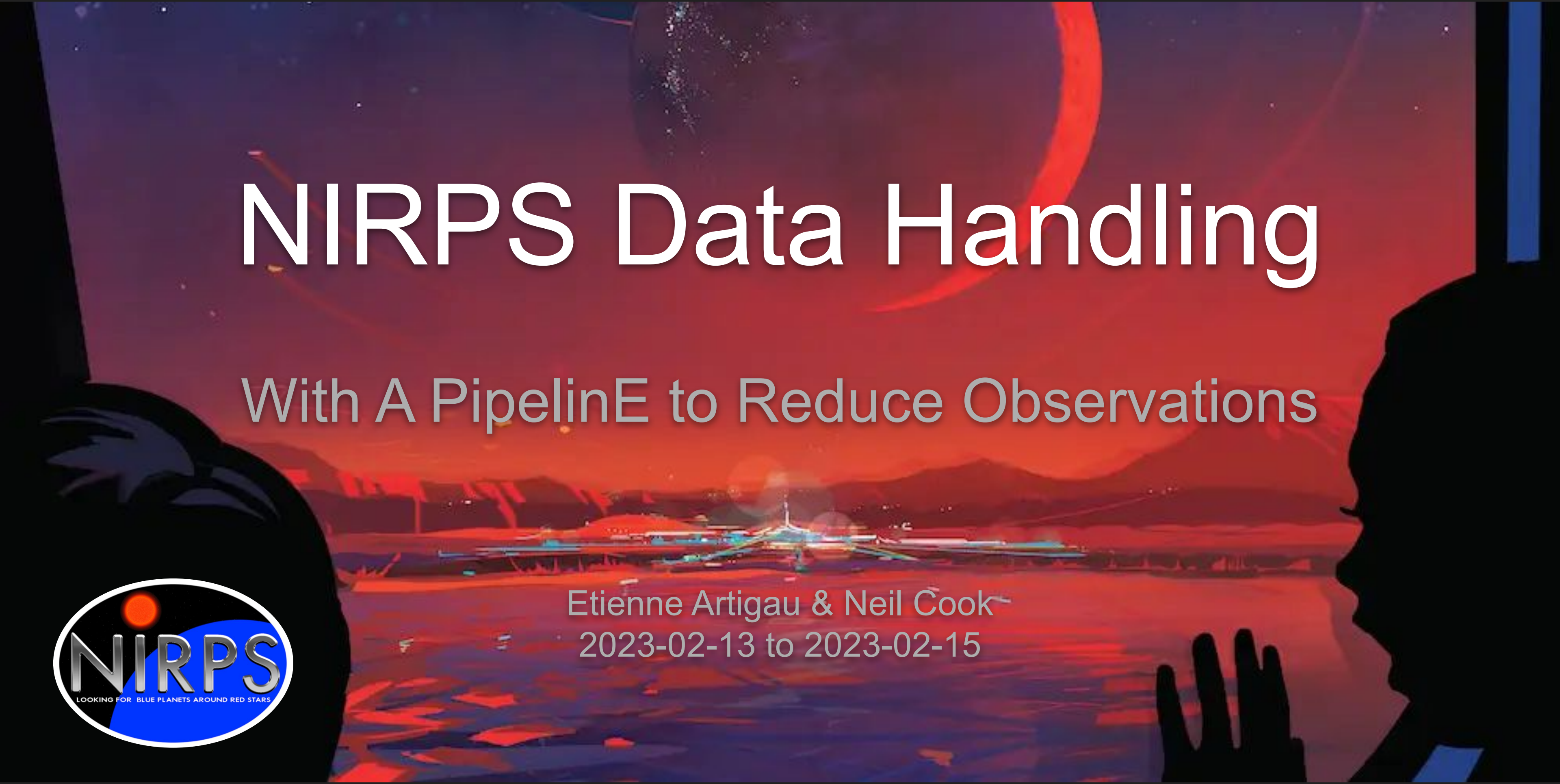

NIRPS Data Handling

With A PipelinE to Reduce Observations

Etienne Artigau & Neil Cook

2023-02-13 to 2023-02-15

Contents

Prerequisites for exercises

- Python 3.9 (i.e. via conda: https://docs.conda.io/en/latest/miniconda.html)
  - astropy, matplotlib, numpy, scipy
- DS9: https://sites.google.com/cfa.harvard.edu/saoimageds9
- dfits / fitsort
  - Python implementation: https://astrom-tom.github.io/dfitspy/build/html/installation.html
  - C implementation: https://github.com/granttremblay/eso_fits_tools
- Download the file bundle (2 GB):
  - https://www.astro.umontreal.ca/~artigau/apero_demo/apero_nirps_demo.tar
- Example solutions: https://github.com/njcuk9999/apero_demo

APERO

- A PipelinE to Reduce Observations
- Python 3 module to reduce observations
- Specifically from echelle spectrographs
    - SPIRou (CFHT)
    - NIRPS (3.6m La Silla)
- 5+ years in the making
- Version History:
    - V0.0.000 2017-10-12 48 versions
    - V0.1.000 2018-01-10 37 versions
    - V0.2.000 2018-04-17 128 versions
    - V0.3.000 2018-09-06 77 versions
    - V0.4.000 2018-12-08 123 versions
    - V0.5.000 2019-05-10 124 versions
    - V0.6.000 2019-12-06 132 versions
    - V0.7.000 2020-10-17 276 versions Current stable: 0.7.275
    - V0.8.000 2023-01-06 ??

total lines: 170583
total empty lines: 12048
total lines of comments: 71963
total lines of code: 86572

APERO

- Paper published in PASP November 2022
- https://ui.adsabs.harvard.edu/abs/2022PASP..134k4509C

Publications of the Astronomical Society of the Pacific, 134:114509 (56pp), 2022 November https://doi.org/10.1088/1538-3873/ac9e74

APERO: A PipelinE to Reduce Observations—Demonstration with SPIRou

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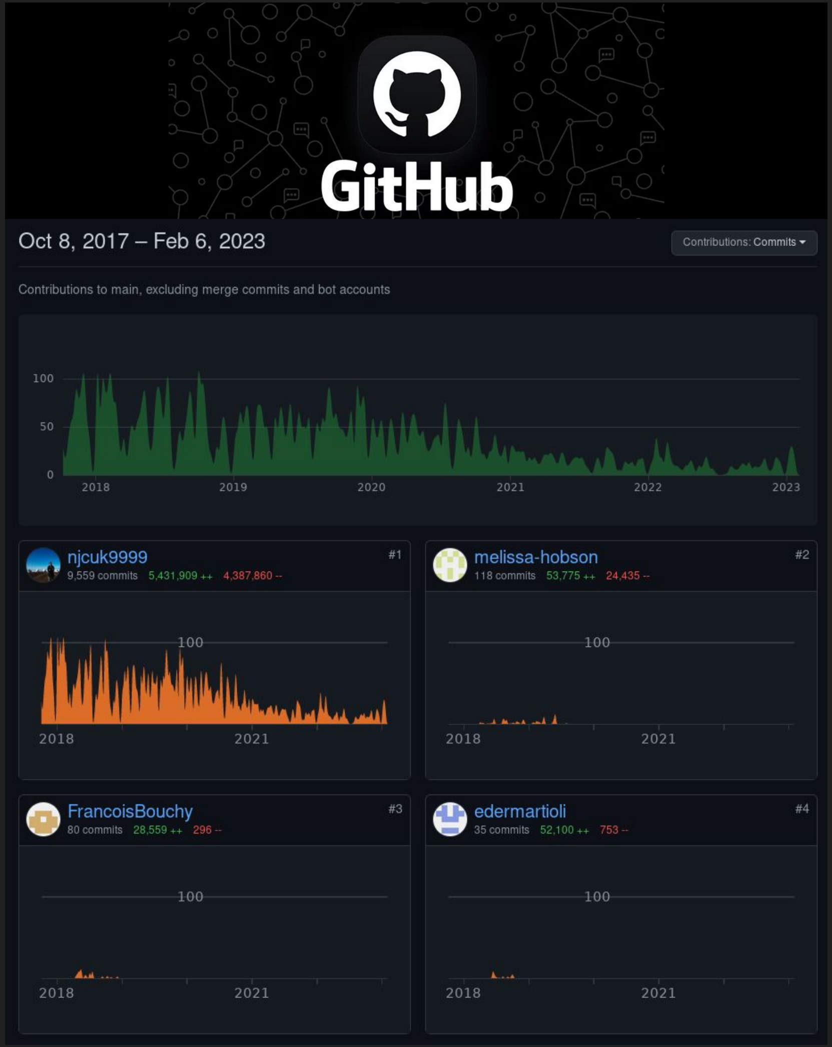
Abstract

With the maturation of near-infrared high-resolution spectroscopy, especially when used for precision radial velocity, data reduction has faced unprecedented challenges in terms of how one goes from raw data to calibrated, extracted, and corrected data with required precisions of thousandths of a pixel. Here we present A PipelinE to Reduce Observations (APERO), specifically focused on Spectro Polarimètre Infra ROUge (SPIRou), the near-infrared spectropolarimeter on the Canada–France–Hawaii Telescope (SPectropolarimètre InfraROUge, CFHT). In this paper, we give an overview of APERO and detail the reduction procedure for SPIRou. APERO delivers telluric-corrected 2D and 1D spectra as well as polarimetry products. APERO enables precise stable radial velocity measurements on the sky (via the LBL algorithm), which is good to at least $\sim 2\ \mathrm{m\,s^{-1}}$ over the current 5 yr lifetime of SPIRou.

Unified Astronomy Thesaurus concepts: Astronomy data reduction (1861); Spectropolarimetry (1973); Radial velocity (1332); Spectroscopy (1558); Calibration (2179); Near infrared astronomy (1093)

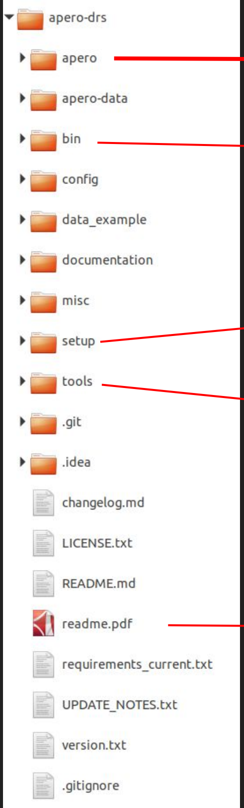
APERO

- Website: http://apero.exoplanets.ca/
  - Installation instructions
  - Lots of documentation
- Github: https://github.com/njcuk9999/apero-drs
  - “main”
    - long term stable
    - In frequent updates
  - “developer”
    - tested and semi-stable
    - Semi frequent updates
  - “stable-test”
    - normally up-to-date with live version
    - has been tested for stability
    - Frequent updates
  - “live”
    - Currently being worked on
  - All other branches most likely feed off “live” unless a fix



Installation directory

- git clone https://github.com/njcuk9999/apero-drs

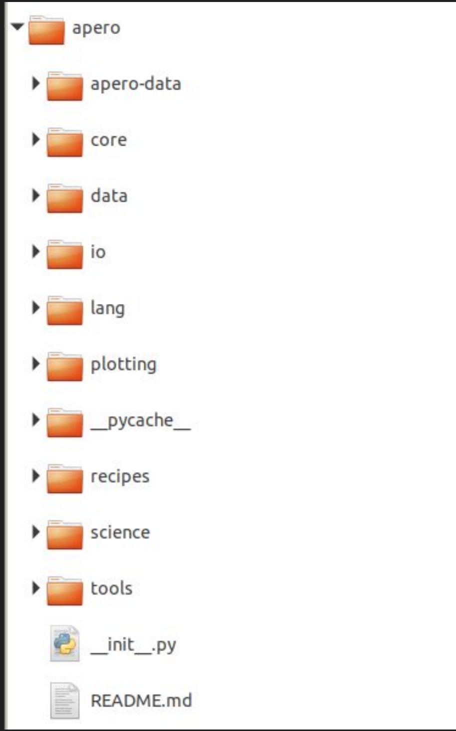


Recipe codes (after installation)

Setup codes

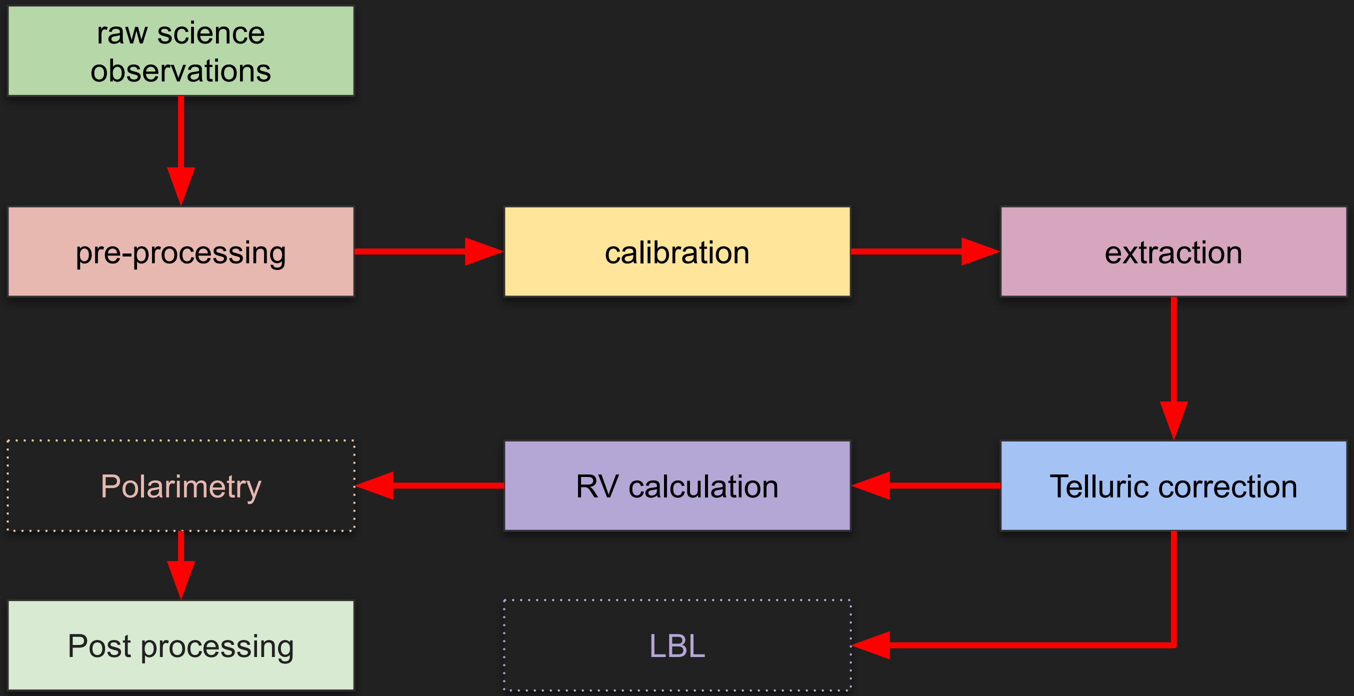
Tool codes (after installation)

How to install and how to use (work in progress)



All the core functionality and code (magic) is in here

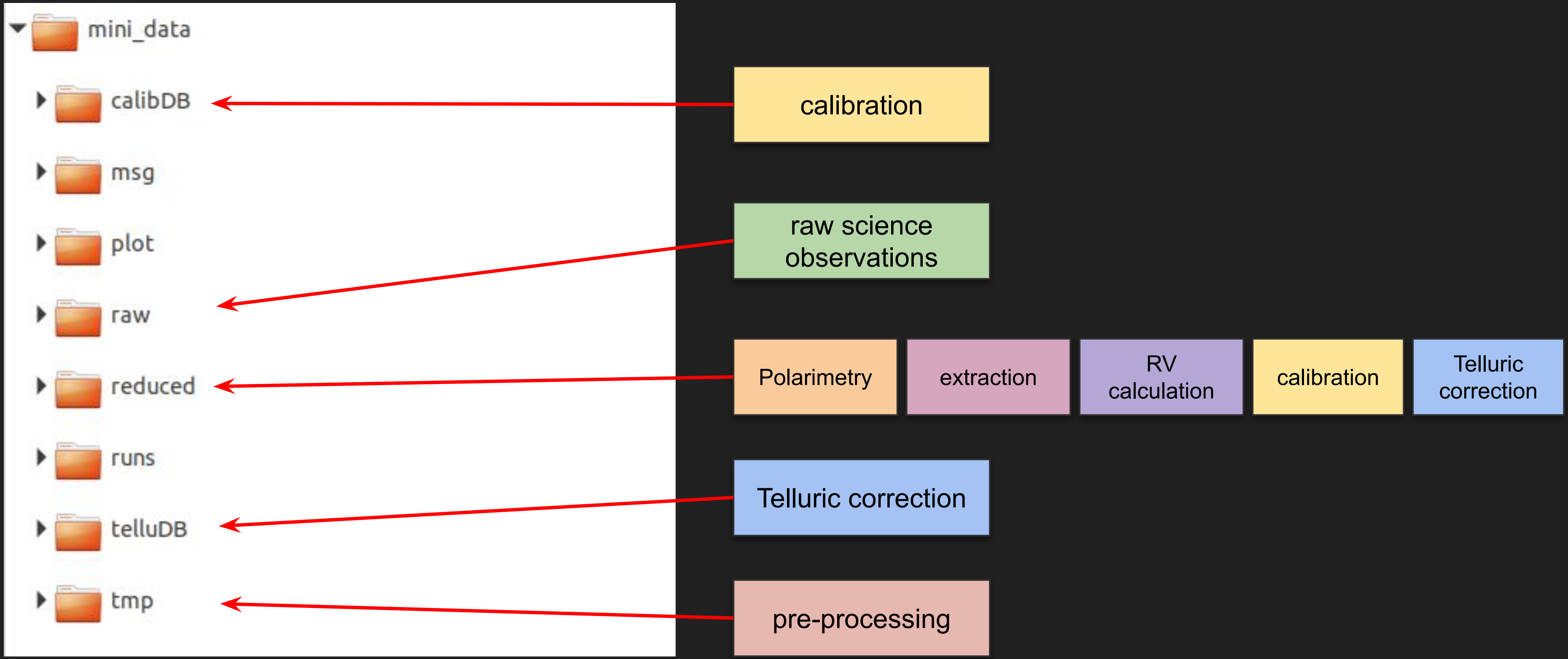
A PipelinE to Reduce Observations



The data directories

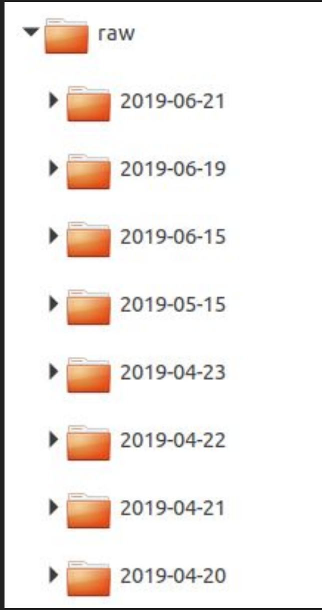
- Paths set during installation process

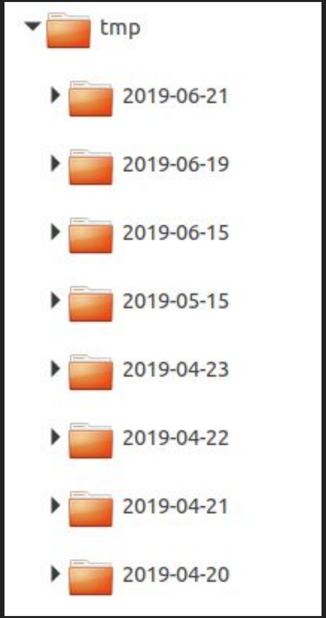
Note: in versions 0.7+ also an “assets” directory for masks and other data supplied by apero

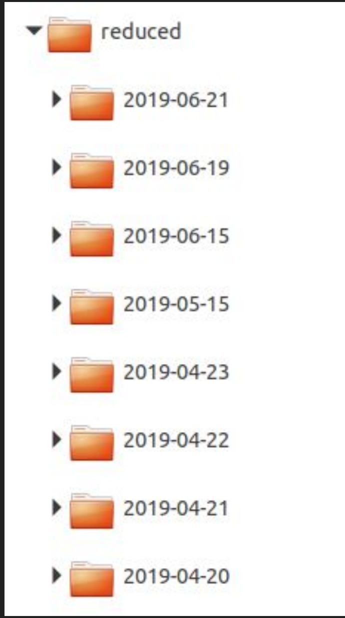


The night directories

- Individual nights stored in sub-directories (directory name is not important)
  - at Montreal we use YYYY-MM-DD (UTC)
  - Processing is independent of sub-directory structure but structure is kept throughout (raw, tmp, reduced)





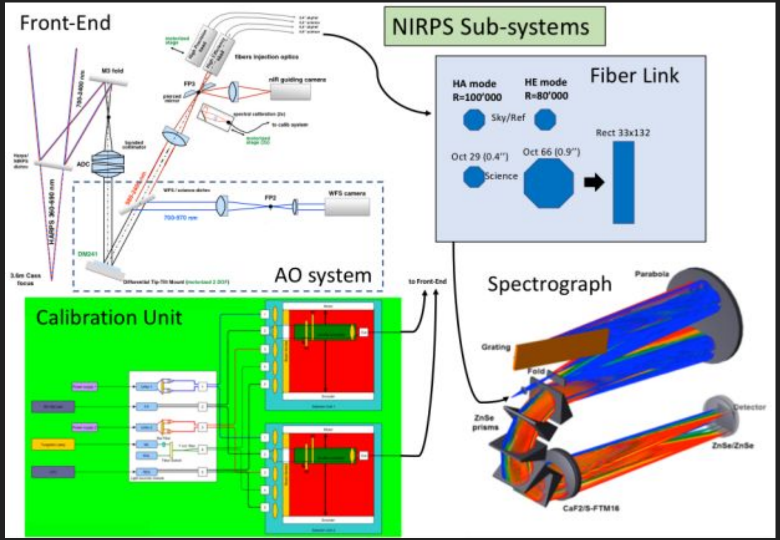


DAY 1

Day 1: Raw and preprocessing Objectives

- Learn about raw NIRPS data
- Exercise 1: Fits-to-ramp
- Exercise 2: Detector cosmetics (preprocessing)

Raw NIRPS observations



- Two fiber modes:
  - NIRPS HA (High Accuracy)
  - NIRPS HE (High Efficiency)
- Two fibers:
  - Science/Sky (A)
  - Calibration/Sky (B)
- APERO observation general notation* for NIRPS:
  - DPRTYPE: {fiber A}_{fiber B}
- Many types of observations:
  - Science observations: “OBJ” or “SKY” or “FLUX” or “TELLU”
  - Calibrations: “DARK”, “FLAT”, “HC”, “FP”

*Sometimes we have to use a more descriptive DPRTYPE (i.e. FLUX_SKY_SKY vs NIGHT_SKY_SKY)

What's makes an observation: 1

Calibration choices are:

FLAT HC

FP DARK

APERO DPRTYPE	HIERARCH ESO DPR TYPE
FLAT_DARK	ORDERDEF,LAMP,DARK
CALIB_FLAT_DARK	FLAT,LAMP,DARK
FLAT_FP	
FLAT_HC	
FLAT_FLAT	FLAT,LAMP,LAMP
HC_DARK	WAVE,UN1,DARK
HC_FP	WAVE,UN1,FP
HC_HC	WAVE,UN1,UN1
HC_FLAT	
FP_DARK	CONTAM,FP,DARK
FP_FP	WAVE,FP,FP
FP_HC	WAVE,FP,UN1
FP_FLAT	
DARK_DARK	DARK
DARK_FP	CONTAM,DARK,FP
DARK_HC	WAVE,DARK,UN1
DARK_FLAT	ORDERDEF,DARK,LAMP
CALIB_DARK_FLAT	FLAT,LAMP,DARK

ones in red are not used for calibration in APERO

What’s makes an observation: 2

Science choices are:

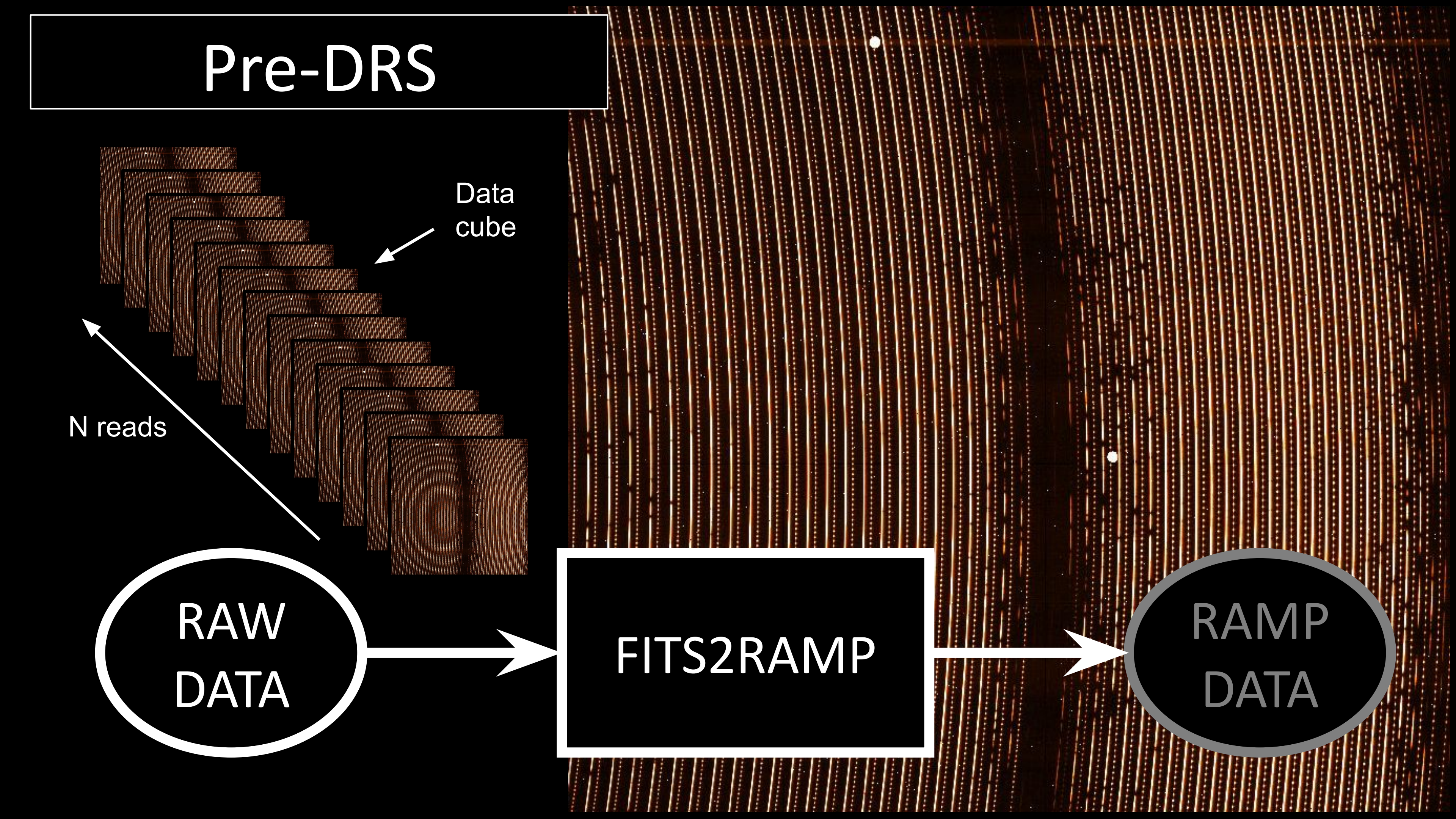
OBJ SKY

EFF TELLU

SUN

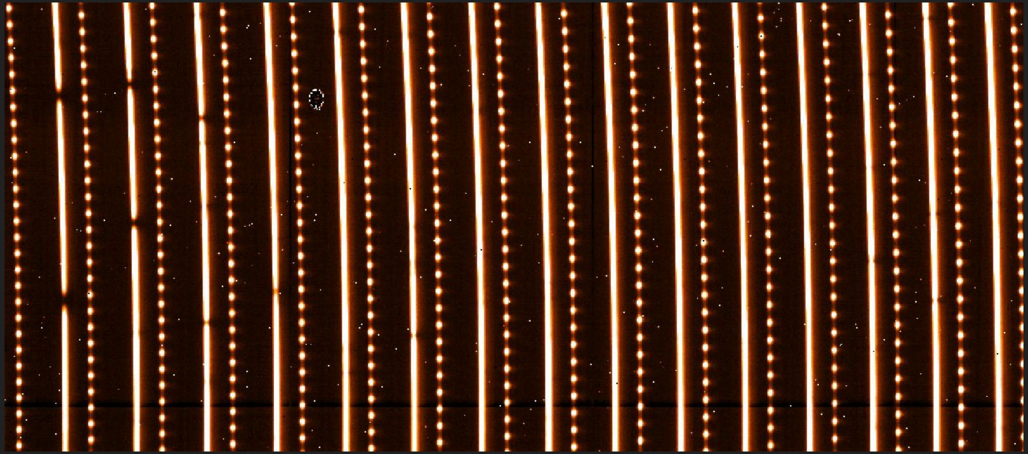
APERO DPRTYPE	HIERARCH ESO DPR TYPE	
OBJ_FP	OBJECT,FP	
OBJ_SKY	OBJECT,SKY	
OBJ_DARK	OBJECT,DARK	
SUN_FP	SUN,FP,G2V	
SUN_DARK	SUN,DARK,G2V	
TELLU_SKY	TELLURIC,SKY	
FLUXSTD_SKY	FLUX,STD,SKY	
FLUX_SKY_SKY	EFF,SKY,SKY	
NIGHT_SKY_SKY	OBJECT,SKY	(TRG_TYPE=SKY)

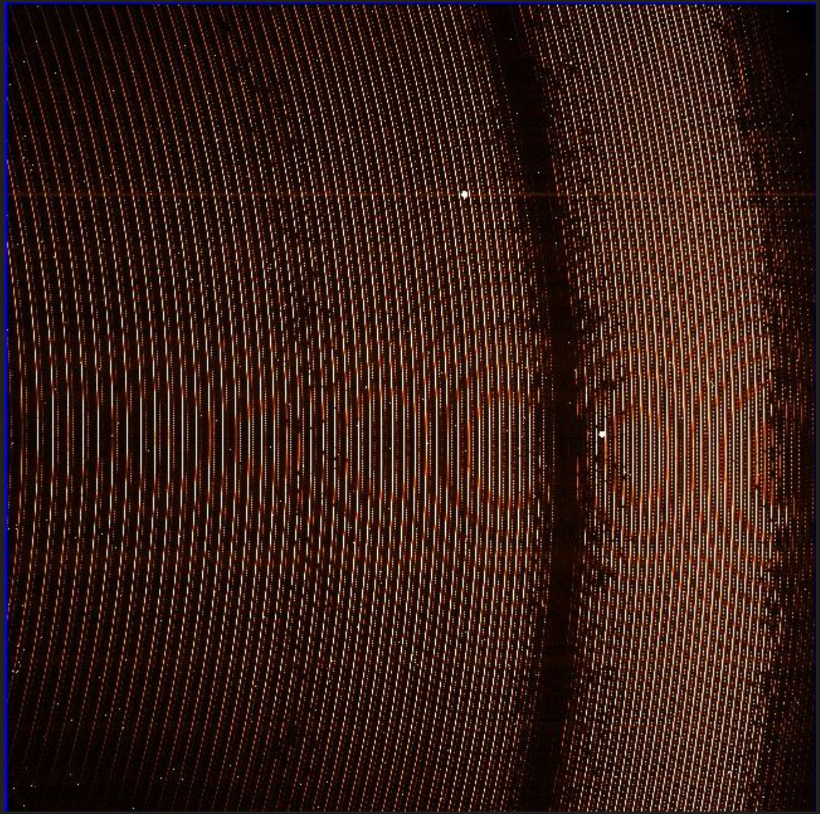
ones in red are not used for calibration in APERO
TRG_TYPE is determined in preprocessing and requires among other thing “SKY” in the object name


Pre-DRS
Data cube
N reads
RAW DATA
FITS2RAMP
RAMP DATA

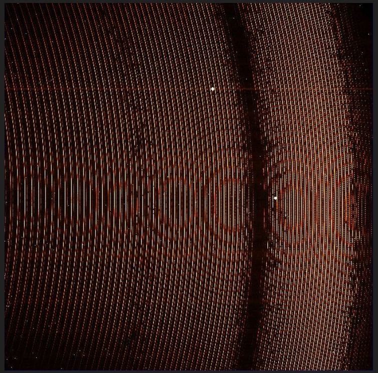
NIRPS raw science observations

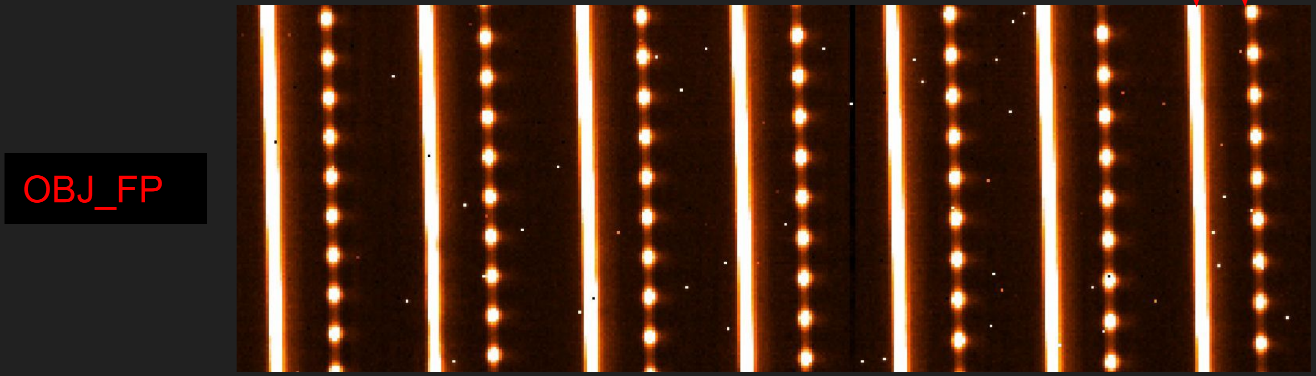
- H4RG detector
- CUBEs : N x 4096 x 4096 [ADU]
- RAMP frames: 4096 x 4096 [ADU/s]
- 4 reference pixels on top/bottom/right/left

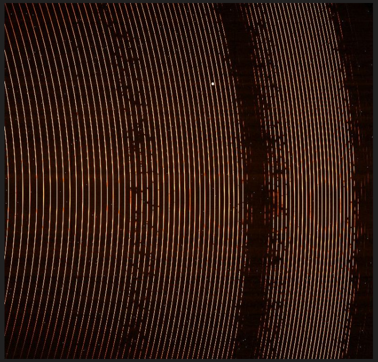


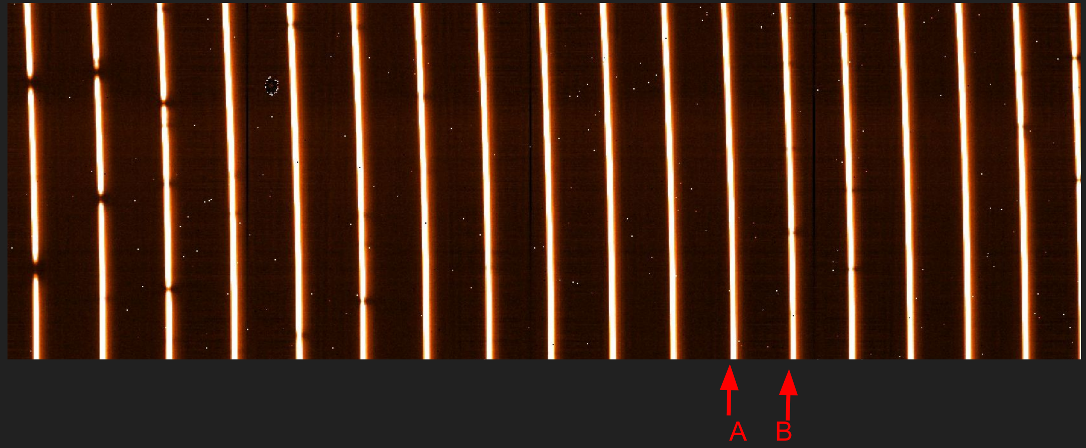


NIRPS HA raw science observations

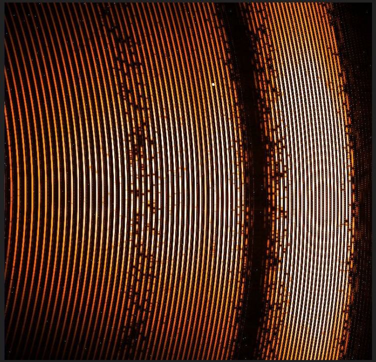


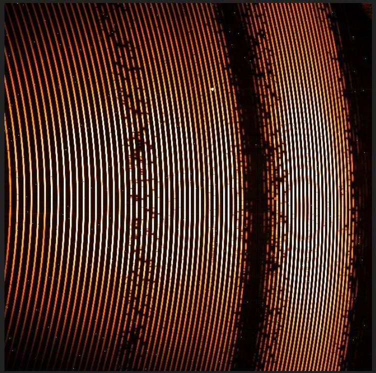




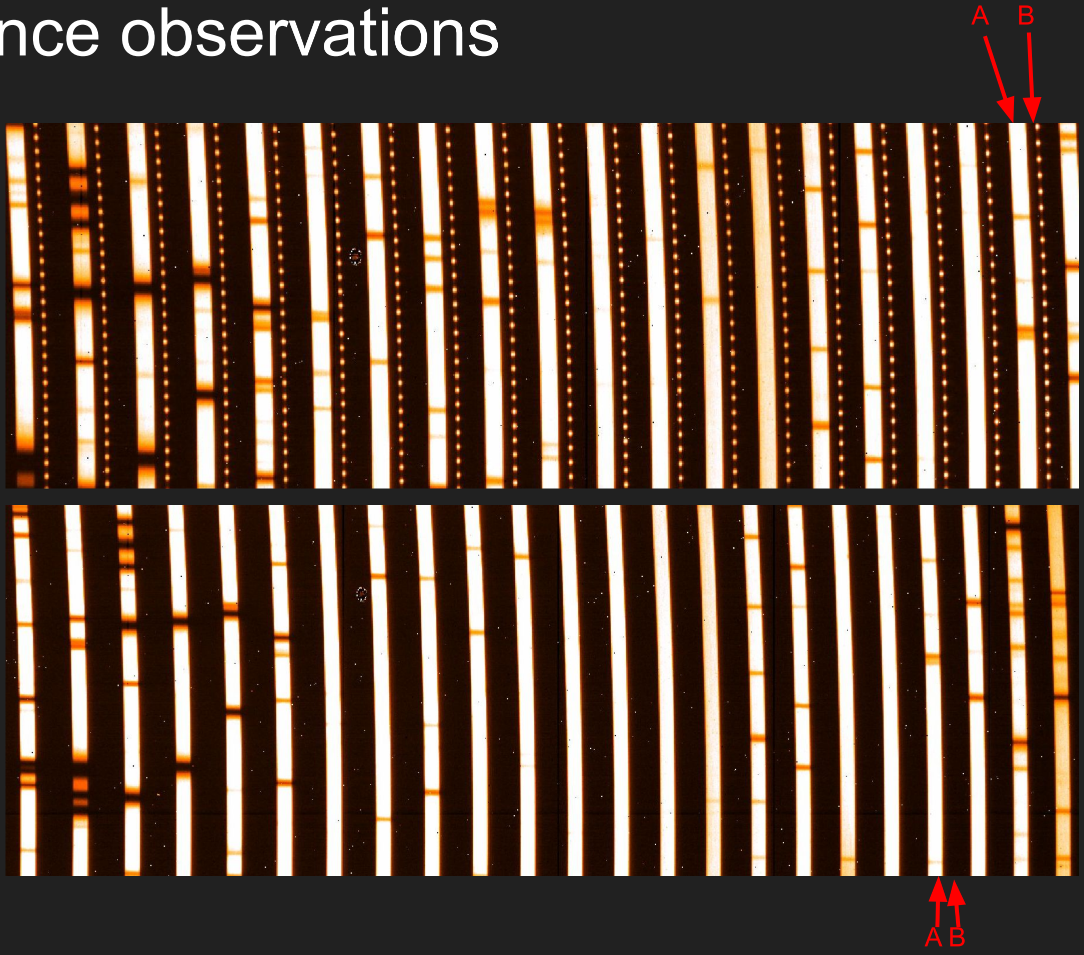


NIRPS HE raw science observations





OBJ_FP



NIRPS RAW Headers: Identifying files

- HIERARCH ESO DPR TYPE
  - the telescope data product type
  - Difference from APERO
  - ESO "OBJECT,SKY" APERO "OBJ_SKY"
  - ESO "ORDERDEF,LAMP,DARK" APERO "FLAT_DARK"
- HIERARCH ESO INS MODE
  - the mode ("HA" or "HE")
- HIERARCH ESO DPR CATG
  - "Test", "Calibration", "Science"
- HIERARCH ESO OBS TARG NAME and/or "OBJECT"
  - Object name
  - APERO cleans/standardizes these and adds DRSOBJN in reduced products
- EXPTIME
  - Frame time = HIERARCH ESO DET UIT (CUBE)
  - EXPTIME = Frame time * (Number frames - 1)

Exercise 1: Cube to RAMP: Correlated double sampling (CDS)

Step 1: Find the ramp and the cube for Proxima (HE)   HIERARCH ESO DPR TYPE = OBJECT,SKY using dfits and fitsort (or python)

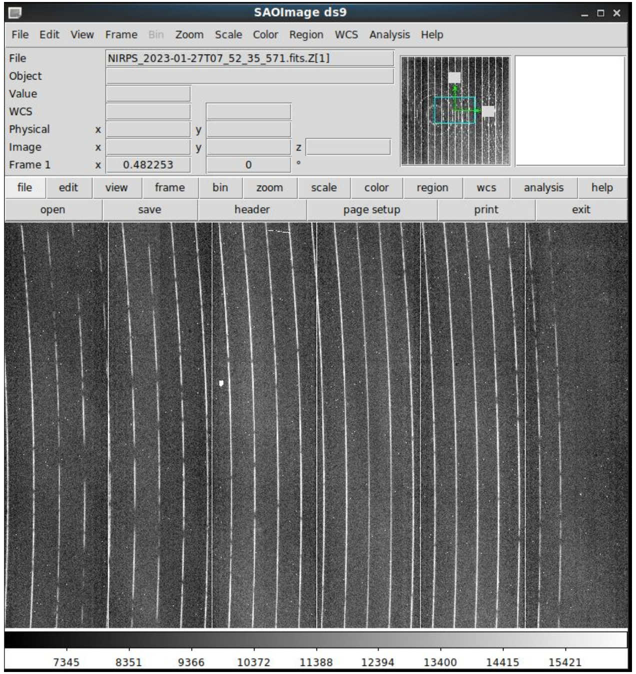
Step 2: Load the cube in ds9

Step 3: In DS9 play with the cube scaling (linear, log, histogram, min max, zscale etc)

Step 4: In DS9 “Animate” the cube to see photons accumulating

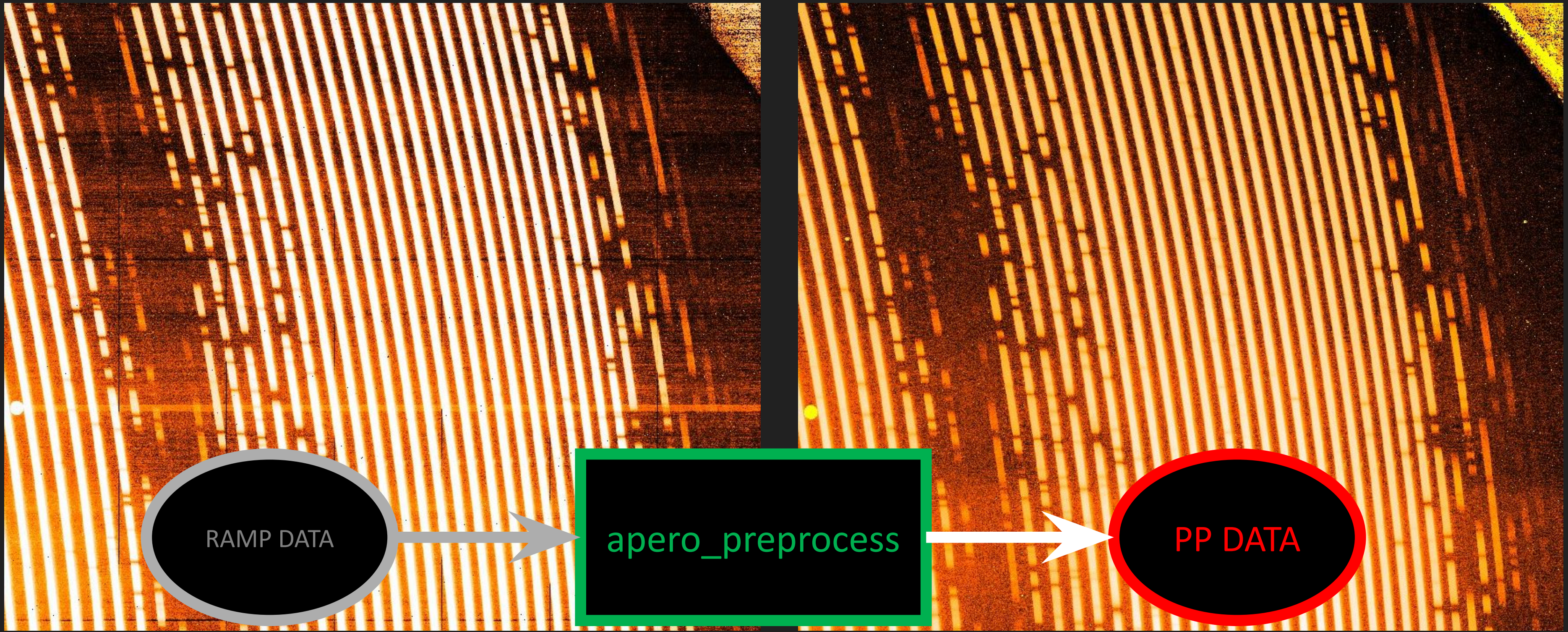
Step 5: In python create CDS “last minus first frame” from the cube. Express the resulting image in ADU/s

Step 6: In DS9 compare to provided ramp image for Proxima



Pre-processing

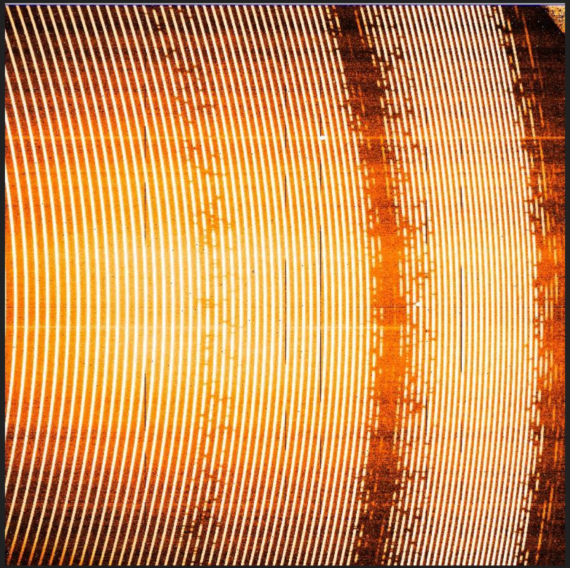
- Needs to be done on every observation (science or calibration)
- Cleans data of many detector effects



Pre-processing

- Images may be flagged as corrupted at this stage
- Image is rotated with respect to the raw images
    - 270 degree rotation clockwise + flip in Y
- Saved in the tmp directory with "_pp" extension added

raw/OBS_DIR/NIRPS_YYYY-MM-DDThh_mm_ss_sss.fits



tmp/OBS_DIR/NIRPS_YYYY-MM-DDThh_mm_ss_sss.fits

Pre-processing

- Useful header keys added

```
DRSOBJN = 'HD85512 '         / APERO-cleaned Target name
TRG_TYPE= 'TARGET  '         / target or sky object
MJDMID  =      59965.28232484947 / APERO calculated Mid Observation time [mjd]
MJDMIDMD= 'header  '         / Mid Observation time calc method
DRSMODE = 'HE      '         / APERO-mode (HA or HE)
DPRTYPE = 'OBJ_SKY '         / APERO-type of file (from pre-process)
PP_OBJN = 'HD85512 '         / cleaned object name to be used by the DRS
PP_OBJNS= 'HD85512 '         / Original object name as in header
PP_RA   =       147.785316 / The RA [in deg] used by the DRS
PP_RAS  = 'header  '         / Source of the ra used by the DRS
PP_DEC  =        -43.50483 / The dec [in deg] used by the DRS
PP_DECS = 'header  '         / Source of the dec used by the DRS
PP_EPOCH=        2451544.5 / The Epoch used by the DRS
PP_PMRA =                0.0 / The pmra [mas/yr] used by the DRS
PP_PMRAS= 'null    '         / Source of the pmra used by the DRS
PP_PMDE =                0.0 / The pmdec [mas/yr] used by the DRS
PP_PMDES= 'null    '         / Source of the pmde used by the DRS
PP_PLX  =        0.0 / The parallax [mas] used by the DRS
PP_PLXS = 'header  '         / Source of the plx used by the DRS
PP_RV   =        0.0 / The RV [km/s] used by the DRS
PP_RVS  = 'header  '         / Source of the rv used by the DRS
PP_TEFF = 'NaN     '         / The Teff [K] used by the DRS
PP_TEFFS= 'header  '         / Source of the Teff used by the DRS
PP_SPT  = '' / The SpT used by the DRS
PP_SPTS = 'header  '         / Source of the SpT used by the DRS
PP_SRCE = 'header  '         / The source of DRS object data
PP_DDATE= '' / The date of source of DRS object data
```

```
PVERSION= '0.7.275 '         / APERO Pre-Processing version
DRSVDATE= '2023-01-27'       / DRS Release date
DRSPDATE= '2023-01-30 17:57:21.122' / DRS Processed date
DRSPID  = 'PID-00016751014411223040-JXLG' / The process ID that outputted this f
INF1000 = 'NIRPS_2023-01-21T06_44_52_548.fits' / Input file used to create output
QCC001N =        3383.757799724514 / Quality control parameter name
QCC001V = 'snr_hotpix'       / Quality control measured value
QCC001L = 'snr_hotpix < 1.00000e+01' / Quality control logic used
QCC001P =                    1 / Quality control param passed QC
QCC002N = 0.007563806672780722 / Quality control parameter name
QCC002V = 'max(rms_list)'    / Quality control measured value
QCC002L = 'max(rms_list) > 3.0000e-01' / Quality control logic used
QCC002P =                    1 / Quality control param passed QC
QCC003N =           200.6388 / Quality control parameter name
QCC003V = 'EXPTIME '         / Quality control measured value
QCC003L = 'EXPTIME < 2.0064e+01' / Quality control logic used
QCC003P =                    1 / Quality control param passed QC
QCC_ALL =                    T
DRSOUTID= 'DRS_PP  '         / DRS output identification code
DETOFFDX=                    0 / Pixel offset in x from readout lag
DETOFFDY=                    0 / Pixel offset in y from readout lag
NBADINTE= 'Not Implemented'          / No. bad px intercept cosmic reject
NBADSLOP= 'Not Implemented'          / No. bad px slope cosmic reject
NBADBOTH= 'Not Implemented'          / No. bad px both cosmic reject
PPLEDFIL= 'BF32620AA5_led_flat.fits' / LED flat file used
```

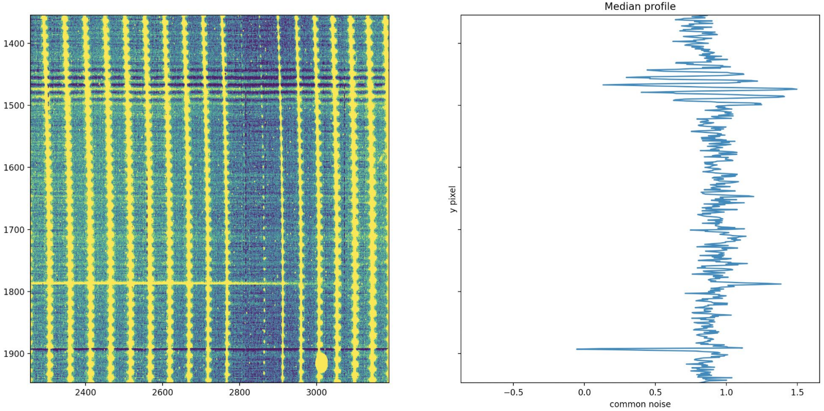
Exercise 2: Looking at detector cosmetics

Step 1: Find the DARK_FP RAMP file

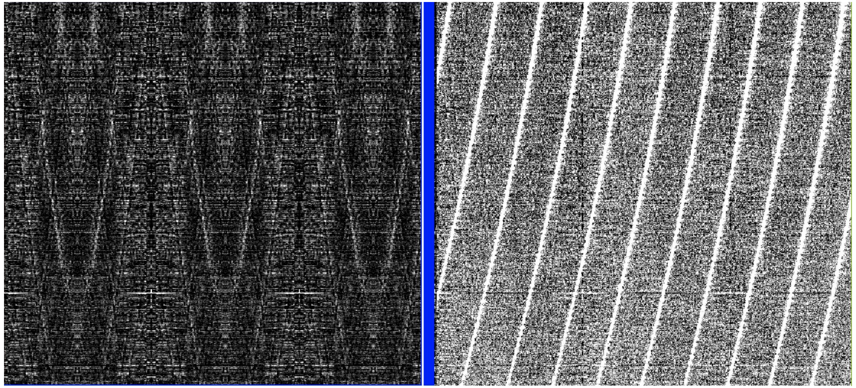
Step 2: In python remove horizontal striping

Step 3: In python remove the “butterfly” pattern

Horizontal striping:



Butterfly pattern:



DAY 2

Day 2: Calibration and Extraction Objectives

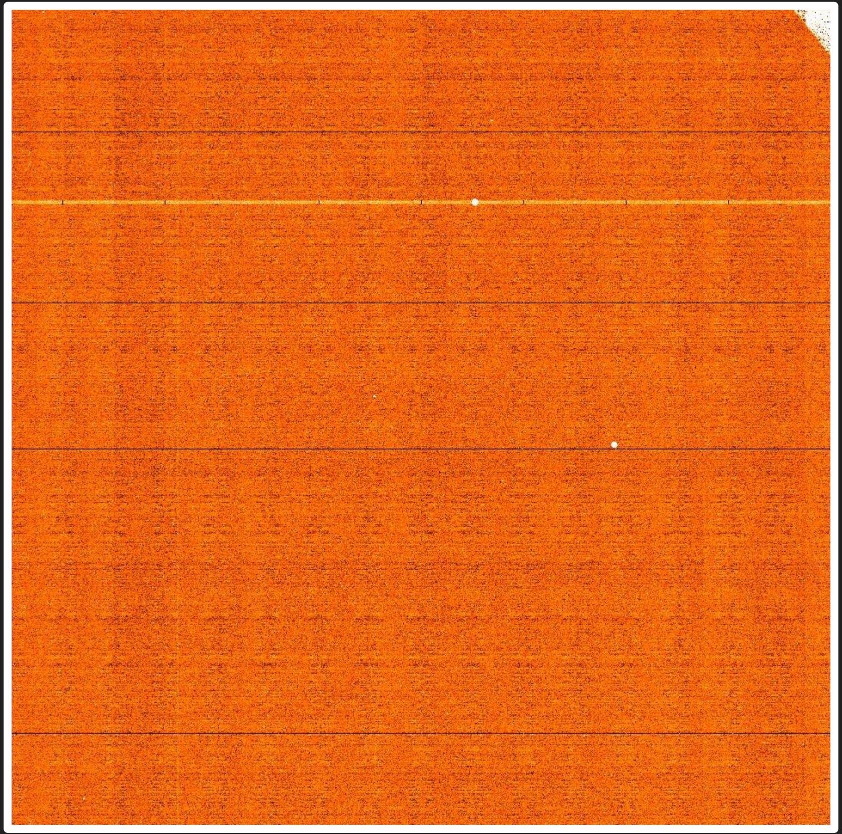
- Learn about calibration and extraction
- Exercise 3: Calibration
- Exercise 4: Extraction

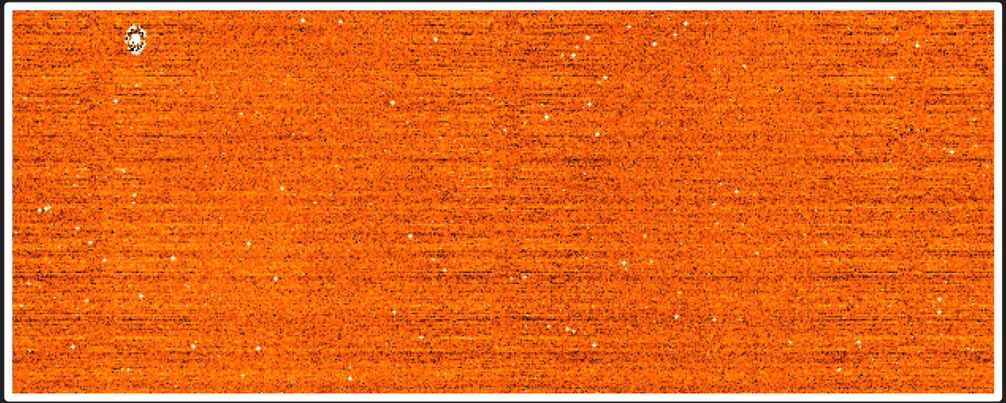
Calibration

Two types of calibration

- “Reference” calibration
    - Only done once - provides a reference frame for all other calibrations
- “Night” calibration
    - Uses the calibrations taken on each night
    - Only for use for science observed on the same night as those calibrations
    - May be used for a different night if calibrations fail
- A specific observation:
    - may use “older calibration” (those taken immediately before observations started that night)
    - may use “closest calibration (those taken closest to an observation (either those at the start of night or end of night, depending on observation time)
- Currently the default is “closest calibrations” but this is the subject of ongoing testing

Calibration quiz 1





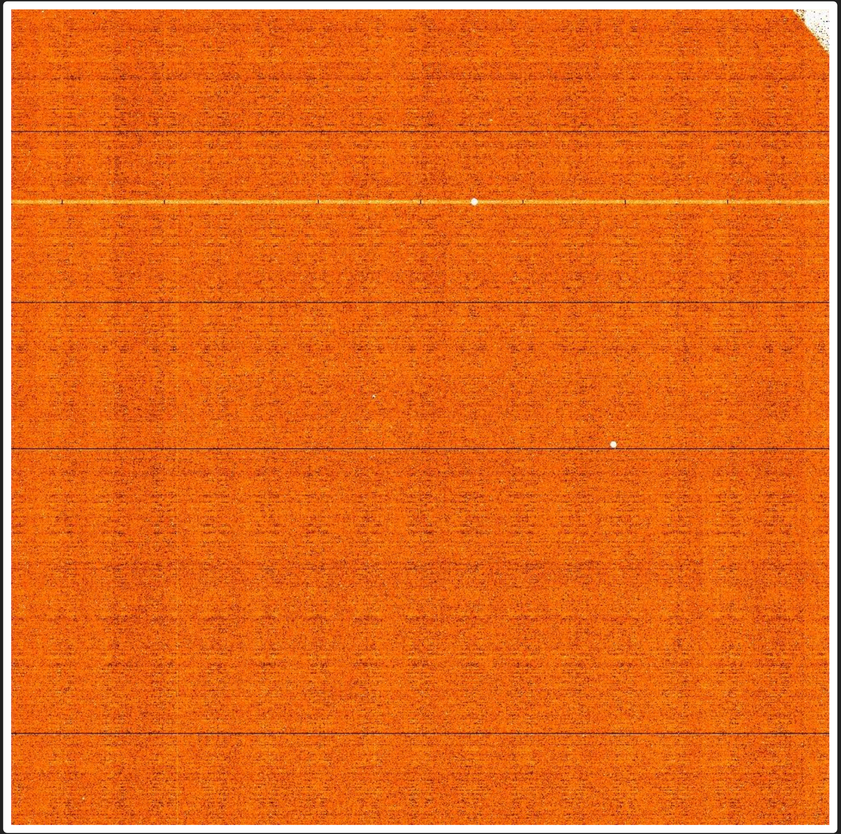
Options:

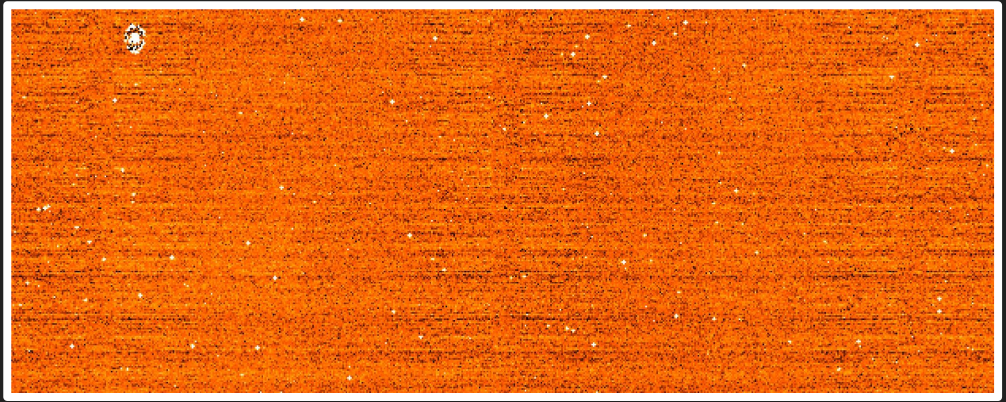
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 1: Answer





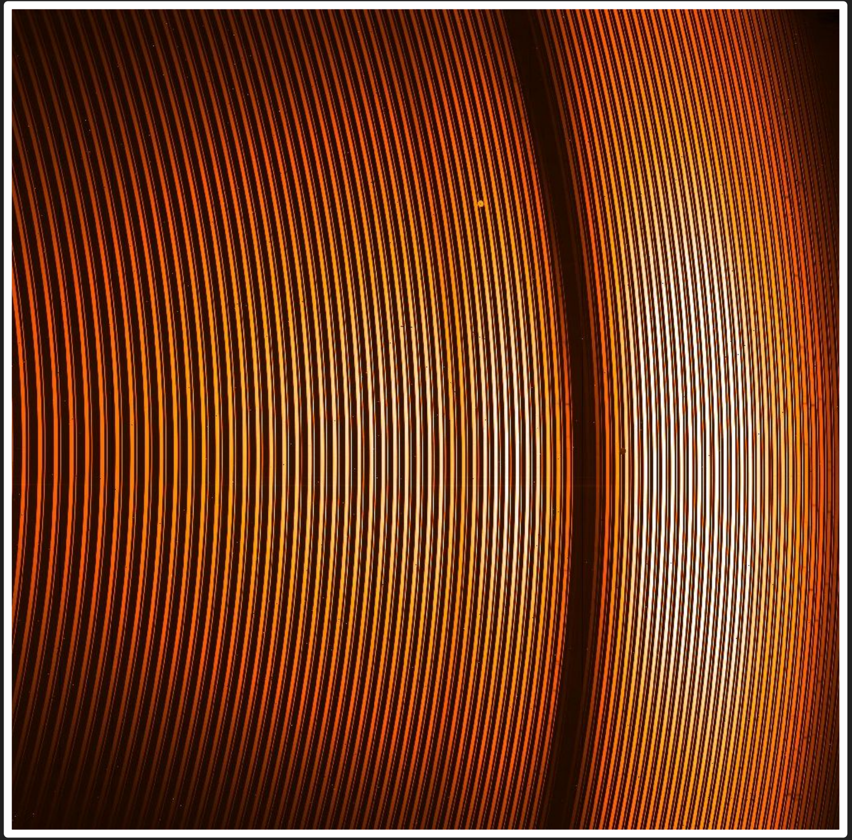
Options:

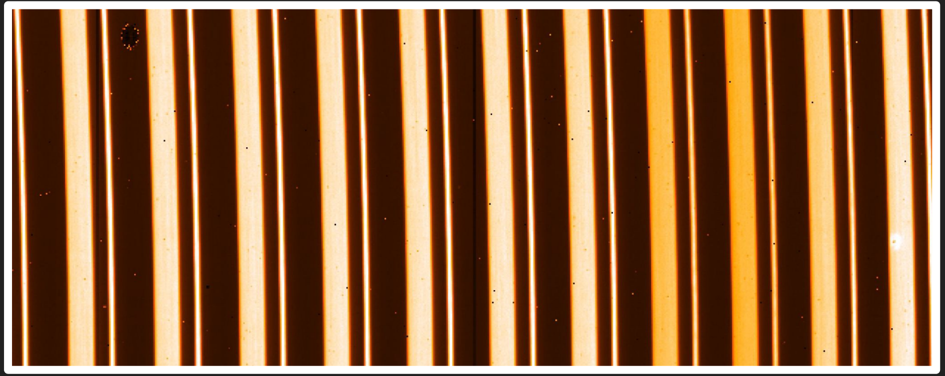
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 2





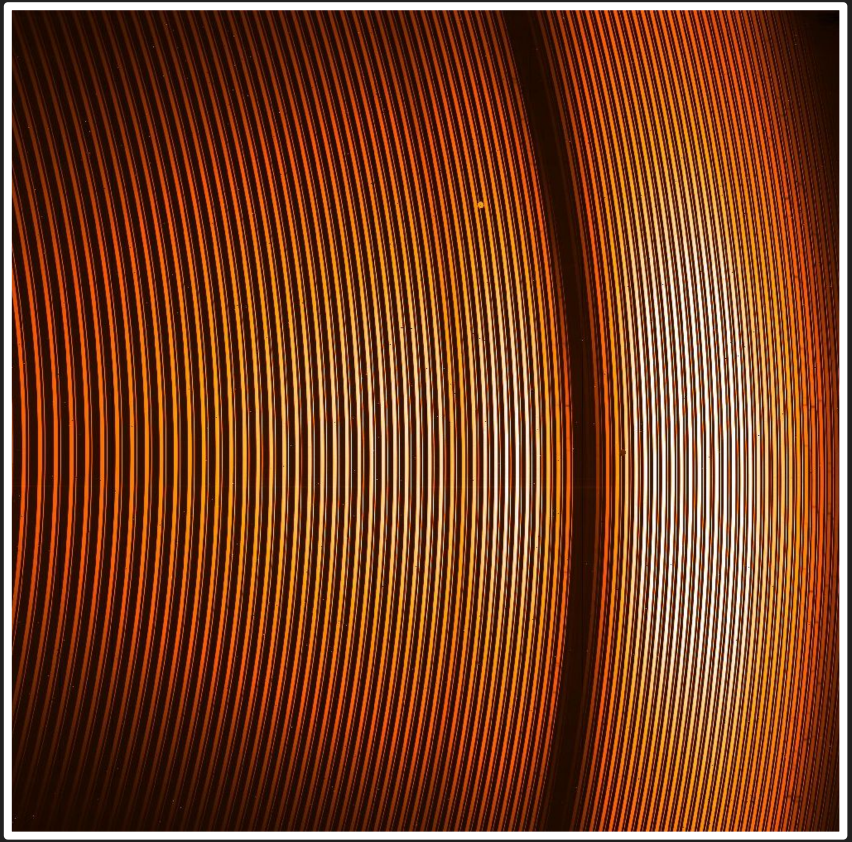
Options:

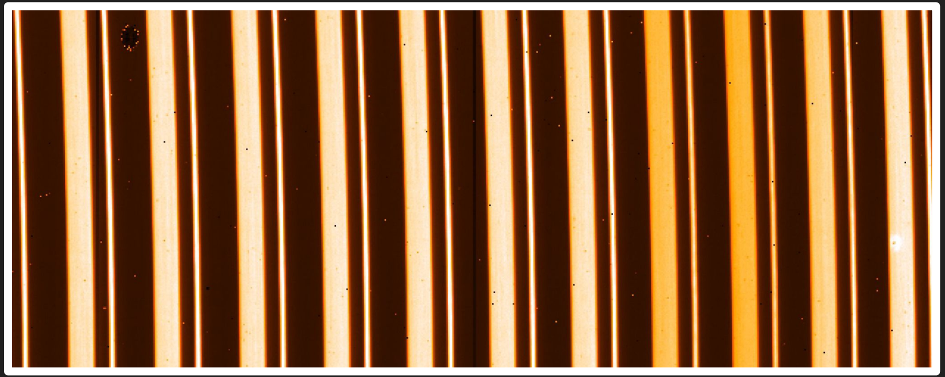
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 2: Answer





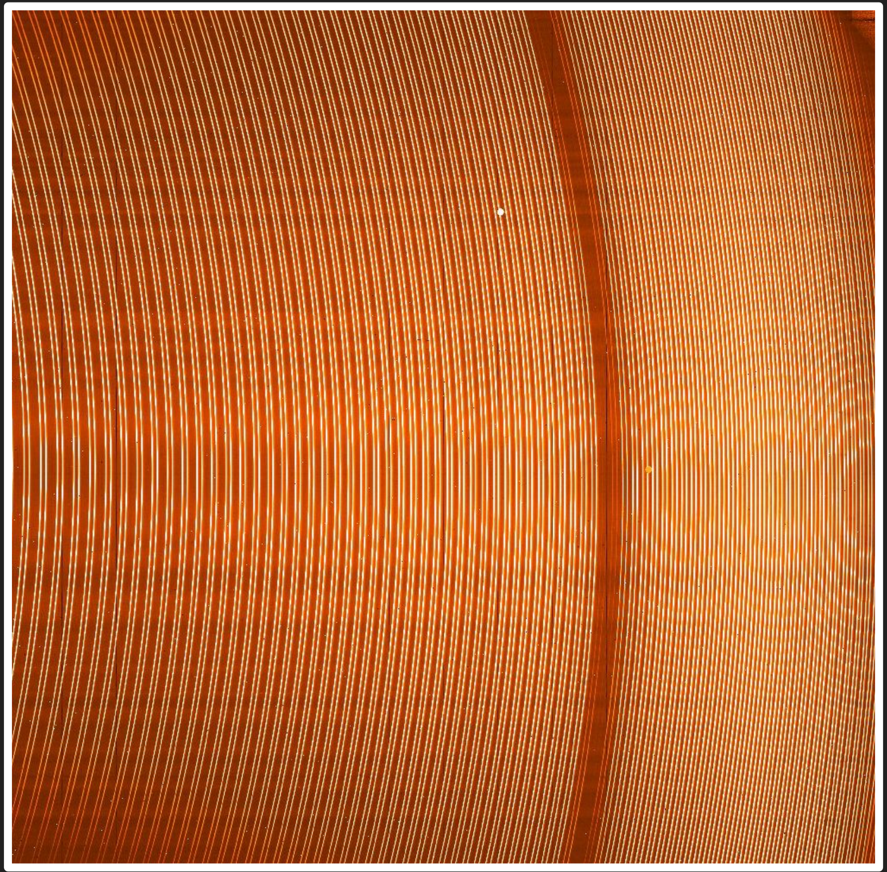
Options:

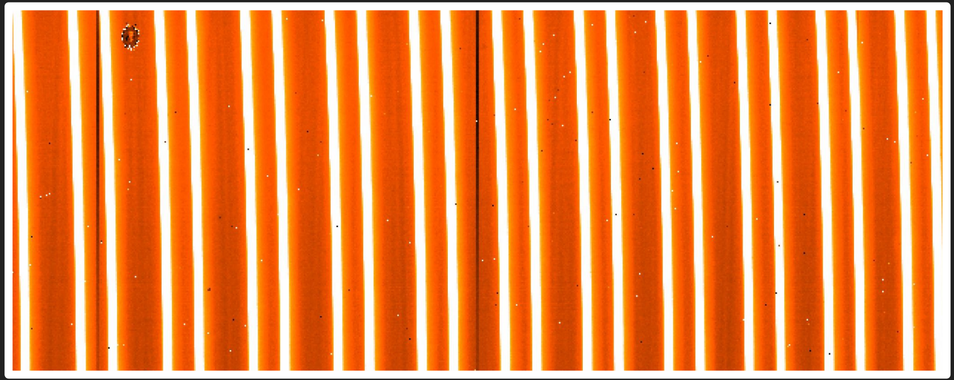
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 2: Answer





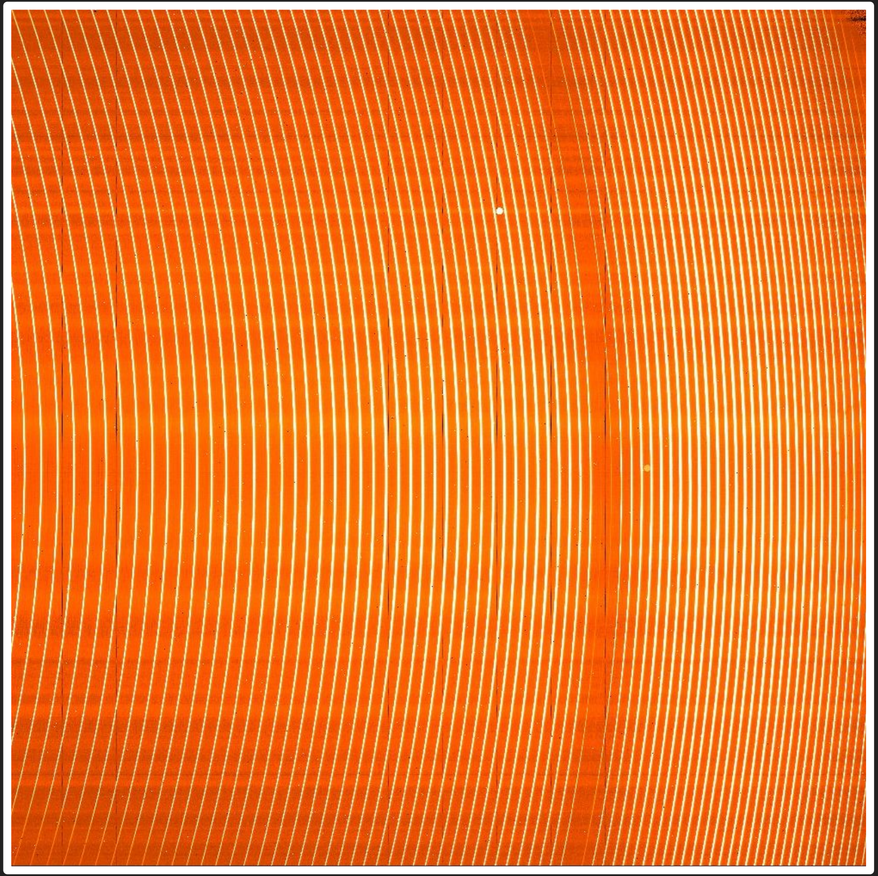
Options:

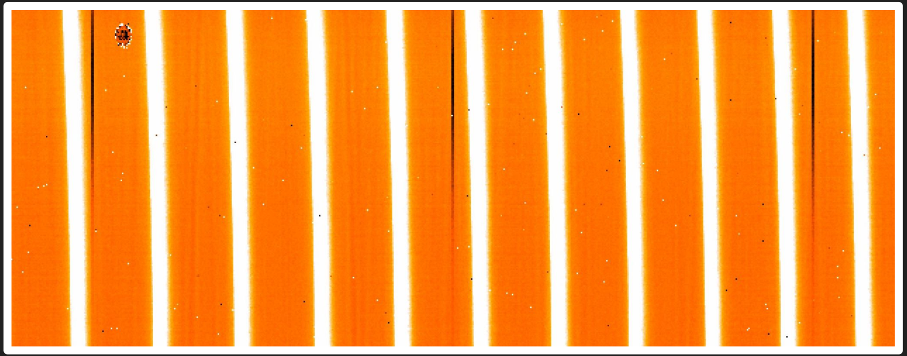
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 3





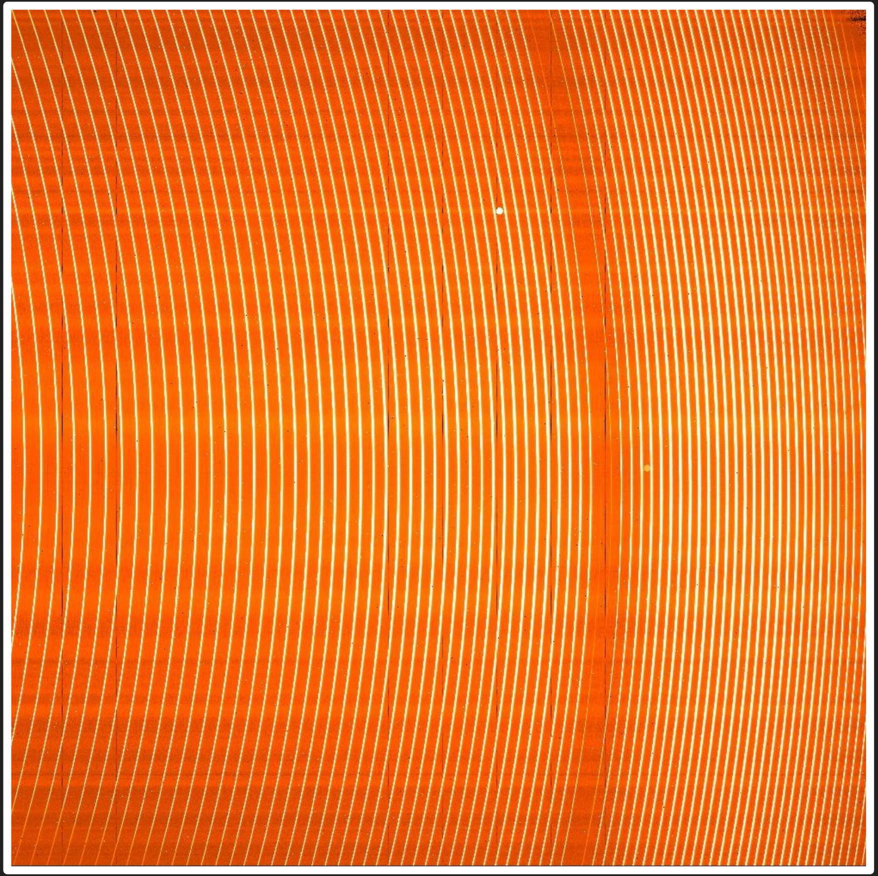
Options:

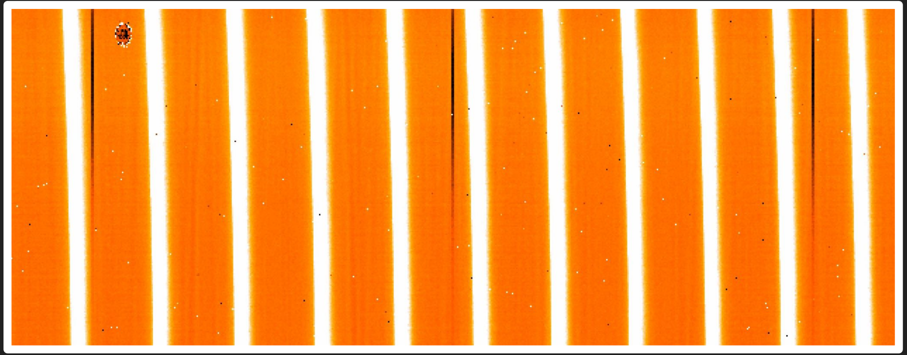
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 3: Answer

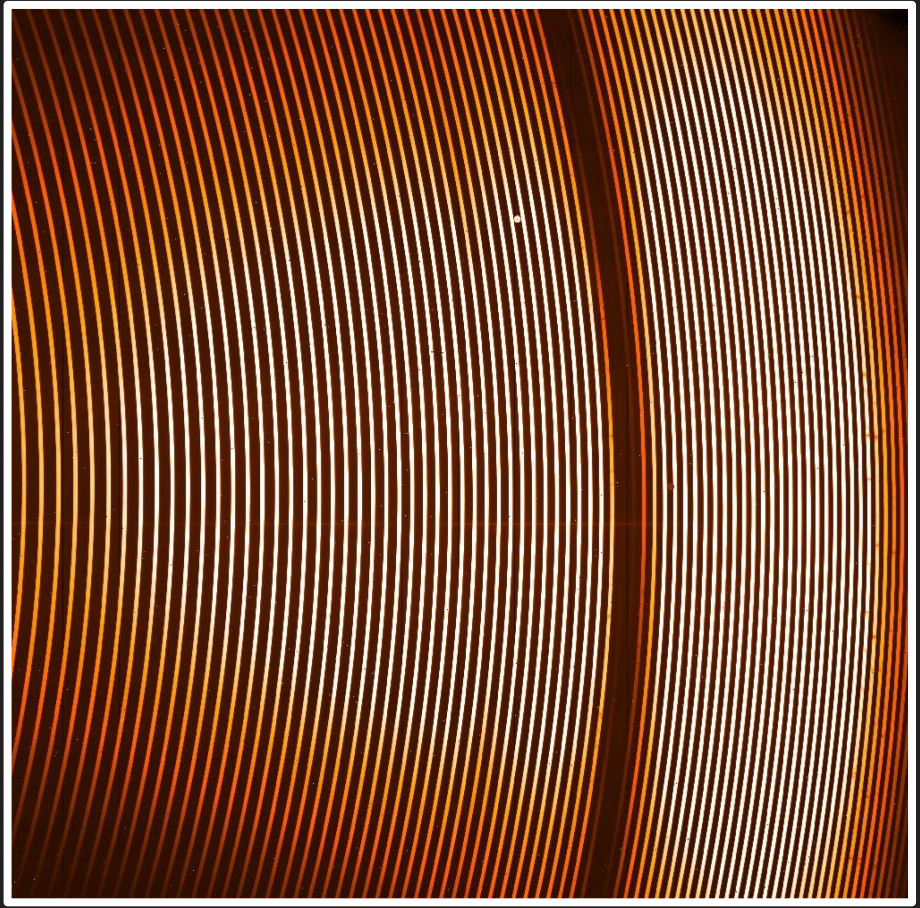


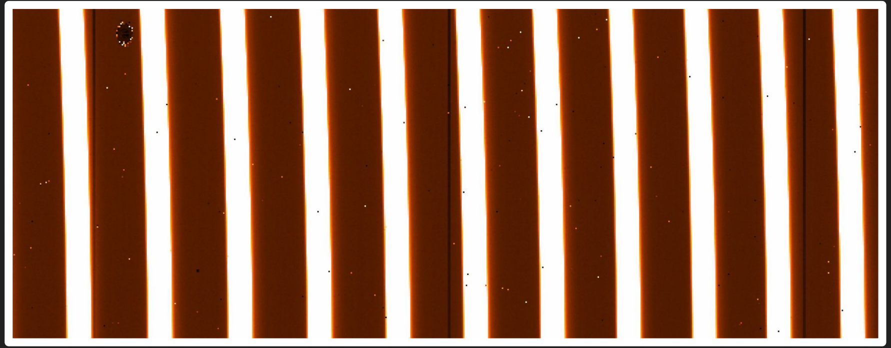


Options:
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:
- HA or HE

Calibration quiz 3: Answer





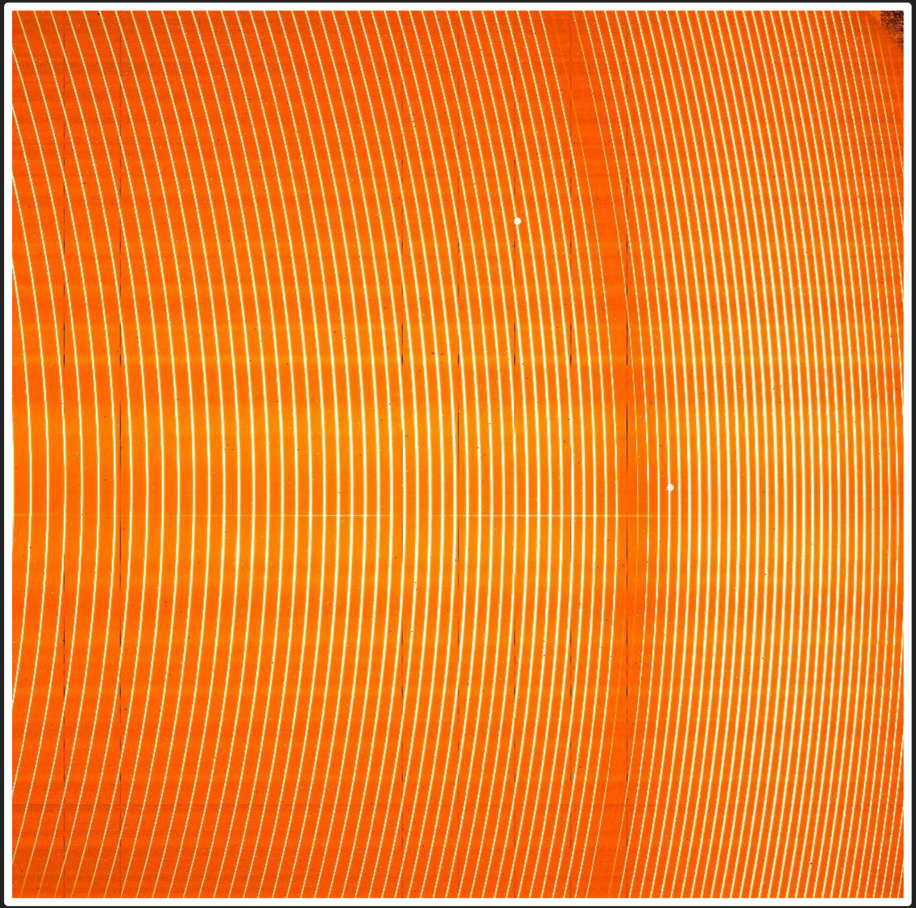
Options:

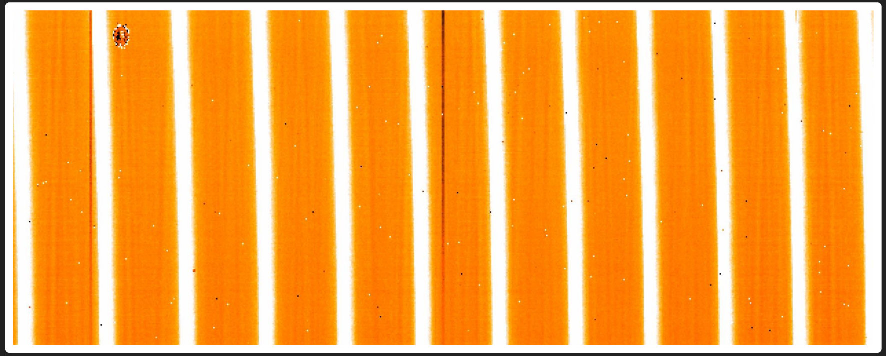
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 3: Answer





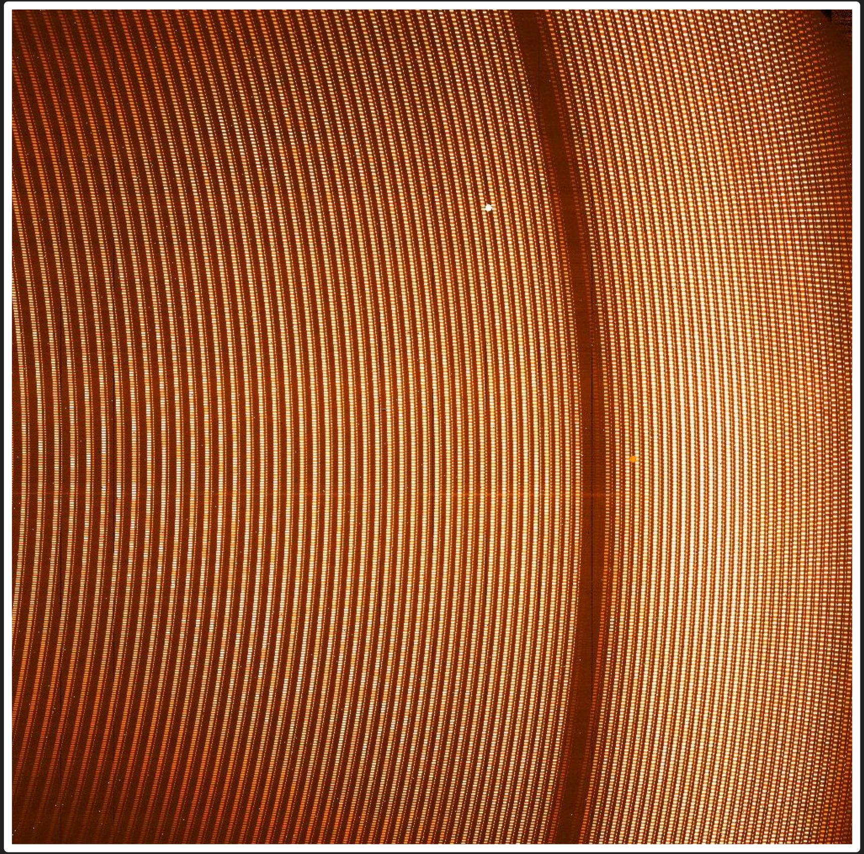
Options:

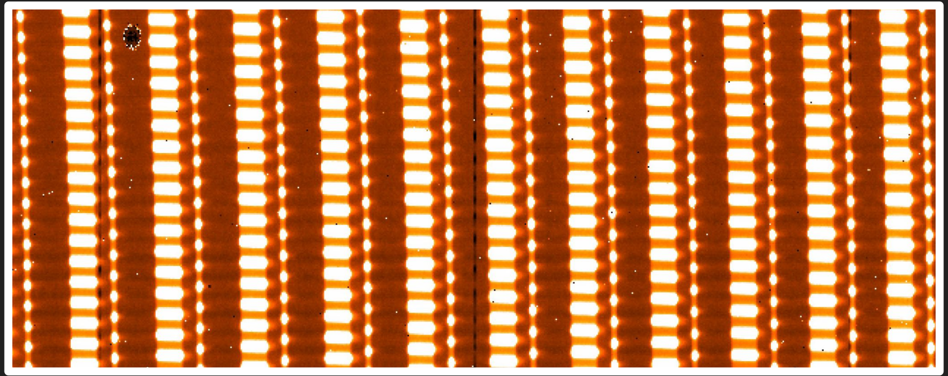
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 4





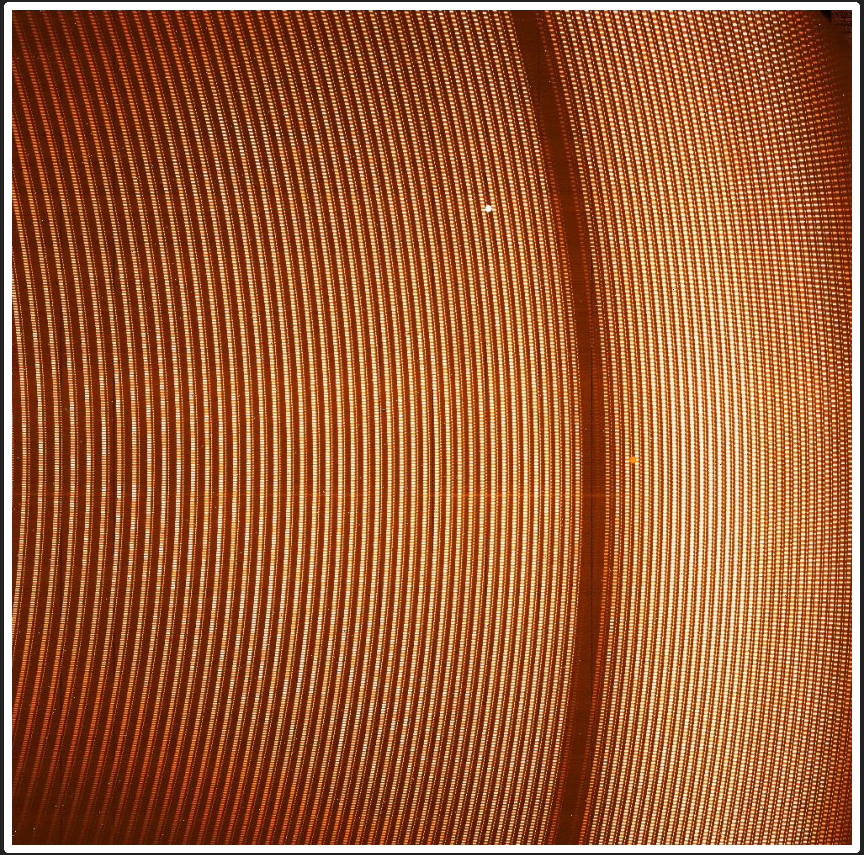
Options:

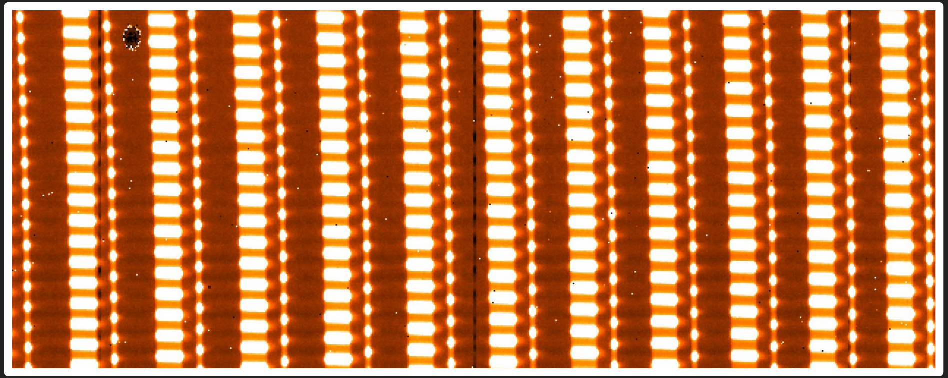
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 4: Answer





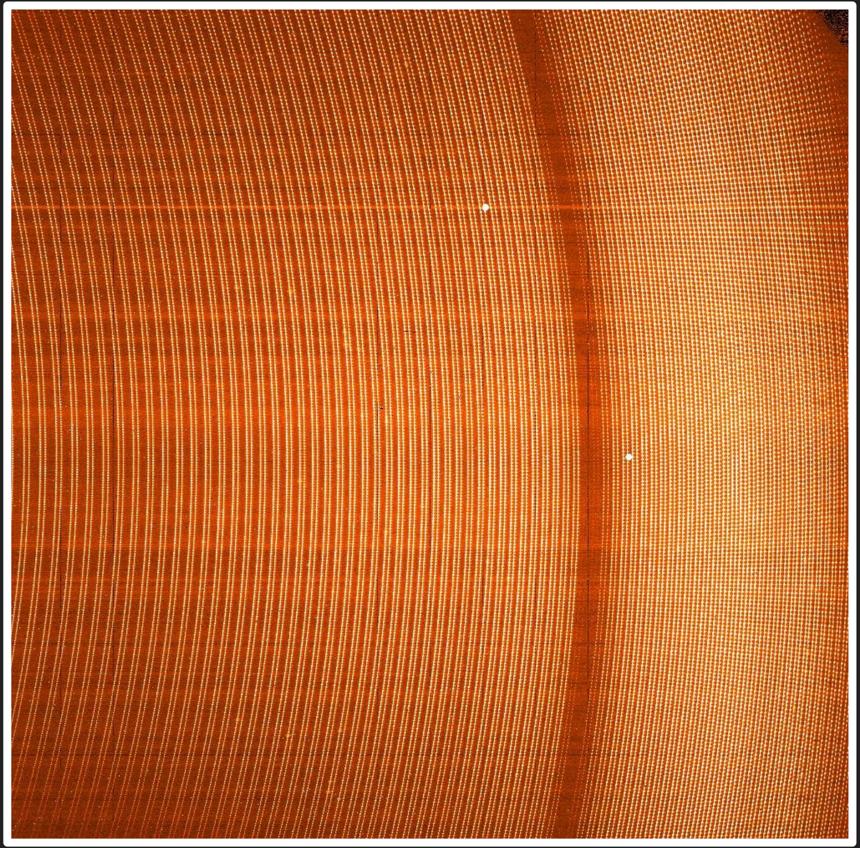
Options:

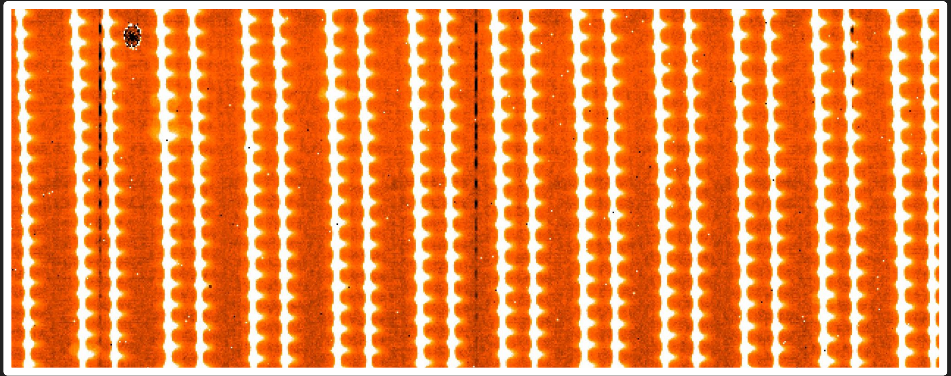
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 4: Answer





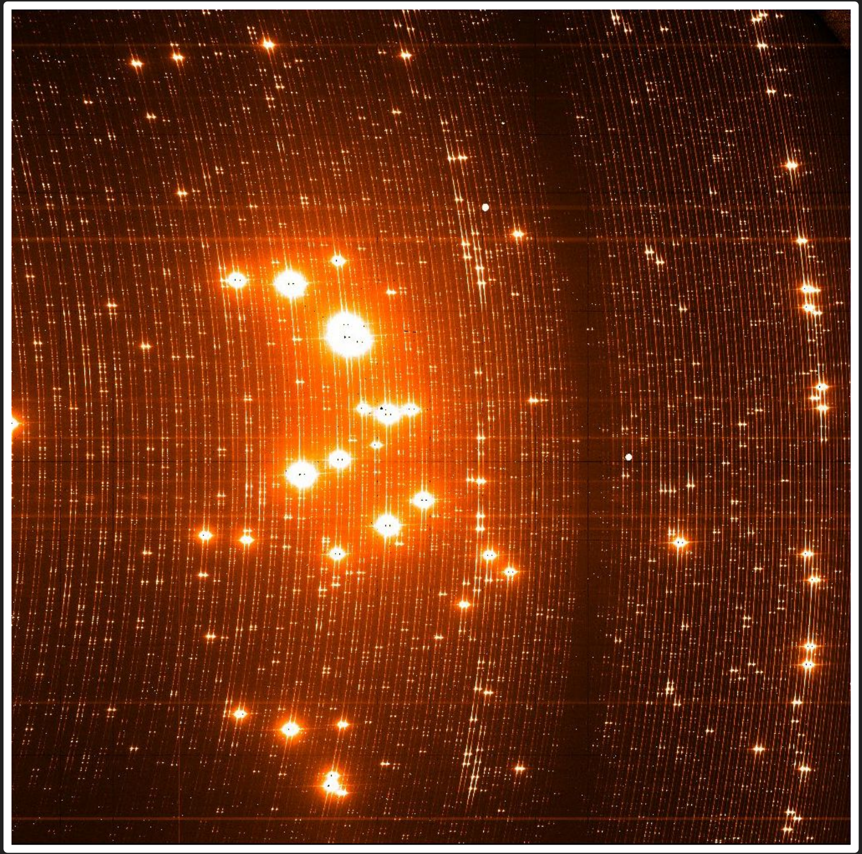
Options:

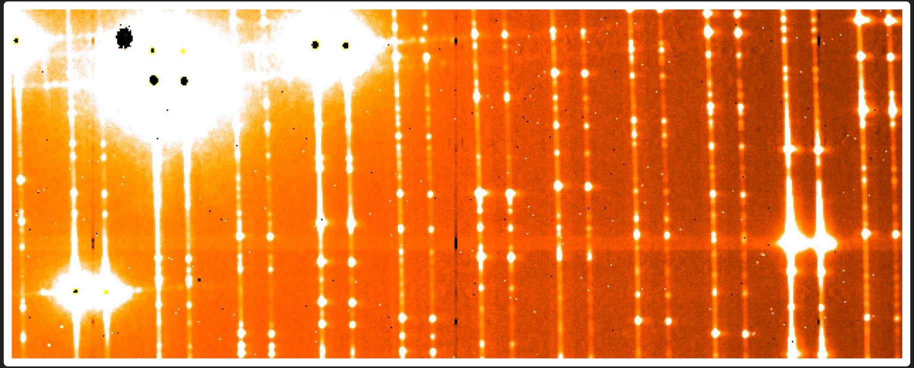
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 5





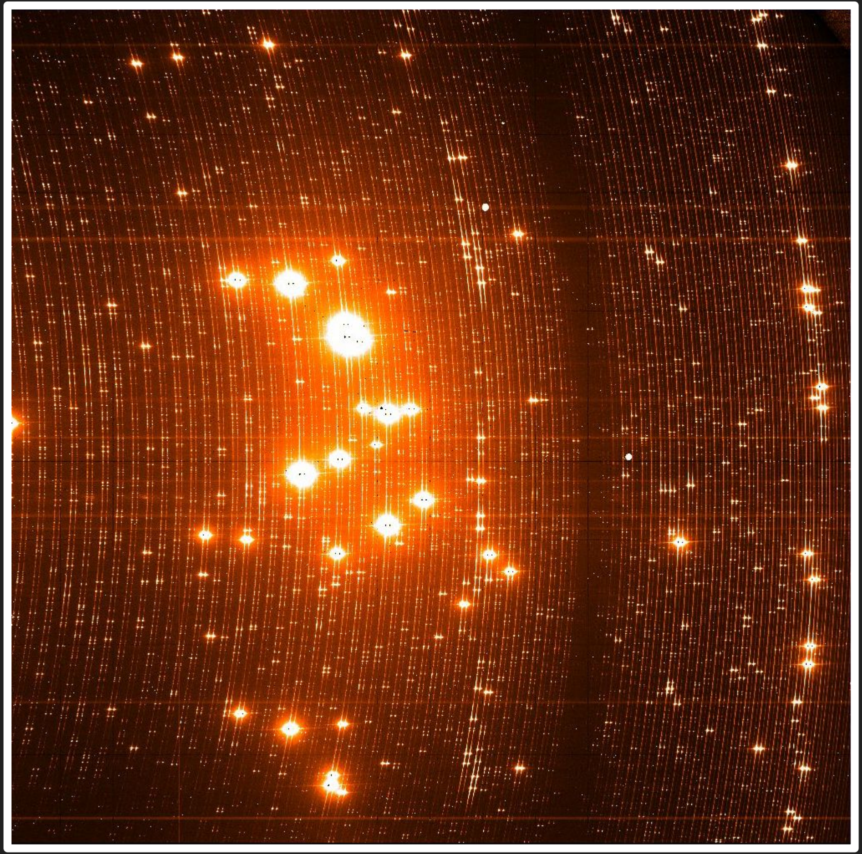
Options:

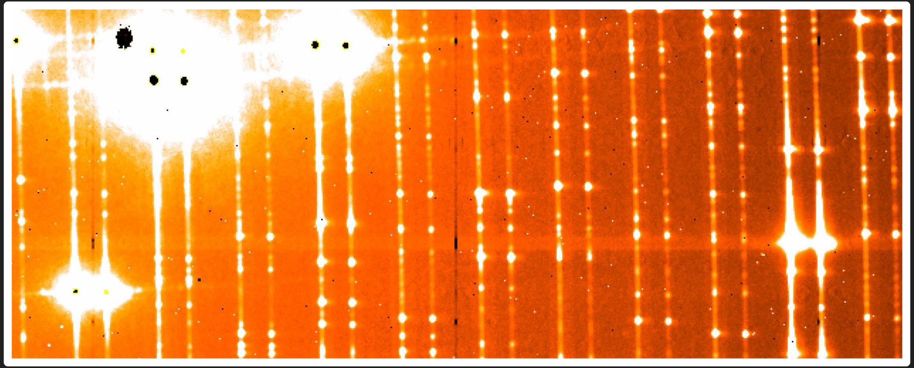
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

- HA or HE

Calibration quiz 5





Options:

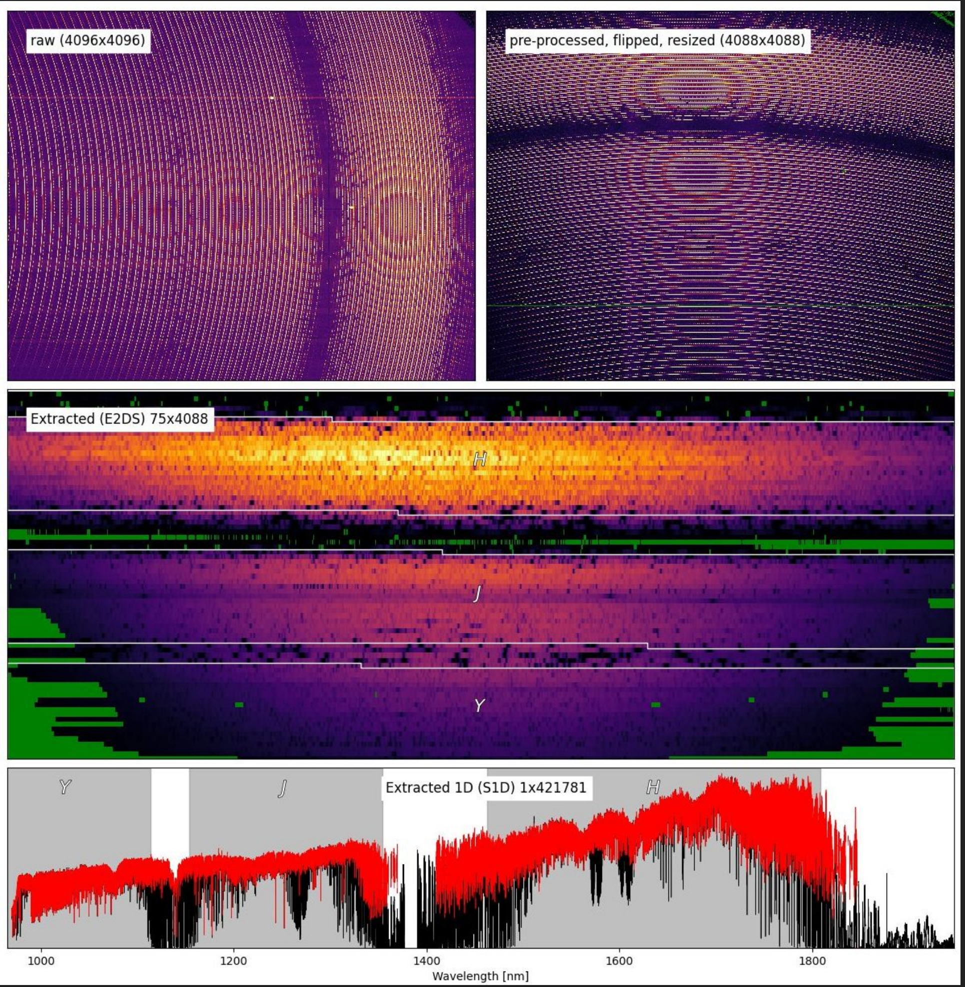
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Mode:

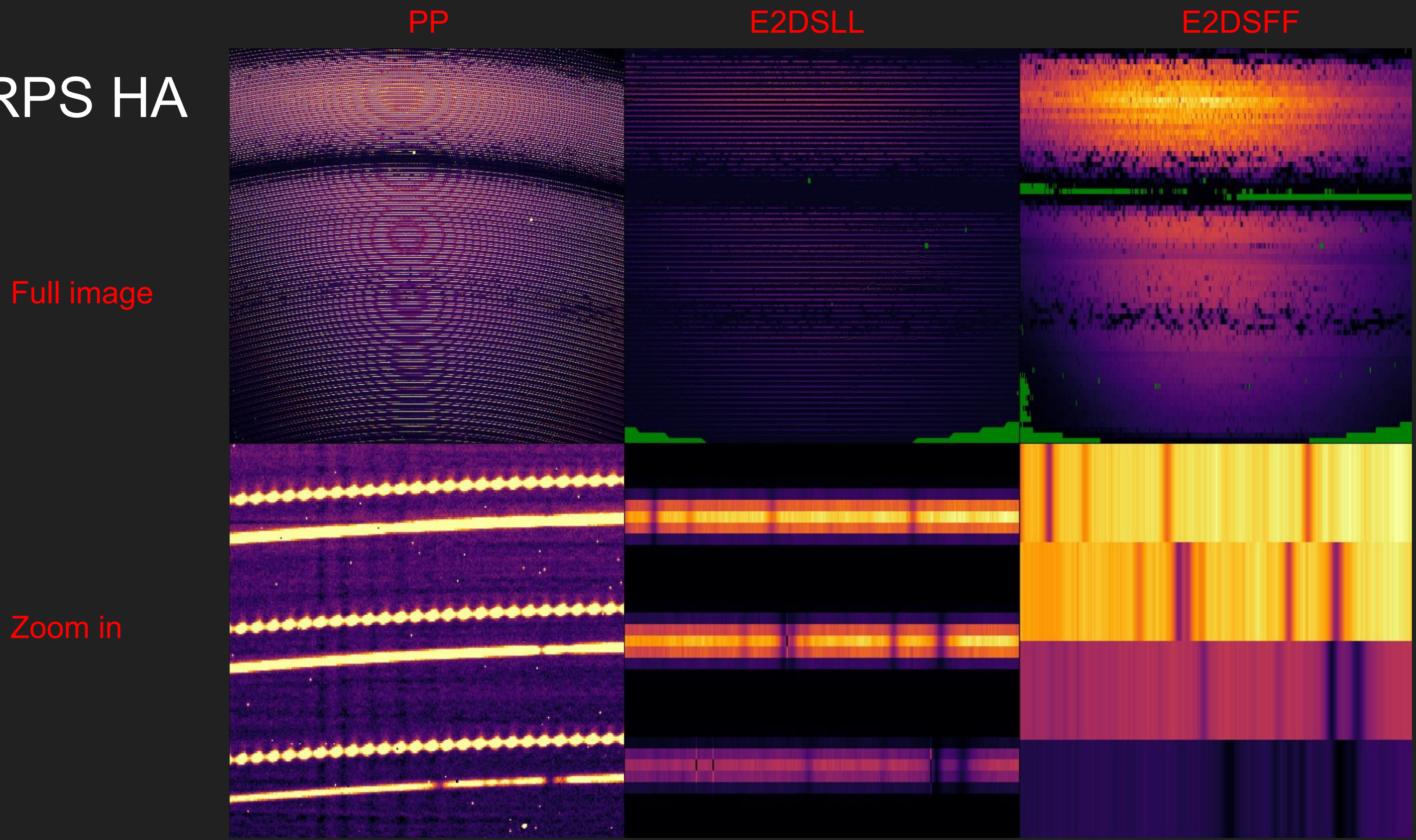
- HA or HE

APERO data

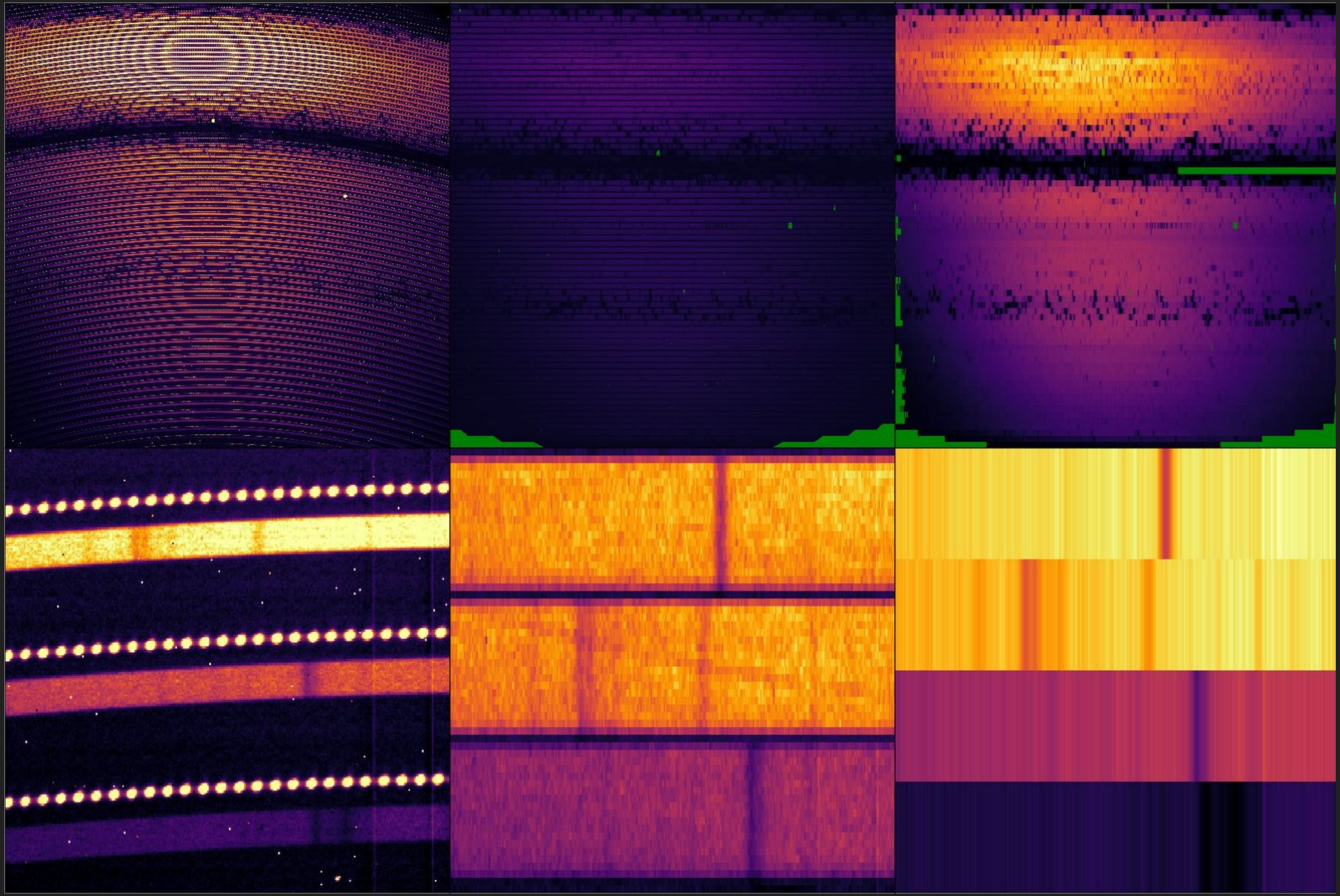
- "Raw" ramp data: 4096 x 4096
  - ESONAME: NIRPS_YYYY-MM-DDThh_mm_ss_sss
    - .../raw/OBS_DIR/{ESONAME}.fits
- Preprocessed data: 4088x4088
    - .../tmp/OBS_DIR/{ESONAME}_pp.fits
- E2DSLL: Pre-extraction image:
  - Shape: order width * 75 x 4088
  - Stacked orders before summing
    - .../red/OBS_DIR/DEBUG_{ESONAME}_pp_e2dsll_{fiber}.fits
- E2DS data: 75 x 4088
  - Extracted file fiber = A or B
    - .../red/OBS_DIR/{ESONAME}_pp_e2ds_{fiber}.fits
  - Extracted + flat fielded file
    - .../red/OBS_DIR/{ESO NAME}_pp_e2dsff_{fiber}.fits
- S1D_v data fiber = A or B
  - 1D spectrum uniform in velocity
    - .../red/OBS_DIR/{ESONAME}_pp_s1d_v_{fiber}.fits
- S1D_w data: 1D spectrum uniform in wavelength
  - 1D spectrum uniform in velocity
    - .../red/OBS_DIR/{ESONAME}_pp_s1d_w_{fiber}.fits



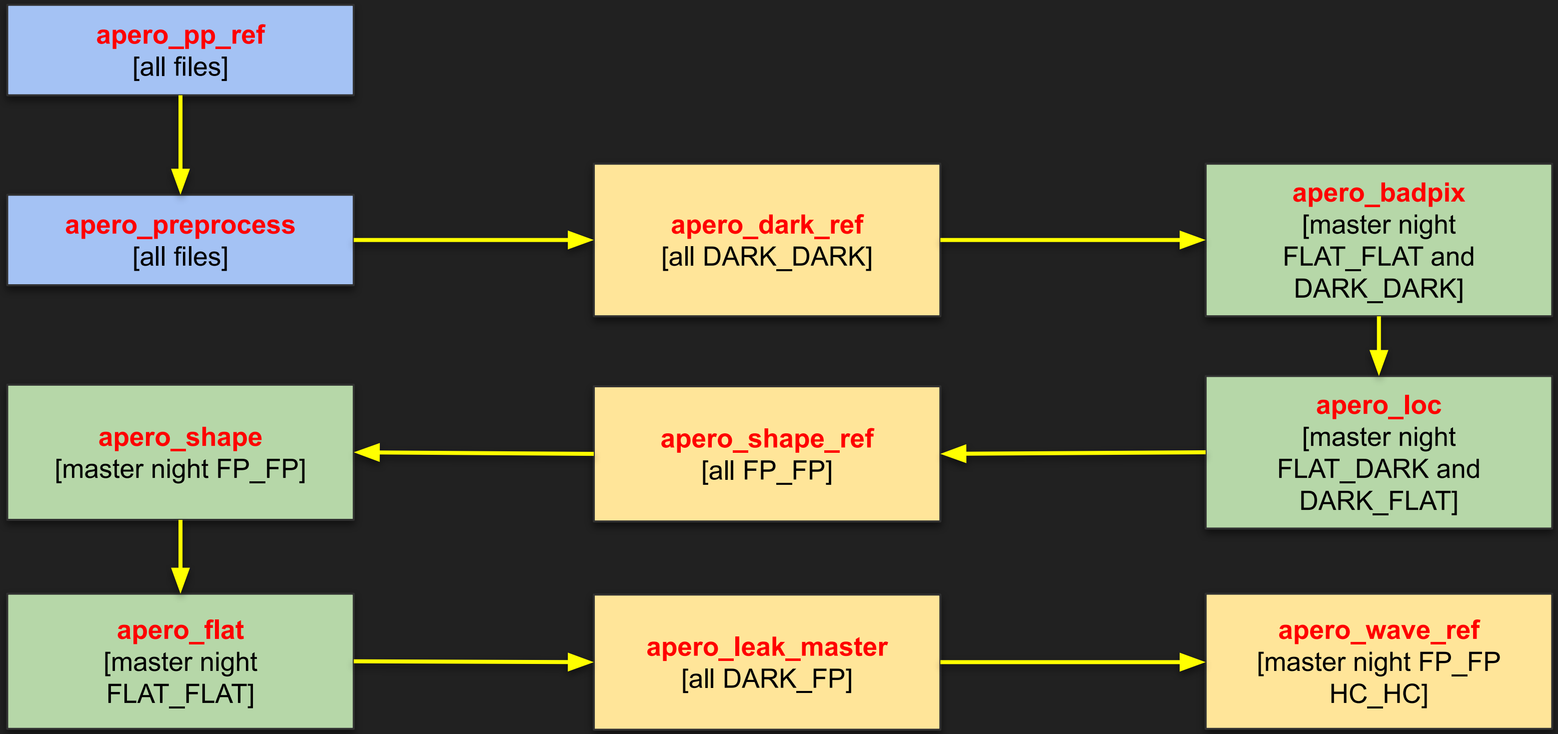
NIRPS HA



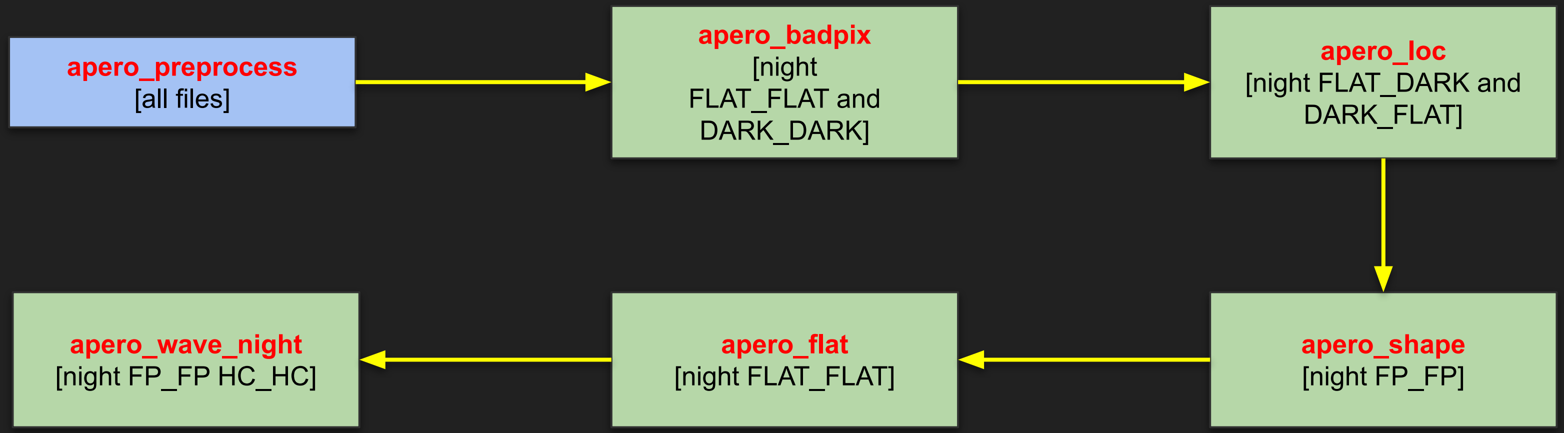
NIRPS HE



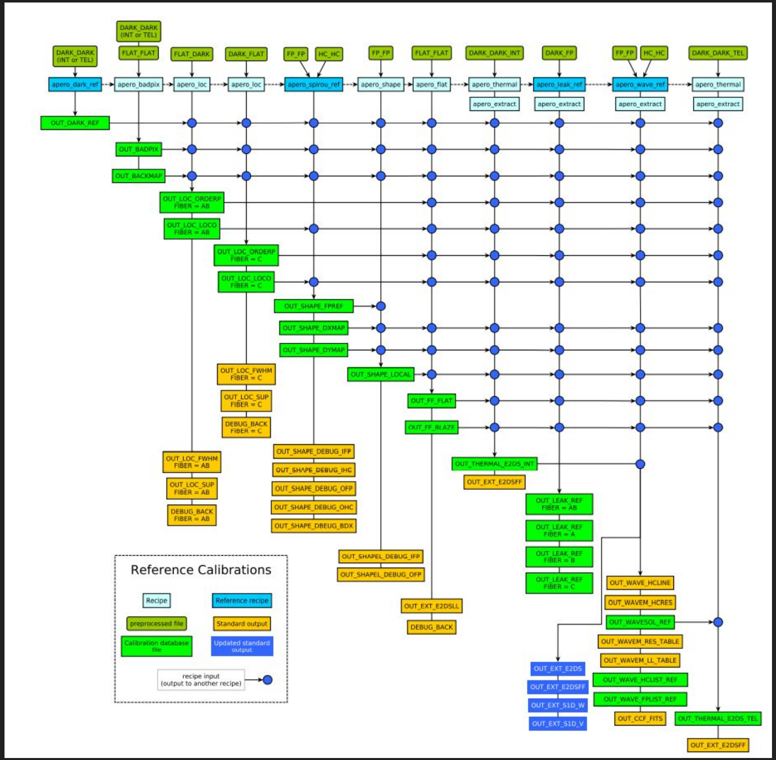
Master calibration sequence

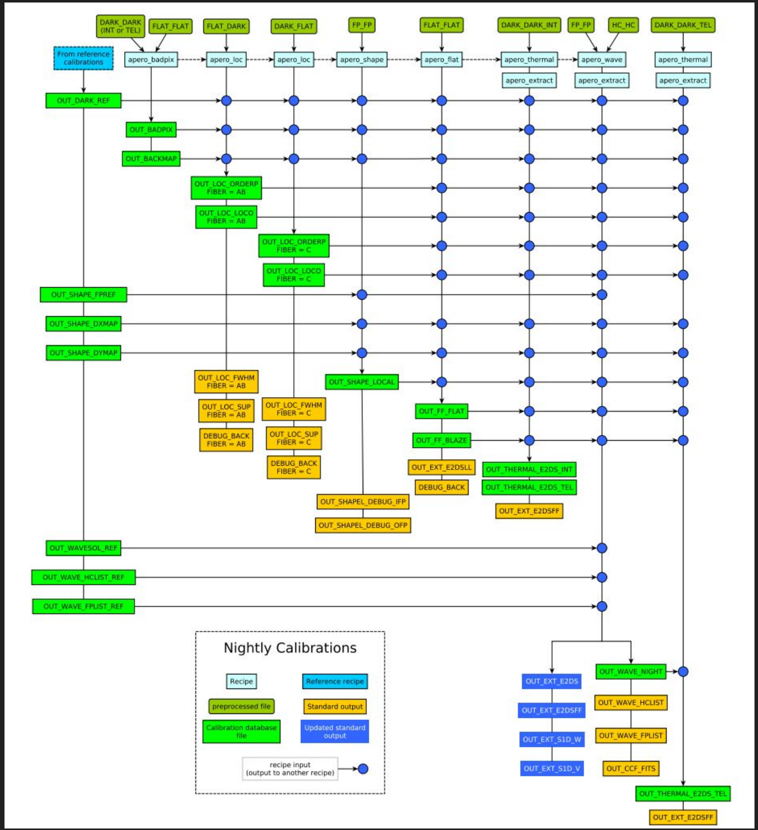


Night calibration sequence



Reference and nightly calibration sequence full flow





Some APERO calibration products: Order localisation

- The y-pixel position of each pixel in each order of the E2DS on the cut down pp image
- All polynomial coefficients are chebyshev polynomials
    - Do not use np.polyval(coeffs, x)
- Science fiber “A”: pp_loco_A.fits
- Calibration fiber “B”: pp_loco_B.fits

- Extension 1: Localisation map
    - Fits Image “LOC_LOCO”
    - Dimensions: 75x4088
- Extension 2: central position localisation coefficient data
    - Fits Table “CENT_TABLE”
    - Columns:
        - ORDER, FIBER, COEFFS_0, COEFFS_1, …, COEFFS_N
- Extension 3: order width localisation coefficient data
    - Fits Table “WIDTH_TABLE”
    - Columns:
        - ORDER, FIBER, COEFFS_0, COEFFS_1, …, COEFFS_N
- Extension 4: parameter data
    - Parameters that were used in this reduction
    - Fits Table

```
# define domain and pixel vector
domain = [0, 4088]
xvector = np.arange(4088)
# transform to a -1 to 1 domain
domain_cheby = 2 * (xvector - domain[0]) / (domain[1] - domain[0]) - 1
# fit values using the domain and coefficients
yvector = np.polynomial.chebyshev.chebval(domain_cheby, coeffs)
```

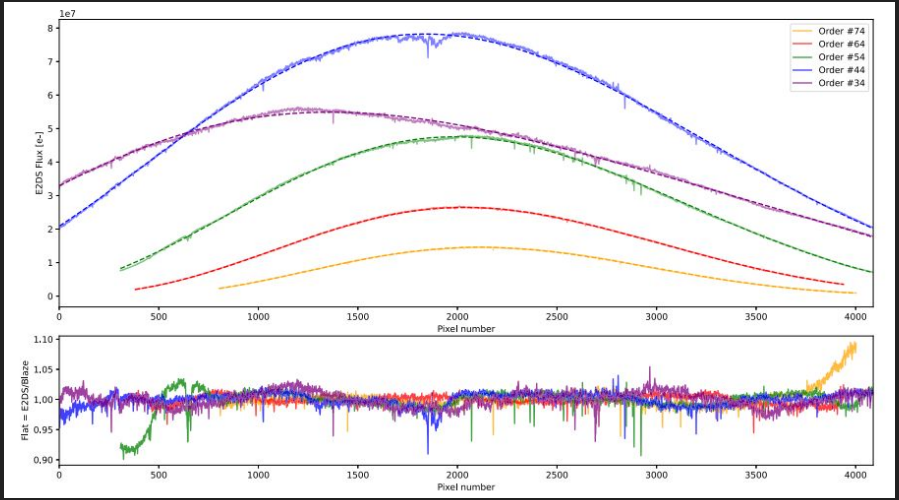
```
from astropy.io import fits
# use extension
loco_a = fits.getdata(filename, ext=1)
# or use extension name
loco_a = fits.getdata(filename, extname='LOC_LOCO')
```

```
from astropy.table import Table
# use extension
cent_table = Table.read(filename, ext=3)
# or use extension name
cent_table = Table.read(filename, extname='CENT_TABLE')
```

```
from astropy.table import Table
# use extension
width_table = Table.read(filename, ext=3)
# or use extension name
width_table = Table.read(filename, extname='WIDTH_TABLE')
```

Some APERO calibration products: Blaze fit

- APERO extract spectra are not saved with blaze correction
- Must apply the blaze correction
- Science fiber “A”: pp_blaze_A.fits
- Calibration fiber “B”: pp_blaze_B.fits



- Extension 1: blaze correct
  - Fits Image: “FF_BLAZE”
  - Dimensions: 75x4088
- Extension 2: parameter data
  - Parameters that were used in this reduction
  - Fits Table

```
from astropy.io import fits
# use extension
blaze = fits.getdata(filename, ext=1)
# or use extension name
blaze = fits.getdata(filename, extname='FF_BLAZE')
# correct image
blaze_cor_image = image / blaze
```

Some APERO calibration products: Wavelength solution

- Wavelength solution (wavelength value of each pixel in the E2DS)
- All polynomial coefficients are chebyshev polynomials
    - Do not use np.polyval(coeffs, x)
- Range: 965 nm - 1947 nm
- Reference wave sol: pp_e2dsff_A_wavesol_ref_A.fits
- Night wave sol: pp_e2dsff_A_wave_night_A.fits
- Extension 1: wave map
    - Fits Image: “WAVESOL_REF” or “WAVE_NIGHT”
    - Dimensions: 75x4088
- Extension 2: wavelength coefficient data
    - Fits Table: “COEFF_TABLE”
    - Columns:
        - ORDER, COEFFS_0, COEFFS_1, …, COEFFS_N
- Extension 3: parameter data
    - Parameters that were used in this reduction
    - Fits Table
- Wavelength also added to the header of all extracted files
    - WAVEFILE // Wavelength solution file name
    - WAVEORDN // Number of orders (N)
    - WAVEDEGN // Degree of polynomial fit (M)
    - WAVEXXXX // Coefficient order n={0, N-1} Coefficient fits m={0, M}
      XXXX = (n*M) + m
    - WAVECYY // Echelle order number for order YY
- Wavelength coefficients also added to e2ds “ORDER_TABLE”

```python
# define domain and pixel vector
domain = [0, 4088]
xvector = np.arange(4088)
# transform to a -1 to 1 domain
domain_cheby = 2 * (xvector - domain[0]) / (domain[1] - domain[0]) - 1
# fit values using the domain and coefficients
yvector = np.polynomial.chebyshev.chebval(domain_cheby, coeffs)
```

```python
from astropy.io import fits
# use extension
wavemap = fits.getdata(filename, ext=1)
# or use extension name
wavemap = fits.getdata(filename, extname='WAVESOL_REF')
```

```python
from astropy.io import fits
# use extension
wavemap = fits.getdata(filename, ext=1)
# or use extension name
wavemap = fits.getdata(filename, extname='WAVE_NIGHT')
```

```python
from astropy.table import Table
# use extension
wavetable = Table.read(filename, ext=2)
# or use extension name
wavetable = Table.read(filename, extname='COEFF_TABLE')
```

```python
# get the keys with the wavelength polynomials from header
wave_hdr = hdr['WAVE0*']
# concatenate into a numpy array
wave_poly = np.array([wave_hdr[i] for i in range(len(wave_hdr))])
# get the number of orders
nord = hdr['WAVEORDN']
# get the per-order wavelength solution
wave_poly = wave_poly.reshape(nord, len(wave_poly) // nord)
```

Which calibration file?

- APERO stores all calibration files in database
  - Uses closest in time to the file being calibrated
  - All APERO reduced files except preprocessed files (and some calibration files) are calibrated.
- All calibrated files are given keywords linking to the best calibration at the time of calibrating that file
  - CDBXXXX: The filename of the best calibration at time of calibrating
  - CDTXXXX: The MJD of the best calibration at time of calibrating
  - XXXX = DARK, BAD, BAC, ORDP, LOCO, BLAZE, WAVE etc
- Good check for nightly calibrations is to do CDTXXXX - MJDMID

Exercise 3: Calibrating a 2D image

Step 1: Find the localization files (A and B)

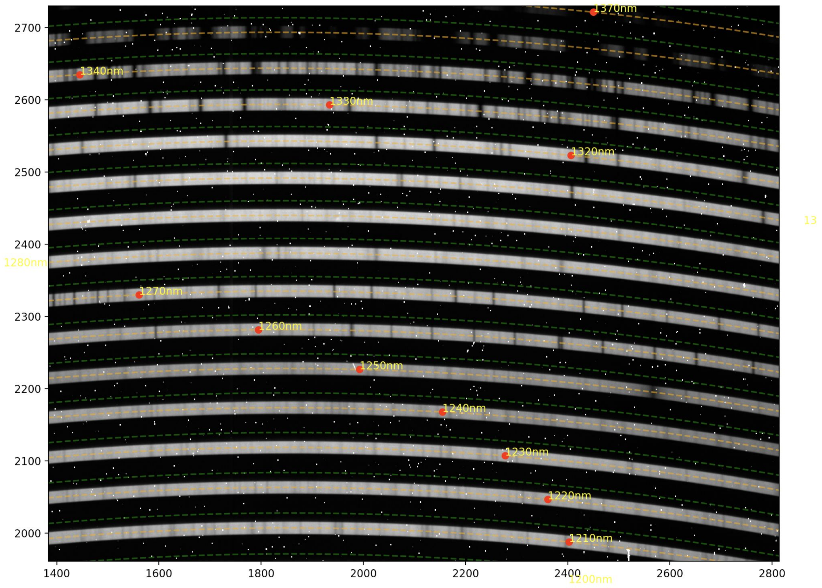
Step 2: Find the wavelength solution file

Step 3: Find the preprocessed Proxima image

Step 4: In python overplot the localization traces on the preprocessed image

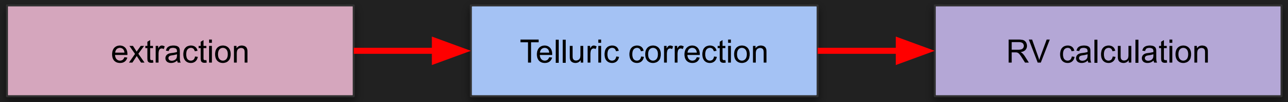
Step 5: In python add the wavelengths at 10 nm intervals to the step 4 plot

i.e. at …, 1200nm, 1210nm, 1220nm, 1230nm, …



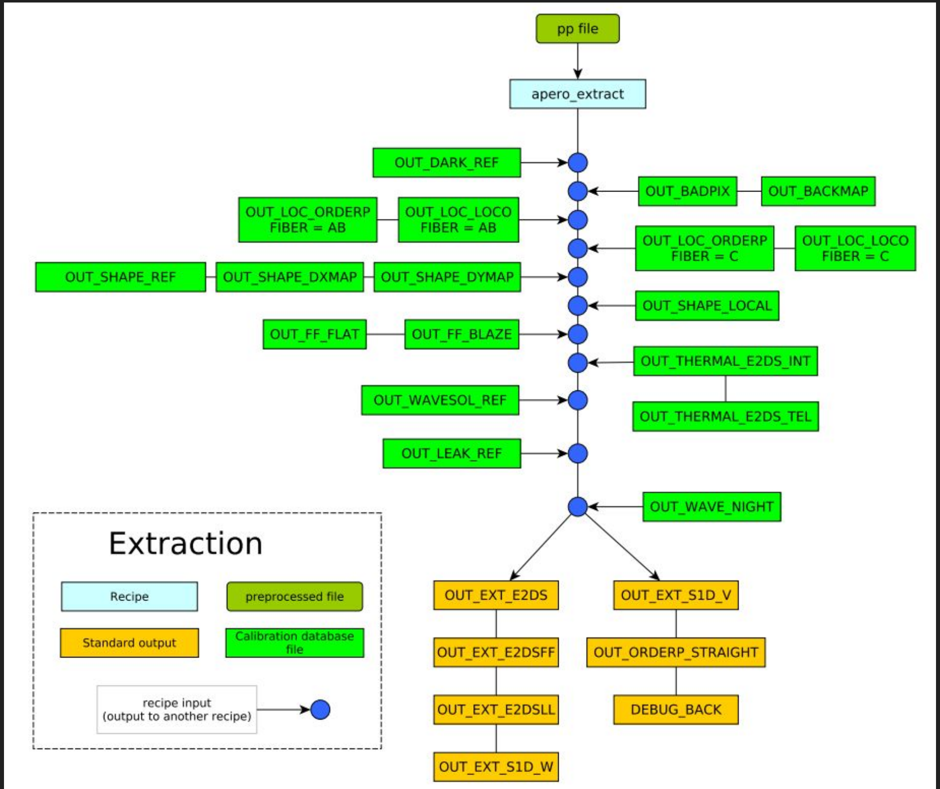
What happens after calibration?

- After a reference sequence is processed night calibrations can be processed
- After night calibrations the route forward depends on what observation was done
- The type of observation determines how far along the pipeline we need to go
- Types of observation:
  - Hot star (for telluric correction)
  - Spectral/RV observation

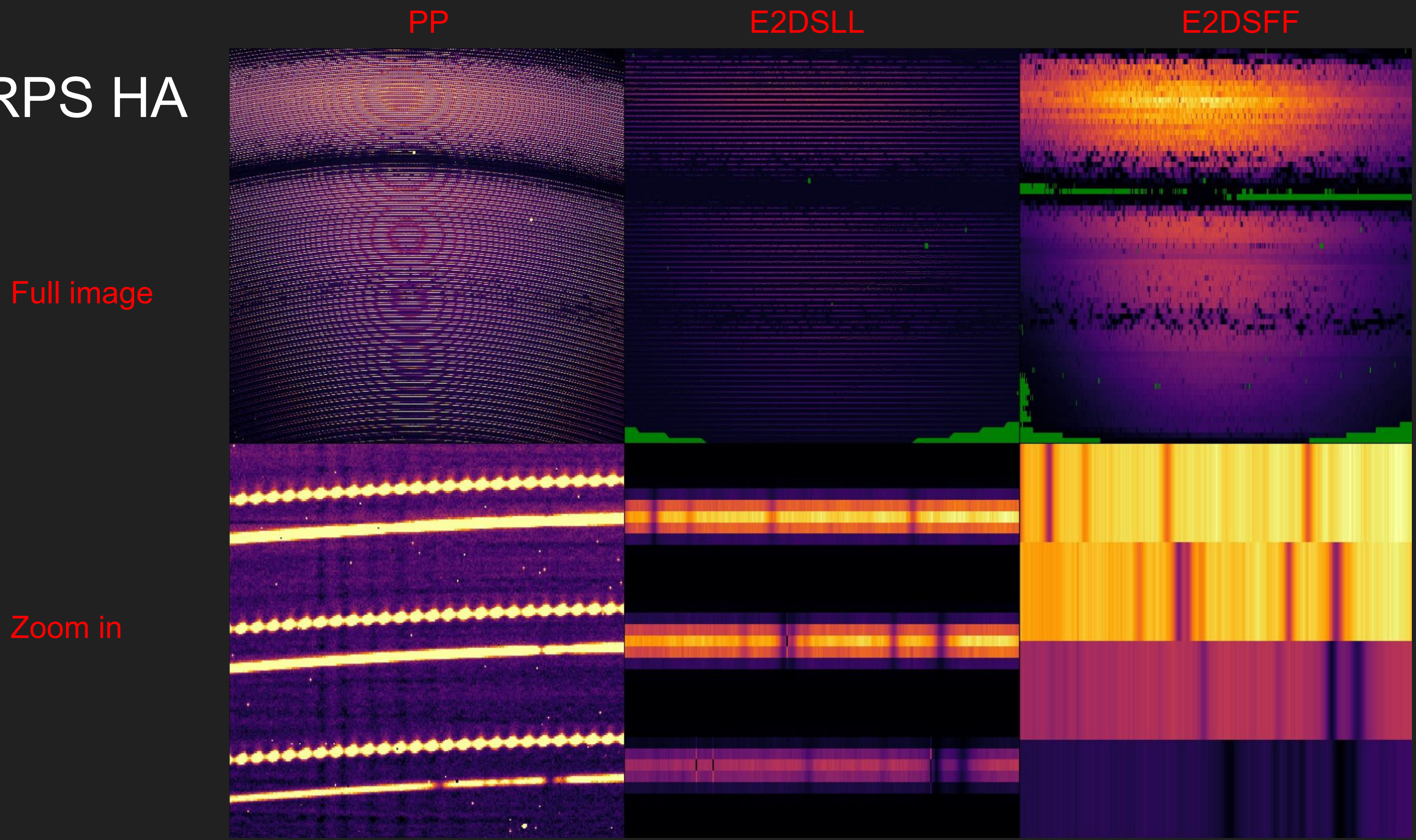


What happens during extraction?

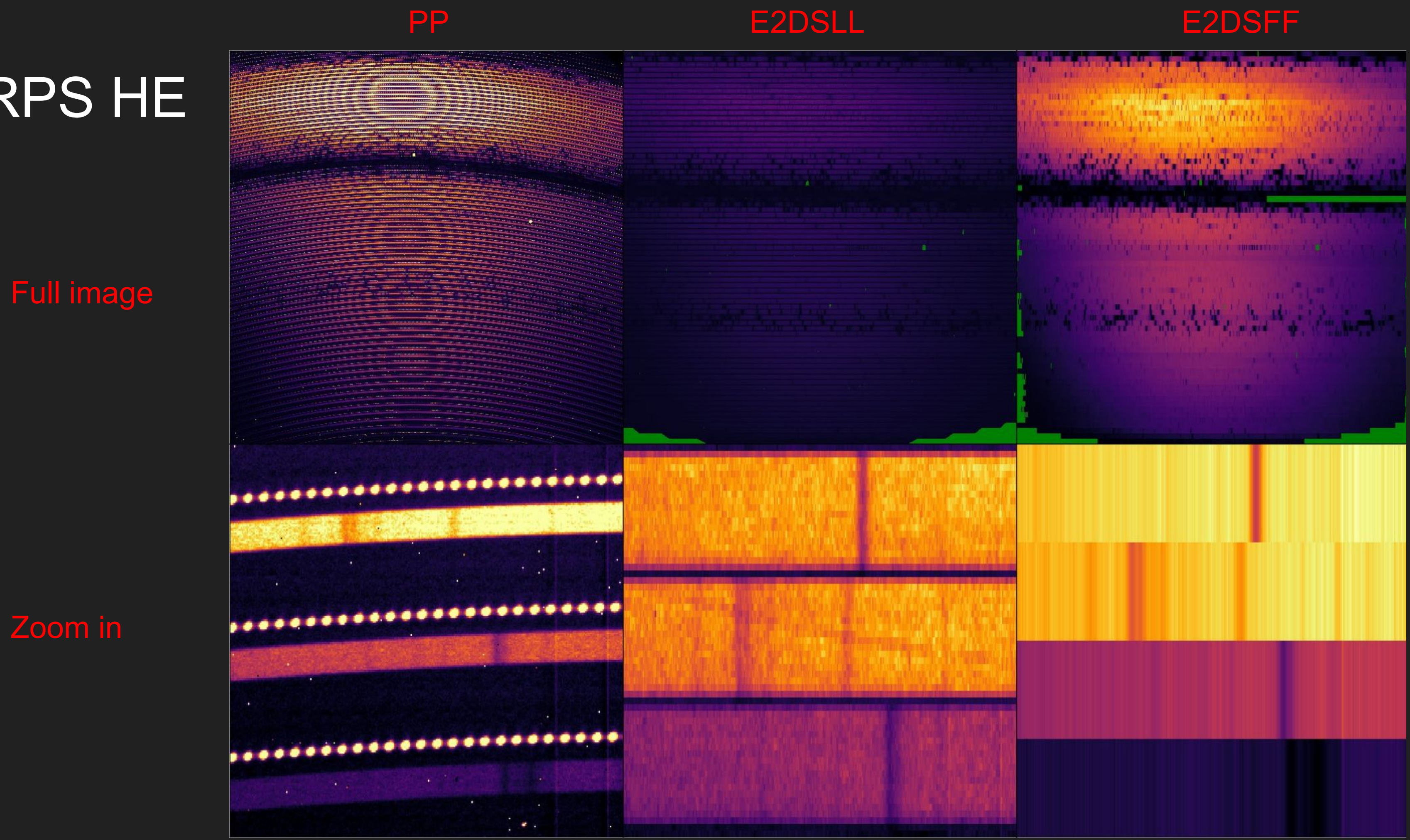
- Start with preprocessed file
- Calibrate
- Straighten orders
  - Correct for tilt
- Optimally extract each order
  - Filter cosmics
- Calculate BERV
- Calculate SNR per order
- Correct for leakage from FP
- Apply flat correction
- Create 2D and 1D outputs



NIRPS HA

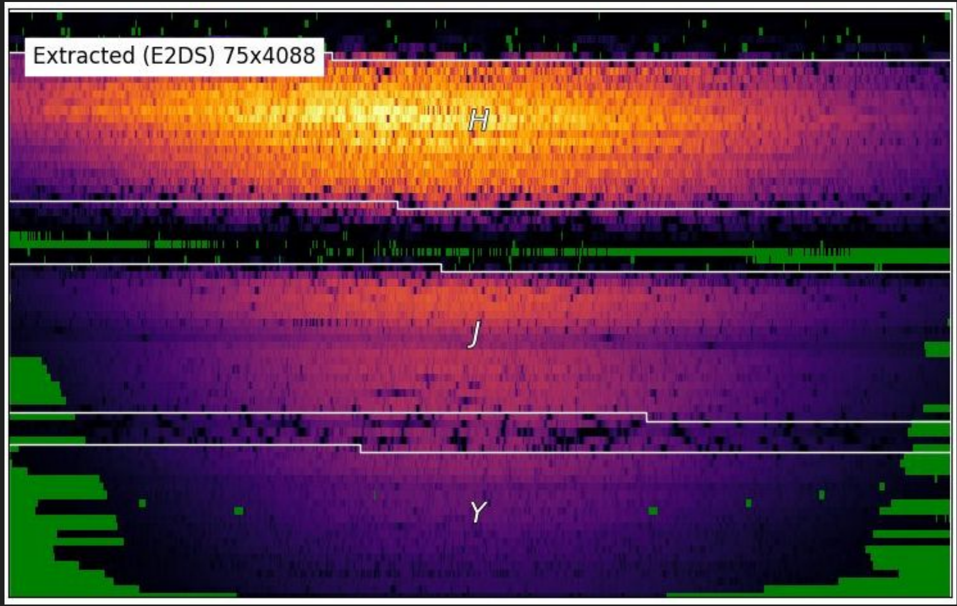


NIRPS HE



The 2D extracted file (E2DS, E2DSFF)

- E2DS = extracted file
  - Science fiber “A”: pp_e2ds_A.fits
  - Calibration fiber “B”: pp_e2ds_B.fits
- E2DSFF = extraction + flat fielded file
  - Science fiber “A”: pp_e2dsff_A.fits
  - Calibration fiber “B”: pp_e2dsff_B.fits
- Extension 1: extracted image
  - Fits Image: “EXT_E2DS” or “EXT_E2DS_FF”
  - Dimensions: 75x4088
- Extension 2: Order table
  - Fits Table: “ORDER_TABLE”
  - Columns:
    - order_num, echelle_num
    - wave {min, max, med, mean} per order
    - snr, ncosmic, fluxval
    - e2ds {min, max, med, mean} per order
    - e2dsff {min, max, med, mean} per order
    - flat {min, max, med, mean} per order
    - Blaze {min, max, med, mean} per order
    - Localisation position coefficients
    - Localisation width coefficients
    - Wave coefficients
- Extension 3: parameter data
  - Parameters that were used in this reduction
  - Fits Table
- Wavelength also added to the header of all extracted files
  - See wave calibration slide



Exercise 4: Extraction, making the S1D

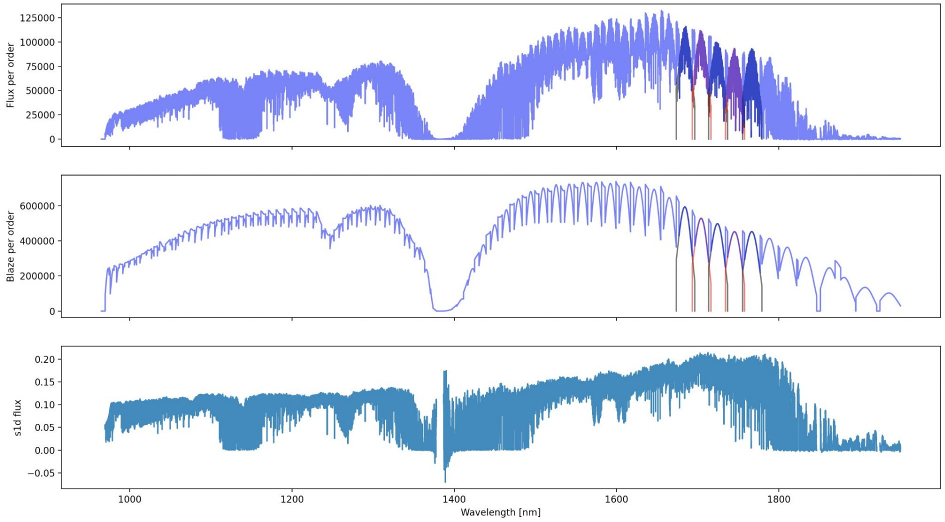
Step 1: Find the e2dsff A file for Proxima

Step 2: Find the associated blaze file using the e2dsff header

Step 3: Get the wavelength solution from the e2dsff (header or ORDER_TABLE extension)

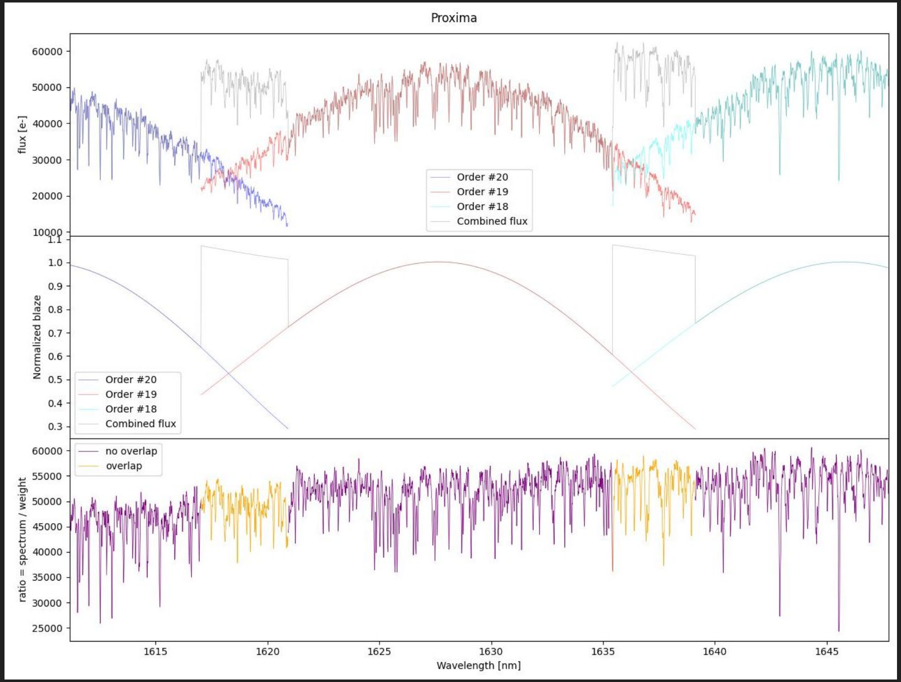
Step 4: In python construct a 1D wavelength grid

Step 5: In python calculate an S1D using the blaze and the flux



The 1D extracted file (s1d_w, s1d_v)

- S1D_W = 1D spectrum constant in wavelength bins
  - Science fiber “A”: pp_s1d_w_A.fits
  - Calibration fiber “B”: pp_s1d_w_B.fits
- S1D_V = 1D spectrum constant in velocity bins
  - Science fiber “A”: pp_s1d_v_A.fits
  - Calibration fiber “B”: pp_s1d_v_B.fits
- Extension 1: extracted image
  - Fits Table: “EXT_S1D_V” or “EXT_S1D_W”
  - Dimensions: 1x4088
  - Columns:
    - Wavelength
    - Flux
    - Eflux
    - Weight
- Extension 2: parameter data
  - Parameters that were used in this reduction
  - Fits Table
- Same header as E2DS, E2DSFF files



Extraction files files

name	description	HDR[DRSOUTID]	file type	suffix	basename	fibers	input file
EXT_E2DS	Extracted 2D spectrum	EXT_E2DS	.fits	_e2ds	-	A, B	DRS_PP
EXT_E2DS_FF	Extracted + flat-fielded 2D spectrum	EXT_E2DS_FF	.fits	_e2dsff	-	A, B	DRS_PP
EXT_E2DS_LL	Pre-extracted straighted stacked spectrum	EXT_E2DS_LL	.fits	_e2dsll	-	A, B	DRS_PP, FLAT_FLAT
EXT_LOCO	Straightened localisation file	EXT_LOCO	.fits	_e2dsloco	-	A, B	DRS_PP
EXT_S1D_W	1D stitched spectrum (constant wavelength binning)	EXT_S1D_W	.fits	_s1d_w	-	A, B	DRS_PP
EXT_S1D_V	1D stitched spectrum (constant velocity binning)	EXT_S1D_V	.fits	_s1d_v	-	A, B	DRS_PP
EXT_FPLIST	FP lines identified from extracted FP fiber	EXT_FPLIST	.fits	_ext_fplines	-	A, B	EXT_E2DS, EXT_E2DS_FF

- Extraction is attempted on every extracted hot star and science file
- Some may fail QC and not be in the telluric database
    - Header key “QCC_ALL” = T if all quality control passed (F otherwise)
    - Header keys for each individual quality control

All files definitions available in documentation:

http://apero.exoplanets.ca/auto/file_definitions/nirps_ha/files.html

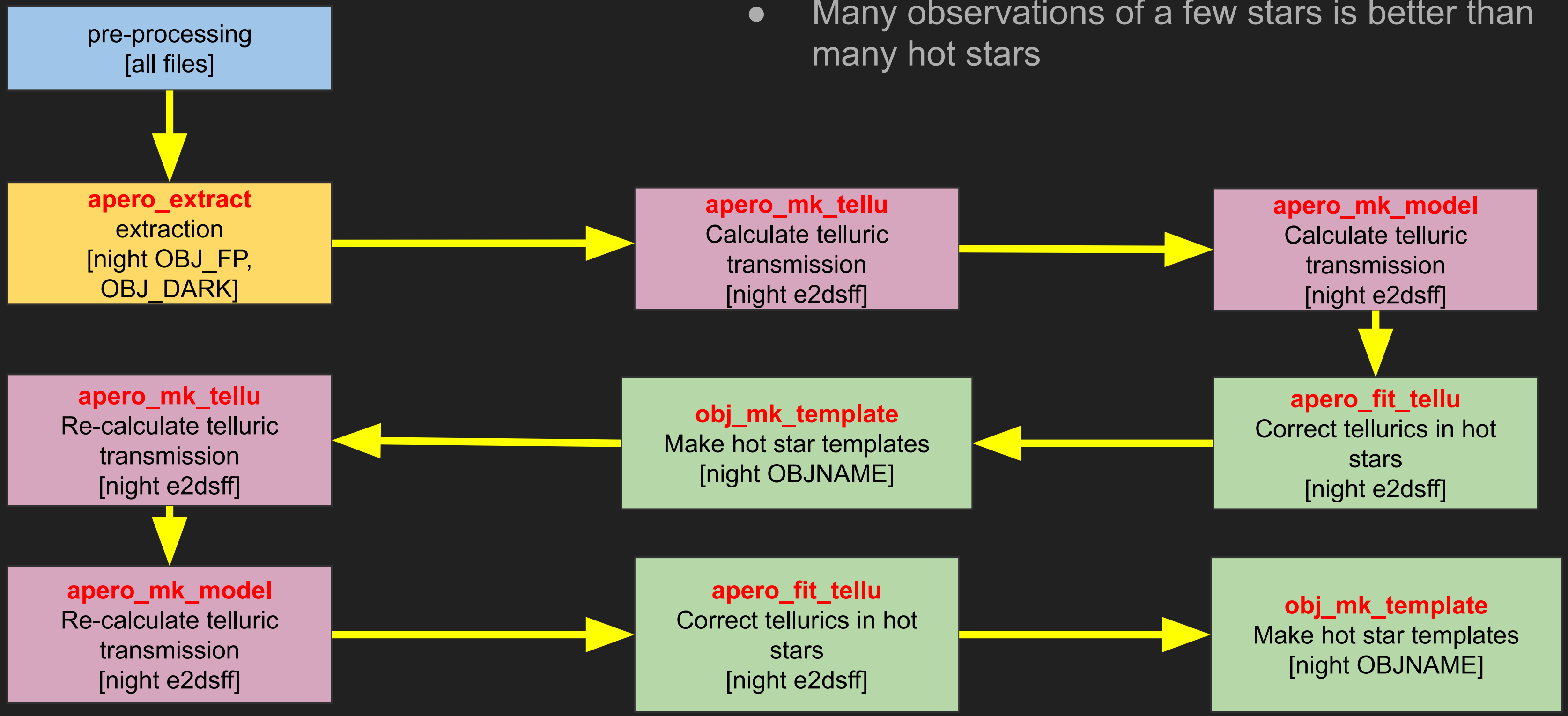
DAY 3

Day 3: Telluric Correction and Radial Velocity Objectives

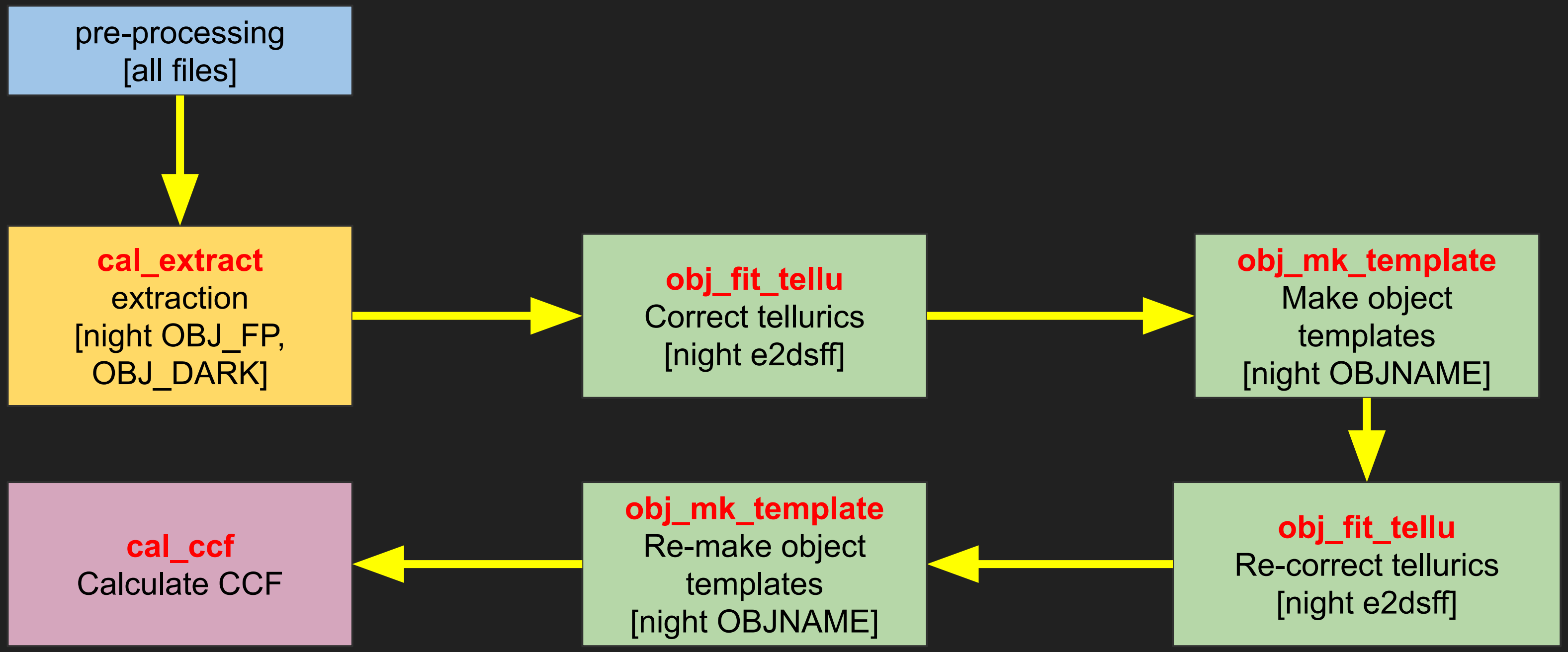
- Learn about telluric correction and radial velocity
- Exercise 3: Telluric correction
- Exercise 4: Radial velocity using the line-by-line approach

Hot Star sequence

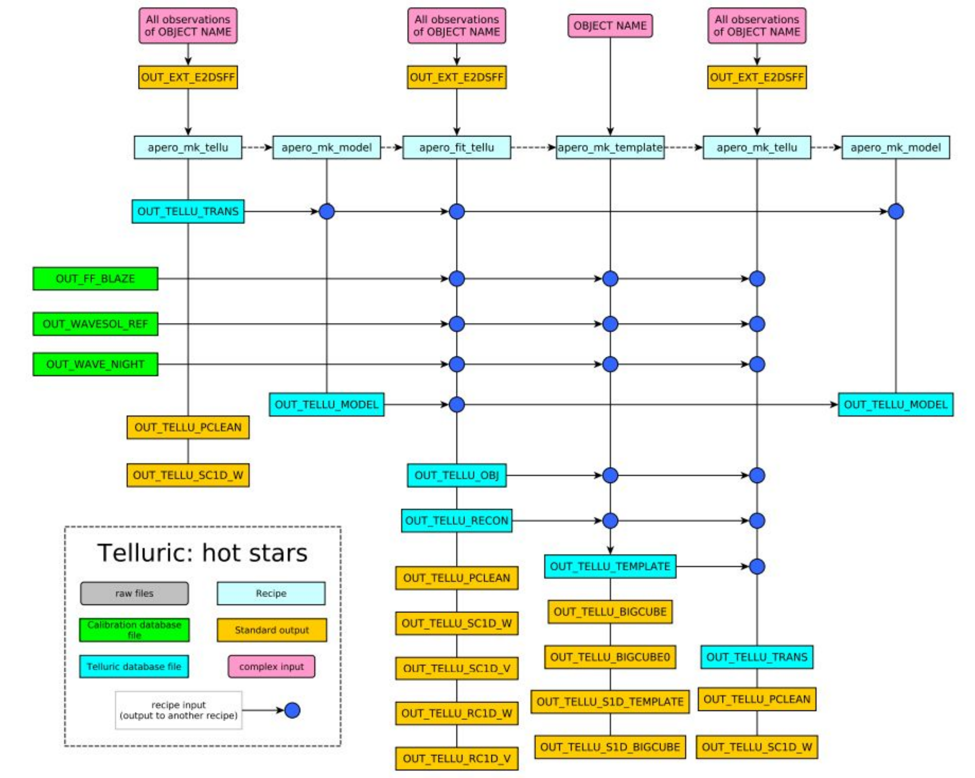
- Hot stars should be observed most nights
- Hot stars are A/B type stars that are fast rotators
- Predefined list of hot stars
- Many observations of a few stars is better than many hot stars

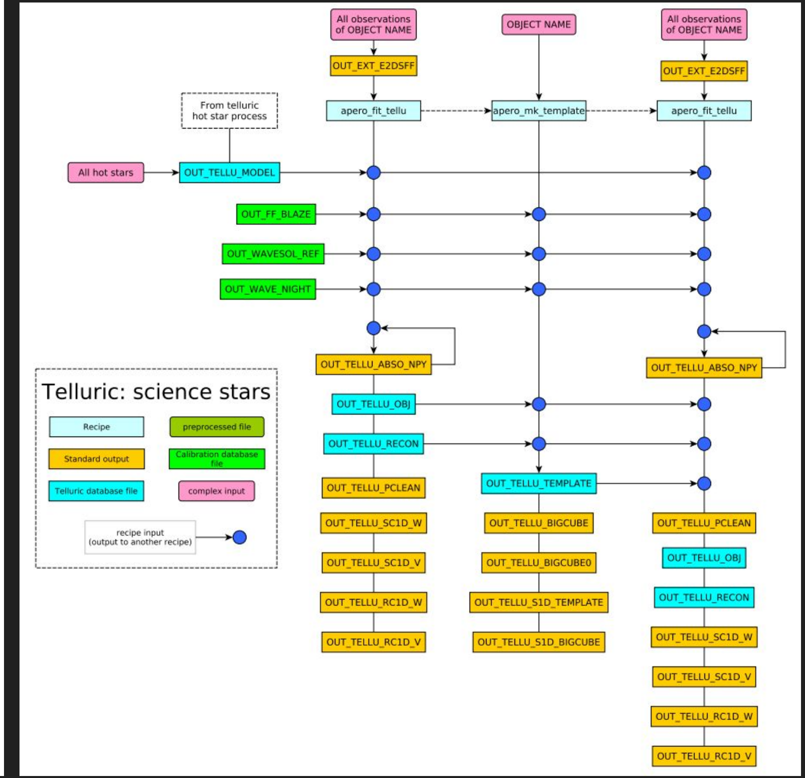


Science star sequence



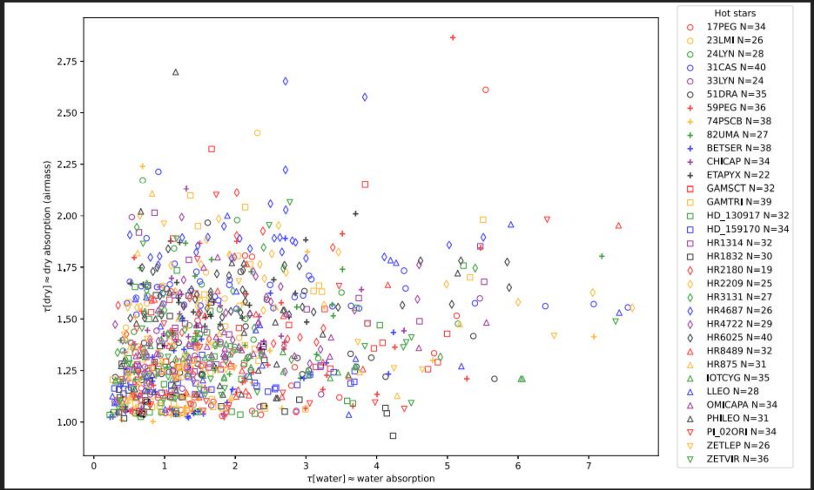
Telluric process - full flow

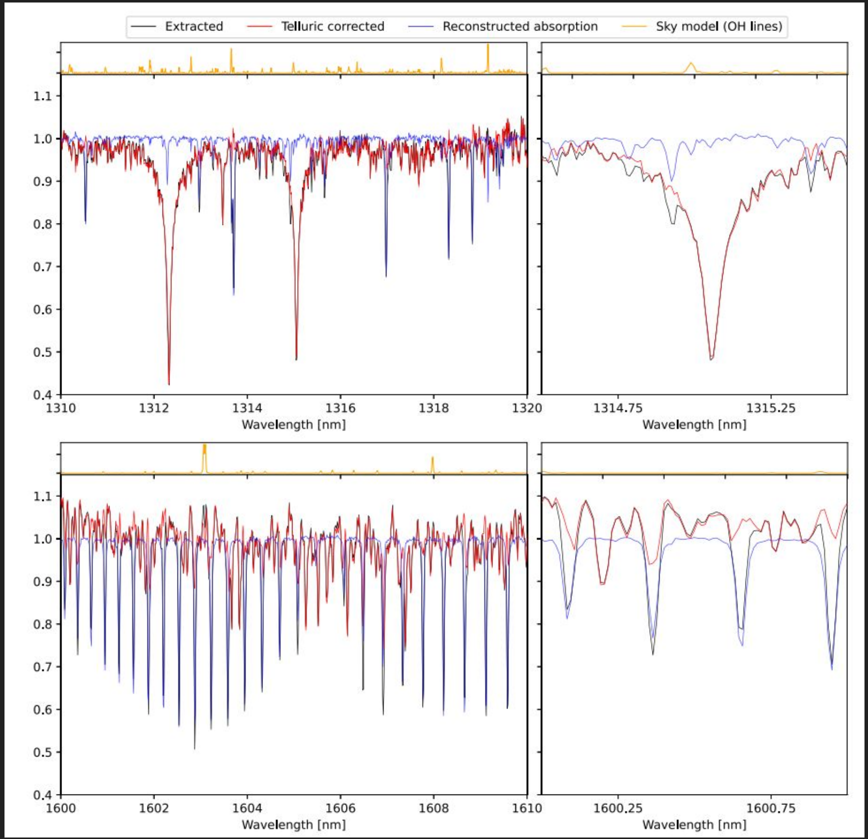




Telluric process

- Pre-clean:
  - Sky correction (using sky modelled from real data)
    - Uses SKY in fiber B if SKY was used
    - Uses just the model if FP in fiber B
  - Use TAPAS + exponents of water and dry components of absorption to remove most tellurics
- Residual fit:
  - Use telluric transmission from hot stars to fit residuals
- Requires database of hot stars for best correction
- Requires lots of observations to build templates of hot stars / science targets for best correction





Telluric files

name	description	HDR[DRSOUTID]	file type	suffix	basename	fibers	dbname	dbkey	input file
TELLU_PCLEAN	Telluric pre-cleaning file	TELLU_PCLEAN	.fits	_tellu_pclean	-	A	telluric	TELLU_PCLEAN	EXT_E2DS_FF
TELLU_CONV	-	-	.npy	_tellu_conv	-	A	telluric	TELLU_CONV	WAVESOL_REF, WAVE_NIGHT, WAVESOL_DEFAULT
TELLU_TRANS	Telluric transmission file	TELLU_TRANS	.fits	_tellu_trans	-	A	telluric	TELLU_TRANS	EXT_E2DS_FF
TELLU_TAPAS	-	-	.npy	-	tapas_spl.npy	-	telluric	TELLU_TAPAS	-
TRANS_MODEL	Telluric transmission model file	TRANS_MODEL	.fits	-	trans_model_{0}	A	telluric	TELLU_MODEL	-
TELLU_OBJ	Telluric corrected extracted 2D spectrum	TELLU_OBJ	.fits	_e2dsff_tcorr	-	A	telluric	TELLU_OBJ	EXT_E2DS_FF
TELLU_RECON	Telluric reconstructed 2D absorption file	TELLU_RECON	.fits	_e2dsff_recon	-	A	telluric	TELLU_RECON	EXT_E2DS_FF
TELLU_TEMP	Telluric 2D template file	TELLU_TEMP	.fits	-	Template	A	telluric	TELLU_TEMP	EXT_E2DS_FF, TELLU_OBJ

- Telluric correction is attempted on every extracted hot star and science file
- Some may fail QC and not be in the telluric database
  - Header key “QCC_ALL” = T if all quality control passed (F otherwise)
  - Header keys for each individual quality control
- Main files:
  - _pp_e2dsff_tcorr_A.fits // the corrected E2DS file
  - _pp_e2dsff_recon_A.fits // the transmission profile

Exercise 5: Telluric correction

Step 1: Find the extracted s1d for Proxima (fiber A)

Step 2: Find the telluric corrected s1d for Proxima (fiber A)

Step 3: Find the associated recon and s1d template

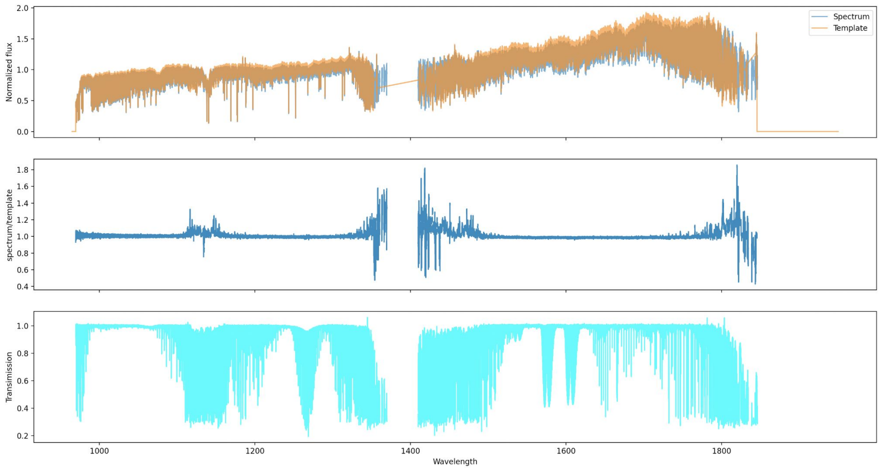
Step 4: Shift the s1d template using the BERV

Step 5: Plot the flux (corrected/uncorrected) and template

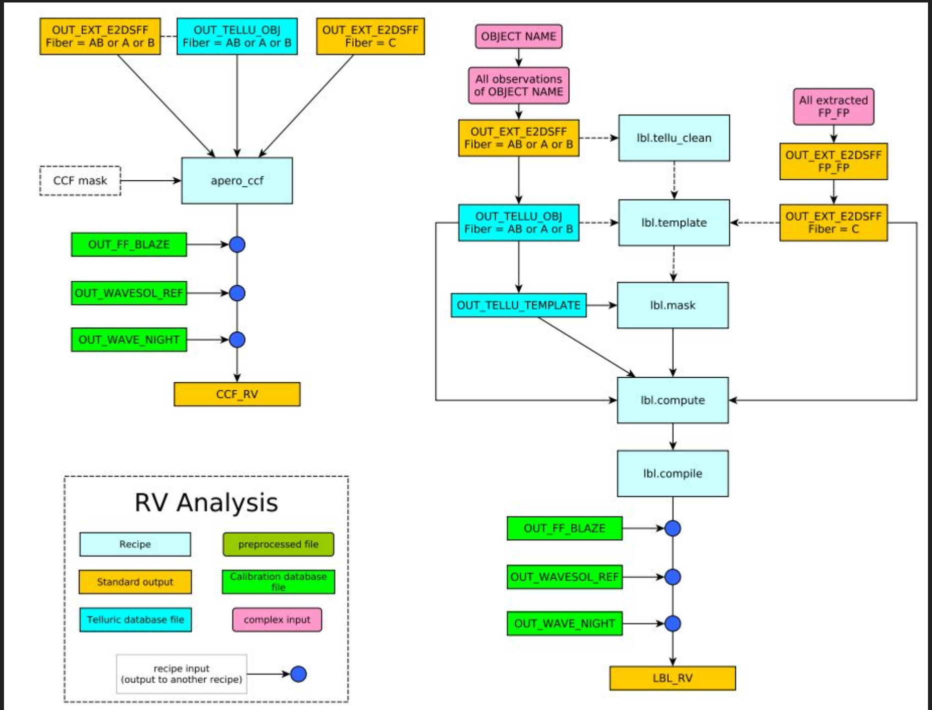
Step 6: Plot the normalized ratio of the corrected flux to template

Step 7: Plot the transmission

Bonus: Plot the OH line model from the pclean file (use fitsinfo to look at the extension names)



Radial velocity analysis



LBL

- Line-by-line velocity measurements
- https://ui.adsabs.harvard.edu/abs/2022AJ....164...84A/abstract

THE ASTRONOMICAL JOURNAL, 164:84 (18pp), 2022 September https://doi.org/10.3847/1538-3881/ac7ce6

Line-by-line Velocity Measurements: an Outlier-resistant Method for Precision Velocimetry

Étienne Artigau[1,2], Charles Cadieux[1], Neil J. Cook[1], René Doyon[1,2], Thomas Vandal[1], Jean-François Donati[3], Claire Moutou[3], Xavier Delfosse[4], Pascal Fouqué[3,5], Eder Martioli[6,7], François Bouchy[8], Jasmine Parsons[1,9], Andres Carmona[4], Xavier Dumusque[8], Nicola Astudillo-Defru[10], Xavier Bonfils[4], and Lucille Mignon[4]
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Received 2022 February 18; revised 2022 June 23; accepted 2022 June 27; published 2022 August 8

Abstract

We present a new algorithm for precision radial velocity (pRV) measurements, a line-by-line (LBL) approach designed to handle outlying spectral information in a simple but efficient manner. The effectiveness of the LBL method is demonstrated on two data sets, one obtained with SPIRou on Barnard's star, and the other with the High Accuracy Radial velocity Planet Searcher (HARPS) on Proxima Centauri. In the near-infrared, the LBL provides a framework for meters-per-second-level accuracy in pRV measurements despite the challenges associated with telluric absorption and sky emission lines. We confirm with SPIRou measurements spanning 2.7 yr that the candidate super-Earth on a 233 day orbit around Barnard's star is an artifact due to a combination of time sampling and activity. The LBL analysis of the Proxima Centauri HARPS post-upgrade data alone easily recovers the Proxima b signal and also provides a 2σ detection of the recently confirmed 5 day Proxima d planet, but argues against the presence of the candidate Proxima c with a period of 1900 days. We provide evidence that the Proxima c signal is associated with small, unaccounted systematic effects affecting the HARPS-TERRA template-matching radial velocity extraction method for long-period signals. Finally, the LBL framework provides a very effective activity indicator, akin to the FWHM derived from the cross-correlation function, from which we infer a rotation period of $92.1^{+4.2}_{-3.5}$ days for Proxima.

Unified Astronomy Thesaurus concepts: Exoplanets (498); Radial velocity (1332); Astronomy data analysis (1858)

Line-by-line velocity

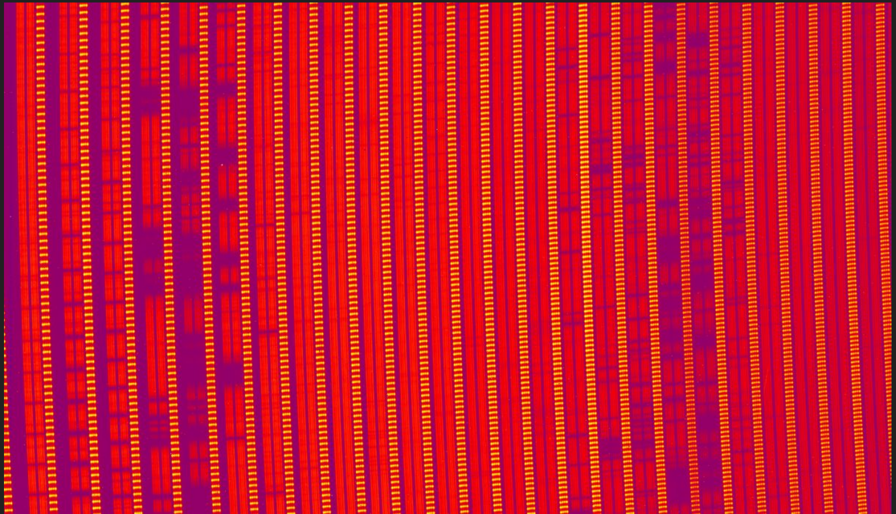
… follow-up on an idea suggested by X. Dumusque

Étienne Artigau

How do you measure RVs very, very, very accurately?

Earth-mass planets induce RV signals at the 1/1000th of a pixel scale on pretty much *any* pRV instrument!

… and that’s when you are lucky!



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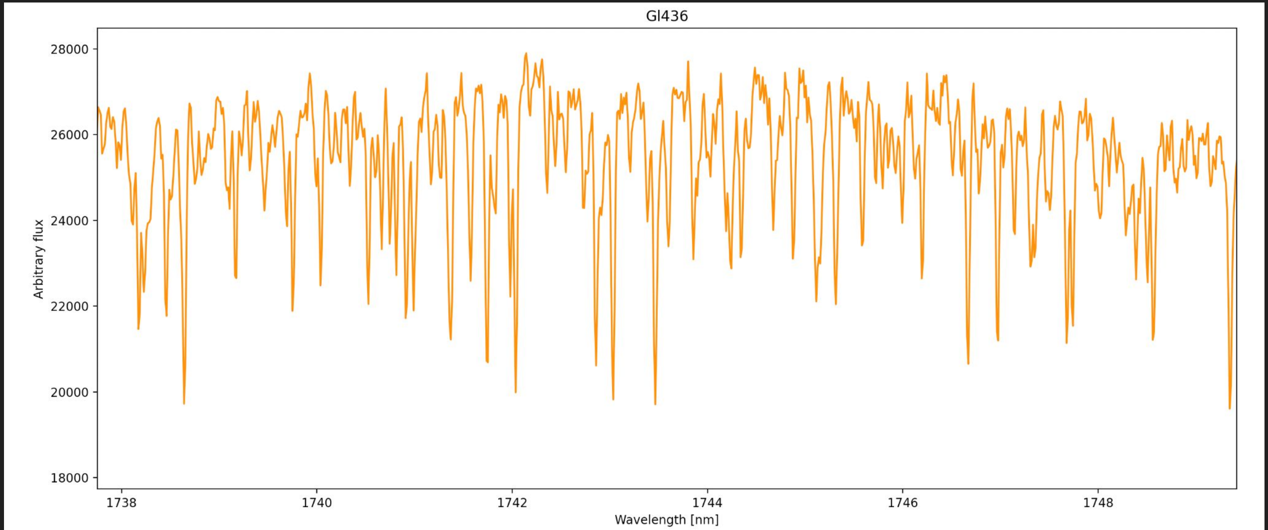

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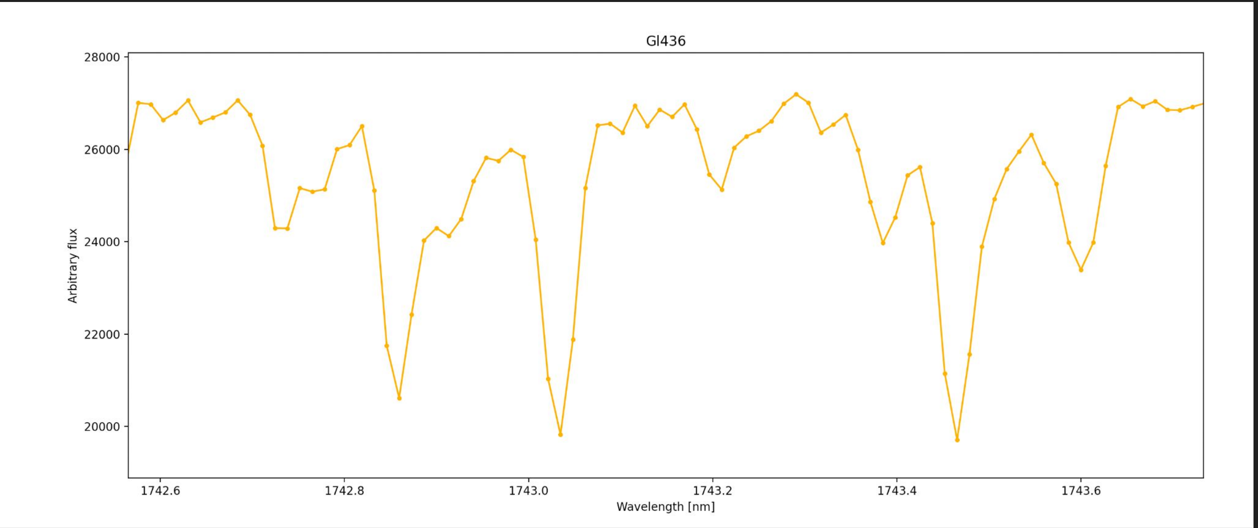
If the screen is 1m wide …

Pixels are ~1 cm wide

Now you need to *reliably* measure the position of the spectrum to within 10μm to find an Earth-sized planet!



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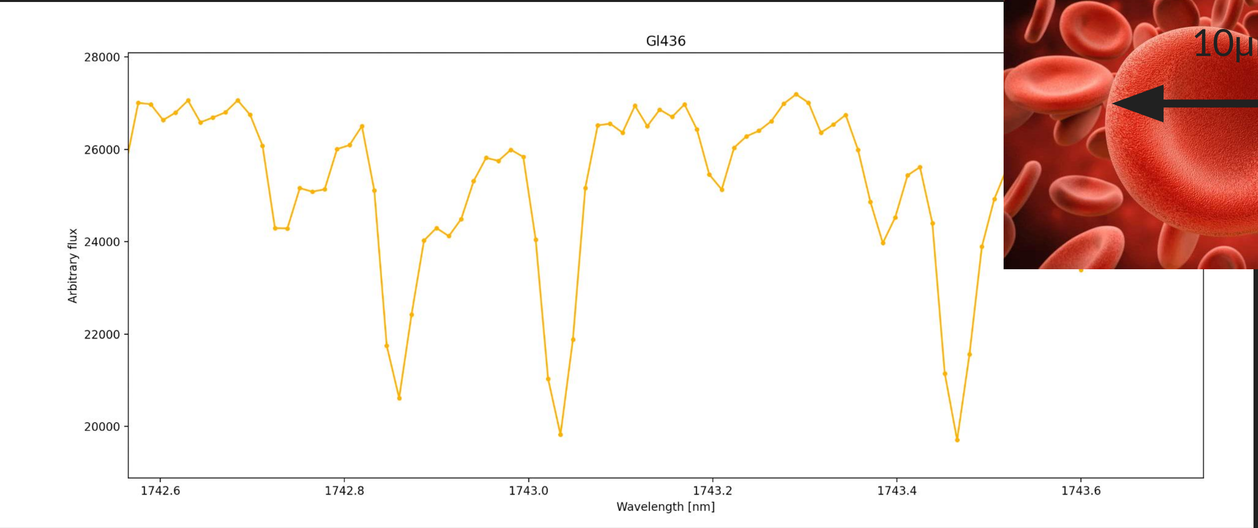

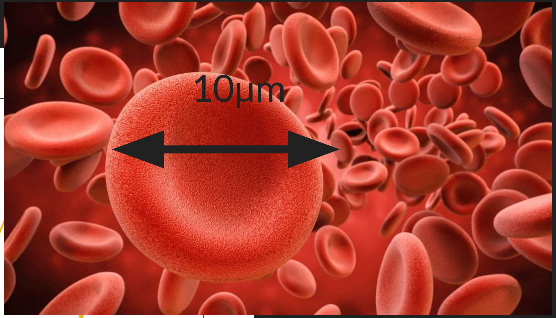

Before we start, some good memories from CEGEP years!

For an arbitrary function f(x) and its derivative f'(x), the for a very small Δx ...

$$f'(x) \approx (f(x+\Delta x) - f(x))/\Delta x$$

If you want to find Δx …

$$\Delta x \approx (f(x+\Delta x) - f(x))/f'(x)$$

Back to the definition of RV measurements

A&A 374, 733–739 (2001)
DOI: 10.1051/0004-6361:20010730

Astronomy & Astrophysics

Fundamental photon noise limit to radial velocity measurements

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Observatoire de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland

Received 27 March 2001 / Accepted 9 May 2001

Abstract. In the past 5 years, improvements in radial velocity measurements have led to discovery of extra-solar planets and progress in asteroseismology programs. Doppler measurements with high precision is close to the limit given by photon noise. In this paper the methodology to compute the fundamental limit of radial velocity measurement given by photon noise is presented and illustrated with a representative sample of synthetic solar-type stellar spectra. Stellar rotational broadening, instrumental spectral range as well as spectral resolution influences are also considered. This study is applied to two dedicated spectrographs in order to help the optimization of radial velocity programs. Current methods of Doppler calculation are discussed and compared.

Key words. techniques: radial velocities – instrumentation: spectrographs – stars: oscillations – stars: planetary systems

Back to the definition of RV measurements

The Doppler shift is then given by:

$$\frac{\delta V(i)}{c} = \frac{A(i) - A_0(i)}{\lambda(i)\,(\partial A_0(i)/\partial\lambda(i))}. \tag{3}$$

Back to the definition of RV measurements

The Doppler shift is then given by:

$$\frac{\delta V(i)}{c} = \frac{A(i) - A_0(i)}{\lambda(i)\left(\partial A_0(i)/\partial\lambda(i)\right)}. \quad (3)$$

template

The derivative of the template expressed in m/s

Back to the definition of RV measurements

Individual dv contributions

$$\frac{\delta V}{c} = \frac{\sum \boxed{\frac{\delta V(i)}{c}} \boxed{W(i)}}{\sum W(i)}.$$

Weight per line

1/SNR: roughly constant over a short domain

$$W(i) = \frac{1}{\left(\frac{\delta V_{\mathrm{RMS}}(i)}{c}\right)^2}. \quad (5)$$

The individual dispersion of the velocity change measured in pixel i is given from Eq. (3) by:

$$\frac{\delta V_{\mathrm{RMS}}(i)}{c} = \frac{[A(i) - A_0(i)]_{\mathrm{RMS}}}{\lambda(i)\left(\partial A_0(i)/\partial\lambda(i)\right)}. \quad (6)$$

Derivative expressed in velocity space

Back to the definition of RV measurements

Individual dv contributions

$$\frac{\delta V}{c} = \frac{\sum \frac{\delta V(i)}{c} W(i)}{\sum W(i)}.$$

Well, we have our optimal velocity and associated errors... this should be the end of the talk, right?

constant over a short domain

$$W(i) = \frac{1}{\left(\frac{\delta V_{\mathrm{RMS}}(i)}{c}\right)^2}. \tag{5}$$

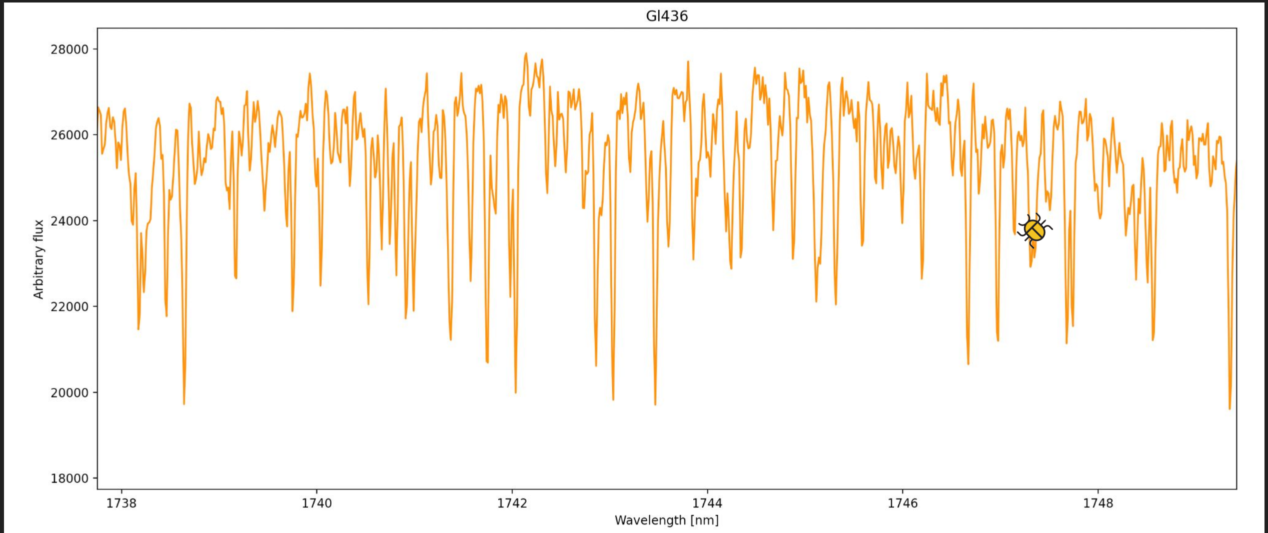
The individual dispersion of the velocity change measured in pixel i is given from Eq. (3) by:

$$\frac{\delta V_{\mathrm{RMS}}(i)}{c} = \frac{[A(i) - A_0(i)]_{\mathrm{RMS}}}{\lambda(i)\,(\partial A_0(i)/\partial\lambda(i))}. \tag{6}$$

Derivative expressed in velocity space

Bugs in the grass

2 m/s photo noise total
sqrt(3)*5 ~ 9 m/s systematic error

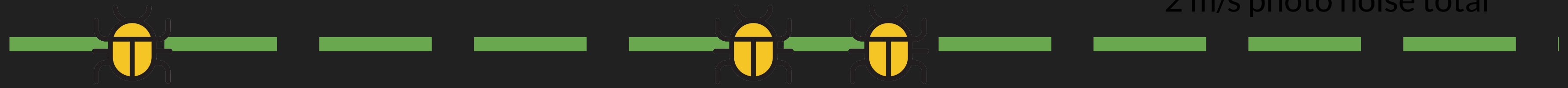


Bugs in the grass

10 segment case

5 m/s global error
50 m/s local error

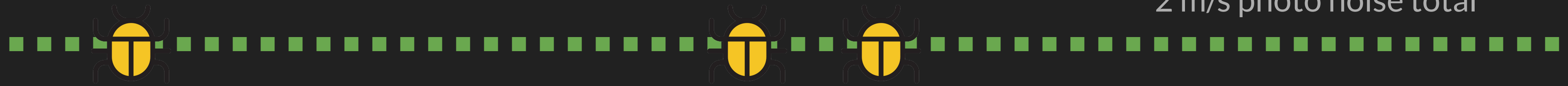
2 m/s photo noise total



- Subdivide in 10 segments
- Each segment has a ~6 m/s photon noise (increase as $N^{1/2}$)
- Locally, each bug contributes at the 50 m/s level (increases as N)
- Each bug contributes at the 8-sigma level to it’s segment (increase as $N^{1/2}$)
- 30% loss in rejecting problematic segments (1/N decrease)

Bugs in the grass

100 segment case



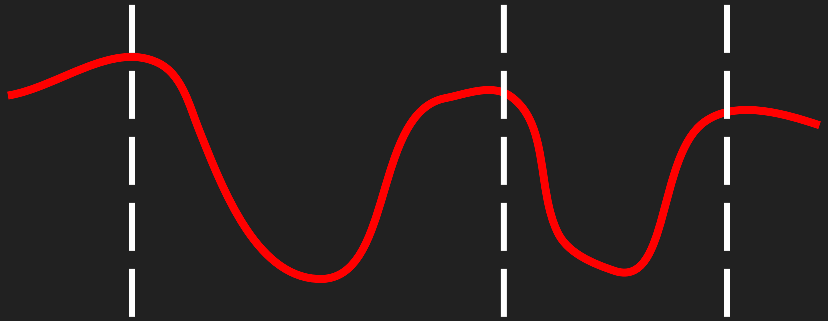
- Subdivide in 100 segments
- Each segment has a 20 m/s photon noise (increase as $N^{1/2}$)
- Locally, each bug contributes at the 500 m/s level (increases as N)
- Each bug contributes at the 25-sigma level to it’s segment (increase as $N^{1/2}$)
- 3% loss in rejecting problematic segments (1/N decrease)

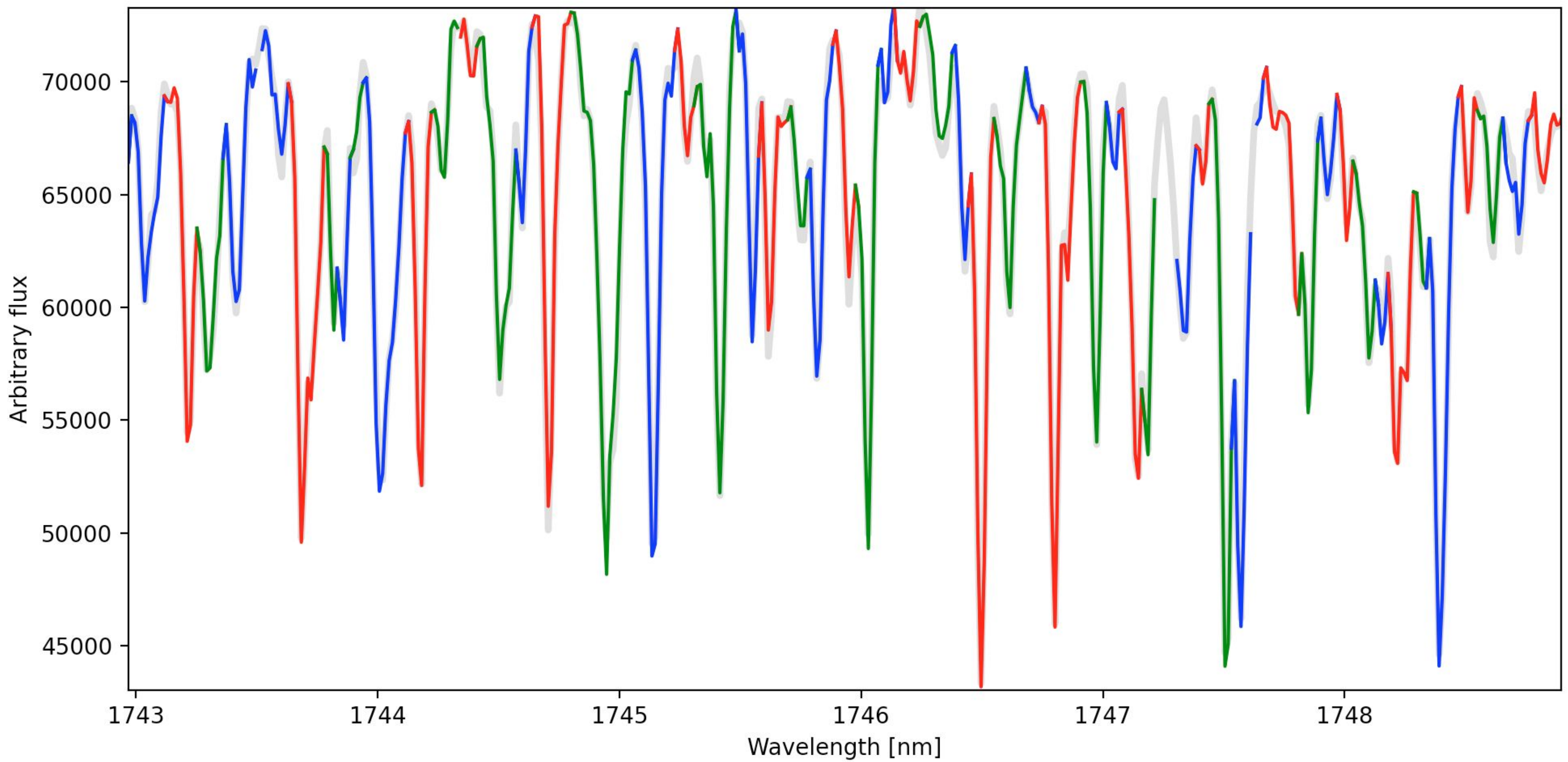
What is the biggest reasonable N value?

- Bigger N leads to little loss in rejecting a ‘domain’
- Far easier flagging of bugs
  - Leftover tellurics
  - Active lines
  - Sky emission lines
  - Detector defects
  - Unknown unknowns
- The smallest features are ‘lines’

Lines ?

- Domain between consecutive maxima in the spectrum
- Exactly the opposite of a CCF mask
- Typically ~10 pixels in length
- About 13 000 - 16 000 useful lines
    - Some lines are counted twice in order overlaps





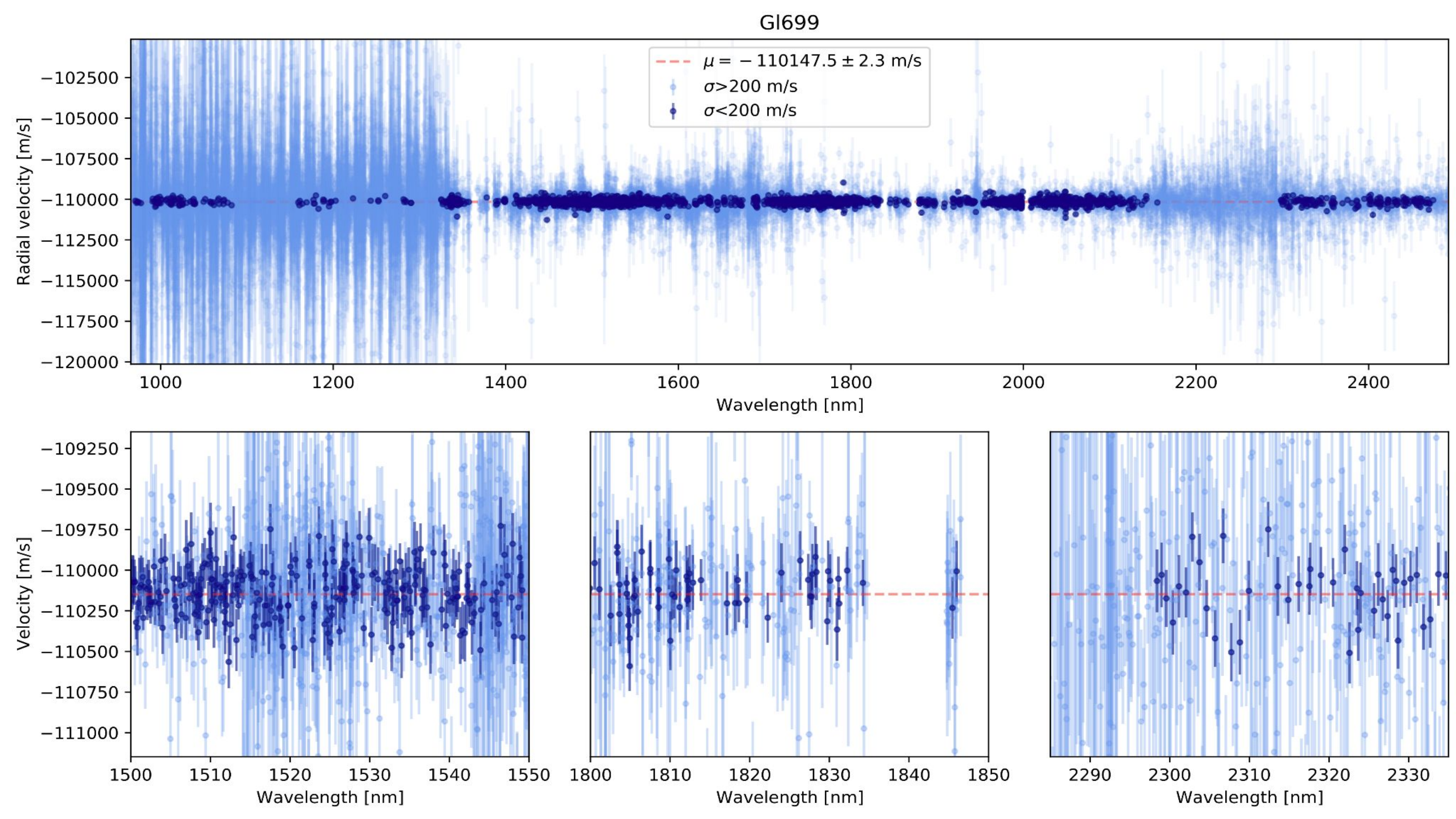
70000
65000
60000
55000
50000
45000
Arbitrary flux
1743
1744
1745
1746
1747
1748
Wavelength [nm]

Back to the definition of RV measurements

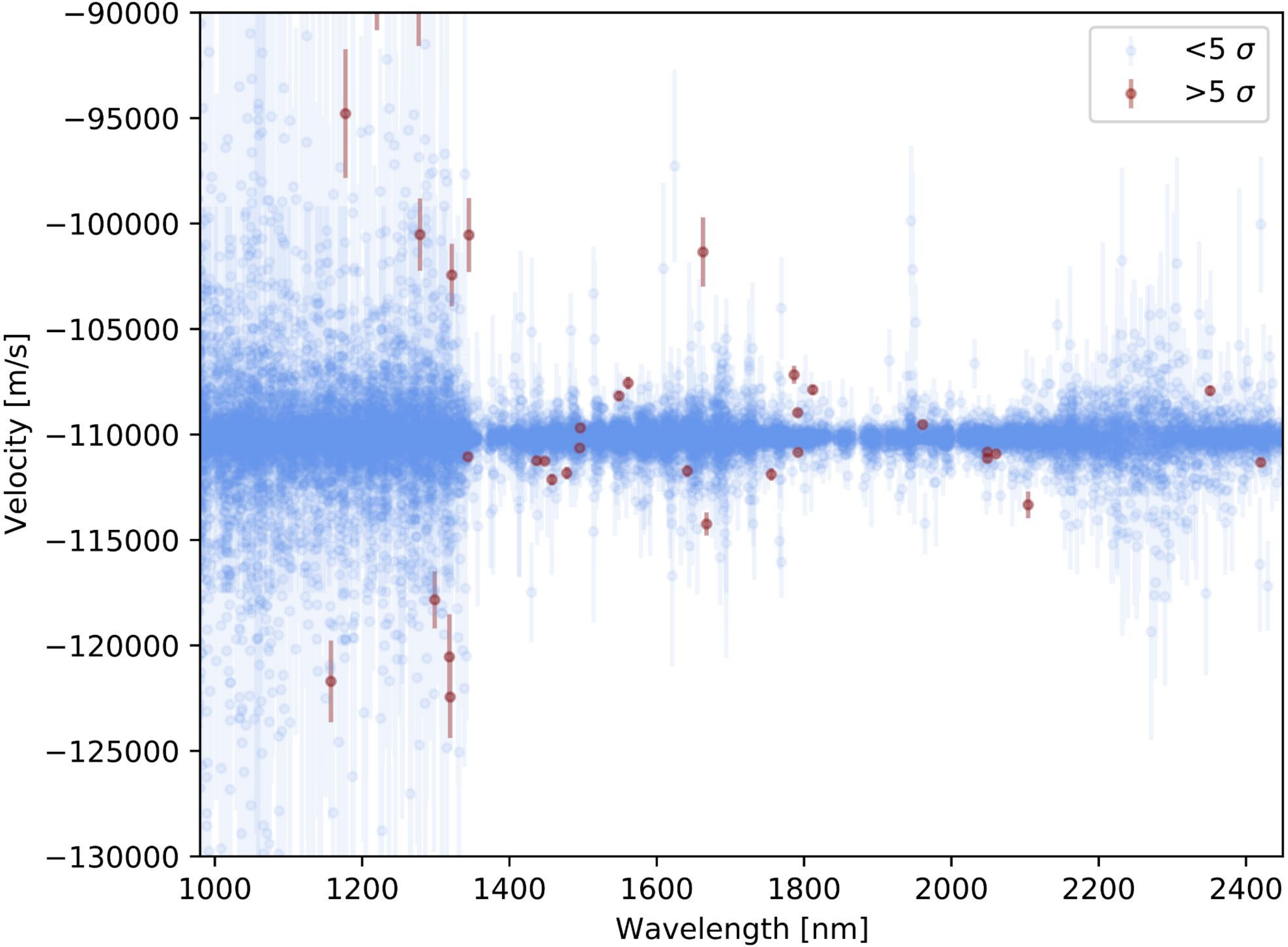
- Within one line, the velocity is simply a weighted sum the the differences between the spectrum and the template
- The weight scales as the derivative of the spectrum square
    - Basically the RV content of the pixel from the template
- Bonus : by construction you get the uncertainty from the line
- Extra-bonus : if you want, you get any higher-order derivative
    - 2nd derivative directly linked to FWHM
    - 3rd derivative linked to bisector tilt
    - Nth derivative… usefulness to be assessed!

The problem is very well constrained

- There are literally no degrees of freedom in constraining the problem
- The template must be provided
  - Bad regions in the template are OK, they will be caught later as ‘bugs’
- The exact boundary of ‘lines’ does not really matter, pixels will be caught in the ‘previous’ or ‘next’ line if they move a bit
- The lines do *not* have weights as they would with a CCF, this is determined from first principles using the RV content and SNR



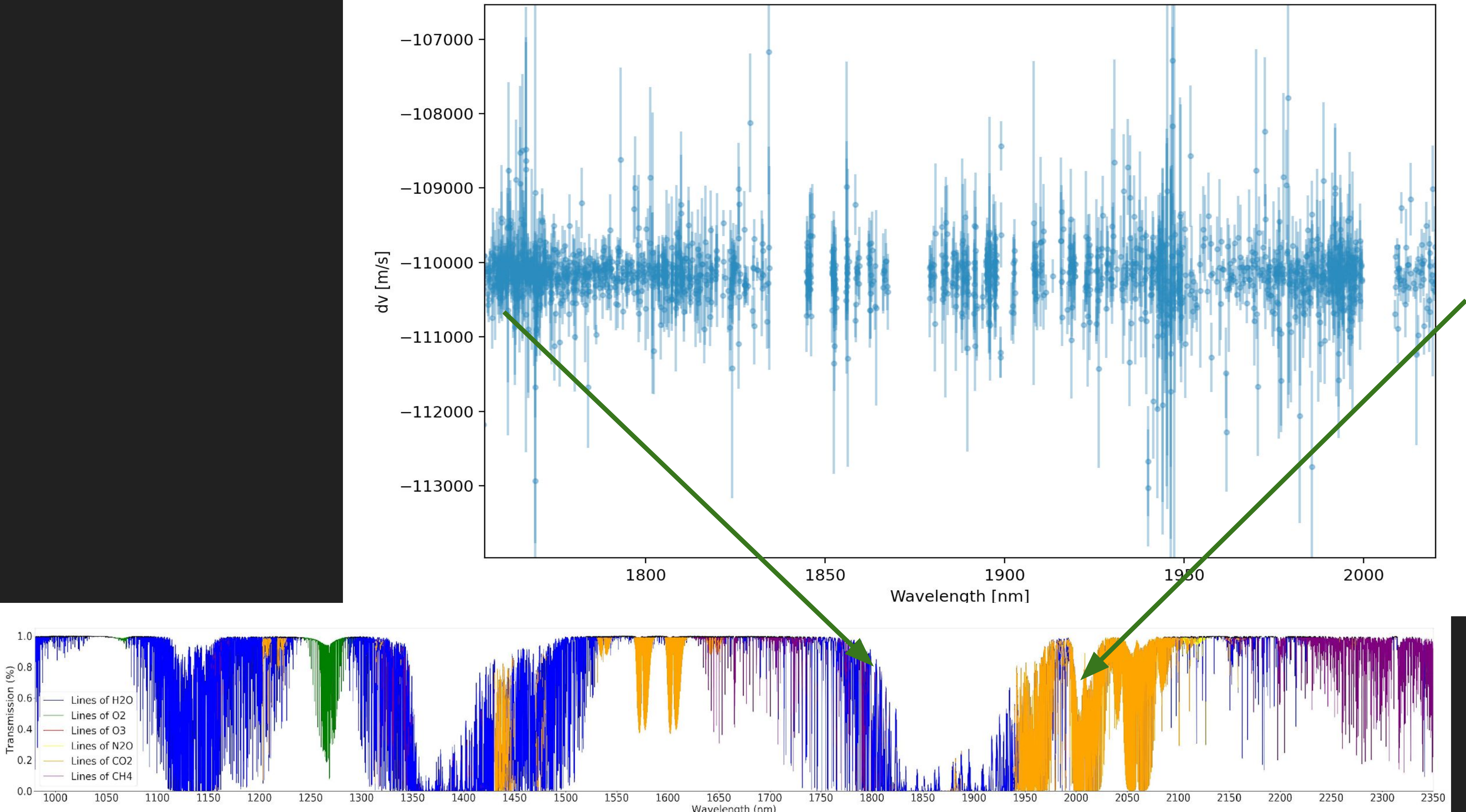
Gl699
$\mu = -110147.5 \pm 2.3$ m/s
σ>200 m/s
σ<200 m/s
Radial velocity [m/s]
Wavelength [nm]
Velocity [m/s]
Wavelength [nm]
Wavelength [nm]
Wavelength [nm]



- ~16 000 lines
- Only ~30 outliers

Behavior with tellurics

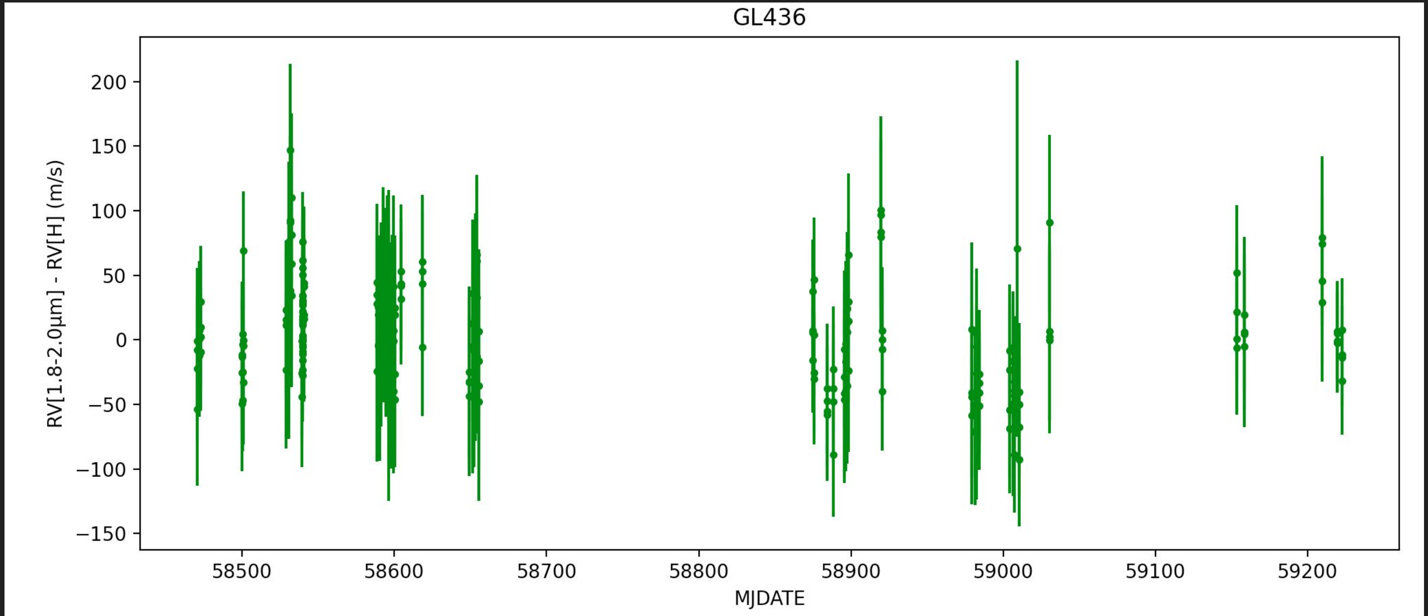
- Telluric residuals are among the most likely bugs in the grass
- Should be rejected as major RV outliers if they coincide with the derivative
- One gets velocities everywhere
- How are we doing ?



−107000
−108000
−109000
−110000
−111000
−112000
−113000
dv [m/s]
1800
1850
1900
1950
2000
Wavelength [nm]
Transmission (%)
Lines of H2O
Lines of O2
Lines of O3
Lines of N2O
Lines of CO2
Lines of CH4
Wavelength (nm)

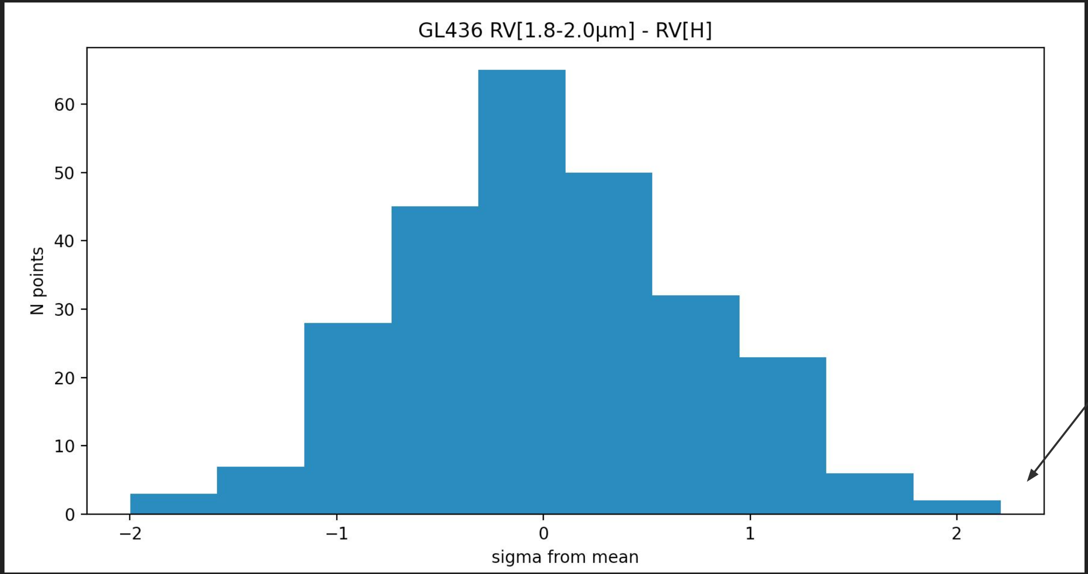
How *not* to do RV measurements!

- Velocity in the 1.8-2.0μm domain versus *H* band



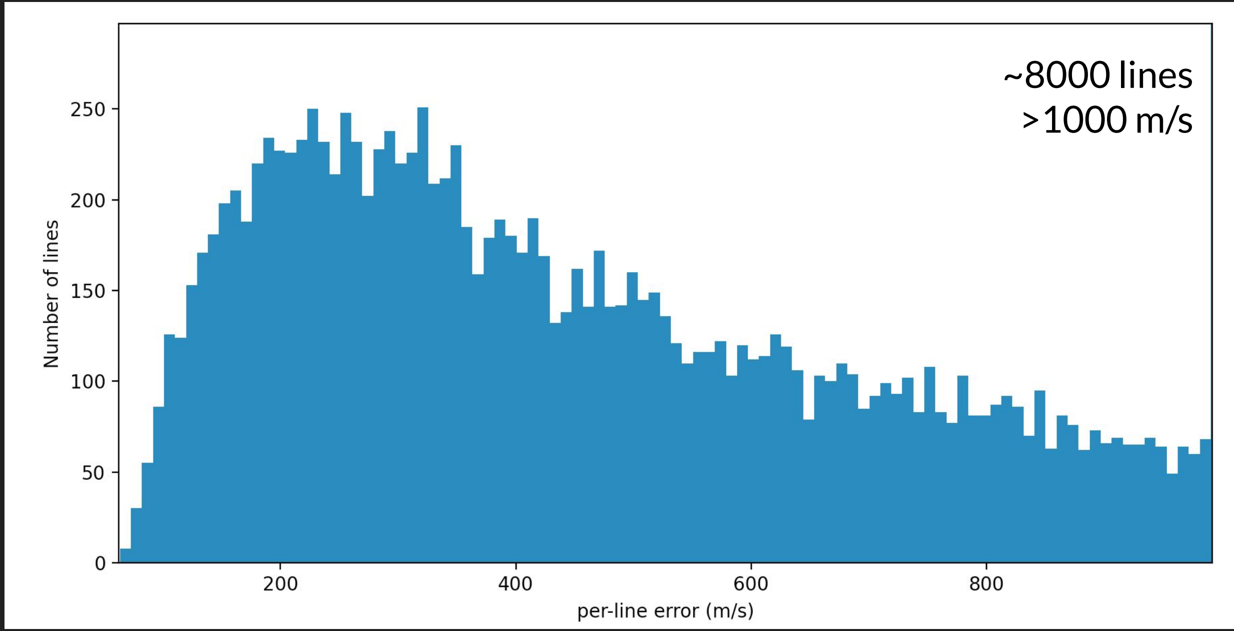
Sado-maso RV measurements

- Velocity in the 1.8-2.0µm domain versus H band

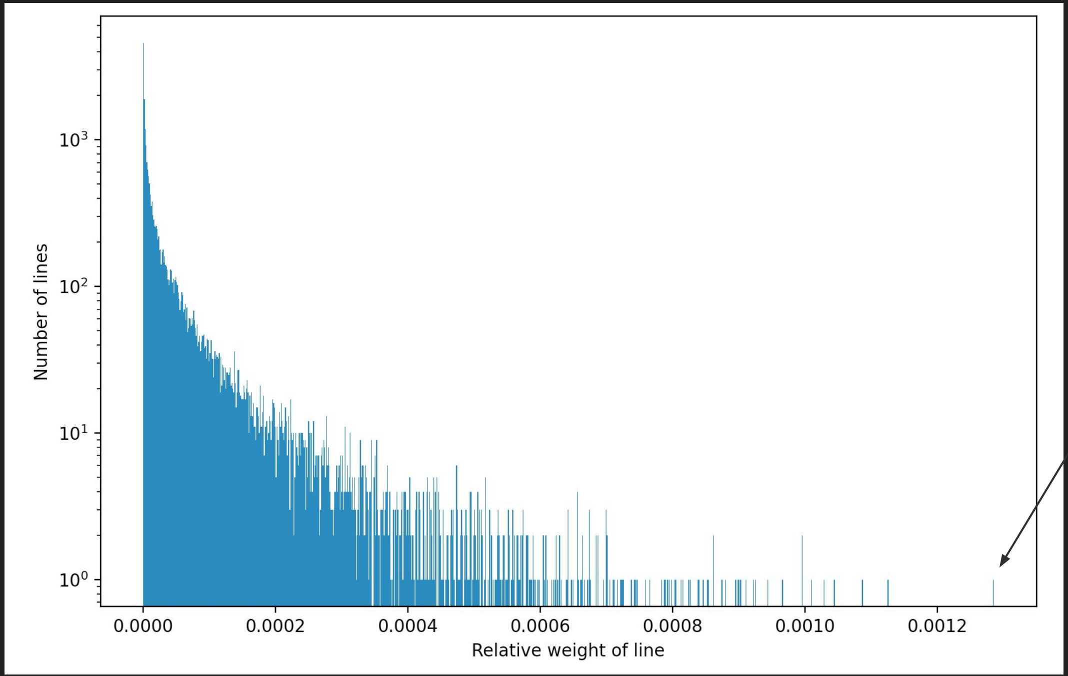


No high-sigma outlier!

Sample GL699 file : Some stats on errors



Sample GL699 file : Some stats on errors

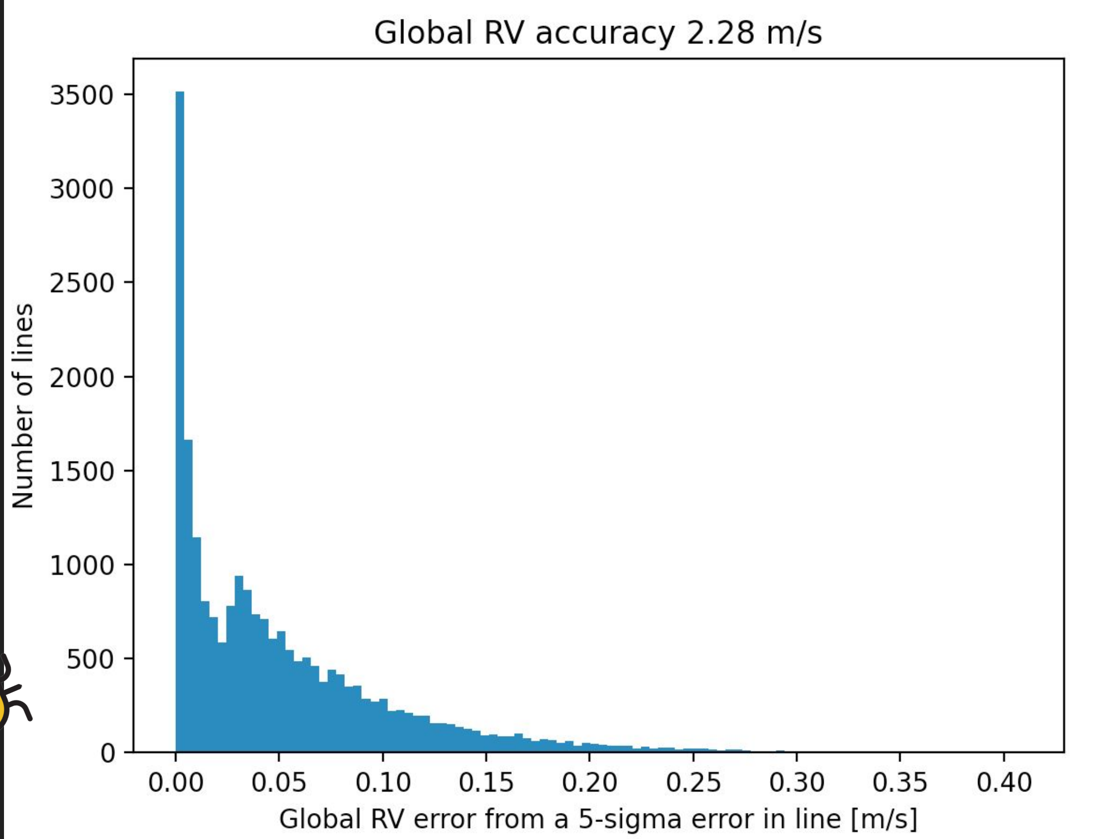


Line with largest weights accounts for ~1/1000th of the total signal

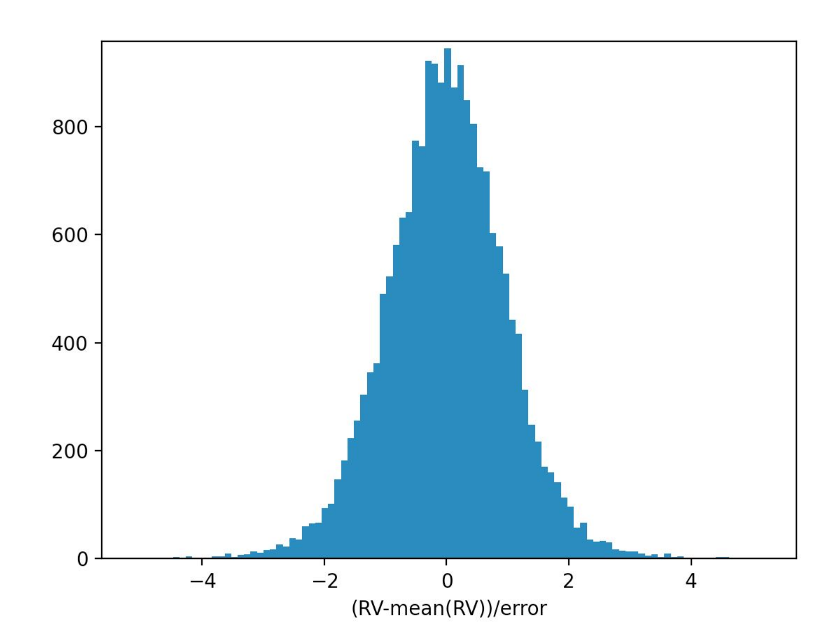
Some stats on errors

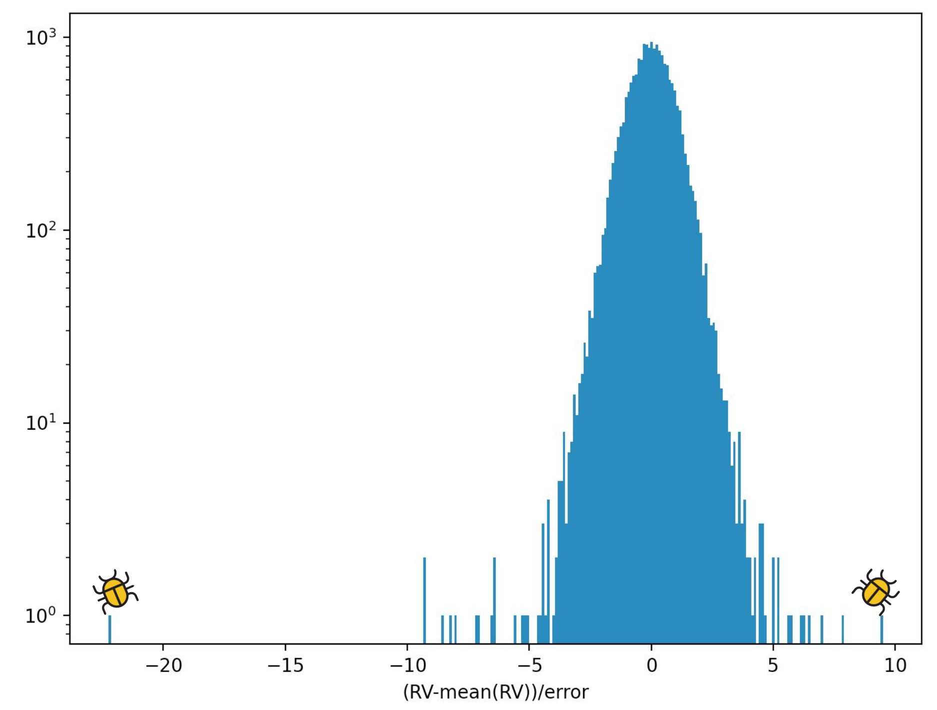
Spurious effects in any line cannot have a global effect above ~25 cm/s

Any >5 sigma event will be caught by sigma-clipping



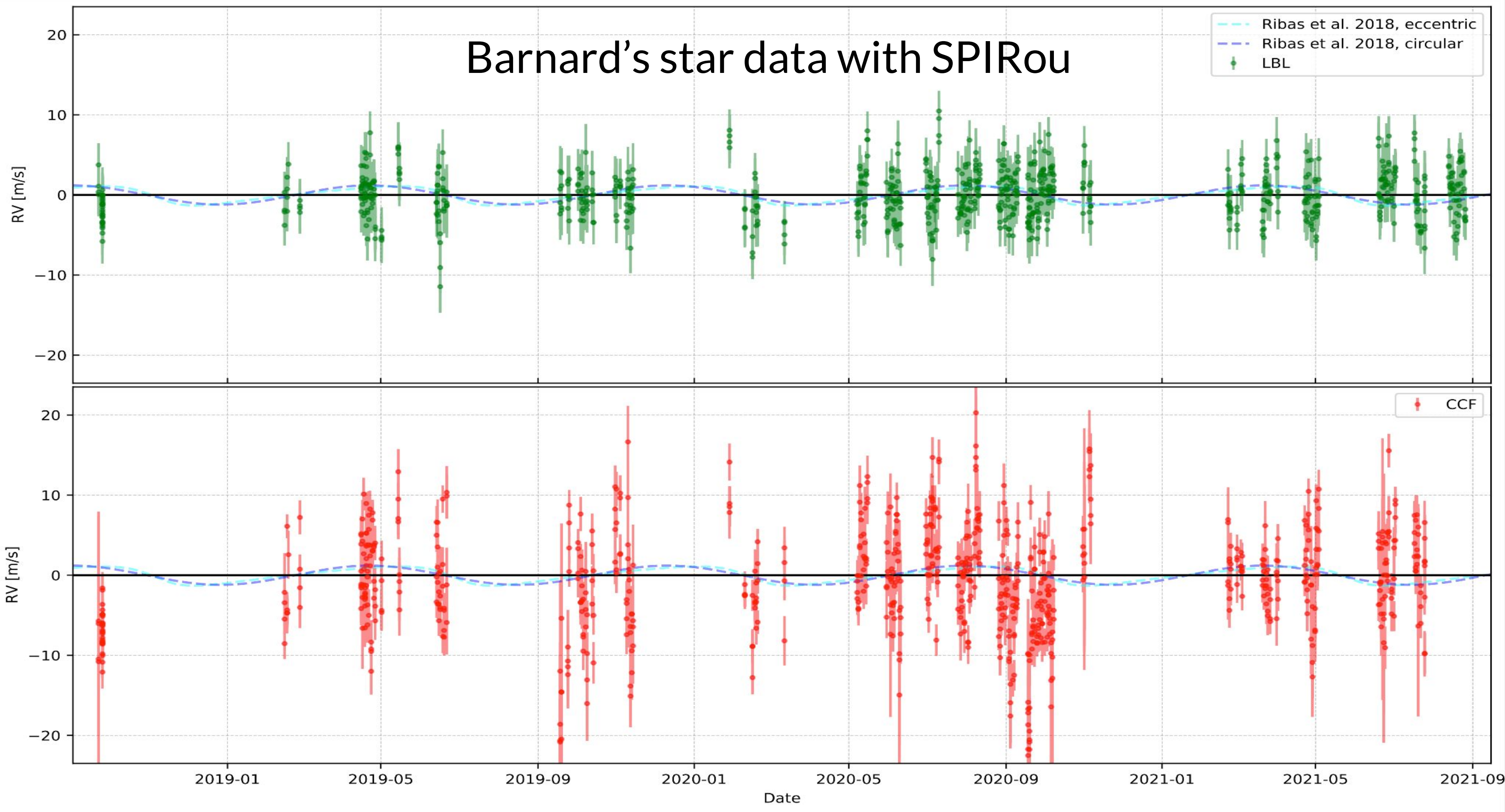
Some stats on errors

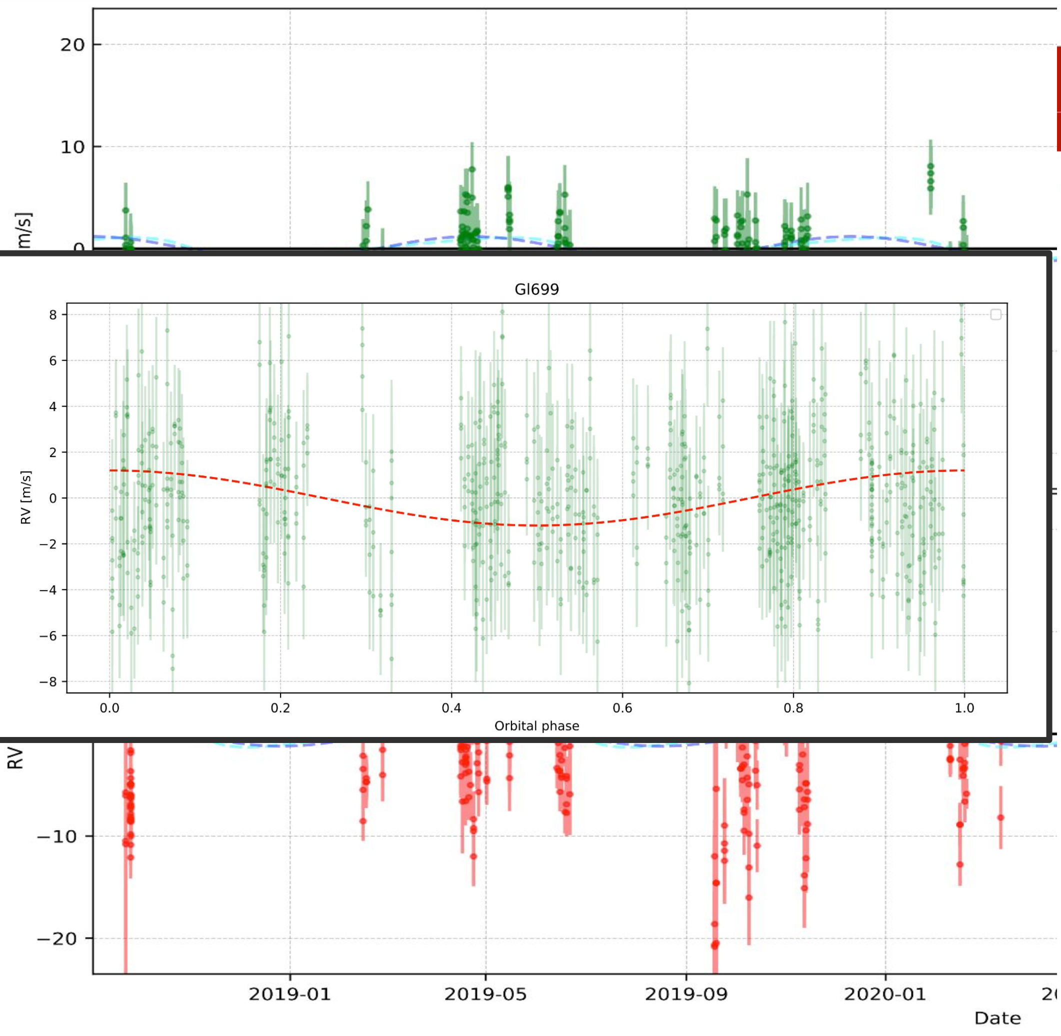




- 0.1 % of points are >5 sigma outliers

Barnard’s star data with SPIRou





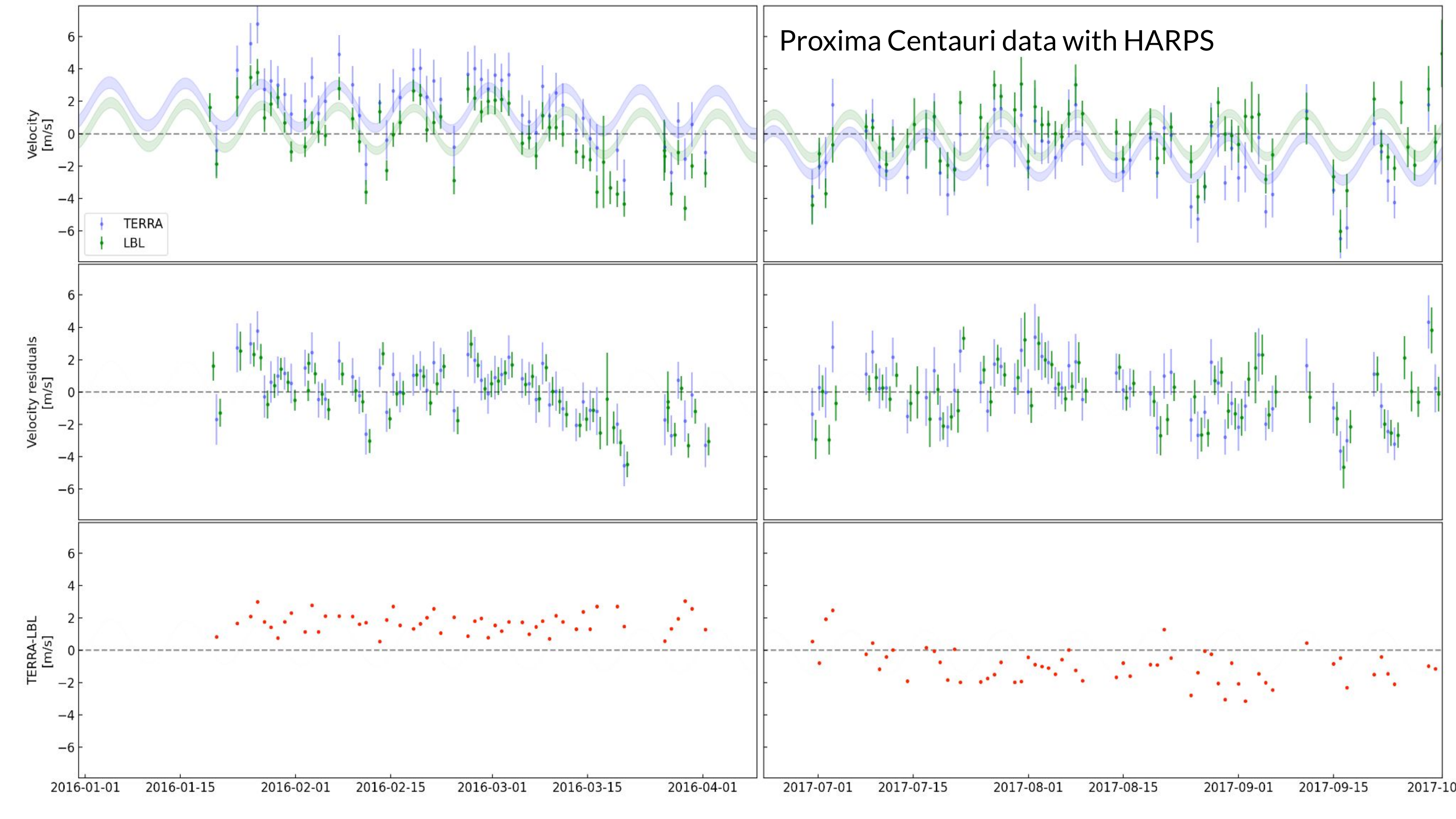
Exoplanet discovered around neighbouring star

By Paul Rincon
Science editor, BBC News website

14 November 2018

Artwork: Barnard's Star b is thought to be quite cold

Astronomers have discovered a planet around one of the closest stars to our Sun.



Proxima Centauri data with HARPS
Velocity [m/s]
Velocity residuals [m/s]
TERRA-LBL [m/s]
TERRA
LBL
2016-01-01
2016-01-15
2016-02-01
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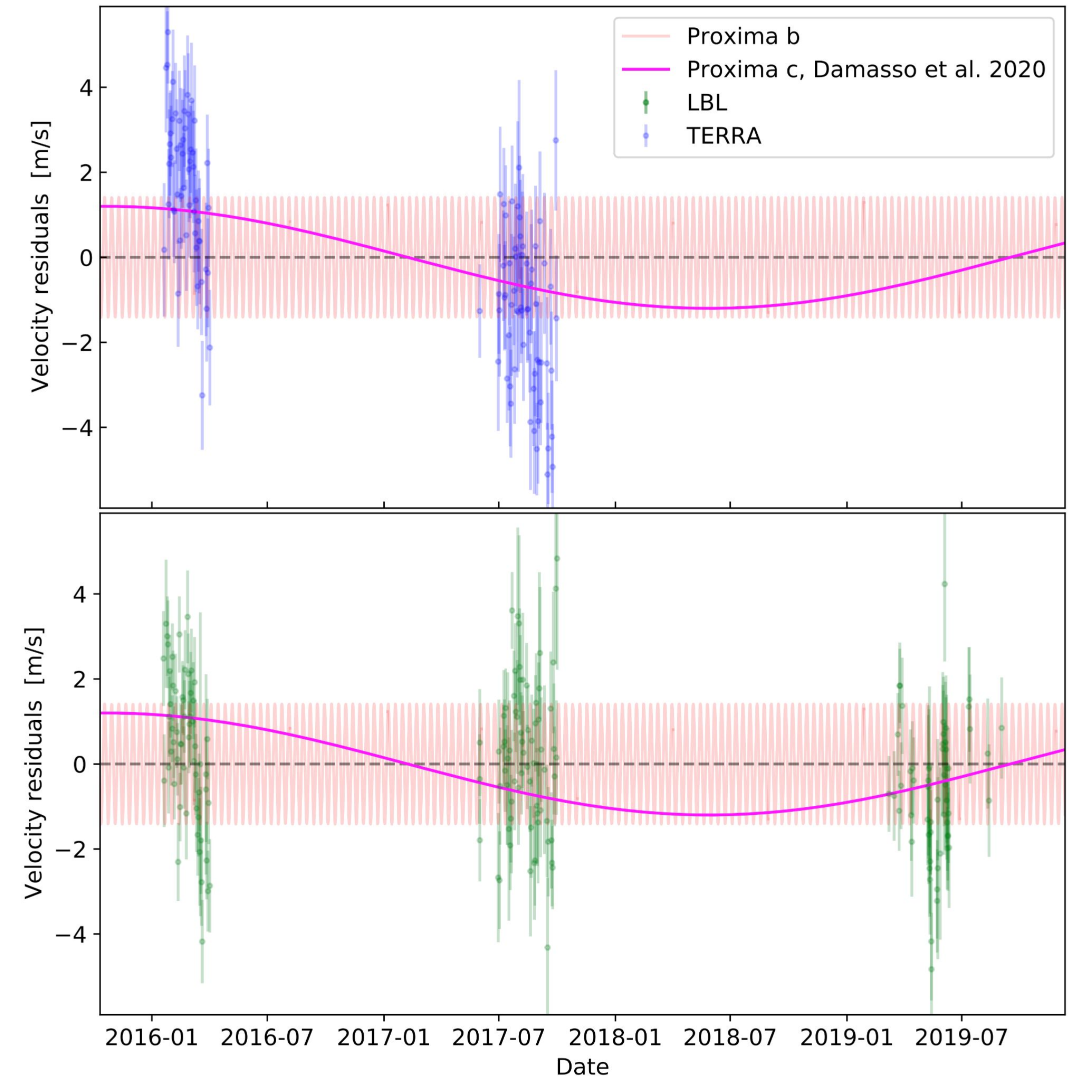

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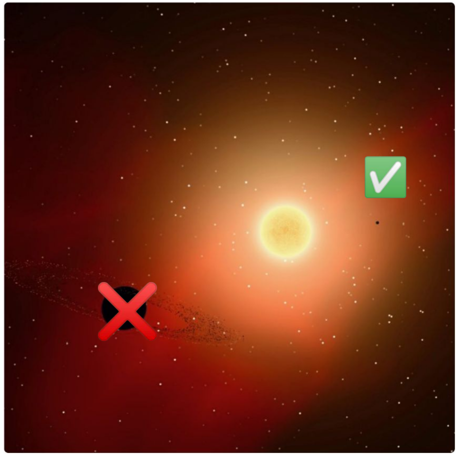
Space

A 2nd exoplanet confirmed for Proxima Centauri

Posted by Paul Scott Anderson | June 9, 2020



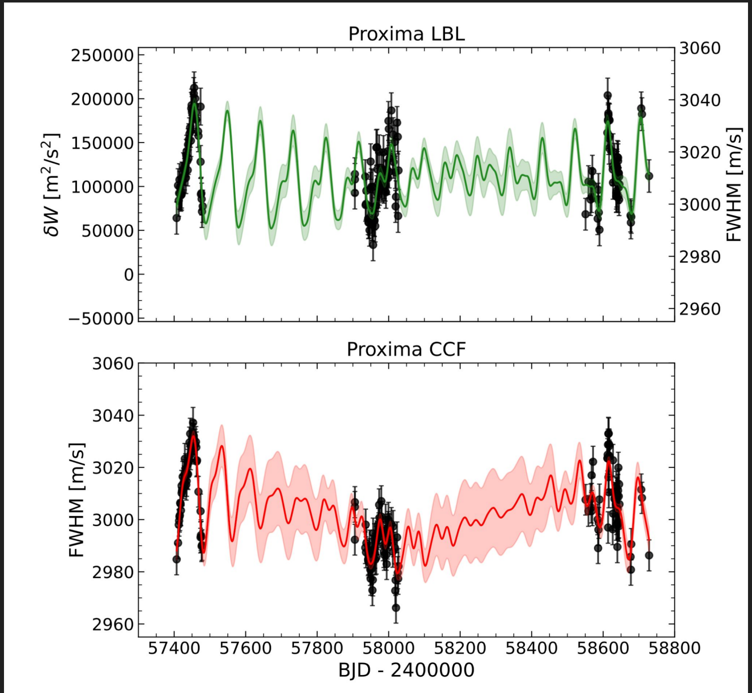
Artist's concept of Proxima Centauri b and c – depicted here as 2 black dots, a larger one and a smaller one – orbiting their red dwarf star. Proxima Centauri c, the larger planet, might also have a ring system. Image via Michele Diodati/ *Medium*.

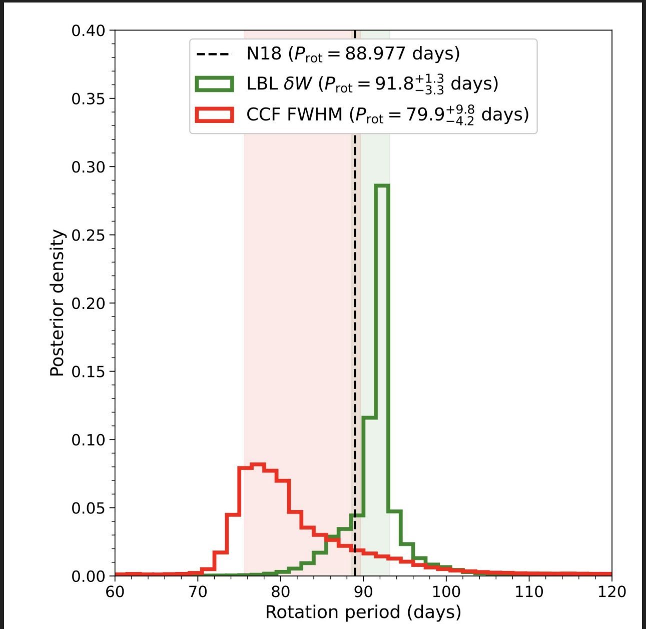
Just a few days ago, scientists announced that the closest known Earth-sized exoplanet, Proxima Centauri b, had been confirmed to orbit the nearest star to our solar system. That's an exciting development, but now, as scientists announced on June 2, 2020, it seems that another possible planet around the same star also has been verified … Proxima Centauri c! Both planets are only 4.2 light-years away.

The peer-reviewed results were published in *Research Notes of the AAS* back in April. Astronomer Fritz Benedict of McDonald Observatory presented the findings at the virtual 236th meeting of the American Astronomical Society.

Evidence for Proxima Centauri c was first announced earlier this year by a research group led by Mario Damasso of Italy's National Institute for Astrophysics (INAF). But the evidence wasn't conclusive. This second planet for Proxima is apparently a lot larger than Earth and orbits its star every 1,907 days. It orbits at about 1.5 times the distance from its star that Earth orbits from the sun. Not an extreme difference, but Proxima Centauri is a red dwarf star, smaller and cooler than our sun, so at that distance, the planet can be expected to be significantly colder than Earth.

2nd derivative as an activity indicator





Exercise 6: Radial velocities using the line-by-line approach

Step 1: Get the tcorr LBL file for Proxima

Step 2: Get the associated recon file for the tcorr Proxima file.

Step 3: Plot a histogram of the sigma away from the mean velocity

Step 4: Plot the “trumpet plot” with the 3.5 sigma outliers and see if they match absorption features.