Towards measuring the expansion history of the Universe

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Cosmology tests using the ELT

1. **Expansion history of the Universe**
   Measuring the expansion rate of the Universe in real time

2. **Changing laws of physics**
   Constraining the variability of fundamental constants

Cosmology tests using the ELT

1. **Expansion history of the Universe**
   Measuring the expansion rate of the Universe in real time

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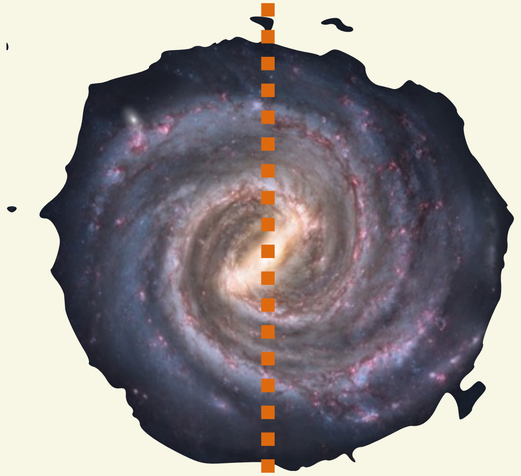
   Constraining the variability of fundamental constants

Expansion history of the Universe

DISTANCE χ



$$1 + z(t_{obs}, t_{em}) = \frac{a(t_{obs})}{a(t_{em})}$$

$$\frac{\mathrm{d}z_{|\chi}}{\mathrm{d}t_{obs}} = [1 + z_{|\chi}(t_{obs})]H(t_{obs}) - H(t_{em})$$

$$\frac{\mathrm{d}z_{|\chi}}{\mathrm{d}t_{obs}} \approx \frac{z_{|\chi}(t_{obs} + \Delta t_{obs}) - z_{|\chi}(t_{obs})}{\Delta t_{obs}}$$

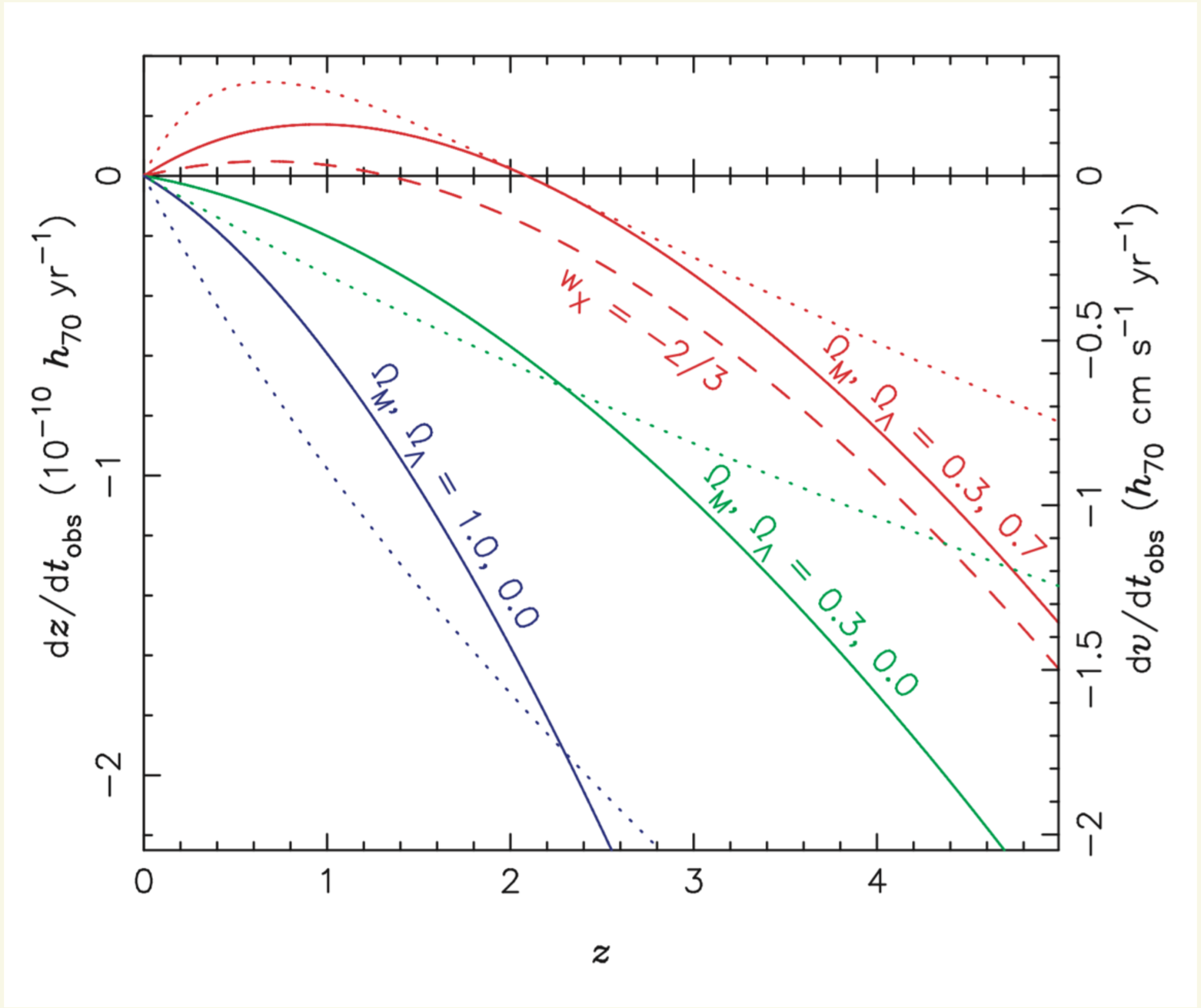
Δt

Δz

$t = t_0$ $\quad$ $t = t_1$

$z = z_0$ $\quad$ $z = z_1$

$\chi = \chi$ $\quad$ $\chi = \chi$



Liske et al. 2008

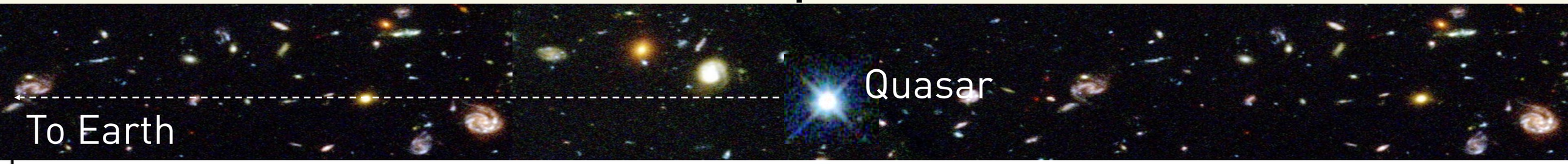
Ideal accelerometer

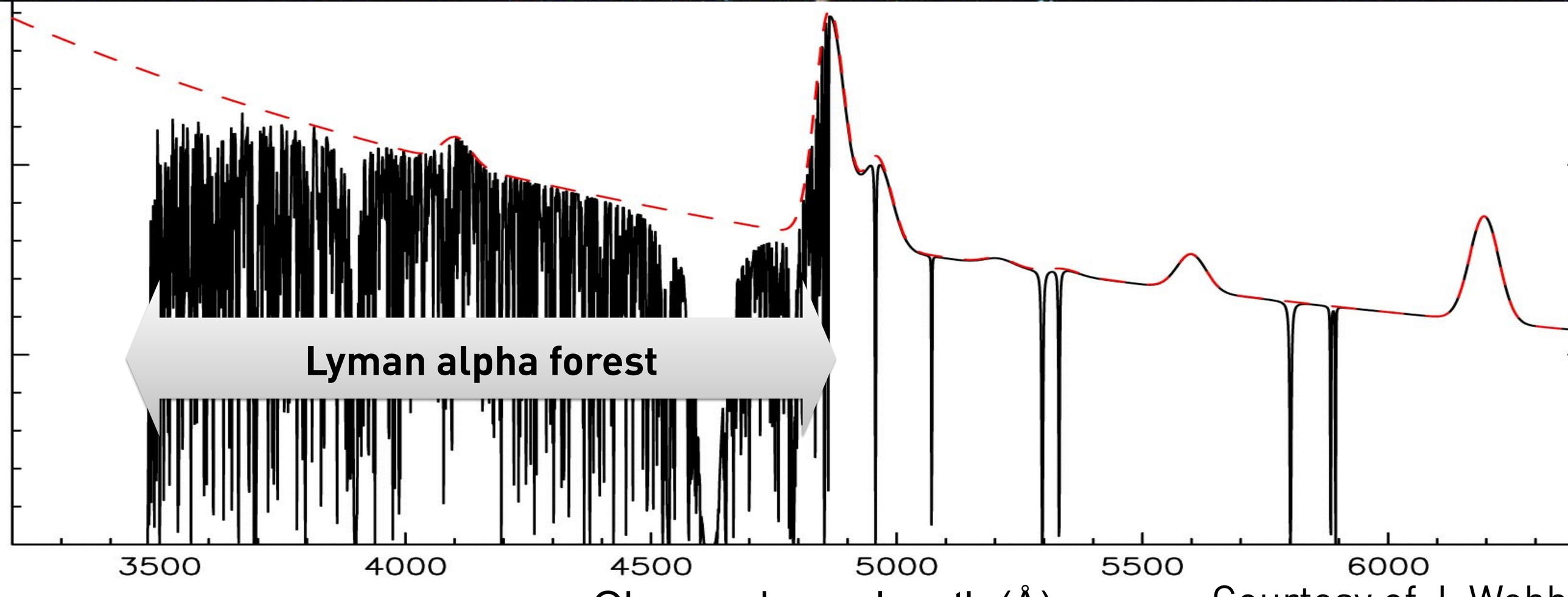
- Checklist:

1. Traces the Hubble flow
2. Exists at a wide range of redshifts
3. As bright as possible
4. Large number of useful spectral lines
5. Sharp spectral features

Lyman alpha forest

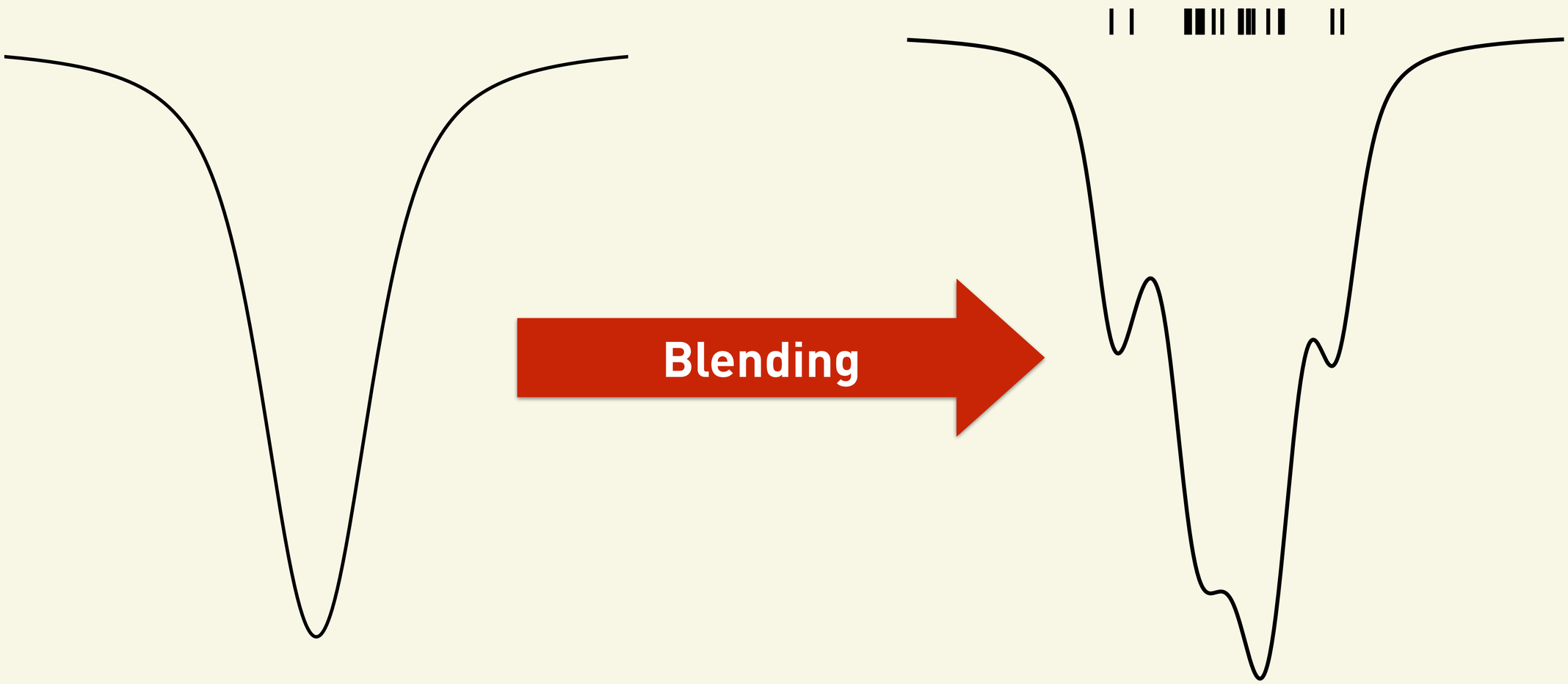
Quasar spectrum



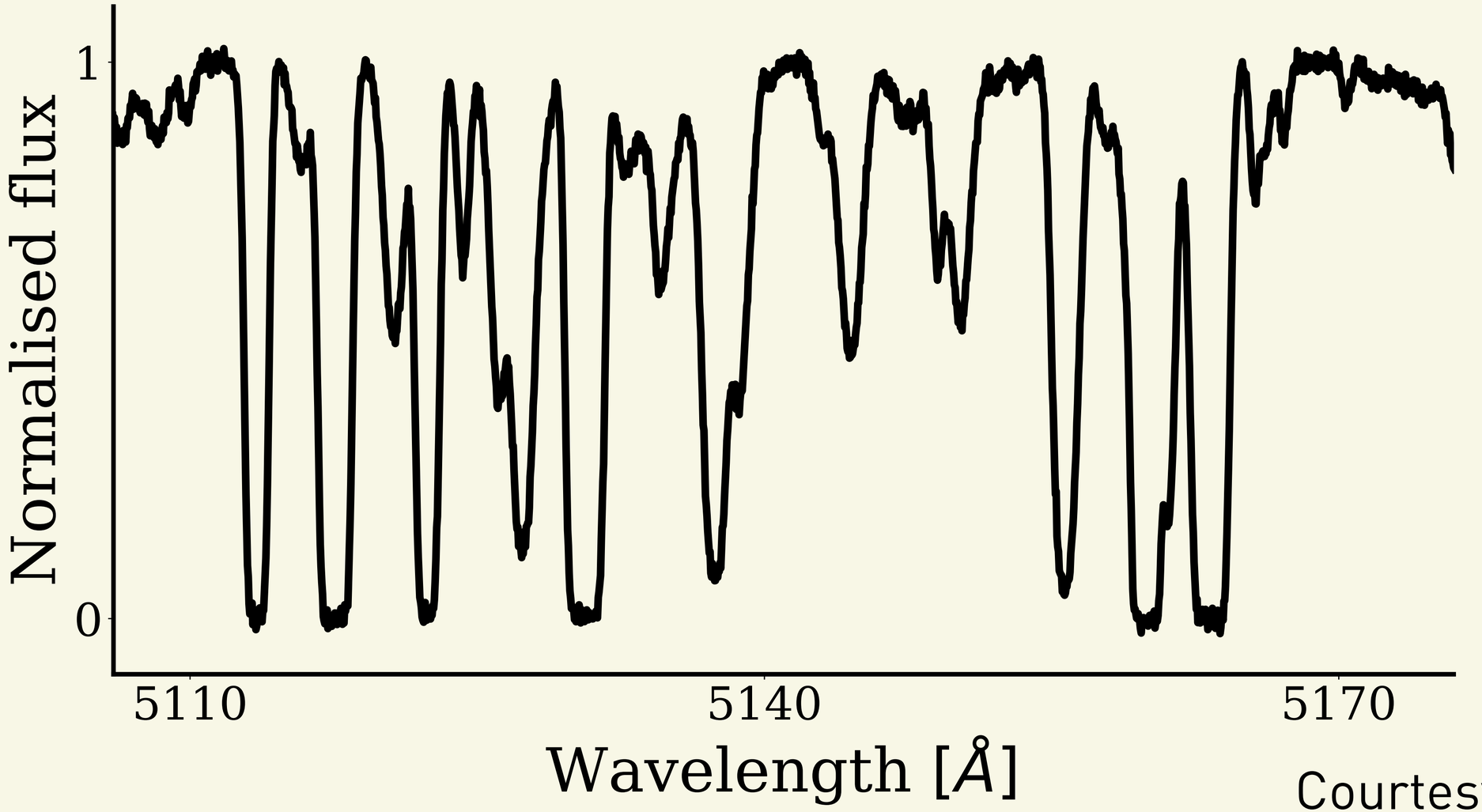


Courtesy of J. Webb

Intergalactic medium



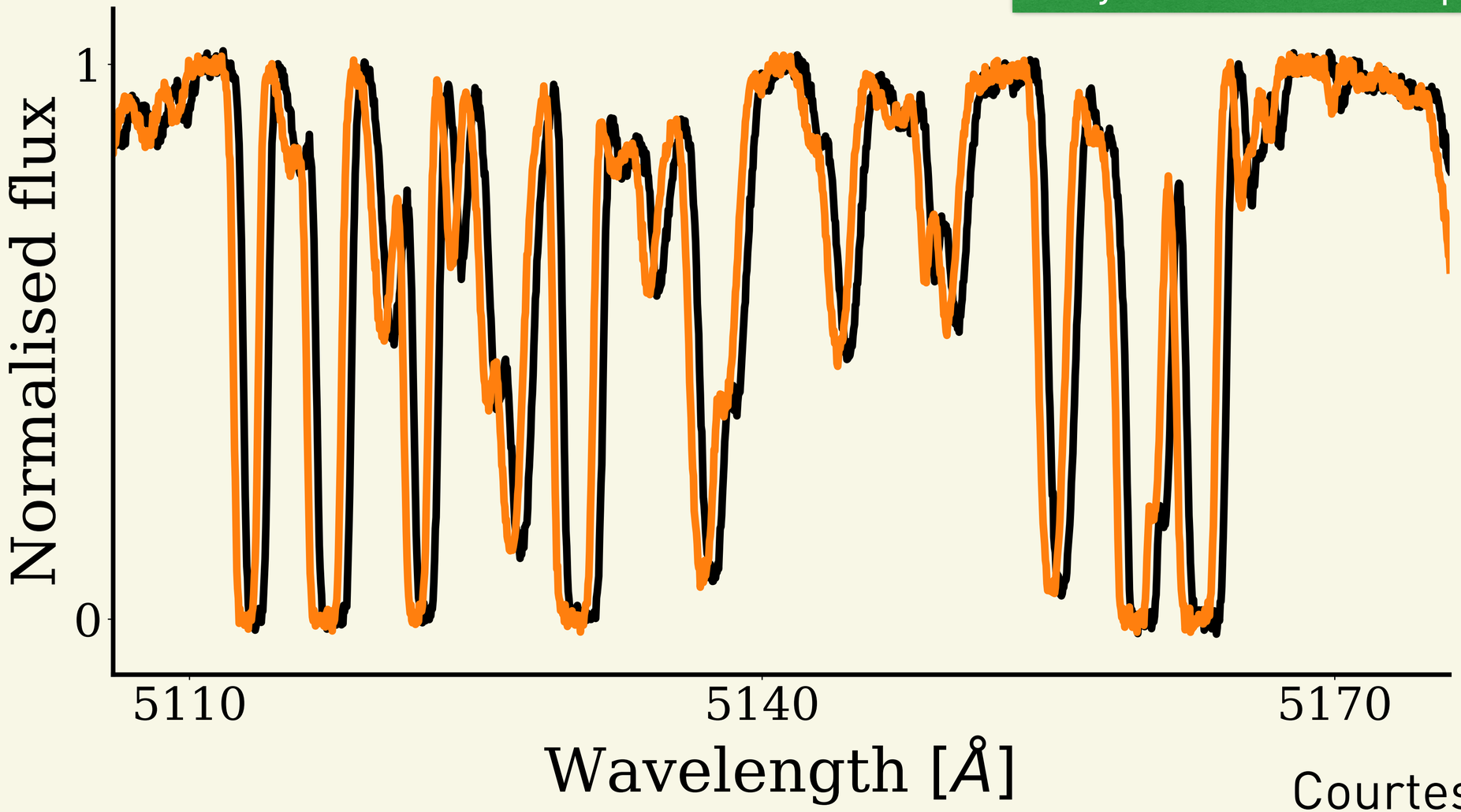
Simulated observations



Courtesy of J. Liske

Simulated observations

10^7 years between epochs



Courtesy of J. Liske

Requirements

- Large sample of bright quasars
- High resolution spectra
- High SNR across multiple epochs
- Wavelength calibration accuracy $\Delta\lambda/\lambda \approx 10^{-10} \rightarrow 3\mathrm{cm/s}$
- Wavelength calibration stable over >10 years

Requirements

- Large sample of bright quasars
- High resolution spectra

ELT

- High SNR across multiple epochs

LFC

- Wavelength calibration accuracy $\Delta\lambda/\lambda \approx 10^{-8} \rightarrow 3\mathrm{cm/s}$
- Wavelength calibration stable over >10 years

Laser Frequency Comb

Frequency of a LFC line

Cardinal number of a LFC line

$$f_n = f_0 + n \times f_r$$

Known frequencies
$\Delta f / f \approx 10^{-11}$

Wavelength of a LFC line

$$\lambda_n = c / f_n$$

Speed of light

LFC at ESO

- HARPS:
  - First tests 2010
  - First commissioning 2015
  - Offered to the community since P101 (2018)
- ESPRESSO:
  - 2 systems (red & blue), not yet offered

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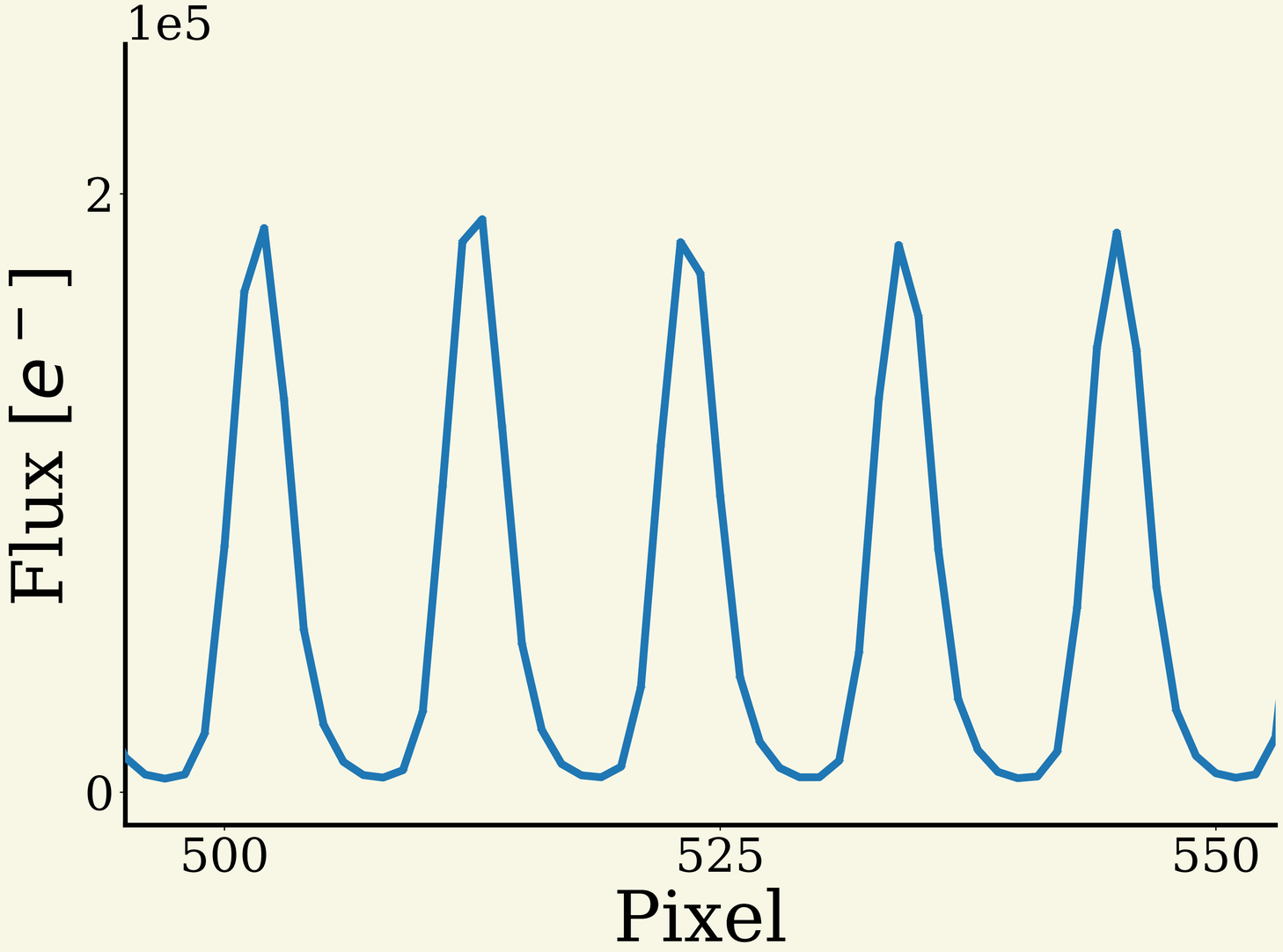
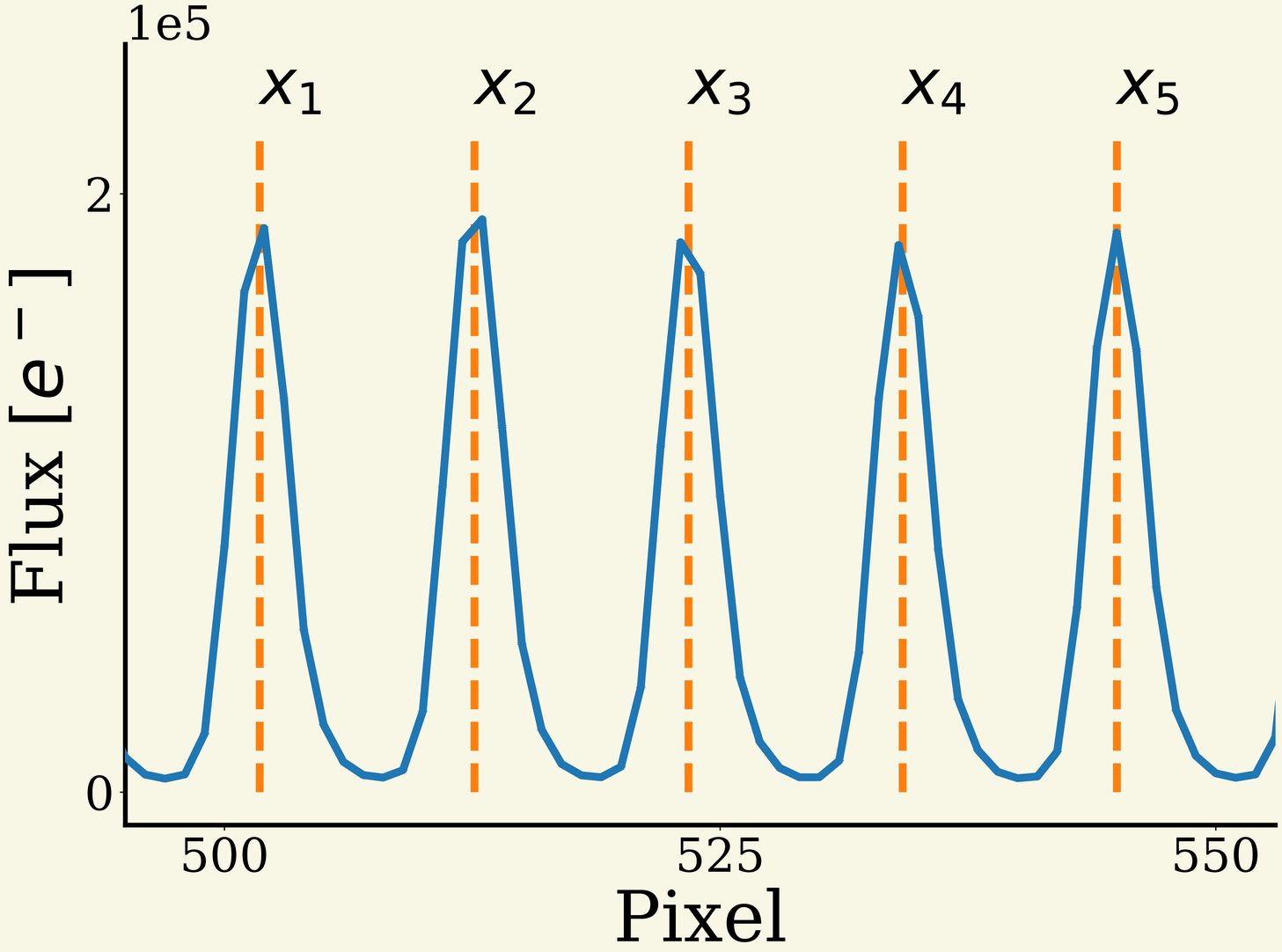
LFC Spectrum



Properties:

- Separation:
  11-15 pixels
- FWHM 3 pixels
- Cover ~3 resolution elements
- 50 > SNR/pix > 200

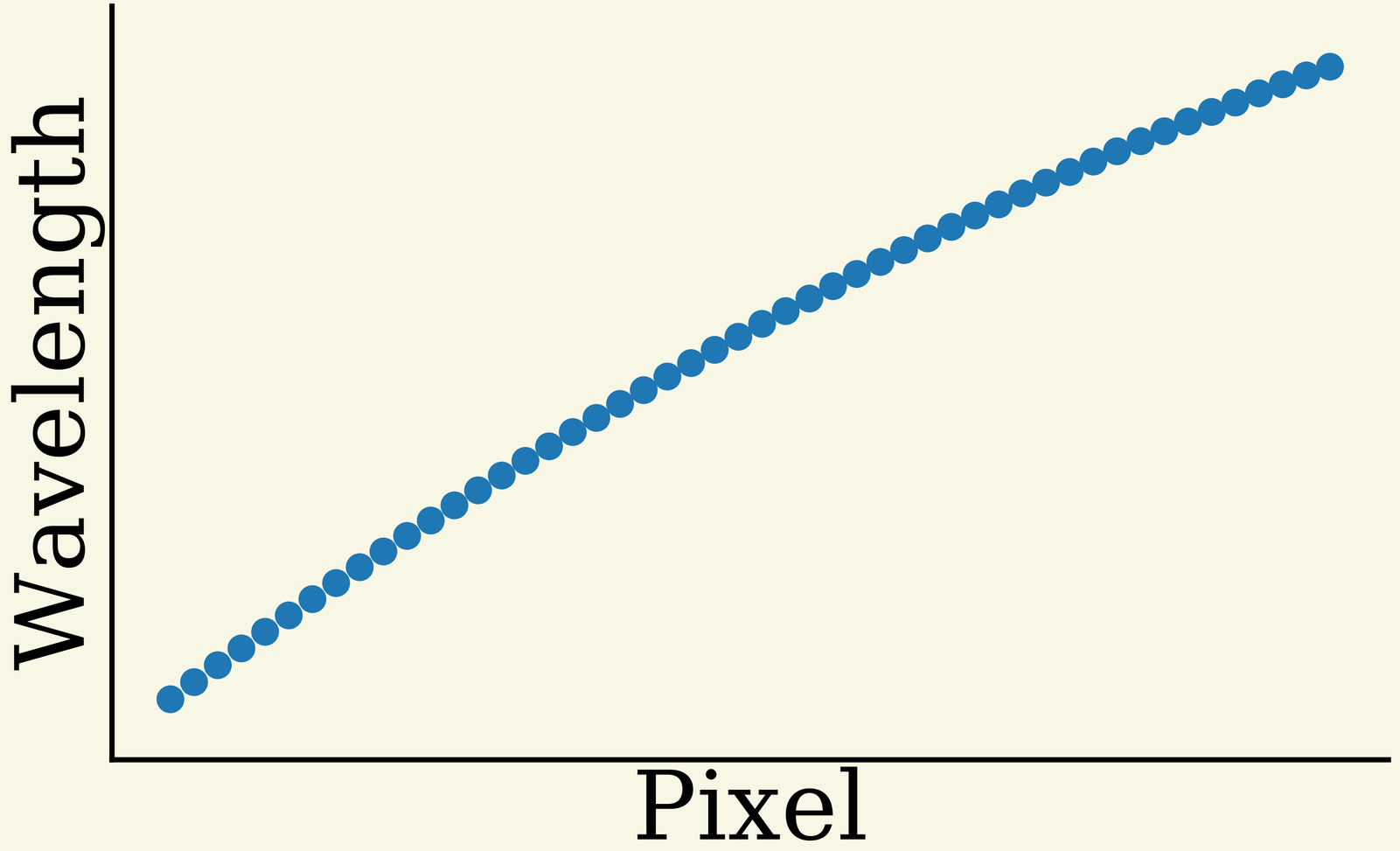
LFC Spectrum



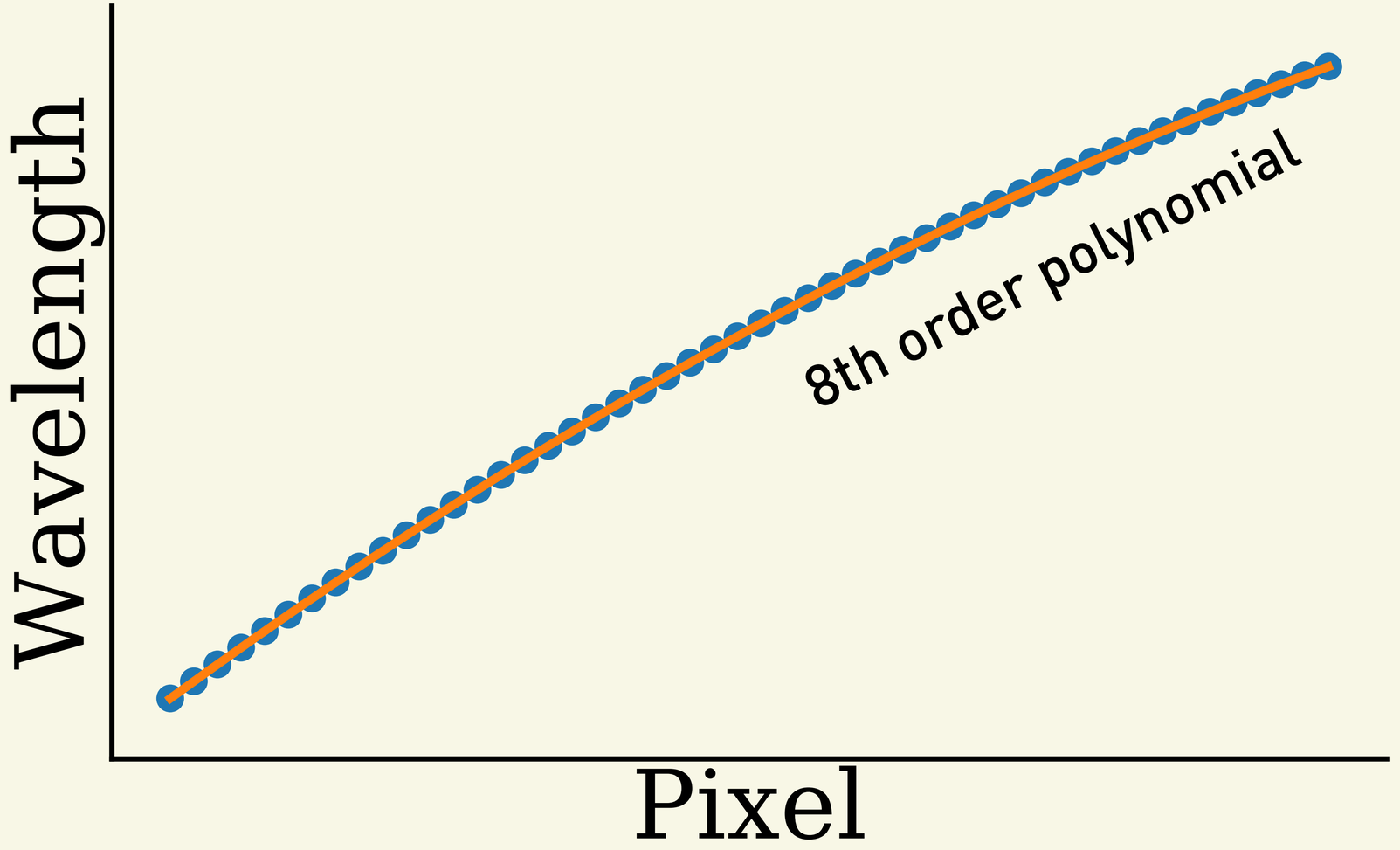
Assumptions:

- Gaussian shape
- Independent of adjacent lines

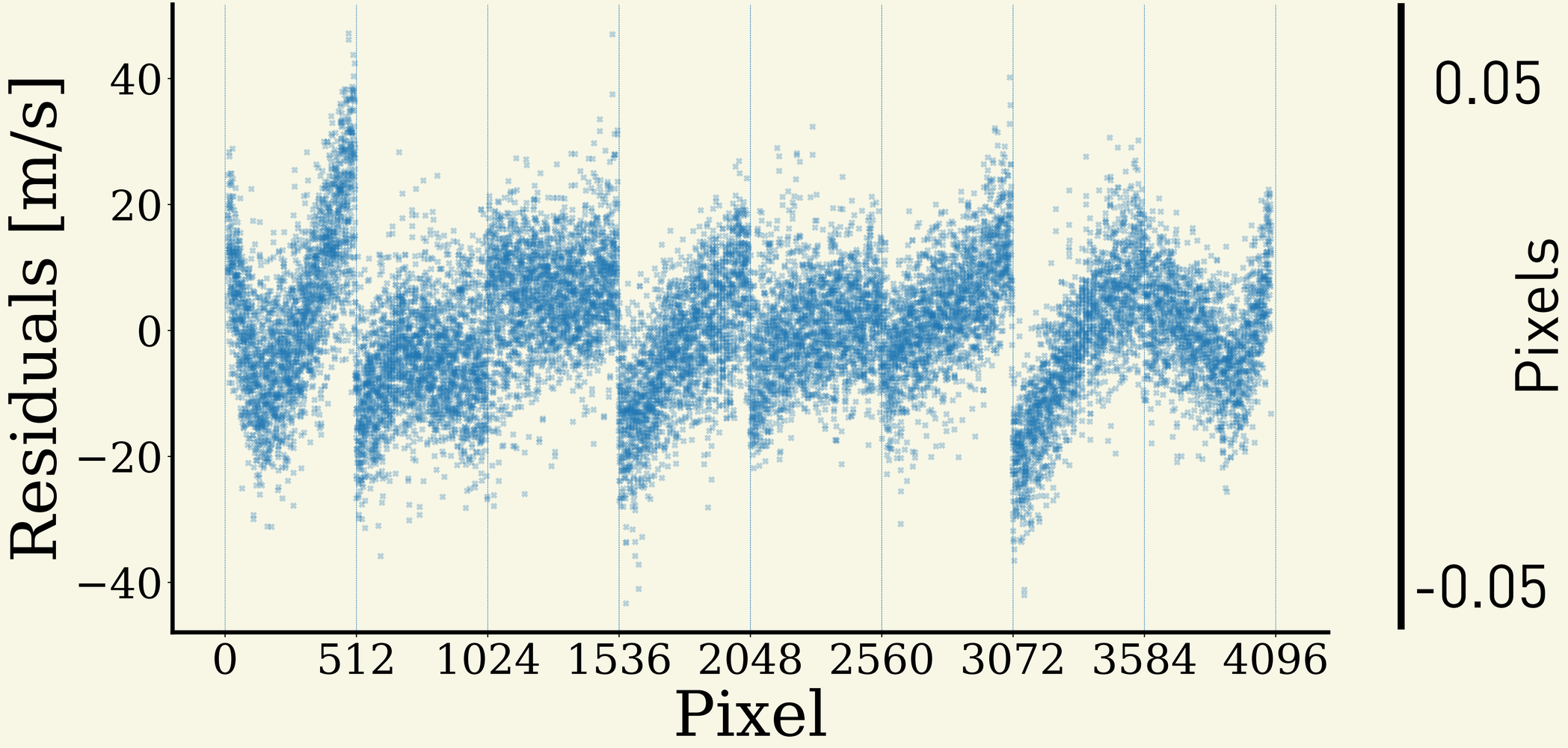
Wavelength solution



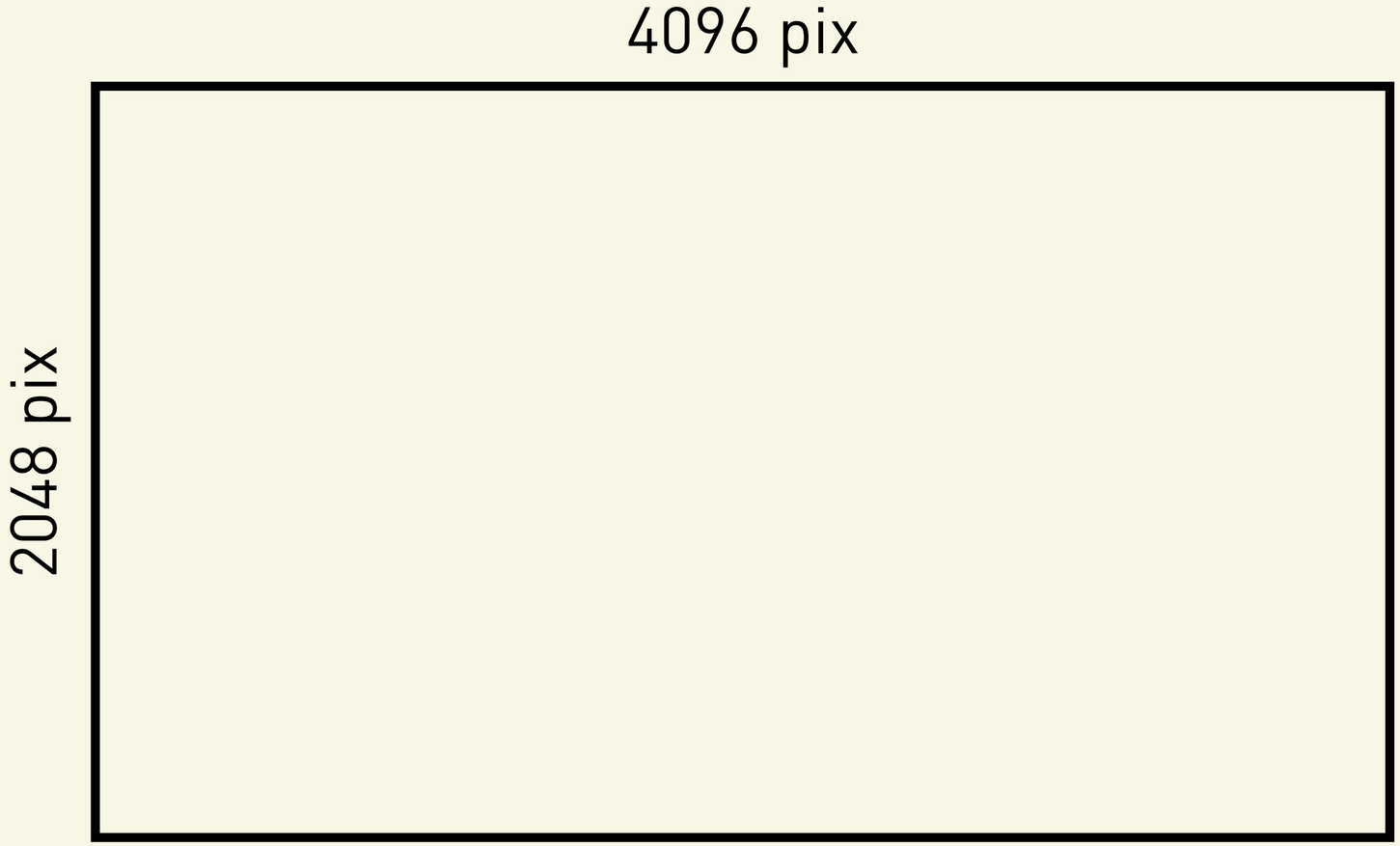
Wavelength solution



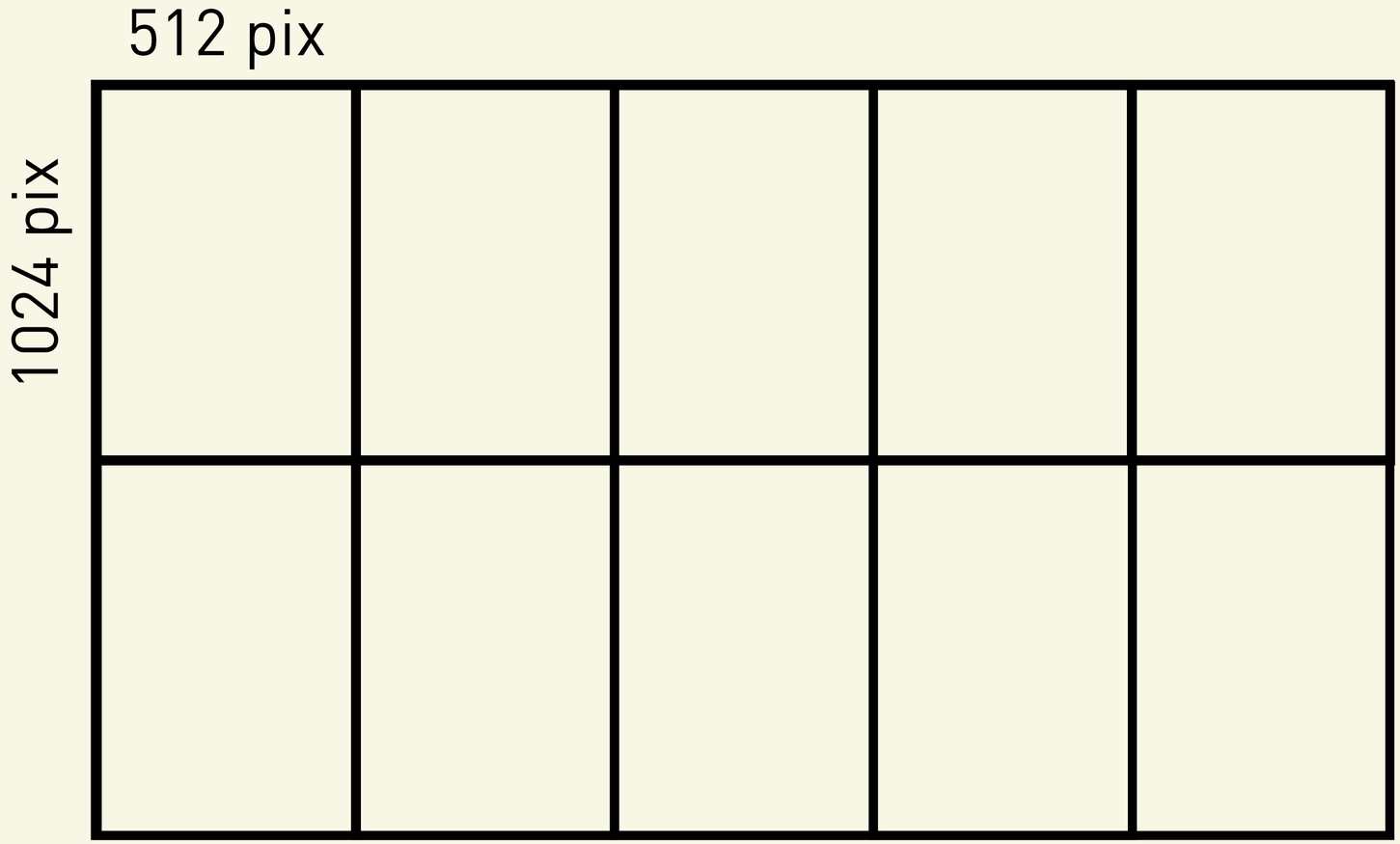
Wavelength solution



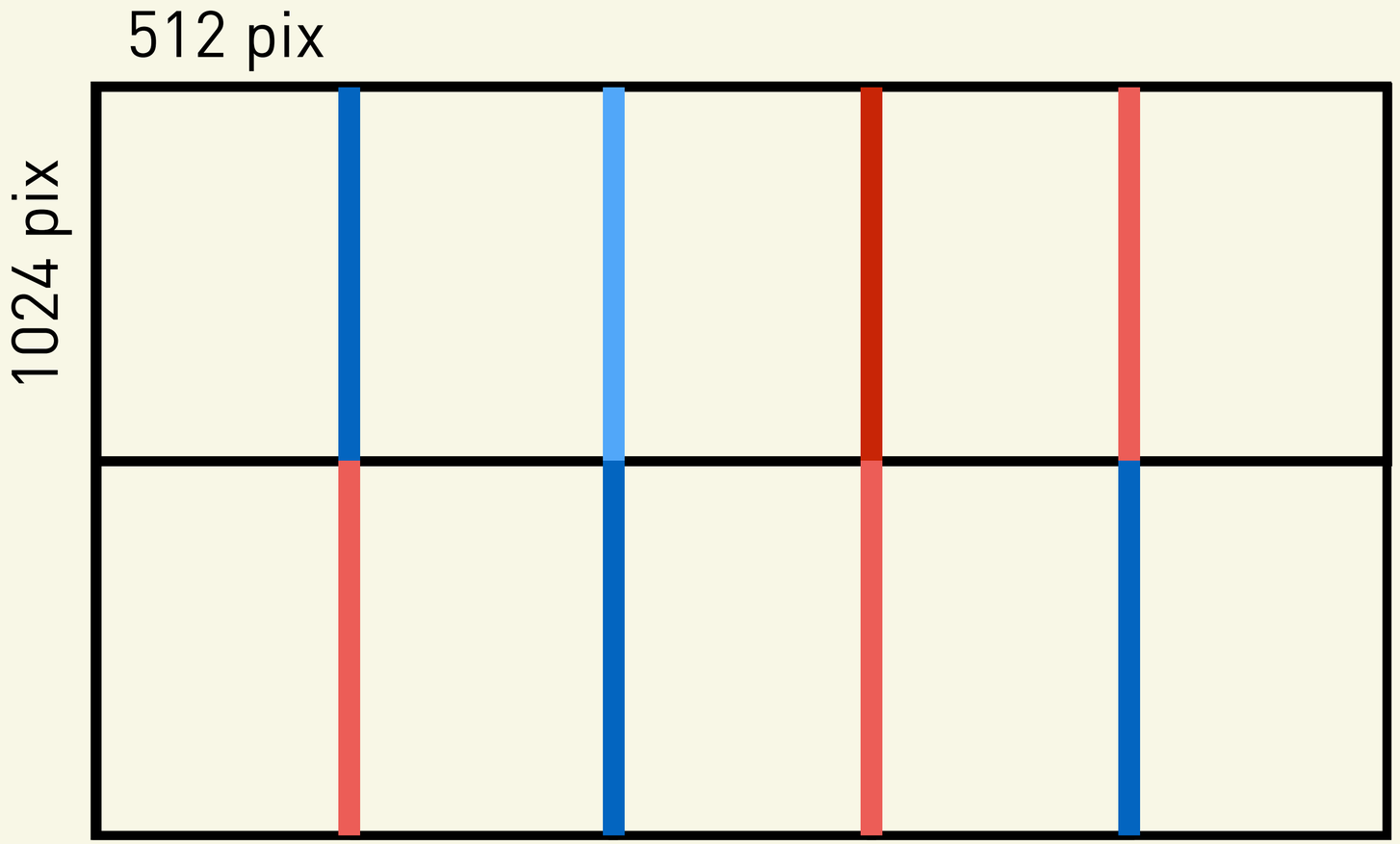
CCD manufacturing



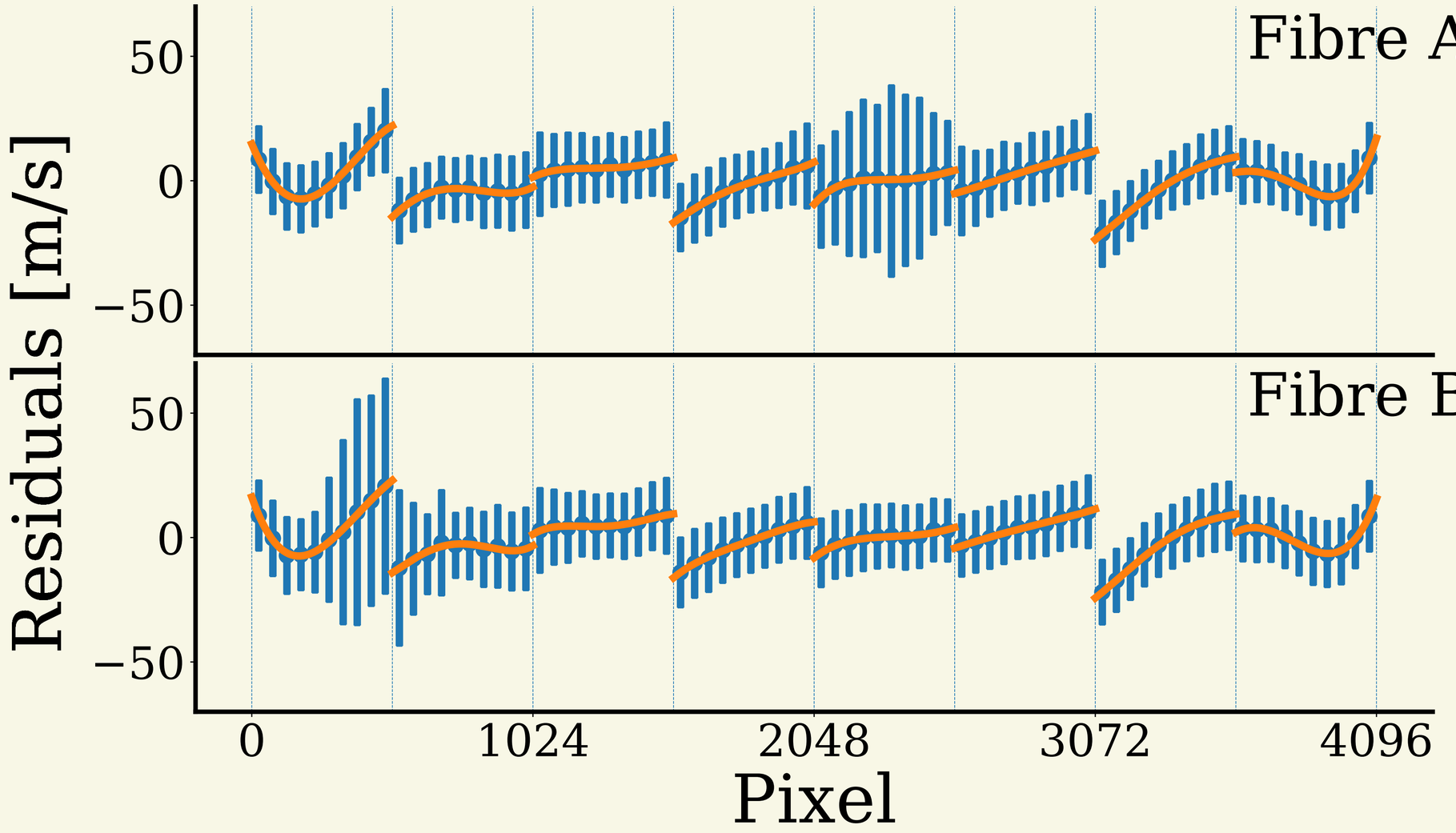
CCD manufacturing



CCD manufacturing



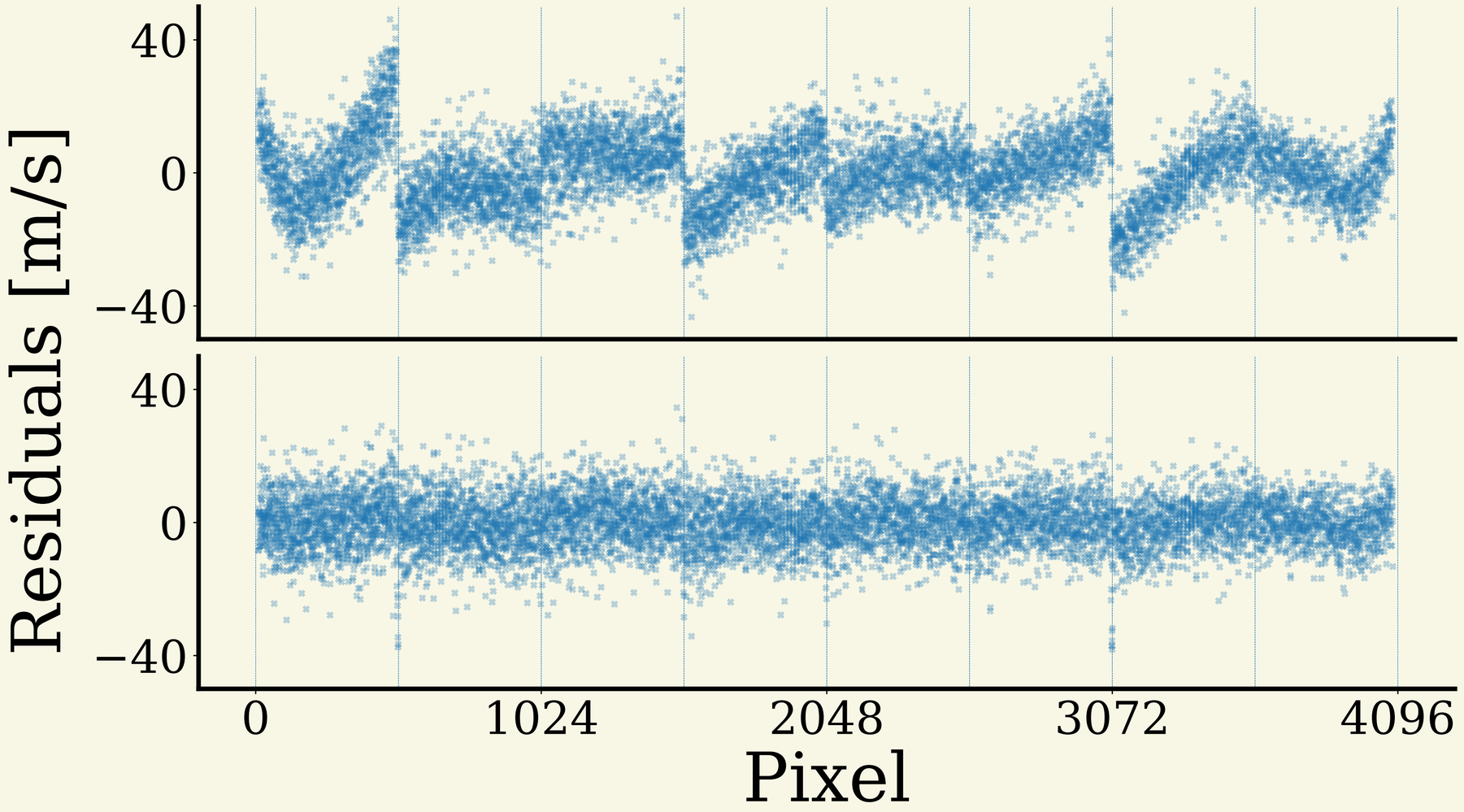
Modelling CCD imperfections



4.8M points

2.4M points

Correcting CCD imperfections



No correction

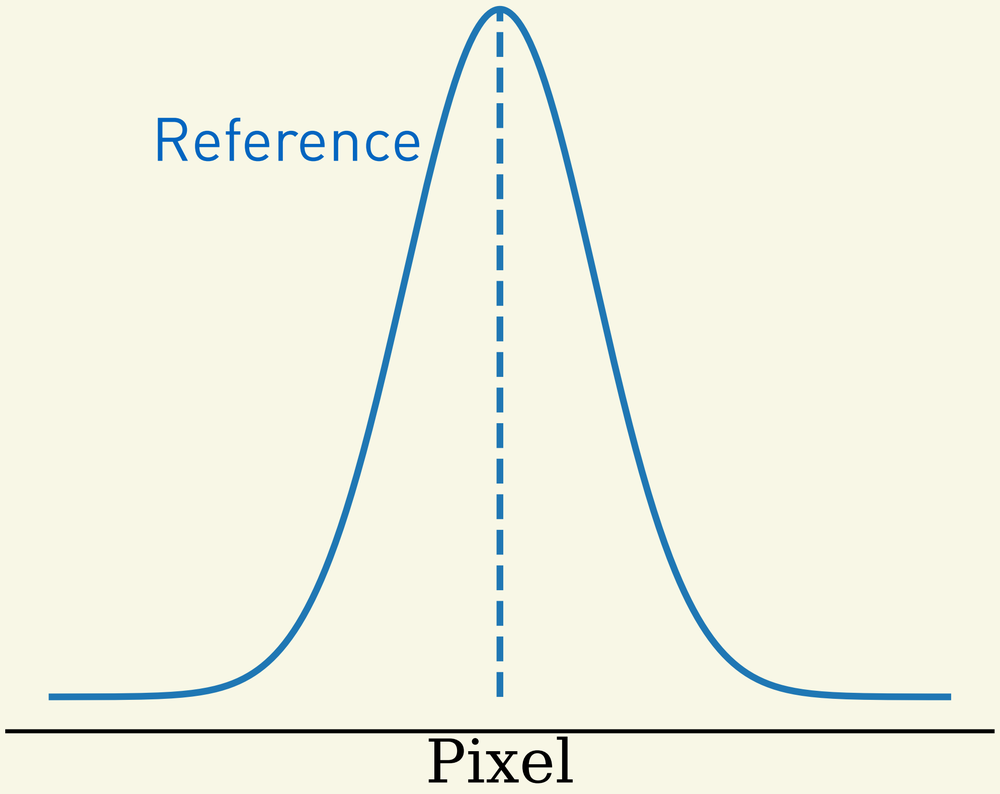
With correction

LFC campaign April 2015

- 2 working LFC systems:
    1. HARPS (18 GHz)
    2. FOCES (25 GHz)
- Goal: to compare the relative stability of two LFCs
- 2 methods:
    1. mean shift of LFC lines weighted by photon noise
    2. mean shift of polynomial wavelength solutions

Methods

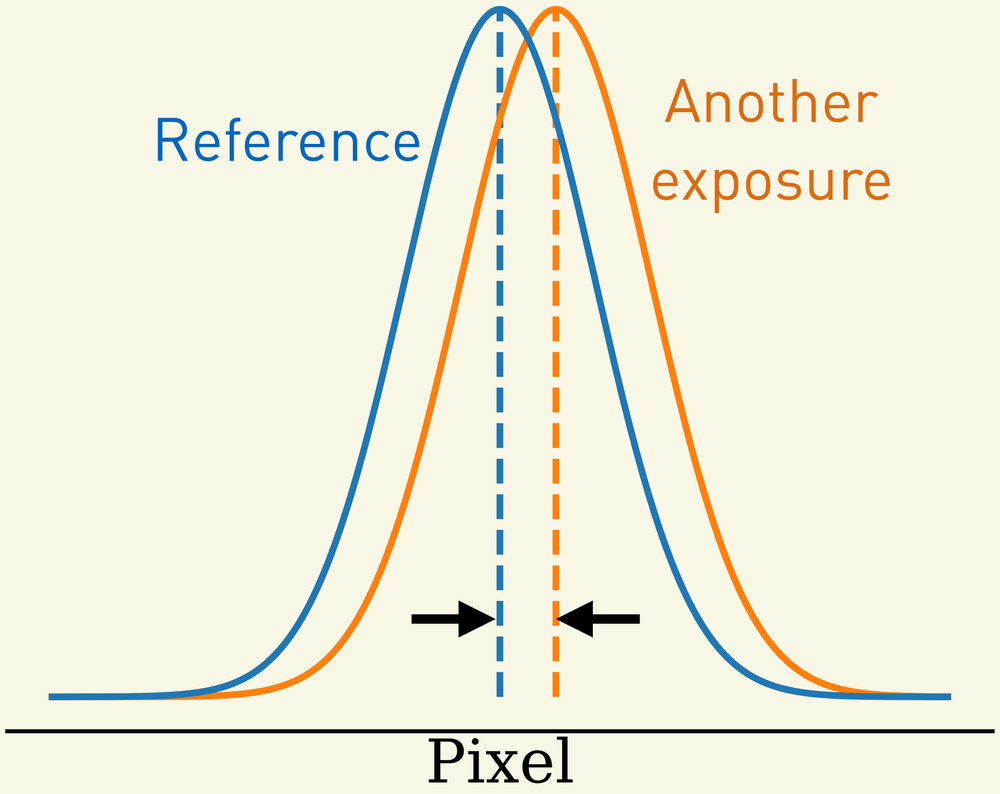
Method 1



Method 2

Methods

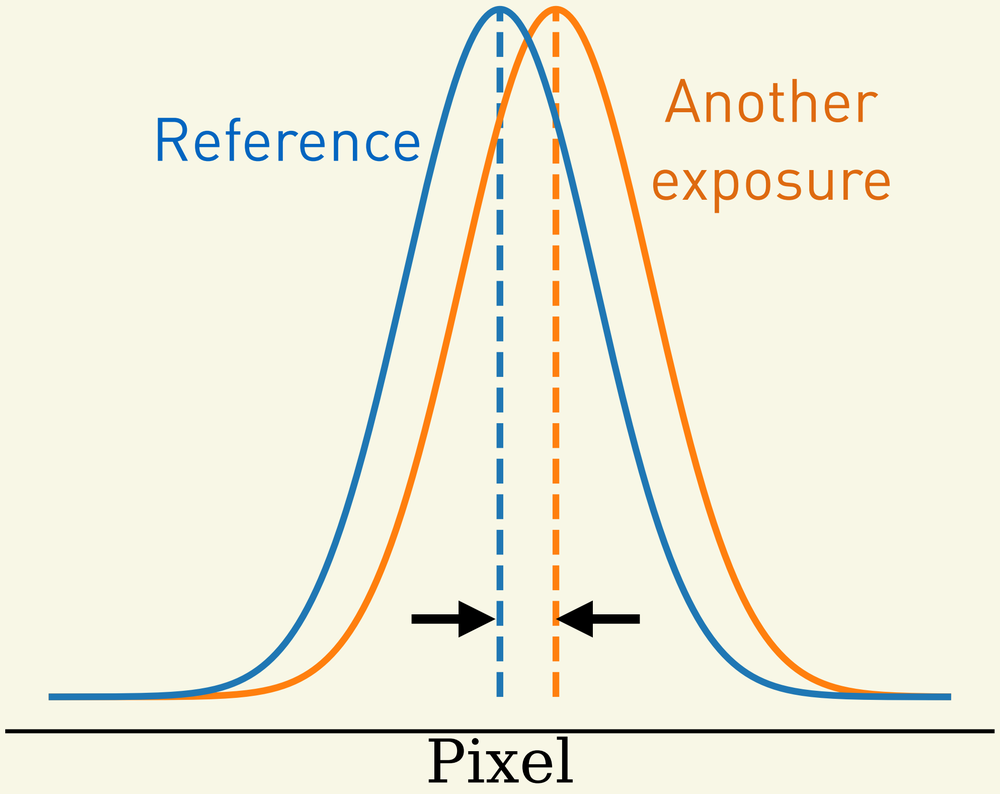
Method 1



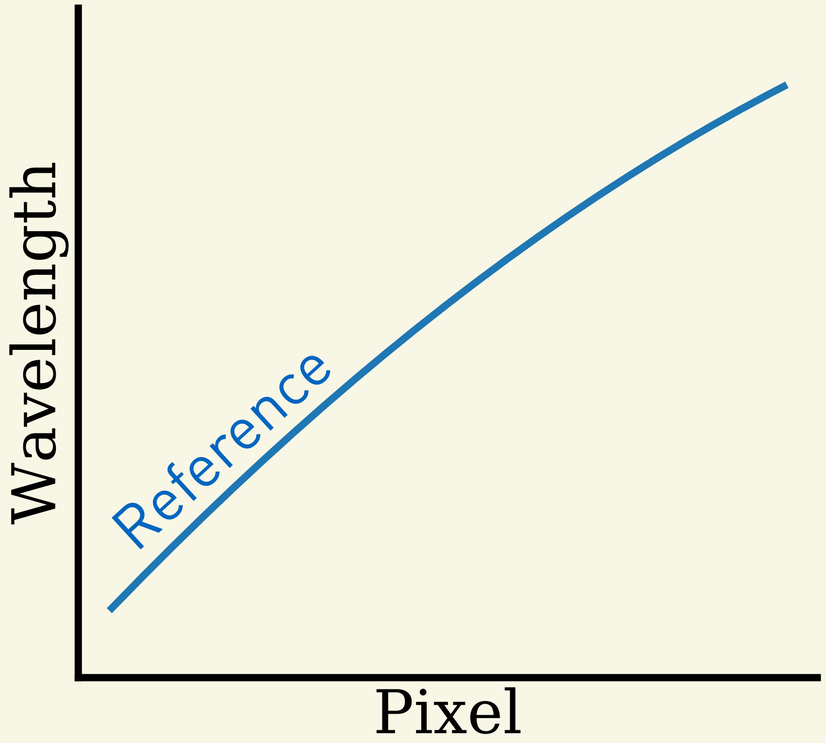
Method 2

Methods

Method 1



Method 2



Methods

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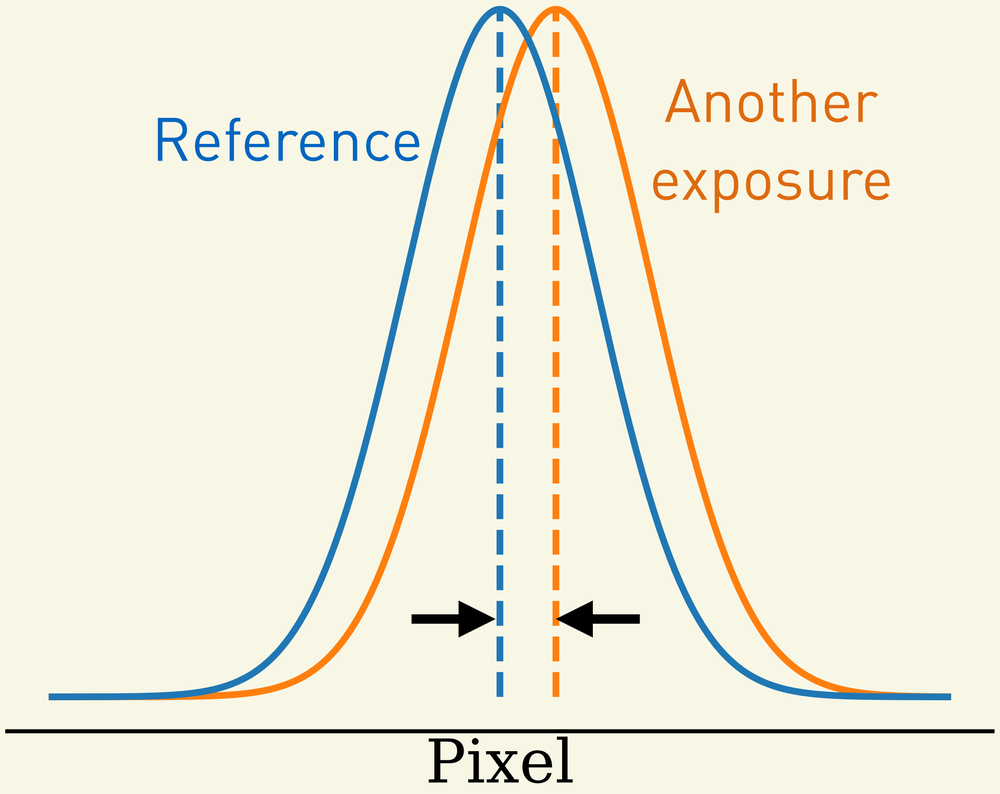
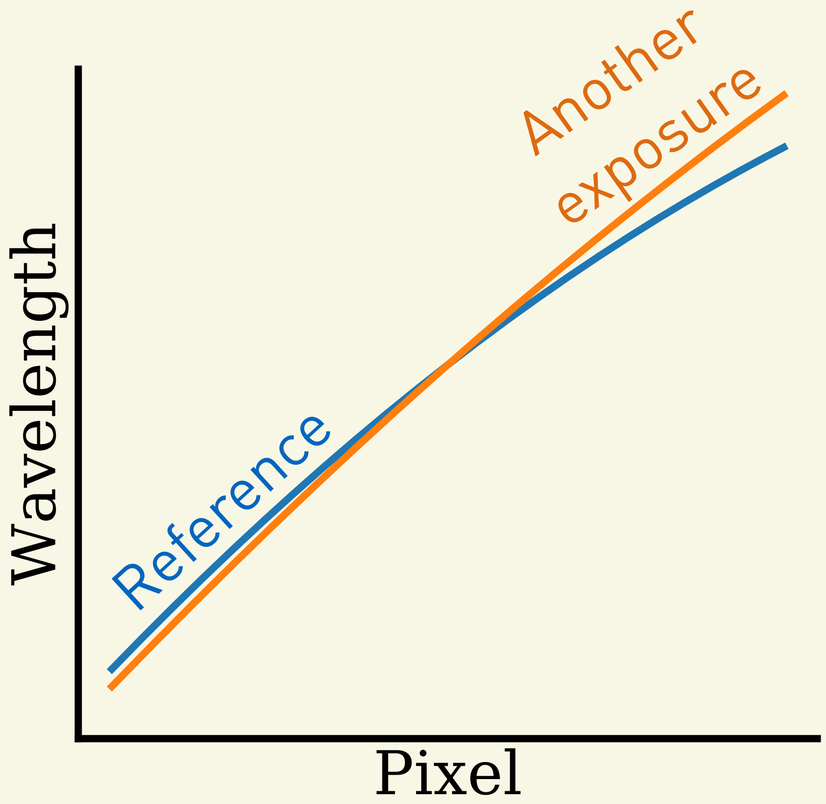
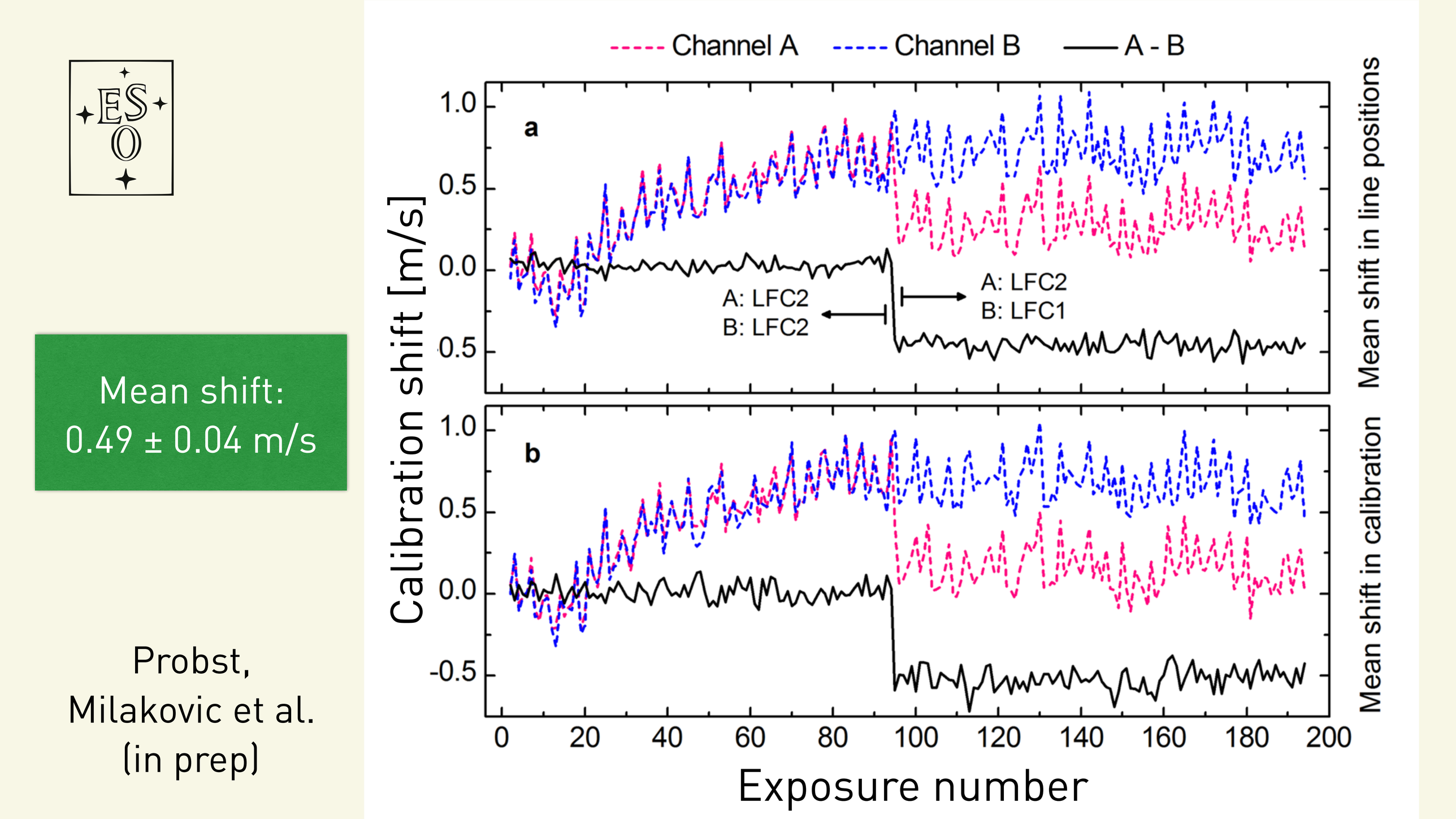


Method 2





Mean shift:
0.49 ± 0.04 m/s

Probst,
Milakovic et al.
(in prep)

Results

- Agreement between the two LFCs:
    1. Method 1: 0.49 ± 0.04 m/s level
    2. Method 2: 0.53 ± 0.05 m/s level

$\Delta\lambda/\lambda \approx 10^{-9}$

(10 nm on the detector)

- Possible causes of disagreement:
    1. Different injection of LFC light into HARPS fibres
    2. Variation in light intensity between LFC1 and LFC2

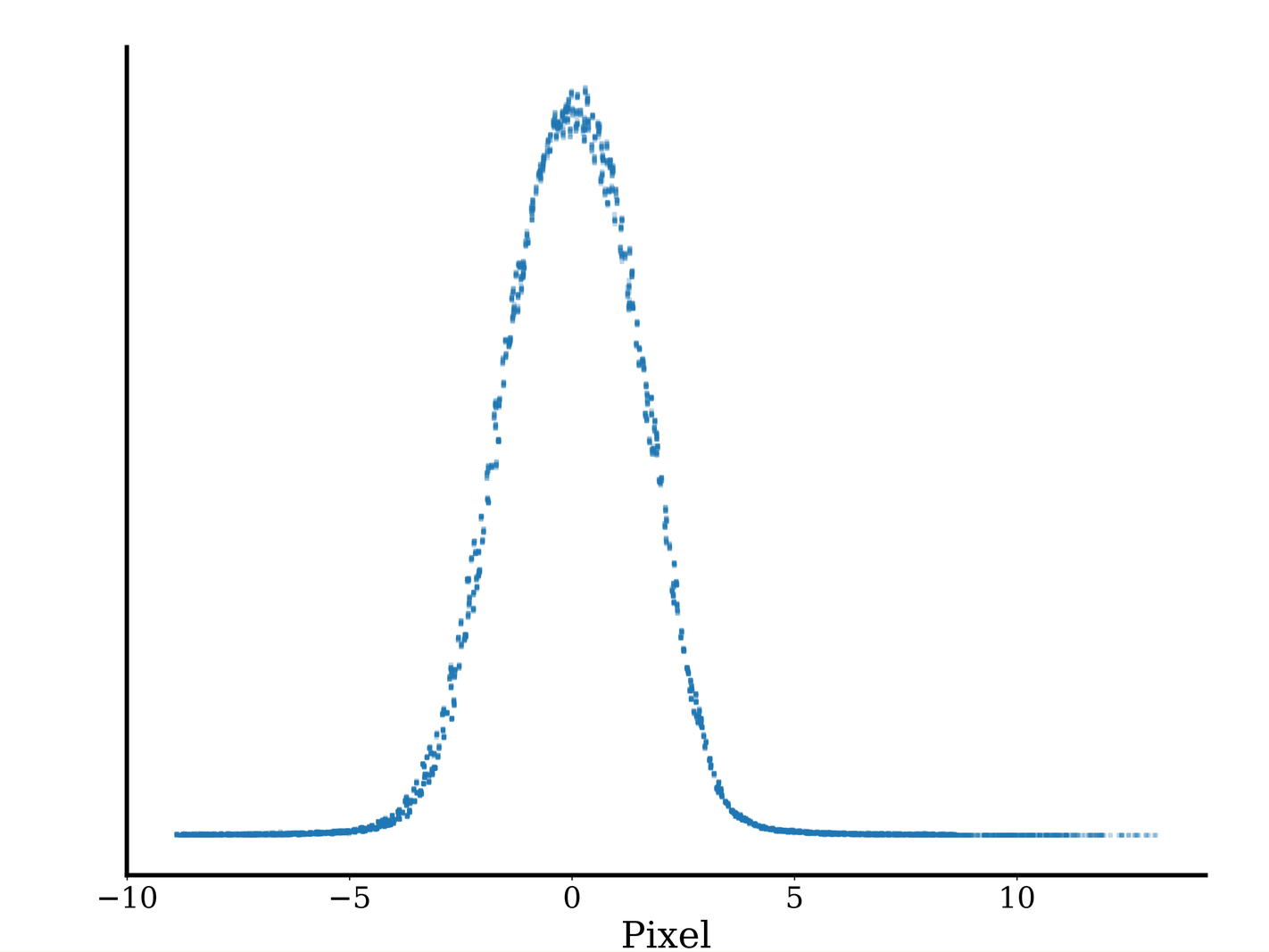
Conclusions

- Measuring the expansion history of the Universe requires the use of ELTs and ultra-stable and ultra-accurate spectrographs
- Gaussian not a good shape ➞ modelling of the line-spread-function
- Instrumental effects:

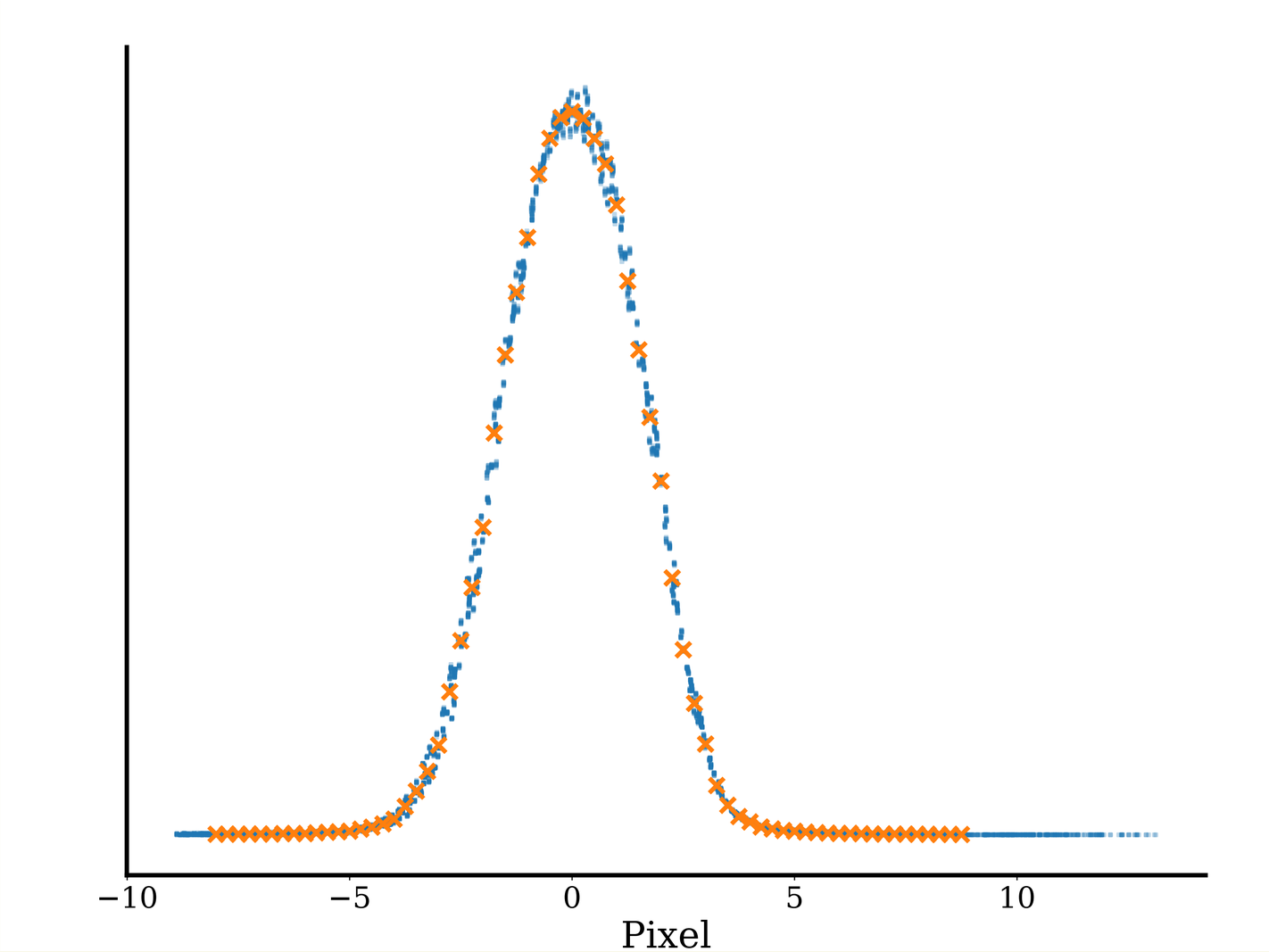
    1. Charge transfer inefficiencies
    2. Flux intensity dependence
    3. CCD pixel size variations and pixel-to-pixel dependence

Extra slides

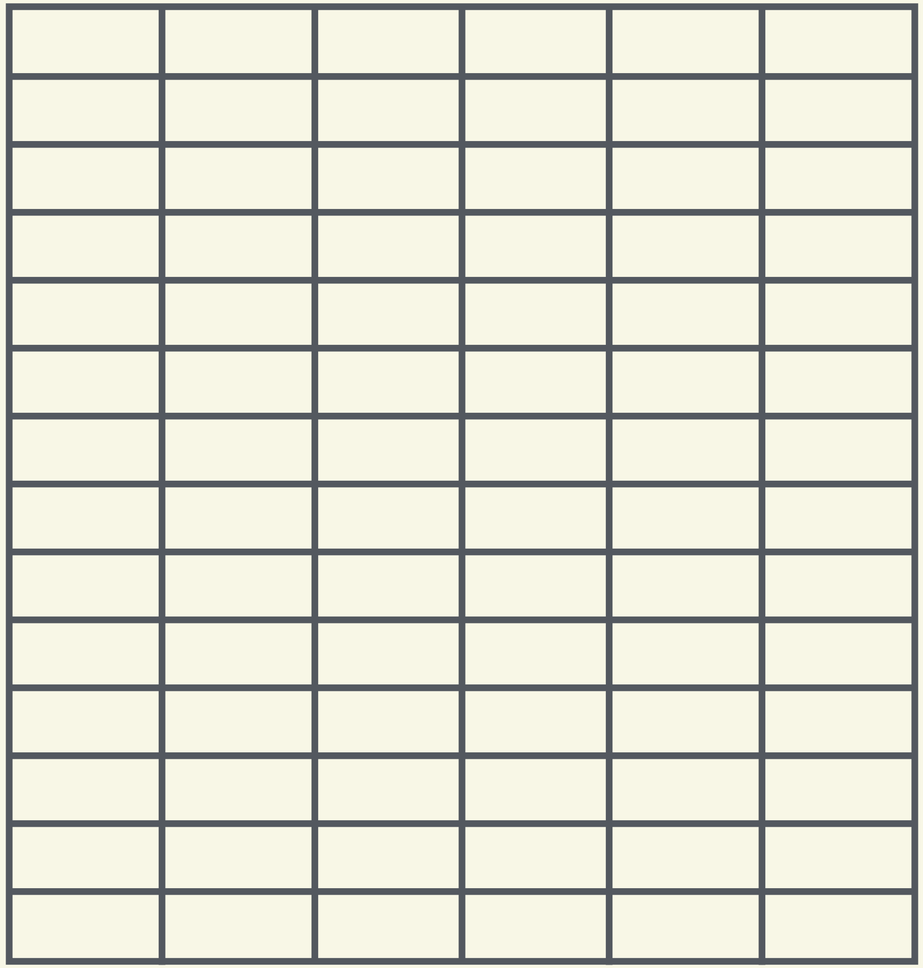
Constructing LSF



Constructing LSF



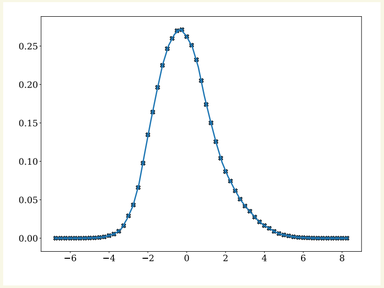
CCD

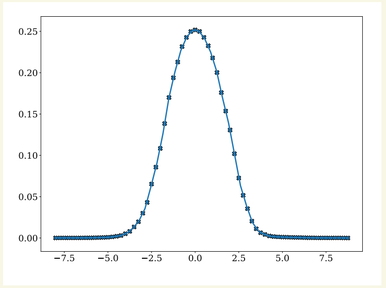


30 orders

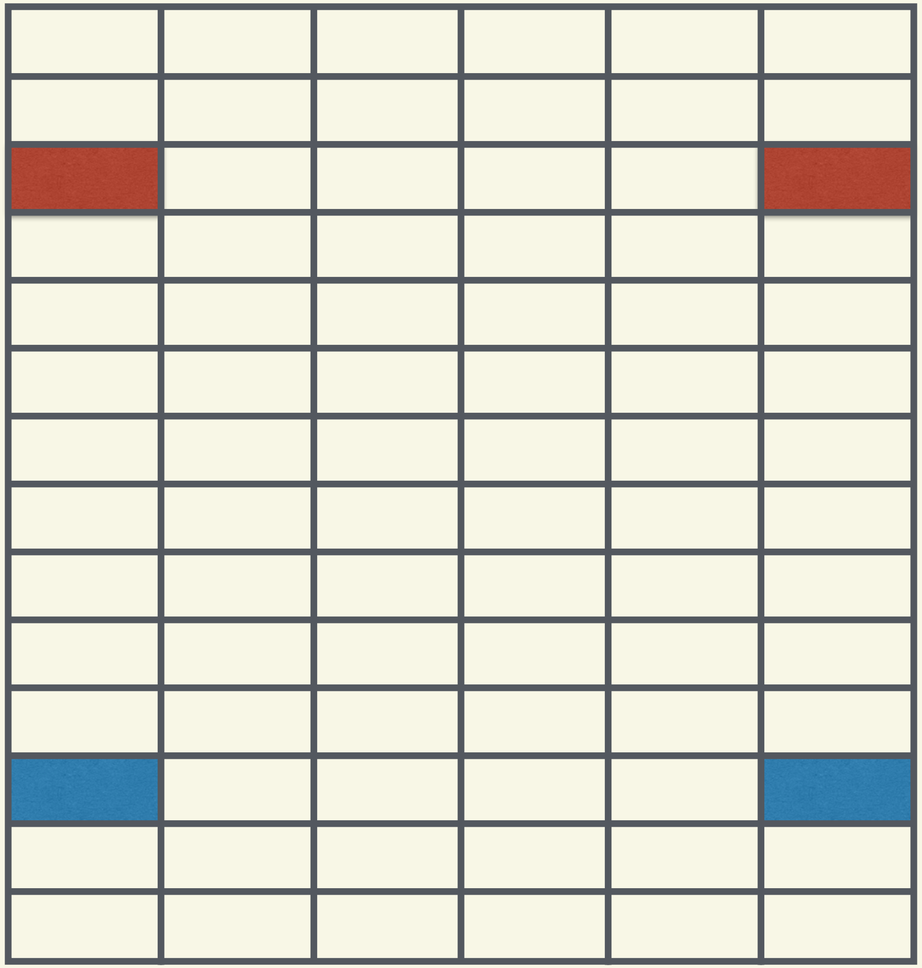
16 segments

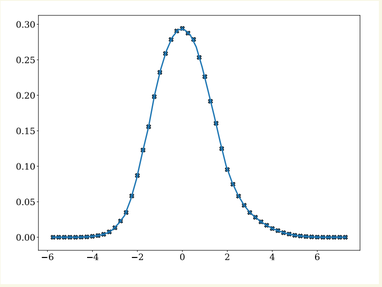
CCD

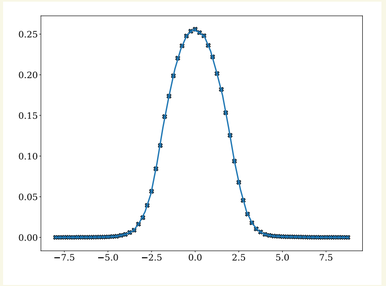




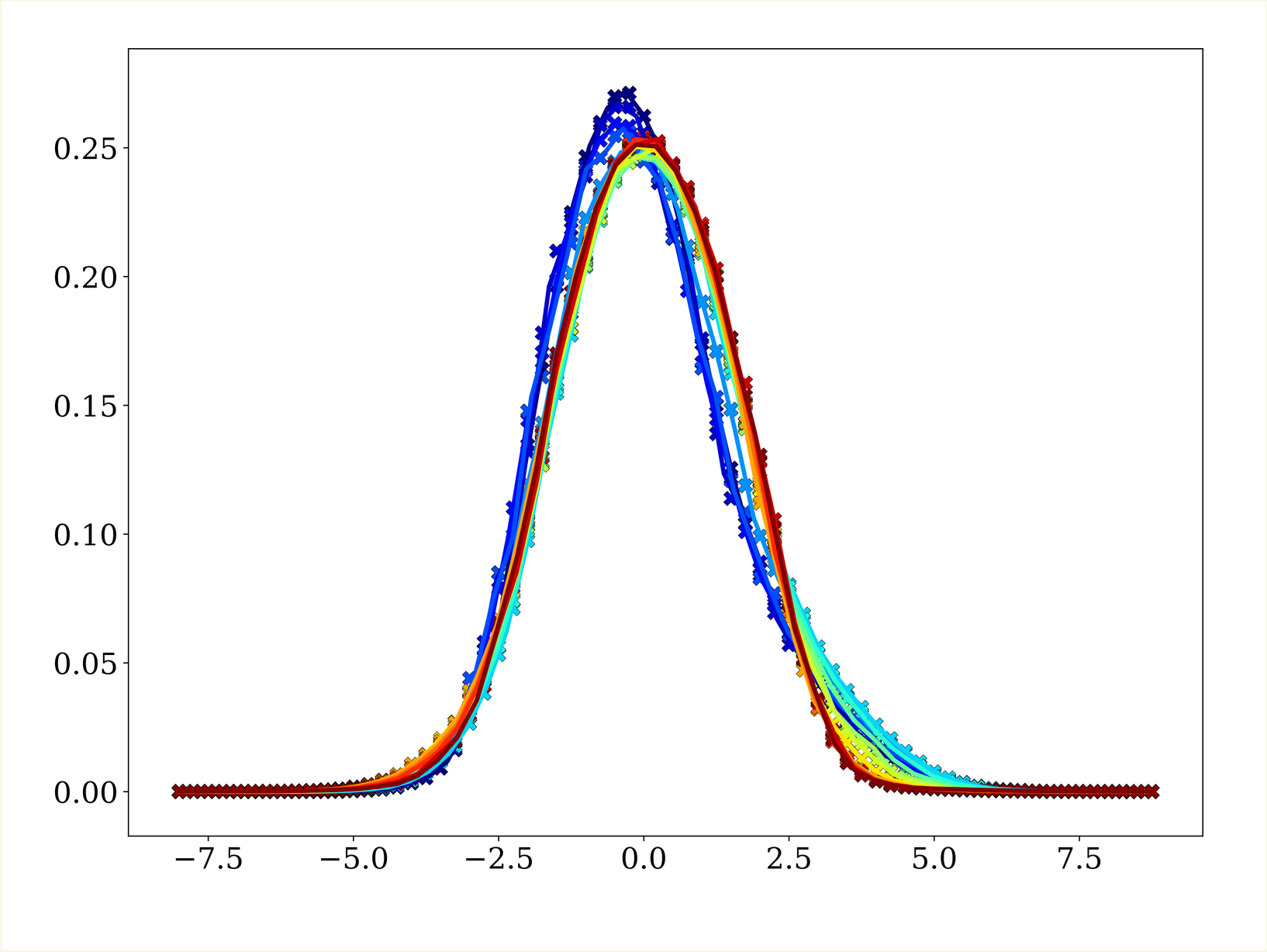
30 orders





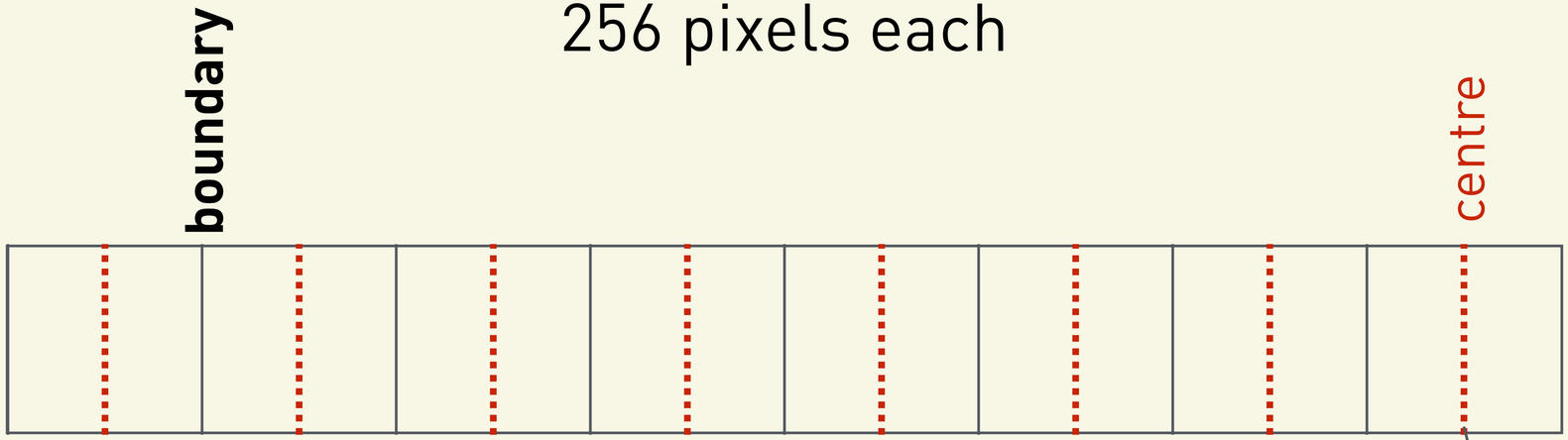


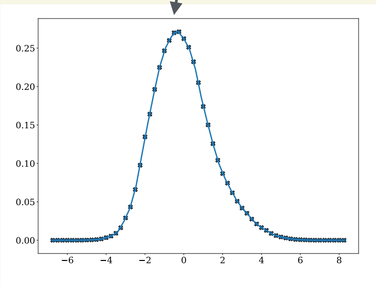
16 segments

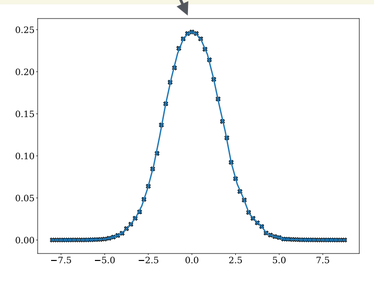

0.25
0.20
0.15
0.10
0.05
0.00
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5

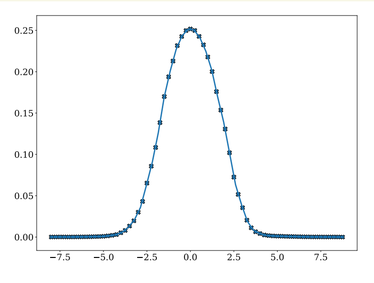
16 segments per order

256 pixels each



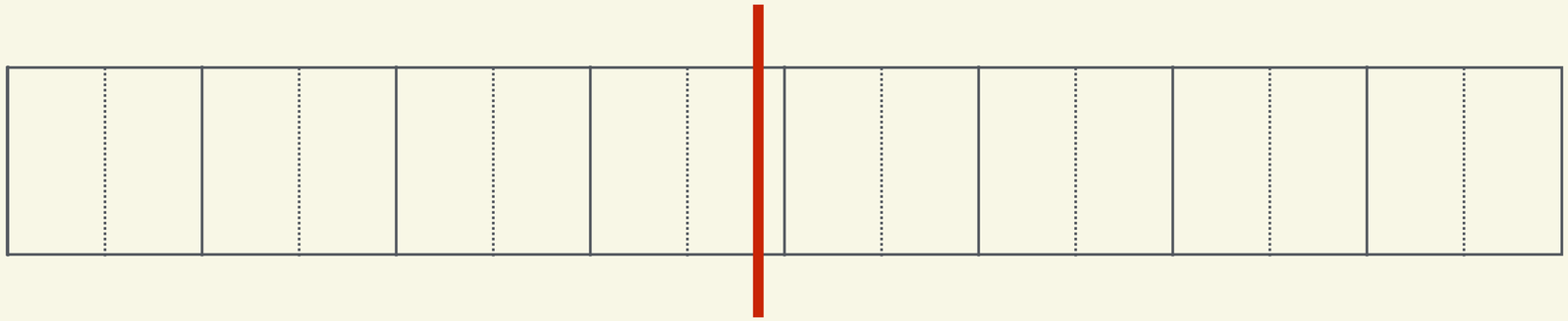


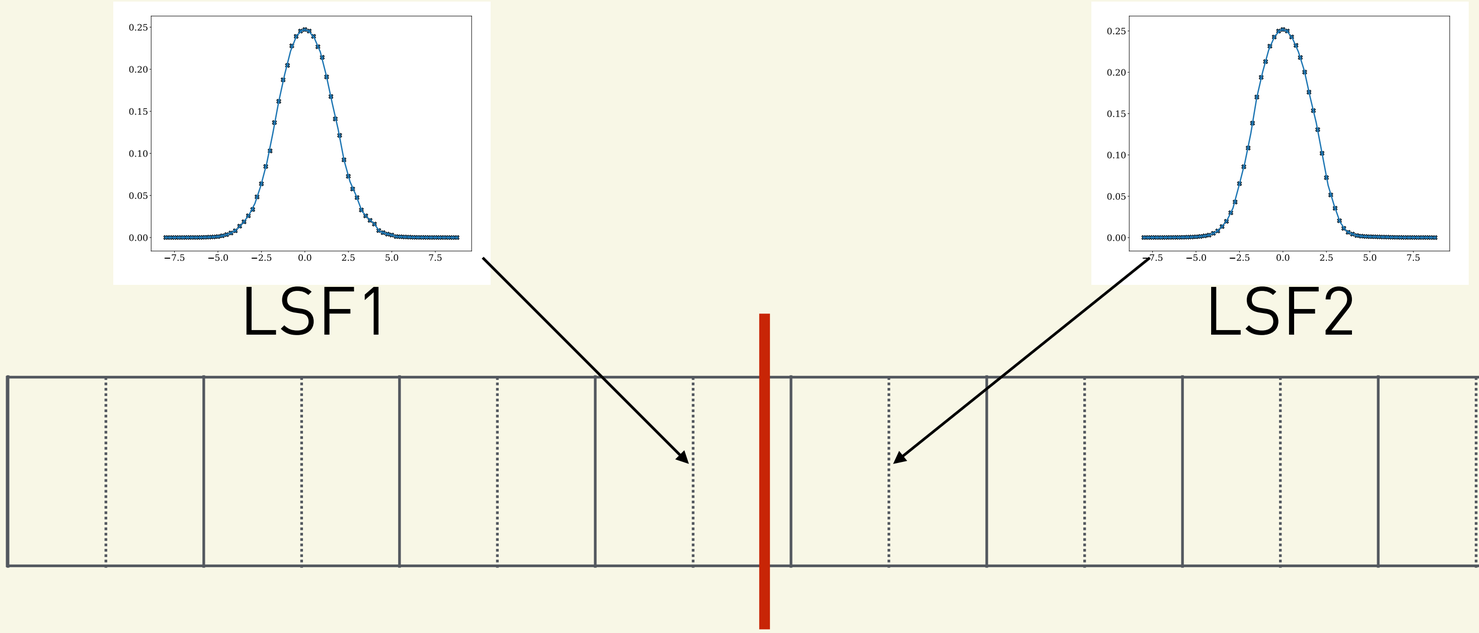


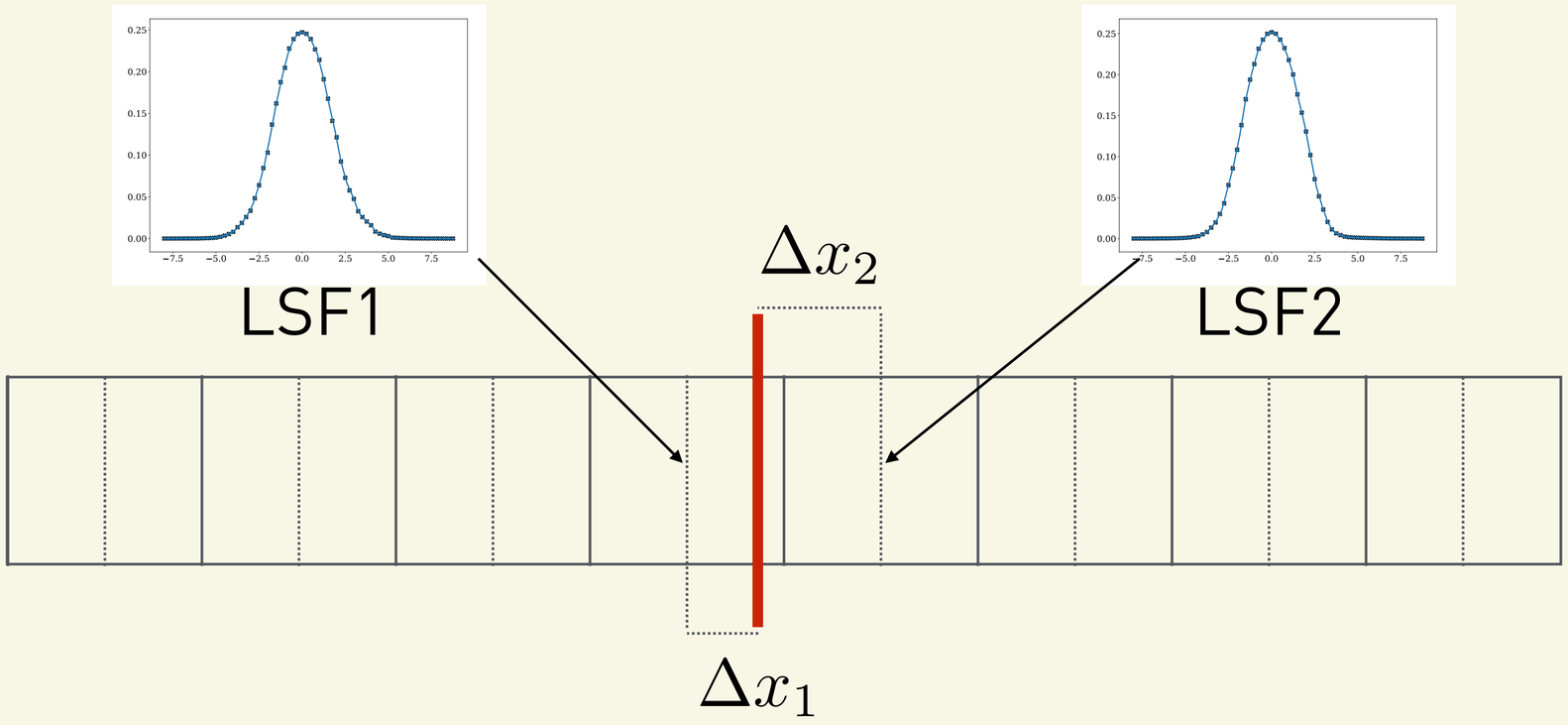


Line barycentre

x




0.25
0.20
0.15
0.10
0.05
0.00
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
LSF1
LSF2



$$LSF_{local} = \frac{\Delta x_2}{\Delta X} \times LSF_1 + \frac{\Delta x_1}{\Delta X} \times LSF_2$$

$$\Delta X = \Delta x_1 + \Delta x_2$$

Line spread function