The 3.6m telescope in La Silla and its jewels:

HARPS & NIRPS

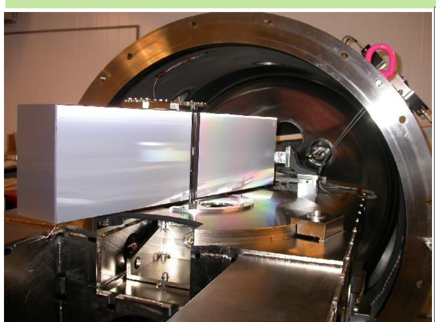
the quest for other worlds

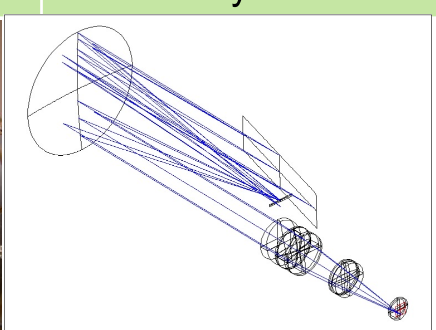
Emanuela Pompei
Gaspare Lo Curto

Basics of HARPS & NIRPS high resolution spectrographs

HARPS

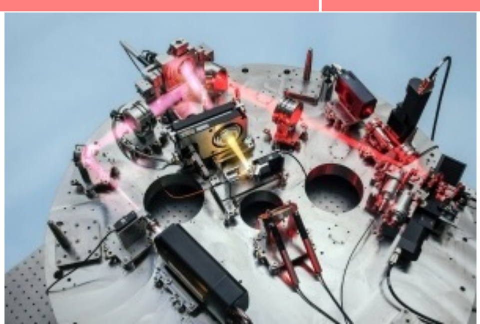
Wavelength coverage	380nm – 690nm
Spectral resolution	115000 (HAM) / 80000 (EGGS)
Light feed	Fiber optics x 2
Aperture on sky	1” (HAM), 1.4” (EGGS)
Detector	2 x E2V, 2K x 4K, 15μm pixels
Environment	Vacuum (<10^{-5} mbars) Ambient (17 ± 0.001K)
Observing modes	Simultaneous reference / Simultaneous sky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

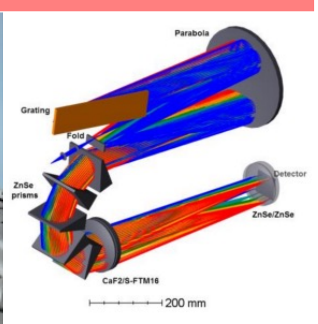




NIRPS

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
Environment	Vacuum (<10^{-5} mbars) Cryogenic (80 ± 0.001K)
Observing modes	Simultaneous reference / Simultaneous sky





A bit of History

Popular Astronomy

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

Astronomical Summaries

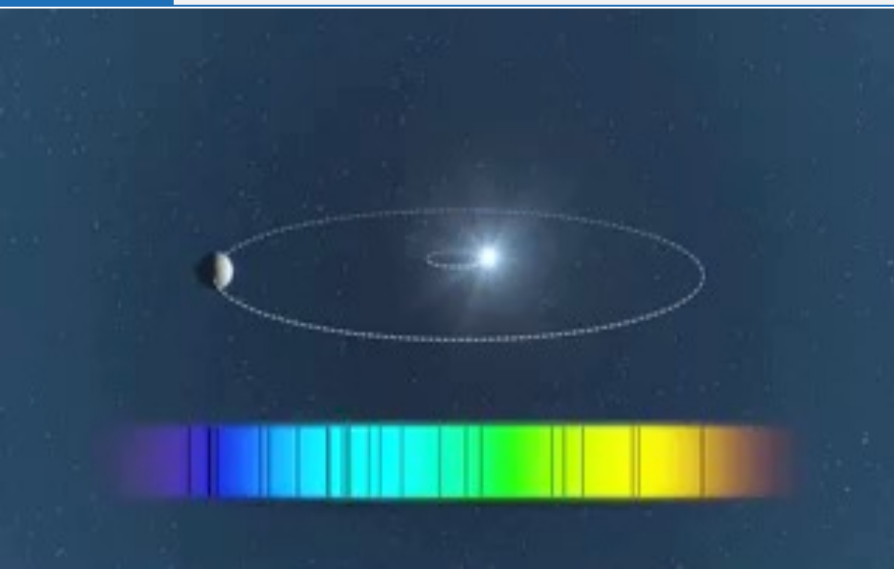
Fifty Years of Progress in Astronomy

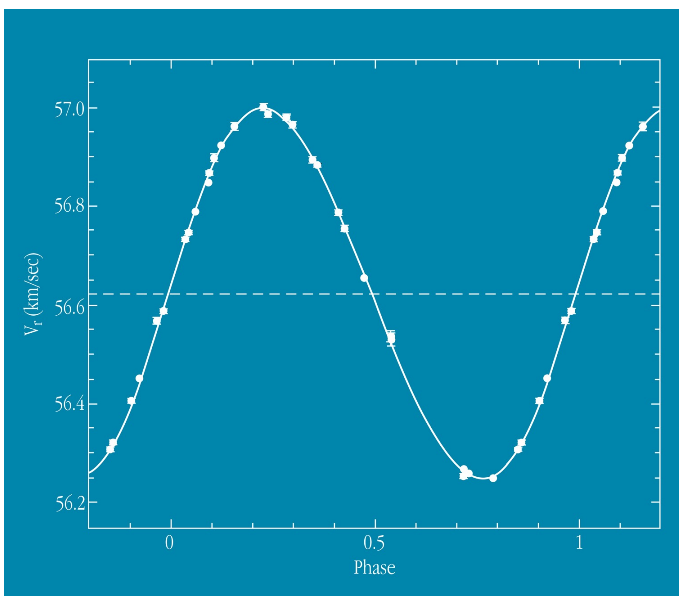
By OTTO STRUVE

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.

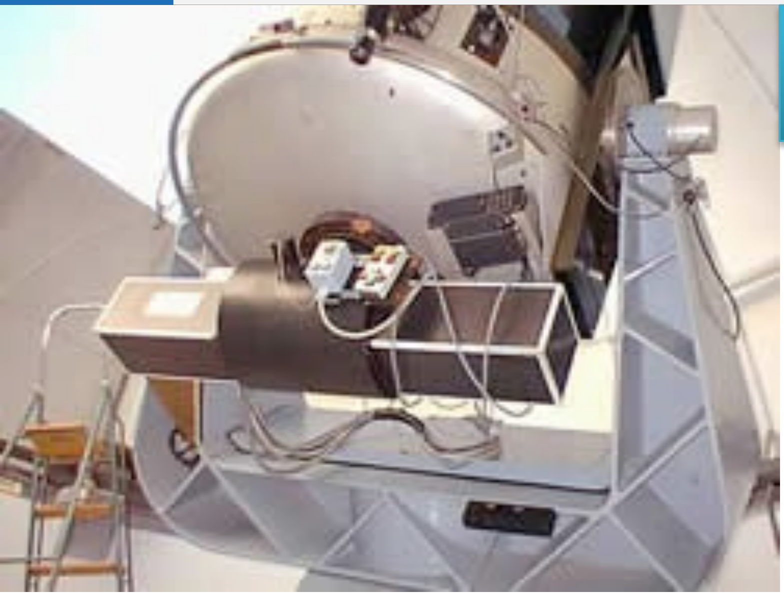
HARPS & NIRPS: how do they detect planets ?





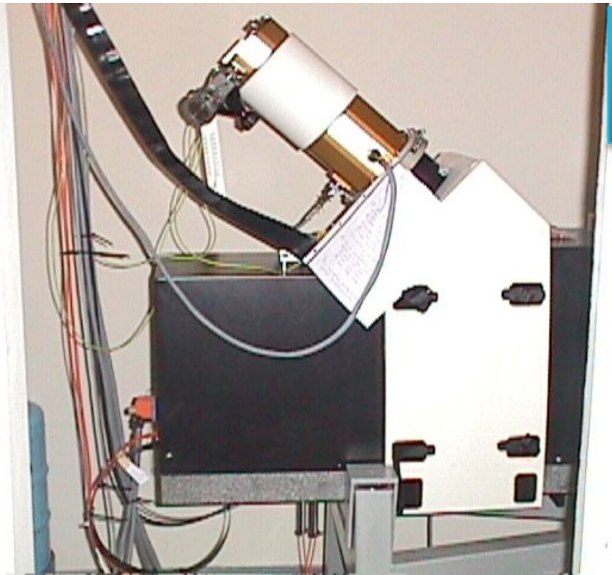
Radial velocity measured via Doppler effect

HARPS & NIRPS
Inherit from a rich past



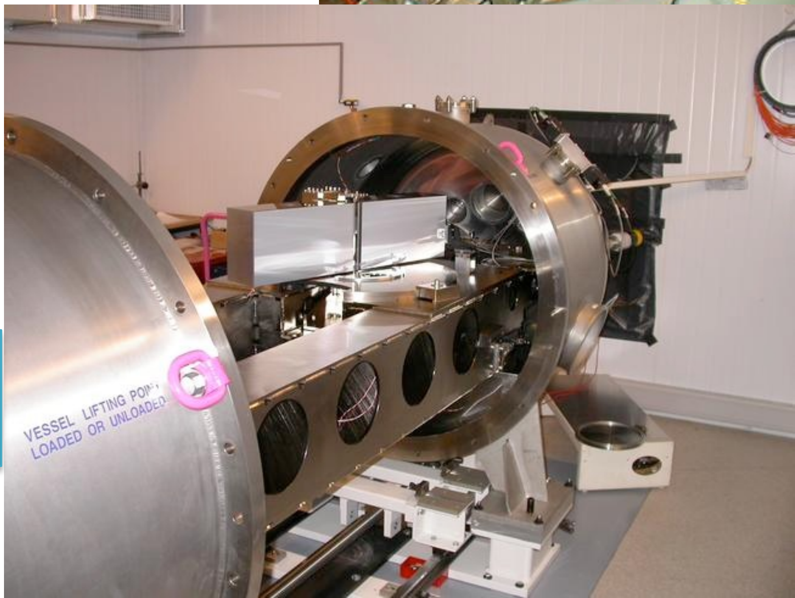
CORAVEL
250m/s

ELODIE
10m/s



CORALIE
5m/s

HARPS
1m/s

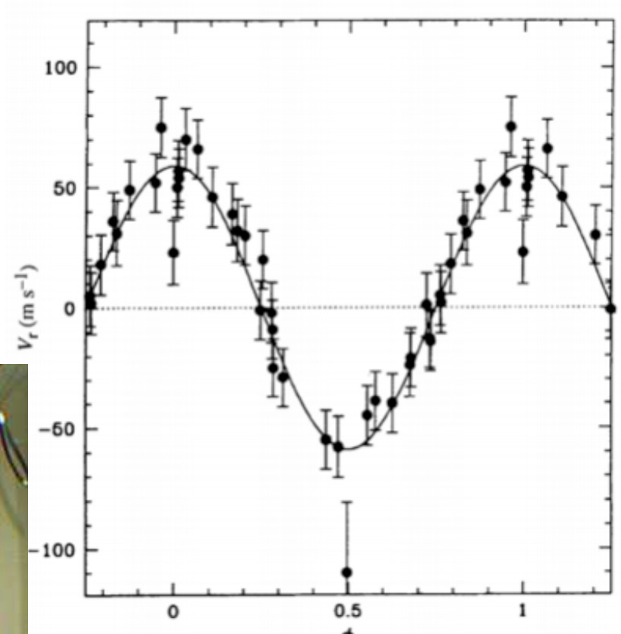


A Jupiter-mass companion to a solar-type star

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.



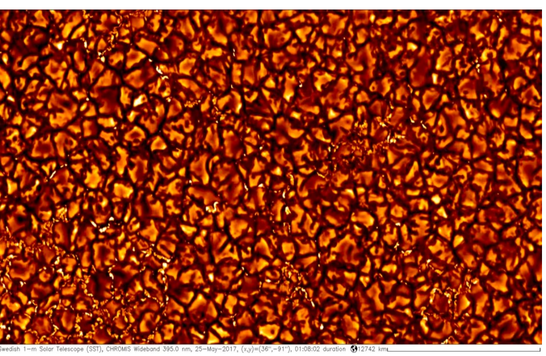
Nobel prize in Physics 2019

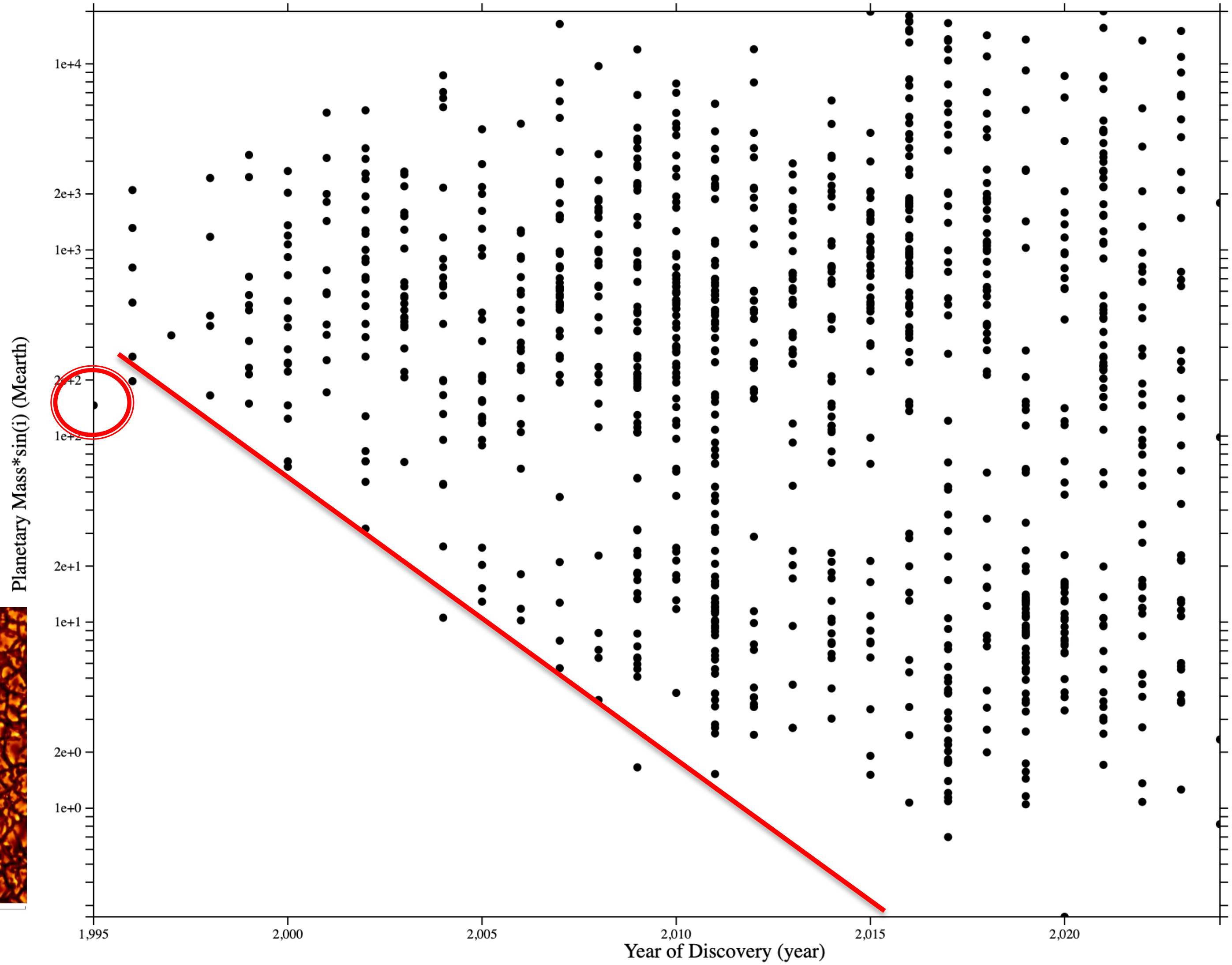
Planets detections (RV only)

Moore's law for Exo-planets ?

Flattening ?

There is more than just the planet…





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

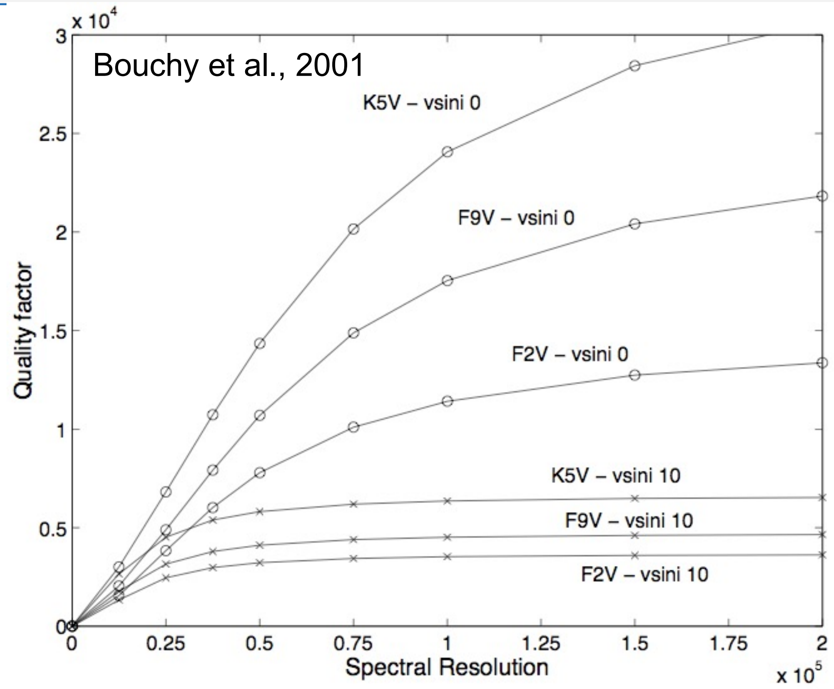
- Jupiter @ 5 AU : 12.7 m s^{-1}
- Super-Earth (5 $M_\oplus$) @ .1 AU : 1.4 m s^{-1}
- Super-Earth (5 $M_\oplus$) @ 1 AU : 0.45 m s^{-1}
- Earth @ 1 AU : 9 cm s^{-1}

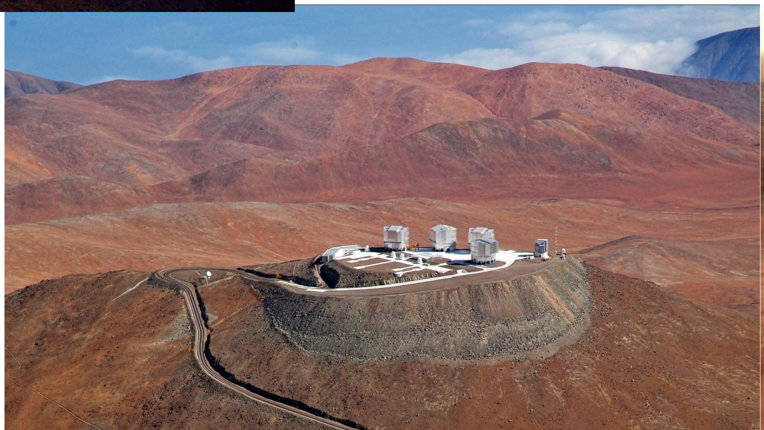
Orbiting a Solar-type star

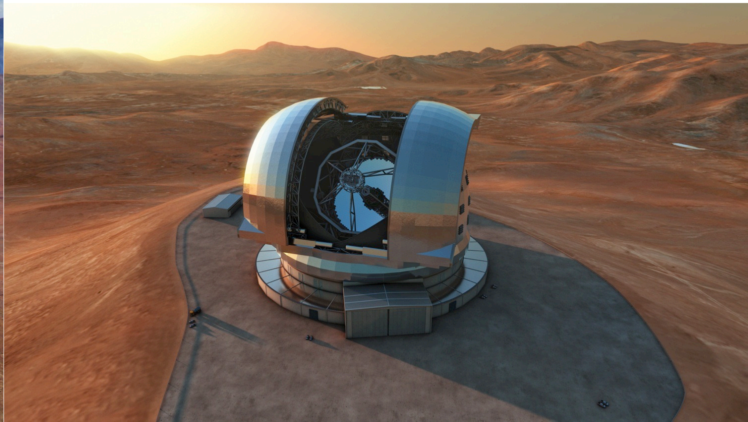
Constraints on spectrograph design

- **Photon noise limit:**

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





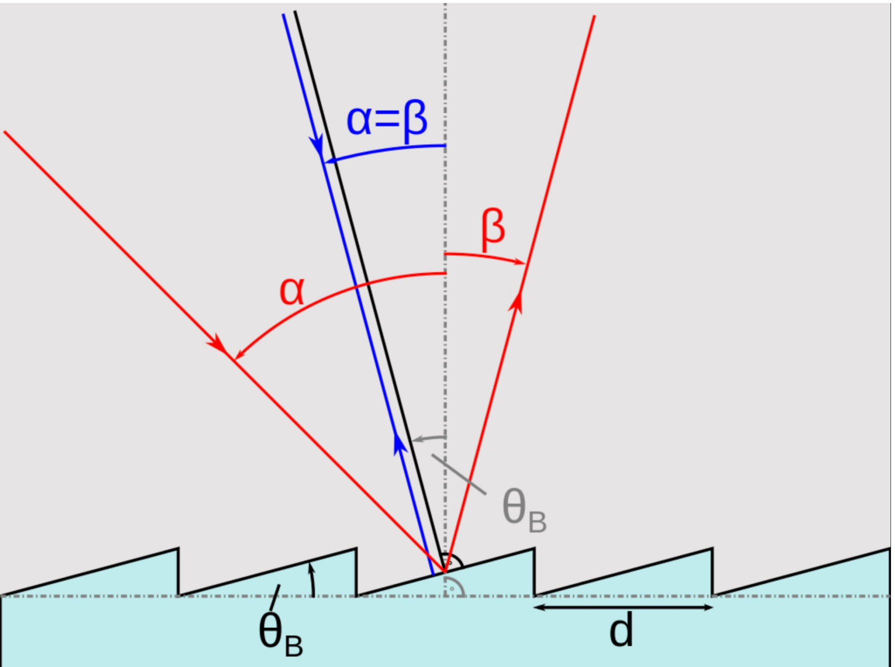


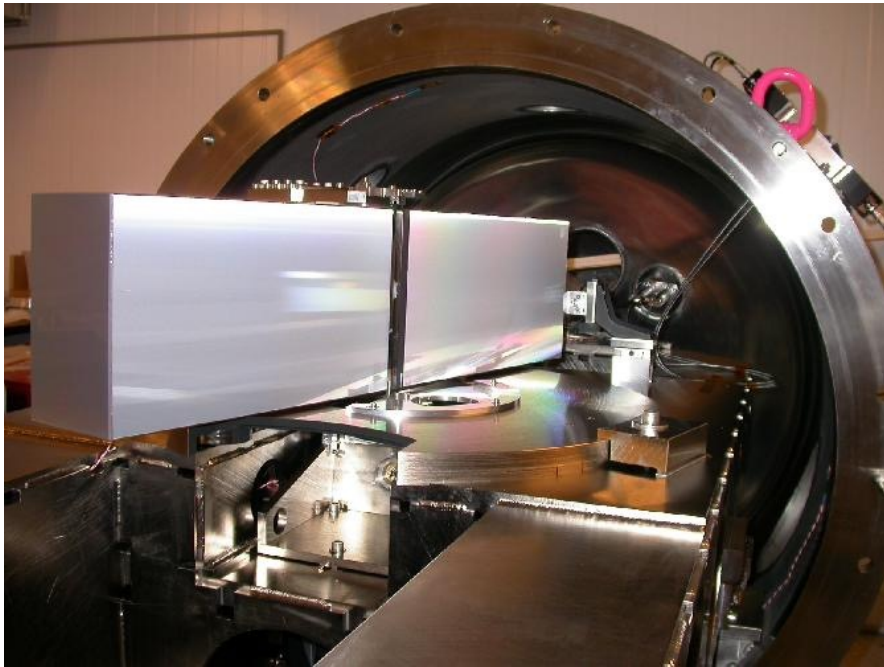
Constraints on spectrograph design

- **Spectral resolution:**

R = λ/Δλ =

2*tan(blaze)*beam/(slit"*M1)





Constraints on spectrograph design

☆ Metrological stability

Silicon lattice constant: 0.54nm

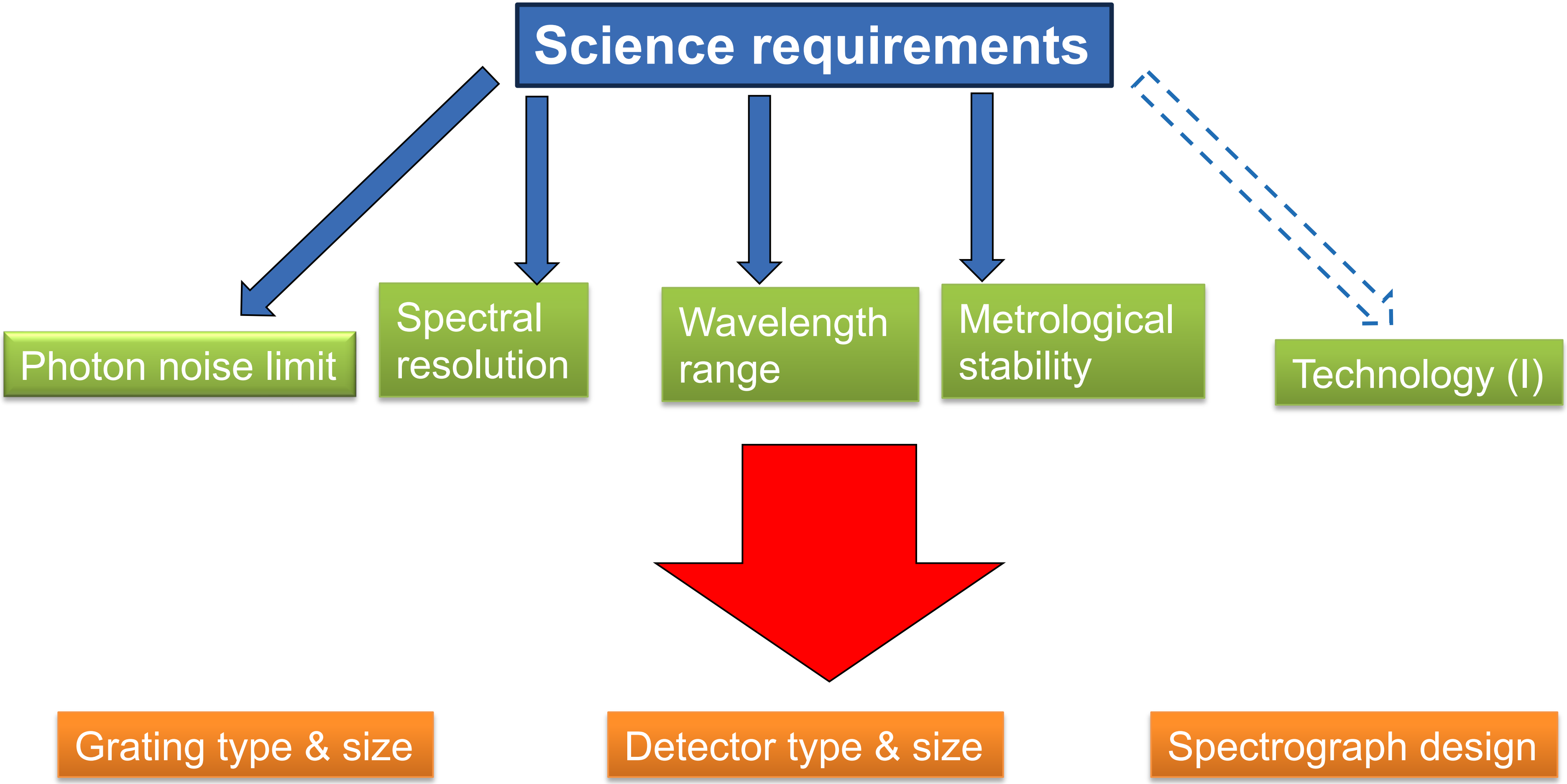
Planet	Mass (M_{Jup})	K (m/s)	HARPS/NIRPS Stability (nm)	ESPRESSO stability (nm)
Mercury	1.74×10^{-4}	0.008	0.14	0.25
Venus	2.56×10^{-3}	0.086	1.6	2.7
Earth	3.15×10^{-3}	0.089	1.6	2.8
Mars	3.38×10^{-4}	0.008	0.14	0.25
Jupiter	1.0	12.4	227	388
Saturn	0.299	2.75	50	86
Uranus	0.046	0.297	5.4	9.3
Neptune	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

☆ 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.

Cooking the instrument (I)

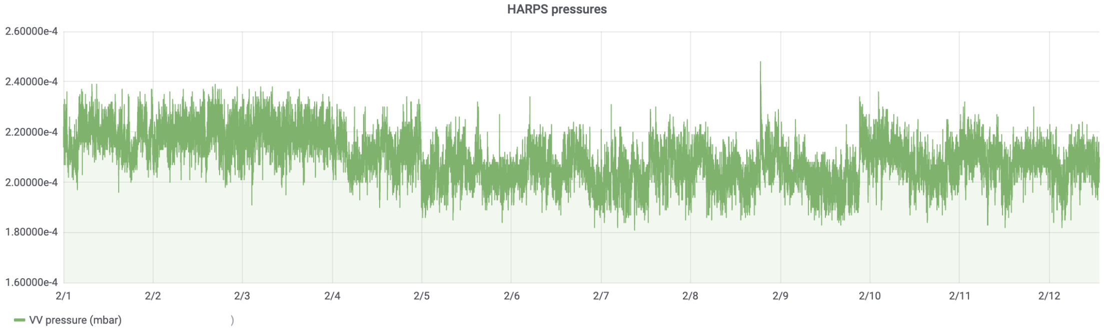


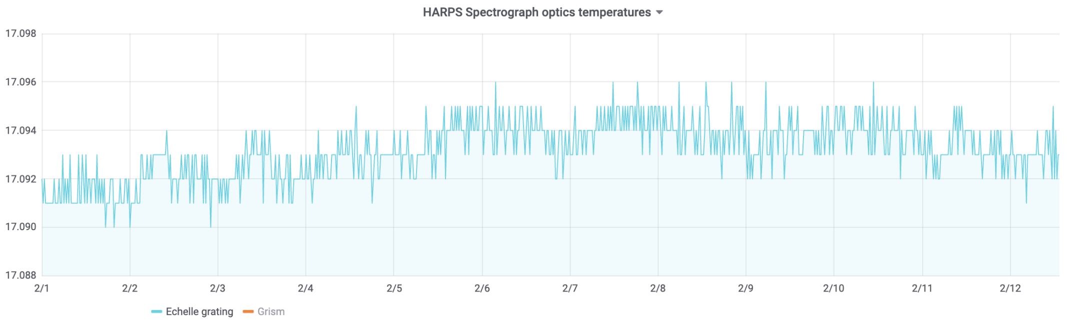
Metrological stability I: spectrograph

No moving parts inside the spectrograph

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

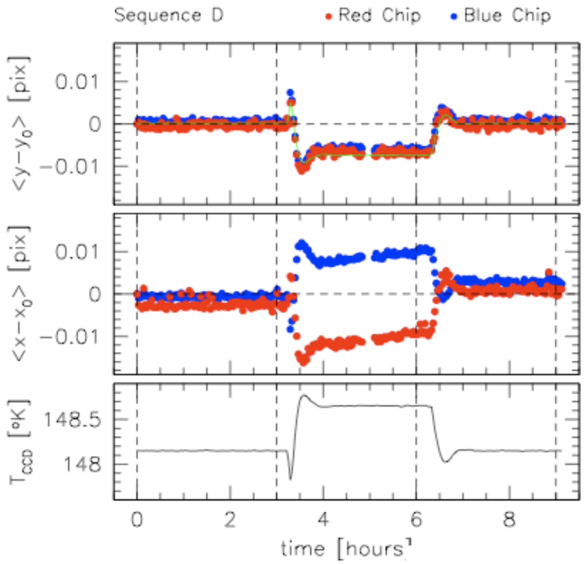
Strict temperature control (grating RMS <1mK / day)

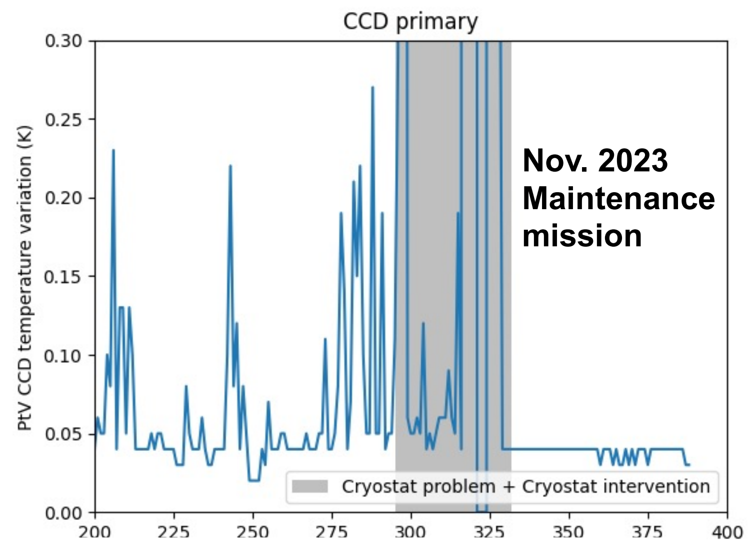


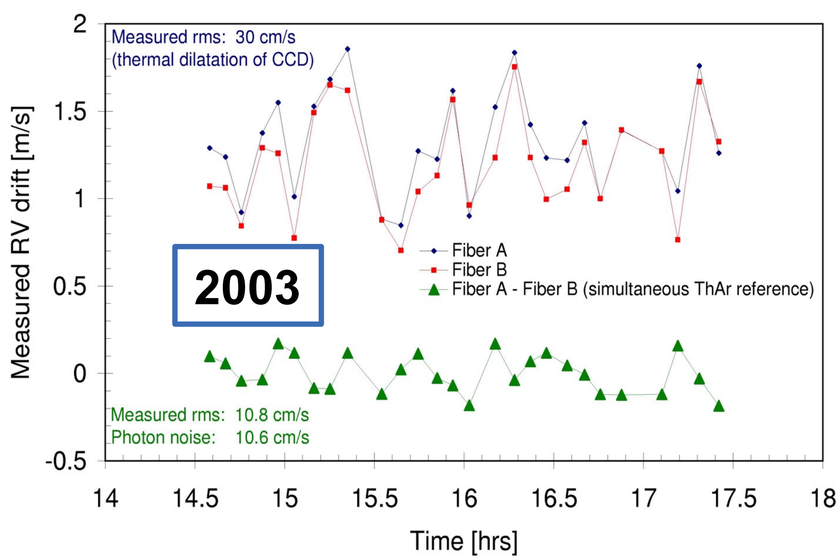


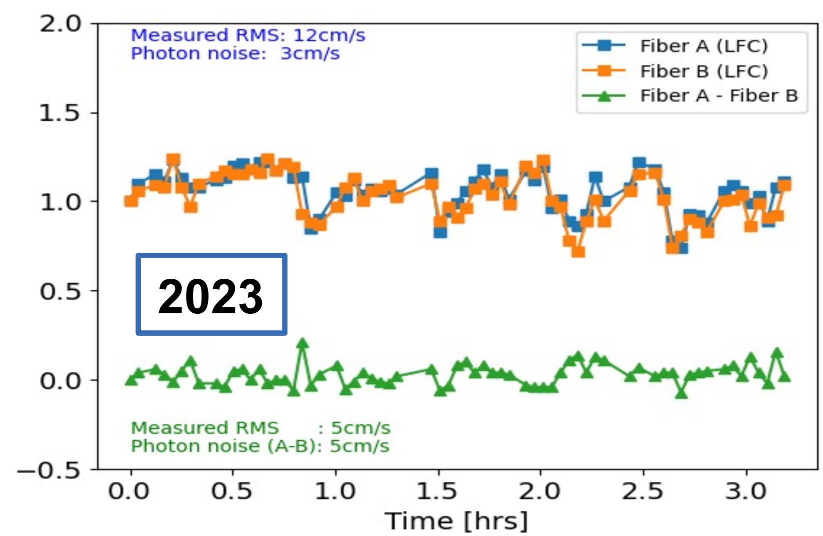
Metrological stability II: Detector Thermal stability

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.









Metrological stability III: light injection

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

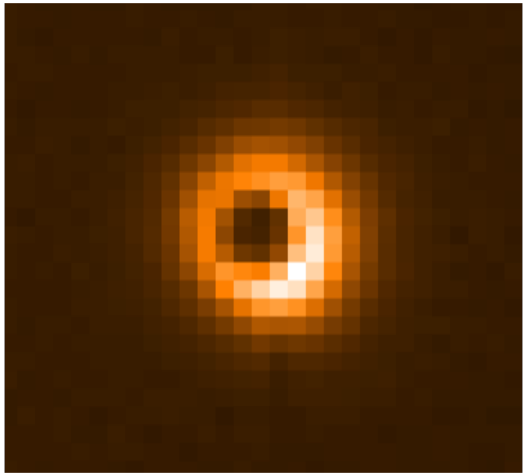
Use **fiber optics** to increase stability of the light injection

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.

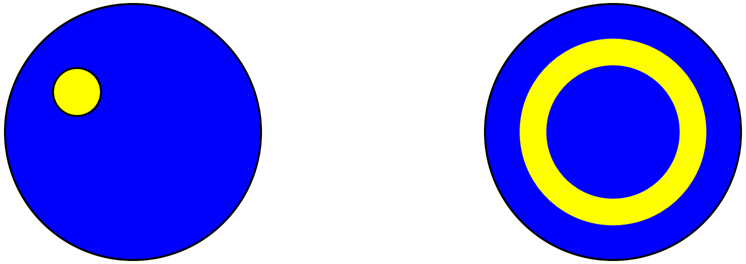
Guiding (without octagonal fibers)

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

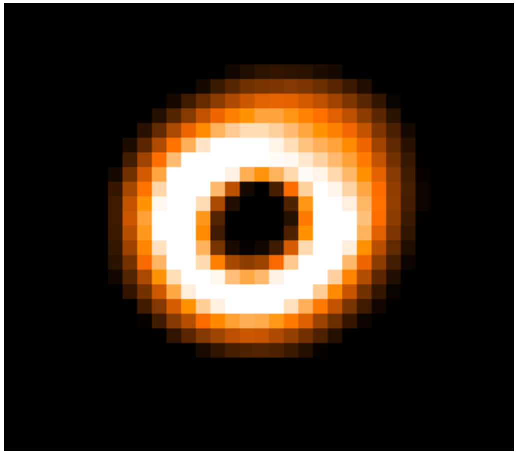


<u>Bad centering</u>

Fiber entrance | Fiber exit

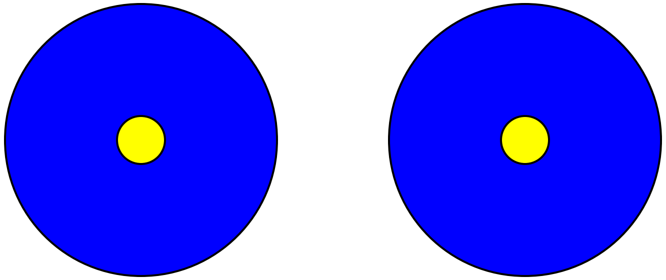


“Good” guiding, 0.1” RMS, ~30 cm/s contribution to RV



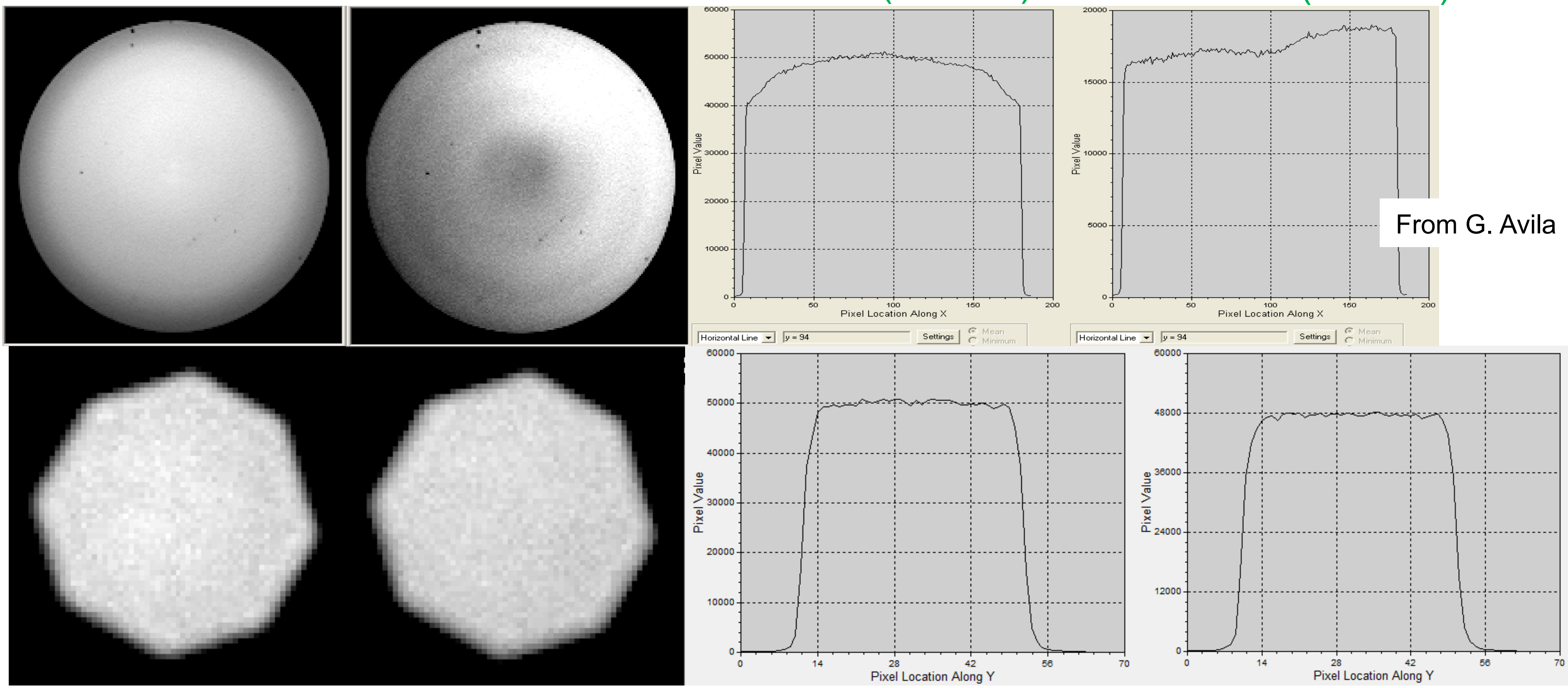
<u>Good centering</u>

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>

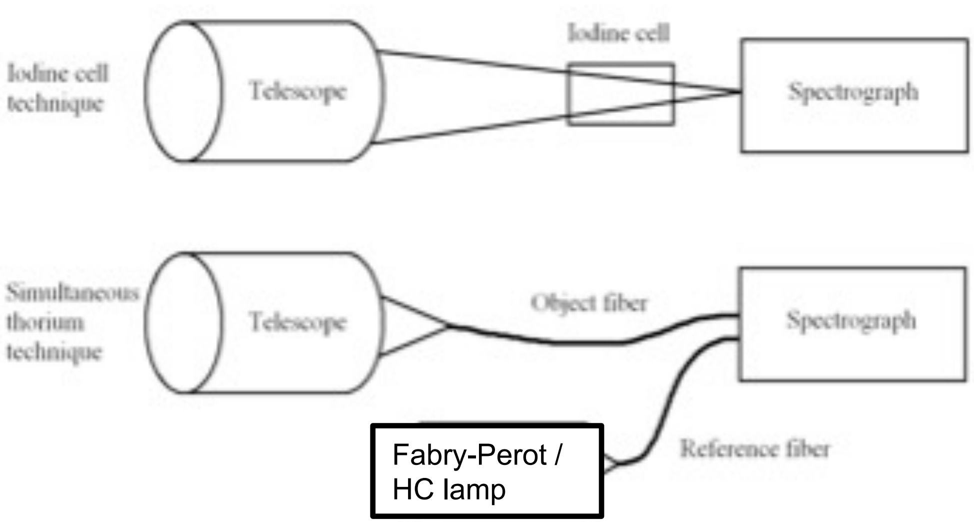
Metrological stability IV: track the unavoidable

Instrument variations are unavoidable…

… track them !

⇒Simultaneous calibration

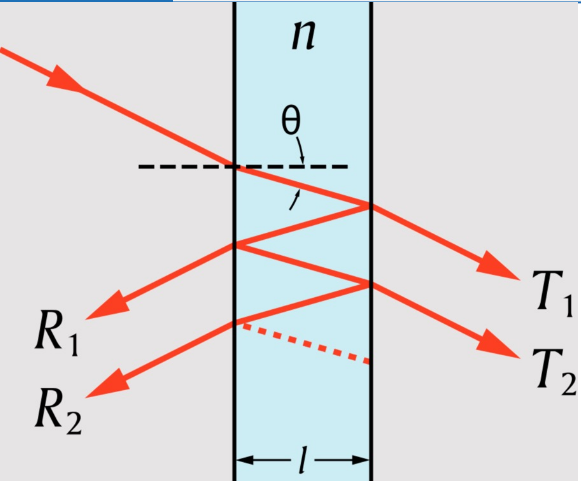
⇒Absorption cells



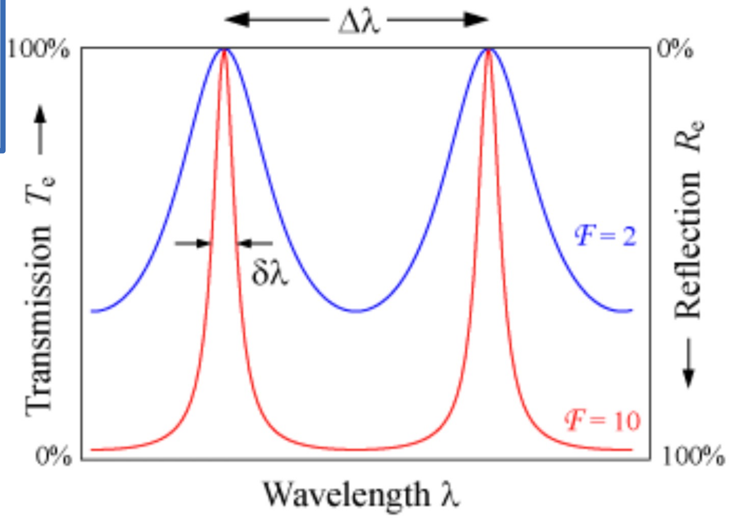
The HARPS experience:

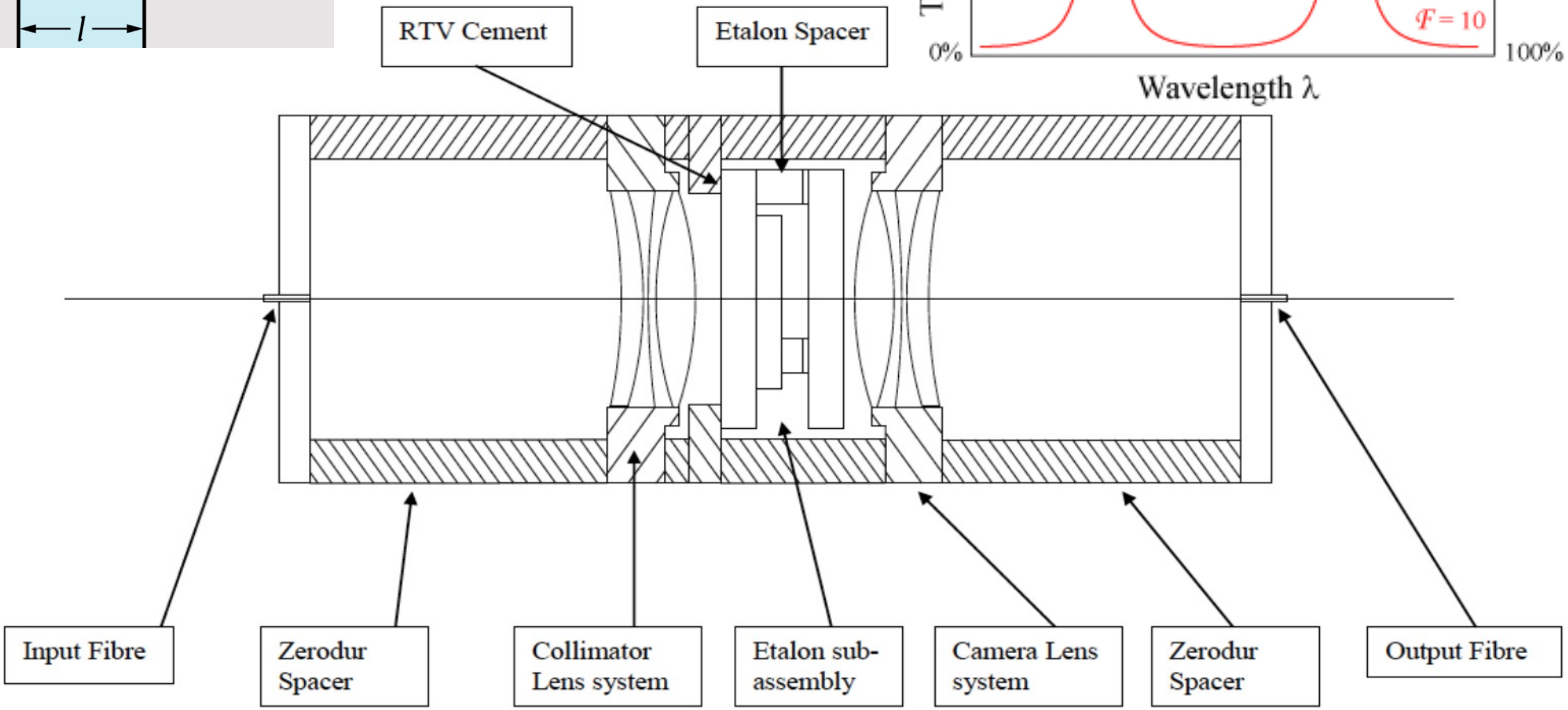
- the instrument drift is generally less than 0.5m/s overnight.
- the RMS of the temperature is less than 1mK in 24 hours
- a 1m/s RV drift was measured simultaneously to a 7mK temperature variation at the echelle

Fabry-Perot units



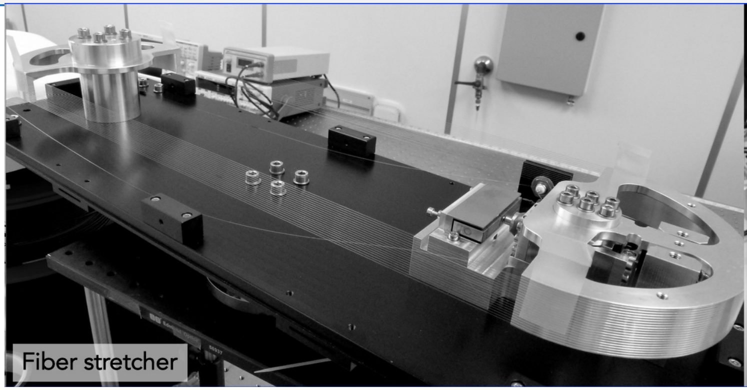
$$\delta = phase\ difference = \left(\frac{2 \cdot \pi}{\lambda}\right) 2 \cdot n \cdot l \cdot \cos\theta$$



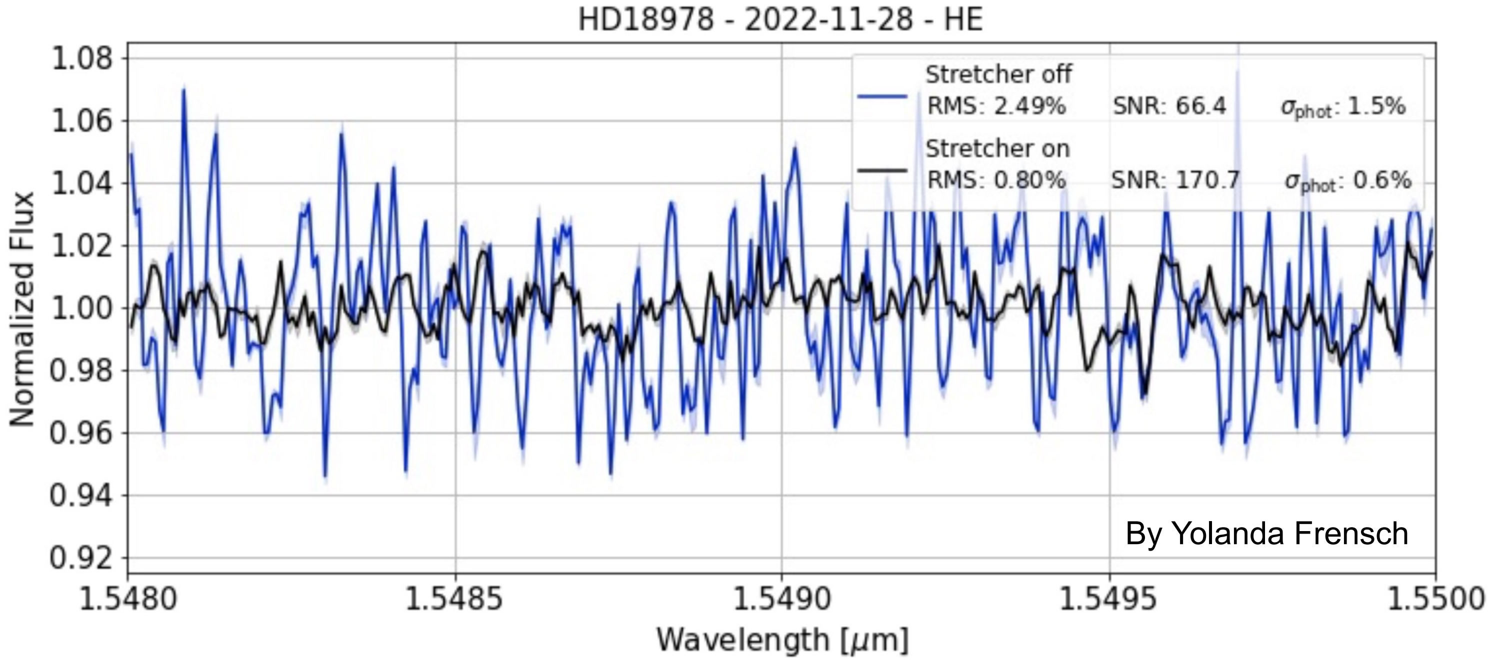


Modal noise

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.

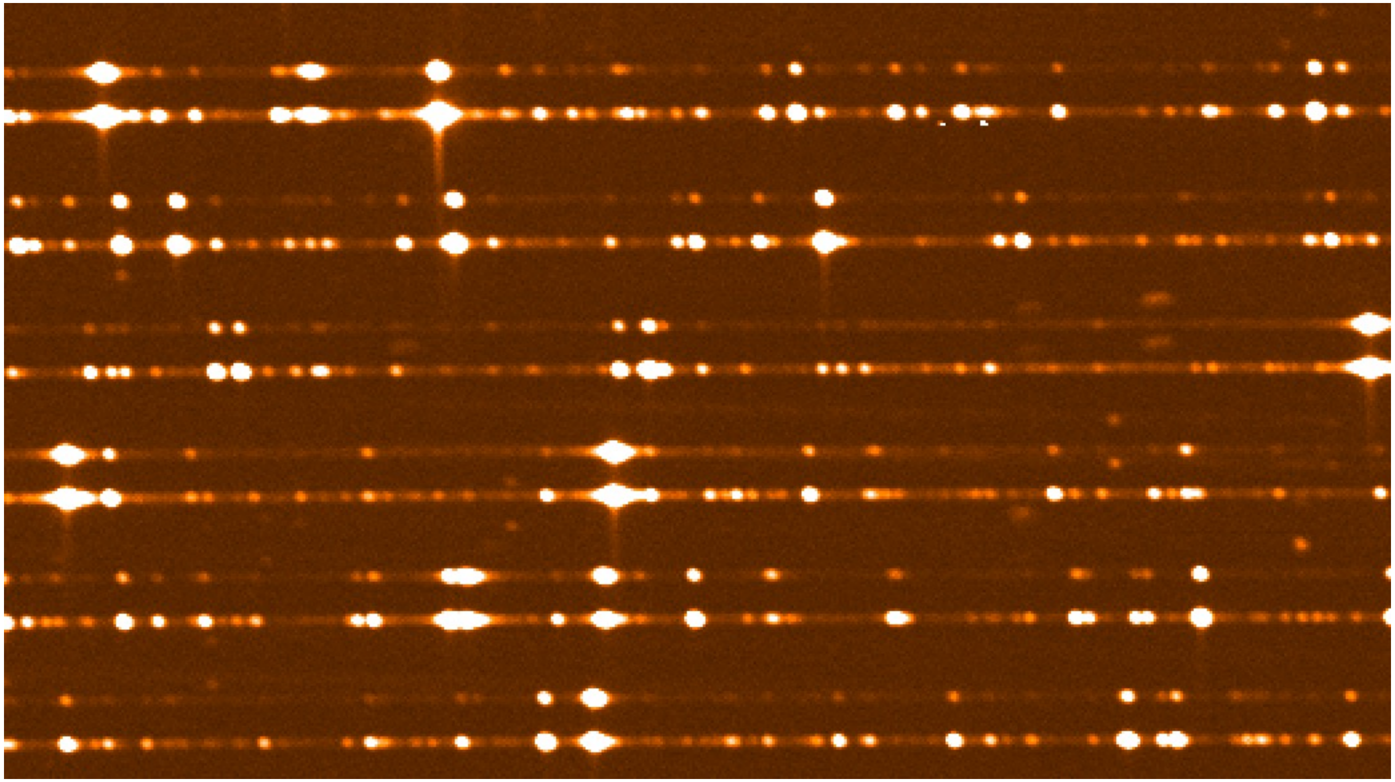


This is why NIRPS (but not HARPS) has a fiber-stretcher to “scramble” the modes and reduce the measurable effect of the modal noise.



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

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

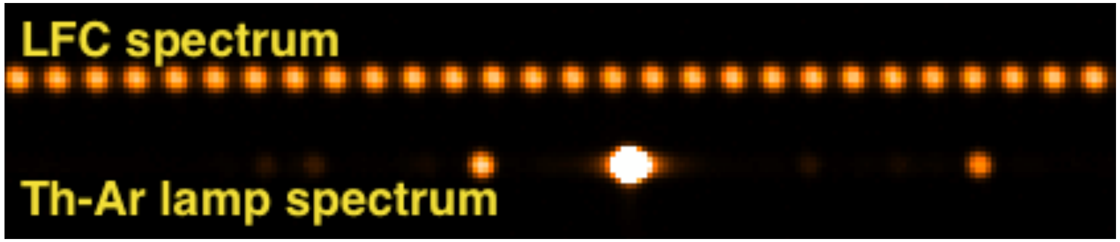
The “ideal calibrator”

- Many lines, equally spaced

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

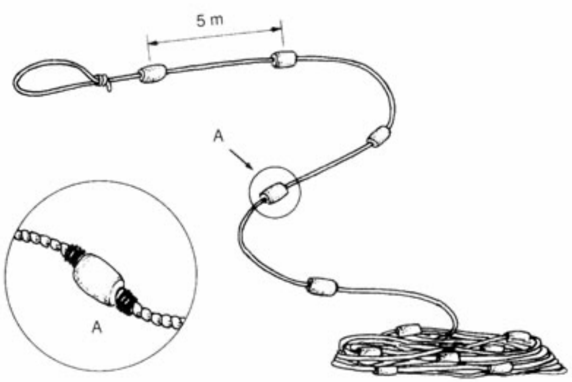
- Lines are not resolved ➔ the instrumental line profile is directly measurable.

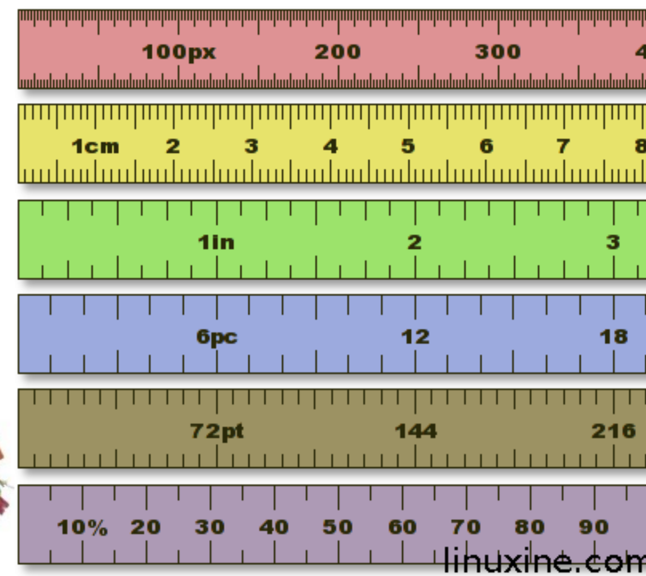
Laser Frequency Combs



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

LFC lines equation

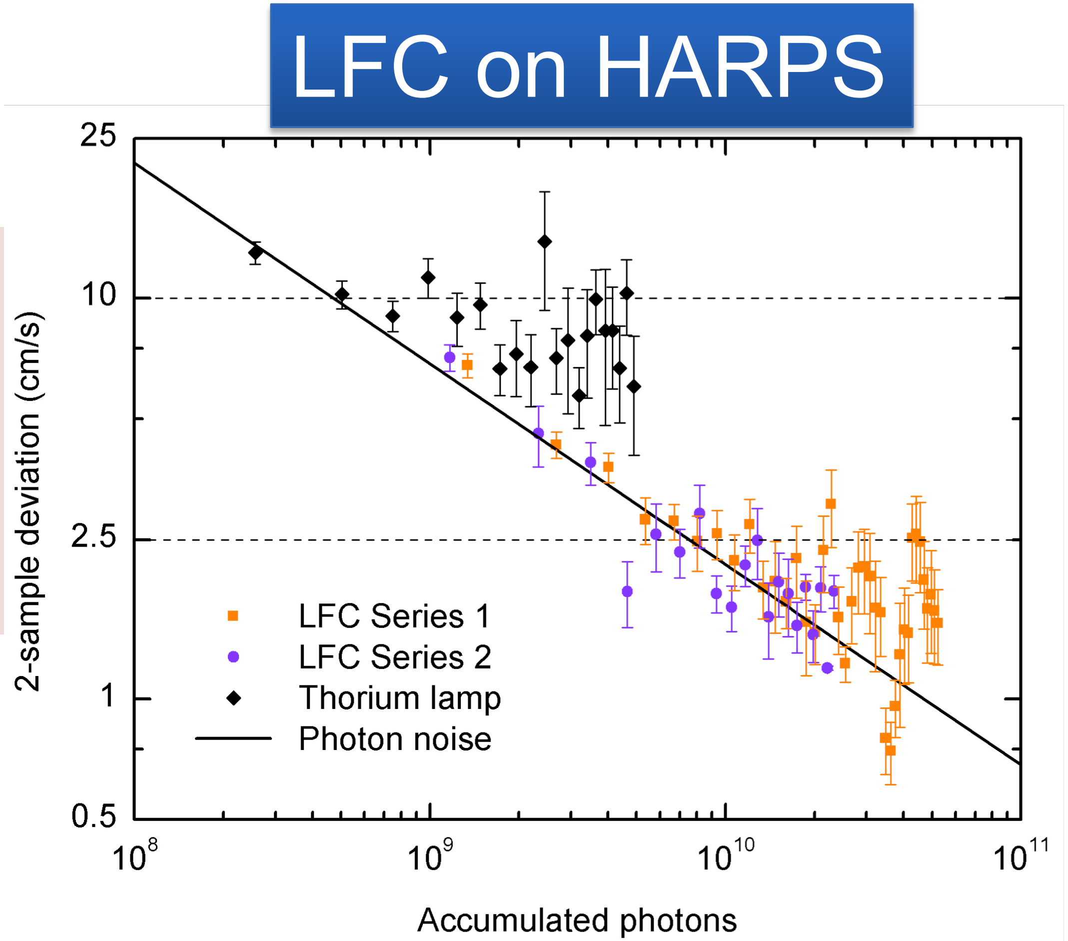




Laser Frequency Comb

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

(Wilken et al., Nature, 2012)



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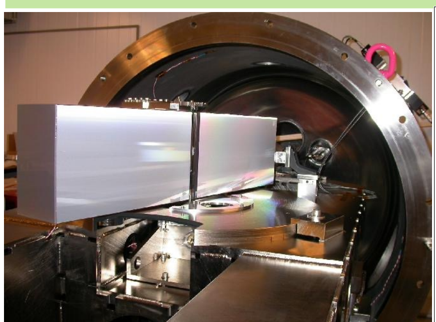
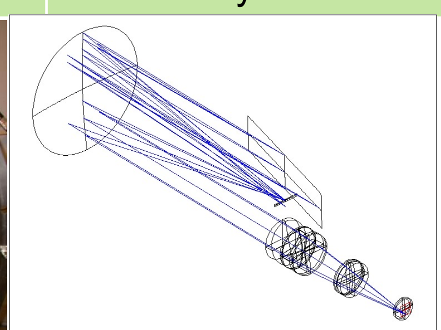

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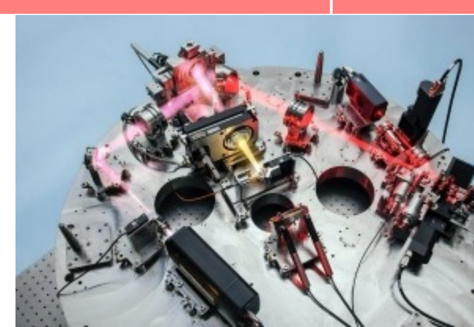
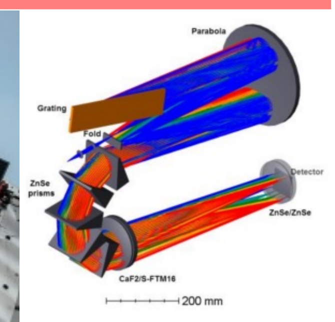
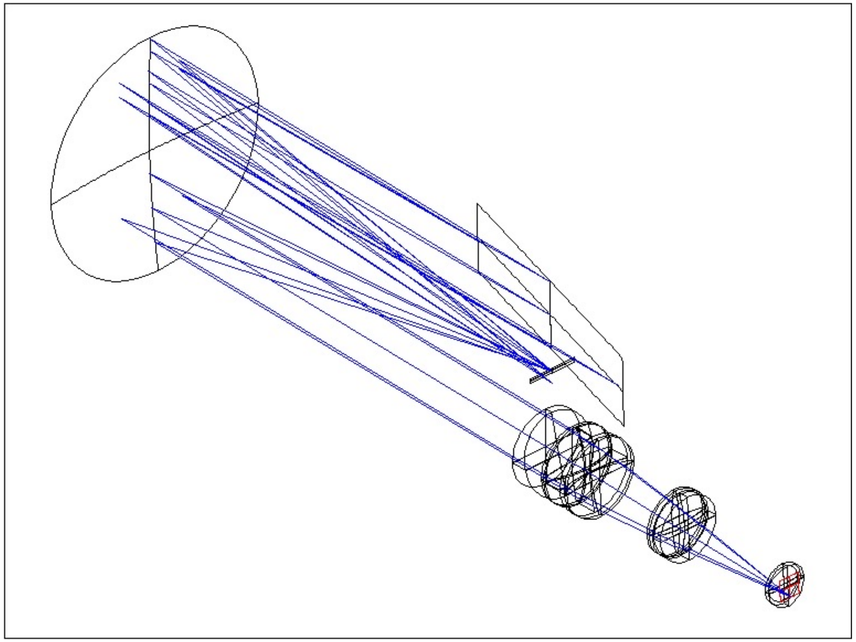
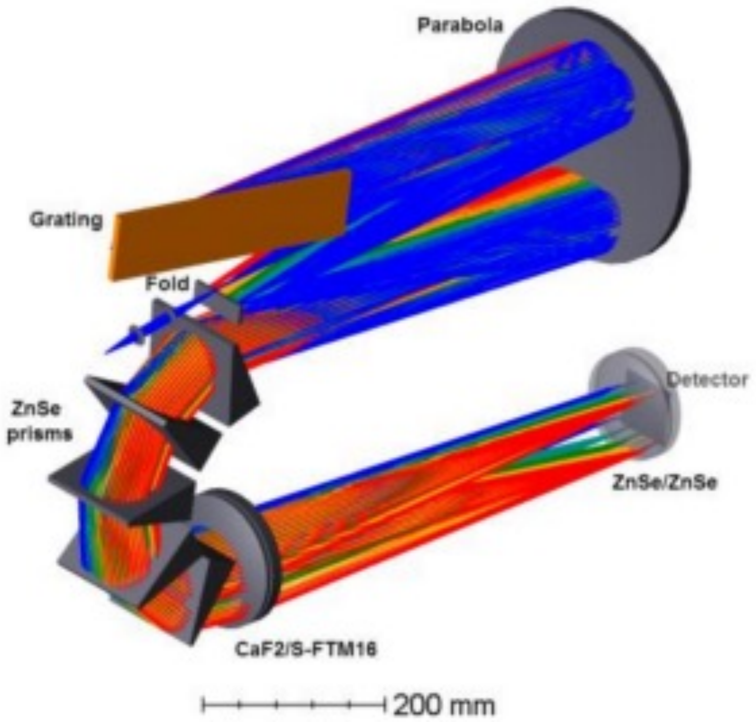



Optical design

HARPS

NIRPS





White-pupil spectrographs with triple-pass collimator to minimize spectrograph size

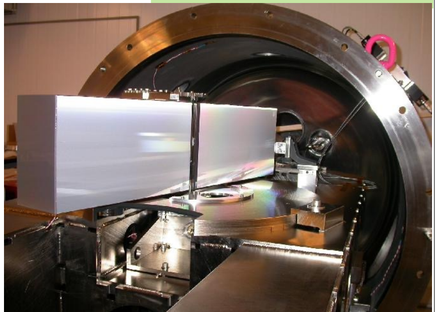
Basics of HARPS & NIRPS high resolution spectrographs

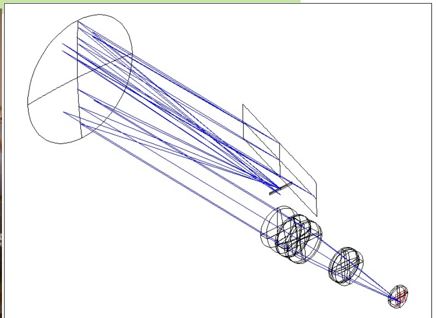
HARPS

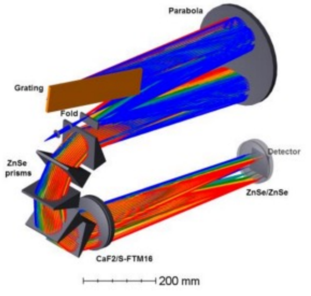
Tip-tils guiding
Octogonal fibers
Double scrambler
Exposure meters
Fabry-Perot for simultaneous reference
ThAr lamp for Wavelength calibration
LFC

NIRPS

Adaptive optics
Octogonal fibers
Fiber stretcher
Double scrambler
Exposure meters
Fabry-Perot for simultaneous reference
U Ne lamp for Wavelength calibration
LFC







Constraints on spectrograph design

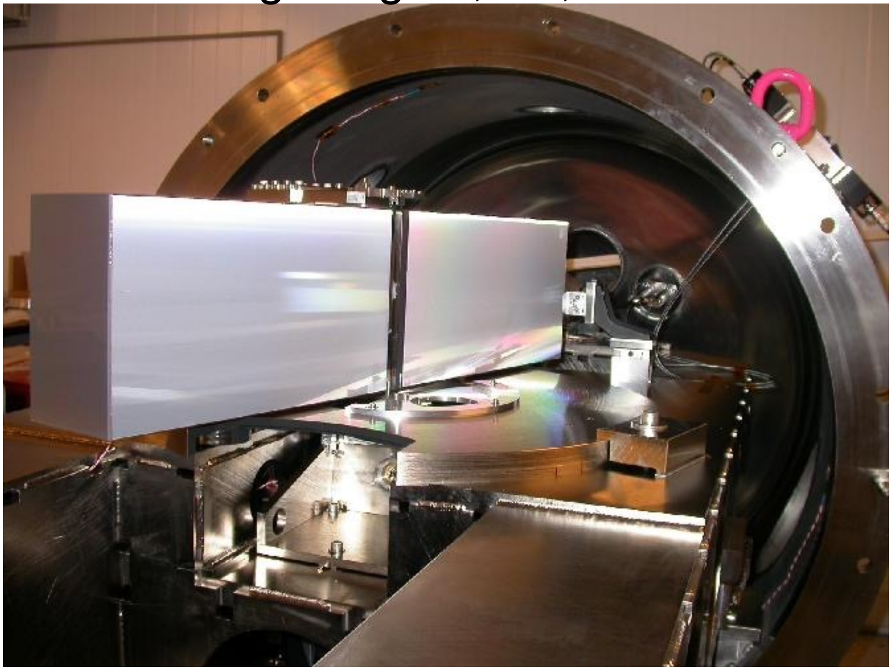
☆ **Spectral resolution:**

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

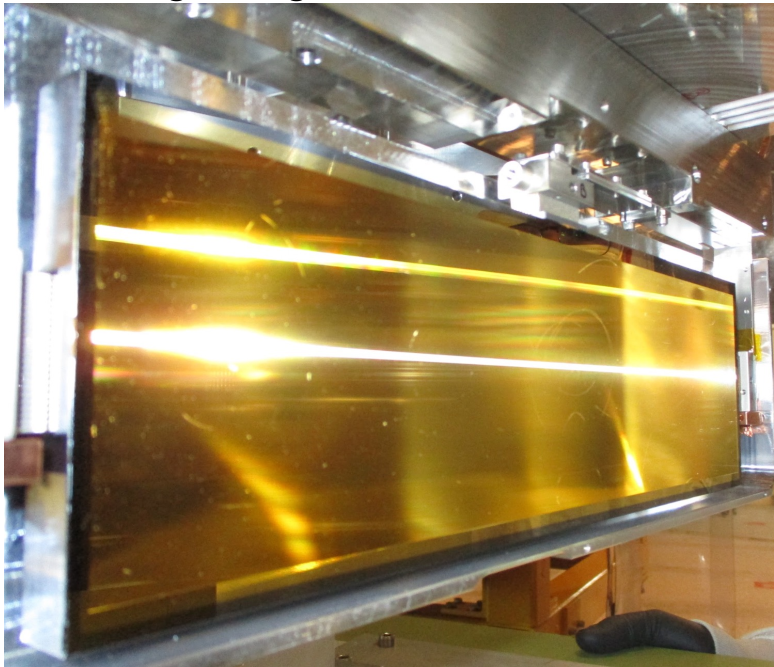
2*tan(blaze)*beam/(slit"*M1)

"Small" beam size thanks to A.O.

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

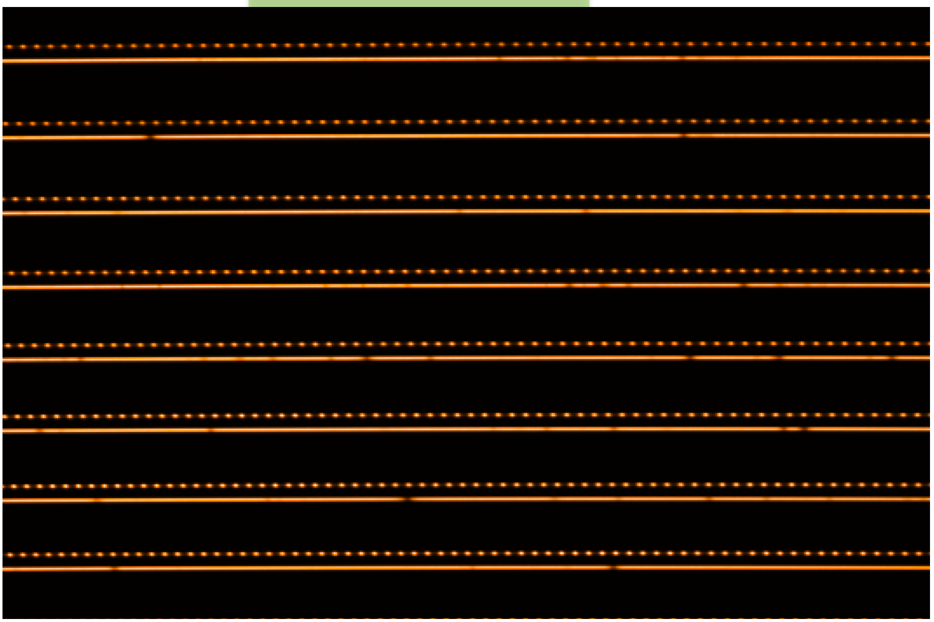


NIRPS grating: Au, R4, 9cm x 32cm

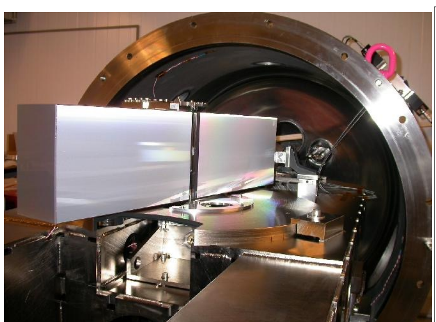


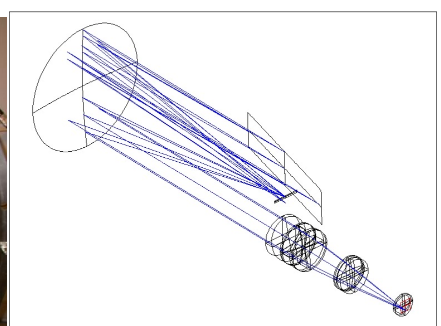
Basics of HARPS & NIRPS high resolution spectrographs

HARPS

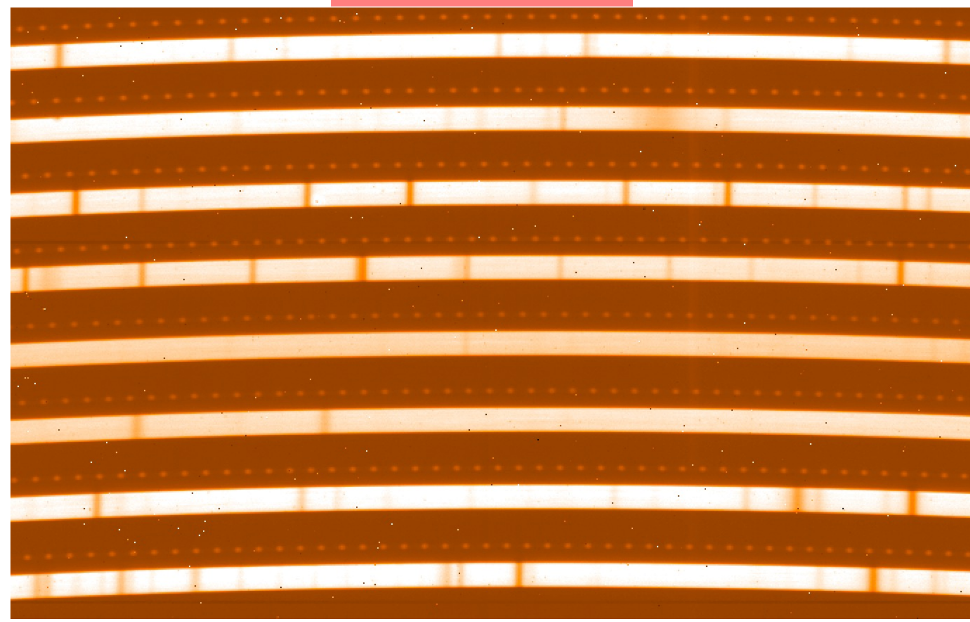


CCD: total number of counts

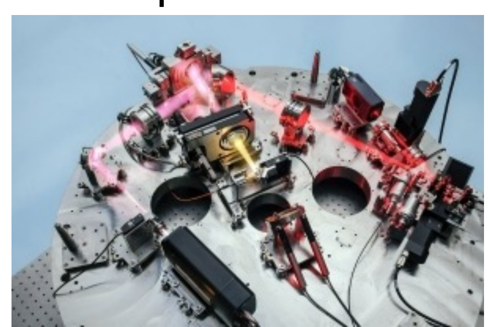


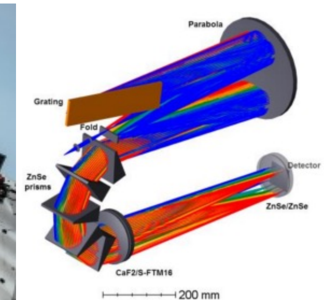


NIRPS

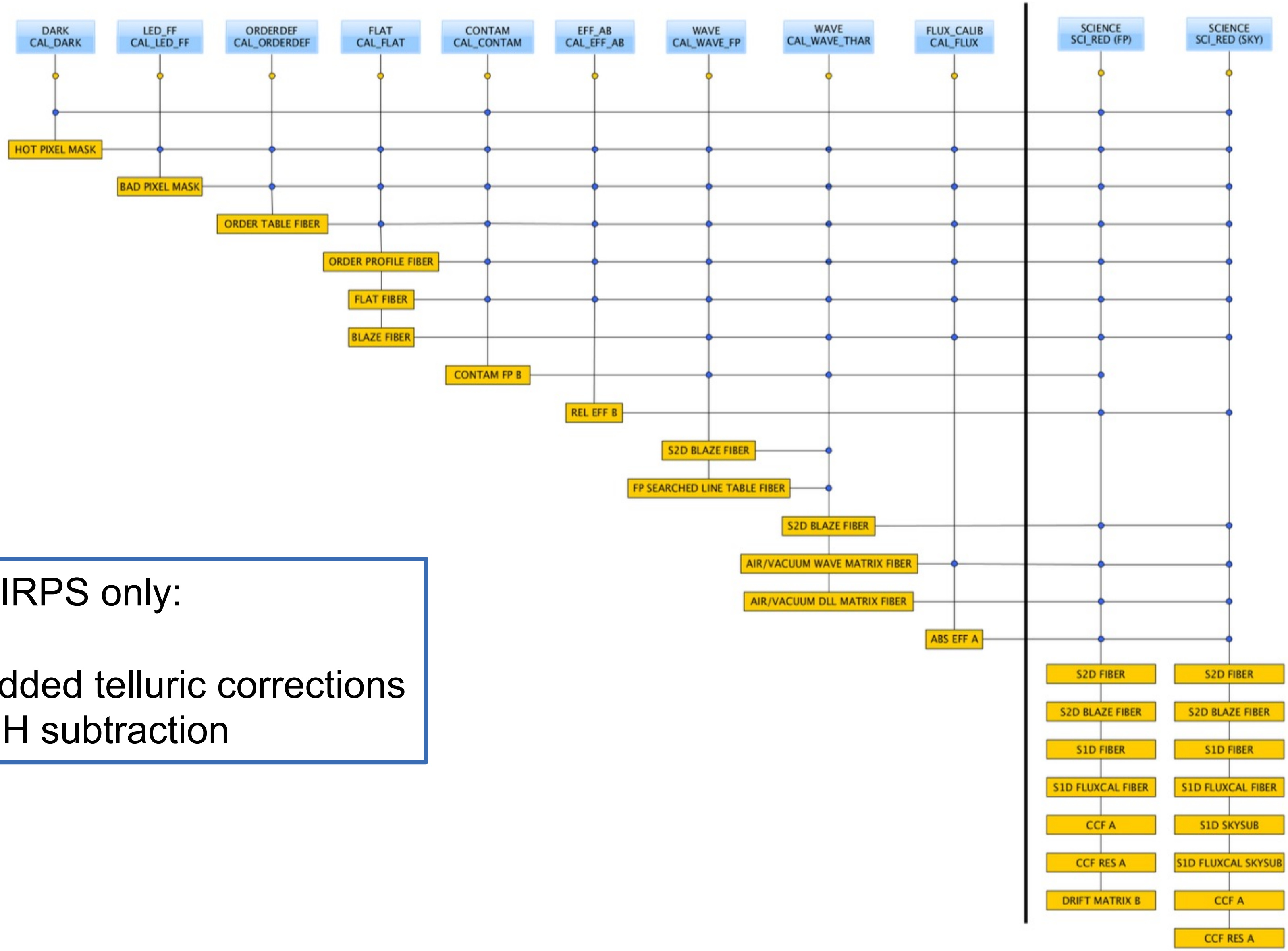


Up-the-ramp sampling: counts per second
5.573s/sample





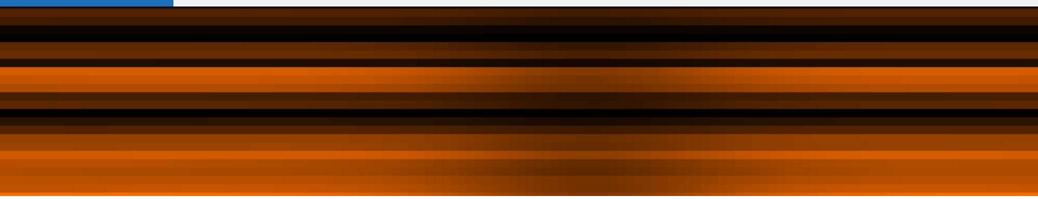
Pipeline

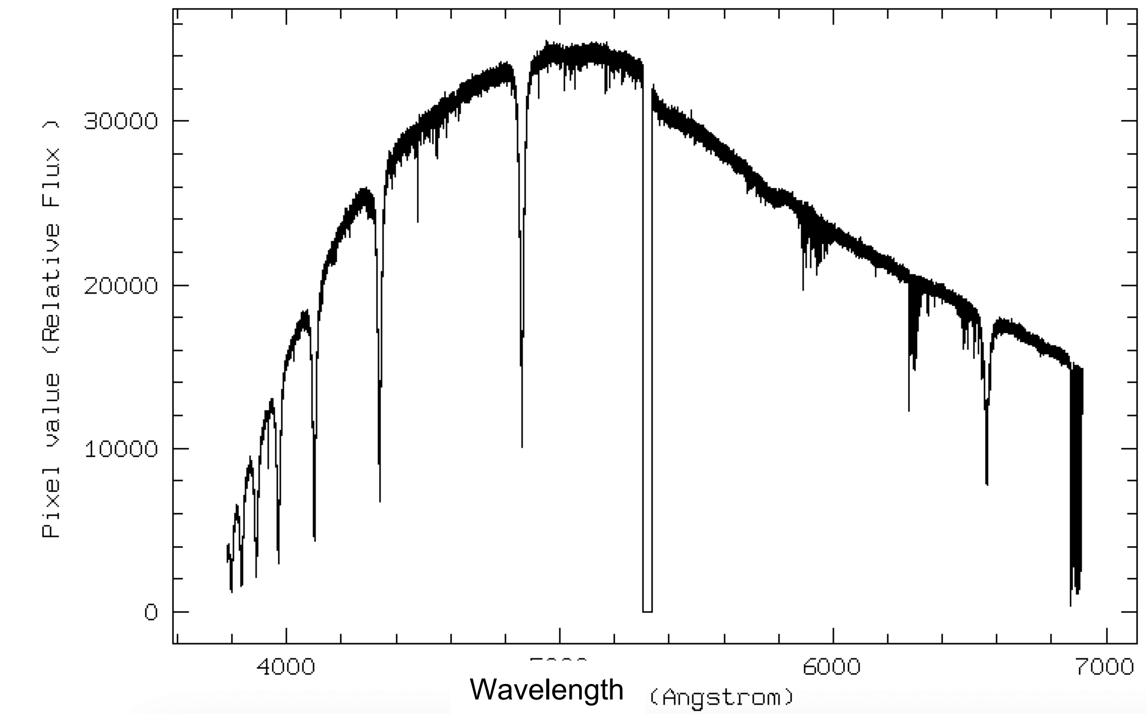


NIRPS only:

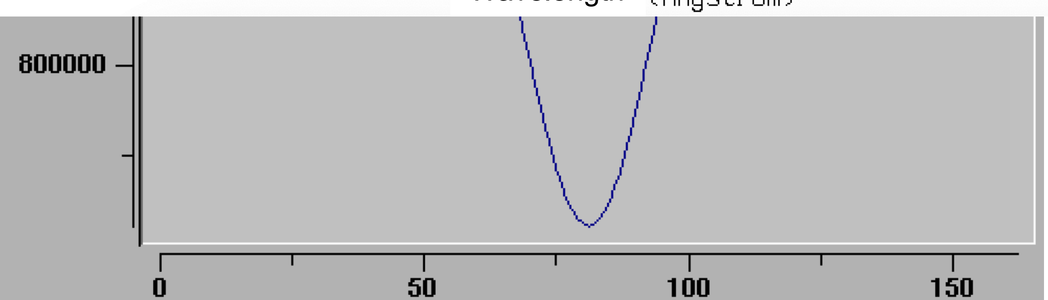
Added telluric corrections
OH subtraction

Pipeline

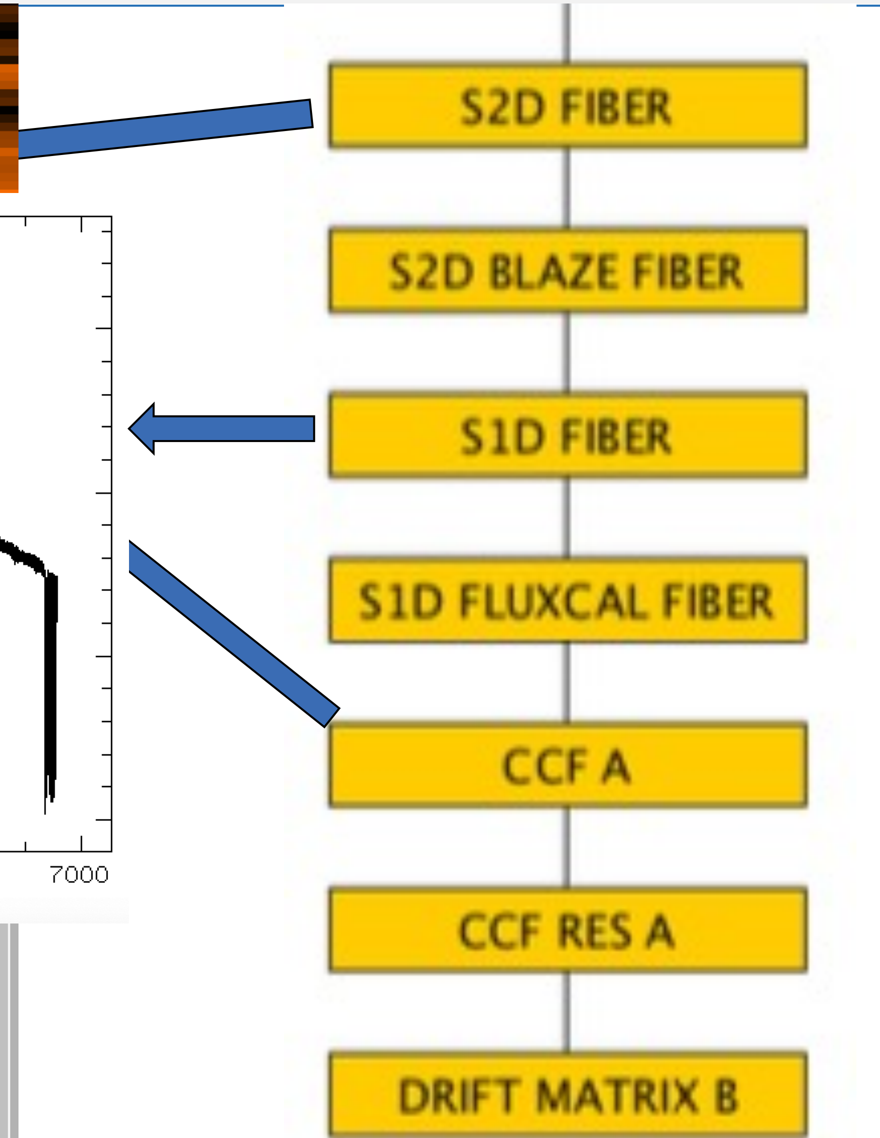




Pixel value (Relative Flux)
30000
20000
10000
0
4000
6000
7000
Wavelength
(Angstrom)



800000
0
50
100
150

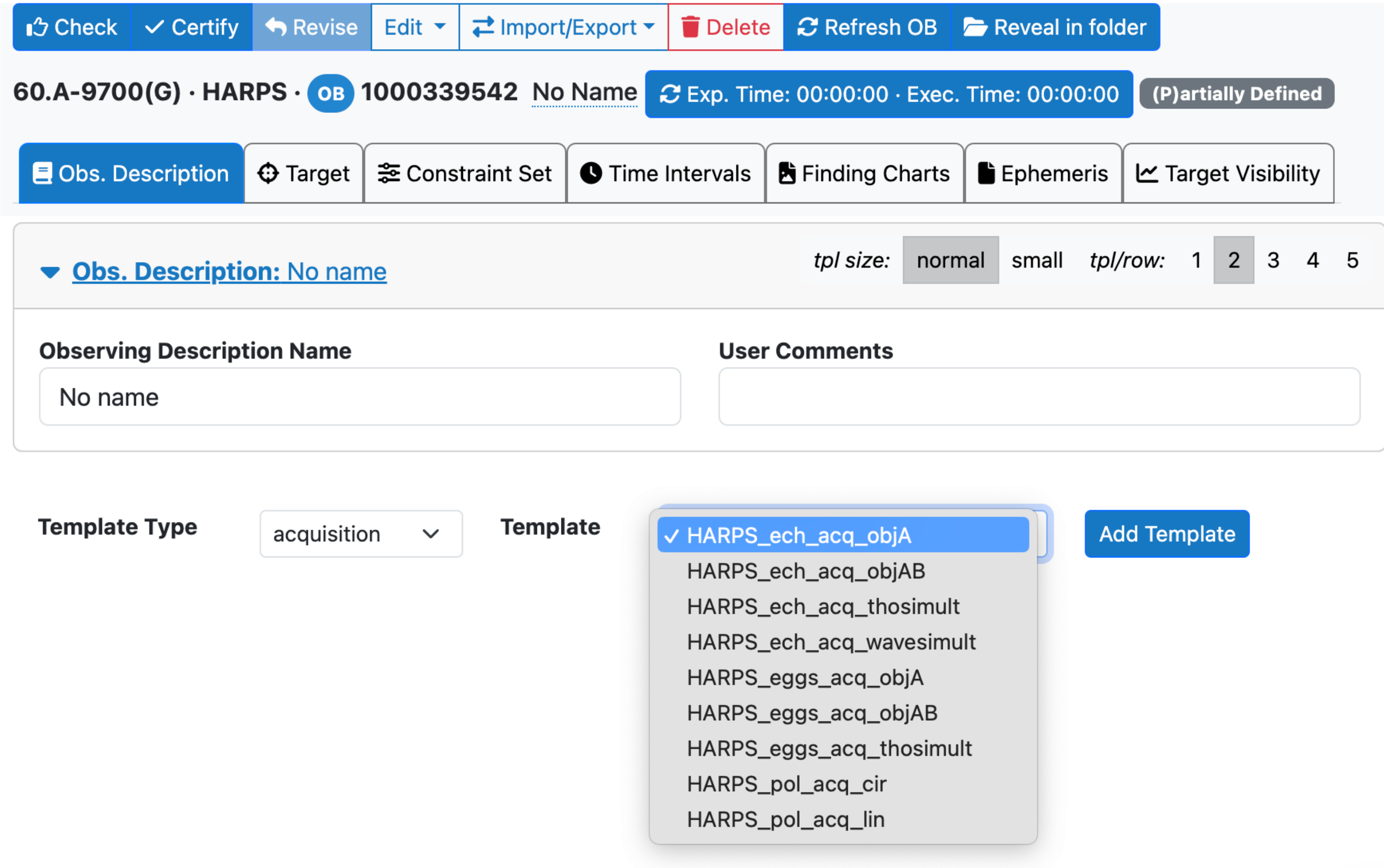


S2D FIBER
S2D BLAZE FIBER
S1D FIBER
S1D FLUXCAL FIBER
CCF A
CCF RES A
DRIFT MATRIX B

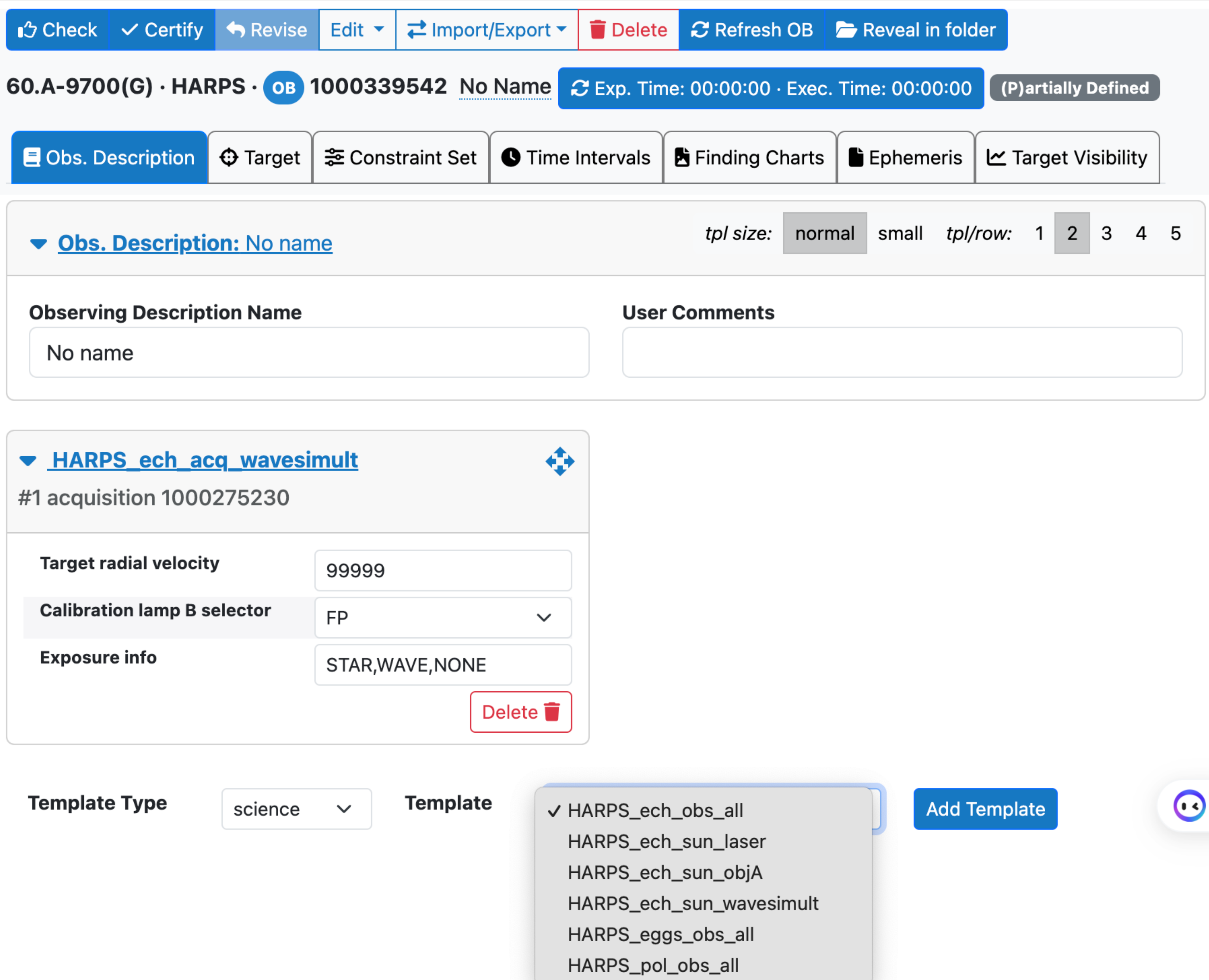
Operations

- 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

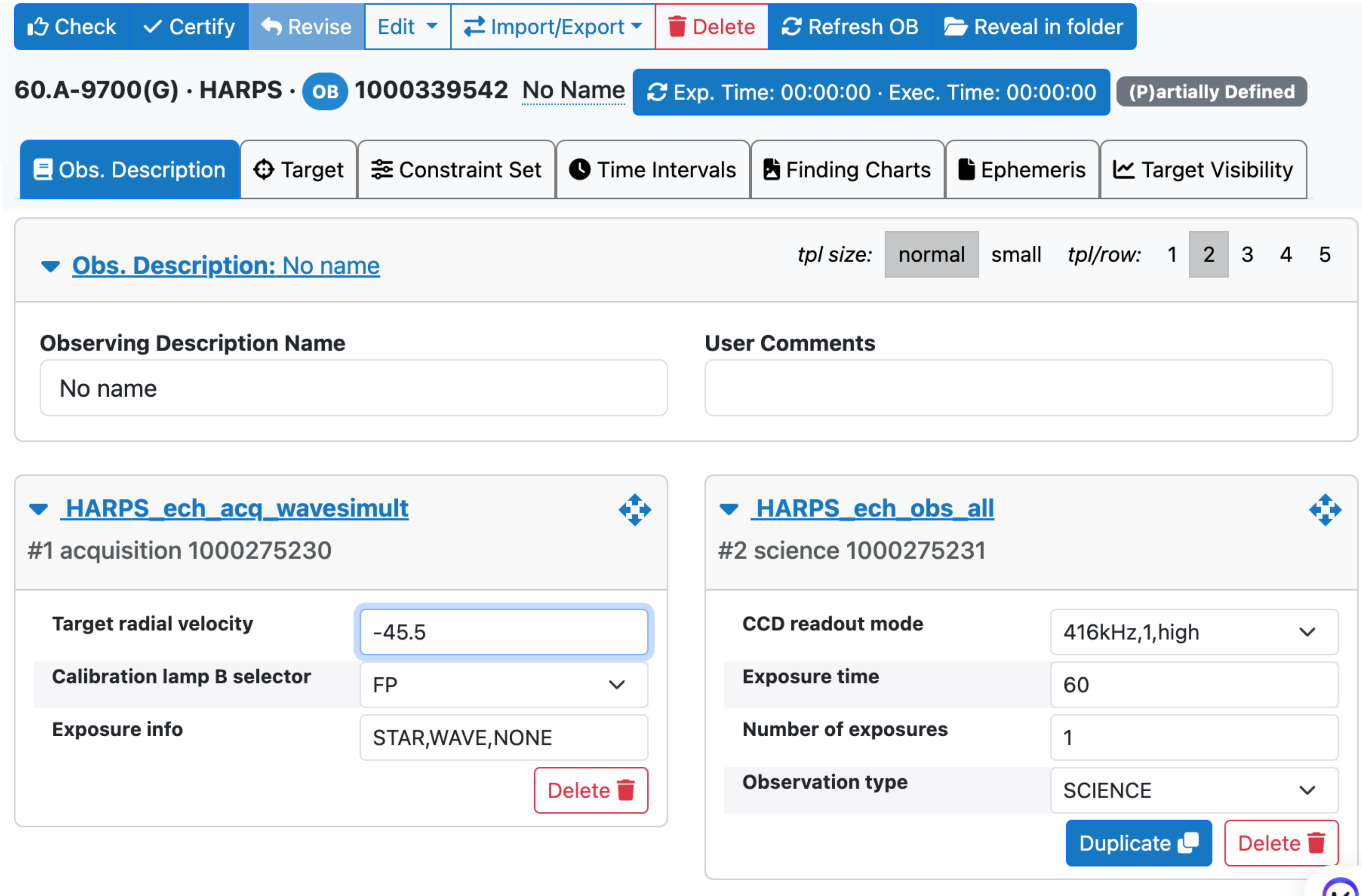
HARPS acquisition



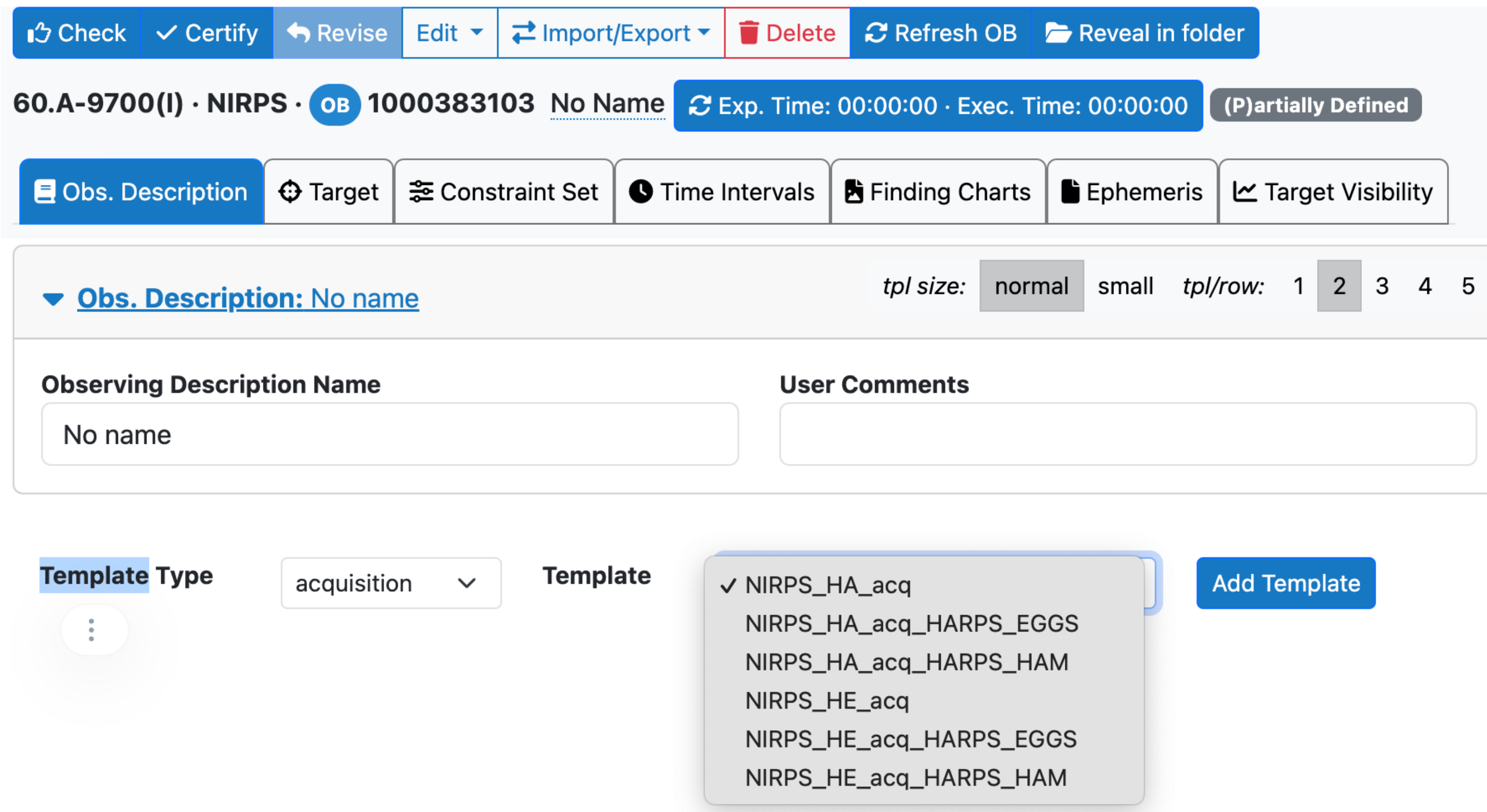
HARPS SCIENCE



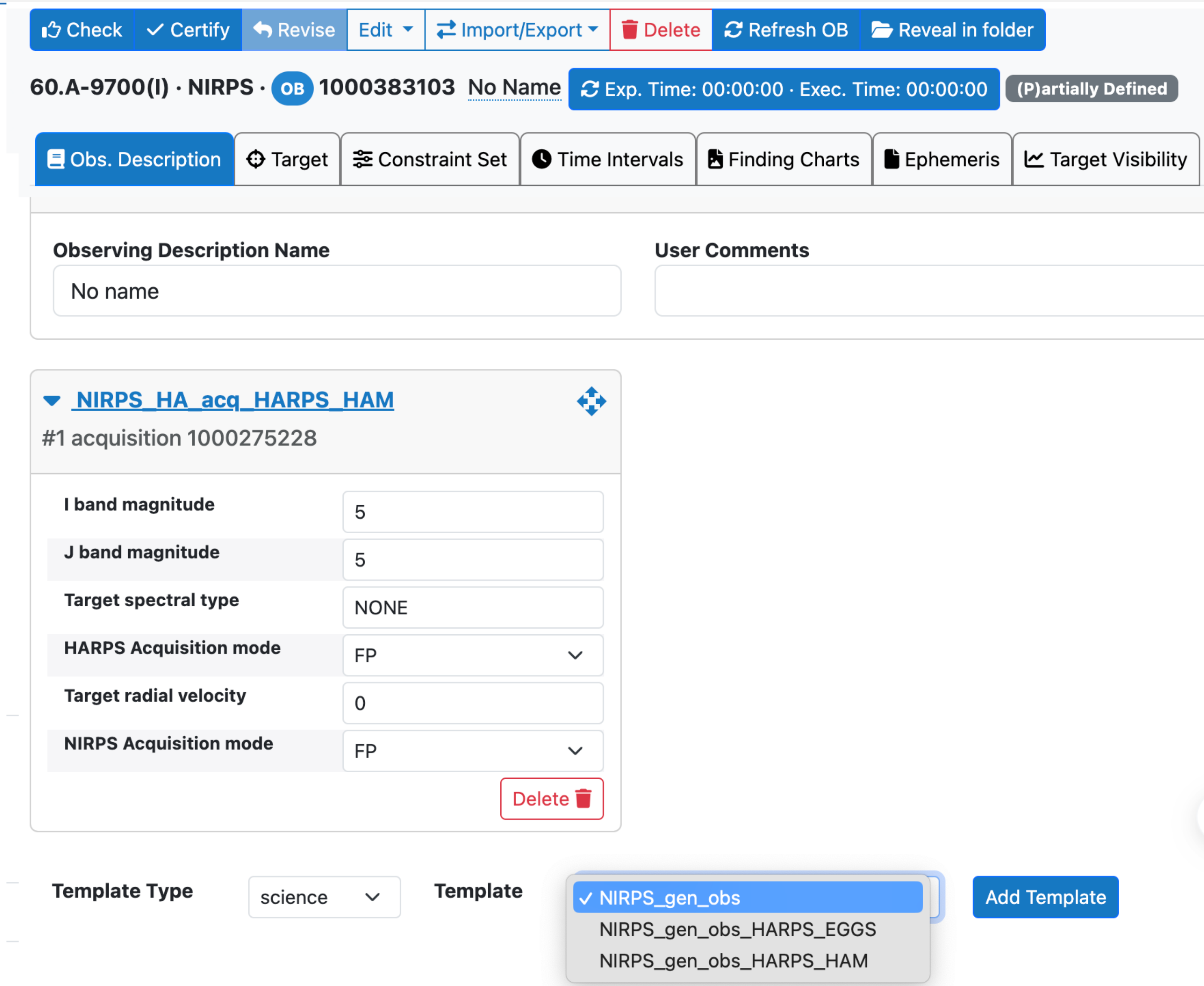
HARPS OB


Check
Certify
Revise
Edit
Import/Export
Delete
Refresh OB
Reveal in folder
60.A-9700(G) · HARPS · OB 1000339542 No Name
Exp. Time: 00:00:00 · Exec. Time: 00:00:00
(P)artially Defined
Obs. Description
Target
Constraint Set
Time Intervals
Finding Charts
Ephemeris
Target Visibility
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
Delete
HARPS_ech_obs_all
#2 science 1000275231
CCD readout mode
416kHz,1,high
Exposure time
60
Number of exposures
1
Observation type
SCIENCE
Duplicate
Delete

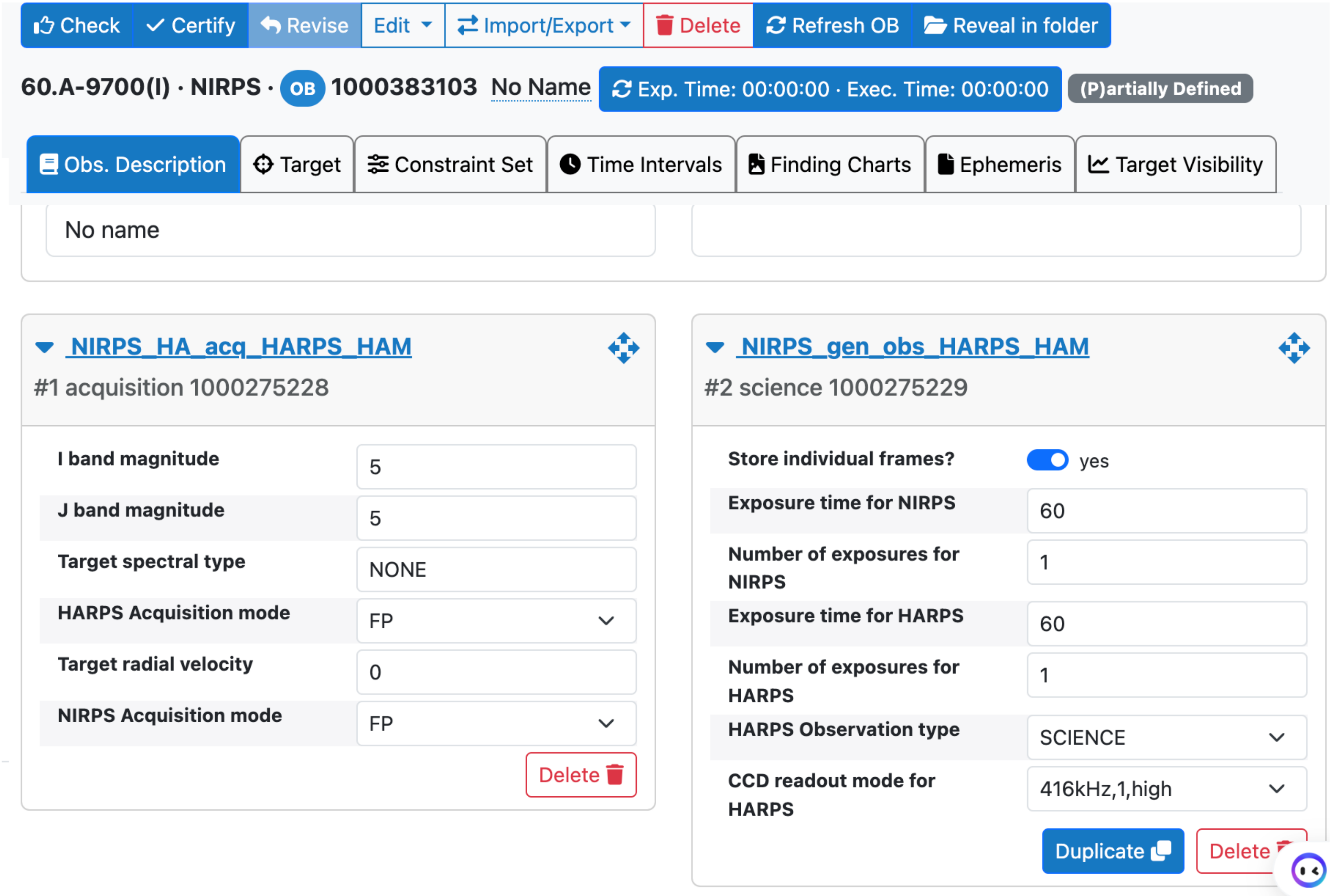
NIRPS + HARPS ACQUISITION



NIRPS + HARPS SCIENCE



NIRPS + HARPS OB



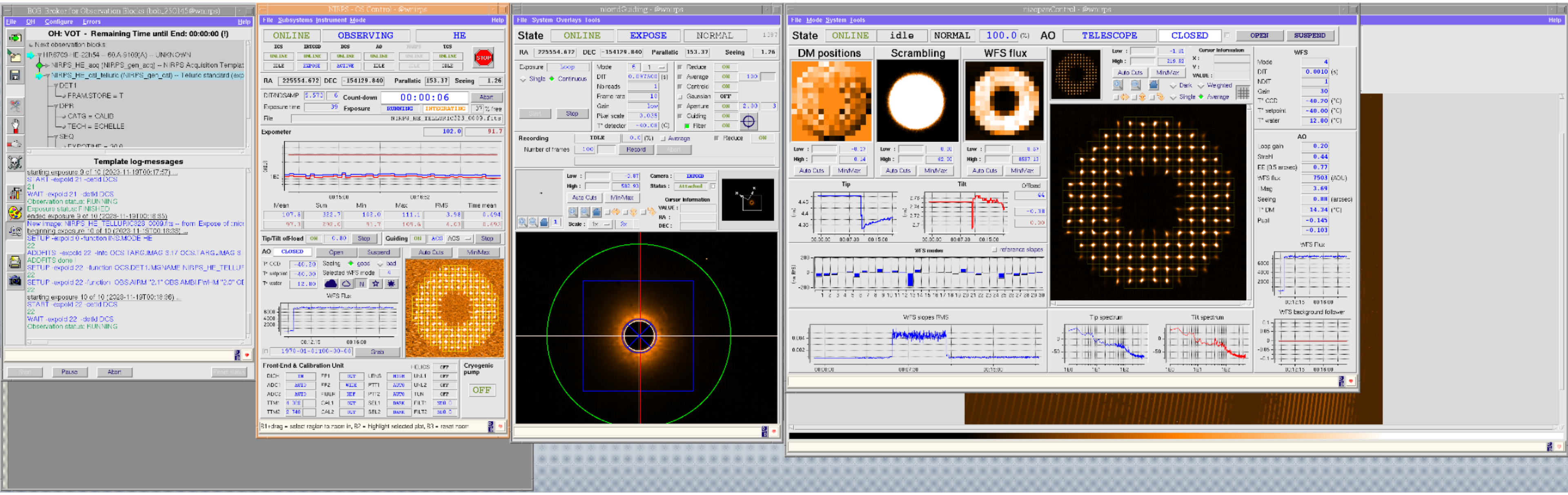
NIRPS Operation panels

BOB

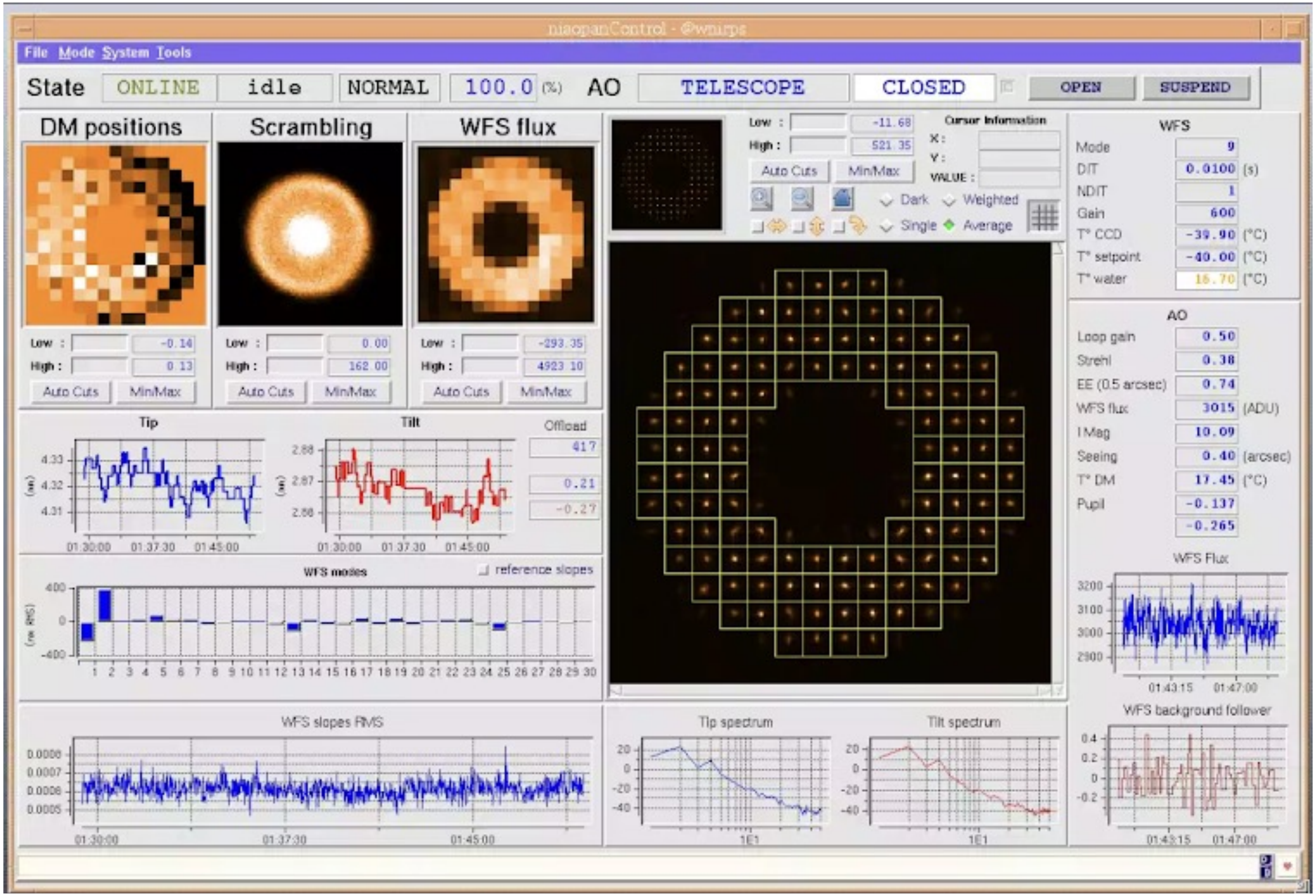
OS

Center & guide

Adaptive Optics



NIRPS AO panel



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.