Instrumentation development at AI SAS: towards exoplanet observations

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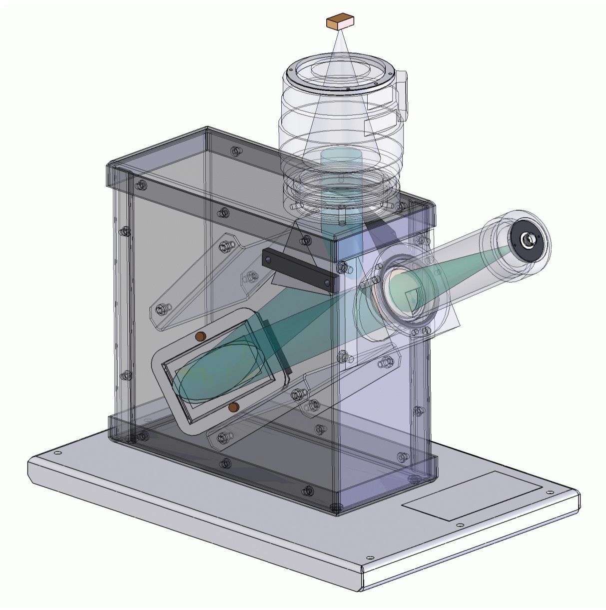
Stará Lesná observatory

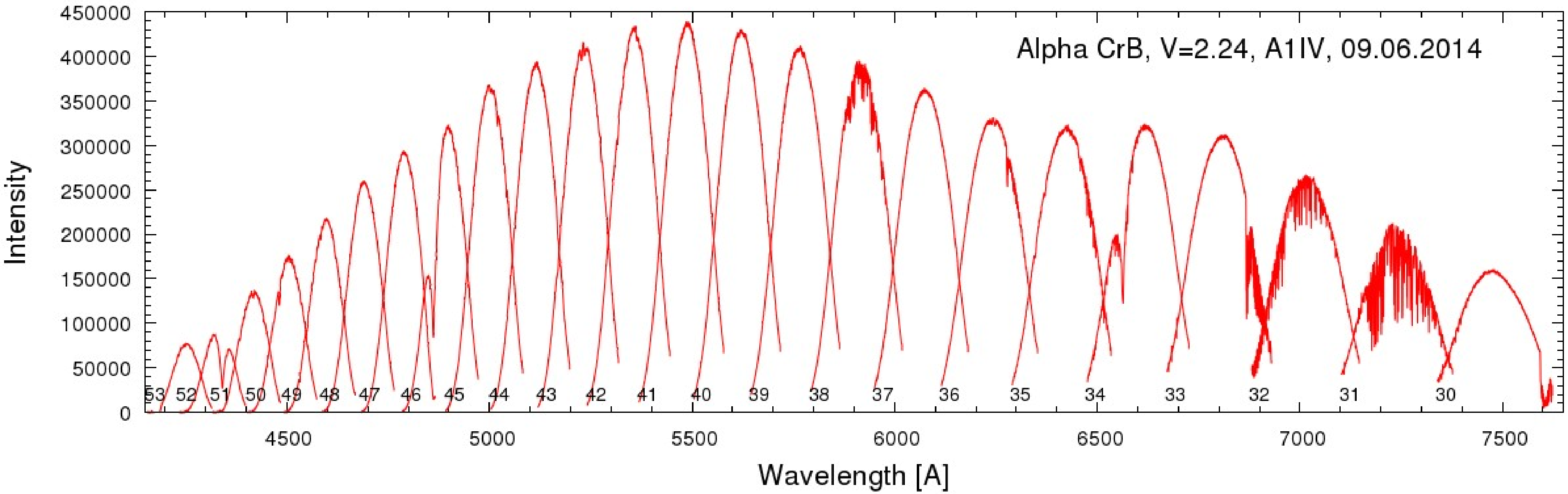
2x 60cm (f/12.5) Zeiss telescopes

- G1: low-cost fiber-fed échelle (Shelyak)
- G2: back-illuminated CCD (FLI): G2

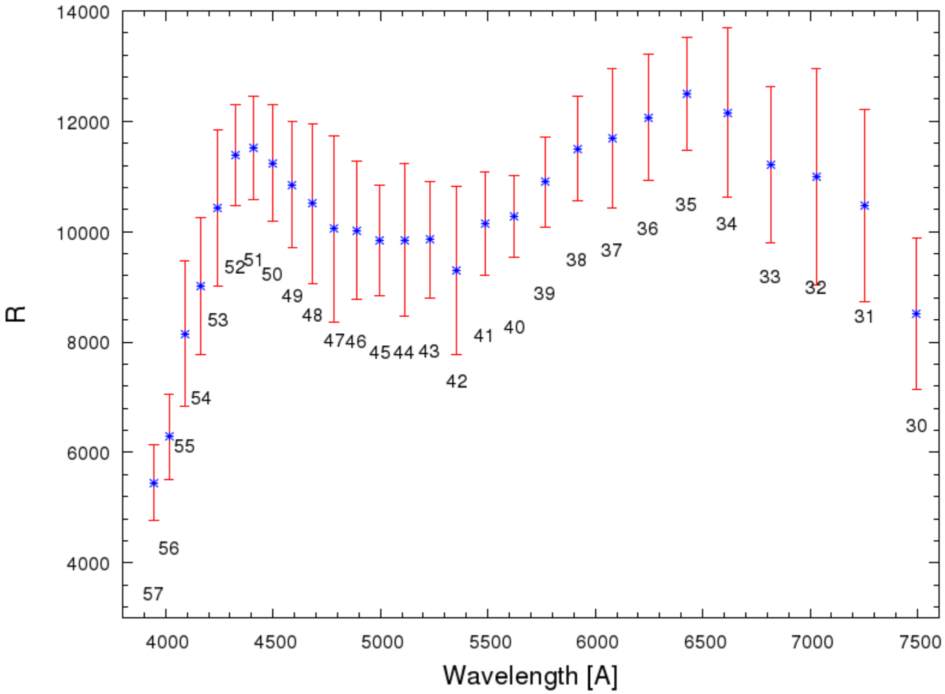
Fiber-fed eShel @ 60cm



- Littrow design with f/5, prism cross-disperser, 125mm collimator
- useful spectral range: 28 orders covering 3920-7100 Å
- 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

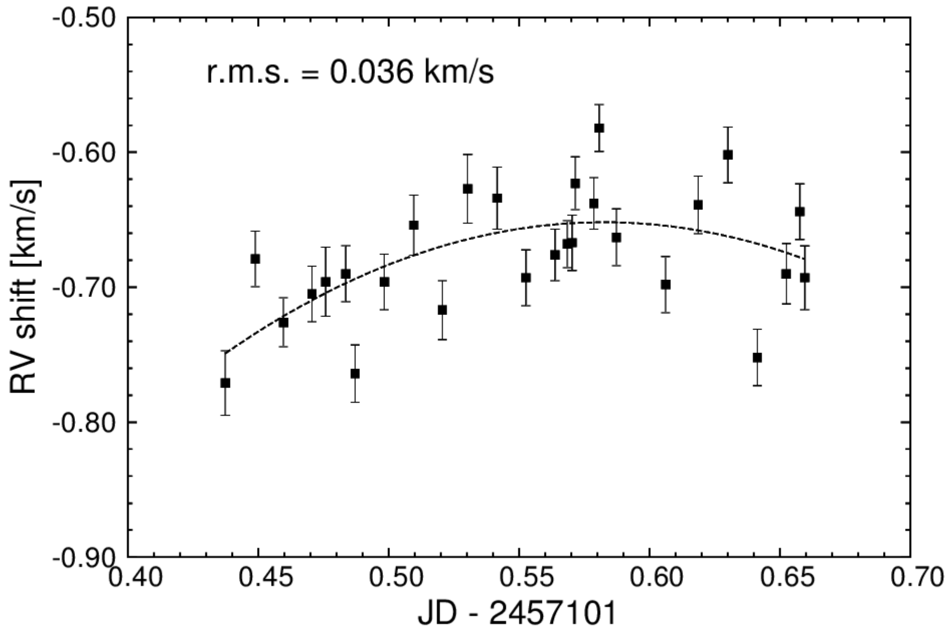


Performance



Resolution measured on non-blended ThAr lines, depends on focusing the Canon lens

R> 10000 for 4300 Å < λ < 7200 Å, from July 2018 (with UV-optimized collimator)



ThAr solution zero-point shifts over one night - limit on the RV accuracy

Magnitude limit: for V=11 star S/N = 15 at 5500 Å for 900-sec exposure

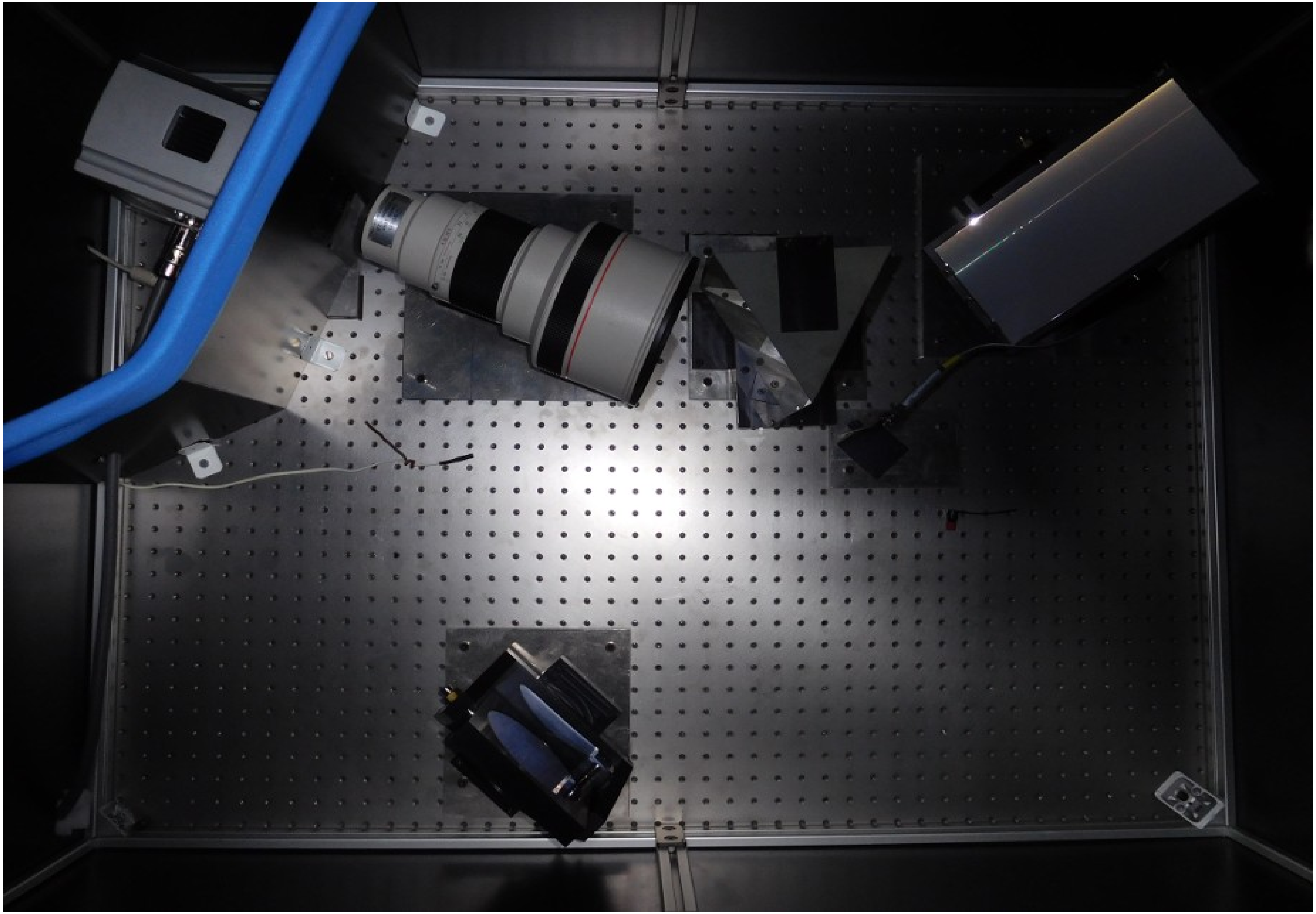
Skalnaté Pleso observatory

1.3m telescope at SP

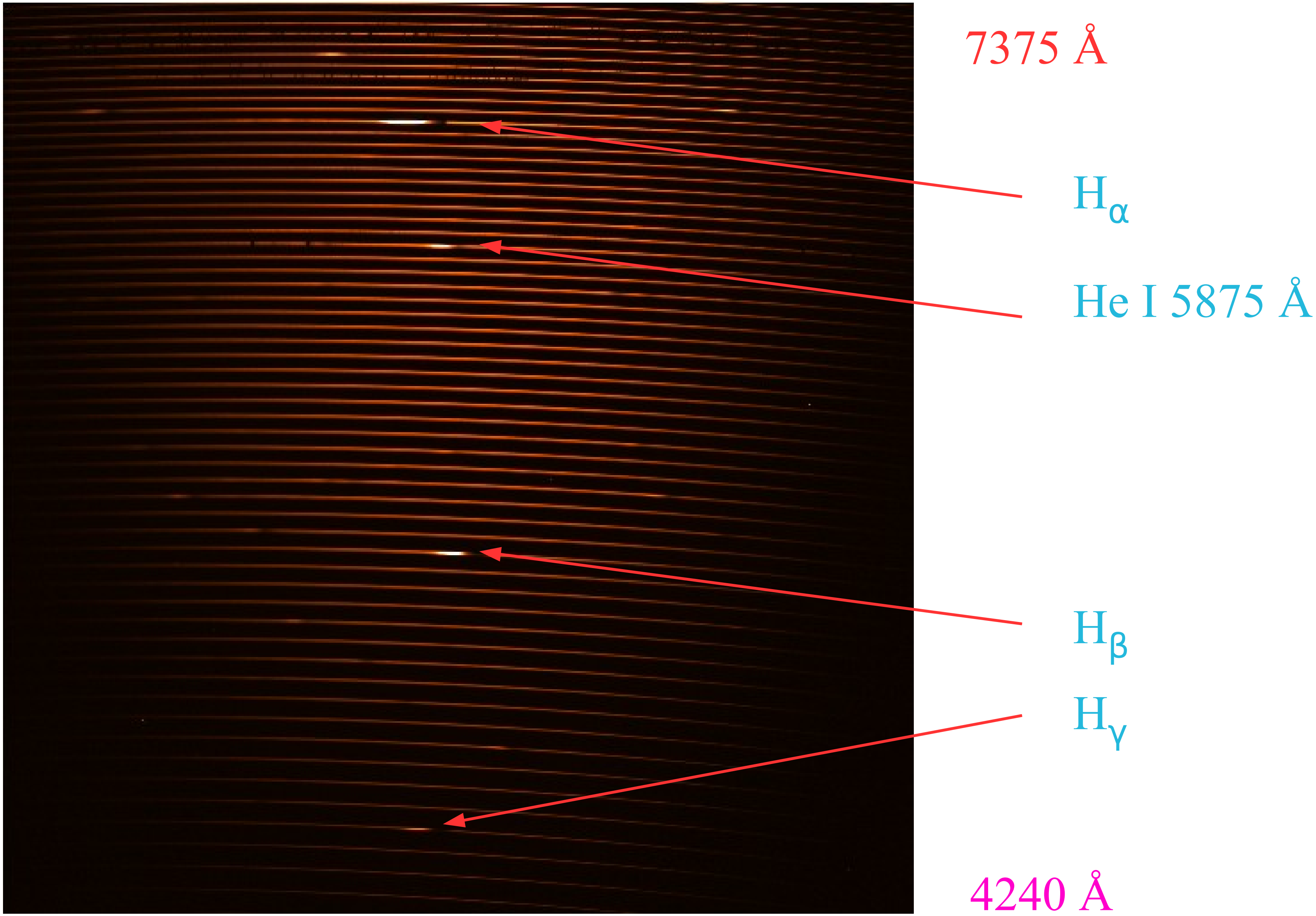
- Astelco systems (2014)
- f/8 alt-az Nasmyth-Cassegrain with thin primary mirror
- active optics control: 9 actuators with a Shack-Hartmann unit
- fast telescope slewing, near-Earth objects, 20 deg/sec, 2 deg/sec/sec
- pointing accuracy ±3 arcsec with pointing model
- full remote control of telescope and dome ==> easy to make robotic
- 2 Nasmyth foci available...

MUSICOS @ 1.3m telescope

- MUSICOS = Multi-SIte COntinuous Spectroscopy
- fiber-fed and optical bench-mounted
- FIGU, fibers, calibration lamps from Shelyak, f/4, WATEC 120N
- grating: 31.6 lines/mm, R2 echelle, 128x254mm
- SF5 glass prism with 57° apex angle
- f/4 on-axis collimator
- Andor iKon DZ-936 (ron $2.9e^-$)
- water-assisted cooling to -100 C
- Canon FD 2.8/400L
- R=25000-40000 (FWHM)
- spectral range 4240-7350 Å



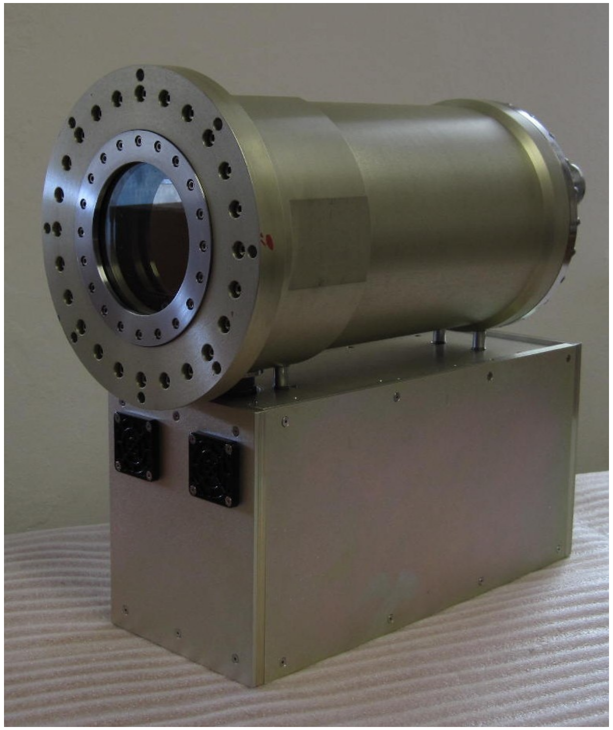
MUSICOS on the optical bench

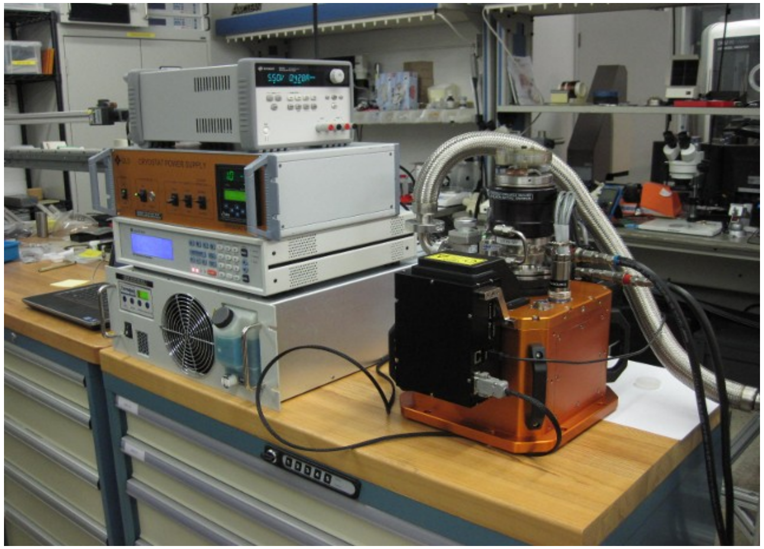


Format of echelle spectrum on the Andor 2k x 2k CCD (P Cygni, 90-sec exposure)

Large-frame CCD

- STA chip, 4kx4k, 15µm pixels (=6x6cm chip)
- fiber interface
- quadruple-mode readout
- Cryotiger cooler to -120 °C
- external shutter and filter wheel
- 20x20' FoV, 1 pixel = 0.28"



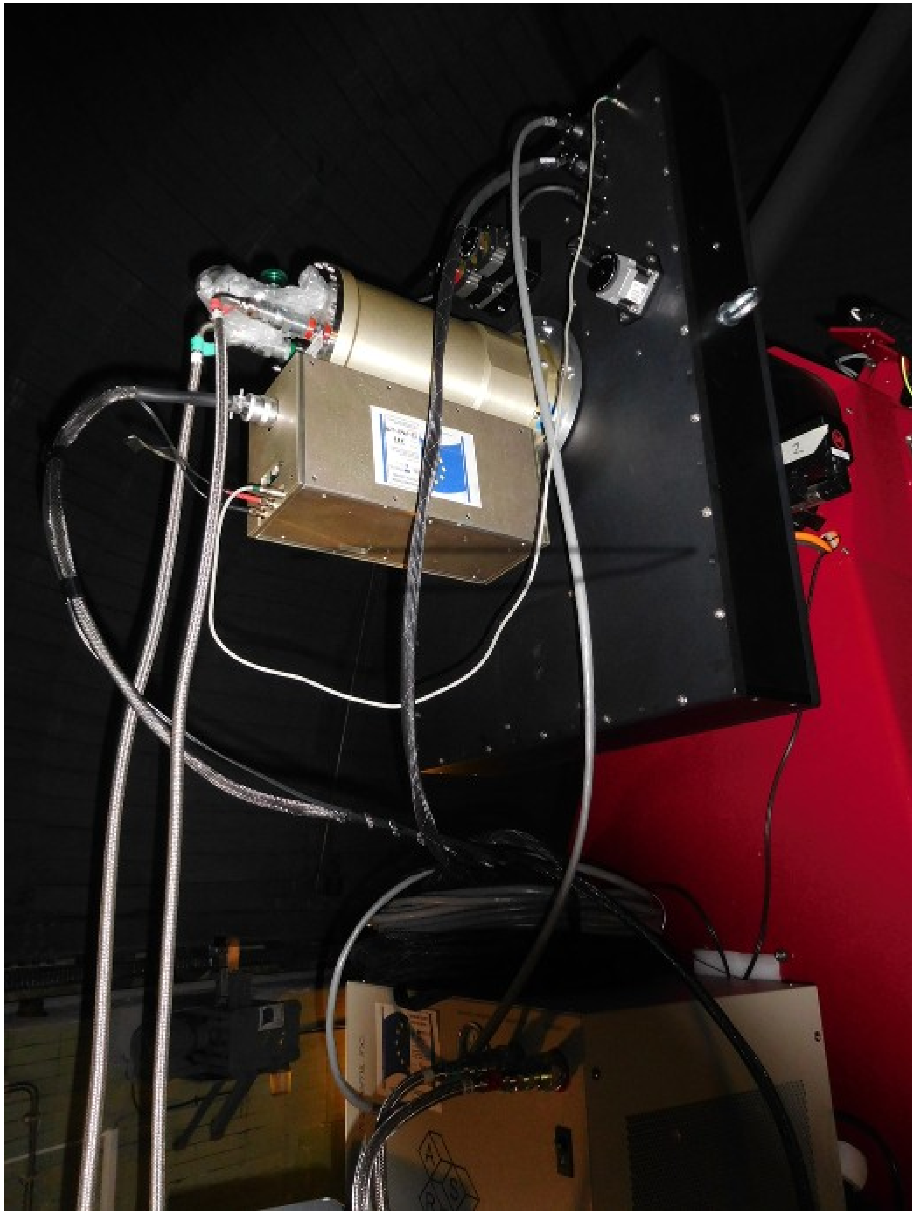


NIR CCD

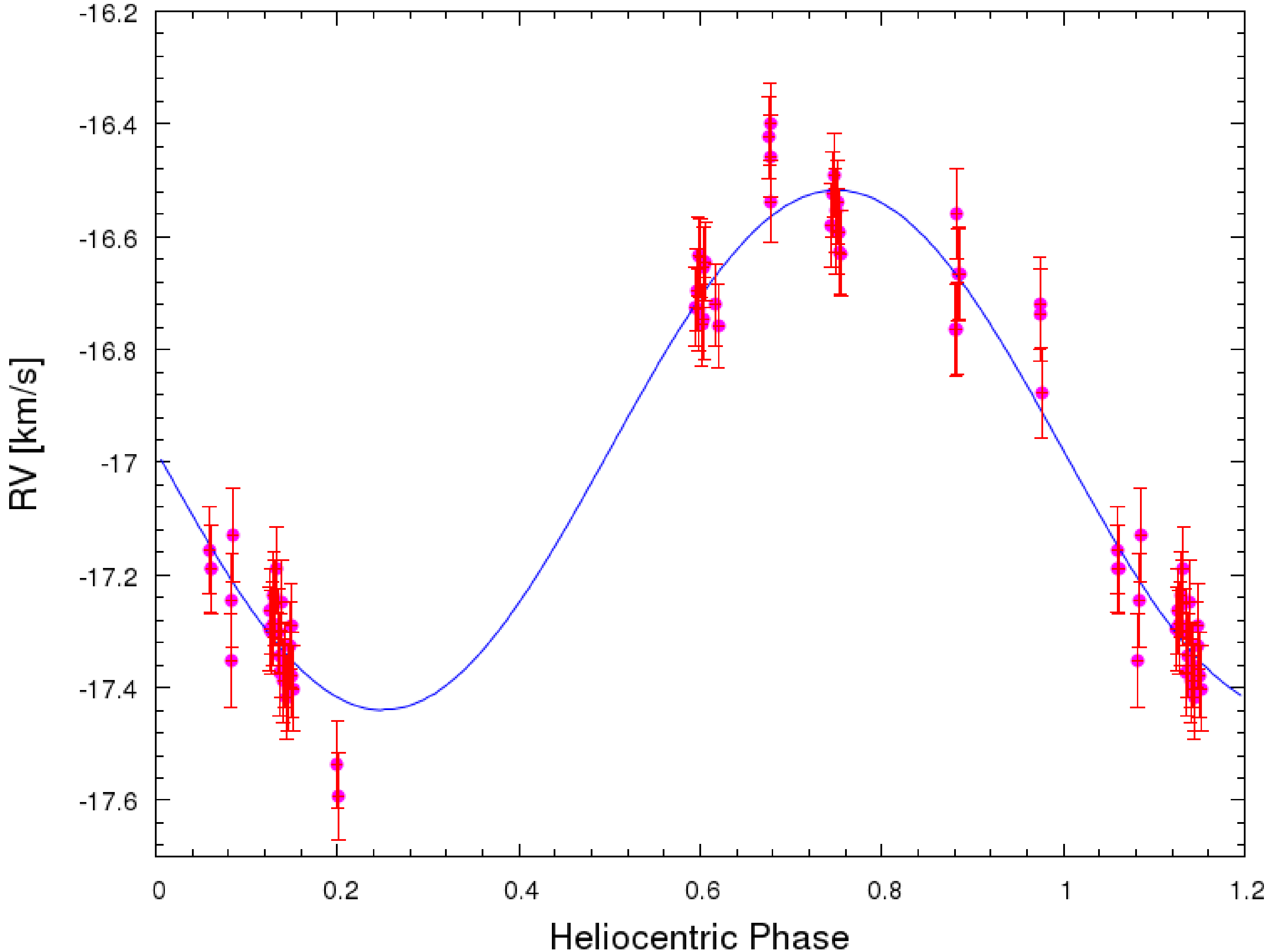
- HgCdTe chip 2k x 2k (Teledyne), 18 µm pixels, 2.5µm cutoff
- Stirling-motor cooling + water assist: 8 hours to 80 K
- fixed J filter, cryogenic filter wheel and foreoptics needed

Filter wheel & shutter

- ACE product
- 100x100mm filter slots
- UBVRI (Bessell)
- 2 wheels, each with 8 positions
- problem: cable and pressure hoses derotation, water condensation

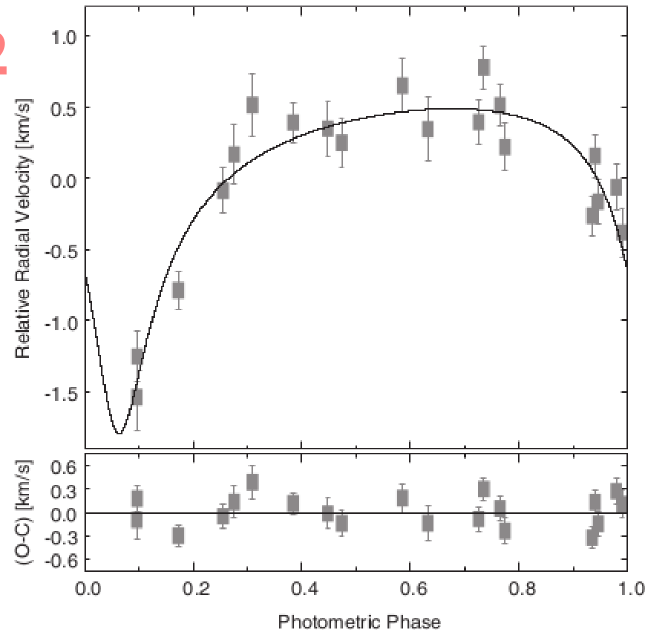


Exoplanet projects at the AI SAS

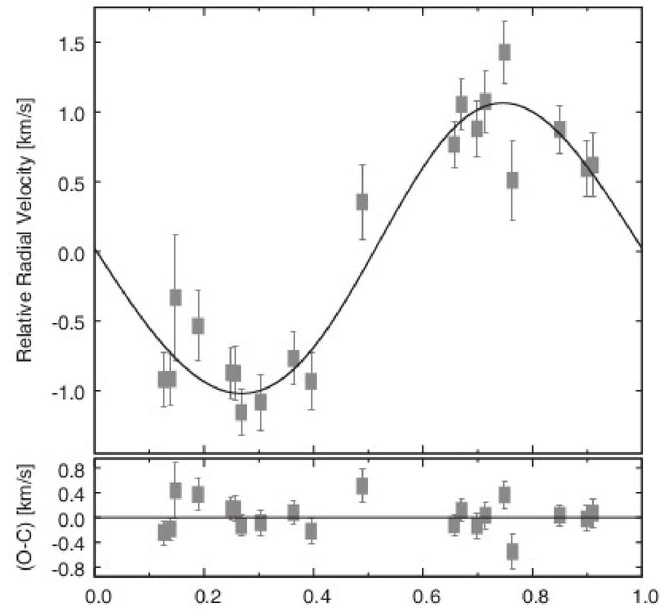


RV variability of τ Boo (Gaussian fit to BFs), data from 10 nights, March 13 to June 6, 2014, rms = 78 m/s, K = 461.1 m/s, P=3.312 days, Pribulla et al., 2015, AN 336, 682

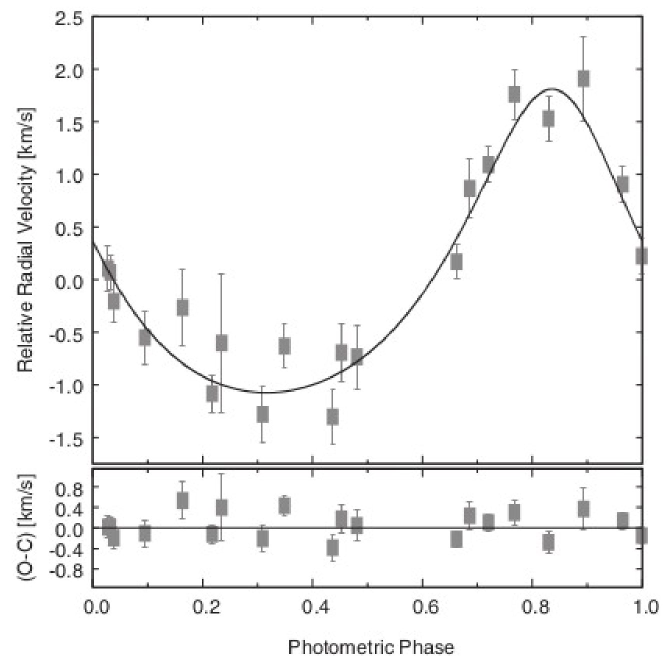
HAT-P-2



WASP-14



XO-3



- RV orbits of three well-known exoplanets with eShel at 60cm telescope at G1 (Stará Lesná)
- RV scatter: 170m/s (HAT-P-2), 220m/s (WASP-14) and 260 m/s
- RV scatter is brightness-limited on 60cm telescope
- Garai et al., 2017, AN, 338, 35

RV precision/accuracy

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):

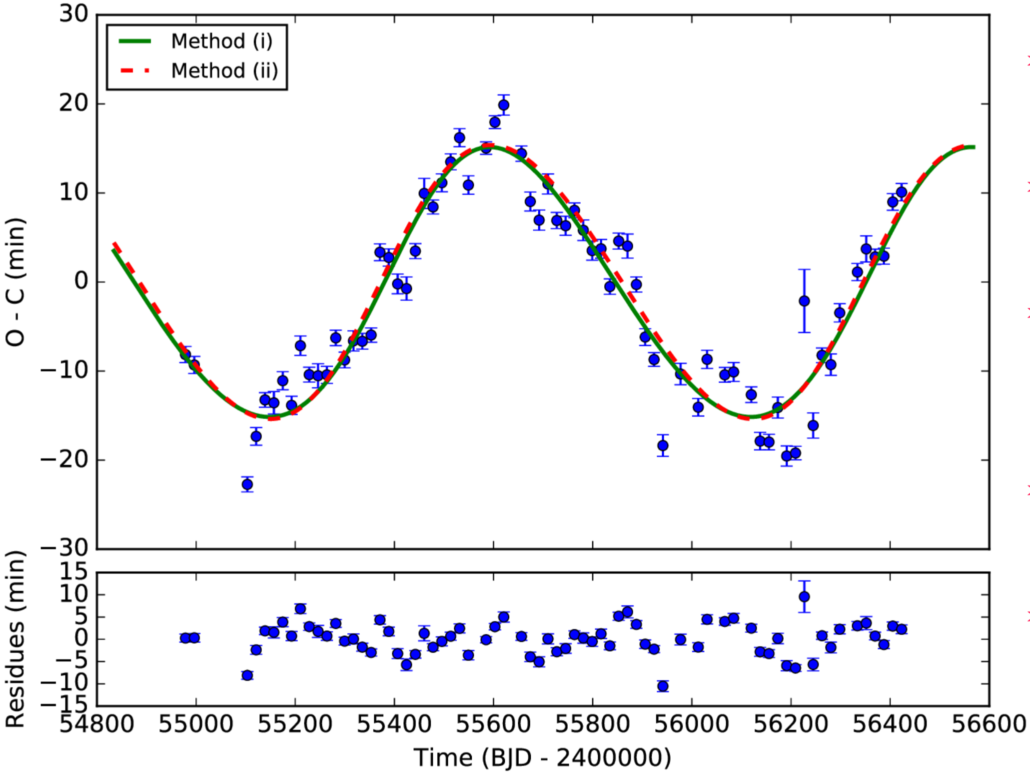
$$\sigma = \text{const}\,\frac{v \sin i}{R^{3/2} B^{1/2} f^{1/2} SNR}$$

RV accuracy depends on:

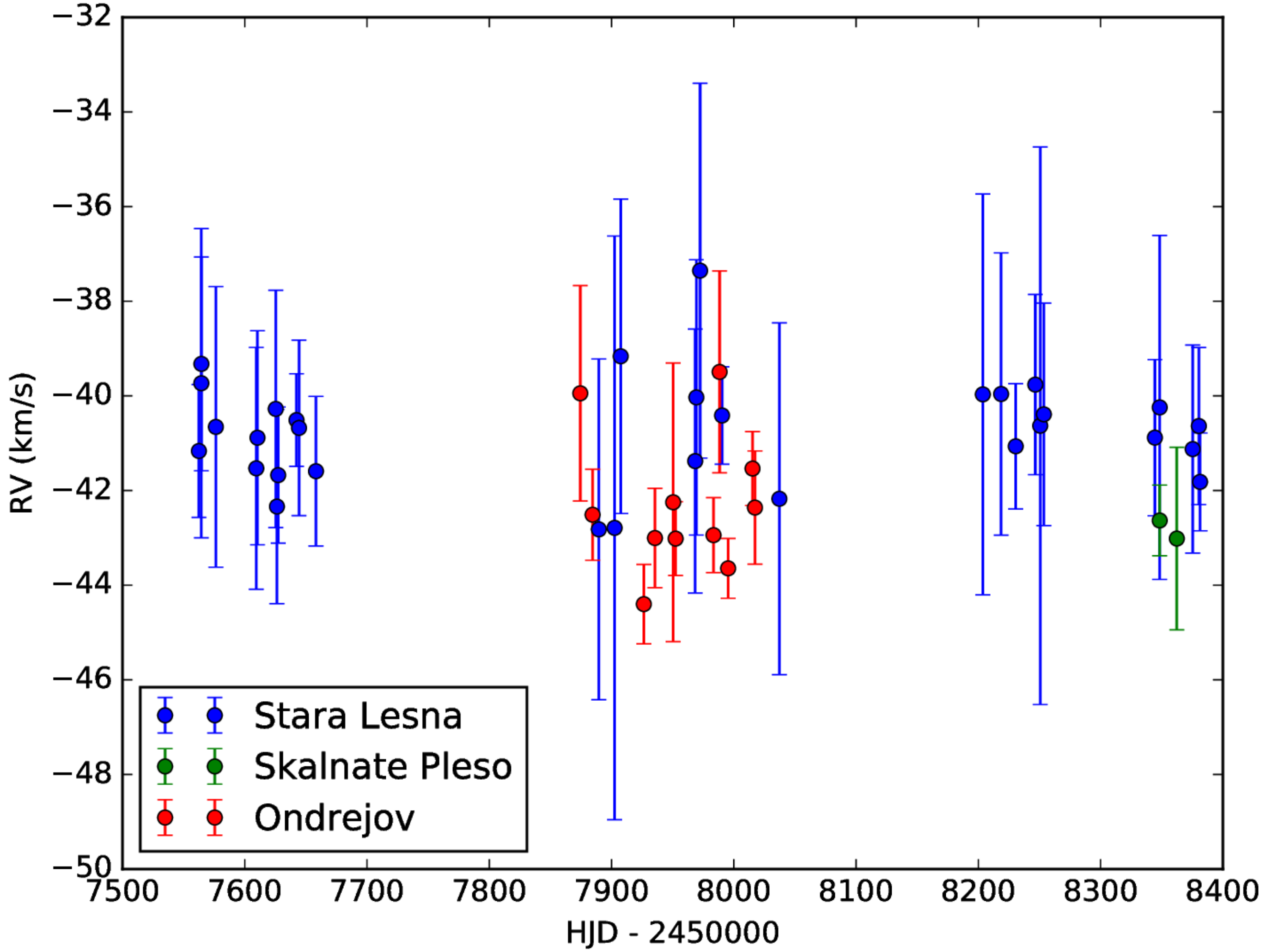
- (i) frequency of ThAr spectra
- (ii) number of ThAr lines for wavelength calibration
- (iii) variations in temperature and pressure
- (iv) instability of ThAr line ratios(changes with time & ThAr current !!!)

Brightness-limited RV precision is about 20 m/s for MUSICOS while only 160 m/s for eShel for a 9 mag star

Kepler-410Ab



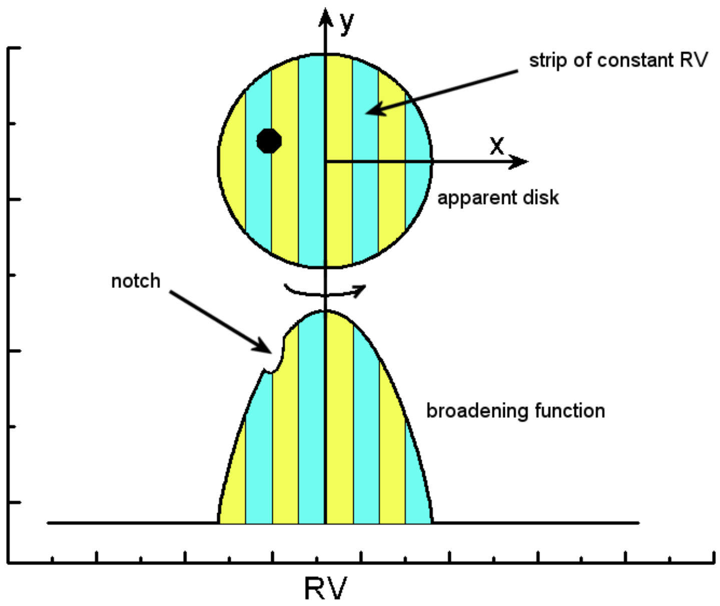
- Kepler-410Ab = HD175289, F6IV parent star
- Neptune-sized planet on a 17.8336 d orbit
- TTV variability observed with about 15-minute amplitude and 970-day orbit seen in the Kepler data
- The perturber must be a star with M > 0.9 Msun
- Expected RV amplitude K ~ 30 km/s (Gajdoš et al., 2017, MNRAS 469, 2907)



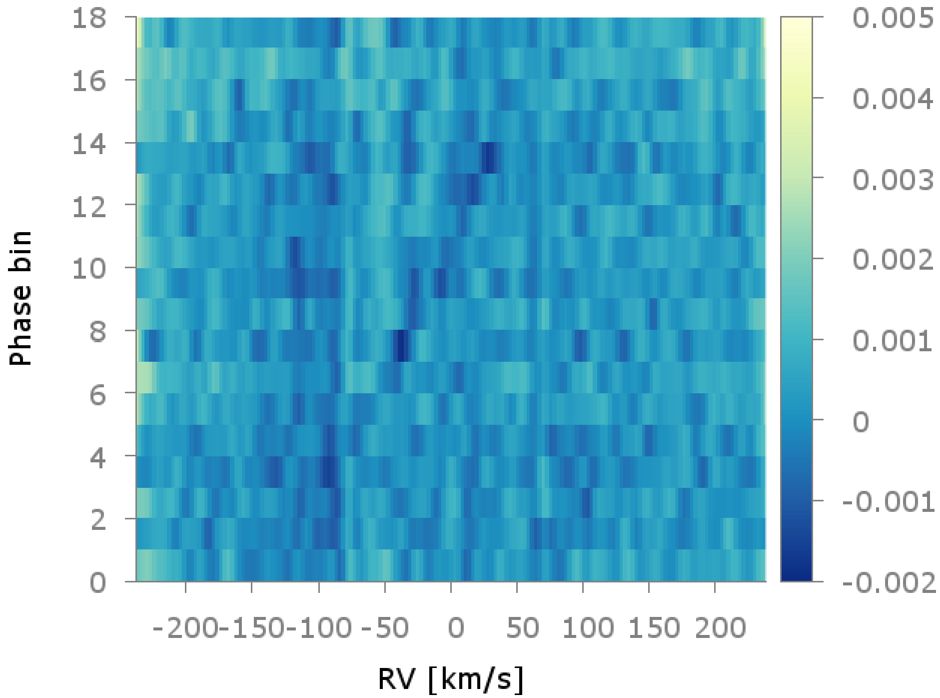
Now almost one cycle covered, observed RV variability < 3 km/s...

Possible explanation of TTV: resonance with a low mass planet

Doppler tomography of exoplanet transits: measuring spin-orbit misalignment



- Measuring spin-orbit misalignment
- requires v sin i » c/R
- Line profile modeled by limb-darkened rotational profile



- Kelt-7b = HD 33643, V=8.54
- F2V fast rotating parent star, v sin i = 74 km/s
- Transiting hot Jupiter P = 2.7347785 d, duration 210.7 minutes
- Spectroscopy with 15-min exposures, typical SNR = 40, 1.3m telescope
- BF = LSD profiles using HD102870 as a template and 4900-5600 Å range

Project Dwarf

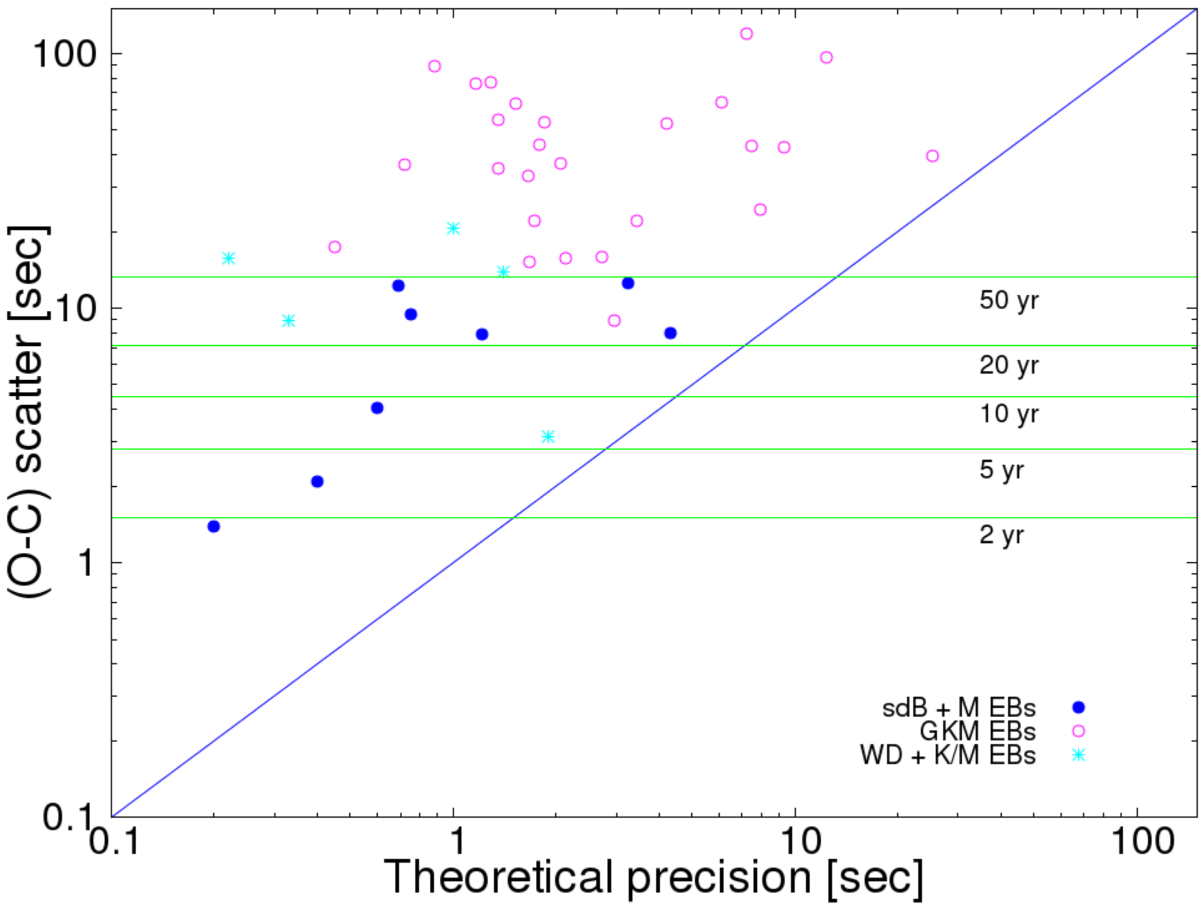
- Detection of sub-stellar bodies via timing variability
- Requires long-term observations, high timing accuracy
- Precise minima: (i) deep and narrow eclipses (ii) bright object (iii) large telescope
- High timing response: (i) massive body around low-mass system, (ii) long orbital period
- Limitations: (i) intrinsic variability of the binary, (ii) other periodic effects (e.g. Applegate, 1992), (iii) errors: JD-HJD-BJD, UTC-EDT

$$\mathrm{Min\,I} = \mathrm{JD}_0 + P\times E + Q\times E^2 + \\ + \frac{a_{12}\sin i}{c}\left[\frac{1-e^2}{1+e\cos\,\nu}\sin(\nu+\omega) + e\sin\,\omega\right]$$

$$\Delta t = \frac{1}{\sqrt{\tau F_\lambda}} 10^{0.2(m_\lambda + X\kappa_\lambda)} \frac{\sqrt{D}}{\sqrt{\pi}Ad}$$

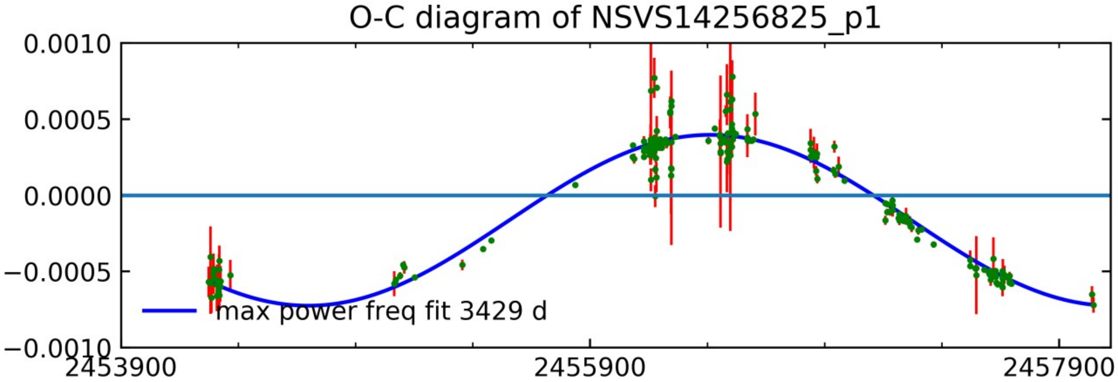
$$\Delta T \approx \frac{2M_3G^{1/3}}{c}\left[\frac{P_3}{2\pi(M_1+M_2)}\right]^{2/3}$$

$$|\Delta t| = \frac{\pi}{4}\frac{A_{\mathrm{OCE}}D^2}{d\,P}$$



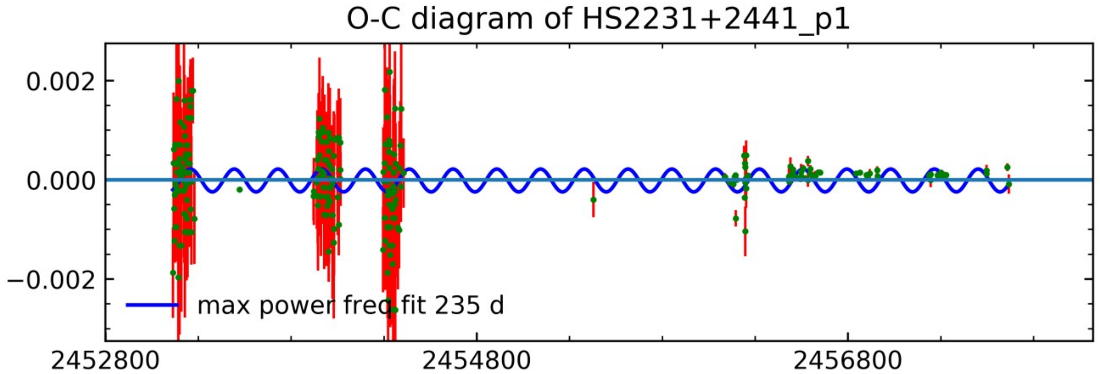
Predicted timing precision vs. observed scatter for different groups of eclipsing binaries, horizontal lines show amplitude of LITE for a Jupiter-mass body orbiting 1 Msun binary

1700 timings obtained by 30 instruments, 75 objects observed



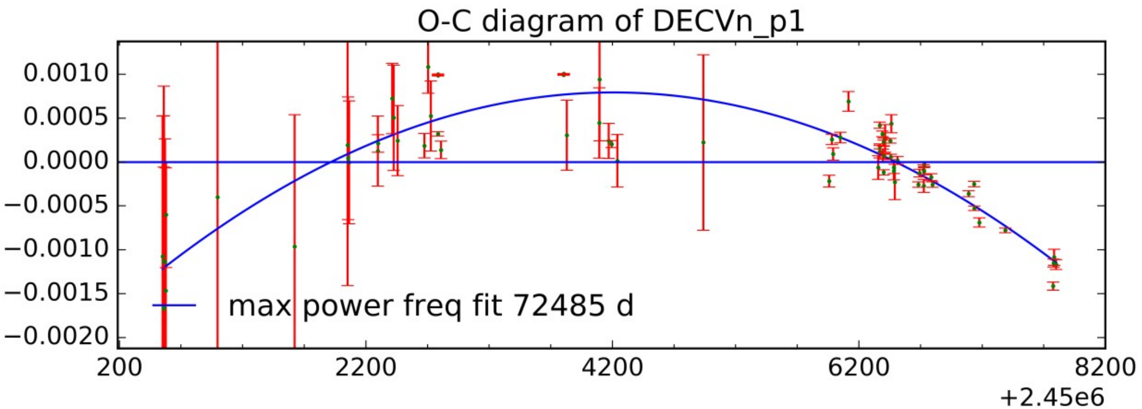
NSVS14256825, P_3=3429 days,

A=0.0005 days, M_1+M_2=0.46+0.21 Msun, $M_3 \sin i_3$= 15 Mjup



HS2231+2441, P_3=235 days,

A=0.0003 days, M_1+M_2=0.3+0.3 Msun, $M_3 \sin i_3$= 50 Mjup

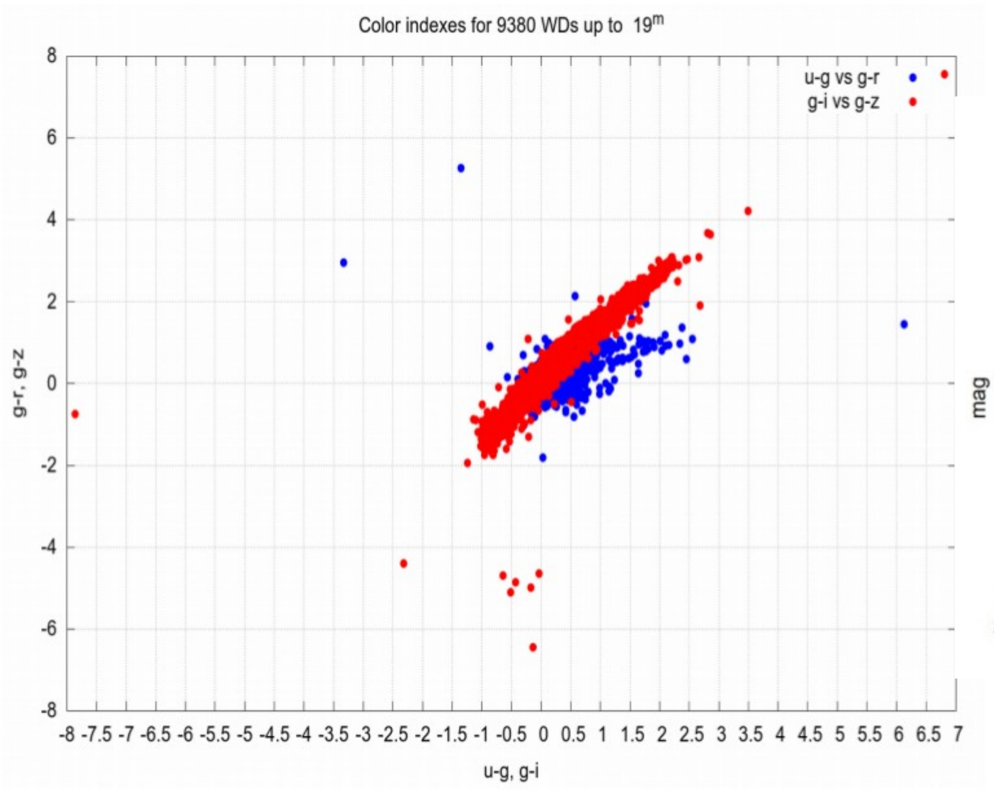


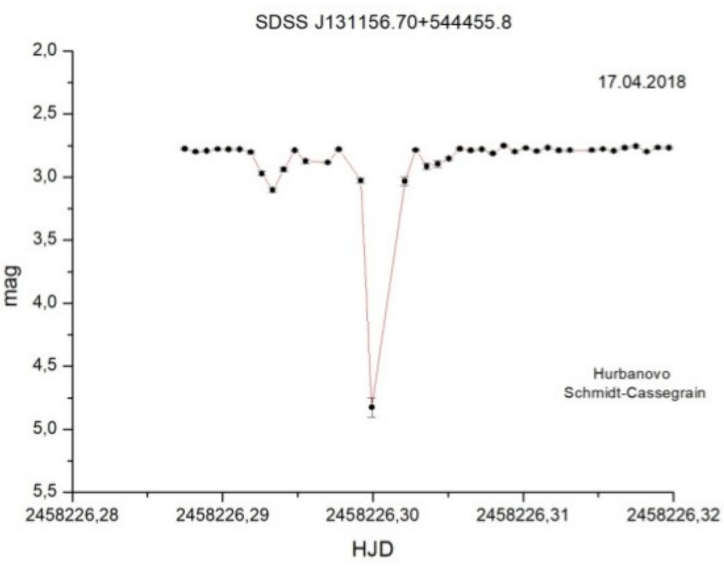
DE CVn, P_3=72485 days,

A=0.0012 days, M_1+M_2=0.51+0.41 Msun, $M_3 \sin i_3$= 6 Mjup

Transiting Earth-size bodies around WDs

- Pros: deep eclipses expected even for Earth-size planets = low photometric precision needed, incidence of WDs is 3-10%
- Cons: short duration of eclipses, low brightness of objects
- Sloan Digital Sky Survey DR7 White Dwarf Catalog - 20000 WDs
- 4 systems with big colour excess selected (one observation possibly in eclipse)





Future instrumentation plans

- cryocooled fore-optics and filter wheel for NIR camera
- upgrade of our coating facility: silver coating of 1.3m telescope for NIR observations
- improving RV-stability of MUSICOS, now RV accuracy reaches 100 m/s, thermally-controlled room to host the spectrograph, iodine cell ?
- improving throughput of MUSICOS: possibly using primary focus of M1 of 1.3m for spectroscopy, coating of optics etc.

Thanks for your attention !