High-Resolution and High-Precision Spectroscopy with HARPS

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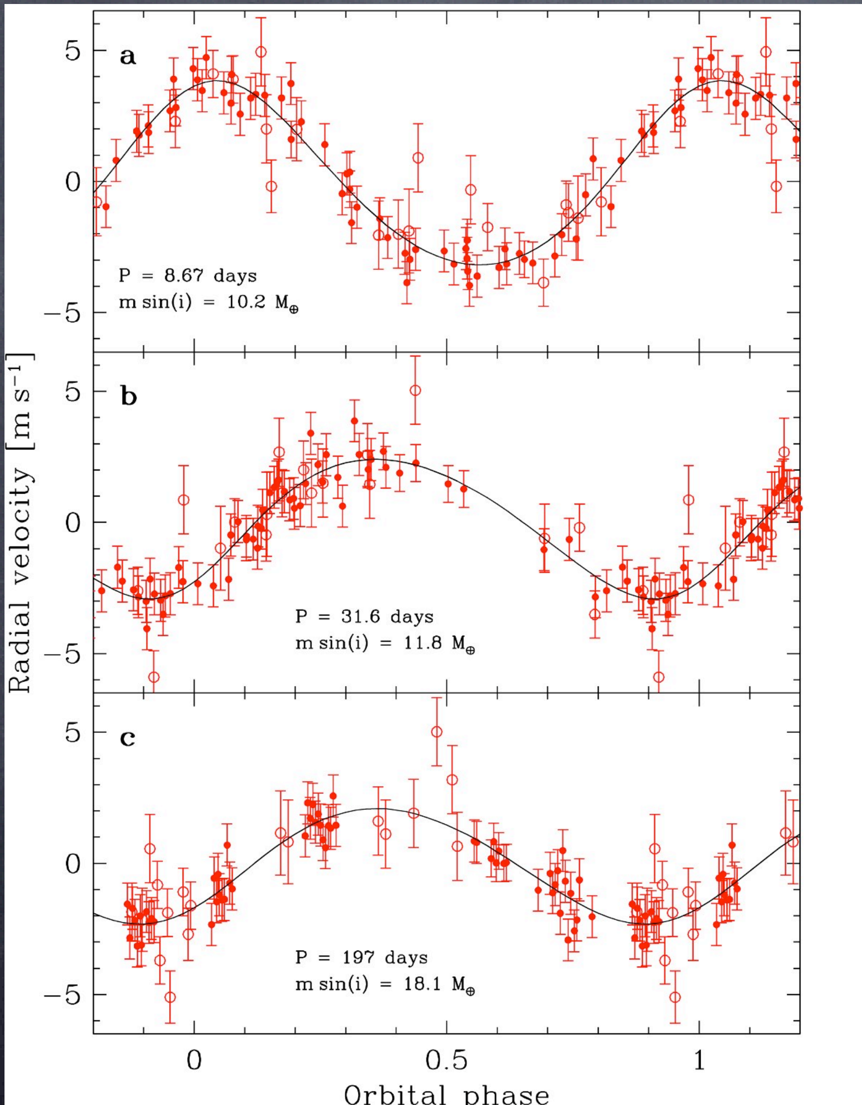
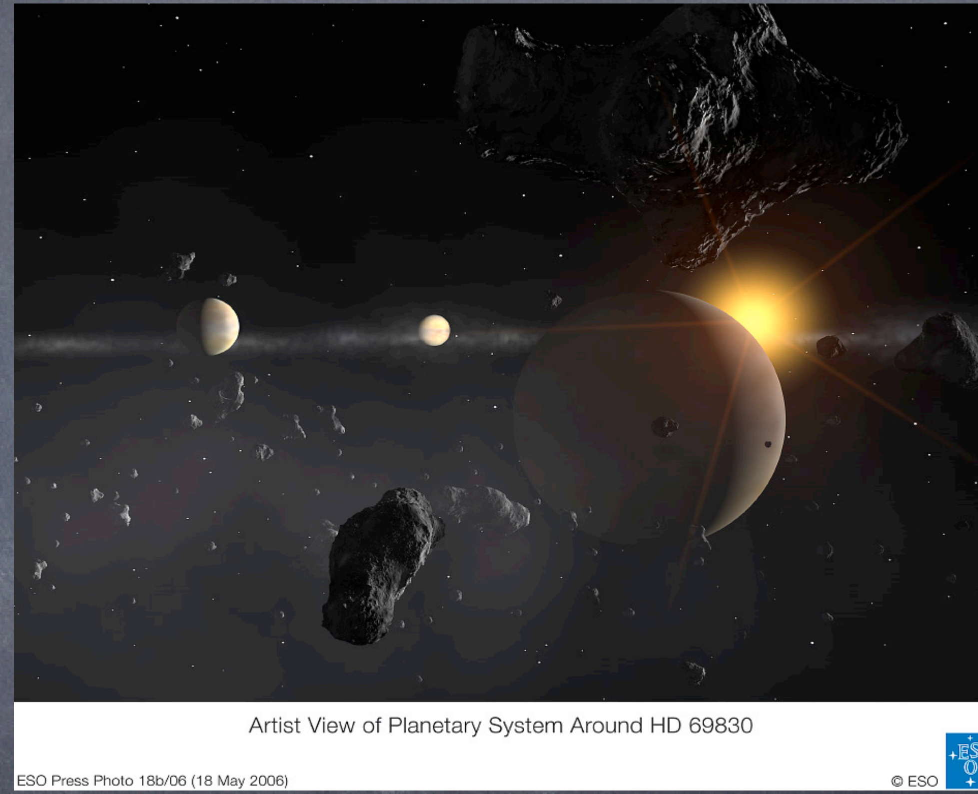
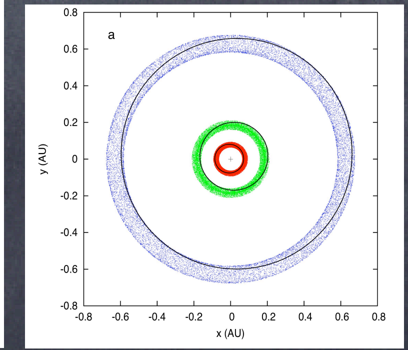
The 2007 ESO Instrument Calibration Workshop

The "State of the Art"



HD69830 - Lovis et al., Nature, 2006



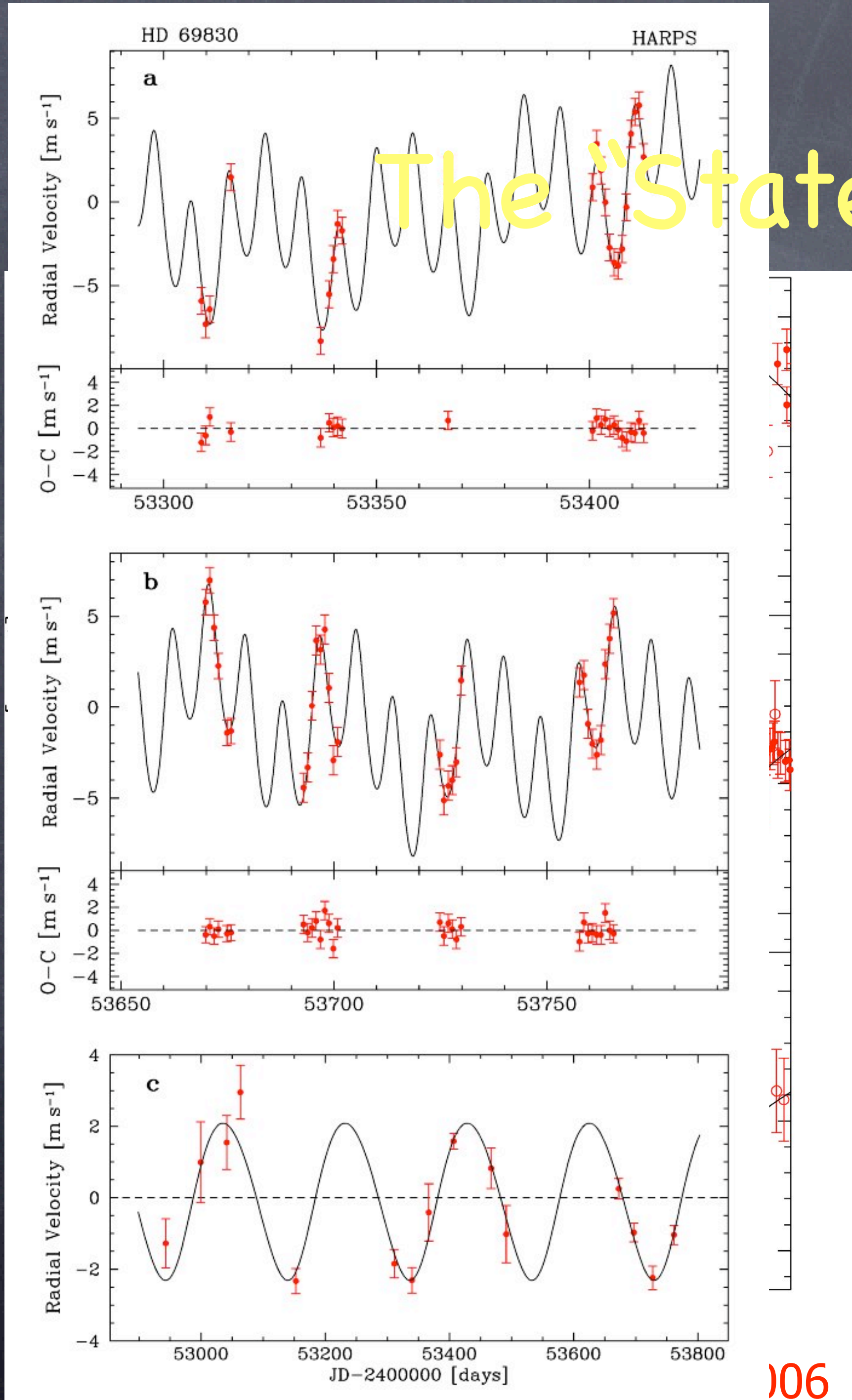


P1 = 8.67 days   M sini = 10.2 $M_{\oplus}$

P2 = 31.6 days   M sini = 11.8 $M_{\oplus}$

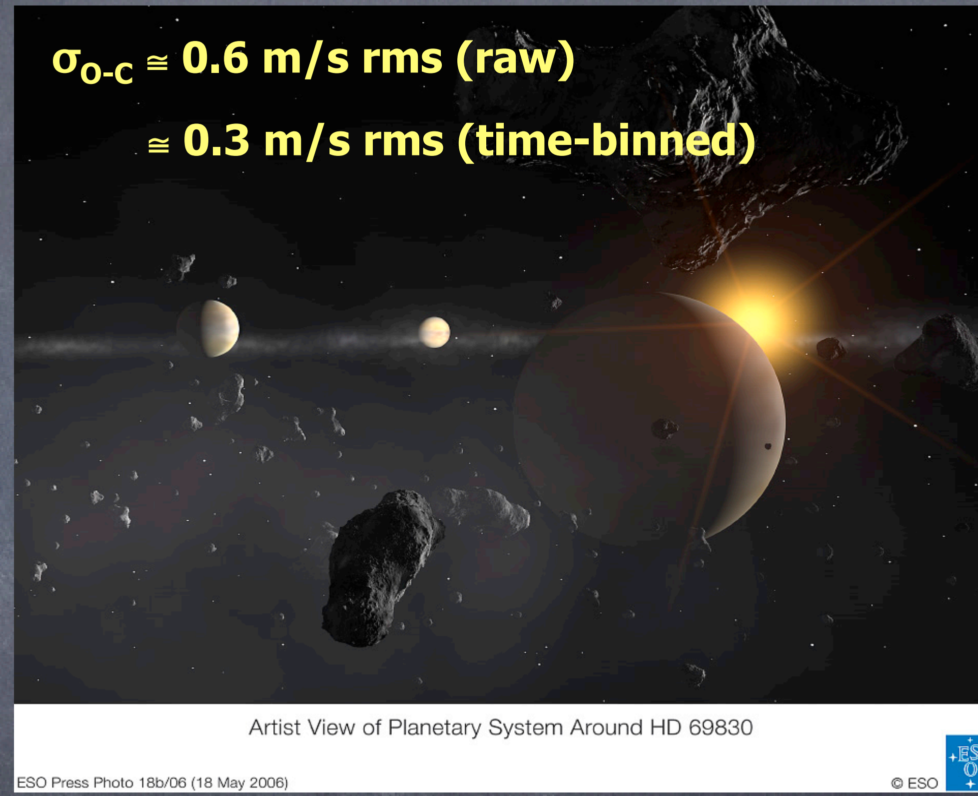
P3 = 197 days   M sini = 18.1 $M_{\oplus}$

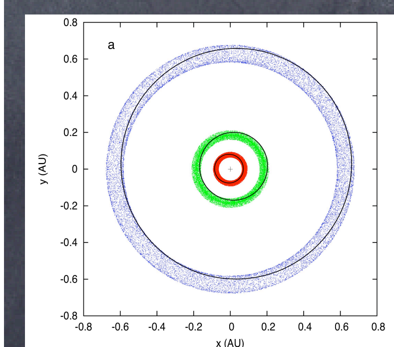
The "State of the Art"



$\sigma_{O-C} \cong$ **0.6 m/s rms (raw)**

$\cong$ **0.3 m/s rms (time-binned)**



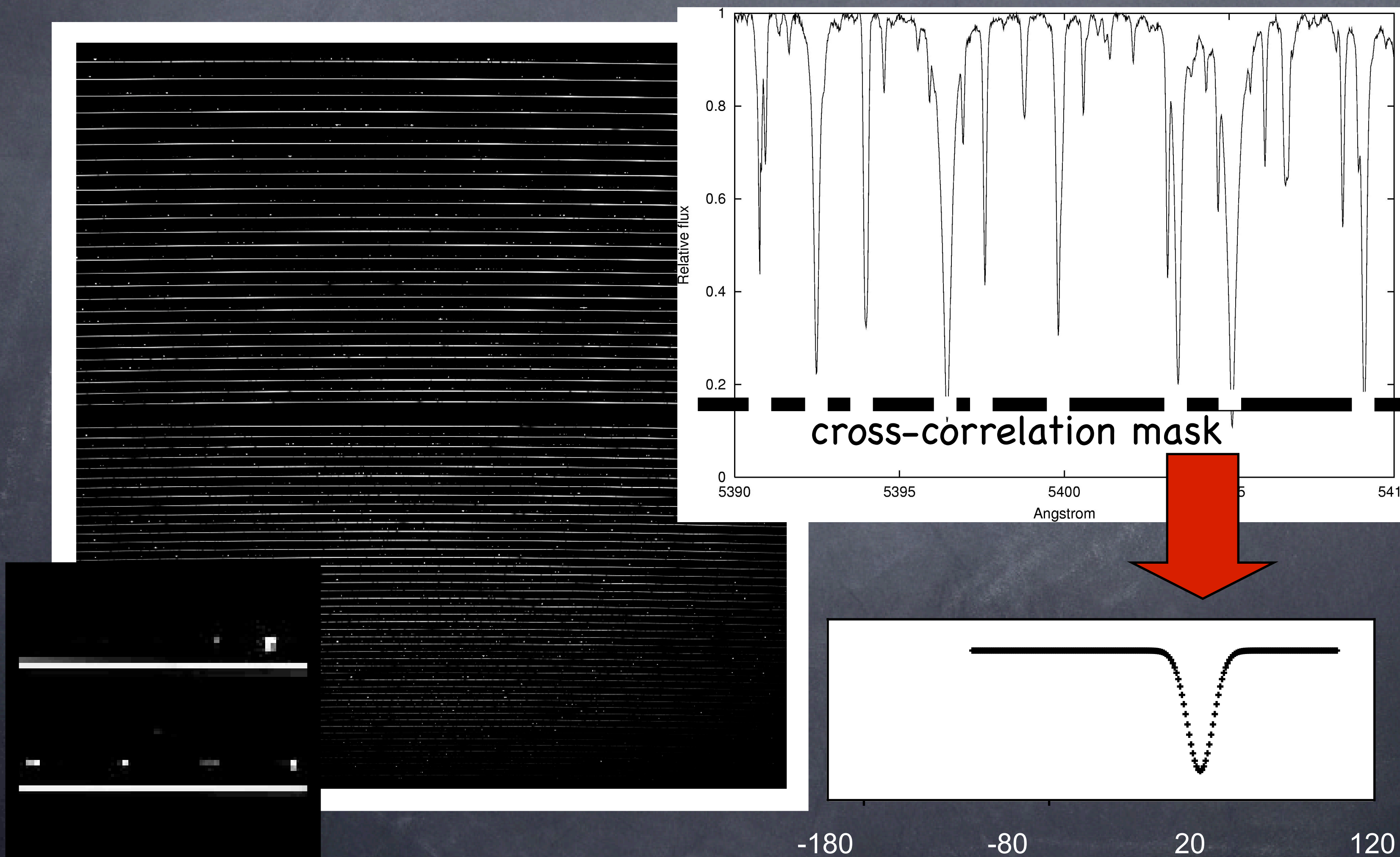


P1 = 8.67 days M sini = 10.2 $M_{\oplus}$

P2 = 31.6 days M sini = 11.8 $M_{\oplus}$

P3 = 197 days M sini = 18.1 $M_{\oplus}$

The Doppler measurement



Possible error sources

- Stellar noise
- Intermediate medium (Earth's atmosphere, etc.)
- Instrumental noise
  - Instrumental stability (from calibration to measurement)
  - Calibration accuracy (ThAr and iodine techniques)

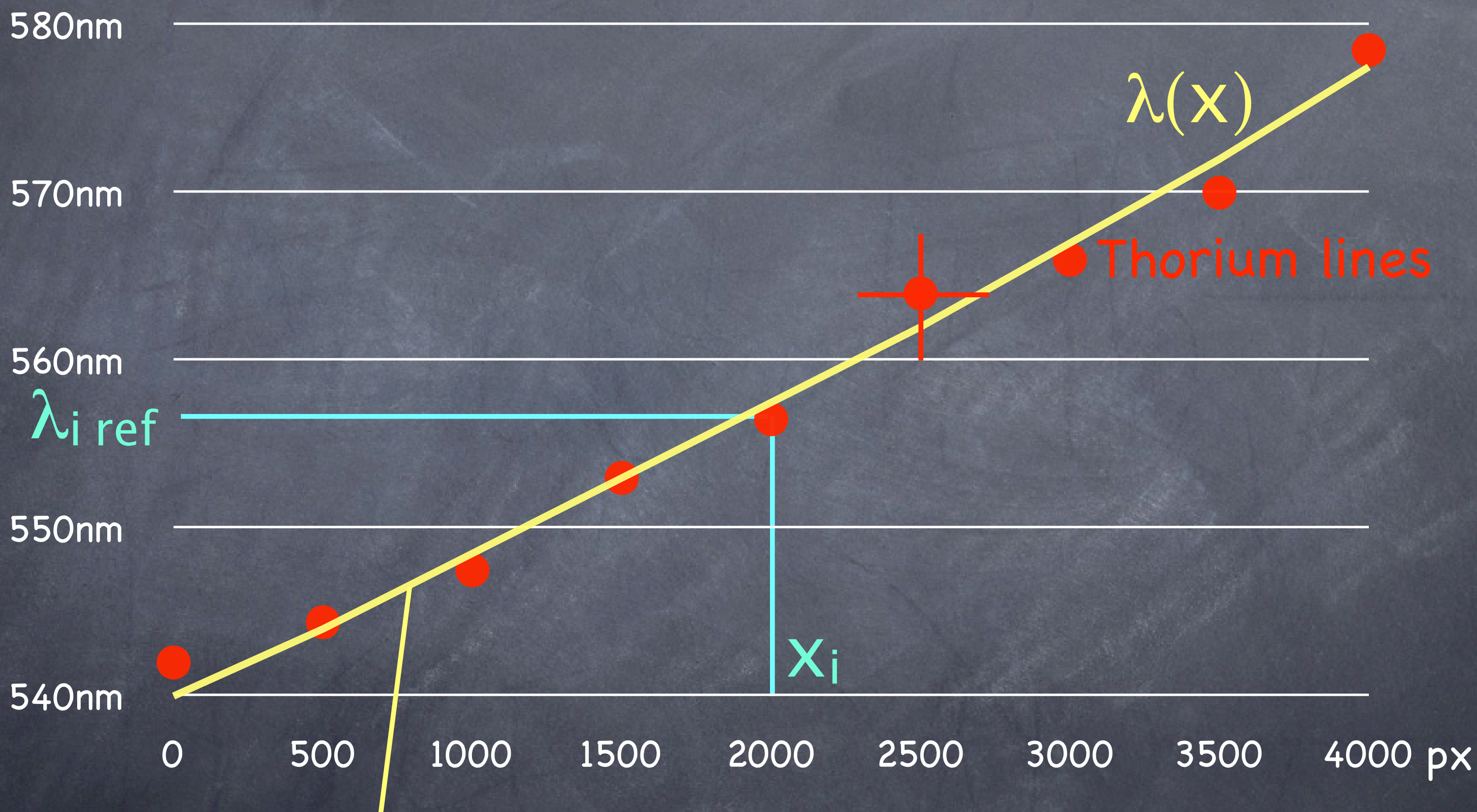
Definition of "calibration"

A process that establishes, under specified conditions, the relationship between the values indicated by the measuring system, and the corresponding values of a quantity realised by a reference standard or working standard.

CCD pixel position

Line position of spectral reference

The wavelength solution



Requirements on $\Delta\lambda/\lambda$: (for 1 ms^{-1})

(Absolute) accuracy:	"none"
Scale factor:	~10^{-5}
Repeatability (global):	~10^{-9}

Calibration errors

- pixel-position precision
  - photon noise
  - blends
  - pixel inhomogeneities, block stitching errors
- accuracy of the wavelength standard
  - systematic errors, Atlas, RSF
  - instabilities (time, physical conditions: T, p, I)
- accuracy of the fit algorithm

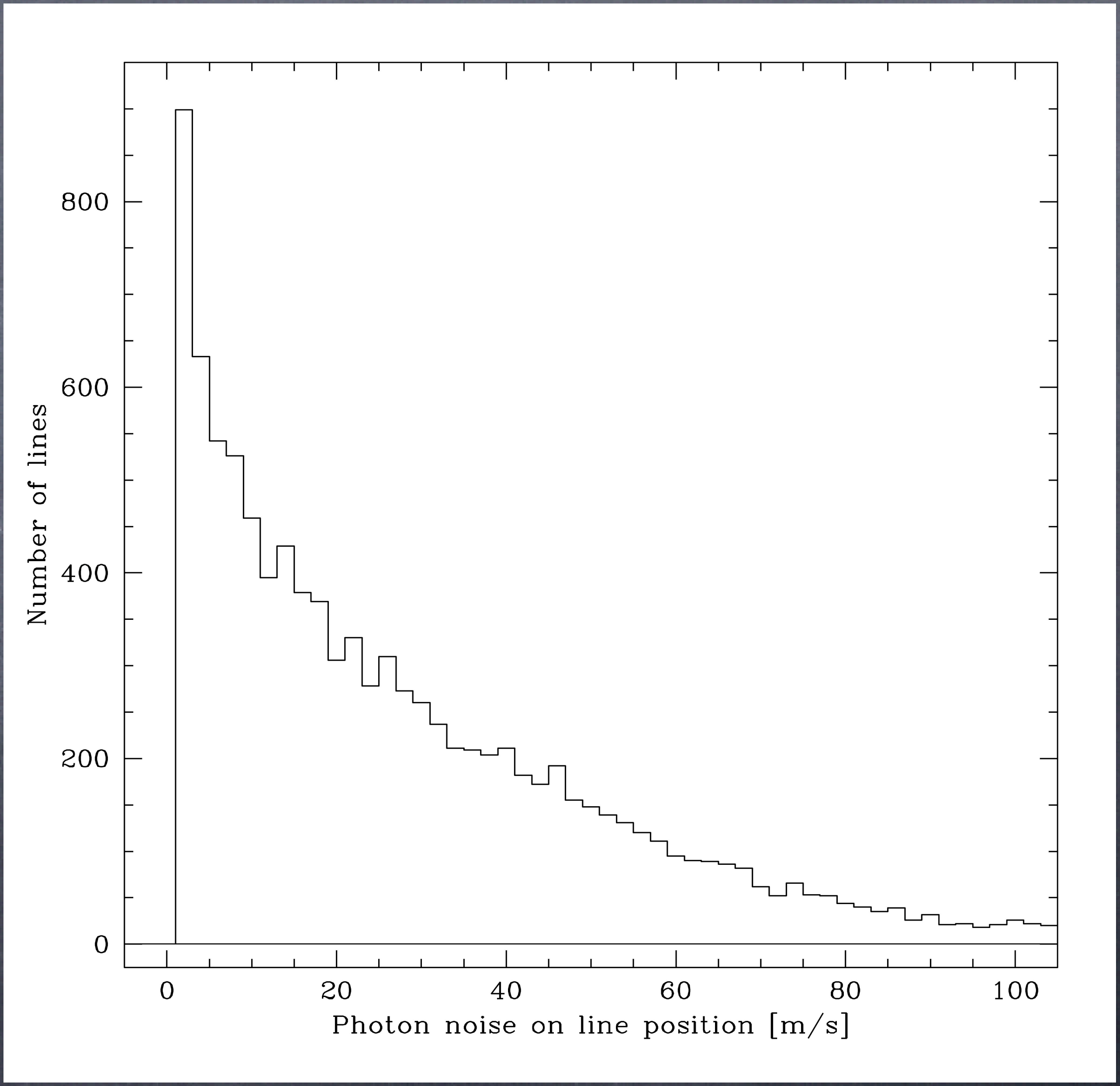
Photon noise

ThAr:

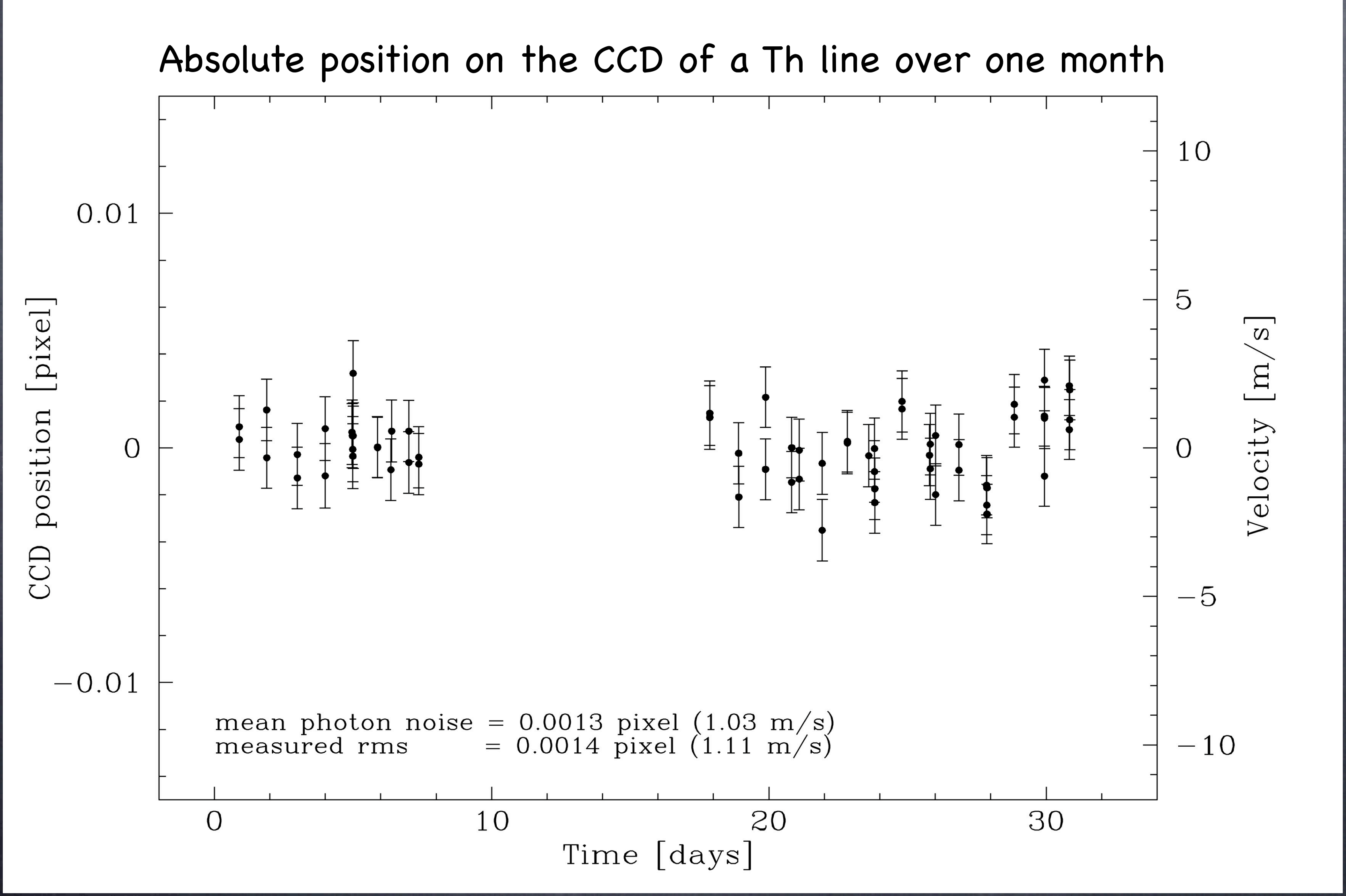
Single line: 1 ms^{-1}

Average: 8 ms^{-1}

Global: 8 cms^{-1}



Line (and Instrumental) stability

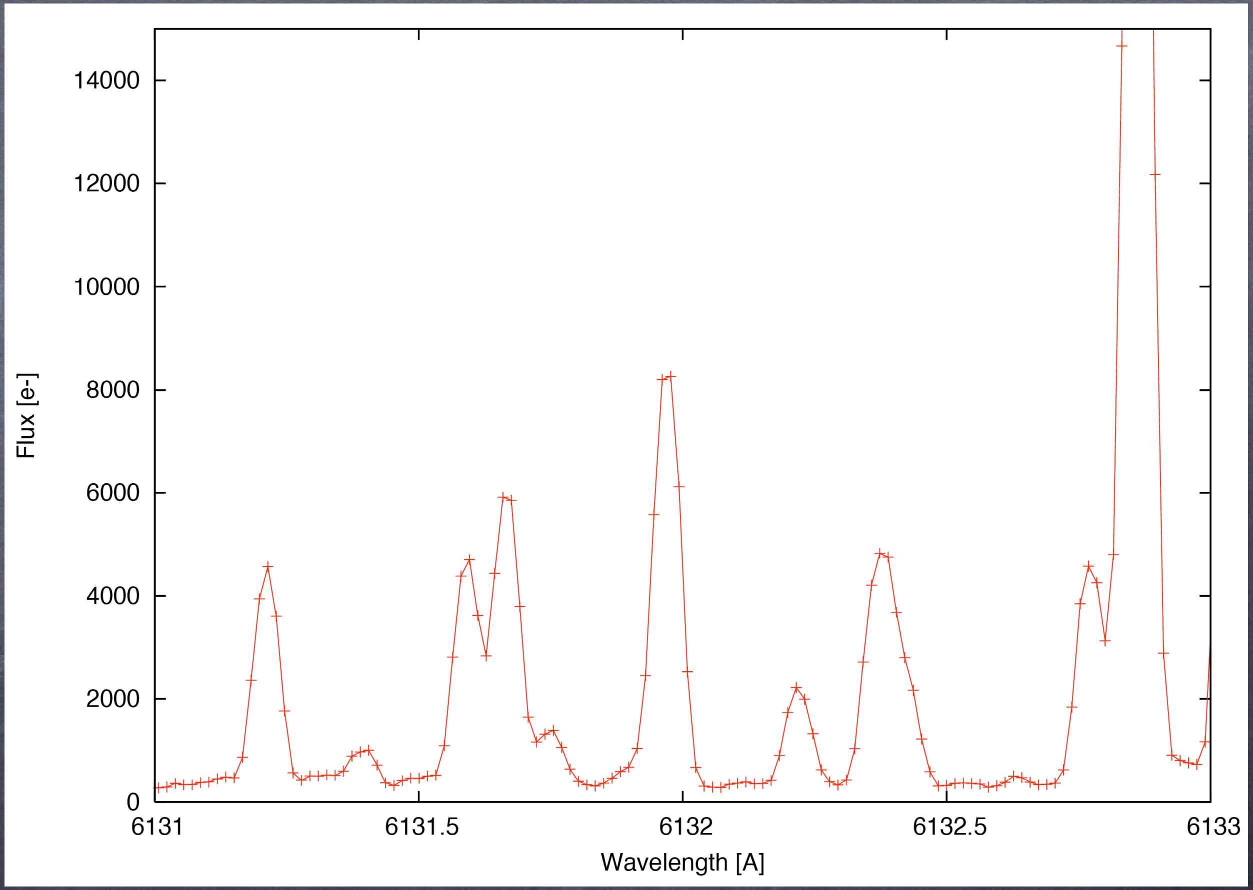


The problems of blends

Isolated lines are very rare!

↓

Fit neighbouring lines simultaneously with multiple Gaussians



Treatment of blends

Isolated lines are very rare!

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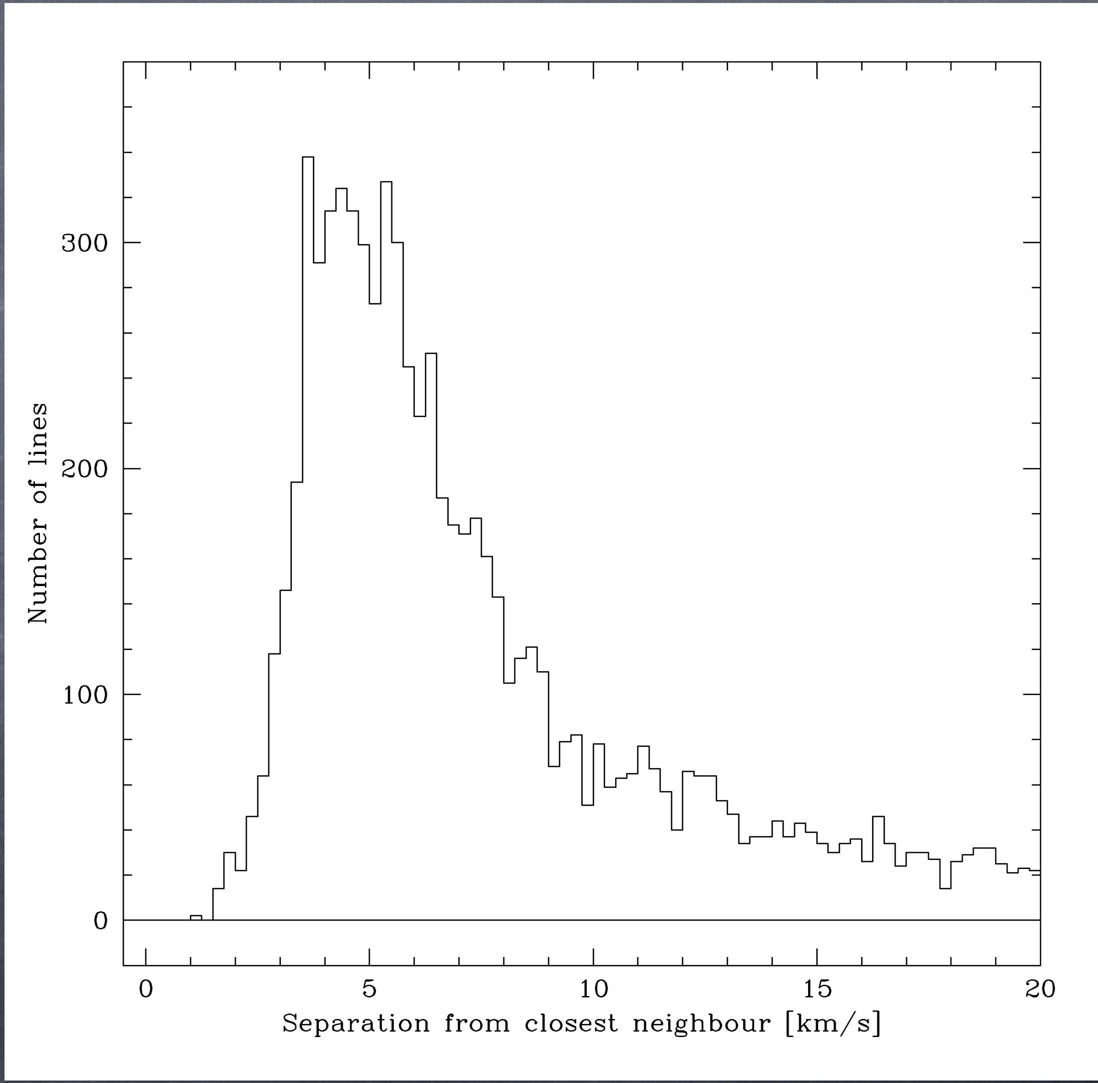
Fit neighbouring lines simultaneously with multiple Gaussians



Calibration errors

- pixel-position precision
  - photon noise (line: 1 - 150 ms^{-1}, global 8 cms^{-1})
  - blends (line < 8 ms^{-1})
  - "pixelisation" (line < 8 ms^{-1})
- accuracy of the wavelength standard
  - systematic errors, Atlas, RSF
  - instabilities (time, physical conditions: T, p, I)
- accuracy of the fit algorithm

Wavelength standard

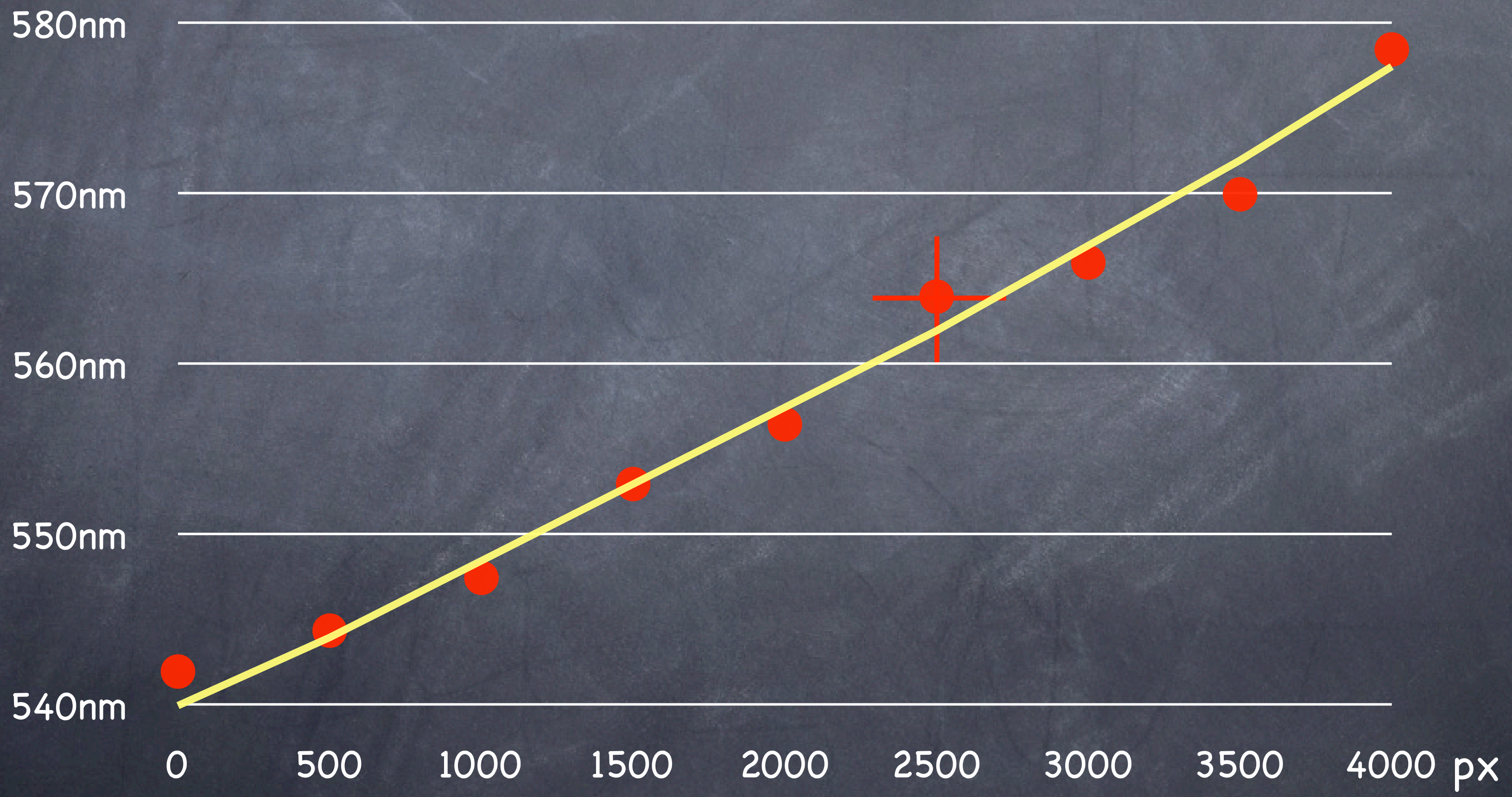
Palmer & Engleman 1983:

Atlas of the Th spectrum
3,000 usable lines at
R~600'000
Accuracy of individual lines:
15-150 m s^{-1}

HARPS ThAr spectra:

Lot of unidentified lines at R~110'000
Best precision ~1-2 m s^{-1} individual lines

The wavelength solution



Build up a new wavelength reference

- The dispersion of the residuals around the wavelength solutions (~50-70 m s^{-1}) is completely dominated by the uncertainties in the input wavelengths!

- More accurate wavelengths would decrease residuals around the fit and stabilize the wavelength solutions

- More than 50% of the detected lines are NOT in the atlas because they were too faint on the FTS scans!

- Use of more lines would better constrain wavelength solutions

New ThAr atlas -> Lovis et al. 2007, in prep.

➡ Use HARPS spectra to build a new ThAr atlas!

Perform a systematic search for lines in the spectrum

➡ Fit a global wavelength solution through all spectral orders

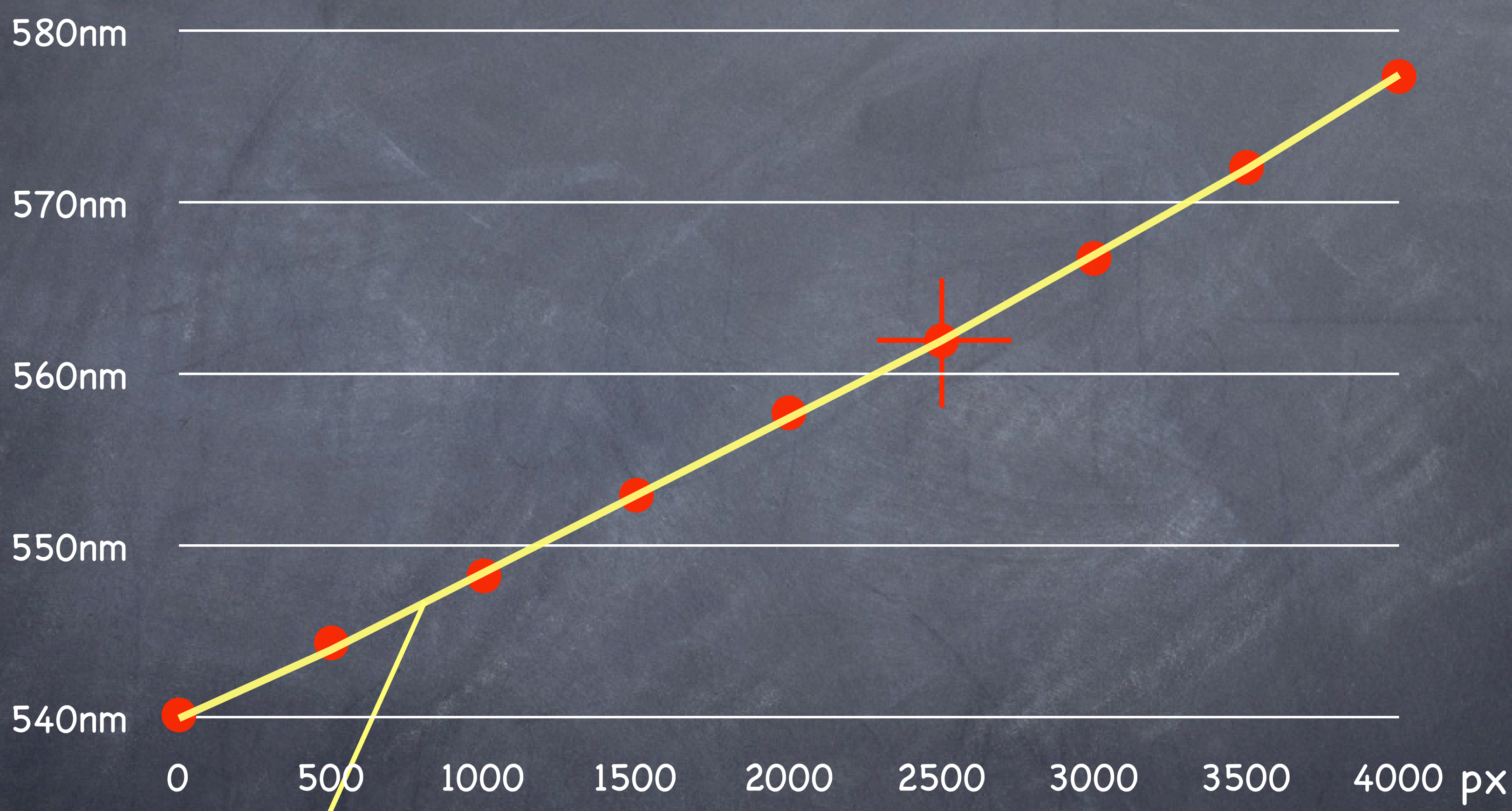
Find the systematic offset of each line and correct its wavelength

➡ New list of ~ 8,600 lines

Internal precision on individual wavelengths ~ 10 m s^{-1}

X^2 ~ 1.5 (residual pixelisation effect of ~ 8 m s^{-1}

The wavelength solution

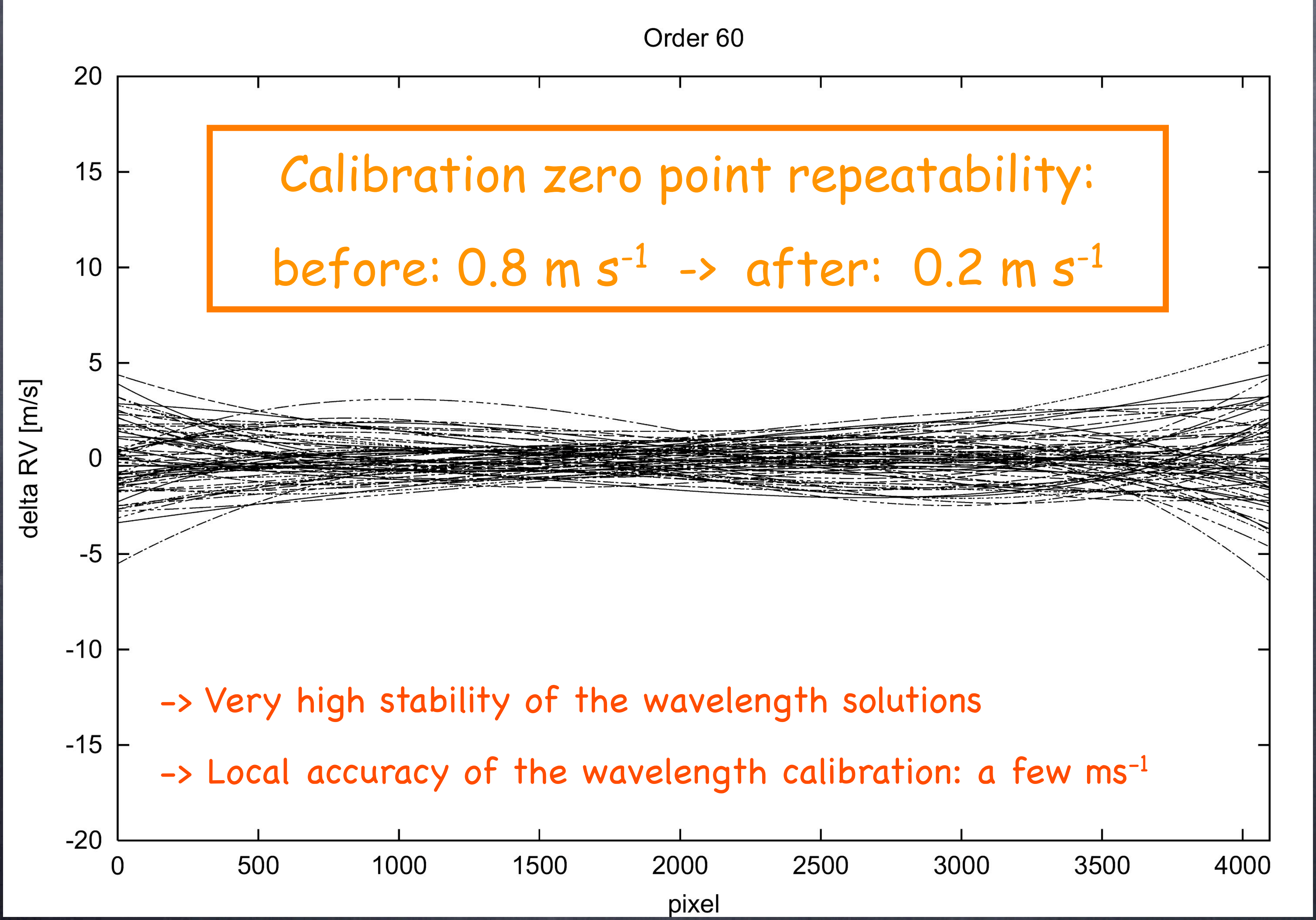


Achieved $\Delta\lambda/\lambda$: (Absolute) accuracy: 5×10^{-8}

Scale factor: 3×10^{-8}

Repeatability: 6×10^{-10} (= 20 cms^{-1})

New ThAr atlas -> Lovis et al. 2006, in prep.



Calibration errors

- pixel-position precision
  - photon noise (line: 1 – 150 ms^{-1}, global 8 cms^{-1})
  - blends (line < 8 ms^{-1}, global 10 cms^{-1})
  - "pixelisation" (line < 8 ms^{-1}, global 10 cms^{-1})
- accuracy of the wavelength standard
  - systematic errors (line < 8 ms^{-1}, global 10 cms^{-1})
  - instabilities (time, physical conditions: T, p, I)
- accuracy of the fit algorithm

Other results from ThAr tests

- Stability of Thorium lines over years: ~< 1 ms^{-1} rms
- Stability of Argon lines over years: ~ 10 ms^{-1} rms (probably due to p variations -> never use for calibration)
- Dependence on lamp current (7-10 mA): < 0.2 ms^{-1} rms
- Dependence on flux (factor 6): < 0.1 ms^{-1} rms

Open questions and limitations

- Long-term stability at < 1 ms^{-1} rms
- Life time, exchange
- Precision at < 0.1 ms^{-1} rms
  - Dynamical range of line intensity
  - Wavelength coverage and spacing uniformity
  - Blends

(valid for thorium and iodine)

The perfect calibrator

- Cover full spectral range
- Constant line spacing
- Lines width < spectrograph resolution
- High density of lines, up to one per ~2-3 RE
- All wavelengths precisely known and stable
- Homogeneous line intensities, close to saturation

The CODEX project: 1cm s^{-1}

For example: Fabry-Perot or laser frequency comb
(see next talk)