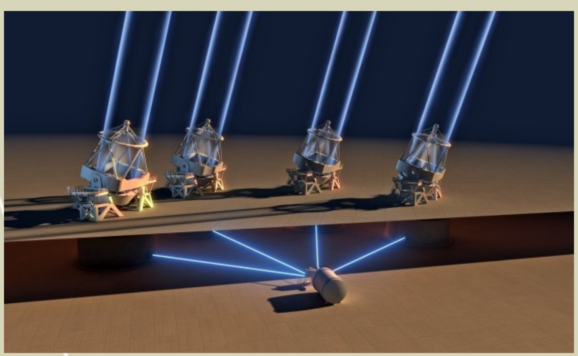
ESPRESSO: the new VLT workhorse for high-precision astronomy

P. Di Marcantonio

on behalf of

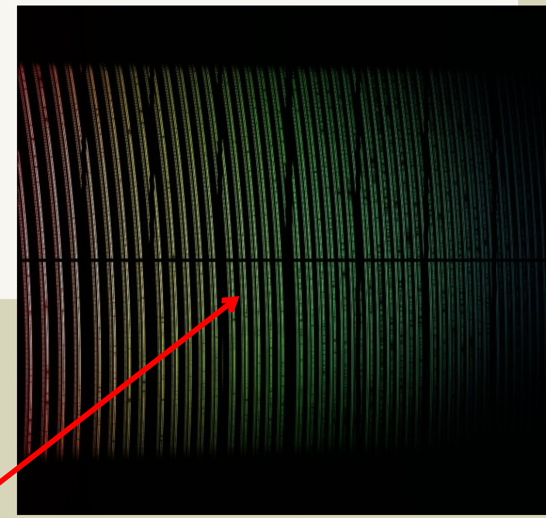
ESPRESSO Team

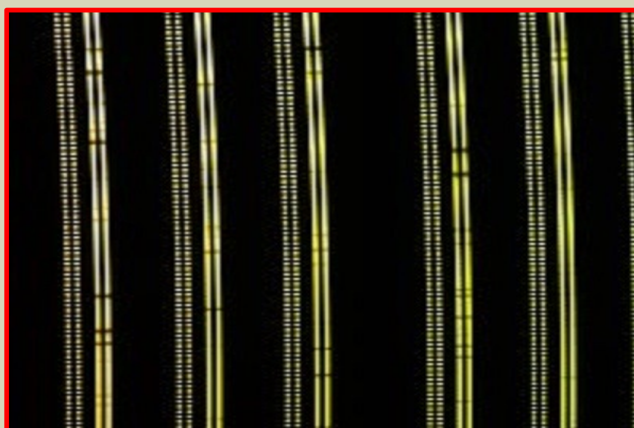
INAF-OATs



Outline of the talk

- the ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectral Observations) instrument
- ESPRESSO at the VLT
- ESPRESSO Data Flow and its final deployment
- ESPRESSO operations
- ESPRESSO "science" software in a nutshell





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The ESPRESSO "facility”

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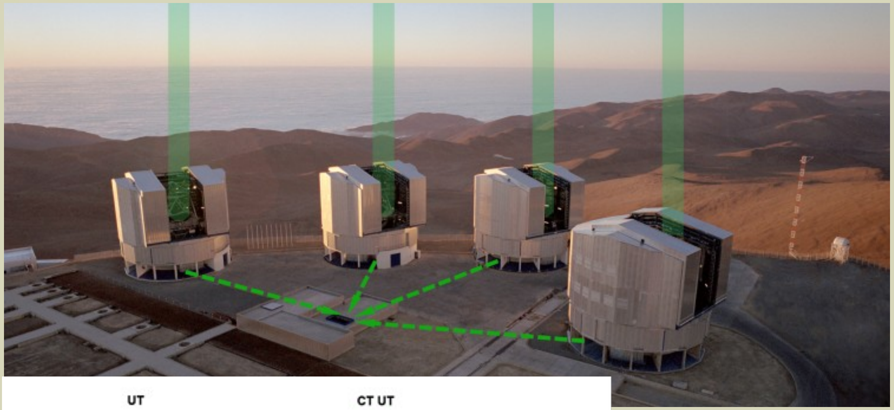

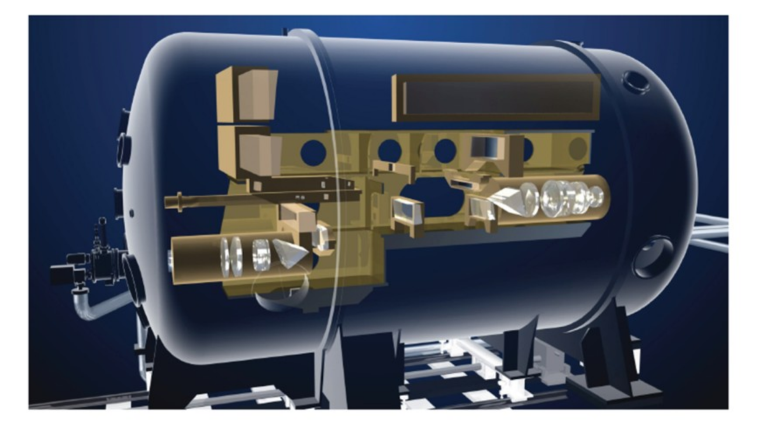

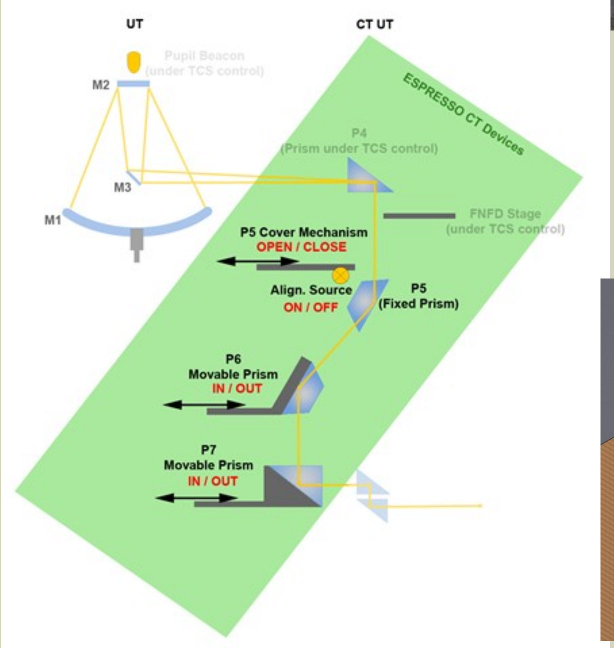

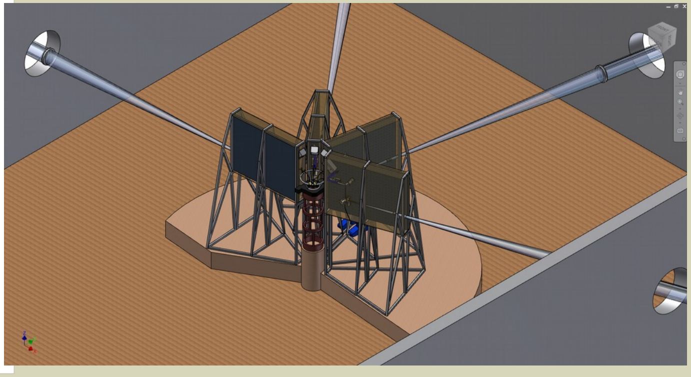

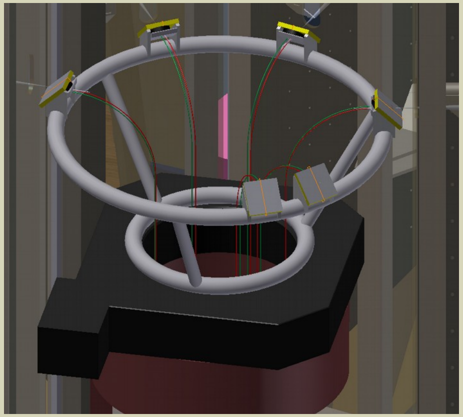

Instrument characteristics

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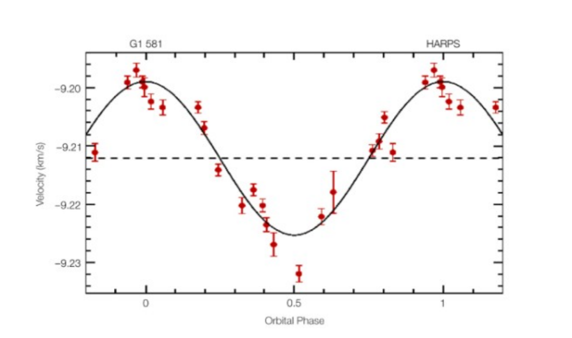
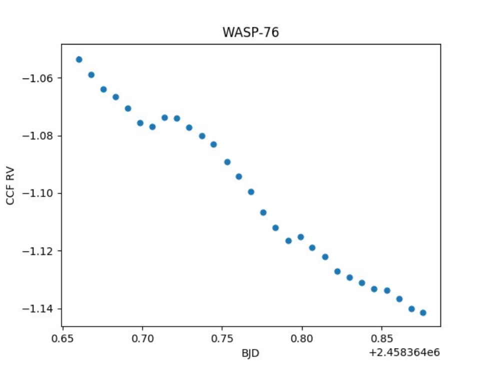
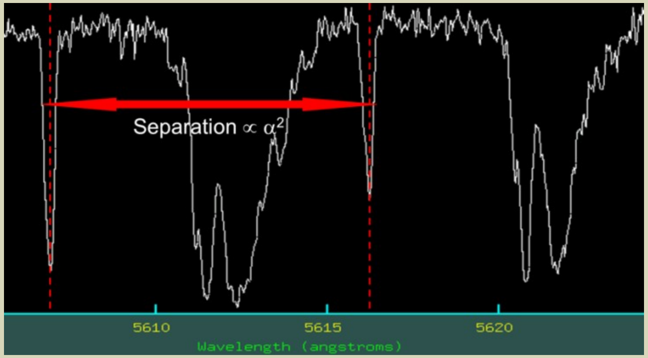
Parameter	singleUHR	singleHR	multiMR
Wavelengths	Blue arm: 380 – 520 nm Red arm: 520 – 780 nm		
Spectral coverage	Full		
Spectra format	Echelle, up to 4 spectra per order (2 fibers, 2 spectra / fiber)		
Resolving power	225'000	134'000	59'000
Aperture on sky	0.5 arcsec	1.0 arcsec	4x1.0 arcsec
Spectral sampling	2.5 pixels	4.5 pixels	10 pixels
Spatial sampling	9 pixels	18 pixels	44 pixels
Available binning	1x1	1x1 or 2x1	4x2 or 8x4
Sky/Simultaneous reference	Yes (mutually exclusive)		
Instrumental RV precision	<10 cm/s	<10 cm/s	~1 m/s

ESPRESSO science





- measurement of high-precision RVs of G, K and M dwarfs to search for rocky planets inside the HZ



- investigate possibly variability of fundamental constants

- study chemical composition of stars in local galaxies, IGM etc.

[the ESPRESSO instrument (FDR movie)]

Optics

IAF-OATs

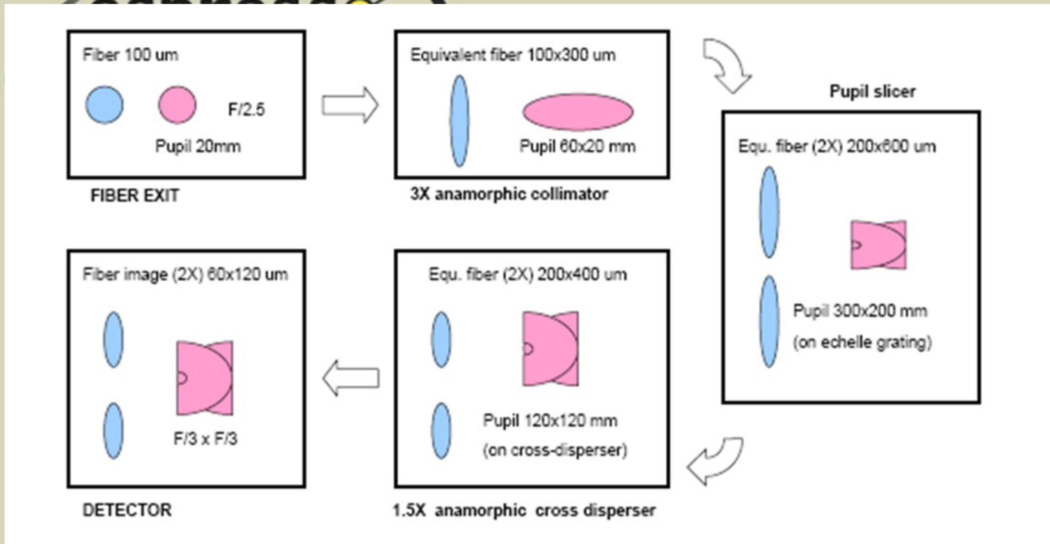


Figure 78. Paraxial image and pupil sizes along the spectrograph optics

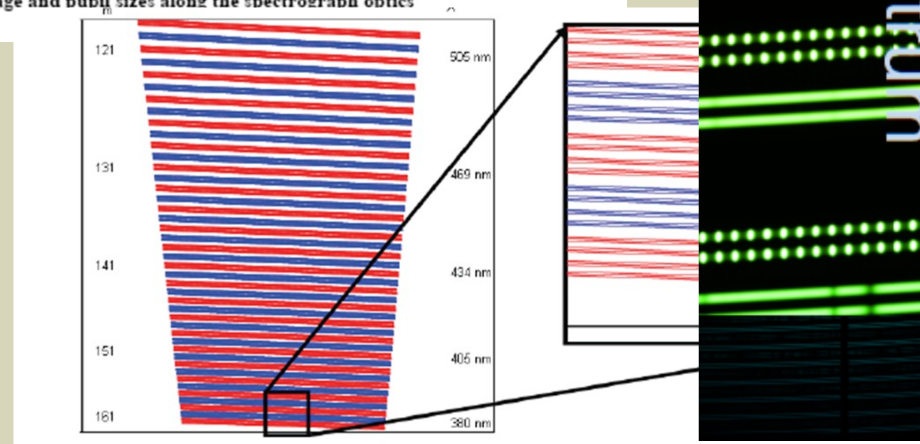
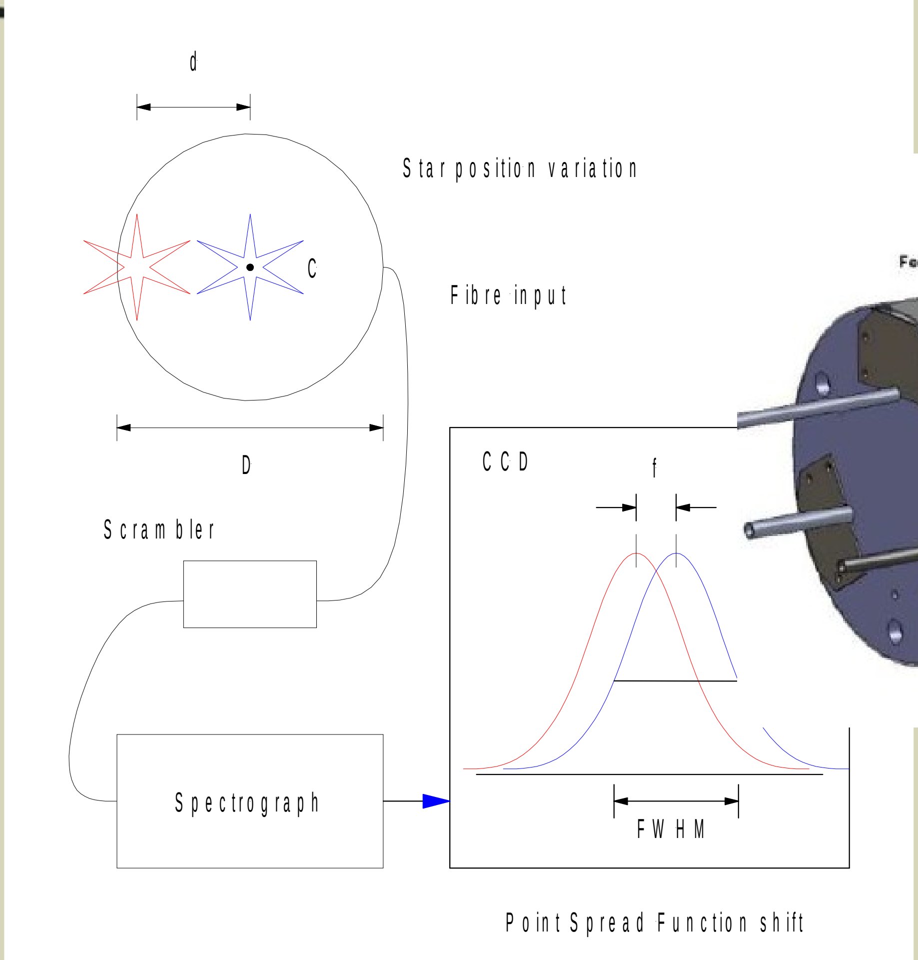
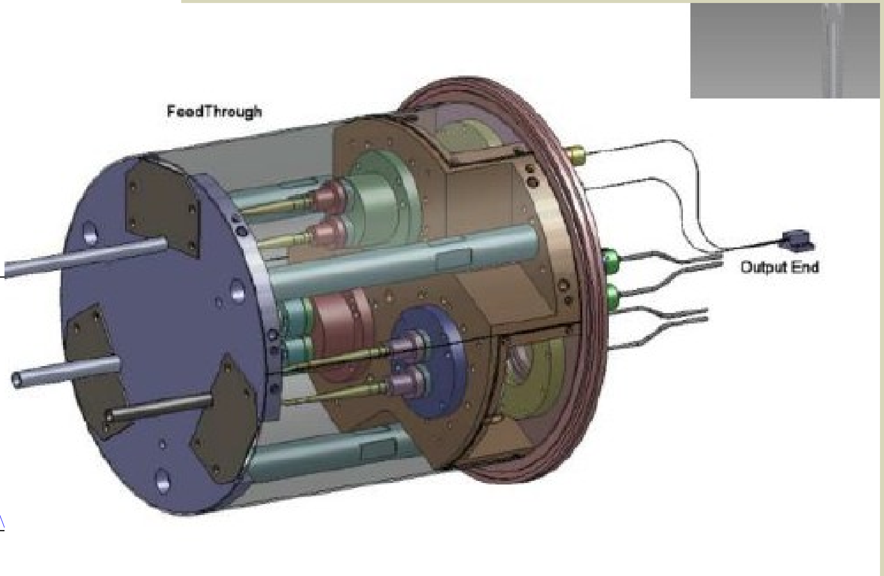


Figure 107. Blue spectral format. The box on the left represents the CCD area.

Scrambler





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ESPRESSO CCDs

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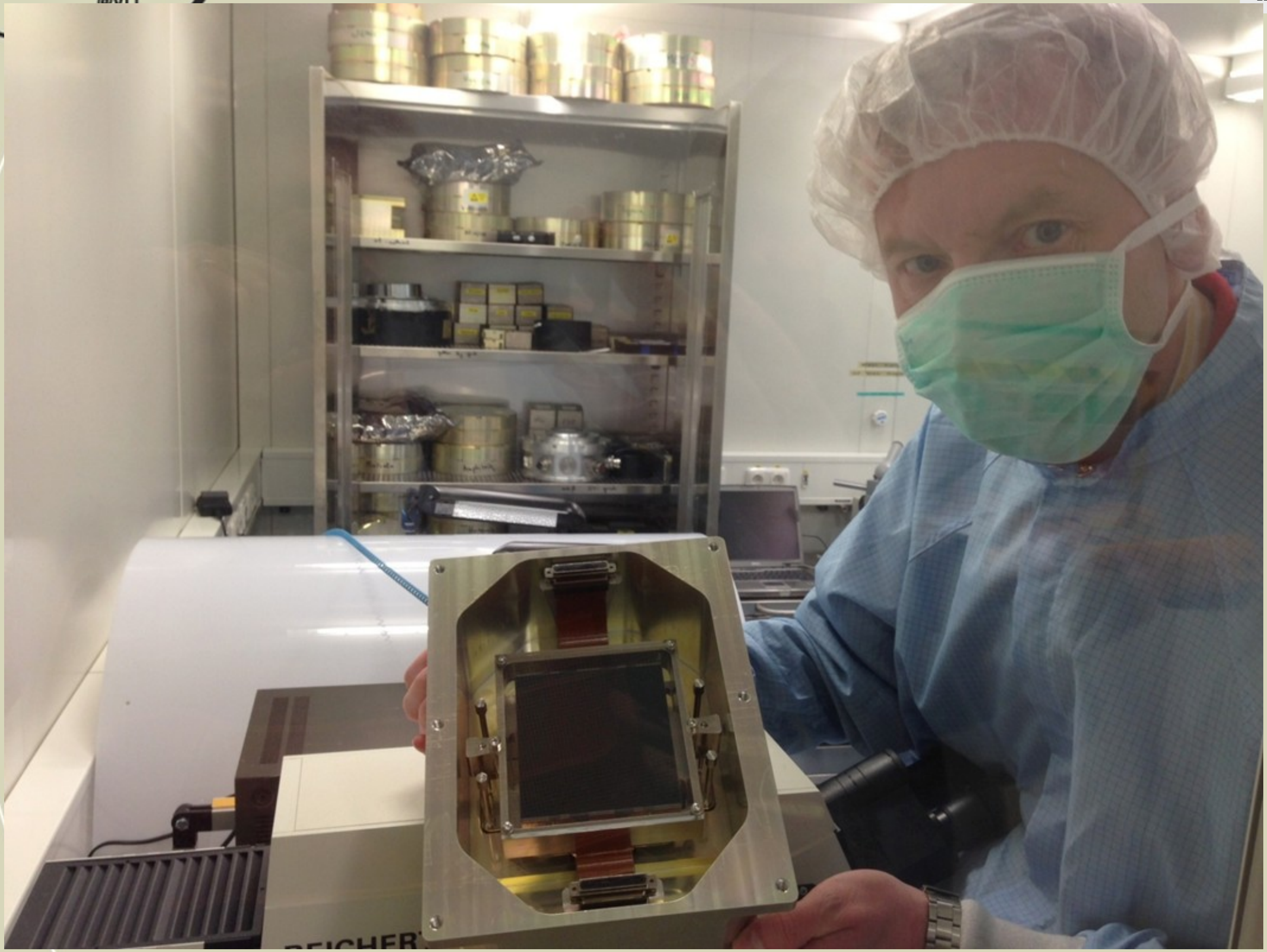
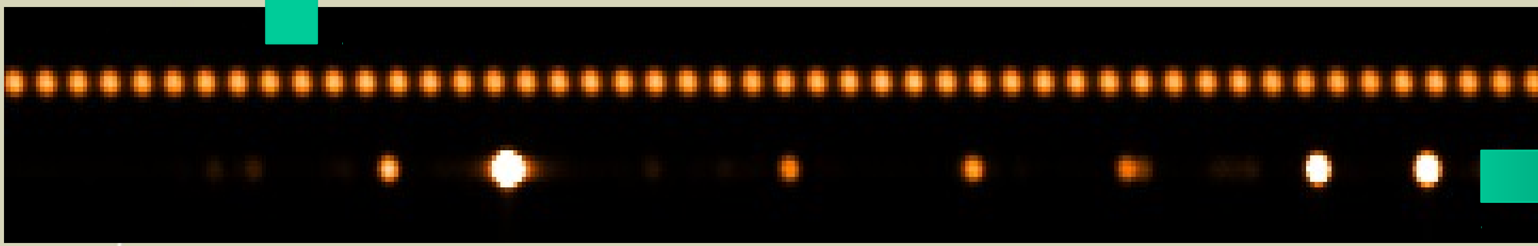


Laser Frequency Comb

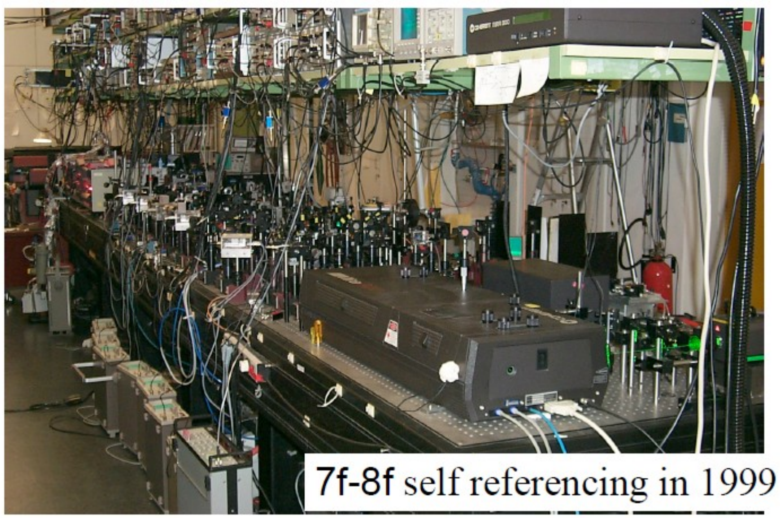
Astro-comb: ~450 lines per order

Th-Ar: ~ 150 lines per order

Astro-comb



Th-Ar



EFTF-FCS Besancon 1999; Opt.Commun. 172, 59 (1999); Phys. Rev. Lett. 84, 3232 (2000) & Phys. Rev. Lett. 84, 5496 (2000)

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The consortium

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Institutes of four countries (1 PI or Co-PI in each)

- Switzerland: Univ. Geneva (Lead, F. Pepe), Univ. Bern
- Italy: INAF Trieste (S. Cristiani, P. Molaro, P. Di Marcantonio), INAF Brera
- Portugal: Univ. Porto (N. Santos), Univ. Lisbon
- Spain: IAC (R. Rebolo Lopez)

Associated partner (Representative in Executive Board)

- ESO (H. Dekker)

ESPRESSO milestones:

- ✓ PDR: end of November 2011
- ✓ FDR: May 2013
  - ✓ ***CT First light***: 25 Sept 2016 on UT4
- ✓ PAE: Q2 – Q3 2017, shipment on Aug 2017
  - ✓ ***ESPRESSO single-UT first light***: 27 Nov 2017 on UT1
  - ✓ ***ESPRESSO 4-UT first light***: 3 Feb 2018
- ➢ Delivery to community: **Oct 2018** (single-UT mode only)
- ➢ Start of GTO: September 2018

AIT @ Paranal

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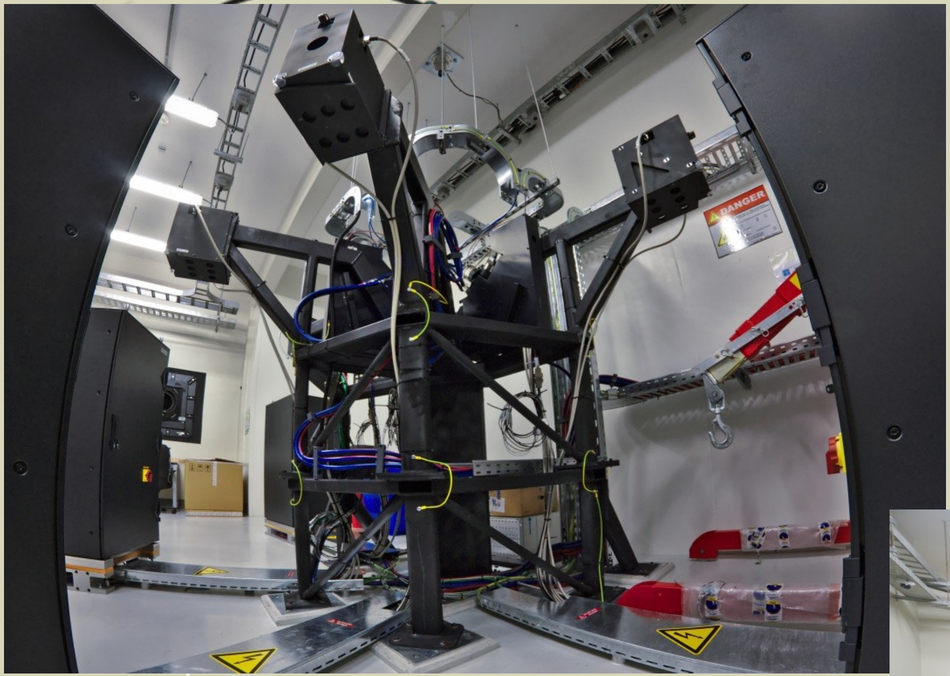
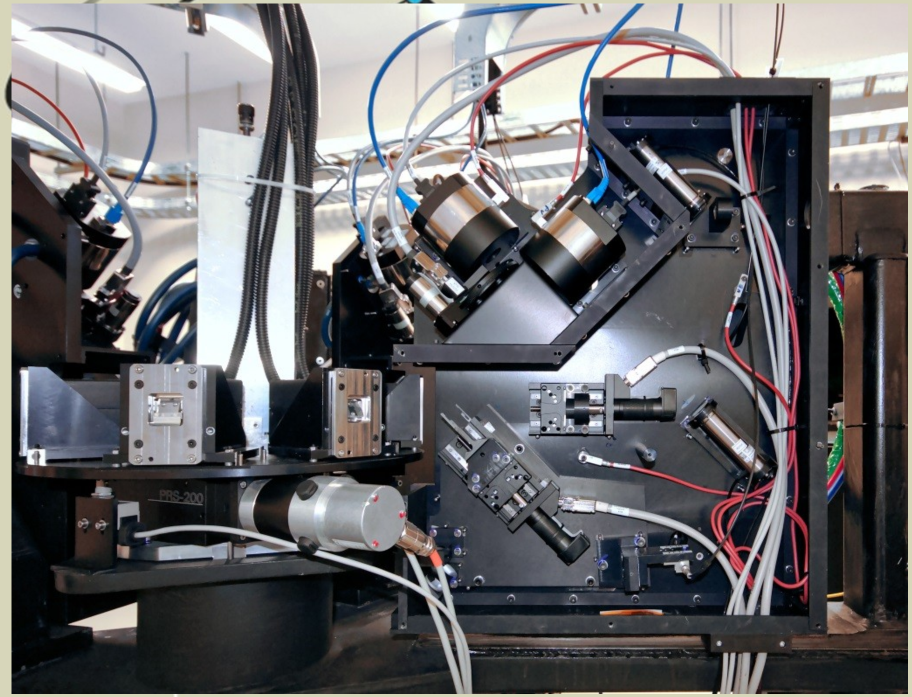
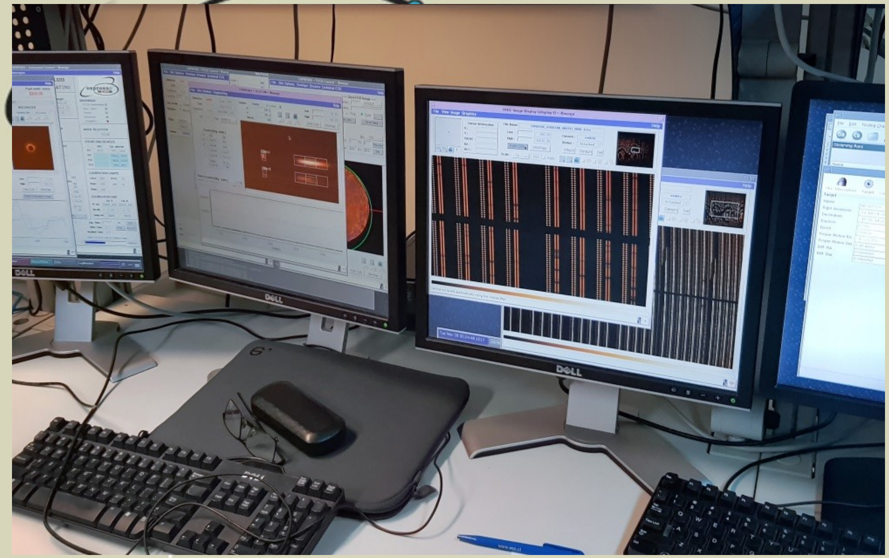


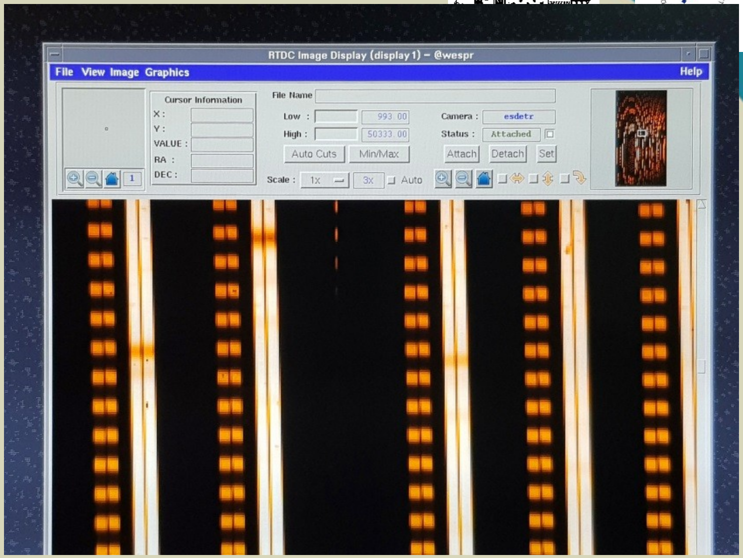
AIT @ Paranal

INAF-OATs



First light(s)





ESPRESSO Data Flow System

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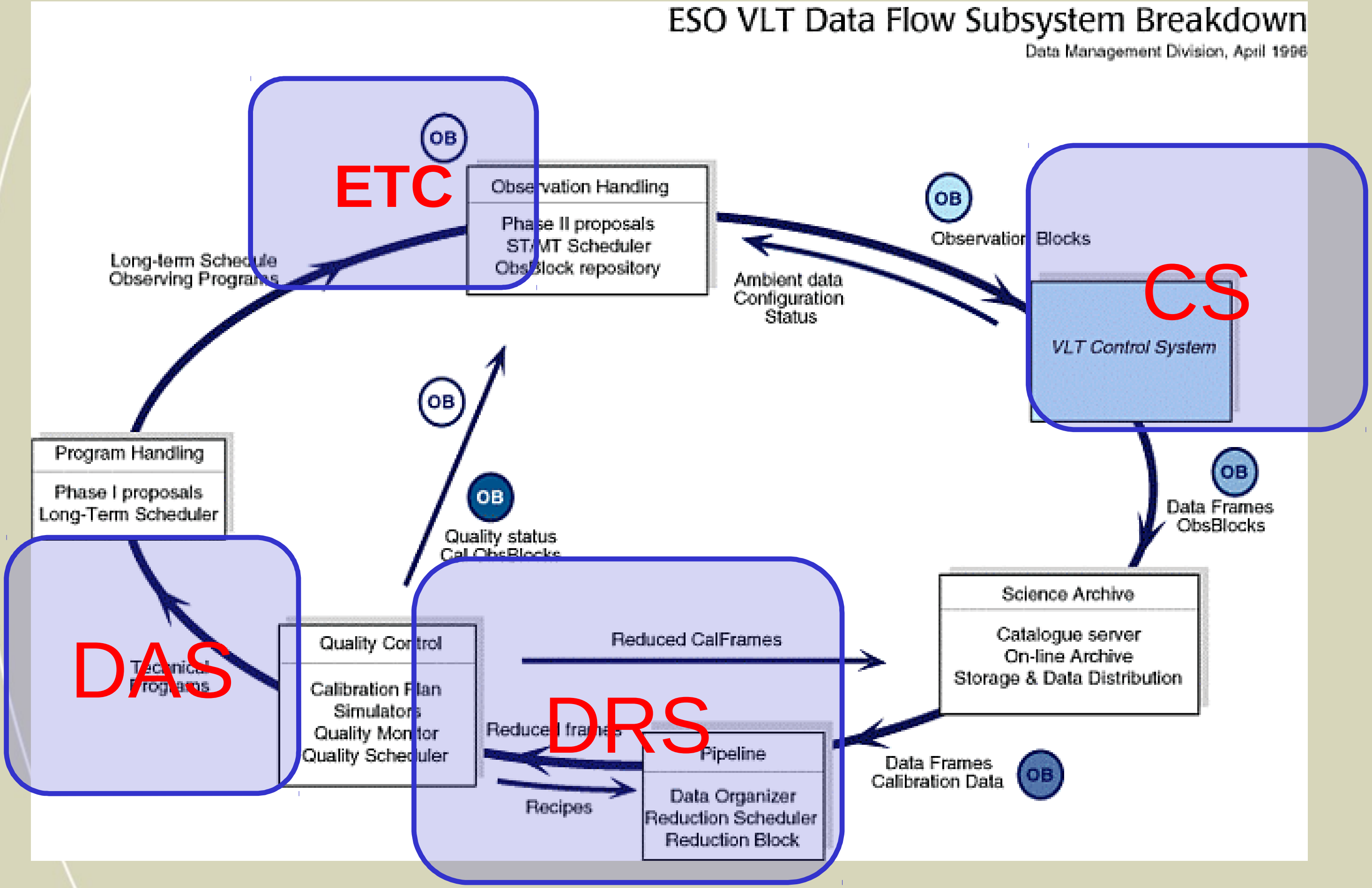

ESPRESSO Data Flow deployment

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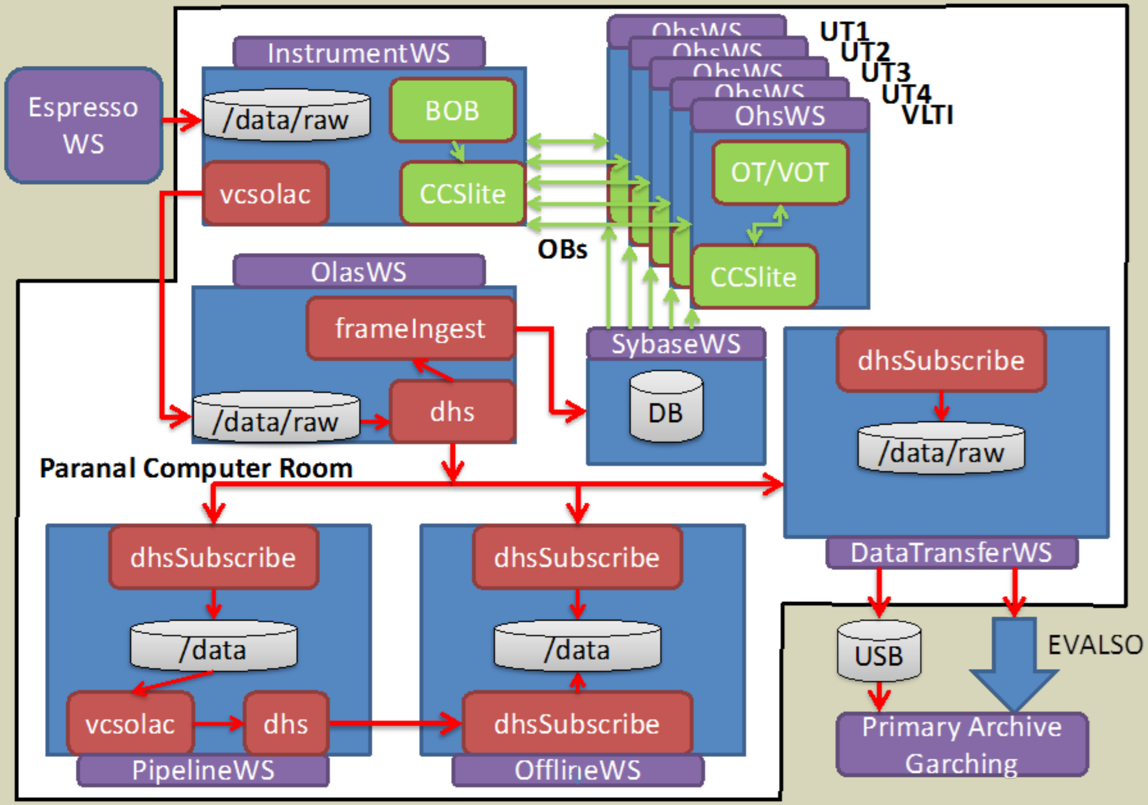
Data Flow model for Espresso (OHS-DHS)



(courtesy C. Guirao)

Exposure Time Calculator

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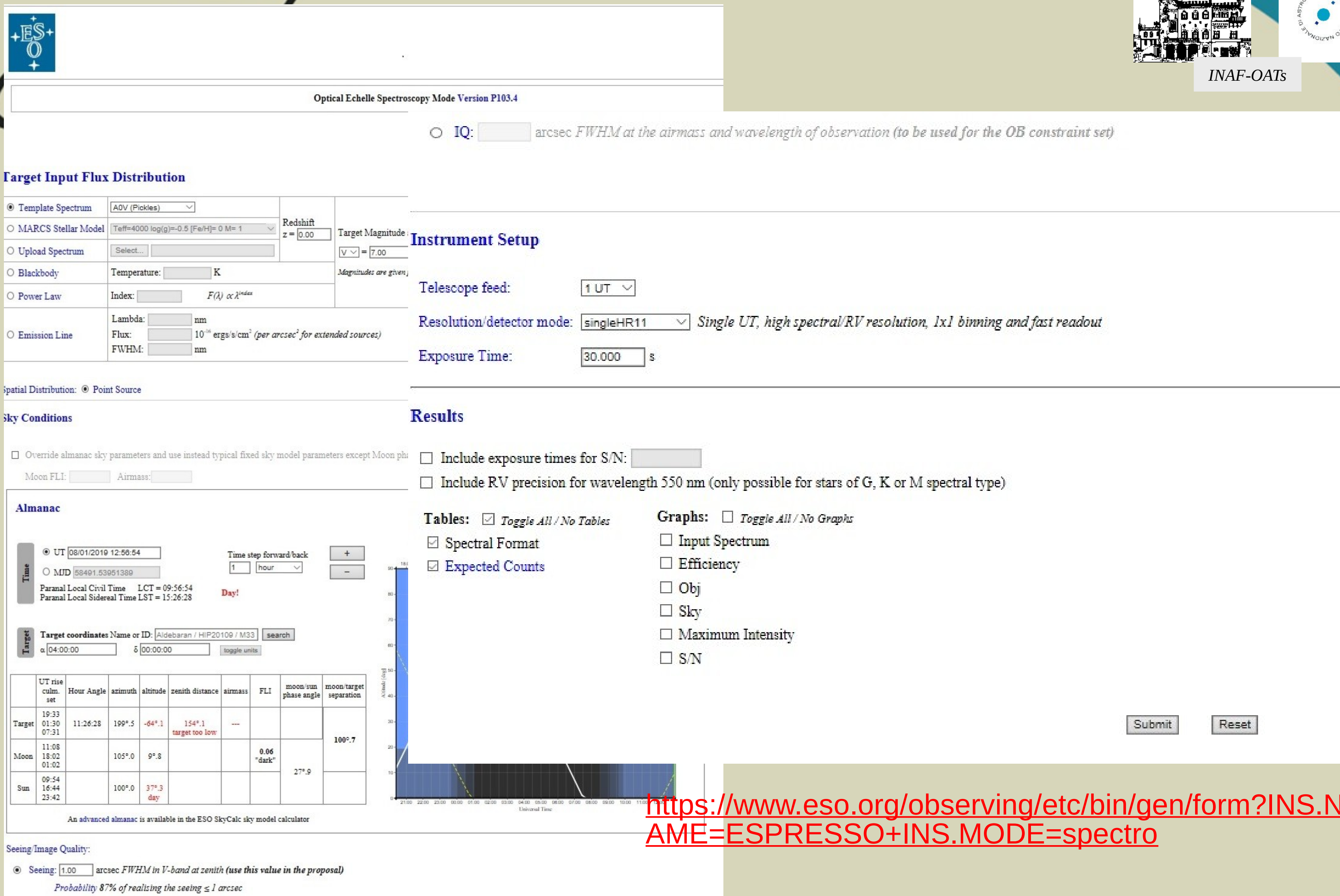
Optical Echelle Spectroscopy Mode Version P103.4

Target Input Flux Distribution

- Template Spectrum: A0V (Pickles)
- MARCS Stellar Model: Teff=4000 log(g)=-0.5 [Fe/H]= 0 M= 1
- Upload Spectrum: Select...
- Blackbody: Temperature: K
- Power Law: Index: $F(\lambda) \propto \lambda^{index}$
- Emission Line: Lambda: nm; Flux: 10⁻¹⁶ ergs/s/cm² *(per arcsec² for extended sources)*; FWHM: nm

Redshift z = 0.00

Target Magnitude: V = 7.00

Magnitudes are given ...

Spatial Distribution: Point Source

Sky Conditions

Override almanac sky parameters and use instead typical fixed sky model parameters except Moon pha...

Moon FLI: Airmass:

Almanac

Time: UT 08/01/2019 12:56:54; MJD 58491.53951389

Time step forward/back: 1 hour

Paranal Local Civil Time LCT = 09:56:54

Paranal Local Sidereal Time LST = 15:26:28

Day!

Target: Target coordinates Name or ID: Aldebaran / HIP20109 / M33 — search

α 04:00:00 δ 00:00:00 — toggle units

	UT rise culm. set	Hour Angle	azimuth	altitude	zenith distance	airmass	FLI	moon/sun phase angle	moon/target separation
Target	19:33 01:30 07:31	11:26:28	199°.5	-64°.1	154°.1 target too low	---			100°.7
Moon	11:08 18:02 01:02		105°.0	9°.8			0.06 "dark"	27°.9	
Sun	09:54 16:44 23:42		100°.0	37°.3 day					

An advanced almanac is available in the ESO SkyCalc sky model calculator

Seeing/Image Quality:

- Seeing: 1.00 arcsec *FWHM in V-band at zenith* **(use this value in the proposal)**

Probability 87% of realising the seeing ≤ 1 arcsec

- IQ: arcsec *FWHM at the airmass and wavelength of observation (to be used for the OB constraint set)*

Instrument Setup

Telescope feed: 1 UT

Resolution/detector mode: singleHR11 — *Single UT, high spectral/RV resolution, 1x1 binning and fast readout*

Exposure Time: 30.000 s

Results

- Include exposure times for S/N:
- Include RV precision for wavelength 550 nm (only possible for stars of G, K or M spectral type)

Tables: Toggle All / No Tables
- [x] Spectral Format
- [x] Expected Counts

Graphs: Toggle All / No Graphs
- [ ] Input Spectrum
- [ ] Efficiency
- [ ] Obj
- [ ] Sky
- [ ] Maximum Intensity
- [ ] S/N

Submit Reset

https://www.eso.org/observing/etc/bin/gen/form?INS.NAME=ESPRESSO+INS.MODE=spectro

Operations

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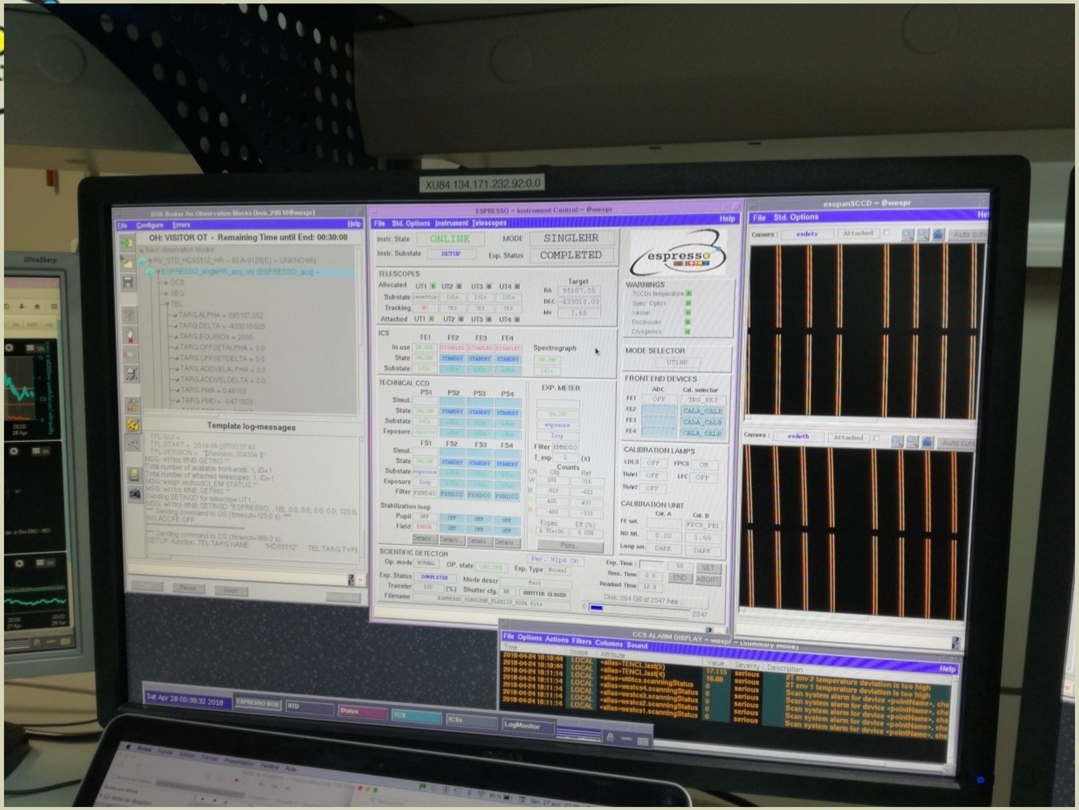

During the observing run, the Observation Block (OB) to be executed is loaded on the Observation Handling (OH) workstation and then sent to the BOB (Broker for Observation Block) tool on the IWS. BOB reads the contents of the OB and executes one by one the templates specified in there. Each template consists in general of a sequence of commands determining completely a scientific exposure. *It allows presetting the telescope, to setup the instrument and detector so that the required scientific observation could be properly performed.*

Acquisition phase

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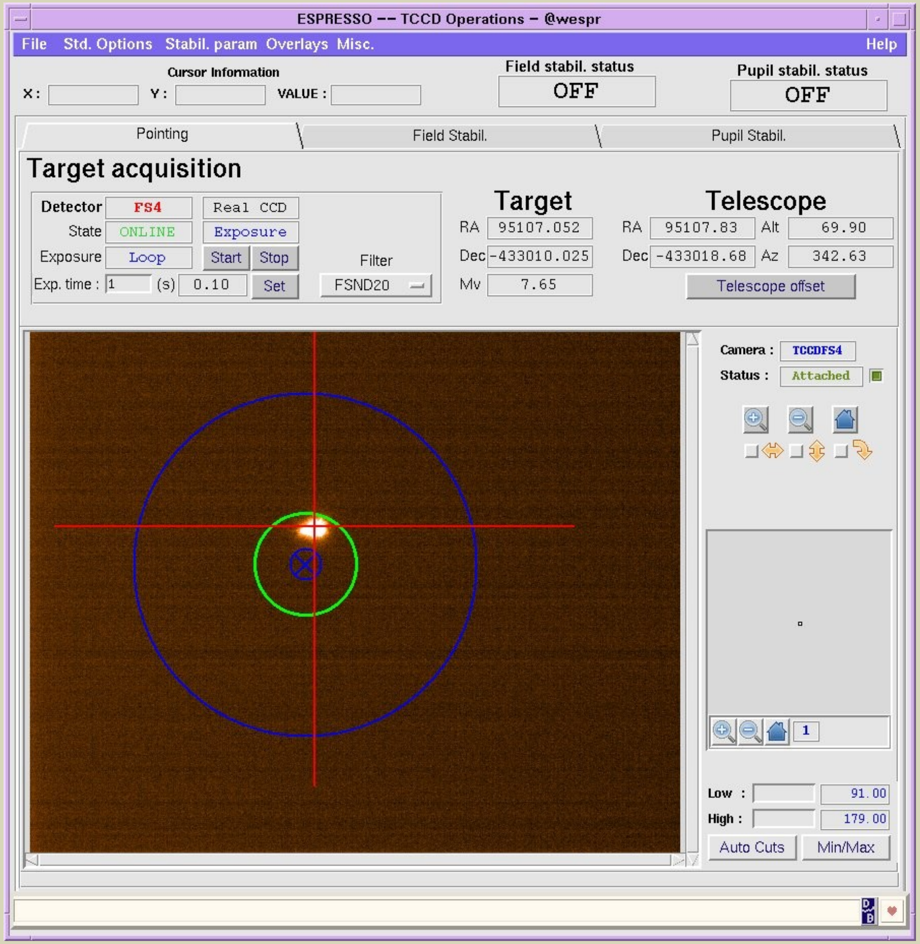
During the acquisition phase, after telescope presetting, a correction is necessary in order to center the object on the fibre entrance.

A carefully designed and tested algorithm is able to find automatically the most luminous object in the field (which usually coincides with the object under interest due to the small instrument field-of-view), computes the required correction and send it to the telescope.



Stabilization phase

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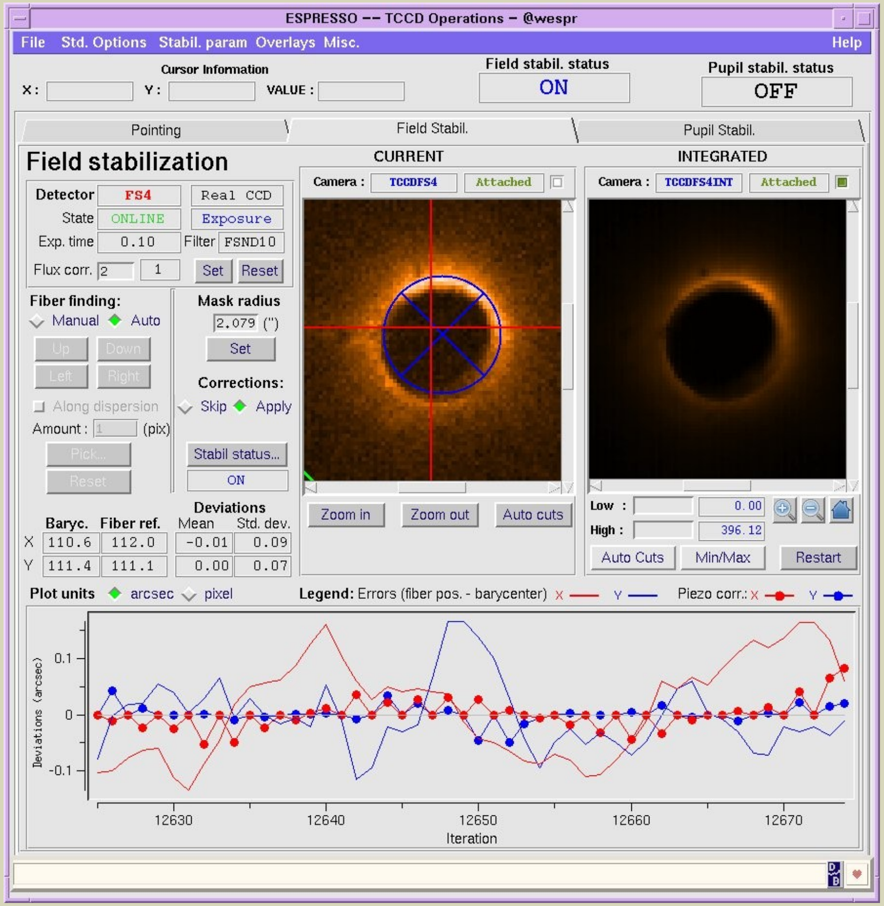
The purpose of the (field) stabilization is to <u>maintain the object centered</u> on the fiber during the whole duration of the scientific exposure. The TCCD(s), one per front end, acquires the image in a *continuous loop up to 7 Hz*; two auxiliary software processes, in real-time, analyze the obtained image and command the low-level piezo tip-tilt devices such to try to keep the object well centered on the fiber.



ESPRESSO exposure meter

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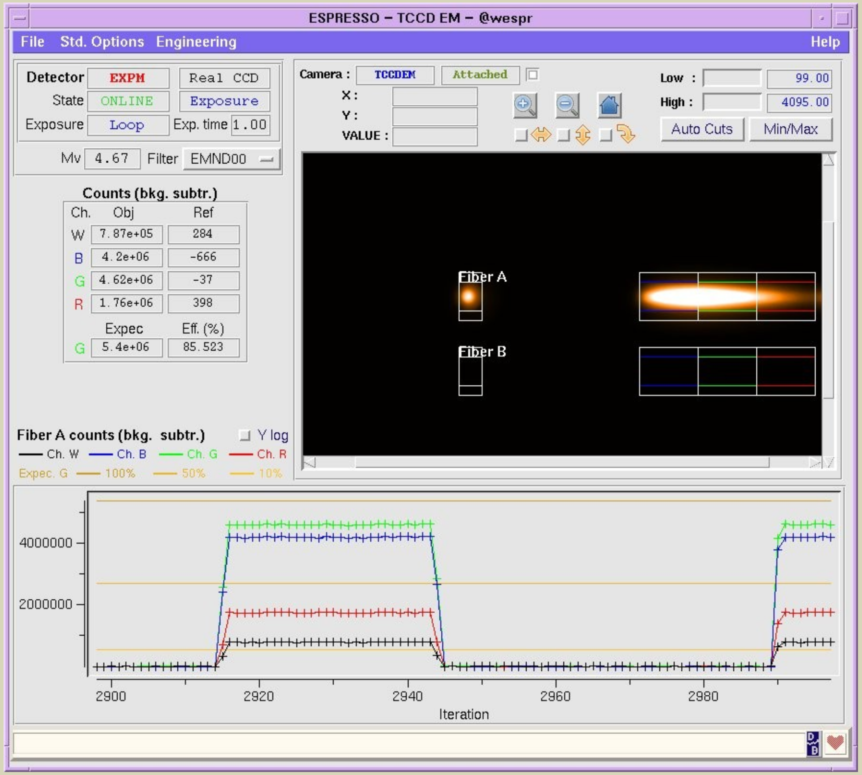
The signal-to-noise ratio of the ongoing scientific exposure is continuously monitored by the <u>ESPRESSO exposure meter</u> (EM). In ESPRESSO, the EM is actually a small spectrograph in itself and a dedicated process continuously computes the counts in three spectra channels from images obtained by a dedicated TCCD.



ESPRESSO degraded mode / 4 -UT

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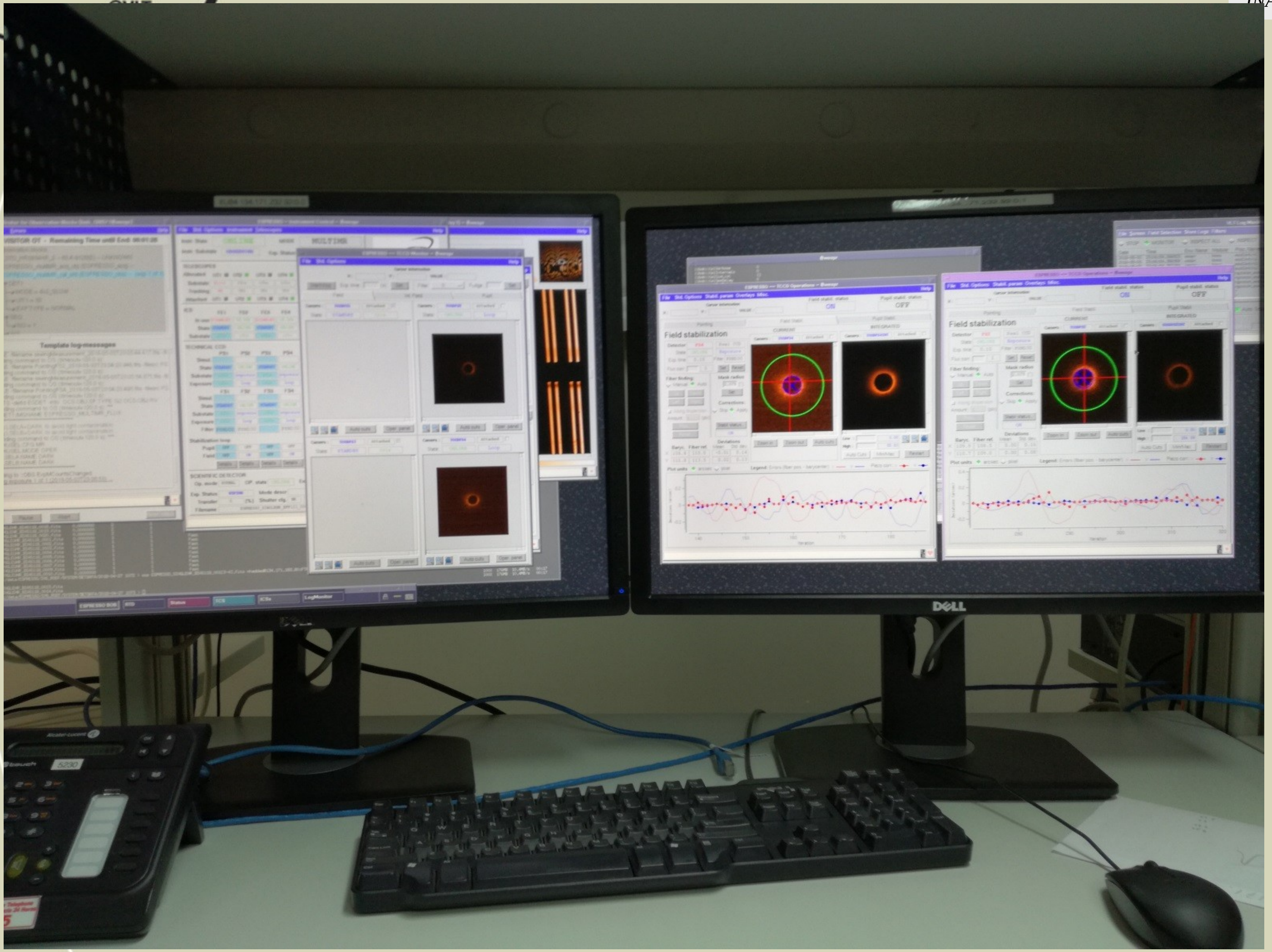
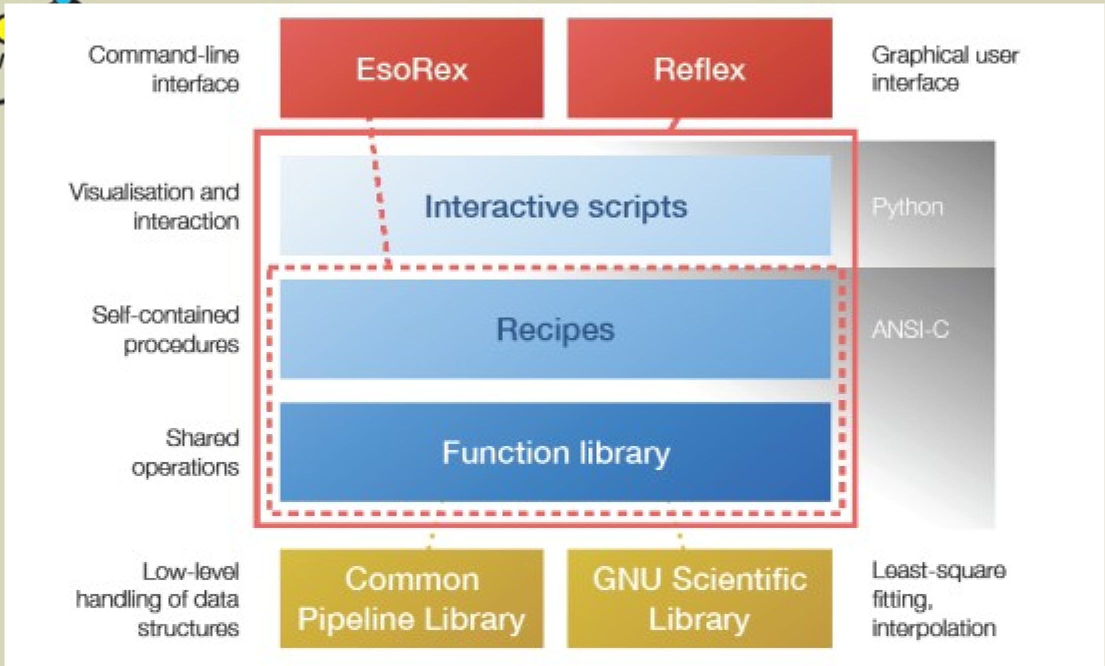


Science software

Thanks to its fixed spectral format and long-term stability, ESPRESSO has been conceived, starting already from the preliminary design phases, as "*truly science-grade products generating machine*".

To this purpose, in addition to the standard **Data Reduction Software (DRS)** package, a dedicated ESPRESSO ***Data Analysis Software (DAS)*** package has been developed with the aim to extract scientific information as soon as reduced data are available.

Pipeline, esorex, esoreflex

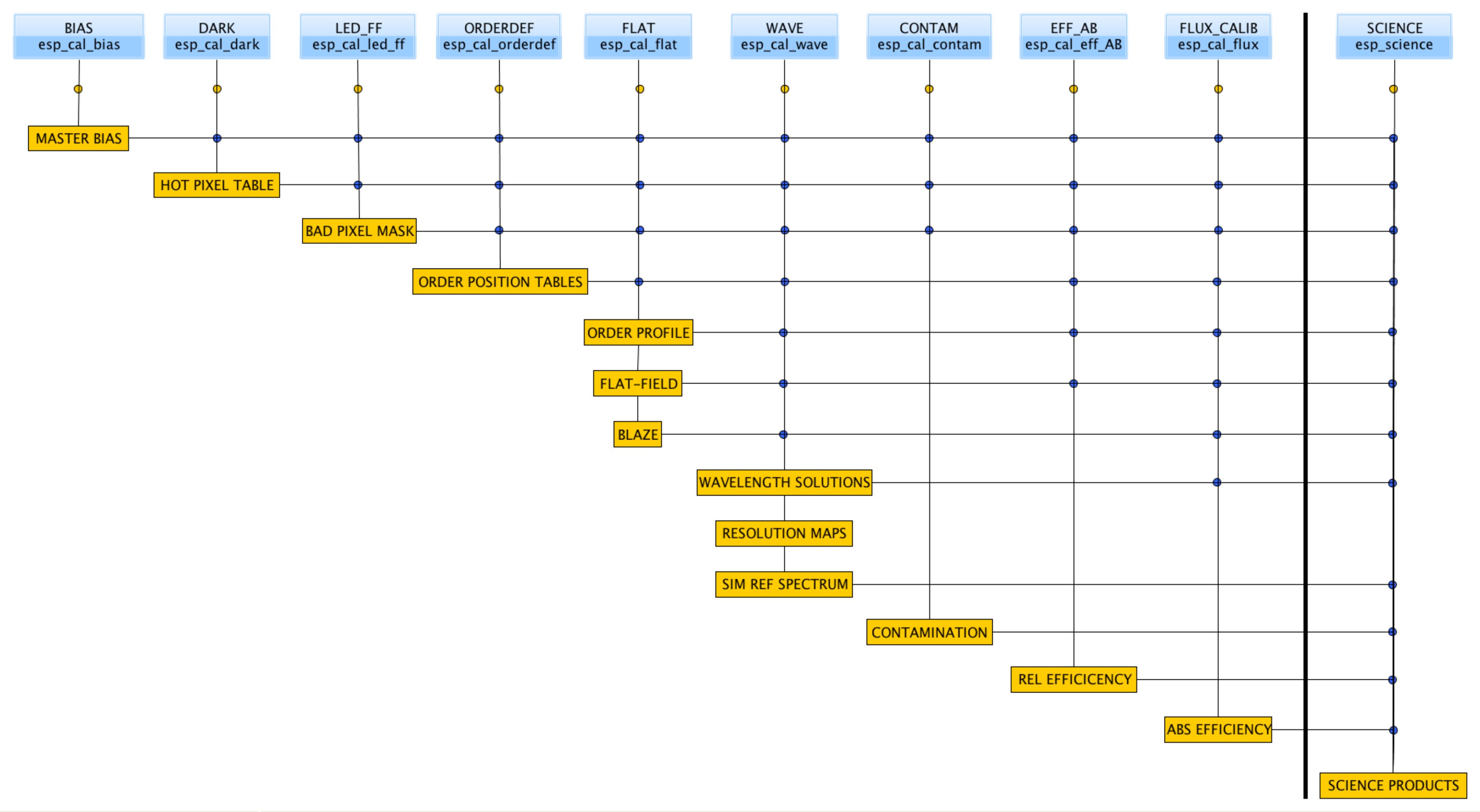


@ Paranal: pipeline as quick-look tools to do a real-time coarse assessment of the quality of calibrations and science observations; runs unsupervised with the help of data organizer (DO) and Reduction Block Scheduler (RBS) via OCA rules;

ESPRESSO specific: each science image can be reduced using the wavelength calibration taken few hours or even minutes before - virtual product functionality

@ Garching: more thorough data processing and evaluation - raw calibration frames into master calibrations; generate quality control parameters to monitor the instrument and detector performance

Data Reduction Cascade



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DRS example results

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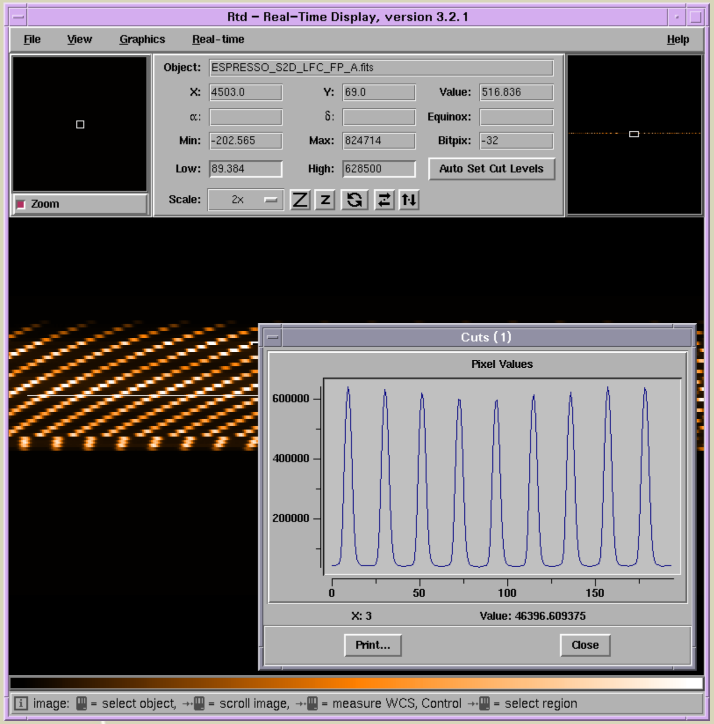
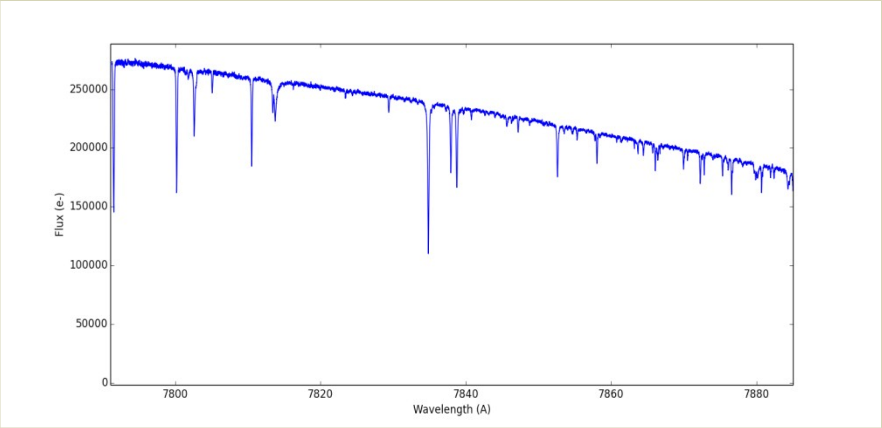


Single two-dimensional (S2D) spectrum extracted from the LFC exposure with one order shown by cuts. Regular spacing and the almost constant flux level could be easily noticed.



Wavelength coverage starts at 378.25 nm for the bluest order of fiber A and ends at 525.1 nm for the reddest order on the blue chip. On the red chip the shortest wavelength is 523.8 nm while the longest wavelength is 788.4 nm.

Additional info:

http://eso.org/sci/software/pipelines/espresso/espresso-pipe-recipes.html/

ESPRESSO Data Analysis

espresso @VLT

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The ESPRESSO DAS comprises a total of 13 recipes. It is split into four branches: one for the *analysis of QSO spectra* and three for the *analysis of star spectra*.

Some of the recipes are common to more branches while others are specific to the treated spectra.

Each DAS branch is managed by a dedicated *Reflex workflow*.

All the recipes are *available off-line at the telescope* on a dedicated workstation and *the users* have the possibility to install the whole package also on *his/her computer*.

Operation	Branch	Name
Co-addition of spectra	star, quasar	espda_coadd_spec
Creation of a spectral mask	star, quasar	espda_mask_spec
Creation of a list of absorption lines	star, quasar	espda_create_linelist
Continuum fitting of a 1D spectrum	quasar	espda_fit_qsocont
Identification of the absorption systems	quasar	espda_iden_syst
Voigt-profile fitting of absorption lines	star, quasar	espda_fit_line
Measurement of the EW of spectral lines	star	espda_compu_eqwidth
Computation of the stellar parameters	star	espda_compu_starpar
Continuum fitting of single orders	star	espda_fit_starcont
Comparison with a synthetic spectrum	star	espda_synth_spec
Computation of the radial velocity using a synth. spec.	star	espda_rv_synth
Computation of the radial velocity	star	espda_compu_radvel
Computation of the stellar activity indexes	star	espda_compu_rhk

DAS workflow example

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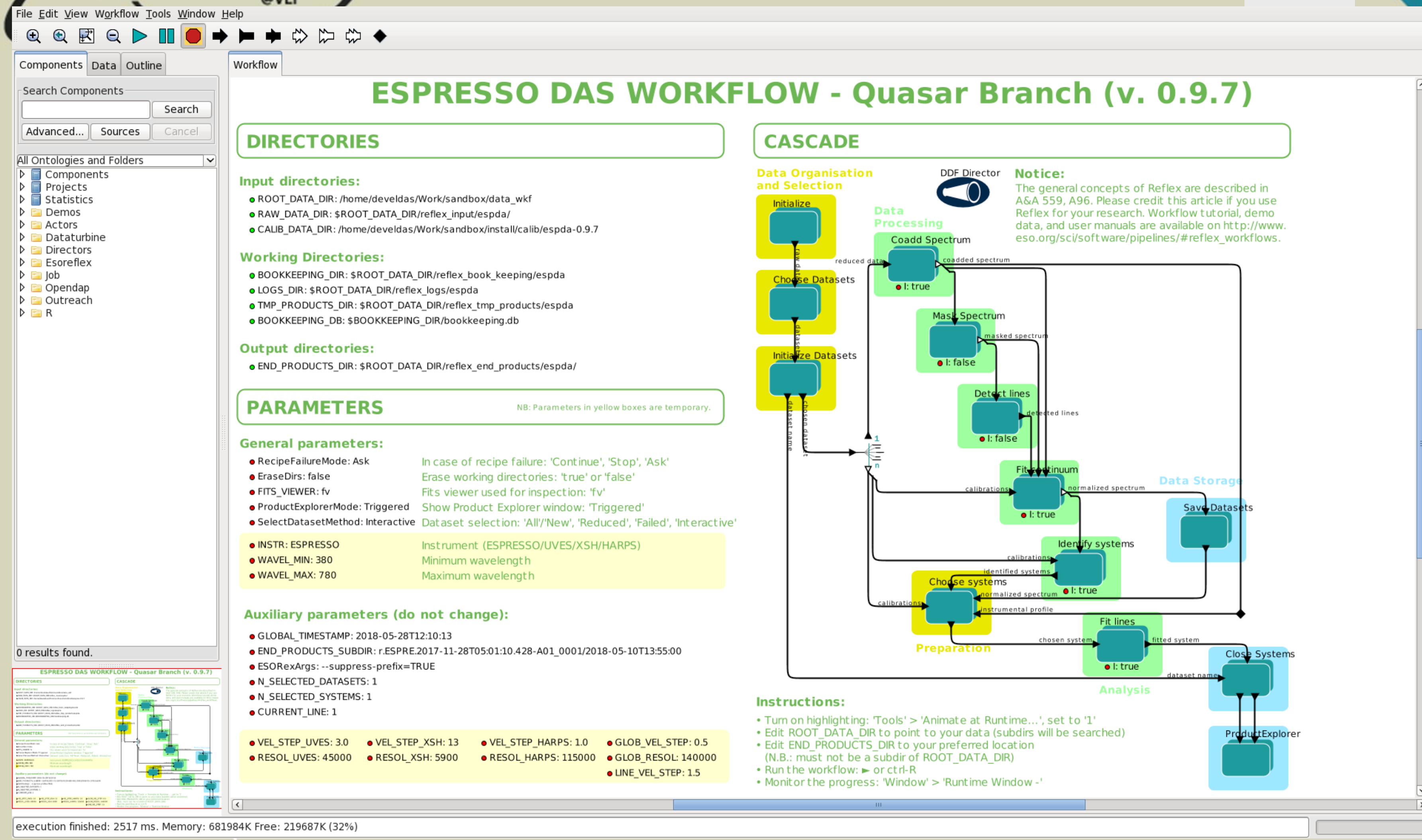

DAS quasar branch results

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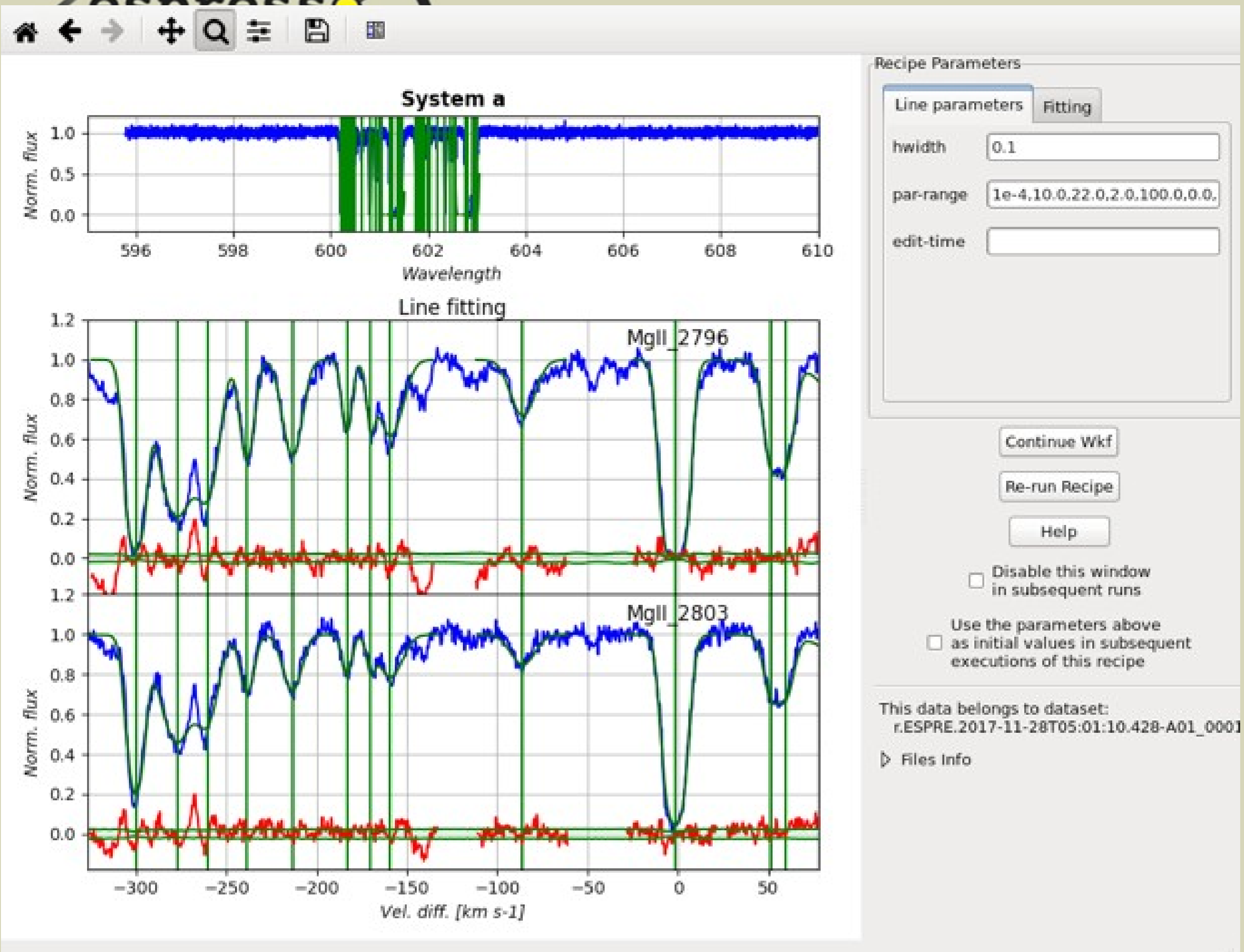

An absorption system (MgII) detected and fitted on the spectrum of quasar HE0515–4414 (observed during the comm 1b run, rebinned at 1 km/s). **Blue:** normalized spectrum; **green:** best-fit composite Voigt profile; **red:** residuals.

DAS star branch results

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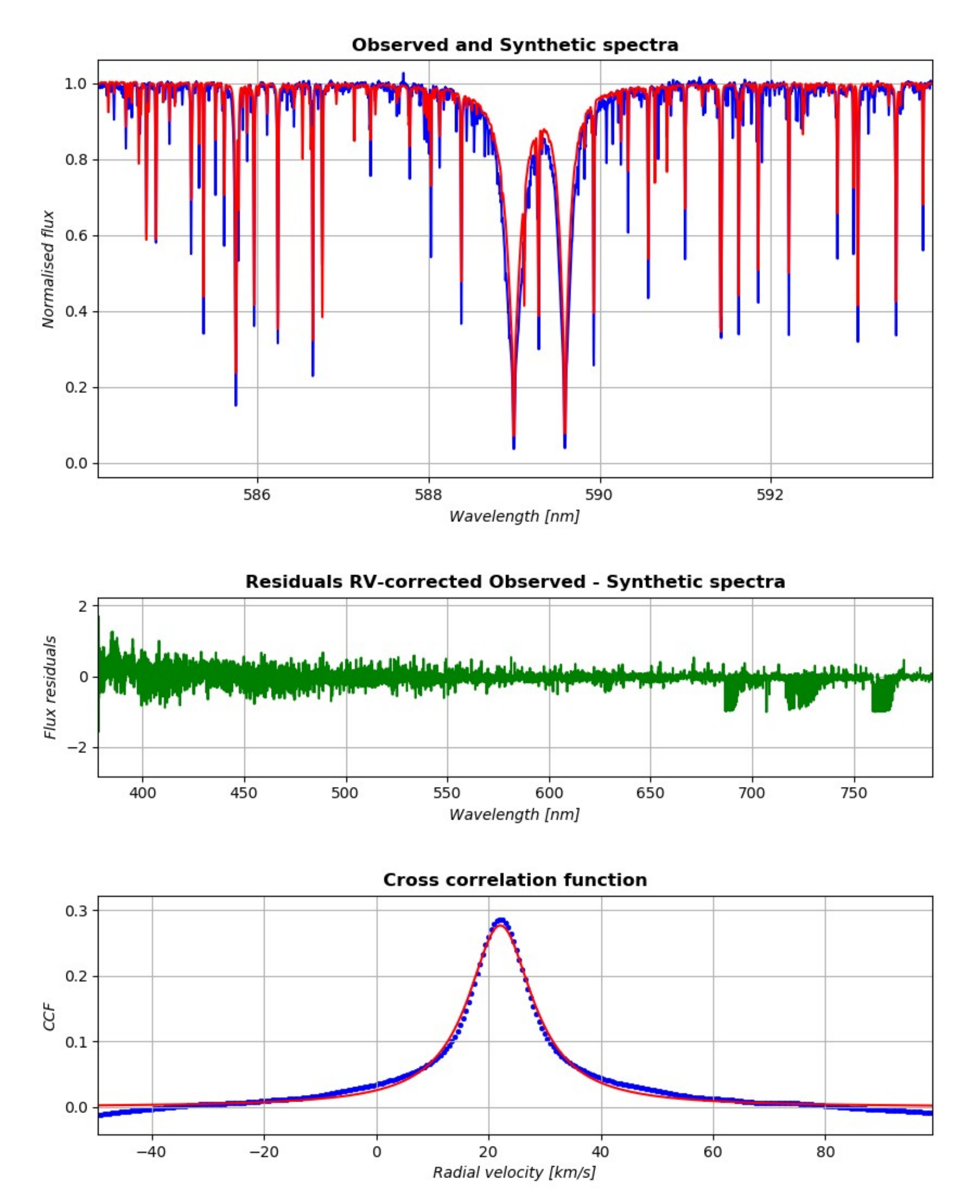

Top: plot of the output for the RV standard star HD 35854; **blue:** the observed normalized merged spectrum corrected for RV compared with the synthetic spectrum (**red**). **Center:** Observed - synthetic flux residuals. **Bottom:** cross-correlation function fitted with a Lorentzian function

First results I

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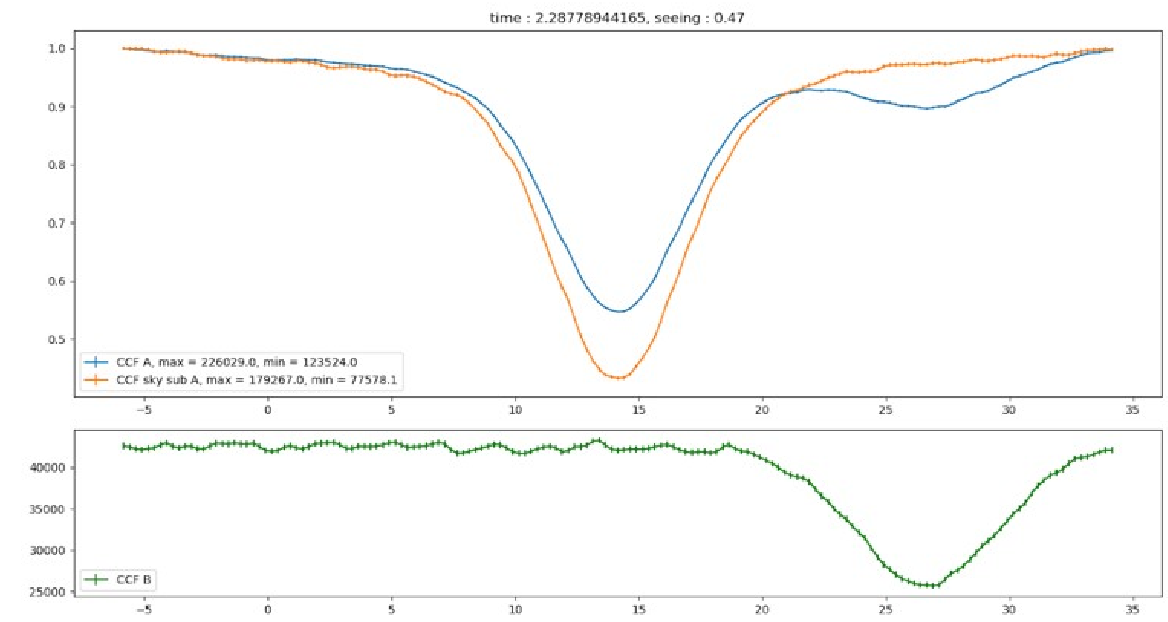
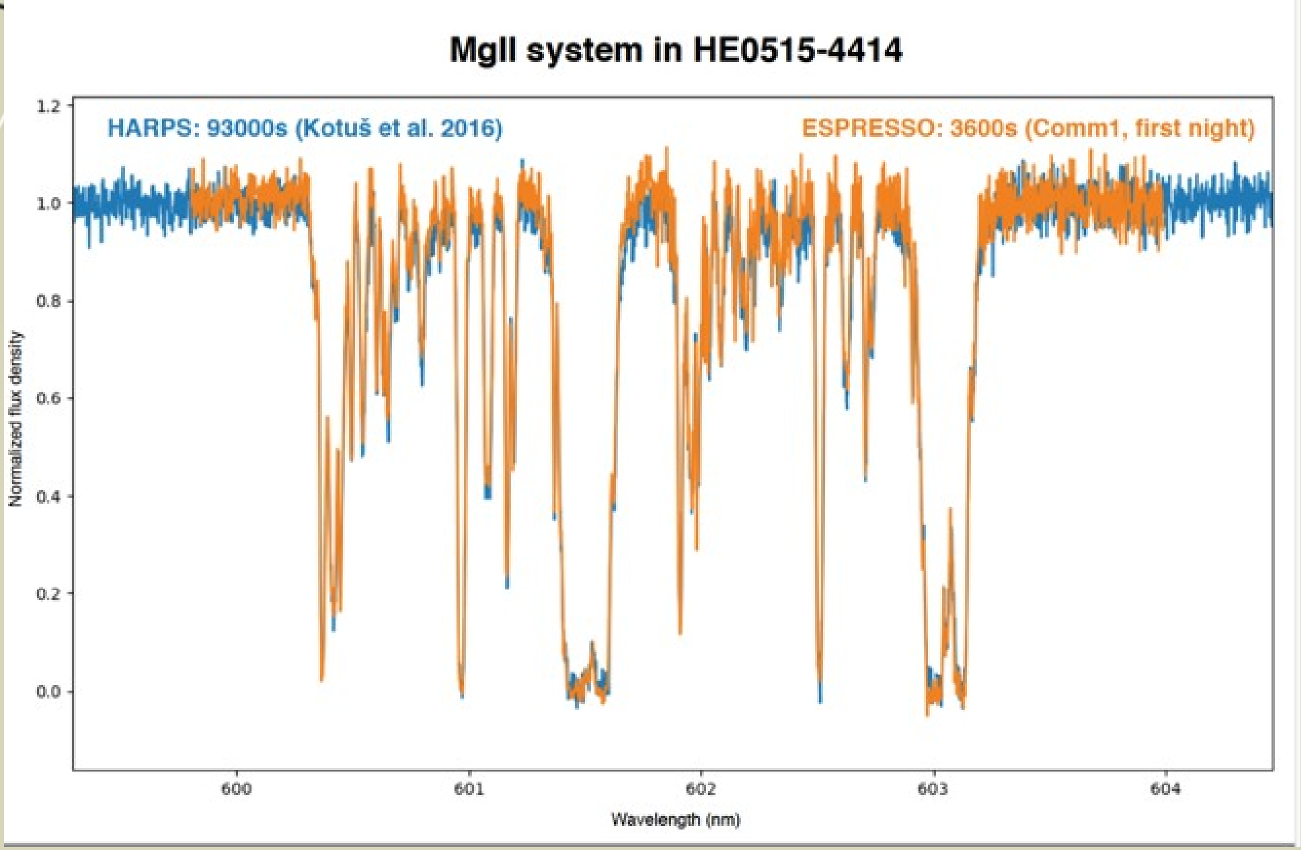


Cross correlation function (CCF) of a RV standard close to the Moon. The **blue line** is the CCF of the star spectrum and the RV dip corresponding to the Moon RV is clearly visible. The **orange line** is the CCF of the star spectrum after subtraction of the sky spectrum. **Bottom panel** show instead the CCF of the sky spectrum alone.

First results II



A comparison of a portion of HE0515-44 taken in 3600s the equivalent of 18 HARPS exposures for a total 93000 sec.

First results III

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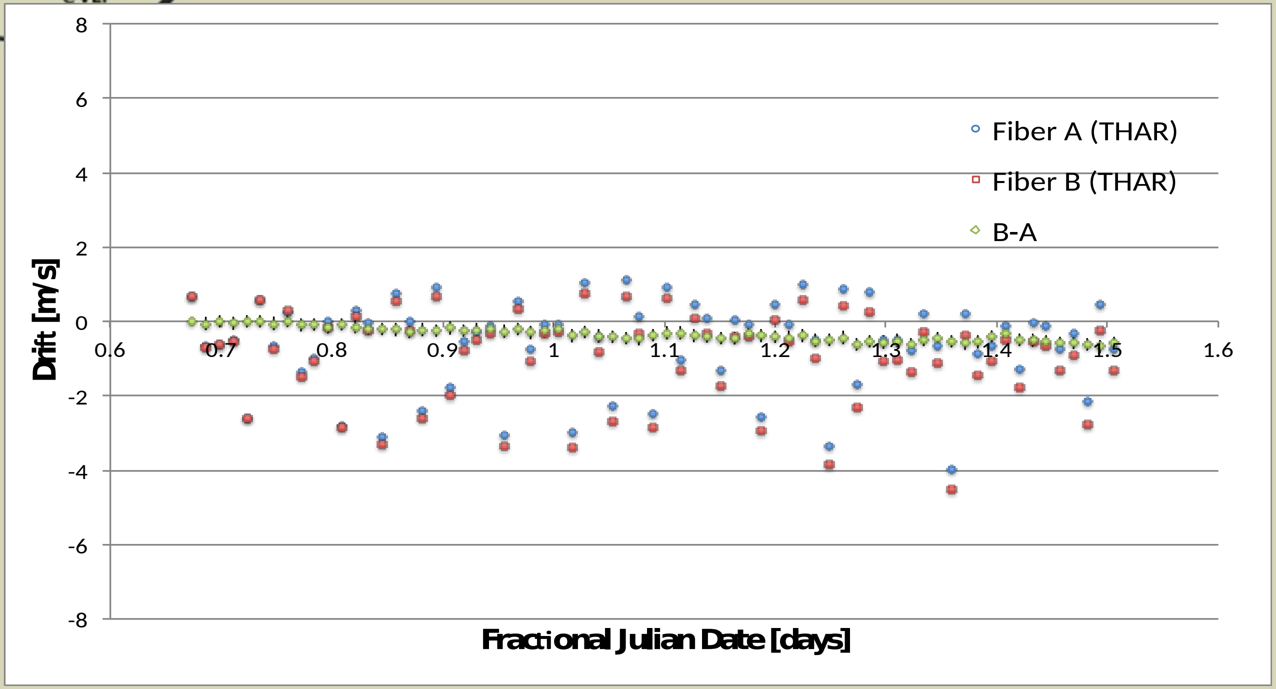

The image shows a drift sequence of more than 20 hours duration. The instrument drifted during this time by less than 1 m s^{-1}. On fiber A and B individually a scatter of about 1 m s^{-1} *rms* is observed, which we consider to be due to the detector itself (self-heating due to fast read-out). The proof is that this scatter is perfectly common-mode. In fact, the differential drift B-A remained small for the whole duration. The 20-hours dispersion is about 18 cm s^{-1}, but if we consider the last 10 hours only, *the dispersion is 9.4 cm s^{-1}*, comparable with the photon noise and compliant with the requirements!

GTO - Fundamental constants

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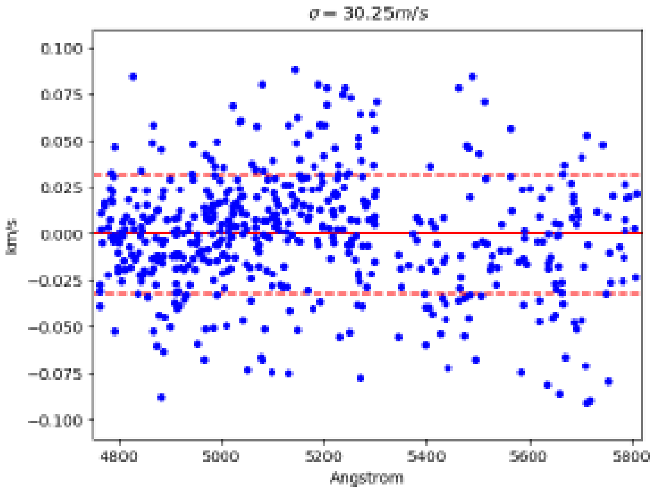
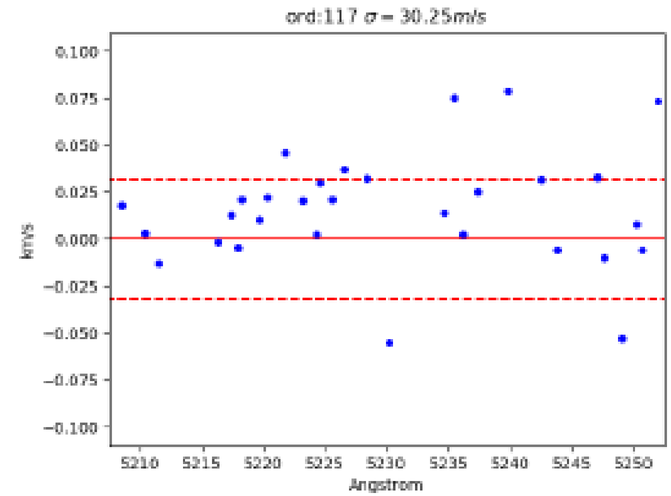


Figure 1 – Radial velocity differences between the solar lines as measured in the ESPRESSO 1UT Single 2x1 mode spectrum of Iris (6-Dec-2017) and the CERES-HARPS solar spectrum calibrated with the Laser Frequency Comb from [9]. The gap at 530 nm is due to the HARPS gap.



Future: HIRES@ELT

HIRES layout

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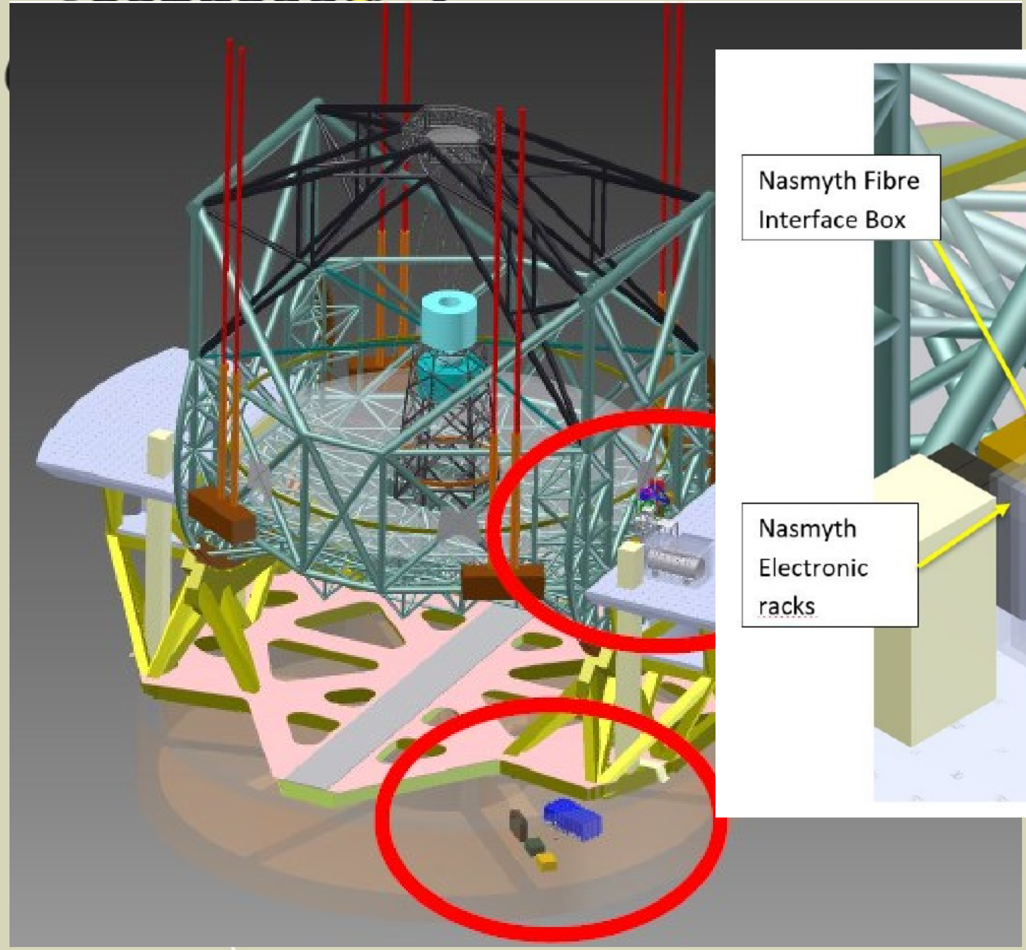

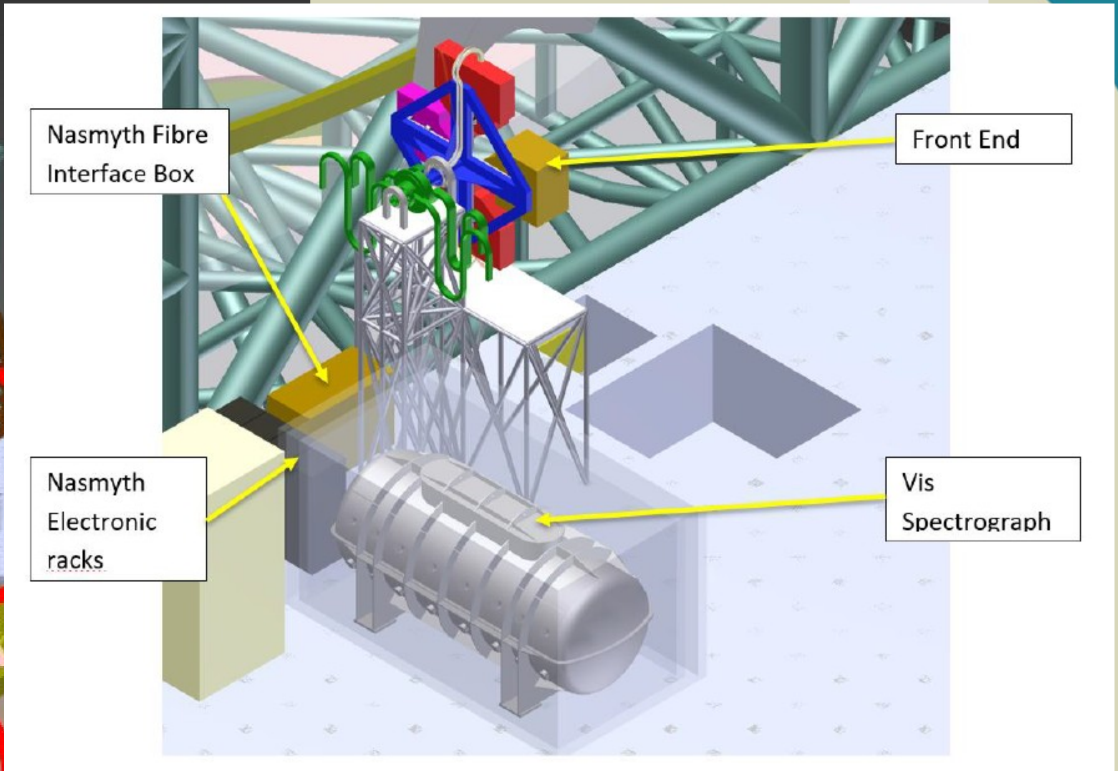

HIRES@ELT: Exoplanets science case

INAF-OATs

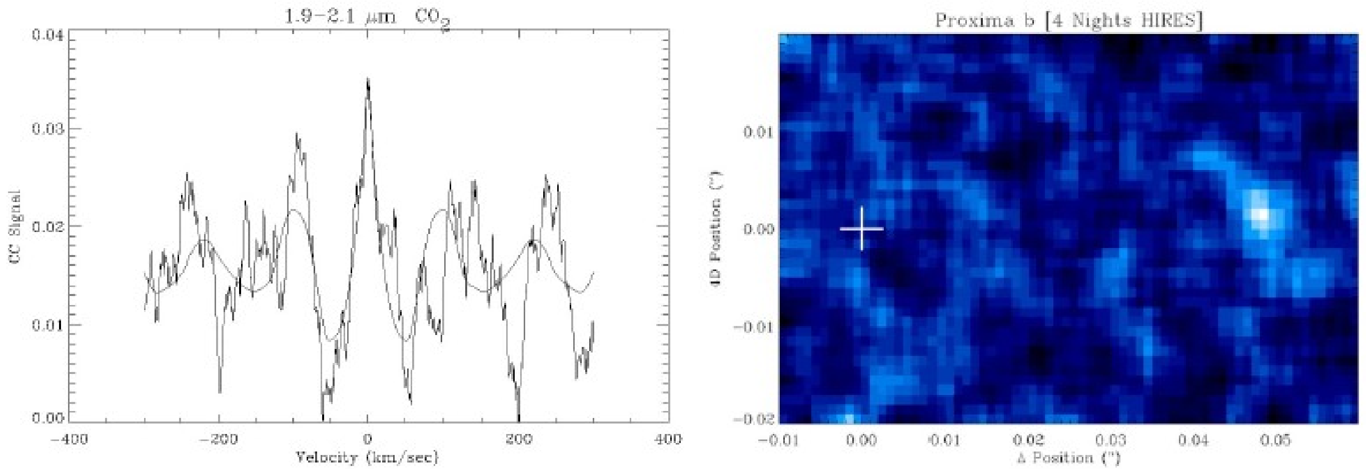

Figure 1 Left: Simulated cross-correlation values of the detection of the CO2 molecule in a Venus-like atmosphere in Trappist-*1b or c, combining data of 4 transits with HIRES. Right: Reflected light cross-correlation signal of the direct surroundings of Proxima Cen.*

HIRES@ELT: fundamental constants science case

INAF-OATs

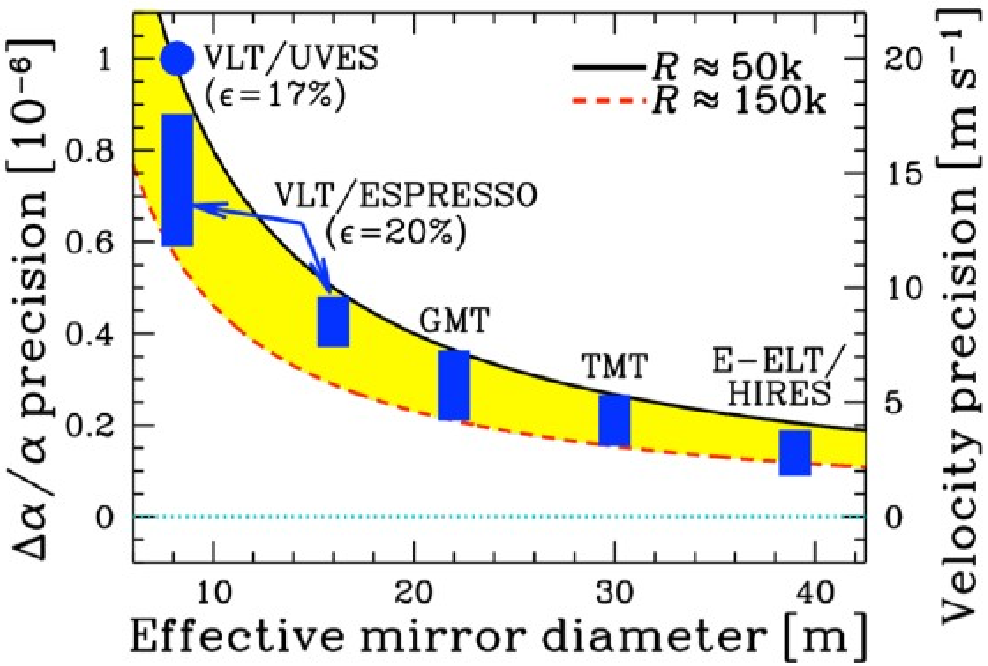

Figure 5 Expected statistical precision on variations in the fine-structure constant, Δα/α, achievable with future high-resolution spectrographs as a function of telescope diameter. The equivalent velocity precision is also shown (assuming a typical variety of metal-ion transitions). The length of the bars indicates the range of precision expected for different spectral resolutions available on those facilities. Two modes of operation for VLT/ESPRESSO are shown, its single-telescope mode (8-m effective diameter), with a range of resolving powers, and its anticipated four-telescope mode (16-m effective diameter), with R up to ≈70,000.

Conclusions

In this talk I have presented ESPRESSO, its DFS, challenges and instrument peculiarities together with some first "results".

- *ESPRESSO*, the next generation ESO VLT high-resolution ultra-stable spectrograph, *is ready for operations*.
- After the very successful commissioning periods where instrument performance have been assessed and validated ESO gave green light *for starting routine observations from October 2018 in single UT mode*.
- 4 UT mode will be offered in 2019 after a final science verification phase.