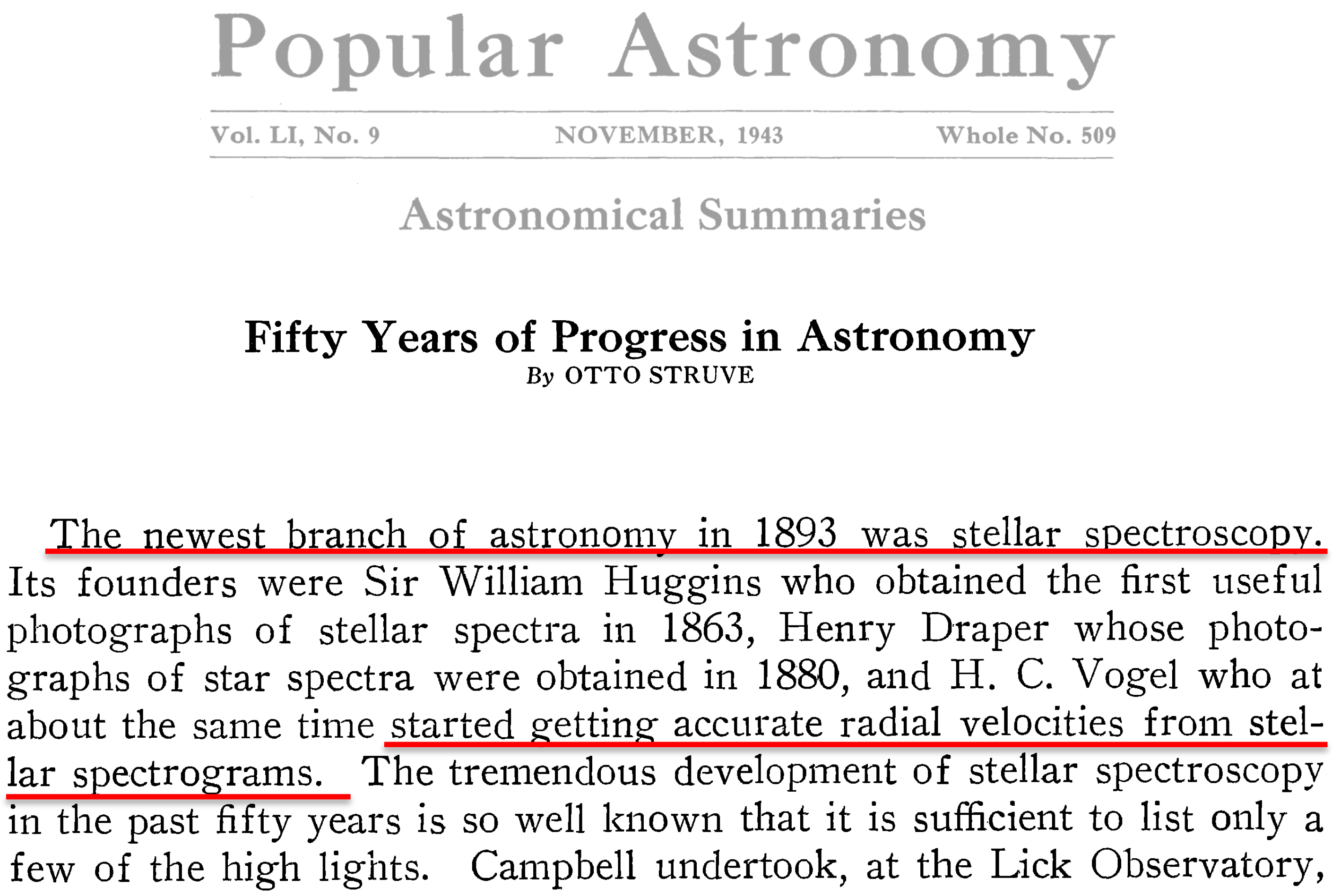
The 3.6m telescope in La Silla and its jewels:

HARPS & NIRPS

the quest for other worlds

Emanuela Pompei
Gaspare Lo Curto

A bit of History



Popular Astronomy

Vol. LI, No. 9 NOVEMBER, 1943 Whole No. 509

Astronomical Summaries

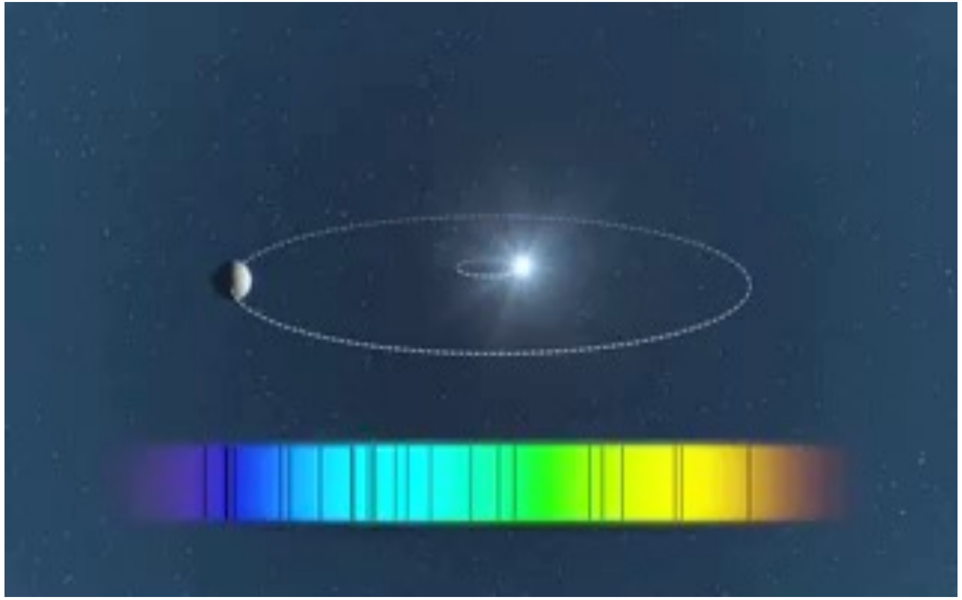
Fifty Years of Progress in Astronomy

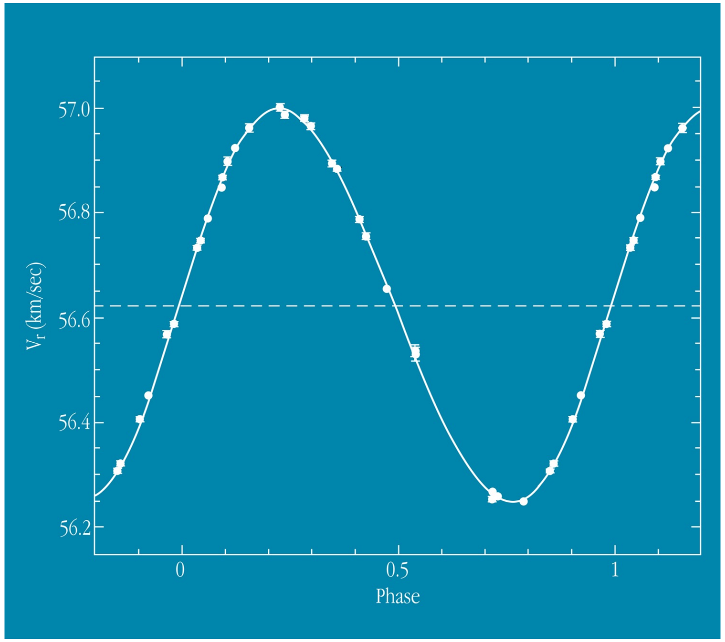
By OTTO STRUVE

The newest branch of astronomy in 1893 was stellar spectroscopy. Its founders were Sir William Huggins who obtained the first useful photographs of stellar spectra in 1863, Henry Draper whose photographs of star spectra were obtained in 1880, and H. C. Vogel who at about the same time started getting accurate radial velocities from stellar spectrograms. The tremendous development of stellar spectroscopy in the past fifty years is so well known that it is sufficient to list only a few of the high lights. Campbell undertook, at the Lick Observatory,

First binary orbit reconstructed in 1889 by Vogel for the star Algol.

HARPS & NIRPS: how do they detect planets ?



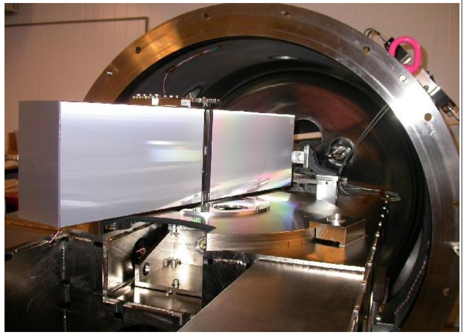


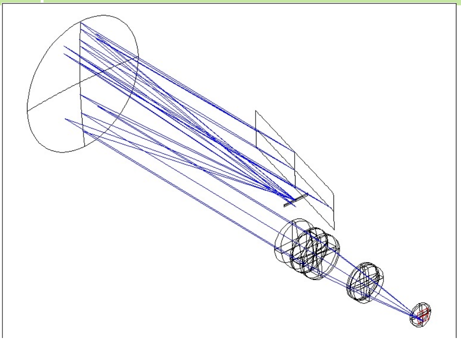
Radial velocity measured via Doppler effect

Basics of HARPS & NIRPS high resolution spectrographs

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(HAM) / 75000(HEM)
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
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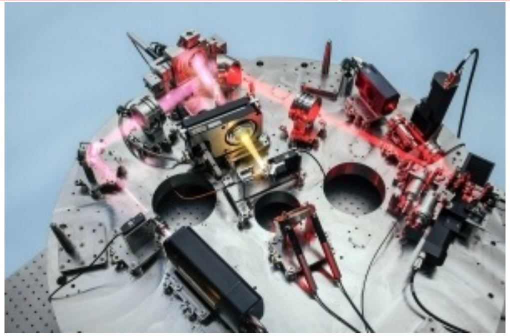
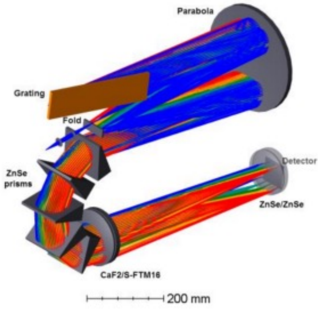
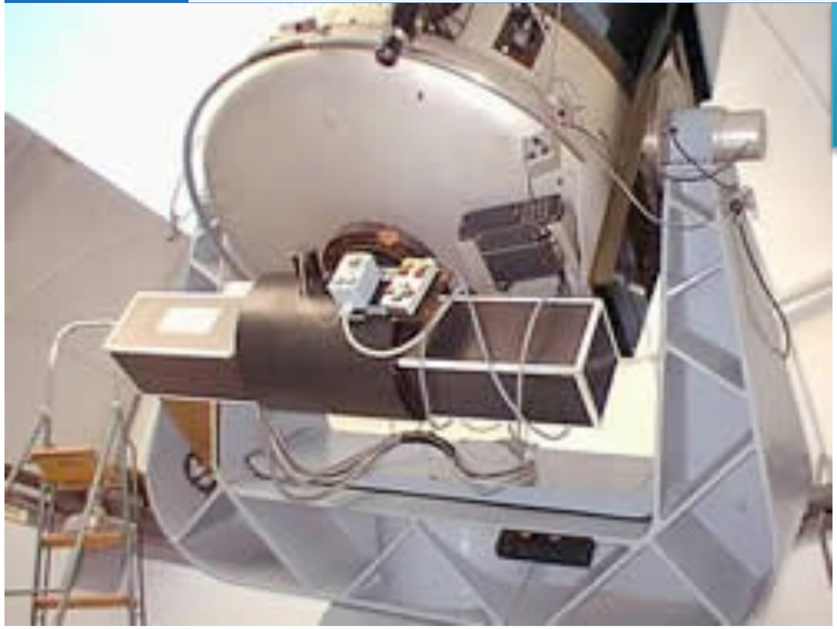
Observing modes	Simultaneous reference / Simultaneous sky





HARPS & NIRPS
Inherit from a rich past

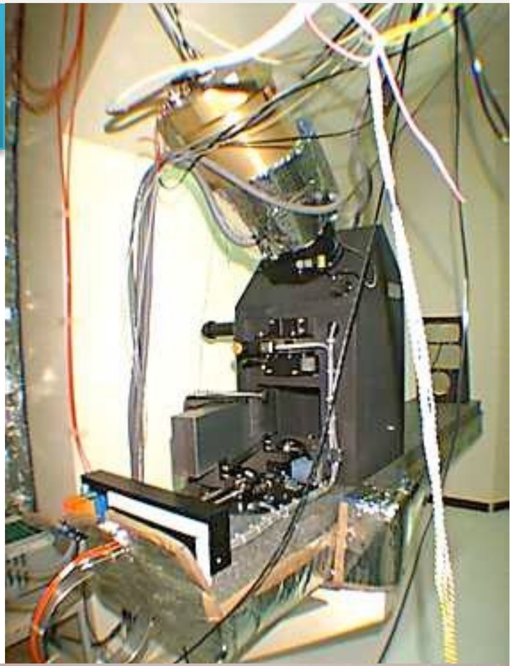


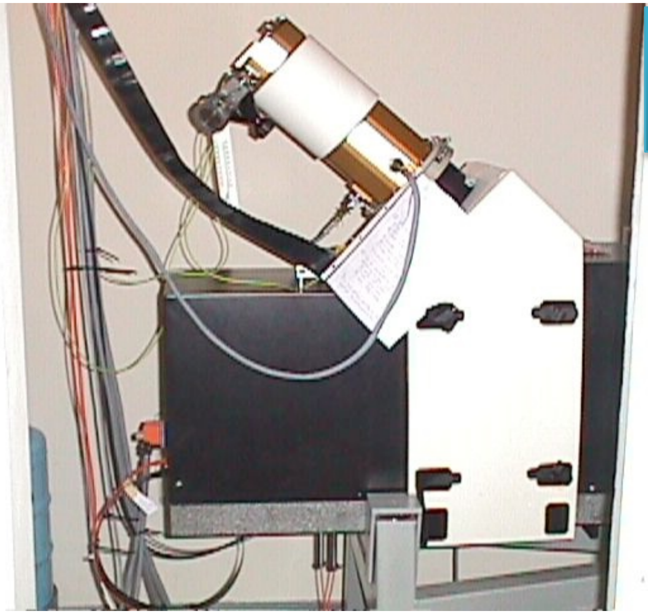
CORAVEL
250m/s

1981

ELODIE
10m/s

1993



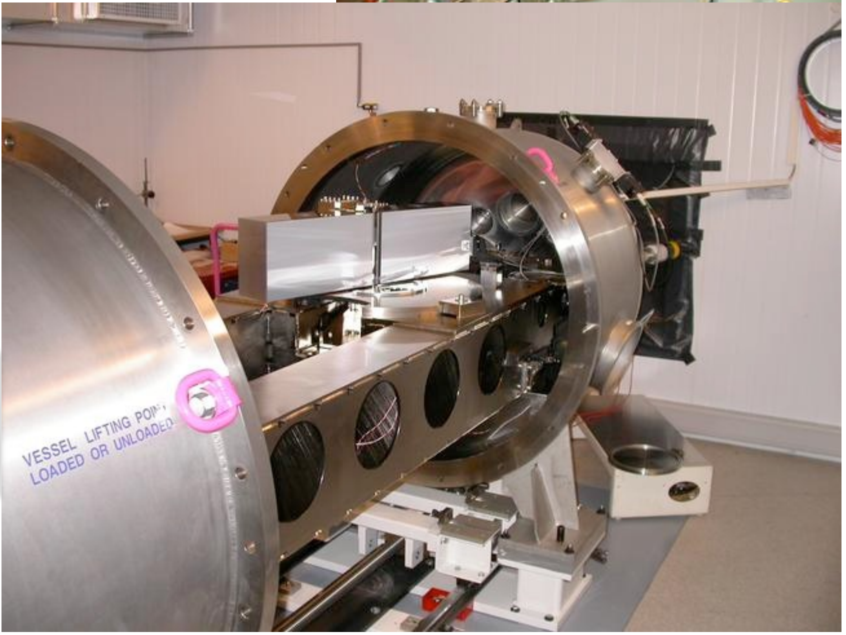


CORALIE
5m/s

1998

HARPS
1m/s

2003

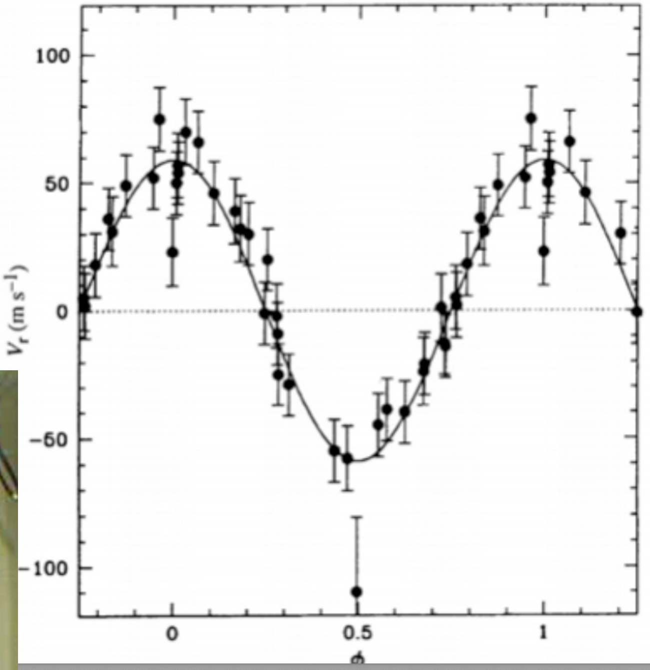


A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.



Nobel prize in Physics 2019

"för upptäckten av en exoplanet i bana kring en solliknande stjärna"

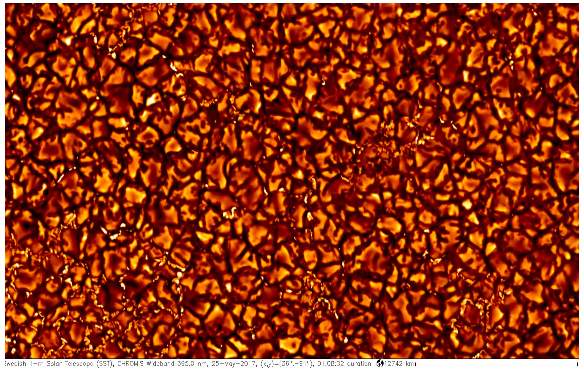
"for the discovery of an exoplanet orbiting a solar-type star"

Planets detections (RV only)

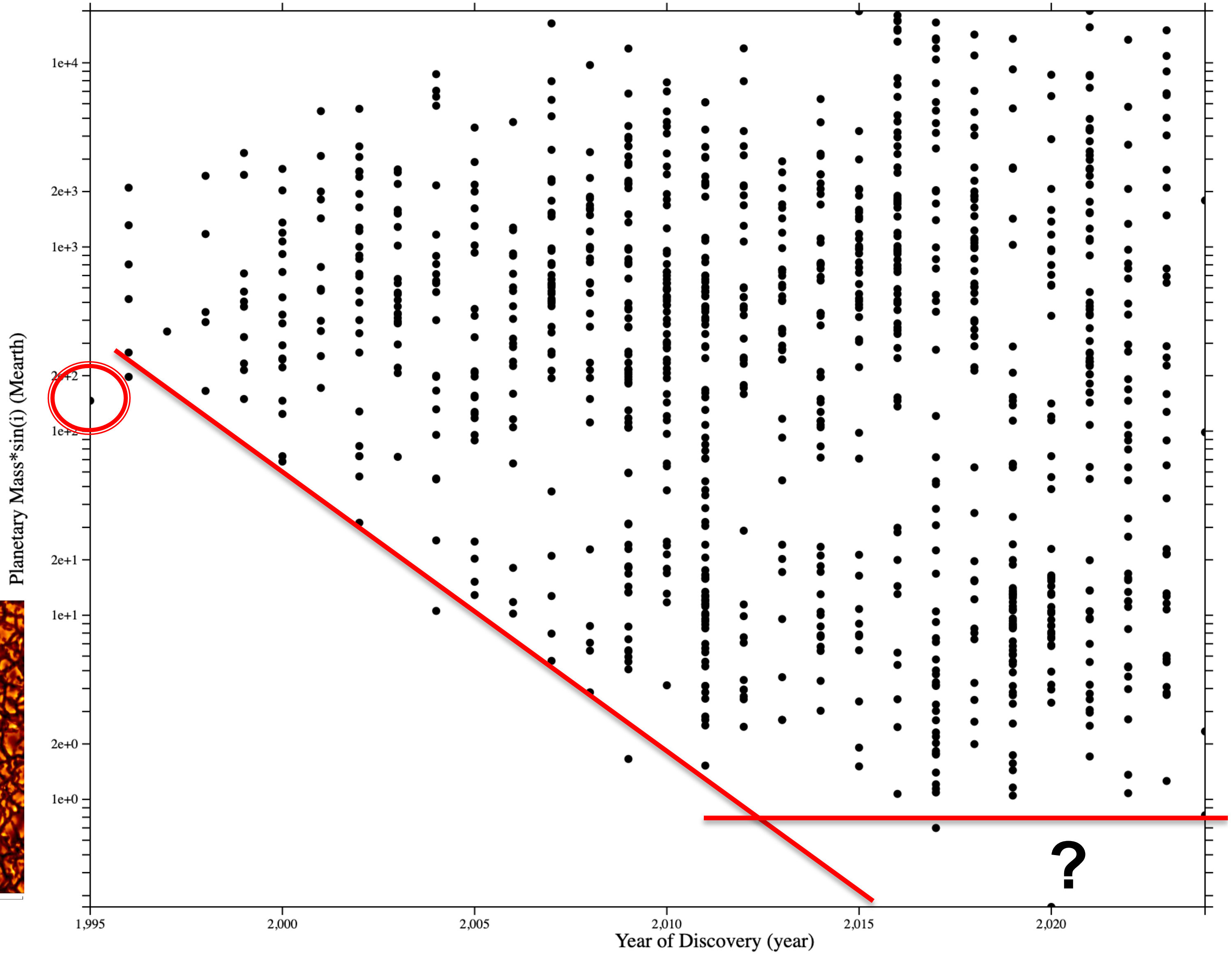
Moore’s law for
Exo-planets ?

Flattening ?

There is more
than just the planet…



Swedish 1-m Solar Telescope (SST), CHROMIS Wideband 395.0 nm, 25-May-2017, (x,y)=(36",-91"), 01:08:02 duration 12742 km



The “planetary signature” ...

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

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

It is easier to detect planets around colder, smaller stars

Motivation for a NIR planet searcher

- 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

Constraints on spectrograph design

☆ Metrological stability

Silicon lattice constant: 0.54nm

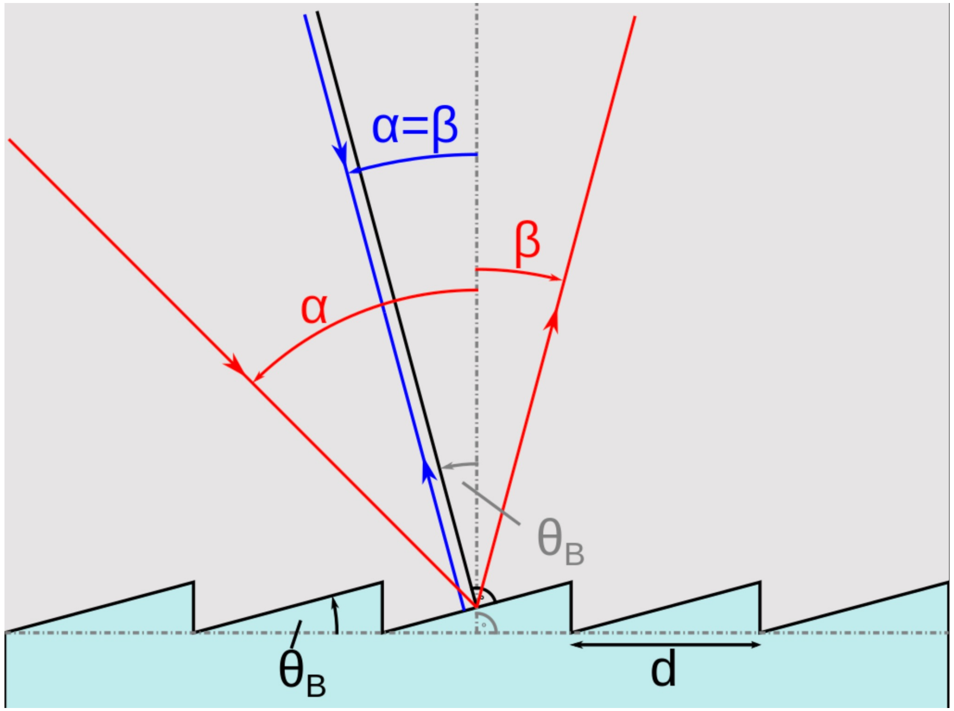
Planet	Mass (M_{Jup})	K (m/s)	HARPS/NIRPS shift (nm)	ESPRESSO shift (nm)
Mercury	1.74×10^{-4}	0.008	0.14	0.25
Venus	2.56×10^{-3}	0.086	1.6	2.7
Earth	3.15×10^{-3}	0.089	1.6	2.8
Mars	3.38×10^{-4}	0.008	0.14	0.25
Jupiter	1.0	12.4	227	388
Saturn	0.299	2.75	50	86
Uranus	0.046	0.297	5.4	9.3
Neptune	0.054	0.281	5.1	8.8
HARPS/NIRPS requirem.		1	18	31
ESPRESSO requirement		0.1	1.8	3.1

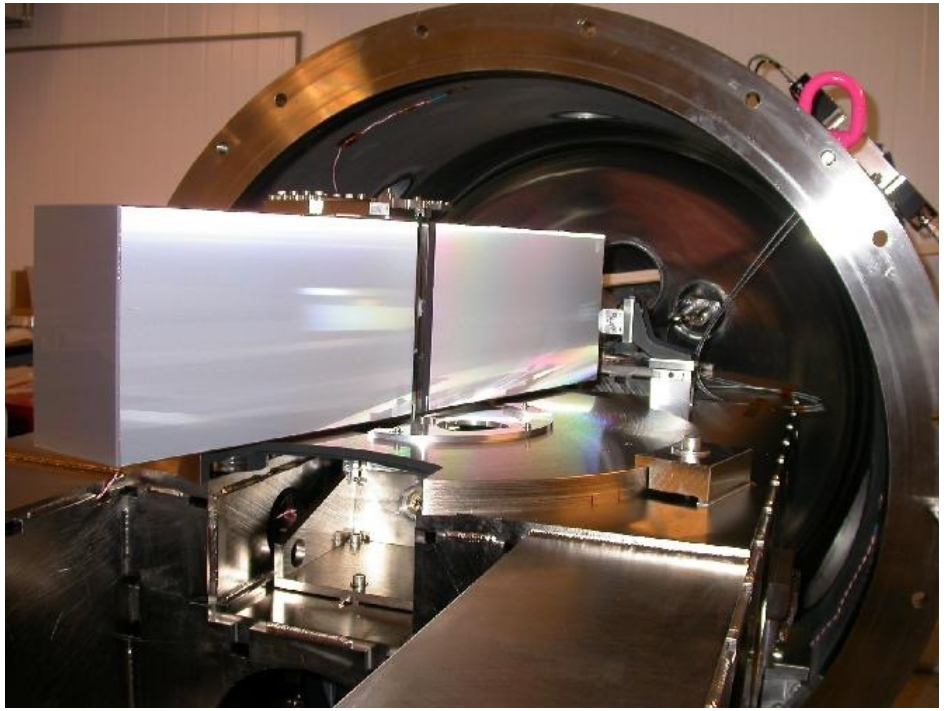
Constraints on spectrograph design

- **Spectral resolution:**

$R = \lambda/\Delta\lambda =$

2*tan(blaze)*beam/(slit”*M1)





Constraints on spectrograph design

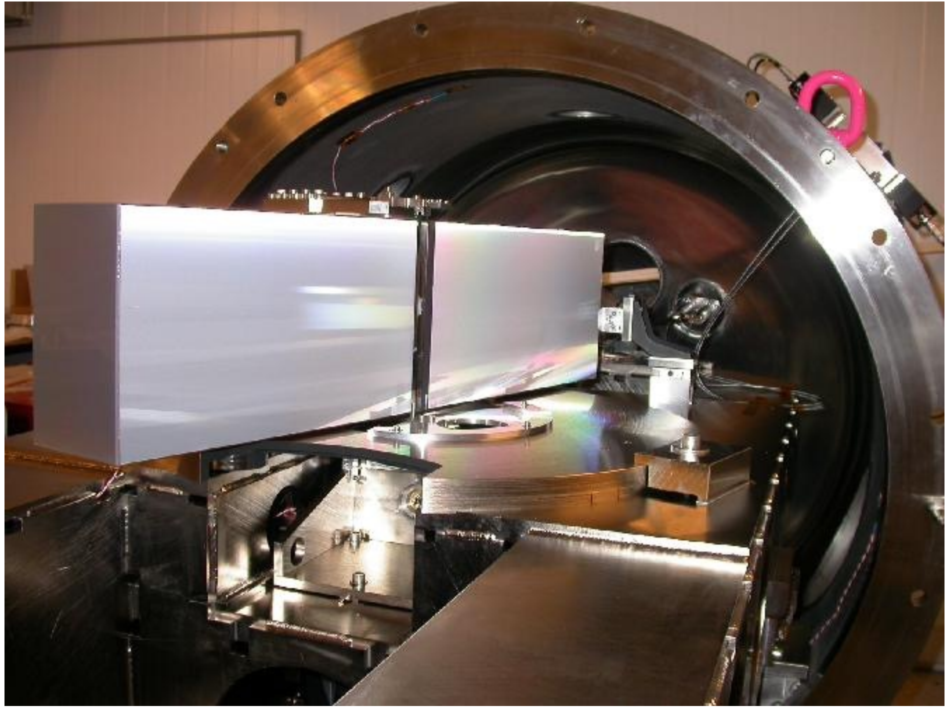
☆ **Spectral resolution:**

$R = \lambda/\Delta\lambda =$

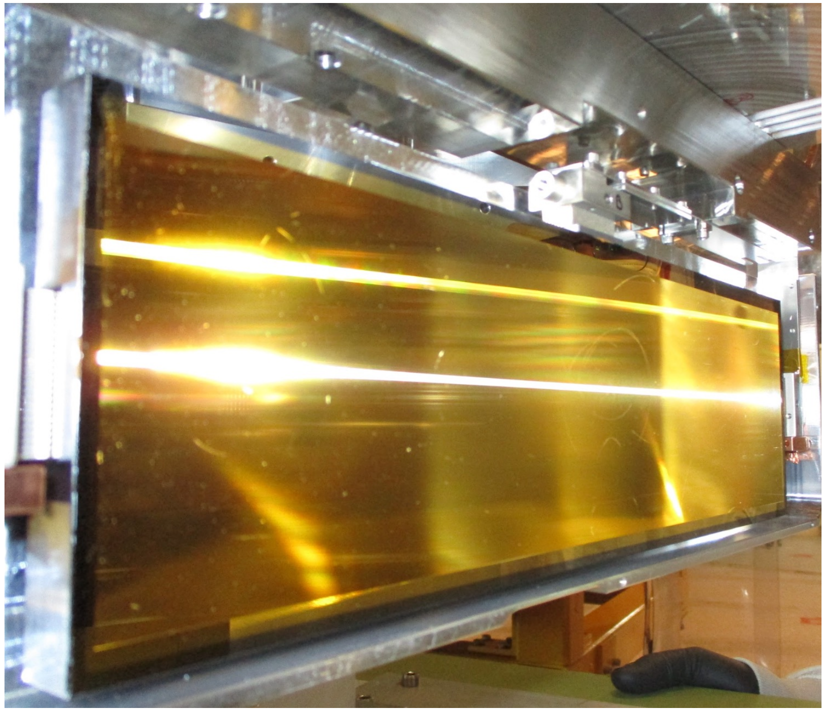
2*tan(blaze)*beam/(slit”*M1)

“Small” beam size thanks to A.O.

HARPS grating: Al, R4, 20cm x 80cm



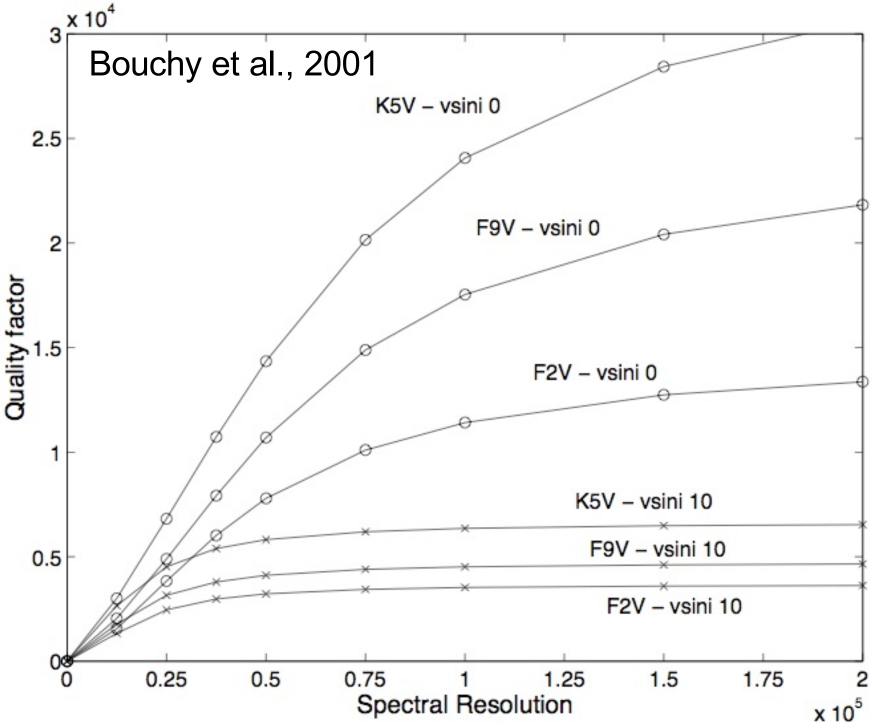
NIRPS grating: Au, R4, 9cm x 32cm

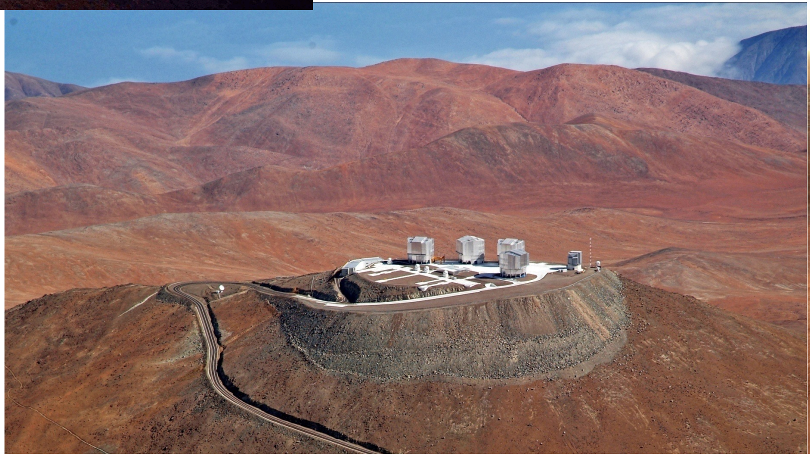


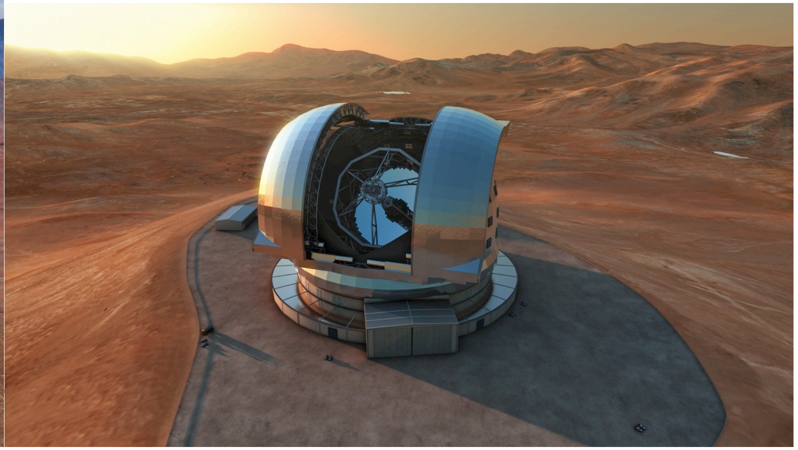
Constraints on spectrograph design

- **Photon noise limit:**

$$< \delta V >_{RMS} = \frac{c}{Q * \sqrt{N_{phot}}}$$





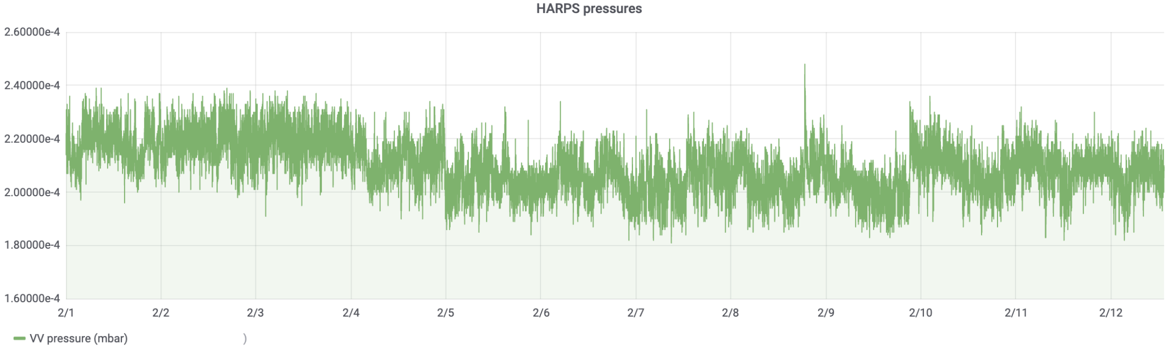


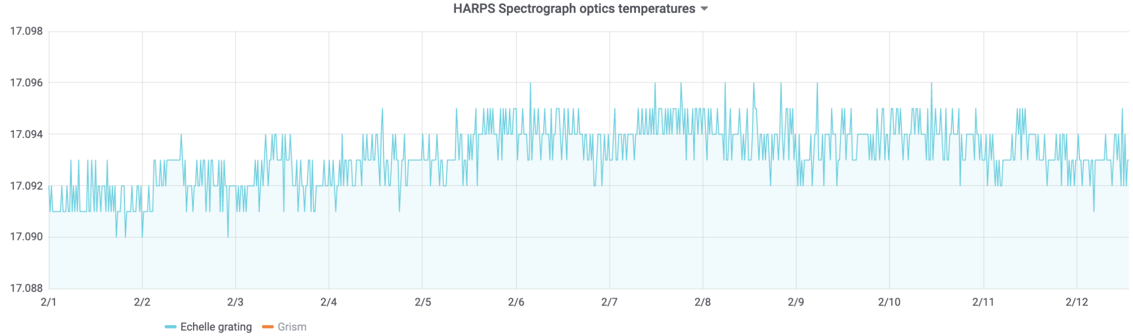
Metrological stability I: spectrograph

No moving parts inside the spectrograph

Stability of the index of refraction ➔ Instrument under vacuum ($<10^{-3}$ mbar)

Strict temperature control (grating RMS <1mK / day)





Metrological stability II: light injection

Variations of light distribution at the entrance slit ➔
➔variation in the lines shapes & positions

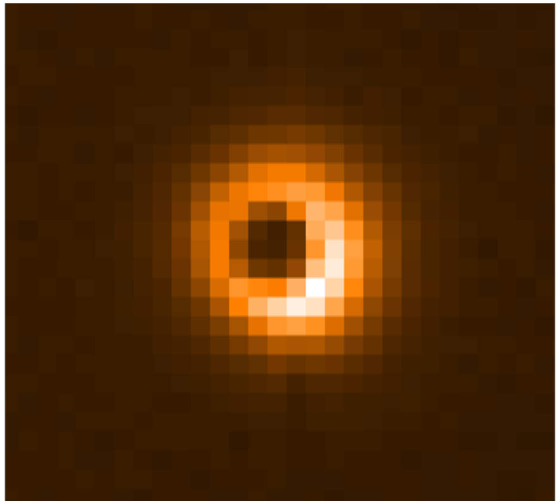
Use **fiber optics** to increase stability of the light injection

Fiber optics are good “scramblers” in the near field,
Not so in the far field.

➔Use a “Double scrambler” at spectrograph’ entrance
to exchange the near & far field.

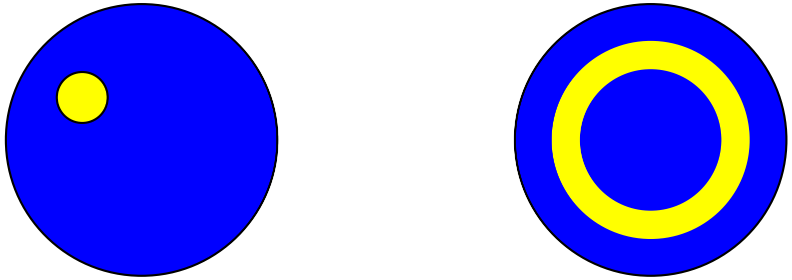
Guiding (without octagonal fibers)

"Bad" guiding, 0.5" de-centering, ~3 m/s contribution to RV

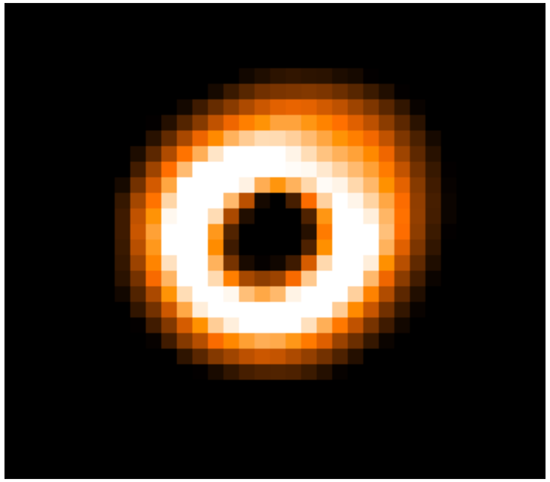


Bad centering

Fiber entrance   Fiber exit

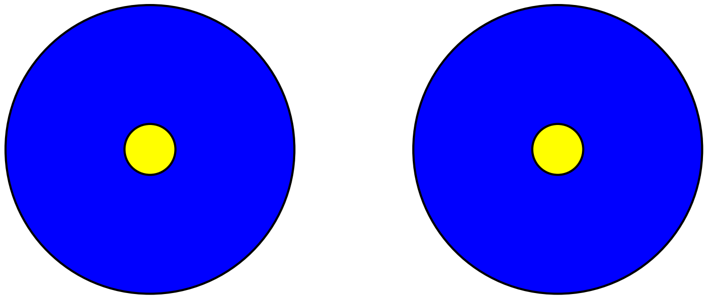


"Good" guiding, 0.1" RMS, ~30 cm/s contribution to RV



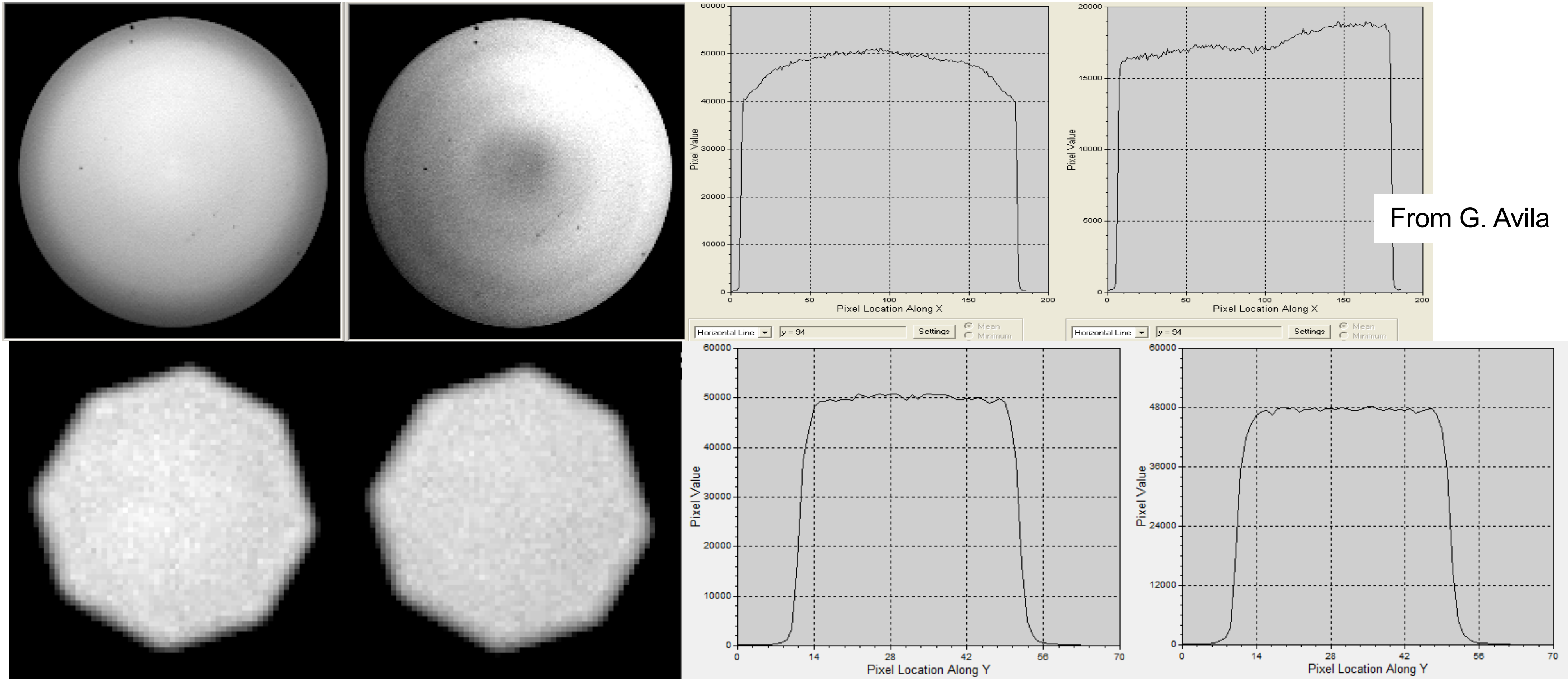
Good centering

Fiber entrance   Fiber exit



Octogonal fibers (near field)

Centered De-centered Centered (section) De-centered (section)

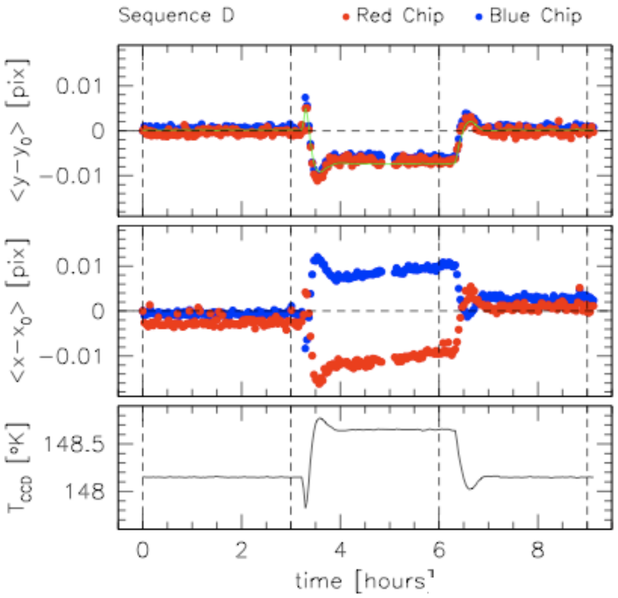


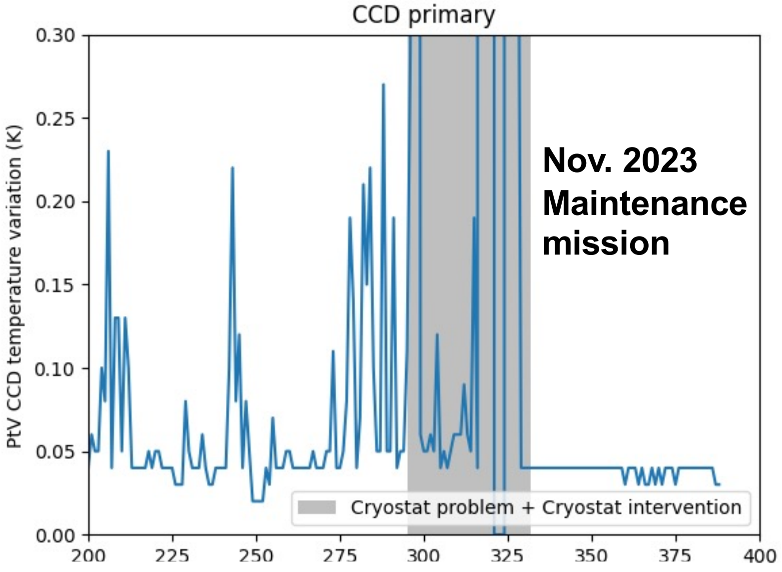
From G. Avila

<u>De-centering errors are within photon noise after double scrambler and octogonal fibers</u>.

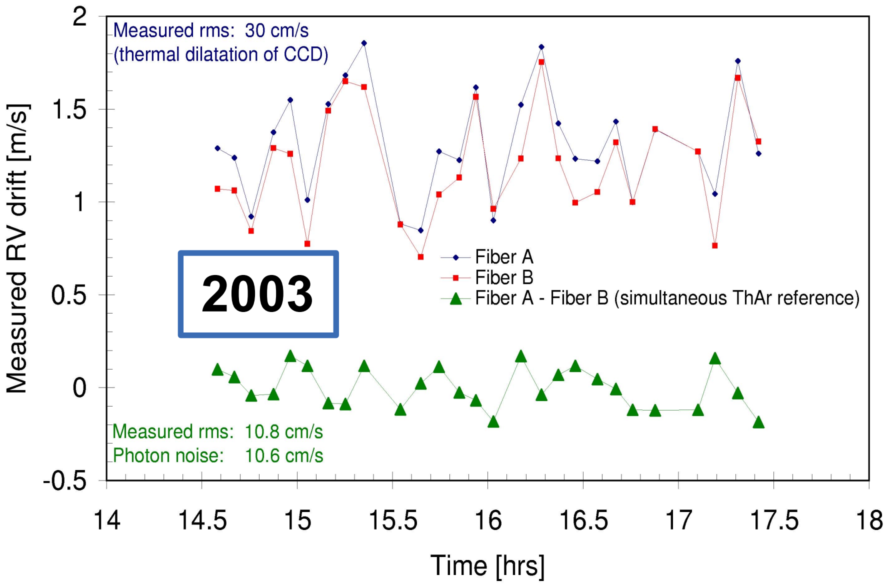
Metrological stability III: Detector Thermal stability

CCDs thermal expansion makes the lines move in pixel space, i.e. simulates a RV effect, that could in principle be corrected by simultaneous calibration.





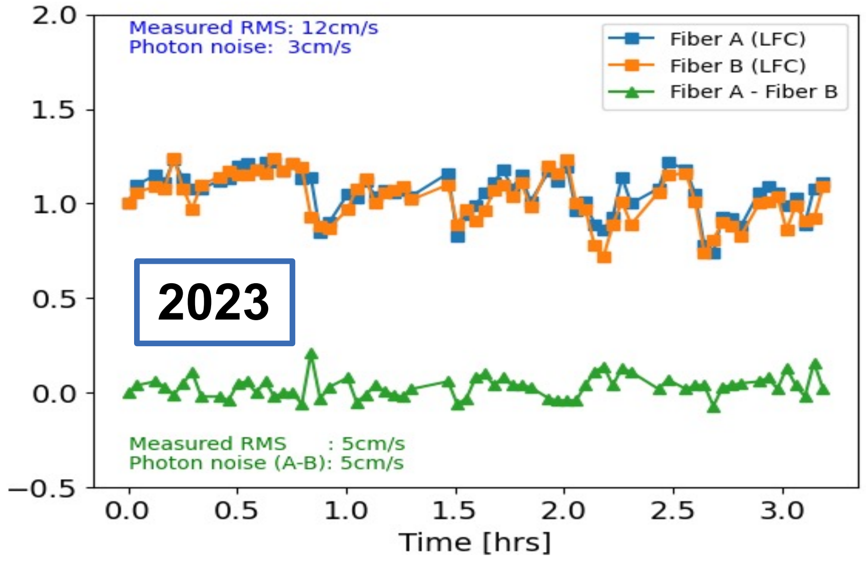
Nov. 2023 Maintenance mission



Measured rms: 30 cm/s
(thermal dilatation of CCD)

2003

Measured rms: 10.8 cm/s
Photon noise: 10.6 cm/s



Measured RMS: 12cm/s
Photon noise: 3cm/s

2023

Measured RMS : 5cm/s
Photon noise (A-B): 5cm/s

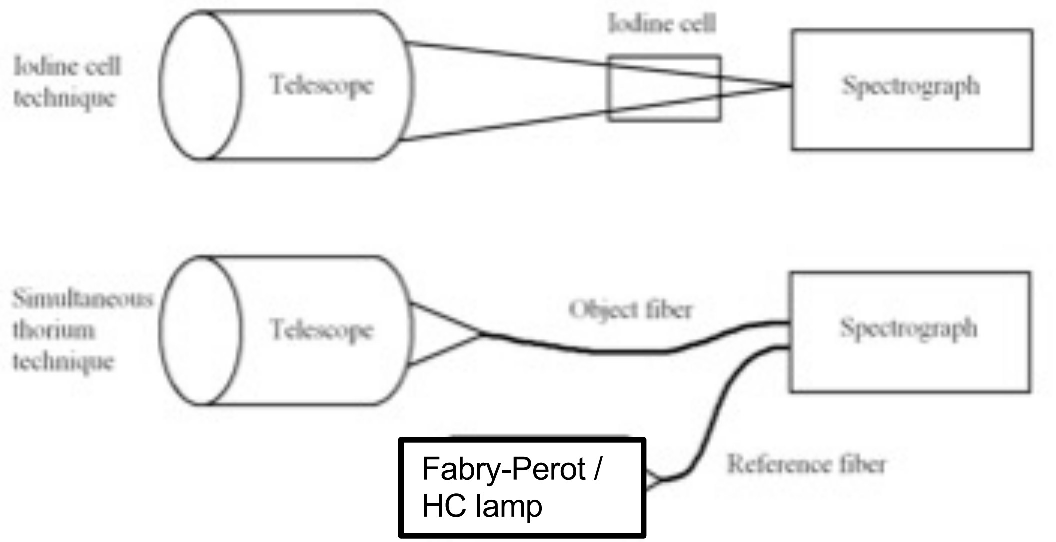
Metrological stability IV: track the unavoidable

Instrument variations are unavoidable…

… track them !

⇒Simultaneous calibration

⇒Absorption cells



The HARPS experience:

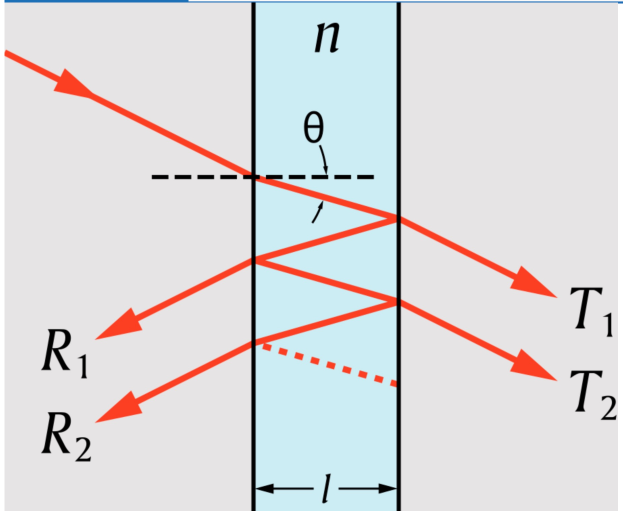
- the instrument drift is generally less than 0.5m/s overnight.
- the RMS of the temperature is less than 1mK in 24 hours
- a 1m/s RV drift was measured simultaneously to a 7mK temperature variation at the echelle

Constraints on spectrograph design

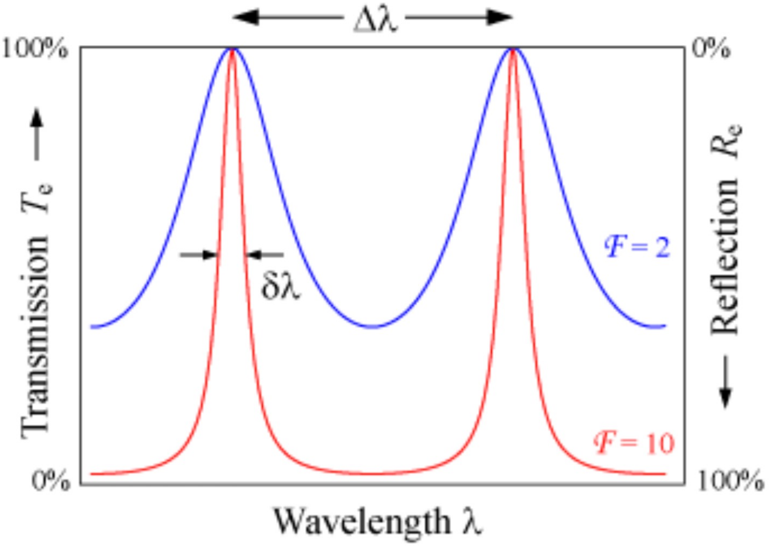
☆ Technology (I) :

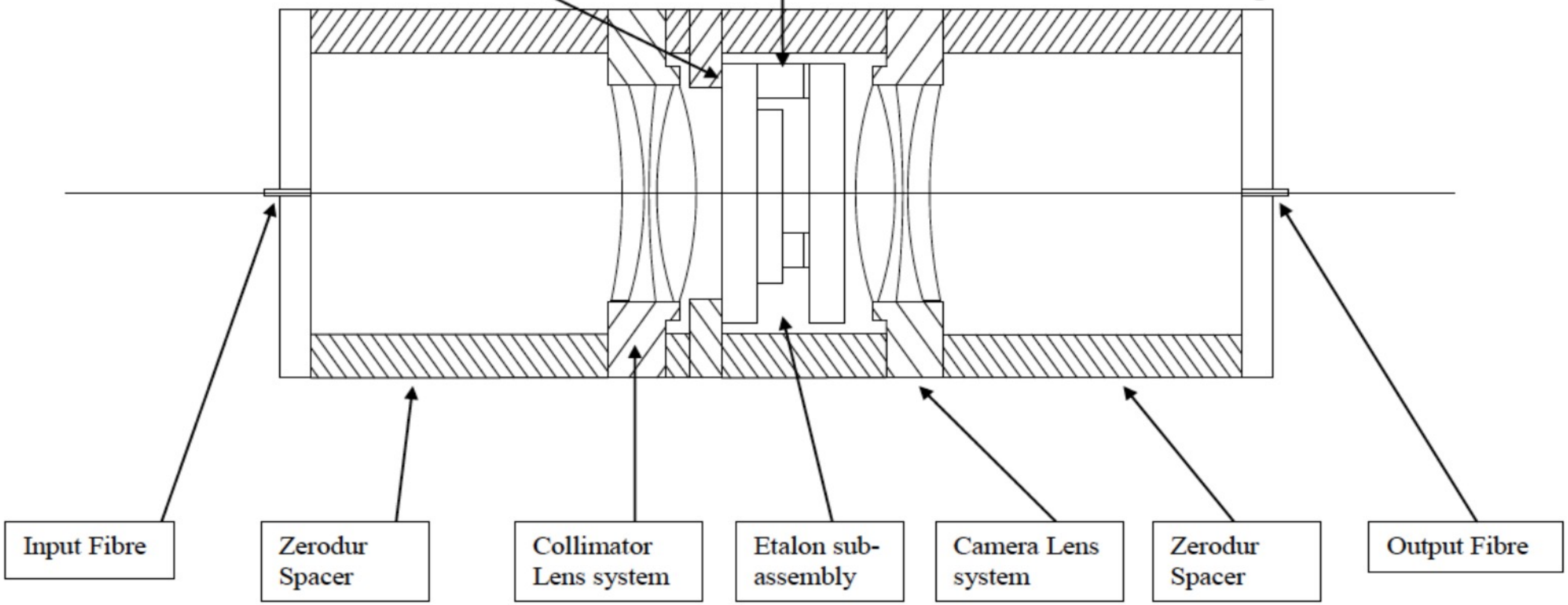
- **Gratings:** groove density, quality, dimension, available blaze angles;
- **Detectors:** detector noise, efficiency, pixel size;
- **Fibers**: transmission and scrambling properties
- **Calibration sources**: ThAr, Fabry-Perot, LFCs.

Fabry-Perot units



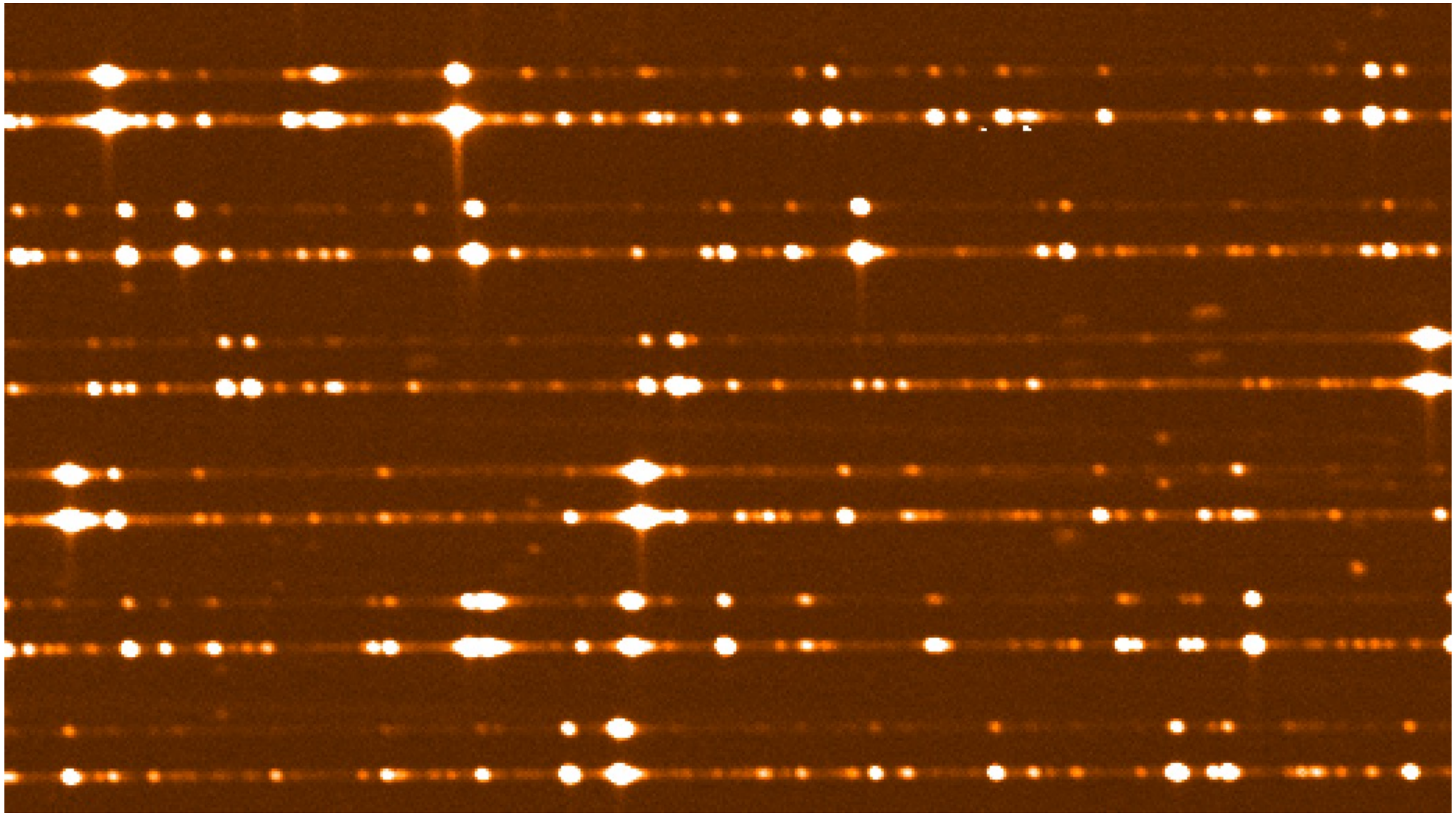
$$\delta = phase\ difference = \left(\frac{2\cdot\pi}{\lambda}\right) 2\cdot n\cdot l\cdot\cos\theta$$





Wavelength calibration

- Associate pixels to wavelengths.
- Use lines atlas (e.g. Palmer & Englmann, 1983 / Redman 2014).
- 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

Limitation of traditional calibrators

- Lines randomly spaced → wavelength range not uniformly sampled
- Lines intensities highly variable → reduction of the photon noise of the calibration
- Lines have variable width → line profile variations

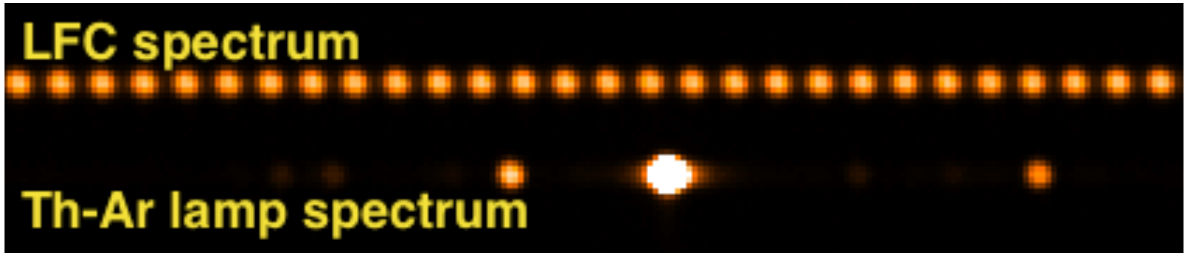
The “ideal calibrator”

- Many lines, equally spaced

- Line intensities can be regulated to increase dynamical range and decrease photon noise

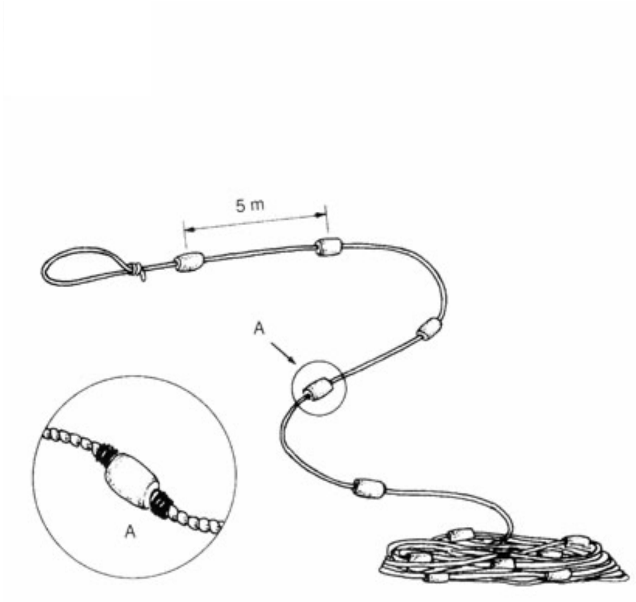
- Lines are not resolved ➔ the instrumental line profile is directly measurable.

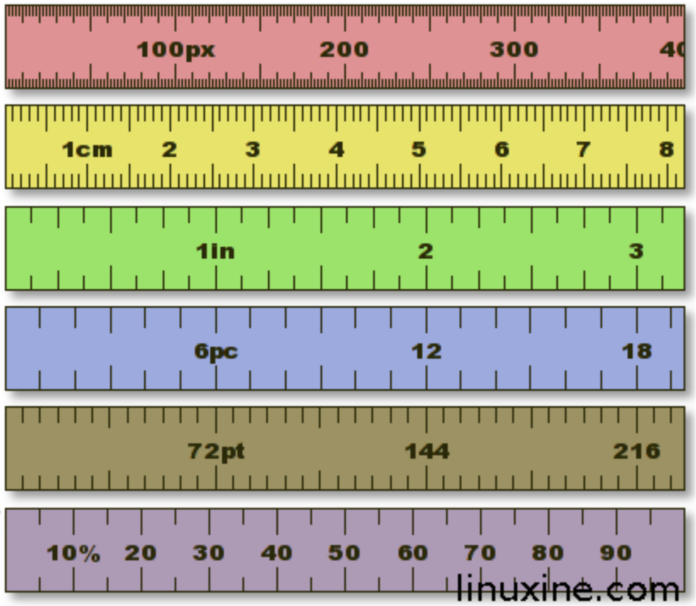
Laser Frequency Combs



$$\omega = \omega_{CEO} + n \cdot \omega_{Rep}$$

LFC lines equation



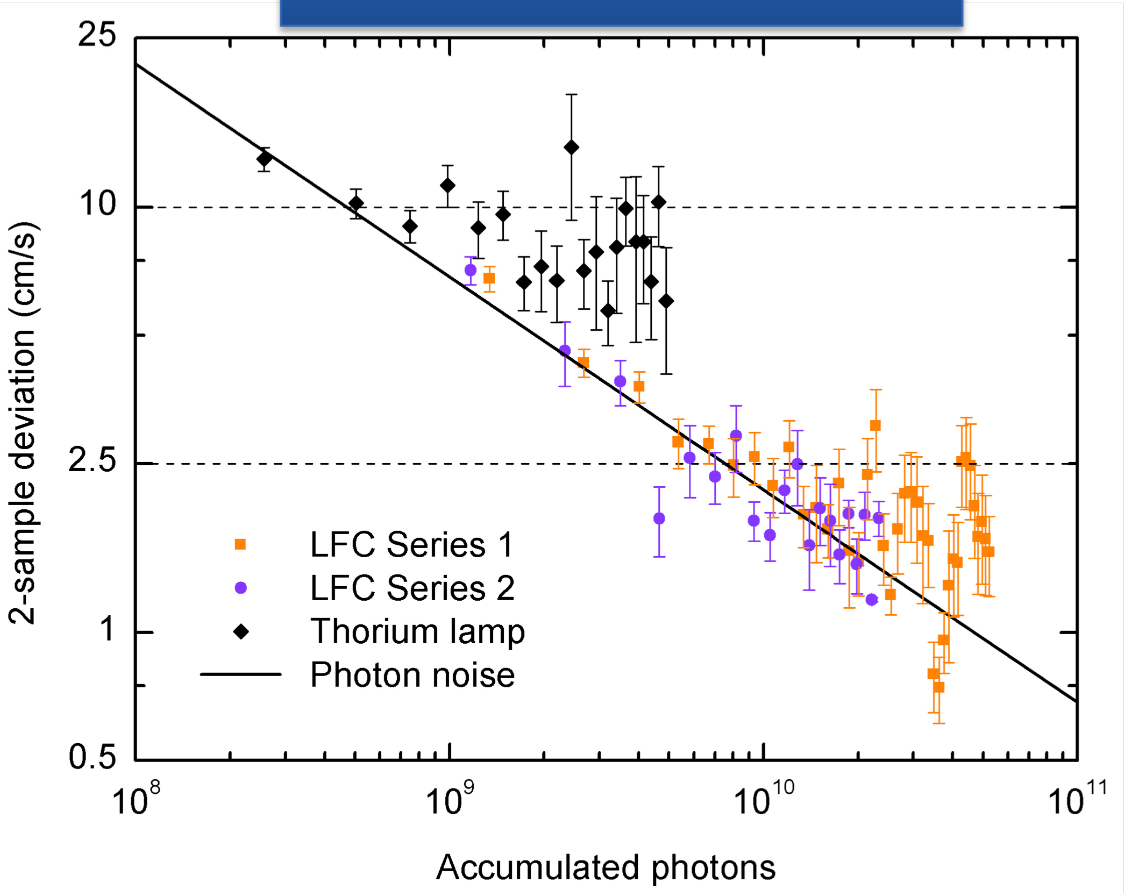


Laser Frequency Comb

Noise in the LFC data is statistical only down to below 2.5 cm/s !!!

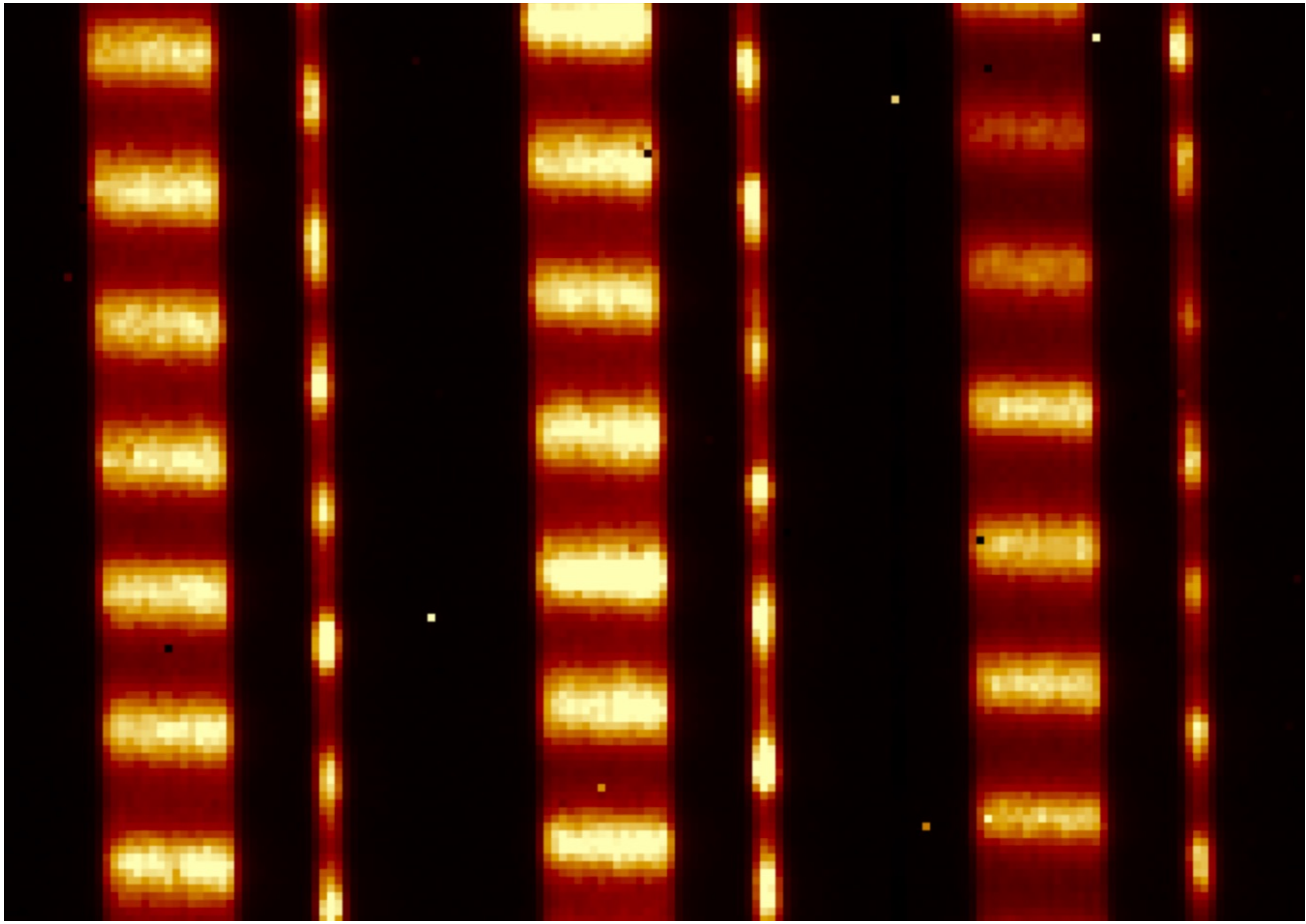
(Wilken et al., Nature, 2012)

LFC on HARPS



Laser Frequency Comb

LFC on NIRPS



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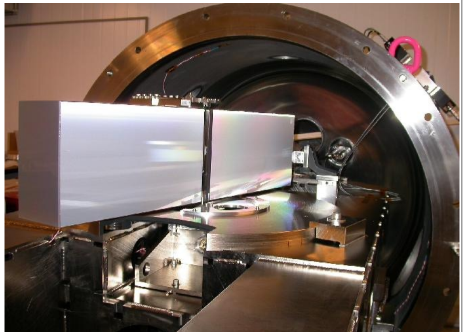

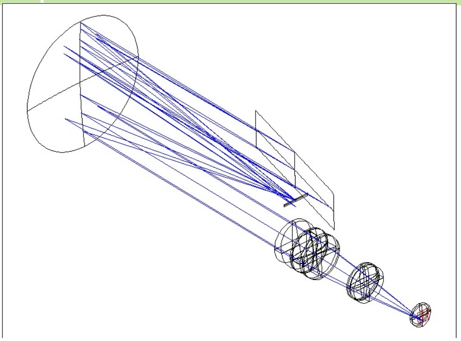

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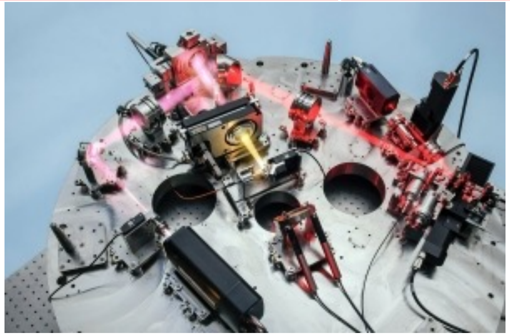
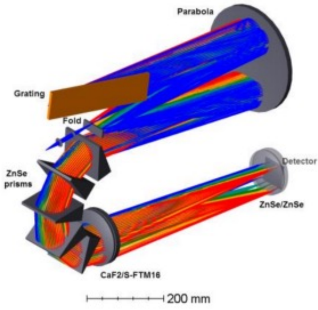
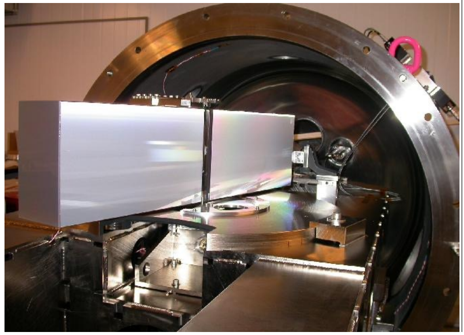


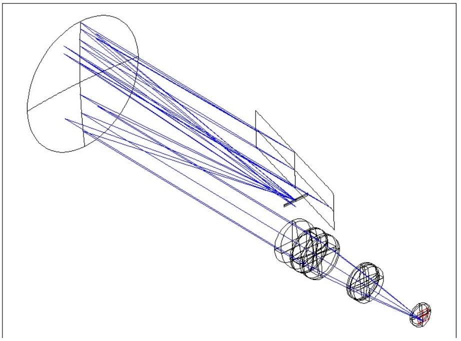


Basics of HARPS & NIRPS high resolution spectrographs

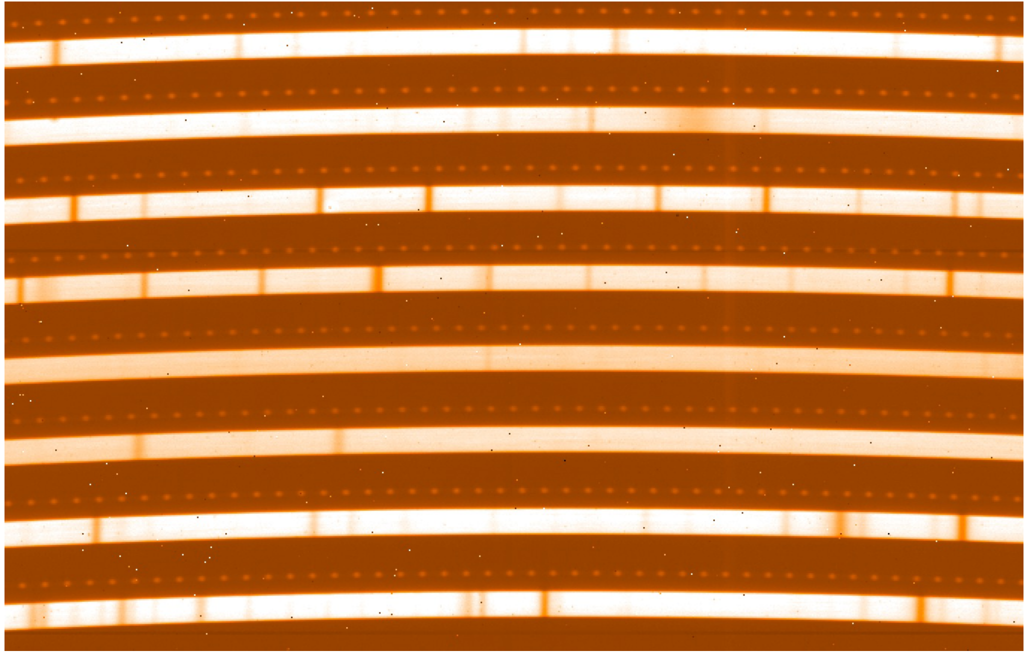
HARPS

CCD: total number of counts

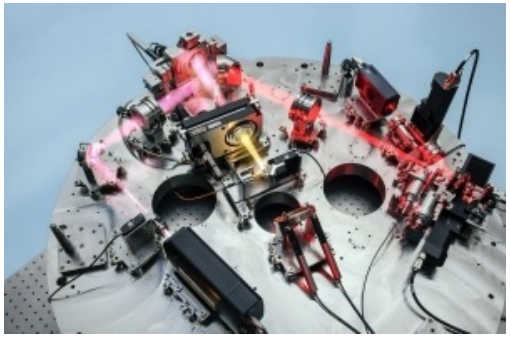


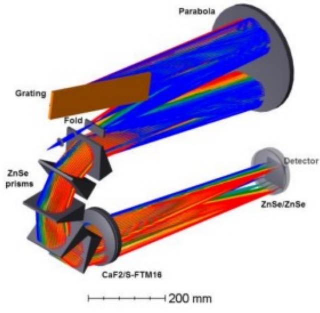


NIRPS

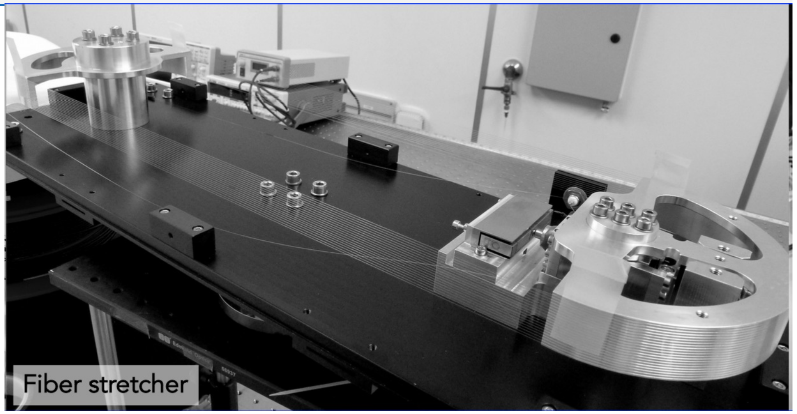


Up-the-ramp sampling: counts per second
5.573s/sample



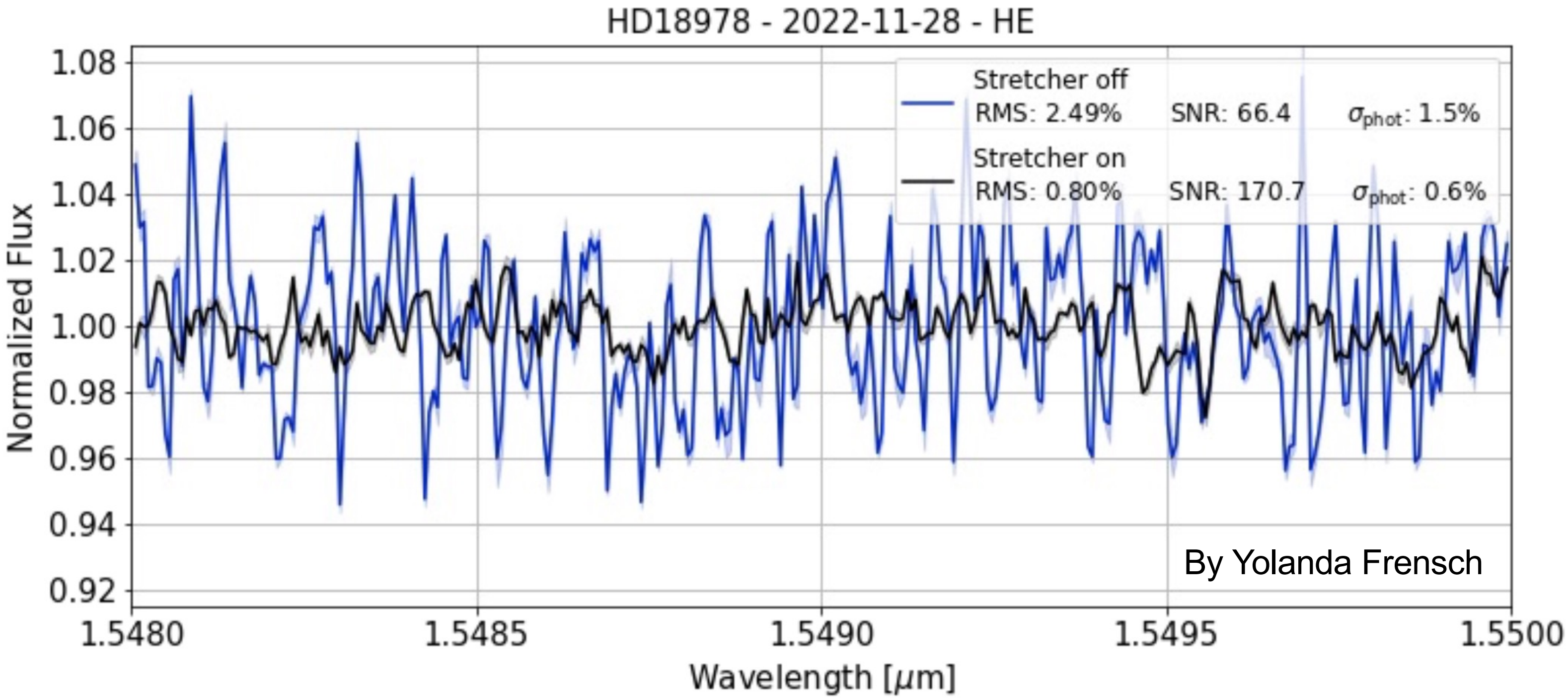


Modal noise



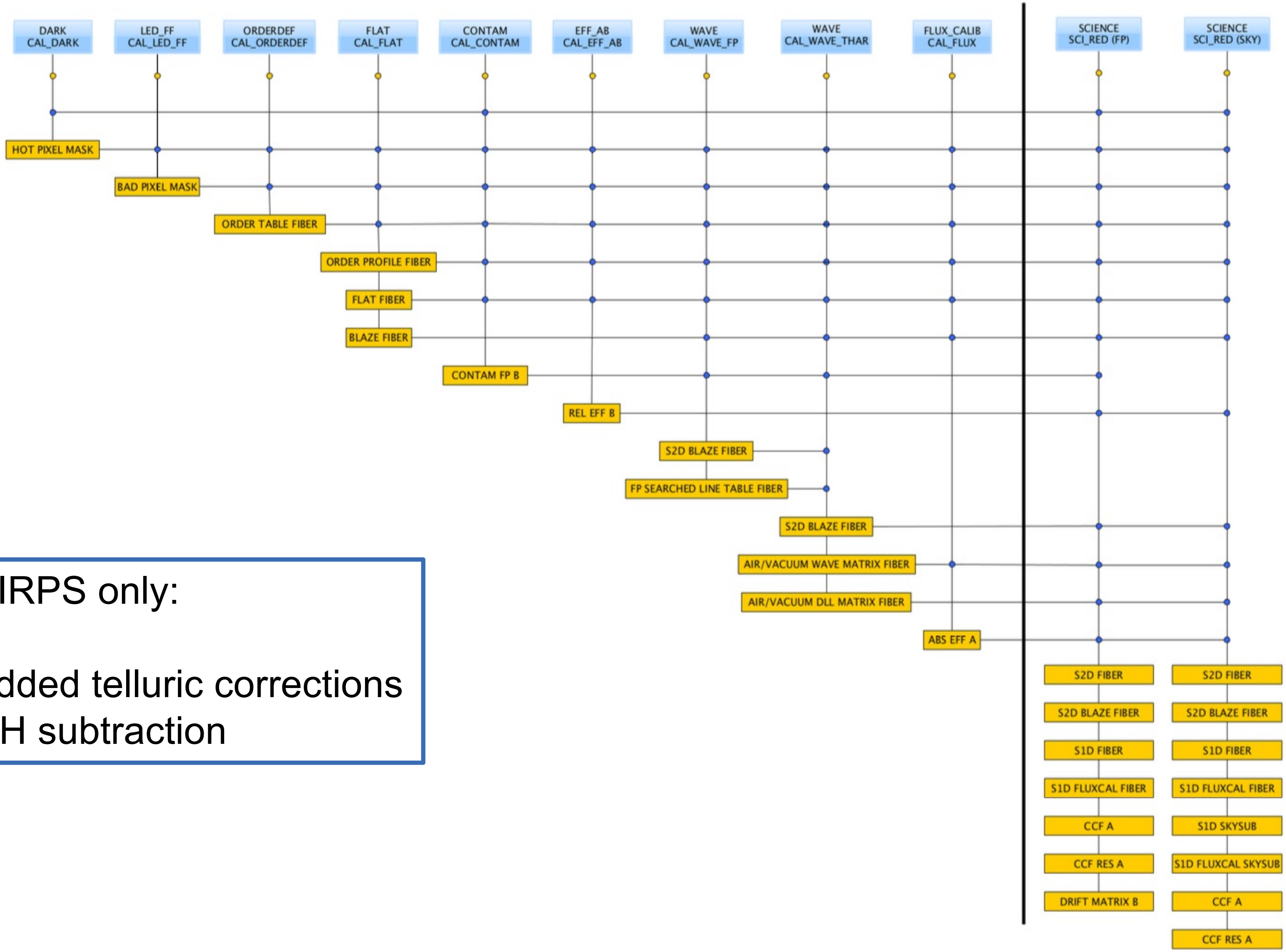
Optical fibers are wave-guides,
the number of propagating modes depends on
the ratio of the fiber core to the wavelength.
In the IR there are much less modes,
and “modal noise” (interference between the modes)
plays an important role.

This is why NIRPS (but not HARPS) has a fiber-stretcher to “scramble” the modes and reduce the measurable effect of the modal noise.



By Yolanda Frensch

Pipeline



DARK CAL_DARK

LED_FF CAL_LED_FF

ORDERDEF CAL_ORDERDEF

FLAT CAL_FLAT

CONTAM CAL_CONTAM

EFF_AB CAL_EFF_AB

WAVE CAL_WAVE_FP

WAVE CAL_WAVE_THAR

FLUX_CALIB CAL_FLUX

SCIENCE SCI_RED (FP)

SCIENCE SCI_RED (SKY)

HOT PIXEL MASK

BAD PIXEL MASK

ORDER TABLE FIBER

ORDER PROFILE FIBER

FLAT FIBER

BLAZE FIBER

CONTAM FP B

REL EFF B

S2D BLAZE FIBER

FP SEARCHED LINE TABLE FIBER

S2D BLAZE FIBER

AIR/VACUUM WAVE MATRIX FIBER

AIR/VACUUM DLL MATRIX FIBER

ABS EFF A

S2D FIBER

S2D BLAZE FIBER

S1D FIBER

S1D FLUXCAL FIBER

CCF A

CCF RES A

DRIFT MATRIX B

S2D FIBER

S2D BLAZE FIBER

S1D FIBER

S1D FLUXCAL FIBER

S1D SKYSUB

S1D FLUXCAL SKYSUB

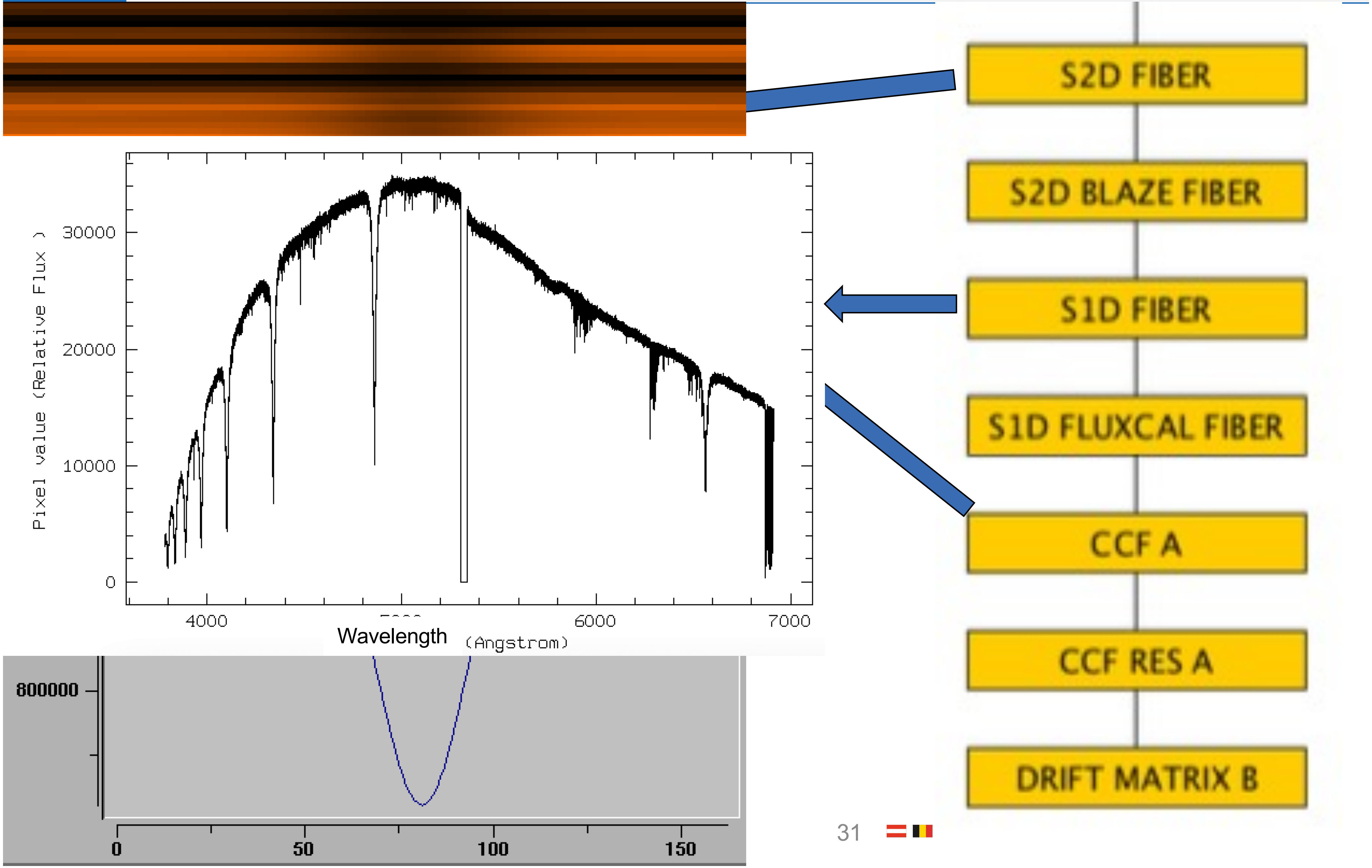
CCF A

CCF RES A

NIRPS only:

Added telluric corrections
OH subtraction

Pipeline



S2D FIBER

S2D BLAZE FIBER

S1D FIBER

S1D FLUXCAL FIBER

CCF A

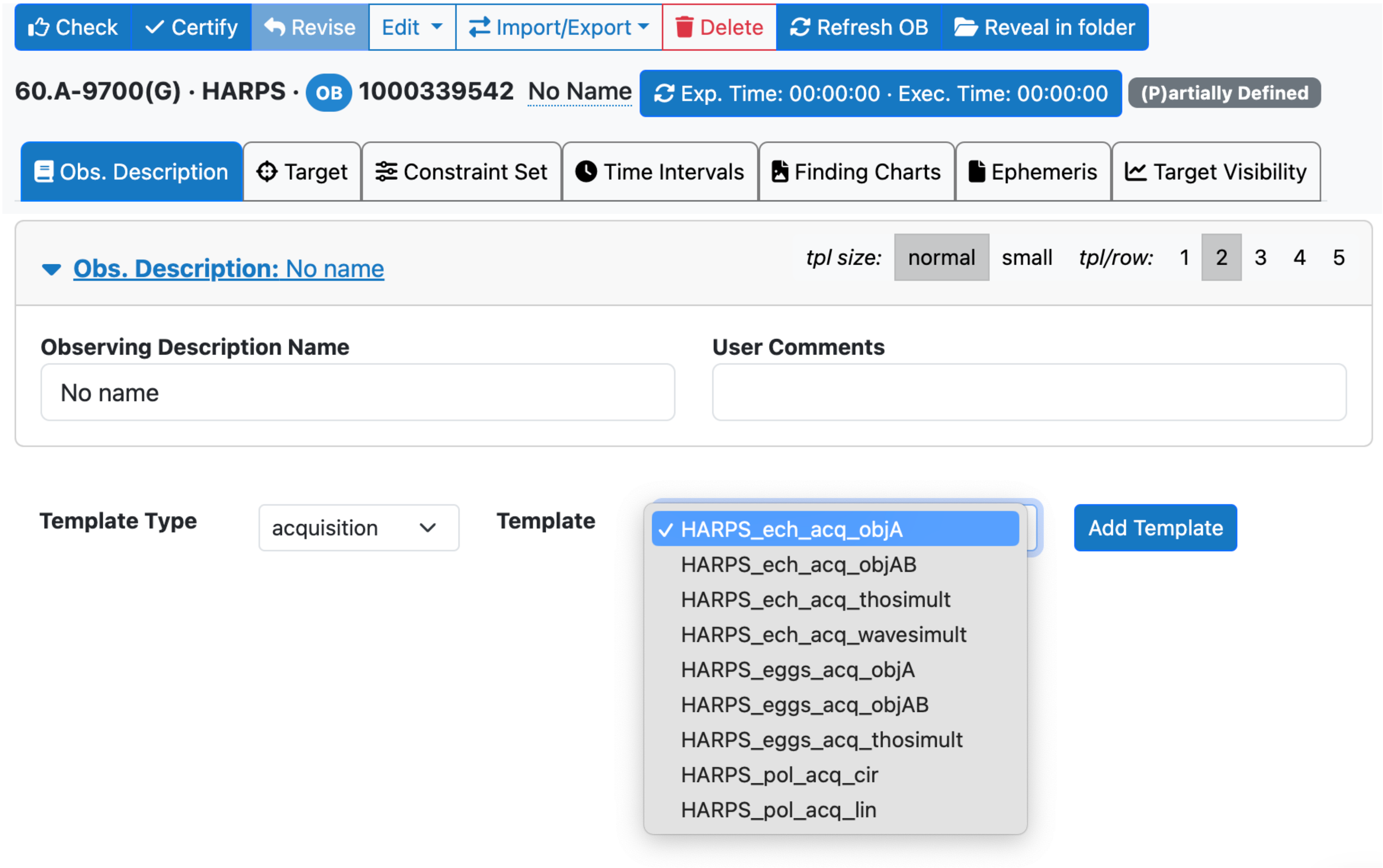
CCF RES A

DRIFT MATRIX B

Operations

- ☐ Very smooth operation strategy
- ☐ NIRPS & HARPS can be operated either together, or individually.
- ☐ NIRPS acquisition is always performed with the support of adaptive optics.
- ☐ An image quality of up to 0.1” is routinely obtained in the acquisition camera.
- ☐ HARPS centering and guiding is preliminary to the start of NIRPS acquisition.
- ☐ Both instrument pipelines are running at the telescope and are distributed to users

HARPS acquisition



60.A-9700(G) · HARPS · OB 1000339542 No Name

Exp. Time: 00:00:00 · Exec. Time: 00:00:00

(P)artially Defined

Obs. Description: No name

tpl size: normal small tpl/row: 1 2 3 4 5

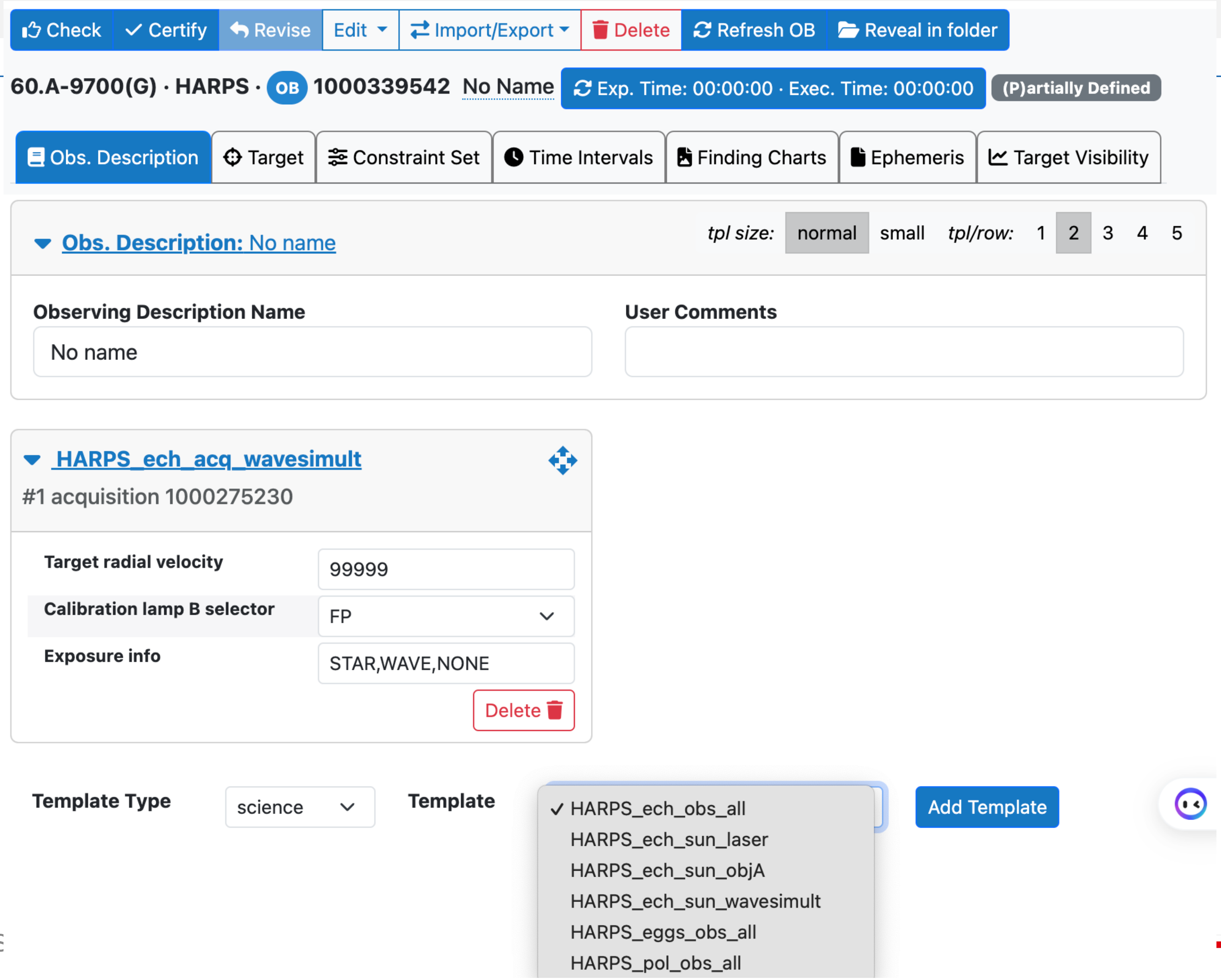
Observing Description Name: No name

User Comments:

Template Type: acquisition

Template: ✓ HARPS_ech_acq_objA

HARPS SCIENCE



60.A-9700(G) · HARPS · OB 1000339542 No Name

Exp. Time: 00:00:00 · Exec. Time: 00:00:00

(P)artially Defined

Obs. Description: No name

Observing Description Name: No name

User Comments:

HARPS_ech_acq_wavesimult

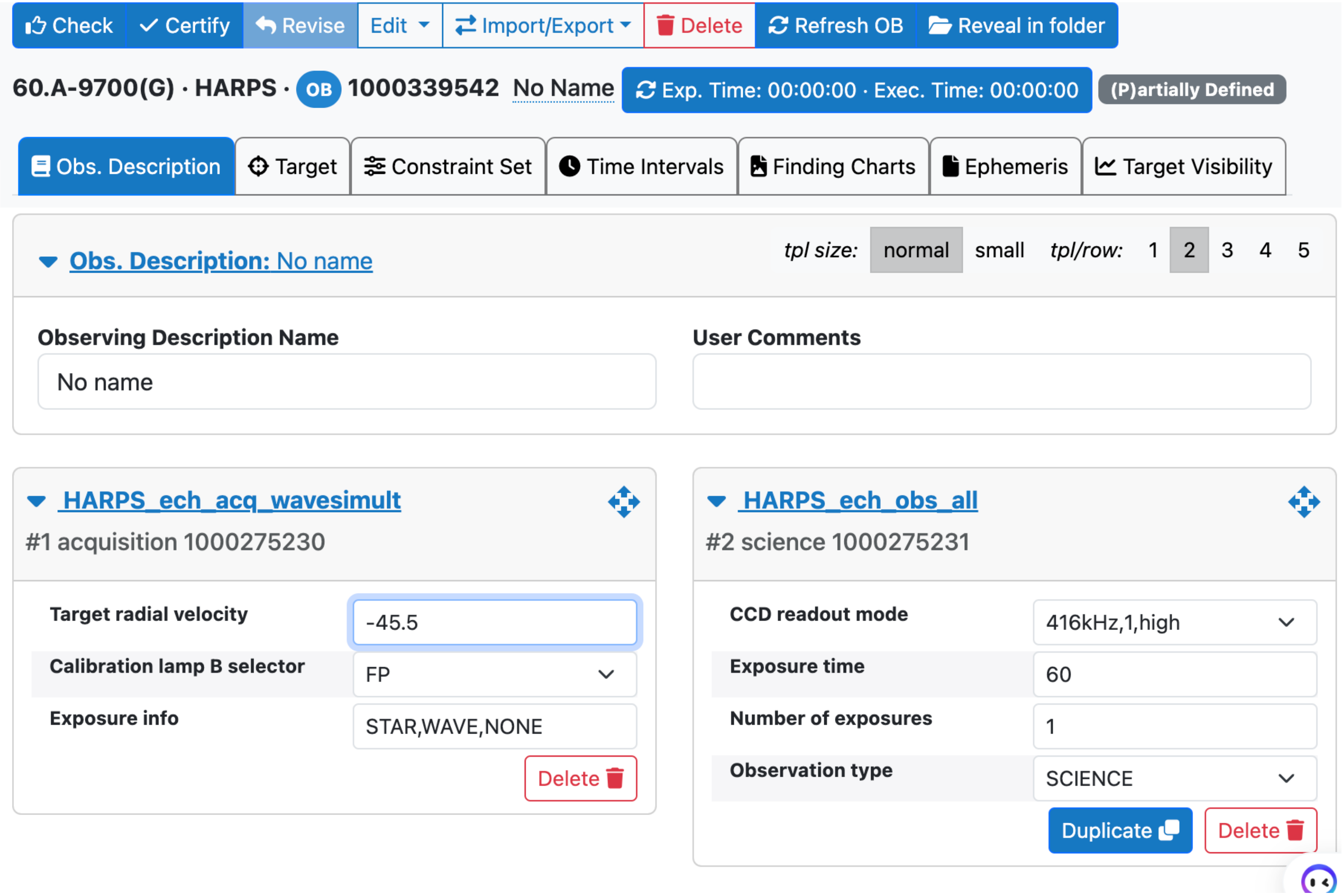
#1 acquisition 1000275230

Target radial velocity	99999
Calibration lamp B selector	FP
Exposure info	STAR,WAVE,NONE

Template Type: science

Template:
- ✓ HARPS_ech_obs_all
- HARPS_ech_sun_laser
- HARPS_ech_sun_objA
- HARPS_ech_sun_wavesimult
- HARPS_eggs_obs_all
- HARPS_pol_obs_all

HARPS OB



60.A-9700(G) · HARPS · OB 1000339542 No Name

Exp. Time: 00:00:00 · Exec. Time: 00:00:00

(P)artially Defined

Obs. Description: No name

tpl size: normal small *tpl/row:* 1 2 3 4 5

Observing Description Name: No name

User Comments:

HARPS_ech_acq_wavesimult

#1 acquisition 1000275230

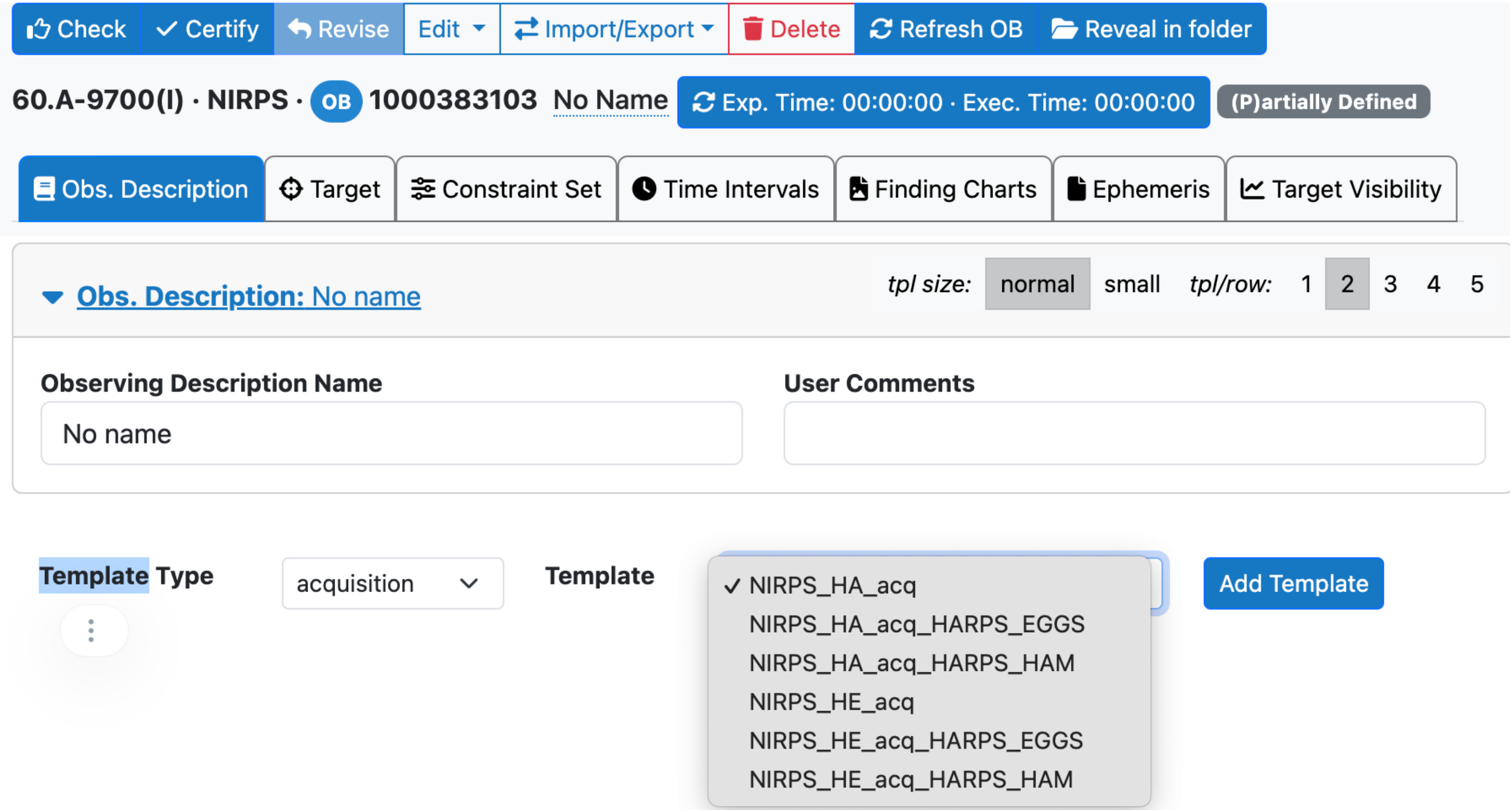
Target radial velocity	-45.5
Calibration lamp B selector	FP
Exposure info	STAR,WAVE,NONE

HARPS_ech_obs_all

#2 science 1000275231

CCD readout mode	416kHz,1,high
Exposure time	60
Number of exposures	1
Observation type	SCIENCE

NIRPS + HARPS ACQUISITION



60.A-9700(I) · NIRPS · OB 1000383103 No Name

Exp. Time: 00:00:00 · Exec. Time: 00:00:00

(P)artially Defined

Obs. Description: No name

Observing Description Name: No name

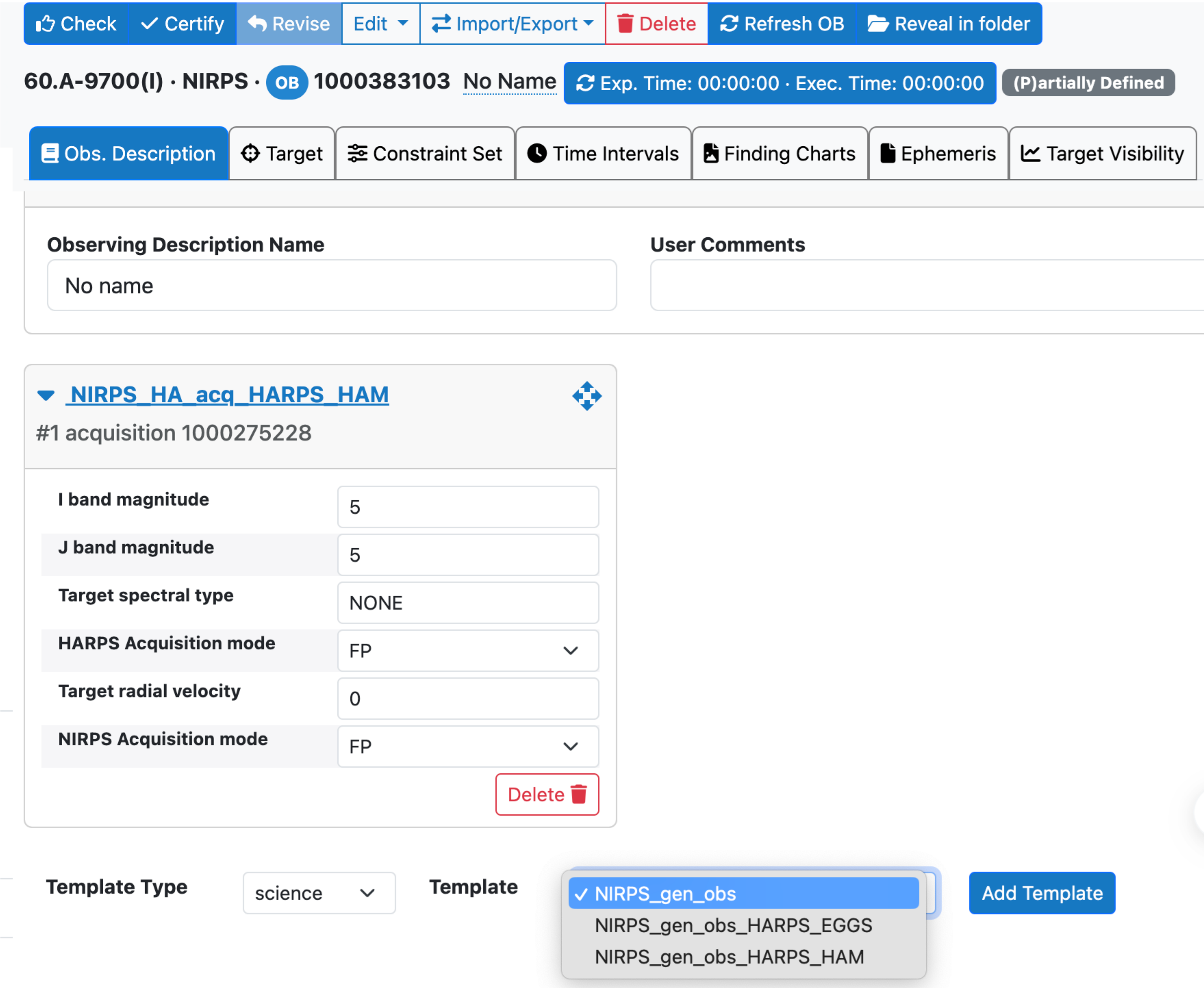
User Comments:

Template Type: acquisition

Template:

- ✓ NIRPS_HA_acq
- NIRPS_HA_acq_HARPS_EGGS
- NIRPS_HA_acq_HARPS_HAM
- NIRPS_HE_acq
- NIRPS_HE_acq_HARPS_EGGS
- NIRPS_HE_acq_HARPS_HAM

NIRPS + HARPS SCIENCE



60.A-9700(I) · NIRPS · OB 1000383103 No Name Exp. Time: 00:00:00 · Exec. Time: 00:00:00 (P)artially Defined

Observing Description Name: No name

User Comments:

NIRPS_HA_acq_HARPS_HAM

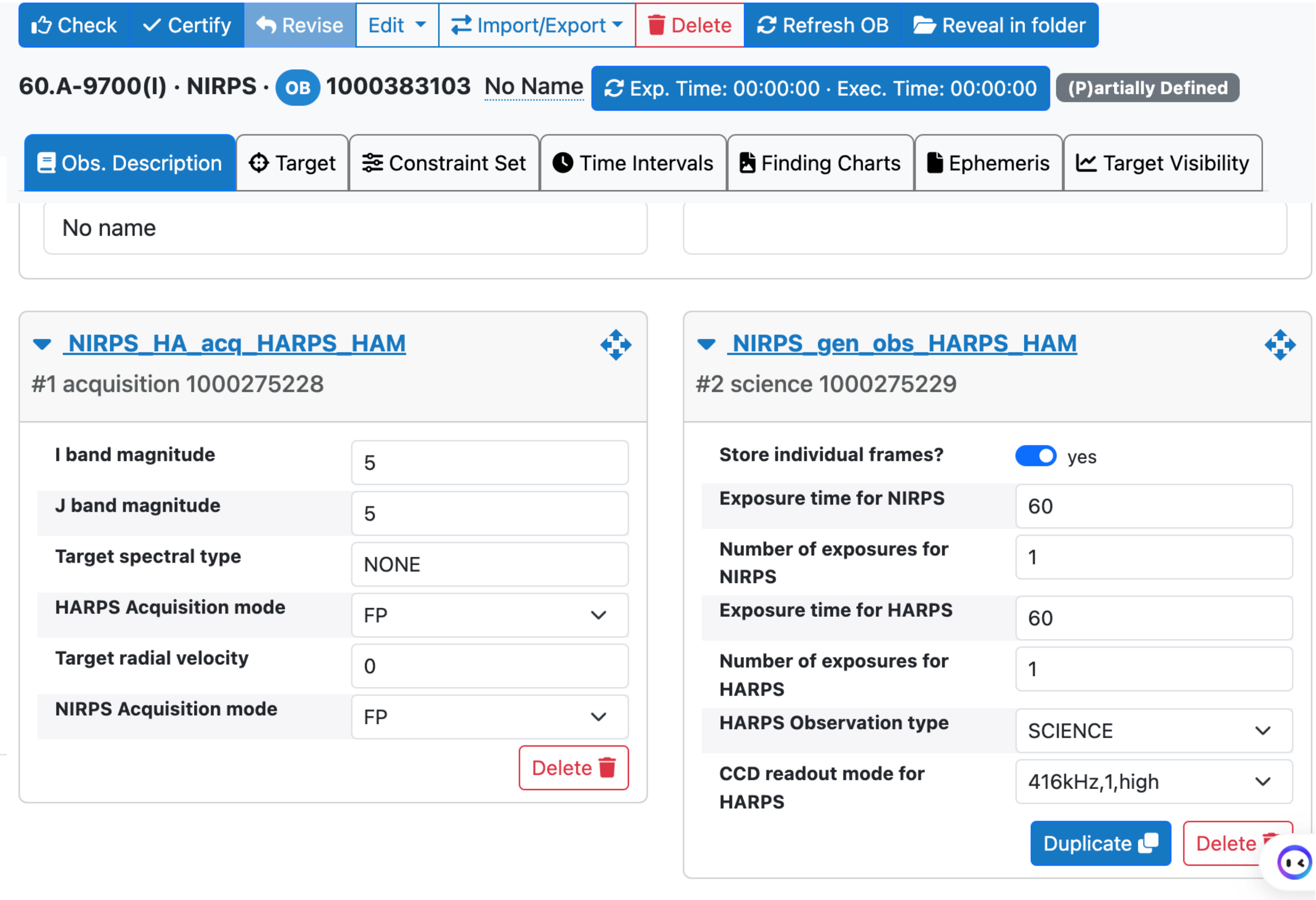
#1 acquisition 1000275228

I band magnitude	5
J band magnitude	5
Target spectral type	NONE
HARPS Acquisition mode	FP
Target radial velocity	0
NIRPS Acquisition mode	FP

Template Type: science

Template:
- ✓ NIRPS_gen_obs
- NIRPS_gen_obs_HARPS_EGGS
- NIRPS_gen_obs_HARPS_HAM

NIRPS + HARPS OB



60.A-9700(I) · NIRPS · OB 1000383103 No Name

Exp. Time: 00:00:00 · Exec. Time: 00:00:00

(P)artially Defined

No name

NIRPS_HA_acq_HARPS_HAM

#1 acquisition 1000275228

I band magnitude	5
J band magnitude	5
Target spectral type	NONE
HARPS Acquisition mode	FP
Target radial velocity	0
NIRPS Acquisition mode	FP

NIRPS_gen_obs_HARPS_HAM

#2 science 1000275229

Store individual frames?	yes
Exposure time for NIRPS	60
Number of exposures for NIRPS	1
Exposure time for HARPS	60
Number of exposures for HARPS	1
HARPS Observation type	SCIENCE
CCD readout mode for HARPS	416kHz,1,high

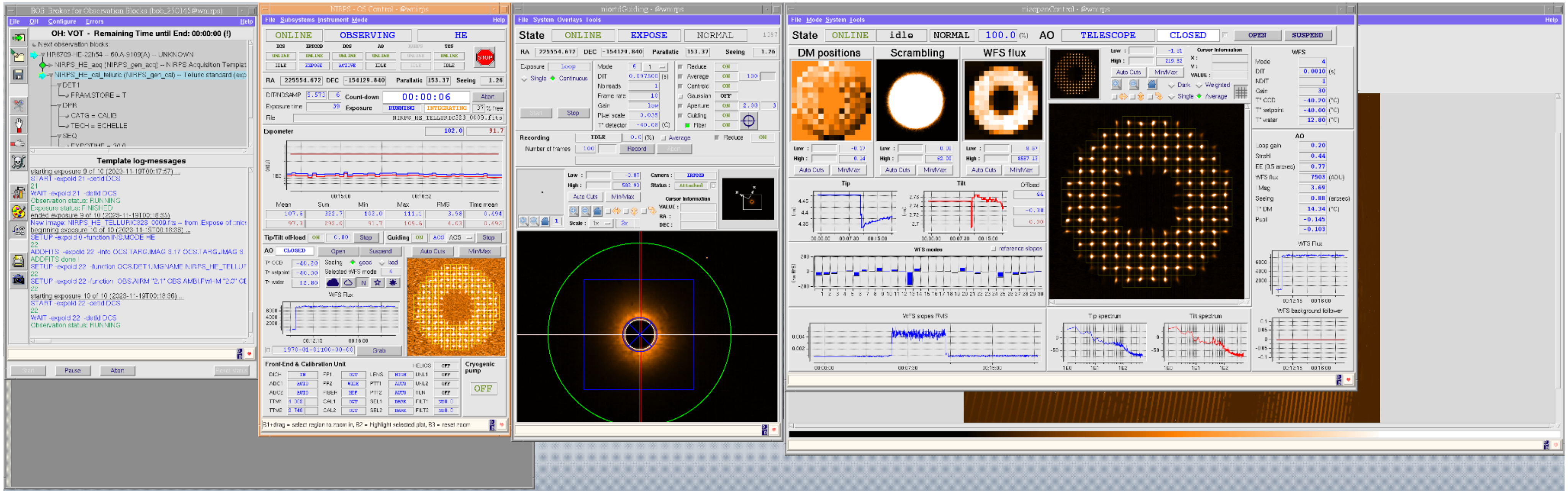
NIRPS Operation panels

BOB

OS

Center
& guide

Adaptive Optics



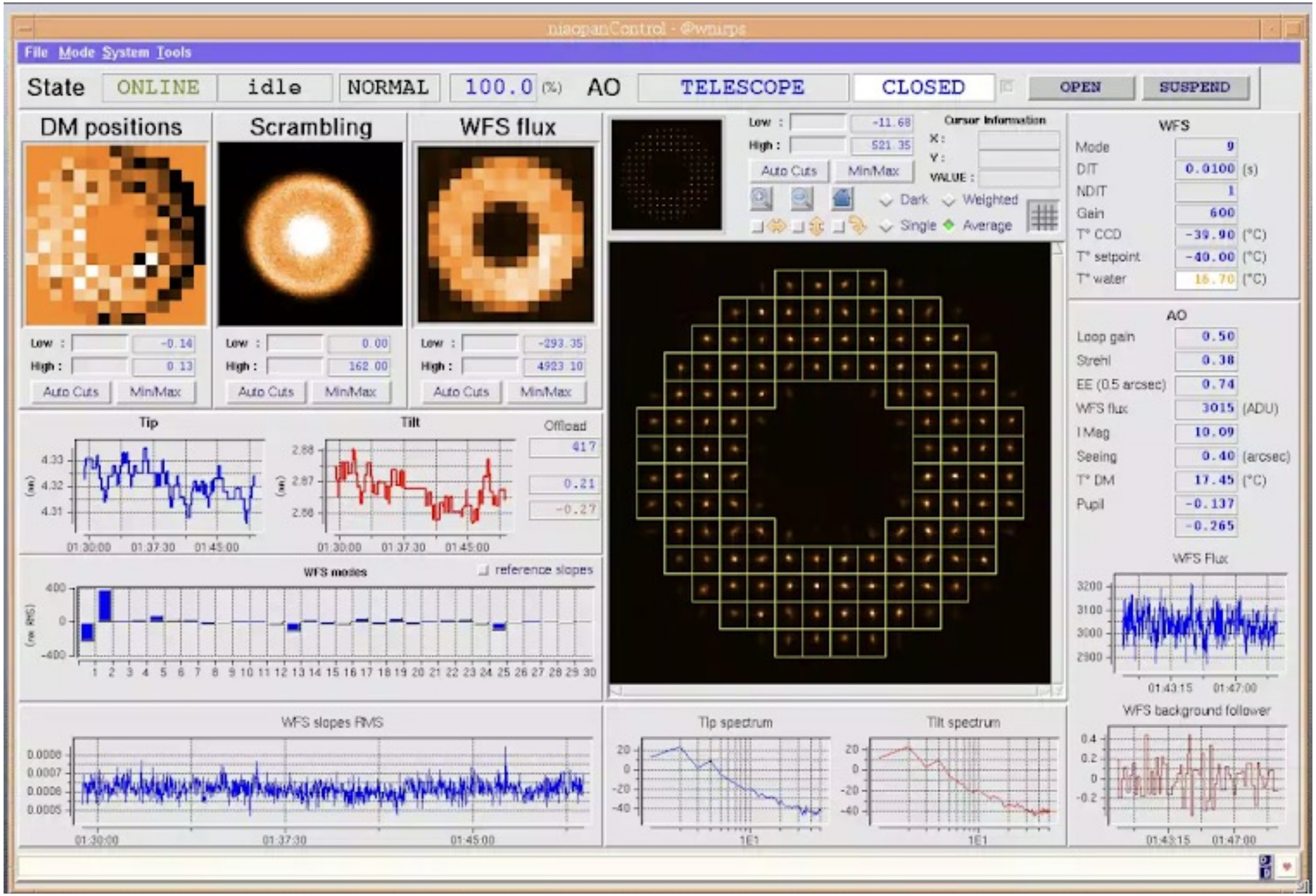
OH: VOT - Remaining Time until End: 00:00:00 (!)

- Next observation blocks:
  - HR6709-HE-22h54 -- 60.A-9109(A) -- UNKNOWN
    - NIRPS_HE_acq (NIRPS_gen_acq) -- NIRPS Acquisition Templat
    - NIRPS_HE_cal_teluric (NIRPS_gen_cal) -- Teluric standard (exp
      - DET1
        - FRAM.STORE = T
      - DPR
        - CATG = CALIB
        - TECH = ECHELLE
      - SEQ

Template log-messages

```
starting exposure 9 of 10 (2023-11-19T00:17:57) ...
START -expoId 21 -detId DCS
21
WAIT -expoId 21 -detId DCS
Observation status: RUNNING
Exposure status: FINISHED
ended exposure 9 of 10 (2023-11-19T00:18:35)
New image: NIRPS_HE_TELLURIC328_0009.fits -- from Expose of ::nic
beginning exposure 10 of 10 (2023-11-19T00:18:35) ...
SETUP -expoId 0 -function INS.MODE HE
22
ADDFITS -expoId 22 -info OCS.TARG.IMAG 3.17 OCS.TARG.JMAG 3.
ADDFITS done !
SETUP -expoId 22 -function OCS.DET1.MGNAME NIRPS_HE_TELLU
22
SETUP -expoId 22 -function OBS.AIRM "2.1" OBS.AMBI.FWHM "2.0" OE
22
starting exposure 10 of 10 (2023-11-19T00:18:36) ...
START -expoId 22 -detId DCS
22
WAIT -expoId 22 -detId DCS
Observation status: RUNNING
```

NIRPS AO panel



State: ONLINE | idle | NORMAL | 100.0 (%)

AO: TELESCOPE | CLOSED

DM positions: Low : -0.14 High : 0.13

Scrambling: Low : 0.00 High : 162.00

WFS flux: Low : -293.35 High : 4923.10

Low : -11.68 High : 521.35

Offload: 417 | 0.21 | -0.27

WFS

Mode 9
DIT 0.0100 (s)
NDIT 1
Gain 600
T° CCD -39.90 (°C)
T° setpoint -40.00 (°C)
T° water 16.70 (°C)

AO

Loop gain 0.50
Strehl 0.38
EE (0.5 arcsec) 0.74
WFS flux 3015 (ADU)
I Mag 10.09
Seeing 0.40 (arcsec)
T° DM 17.45 (°C)
Pupil -0.137 -0.265

Final remarks

- Both instruments are at the top of their rank,
  inherit an experience several decades long,
  and are the product of continuous innovation.
- The ensemble HARPS + NIRPS is the first Extreme-Precision RV instrument ranging from 380nm to 1850nm.
- HARPS is the spectrograph with the longest baseline for LFC calibrations to date.
- Despite the overall complexity the operation scheme is very easy.
- Both instruments have online pipelines that supply final science data products.