The UVEX project

UtraViolet EXplorer spectrograph

Exploitation and data reduction

By Christian Buil and Valérie Desnoux

Spectroscopy Workshop
ASW2020
AAVSO

November 8, 2020

The UVEX project

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Content:

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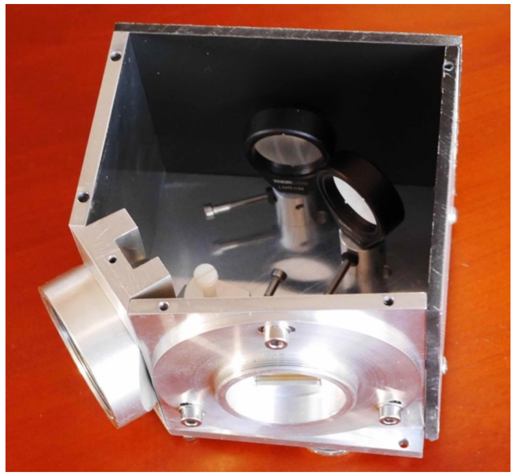
UltraViolet EXplorer spectrograph

Origin of UVEX project

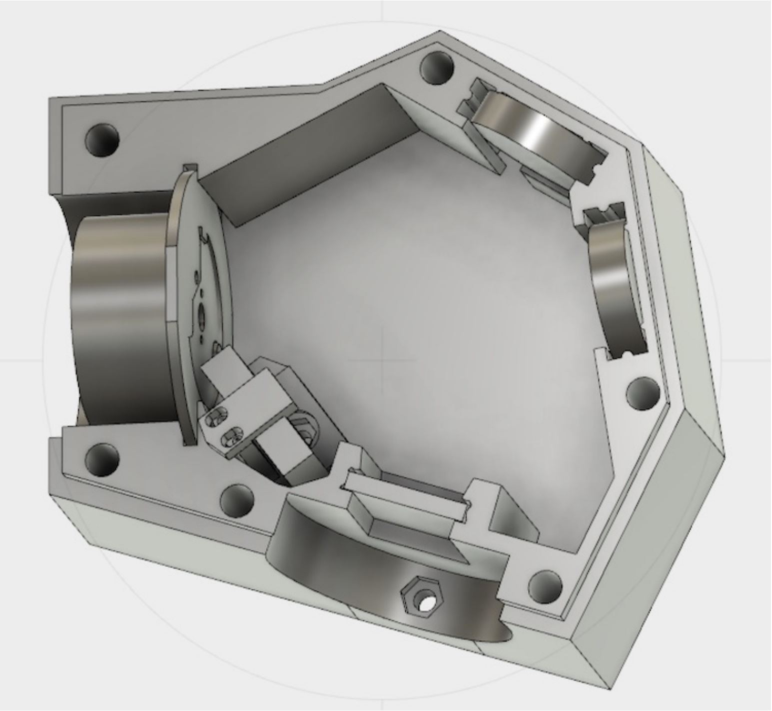
Origin of UltraViolet EXplorer spectrograph project (1/4)

My initial objective (2014) :

- **A low cost spectrograph, that you can build yourself (public domain)**
- **Easy to find components (ThorLabs, Edmund, …)**
- **High performances for education and science**
- **Access to UV et IR spectral domain (new for amateurs)**
- **Create a community**

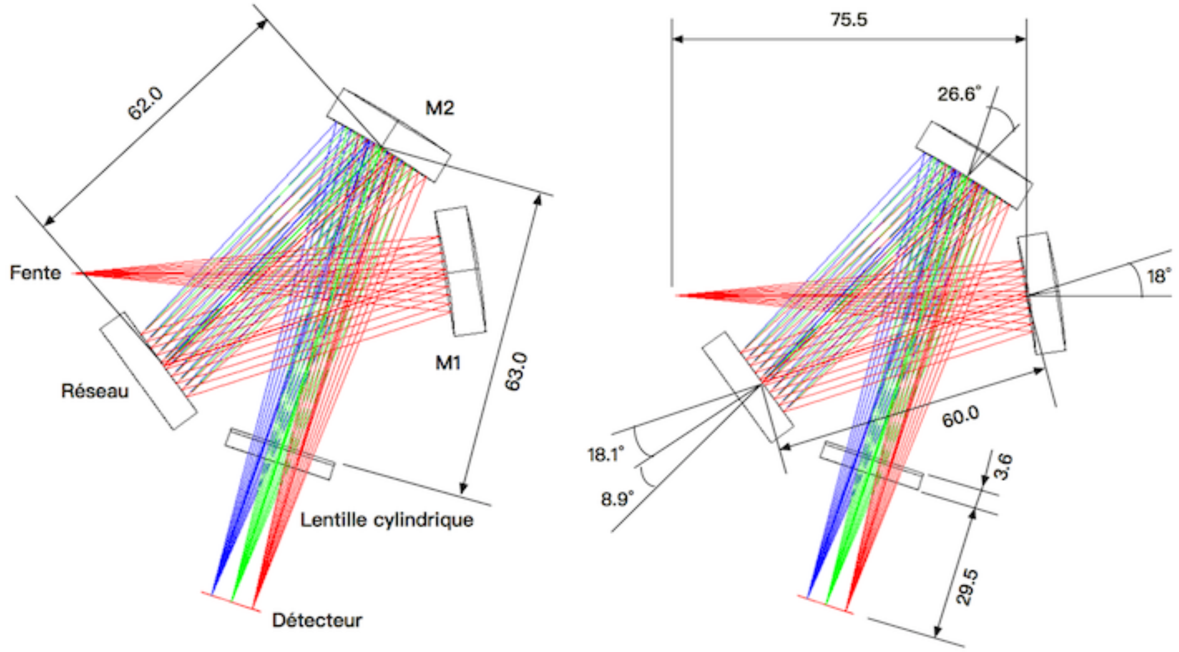


The first UVEX prototype : 2014



First 3D printing prototype : 2017

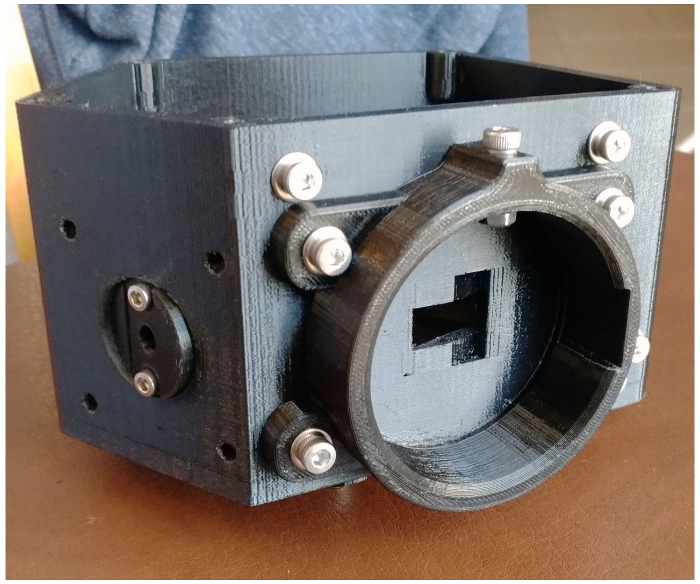
UVEX is a classical Czerny-Turner + a cylindric lens for correct astigmatism



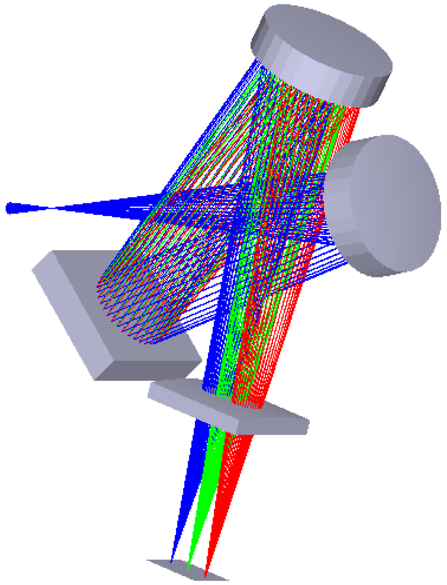
Origin of UltraViolet EXplorer spectrograph (2/4)

The Nice's people UVEX team : Stéphane Ubaud, Pierre Dubreuil, Alain Lopez et Jean-Luc Martin, Christian Buil (Antibes, French Rivera, spring 2018)

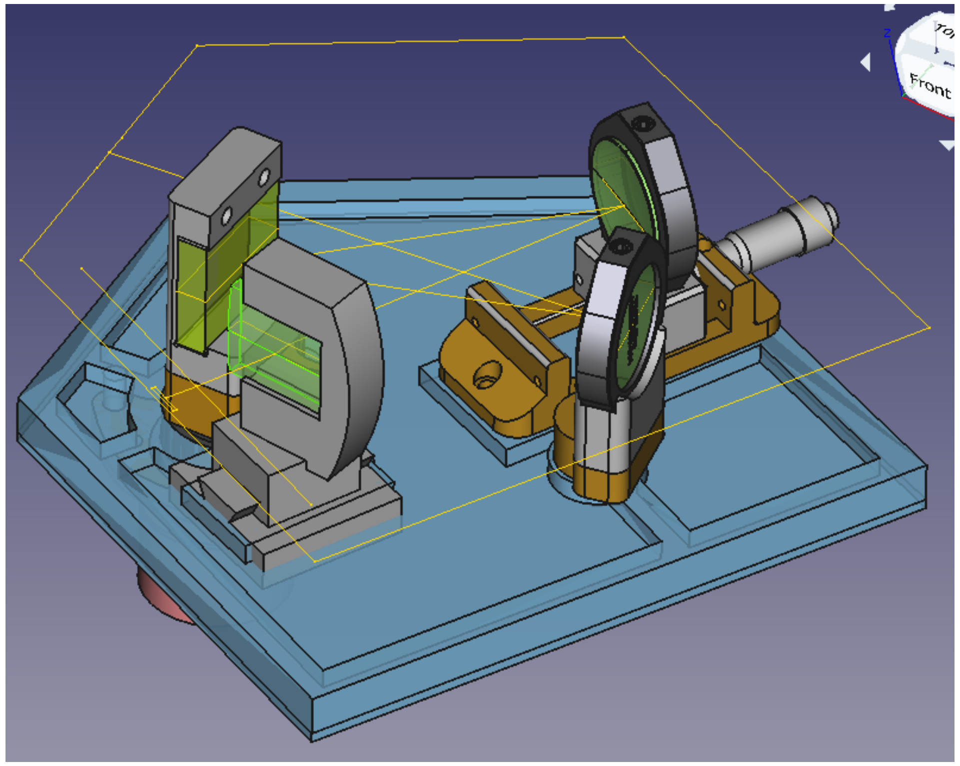
UVEX official site : http://spectro-uvex.tech

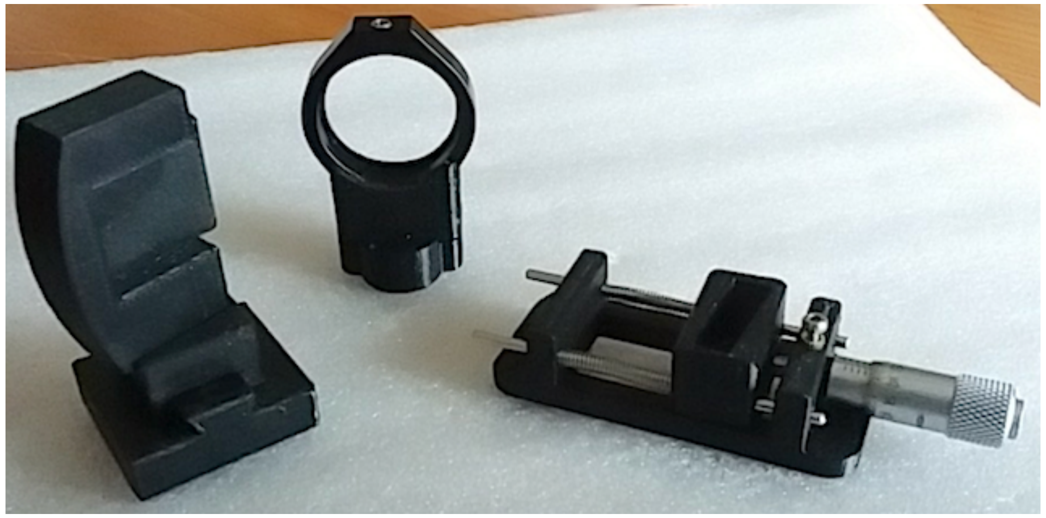


Current 3D printing version (V3)



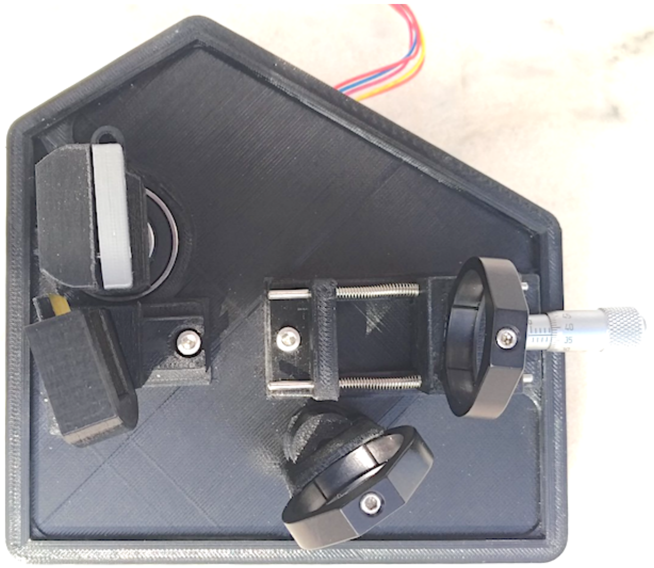
We learned a lot… an UVEX V4 3D printing is coming !

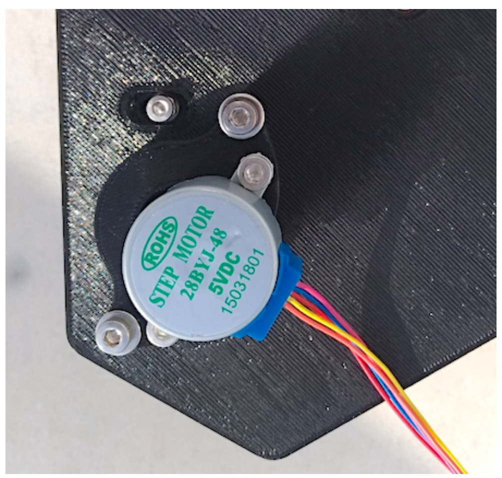


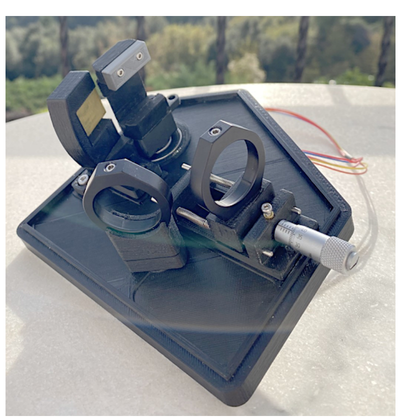


Motorized grating rotation, magnetic support for the grating for instant removal, fine tuning of spectrum focus, robust interface for the camera and more…

Origin of UltraViolet EXplorer spectrograph (3/4)



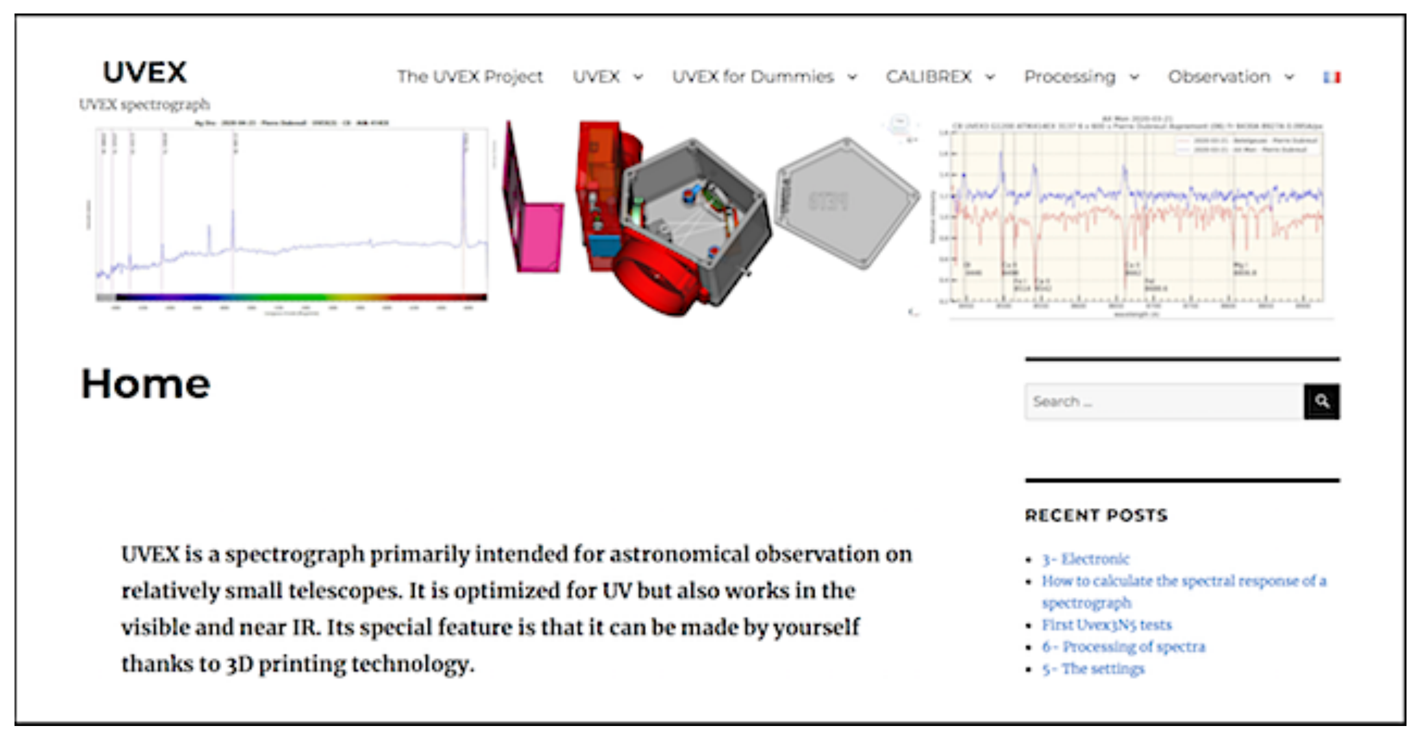




UVEX 3D V4

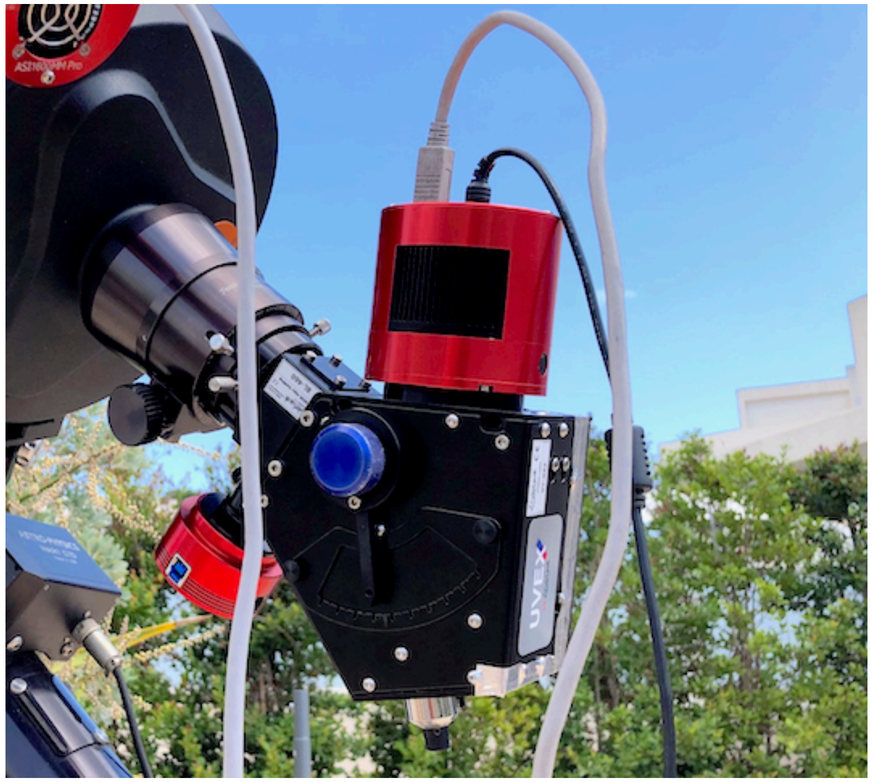
Planned for spring 2021

http://spectro-uvex.tech



Origin of UltraViolet EXplorer spectrograph (4/4)

And a commercial and industrial version of UVEX is also coming…



UVEX by Shelyak

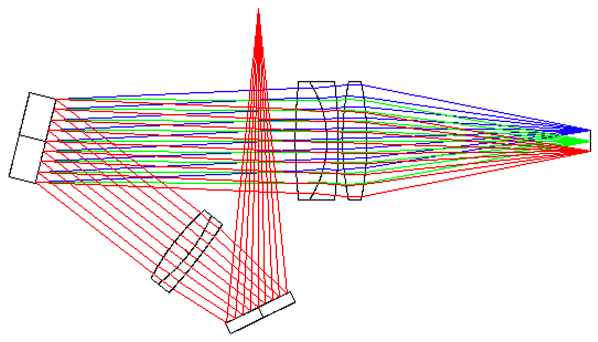
Shelyak INSTRUMENTS

The UVEX project

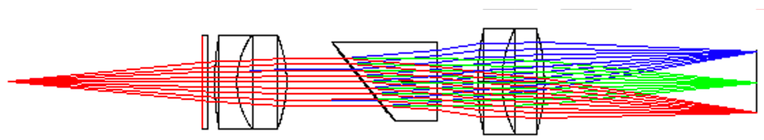
UltraViolet EXplorer spectrograph

UVEX properties

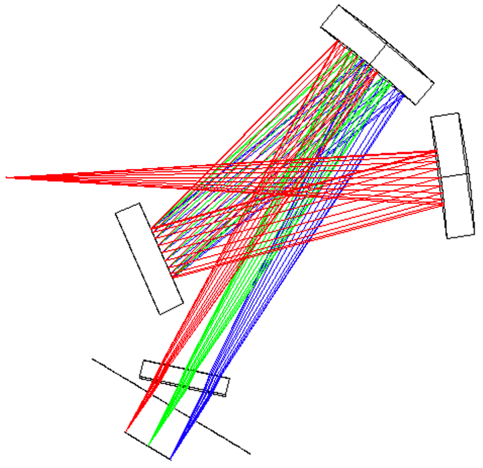
UVEX spectrograph is not necessary better than a LISA or Alpy600 in term of observation of faint object !



LISA
D=400 A/mm, Gy=0.59, T=0.57



ALPY600
D=550 A/mm, Gy=0.95, T=0.54



UVEX
D=330 A/mm, Gy=0.81, T=0.55

So why UVEX ?

(1) For the extreme spectral range coverage, from UV (atmosphere cut-off) to IR (silicium detector cut-off) - ***thanks to the achromatism of Czerny-Turner optical formulae***

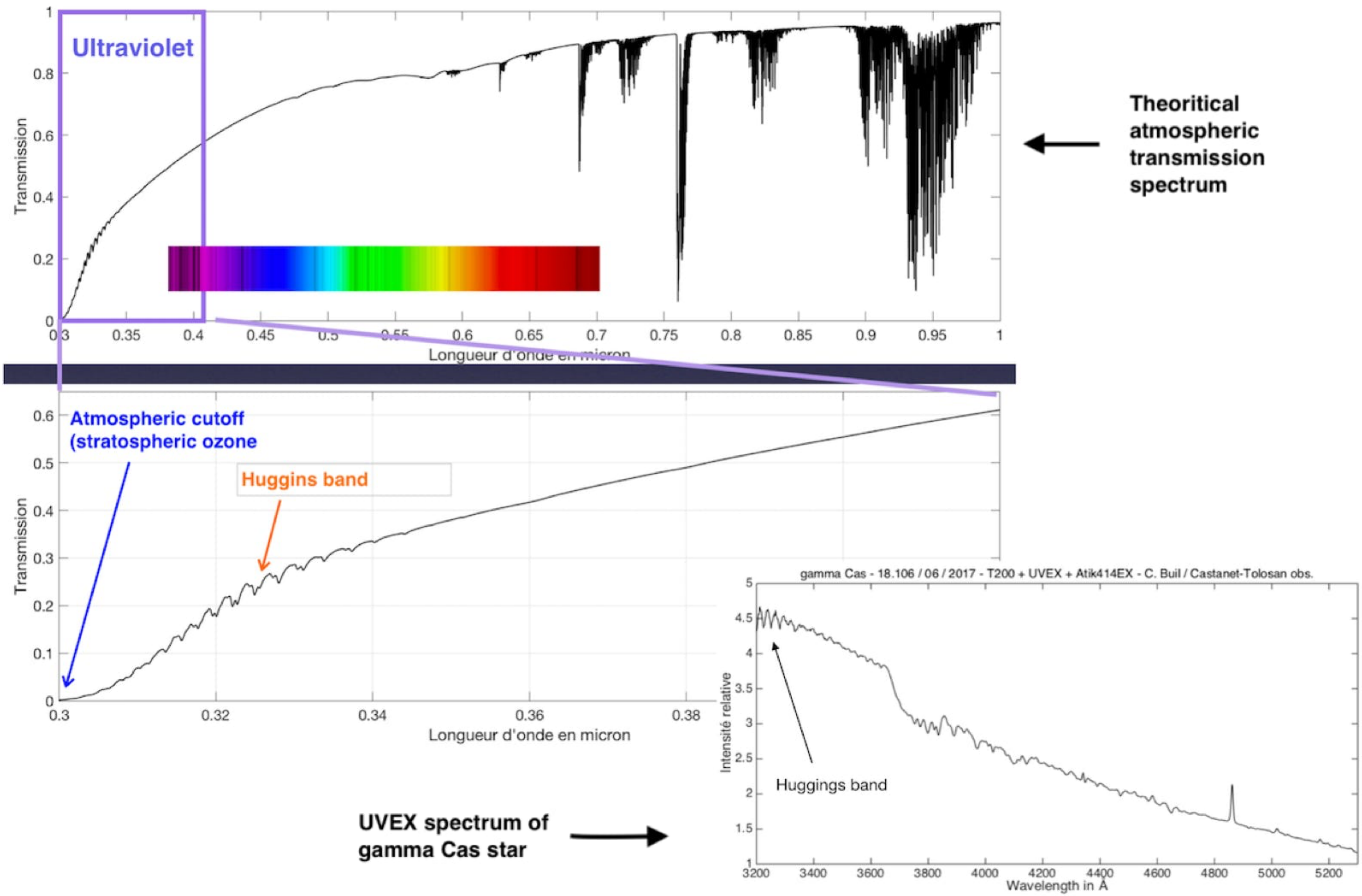
(2) For the flexibility of use (you can change easily grating and slit or add a fiber optic)

(3) For the mechanical stability (Shelyak concept)

(4) For the remote options (focus + grating rotation)

UVEX properties (2/8)

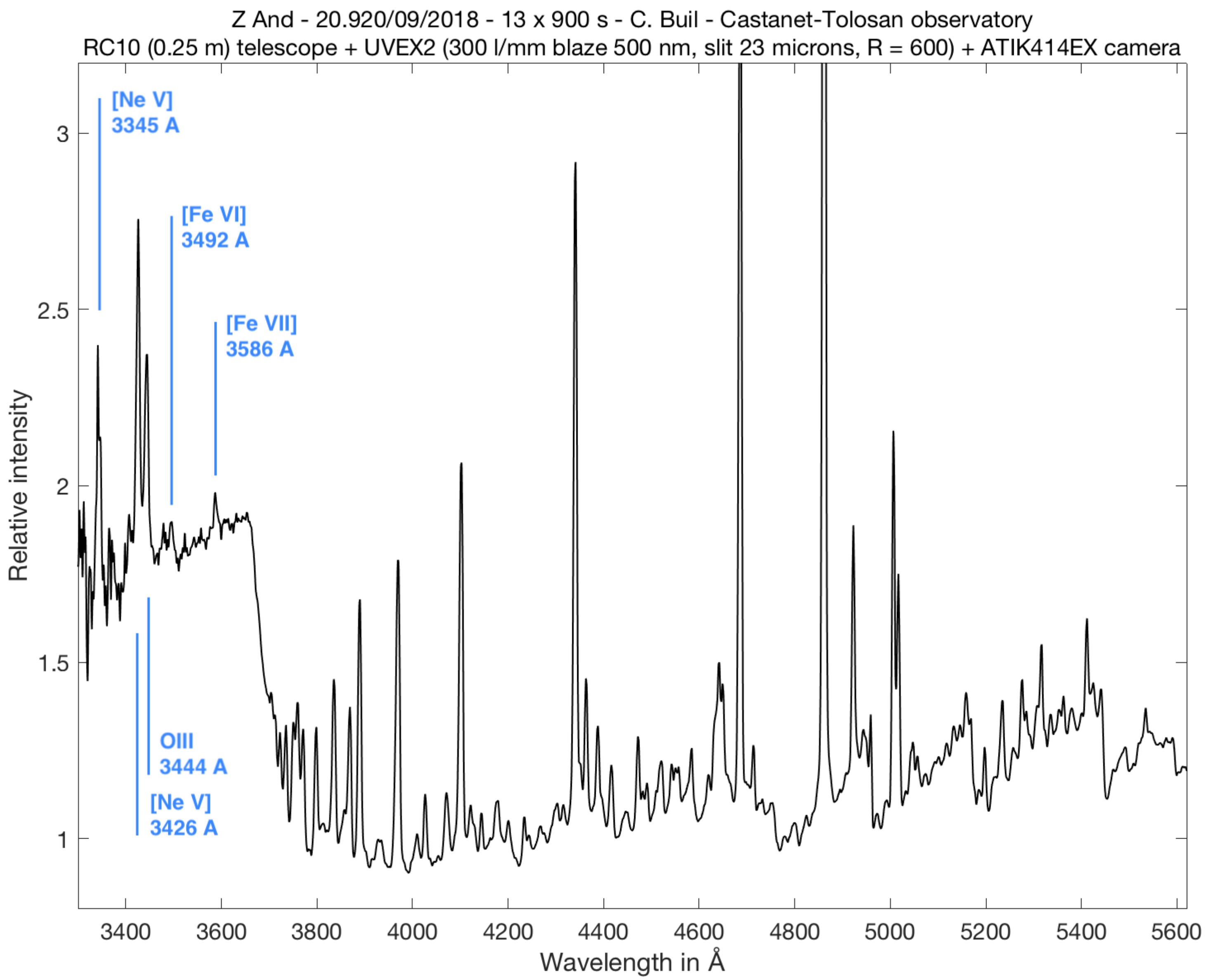
Toward the Ultra-Violet



UVEX properties (4/8)

Toward the Ultra-Violet

Symbiotic star



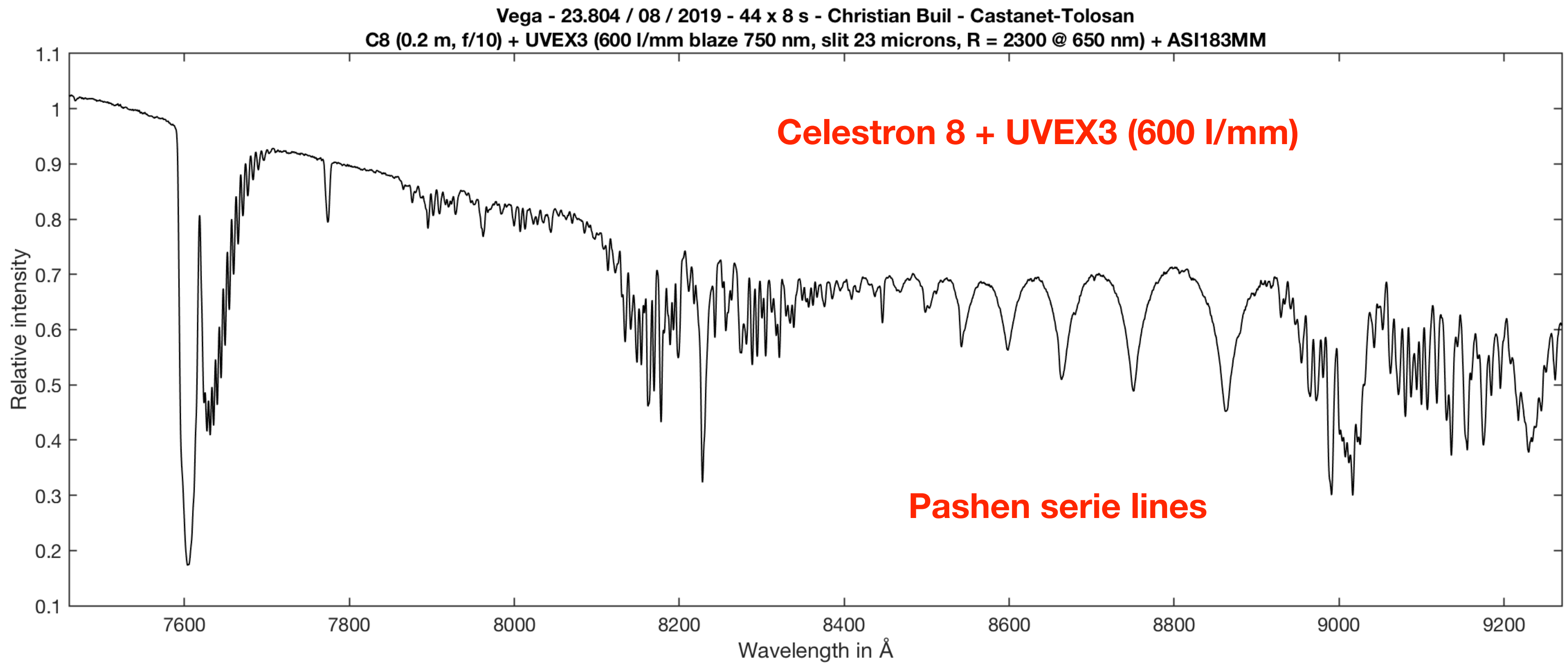
3D printing UVEX V2 model

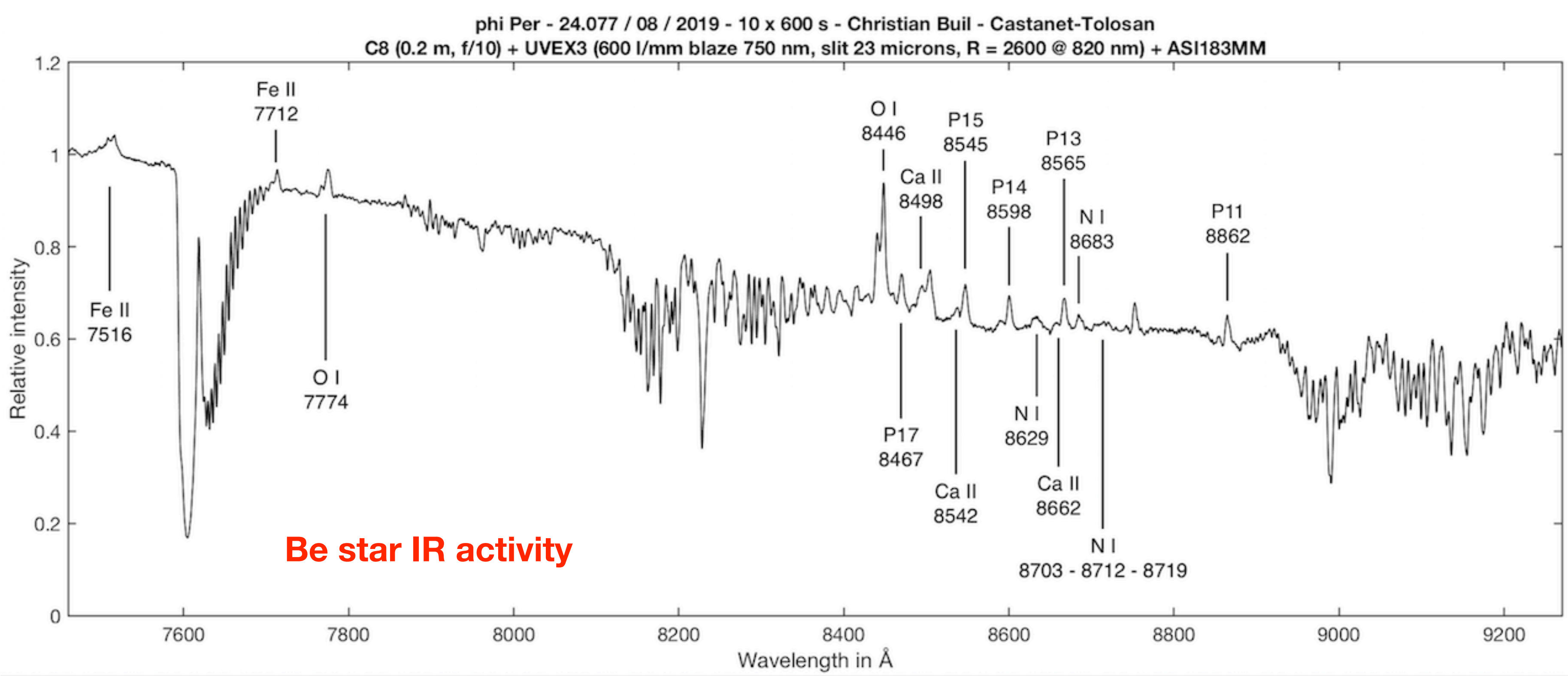
UVEX properties (5/8)

Toward the Infra-Red

UVEX can be renamed IREX (for InfraRed Explorer !)

Select IR blazed grating





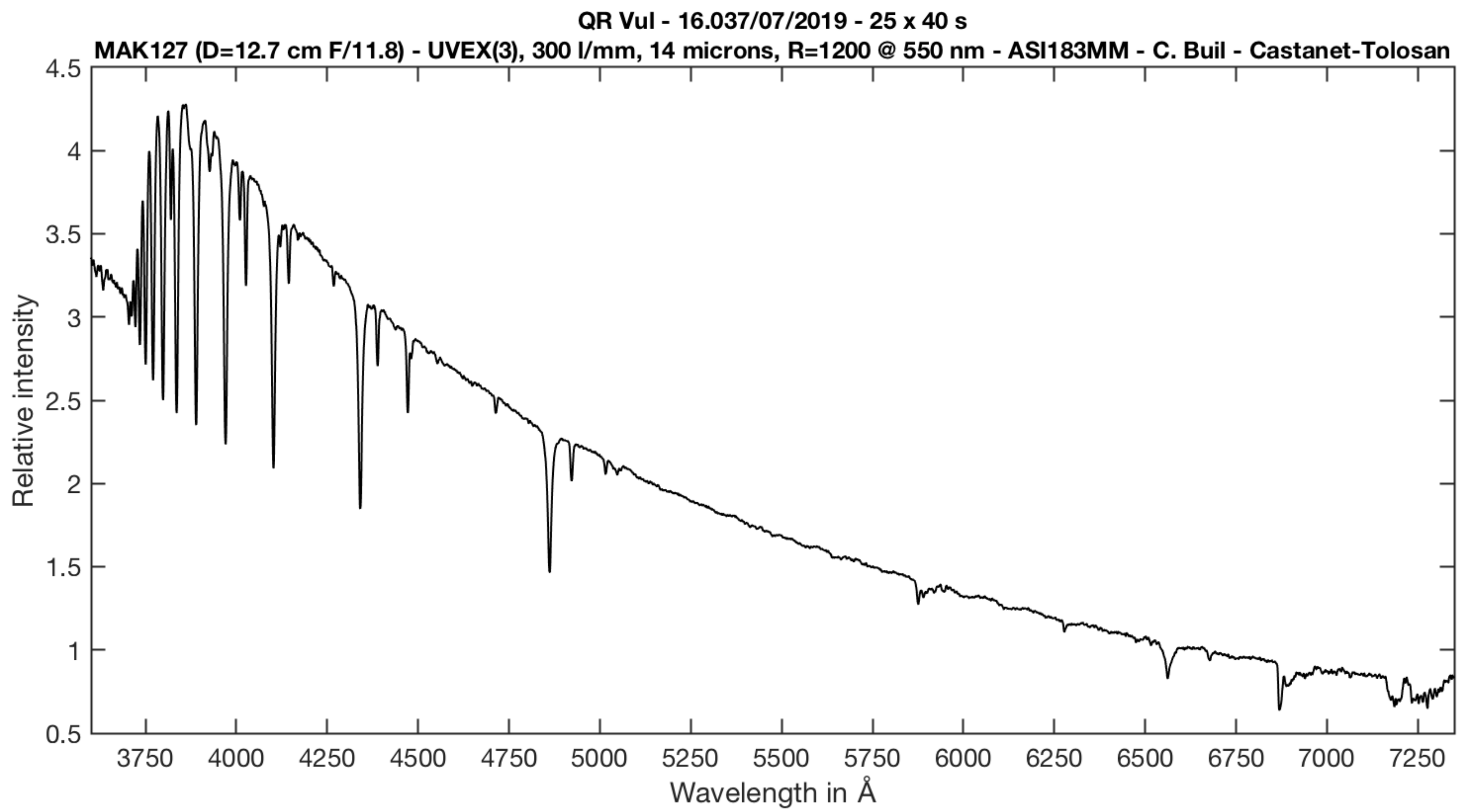
3D printing UVEX V3 model

Note the modest telescope used for interesting science…

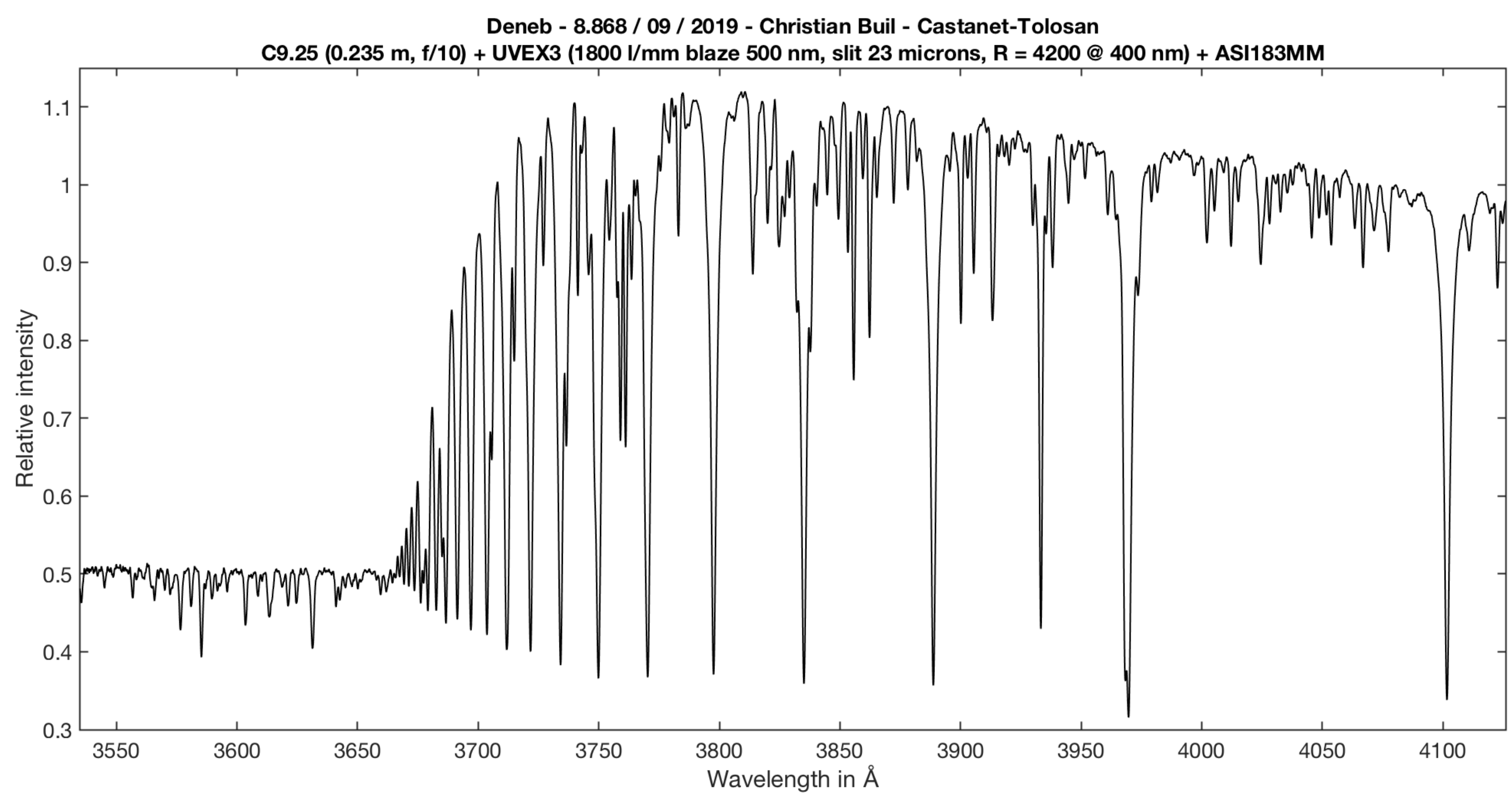
UVEX properties (6/8)

Large choice of gratings

Be star QR Vul
300 lines/mm grating and
Maksutov 127 mm telescope
(R=1200)



Blue spectrum of Deneb
1800 lines/mm grating and
C9.25 telescope
(R=4200)



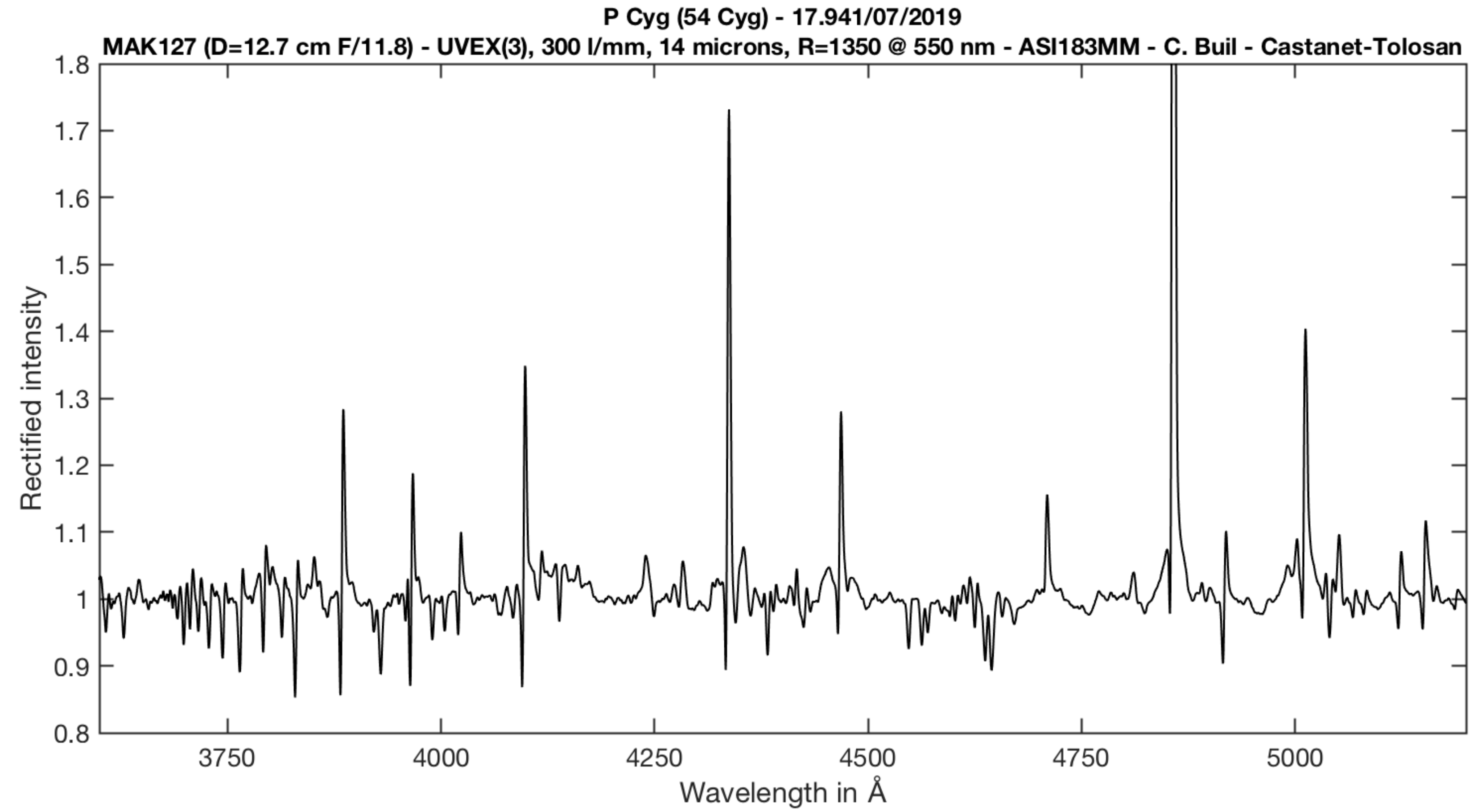
UVEX properties (7/8)

Optimized for small and medium sized telescopes (100 to 300 mm) + F/D > 7

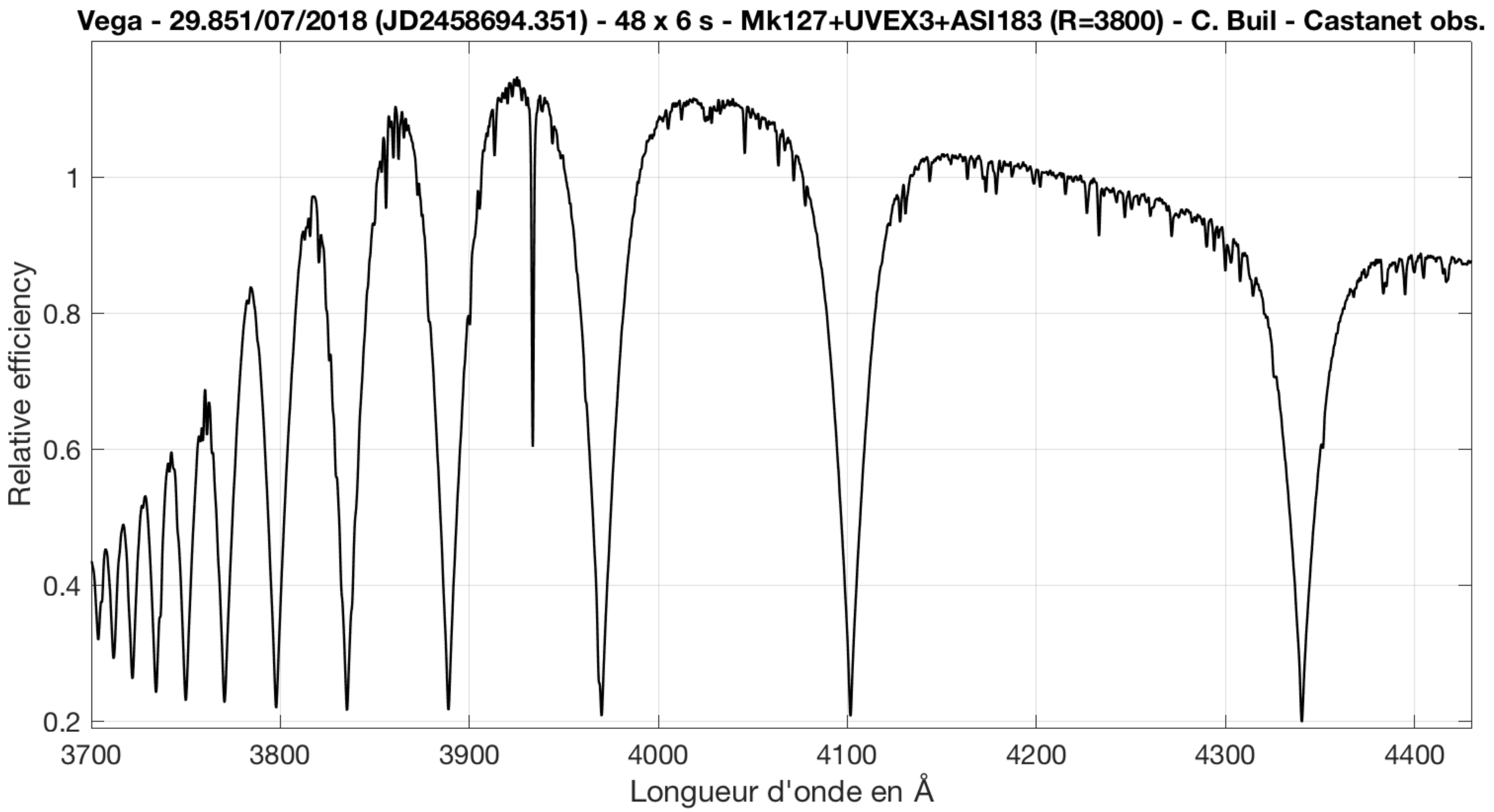
Do not hesitate to use UVEX on a small telescope.

Here an economical Maksutov 127 mm f/11.8, a narrow slit and a small pixel modern CMOS camera, for an excellent spectral resolution and… a real pleasure to use !

My preferred configuration



P Cyg star spectrum on a small telescope
300 l/mm + 14 microns slit - R = 1350

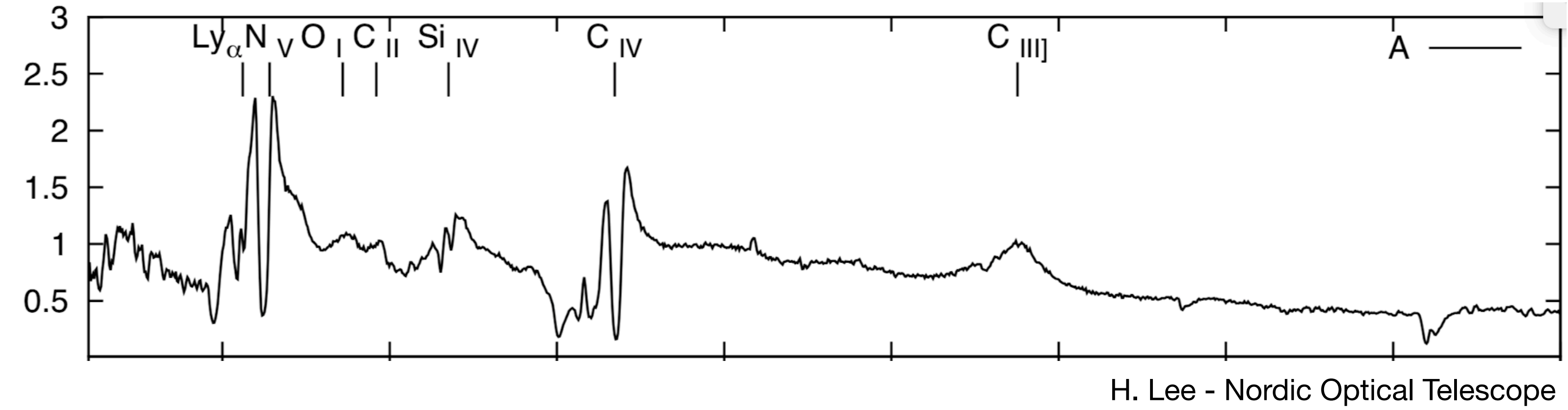


Vega spectrum on a small telescope
1200 l/mm + 14 microns slit - R= 3800

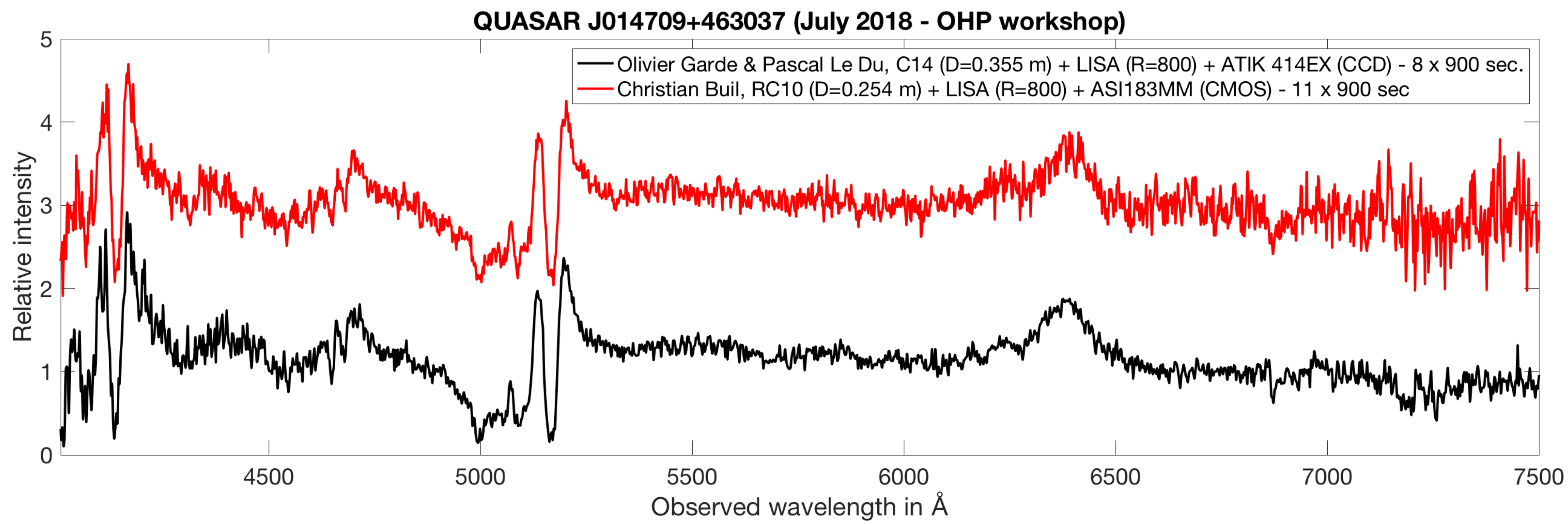
UVEX properties (8/8)

You can also observe faint objets !

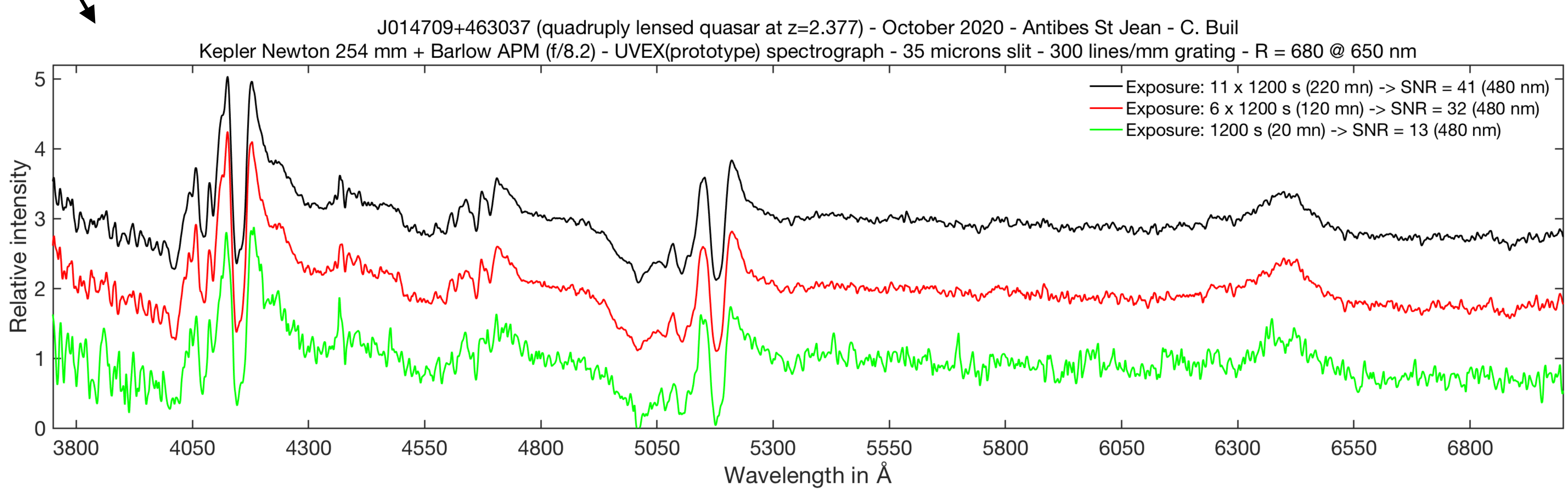
J014709+463037
Quadruply lensed quasar
z = 2.377 - V = 15.4



LISA spectra



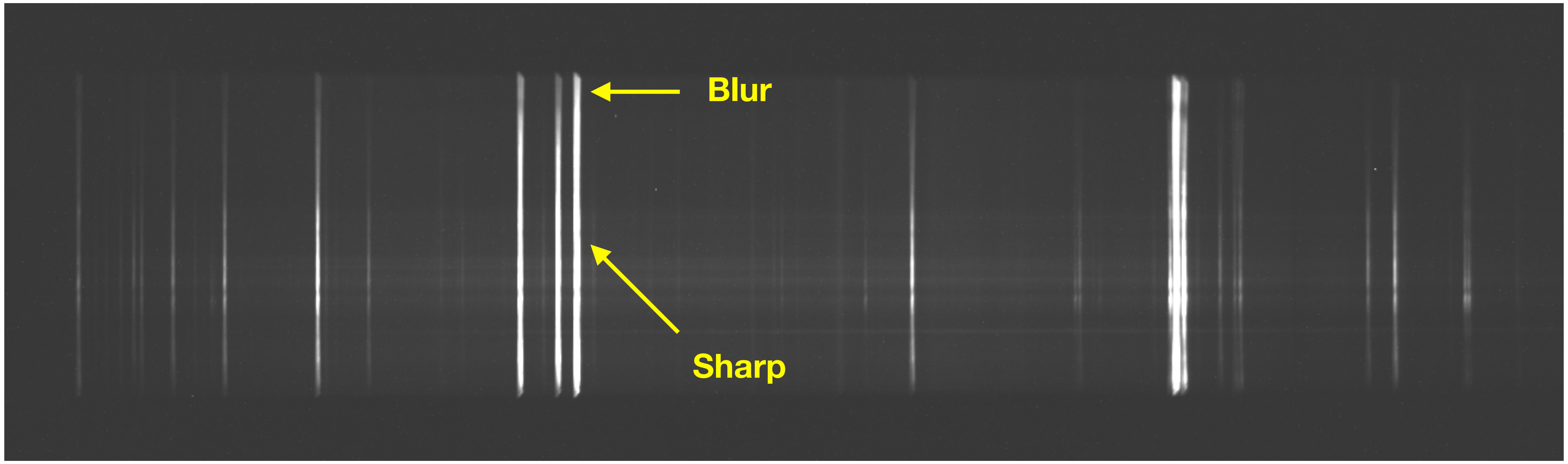
UVEX spectra



CMED : Med 3x3 - Gauss 0.7 - Bin 2x2

UVEX properties (9/9)

Because the presence of significant field aberrations, UVEX is not well adapted to the observation of extended object



Messier 42 spectrum (6 x 300 s) - 600 l/mm - 23 microns slit - Telecope : 250 mm at f/8.2 - ASI294MM camera

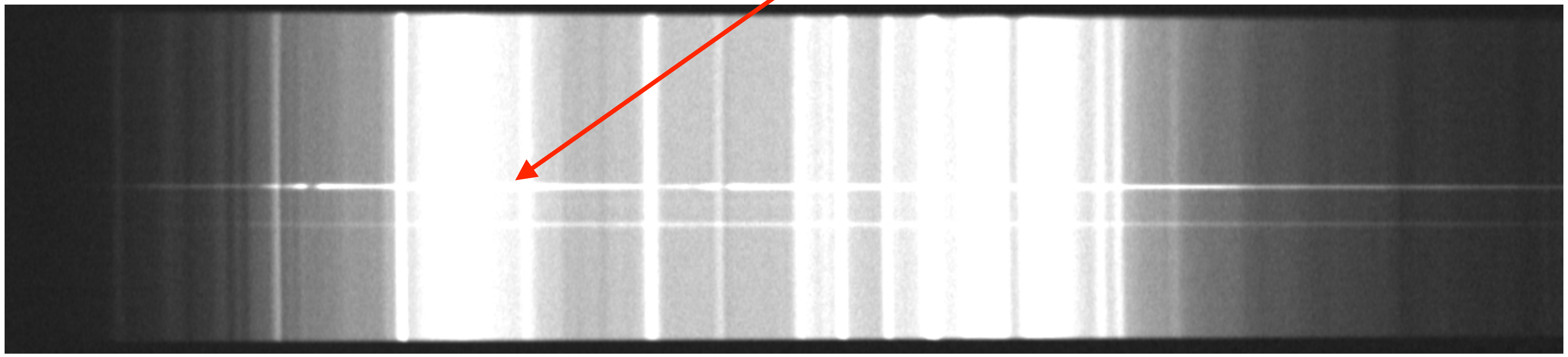
Not ideal condition : polluted sky + Moon light

Example of J014709+463037

Quadruply lensed quasar

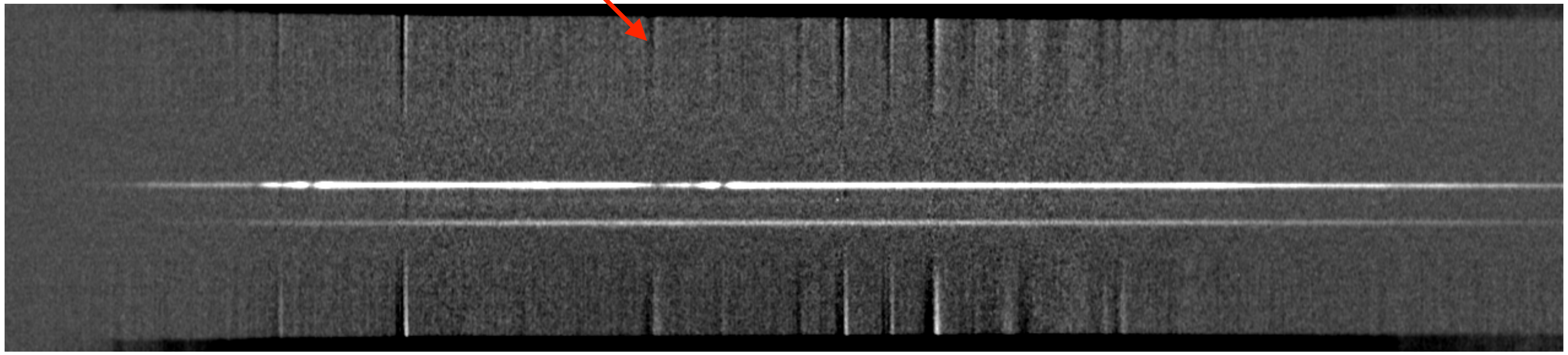
z = 2.377 - V = 15.4

Image before sky subtraction



Effect of UVEX field aberration -> residual sky

After sky removed :
imperfect sky substraction



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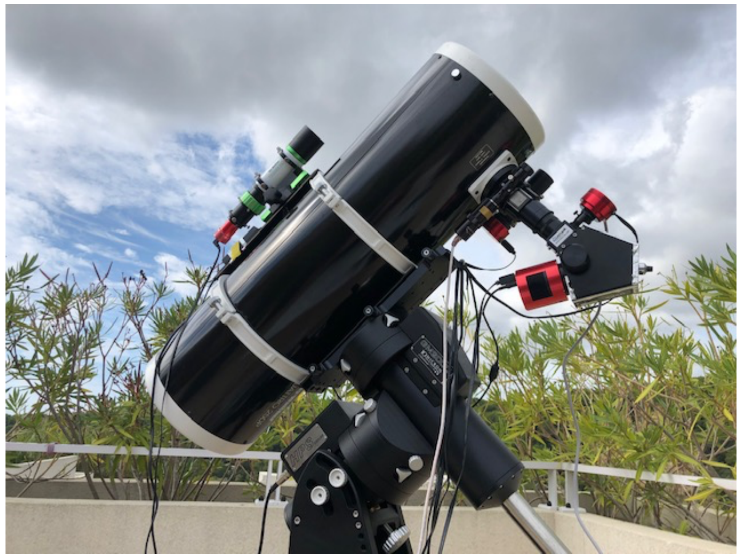
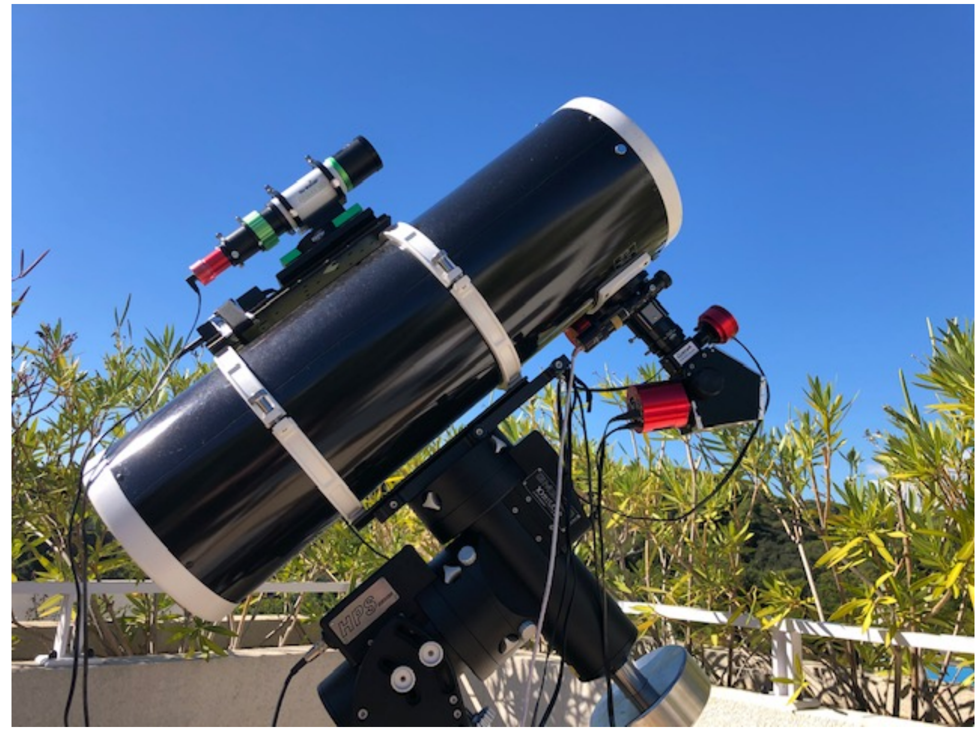
Example of telescope adaptation



Accommodation on a fast Newton telescope (1/2)



Example: from f/4 to f/8 (Kepler model)

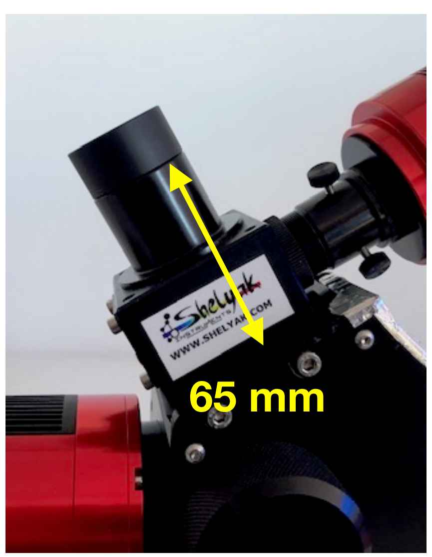
… use of an apochromatic lens - APM 2.7 x model very recommended

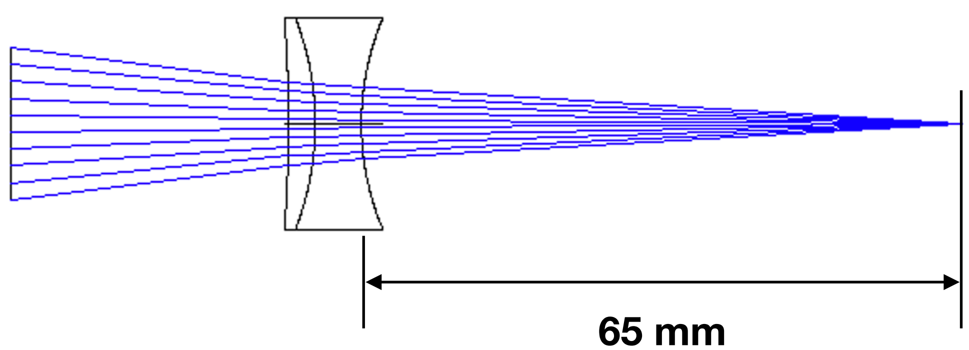
APM Comacorrecting 1 1/4" ED Barlow Element 2.7 x

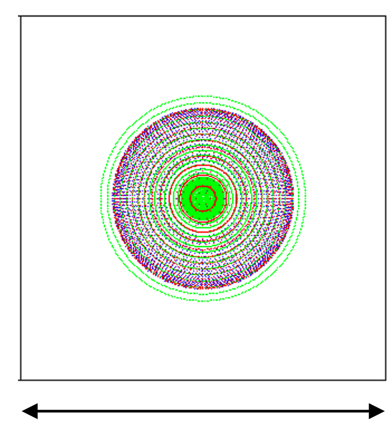
volume weight: 1,00 kg
products weight: 0,05 kg
delivery time: in stock
product number: APM-Komakorr-Barlowelement
EAN Code: 4251404700645

115,00 EUR
incl. 16 % VAT excl. shipping costs
Netto Export Preis: 99,14 EUR

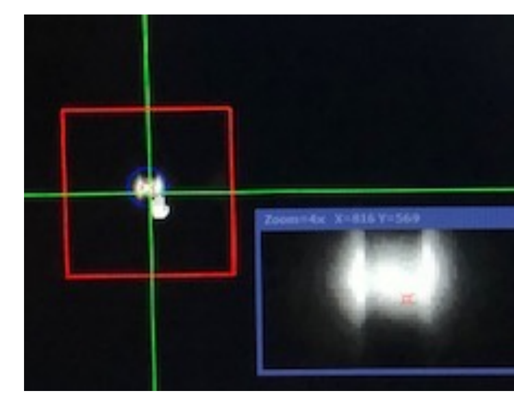
Typical computed spot-diagram from 365 to 900 nm



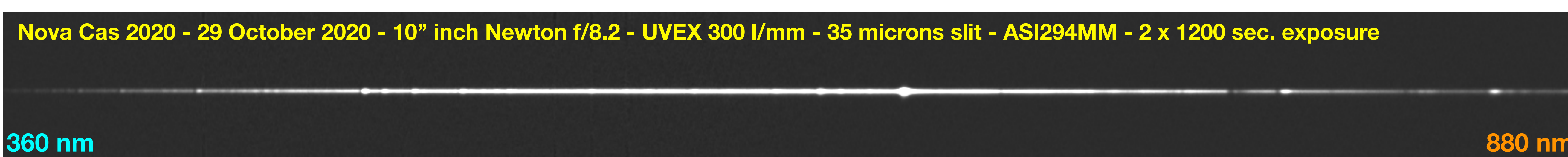




23 microns



Star on a 35 microns slit

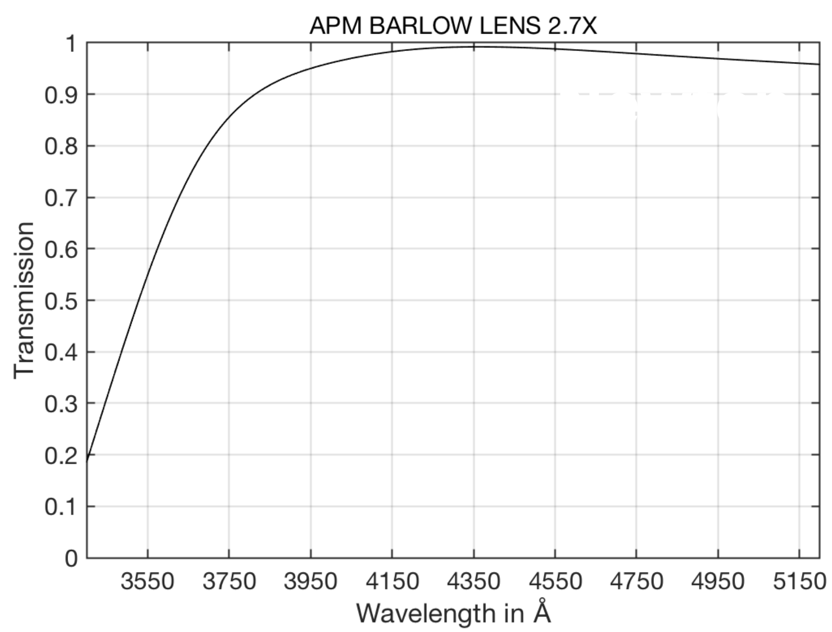


Accommodation on a fast Newton telescope (2/2)

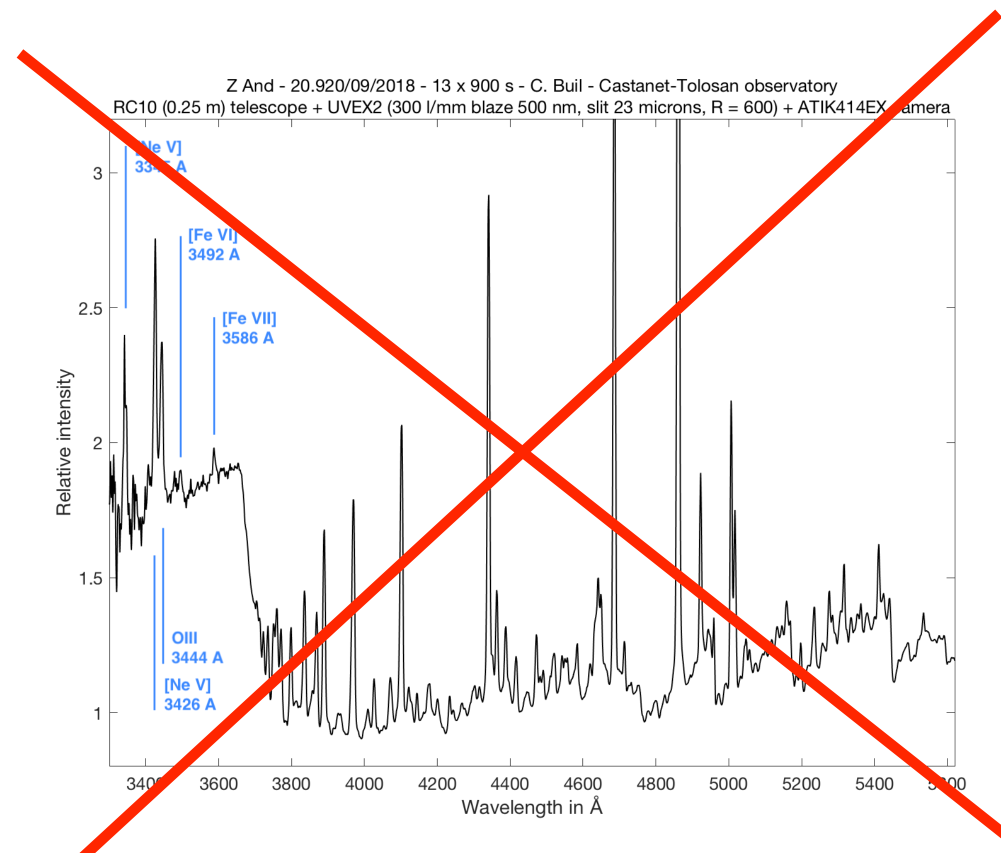
The classical limitations of refractive optics (here a Barlow):

- **Residual chromatism aberration (well fixed by APM lens)**
- **Limitation in spectral transmission…**

APM Barlow on UVEX



Measured transmission of APM Barlow



Can't observe down to 360 nm (but not so bad!)

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Diffraction order overlap

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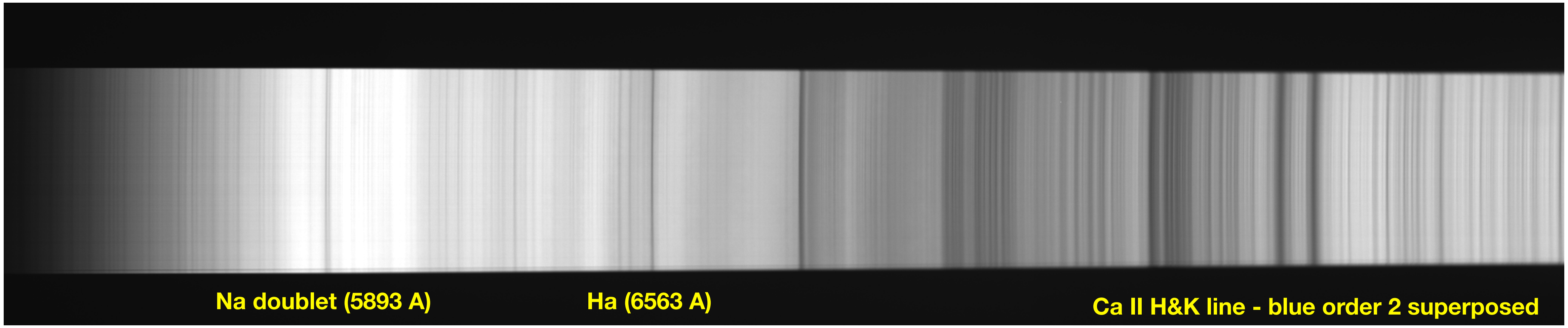
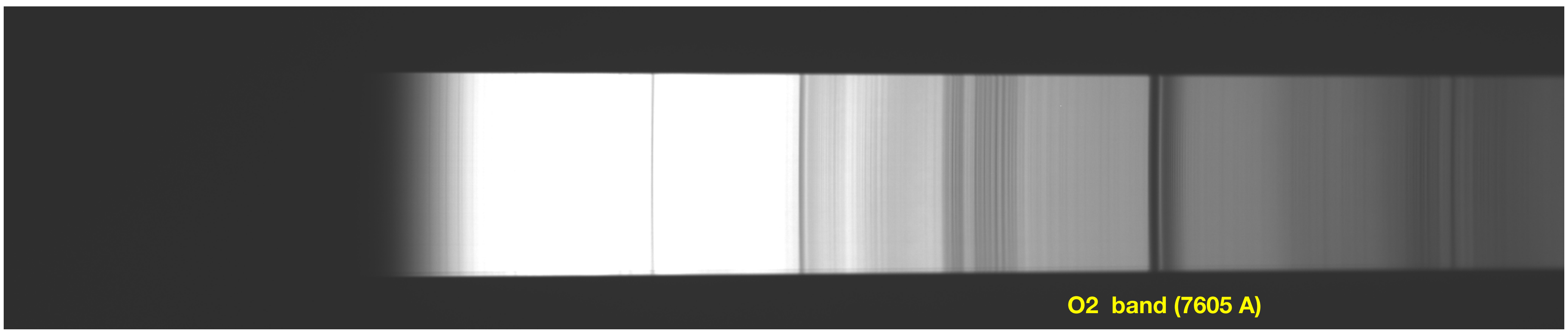
Order overlap (1/3)

Example for a daylight spectrum

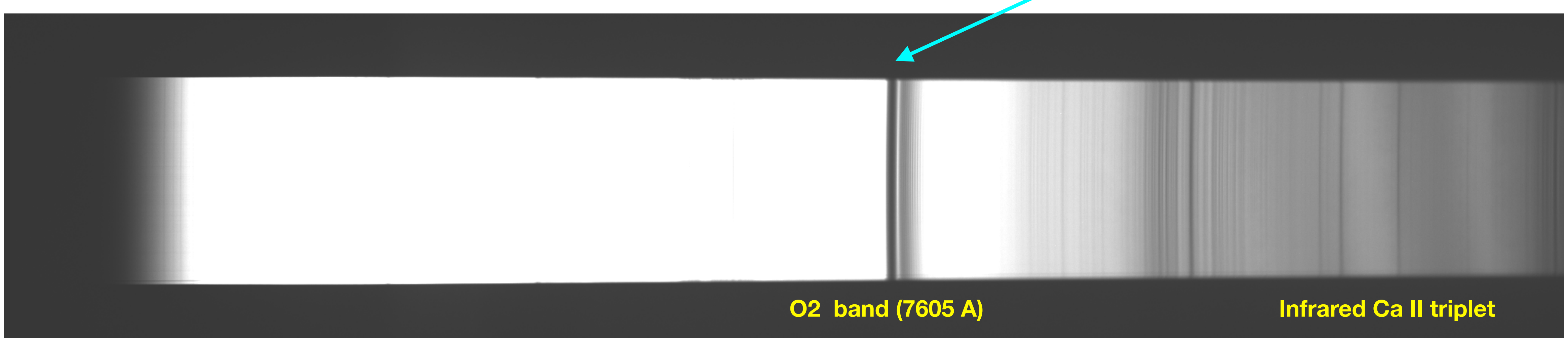
Here the blue order #2 recover the IR order #1



UVEX - 600 l/mm blaze 750 nm - slit 23 microns - ASI294MM camera - no order filter



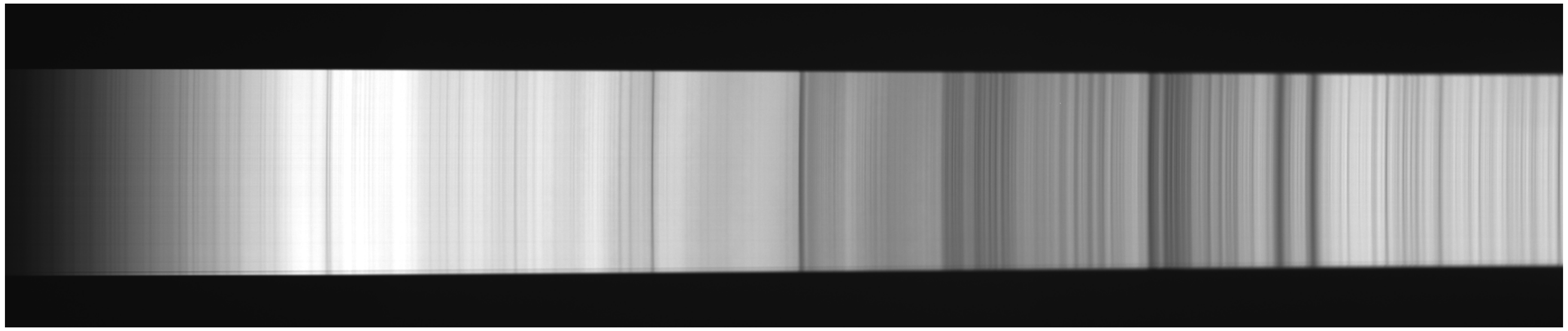
UVEX - 600 l/mm blaze 750 nm - slit 23 microns - ASI294MM camera - RG610 order filter added -> a pure infrared spectrum



UVEX - 600 l/mm blaze 750 nm - slit 23 microns - ASI294MM camera - RG610 order filter added - shifted by a simple grating rotation

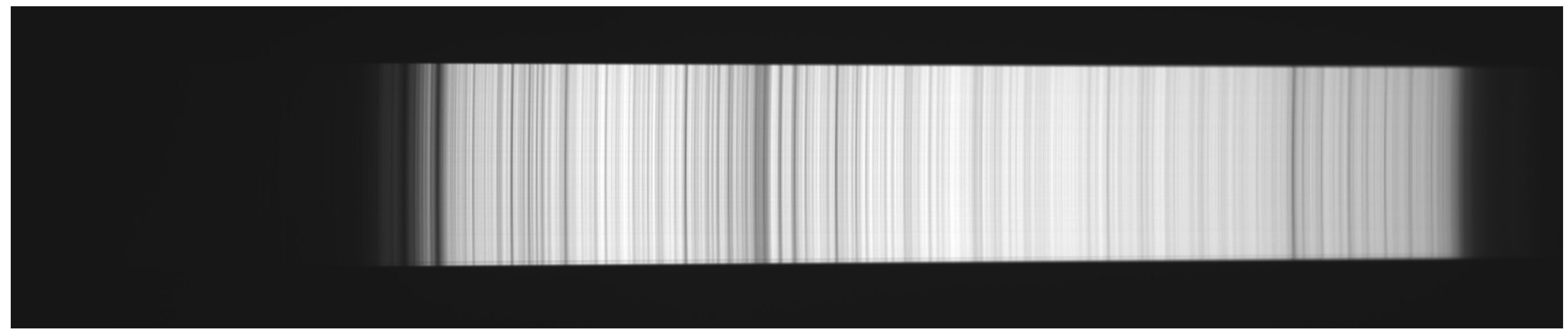
Order overlap (2/3)

How to work at order #2



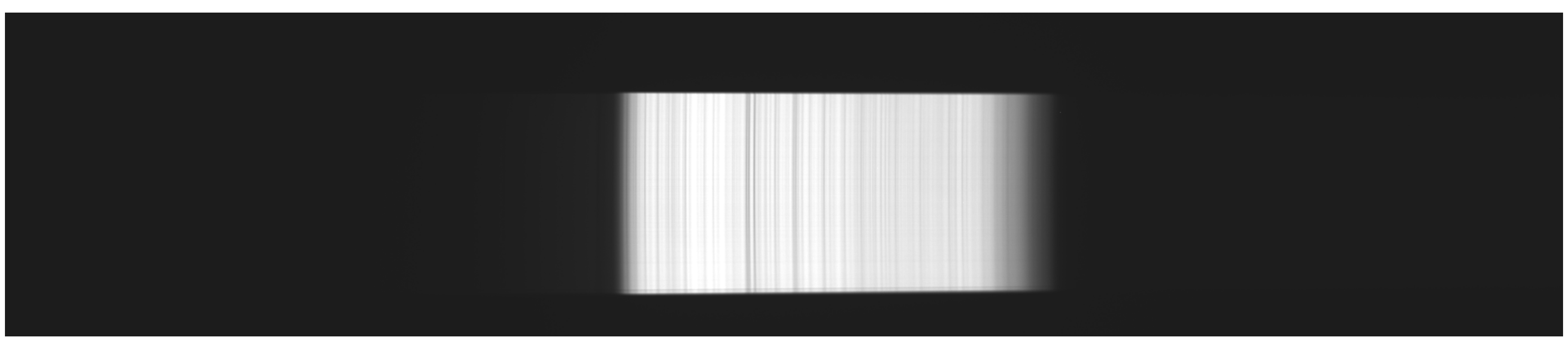
Standard 600 l/mm blaze 750 nm spectrum

ASI294MM CMOS camera (19.2 mm wide)

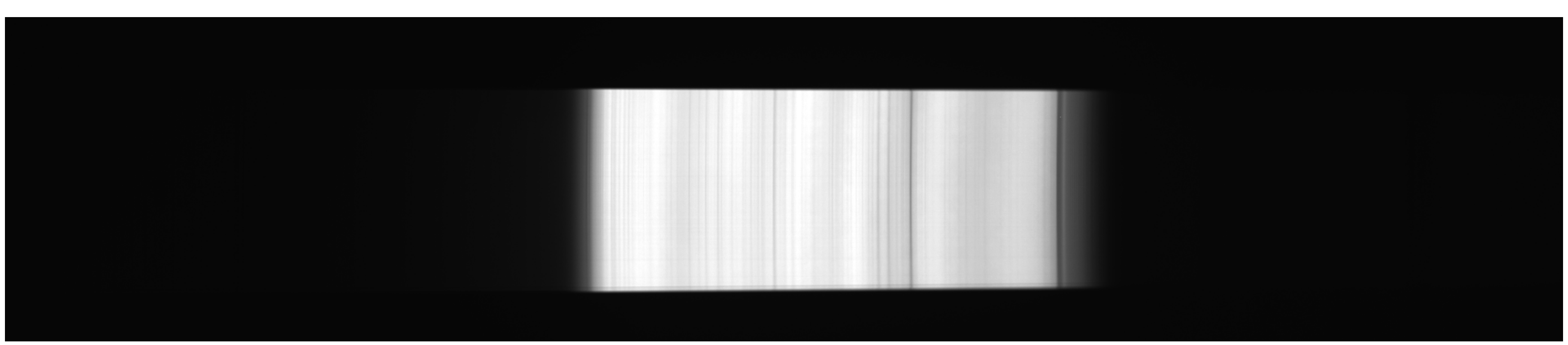


Add of a pass-band filter Astrodon Series Gen 2 Blue

Band-pass of Astrodon blue filter at second order.
The 600 l/mm is now equivalent to 1200 l/mm + excellent blaze effect



Astrodon Green band filter



Astrodon Red band filter
Isolate Halpha at R=3000 by using a 600 l/mm grating

Order overlap (3/3)

Practical implementation of a filter order

Adopt an external filter wheel

Can be manual or motorized

The UVEX project

UtraViolet EXplorer spectrograph

Spectral calibration

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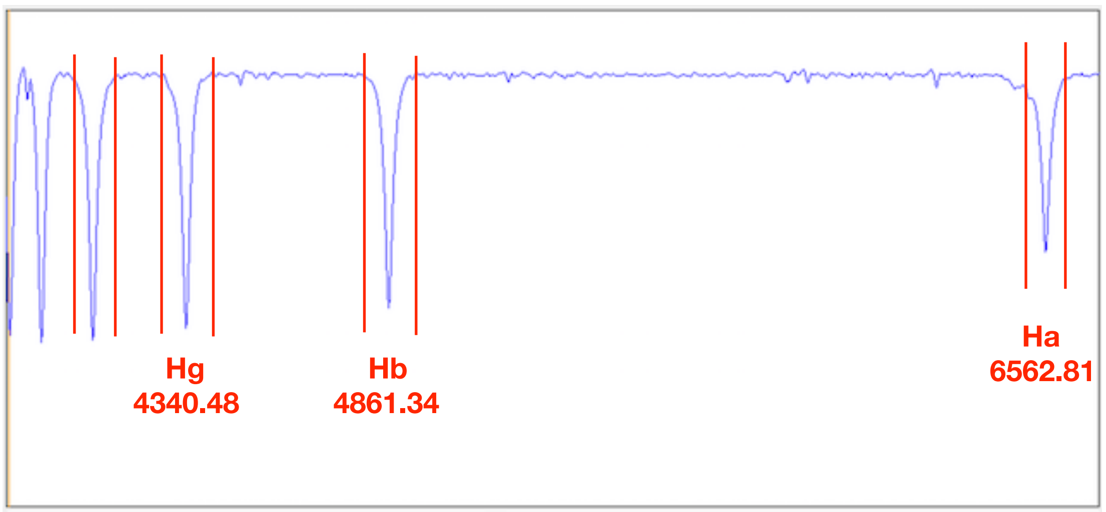
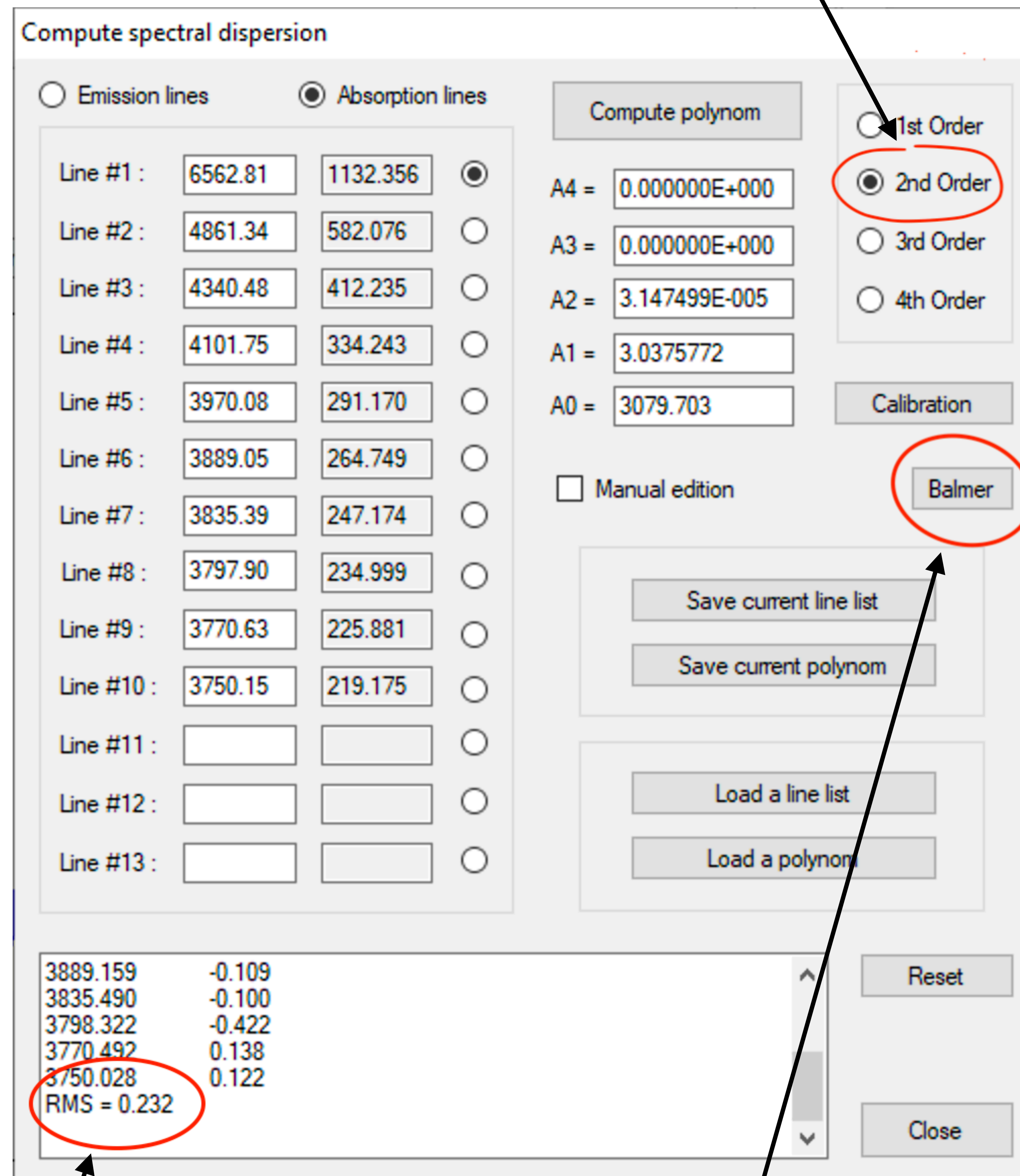
Spectral calibration (1/3)

Second degree is optimal

My favorite method : on the sky !

(1) Balmer lines a A or B type star are useful references.





(2) Fit a 2 nth degree (only) in lambda

Point (2) is a very important optical property of UVEX : the dispersion function can be extrapolated toward the UV and the IR with a reasonable precision.

(Alp600 or LISA spectrograph for example, can't)

UVEX data's are simple to calibrate

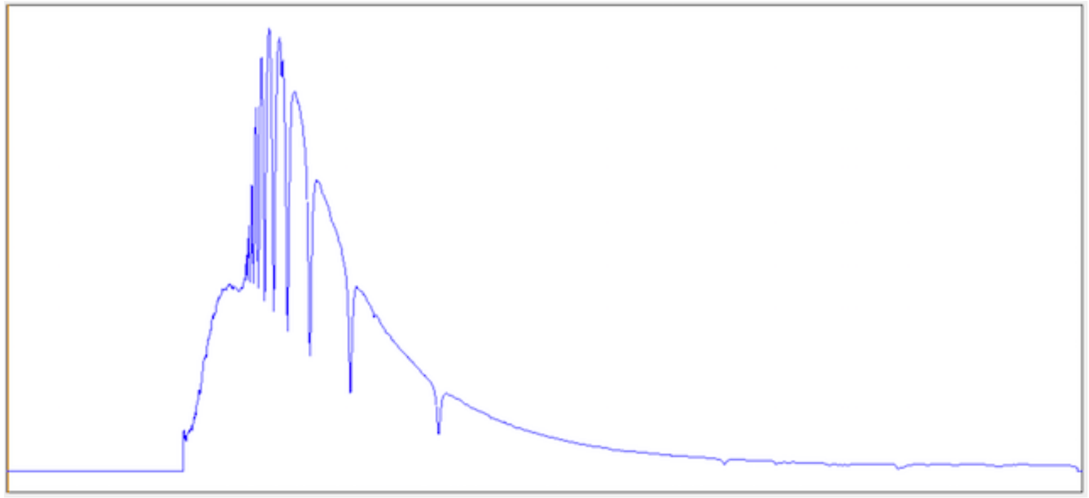
Preselected Balmer lines list

High precision dispersion law (better then 1/10 of pixels !)

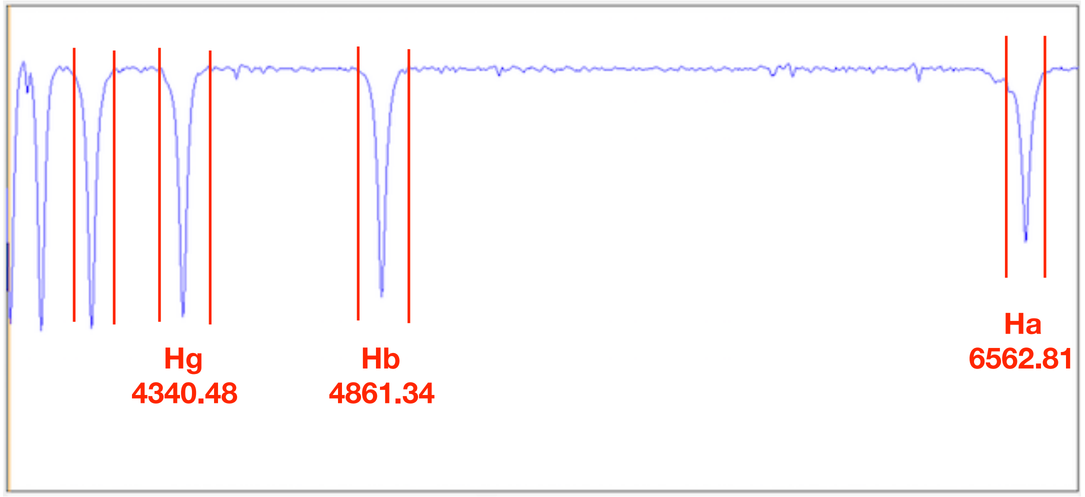
Spectral calibration (2/3)

A tip for a maximal precision…

Uncalibrated RAW spectrum profile



Remove the continuum by using the ISIS tool « Continuum », then measure the lines position on the rectified continuum profile by using ISIS tool « Calibration »



Spectral calibration (3/3)

Alternate method : Find dispersion function or the zero point by using artificial sources

Example of line emission lamps

PenRay type or domestic FluoCompact (Hg lines)

Example of FluoCompact UV spectrum

UVEX version 1200 lines/mm (dispersion : 84.2 A/mm)

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Find instrumental response

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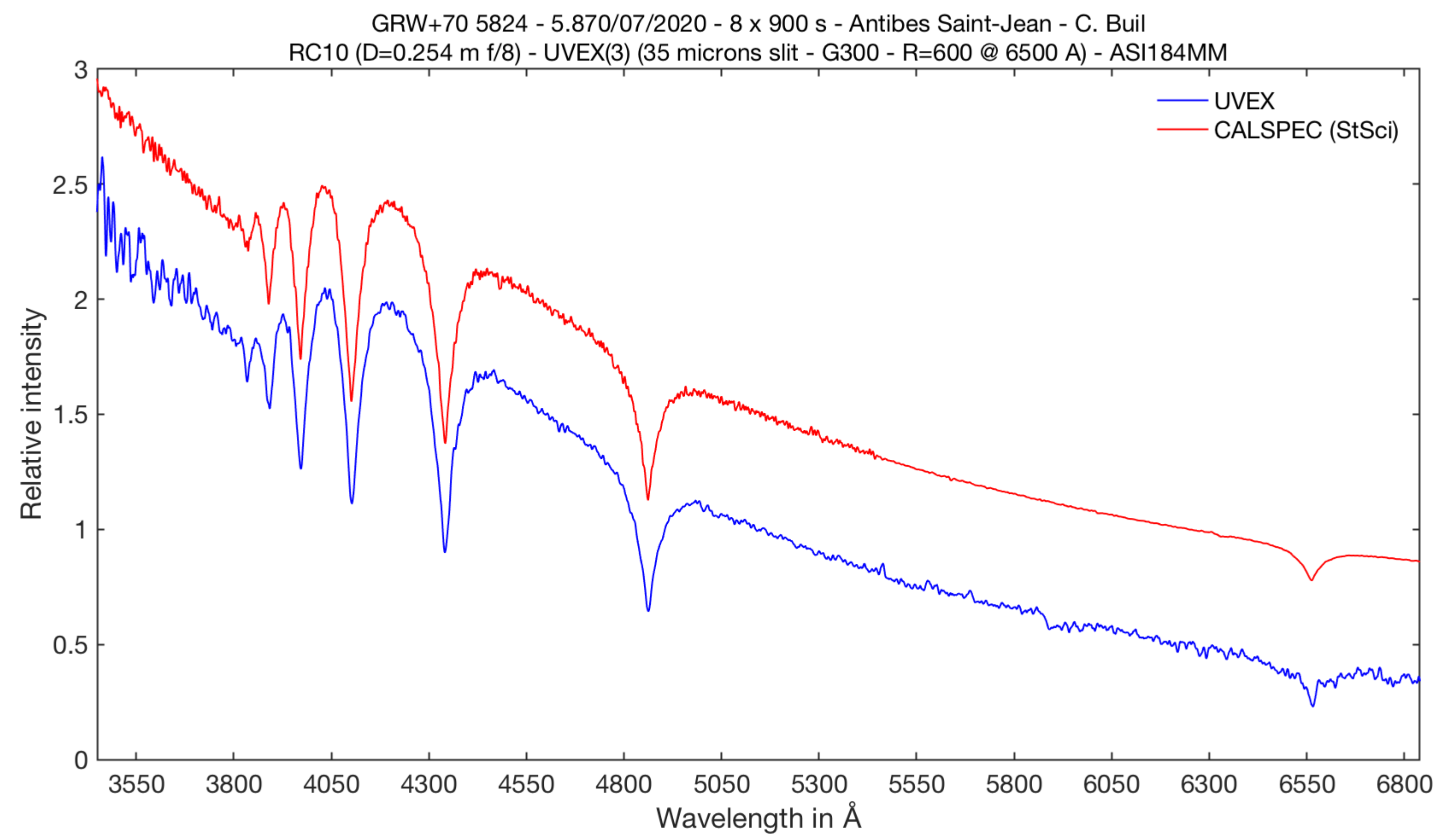
Instrumental response (1/5)

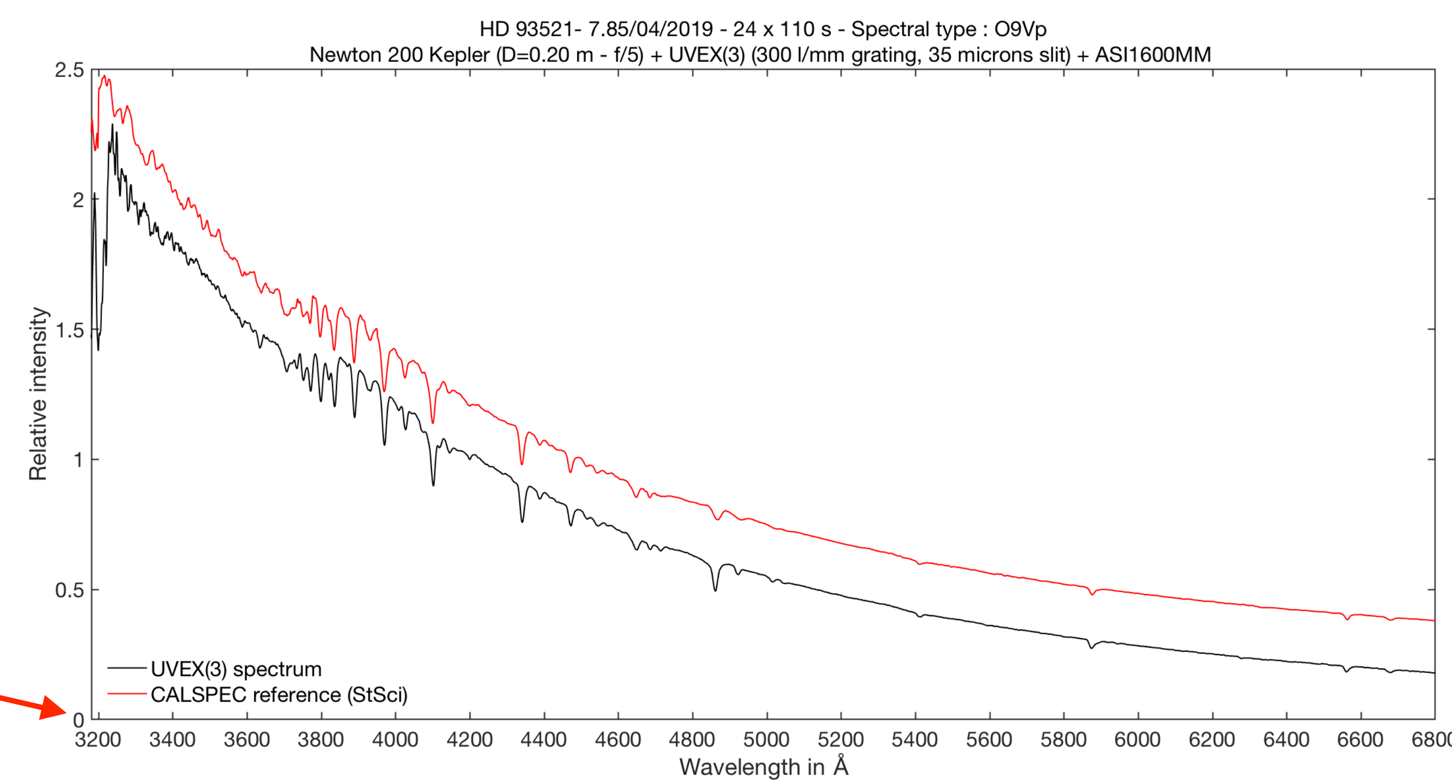
Use Blue star as reference star, to compute instrumental response if you want to get good accuracy on blue range

White dwarf star →



O type star →

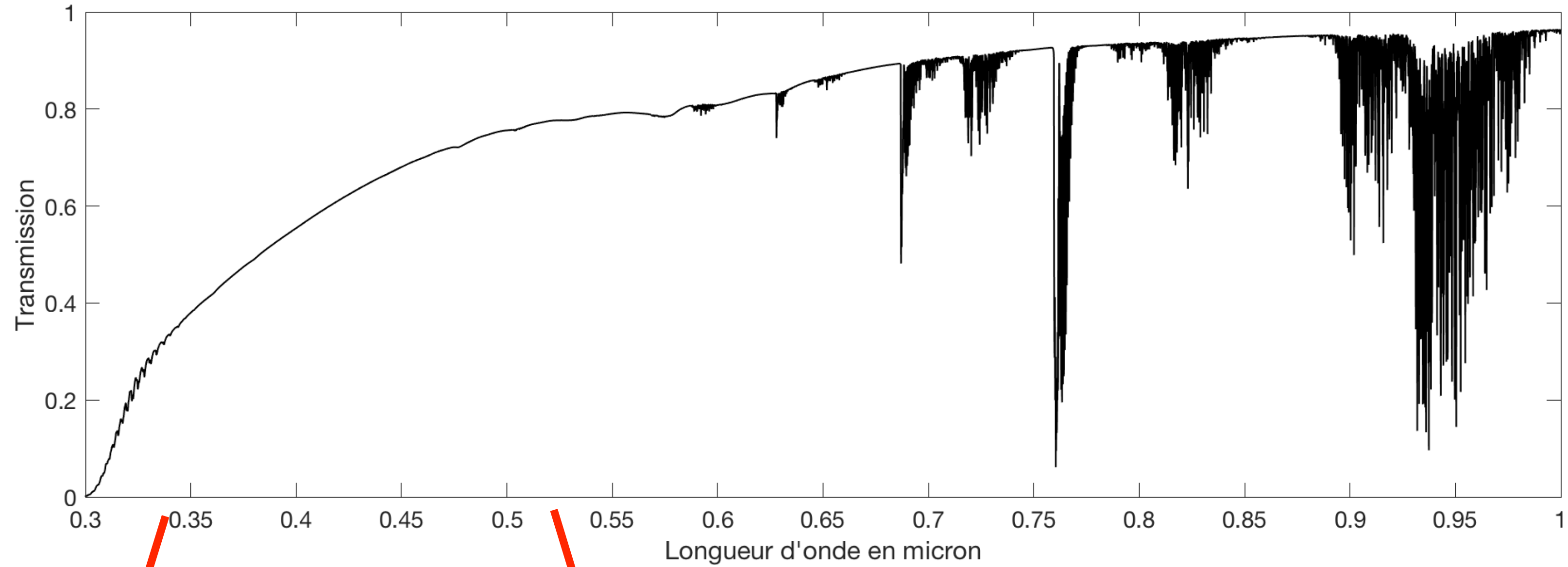
Note the wavelength, near atmospheric UV cutoff (320 nm !)

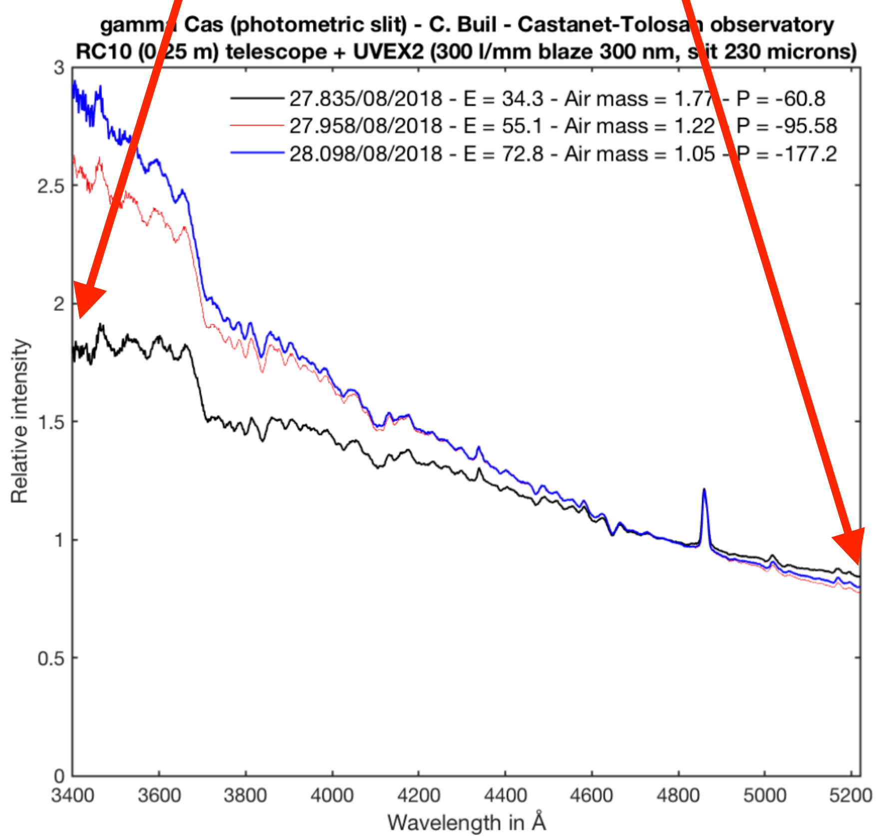


Instrumental response (2/5)

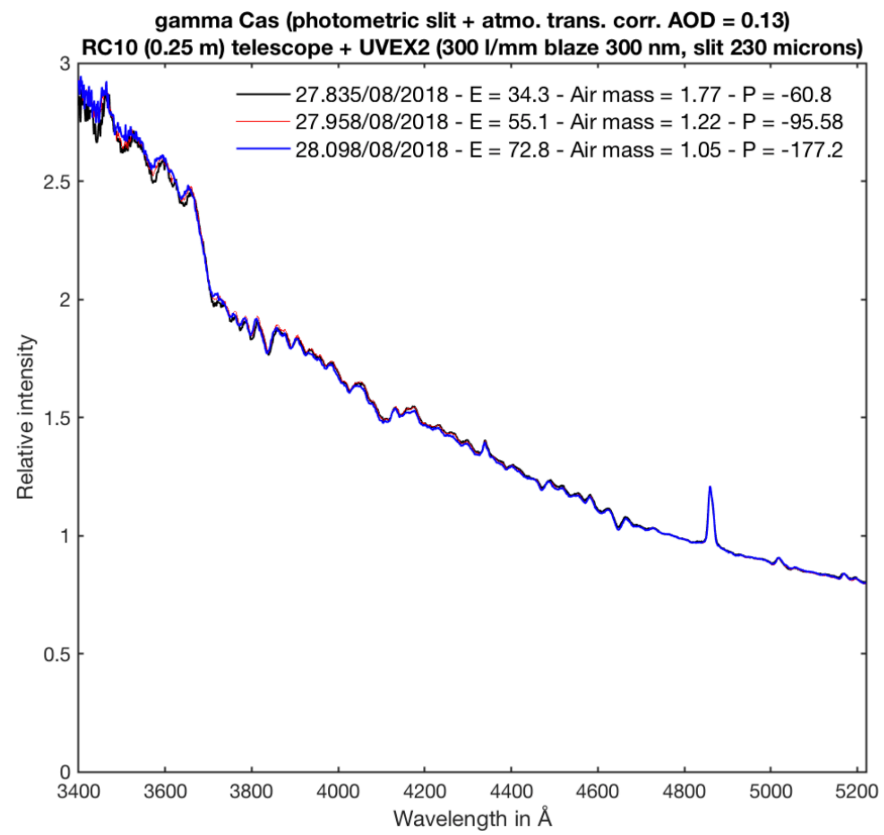
Take into account the atmospheric transmission (very critical for UV observations).

Atmospheric transmission is function of wavelength and airmass





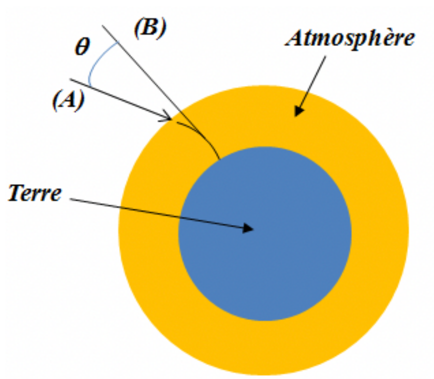
Before atmospheric correction

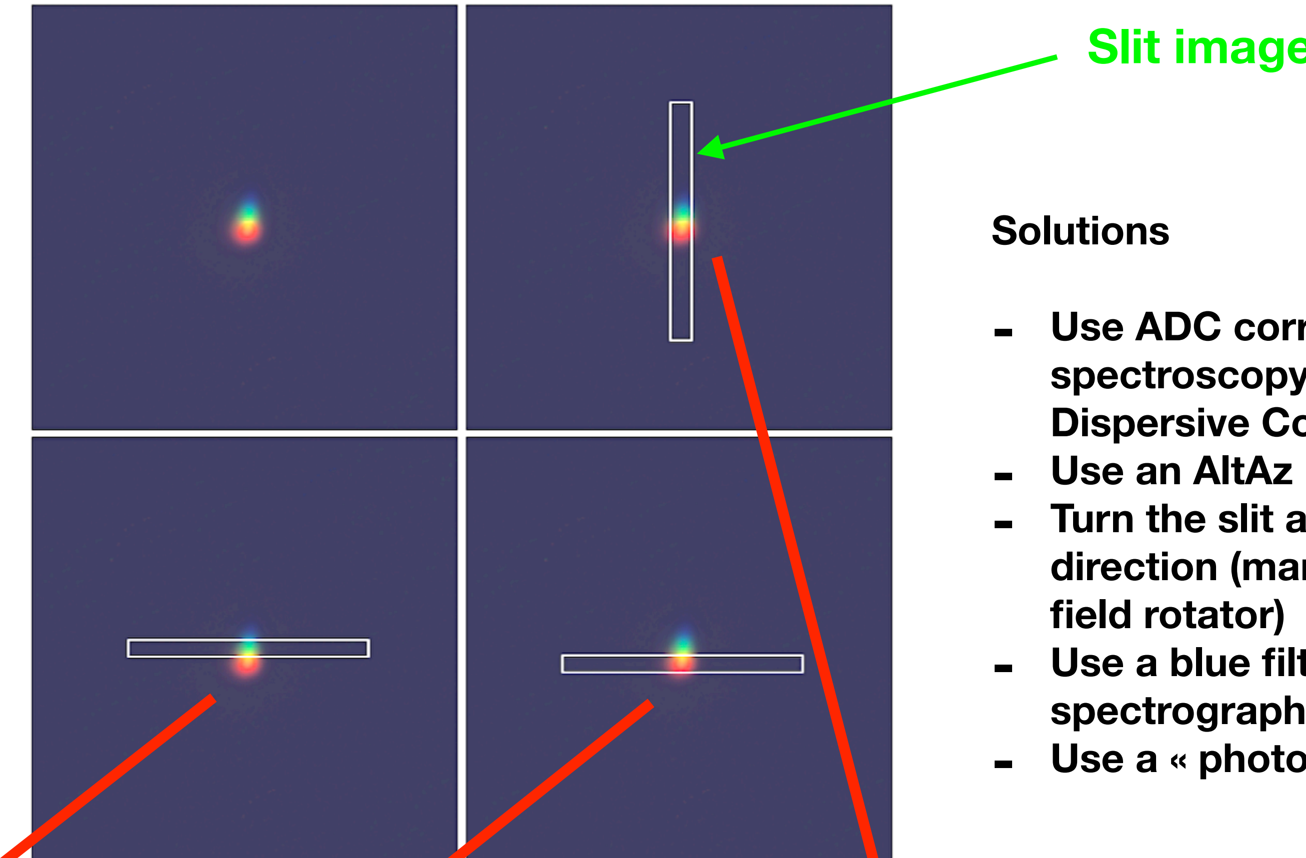


After correction (ISIS atmospheric transmission model)

Instrumental response (3/5)

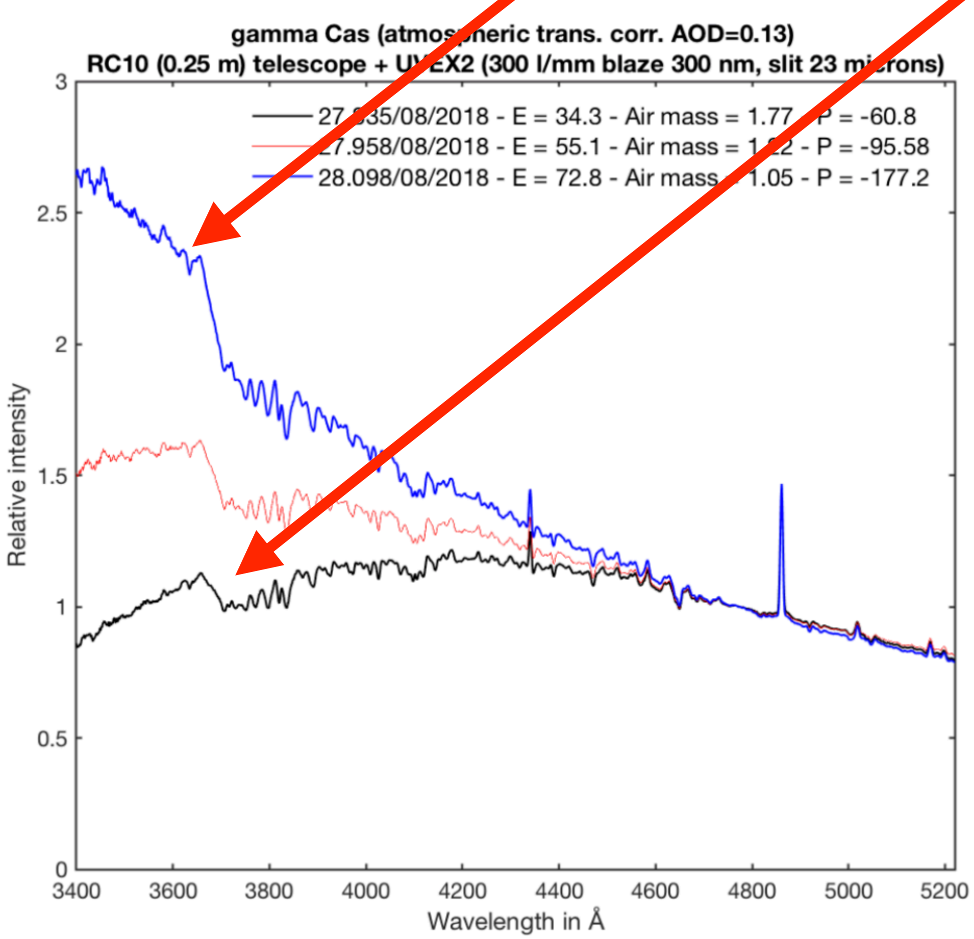
The effect of atmospheric differential refraction can be also dramatic in UV !

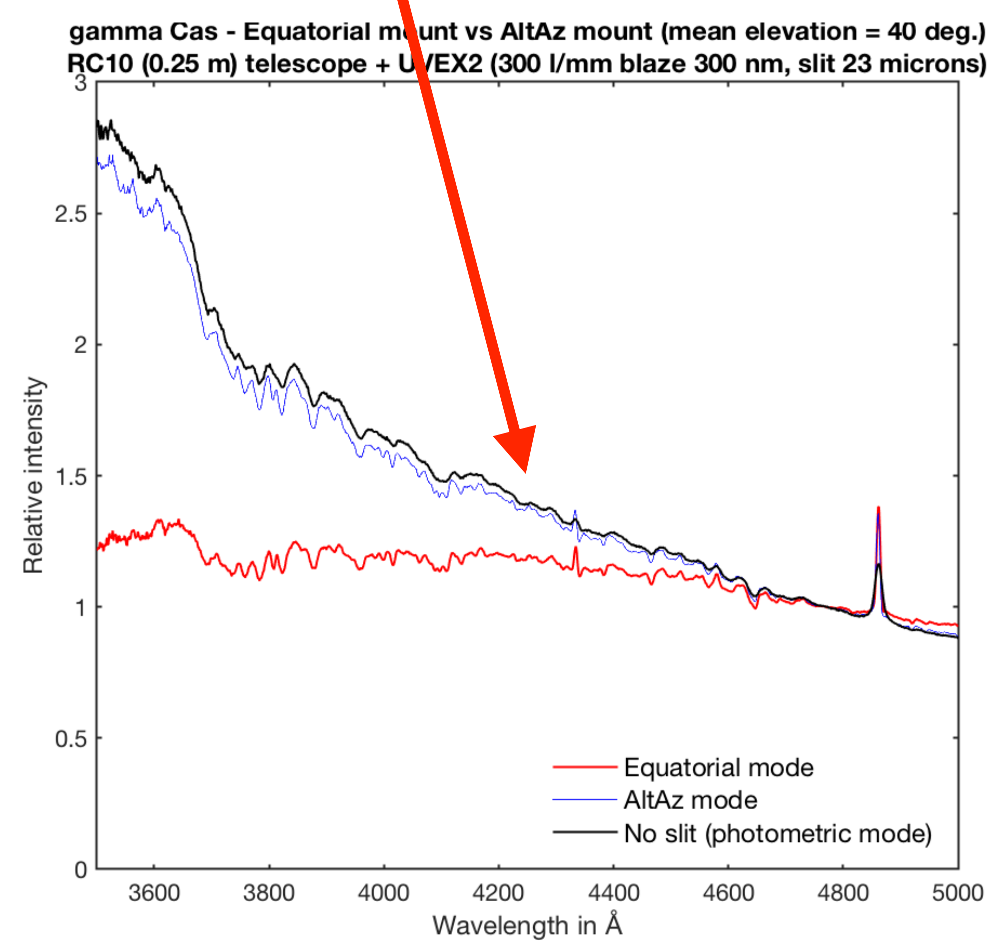




Solutions

- **Use ADC corrector suited for spectroscopy (Atmospheric Dispersive Corrector)**
- **Use an AltAz mount**
- **Turn the slit along parallactic direction (manual, motorized field rotator)**
- **Use a blue filter in front the spectrograph**
- **Use a « photometric slit »…**

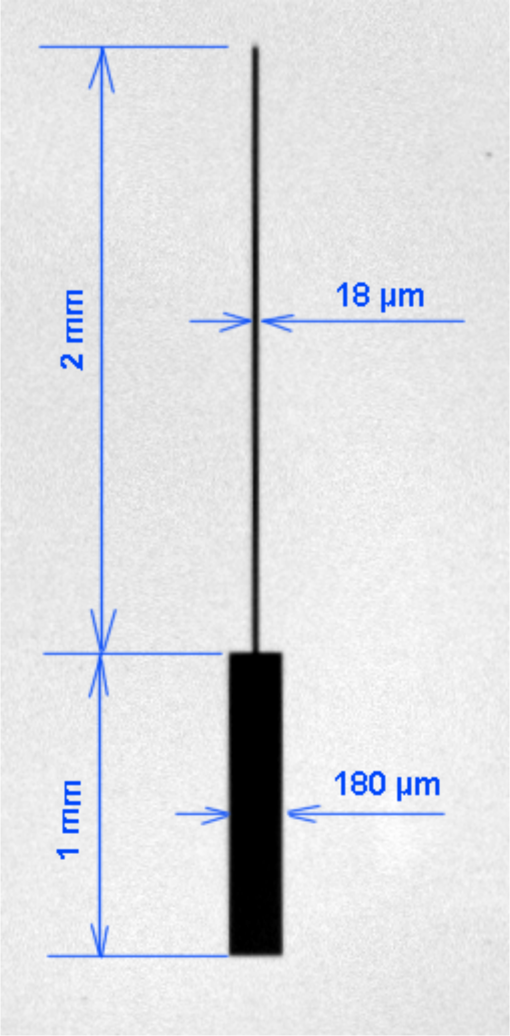




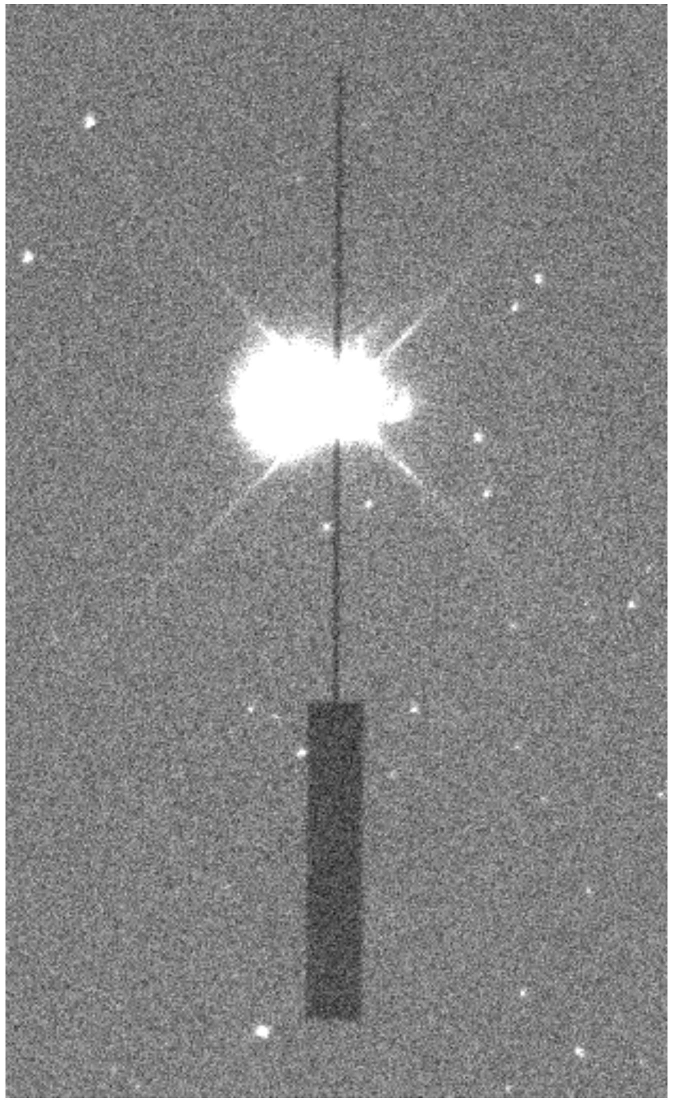
Instrumental response (4/5)

The photometric slit solution

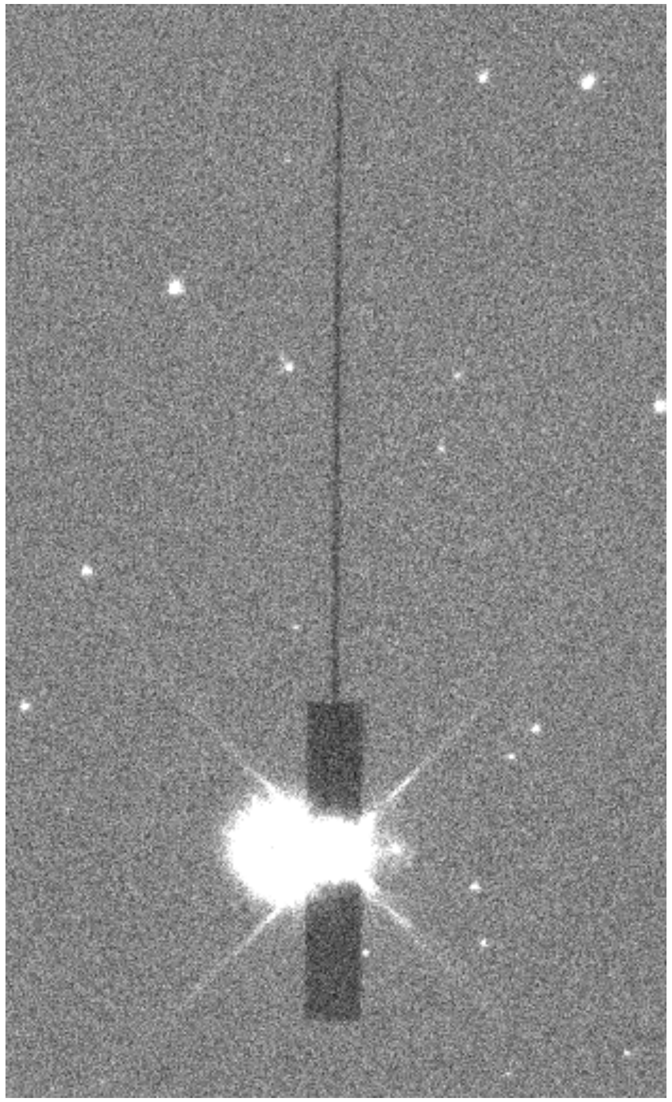
Strategy : use the narrow part for taking a high res spectrum, use the large part for taking a photometric spectrum to correct in a second time the high res spectrum from the differential atmospheric dispersion (instrumental response)



Typical photometric slit (Shelyak model)



Star on the narrow part



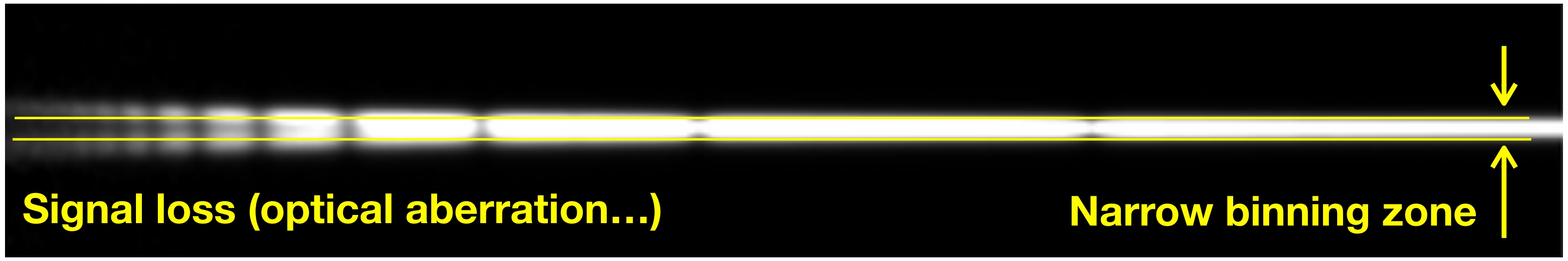
Star on the large part

Instrumental response (5/5)

Be careful during binning operation in presence of residual chromatism

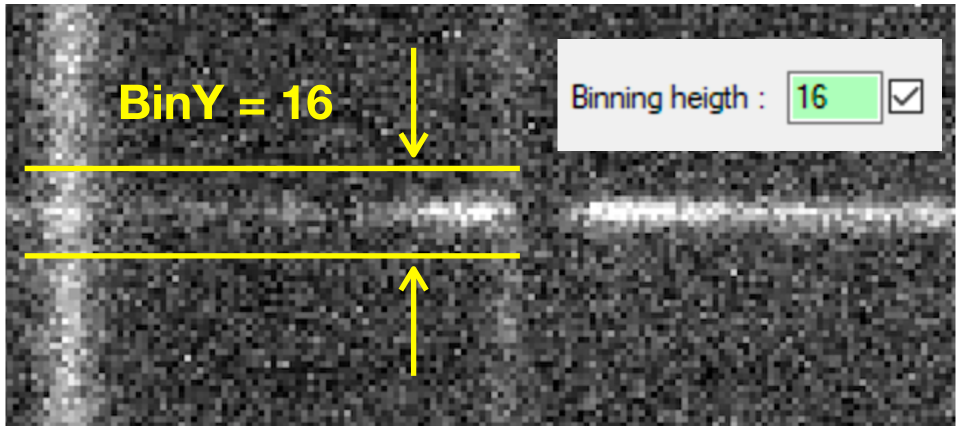
(Schmidt-Cassegrain spherochromatism for example)

Central obstruction image



UV

Largest 2D trace here (unfocused telescope image) = Possible loss of photons + radiometric error



Prefer a large binning zone + optimal Y-binning algorithm

The UVEX project

UtraViolet EXplorer spectrograph

Take a flat-field

Flat-field (1/2)

Use the highest color temperature available halogen lamps for a max. UV signal and take very high Signal to Noise Ratio flat-field (many exposure added)

But the actual calibration module solution for UVEX is not compatible (moderate color temperature of internal lamp + absorber)

So… I move the source in front the telescope aperture… a very manual method :-(

Mandatory for correct low and high frequency wavelength variations of the instrumental gain

Typical flat-field image (ZWO CMOS camera ASI294MM)

Tip : Use the command « FLAT_OPT » for reduce noise in this part of the flat-field (localized Gaussian filtering)

For wavelengths down to 365 nm : mixed method, see : http://www.astrosurf.com/buil/instrument_response/

Flat-field (2/2)

Sample of usuable continuum lamps

« Classic » halogen 3000 K lamp (not easy to find currently)
and SOLUX M16 4700K (daylight lamp / museum lamp)

The UVEX project

UltraViolet EXplorer spectrograph

About the detector

Photon detector today (1/8)

The detector is of course a central element of any spectrograph

Now, CMOS detectors replace CCD detectors

QHY model

ZWO model

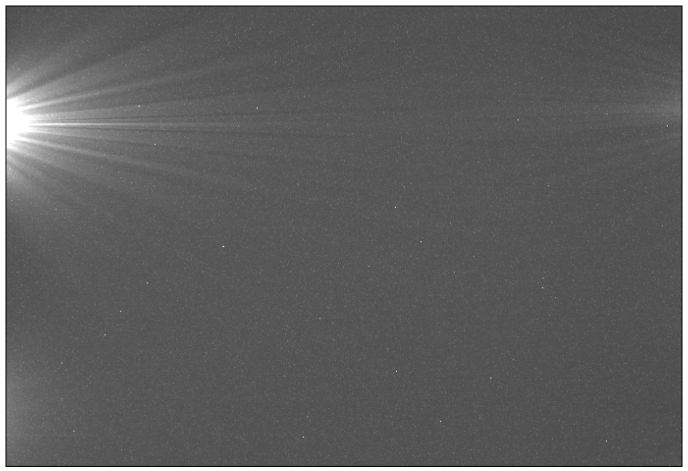
ATIK model

The good news :

- The Read-Out-Noise (RON) is lower (1.5 e- typ.) ——> very important for spectroscopy
- The Quantum Efficiency go up to 80% (thinned technology) ——> important for spectroscopy
- For equivalent surface size, the CMOS is less costly

The bad news :

- Very small pixel size, often not adapted to actual spectrograph
- AmpGlow (but the problem is fixed on the most recent chips) ————>
- Presence of the Random Telegraph Signal noise (RTS)…



A CMOS specific problem…

Random Telegraph Signal : a non-Gaussian noise that manifests as pixels popping up or down in the image at random, with a lifetime of a fraction of a second to a few seconds (salt and pepper noise)

→

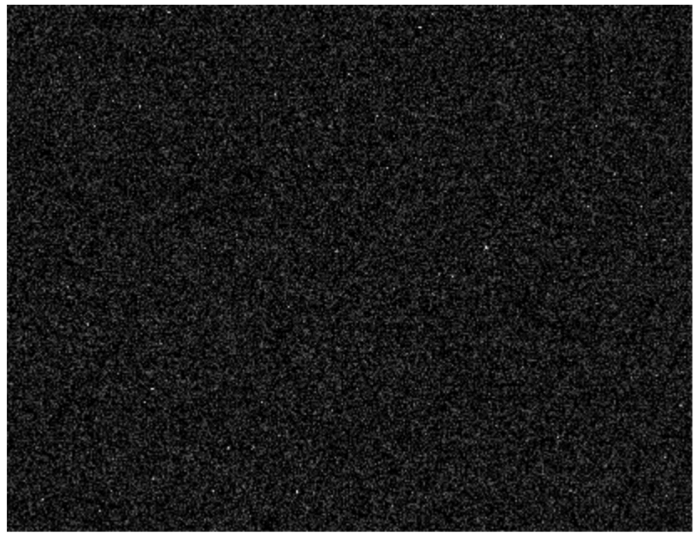
→

- Reduce detectivity of faint object (limiting magnitude)
- Add possible artifact (false detection)

Photon detector today (3/8)

Not all sensors are similar !

Sony IMX183 sensor	Sony IMX571 sensor

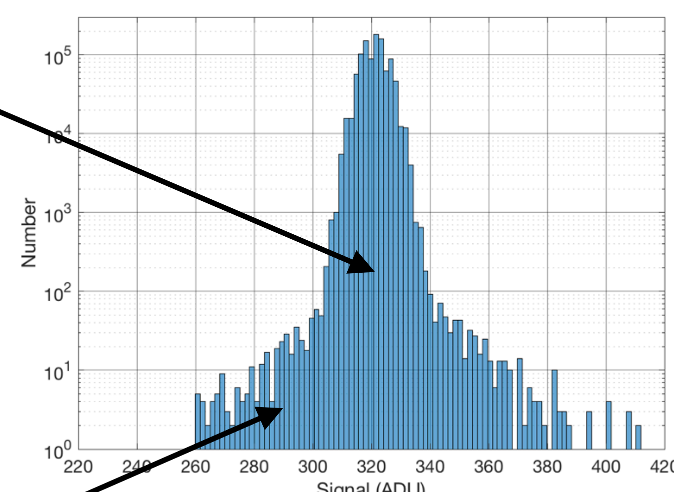


ASI183MM

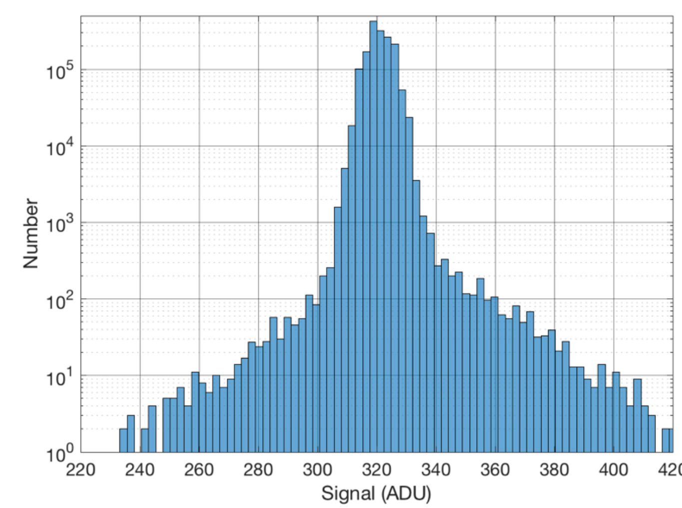
ASI294MM

Gaussian noise distribution

RTS noise distribution (non Gaussian)



ASI183MM



ASI294MM

Histogram: Number of pixels for a given intensity value (signal in Analog Digital Unit)

Chip data-sheet (or standard deviation measure) of the noise : 1.58 electron

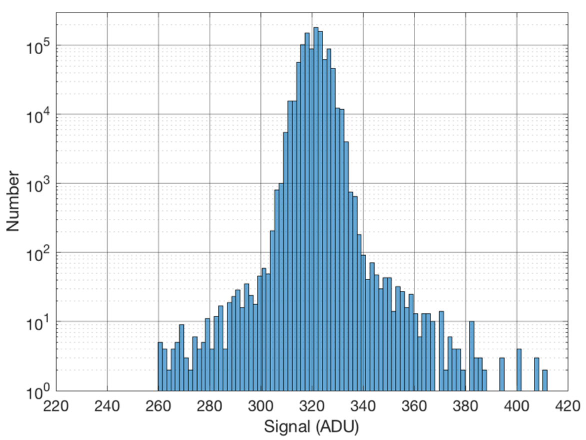
Chip data-sheet (or standard deviation measure) of the noise : 1.43 electron

But… based on the effective global noise (Gaussian + non Gaussian) IMX571 is not as good as the IMX183 sensor

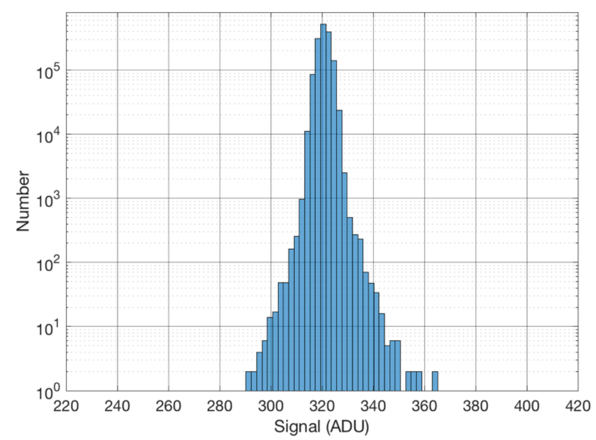
Photon detector today (4/8)

Thanks to the small pixel size of « normal » CMOS sensor (2 to 5 microns) :
If the image spectrum is oversampled, some processing can be applied for reducing the noise and preserve spectral resolution during data reduction.

An intuitive and elementary method :
Simple binning before profile spectral extraction



ASI183MM
Binning 1x1 - Pixel size : 2.4 microns
Noise : 1.58 e-



ASI183MM
Binning 2x2 - Pixel size : 4.8 microns
Noise : 0.81 e-

Original bin. 1x1

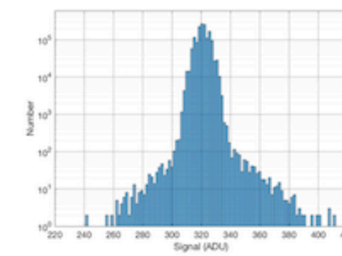
Binning 2x2
The RSB increase by a factor 2 and RTS noise is well removed

This mean effect is often sufficient

A more sophisticated algorithm
(Cmos-MEDian) - available under ISIS

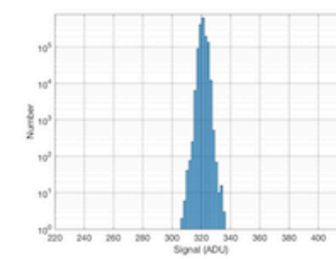
CMED algorithm work-flow | **Histogram of ASI183MM offset**

Acquisition at bin 1x1 (mandatory)



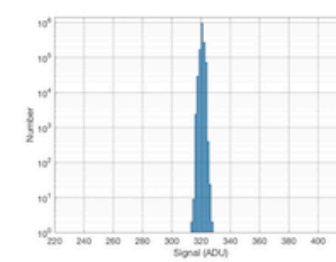
↓

Median filtering (3x3 or 5x5 kernel)



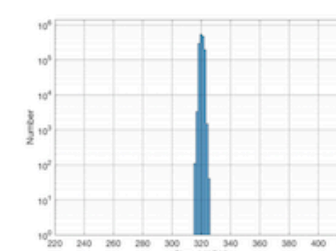
↓

Gaussien filtering (FWHM = 2 - 4 pixels)



↓

Reduction of image size by binning (optional)



↓

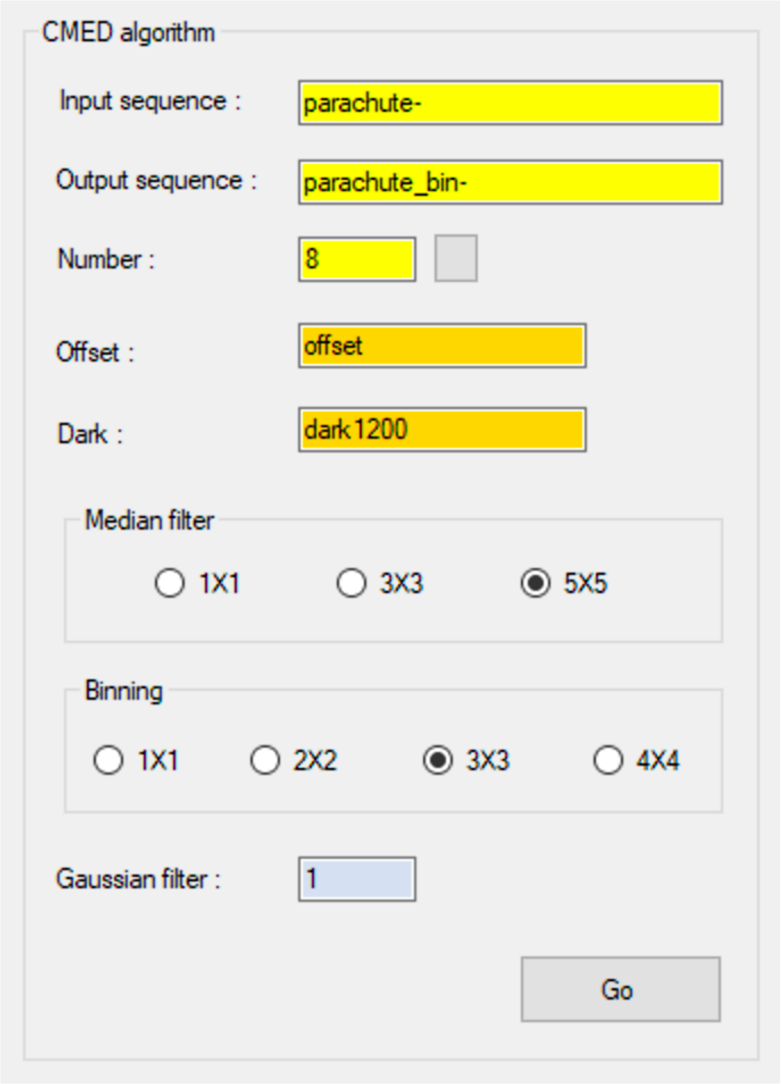
Final image (standard processed)

Photon detectors today (5/8)

CMOS noise filter tool under ISIS

You can select (and experiment !)

- **median method**
- **binning method**
- **classical gaussian convolution**
- **or a mixture…**



How to compute the spectral pixel sampling ? (number of pixels per FWHM)

A practical example for UVEX + ASI183MM camera (2.4 microns pixel size)

Consider UVEX spectrograph equipped with 300 lines/mm grating. The linear dispersion of this configuration is P = 330 A/mm.

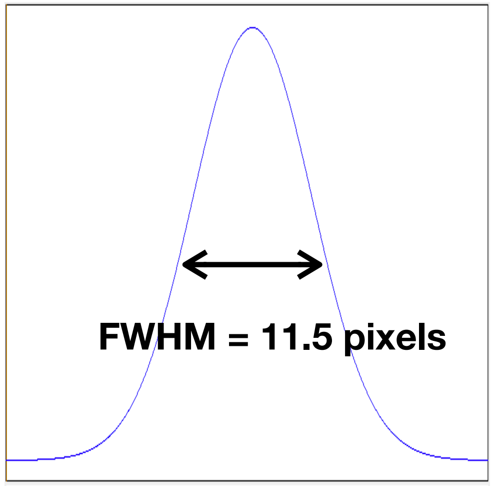
Suppose a spectral resolution of R=λ/Δλ = 600 at 5500 A (35 microns entrance slit).

The FWHM (Full Width at Half Maximum) of a monochromatic spectral line (spectral impulsion) is : FWHM =λ / R = 5500 / 600 = 9.2 A.

The linear value is FWHM = FWHM / P = 9.2 / 330 A = 0,028 mm.*

If p is the pixel size (p=0.0024 mm), the sampling factor (S) of the impulsion line is :

S = FWHM / p = 0.028 / 0,0024 =* ***11.5 pixels***



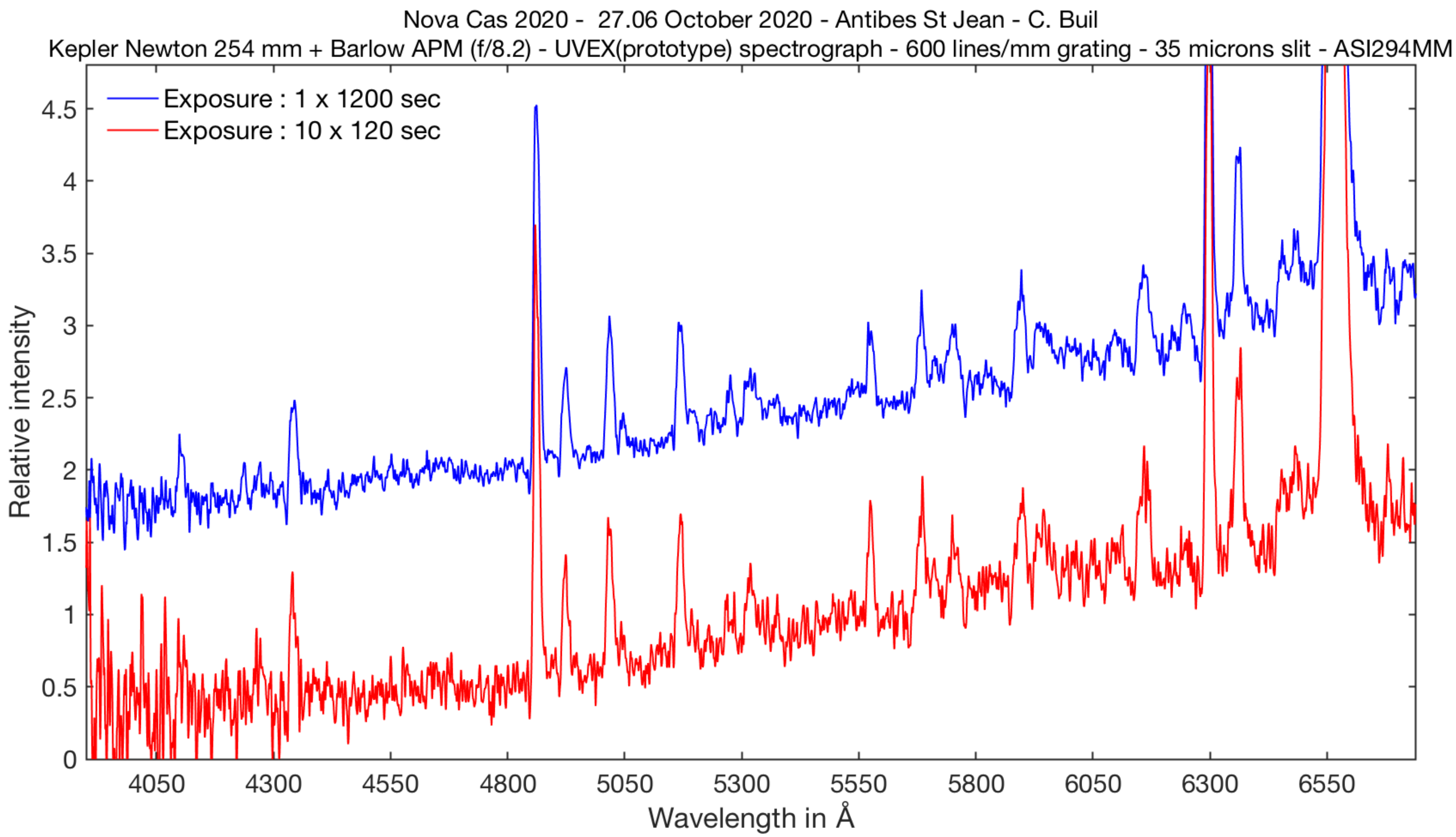
Note : We have more than 11 pixels in the half wide of a spectral line. The oversampling is huge ! Remember, the minimum sampling according Shannon criteria (or Nyquist) is S = 2.

Linear dispersion (P) of UVEX in function of the grating selected :

- **300 lines/mm -> P=330 A/mm**
- **600 lines/mm -> P = 168 A/mm**
- **1200 lines/mm -> P = 84 A/mm**
- **1800 lines/mm -> P = 56 A/mm (note : only usable for blue and UV observations)**

Photon detectors today (7/8)

A general rule for spectrography (true for CCD & CMOS) : for faint objects, always prefer a long exposure to a fraction of this long exposure.



10 exposures (120 sec. each) : Signal to Noise Ratio = 4.6 at 4500 A)
1 exposure (1200 seconds) : Signal to Noise Ratio = 9 (at 4500 A)

Photon detectors today (8/8)

Wich camera for UVEX ?

Parameters for popular ZWO CMOS cameras (and QHY equivalent)

	ASI1600MM	ASI183MM	ASI294MM
Size	4656 x 3520	5496 x 3672	4144 x 2822
Pixel	3.8 microns	2.4 microns	4.63 microns
ADC	12 bits	12 bits	14 bits
Gain (200)	0.467 e-/ADU	0.360 e-/ADU	0.344 e-/ADU
RON	1.34 e-	1.58 e-	1.43 e-
Dark -15°C	0.0083 e-/s	0.0011 e-/s	0.0010 e-/s

and quantum efficiency ->

Wavelength	ASI1600MM	ASI183MM	ASI294MM
3500 A	(16 %)	(25 %)	(28 %)
3800 A	30 %	50 %	52 %
4000 A	45 %	66 %	72 %
4500 A	61 %	78 %	82 %
5000 A	62 %	80 %	84 %
5500 A	56 %	71 %	74 %
6000 A	48 %	57 %	62 %
6500 A	41 %	45 %	55 %
7000 A	30 %	40 %	49 %
7500 A	26 %	33 %	37 %

A possible merit function : $\mathrm{D}^{\star} = \frac{f\ \mathrm{QE}\ p^2}{\mathrm{RON}}$

f is the binning factor, QE is the quantum efficiency at a given wavelength, *p* is the physical width of the pixel, RON is the read noise in the raw image.

If CMED is applied (oversampling case) : $\mathrm{D}^{\star} = \frac{f\ \mathrm{QE}\ p^2}{0,47 \times \mathrm{RON}}$

A high value of D* is better

D* at 500 nm

	ASI294MM	ASI183MM Unbinned	ASI183MM Standard binning	ASI183MM Optimal binning
f	1	1	2	2
QE	0.84	0.80	0.80	0.80
p	4.63 microns	2.40 microns	2.40 microns	2.40 microns
RON	1.43 e-	1.58 e-	1.58 e-	1.58 e-
D*	**12.6**	**2.9**	**5.8**	**12.4**

D* is equivalent for ASI183MM (after processing) and ASI294MM !

ASI183MM offers a better cosmetic aspect (less RTS + binning) and more flexibility (for example, it can be used with a 10 microns slit)

ASI294MM offers a larger spectral coverage (superior to 45%) and a better blue and red QE.

Other criteria are the price, the slit width (w), the seeing and the sampling (+spectral resolution).

For w =< 23 microns (<10 inches telescope), choose ASI183MM

For w > 23 microns (10+ inches telescope) , choose ASI294MM

The UVEX project

UtraViolet EXplorer spectrograph

Thank you very much !