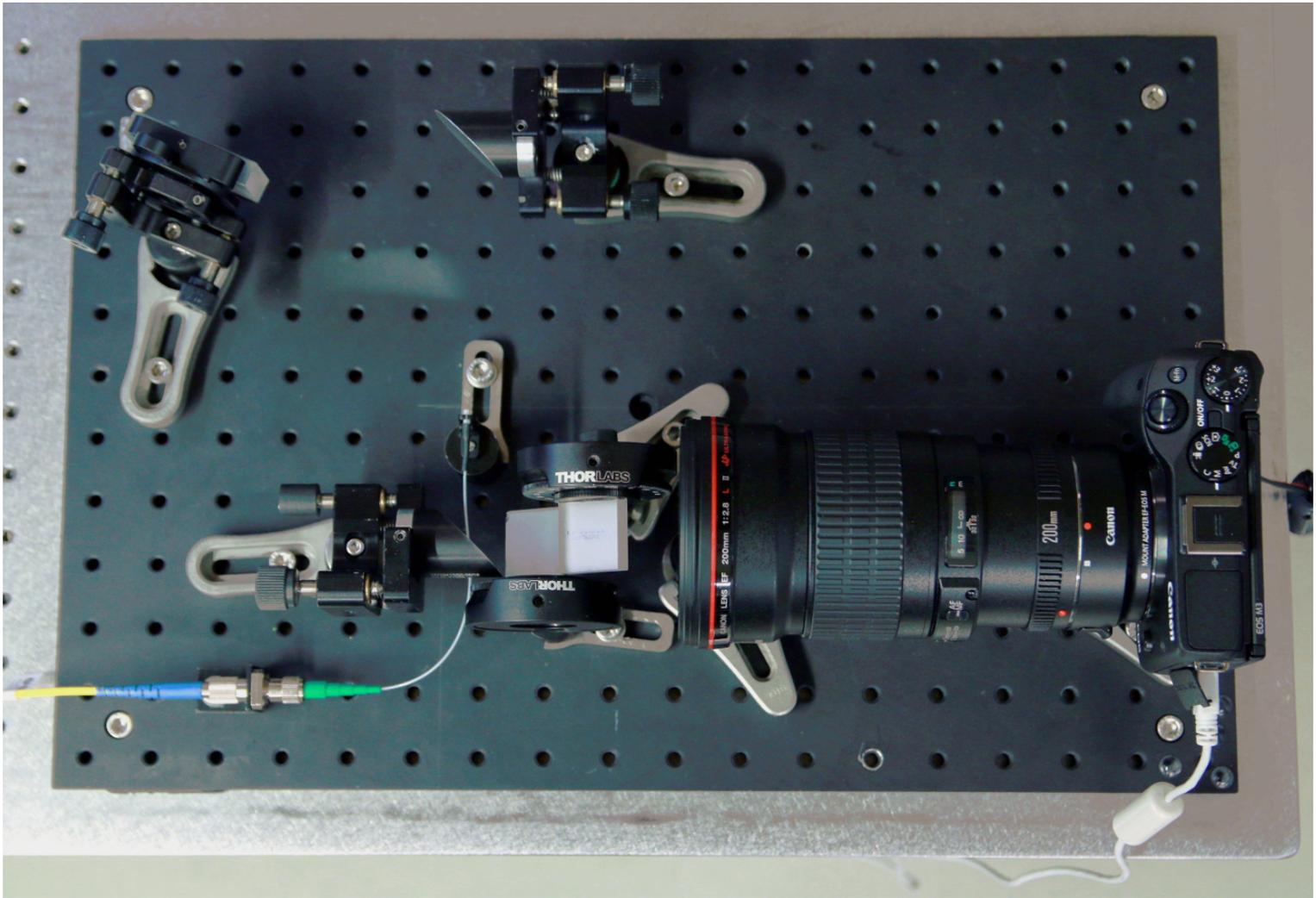
*... from test campaigns on HARPS*

- Effective scrambling of MMF is critical
- Fiber illumination should be carefully optimized
- Signal level must be kept as constant as possible
- Charge transfer inefficiency effects must be well understood
- Systematic errors from the pipeline should be avoided

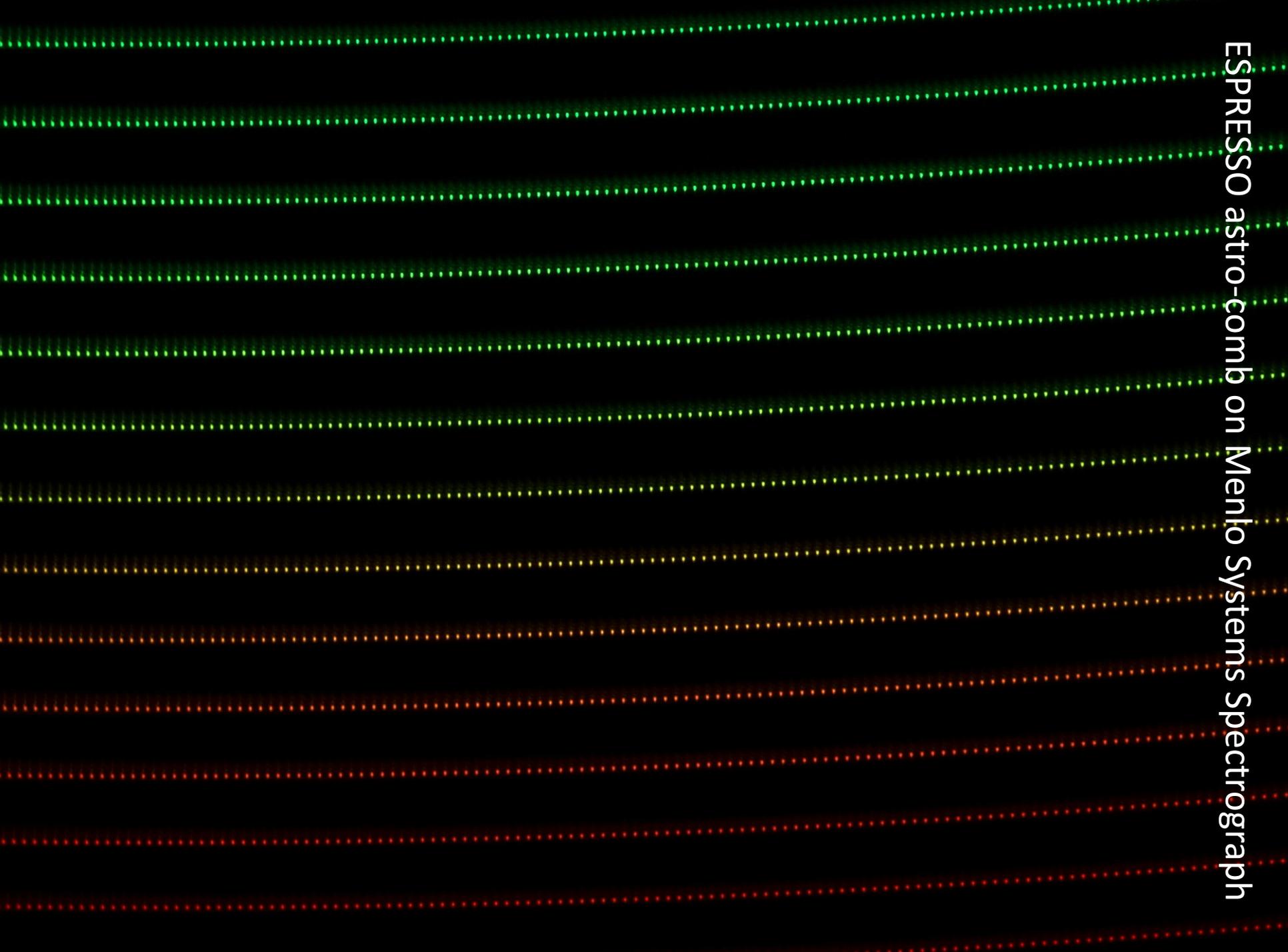
# **ESPRESSO LFC**

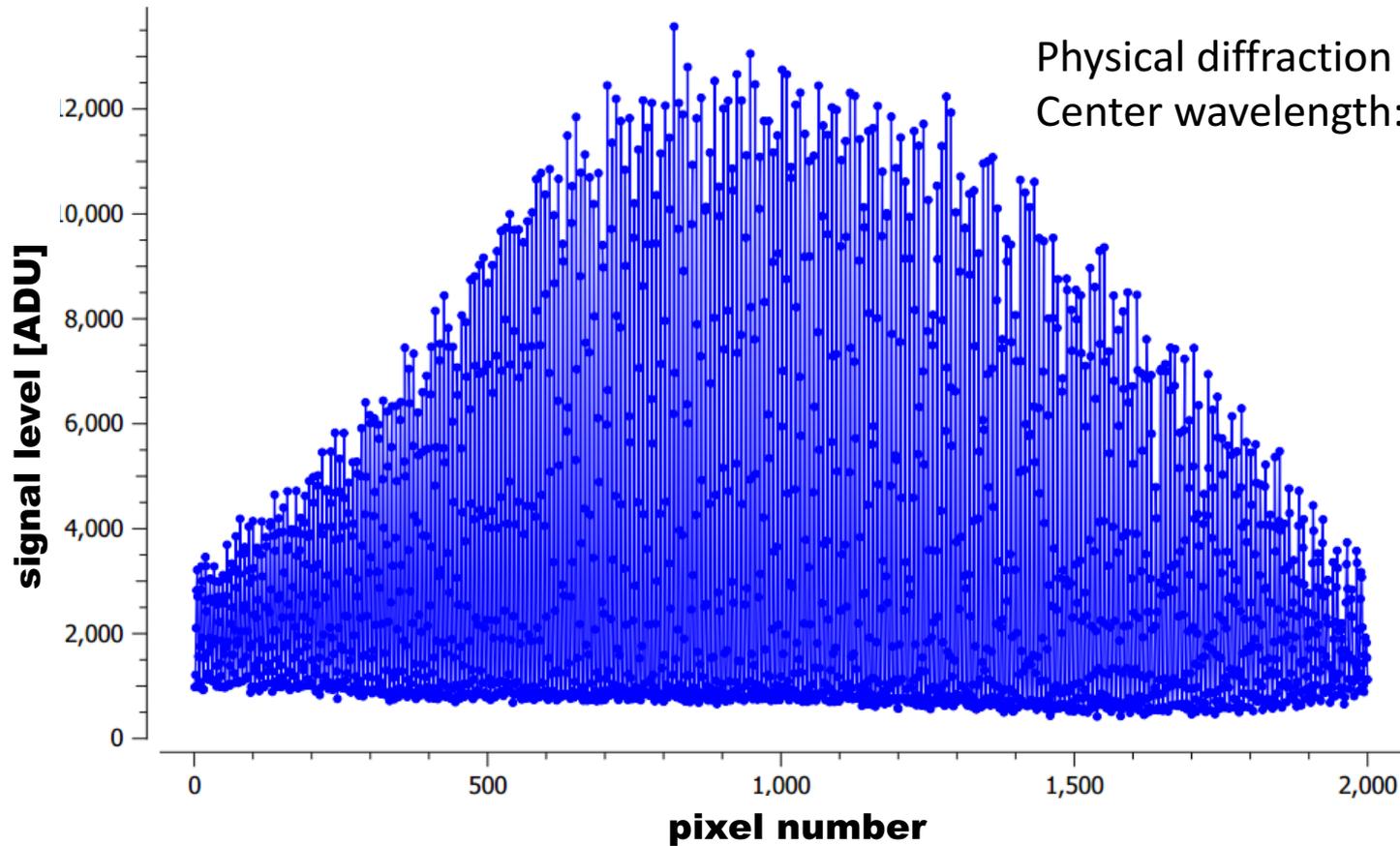
*laboratory characterization*

# Spectrograph for astro-comb characterization



# ESPRESSO astro-comb on Mento Systems Spectrograph





- spectral background of 6 %, caused by noise in fiber amplifier
- can already be decreased to 3 %, further optimizing is underway

# Thank you!



## MenloSystems

**Dr. Tilo Steinmetz**

**Product Manager – AstroComb**

E-Mail: [t.steinmetz@menlosystems.com](mailto:t.steinmetz@menlosystems.com)

Phone: +49 89 189166 0

Menlo Systems GmbH

Am Klopferspitz 19a

D-82152 Martinsried, Germany

[www.menlosystems.com](http://www.menlosystems.com)