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Fundamentals of Instrumentation

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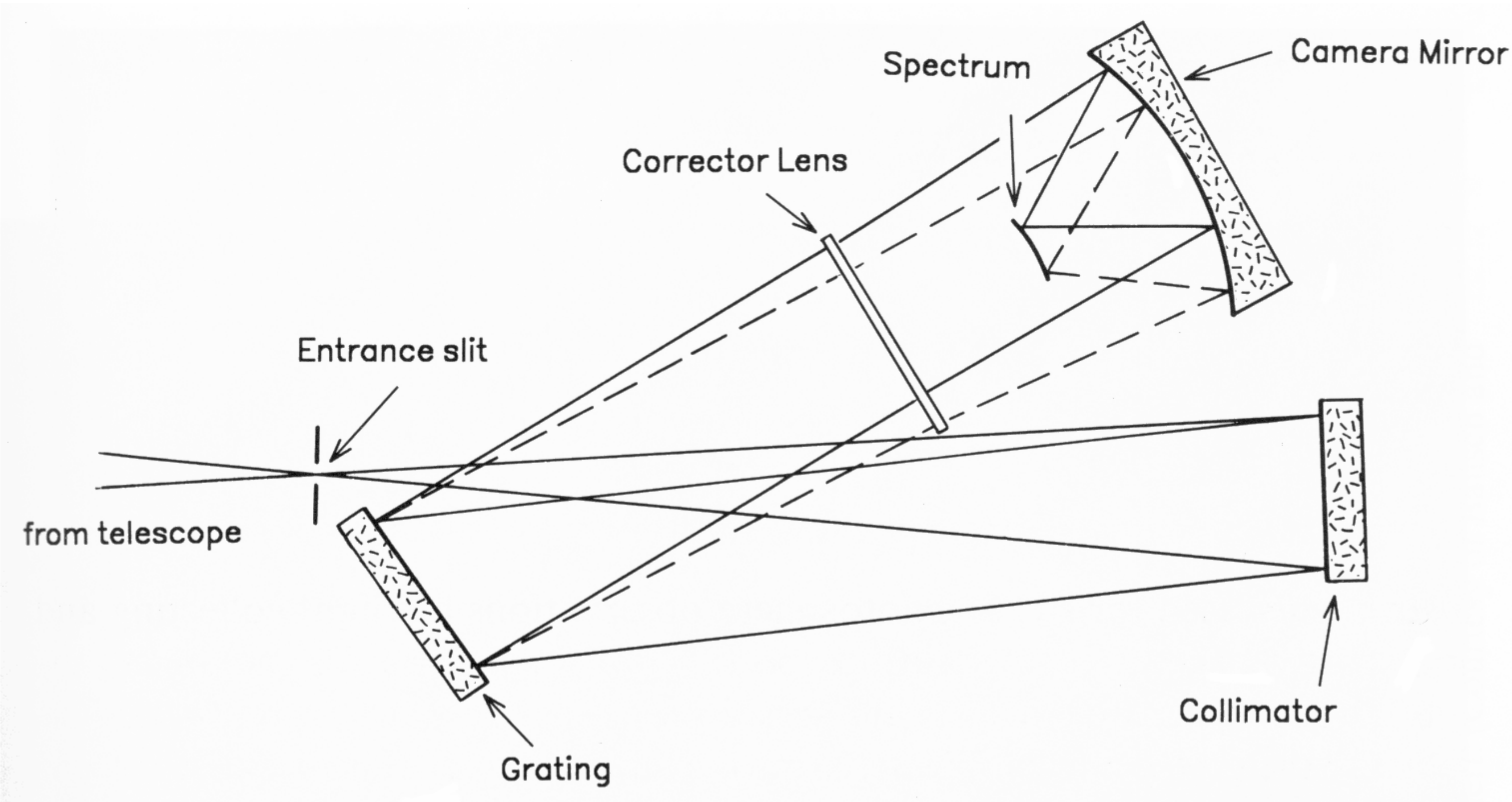
Cross-Dispersed Echelle Spectrographs

Layout of a Grating Spectrograph



Unblazed Reflection Grating with Groove Width b and Separation σ

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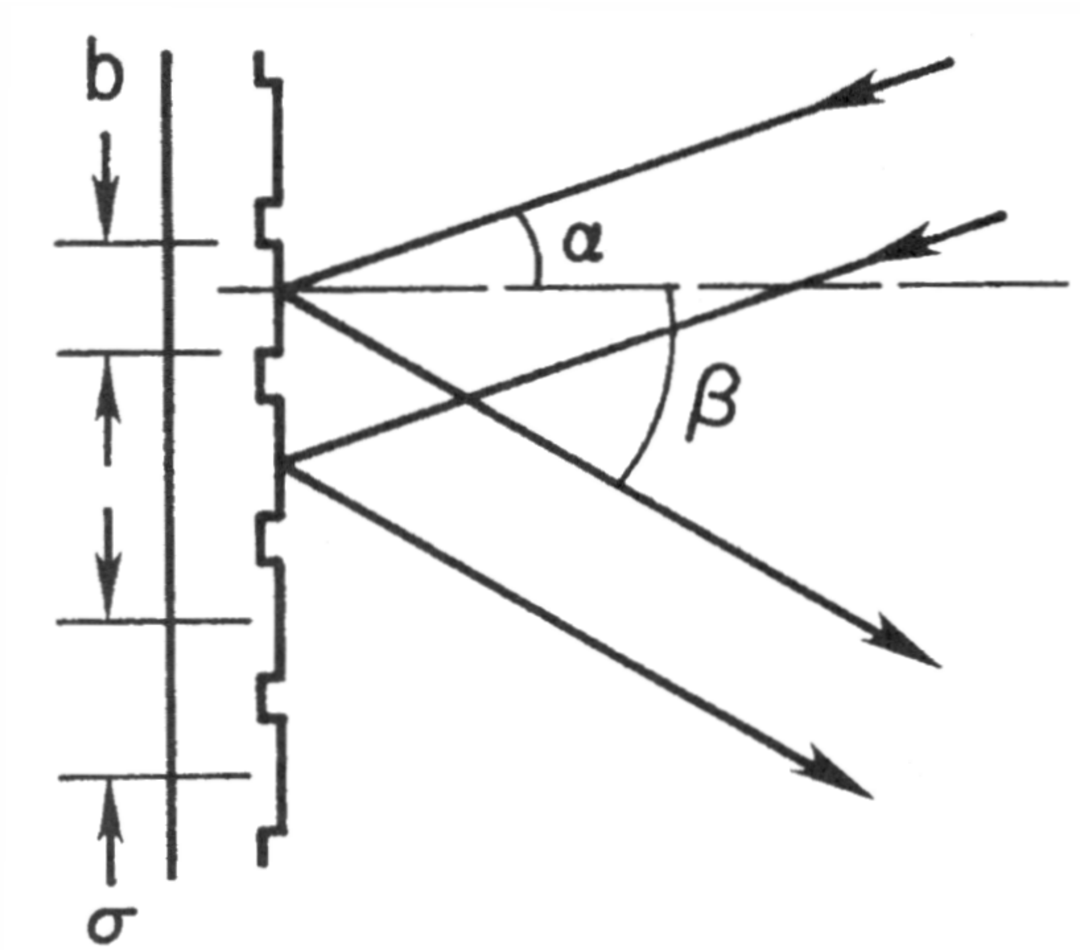

Fundamental Relations

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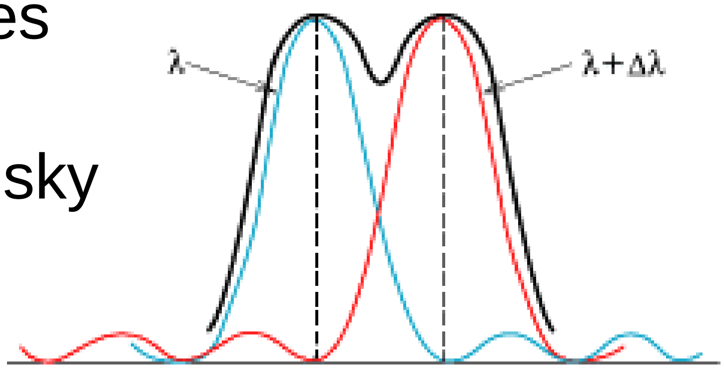
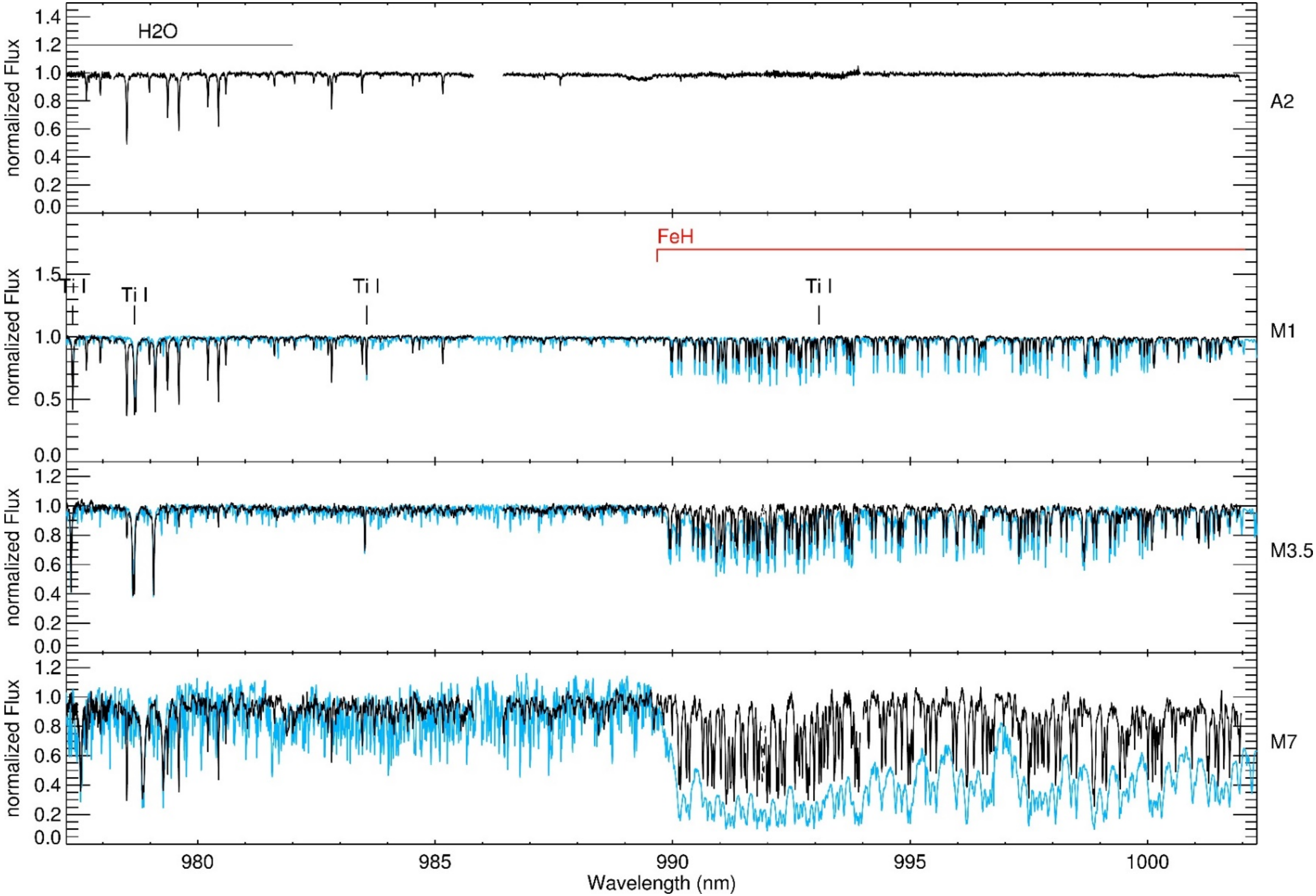
- Grating equation: $m\lambda = \sigma(\sin\beta + \sin\alpha)$
  - m is the diffraction order
- Angular dispersion: $\frac{d\beta}{d\lambda} = \frac{m}{\sigma\cos\beta} = \frac{\sin\beta + \sin\alpha}{\lambda\cos\beta}$
  - "Spread" of spectrum on detector
- Resolution: $R = \frac{\lambda}{\Delta\lambda} = \frac{W(\sin\beta + \sin\alpha)}{\varphi D} = \frac{\lambda m W}{\varphi D \sigma} = \frac{\lambda m N}{\varphi D}$
  - Ability to separate adjacent lines
  - W length of grating
  - φ angular slit (or fiber) size on sky
  - D telescope diameter
  - N total number of grating lines



A Small Section of CARMENES Spectra



Reiners et al. (A&A 2018)

RV Accuracy for Stars with Different Rotation Rates

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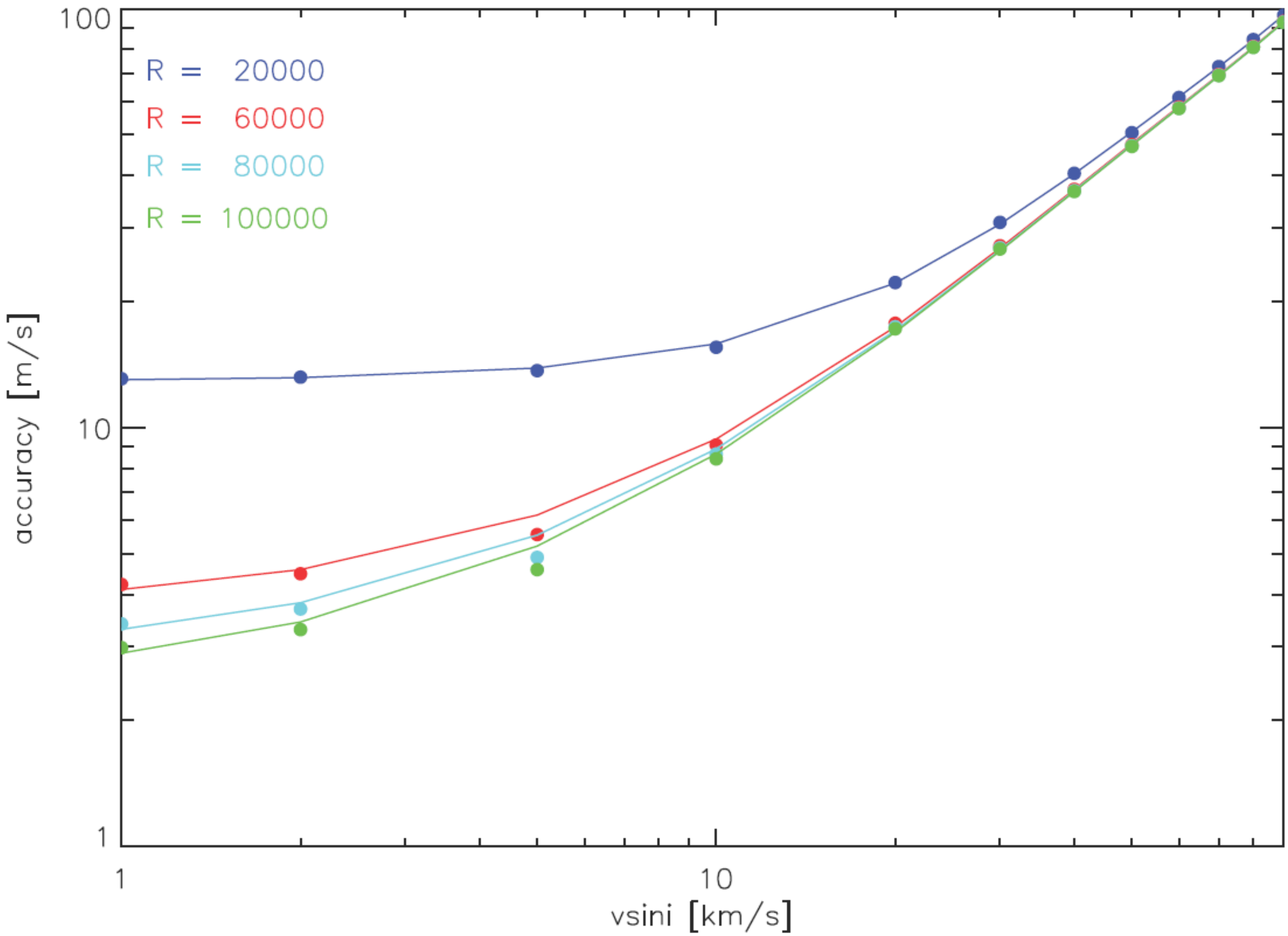

The Quest for High Spectral Resolution

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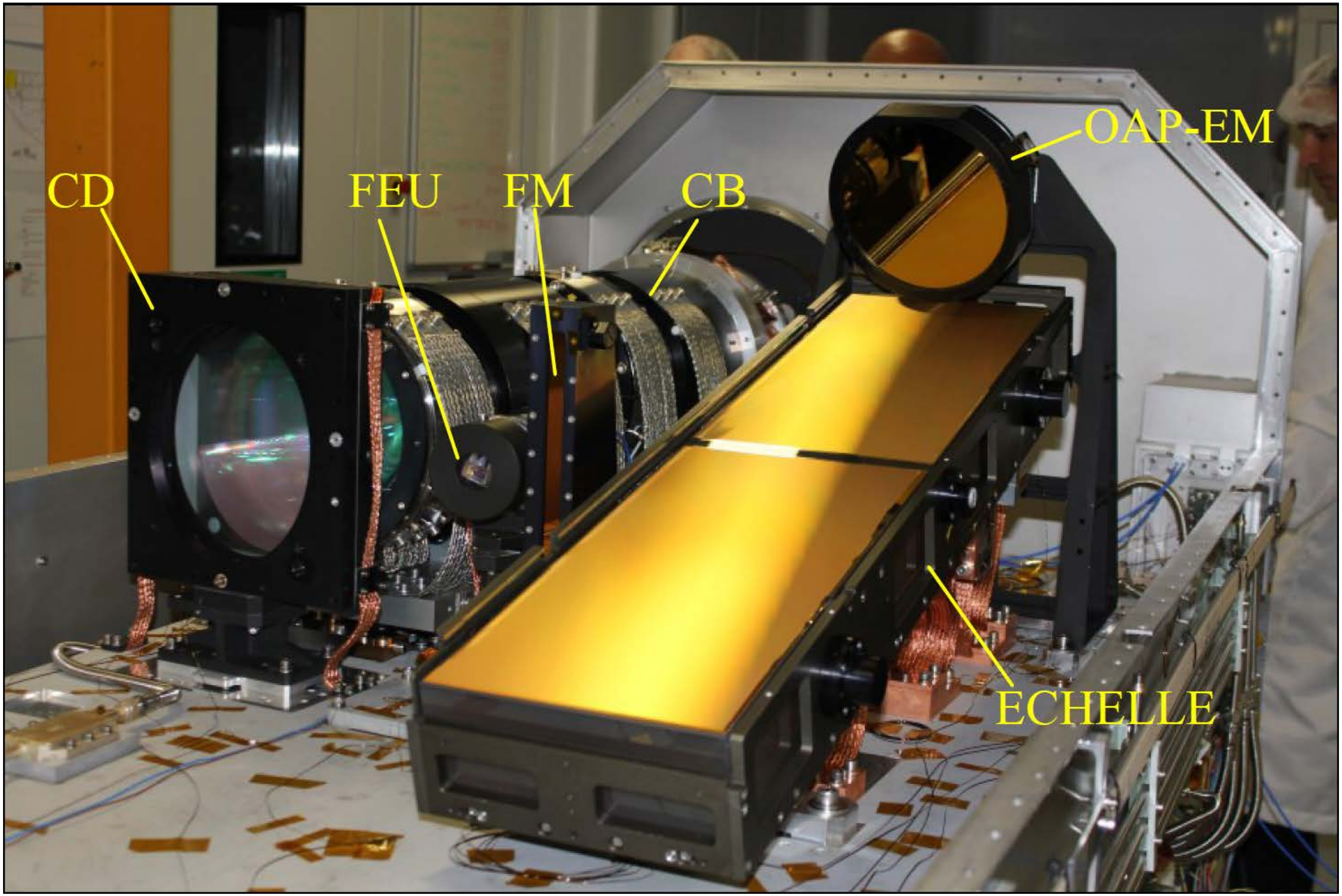
- Best RV precision for $R \gtrsim 80{,}000$
- Resolution: $R = \frac{W(\sin\beta + \sin\alpha)}{\varphi D} = \frac{\lambda m W}{\varphi D \sigma} = \frac{\lambda m N}{\varphi D}$
- Use large m, large N (i.e., large grating)
- Larger telescope → larger spectrograph
- Smaller slit (in arcsec) → smaller spectrograph
  - But loses light if < seeing disk
  - Trick: image slicing ("cut and stack" star image)
- Attractive alternative: use adaptive optics (in that case $\varphi \approx \lambda/D$)

Interior of the CARMENES NIR Spectrograph



CARMENES Vacuum Tank

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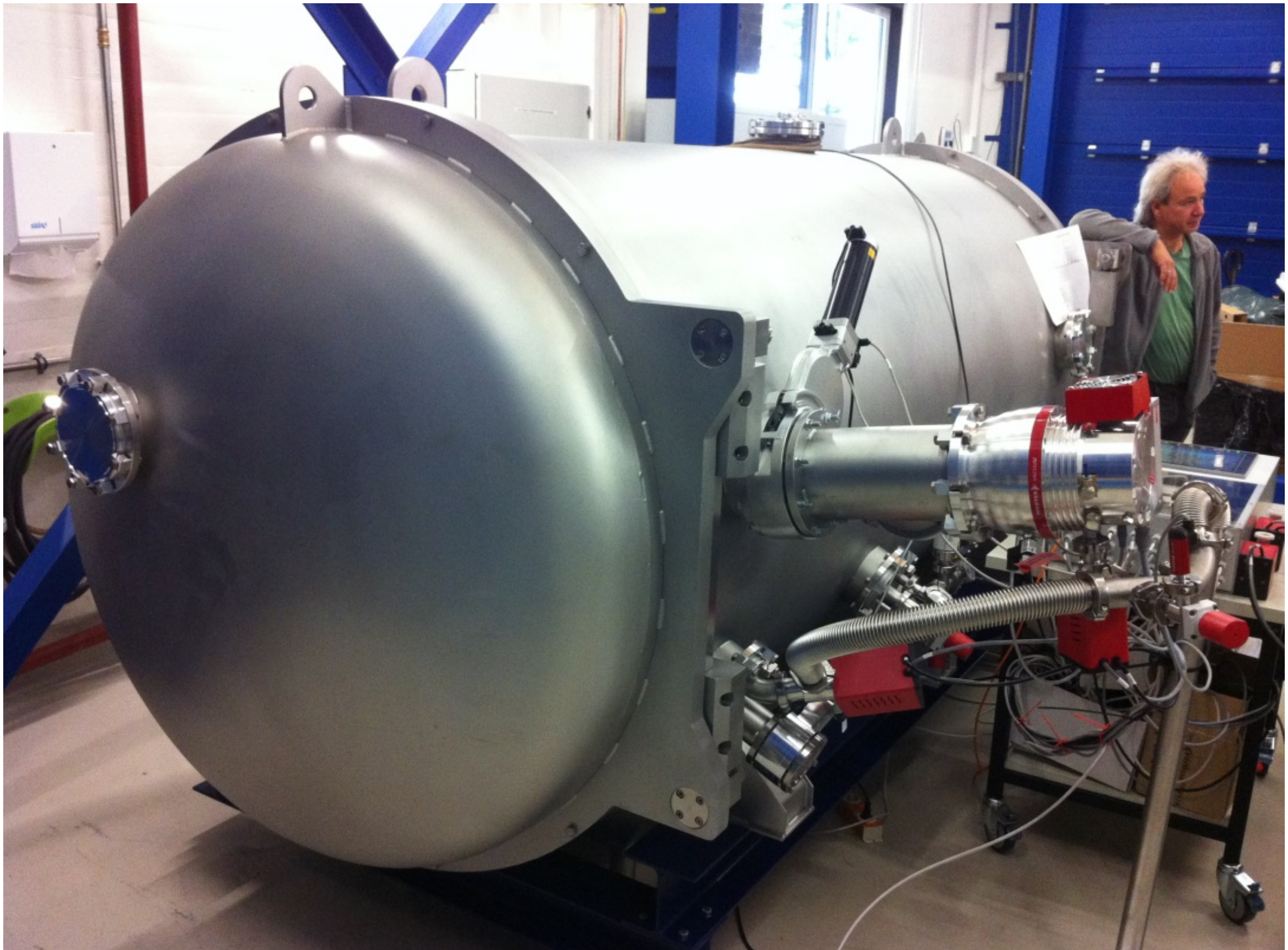

Grating Geometry

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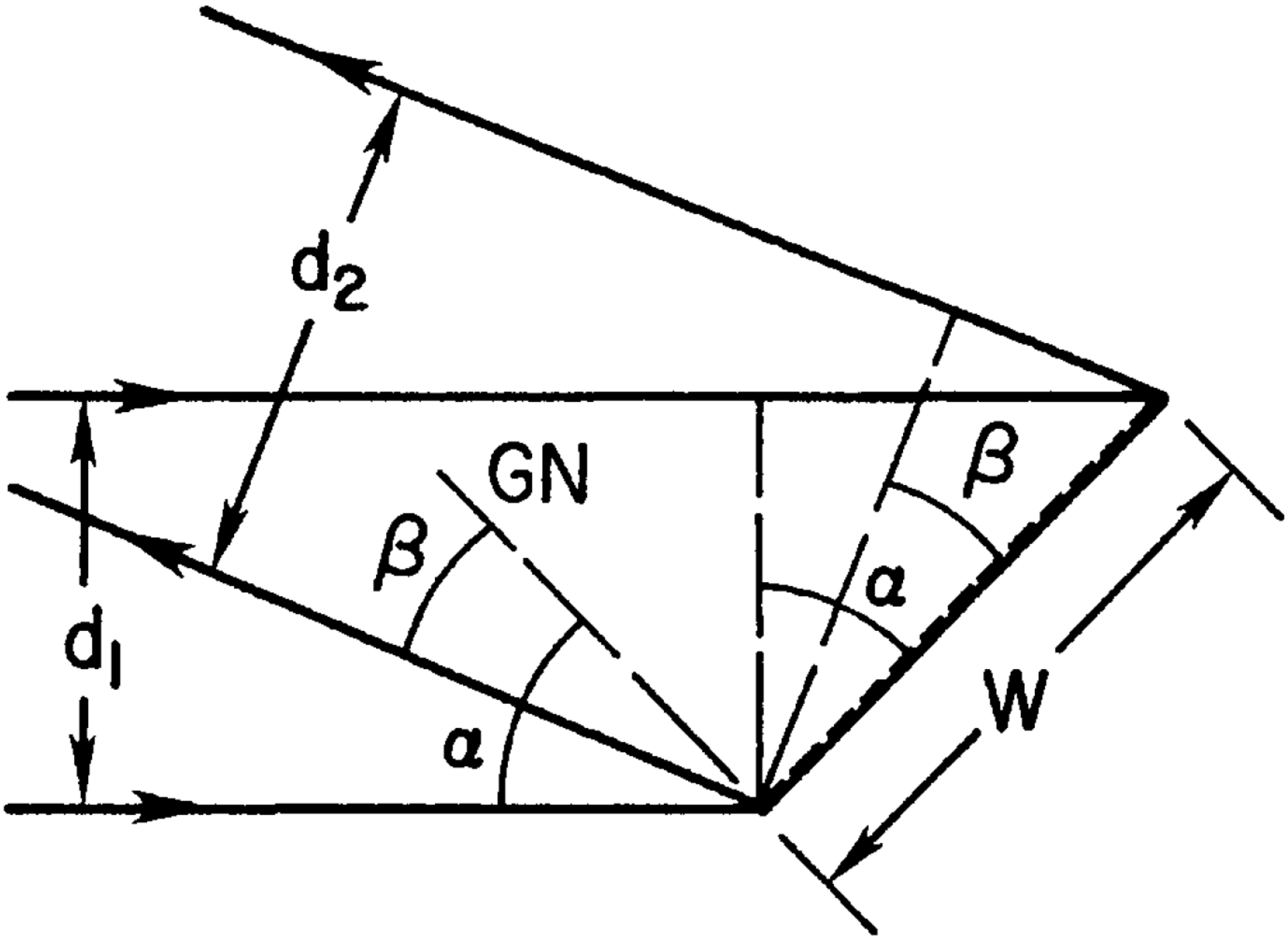

Littrow Configuration

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- Best resolution for $\alpha = \beta$ (Littrow configuration)
- Resolution in Littrow configuration:

$$R = \frac{2W}{\varphi D} \sin \beta$$

$$= \frac{2d_1}{\varphi D} \tan \beta$$

Typical Values for Echelle Spectrograph

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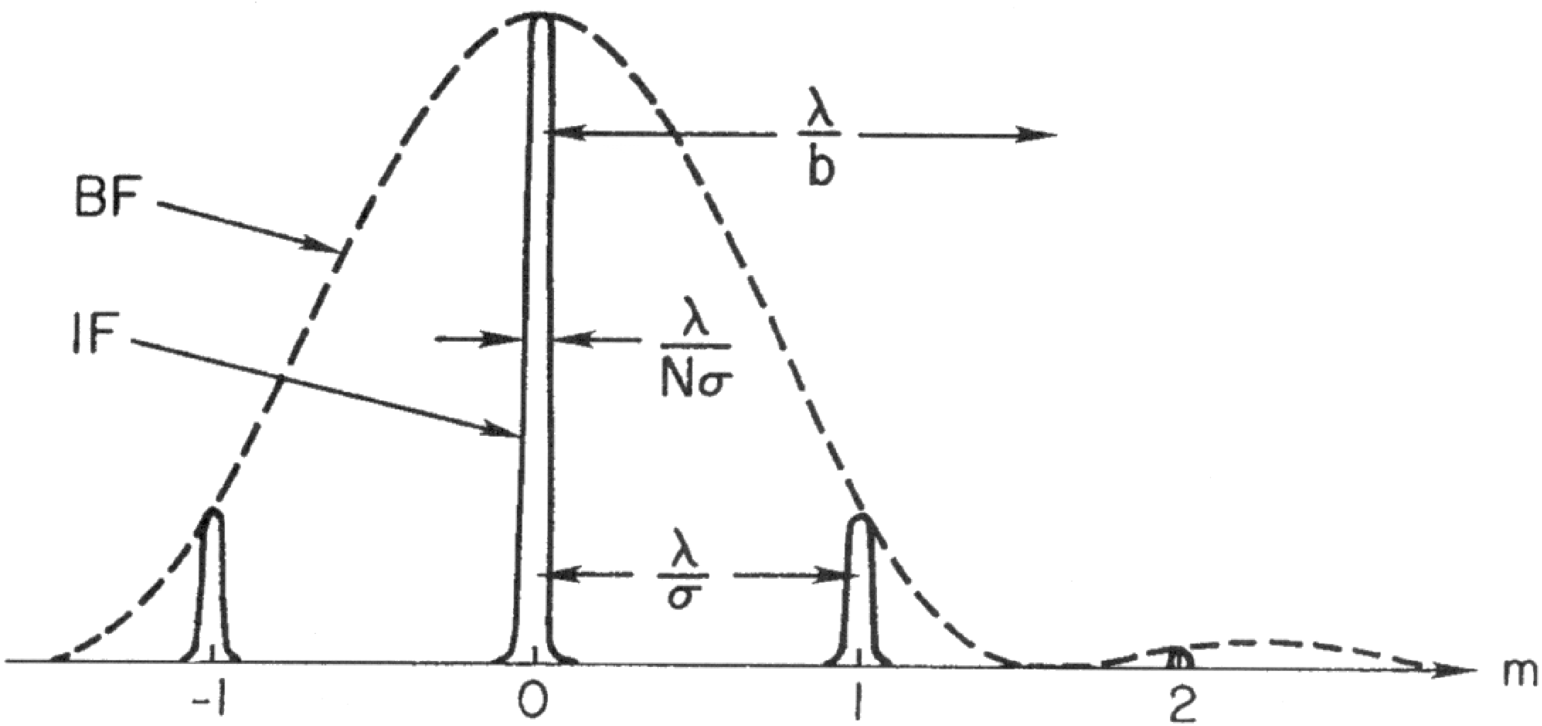
- Approximate values for CARMENES VIS:
  - $\lambda = 8{,}000\ \text{Å}$
  - $m = 77$
  - $\sigma^{-1} = 31.6\ \text{mm}^{-1}$
  - $d_1 = 15\ \text{cm}$
  - $\tan\beta = 4$ (i.e., $W = 60\ \text{cm}$)
  - $\varphi = 1.5''$, sliced in two
  - $D = 3.5\ \text{m}$
- Resolution: $R \approx 94{,}000$

Intensity Pattern of Single Diffracted Wavelength



BF = Blaze Function IF = Interference Factor

Reflection Grating with Facets Tilted to Shift Blaze Function by 2δ

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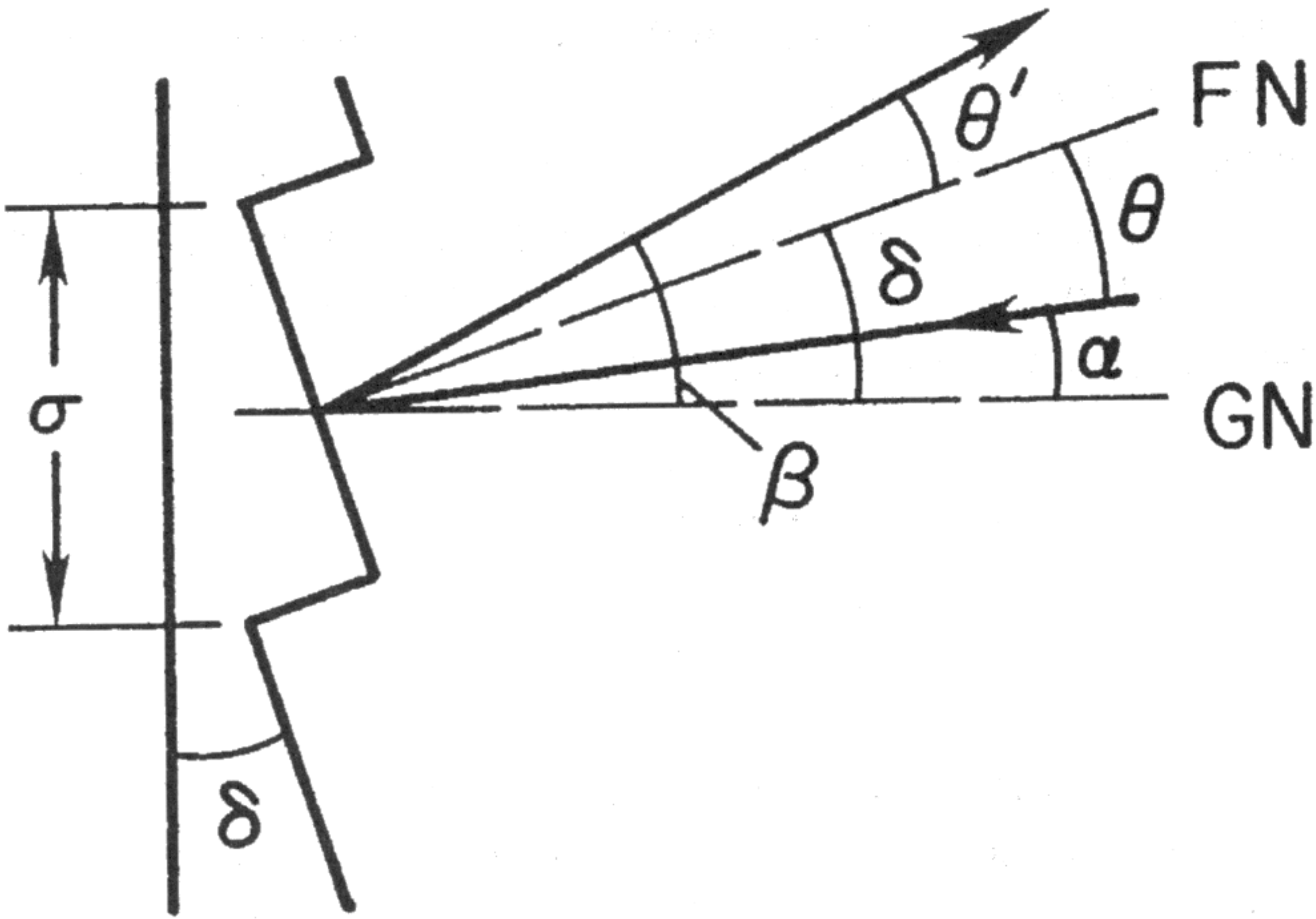
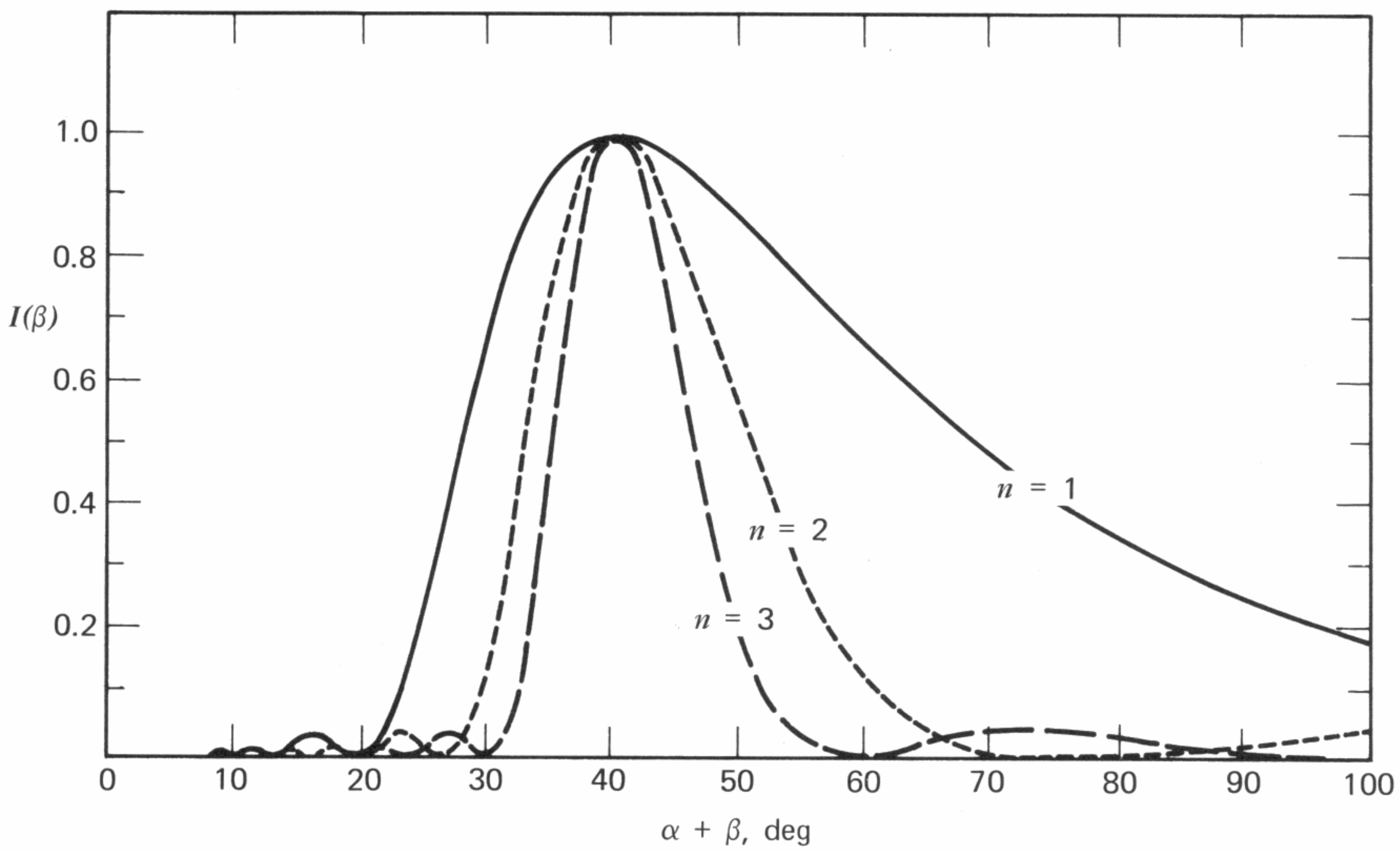
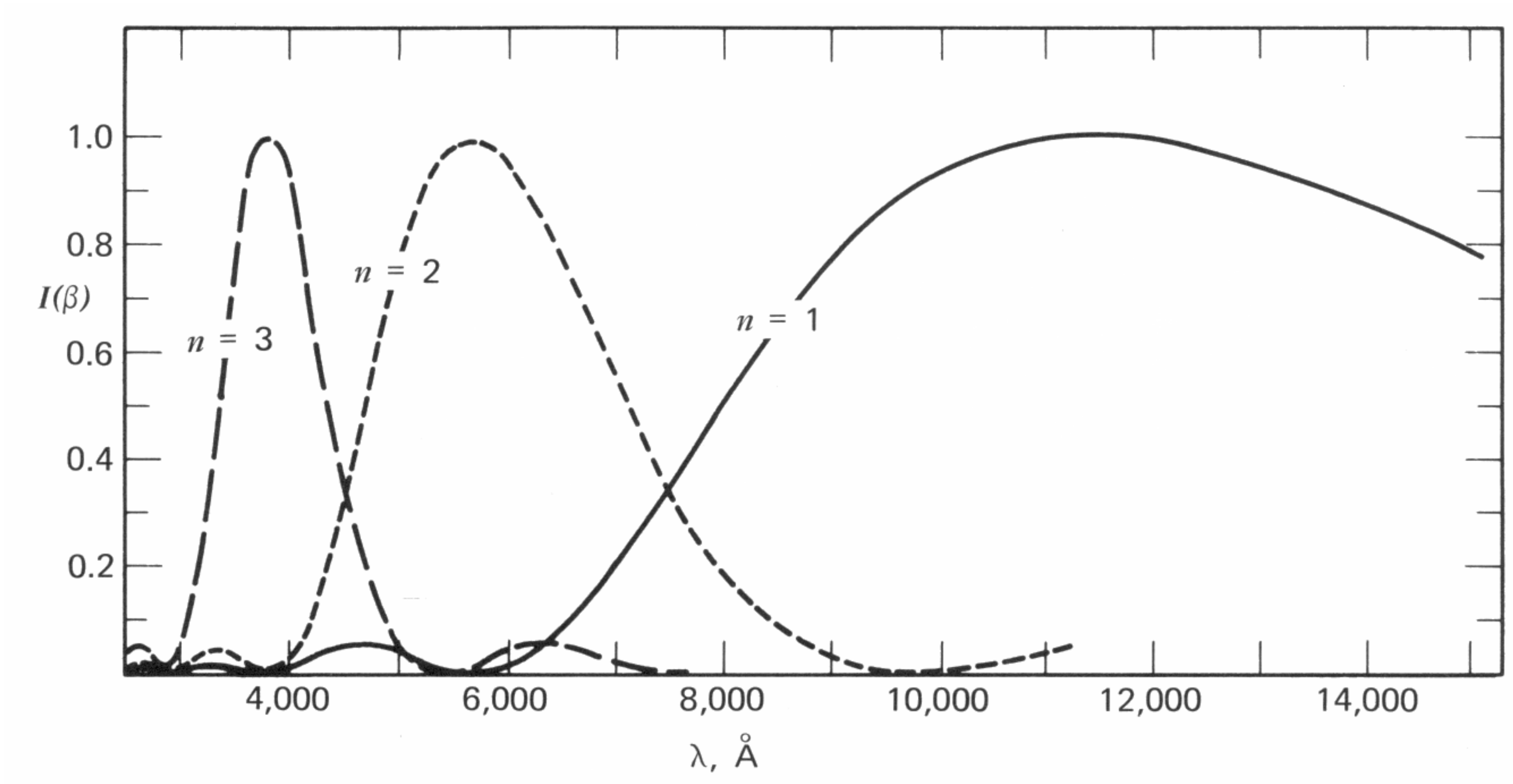


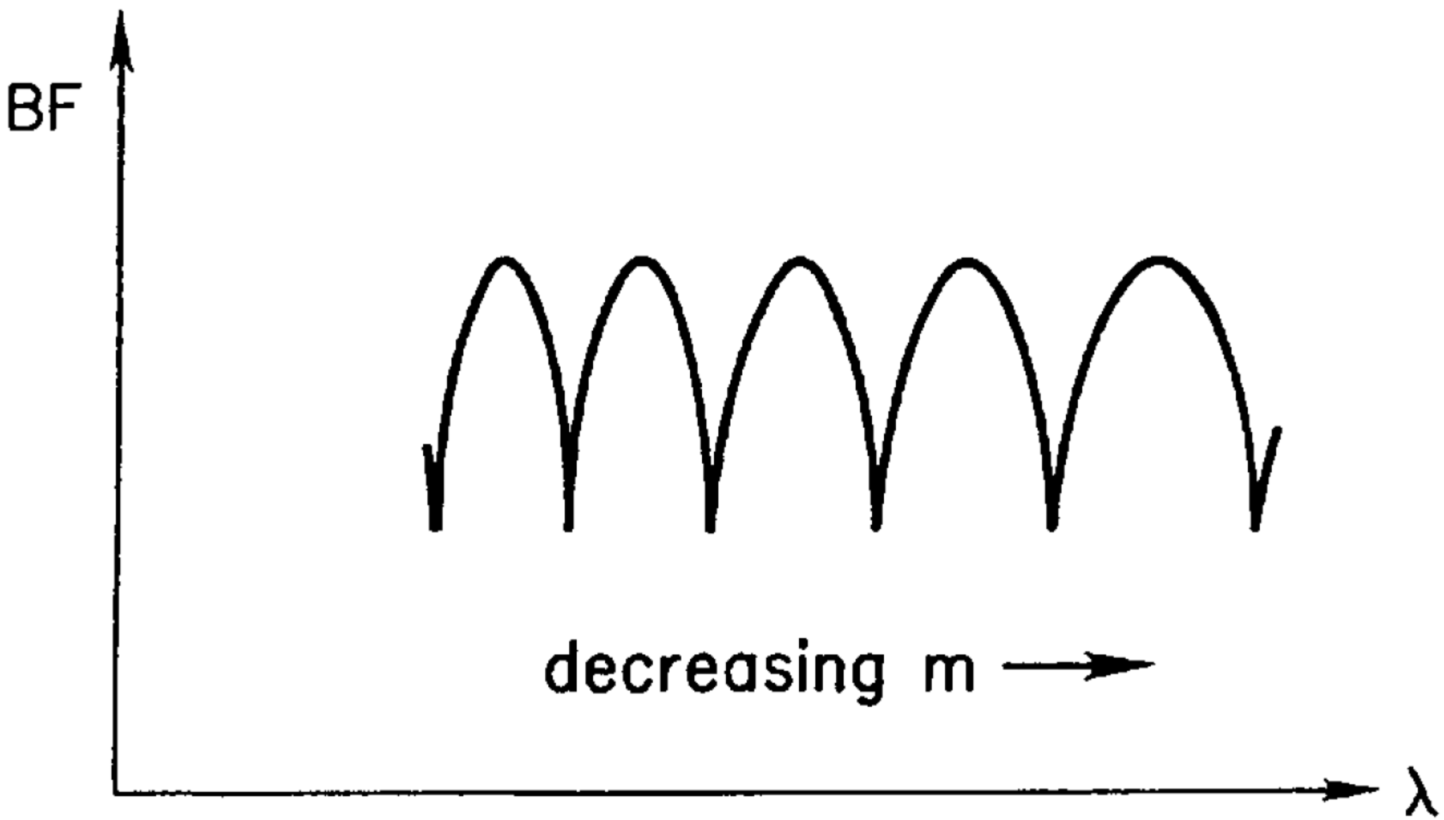
Blaze Function for Three Orders



Blaze Function Plotted Against Wavelength



Blaze Function for Echelle in Littrow Configuration



The Necessity of Order Sorting

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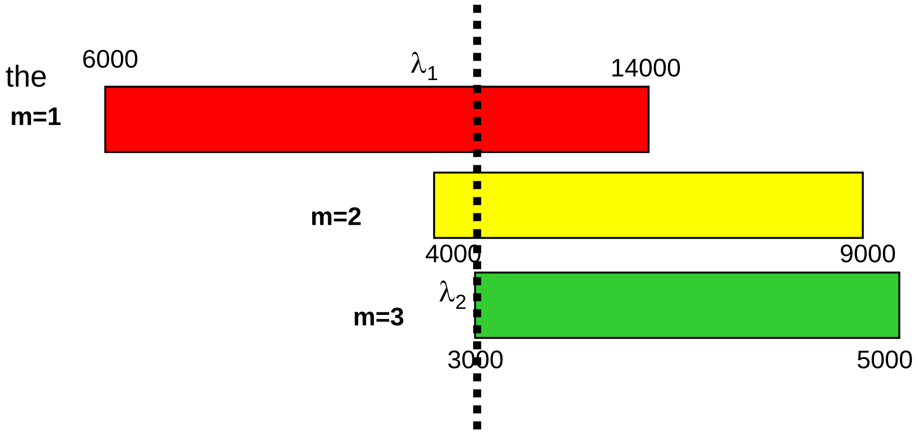
1200 gr/mm grating

Schematic: orders separated in the vertical direction for clarity



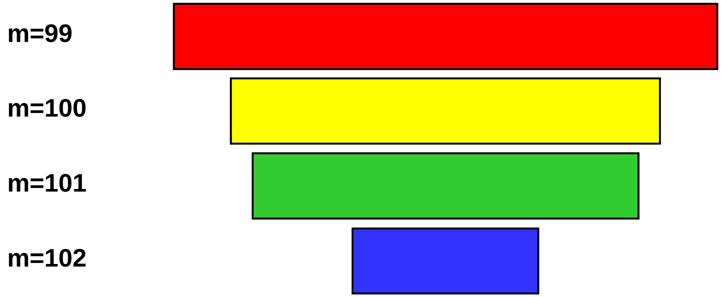
You want to observe λ_1 in order m=1, but light λ_2 at order m=2, where $\lambda_1 \neq \lambda_2$ contaminates your spectra

Order blocking filters must be used

Order Overlap for Echelle Grating

79 gr/mm grating

Schematic: orders separated in the vertical direction for clarity



In reality:

Need interference filters but why throw away light?

Order Sorting

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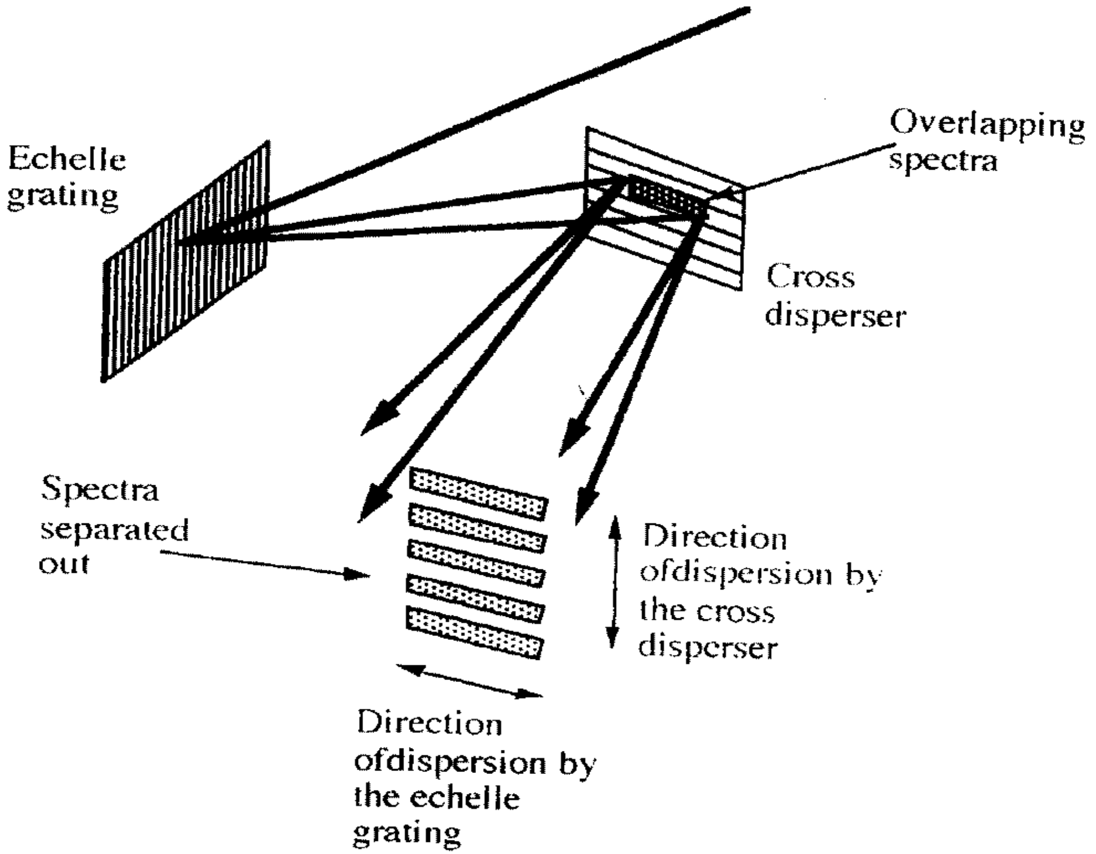
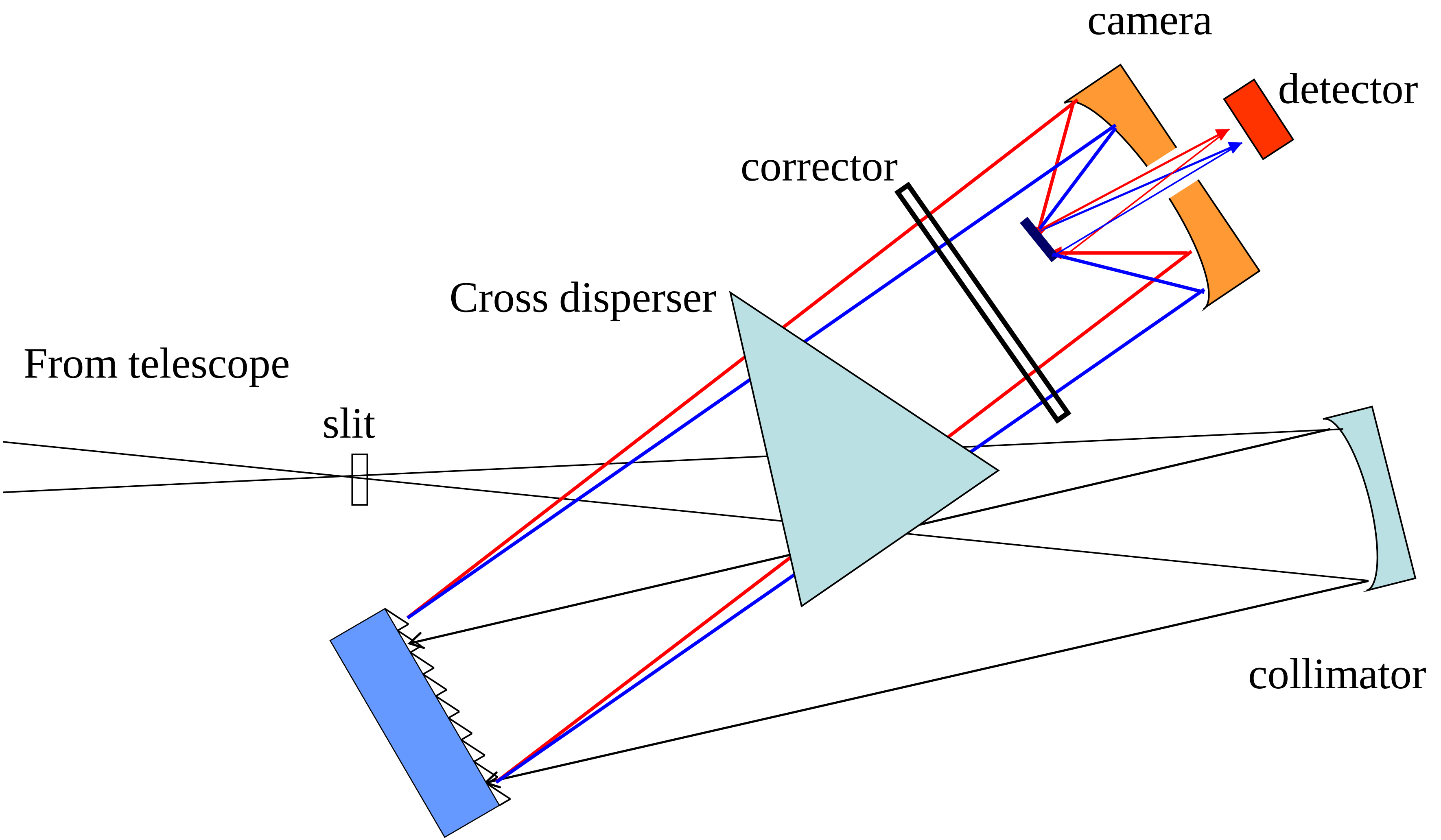
- If no measures are taken, different wavelengths (from different orders) fall on the same pixel
  - 1^{st} order 9000Å, 2^{nd} order 4500Å, 3^{rd} order 3000Å
- Bandpass filter can be used to select desired order (= desired wavelength range)
- Cross-dispersion can be used to record large spectral range in one shot

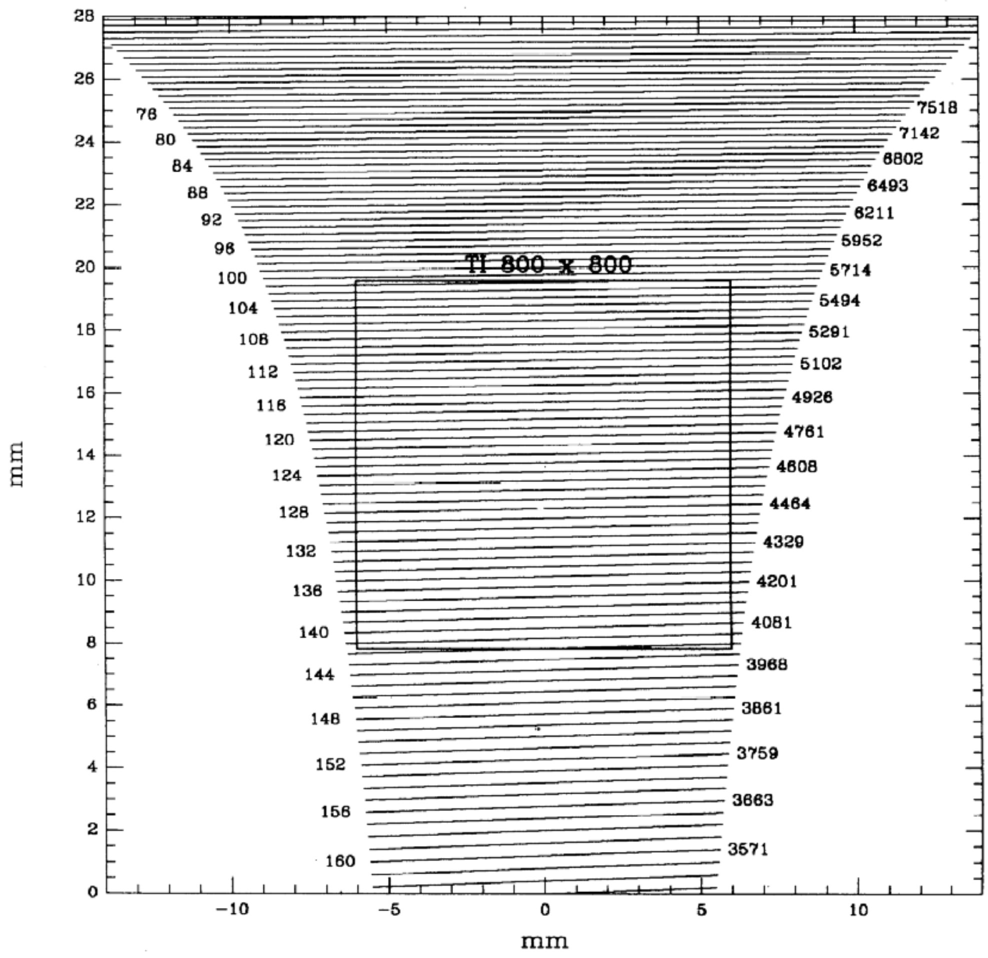
The Cross-Dispersion Principle

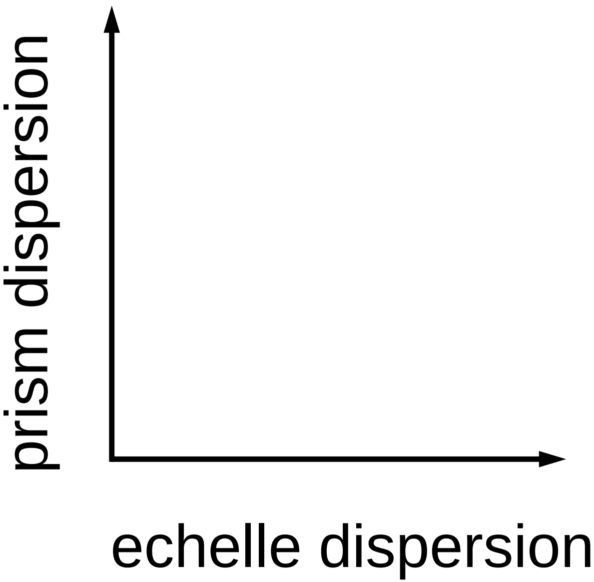


Cross-Dispersed Spectrograph

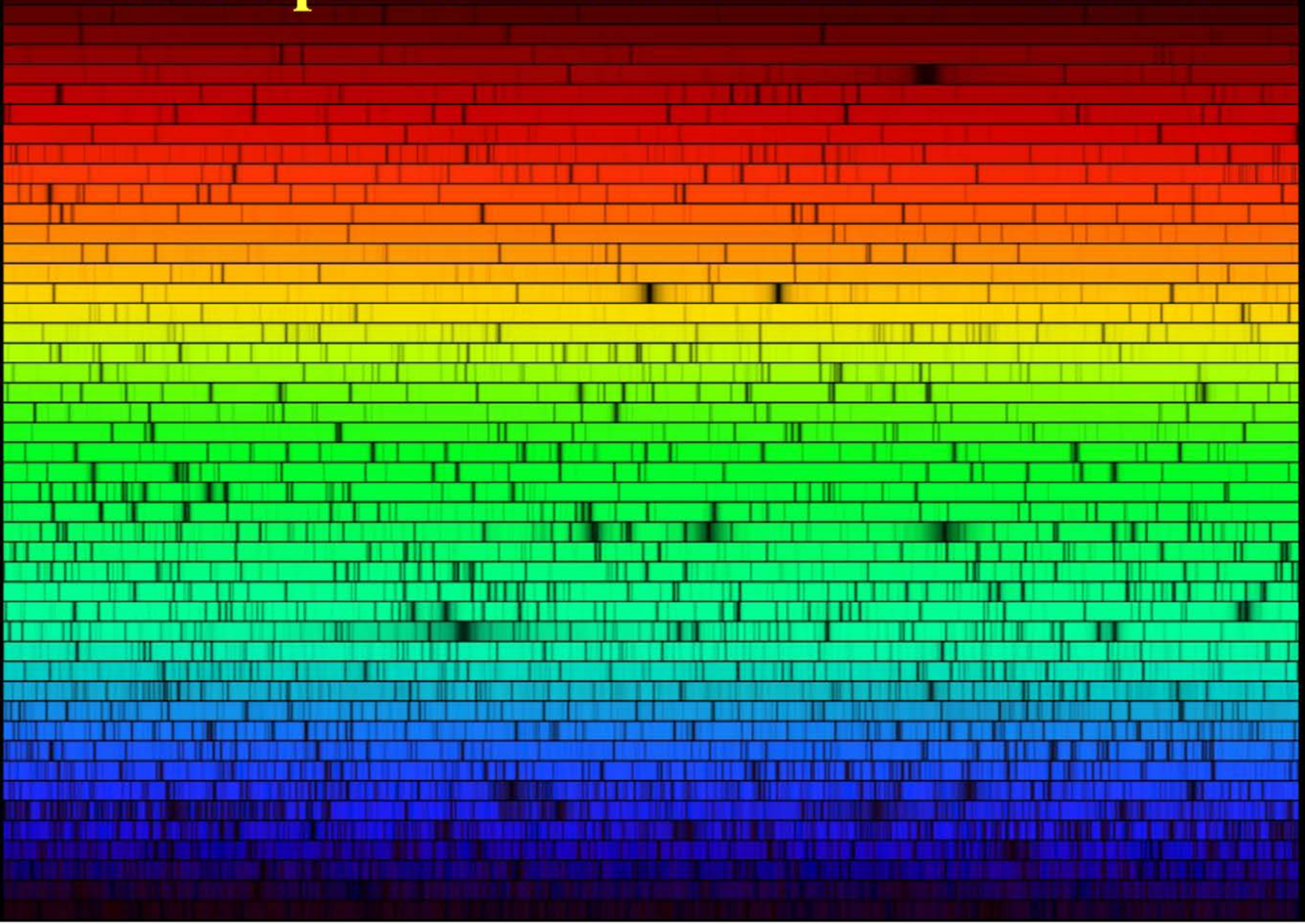


Cross-Dispersed Echelle Format

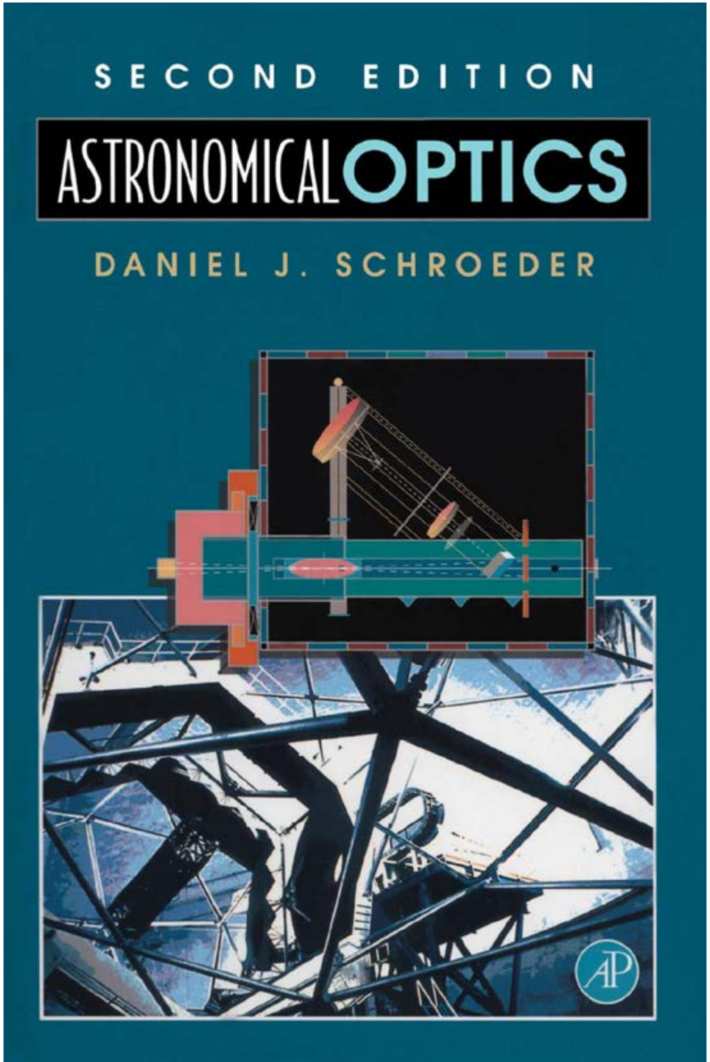




Solar Spectrum Taken With An Echelle



Recommended Reading



Fundamental Limit for RV Precision

A Frequently Asked Question

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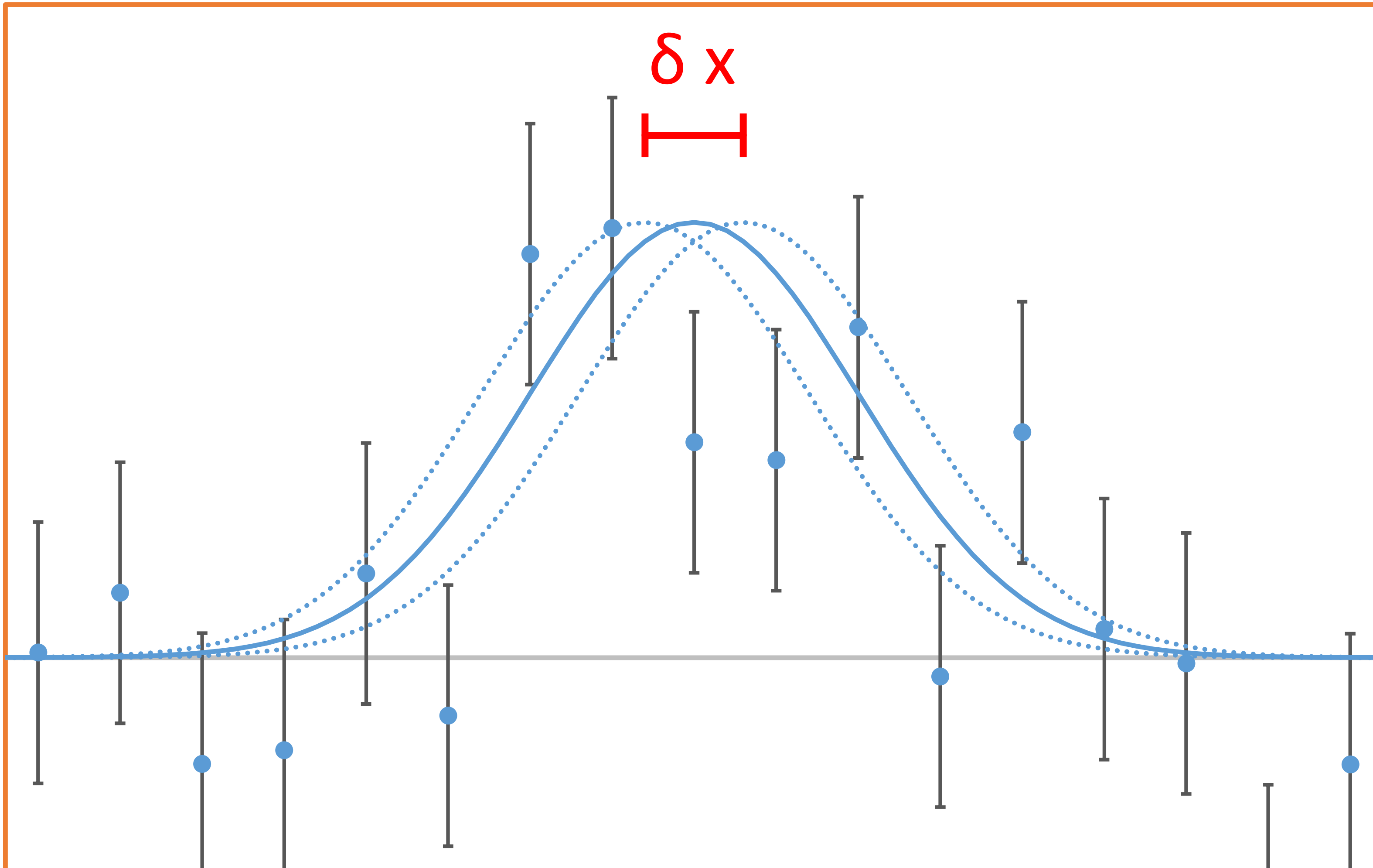
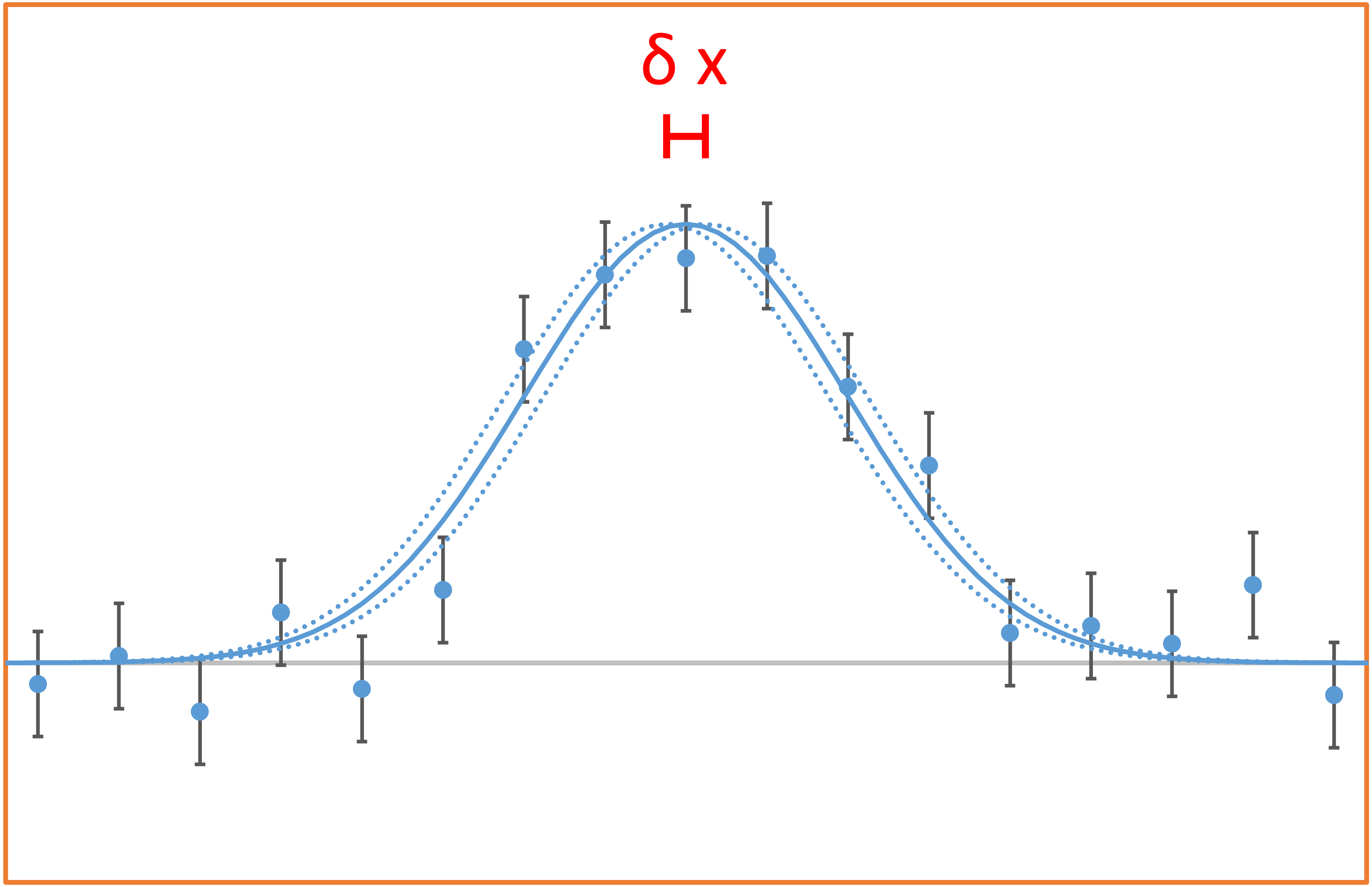
- Typical spectrograph resolution is $R = 100{,}000$
- This corresponds to a Doppler velocity $\Delta v = c\,\Delta\lambda/\lambda = c/R = 3\ \mathrm{km}/s$
- We can use these instruments to measure Doppler shifts with amplitude $\approx 1\,\mathrm{m}/s$
- How is that possible???

Precision of Line Position Determination



Same for Data with Smaller Error Bars



Signal-to-Noise Ratio and Measurement Precision

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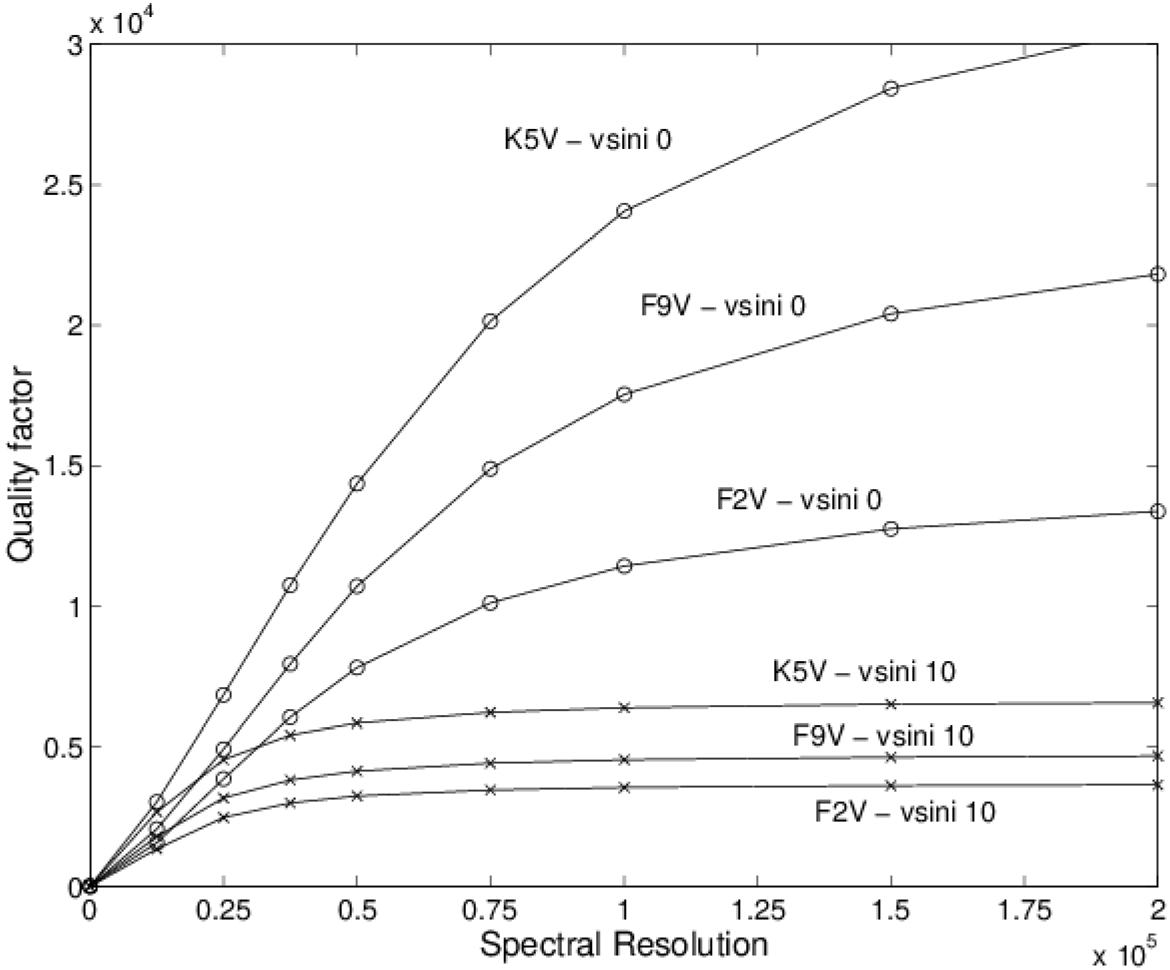
- Measurement precision: $\delta x \approx \mathrm{FWHM}/\mathrm{SNR}$
- Fundamental limit: photon noise, $\mathrm{SNR} = N/\sqrt{N} = \sqrt{N}$
- Example: Gaia Satellite
  - Resolution ~ 0.1", astrometric precision ~ 20 μas
- Application to Doppler spectroscopy: $\delta v \approx \Delta v/SNR = c/(R \cdot \mathrm{SNR})$
  - For $R = 100{,}000$, $\mathrm{SNR} = 100$: $\delta v = 30\,\mathrm{m/s}$

Doppler Precision and Spectral Information Content

- Stellar spectra have many spectral lines.
- Each line provides a statistically independent measurement of the stellar RV.
- Averaging over n lines reduces the uncertainty by a factor $\sqrt{n}$.
- In practice: calculation of correlation function
- Aggregate amount of spectral information in factor Q: $\delta v \approx c/(Q \cdot \mathrm{SNR})$
  - Q depends on wavelength range, resolution R, and stellar spectrum

Quality Factor for $3800\ \text{Å} \leq \lambda \leq 6800\ \text{Å}$



Bouchy et al. (2001)

Spectrograph Stability and Calibration

Spectrograph Stability

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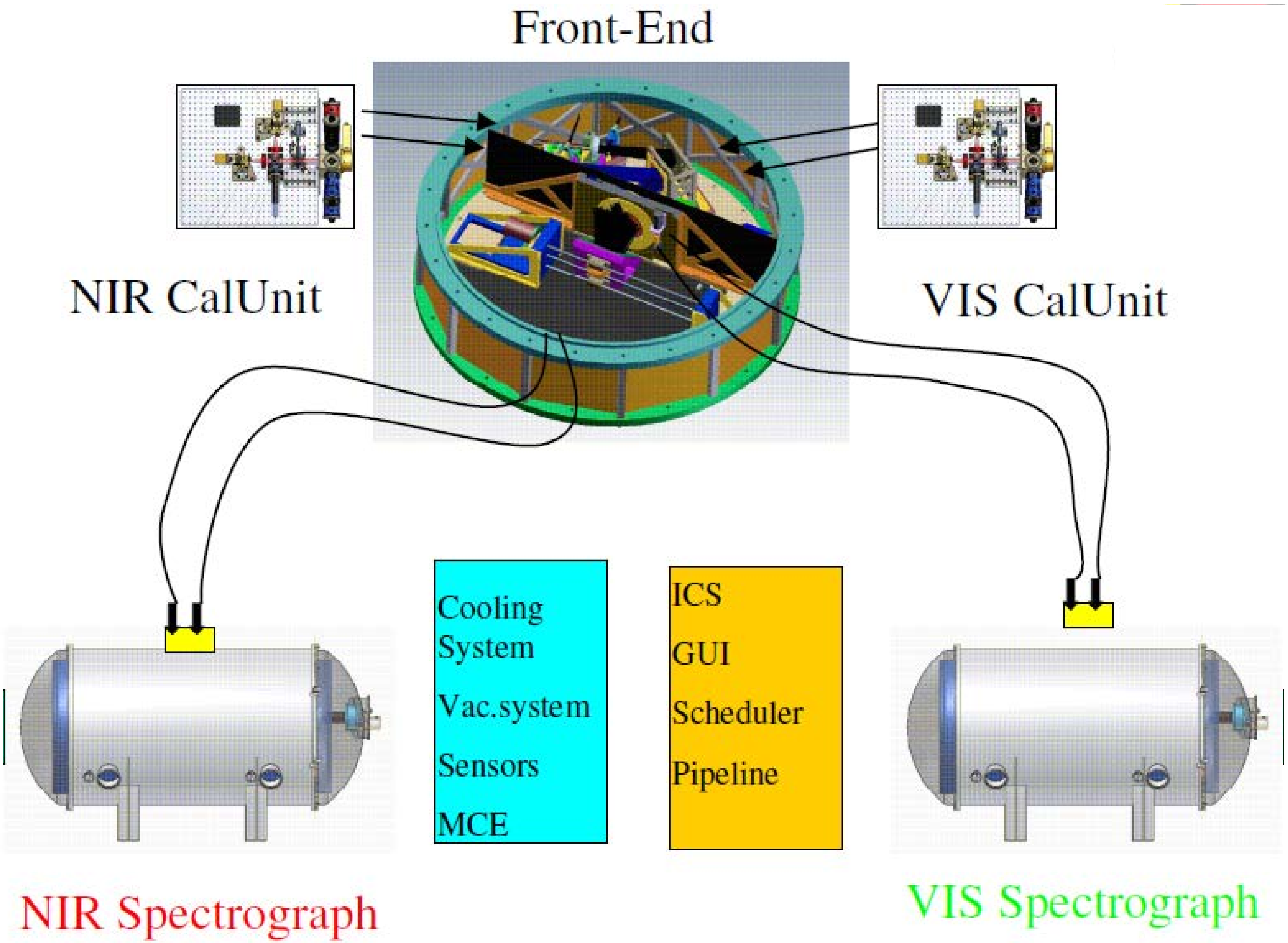
- $1\,\mathrm{m/s}$ corresponds to $\sim 1/1000$ detector pixel
  - $\sim 15\,\mathrm{nm}$, ~ 30 Silicon atoms
- Extreme instrument stability required
  - Vacuum to eliminate pressure fluctuations
  - Thermal stability (typically on mK level)
  - No moving parts
  - Undisturbed operation
  - Simultaneous calibration

CARMENES Overall Instrument Layout



CARMENES NIR Spectrograph Installed at CAHA

Stellar Spectrum with Calibration Lines

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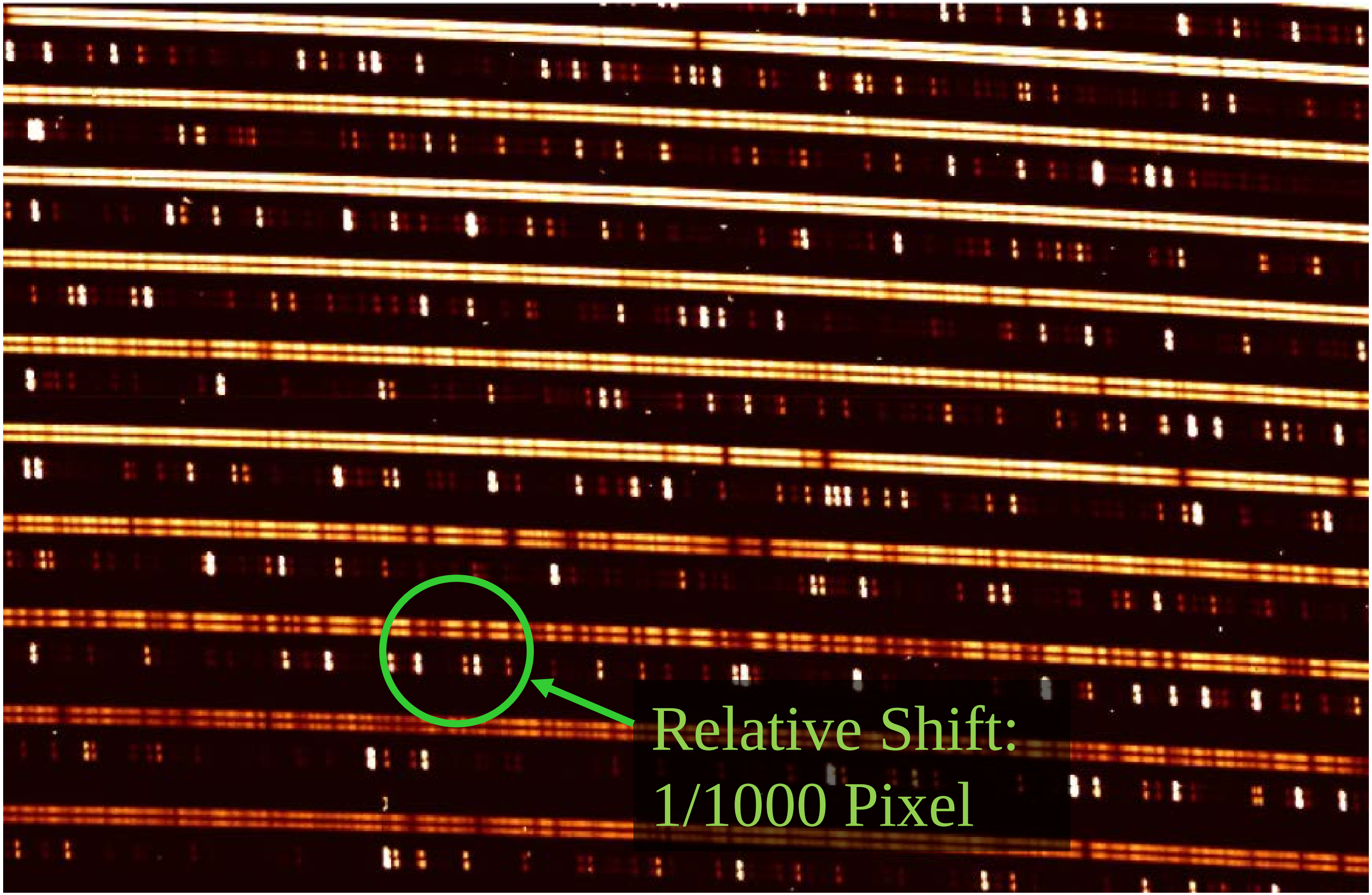
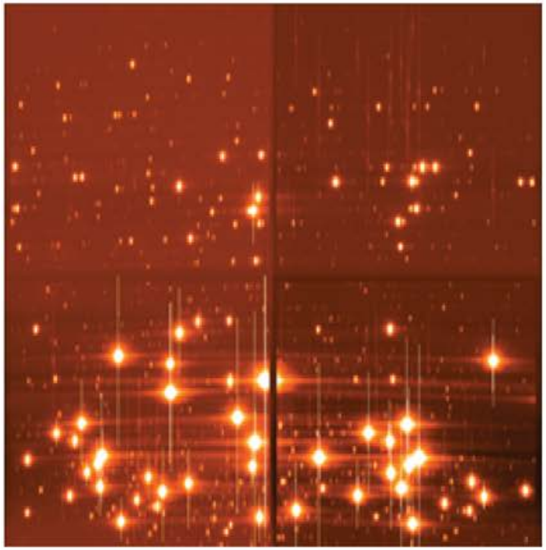
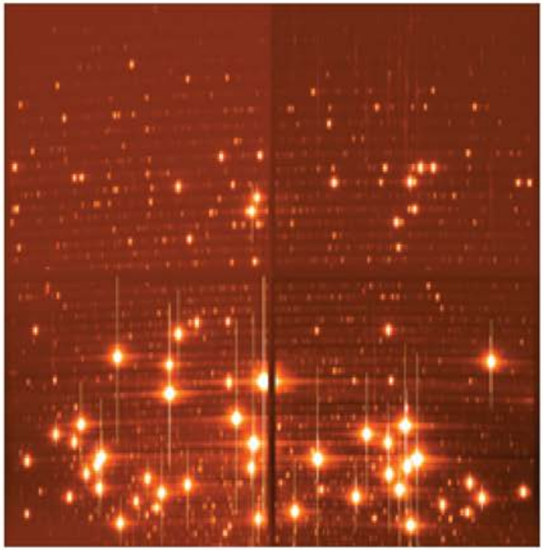


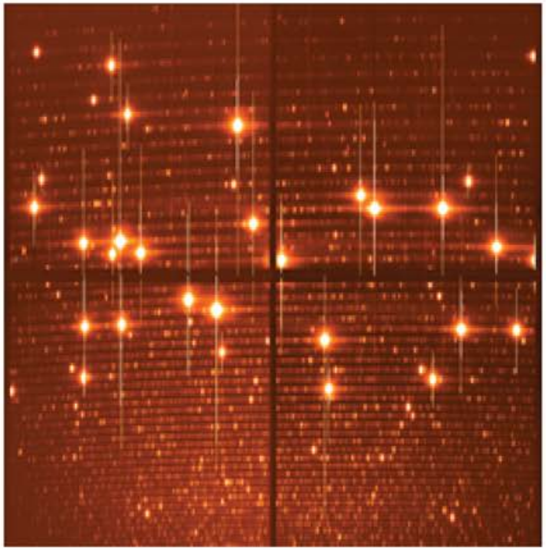
Calibration Lamp Exposures: Problems with Bright Lines



Th-Ne

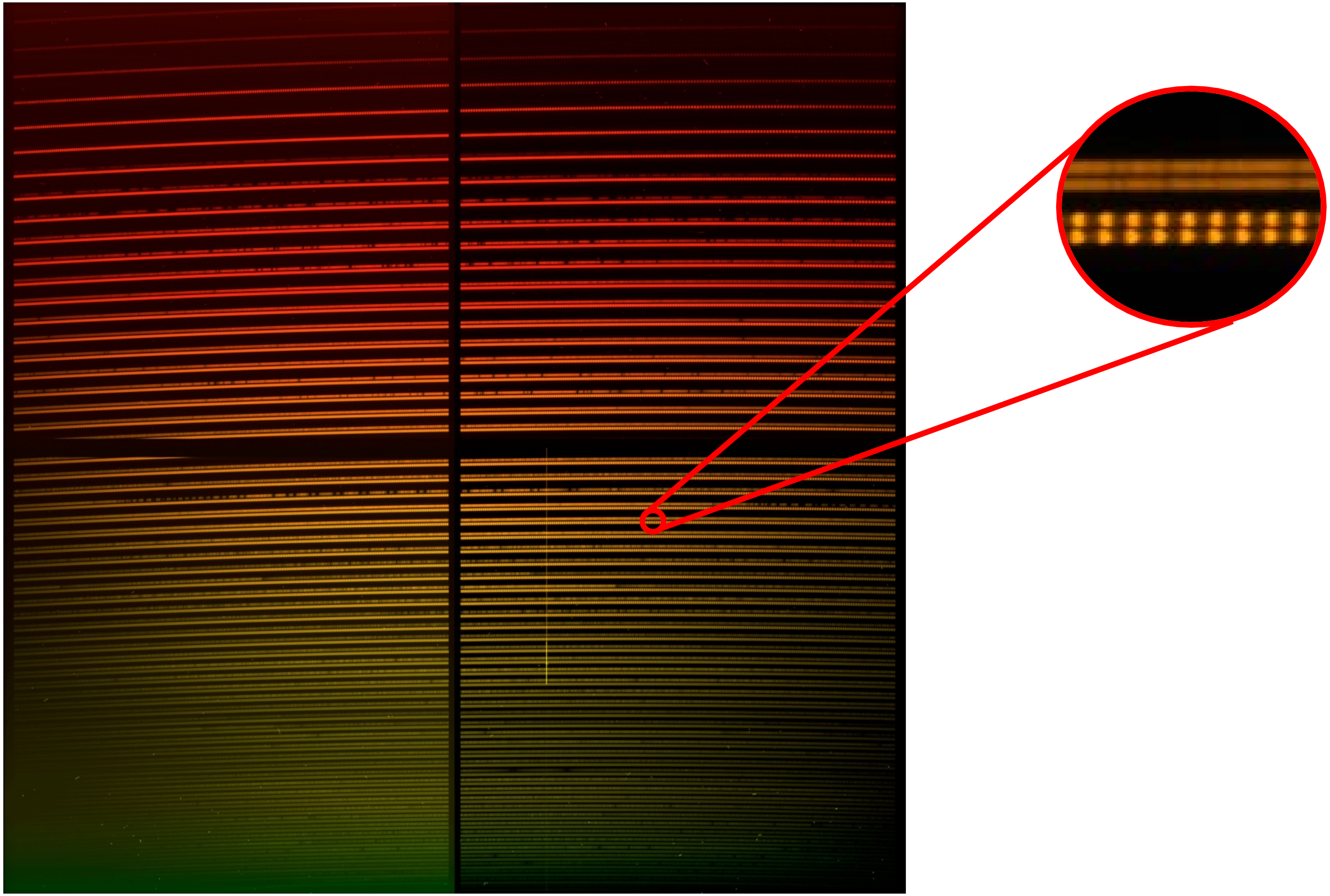


U-Ne



U-Ar

CARMENES VIS Spectral Format with Febry-Pérot



VIS 61 orders
0.52-0.96 µm

Spectrograph Input Stability

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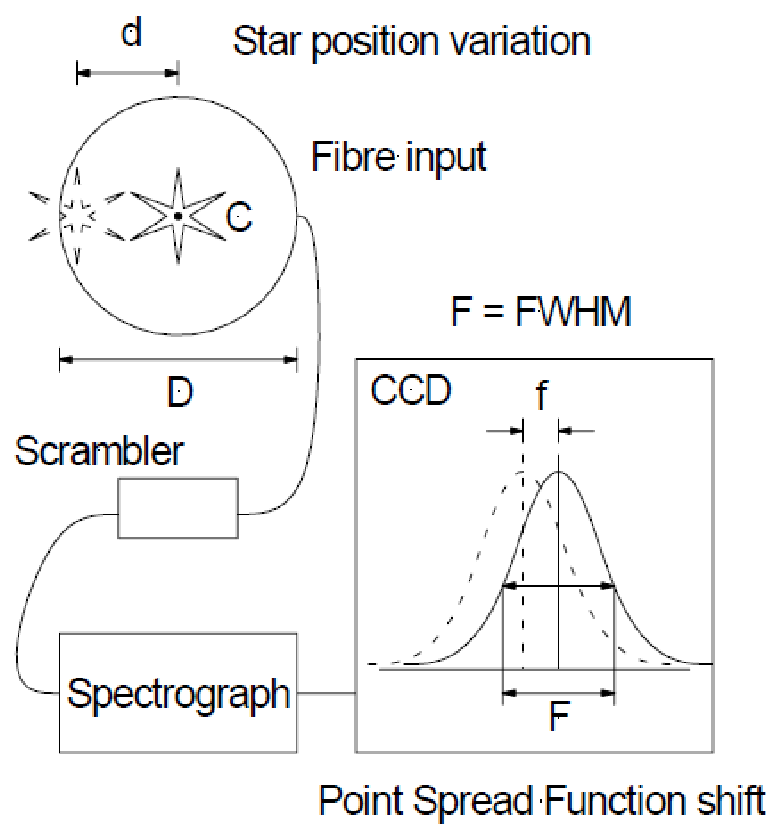
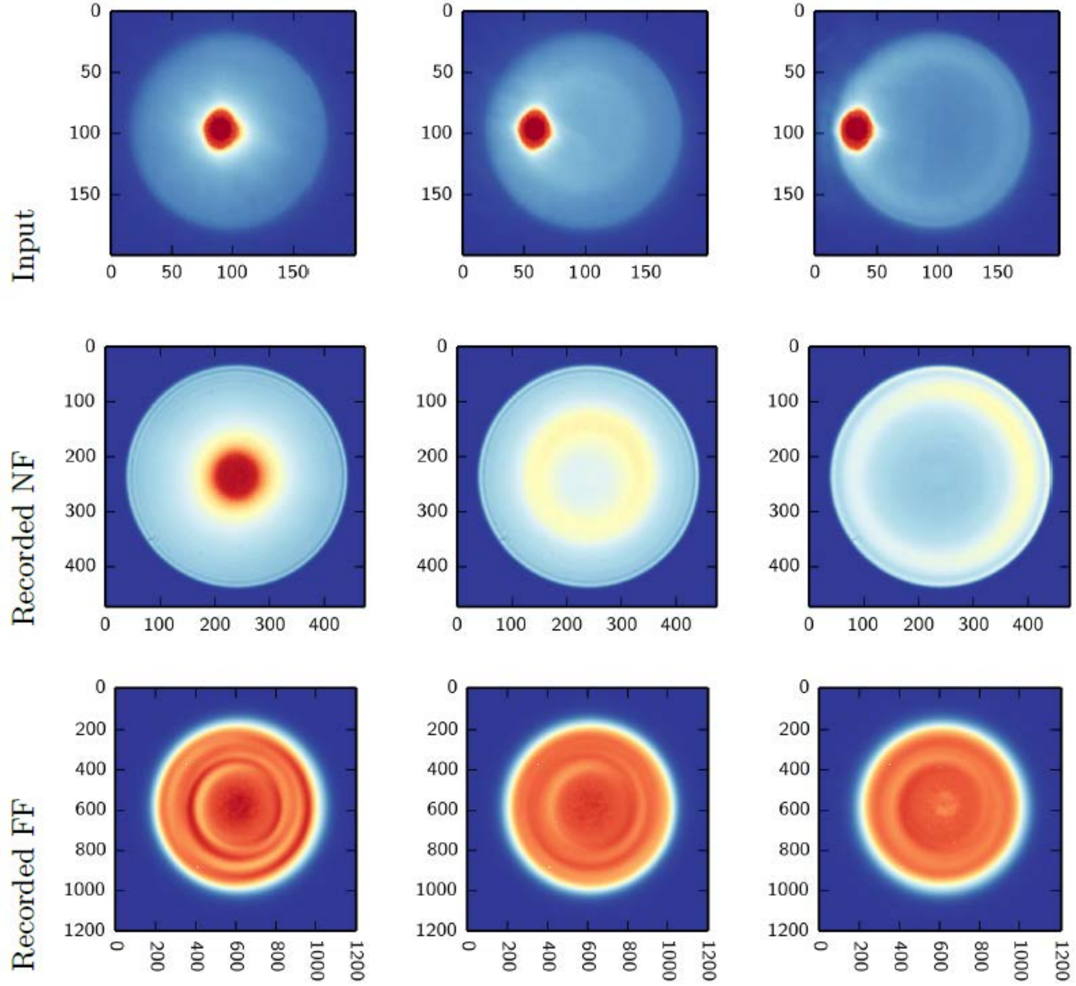
- At each λ, spectrograph images slit to detector
- ⇒ image motion looks like RV variation
- Optical fiber coupling
  - Fiber output is always more stable than input
- Octagonal fiber or scrambler for even better stability

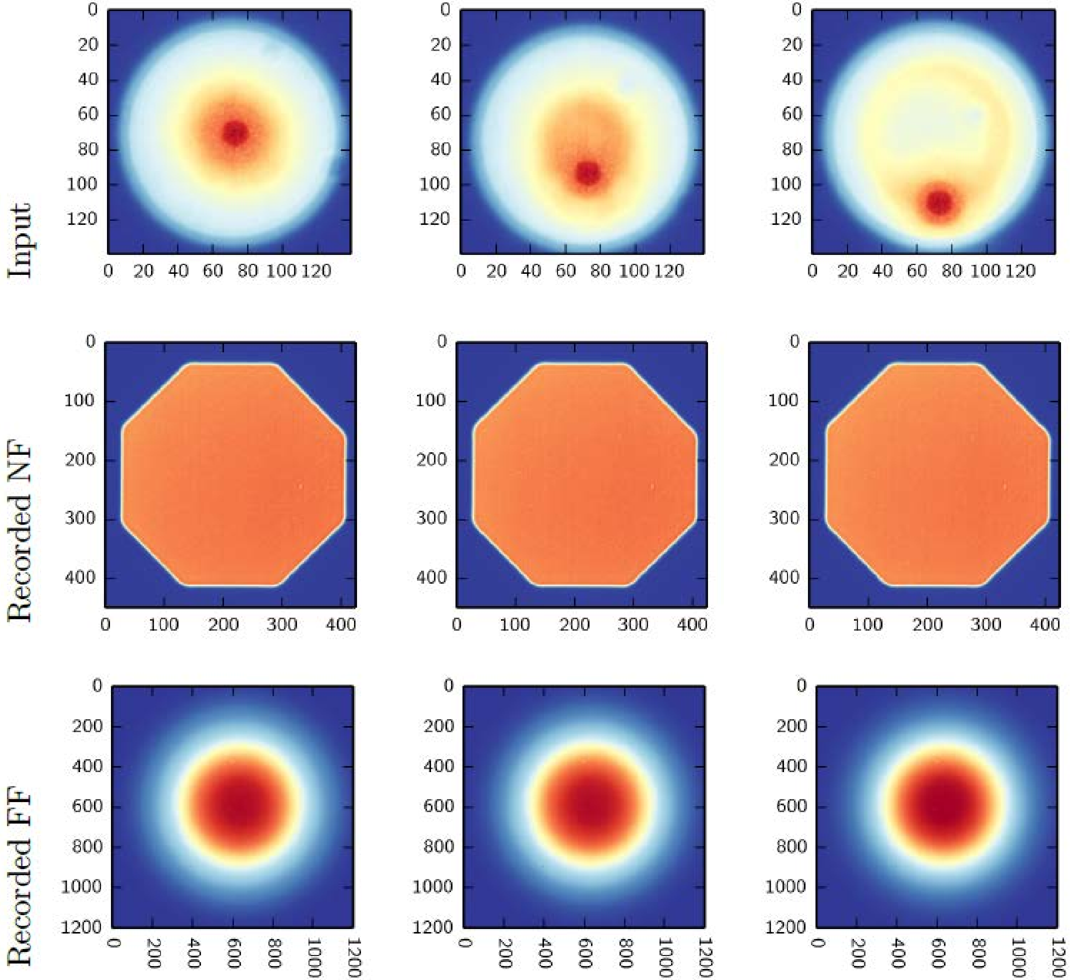


Avila & Singh (2008)

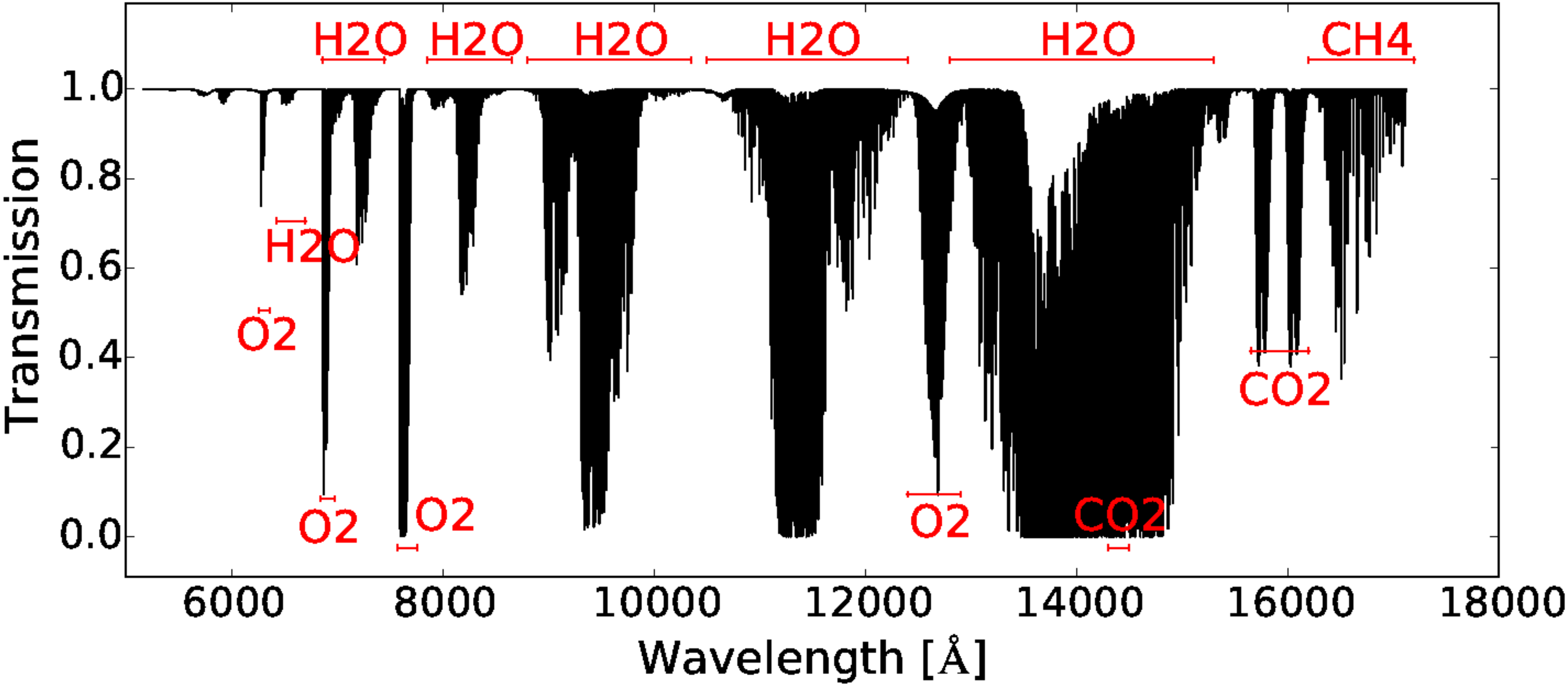
Round Fiber Input and Output



CARMENES Fiber Link (Circular + Octagonal)



Telluric Absorption



The Seven Challenges of EPRV

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Challenge 1:	Basic physics (photon noise)
Challenge 2:	Stable spectrographs
Challenge 3:	Stable coupling
Challenge 4:	Stable and precise calibration
Challenge 5:	Stable and precise data reduction
Challenge 6:	Unstable stars
Challenge 7:	Unstable atmosphere