Know your SPIRou data!

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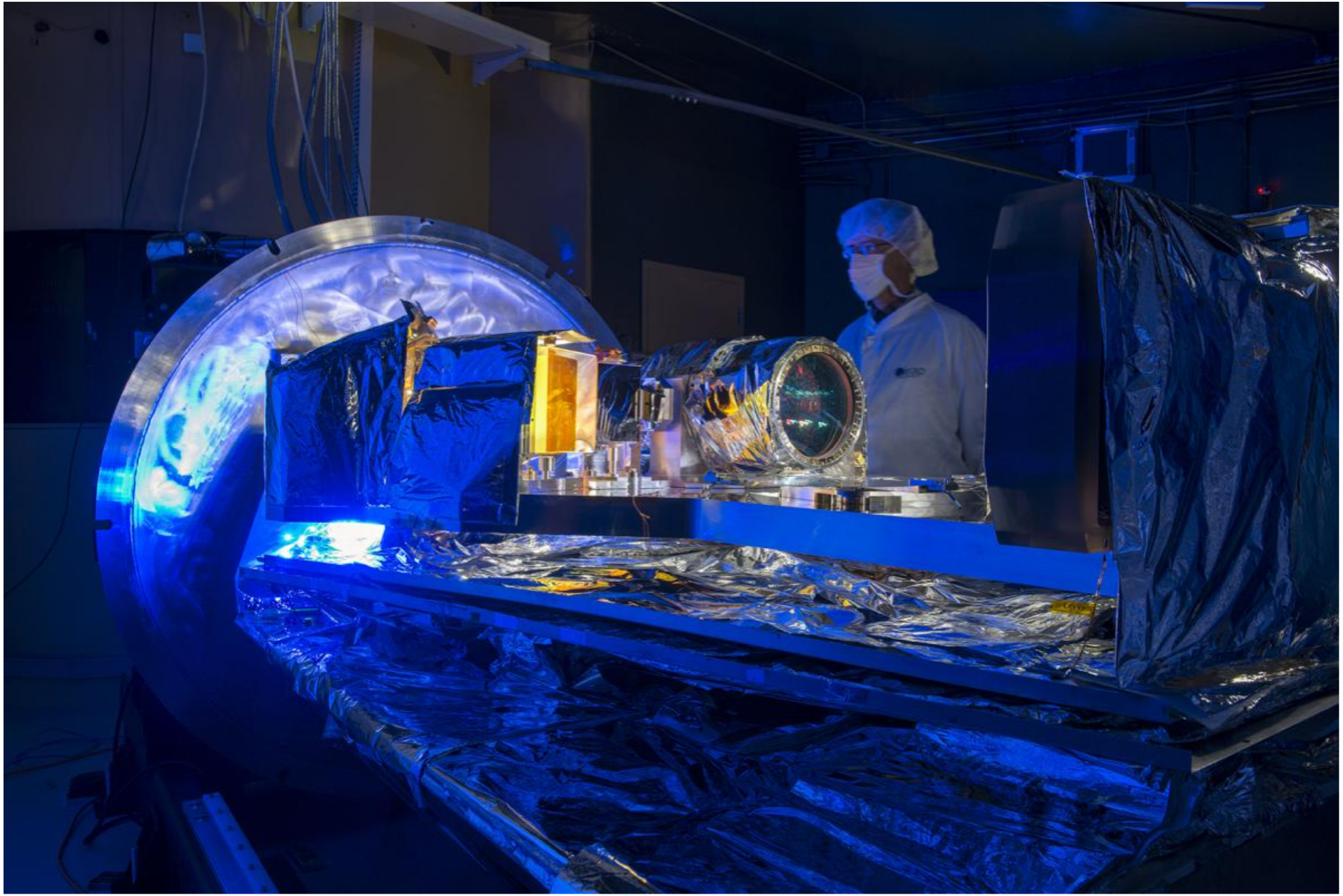
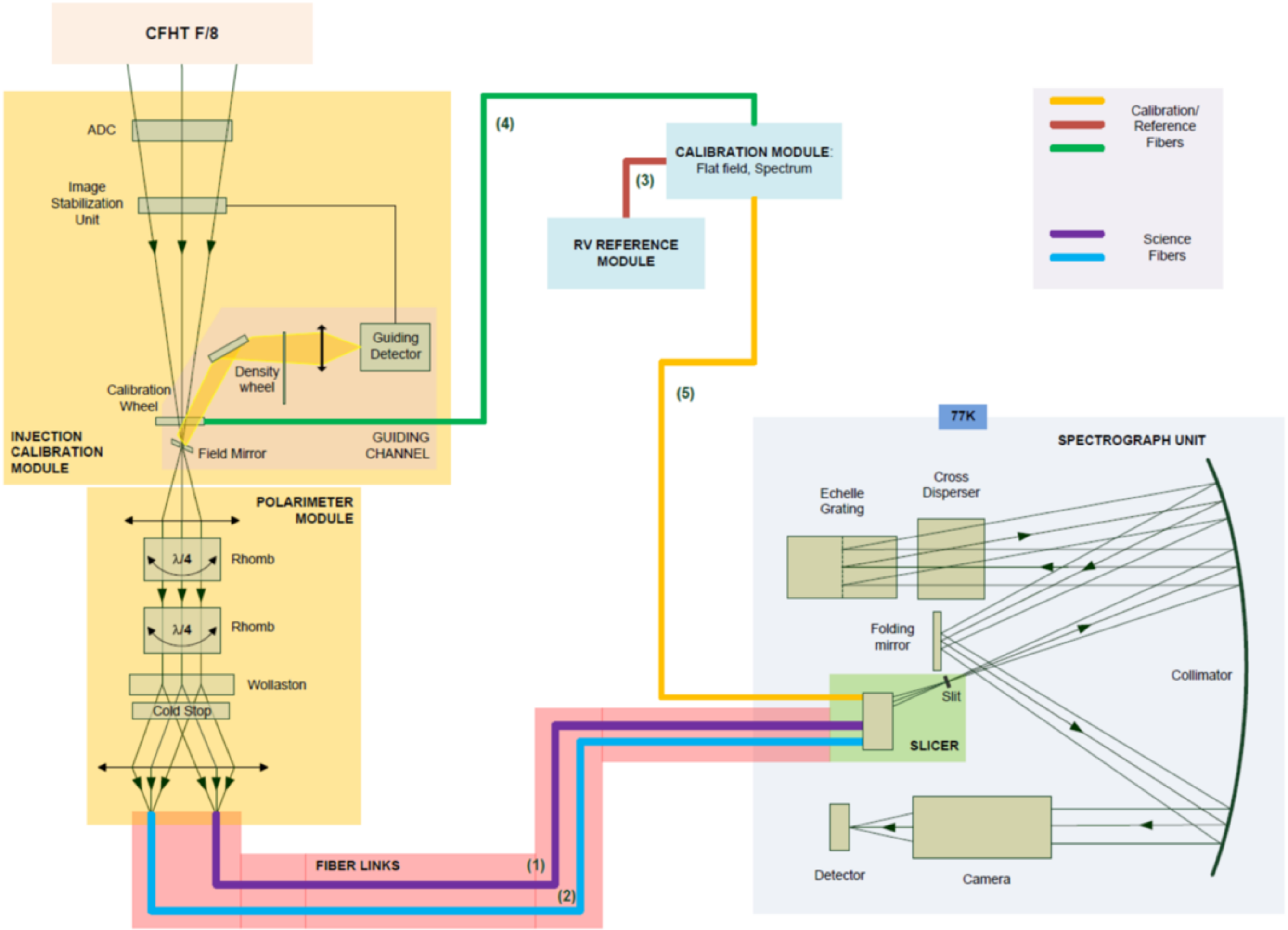




CFHT F/8
ADC
Image Stabilization Unit
Guiding Detector
Density wheel
Calibration Wheel
Field Mirror
INJECTION CALIBRATION MODULE
GUIDING CHANNEL
POLARIMETER MODULE
λ/4
Rhomb
λ/4
Rhomb
Wollaston
Cold Stop
FIBER LINKS
(1)
(2)
(4)
(3)
(5)
CALIBRATION MODULE: Flat field, Spectrum
RV REFERENCE MODULE
Calibration/ Reference Fibers
Science Fibers
77K
SPECTROGRAPH UNIT
Echelle Grating
Cross Disperser
Folding mirror
Collimator
Slit
SLICER
Detector
Camera

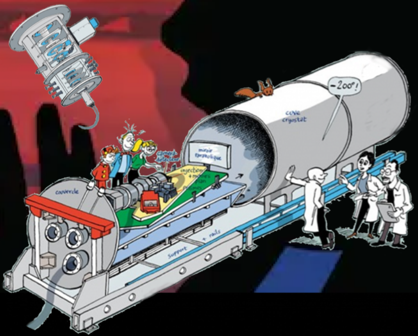
You’ve got some SPIRou data?

- Since 2019A SPIRou is the most requested CFHT instrument
- Lots of SLS and PI targets have been observed since February 2019
- You want to analyze your data but you are not familiar with the way they are obtained, reduced and distributed
- Lucky you, APERO does everything for you

Using APERO for SPIRou

Version 0.6.132 (2020-10-15)

A primer by Neil Cook

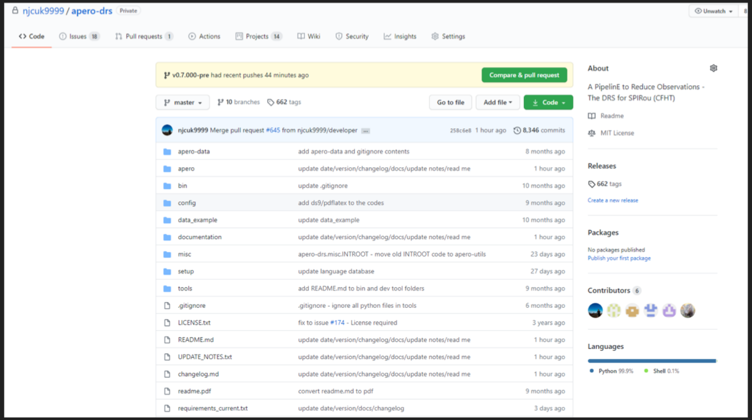


SPiRou

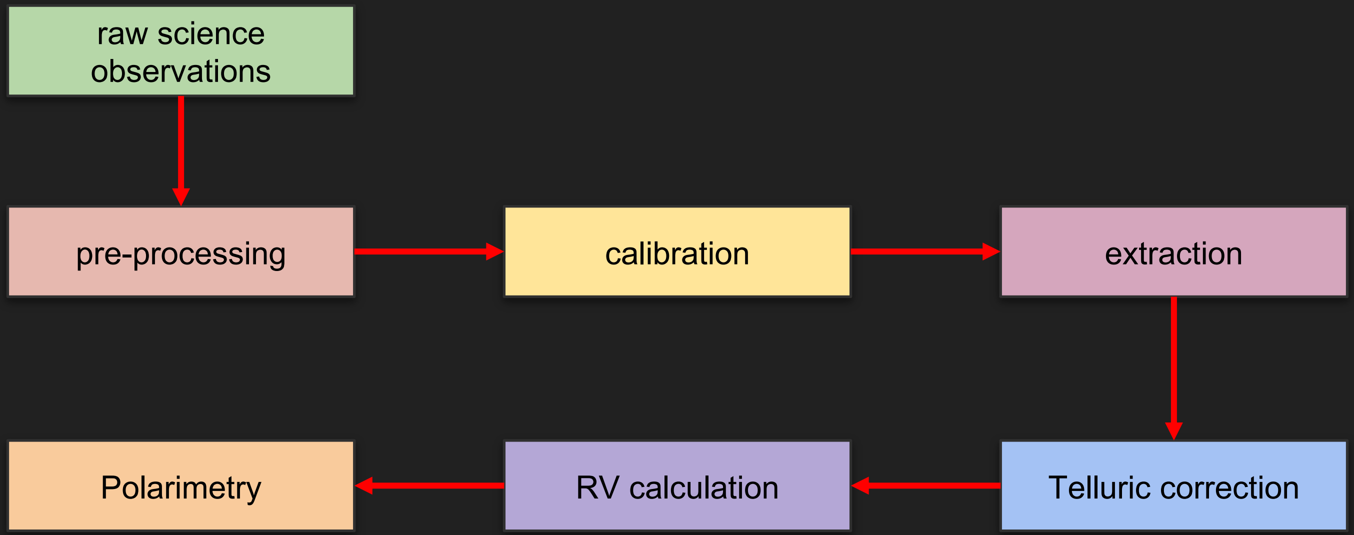
Contents

APERO is on github

- Currently private : give Neil your github username and he will add you!
  - Repository here: https://github.com/njcuk9999/apero-drs
  - Add your name and github username here (currently 33 people): https://docs.google.com/spreadsheets/d/1eJNiQPIJyaI_2SQnsEvcmaDVnJ00RAAsIHKYjEX_nBc/edit?usp=sharing



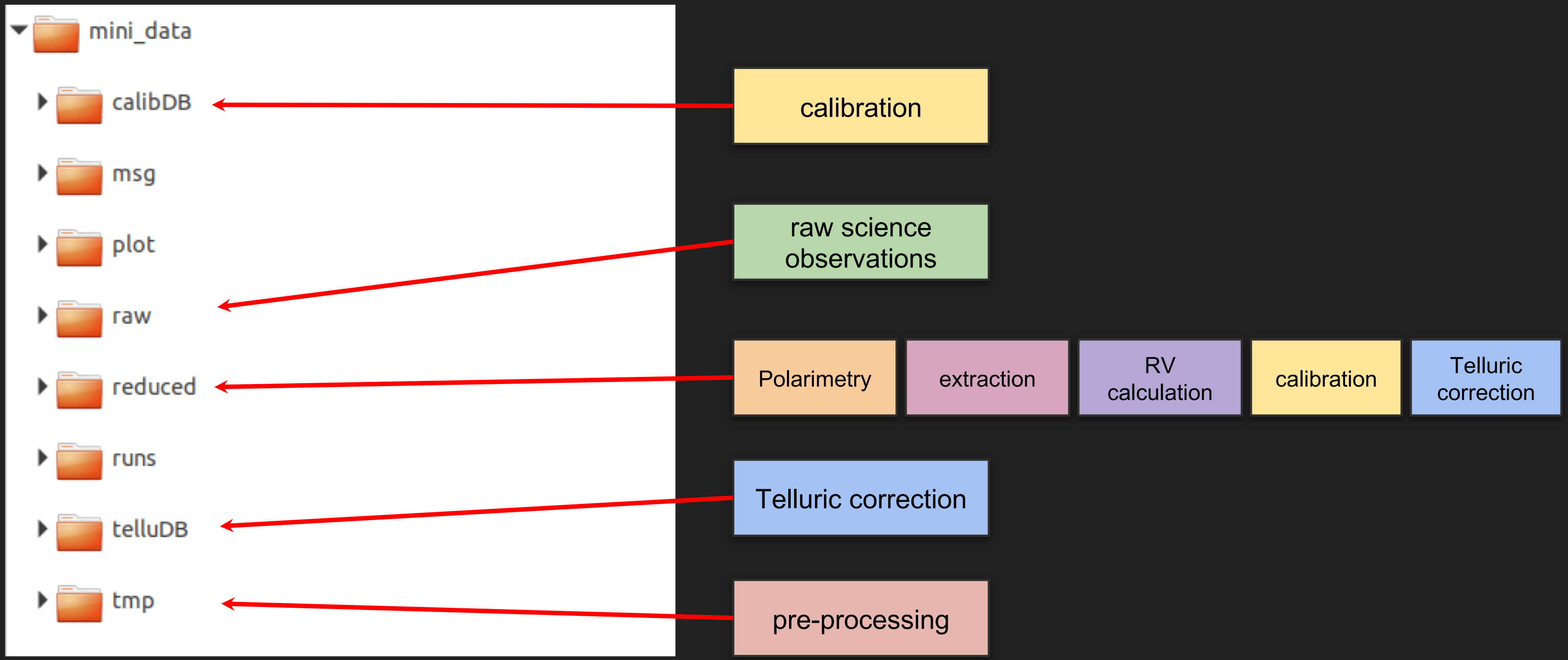
A PipelinE to Reduce Observations



The data directories

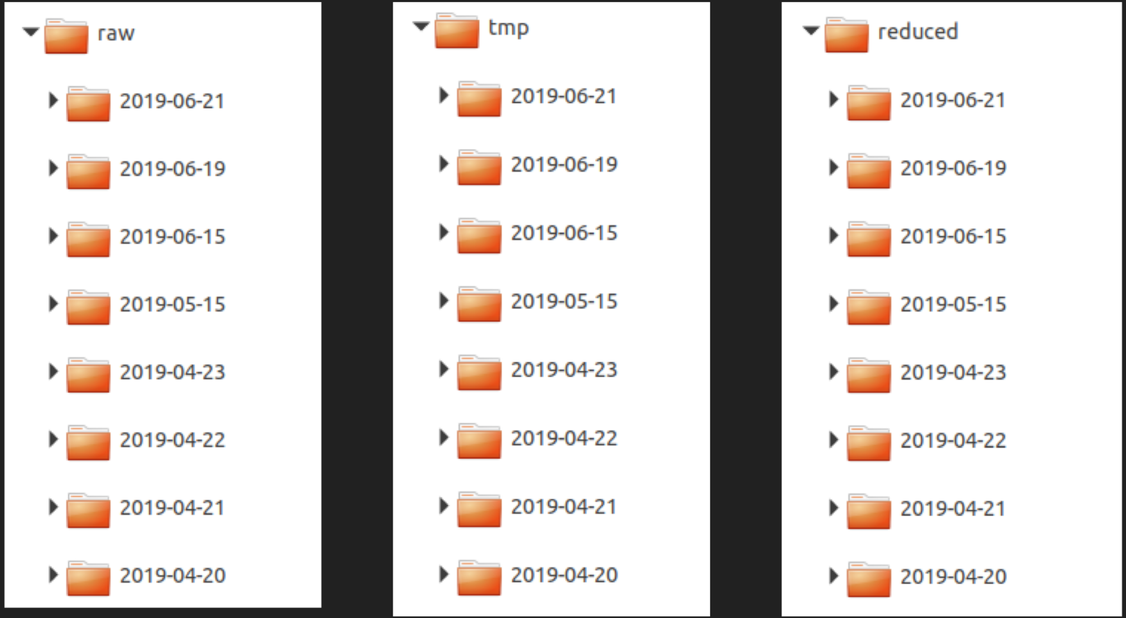
- Paths set during installation process

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)
  - Montreal and LAM use YYYY-MM-DD (UTC)
  - CFHT uses 19AQ08-Apr19
  - Processing is independent of sub-directory structure but structure is kept throughout (raw, tmp, reduced)



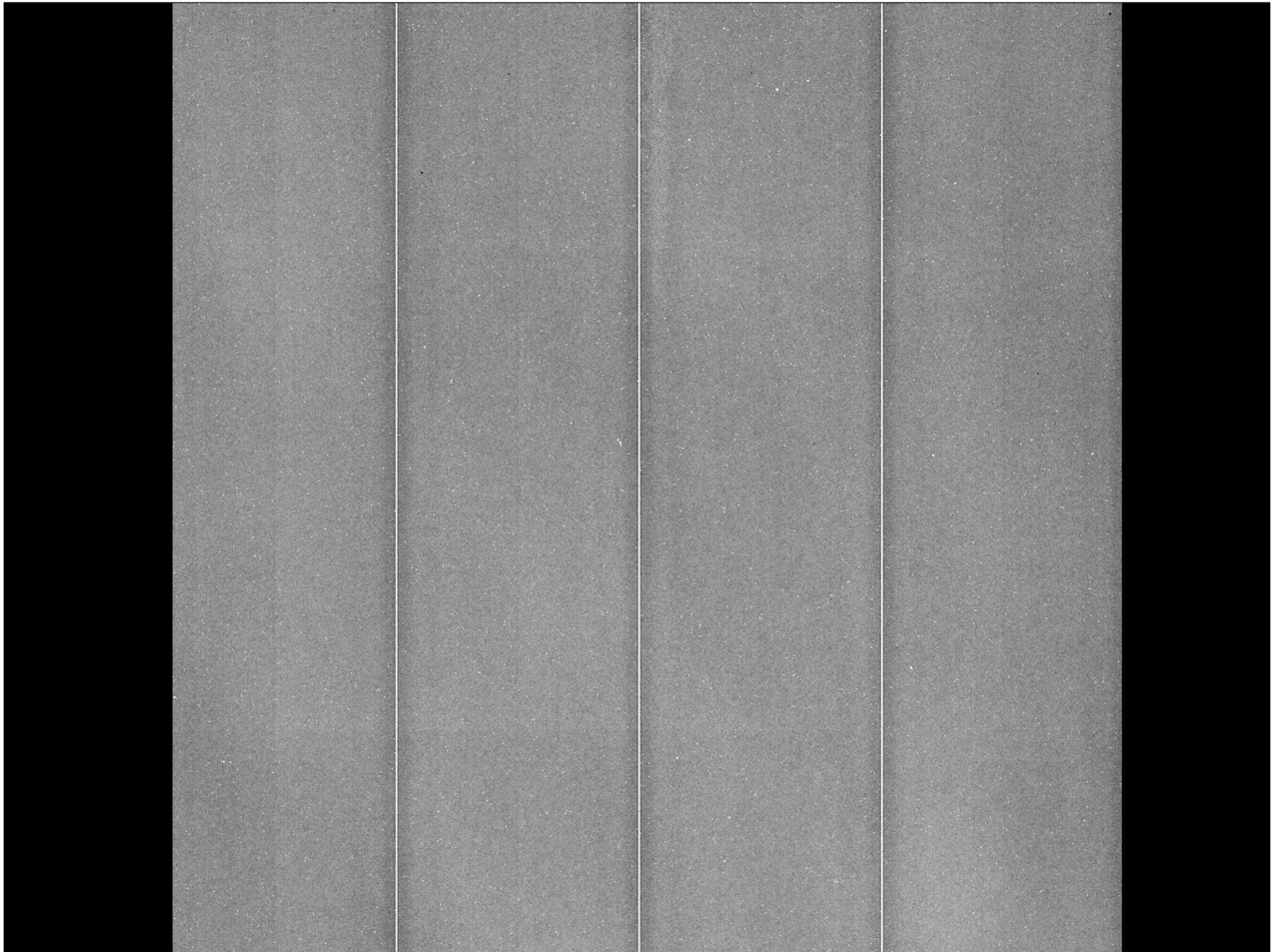
The Grand Plan

- PIs get science-ready data through the CADC archive (needs an account)
- The data package includes a number of intermediate
    - Single spectrum (all orders merged) from 0.95-2.5µm, CCF and polarization products
    - Most instrumental effects are corrected for
    - Relevant intermediate products are provided
    - Ramp and raw frames are provided
- Calibrated data are being re-processed frequently as the DRS improves
    - PI-friendly description of the updates on the SPIRou website
    - Don't panic when your data is re-released...

r.fits

[ramp]

- 4096x4096xN
  - These are huge files (up to a few Gb each)!
- Individual images taken every 5.572s; used to compute the per-pixel time-derivative of flux
- The ramp is generally *not saved* by IR instruments
  - Not saved in WIRCam
  - We save these frames in the hope of improving the per-frame filtering of data in the future



r.fits

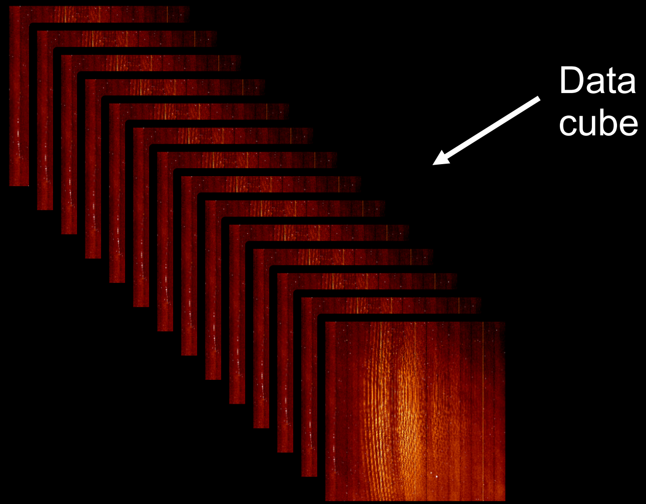
[ramp]

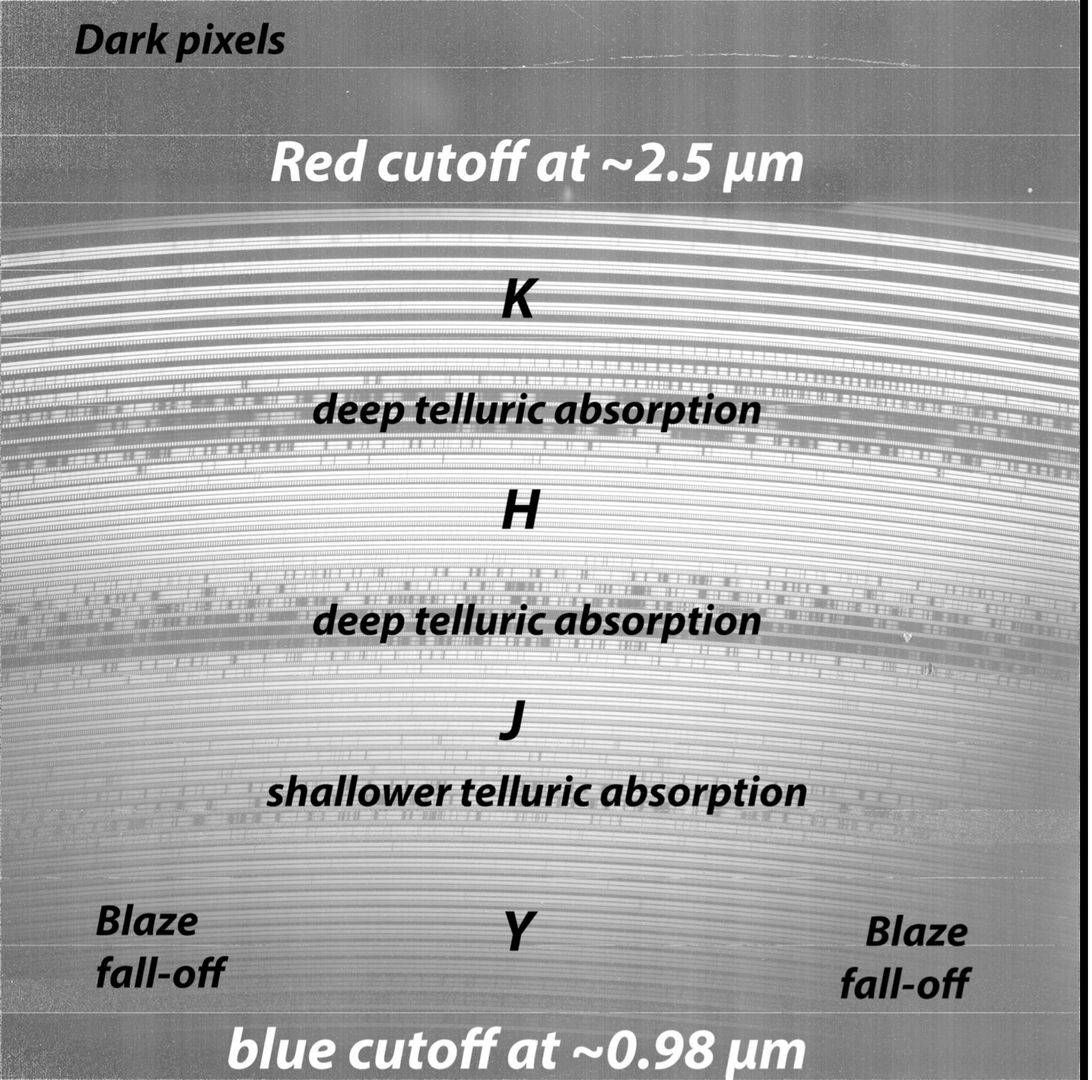
- Accumulation of signal for a bright A star over 56 frames
- Middle of *H* band only

Raw observations

- Three fibers   two science=A,B   one reference=C
- A and B are used for polarization but are combined for intensity: AB
- APERO observation notation:
  - {fiber AB}_{fiber C}
- Many types of observations
  - Science observations: OBJ in AB   FP or DARK in C
    - OBJ_FP   OBJ_DARK
  - Hot stars (for telluric correction): OBJ in AB   DARK in C
    - OBJ_DARK
  - Calibrations: different combinations in AB and C
    - Combinations of DARK, FLAT, FP, HC1, HC2
    - DARK_DARK, DARK_FLAT, FLAT_DARK, FLAT_FLAT, FP_FP, HC1_HC1, DARK_FP etc…
  - Sky observations, Laser Frequency comb (LFC_LFC) etc

Pre-DRS

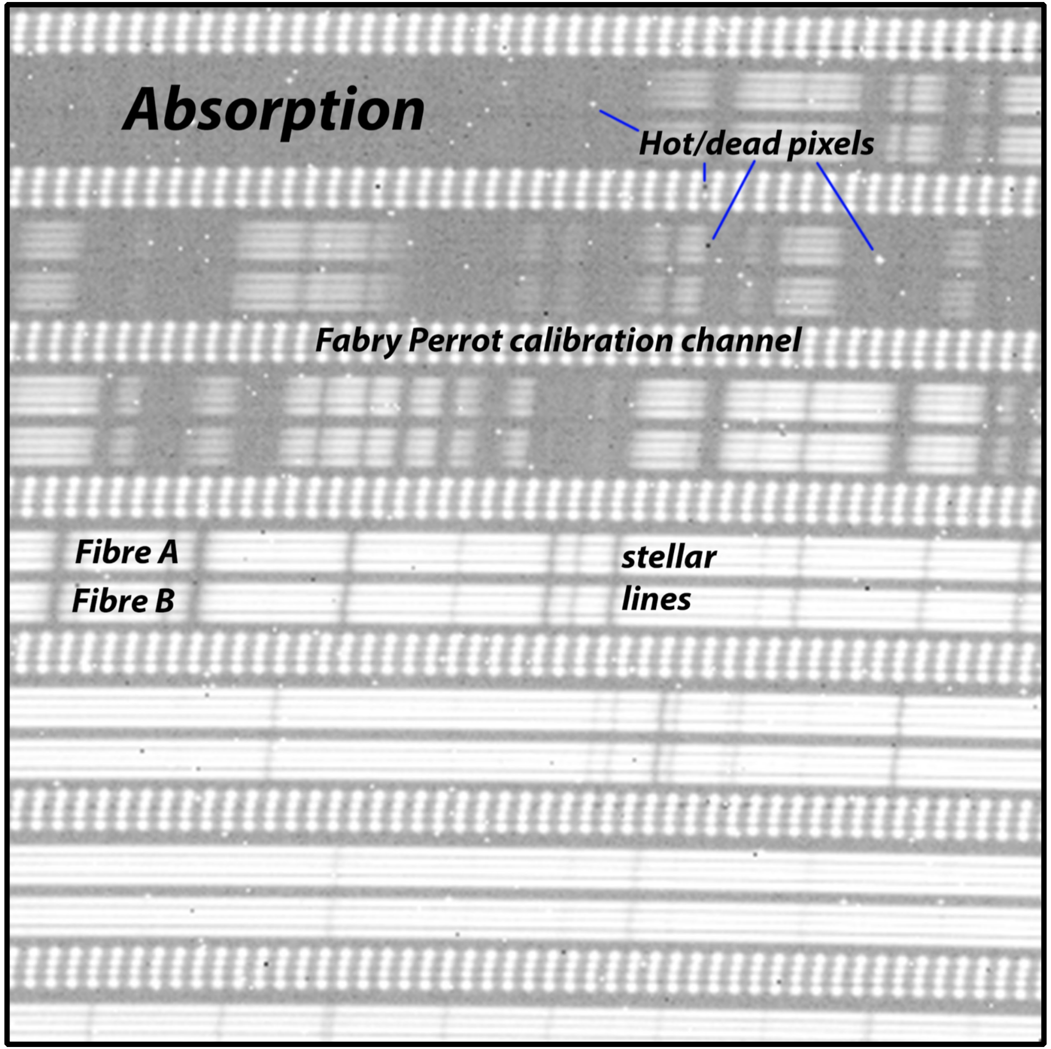




o.fits

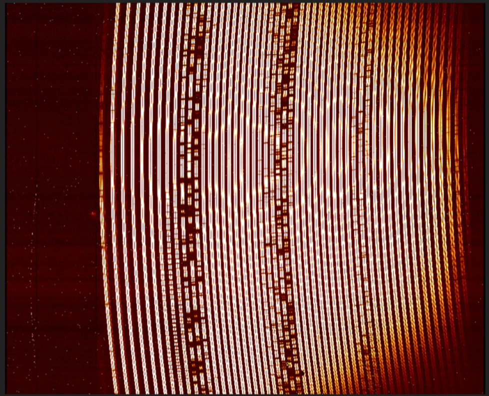
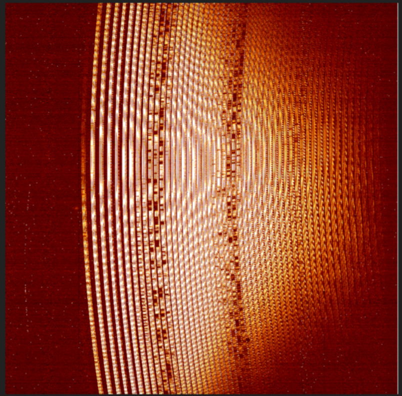
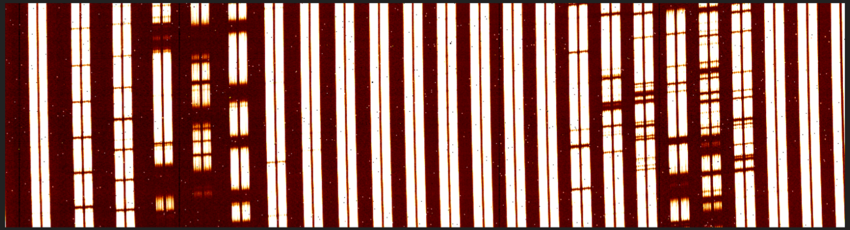
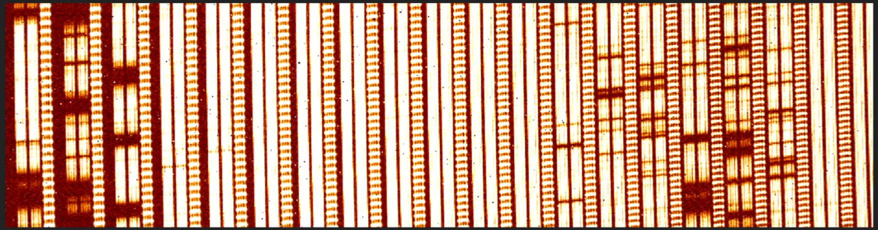
[object]

- Ext 1: The 'slope' image, this is the closest analog to a CCD image
- Ext 2: Intercept of the slope. This is more or less the equivalent of a bias. *Mostly for engineering*.
- Ext 3: Formal error on the slope. To be used for pixel quality assessment.
- Ext 4: Number of unsaturated readouts (normally equal to Nread). To be used for pixel quality assessment.

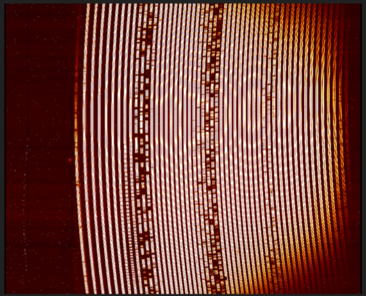

Absorption
Hot/dead pixels
Fabry Perrot calibration channel
Fibre A
Fibre B
stellar
lines

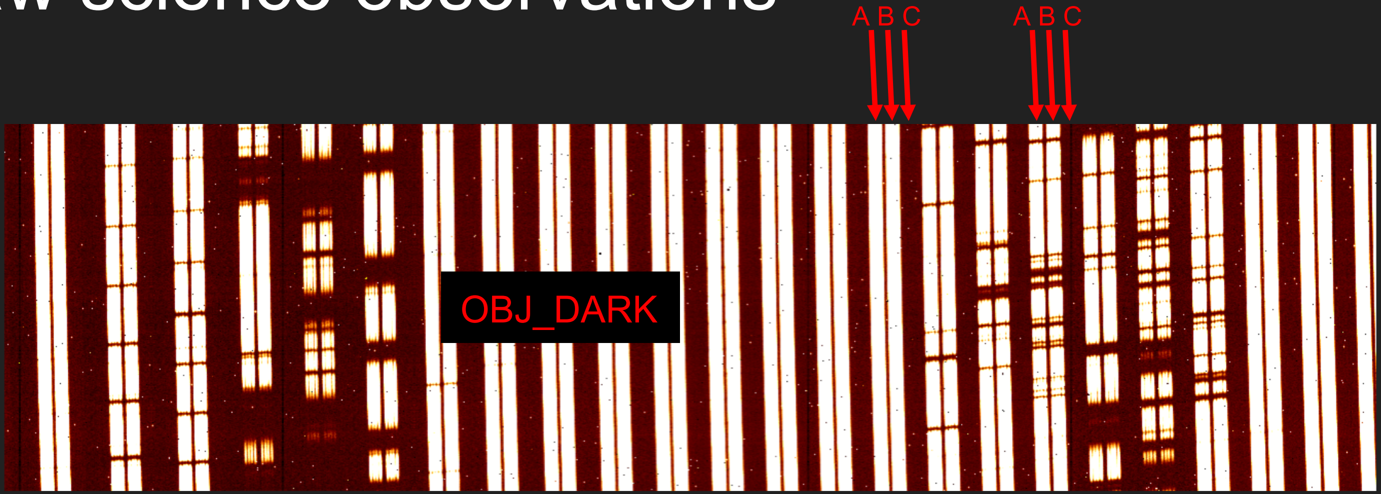
SPIRou Raw science observations

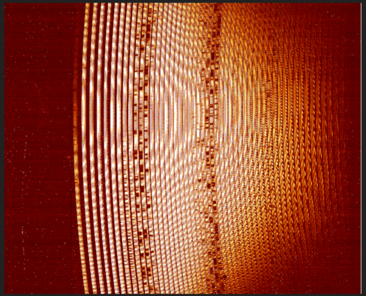
- H4RG detector
- Raw frame: 4096 x 4096 pixels

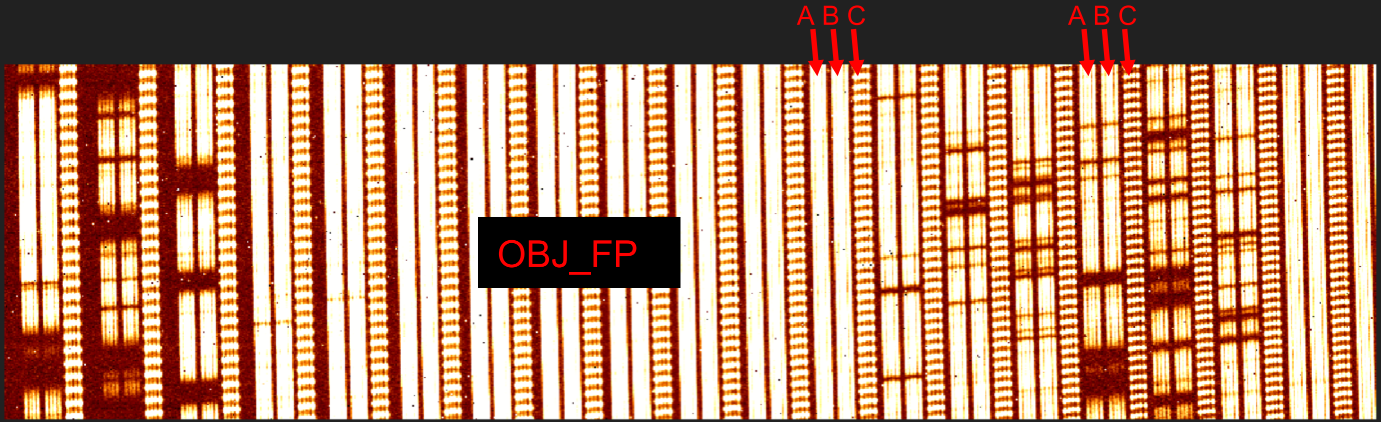





SPIRou Raw science observations









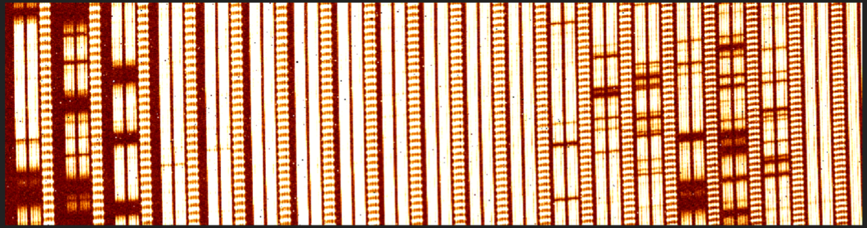
SPIRou Raw science observations

OBJ_DARK

- Fibers A and B: OBJ
- Fibers C: DARK

- Header:
  - SBCCAS_P = pos_pk
  - SBCREF_P = pos_pk
  - TRG_TYPE = TARGET or SKY
  - OBJECT = Object name

- Can be hot star (telluric), science observation or sky observation



OBJ_FP

- Fibers A and B: OBJ
- Fibers C: FP

- Header:
  - SBCCAS_P = pos_pk
  - SBCREF_P = pos_fp
  - TRG_TYPE = TARGET
  - OBJECT = Object name

- Science observation

What's in a calibration?

Quiz time: the next slides show some raw images - try to guess what is in each fiber (AB and C).

Choices are:

FLAT HC FP DARK →

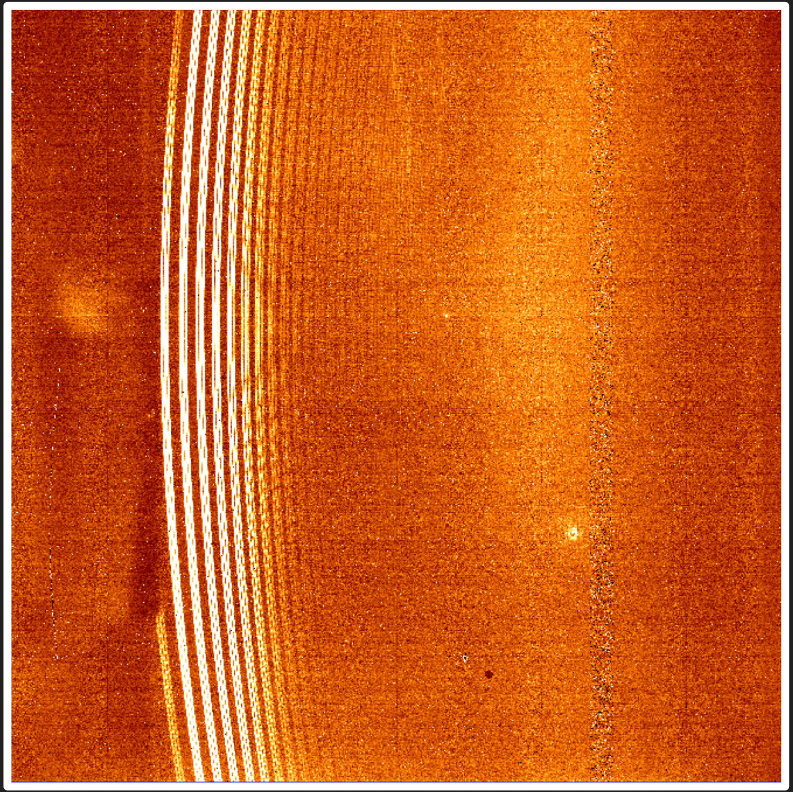
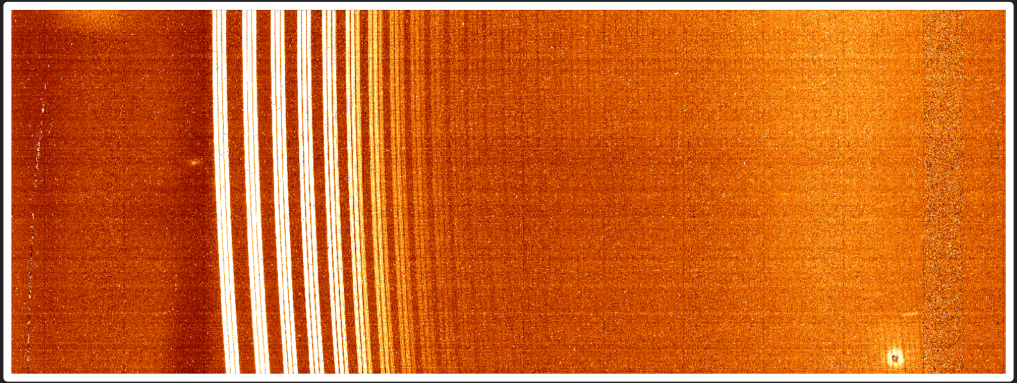
FLAT_DARK, FLAT_FP, FLAT_HC, FLAT_FLAT

HC_DARK, HC_FP, HC_HC, HC_FLAT

FP_DARK, FP_FP, FP_HC, FP_FLAT

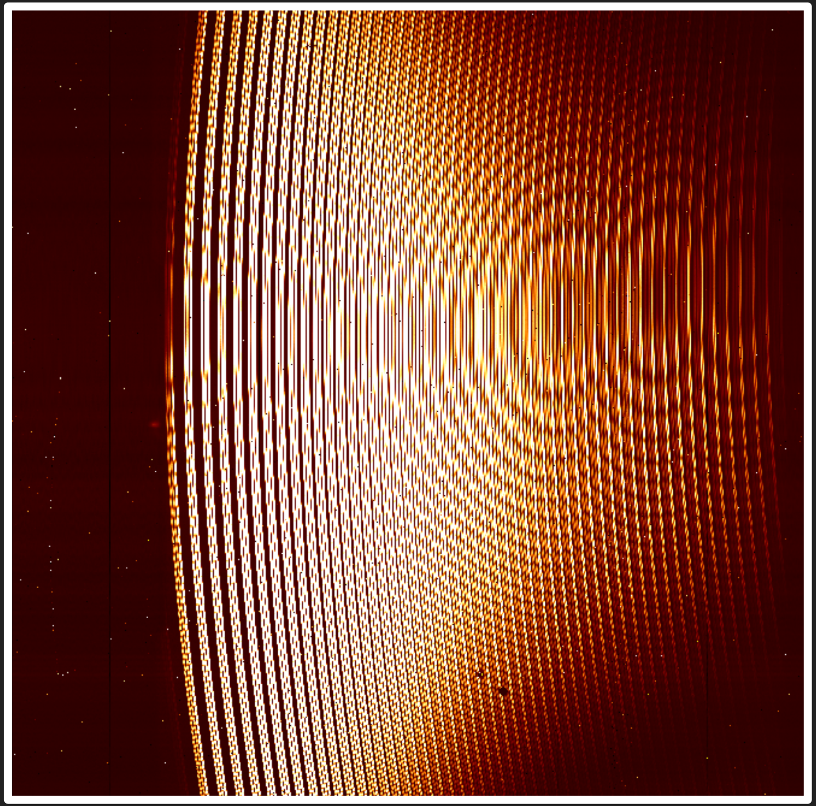
DARK_DARK, DARK_FP, DARK_HC, DARK_FLAT

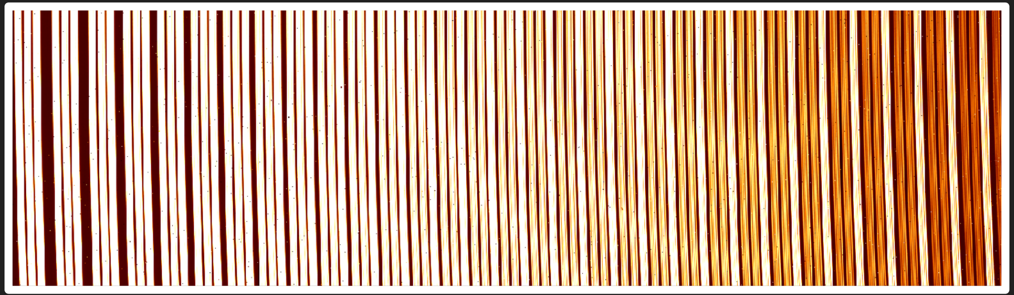
- Hint: ones in red are not used for calibration
- Note: DARK_DARK come in two flavours:
  - DARK_DARK_INT (internal darks) → just the fiber + detector
  - DARK_DARK_TEL (telescope darks) → through the cassegrain

Options:

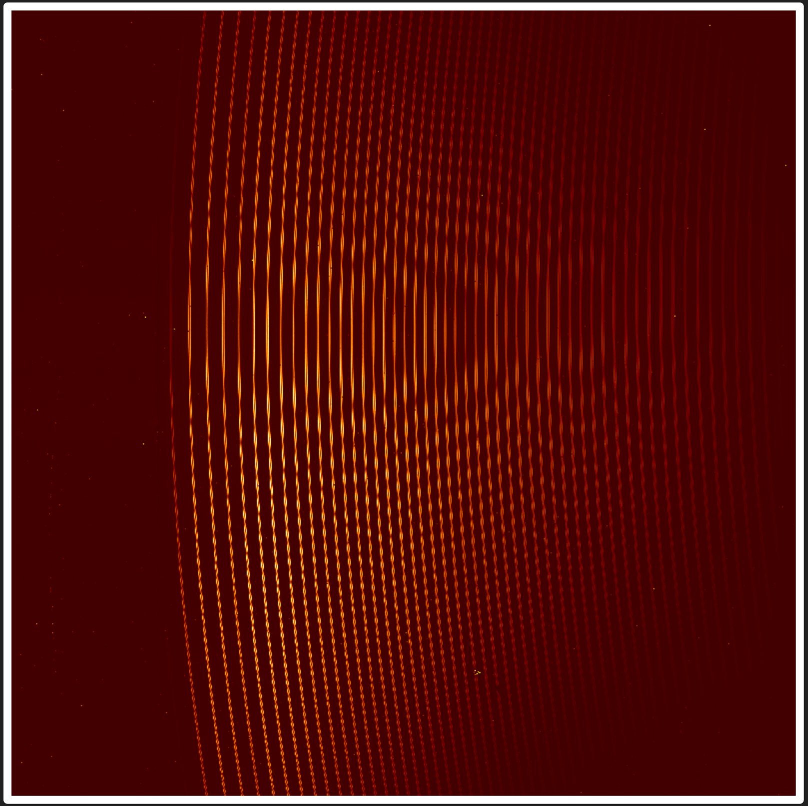
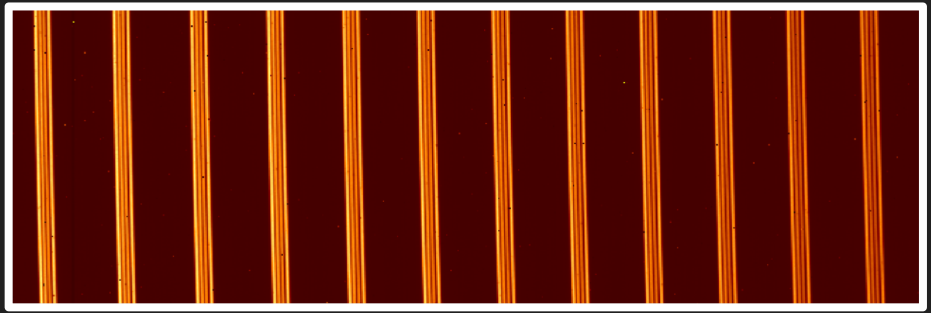
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT





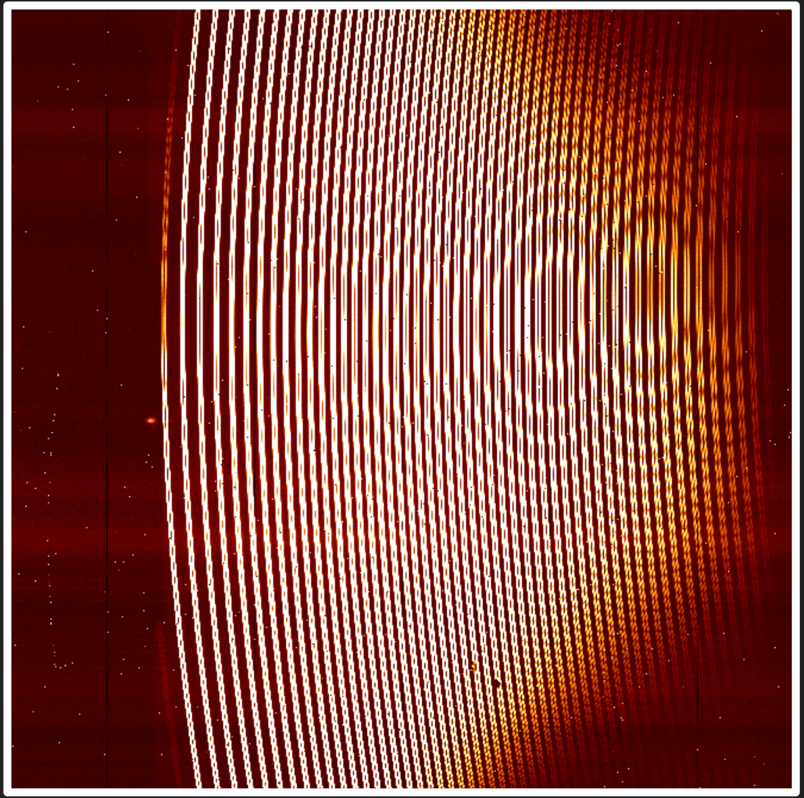
Options:

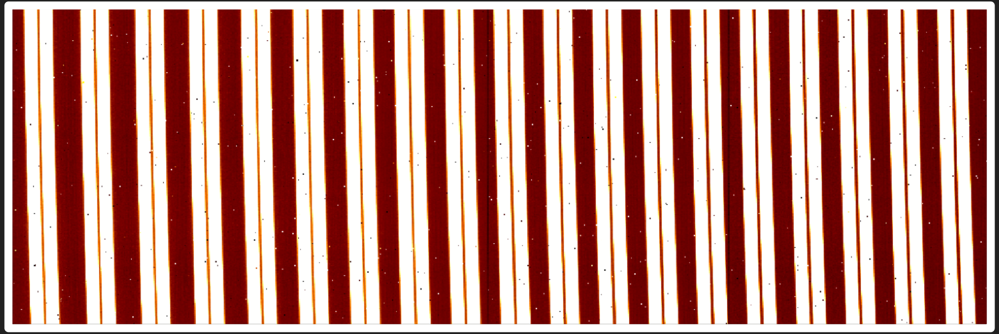
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

Options:

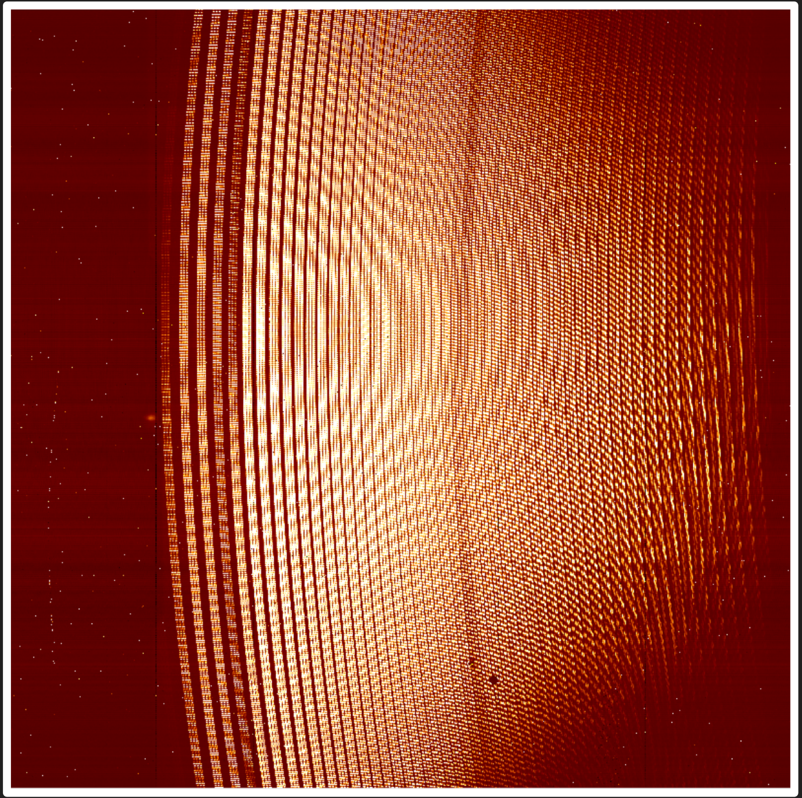
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

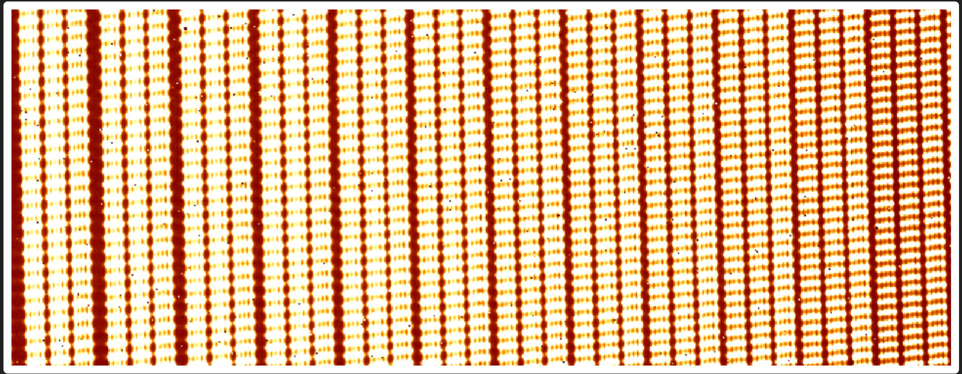




Options:

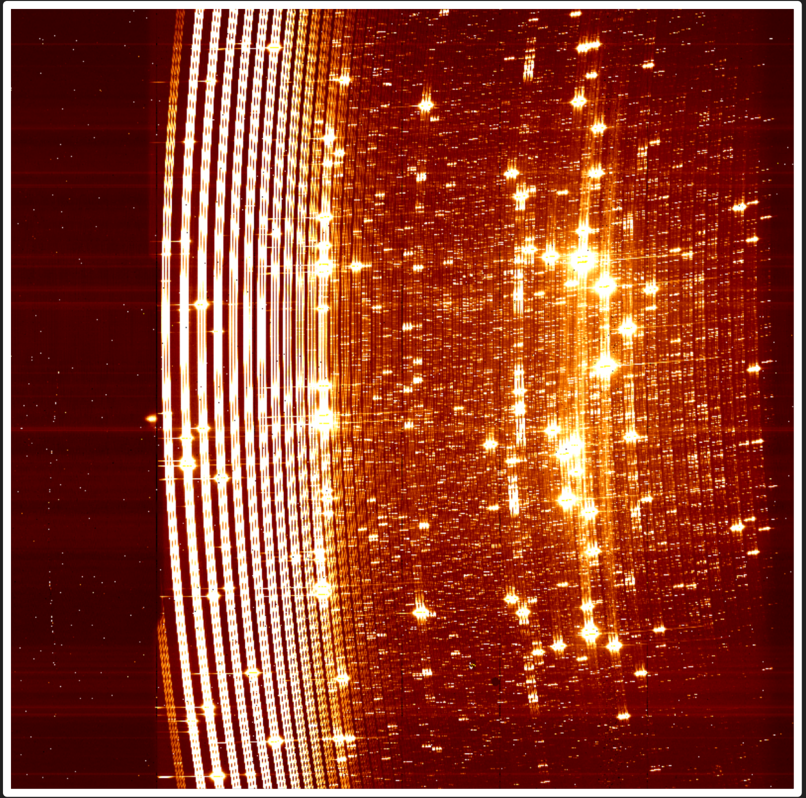
- FLAT_DARK
- FLAT_FLAT
- HC_HC
- FP_FP
- DARK_DARK
- DARK_FP
- DARK_FLAT

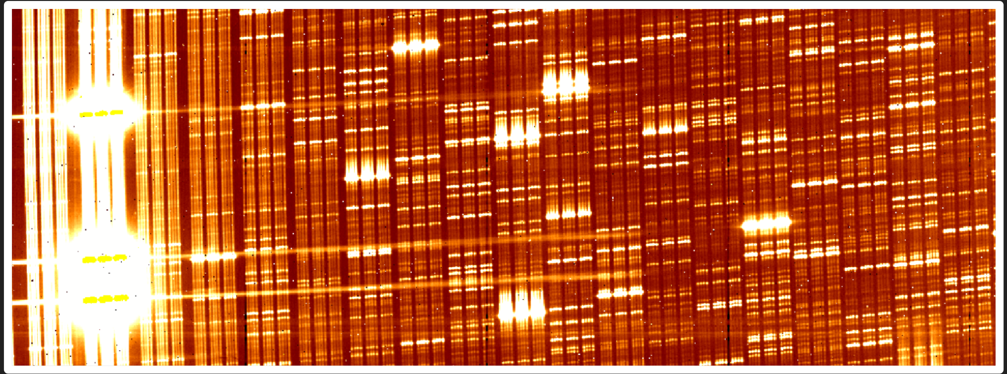




Options:

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





Options:

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

Useful list of SPIRou raw files

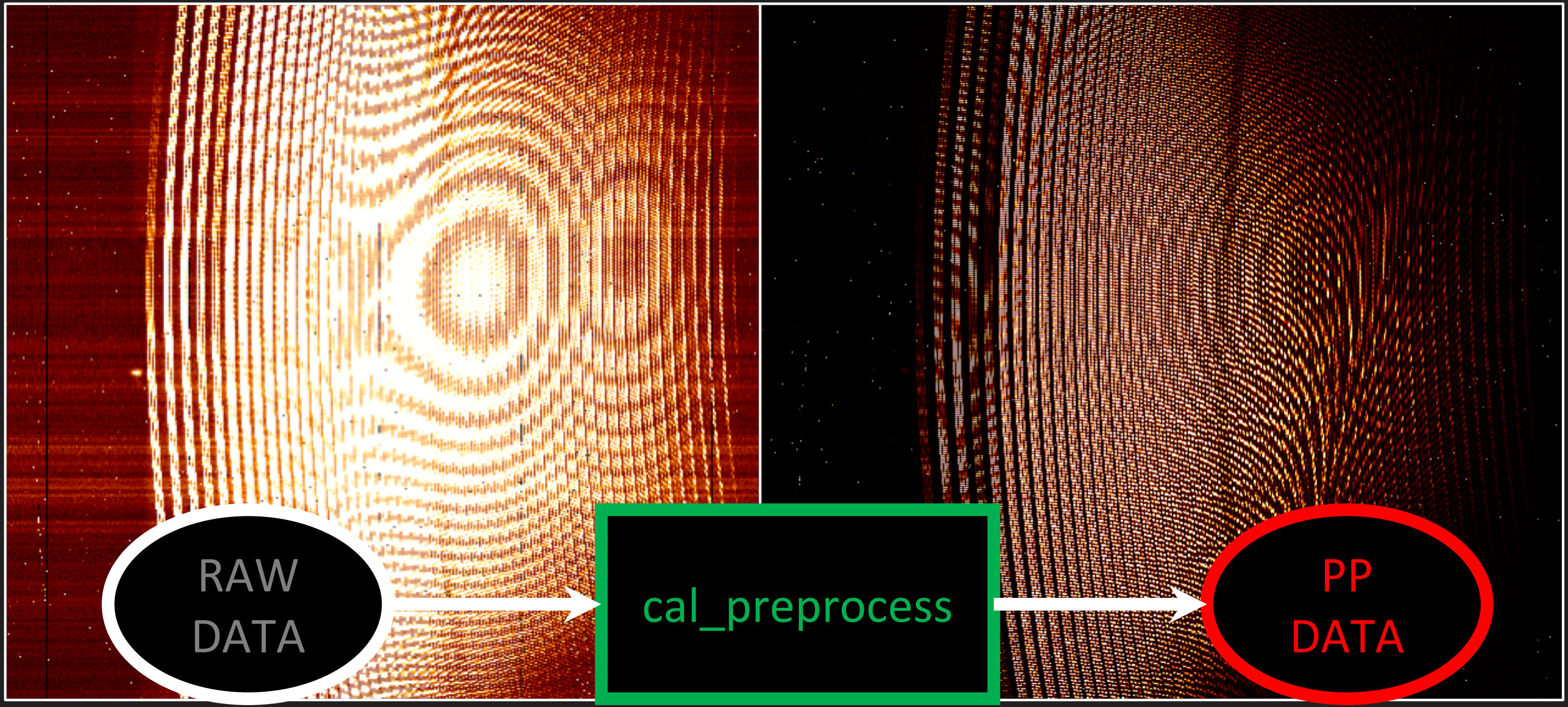
DPRTYPE	SBCCAS_P	SBCREF_P	SBCALI_P	OBSTYPE	TRG_TYPE	EXT.
DARK_DARK_INT	pos_pk	pos_pk	P4	DARK	CALIBRATION	d.fits
DARK_DARK_TEL	pos_pk	pos_pk	P5	DARK	CALIBRATION	d.fits
OBJ_DARK	pos_pk	pos_pk	?	OBJECT	TARGET	o.fits
DARK_DARK_SKY	pos_pk	pos_pk	?	OBJECT	SKY	o.fits
DARK_FP_SKY	pos_pk	pos_fp	?	OBJECT	SKY	o.fits
OBJ_FP	pos_pk	pos_fp	?	OBJECT	TARGET	o.fits
FP_FP	pos_fp	pos_fp	?	ALIGN	CALIBRATION	a.fits
LFC_LFC	pos_rs	pos_rs	?	ALIGN	CALIBRATION	a.fits
FLAT_DARK	pos_wl	pos_pk	?	FLAT	CALIBRATION	f.fits
DARK_FLAT	pos_pk	pos_wl	?	FLAT	CALIBRATION	f.fits
FLAT_FLAT	pos_wl	pos_wl	?	FLAT	CALIBRATION	f.fits
HCONE_DARK	pos_hc1	pos_pk	?	COMPARISON	CALIBRATION	c.fits
HCTWO_DARK	pos_hc2	pos_pk	?	COMPARISON	CALIBRATION	c.fits
FP_HCONE	pos_fp	pos_hc1	?	COMPARISON	CALIBRATION	c.fits
FP_HCTWO	pos_fp	pos_hc2	?	COMPARISON	CALIBRATION	c.fits
HCONE_FP	pos_hc1	pos_fp	?	COMPARISON	CALIBRATION	c.fits
HCTWO_FP	pos_hc2	pos_fp	?	COMPARISON	CALIBRATION	c.fits
DARK_HCONE	pos_pk	pos_hc1	?	COMPARISON	CALIBRATION	c.fits
DARK_HCTWO	pos_pk	pos_hc2	?	COMPARISON	CALIBRATION	c.fits
HCONE_HCONE	pos_hc1	pos_hc1	?	COMPARISON	CALIBRATION	c.fits
HCTWO_HCTWO	pos_hc2	pos_hc2	?	COMPARISON	CALIBRATION	c.fits

- Note “DPRTYPE” set in preprocessing (so not in the raw files)
- This table can be found here: https://github.com/njcuk9999/apero-drs#71-input-files
- Raw files will have the following keys to ID the files:
  - SBCCAS_P: the position of the cassegrain fiber
  - SBCREF_P: the position of the reference fiber
  - SBCALI_P: the position of the calibration wheel
  - OBSTYPE: The observation type
  - TRG_TYPE: The target type

Overview of the reduction process

Pre-processing

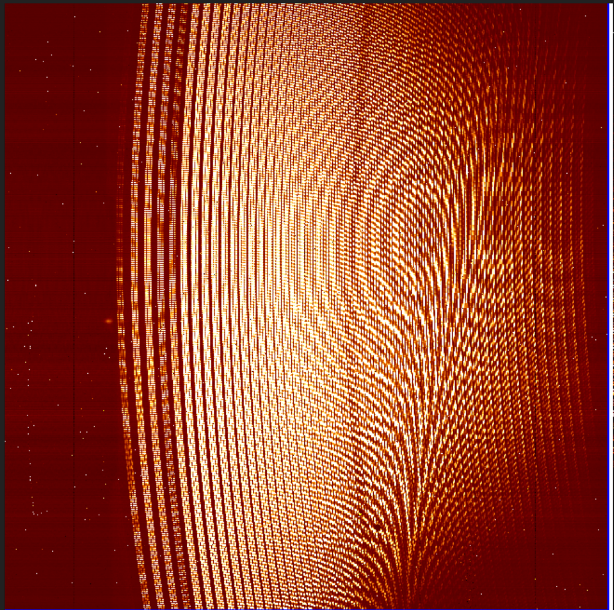
- Needs to be done on every observation (science or calibration)
- Cleans data of many detector effects



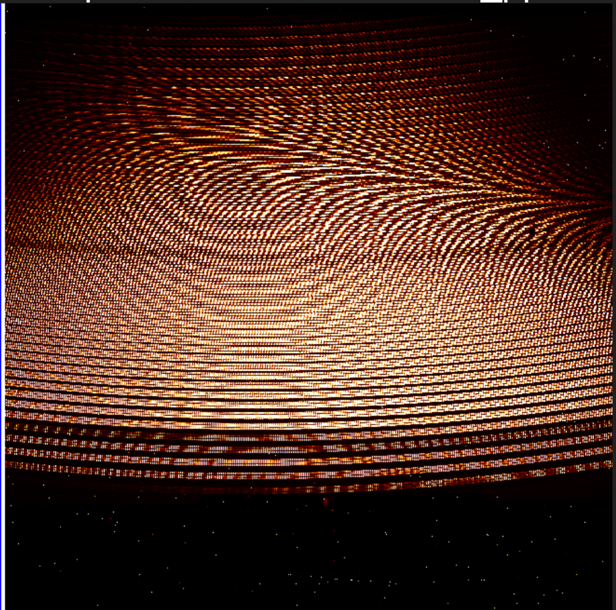
Pre-processing

- Images may be flagged as corrupted at this stage (texp < 0.1 treq)
- Image is rotated with respect to the raw images
- Saved in the tmp directory with “_pp” extension added

raw/2019-04-20/2400412a.fits



tmp/2019-04-20/2400412a_pp.fits

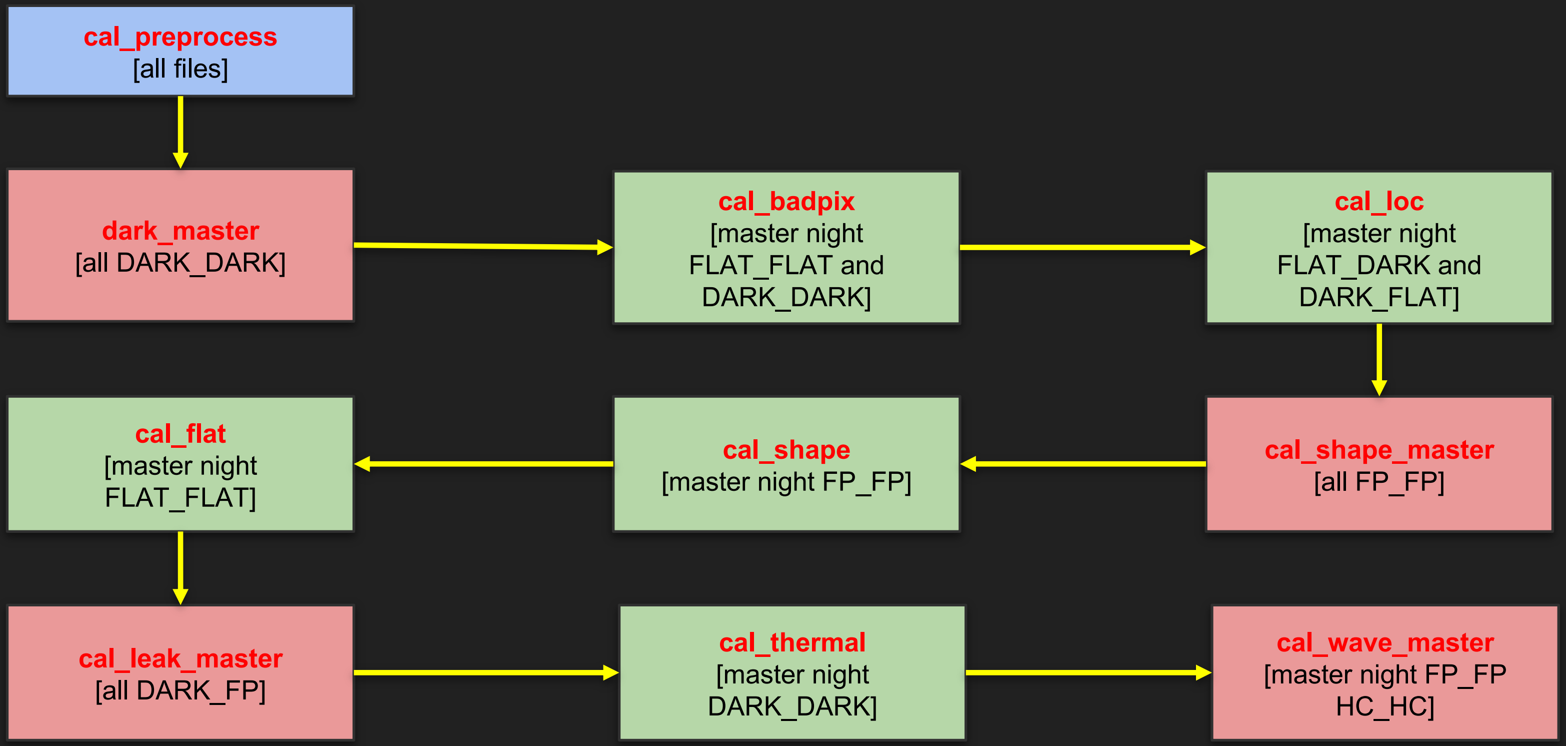


Calibration

Two types of calibration

- “Master” calibration
  - Only done once - provides a reference frame for all other calibrations
- “Night” calibration
  - Uses the calibrations taken on each night
  - Intended for science observed on the same night as those calibrations
  - May be used for a different night if calibrations fail
- Two modes:
  - “older calibration” (those taken immediately before observations started that night)
  - “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
- Think about earthquake

Master calibration sequence

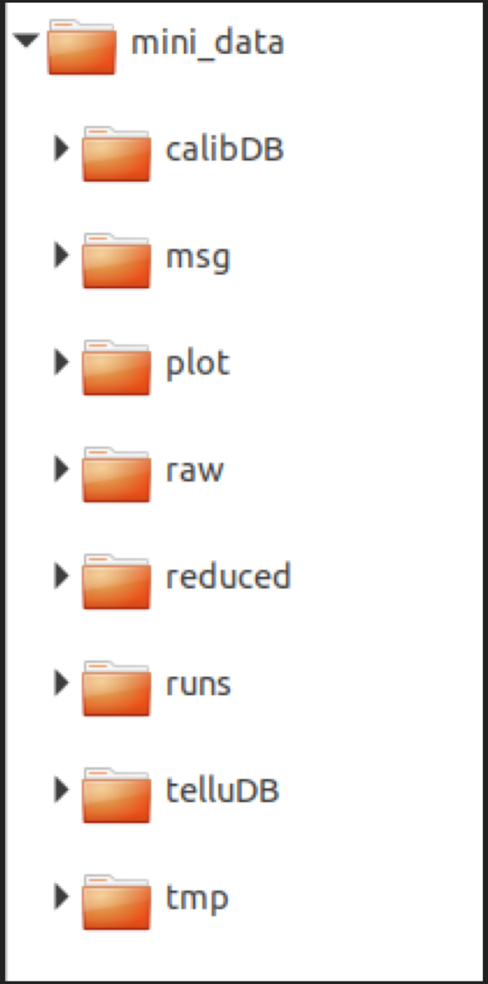


Night calibration sequence

Calibration Database

Note that although only certain files are used in each calibration recipe they also rely on the output of previous steps

- All calibrations (good and bad) are saved to the reduced directory
- Calibrations that pass quality control are saved to the "calibDB"
- Calibrations that pass quality control are added to the database
  - Filename: "master_calib_SPIROU.txt"
- Other recipes use the calibration database and select based on observation time
  - MJDMID = MJDEND - EXPTIME/2



master_calib_SPIROU.txt

- Just a simple text file (for now)
- Columns:
  - Calibration key, master flag, night directory, filename, human time, unix time
  - Can remove calibration simply by commenting a line (start with a #)
- Each calibration has a unique key
  - Dark_master → DARKM
  - Bad pixel map → BADPIX
  - Master wave solution → WAVEM
- Calibrations are selected based on time in the header compared to time in this file:
  - By default the closest calibration is used
  - Can switch to older (closest in time that is older)

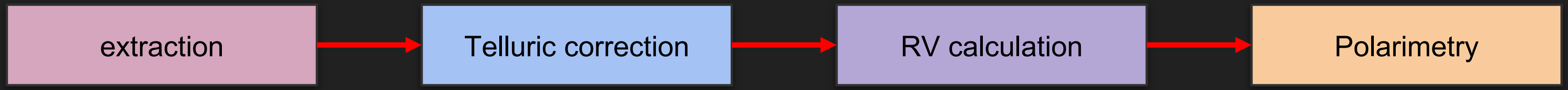
```
# Default files (Copied from apero-
WAVEM_D_AB 1 None MASTER_WAVE_SPIRO
WAVEM_D_A 1 None MASTER_WAVE_SPIROU
WAVEM_D_B 1 None MASTER_WAVE_SPIROU
WAVEM_D_C 1 None MASTER_WAVE_SPIROU
LEAKM_C 1 2018-05-29 MASTER_LEAK_C.
LEAKM_AB 1 2018-05-29 MASTER_LEAK_A
LEAKM_A 1 2018-05-29 MASTER_LEAK_A.
LEAKM_B 1 2018-05-29 MASTER_LEAK_B.

# DRS processed

DARKM 1 2019-06-21 2019-06-21_24266
BADPIX 1 2019-04-20 2019-04-20_2400
BKGRDMAP 1 2019-04-20 2019-04-20_24
ORDER_PROFILE_C 1 2019-04-20 2019-0
LOC_C 1 2019-04-20 2019-04-20_24003
ORDER_PROFILE_AB 1 2019-04-20 2019-
LOC_AB 1 2019-04-20 2019-04-20_2400
SHAPEX 1 2019-04-20 2019-04-20_2400
SHAPEY 1 2019-04-20 2019-04-20_2400
FPMASTER 1 2019-04-20 2019-04-20_24
```

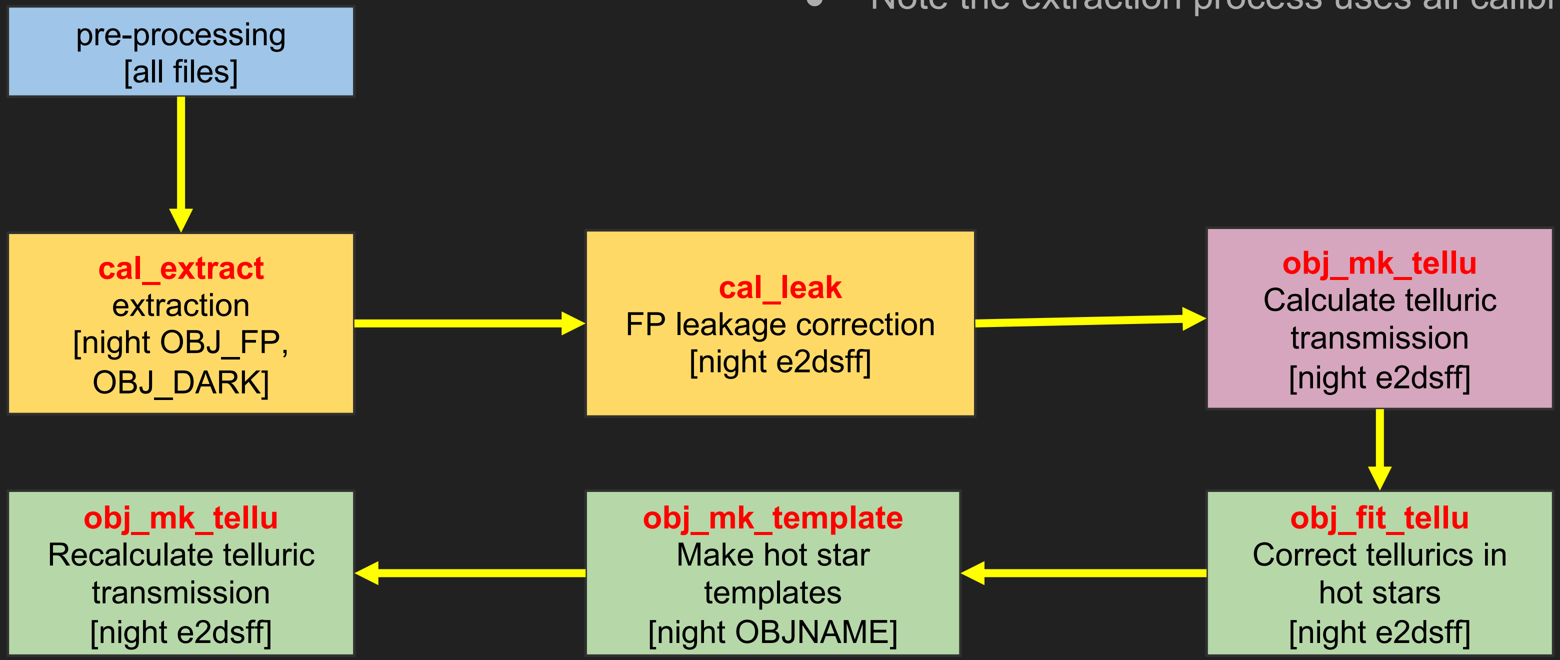
What happens after calibration?

- After a master 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
  - Polar observation



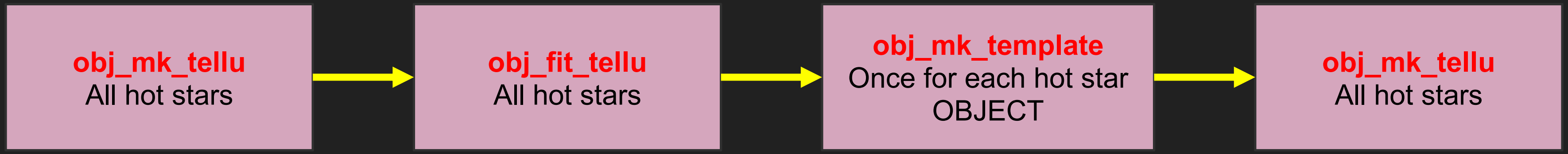
Telluric sequence

- Hot stars are observed most nights: they are early A fast rotator stars
- If a good hot star template is available steps in green could be skipped
- Note the extraction process uses all calibration steps



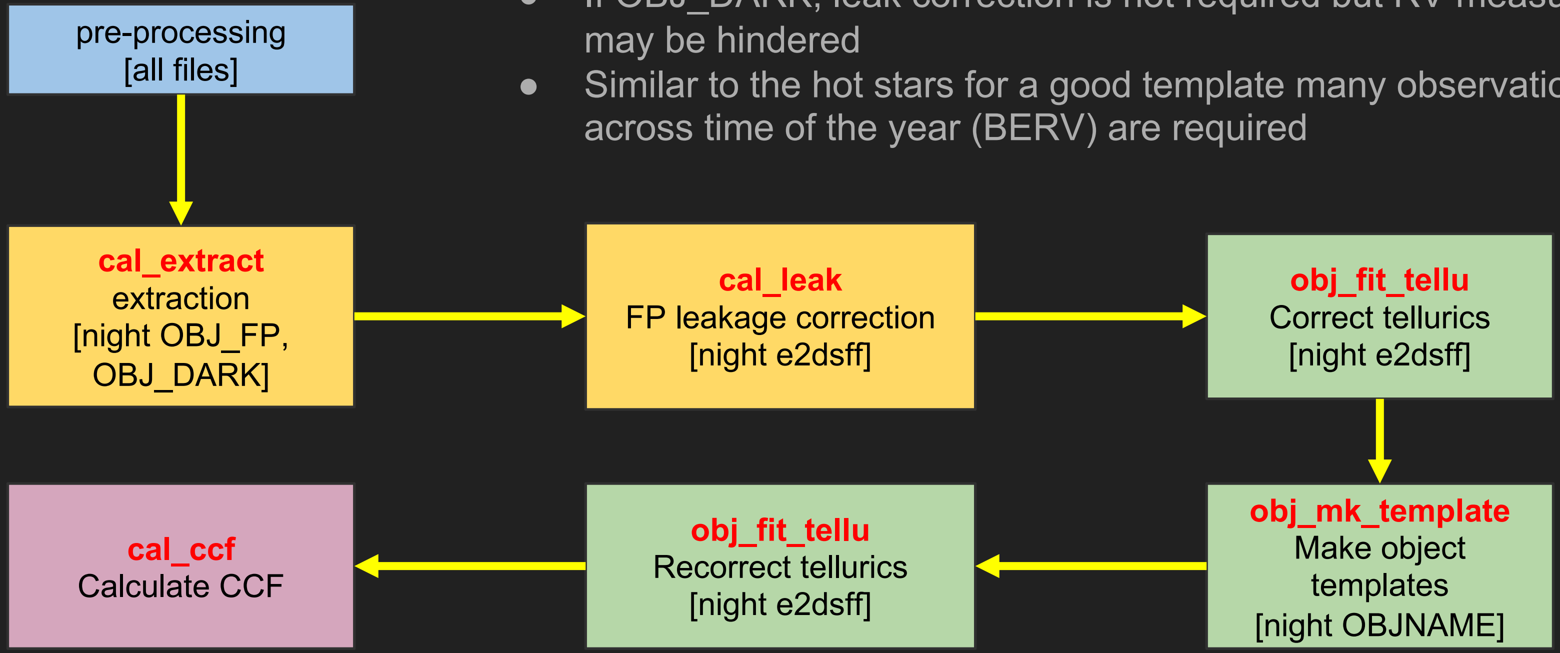
Telluric sequence

- In practice one needs many hot stars to make a good template and hot stars must be spread across airmass / time of the year (BERV) / water vapor column density
- Also obj_fit_tellu requires at least as many telluric transmissions as PCA components
- Thus for the best possible telluric database:
  - all telluric transmission should be calculated before any telluric star is corrected for tellurics
  - all hot stars should be corrected for tellurics before a hot star template is made
  - All telluric transmission should be recalculated after a template has been constructed
- All telluric outputs are saved to the telluric database (telluDB directory) similar to the calibration database

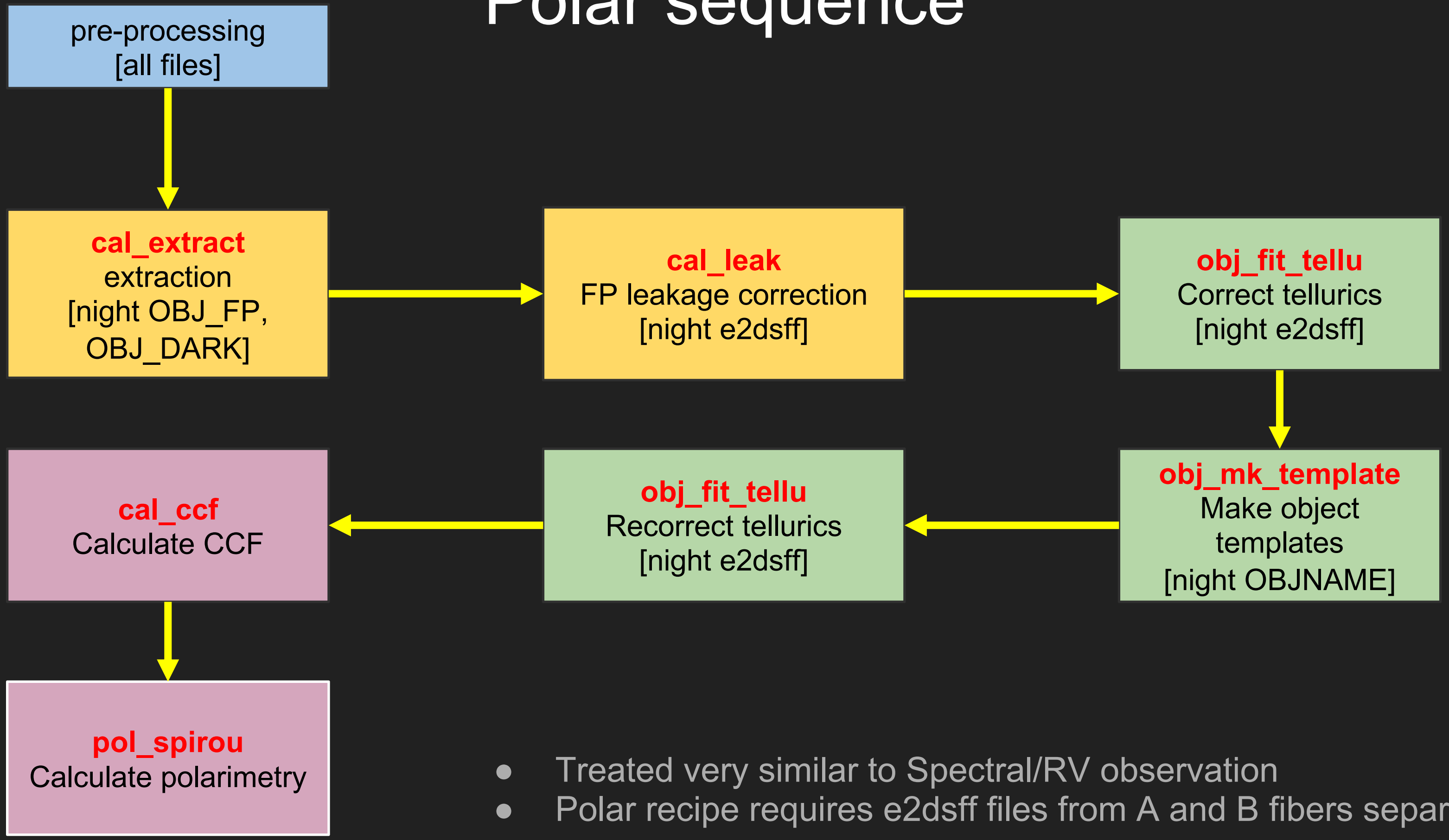


Spectral/RV sequence

- Note the extraction process uses all calibration steps
- If a good object template is available steps in green could be skipped
- If OBJ_DARK, leak correction is not required but RV measurement may be hindered
- Similar to the hot stars for a good template many observations across time of the year (BERV) are required



Polar sequence

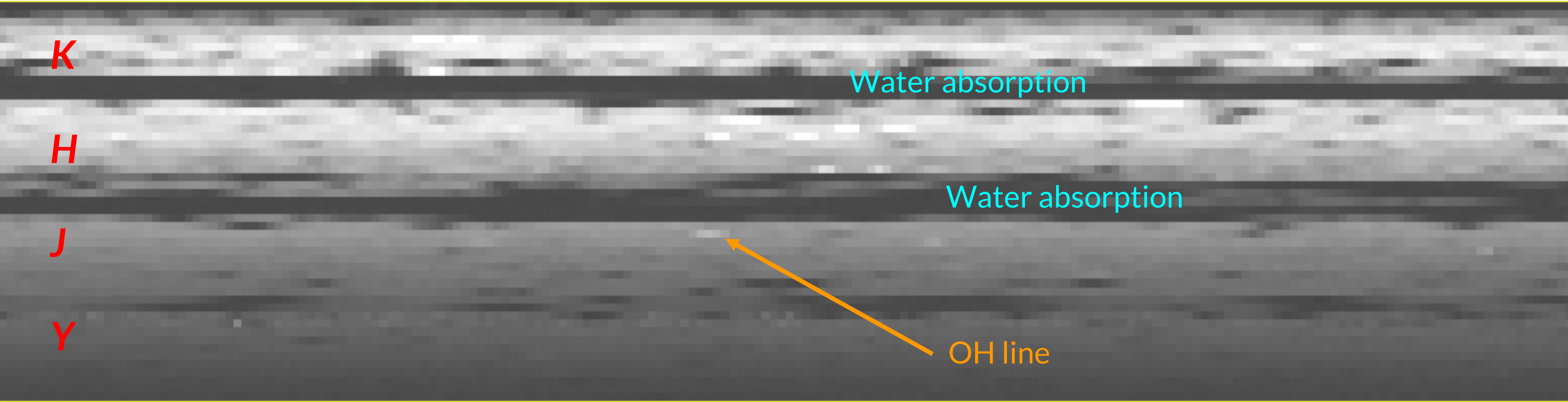


- Treated very similar to Spectral/RV observation
- Polar recipe requires e2dsff files from A and B fibers separately

e.fits

[extracted]

- As FITS images:
- Ext 1-4: AB, A, B and C extracted spectra, 4088x49 pixels
- Ext 5-8: AB, A, B and C wavelength maps, 4088x49 pixels
- Ext 9-12: AB, A, B and C blaze maps, 4088x49 pixels



s.fits

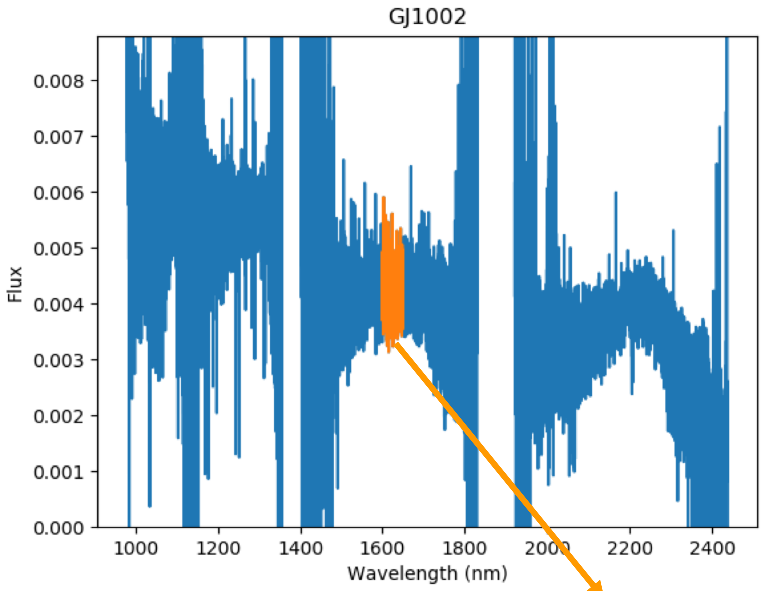
[science]

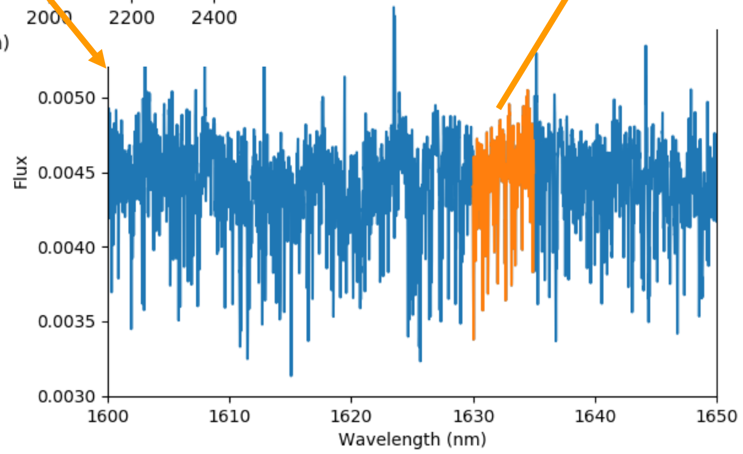
- Stitched spectrum over the entire 0.95-2.5µm domain
  - As FITS binary tables
  - Extensions for AB, A, B and C fibre configurations
- No discontinuity at the edges of order
  - Blaze-weighted mean of overlapping orders
  - Tapered weight fall-off at the end redder orders
  - By construction, cannot create artifacts smaller than 200 km/s

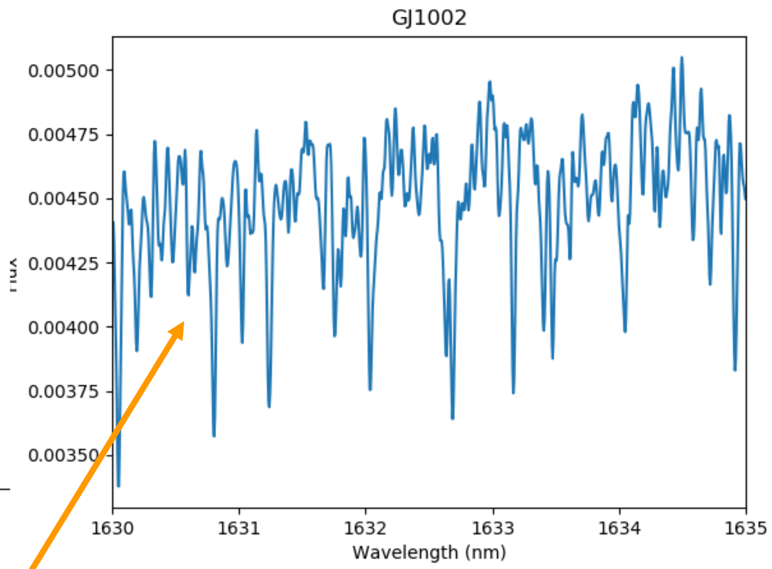
s.fits

[science]

- Comes into two flavours
  - Uniform in wavelength spacing (0.05 nm/pixel)
  - Uniform in velocity space (1 km/s/pixel)
- Convenient for cross-correlation and convolution over the entire domain
- Provided without telluric correction for AB, A, B and C
- Provided with telluric correction for AB
  - Deep water bands are filled with NaNs







- **A single *s.fits* file provides an impressive amount of information!**

p.fits

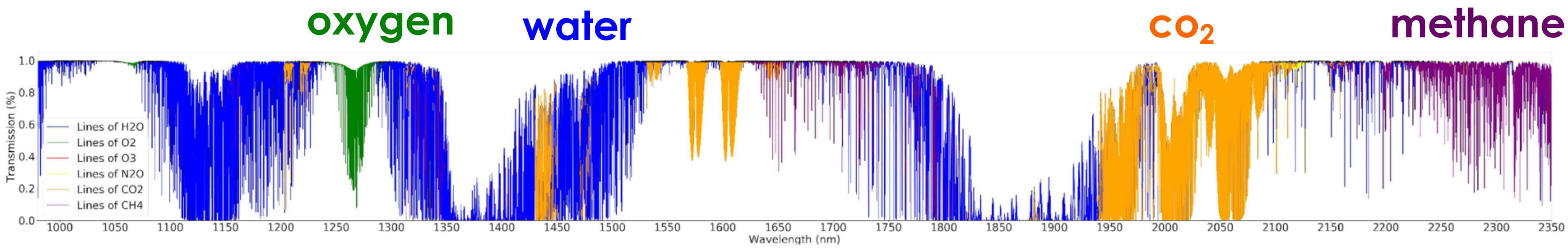
[polarimetry]

- Only available for full polarimetric sequences
- Similar to e.fits in format: 4088x49 as a FITS image
    - Polarized spectrum and corresponding errors
    - Intensity spectrum and corresponding errors
    - Null spectrum
    - Blaze and wavelength spectra

Polarimetry

- From p.fits to LSD profiles (out of APERO)
- From LSD to longitudinal magnetic field
- Look for rotation period

Telluric subtraction

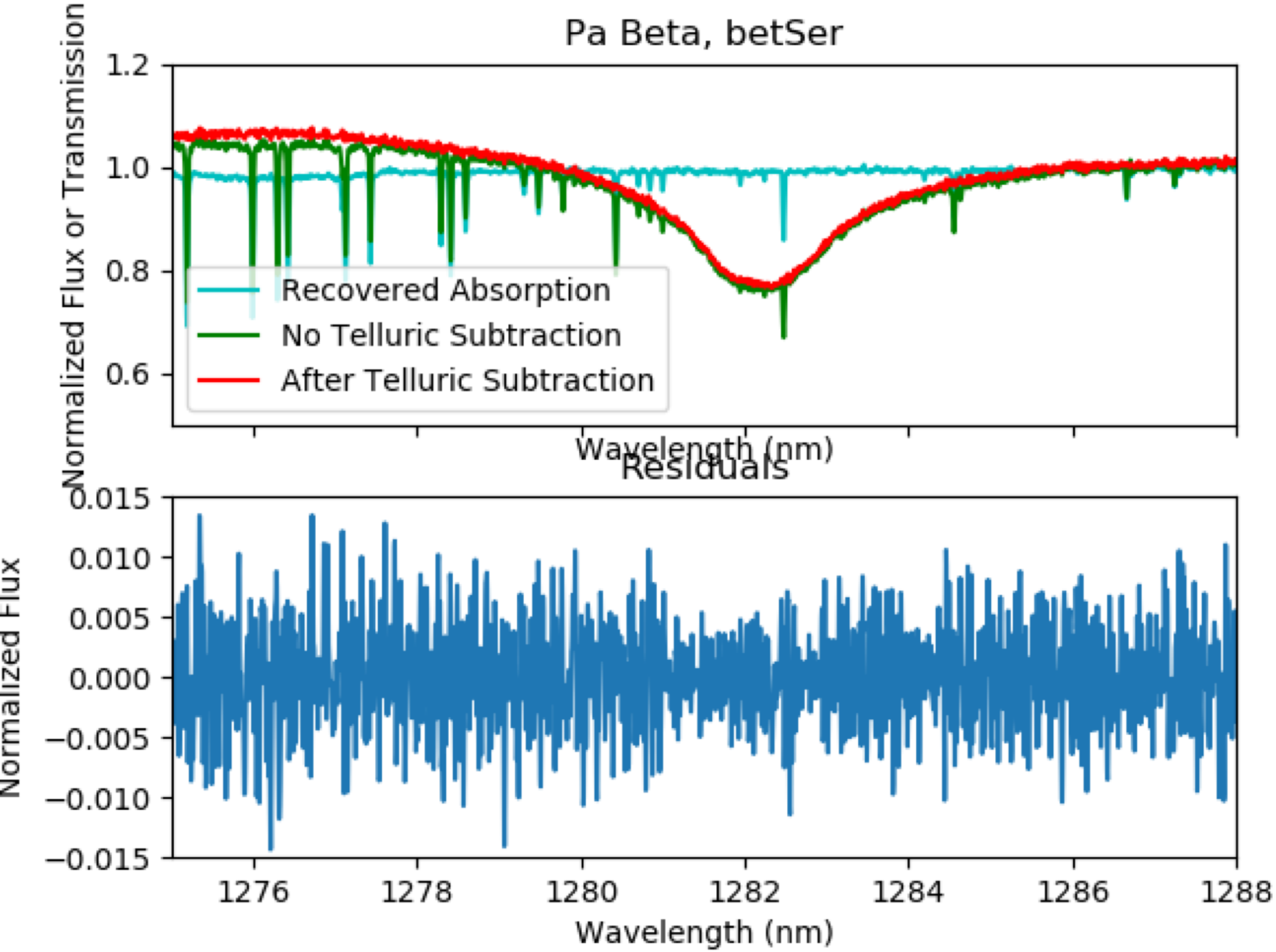


Telluric subtraction

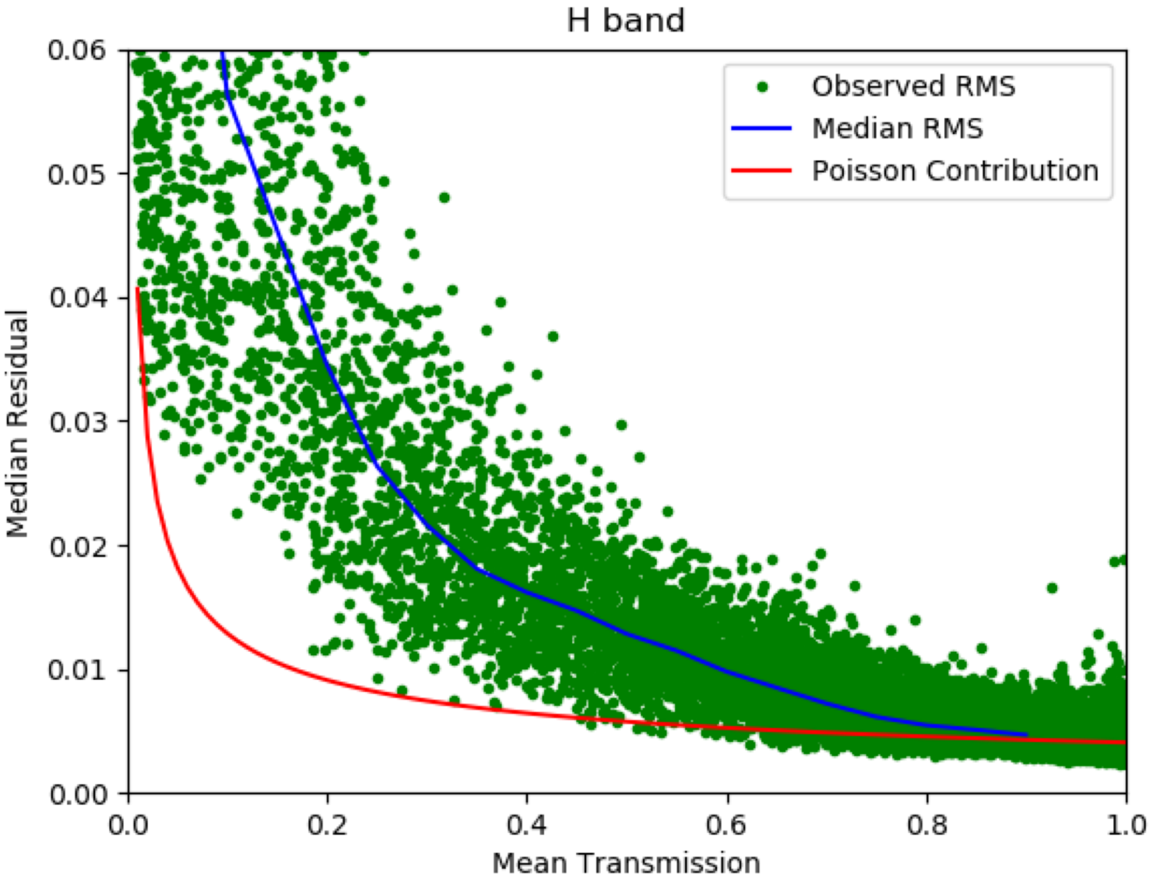
- Telluric lines are all over the place in the near-infrared
- The DRS provides telluric-subtracted spectra
- You ***must*** check the level of absorption at your favorite wavelength before interpreting the data!

Telluric subtraction

- Observe ~2 hot bright rapidly rotating stars every night
- Construct a library of line-of-sight absorbers
- Subtract telluric absorption from all science data
- … does it work?
  - Yes, but it comes with some limitations

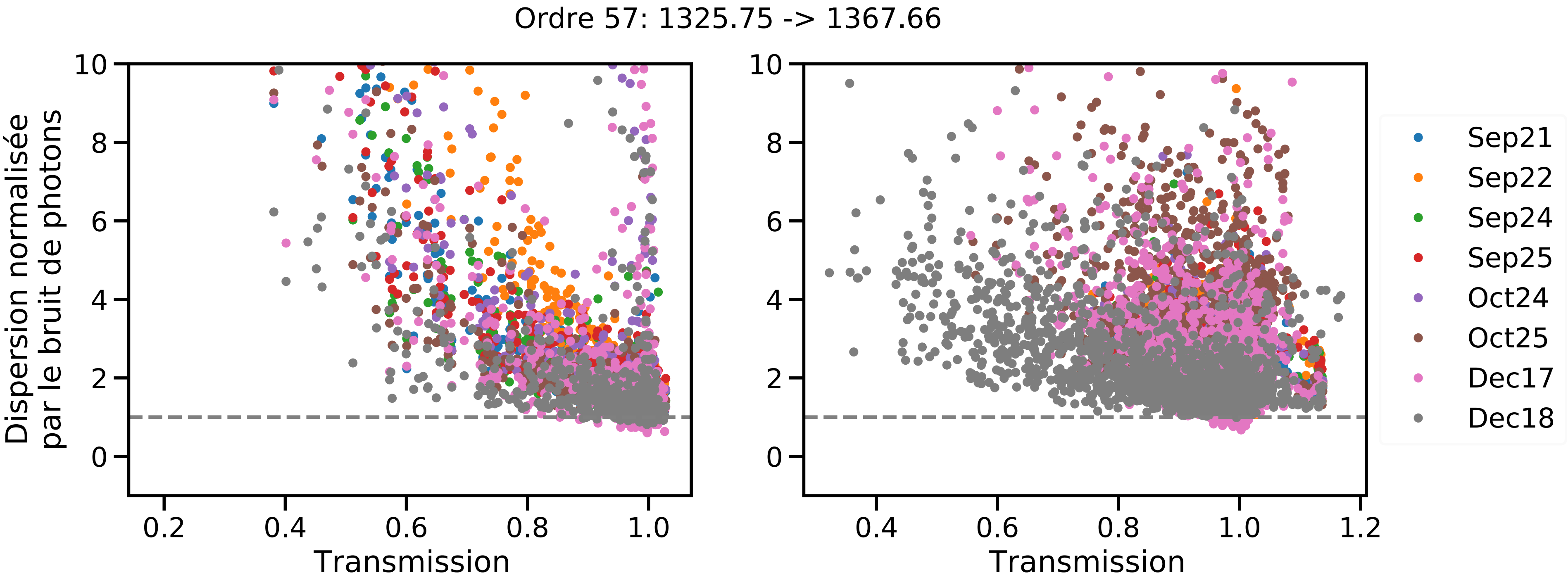


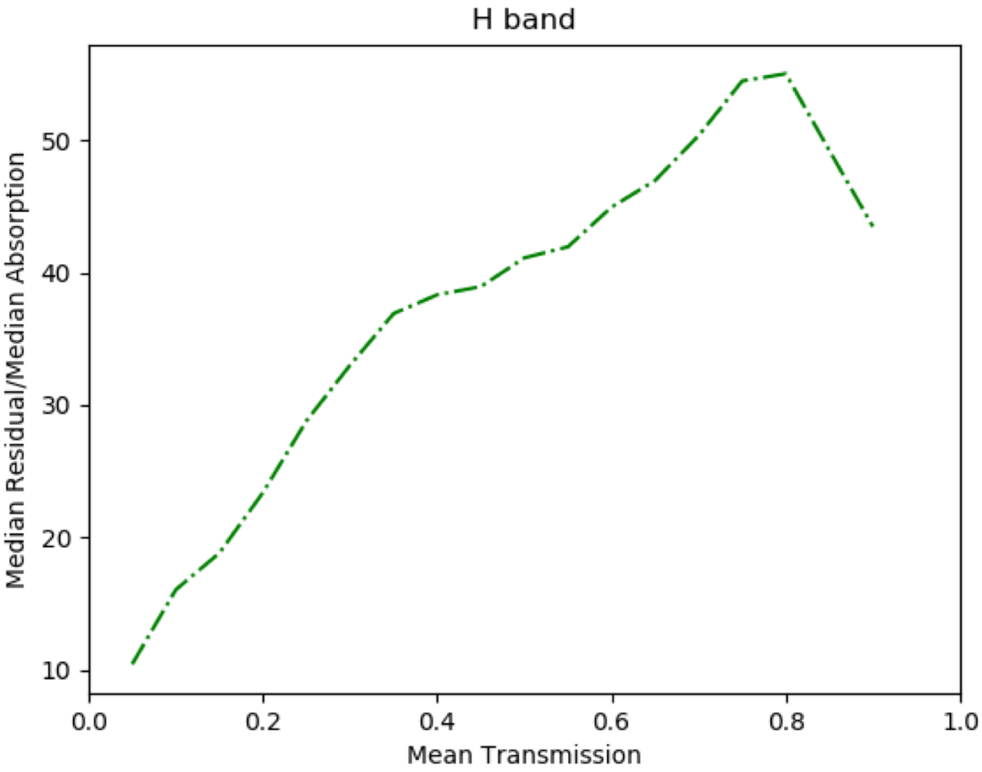
Pa Beta, betSer
Normalized Flux or Transmission
1.2
1.0
0.8
0.6
Recovered Absorption
No Telluric Subtraction
After Telluric Subtraction
Wavelength (nm)
Residuals
Normalized Flux
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
1276
1278
1280
1282
1284
1286
1288
Wavelength (nm)



- Telluric absorption residuals increase slowly with absorption
- In a perfect world, one would only get an increased Poisson noise due to lower transmission

Improvement of DRS reduction over 2 years (from Guillaume Gaisné's PhD thesis)



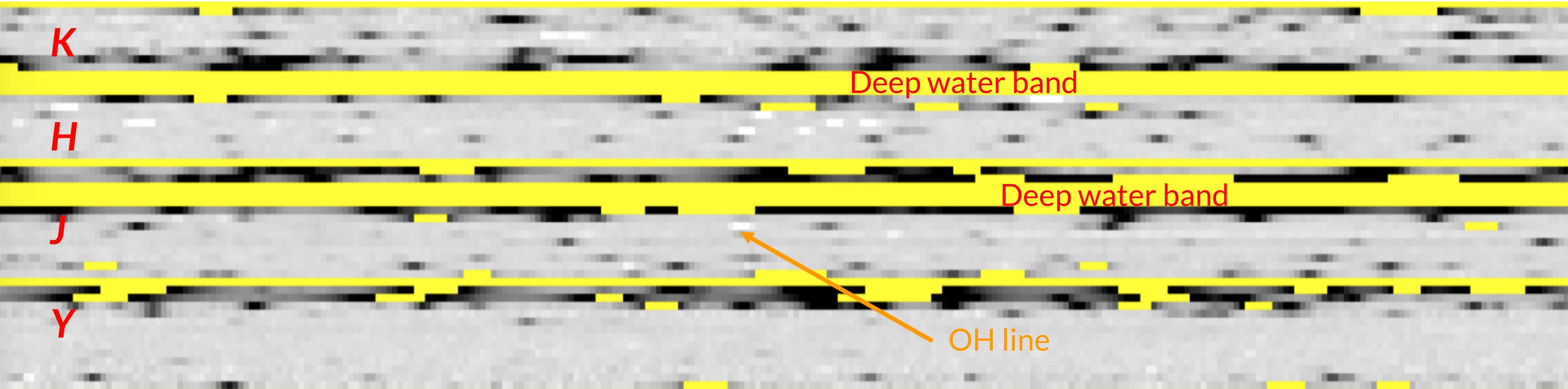


- The fractional quality of telluric correction depends on absorption
- For moderate absorption (0-50%), lines are subtracted to better than 1 part in 40.
    - If you have an SNR of 100 and the local absorption is <10%... you are all fine!
- Deep absorption (>50%) is more poorly corrected

t.fits

[tellurics]

- Ext 1: Same as *e.fits* but after telluric correction
  - Only for AB; we assume that tellurics do not affect polarisation
- Ext 2: Recovered telluric absorption
  - NaNs where absorption is too strong for proper reconstruction



v.fits

[velocity]

- The cross-correlation function of RV data with a default CC mask
  - CCF line lists are expected to evolve
    - Ultimately one adapted to your spectrum
- Think of it as the mean line profile
  - 49+1 CCF profiles

CCF determination of RVs

- Choice of mask: best from telluric-corrected template of the same star
- Except for some targets with low SNR or small BERV excursion
- Use so-called neg masks: GL846_neg.mas
- 1 or 2 ST difference does not matter: 5 masks would be enough for all old M dwarfs
- Eder’s spirou-ccf package: see TOI-1759 paper for a description of the different steps
- Choice of line weights: line depth and mean RV dispersion around the line center within n FWHM

CCF template

- Normalize each spectrum to the continuum measured on the template
- CCF template is the weighted mean of all spectra, where order weights combine RV content (Q factor) and dispersion in each order
- RV is the velocity shift that best matches an individual CCF to the template CCF

CCF outputs

- CCF gives RV, FWHM, bisector
- Allows discarding activity as a possible source of periodic variations

Line-by-line velocity

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

Étienne Artigau

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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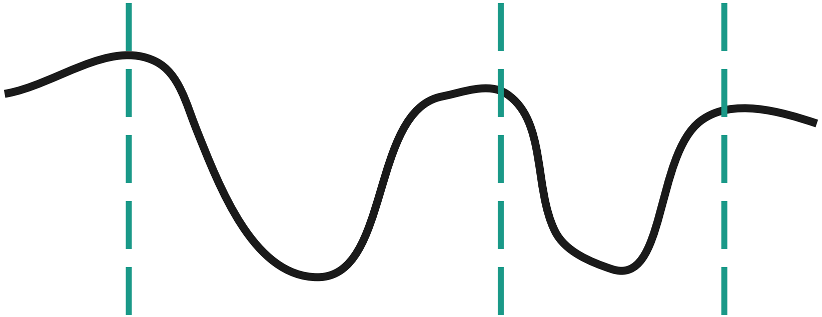
Received 27 March 2001 / Accepted 9 May 2001

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

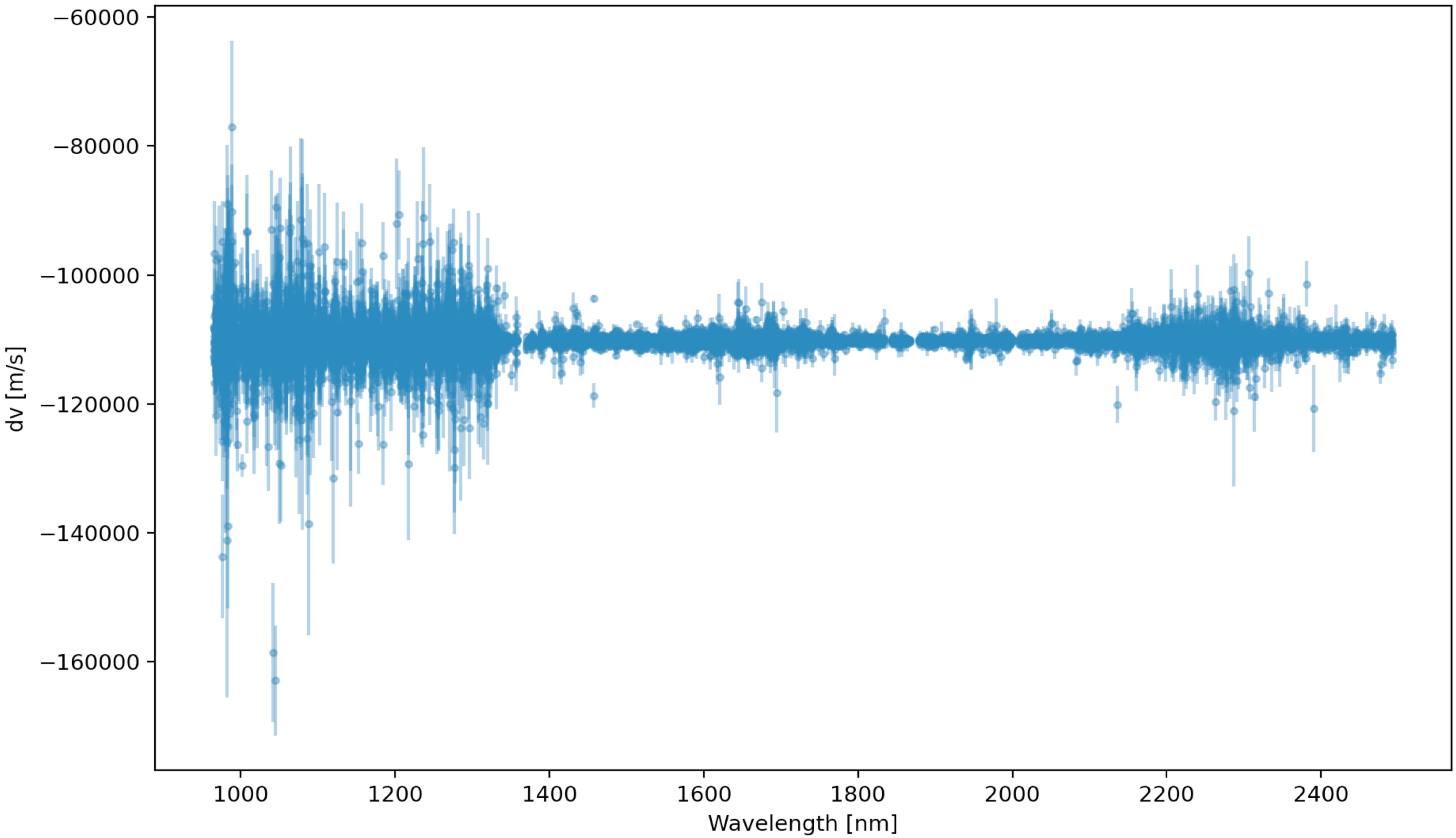
Lines ?

- 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

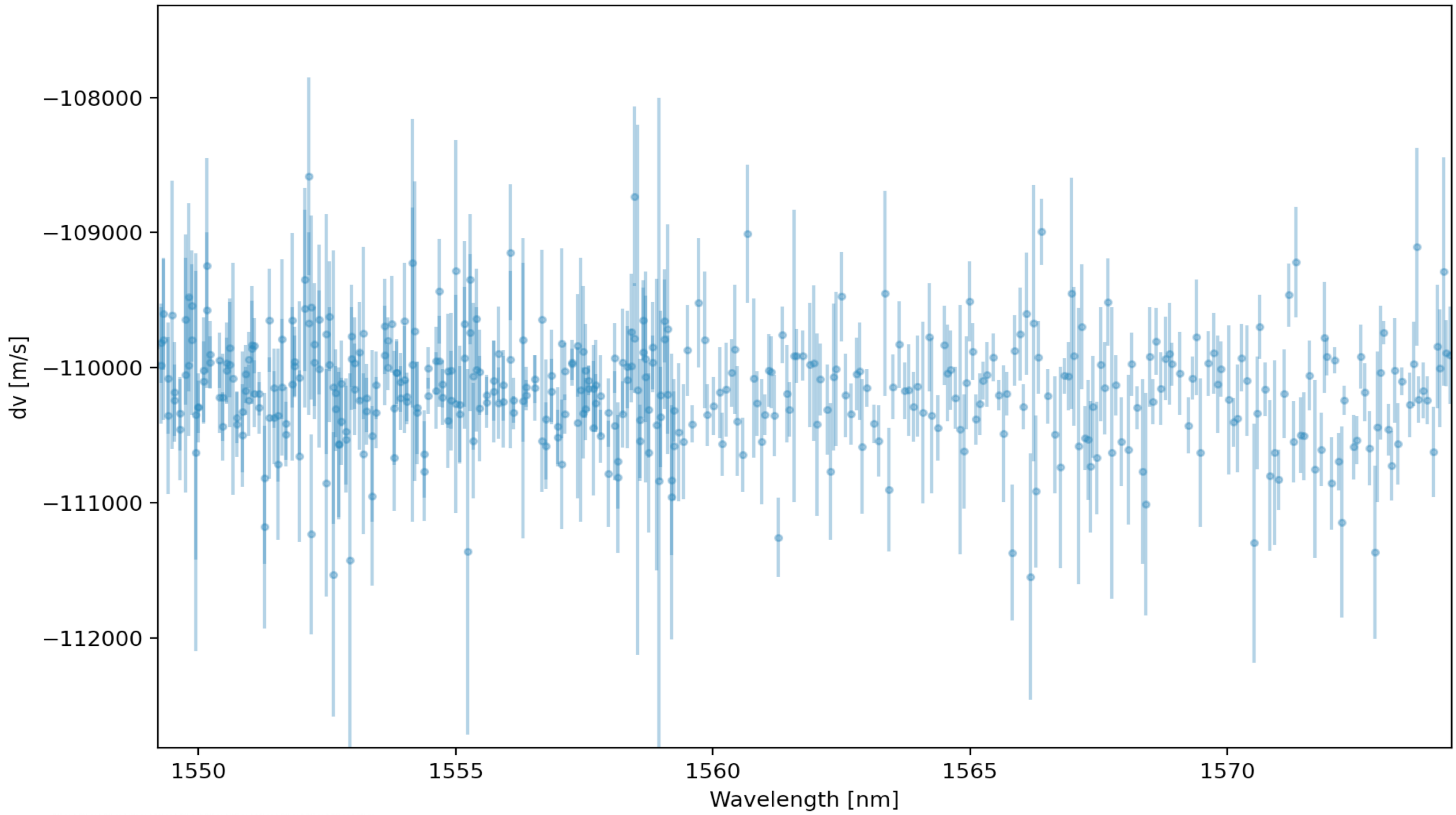


Back to the definition of RV measurements

- Within one line, the velocity is simply a weighted sum of 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



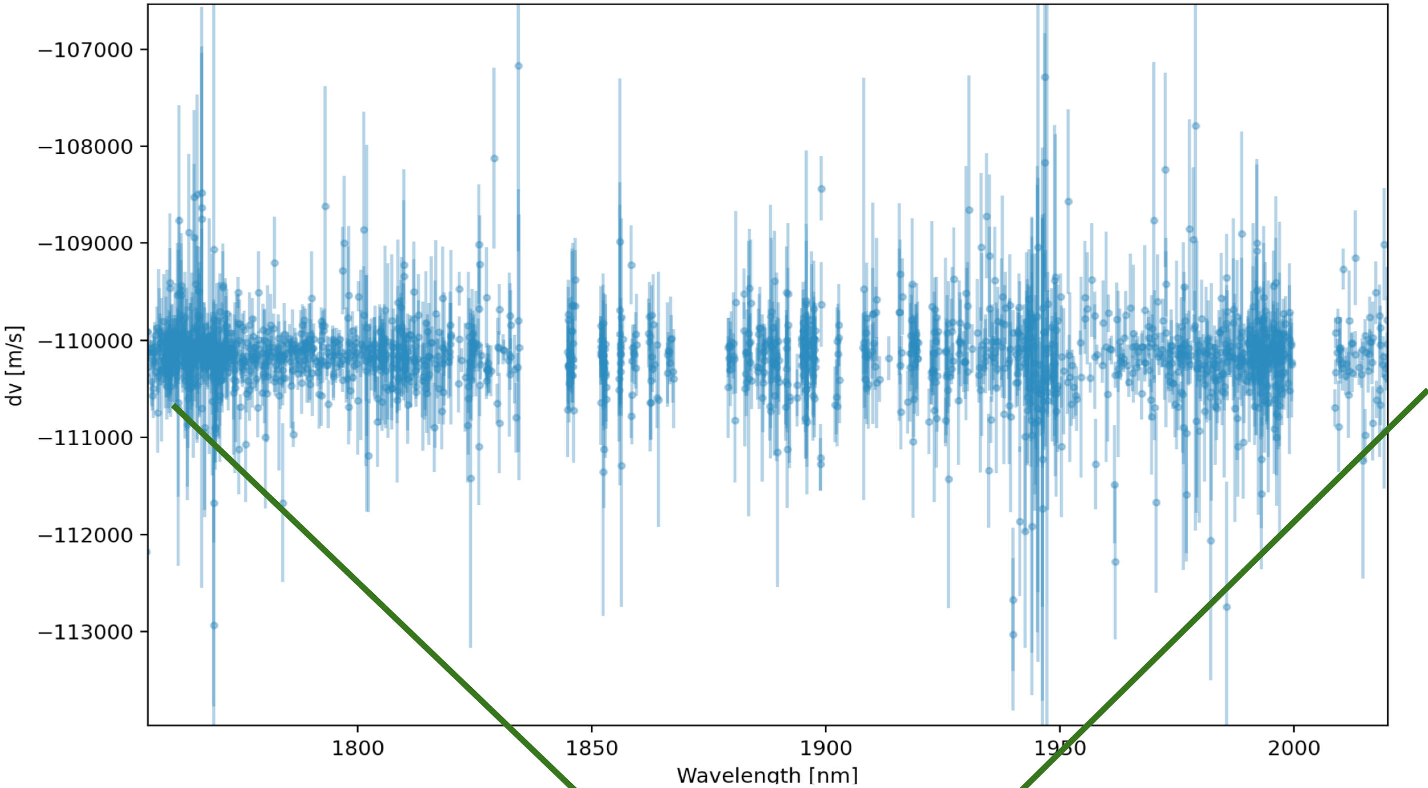
−60000
−80000
−100000
−120000
−140000
−160000
dv [m/s]
1000
1200
1400
1600
1800
2000
2200
2400
Wavelength [nm]

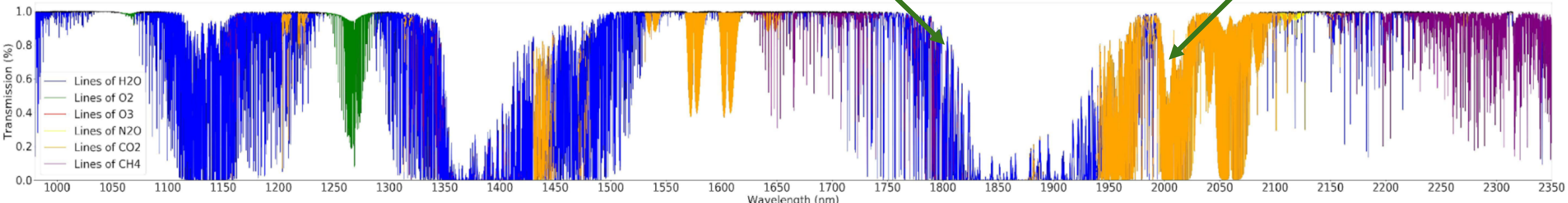


−108000
−109000
−110000
−111000
−112000
dv [m/s]
1550
1555
1560
1565
1570
Wavelength [nm]

Behavior with tellurics

- Telluric residuals produce the most likely outliers
- Should be rejected by the LBL technique because of large uncertainties
- Allows getting velocities even in telluric-affected zones
- 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)

Drift correction

- RV drifts during the night: this is the purpose of the reference fiber
- Drift is measured with respect to aft / mor calibrations
- Neutral density adds a small correction from bright to faint stars
- Computed from FP data: drift.rdb

Zero-point correction

- ZP may drift from run to run
- ZP may change with thermal cycles
- Use stable stars: common variations reflect the ZPC
- Choice of GP (but jumps are not continuous), rolling mean/median, or nightly average

Matern 3/2 vs rolling mean