Echelle spectroscopy with a small telescope

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Principal parameters of a spectrograph

- Spectral resolution *R*
- Optical efficiency=throughput
- Useful spectral range
- RV stability

$$R = \frac{\lambda}{\Delta\lambda} = \frac{c}{\Delta\nu}$$

$$R = \frac{f_{\text{coll}}}{w}\frac{n^2}{d^2}\left(\frac{\sin\alpha + \sin\beta}{\cos\alpha}\right)$$

$$R = \frac{W}{sD}\frac{n^2}{d^2}\left(\frac{\sin\alpha + \sin\beta}{\cos\alpha}\right)$$

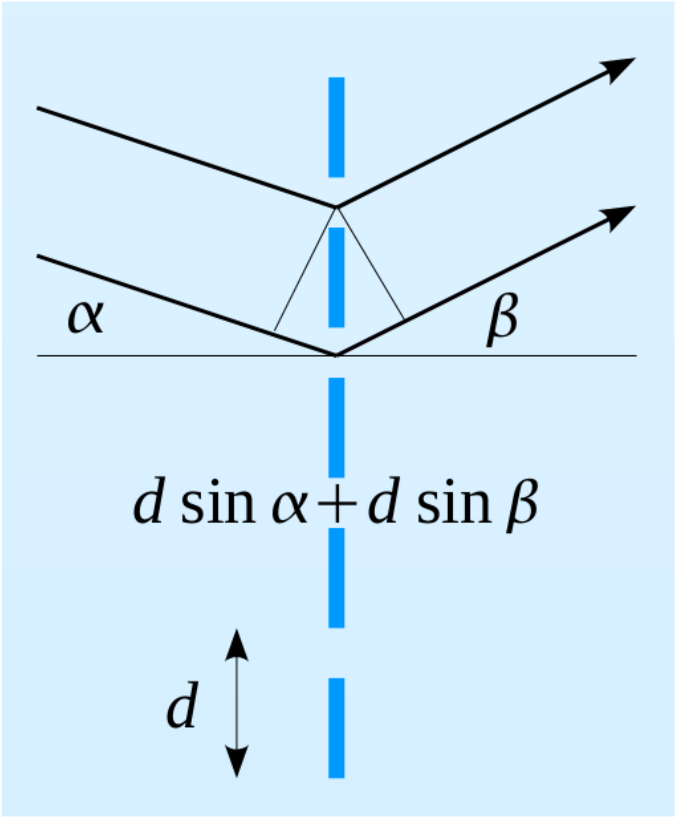
Design

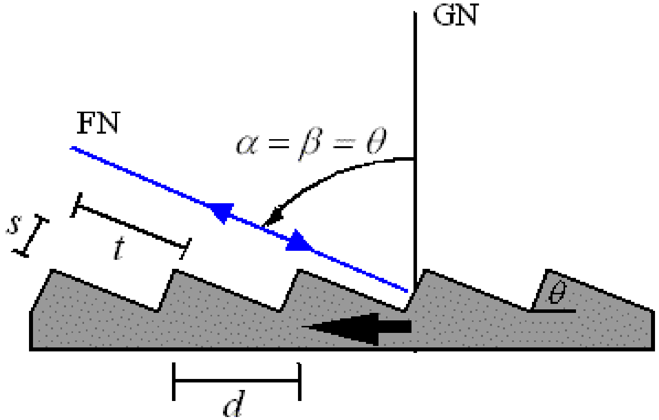
- fiber-fed, slit-mounted
- long-slit, echelle, multi-object/fiber
- single-channel, double channel, white-light
- image slicers
- Littrow configuration: angle of incidence equals to angle of diffraction

Echelle spectroscopy

- long-slit spectrographs: usually first or second interference order used, low order overlap
- echelle spectrographs: high orders, total order overlap, cross-dispersers necessary
- High resolution: high order (*n*), or/and small distance between grooves (*d*)
- blaze angle: improvement of efficiency to facet normal direction (=wavelength)

$$\sin\alpha + \sin\beta = \frac{n\lambda}{d}$$

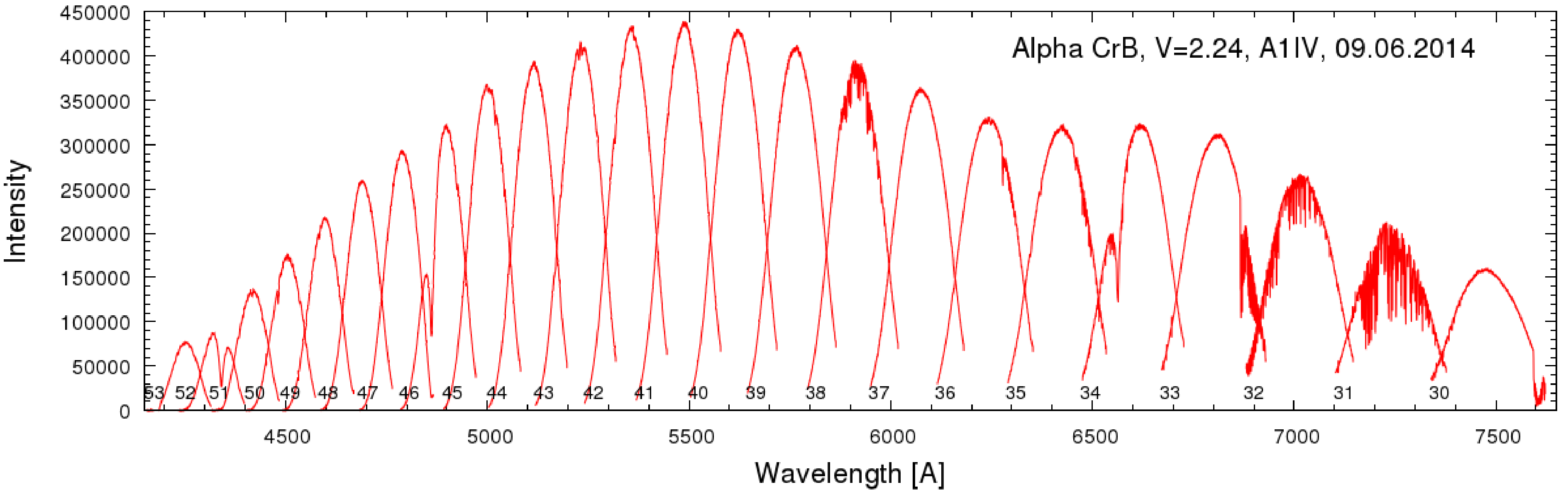




Echelle
order distribution

- Blaze function = distribution of maximum intensity
- Order overlap, free spectral range

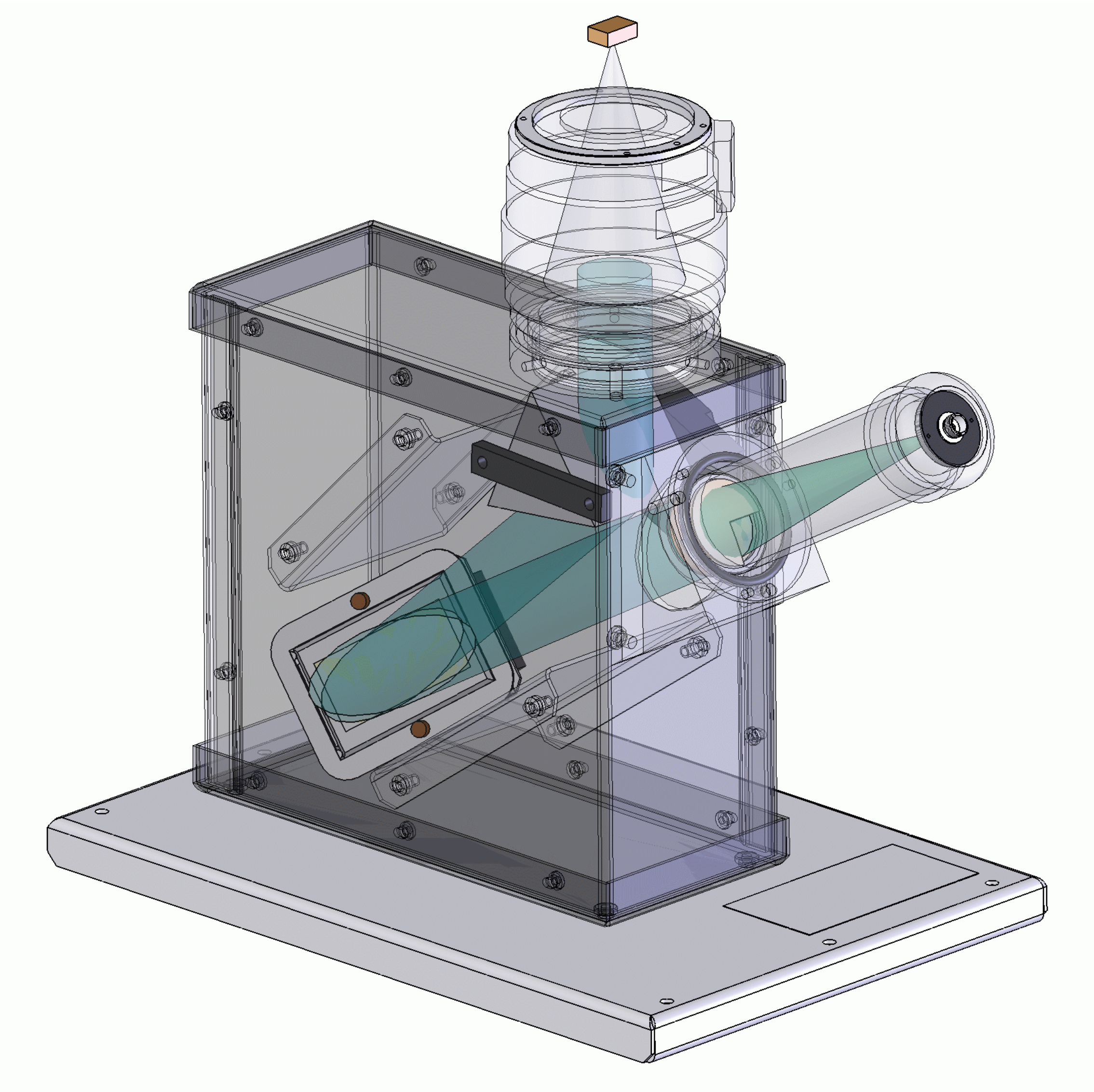
$$I(\beta) = \left[\frac{\sin(\pi b \cos\phi[\sin(\alpha-\phi)+\sin(\beta-\phi)]\lambda}{(\pi b \cos\phi[\sin(\alpha-\phi)+\sin(\beta-\phi)]/\lambda} \right]^2$$

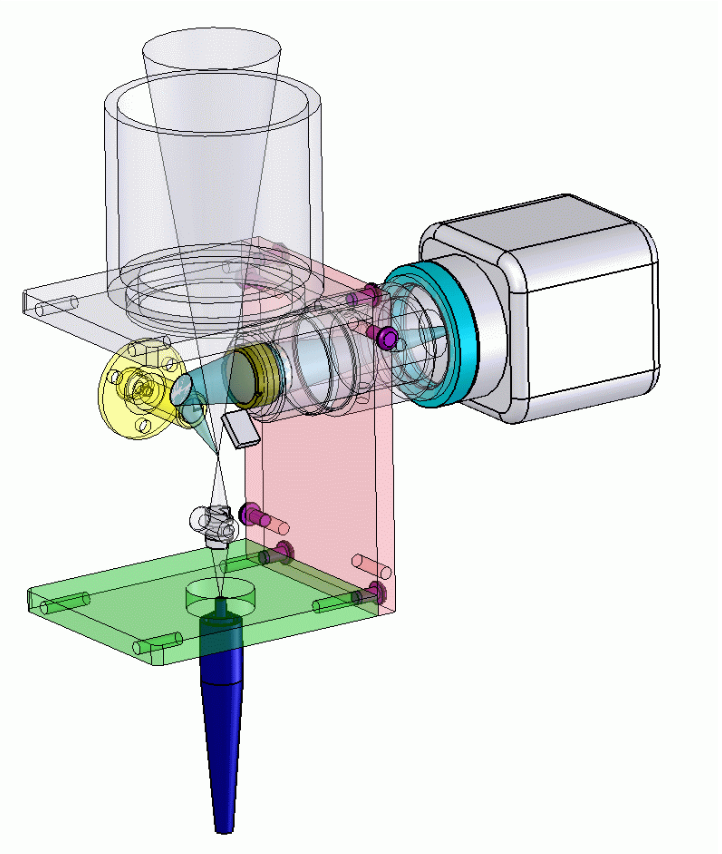


eShel @G1 60/750cm Zeiss

eShel spectrograph design & parameters

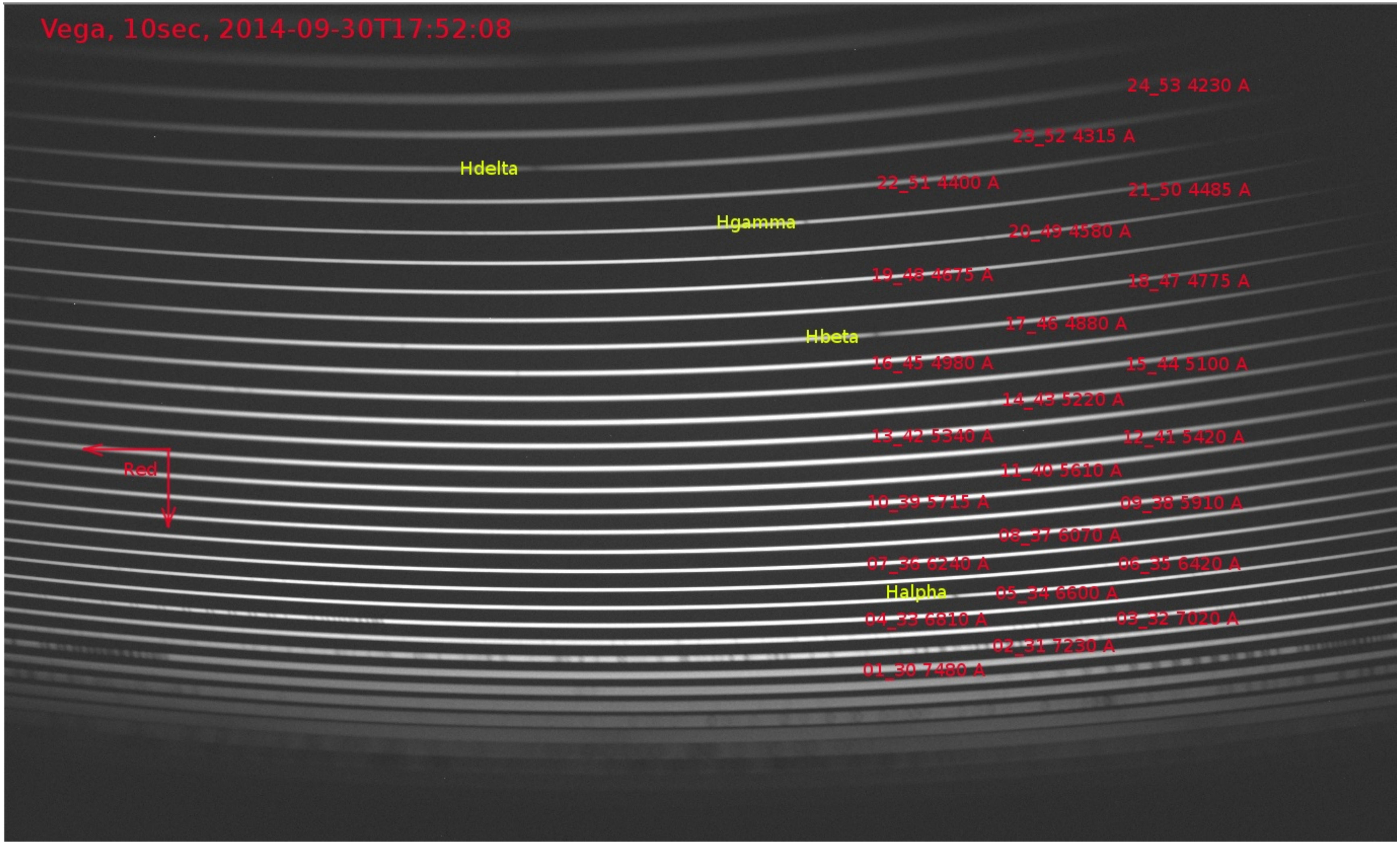
- Littrow design with f/5, prism cross-disperser, 125mm collimator
- fiber-fed
- R2 echelle grating, 79 grooves/mm
- spectral resolution R=11000
- useful spectral range: 24 orders covering 4100-7600 Å
- Canon f/1.8 lens: chromatic aberration
- 50 micron object fiber, 200 micron calibration fiber
- calibration lamps: ThAr, Tungsten, blue LED
- CCD detector: ATIK 460EX camera, ron = 5.1 e-, gain 0.26, 2749 x 2199 pixels, 4.54 um pixel
- f/6 FIGU, WATEC 120n guiding camera



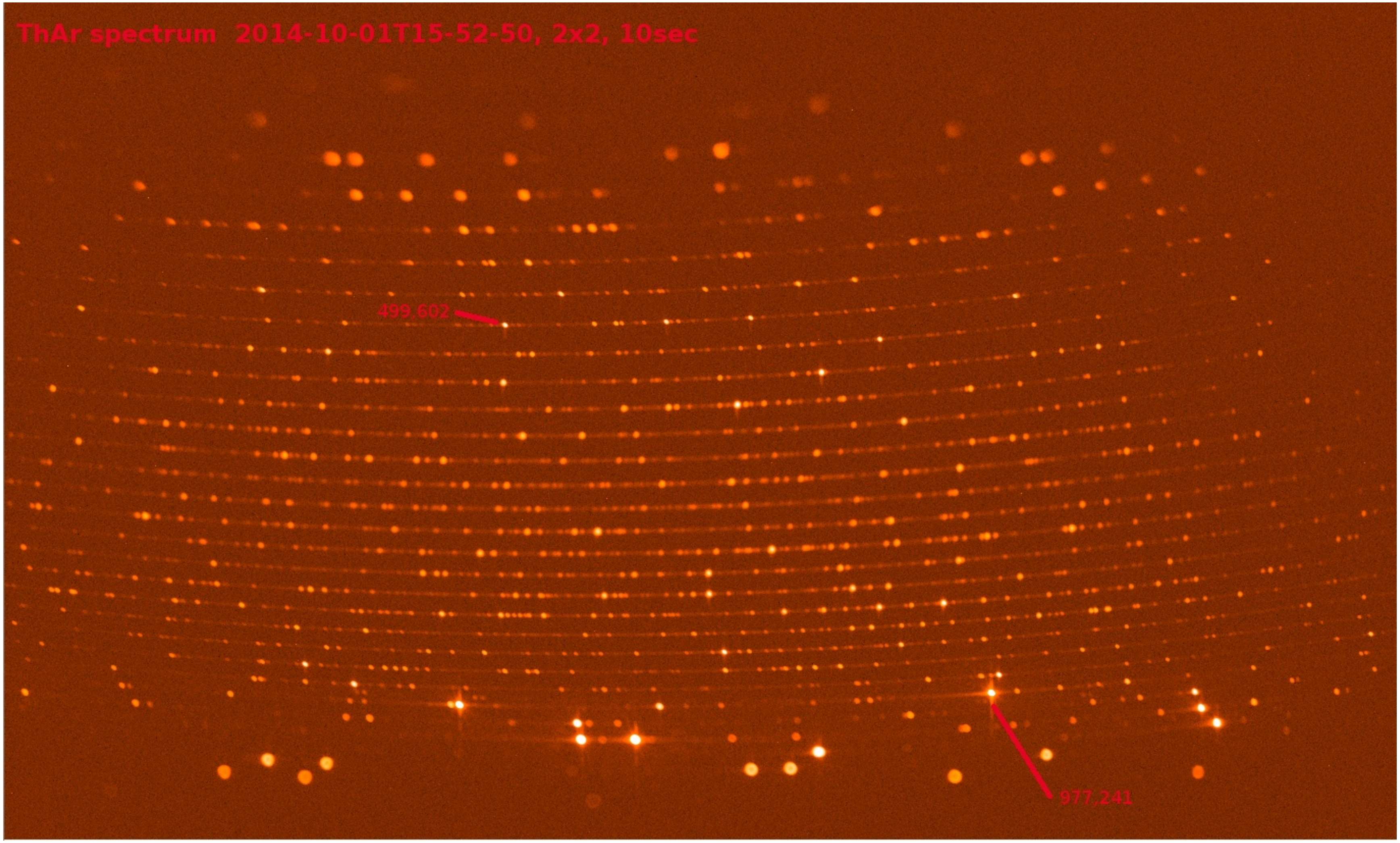


EShel and FIGU optical layout

Echelle orders layout



ThAr spectrum

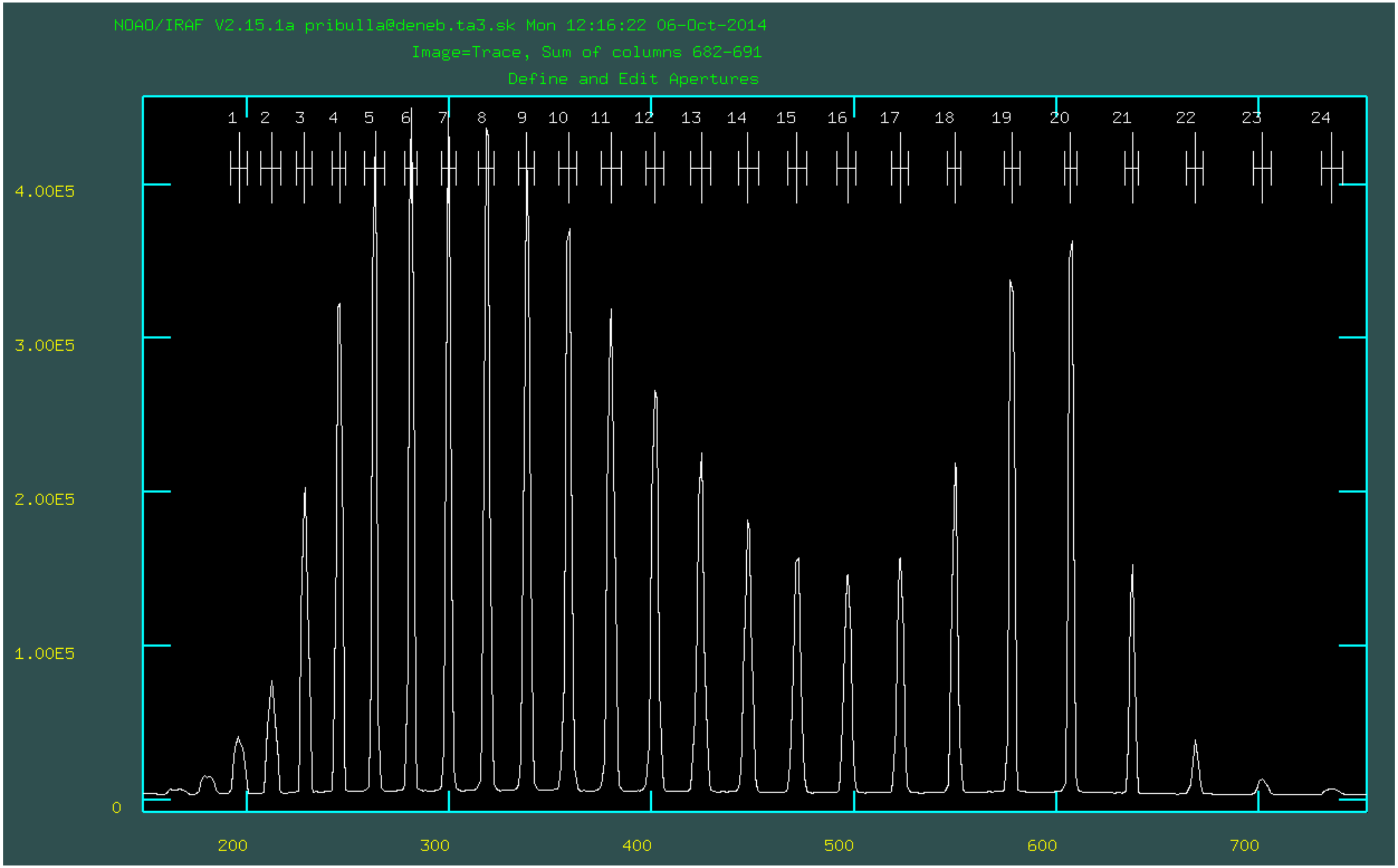


Reduction basics with IRAF

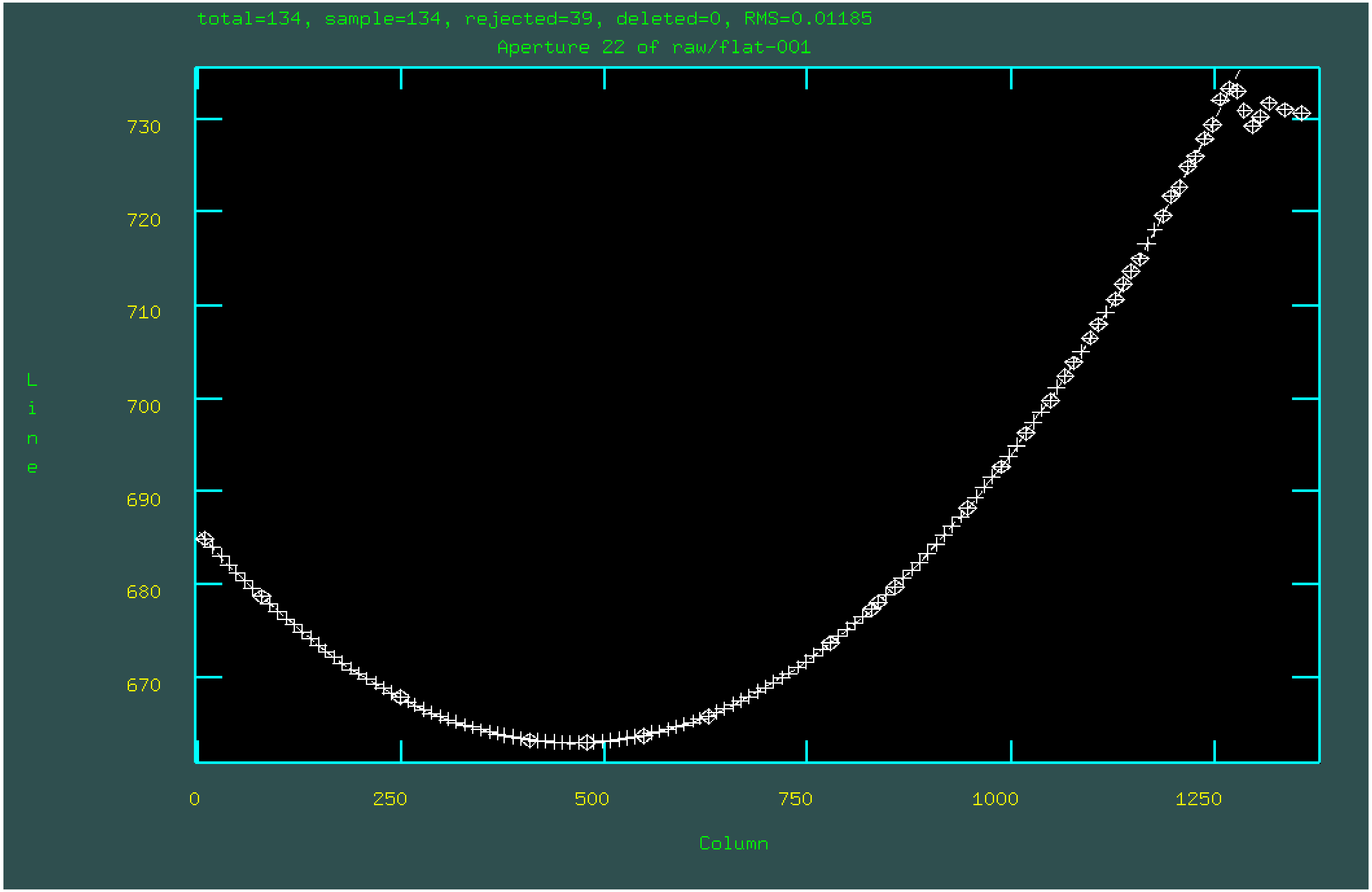
Reduction steps

- overscan, dark, flatfield correction
- combining multiple exposure spectra (faint objects), ccr cleaning
- cosmic hit cleaning (W. Pych code)
- tracing and extracting echelle orders with background fit -> 2D spectra
- ThAr re-identification, reference selection and weighting
- reference spectra and wavelength solution of 2D spectra
- SNR 2D spectra
- continuum normalization of 2D spectra
- order combining to 1D spectra
- spectrophotometry of 1D spectra

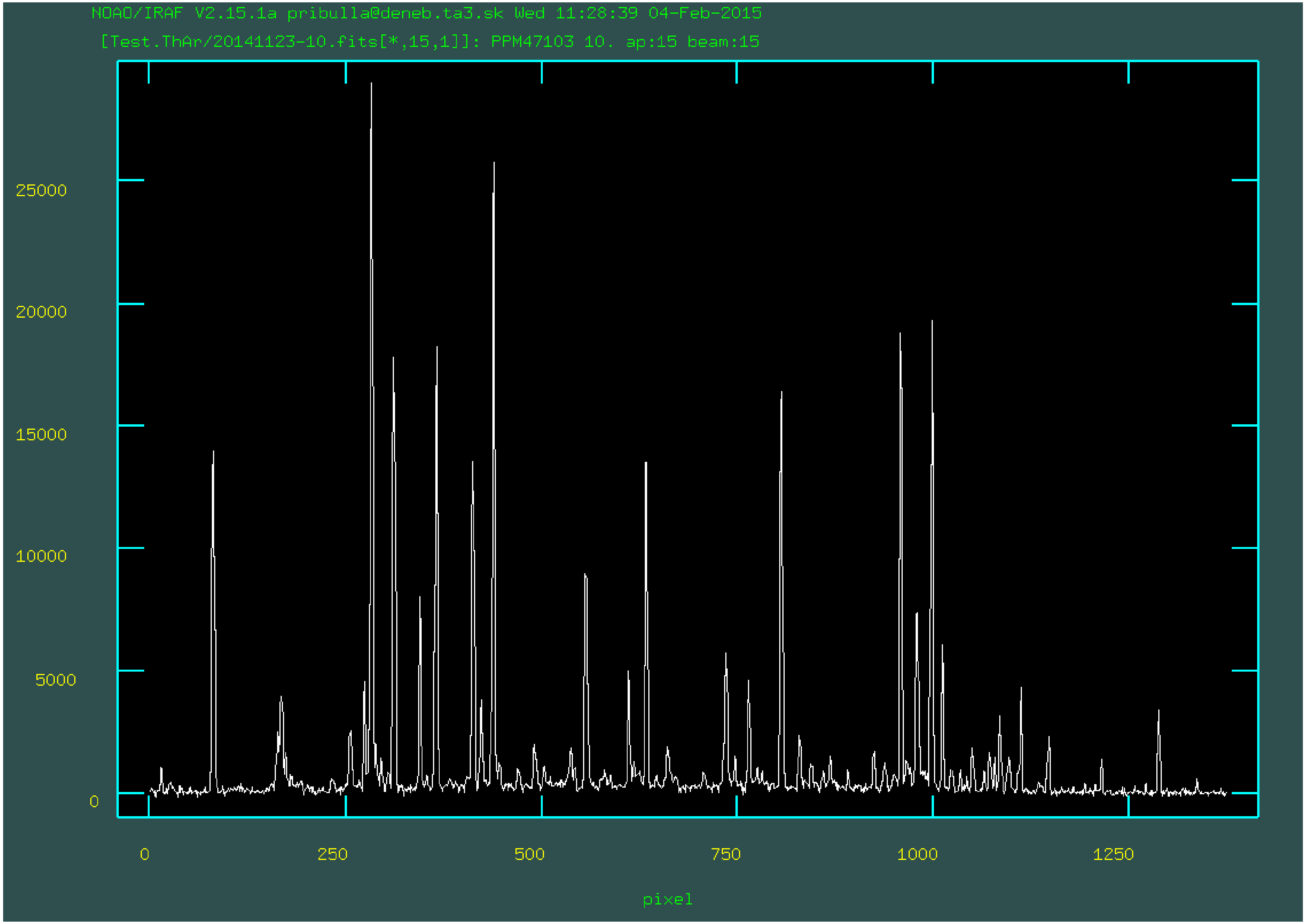
Marking apertures (=interference order) & defining background



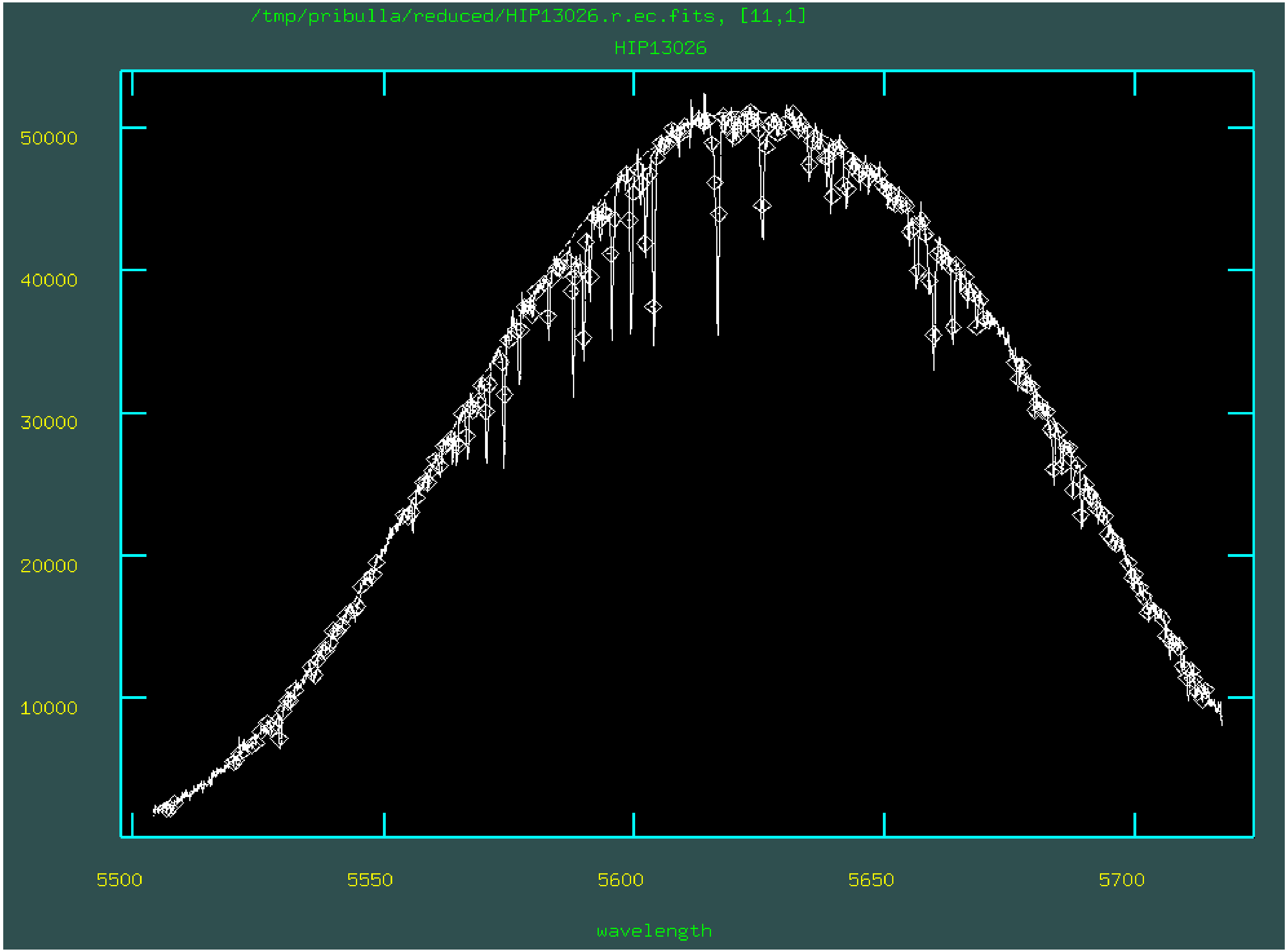
Tracing aperture shape



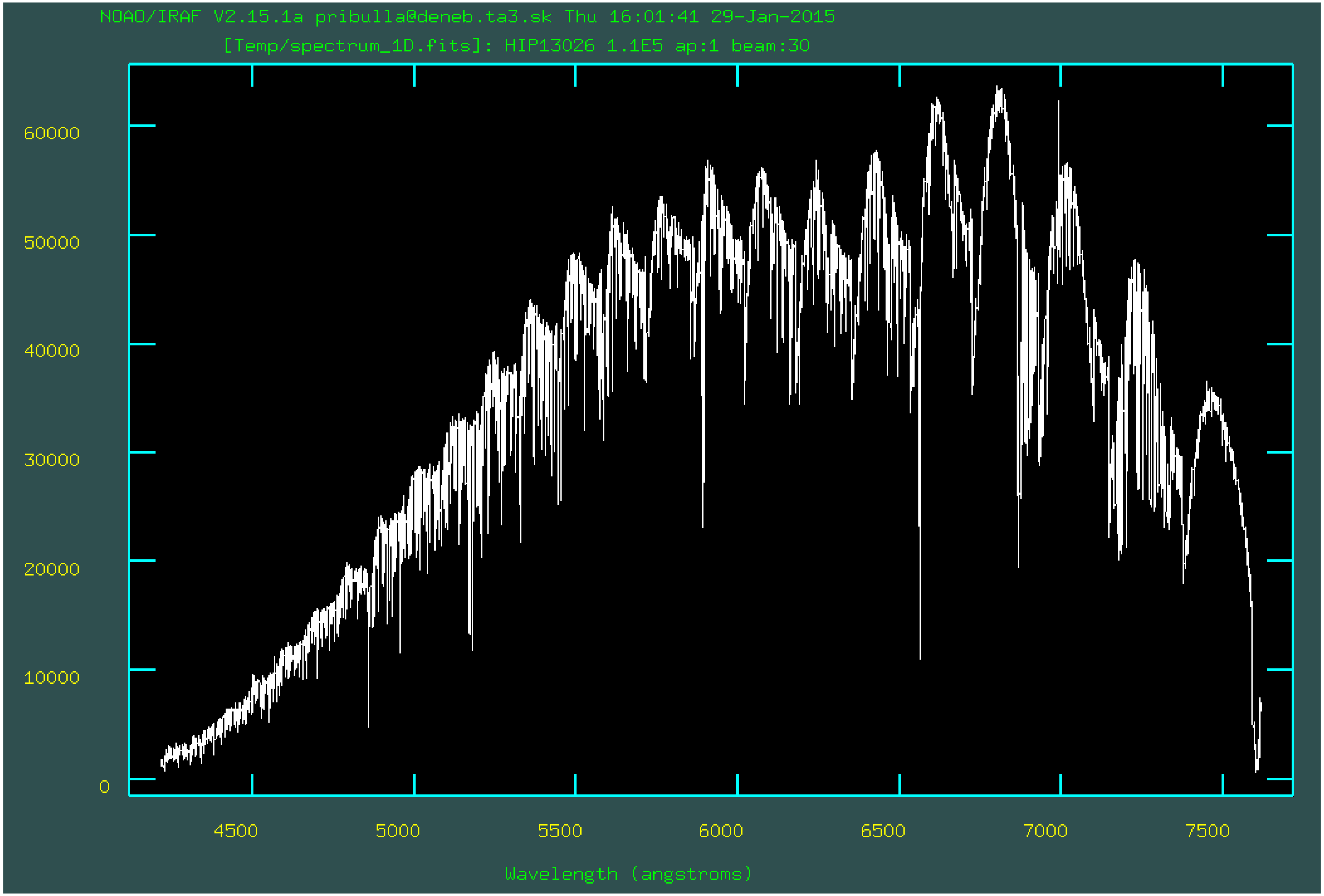
ThAr identification and wavelength solution



Aperture extraction and continuum normalization

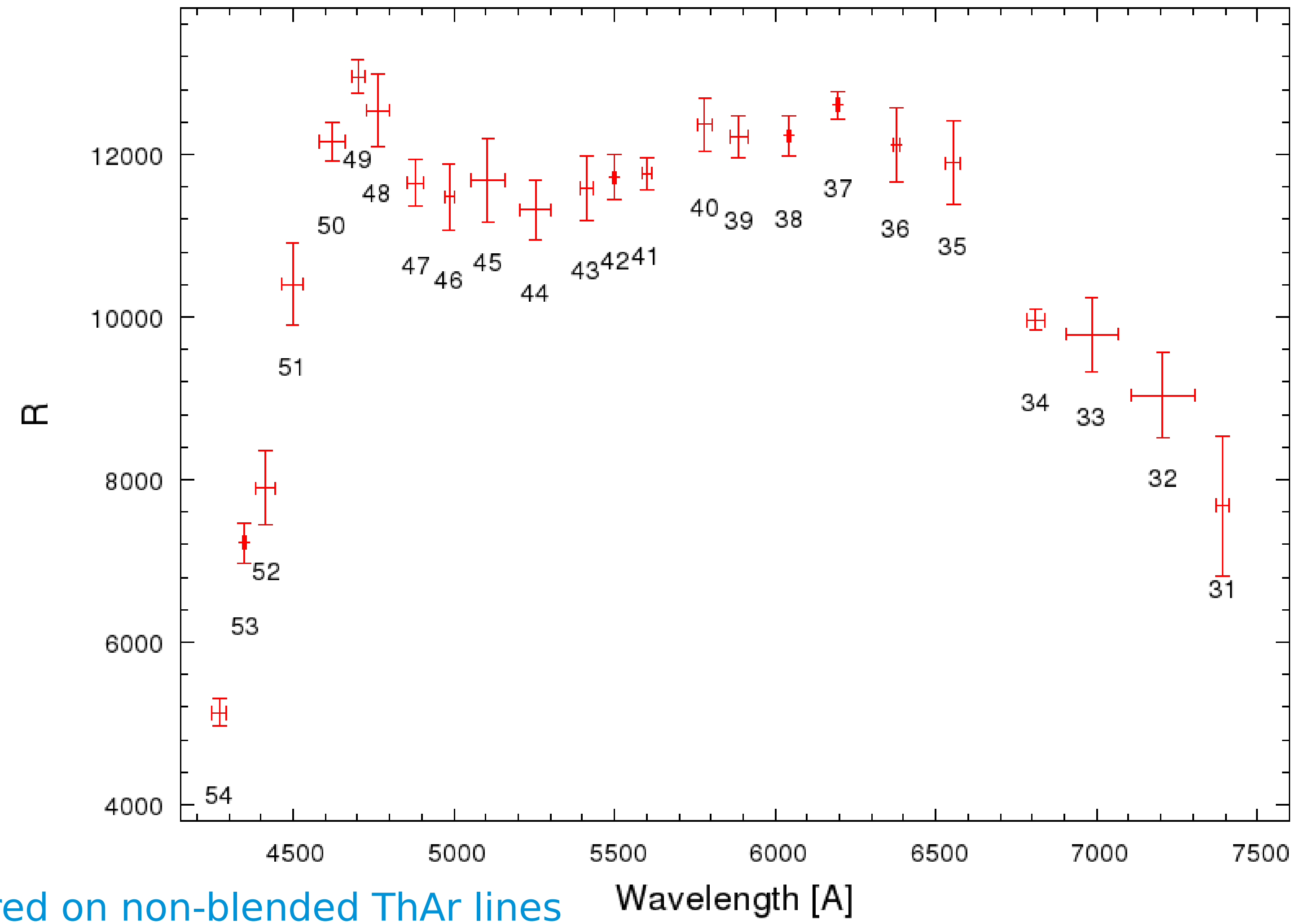


Combining spectral orders: from 2D to 1D spectra



First results with eShel @G1

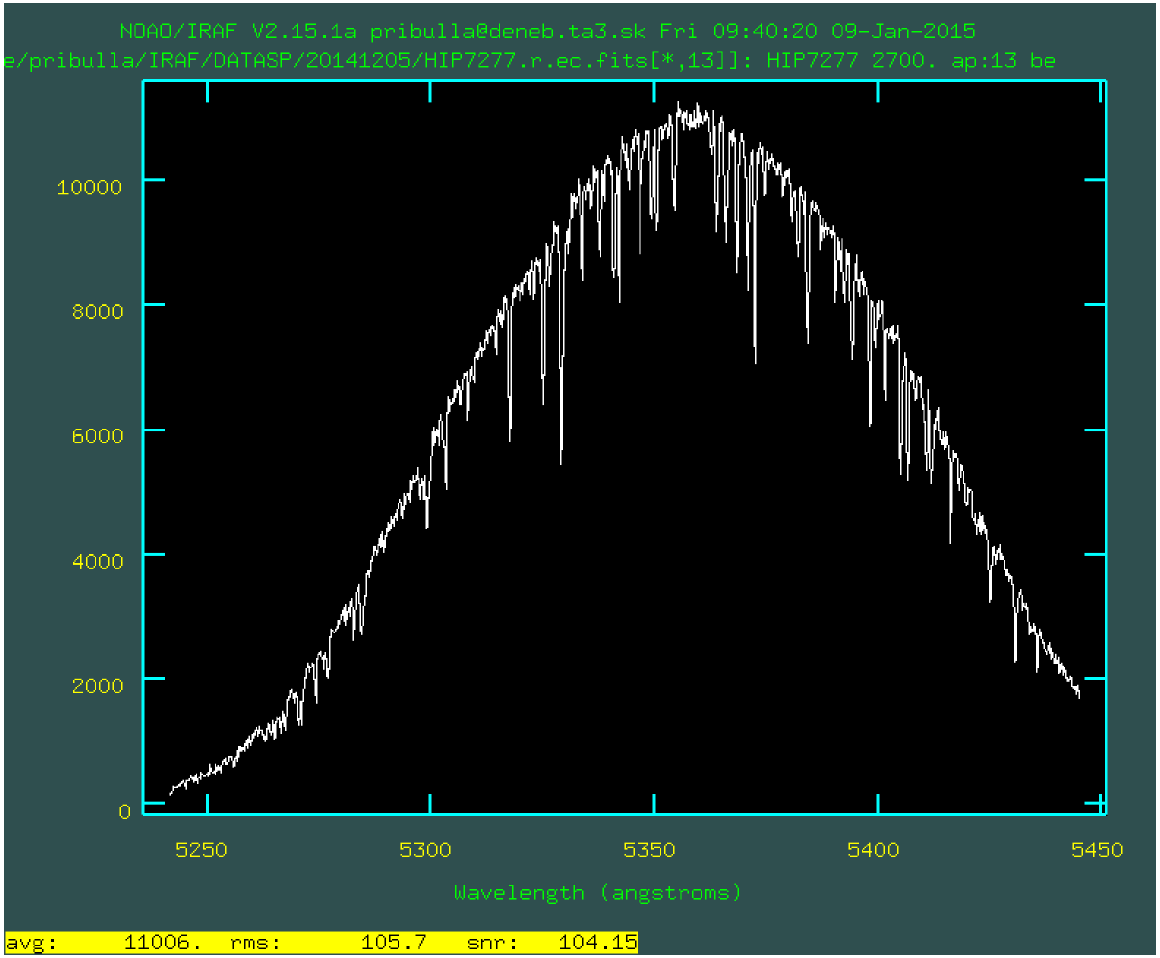
Resolving power



- Measured on non-blended ThAr lines
- Depends on focusing the Canon lens
- R> 10000 for 4600 Å < λ < 6700 Å

S/N ratio @ 60cm of G1

- brightness and SED of the object
- Exposure time
- telescope diameter
- telescope and spectrograph throughput
- CCD QE
- spectral resolution
- seeing and angular diameter of fiber
- atmospheric extinction (airmass)

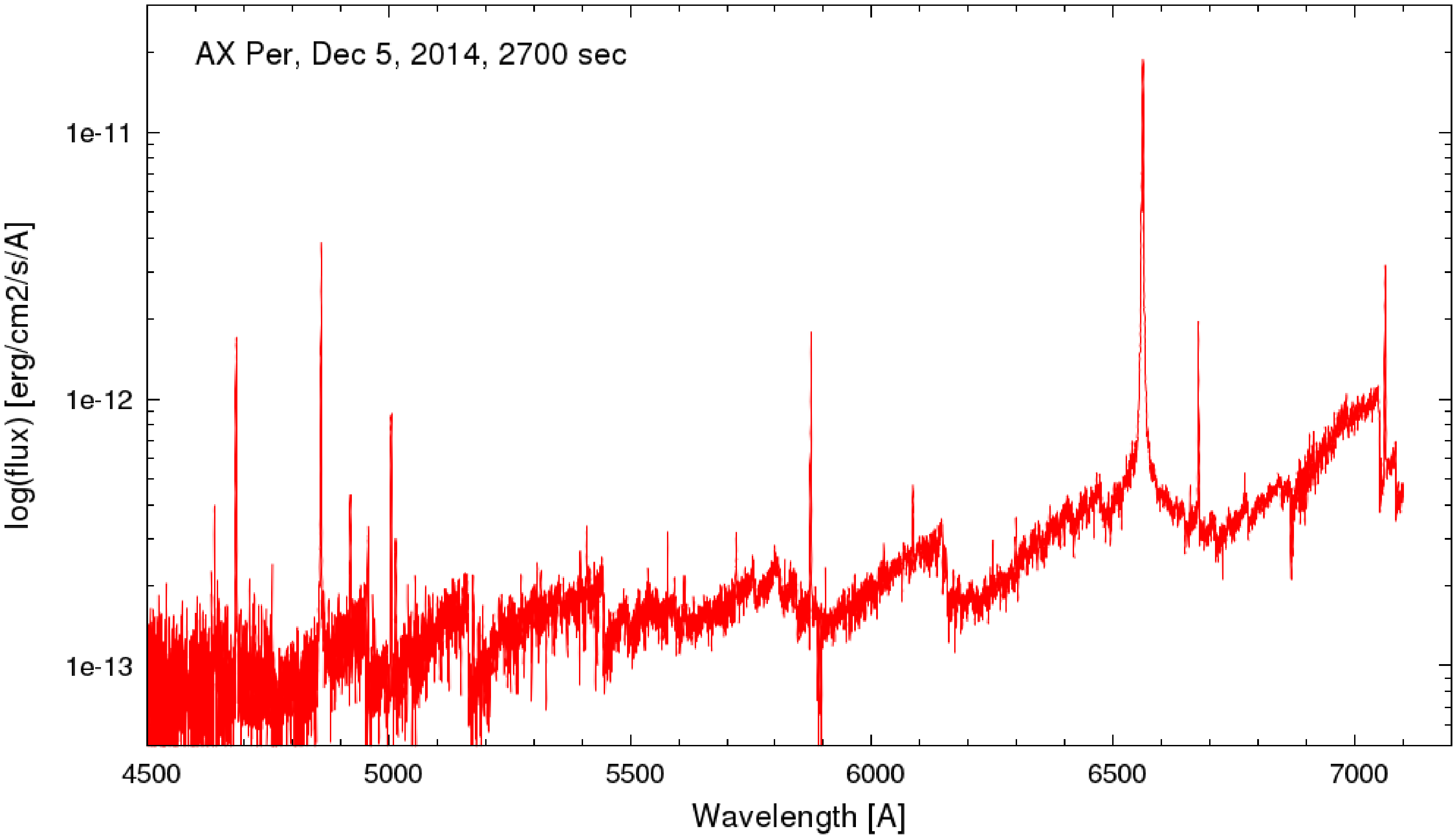


HIP7277: B =8.48, V=7.96, F8 spectral type, 900 sec exposure on December 5, 2014: S/N=60 (6600 Å), S/N=47 (5200 Å) and S/N = 20 (4500 Å)

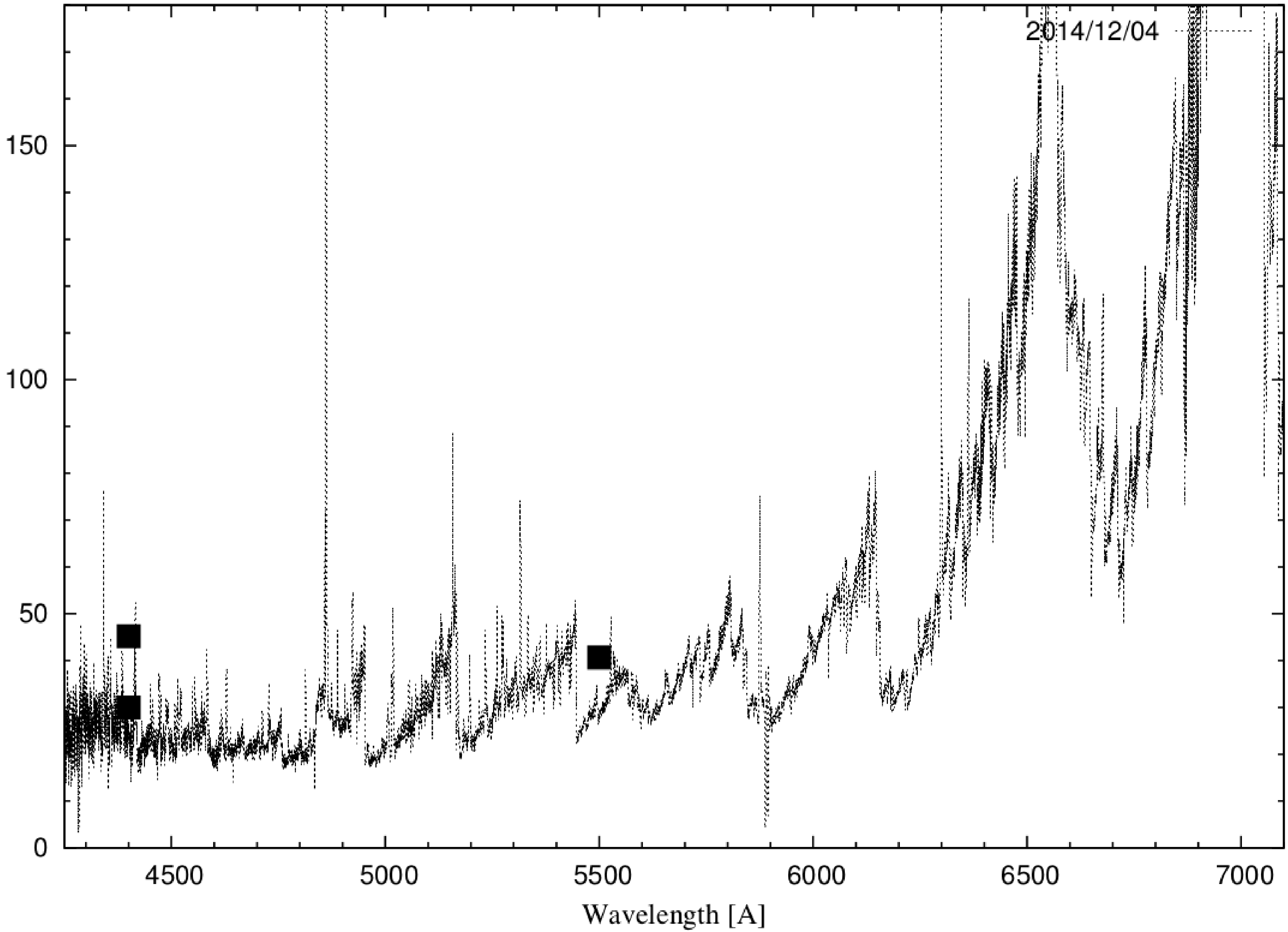
TYC 1877-1060-1: B =10.04, V=9.75, B5 spectral type, 3x900 sec exposure on December 4, 2014: S/N=45 (6600 Å), S/N=45 (5200 Å) and S/N = 21 (4500 Å)

Spectrophotometric calibration

- Calibration to fluxes, e.g. erg/s/m^2/Å
- Complicated by (i) fiber opening/slit loses, (ii) chromatic atm. refraction (for low X), (iii) atmospheric extinction, k = k(λ) (iv) blaze function (v) order overlap
- Multi-colour photometry improves the fluxes

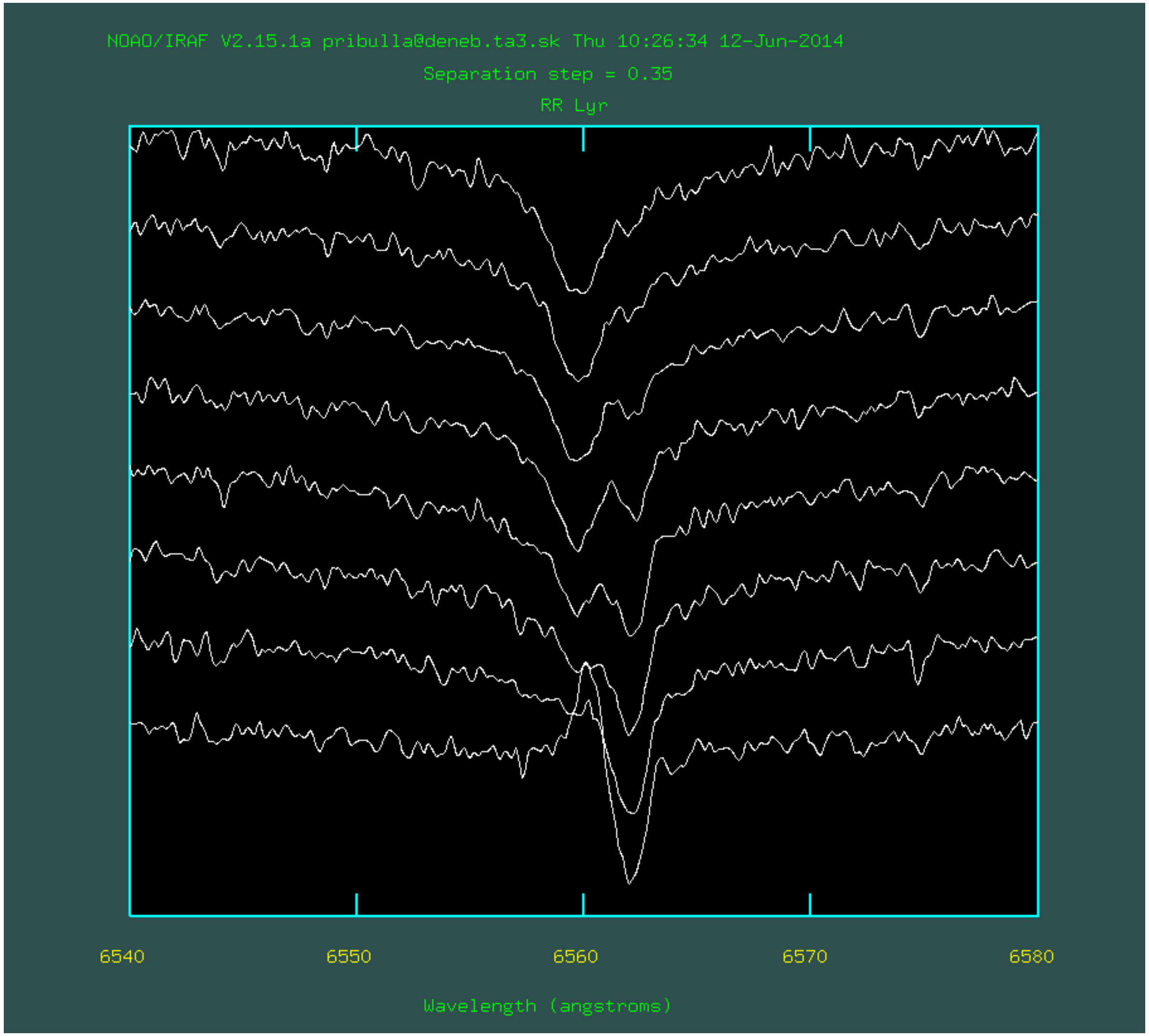


Spectrophotometric calibration vs. VR



Pulsating stars

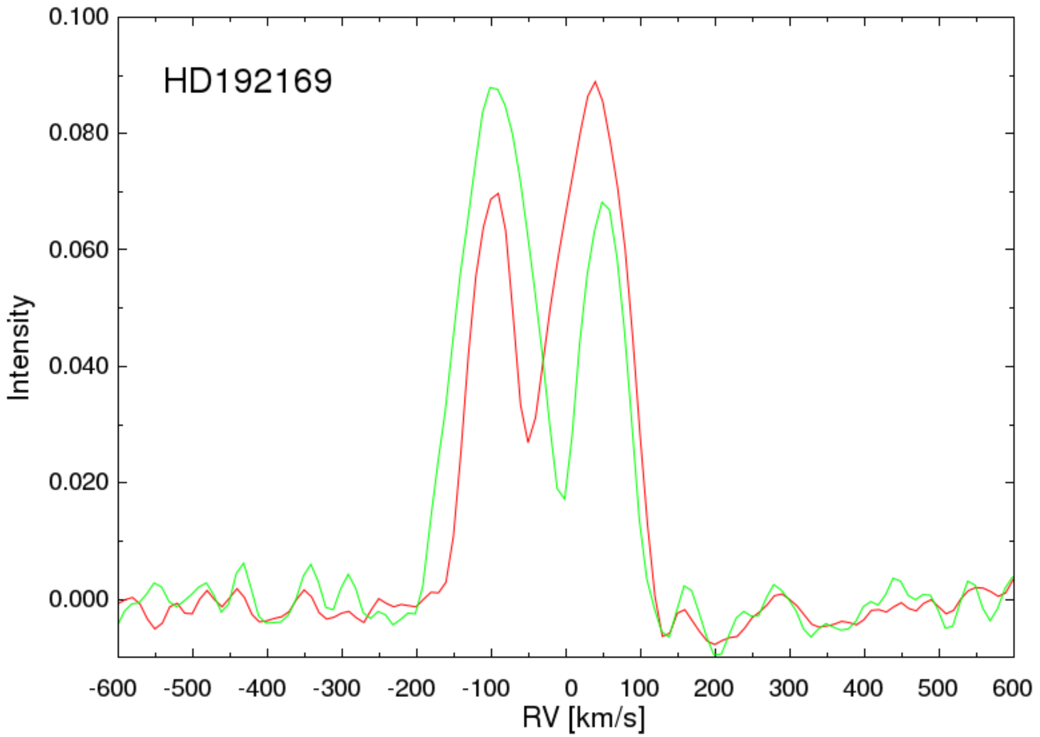
- Test observations of: RR Lyr (V=7.06, sp. type A8-F7)
- Possibly non-radial pulsations of δ Sct star if v sin i large

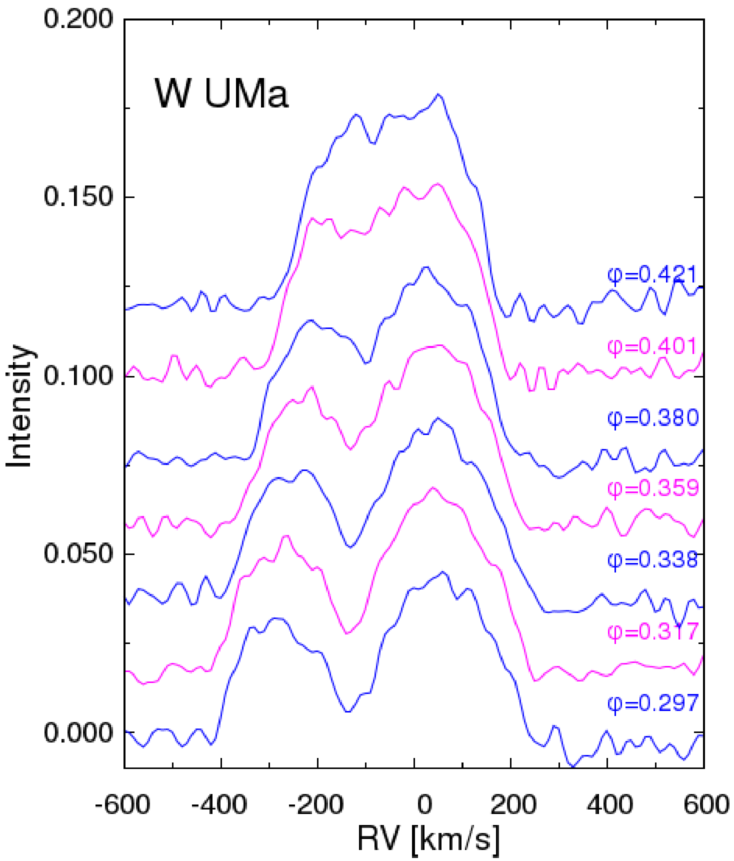


RR Lyr 8x900 sec sequence, Hα, June 12, 2014

Binary stars

- Test observations of: W UMa (contact EB, V=7.75), HD192169 (newly-discovered detached EB, V=9.03, F8V), V501 Aur (T Tau, non-eclipsing, V=10.88, K0), PPM47103 (newly-discovered detached EB, V=9.75, B5)
- W UMa, HD192169 and V501 Aur analyzed by the BF technique, spectrum of HD128167 (V=4.47, F4V, *v* sin *i* = 7.3 km/s) as the template, BFs extracted from 4900 - 5985 A range with 10 km/s step



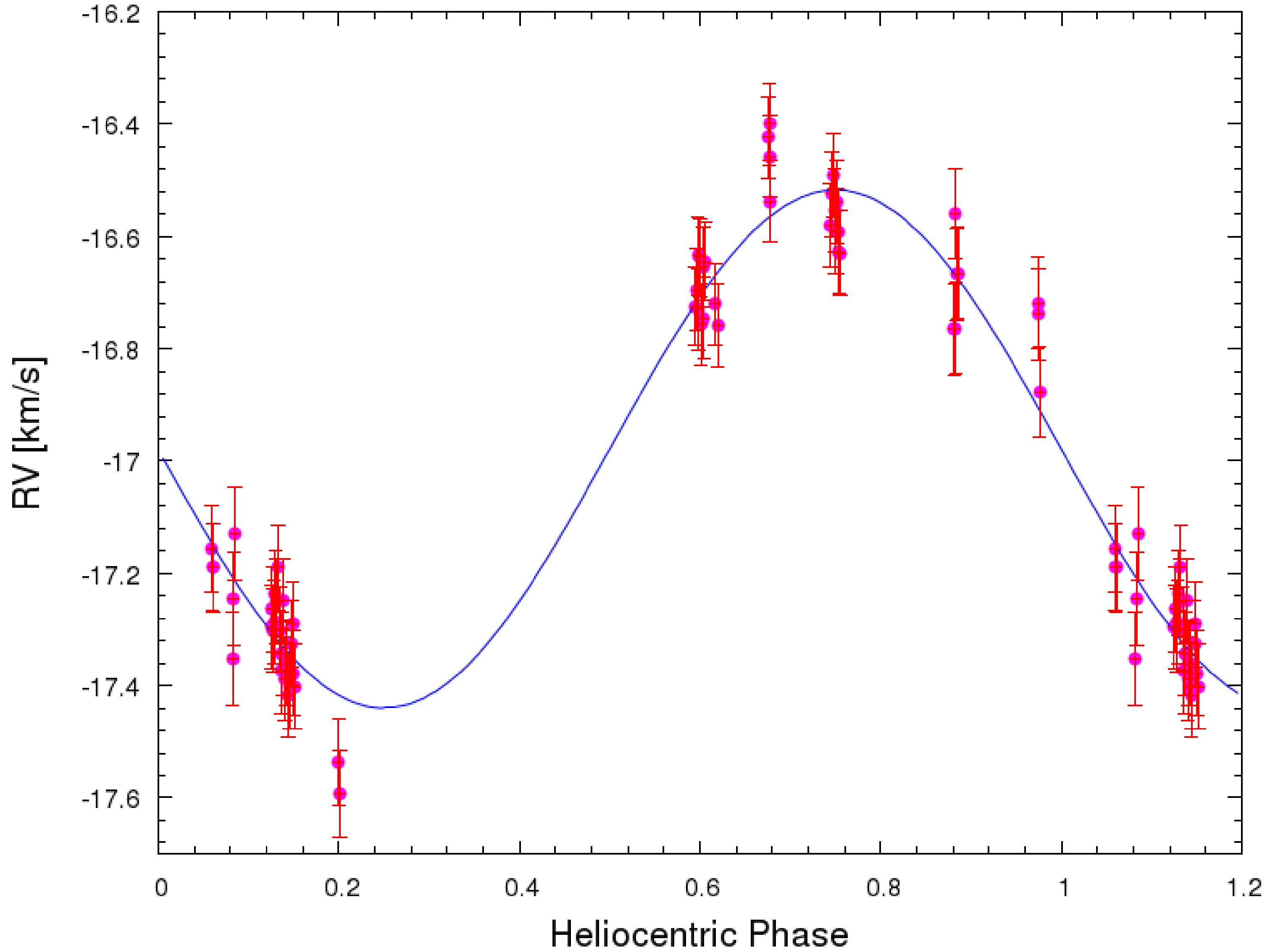


Exoplanets

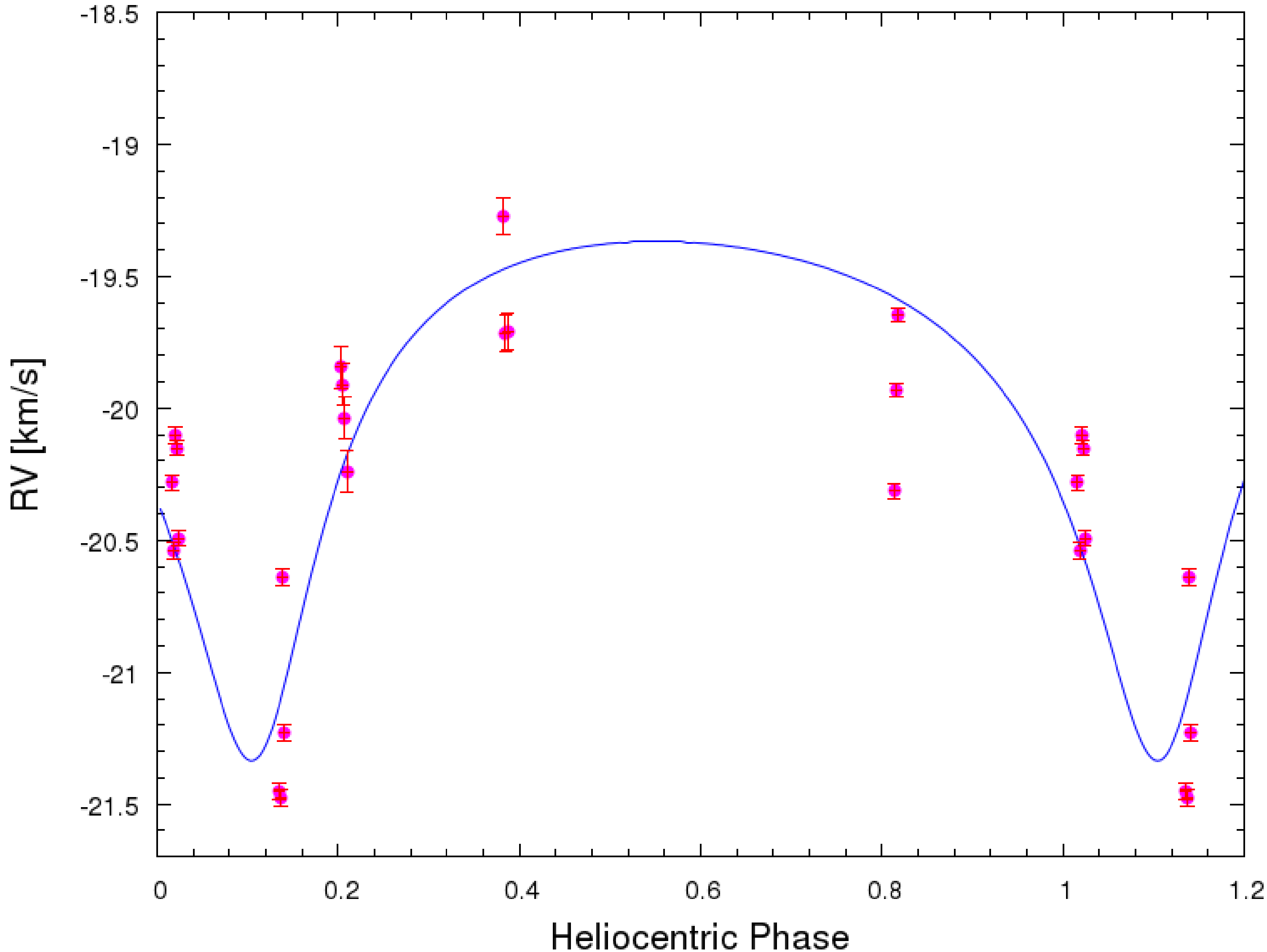
- RV precision depends on (i) signal-to-noise ratio SNR (ii) projected rotational velocity v sin i, (iii) spectral resolution R, (iv) wavelength coverage B, (v) line density f as (Hatzes, 2010):

$$\sigma = \text{const}\,\frac{v \sin i}{R^{3/2} B^{1/2} f^{1/2} SNR}$$

- Test observations transiting system HAT-P-2 (V=8.69, sp. type F8V, K = 984 m/s, P = 5.633 days), non-transiting system τ Boo   (V=4.49, sp. type F6IV+M2, K = 461 m/s, P = 3.312 days)
- Instrumental effects: (i) frequency of ThAr spectra (ii) number of ThAr lines for wavelength calibration (iii) variations in temperature and pressure (iv) instability of ThAr line ratios
- Telluric features: RV precision improvement



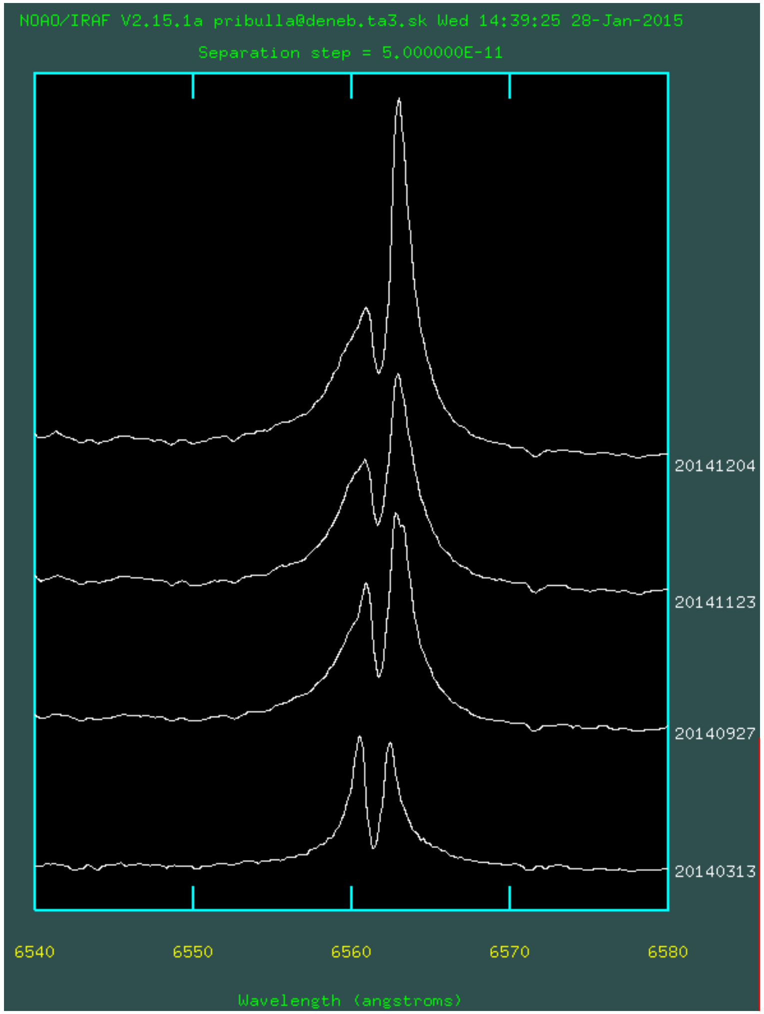
RV variability of τ Boo (Gaussian fit to BFs), data from 10 nights, March 13 to June 6, 2014, rms = 78 m/s, K = 461.1 m/s, P=3.312 days



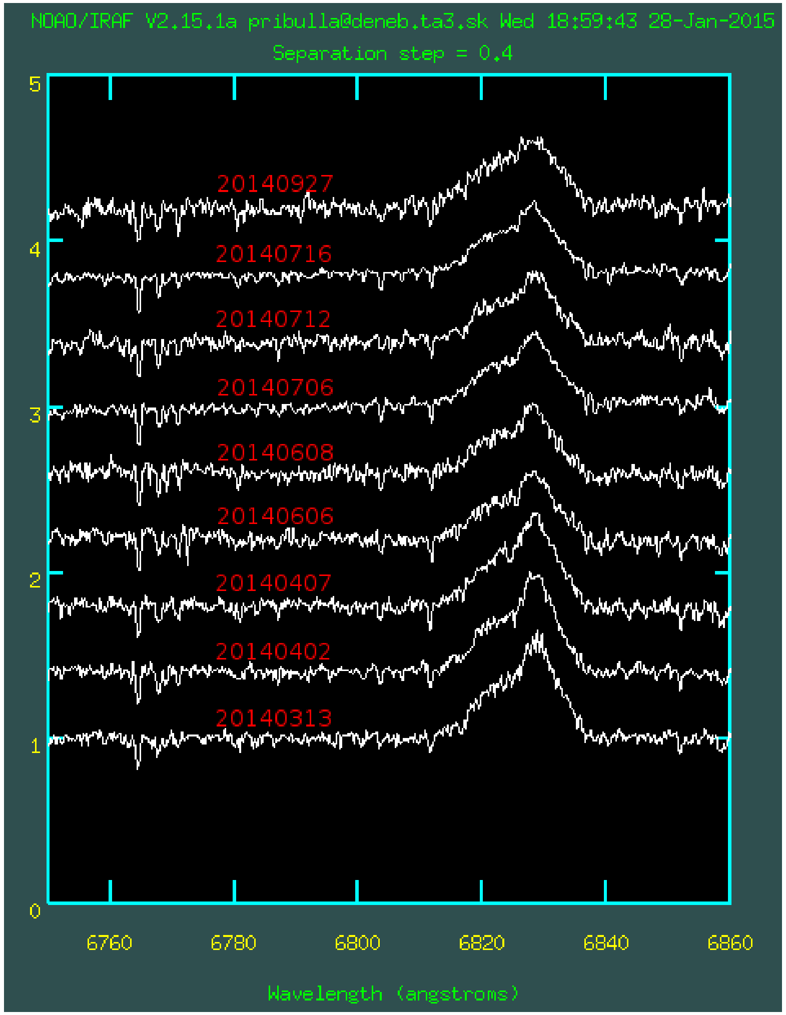
RV variability of HAT-P-2 (Gaussian fit to BFs), data from 5 nights, March 14 to July 3, 2014, rms = 326 m/s, K = 983.9 m/s, P=5.633 days

Symbiotic stars & novae

- Easy to record emission lines but risk of saturation in Hα, spectrophotometry

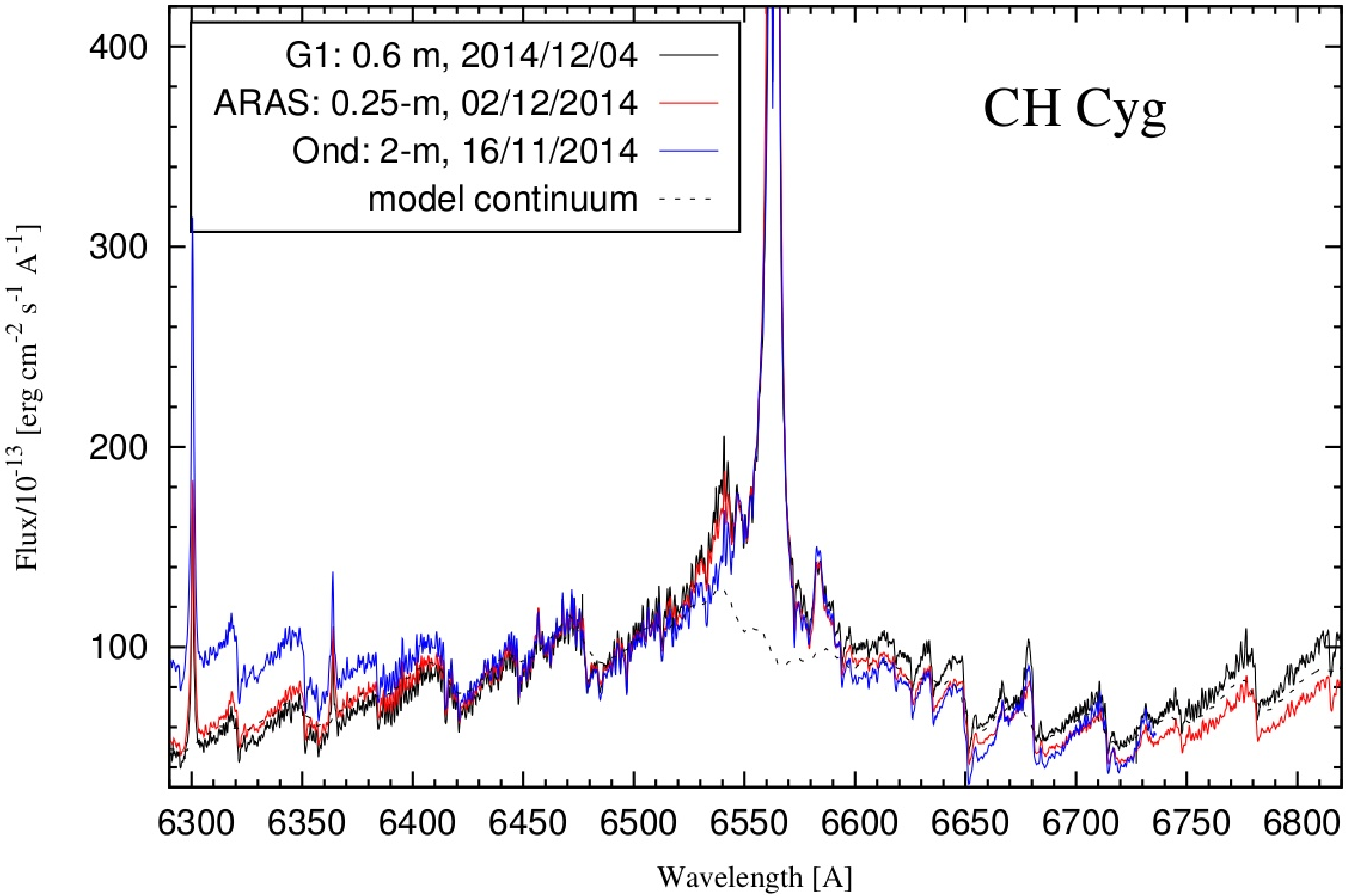


CH Cyg, Hα



AG Dra, Raman-scattered line, 6826 Å

CH Cyg



G1: 0.6 m, 2014/12/04
ARAS: 0.25-m, 02/12/2014
Ond: 2-m, 16/11/2014
model continuum
CH Cyg
400
300
200
100
Flux/10^{-13} [erg cm^{-2} s^{-1} A^{-1}]
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
Wavelength [A]

Objects to observe with eShel @60cm telescope

- Novae in the "fireball" stage, up to V=10
- Symbiotic stars, emission lines can be well recorded even for V=12 objects
- Eclipsing binaries: limited to bright and long-period orbital systems, minimum phase resolution is 2%
- Exoplanet host stars with RV amplitudes > 200-300 m/s - needs better thermal stability
- Whatever brighter than V=10.5 mag

Observation planning basics & standards

- Faint objects: multiple exposures
- Exposure time ≤900 sec (cosmic hits accumulation)
- Precise RVs ==> frequent ThAr, sufficient intensity of ThAr
- Flatfields (tungsten + LED) necessary to define orders
- Perfect guiding
- seeing depends on X ==> observe close to meridian

Standards stars

- Telluric templates: correction of telluric features (mostly H_2O, O_2) red of Na I D doublet: bright, early-type, rapid rotators, close to the object
- IAU RV standards: checking the zero point of the RV system: bright, single stars, slow rotators
- Spectrophotometric standards: to determine fluxes: bright stars, few lines (e.g., DA stars, early-type stars)

Thanks for your attention !