Laser Frequency combs at ESO

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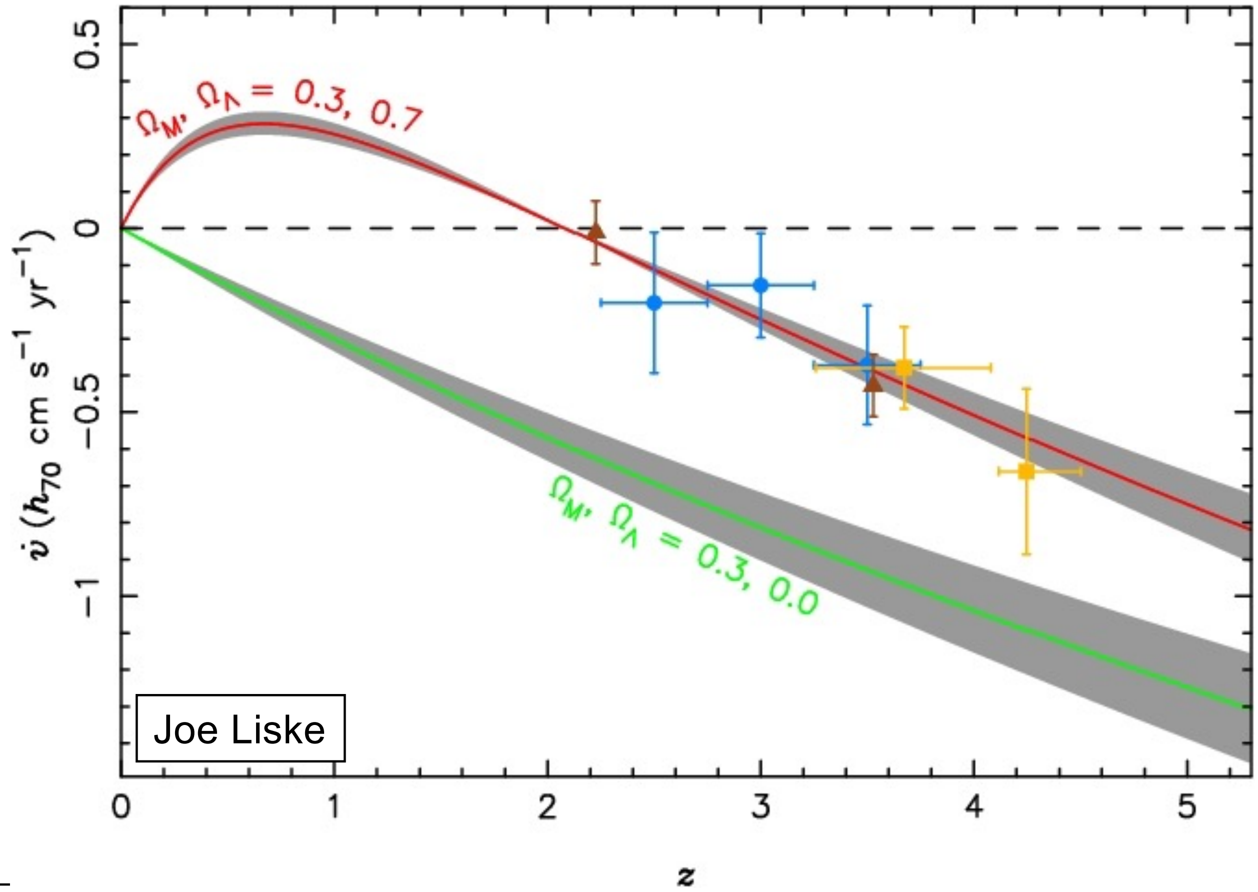
the HARPS & NIRPS teams

Need for extremely precise wavelength calibrations

- **Direct measurement of the expansion of the Universe**
- **Variation of the fundamental constants**
- **Search for Earth-like planets with radial velocities**

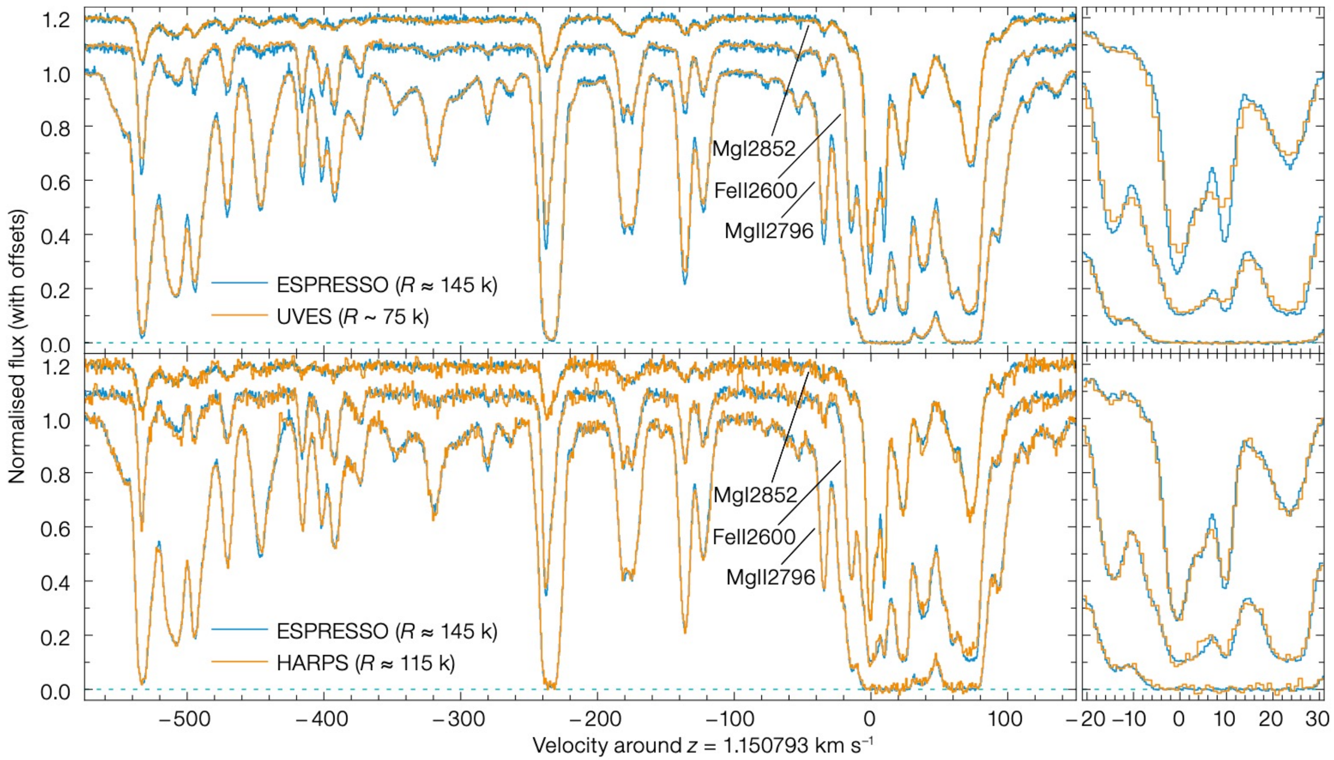
Direct measurement of the expansion of the Universe

Requires a precision of ~cm/s over decades



Variation of the fundamental constants

Local accuracy
Is fundamental !



The “planetary signature” … (RV)

$$K_1 = \frac{m_p \sin i}{(m_* + m_p)^{2/3}} \sqrt[3]{\frac{2\pi G}{P}} \frac{1}{\sqrt{1-e^2}}$$

The inclination angle “i” is unknown => only the minimum mass can be determined

Jupiter	@ 5 AU	: 12.7 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ .1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	**@ 1 AU**	**: 9 cm s^{-1}**

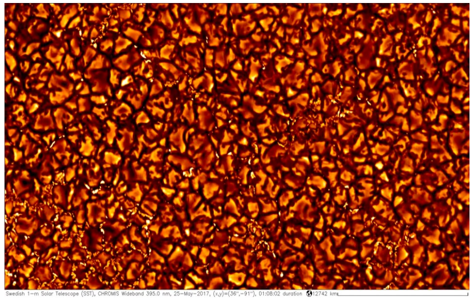
Orbiting a Solar-type star

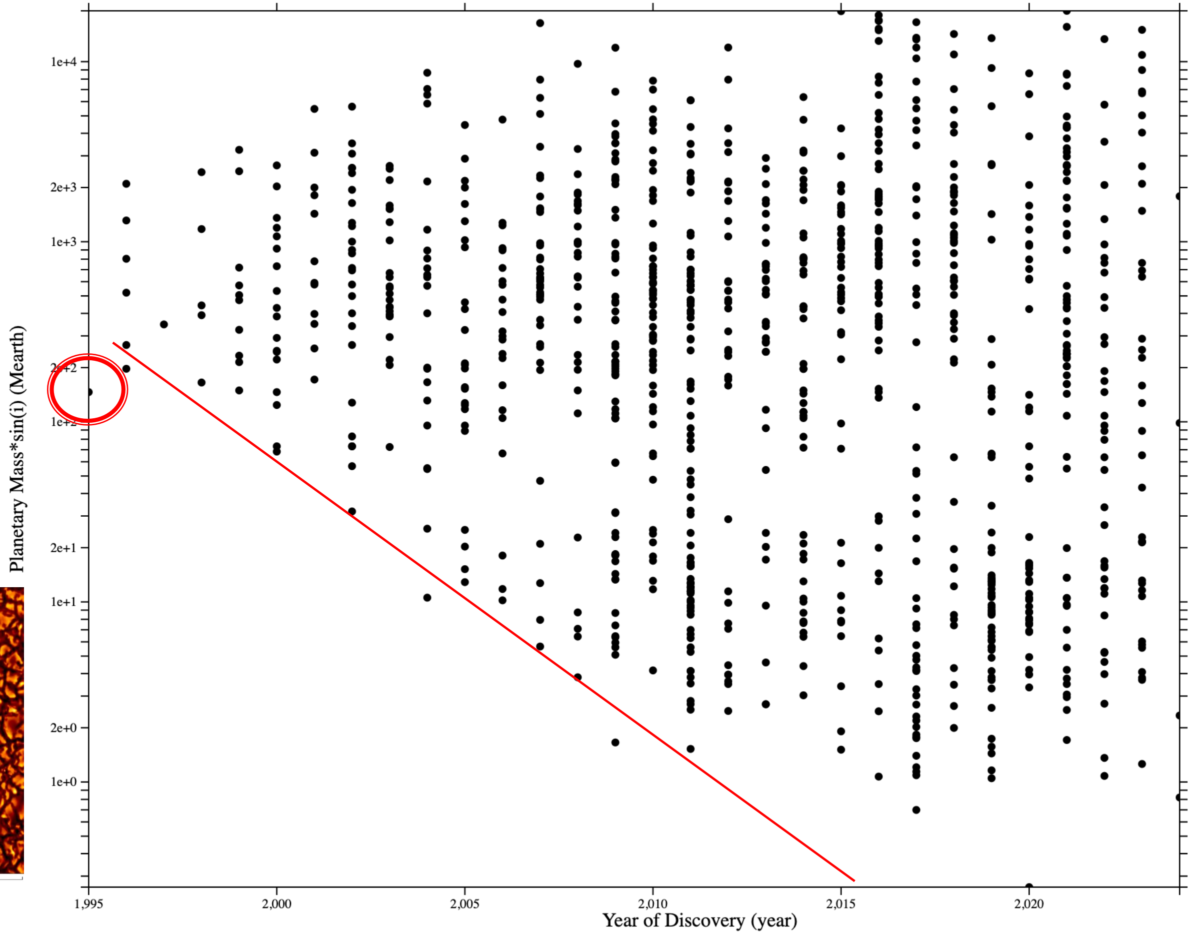
Planets detections (RV only)

Moore's law for Exo-planets ?

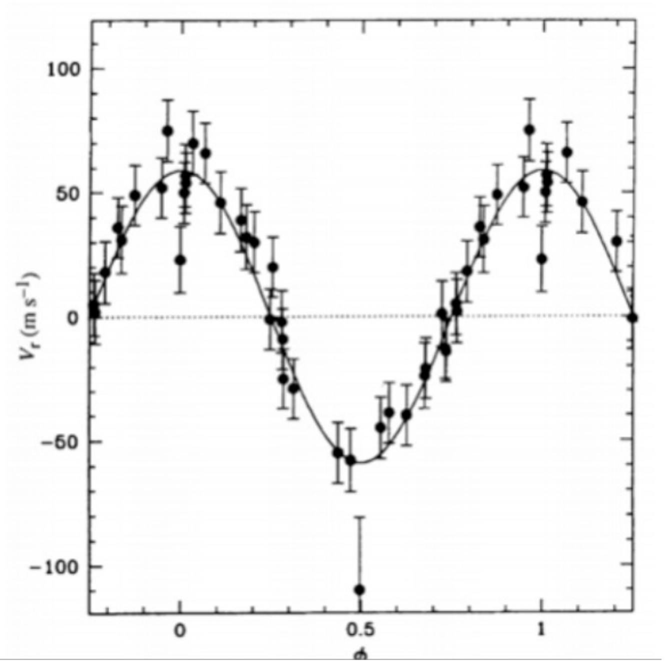
Flattening ?

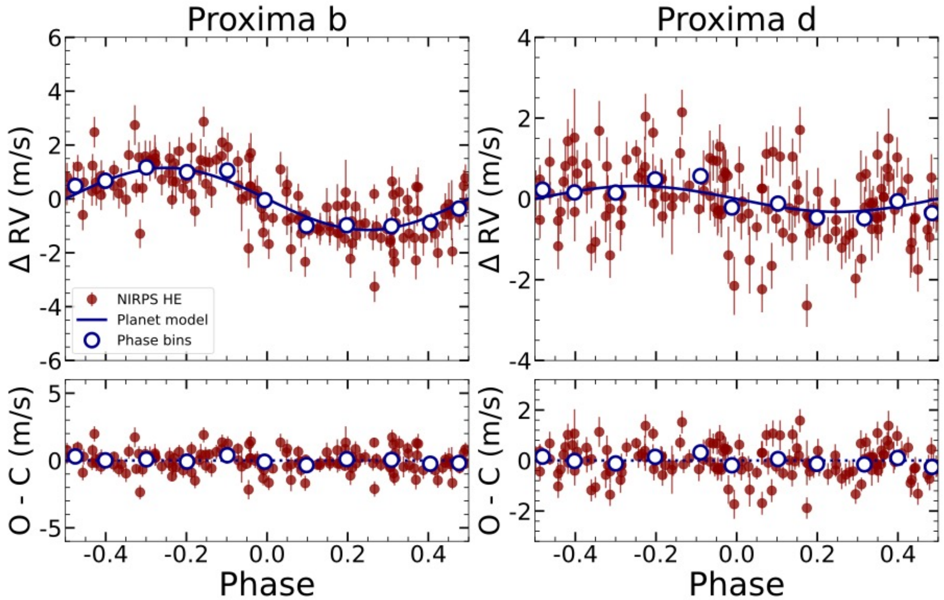
There is more than just the planet…





Is wavelength calibration really critical ?

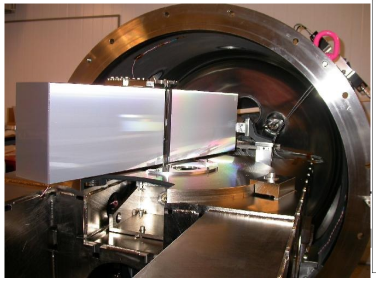


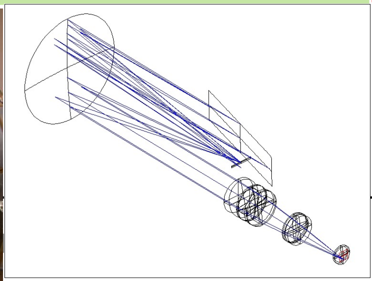


What instrument for this science ?

HARPS

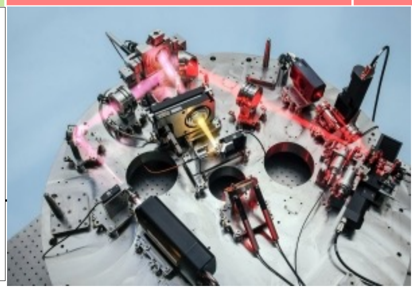
Wavelength coverage	380nm – 690nm
Spectral resolution	115000 (HAM) / 80000 (EGGS)
Light feed	Fiber optics x 2
Aperture on sky	1” (HAM), 1.4” (EGGS)
Detector	2 x E2V, 2K x 4K, 15μm pixels
Environment	Vacuum (<10^{-5} mbars) Ambient (17 ± 0.001K)
Observing modes	Simultaneous reference / Simultaneous sky / Polarimetry

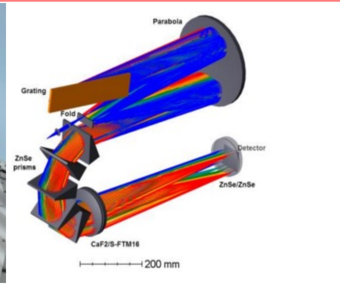




NIRPS

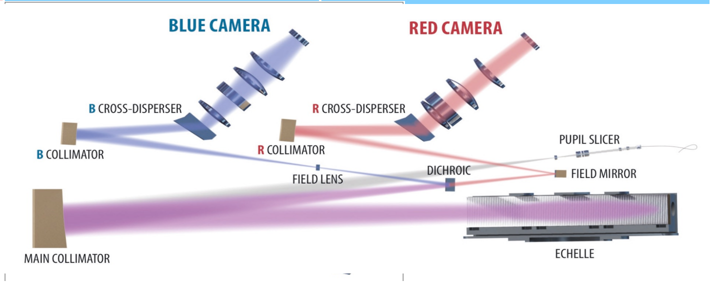
Wavelength coverage	971nm – 1854nm
Spectral resolution	82000(HA) / 75000(HE)
Light feed	Fiber optics x 2 Adaptive Optics assisted
Aperture on sky	0.4” (HAM), 0.9” (HEM)
Detector	Hawaii 4RG, 4K x 4K, 15μm pixels
Environment	Vacuum (<10^{-5} mbars) Cryogenic (80 ± 0.001K)
Observing modes	Simultaneous reference / Simultaneous sky



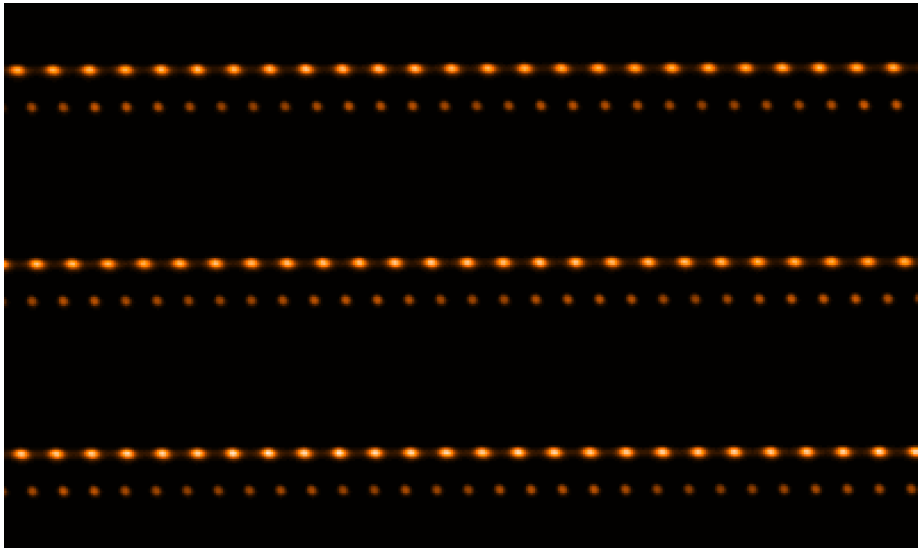


ESPRESSO

Wavelength coverage	380nm – 760nm
Spectral resolution	134000 (HR) / 190000 (UHR) / 70000 (MR)
Light feed	Fiber optics x 2
Aperture on sky	1” (HR), 0.5” (UHR)
Detector	2 x E2V, 9K x 9K, 15μm pixels
Environment	Vacuum (<10^{-5} mbars) Ambient (17 ± 0.001K)
Observing modes	Simultaneous ref. / Simultaneous sky /



How does the raw data look like ?

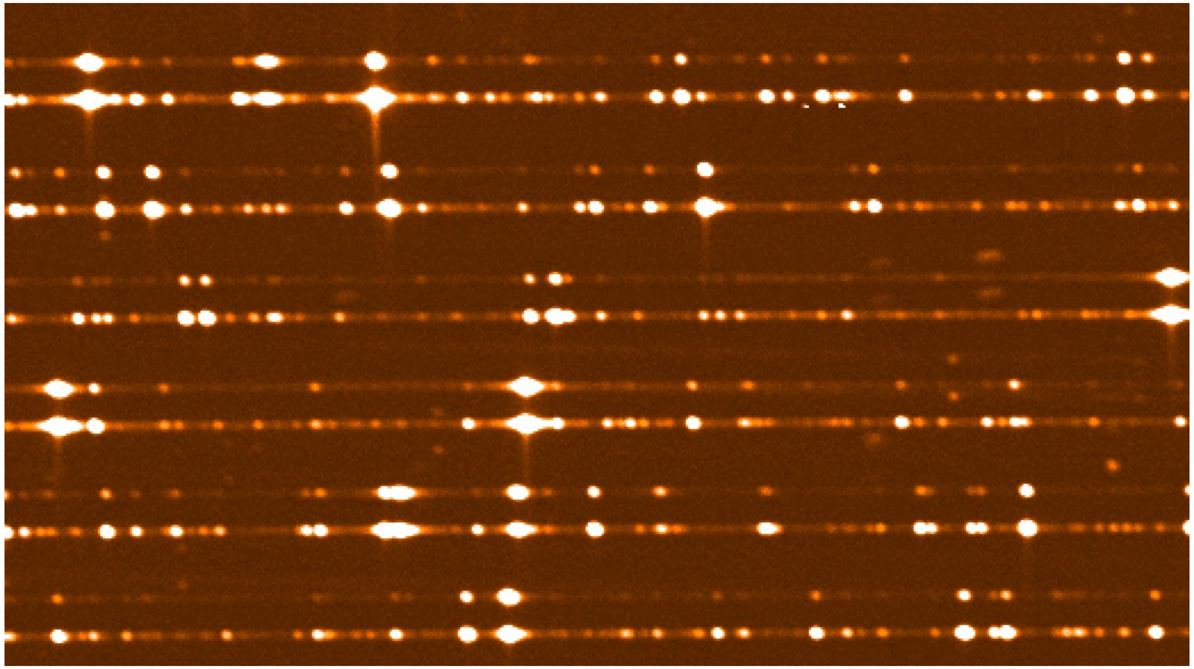


Wavelength calibration

Associate pixels to wavelengths.

Use lines atlas (e.g. Palmer & Englmann, 1983).

Associate patterns in the spectrum with the line list.



5000.2463 ThI
5002.0972 ThI
5002.8933 ThI
5003.5981 ThI
5004.1279 ThI
5005.9752 ThI
5008.1897 ThII
5009.3344 ArII
5009.9367 ThI
5010.4174 ThI
5011.4774 ThI
5012.2754 ThI
5013.1647 Th

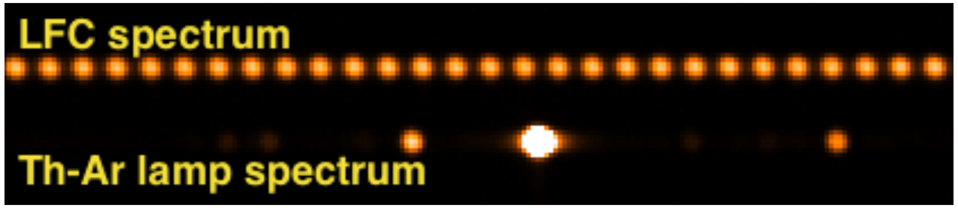
From radial velocity to detector space

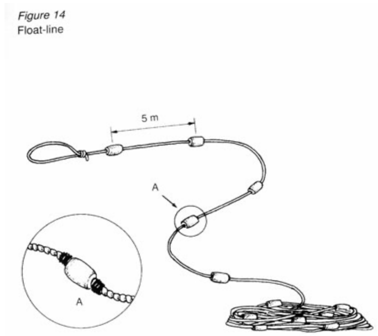
	HARPS	ESPRESSO
RV precision	1 m/s	10 cm/s
Distance on CCD	17 nm	16 Å

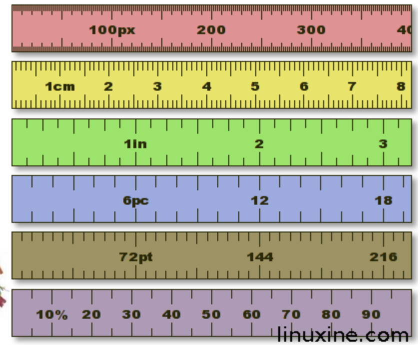
Silicon lattice constant: 5.4 Å

Limitation of traditional calibrators

- ThAr (hollow cathode lamps):
  - Low line density
  - Blending
  - High dynamics
  - 20cm/s – 30cm/s scatter
  - Uncertainty on the line positions (20-80m/s)

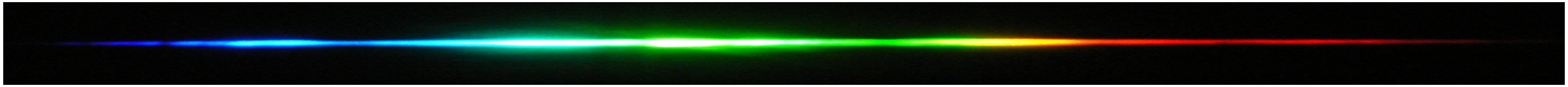






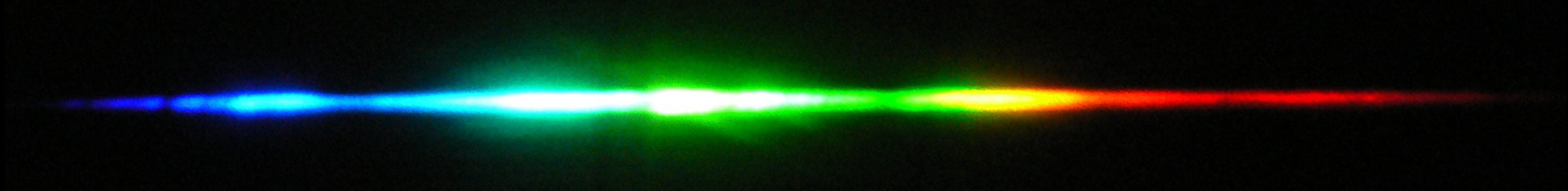
- Iodine absorption cells:
  - Reduced throughput
  - High dynamics
  - Limited wavelength coverage (~ 500nm – 650nm)
  - Spectral information “destroyed” by the I_2 forest

The ideal calibrator



- ✧ As many as possible, non-blended, equally spaced lines
  (line spacing tuned to the resolution of the spectrograph)
- ✧ Smooth intensity distribution across the spectrum
- ✧ Unresolved lines
- ✧ Extreme stability (better than $2*10^{-11}$)

The quest for the ultimate RV precision



2005: Nobel prize to T. Hänsch and J. Hall for their work on laser precision spectroscopy and the LFC

2007-2012: “demonstrator program” on HARPS

2015-ongoing: routine operation of a LFC on HARPS

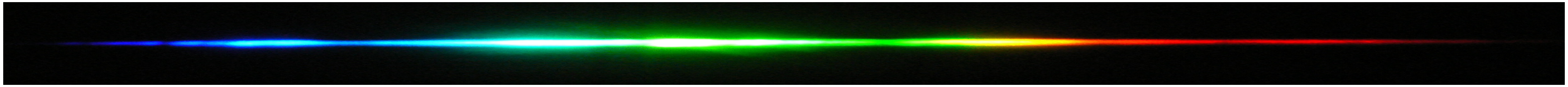
2019: LFC installed on ESPRESSO

2023: LFC (CSEM) installed on NIRPS

Typical LFC requirements

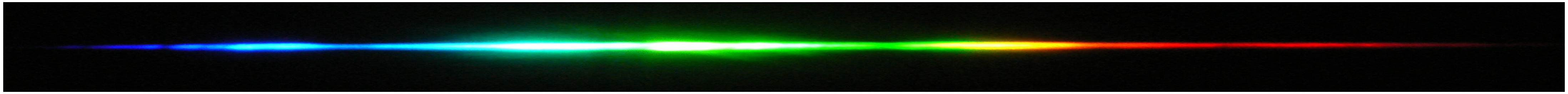
Wavelength range	480nm – 680nm
Line position accuracy	<2E-11
Wavelength stability	<2E-11 in 10 years
Photon luminosity	>1E-9W / mode
Minimum exposure time	1s
Attenuation of the side modes	>50dB
Lines distribution	ω = ω0 + nωR ; ωR=18GHz
Spectrum intensity stability	<10% PtV in 24 hours
Relative intensity between lines	Dynamic <5, stability <50% in 10 hours
Line profile	Uresolved: FWHM << λ/R
Polarization	NO
Lifetime	10 years
Detector scan	Yes

LFCs at ESO



• HARPS	2015	MENLO
• ESPRESSO	2019	MENLO
• NIRPS	2023	CSEM
• ESPRESSO	2022 – 2025	Tests of “blue” fiber from MENLO
• ESPRESSO	2024	Tests of visible LFC from CSEM

From the off-the-shelf LFC to the Astro-comb



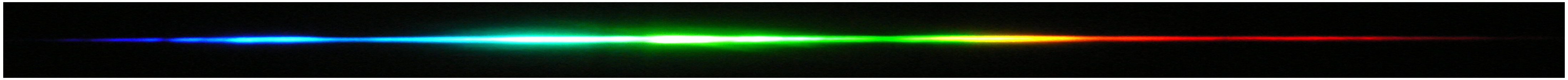
Off the shelf LFC:

- Repetition frequency: 250MHz
- Central wavelength: ~ 1060nm (Yb fiber laser)
- Pulse width: ~ 100fs => wavelength coverage ~ 40nm

Astro-comb (for HARPS):

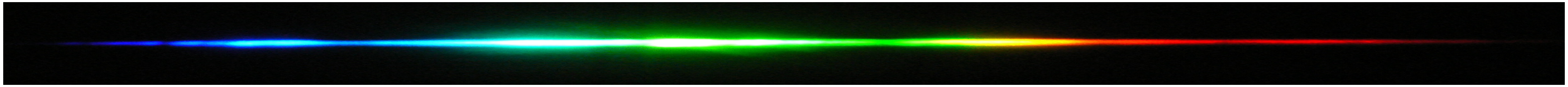
- Repetition frequency: ~ 18GHz
- Central wavelength: 530nm
- Wavelength coverage: > 200nm

From the off-the-shelf LFC to the Astro-comb

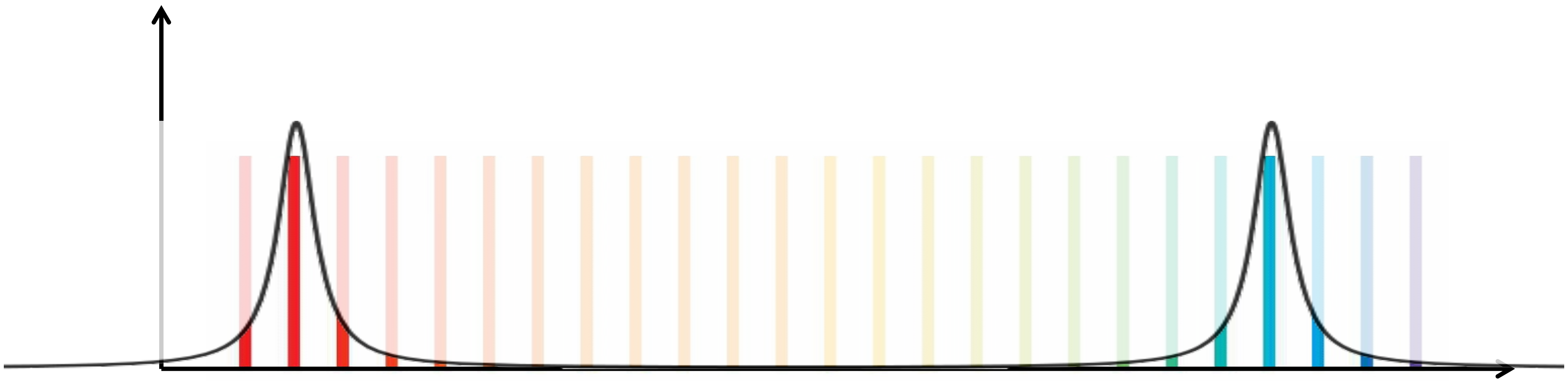


- Filtering via Fabry-Perot cavities
- Spectral broadening via non linear processes in a Photonic Crystal Fiber (PCF)
- Coupling to the spectrograph

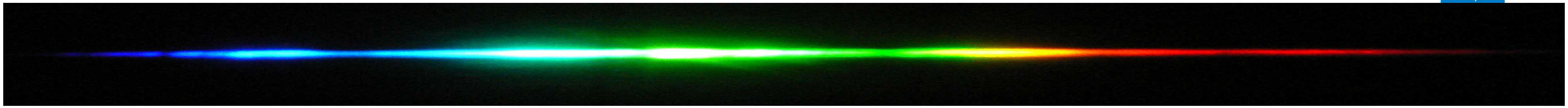
Fabry-Perot cavities (HARPS)



- Filtering factor: 72
- Finesse (FSR/FWHM) ~ 2000
- Temperature compensated (closed loop)
- Need to suppress by at least 50dB the unwanted modes
- Three FPC used in series for better suppression



Spectral broadening (HARPS)



The natural coverage of the LFC is $\lambda^2/(100fs)/c \sim 40nm$

We request at least 200nm

Broadening is performed via highly non-linear processes in the PCF (Photonic Crystal Fiber):
four wave mixing: 3 photons -> 1 photon: $\omega_{out} = \omega_1 \pm \omega_2 \pm \omega_3$

Challenges:

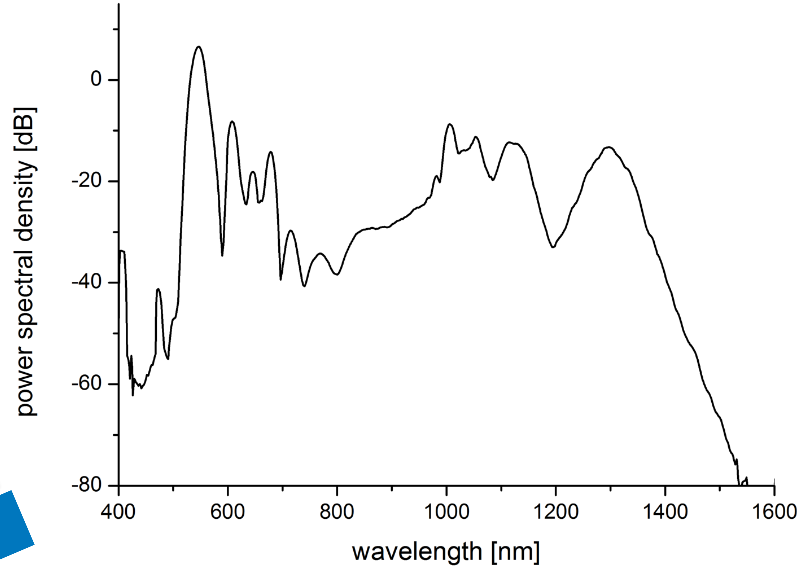
- Need high power
- Amplify modes suppressed by the FPC
- Output is not “deterministic”
- Reliability / lifetime

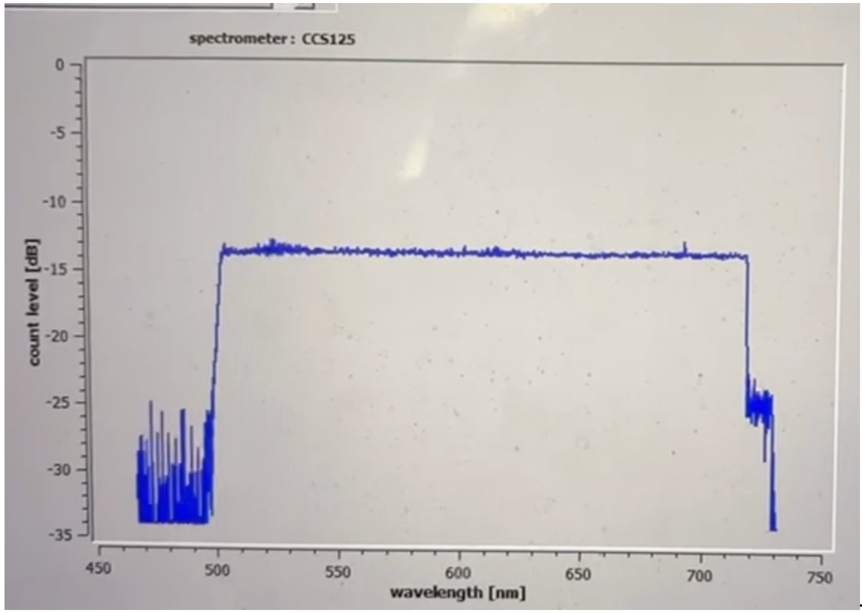
Spectral flattening (SLM)

Huge dynamics

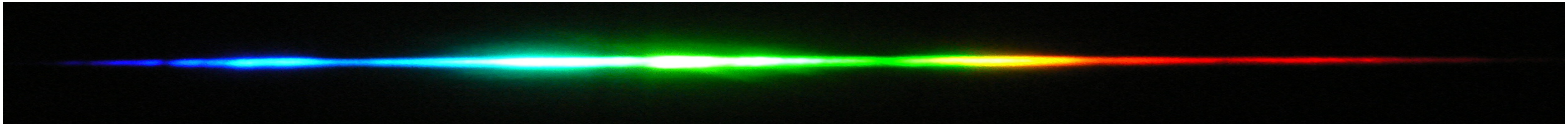
Need to flatten to maximize amount of useful information

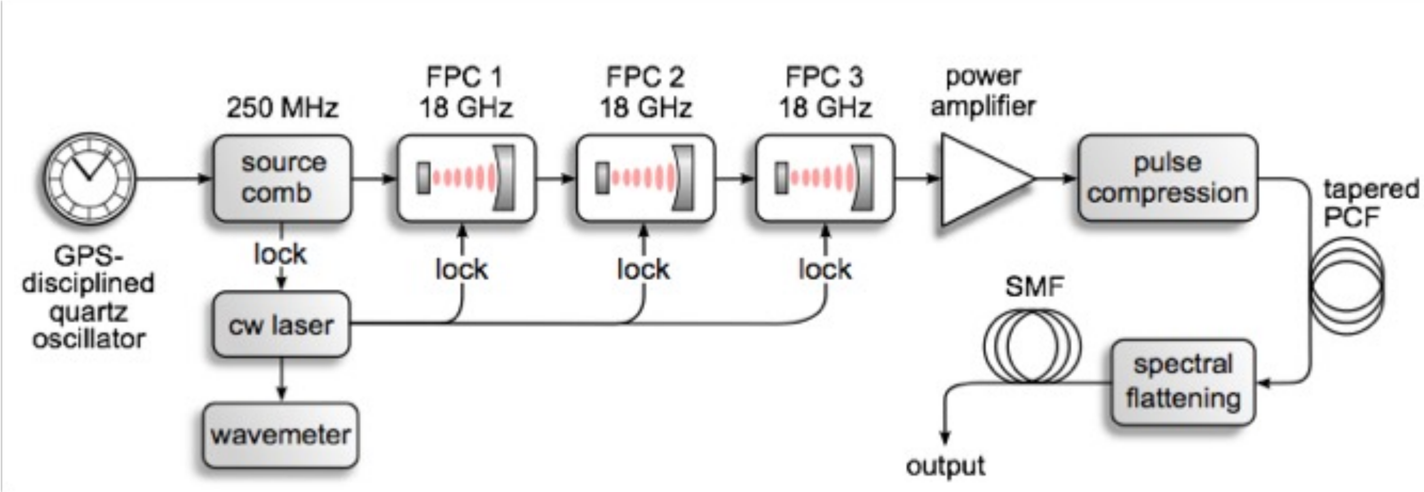
Use Spatial Light Modulator (SLM)





The HARPS LFC by MENLO - 2015

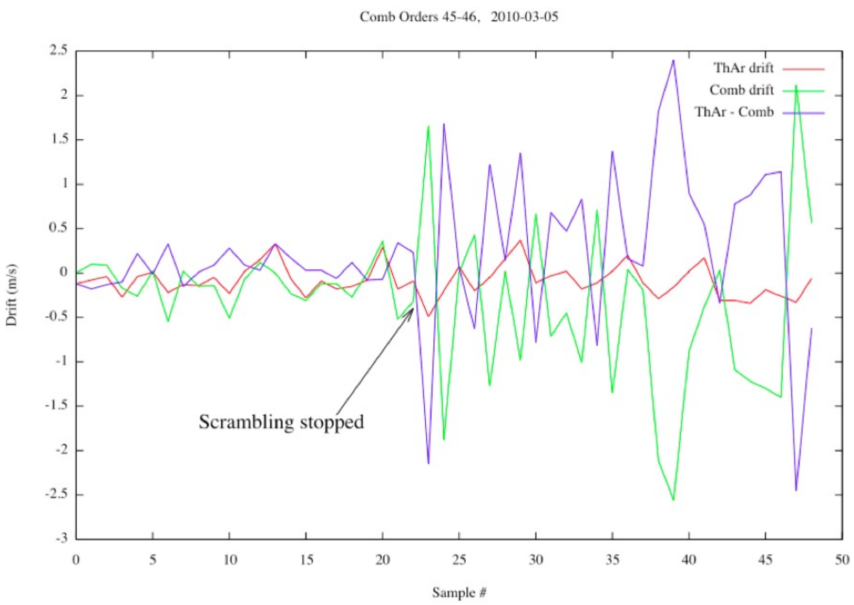


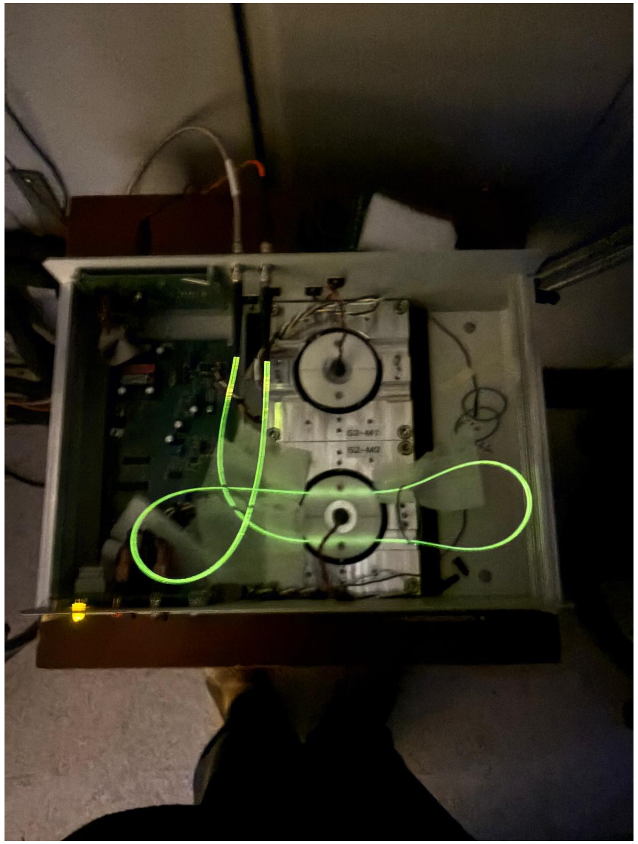


Probst R. et al. SPIE 2016

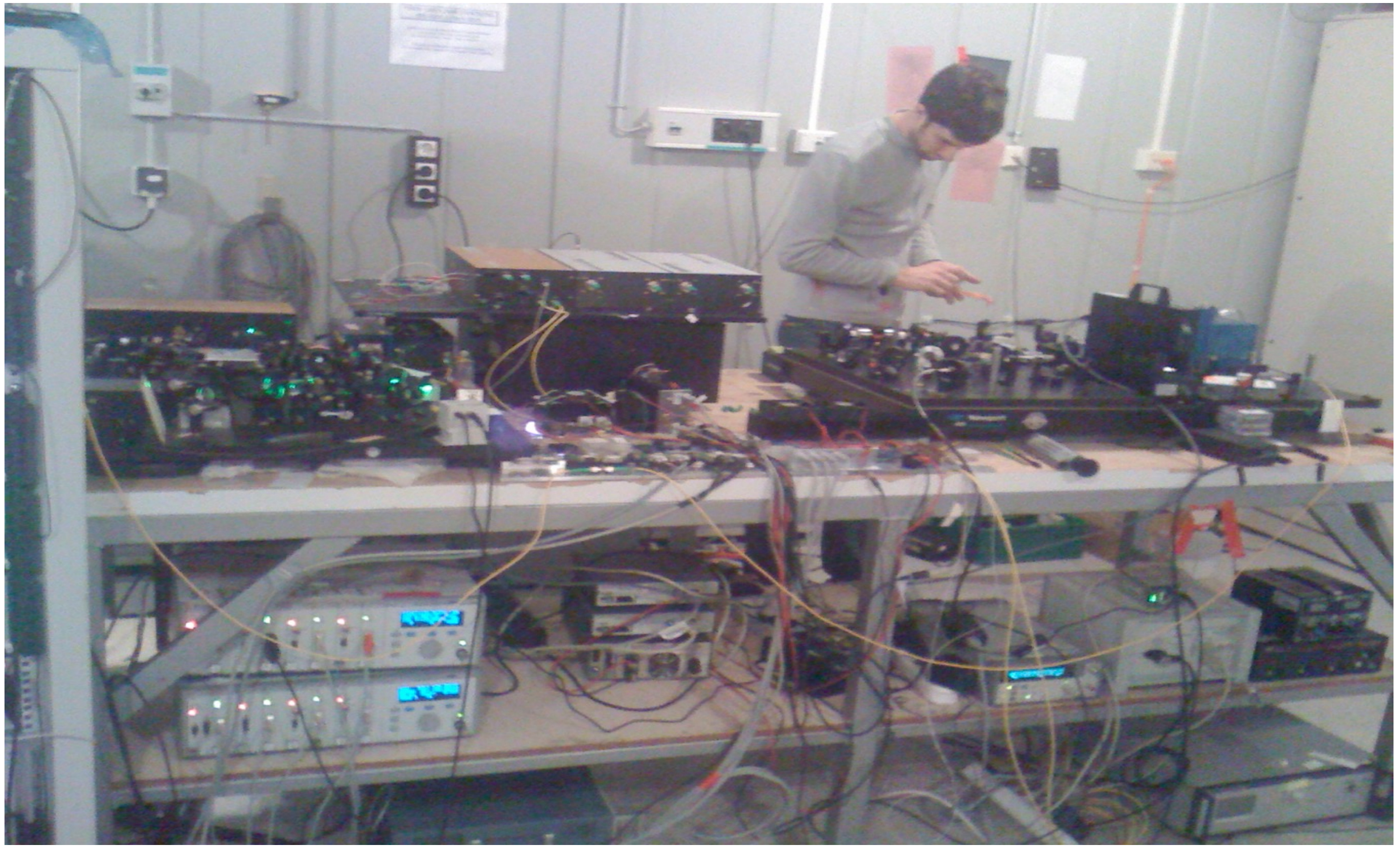
The light path from LFC to spectrograph

- Couple from the single mode PCF to a multimode fiber
- Destroy temporal coherence => dynamic scrambling
- Fill as many as possible spatial modes => static scrambling





Test of the first ”astrocomb” on HARPS: 2010



The HARPS LFC by MENLO

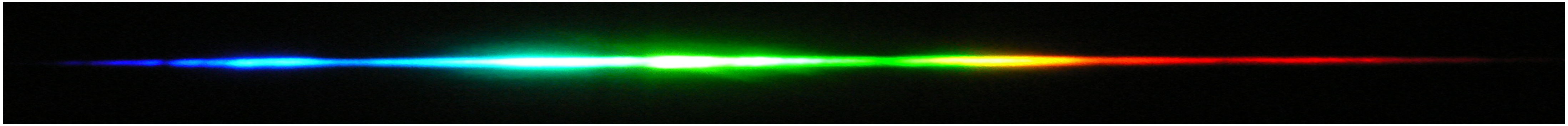
HARPS LFC Operations timeline

- First tests in 2010 → oh, we need a scrambler !
- Final installation in La Silla in April 2015
- Operational since Oct. 2016 (upgraded injection, scrambler)
- Repeated issues with phase stabilization (XPS)
- Failure of a pump diode
- Cooling of the bredboard started in 2021
- Overall availability rate ~ 50% until 2021 ← Environment ? EM ? Humidity / Temperature ?
- From June 2023, downtime: ~ 13%.
- ~12000 LFC spectra acquired so far

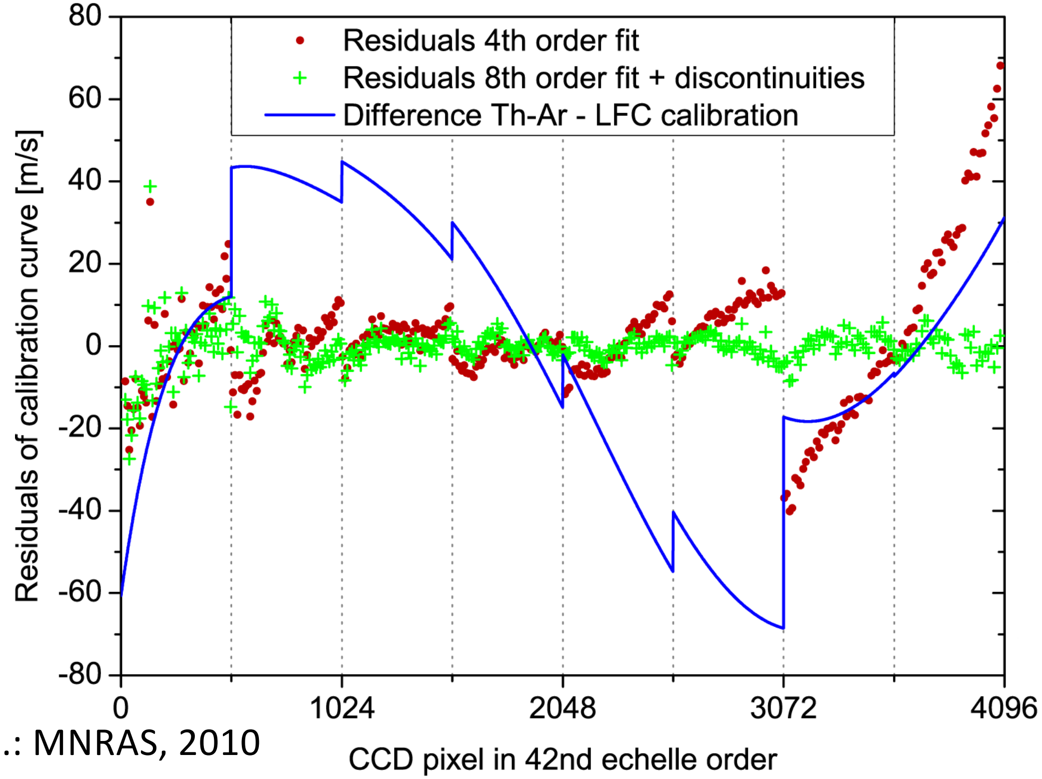
ESPRESSO LFC Operations timeline

- Installed in 2019
- Environment stabilized in 2021 (improved thermal control)
- Blu fiber installed in 2022
- Many problems due to reliability, background variability
- Blue fiber removed in 2025
- System appears more reliable

The CCD geometry

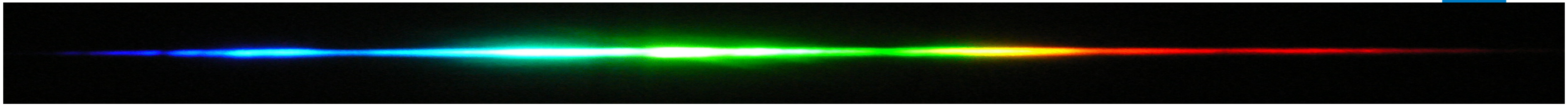


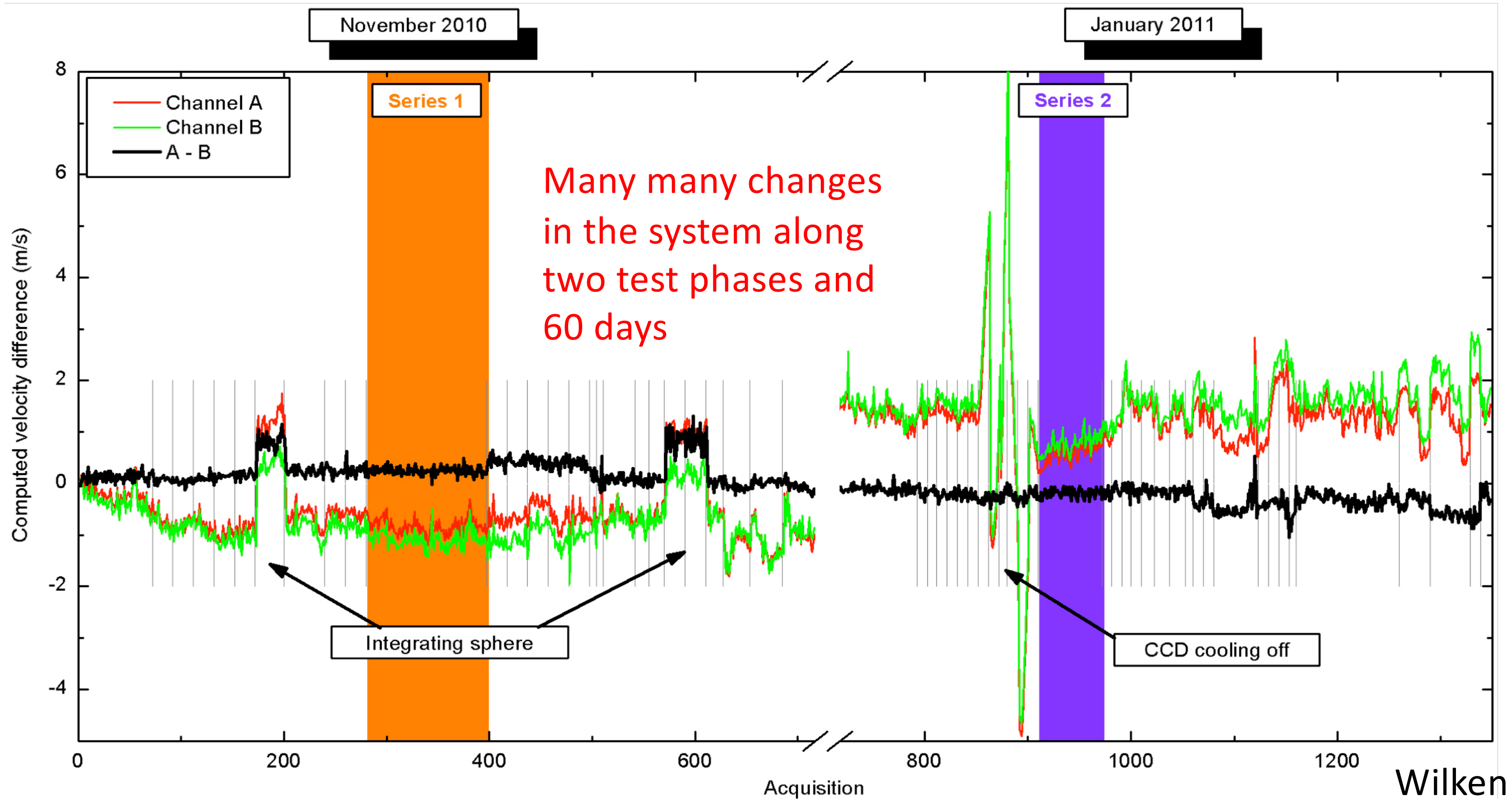
Clear detection of the CCD stitching pattern every 512 pixels



Wilken, T. et al.: MNRAS, 2010

Stability

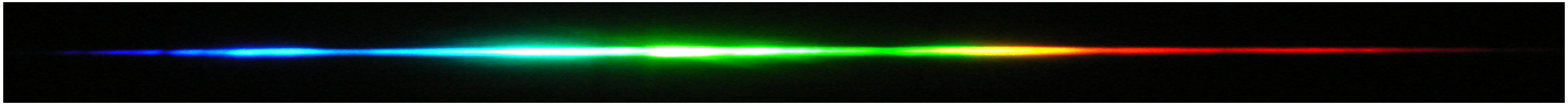




Many many changes in the system along two test phases and 60 days

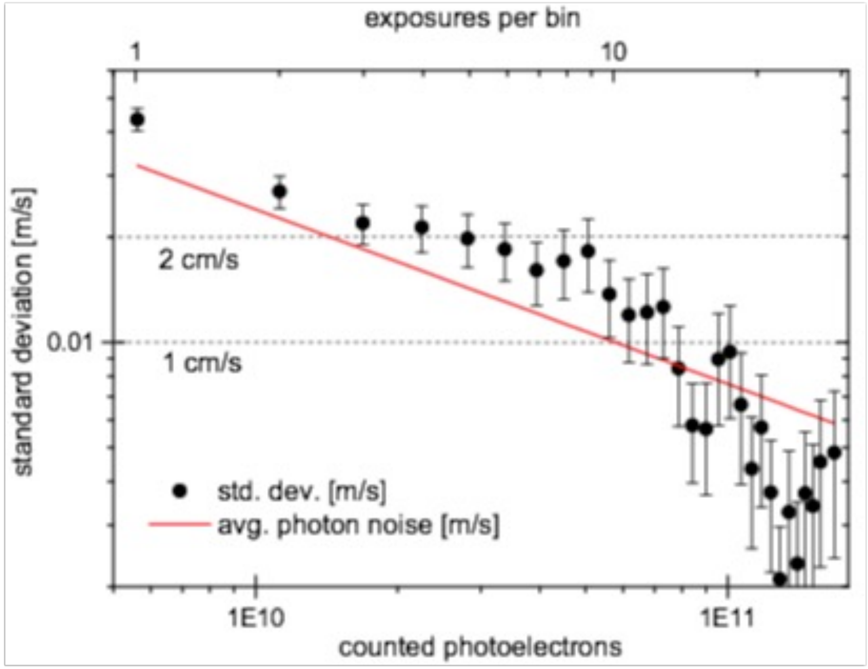
Wilken, T. et al., Nature, 2012

Stability



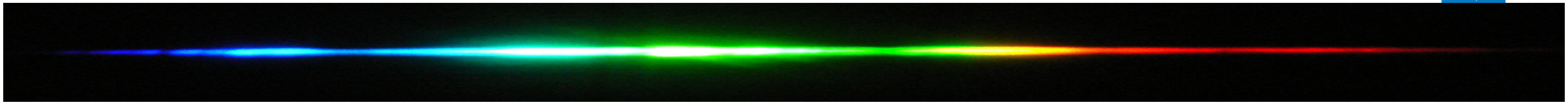
$$\sigma_y^2(\tau) = \frac{1}{2}\langle(\bar{y}_{n+1} - \bar{y}_n)^2\rangle$$

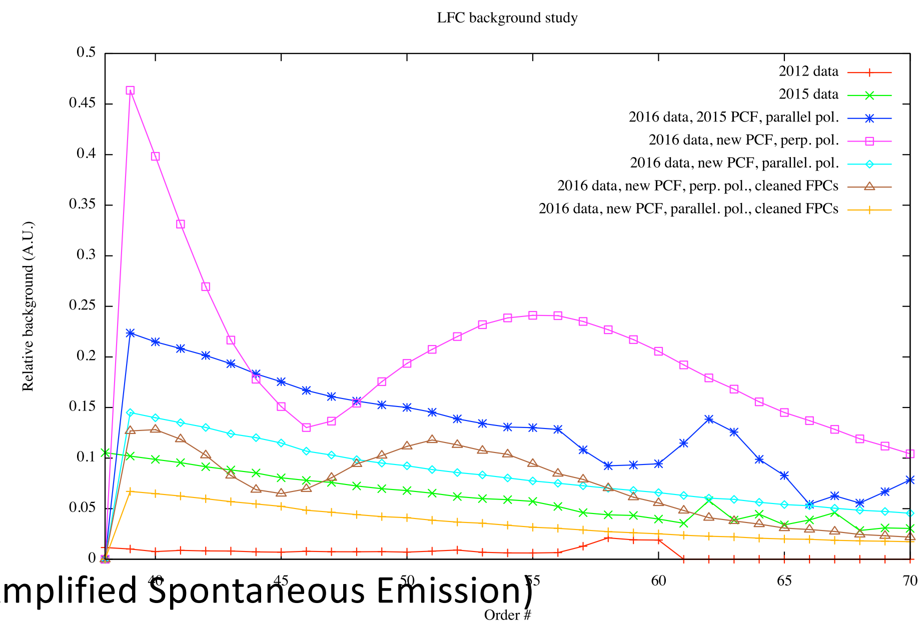
Noise in the LFC data is
Statistical down to
1 cm/s !!!



Probst, R. et al., SPIE, 2016

Spectral background

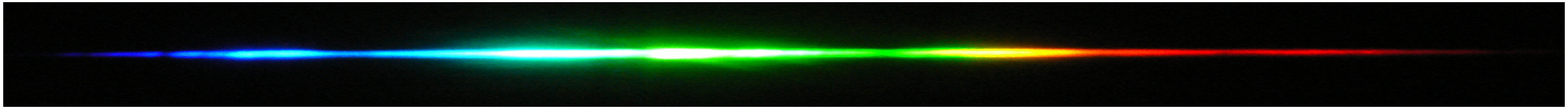




- Likely due to ASE (Amplified Spontaneous Emission)
- Increases with amplifiers current
- Increases with degradation of FP coatings
- Polarization dependent

Trade-off: PCF lifetime is also polarization dependent (better in the "other" polarization)

LFC on sky – Stellar RVs



Star	N	δRV (m/s) (ThAr-LFC)	STD(δRV) (m/s)	RV_err	LFC Calib. Stability (cm/s)	SNR @ 550nm	T (K)	FWHM (km/s)
HD330075	4	-31.11	0.54	1.72	12 ± 3	65	6295	6.82
HD75289	8	-30.43	0.30	0.77	12 ± 3	214	6120	8.60
HD76700	4	-31.53	0.30	1.04	12 ± 3	100	5726	7.27
HD85512	5	-35.43	0.39	1.31	14 ± 3	128	4715	6.04

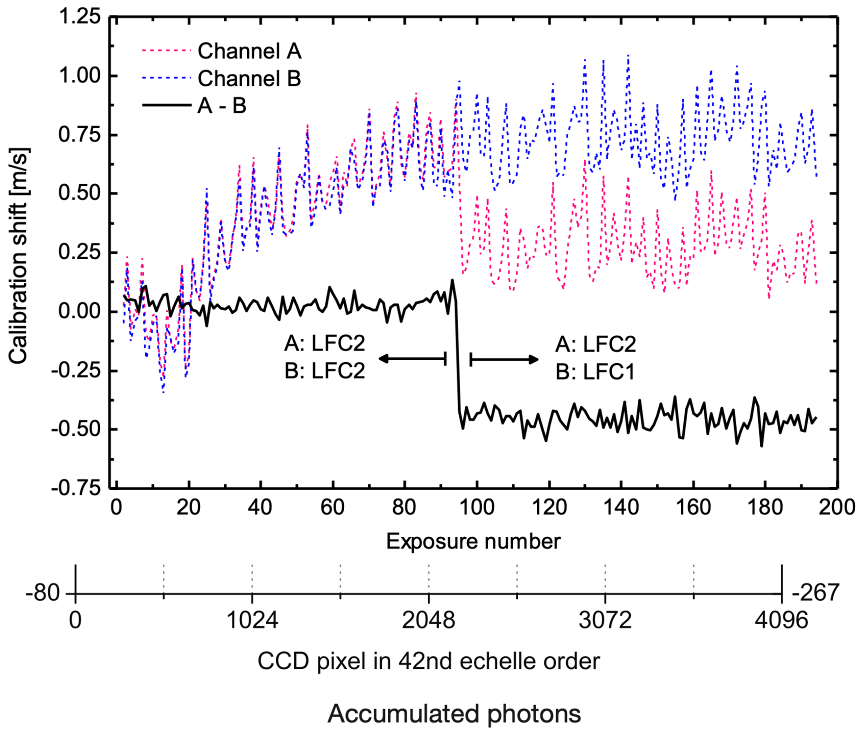
- Offset ThAr – LFC calibration (expected)
- Calibration stability limited to ~ 12cm/s !

→ Improve data reduction software

HARPS – LFC publications

- Milaković, D.: Δα/α from QSOs (2021)
- González Hernández, J. I.: Sun Gravitational redshift (2020)
- Molaro, P.: A LFC-calibrated solar atlas (2013)

- Zaho, Fei on line profile from LFC, A&A, 2021
- Probst, R. on LFC, Nature 2020
- Zhao, Fei on line profile from LFC, IAUS, 2014
- Wilken, T. on LFC, Nature 2012
- Wilken, T. on LFC, MNRAS, 2010



HARPS LFC operations

Daily calibrations are performed:

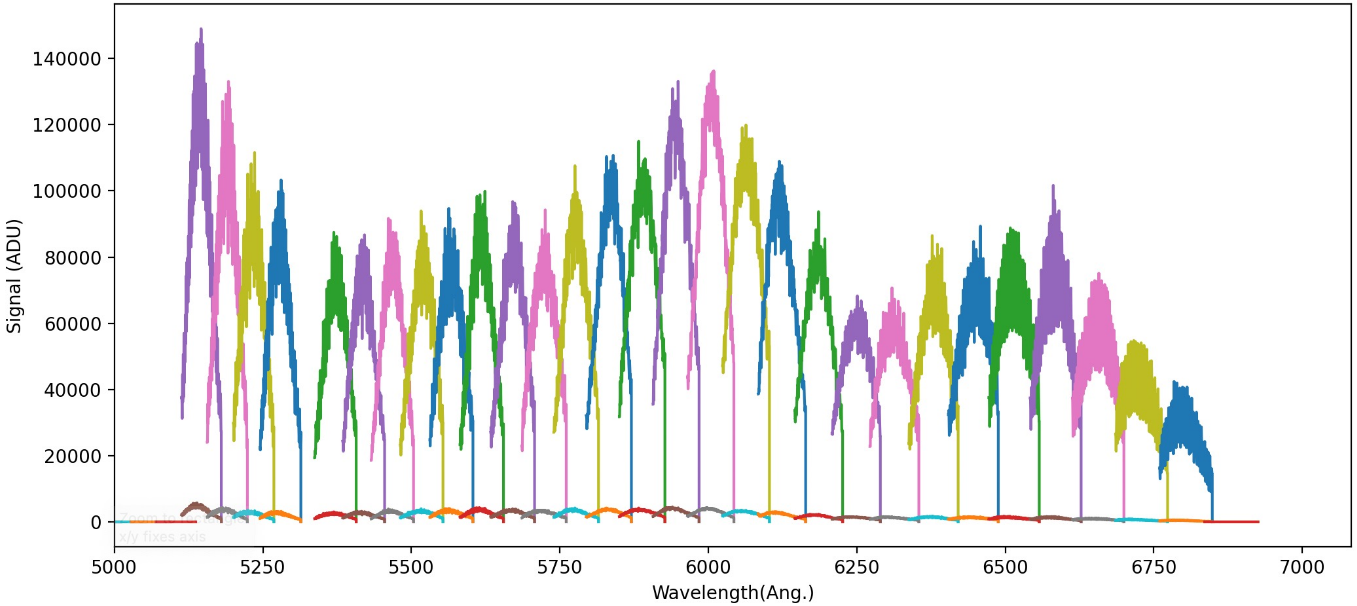
LFC-LFC x 6
LFC-FP
FP-LFC

Wait 5 minutes with LFC ON
Before opening the shutter !

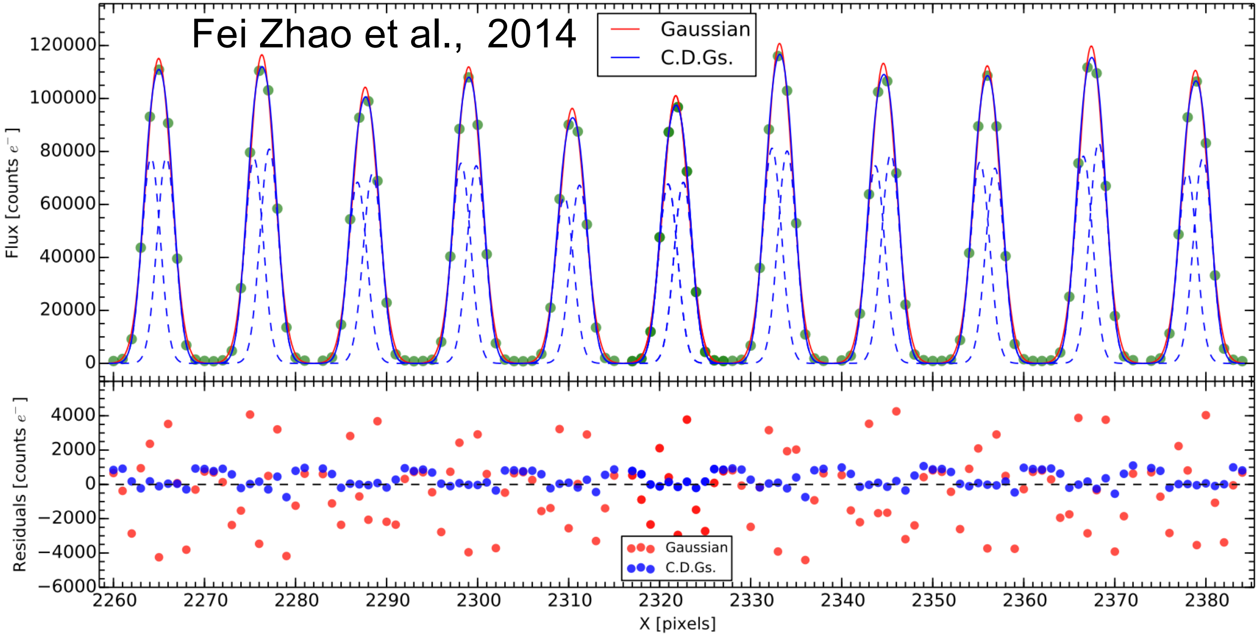
About 200 hours of usage per year

Only 1 PCF changed so far !

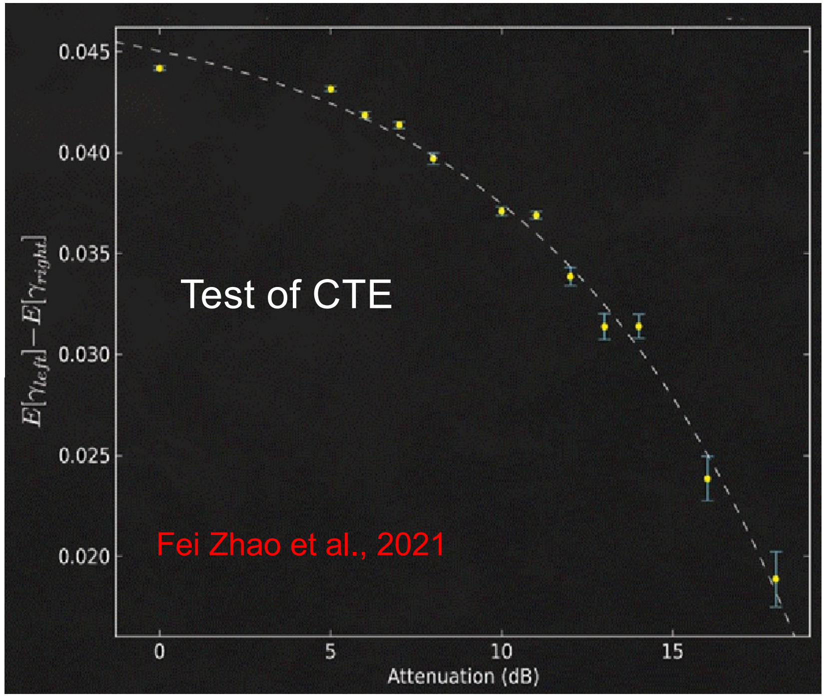
“Red” PCF
covers ~ 5100A – 6900A



Instrumental PSF

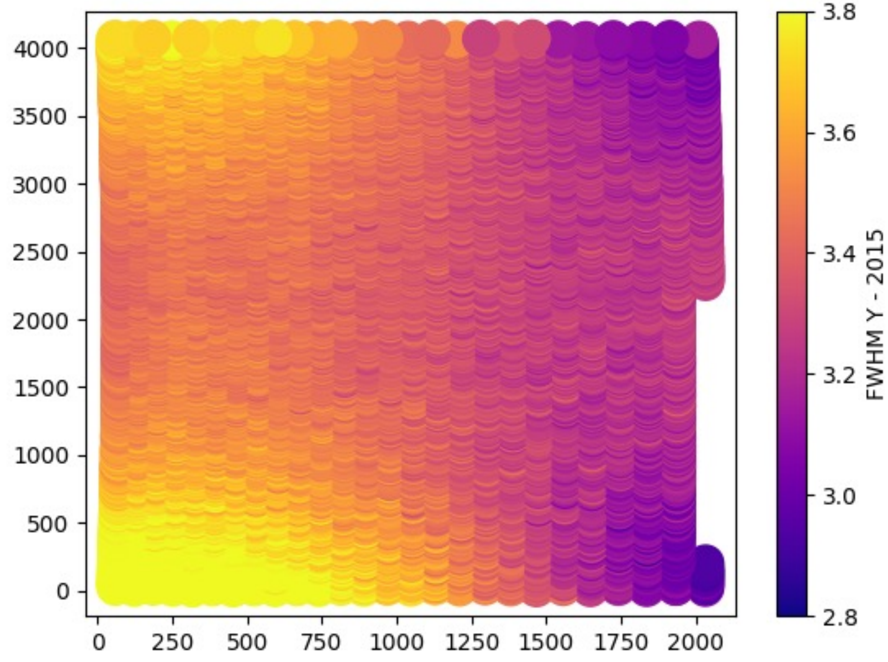


'Constrained' double gaussian fit
Scatter of residuals reduced by a factor of 4.

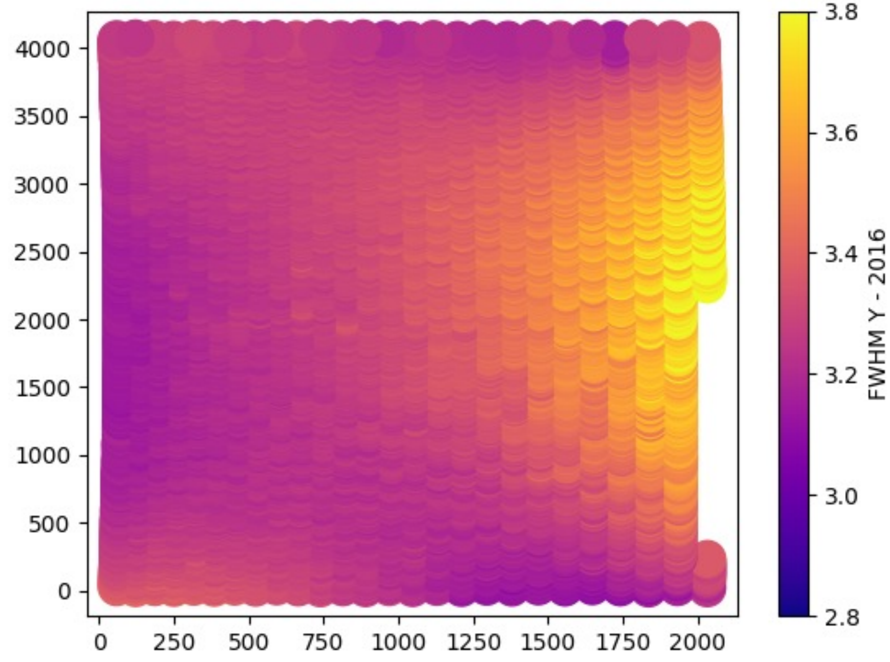


Stability of the instrumental PSF

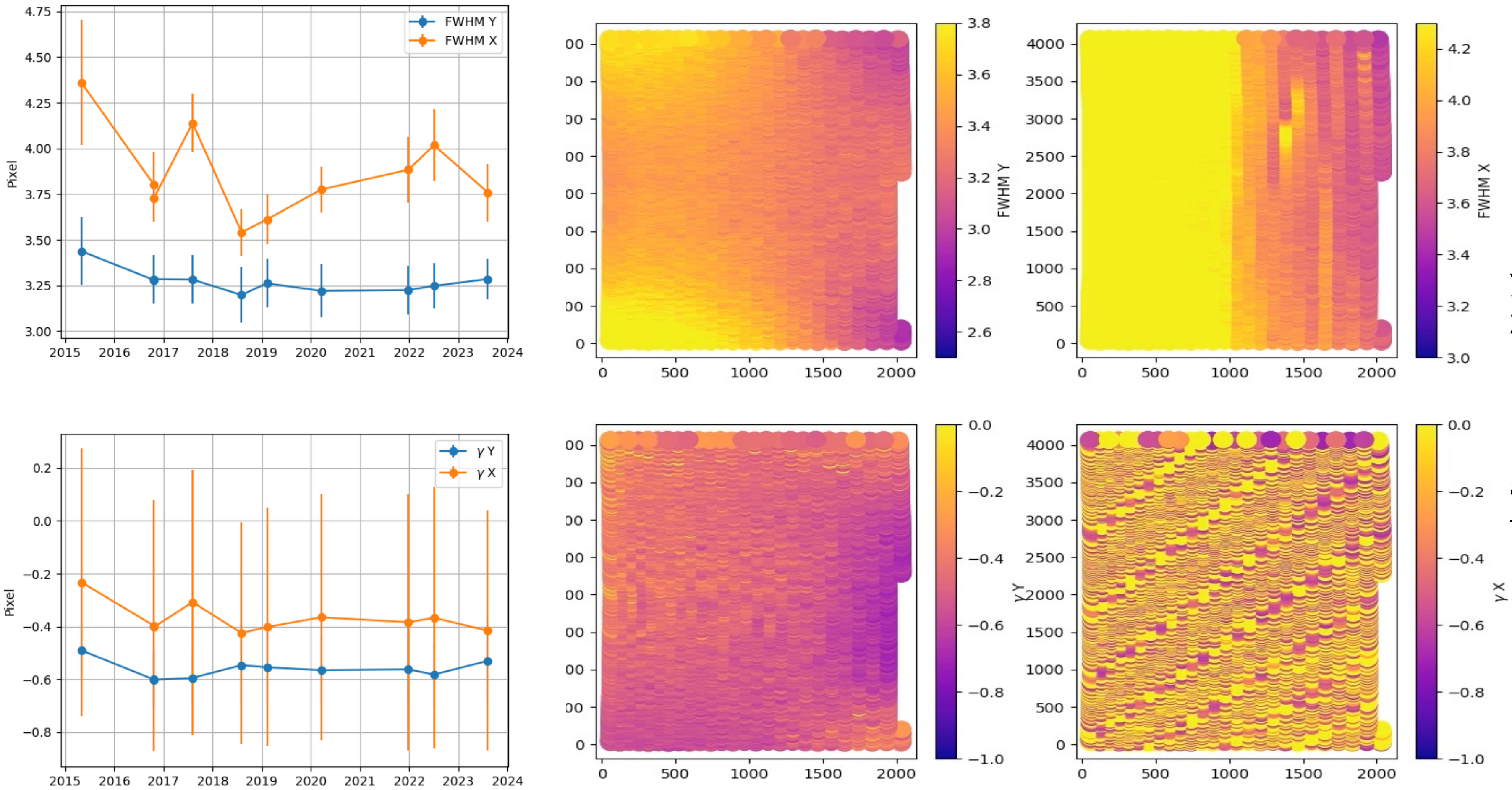
FWHMY **before** the fiber-link exchange



FWHMY **after** the fiber-link exchange



Stability of the instrumental PSF

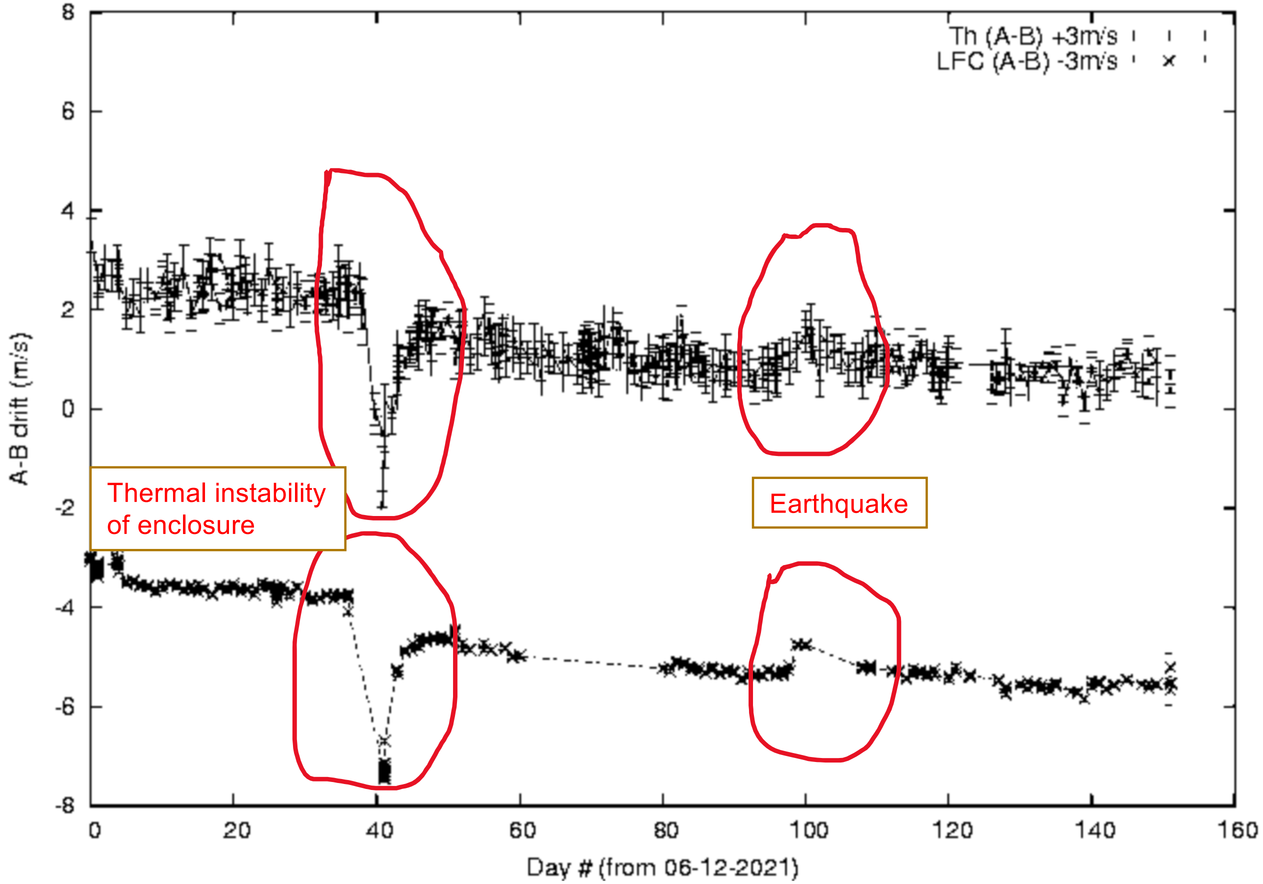


HARPS LFC,

yearly spectra 2015 – 2023

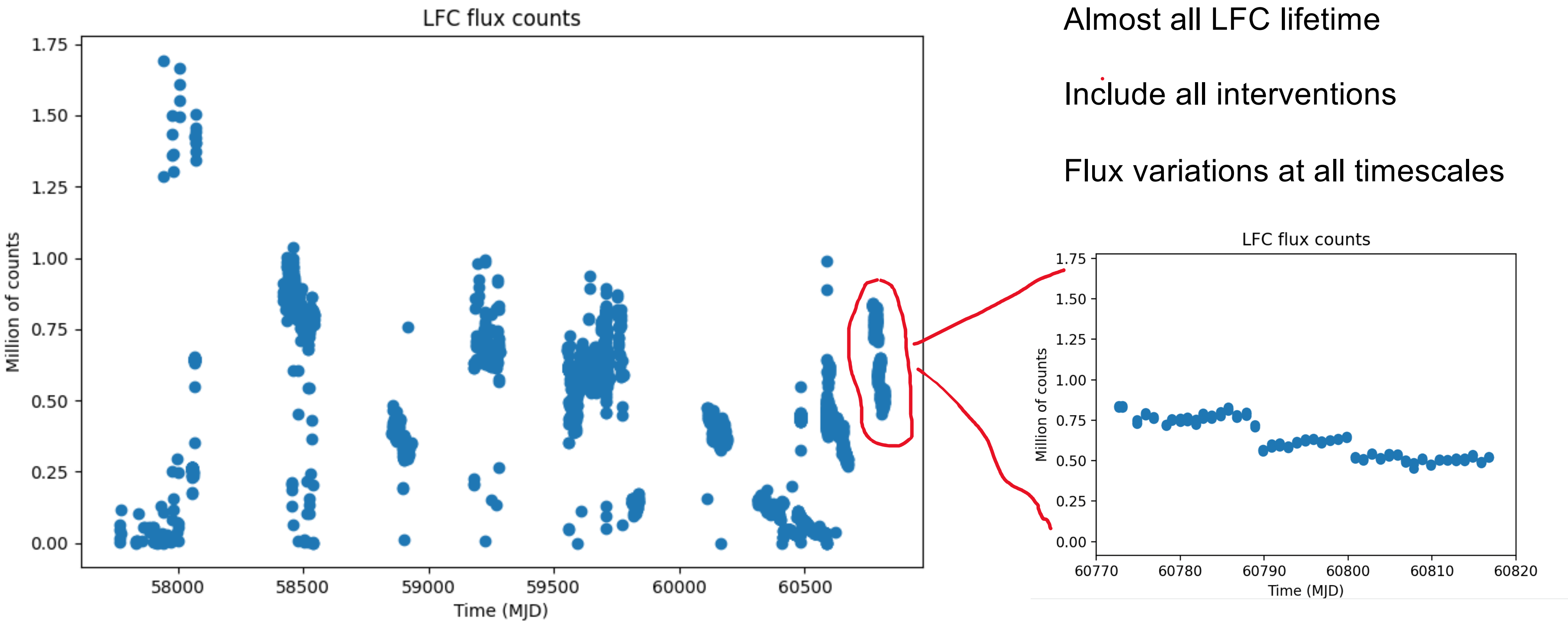
First spectrum acquired before fiber-link exchange.

Stability of the instrumental PSF



~ 3m/s A-B **differential** drift in 150d ➔ 2cm/s/day

LFC flux variation across time

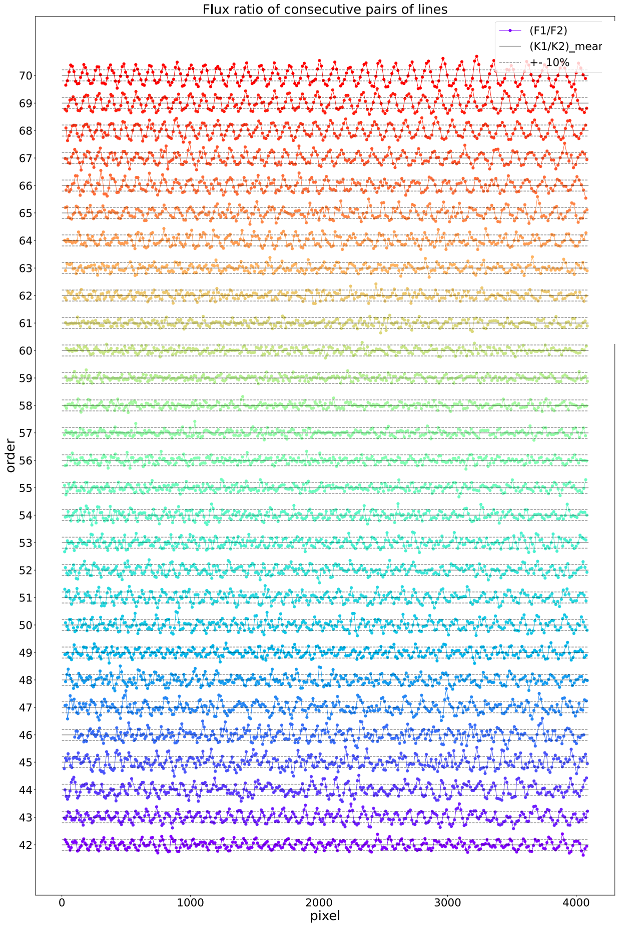


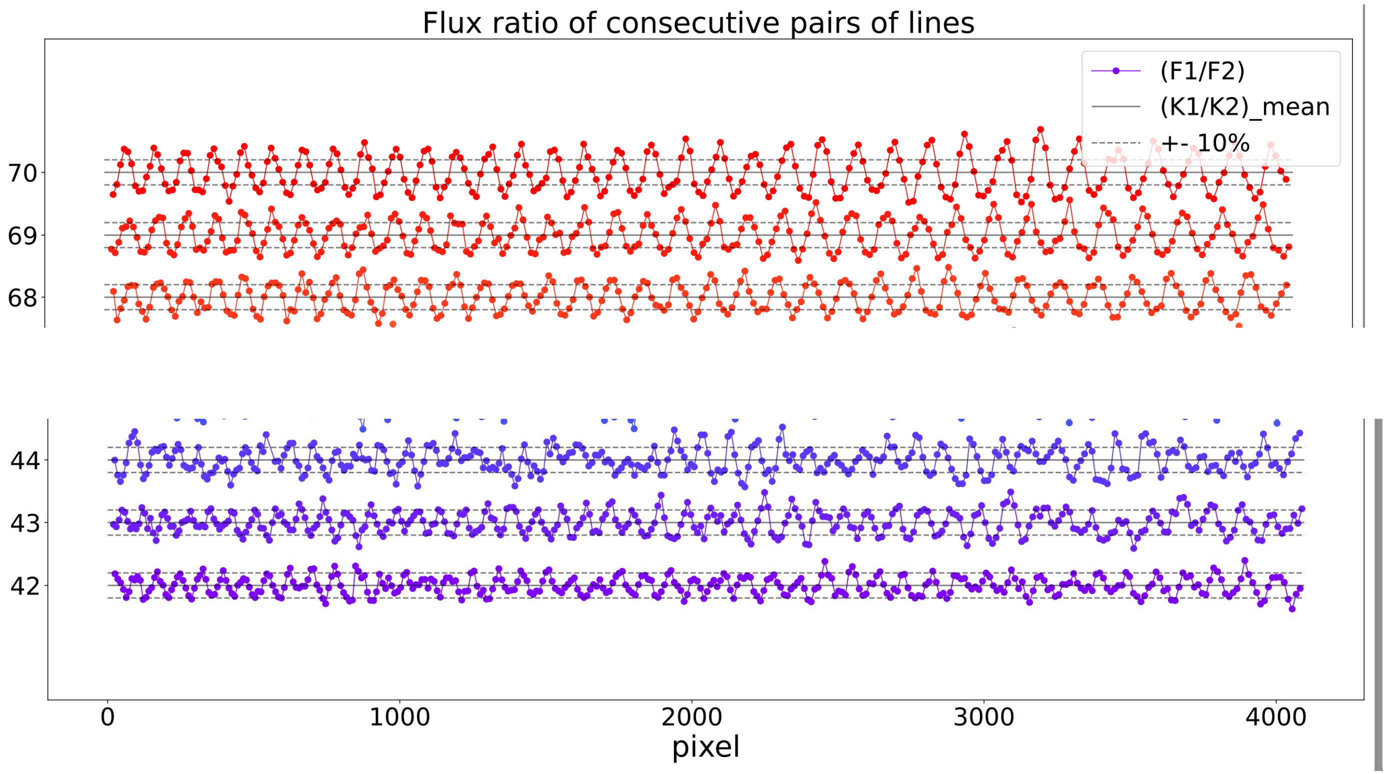
Almost all LFC lifetime

Include all interventions

Flux variations at all timescales

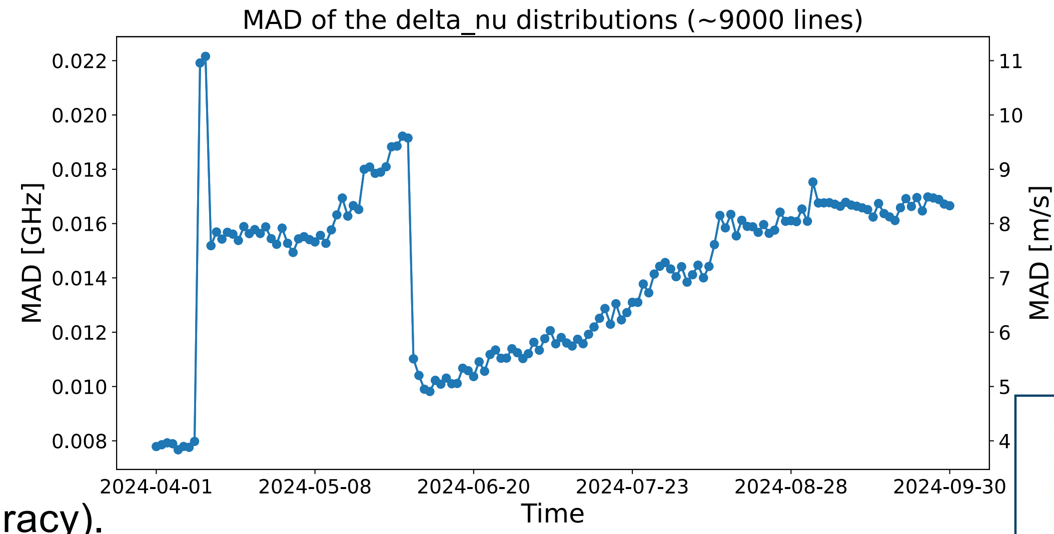
Flux ratio between nieghboring lines



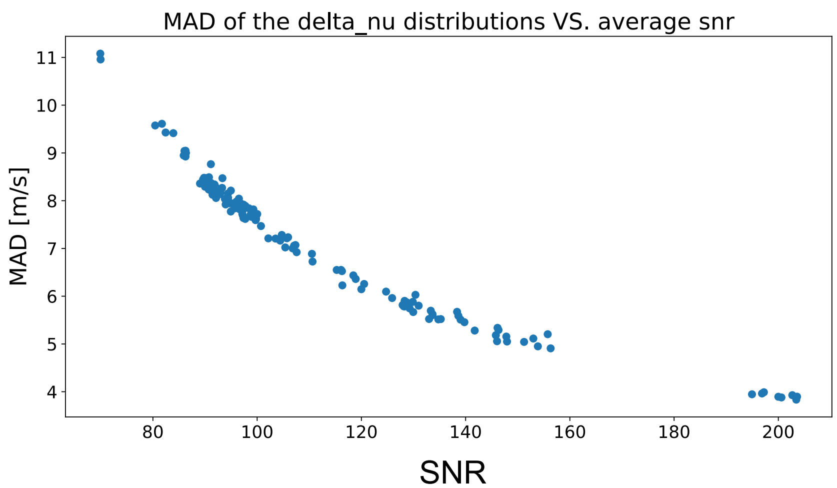


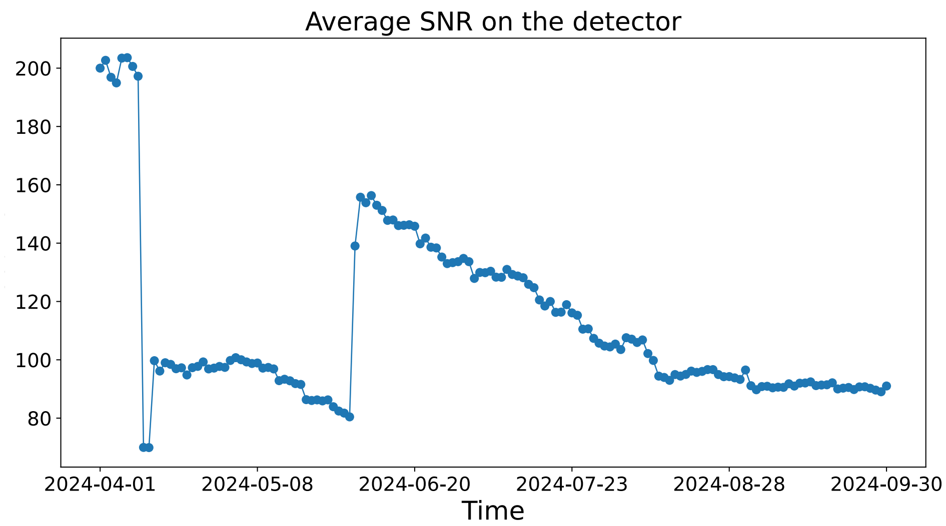
Work by Sara Tavella

Repetition frequency measurement as a sanity check



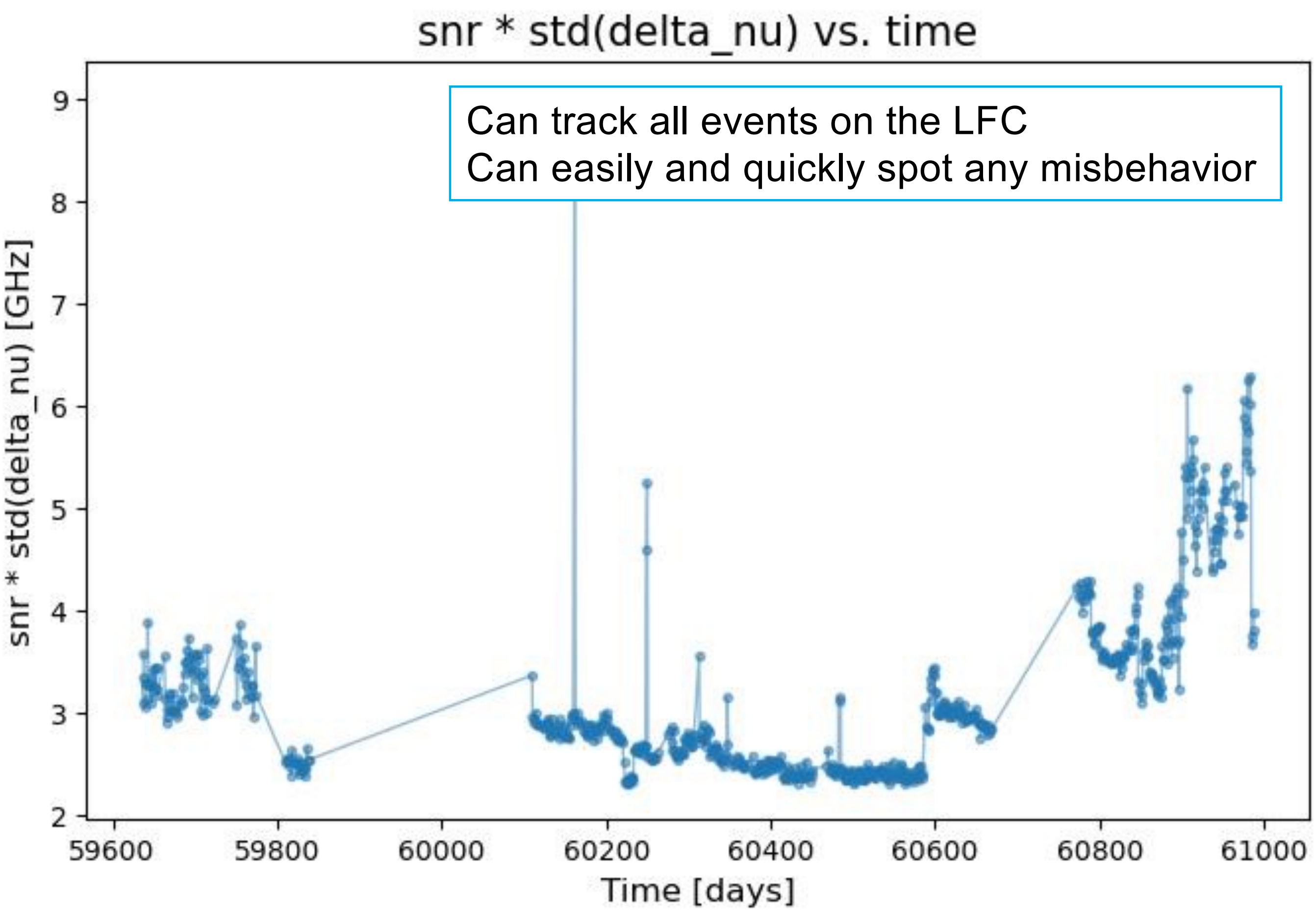
In a period of 6 months the deviation of the repetition frequency measurements from the nominal value of 18GHz follows strictly SNR, and its RMS reaches a value of 4m/s (local accuracy).





Work by Sara Tavella

Repetition frequency measurement as a sanity check



Work by Sara Tavella

Maintenance strategy

- “Hotline” with manufacturer
- Close monitoring by local staff
- Identify “KPI” to send alert (signal level, repetition frequency, temperatures)
- Large overall FTE commitment along the years by both LFC & INS teams.

Perfect LFC = perfect data ? No !

- Injection → stability
- Environment → reliability
- LSF fitting → data analysis and interpretation

The LFC team and the instrument team have to work closely together

Summary

- Environmental effects (EM, T, R.H.) impact severly the LFC reliability
- Stability of the injection is critical to transfer the LFC precision to the instrument
- Close follow-up is needed, both by the manufacturer and by the end user
- The HARPS LFC is in routine operations with a much improved availability rate since 2023
- The ESPRESSO LFC has recently improved his stability
- The NIRPS LFC is still suffering from high noise

Thank you!

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