ESO Calibration Workshop: The second generation instrument and friends

Vitacura, January 2017

High-accuracy wavelength calibration - ESPRESSO

F. Pepe (UniGe)

The observables

Propagation of light wave from stable source at infinity:

$$\vec{E}(\vec{x},t) = \vec{A} \cdot e^{-i(\vec{k}\vec{x}-\omega \cdot t)}$$

which is a solution of wave equations if:

$$c_n = \frac{\omega}{k}, \text{ where } k = \left|\vec{k}\right|$$

c_n is the speed of light in a medium with refractive index n = n(k)

Independent observables are:

$\vec{A}$ = Amplitude of electric field

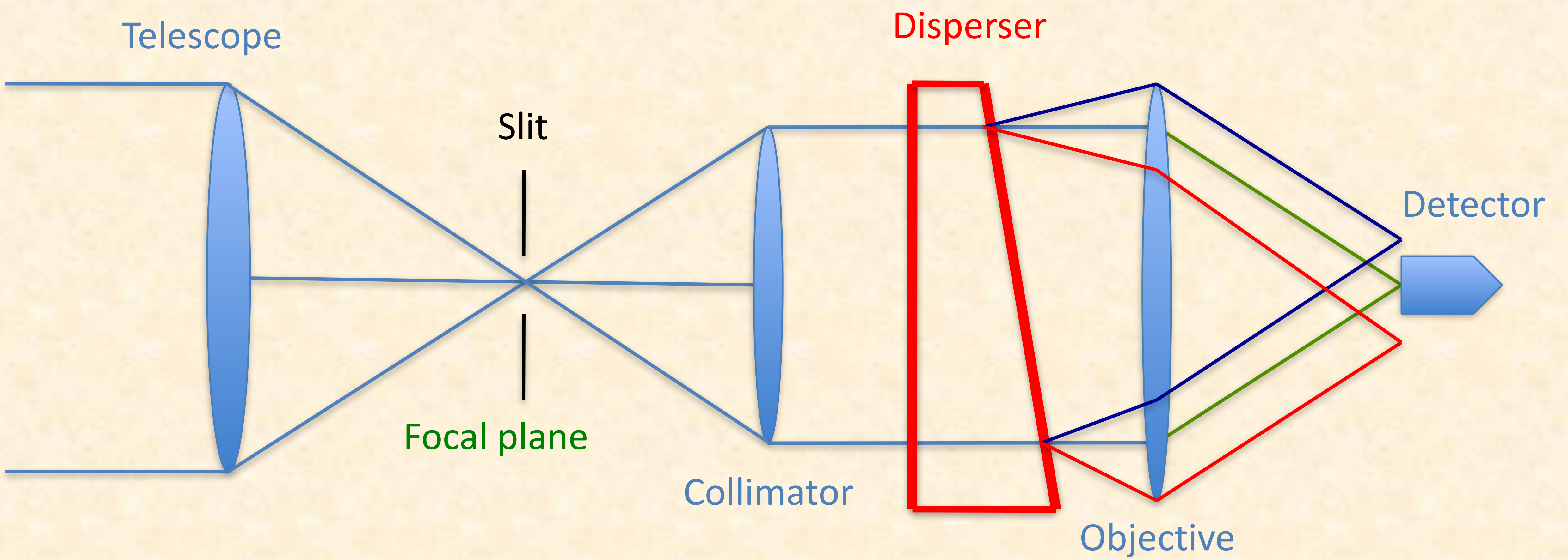
$\vec{k}$ = Direction vector projected on sky

ω = Frequency or k = Wave vector

The distance between two spatial maxima of the light wave in a given medium and at fixed *t* is called wavelength and results to be:

$$\lambda_n = \frac{2\pi}{n(k) \cdot k}$$

General spectrograph layout

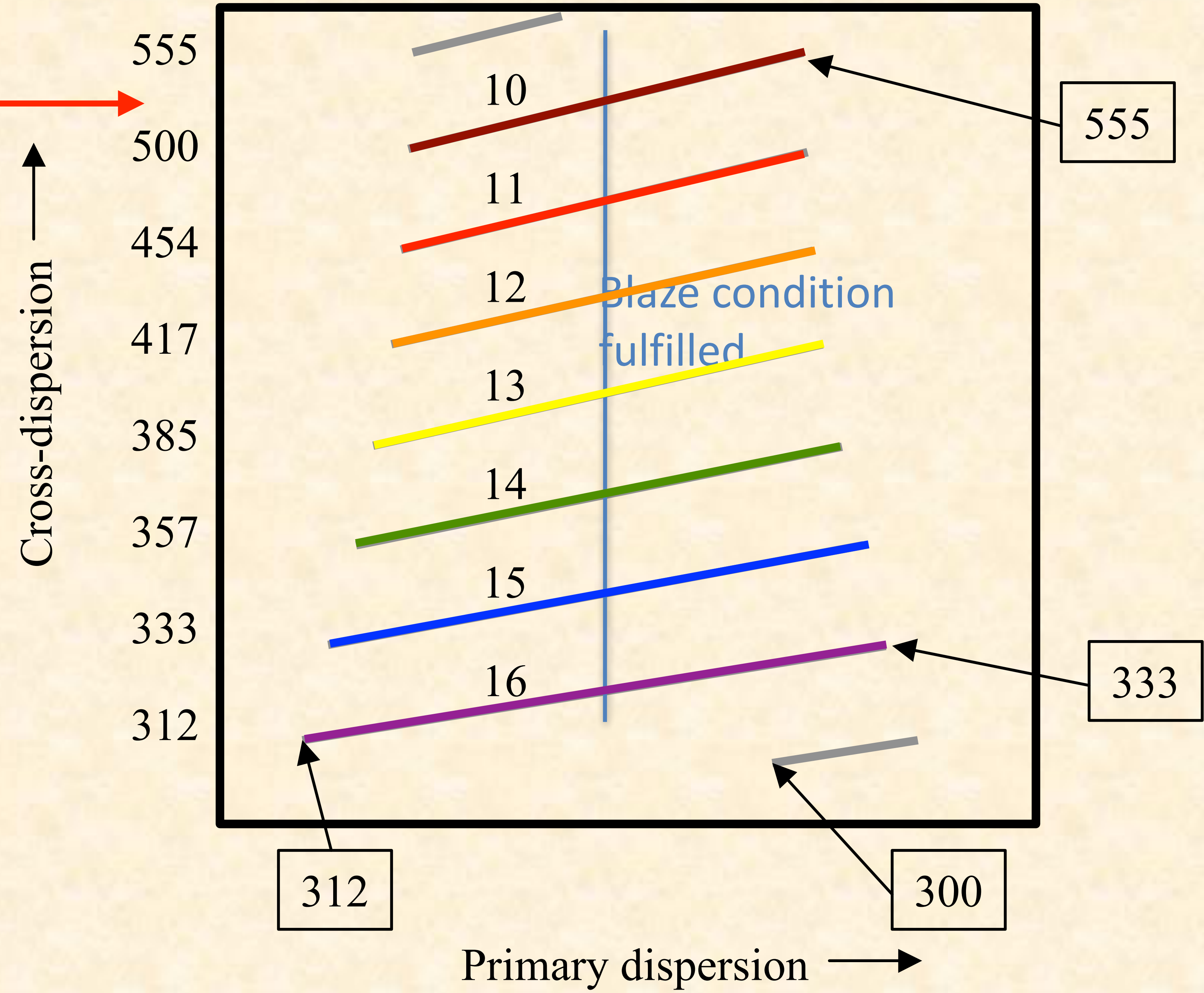


The disperser separates (encodes) the wavelengths in angular direction. To avoid angular mixing, the beam is previously collimated.

Multiple orders

Intermediate focal plane
'white spectrum'

All orders superposed



- Many orders to cover desired $\lambda\lambda$: Free spectral range $F_\lambda = \lambda/m$
- Orders lie on top of each other:
  $\lambda(m) = \lambda(n) \times (n/m)$
- Solution:
  - use narrow passband filter to isolate one order at a time
  - cross-disperse to fill detector with many orders at once

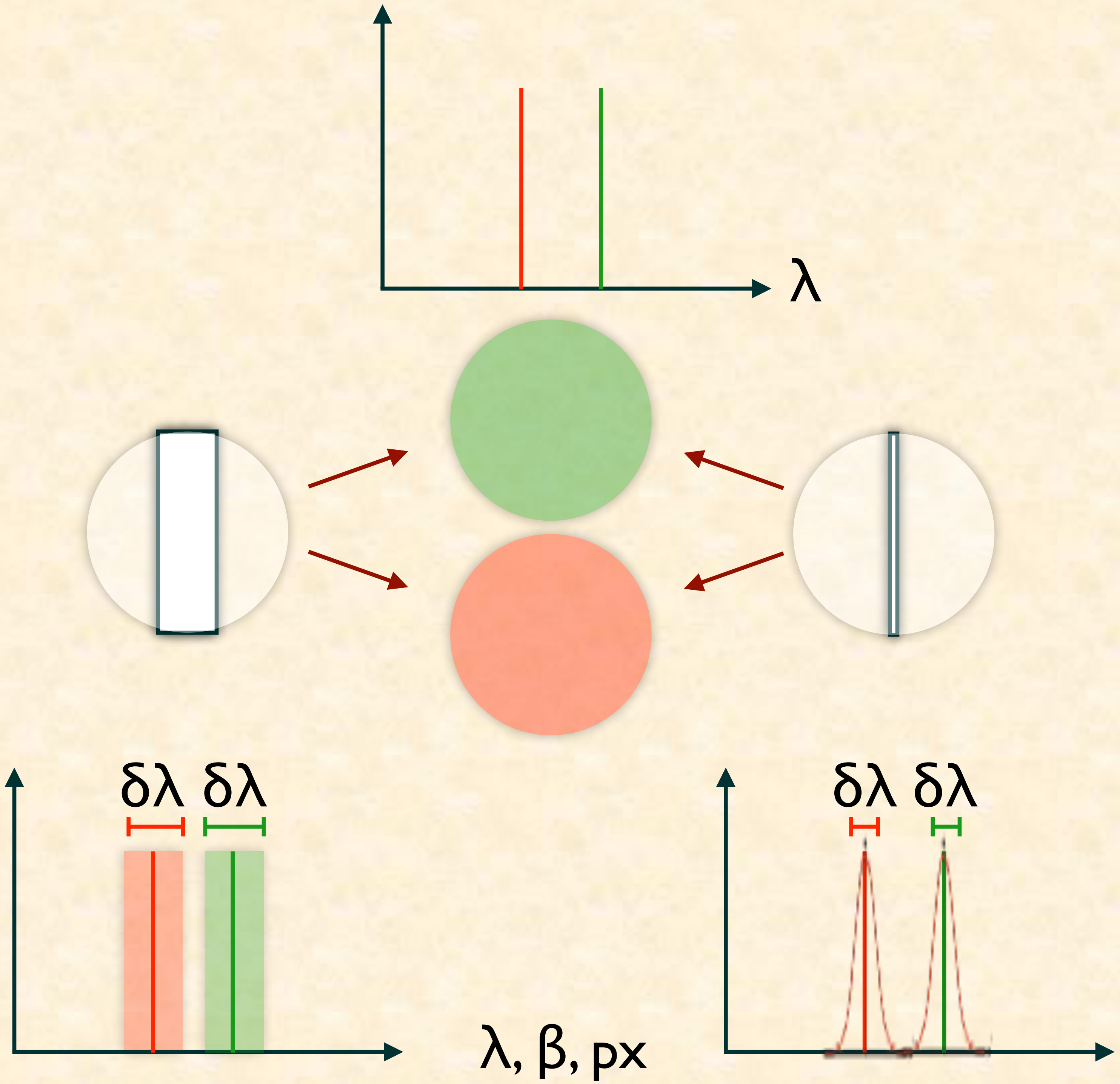
Cross dispersion may use prisms or low dispersion grating

Resolving power and IP

Input spectrum

Slit/fiber illumination

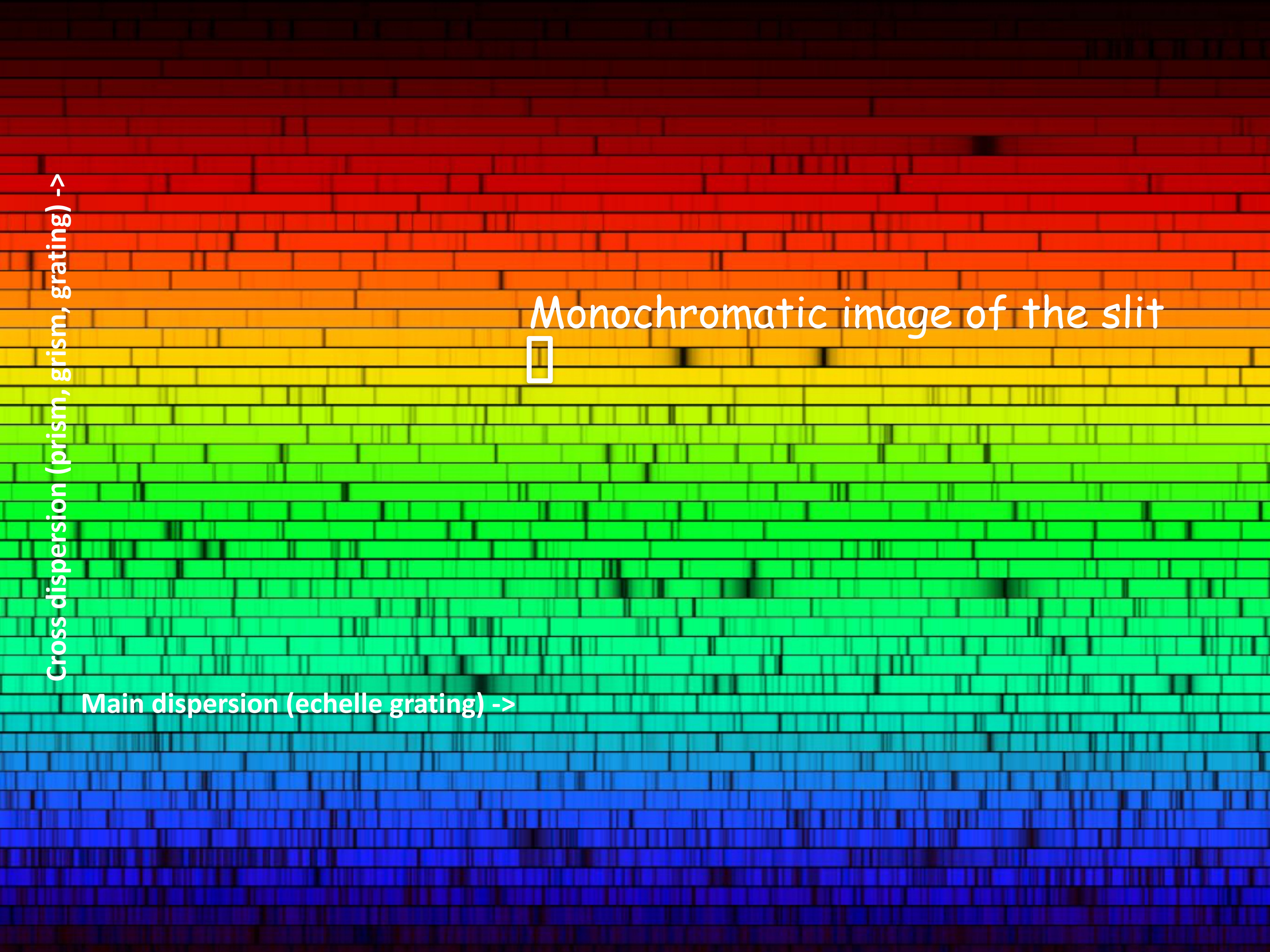
Output spectrum CCD



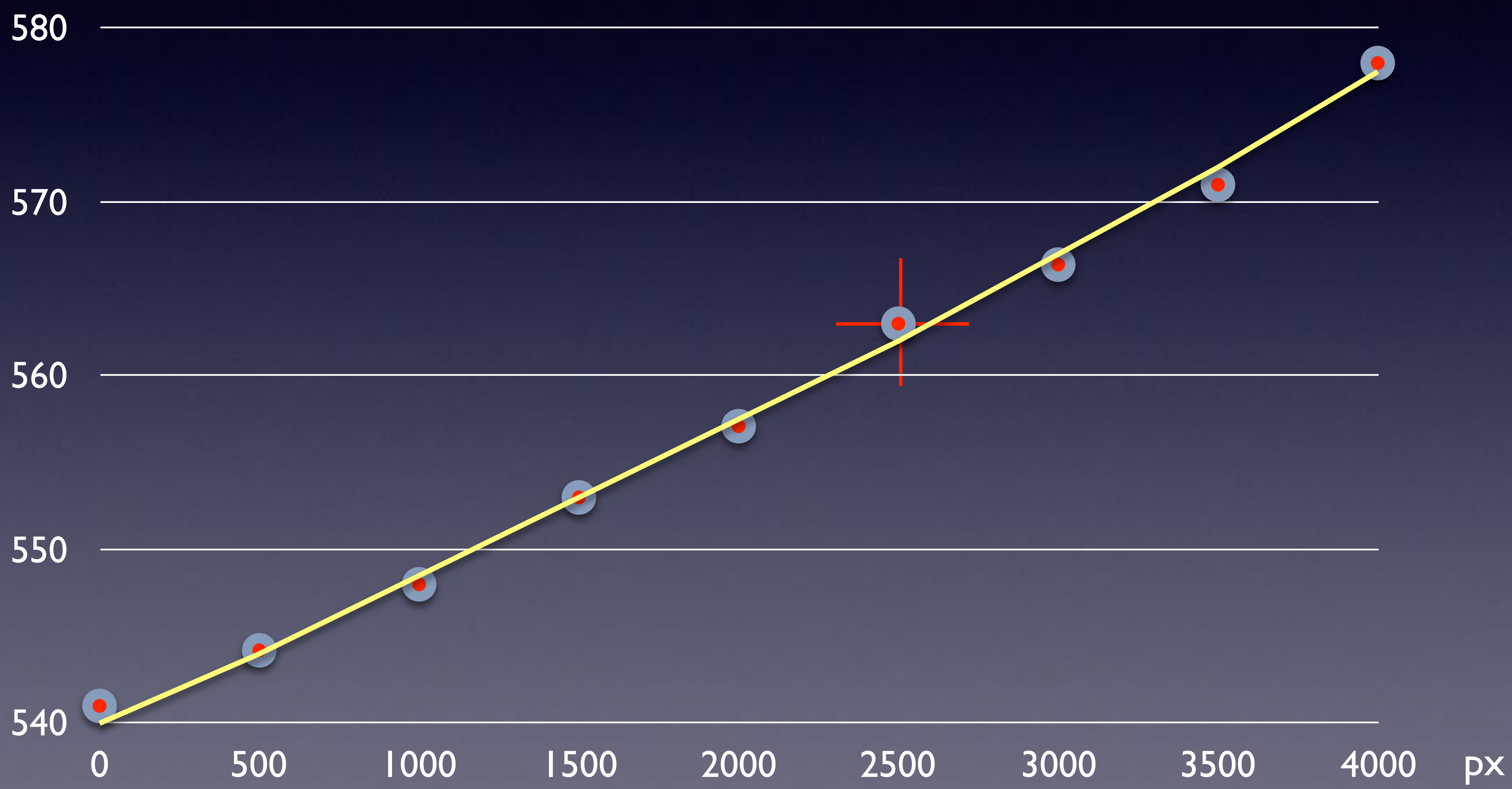
$R := \lambda/\delta\lambda$

Resolution

Resolving power

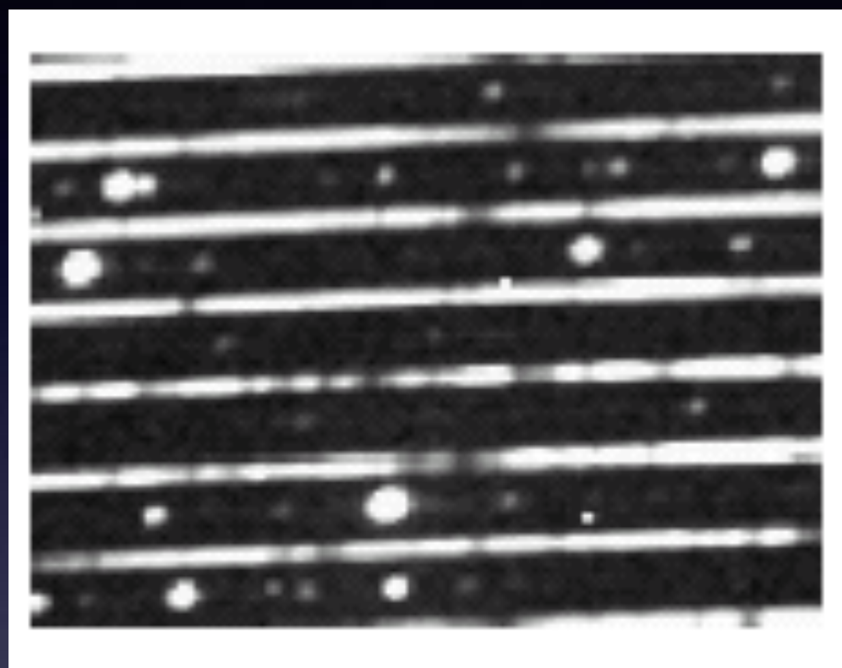

Monochromatic image of the slit
Cross dispersion (prism, grism, grating) ->
Main dispersion (echelle grating) ->

The wavelength calibration



The two main techniques ...

Simultaneous reference

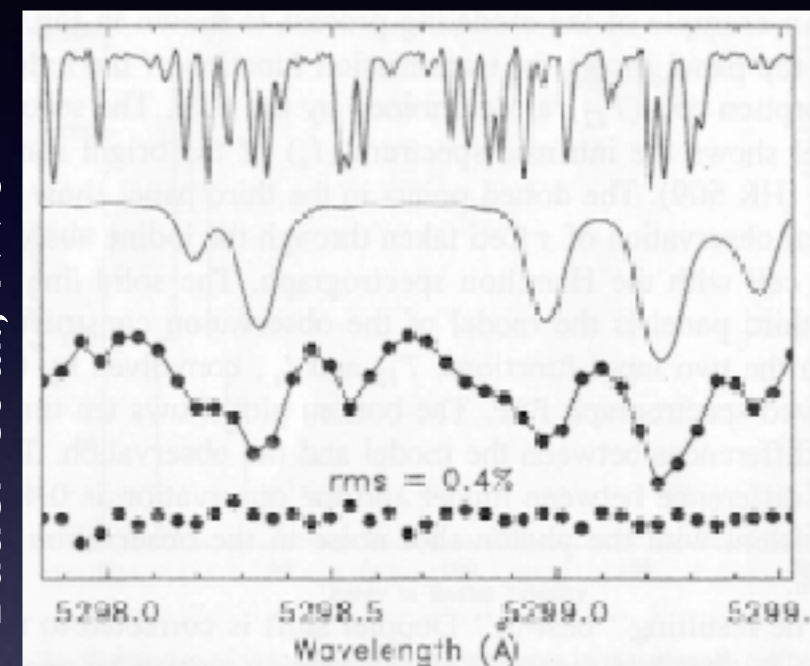


Baranne et al., 1996

‘HARPS-like’

- No differential IP changes allowed in time OR between fibres allowed
- Not suitable for slit spectrographs
- No losses, wide wavelength range
- IP modeling is POSSIBLE

Self reference (iodine cell)

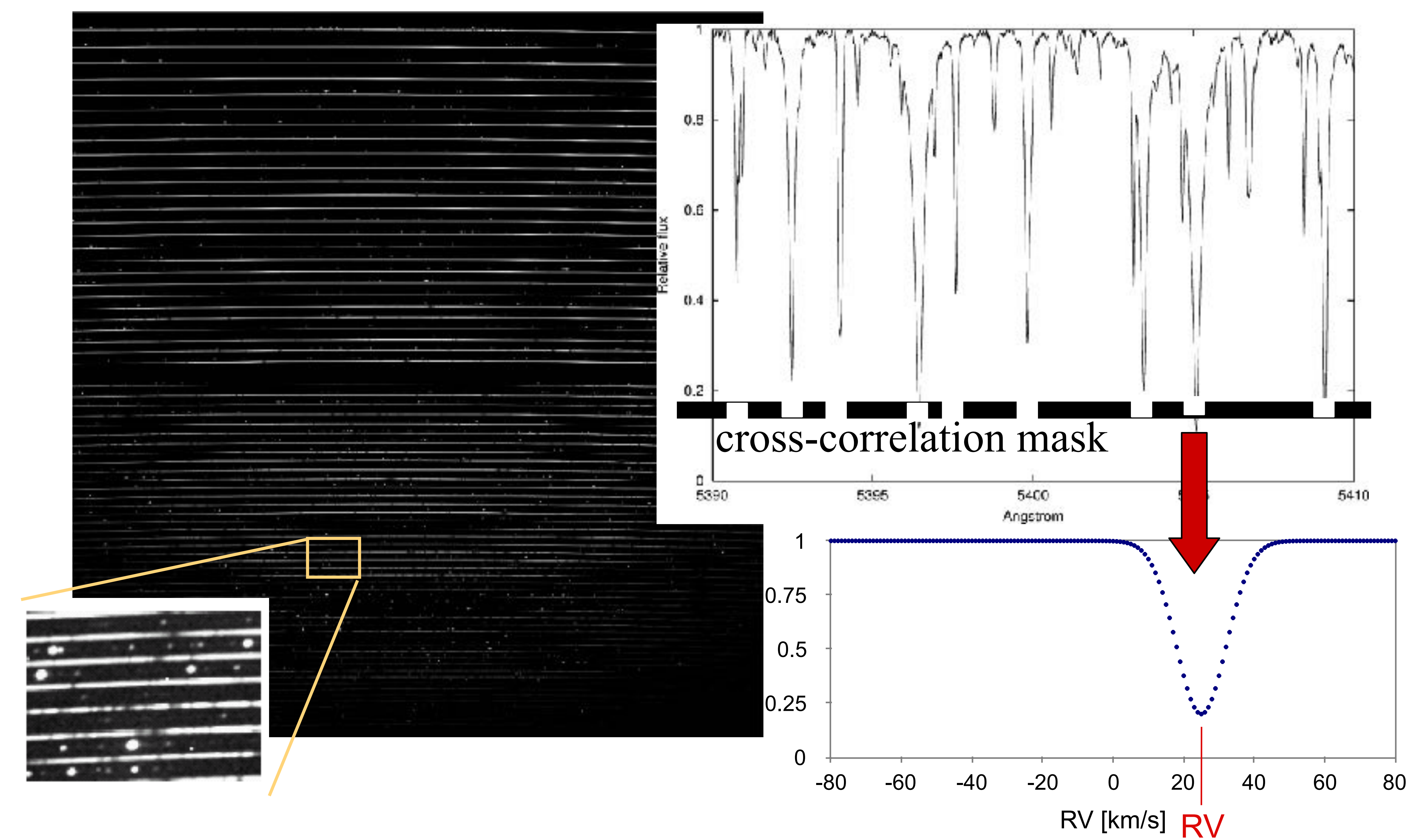


Butler et al., 1996

‘HIRES-like’

- IP may change may change with time as long as star and iodine affected identically
- Suitable for any/slit spectrographs
- Absorption, restricted wav. range
- REQUIRES ‘de-convolution’

Calibration and RV-information extraction



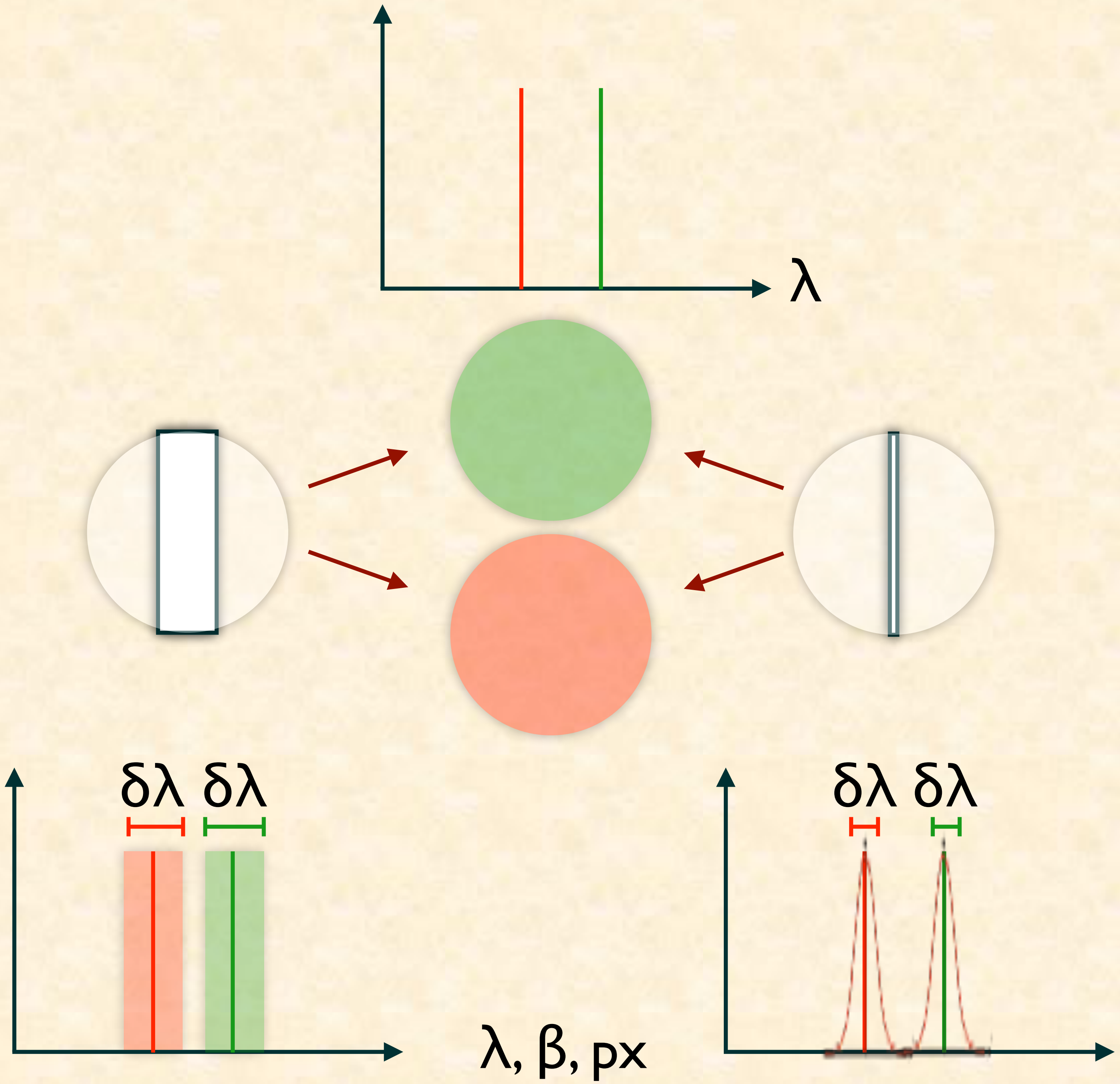
$$CCF(\mathrm{v_R}) = \int_{\lambda} M(\lambda,\mathrm{v_R}) \cdot I(\lambda), \quad \text{where} \quad M(\lambda) = \sum_{i} \theta_i(\lambda - \lambda_i) \cdot w_i$$

Resolving power and IP

Input spectrum

Slit/fiber illumination

Output spectrum CCD

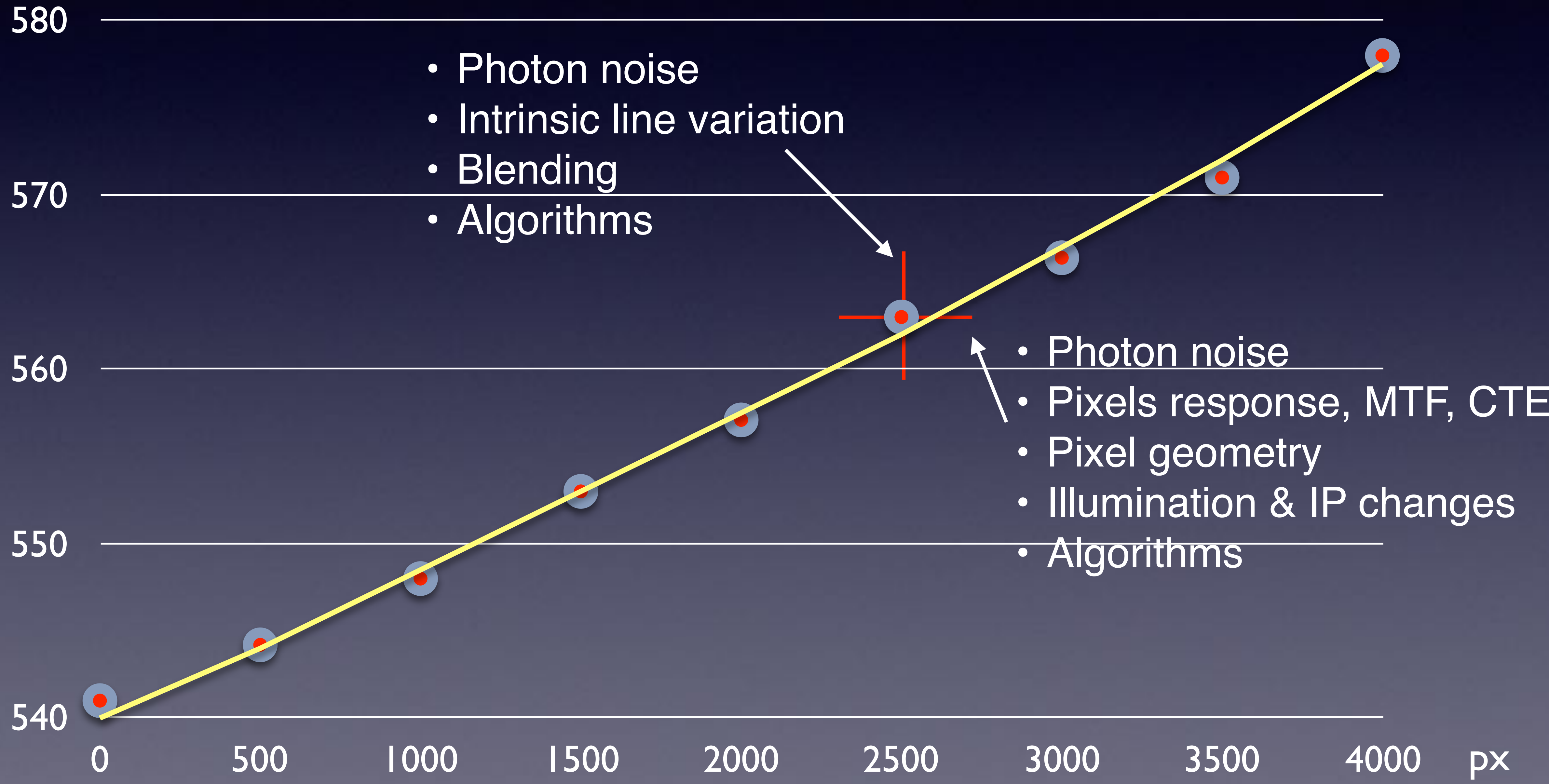


R := λ/δλ

Resolution

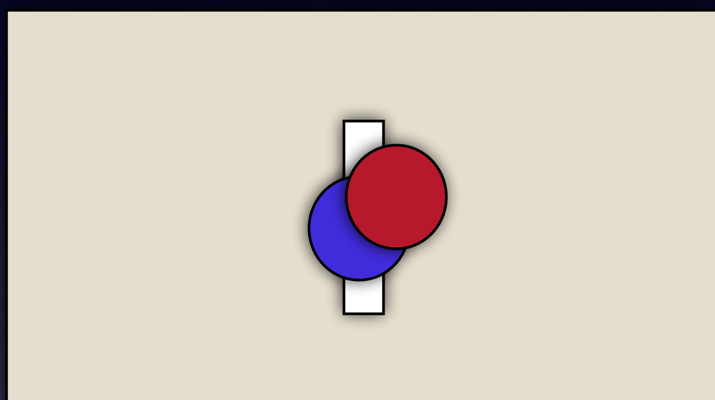
Resolving power

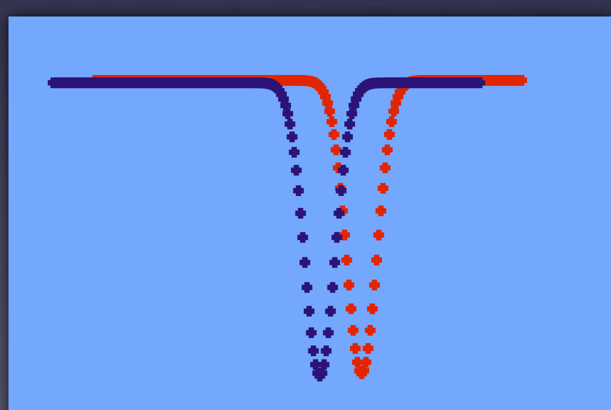
The wavelength calibration



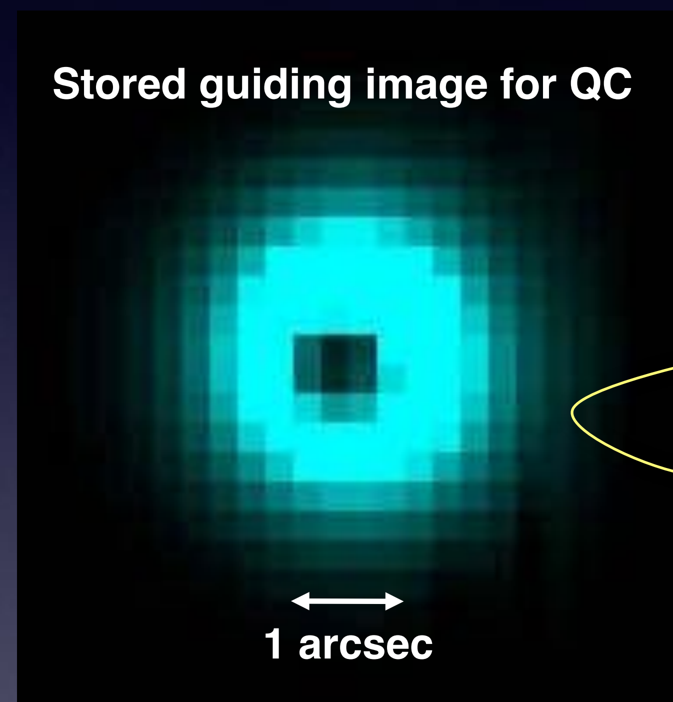
1. Illumination effects on IP

Slit-fed spectrograph



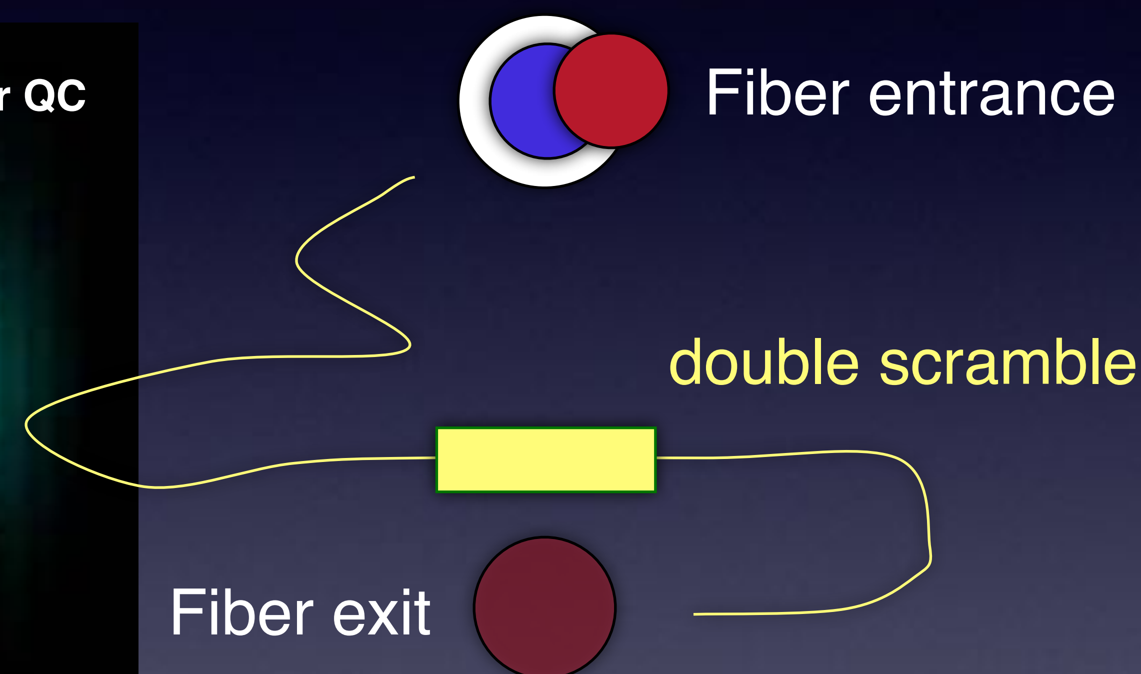


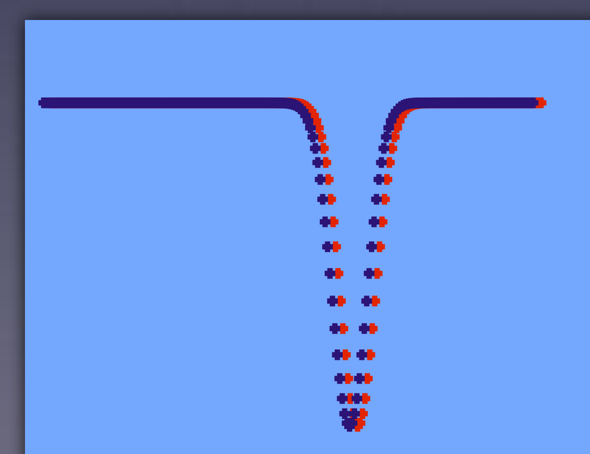
Δ RV



Guiding error:
0.5" → 2-4 m/s
(e.g. in HARPS)

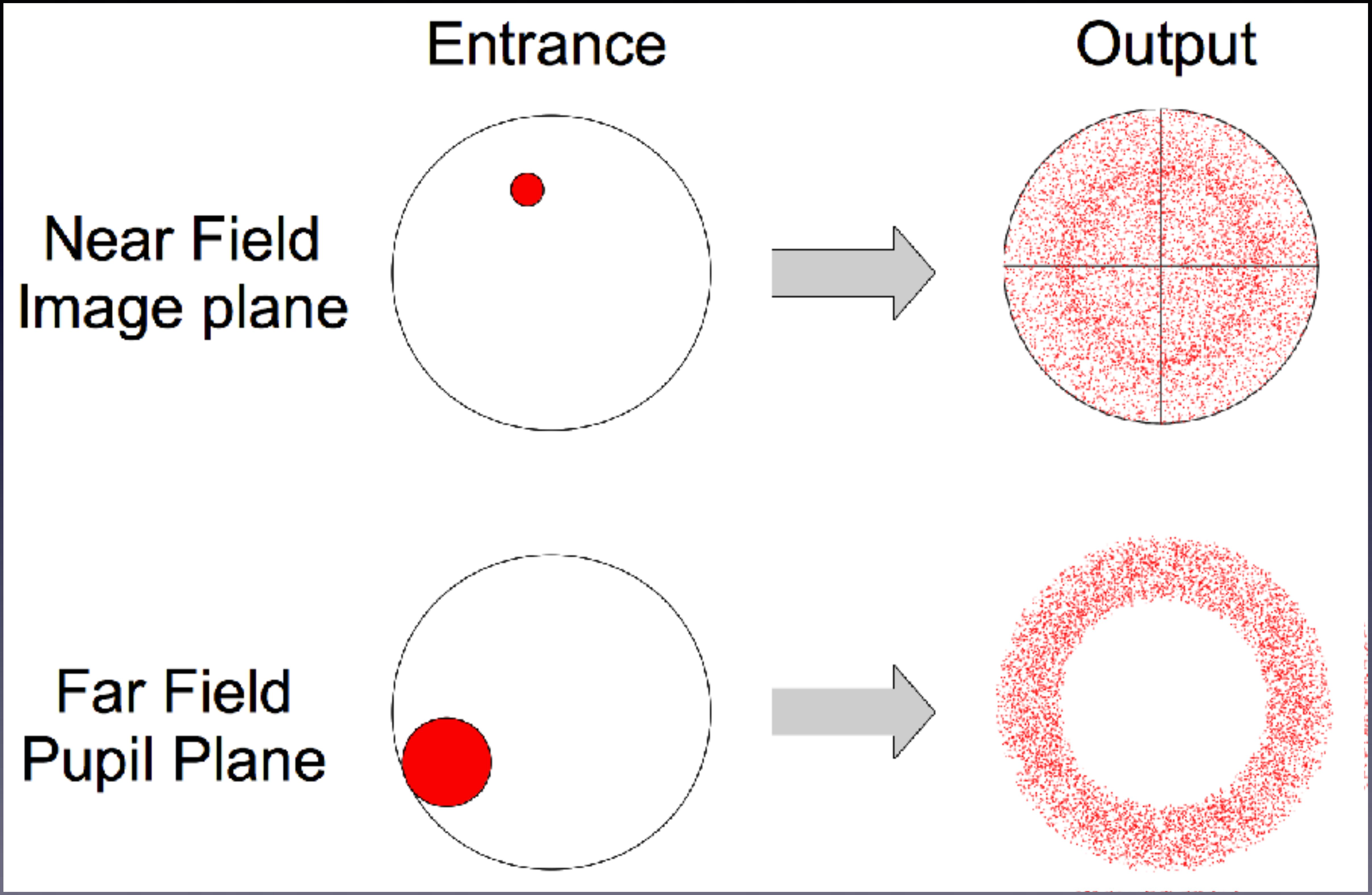
Fiber-fed spectrograph





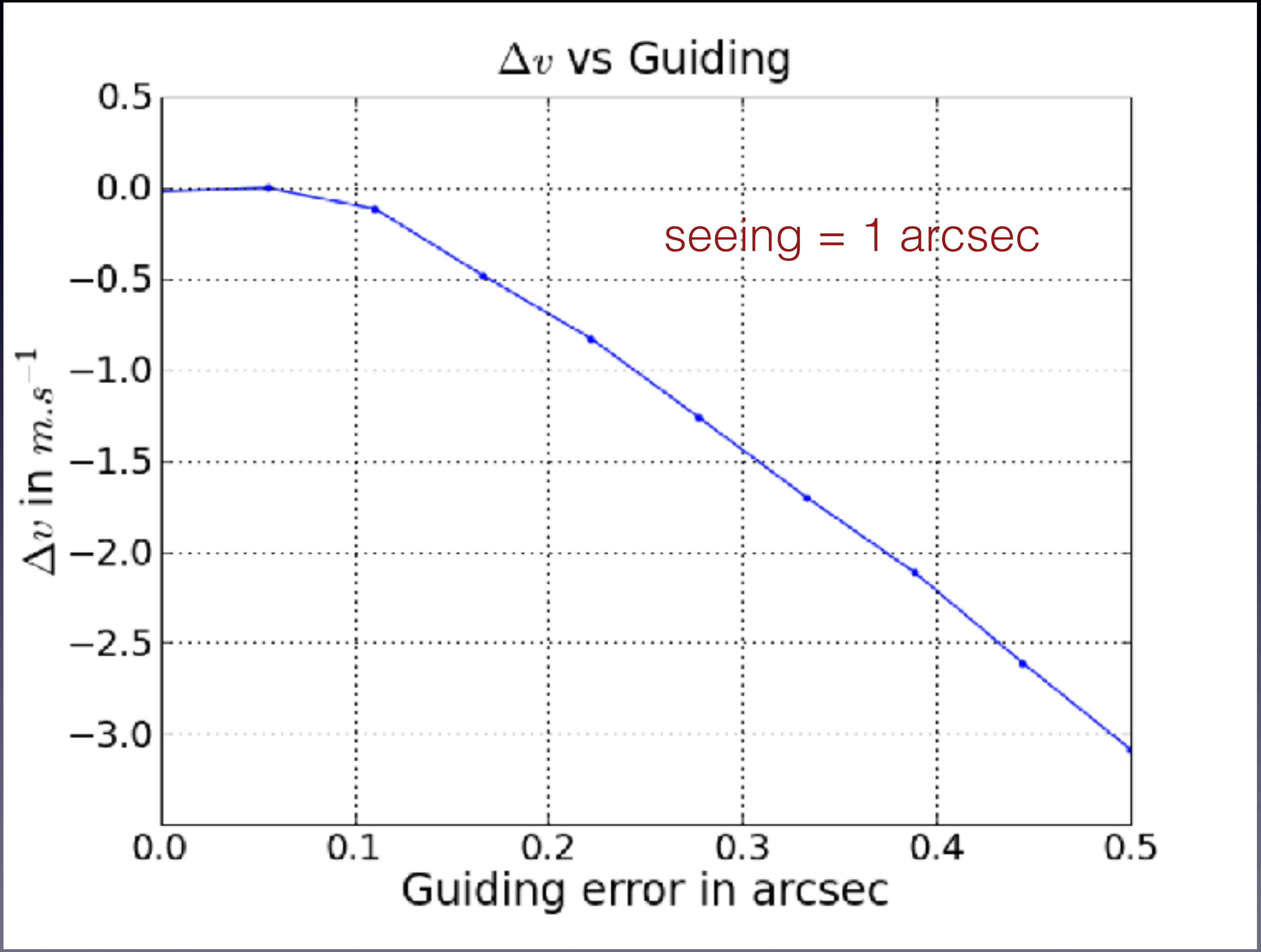
Δ RV

‘Scrambling’ properties of circular fiber

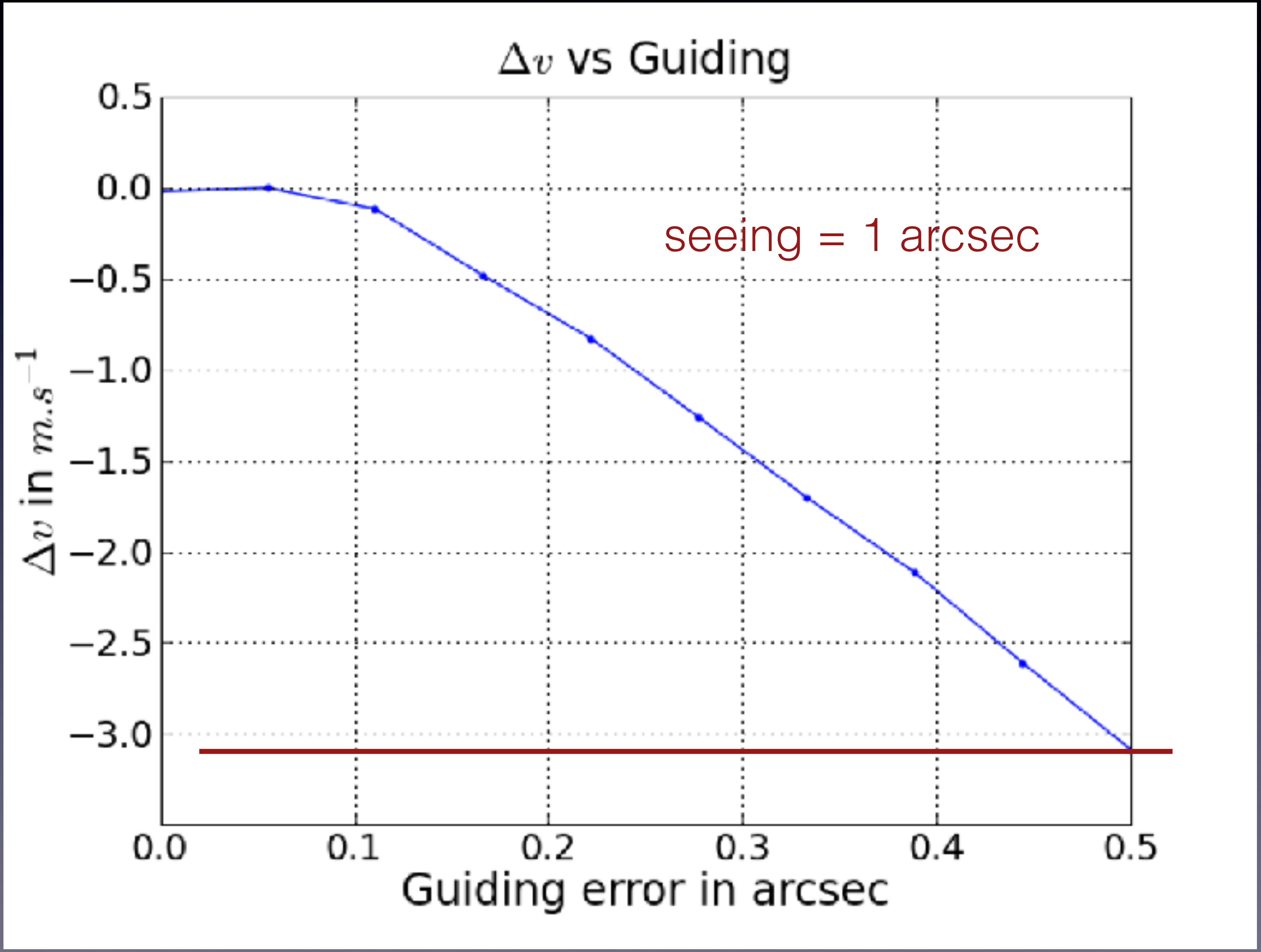


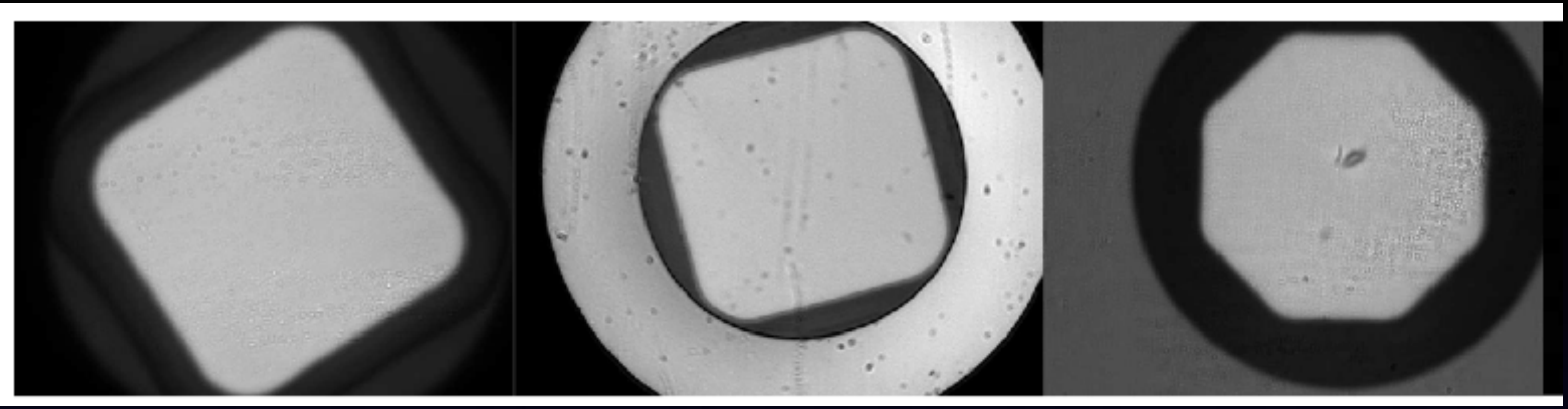
Chazelas et al. 2008, 2010

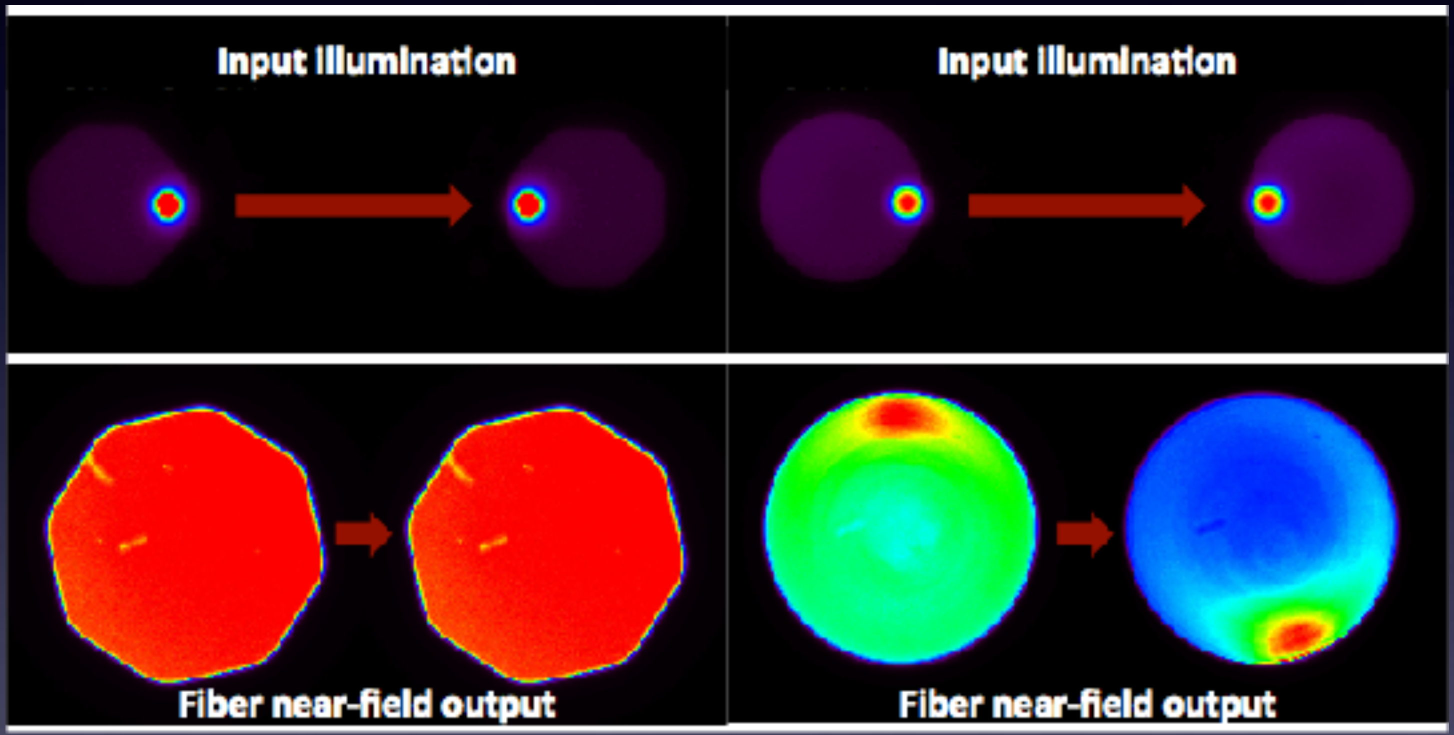
HARPS' residual guiding effects



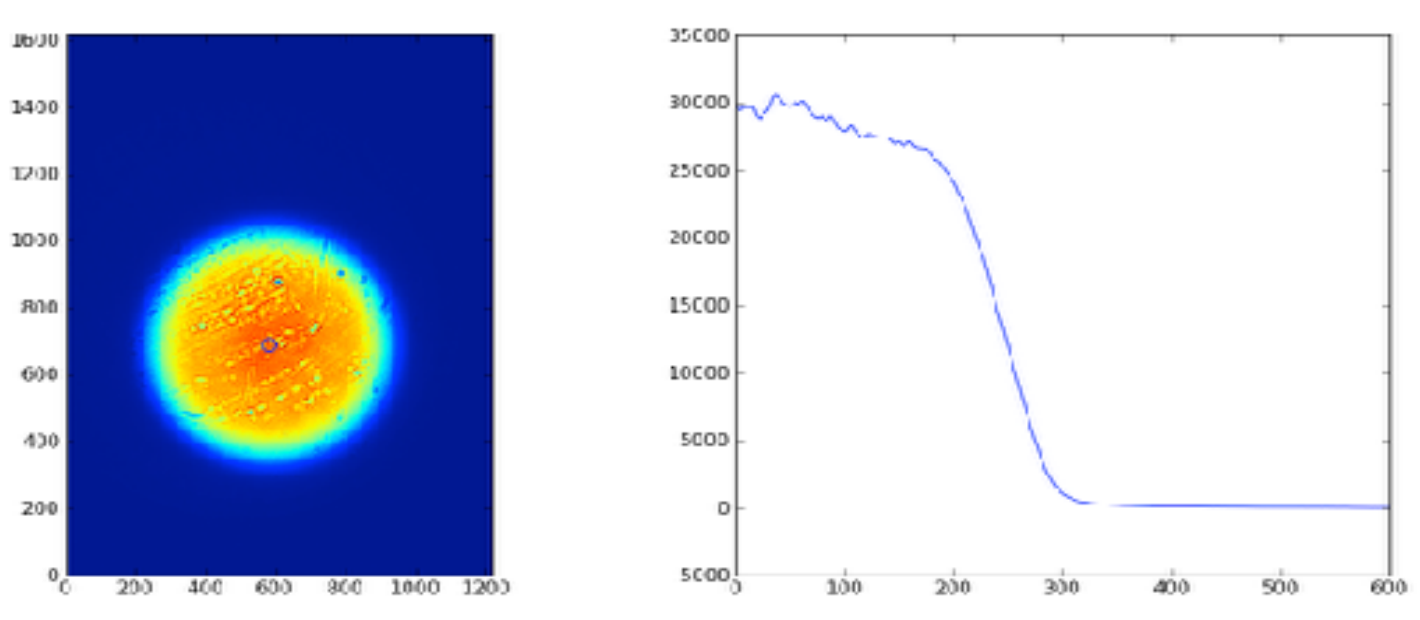
HARPS' residual guiding effects





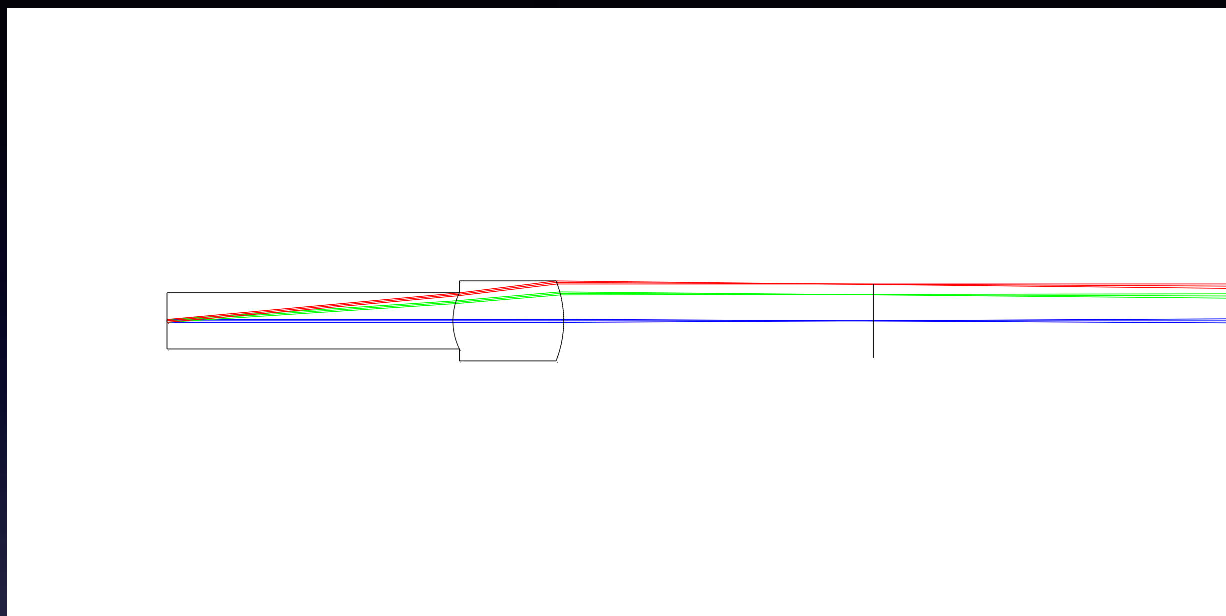


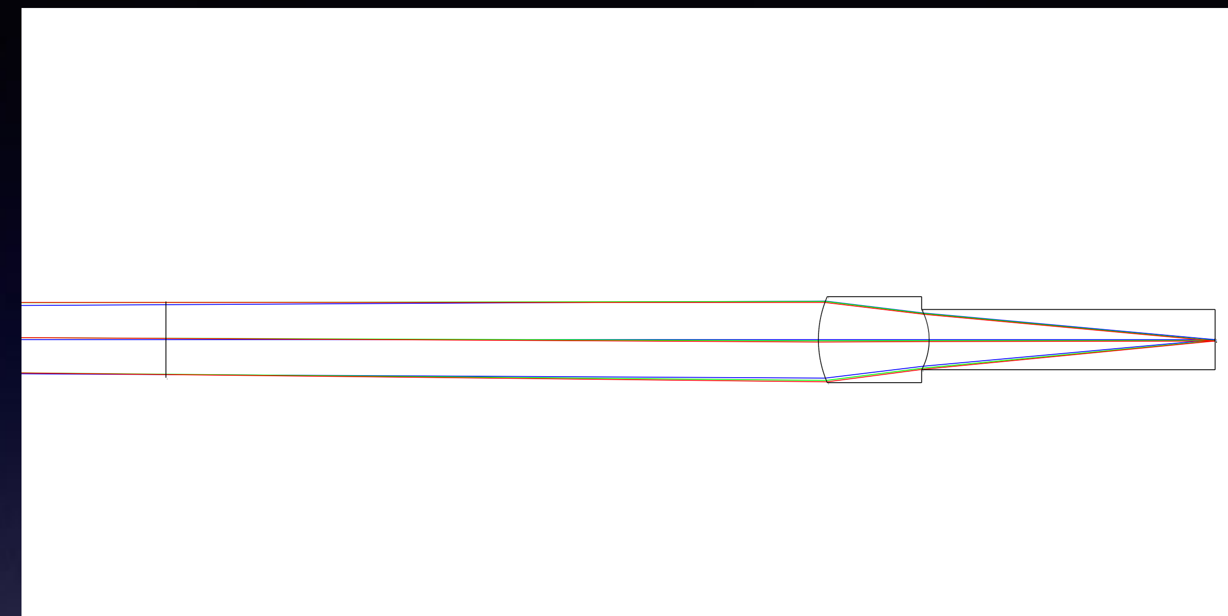
Near field
from HPF@PSU



Far field
from B. Chazelas, private communication

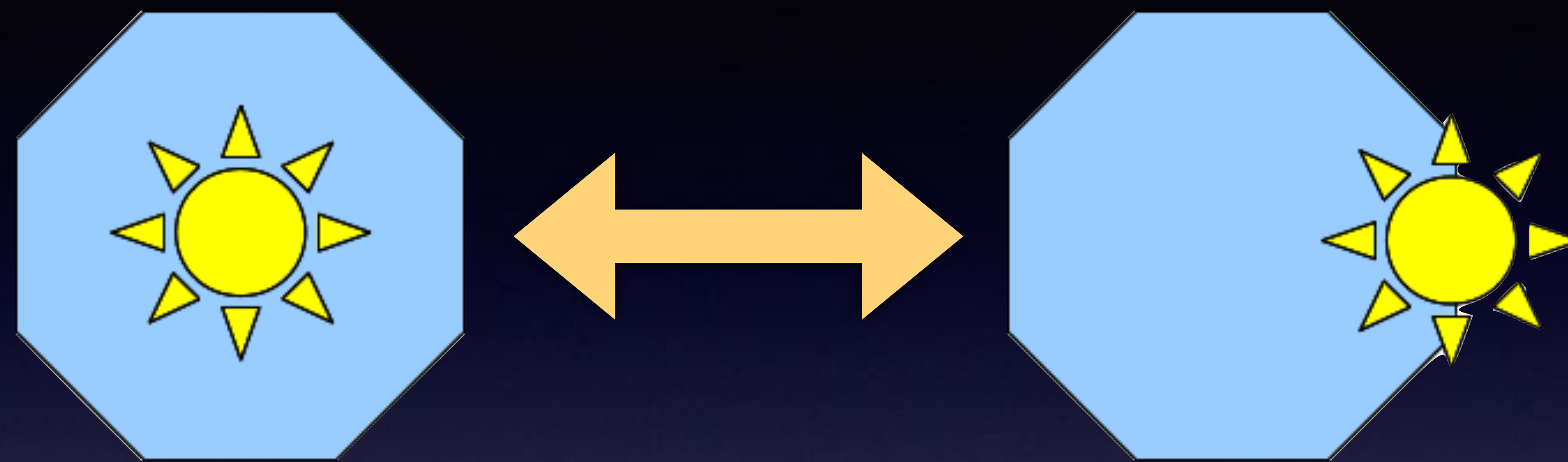
The HARPS/ESPRESSO double scrambler



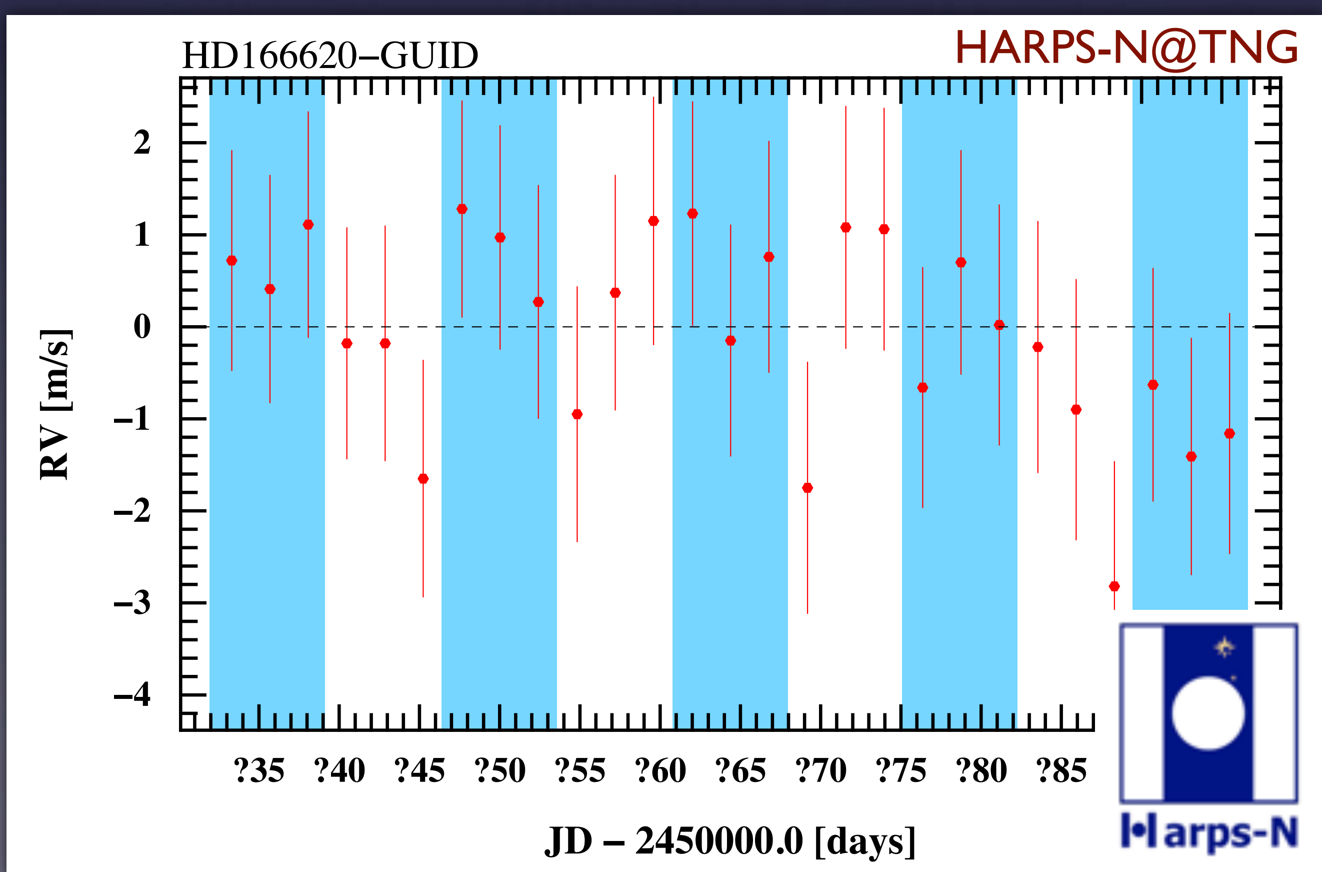


- Octagonal-double scrambler-octagonal
- Total efficiency: 72% absolute in F/4-beam (including giber-input optics F/8->F/4, 28m long fibers, scrambler, fiber-exit optics F/4->F/7.5)
- FRD induces about 10% losses per fiber at F4->F4
- Small lenses directly cemented on fiber tip: No need for AR coating, tele centricity 'built in', no problems with fiber termination, F-number matching 'built in'
- Both fibers in same ferrule and cemented on same lens at fiber exit -> stability

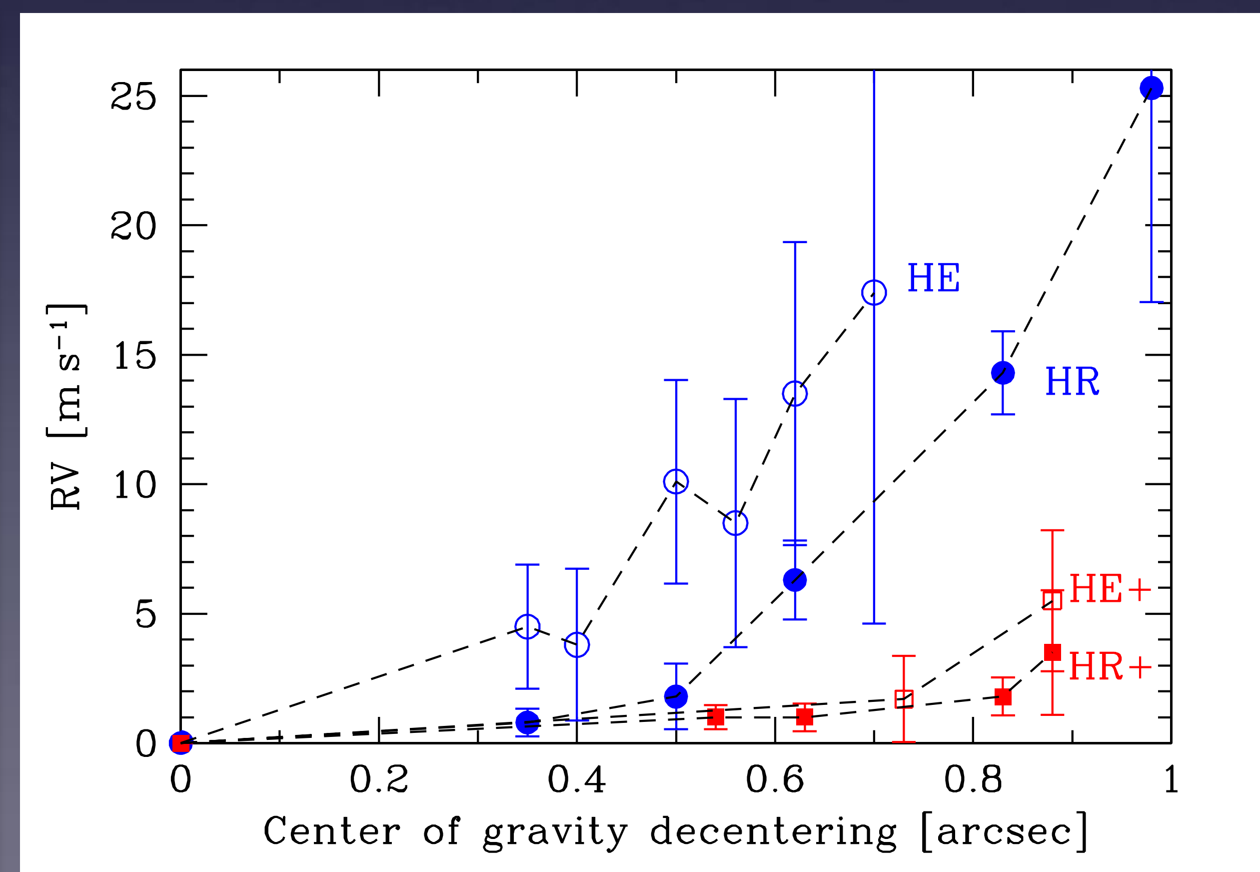
Solution: Double-scrambled octagonal fibers



Cosentino et al. 2014



Bouchy et al. 2013



Finite number of modes and coherence

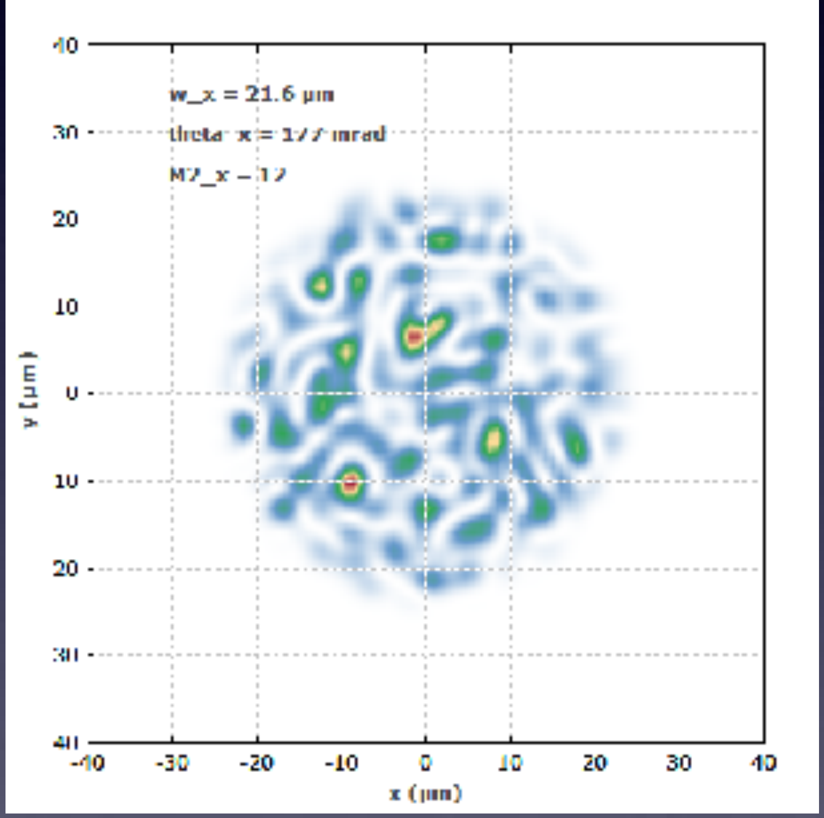
Number of modes 'transported' by a fiber is finite:

$$M = \frac{V^2}{2} = 2 \cdot \left(\frac{\pi r}{\lambda} NA \right)^2$$

Problem: The spectrograph IP depends on mode population

Solutions:

- Populate all modes (injection). Produce spatial and temporal 'scrambling'
- Mix very different modes (image scrambler)
- Change the transported modes by shaking and moving the fiber

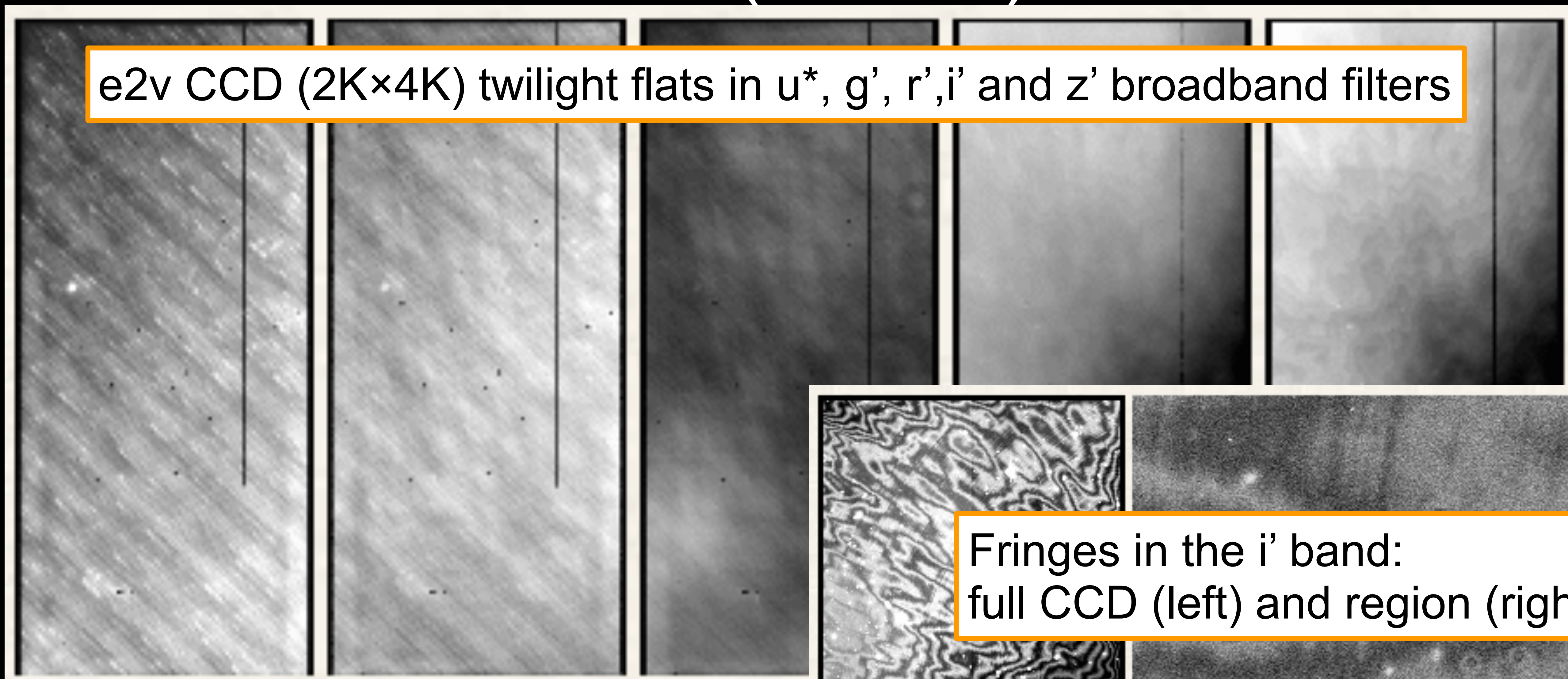


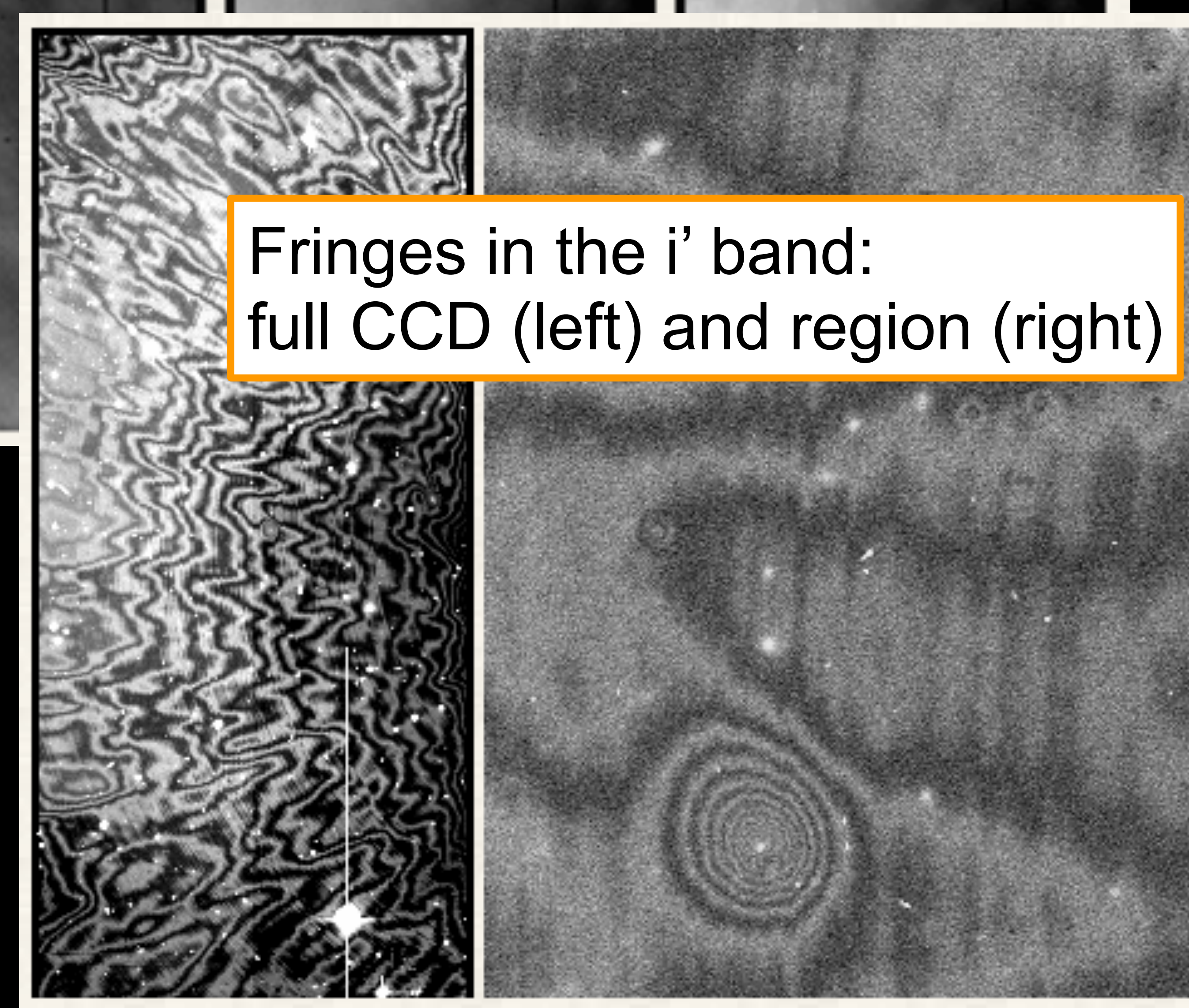
From http://www.rp-photonics.com/

Still a problem:

- Little number of modes at IR wavelength (bad averaging!)
- Self-coherence of very coherent sources (e.g. LFCs!)

2. Flat-field (PRNU) effects

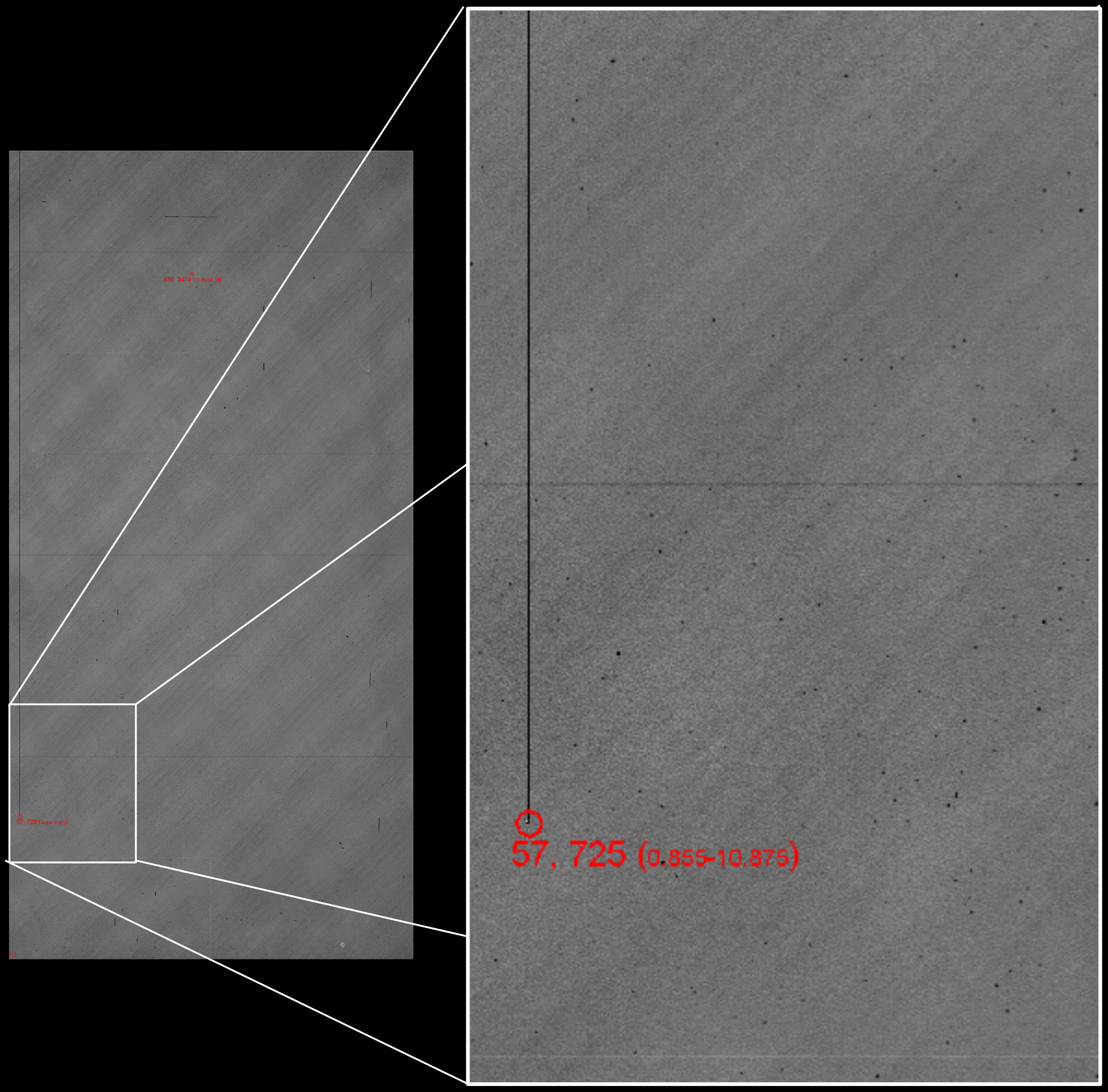


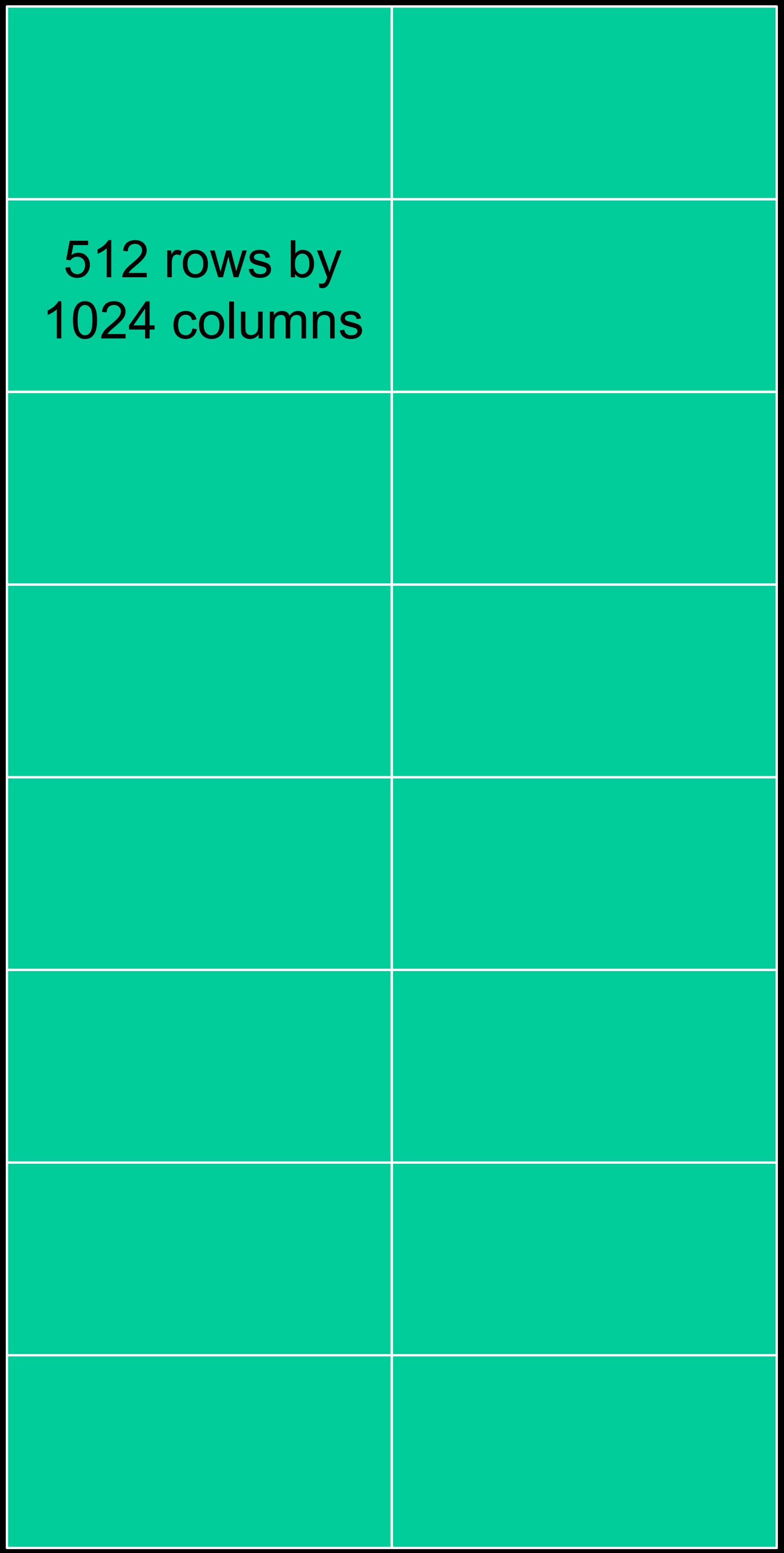


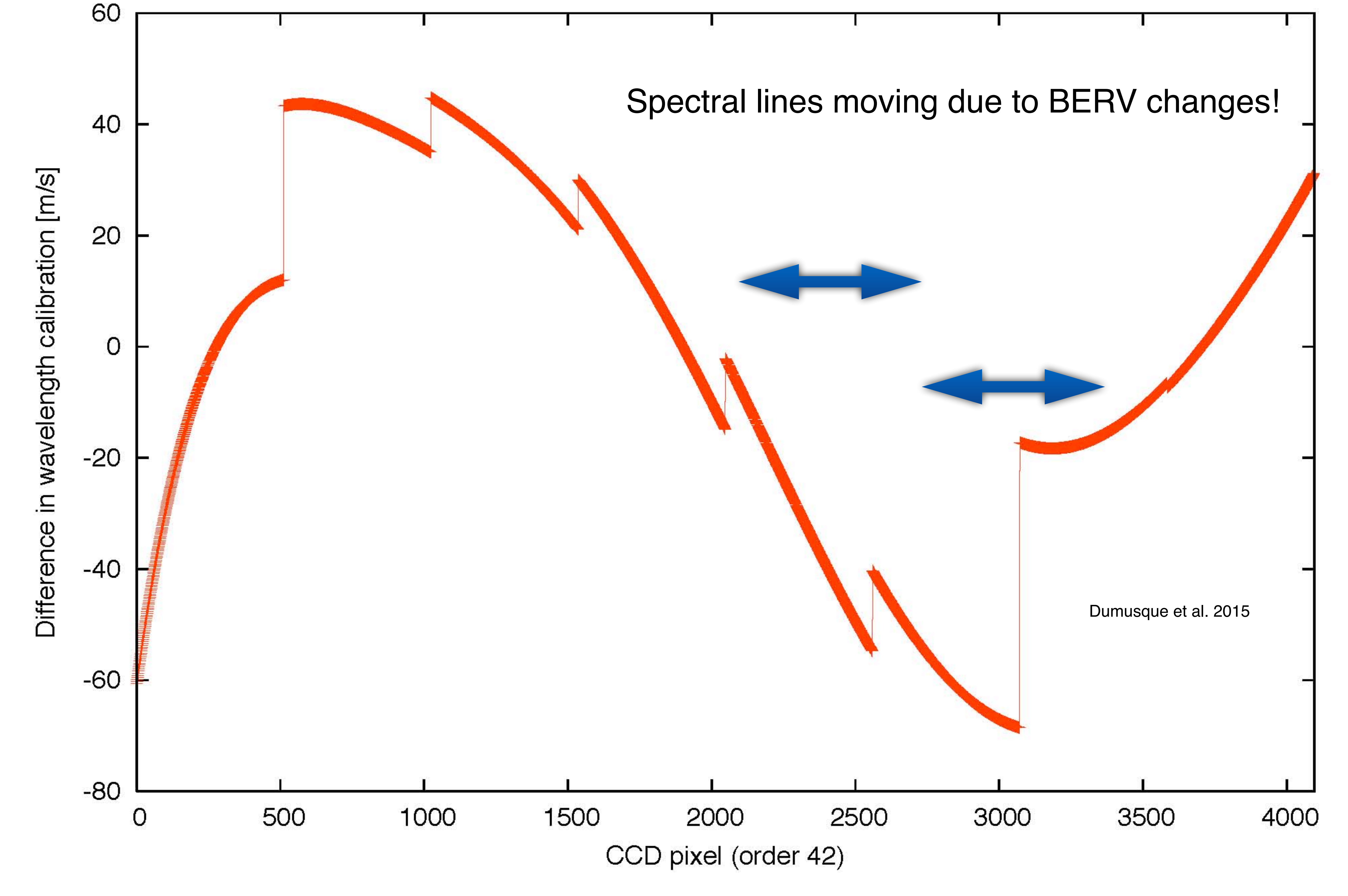
Solutions:

- Fast camera beam
- Stable instrument and CCD
- Deep-depleted CCD
- Frequent characterisation
- High SNR spectral flats

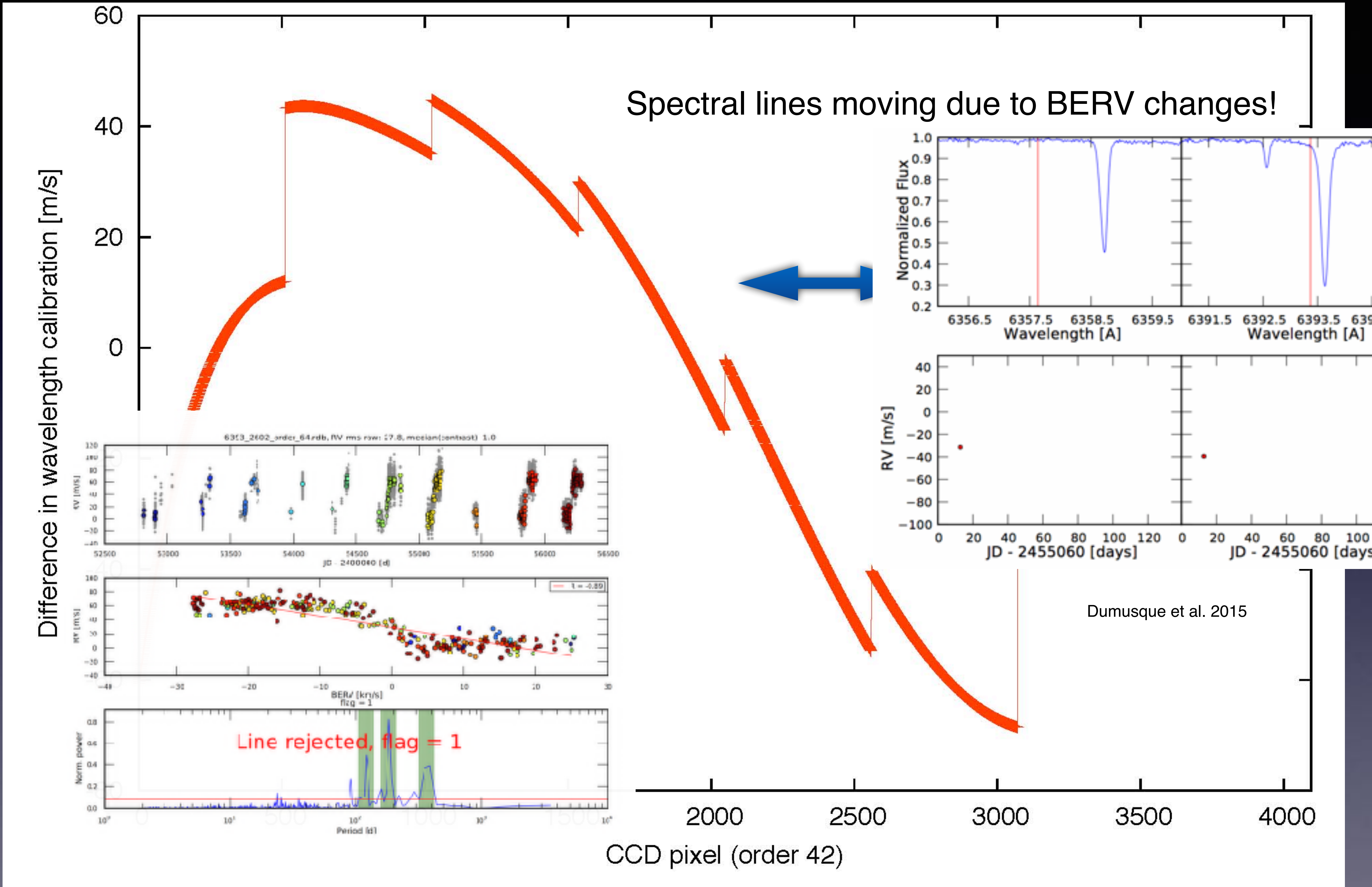
3. Pixel geometry and block stitching







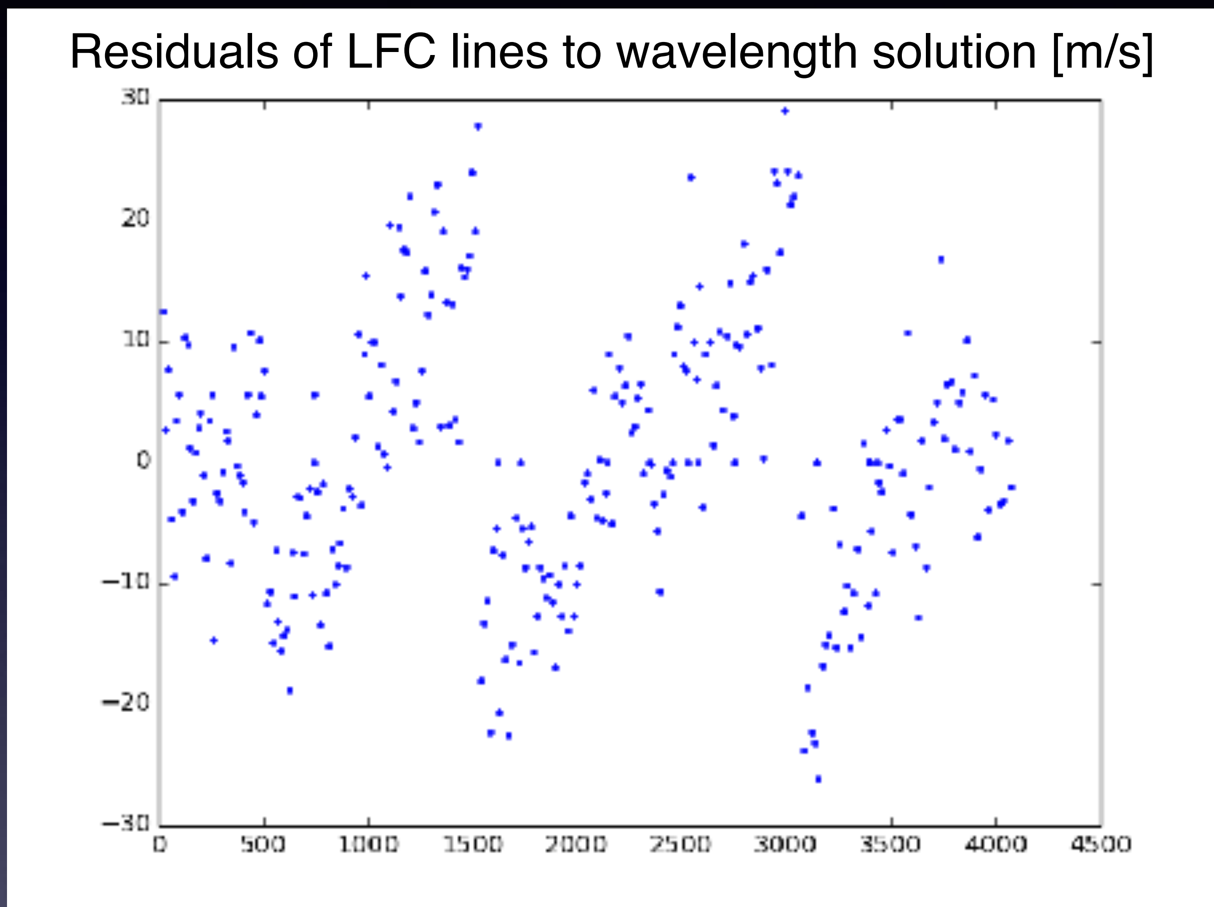
Steinmetz et al., 2008



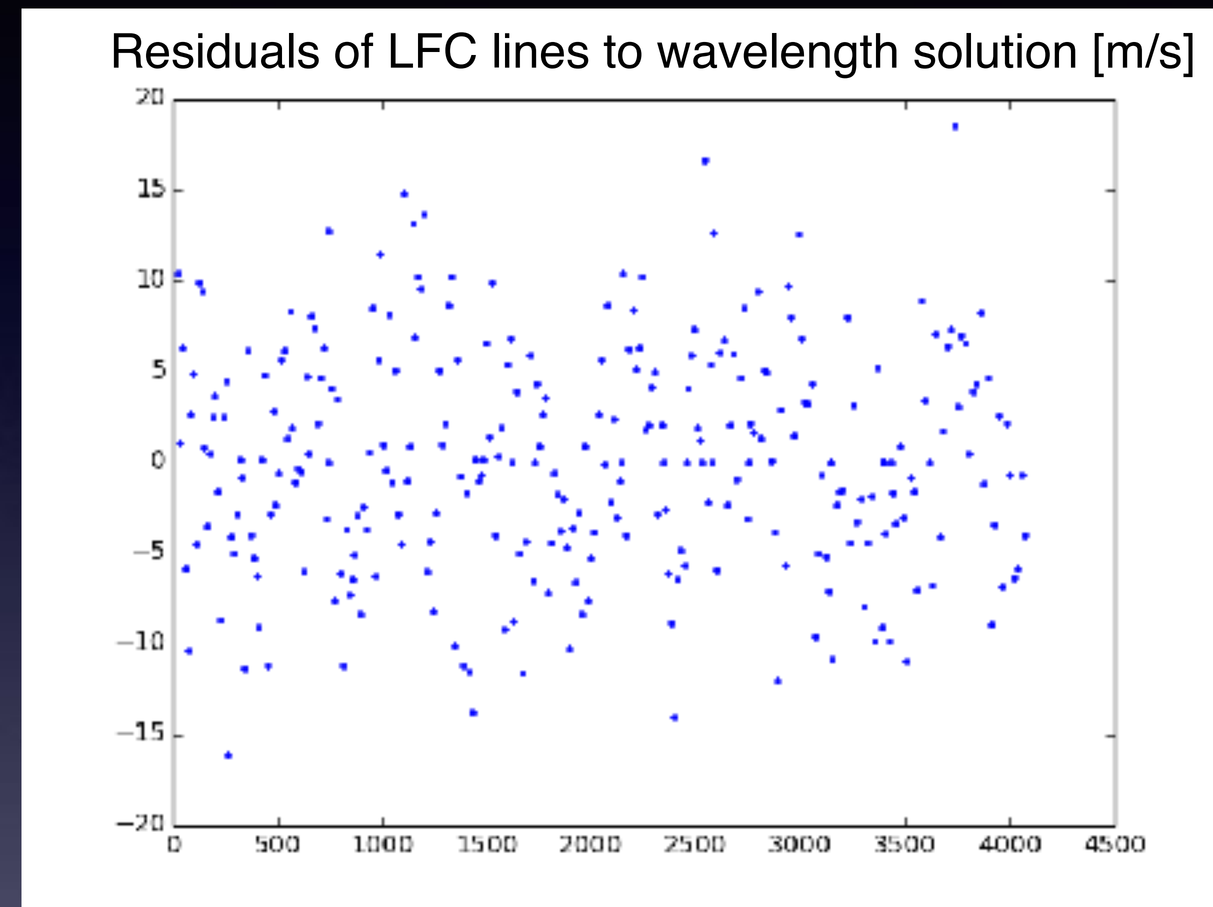
Steinmetz et al., 2008

Solution: Just ‘measure' pixel with FF!

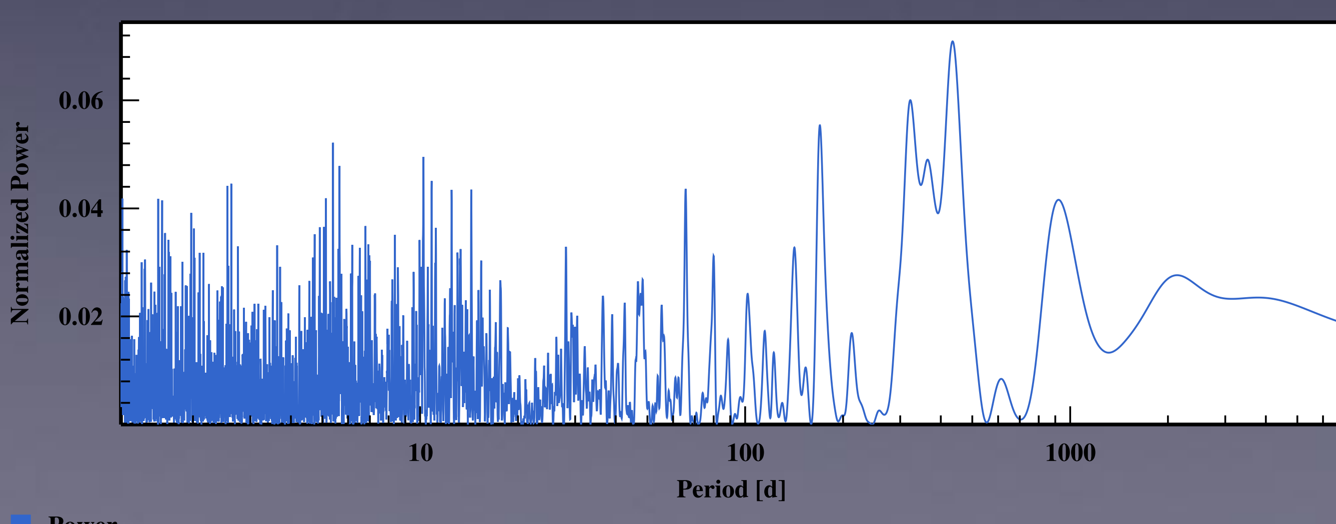
Before

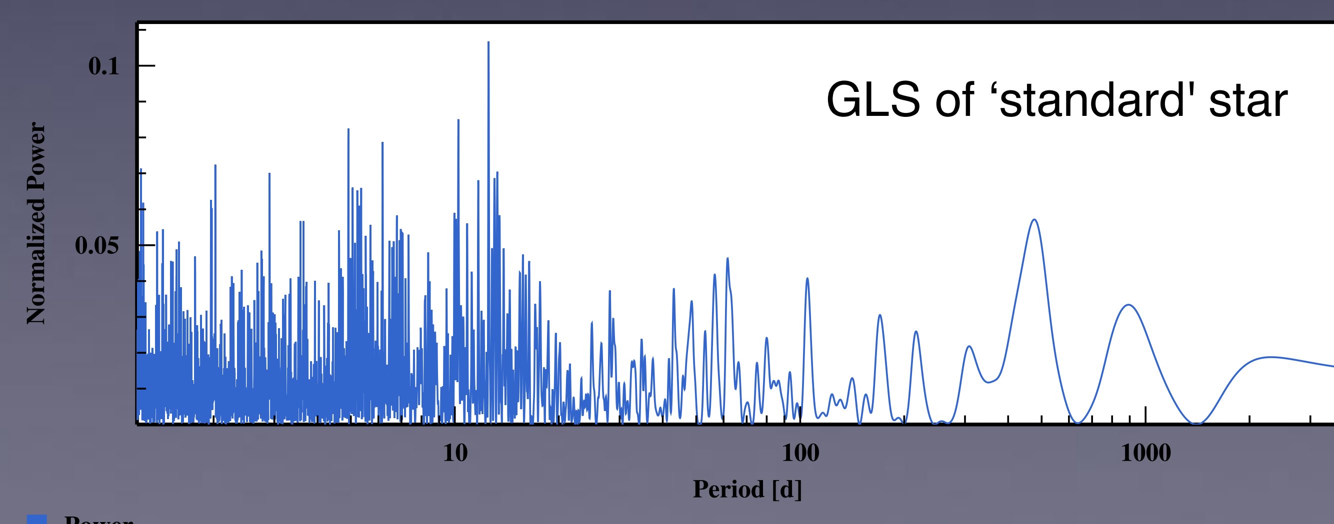


After



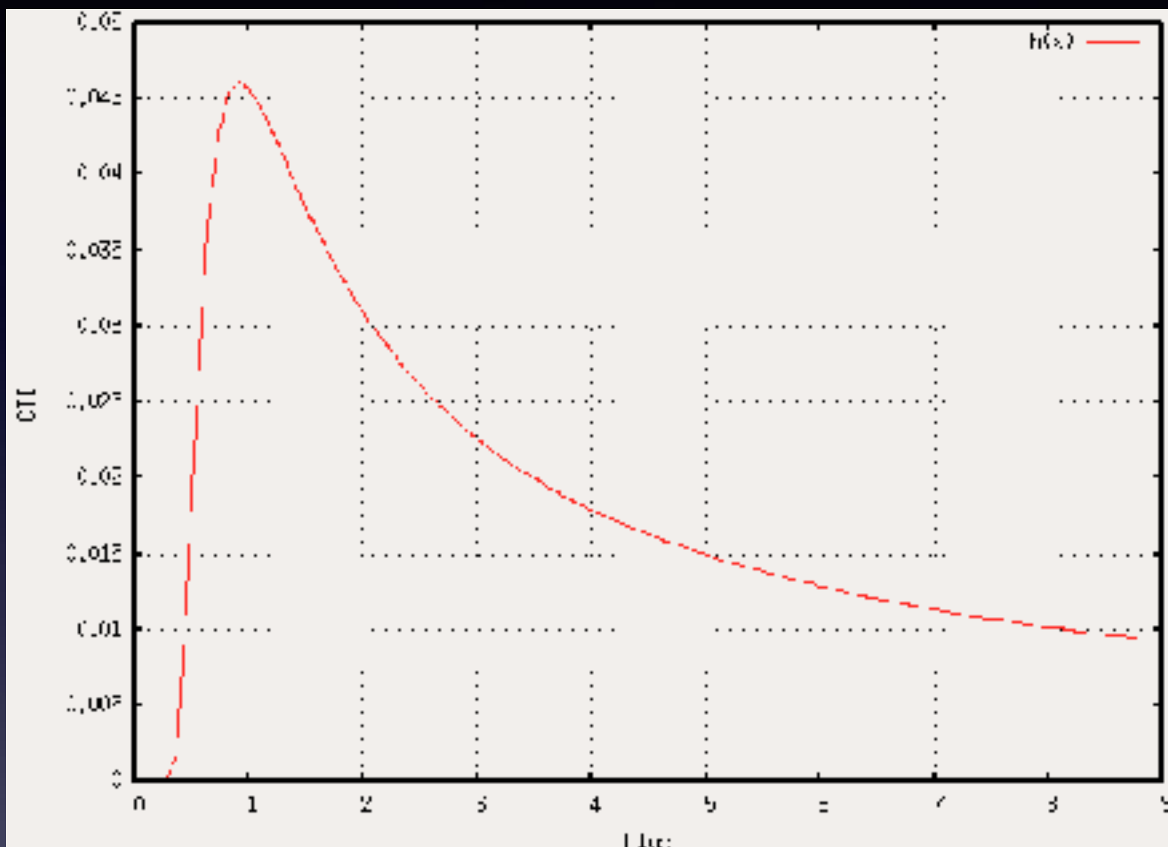
Coffinet et al., in prep.

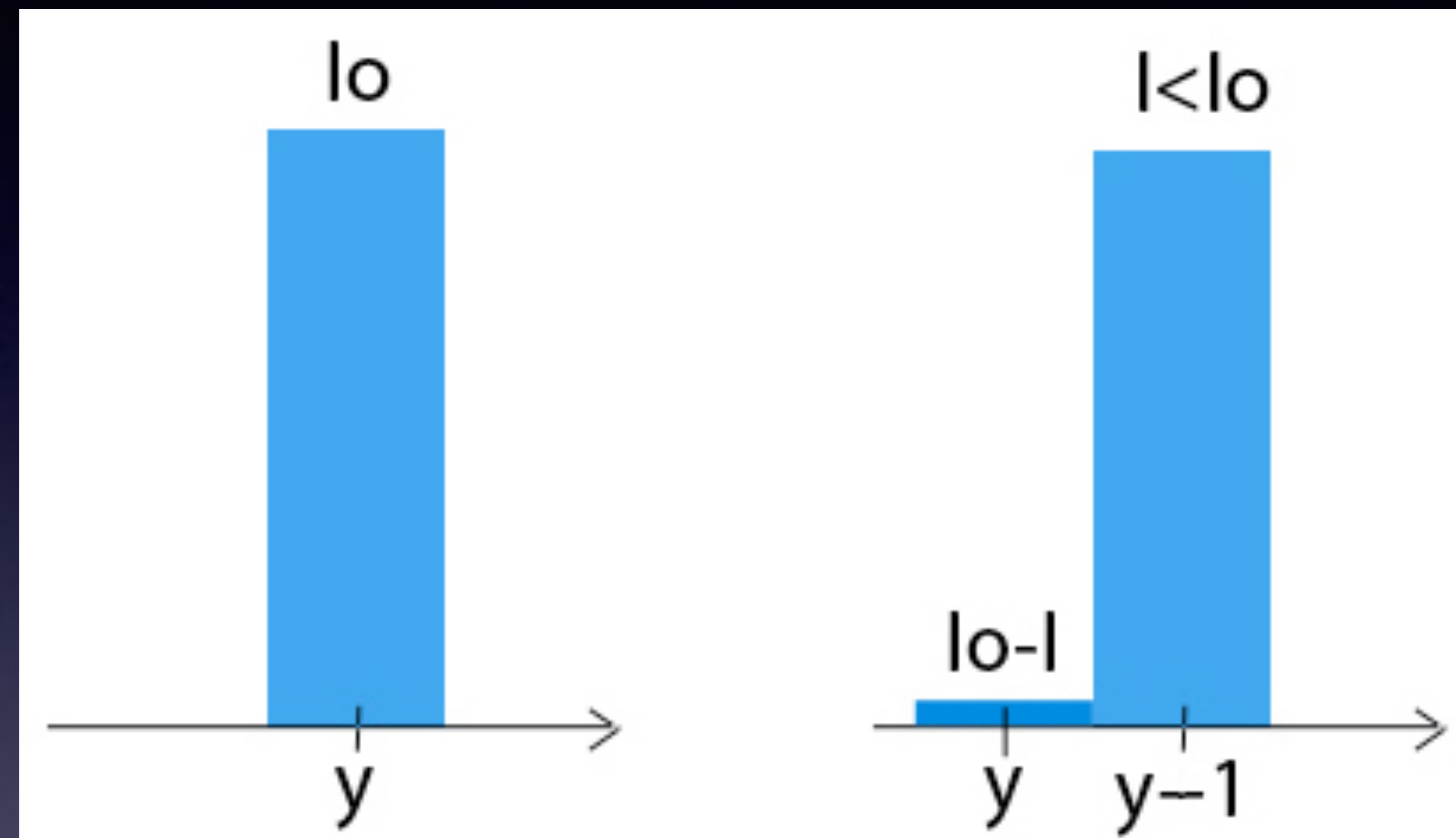




4. CTE Problem

CTI vs Flux

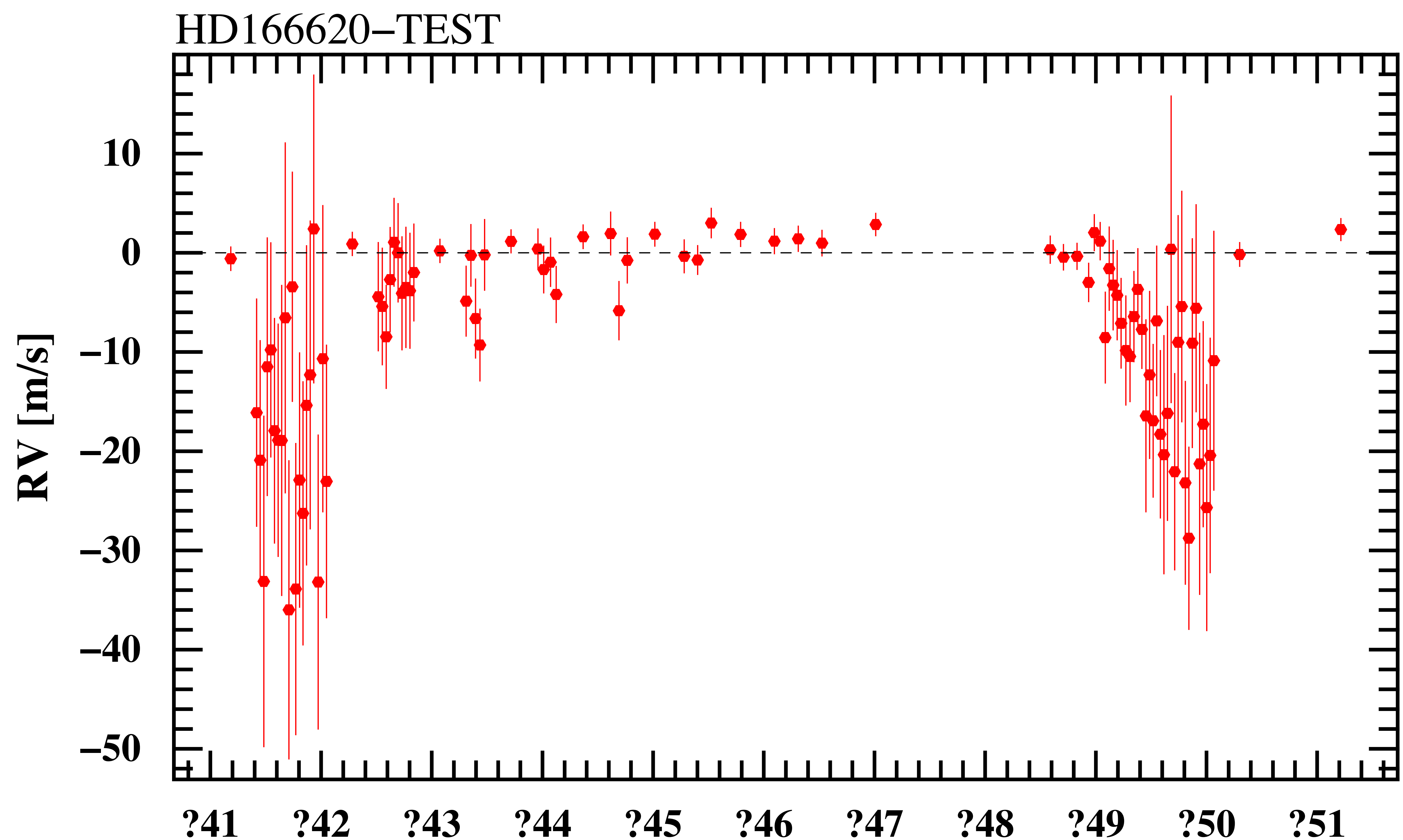




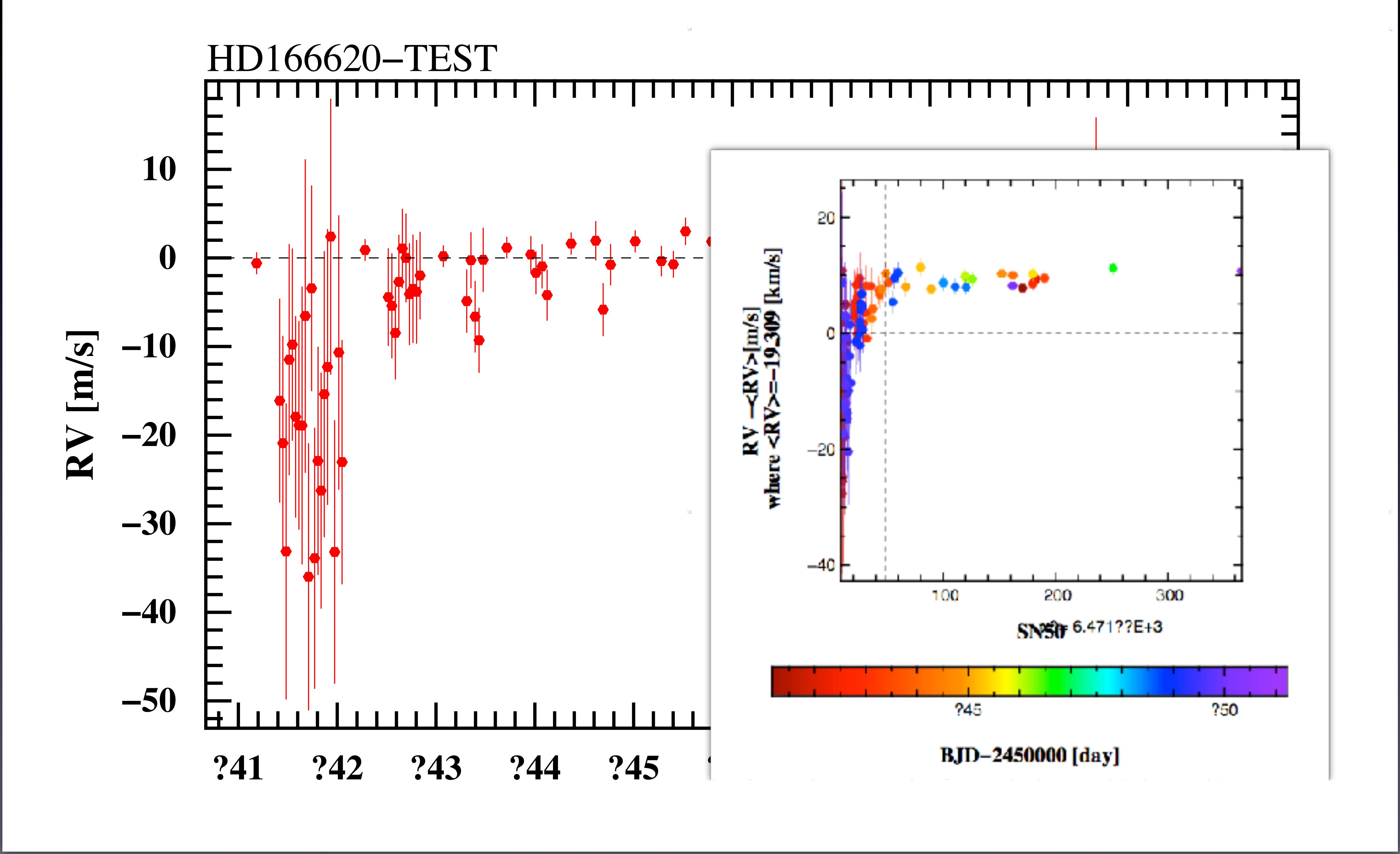
Solutions:

- Recover original flux-pixel distribution by recursive correction on raw frame
- High-CTE CCDs (at least six 9’s, but difficult to get!)
- Possibly ‘pre-‘ or ‘post flash’ to increase number of electrons in pixel

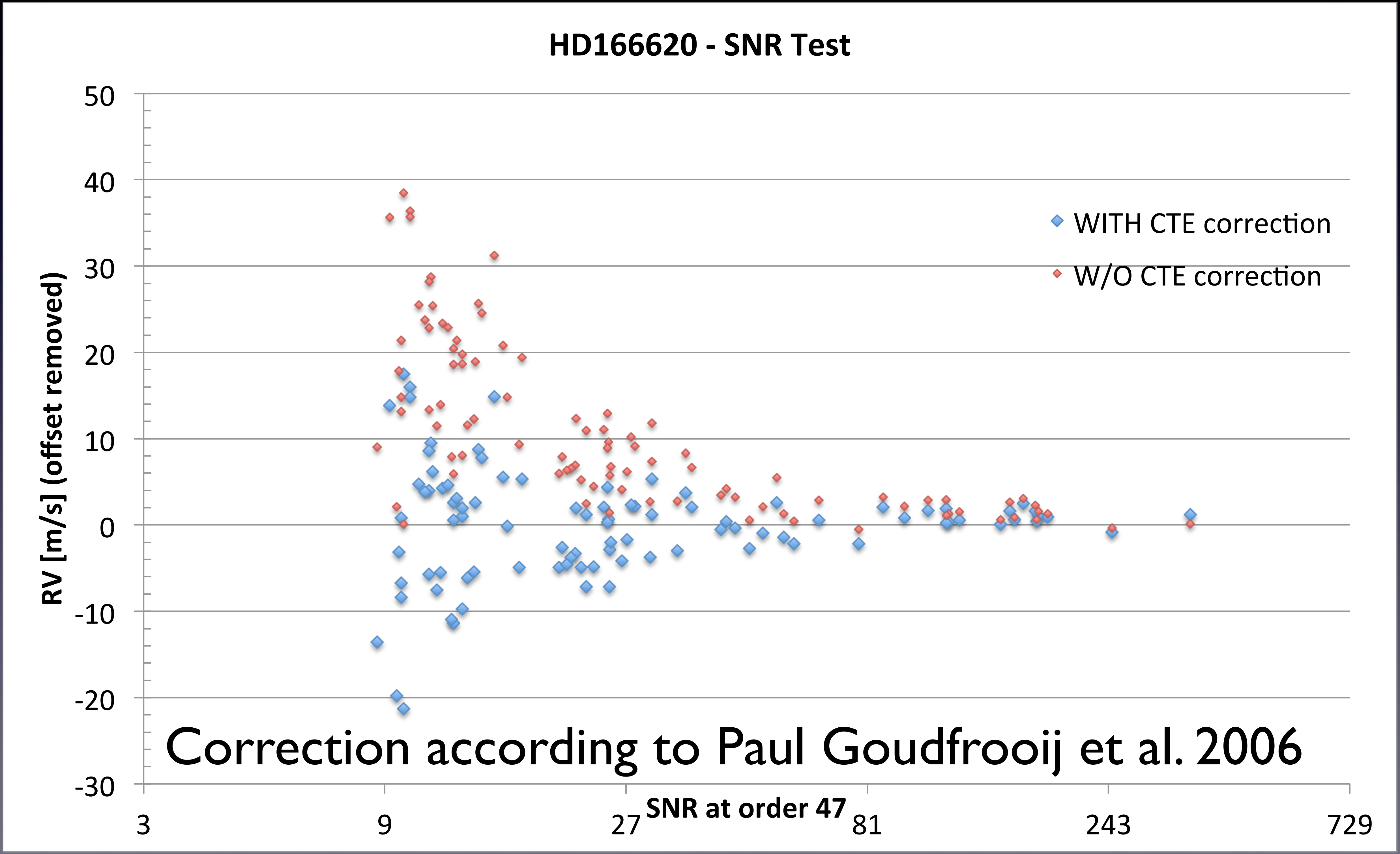
CTE Problem: SNR test



CTE Problem: SNR test



CTE Problem: solution

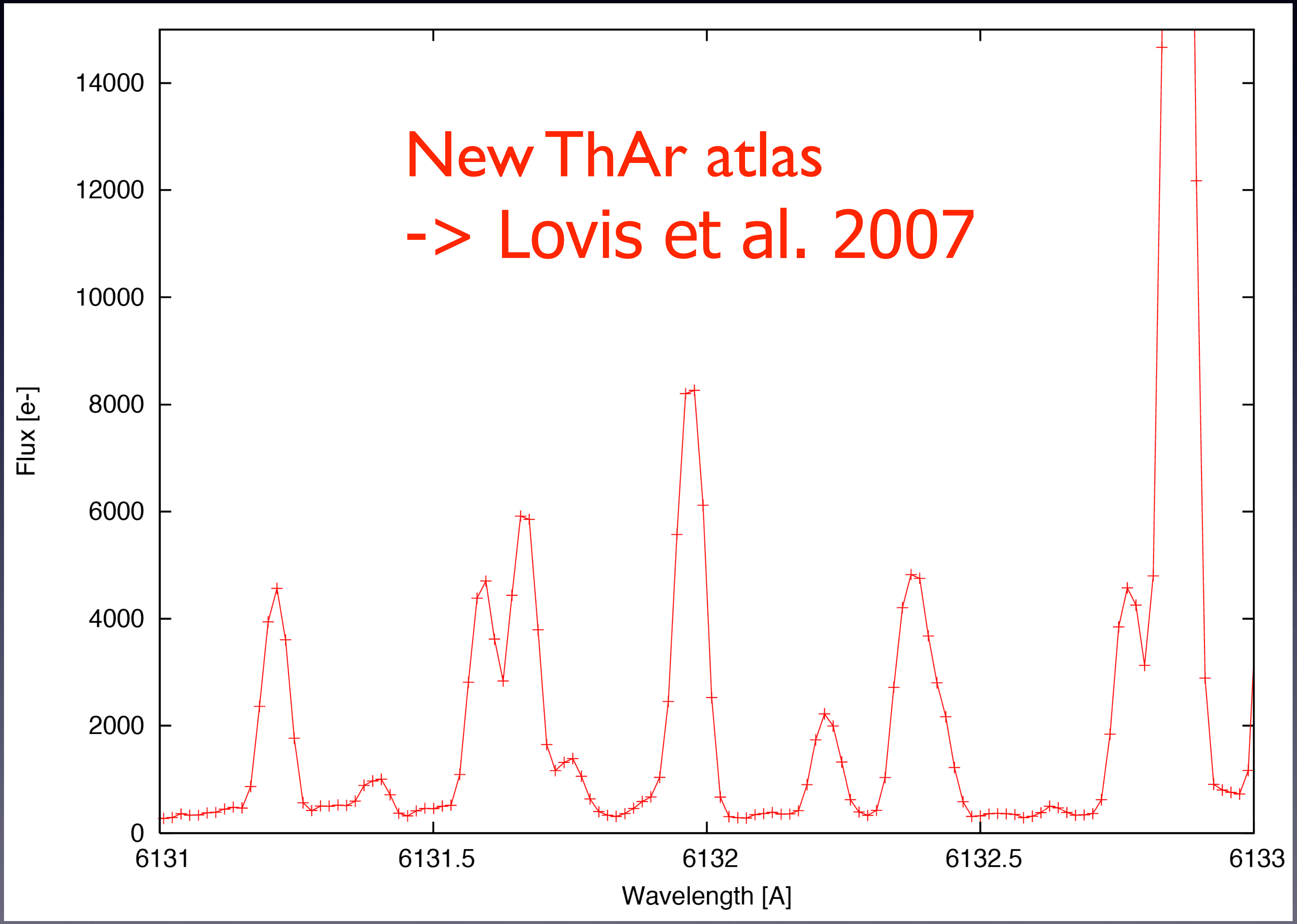


5. Calibration-source (bloody ThAr ;-)

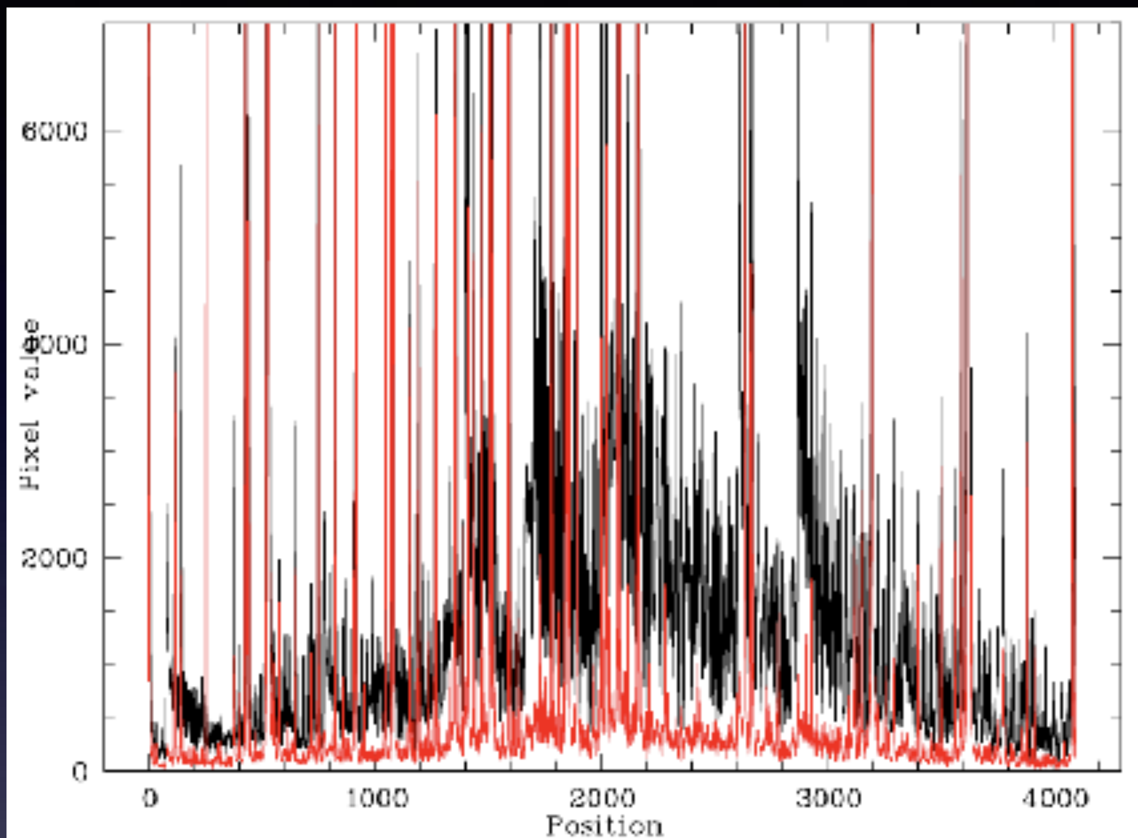
Isolated lines are very rare!

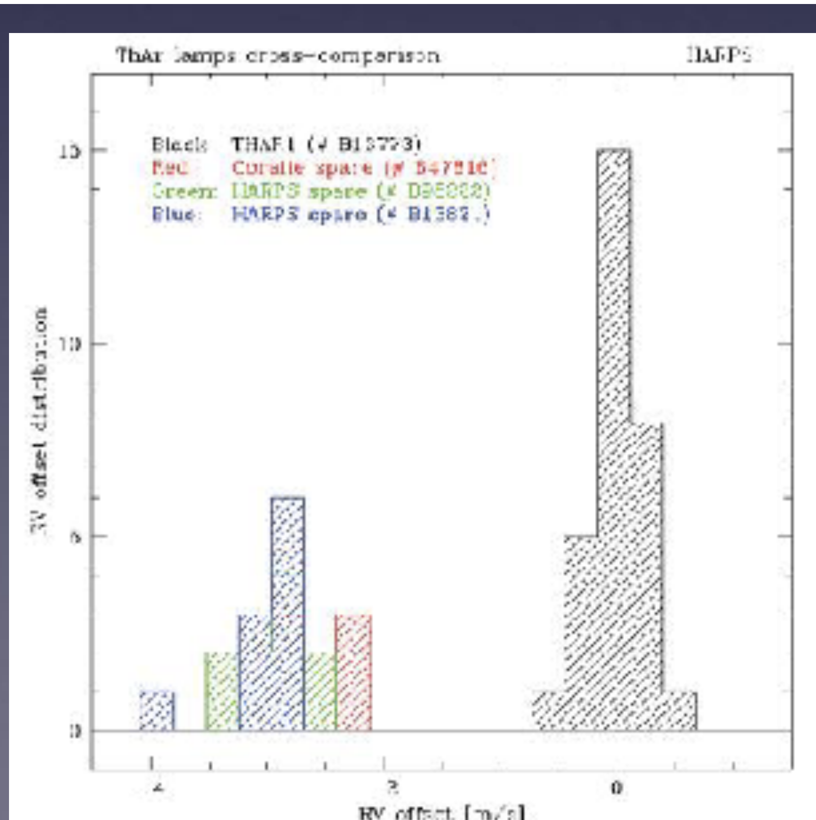
↓

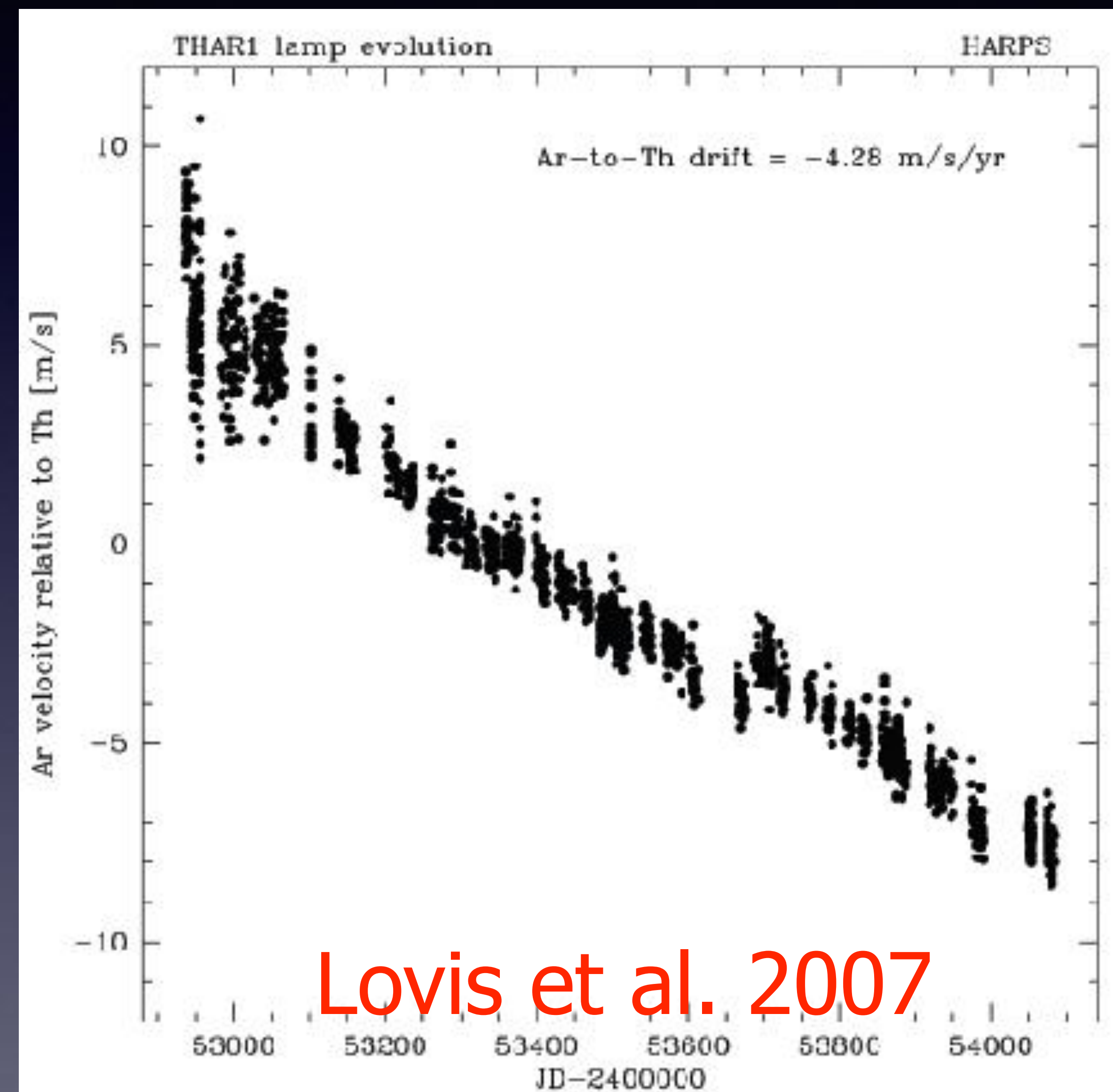
Fit neighbouring lines simultaneously with multiple Gaussians



Various ThAr-lamp issues

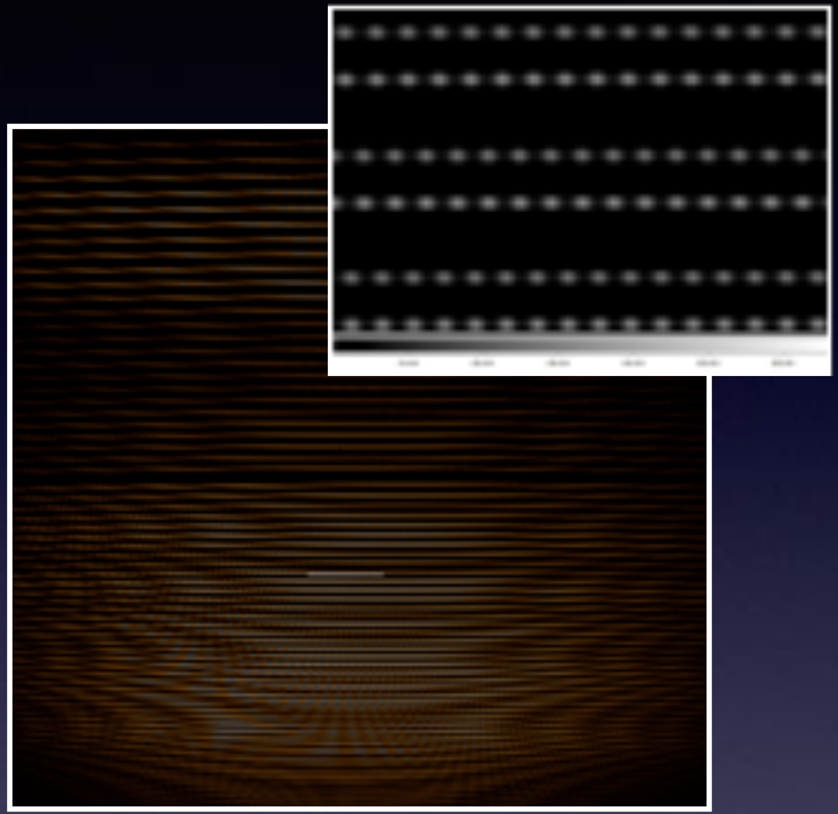




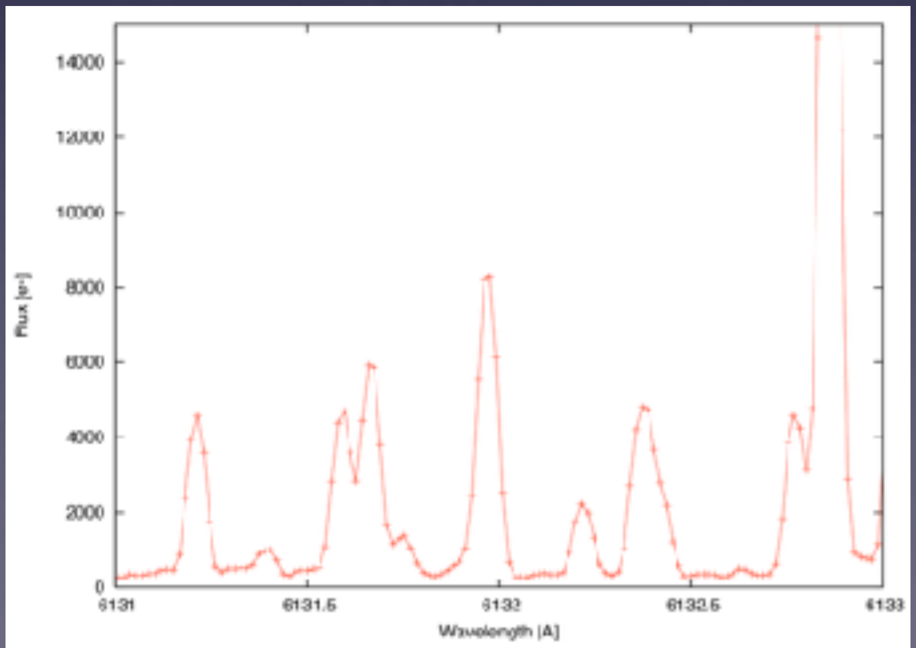


The search for the ideal source

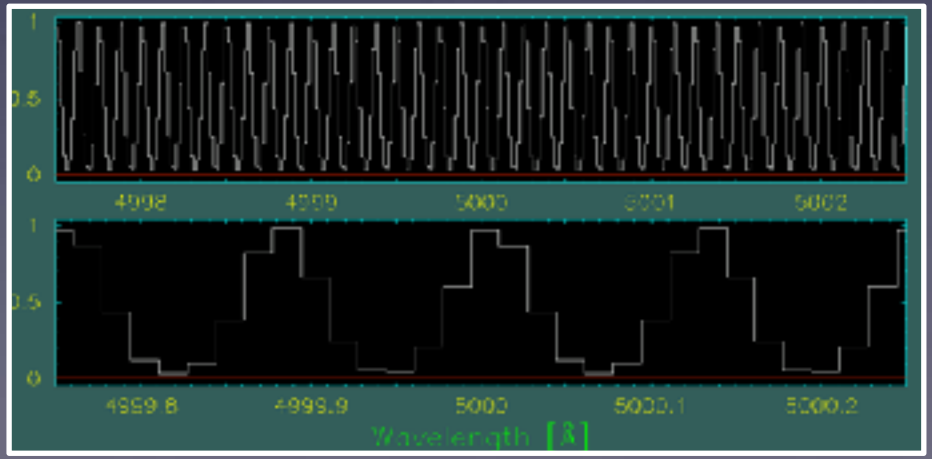
- ✓ Cover full spectral range
- ✓ High spectral resolution (again)
- ✓ Equally dense and unresolved lines
- ✓ No blends
- ✓ Knowledge of theoretical wavelengths
- ✓ Stability (repeatability) of 10^{-11} over > 20 years



Etalon raw frame



ThAr lamp



Laser comb or etalon

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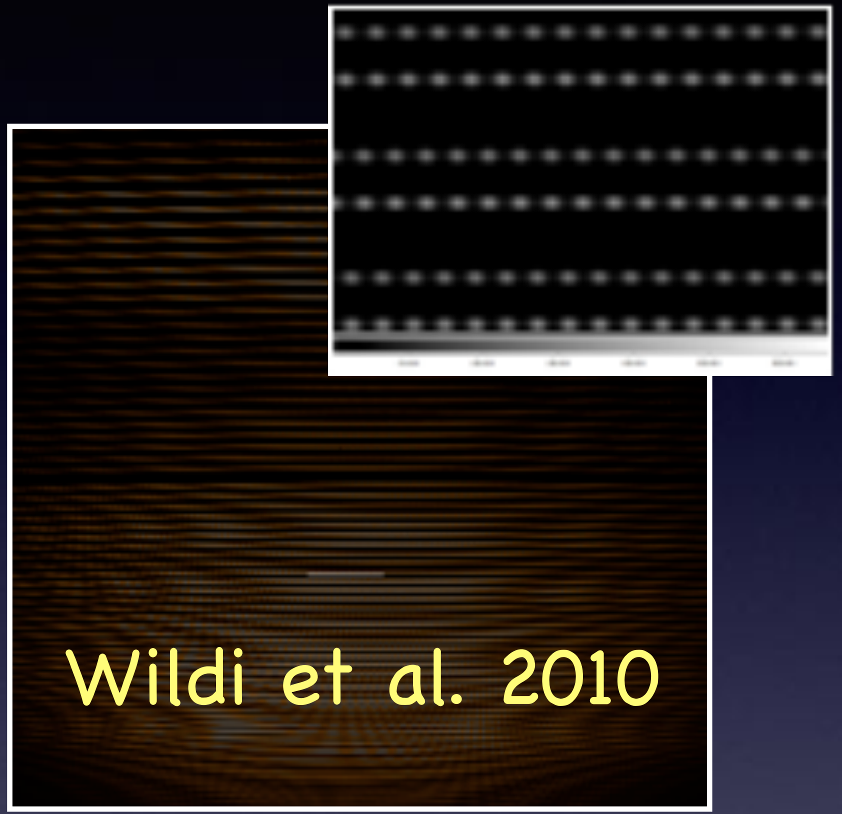
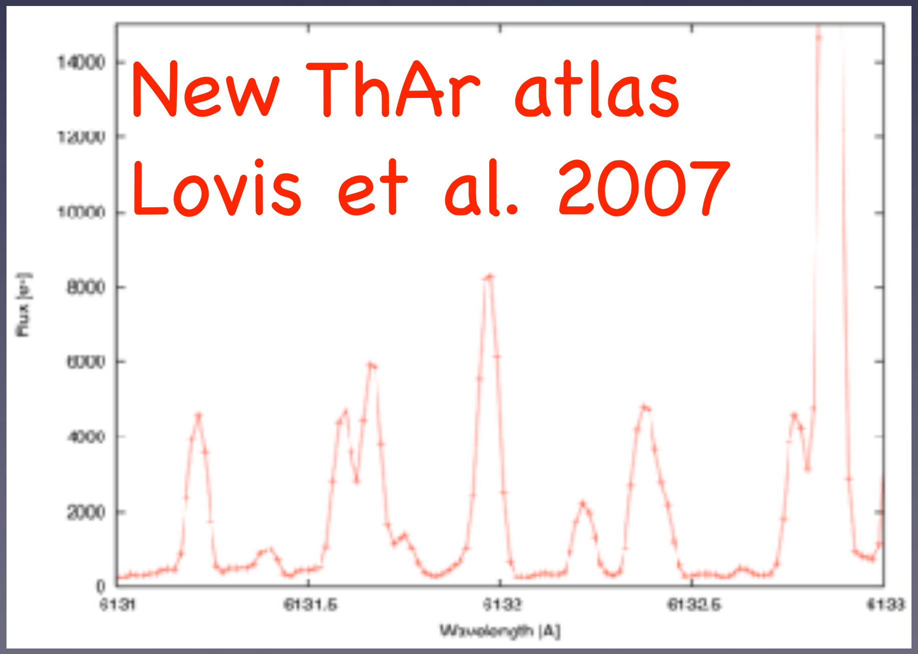


Etalon raw frame



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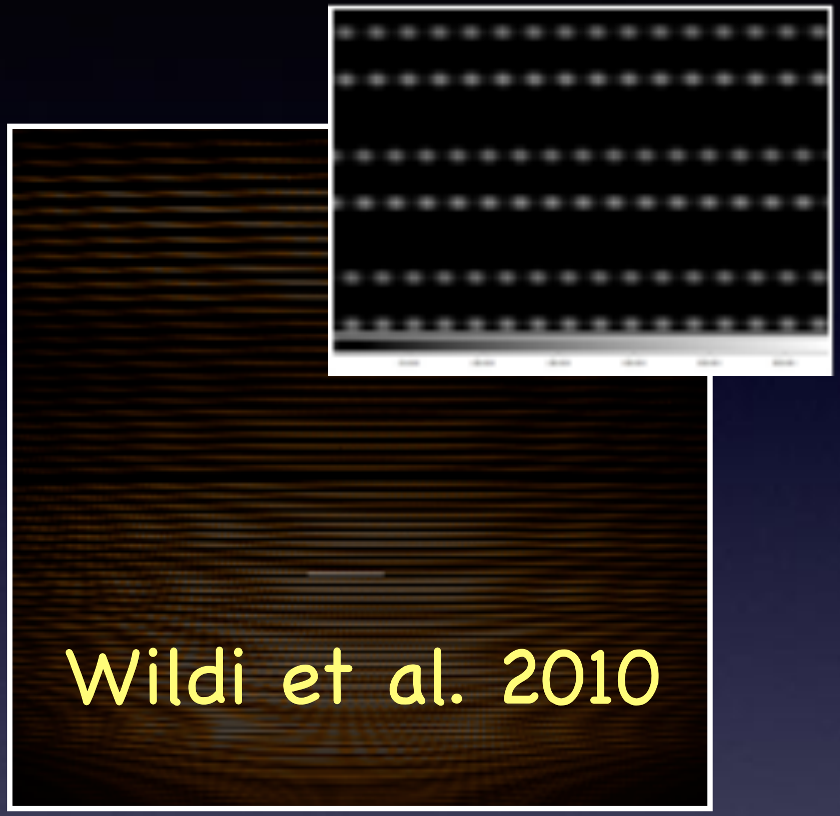

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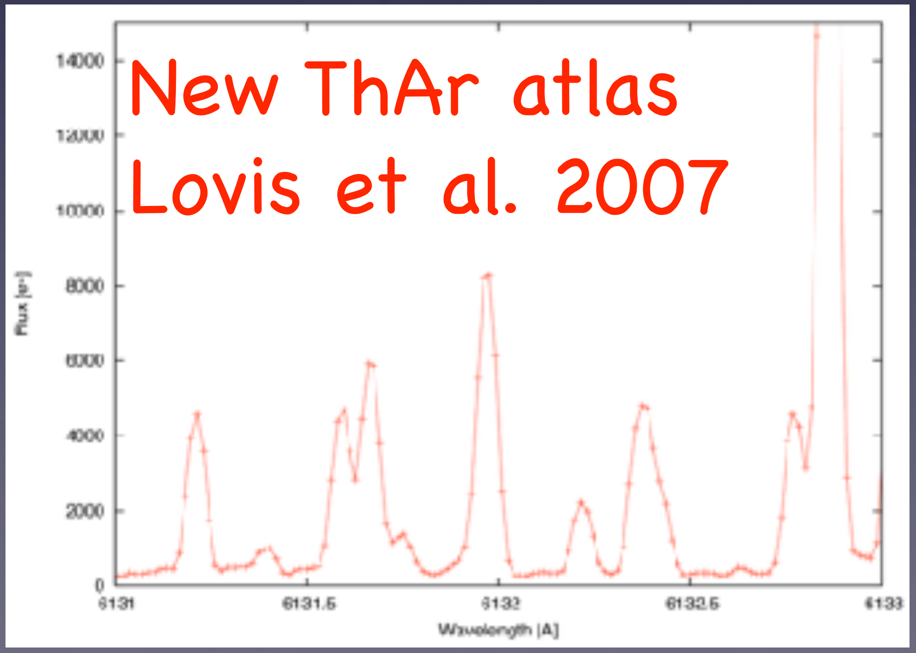


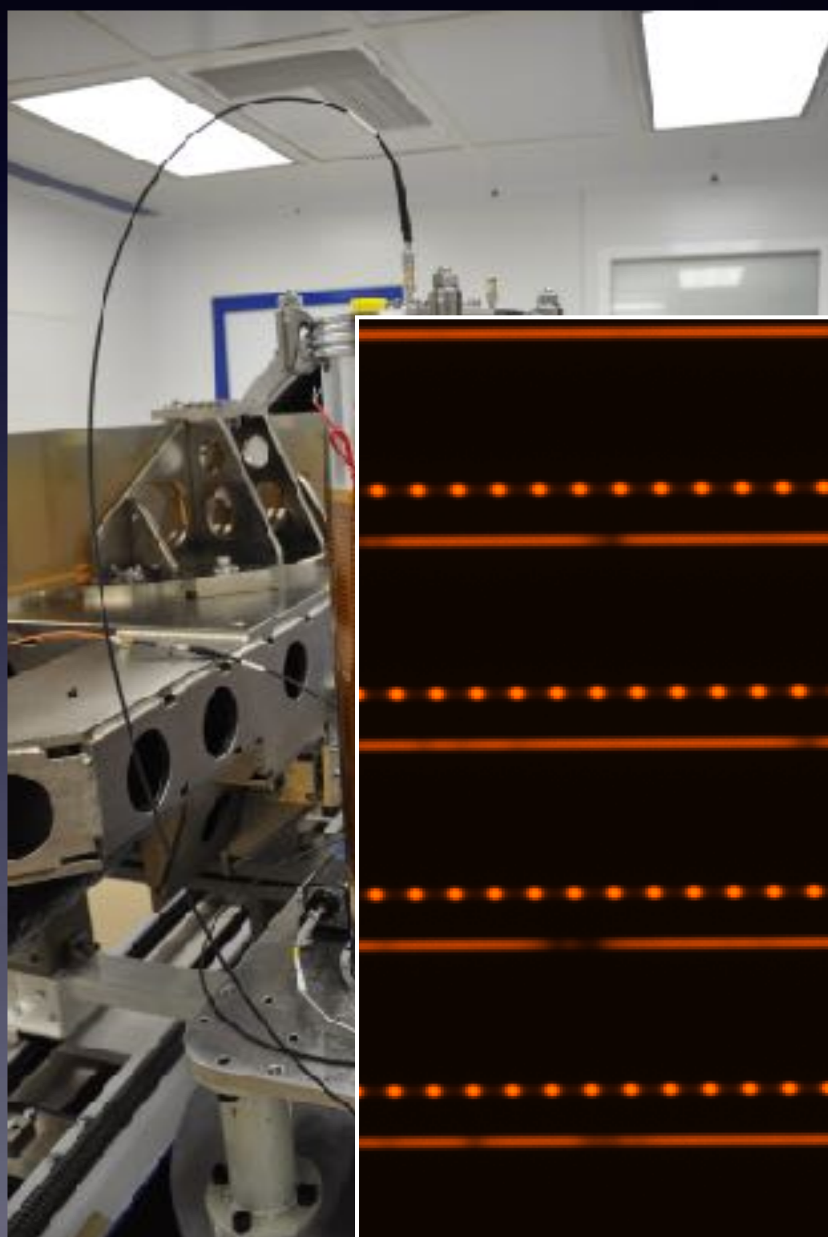
ThAr lamp

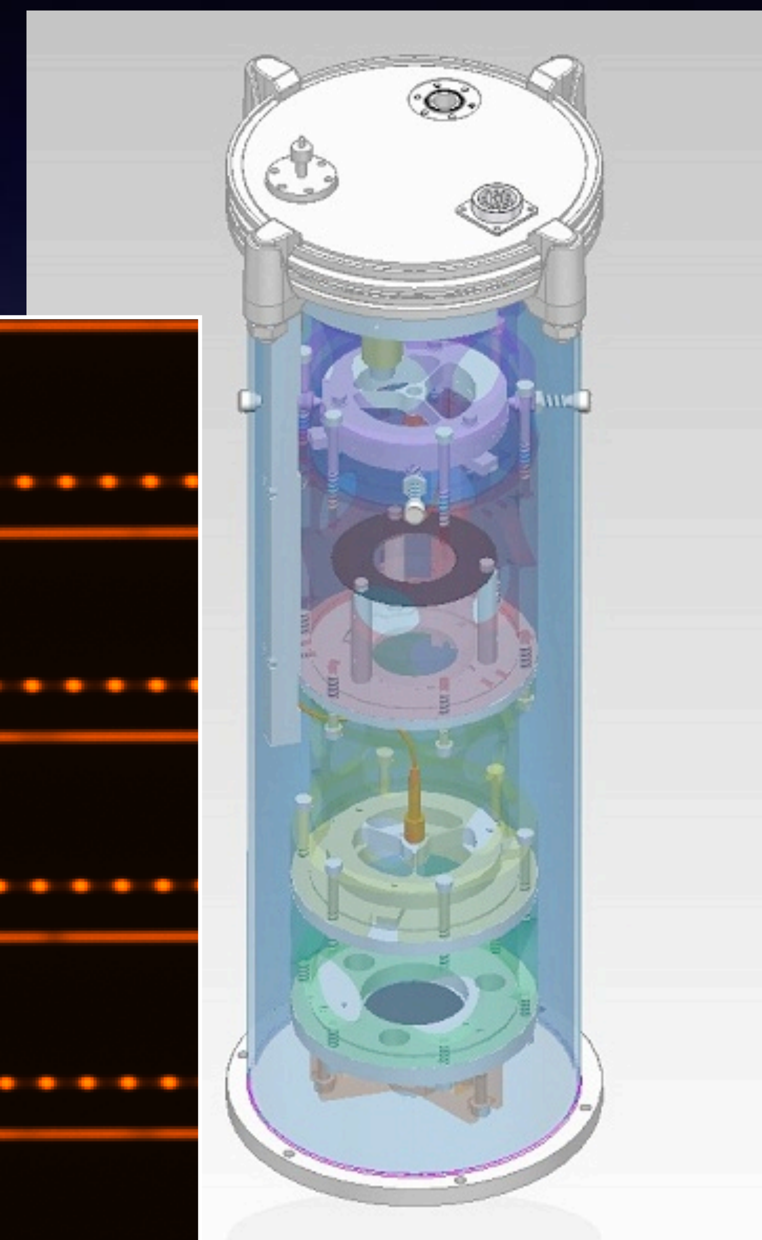
Laser comb or etalon

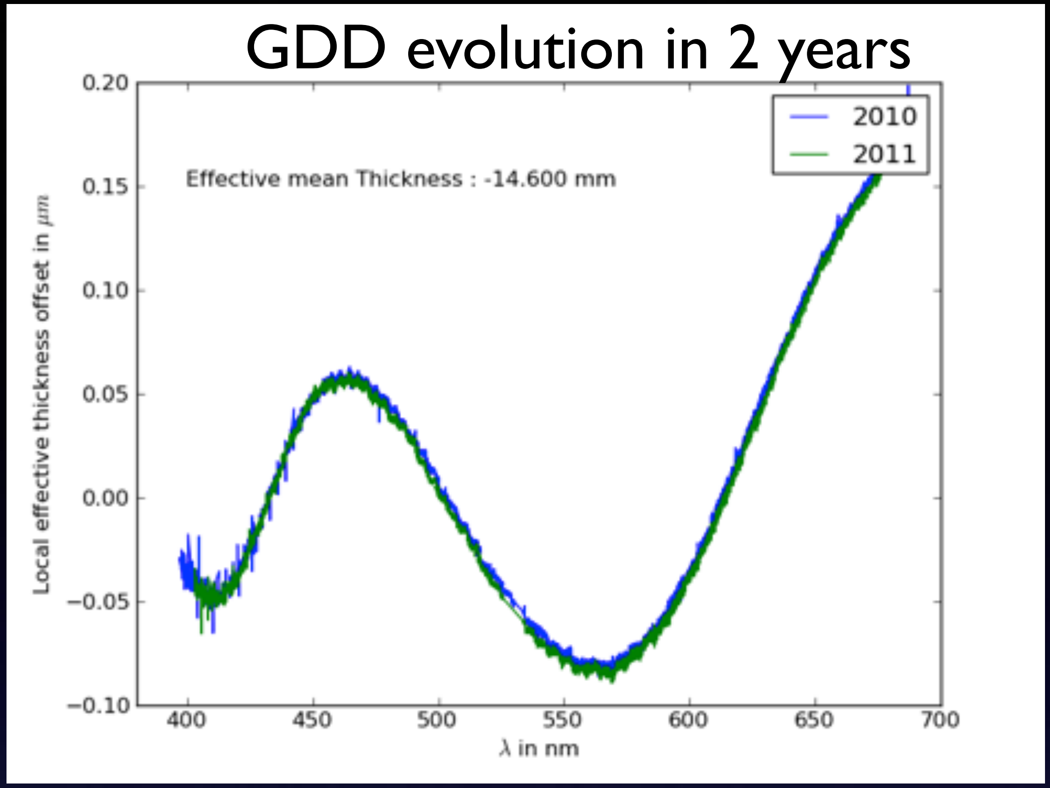
For LFC: See talk by Gaspare Lo Curto

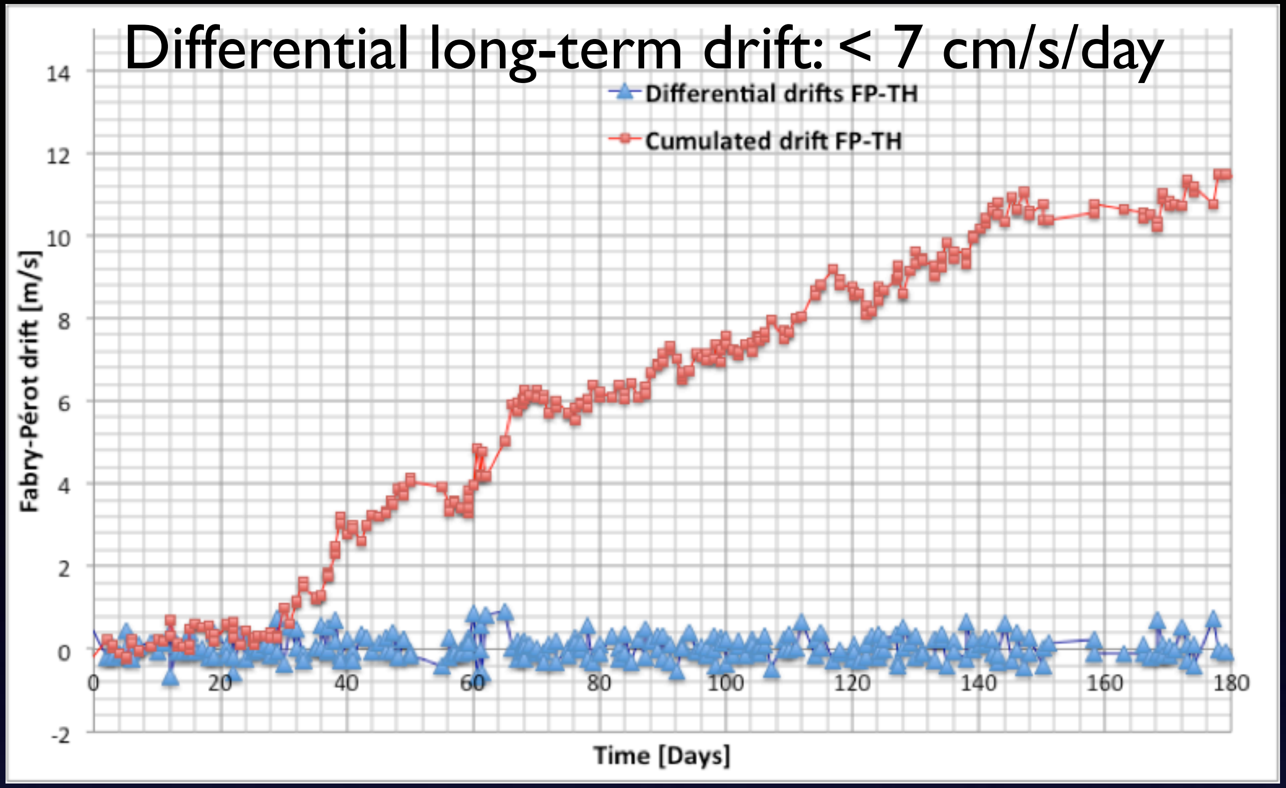
Optimized Fabry-Pérot Calibration Source

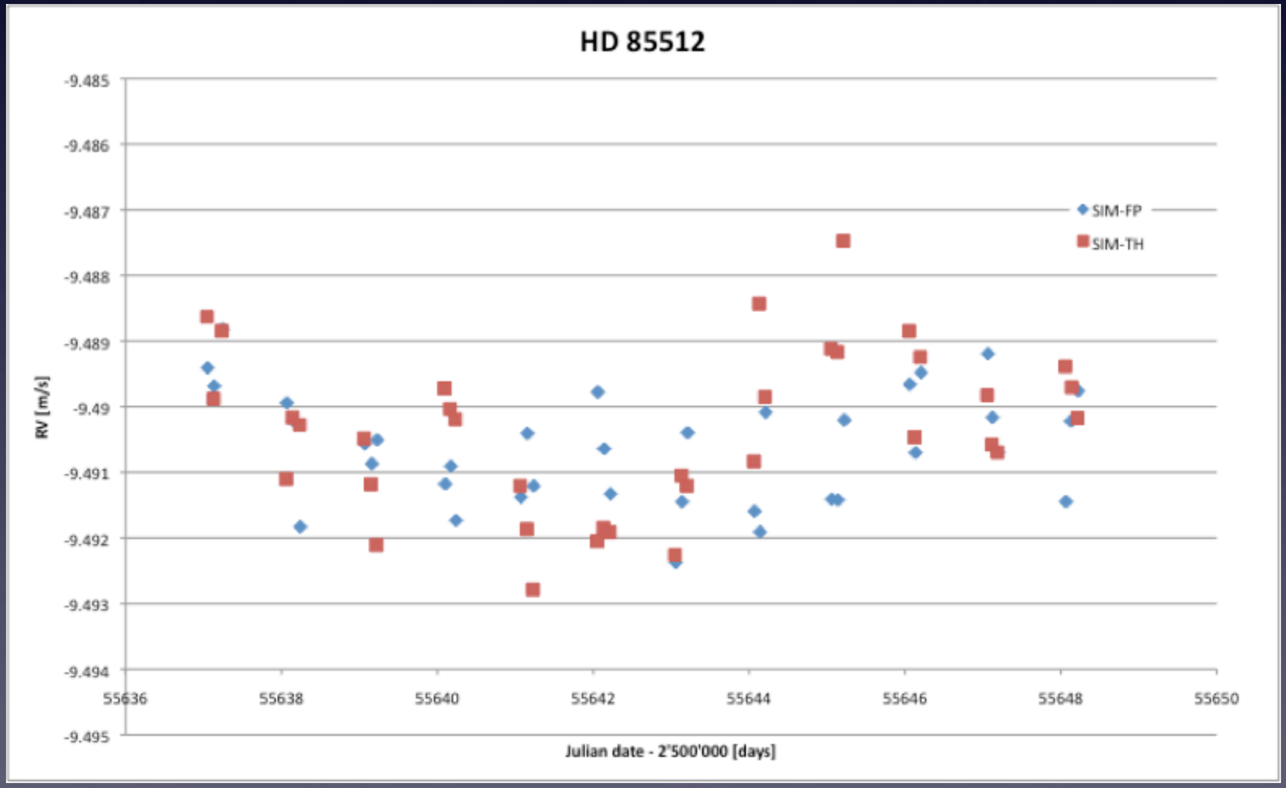
Optimized Fabry-Pérot Calibration Source

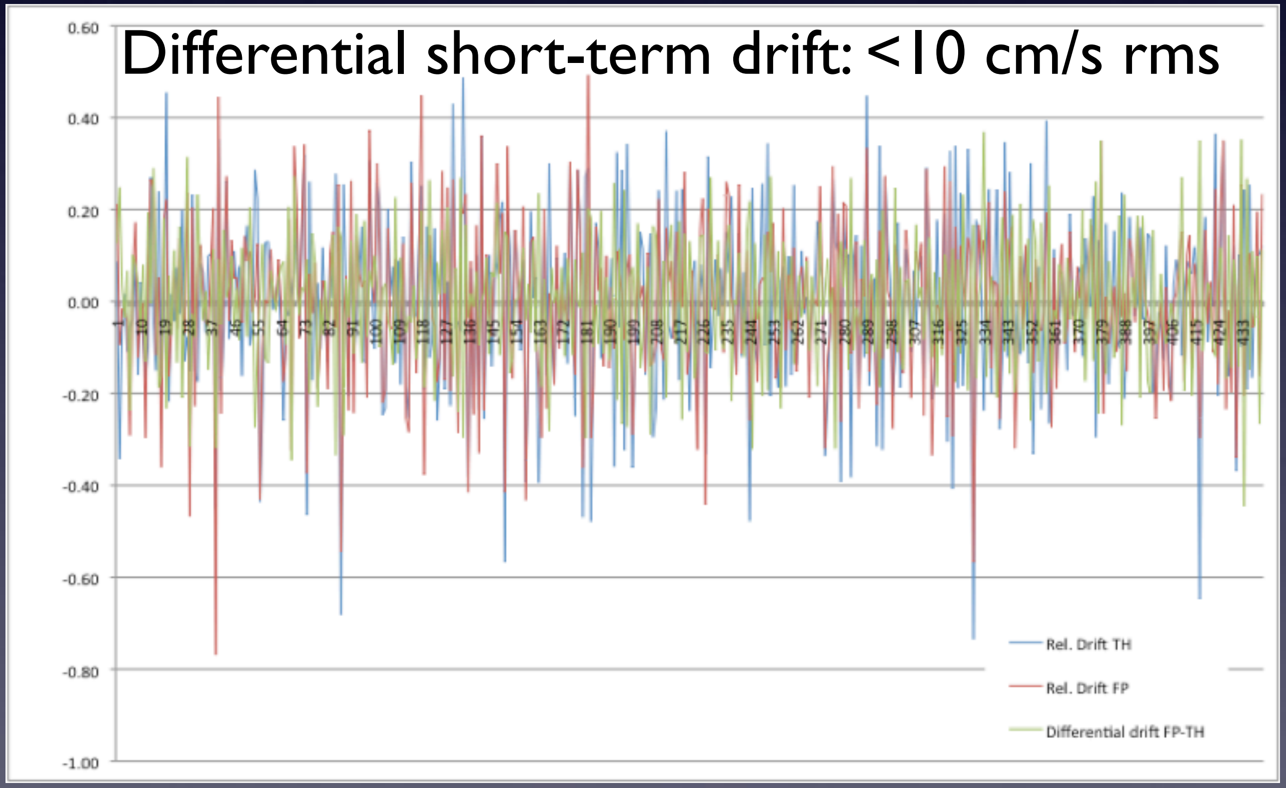








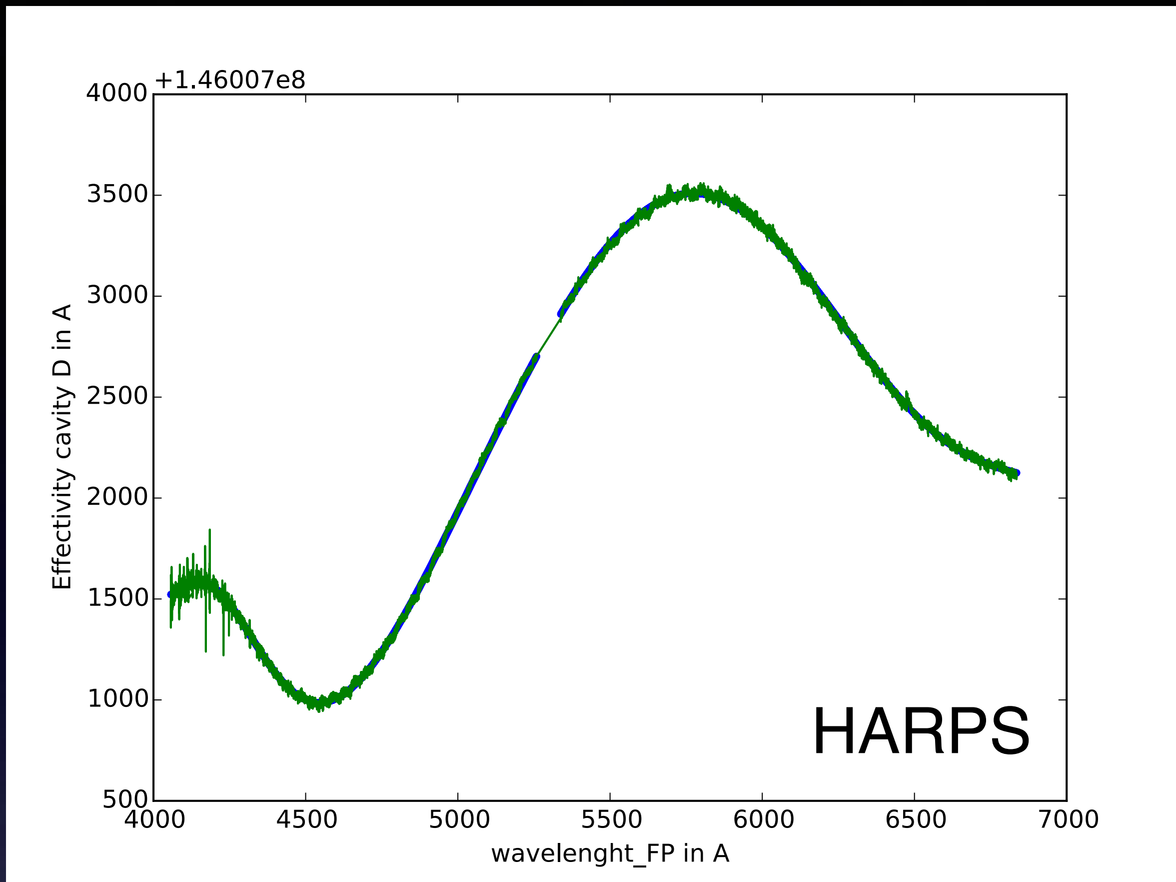


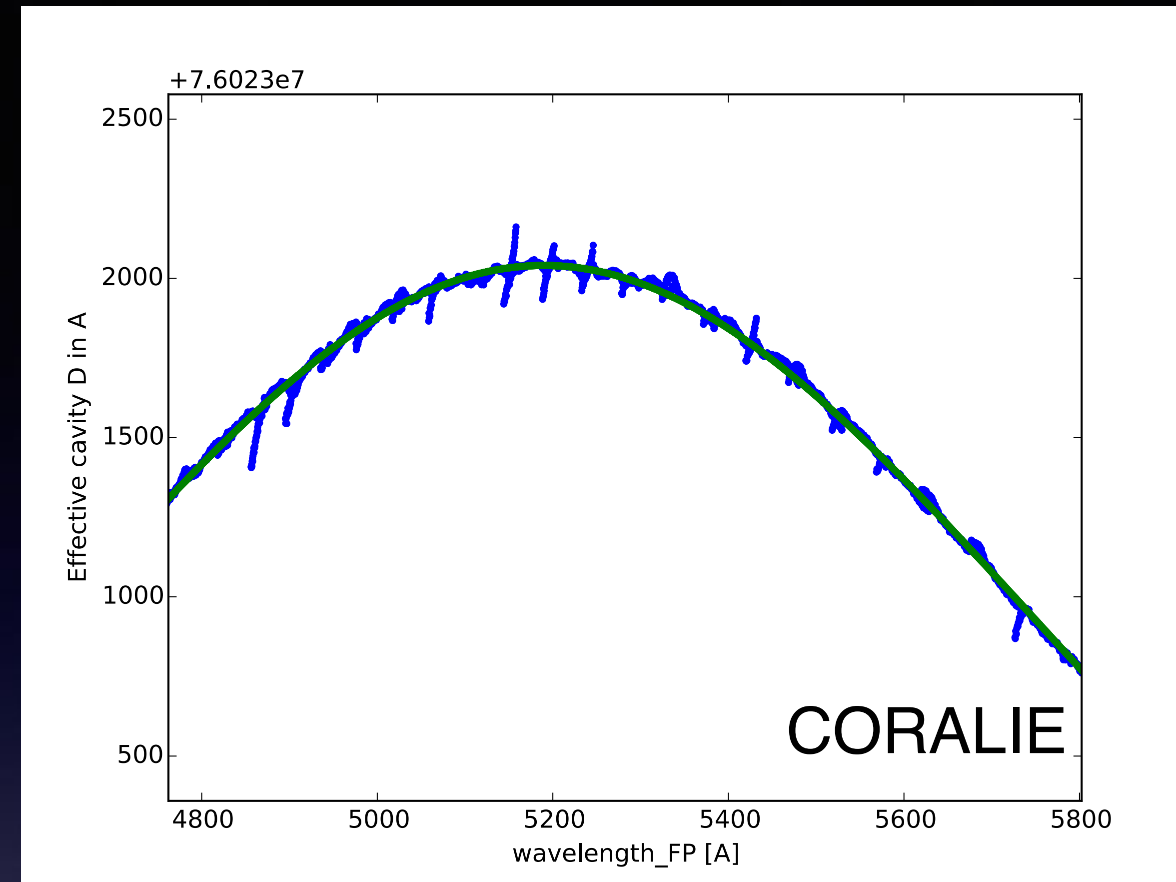


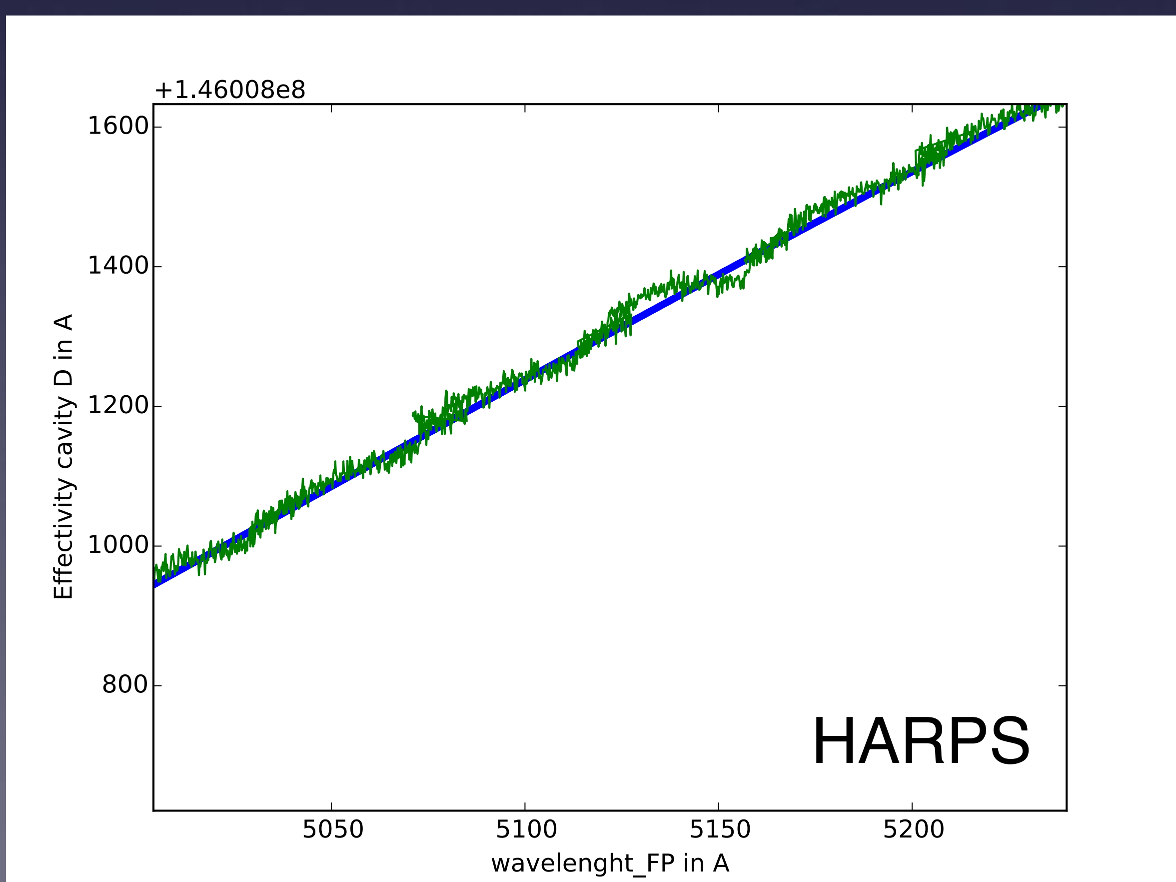
Problem: FP is NOT an absolute reference

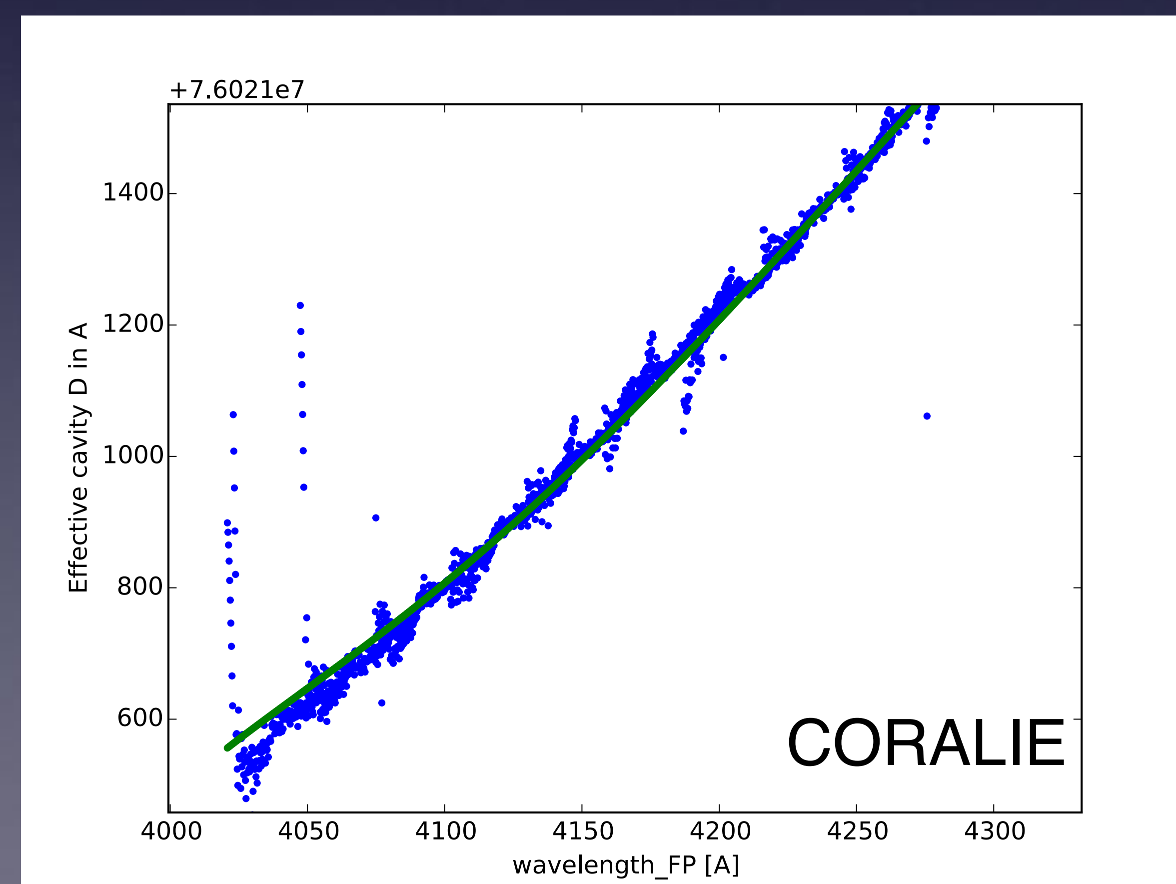
Alternative 1: Active control (with external source)

Alternative 2: Passive control (with external source) … ESPRESSO's solution









Cersullo et al., in prep.

ESPRESSO's solution

	Fiber A	Fiber B	
1.	ABS	ABS	General solution on both fibers
2.	FP	FP	Determine high-degree coefficient
3.	ABS	FP	Determine low-degree coefficients on A and establish reference spectrum for drift on B
4.	STAR	FP	Perform RV measurement and drift subtraction

At present ABS = ThAr or LFC with partial wavelength coverage

Cersullo et al., in prep.

First ESPRESSO calibration frames a