

Standard Methods for **Measuring RVs and their Uncertainties**

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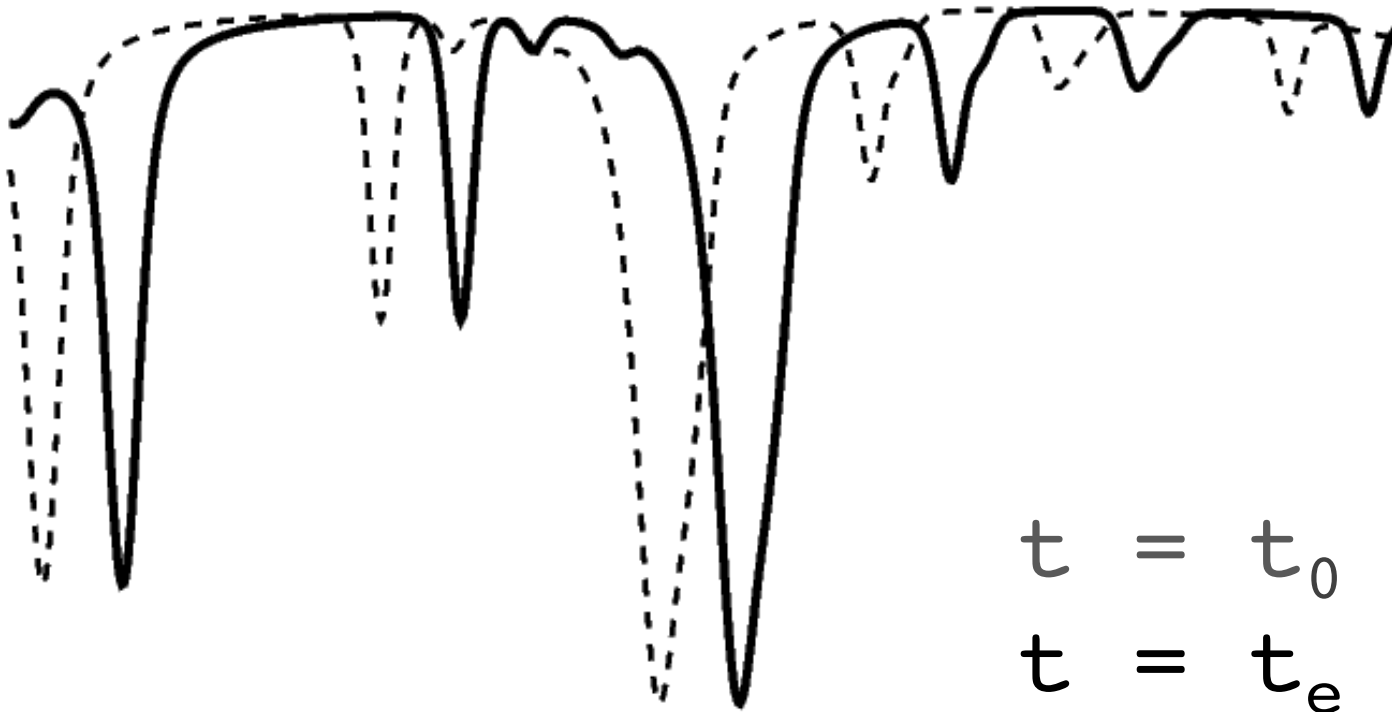
2020 Sagan Summer Workshop

Outline

- What are we measuring when we **measure RVs**?
- **Standard methods** for measuring RVs.
- Origin and mitigation of “measurement **errors**”.
- **Non-standard** methods for measuring RVs.

flux

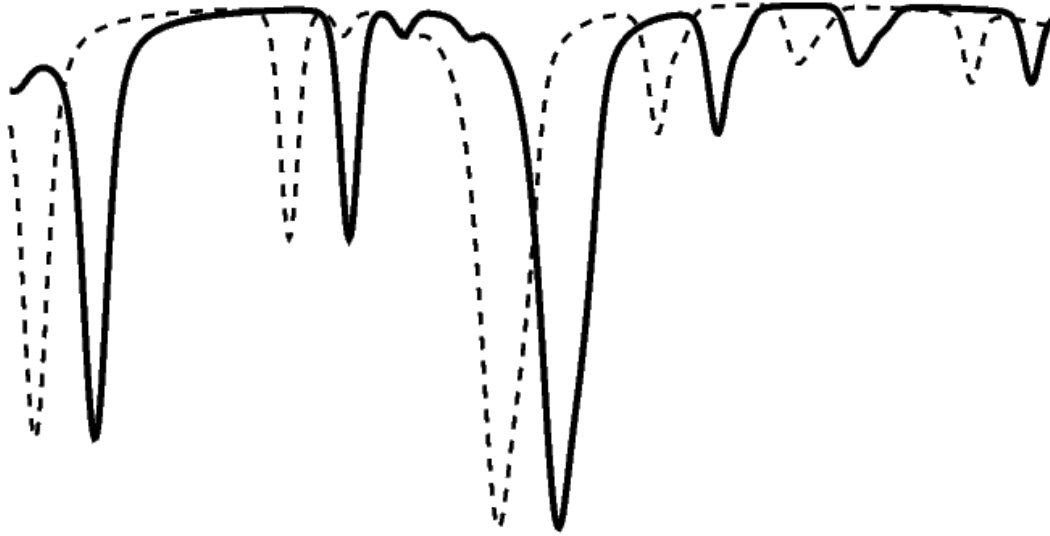
$$\lambda_e = \lambda_0 \cdot (1 + z)$$



$t = t_0$

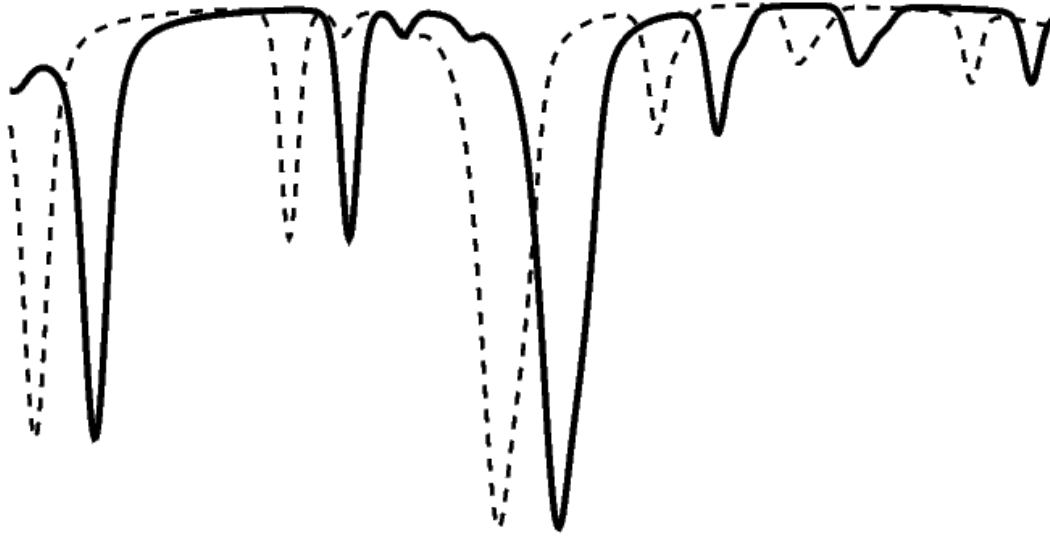
$t = t_e$

wavelength



What do we actually **measure**?

1. **Spectra** at different epochs
2. **Wavelengths** for spectrum at each epoch
3. **Barycentric** correction
4. **Doppler shift** between each spectrum w.r.t. reference



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Standard methods for measuring RVs.

- Cross Correlation Function (CCF)

used for stabilized spectrographs.
(or getting less-precise RVs)

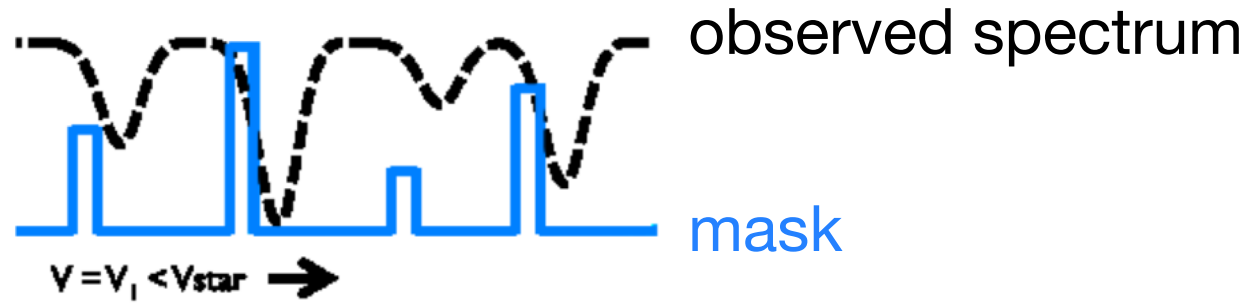
Baranne et al. 1996

- Forward Modeling

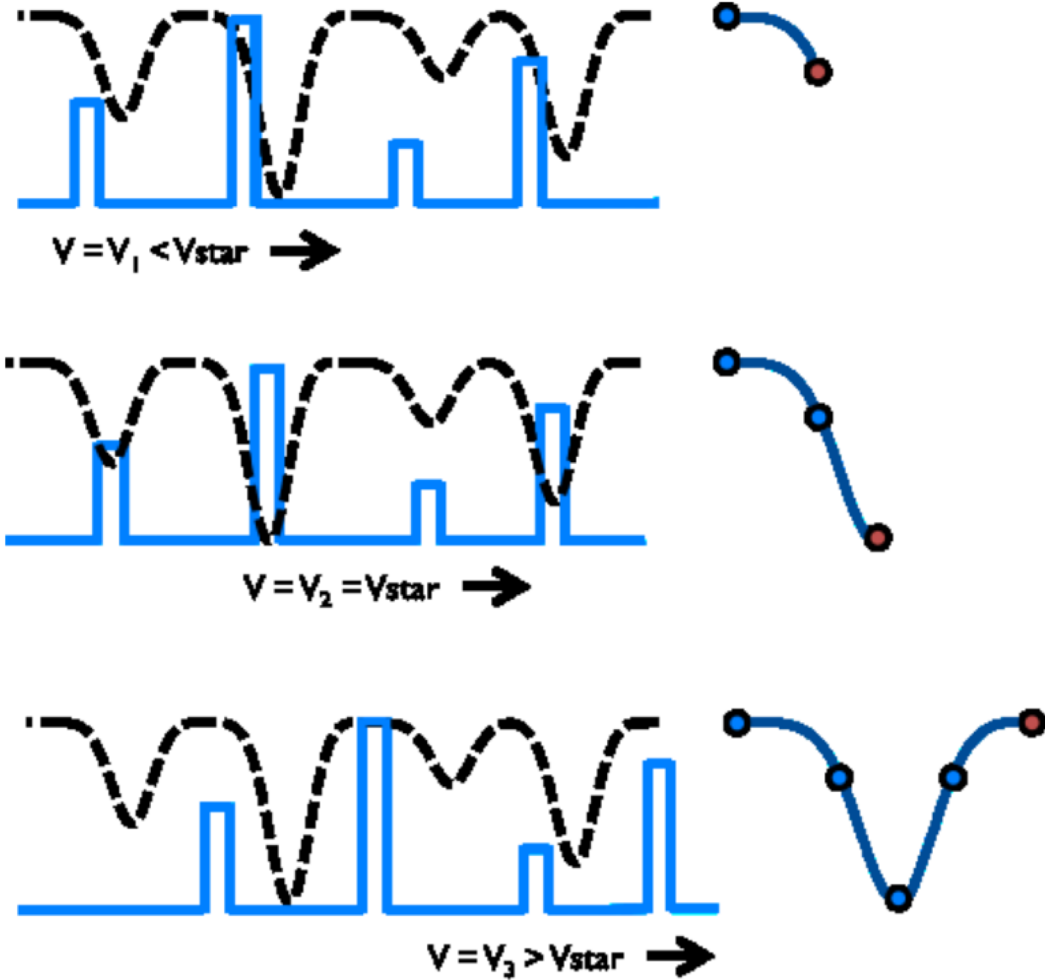
used for both stabilized spectrographs
and absorption cell calibration.

Butler et al. 1996

CCF

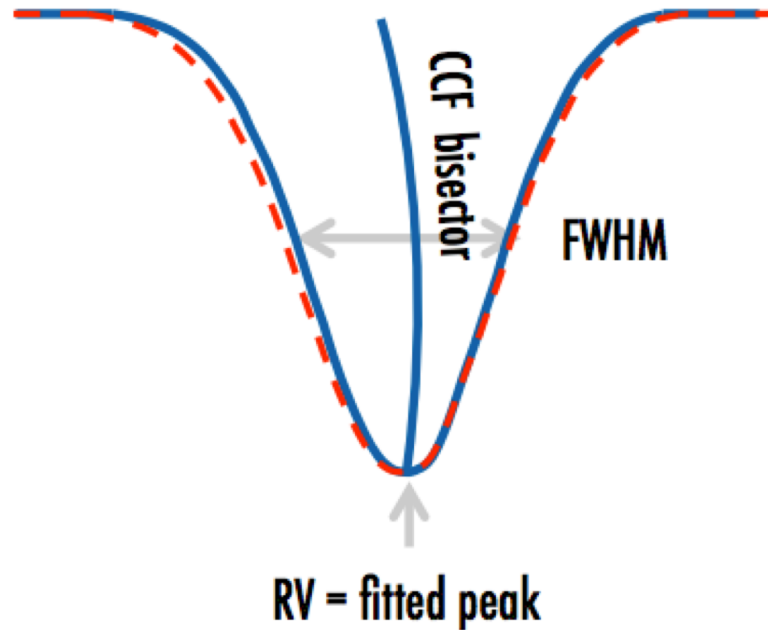


CCF

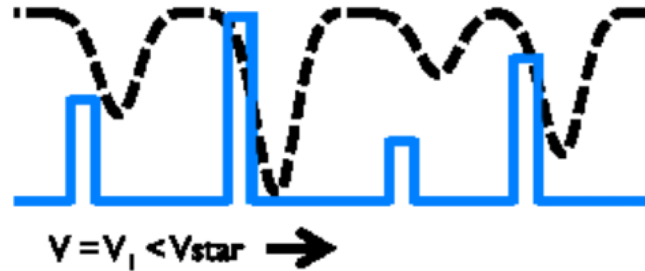


CCF

fit a gaussian to find RV
plus activity indicators



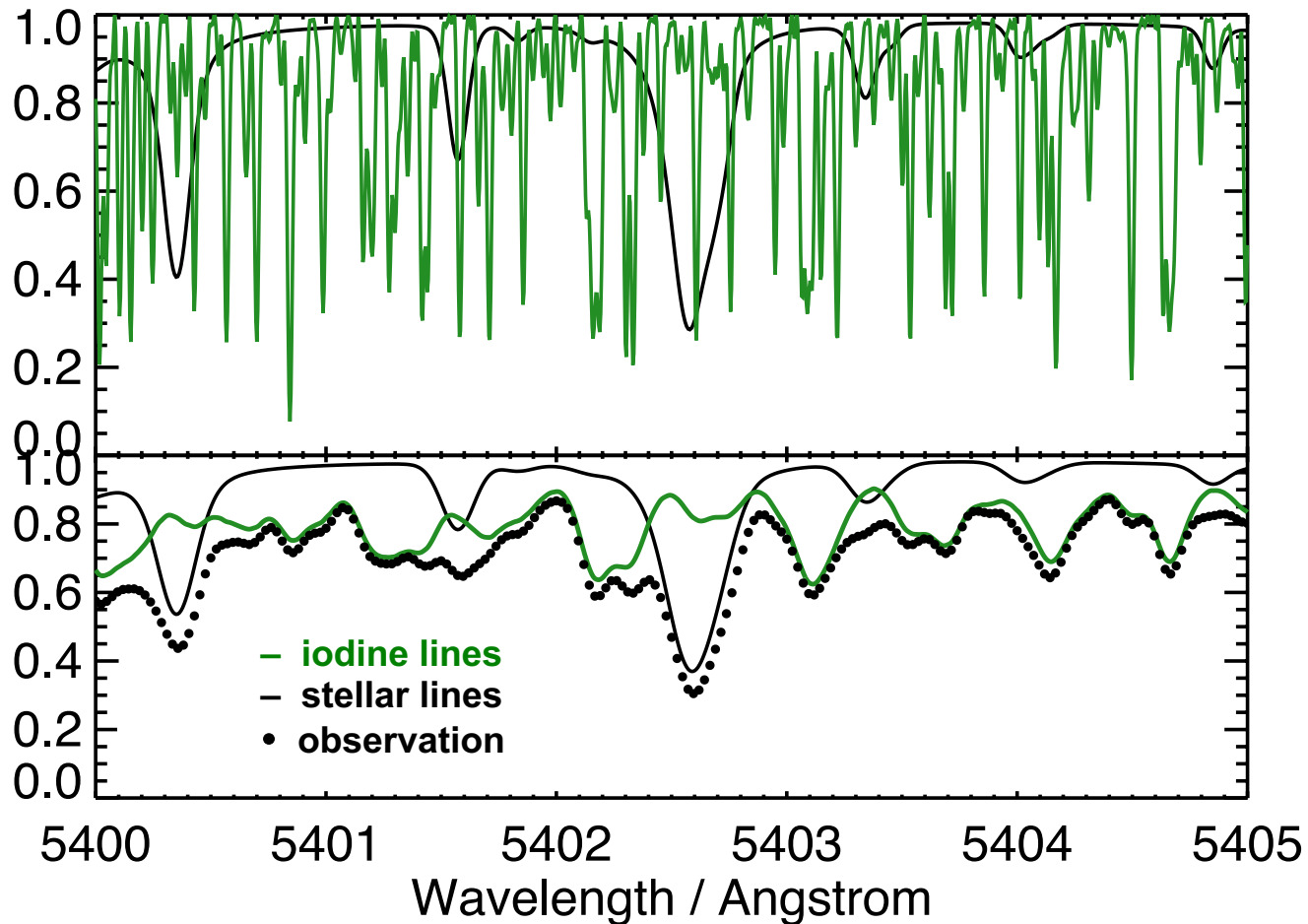
CCF

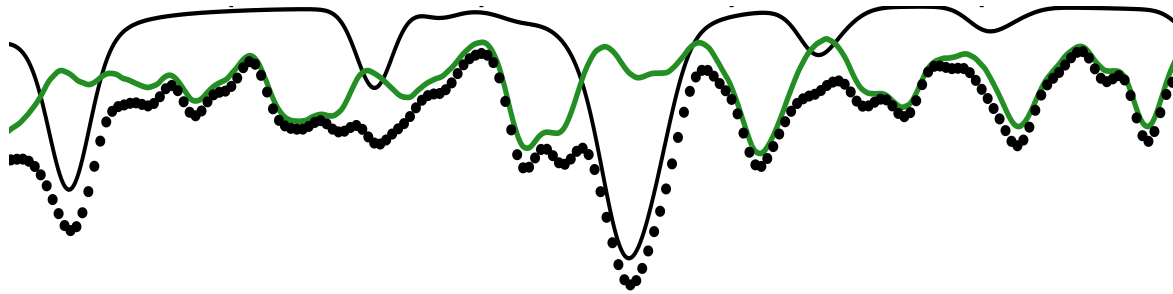


Flavors of **Masks**

- Customized binary masks
- Cosine-shaped or other shaped masks
- Full stellar spectrum / template

Forward Modeling

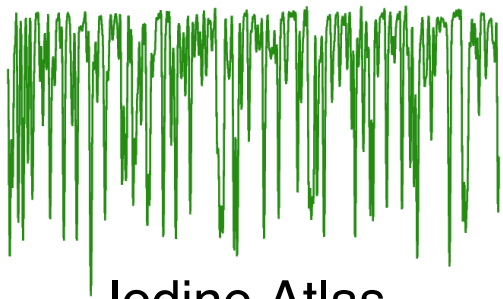




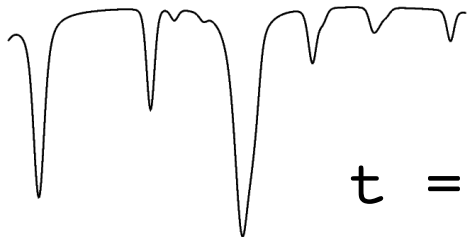
Model

Reference Spectra

Model Parameters

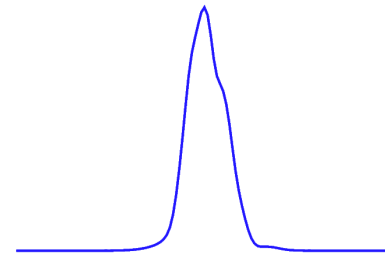


Iodine Atlas

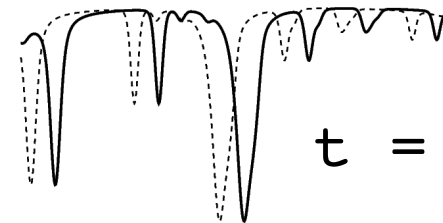


Stellar Template

$$t = t_0$$



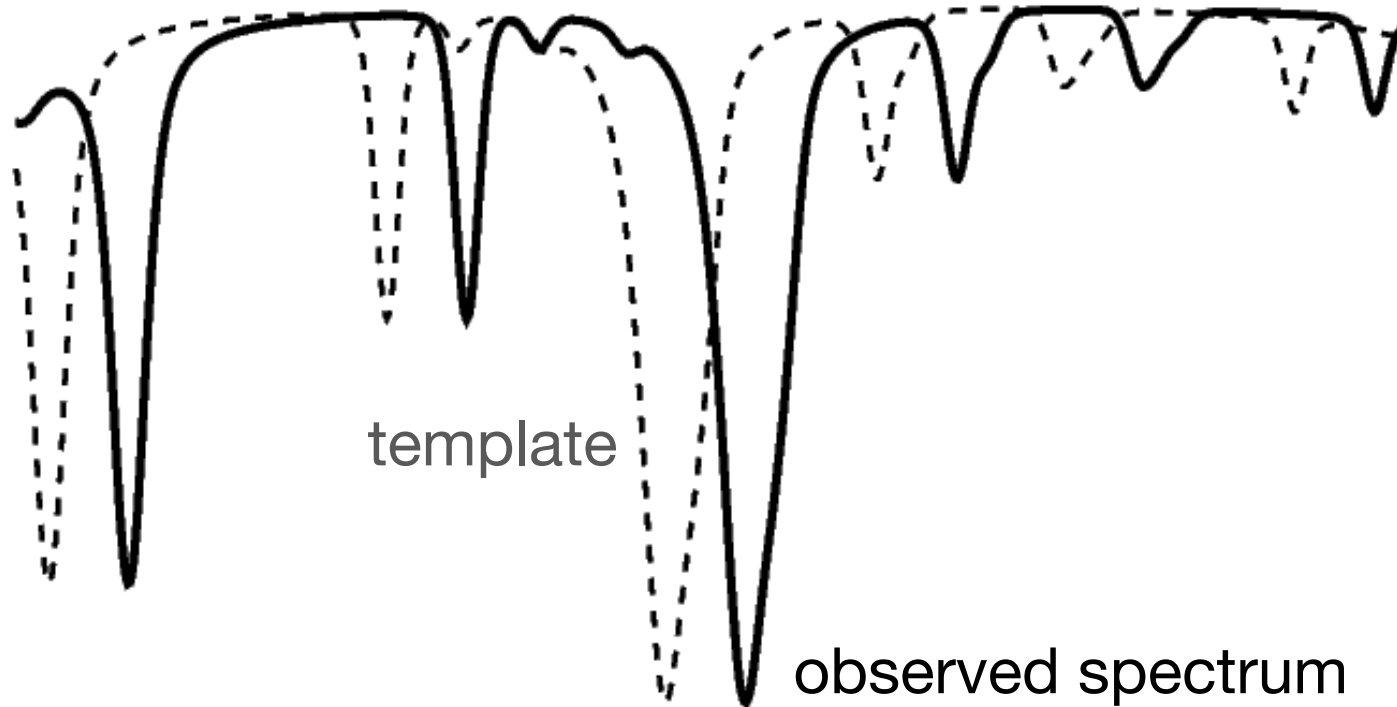
Line Spread Function



$$t = t_e$$

Wavelength Solution
including z

Forward Modeling



$$\lambda_e = \lambda_0 \cdot (1 + \mathbf{z})$$

Stellar Template

They are typically empirically derived.

- Deconvolution

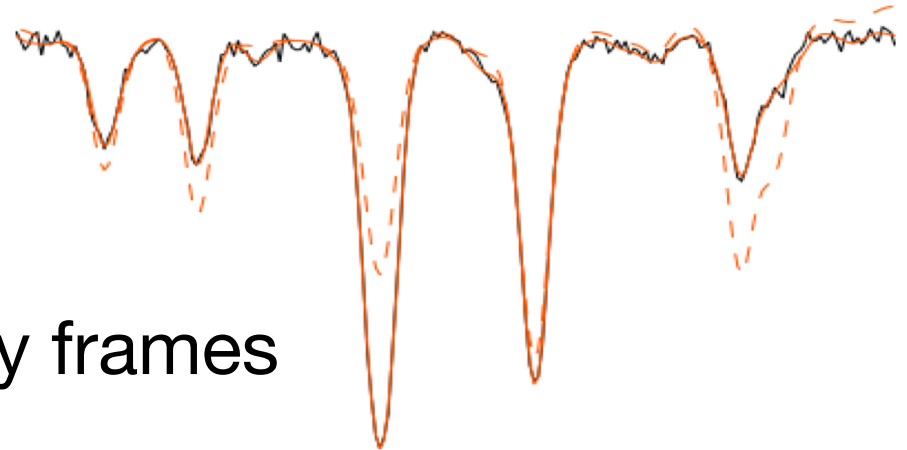
Butler et al .1996

- Shift and stack many frames

Anglada-Escudé & Butler 2012

- Shift, stack, morph

Petersburg et al. 2020



What can go wrong?

Origin and mitigation of “measurement errors”.

Fun Fact #1

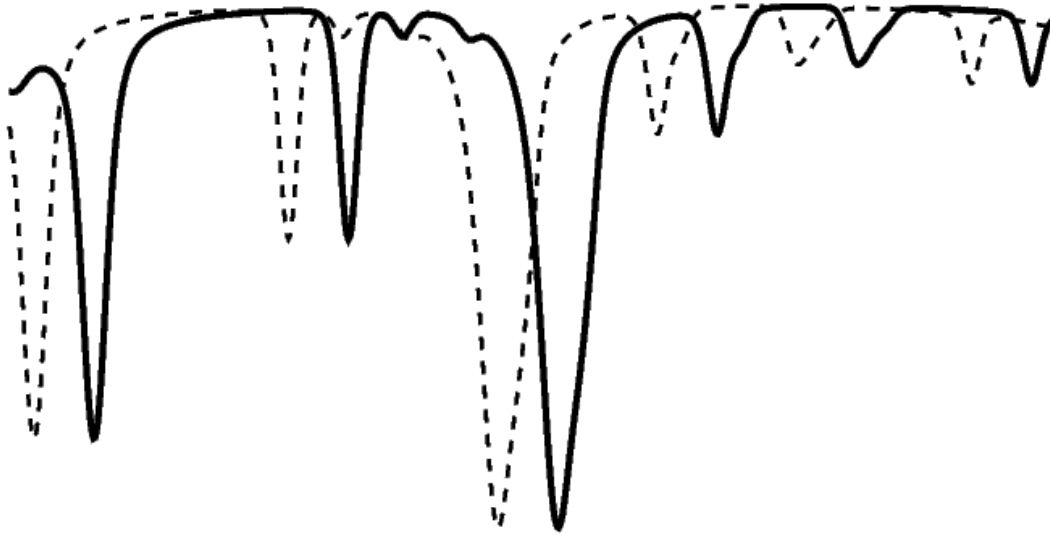
How precise do you think we could measure the **absolute RV** of a star w.r.t. our solar system?

- A. As precise as our relative RV measurement (i.e. < 1 m/s).
- B. < 10 m/s
- C. < 100 m/s
- D. < 1000 m/s

What can go wrong?

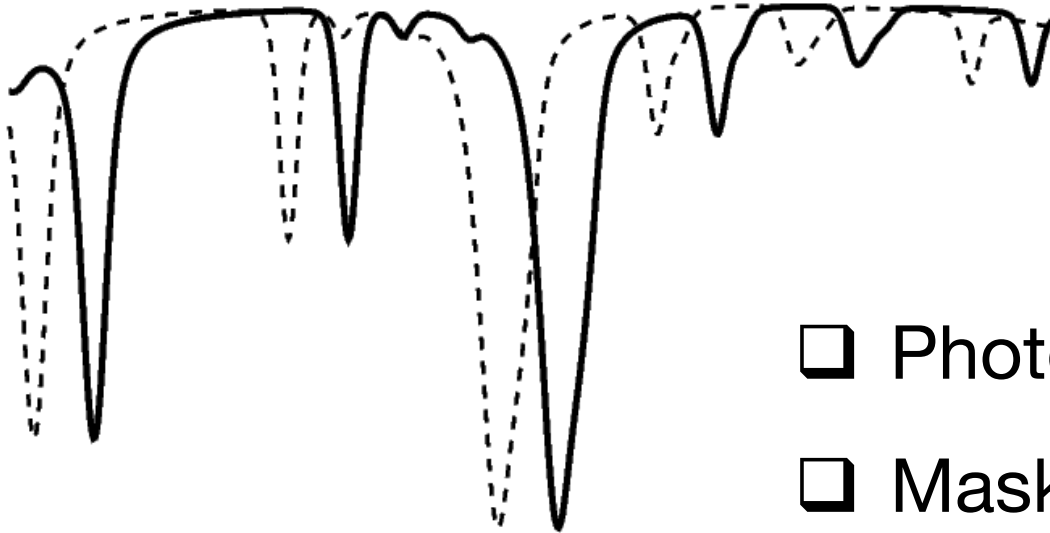
Origin and mitigation of “measurement errors”.

Errors in Measuring RVs



Any change in the observed stellar spectrum that is **not caused by the Doppler shift** due to planets.

Errors in Measuring RVs



- Photon error
- Mask or Template
- Contamination
- Stellar Variation

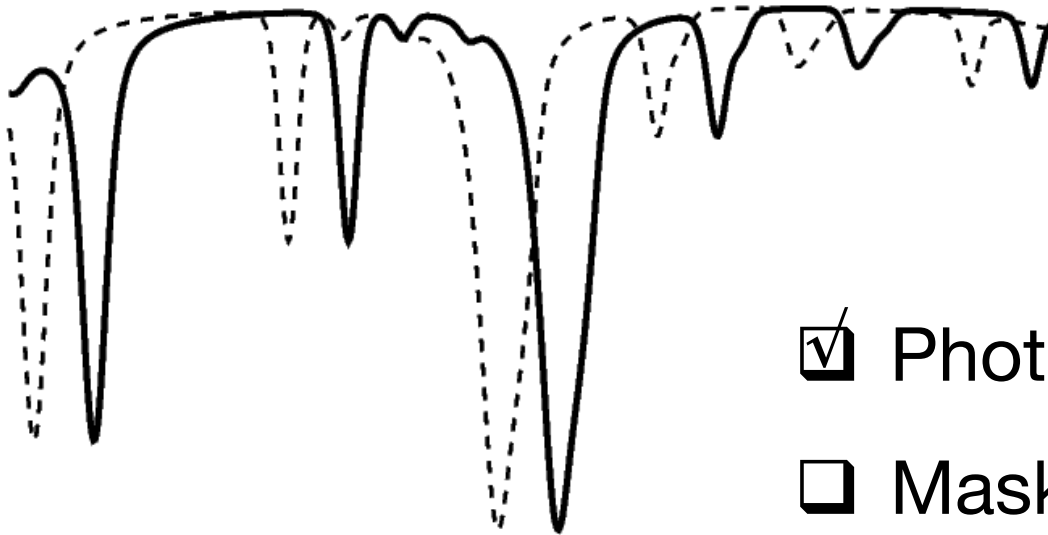
All things equal, under idealized situations*,

CCF = Forward Modeling

*Same photon noise, same template, eliminating contamination completely, no stellar variation

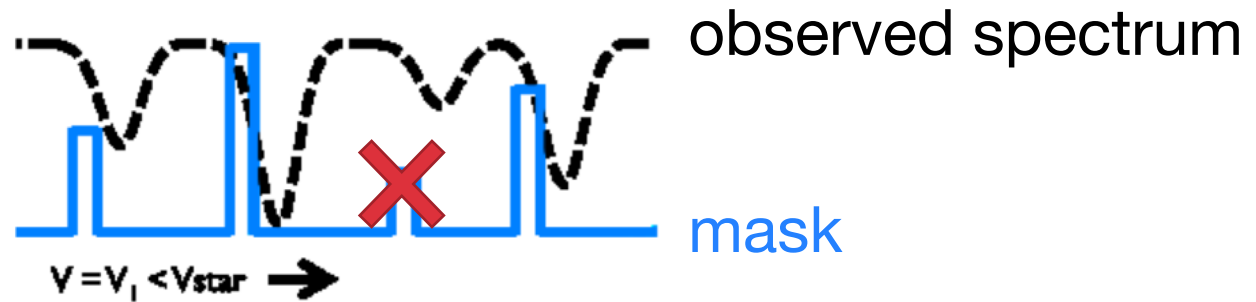
*With proper and reliable **continuum normalization**

Errors in Measuring RVs



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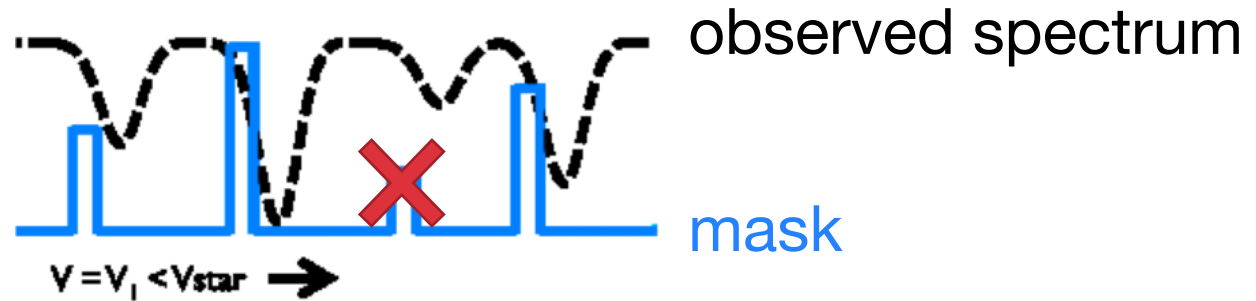
CCF



Error in the mask/template

e.g. a missing line, wrong shapes of some lines

CCF

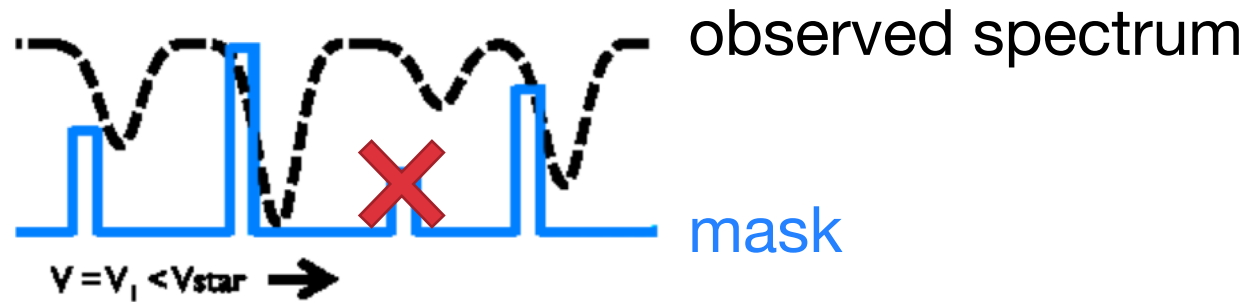


Error in the mask/template

e.g. a missing line, wrong shapes of some lines

→ Constant RV offset

CCF



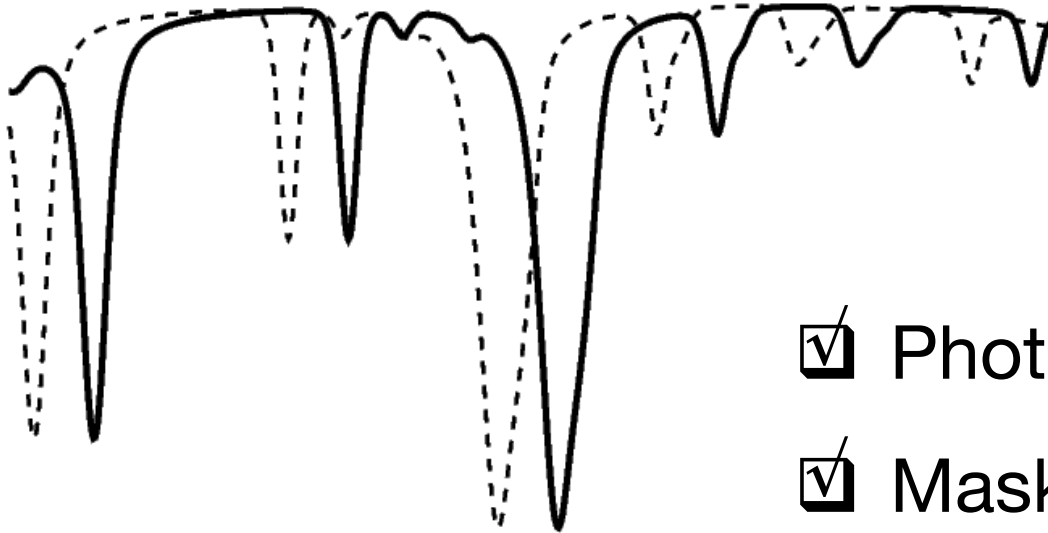
Error in the mask/template

e.g. a missing line, wrong shapes of some lines

➔ Constant RV offset

Error occurs when template defects interact with non-Doppler changes in the observed spectra!

Errors in Measuring RVs



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Solar Contamination

Telluric Emission

Telluric Absorption

Contamination

“Root” Solution

Solar Contamination

avoid moon; sky fiber

Telluric Emission

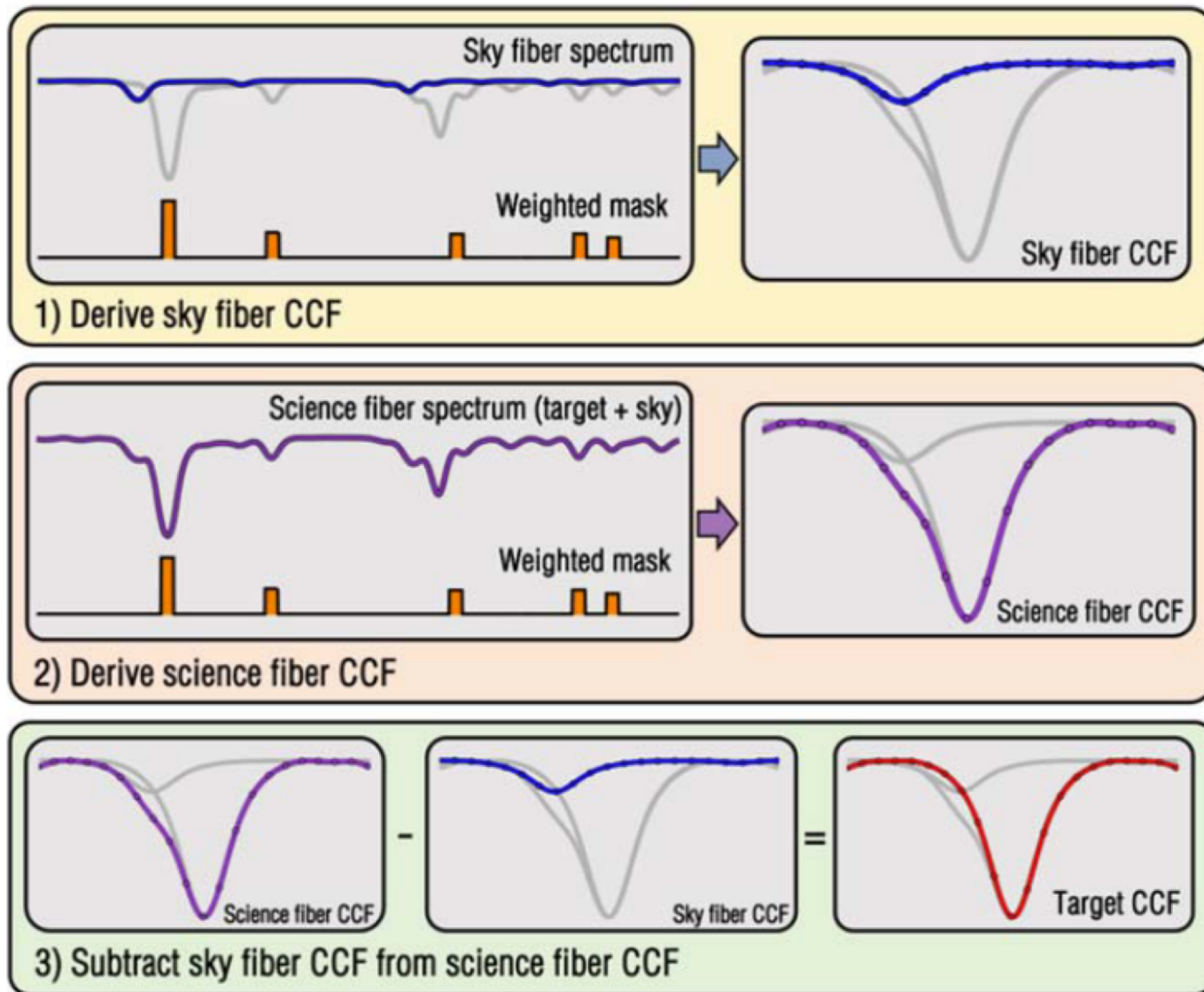
dark site; sky fiber

Telluric Absorption

going to space [!]

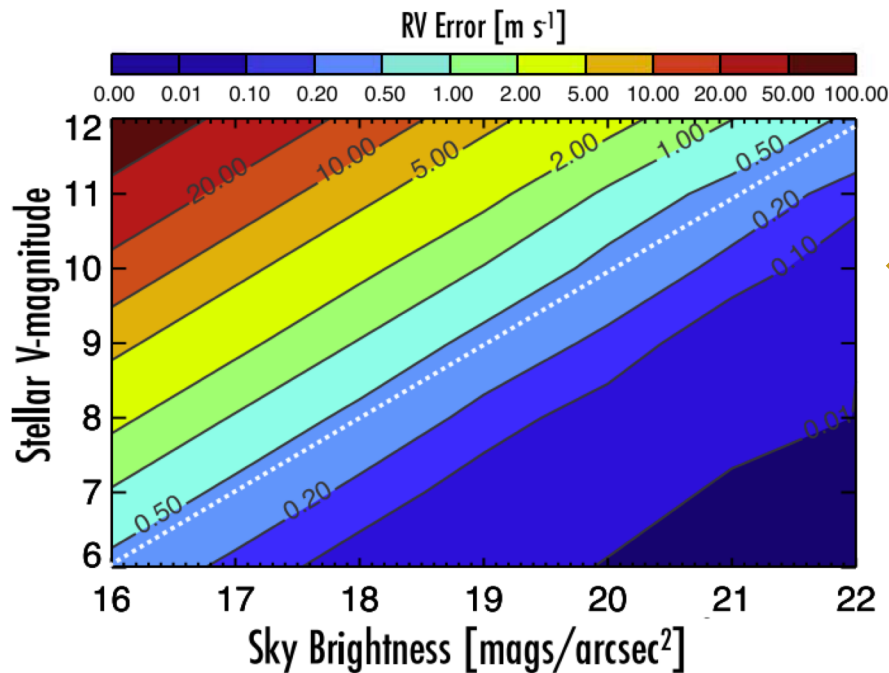
Contamination

Solar Contamination



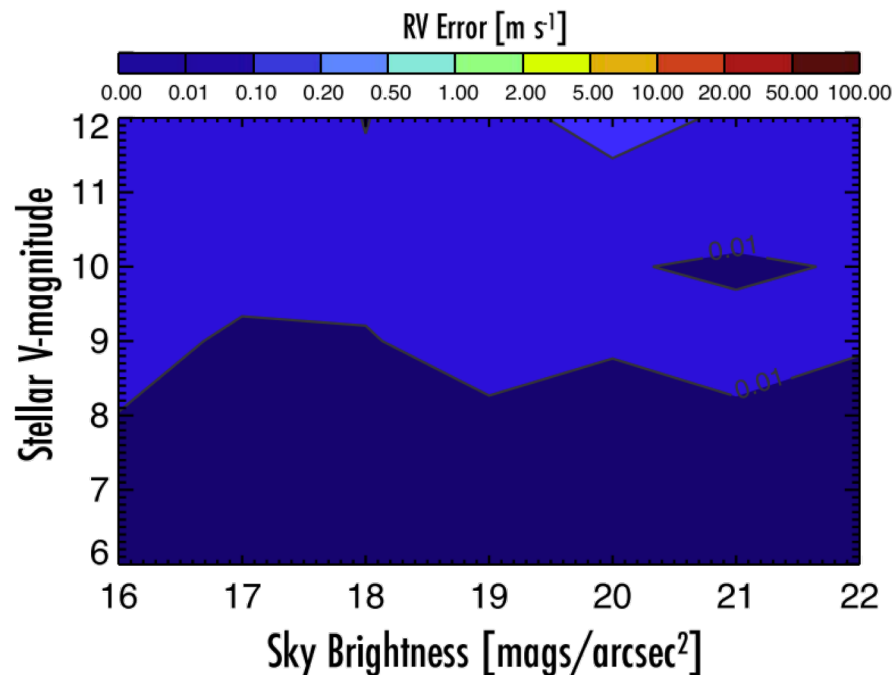
Solar Contamination

Uncorrected Error due to Solar Contamination



← Before

Direct Sky Subtraction Residual

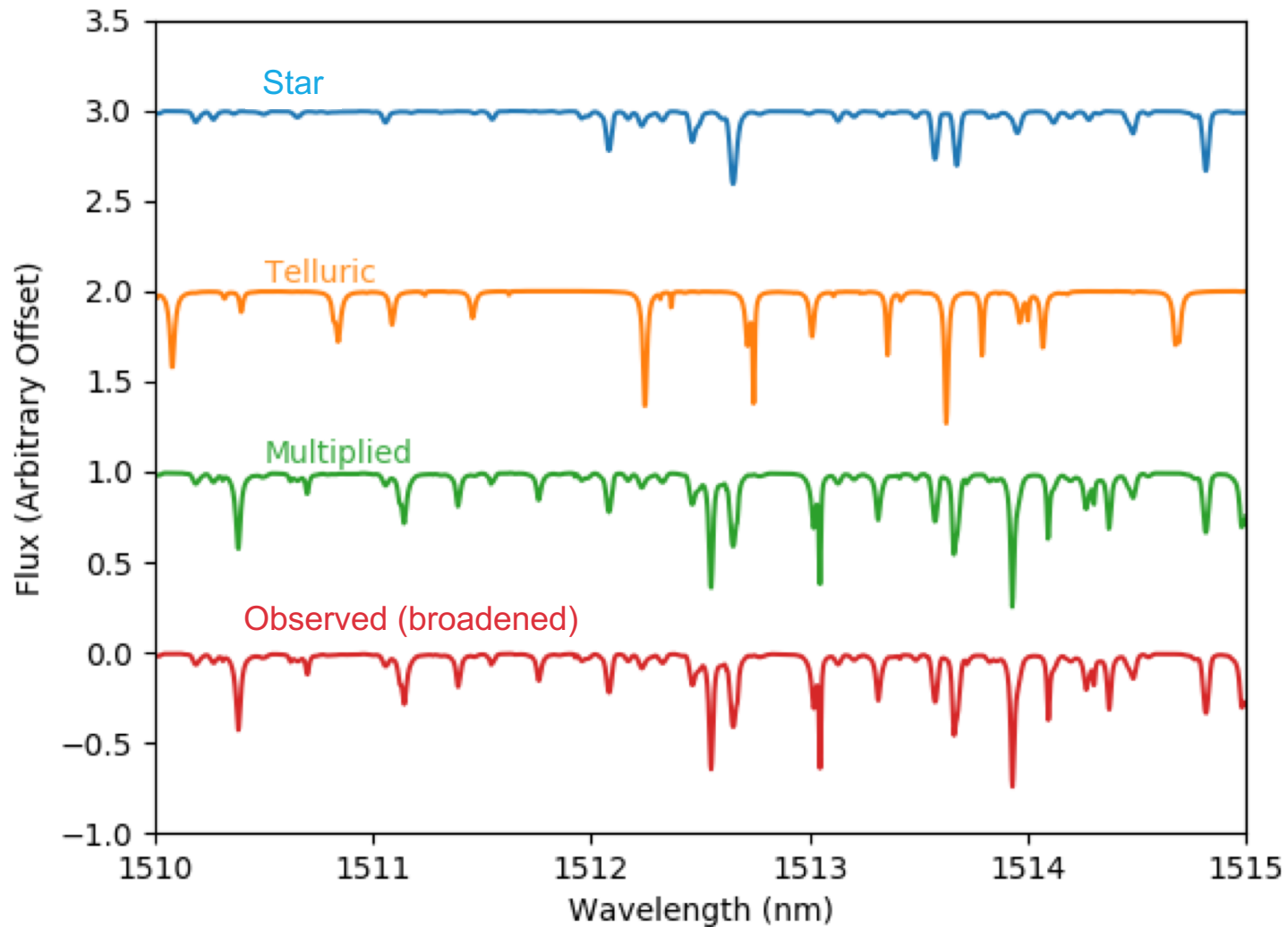


After →

No photon errors.

Roy et al. 2020

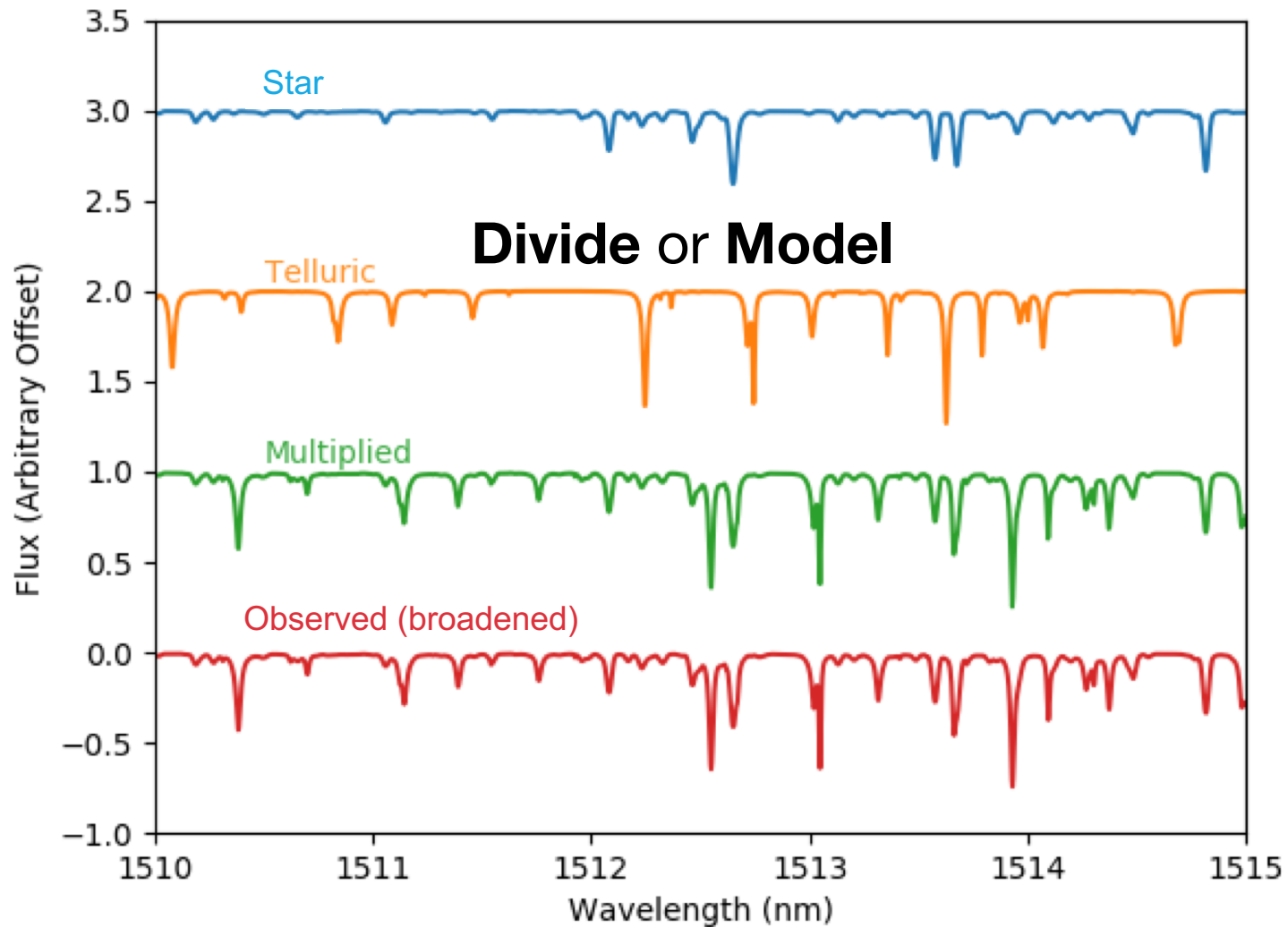
Telluric Absorption



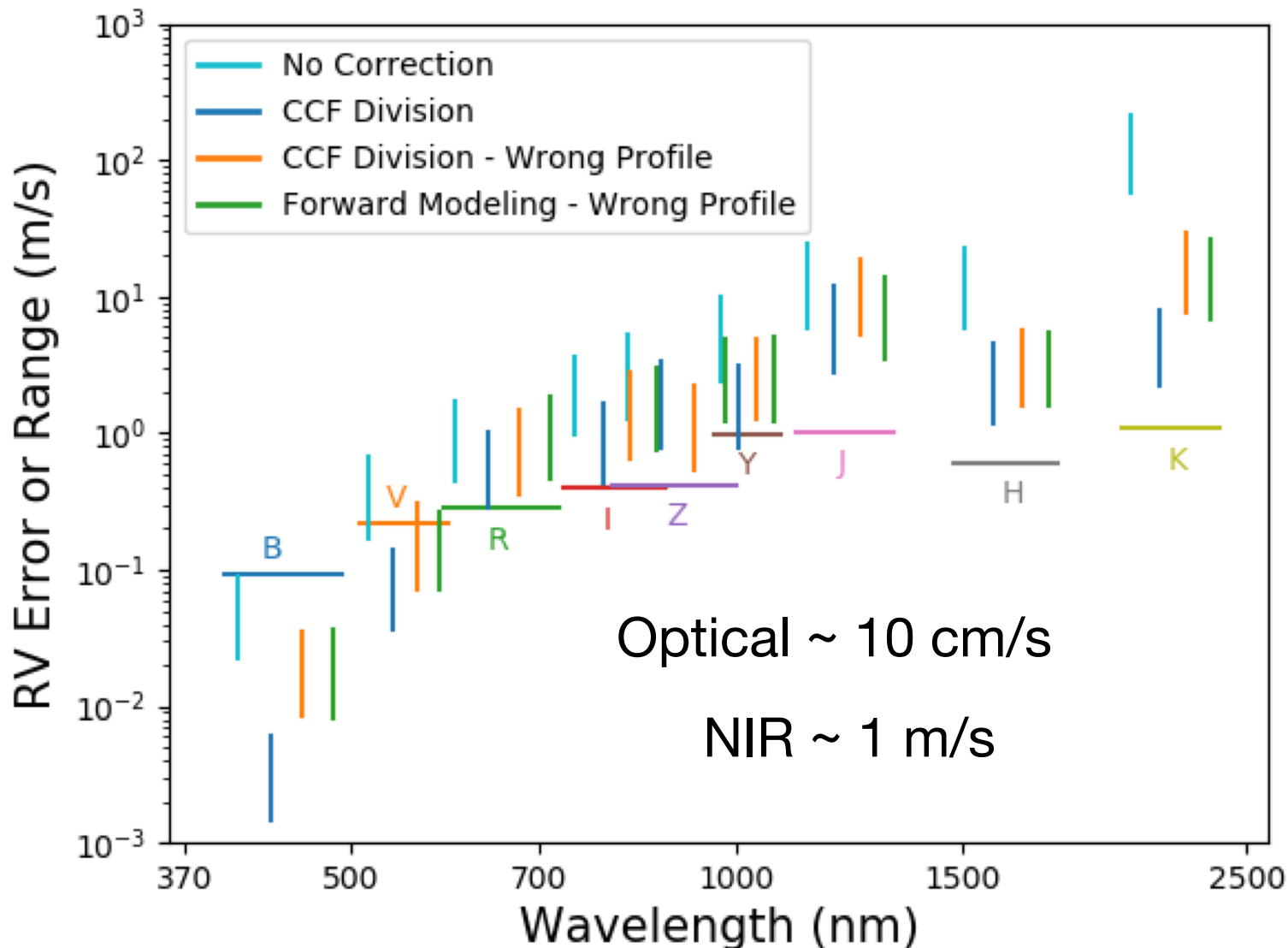
Ref: Cullen Blake's talk.

Wang, Latouf, et al. 2020 in prep.

Telluric Absorption



Telluric Absorption



No photon errors.

Wang, Latouf, et al. 2020 in prep.

Fun Fact # 2

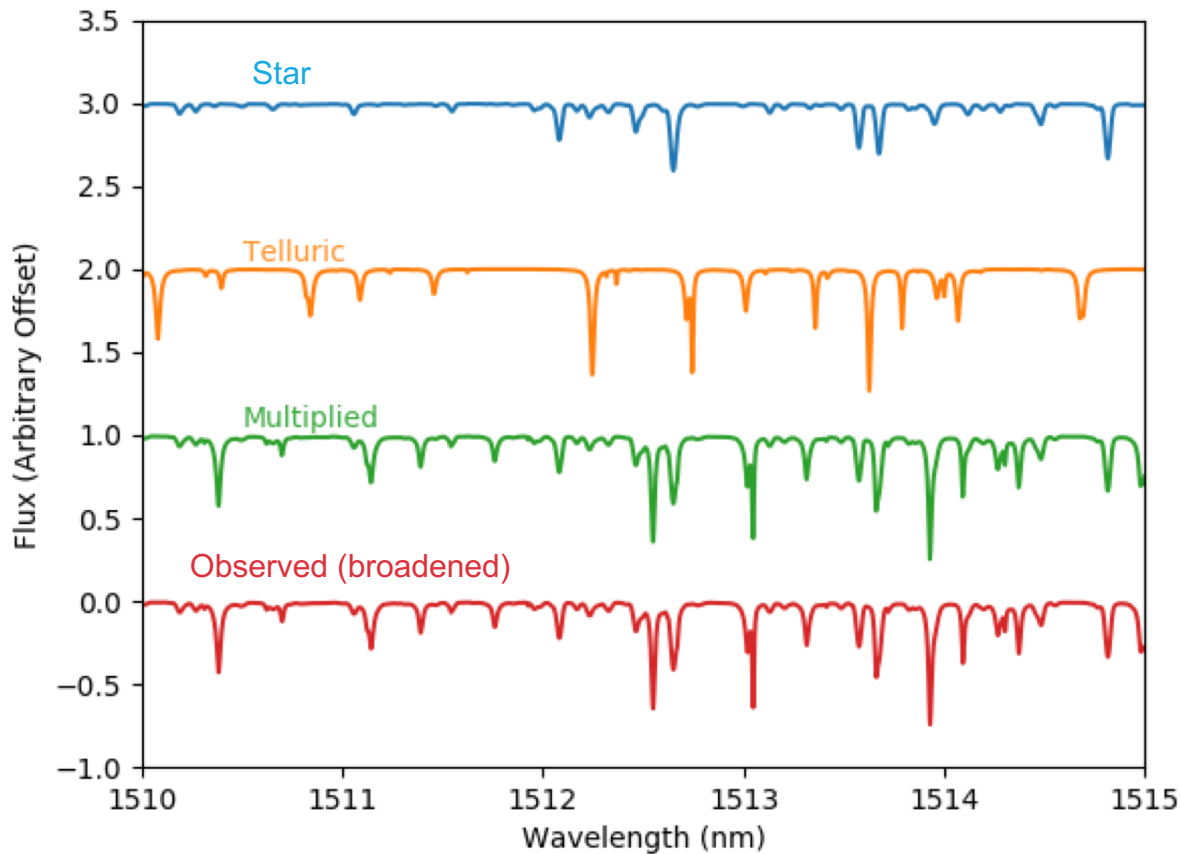
When we know the telluric absorption lines perfectly, dividing them out then performing CCF **does not eliminate the errors completely.**
Why?

Fun Fact # 2

When we know the telluric absorption lines perfectly, dividing them out then performing CCF **does not eliminate the errors completely**.
Why?

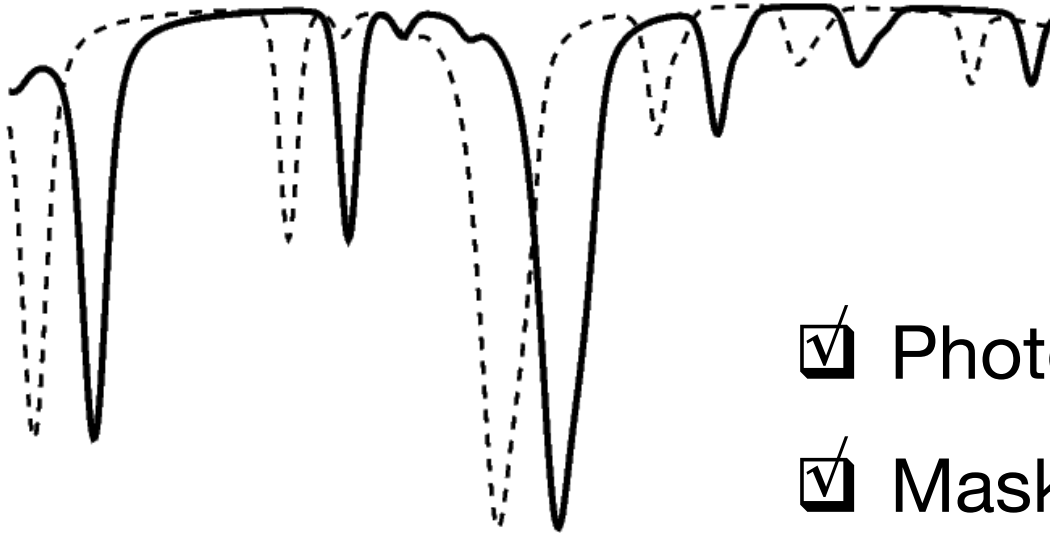
Convolution does not distribute over multiplication!

Fun Fact # 2



**Convolution
does not
distribute
over
multiplication!**

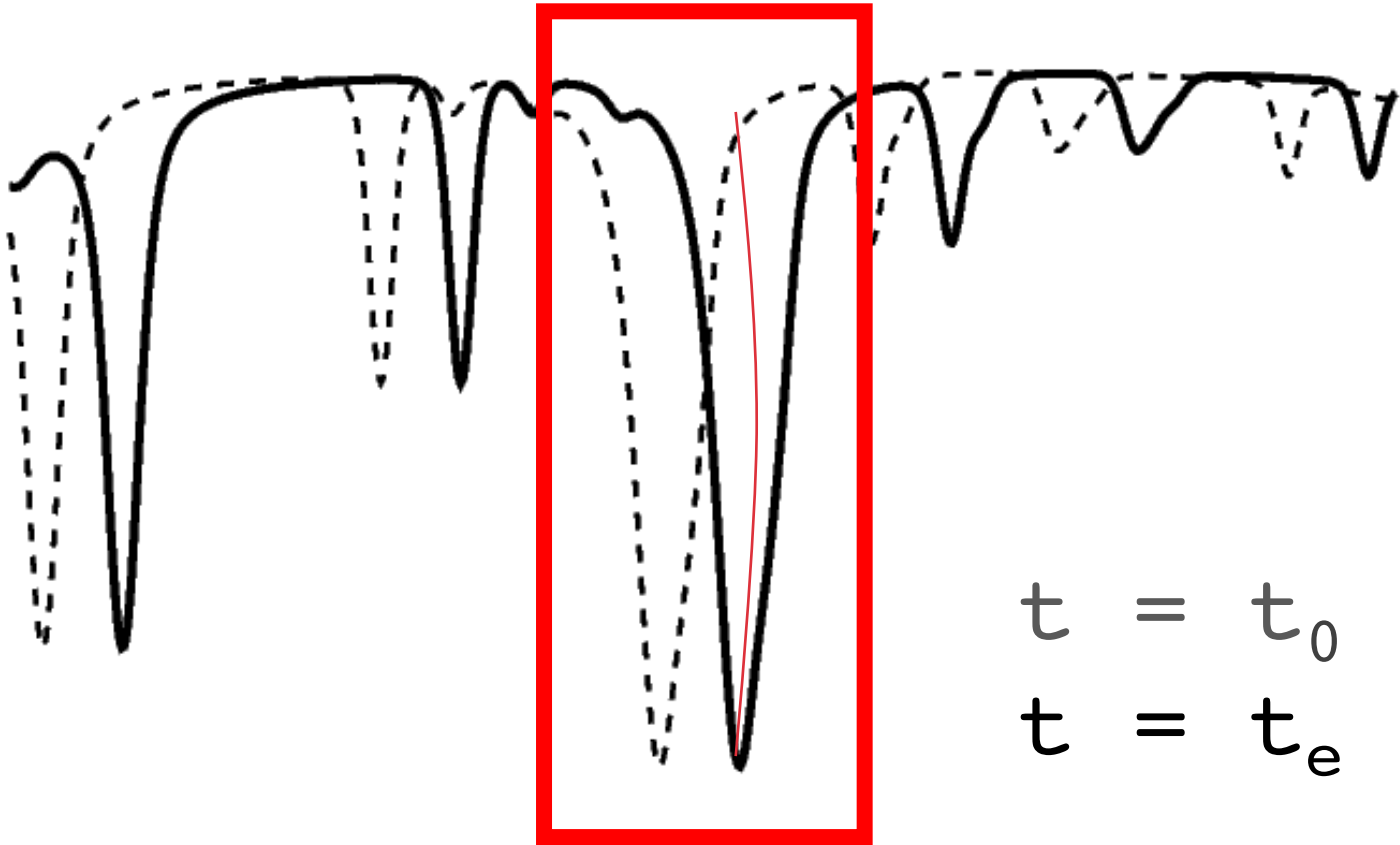
Errors in Measuring RVs



- Photon error
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- Contamination
- Stellar Variation

Stellar Variation

$$z = z_{\text{star}} + z_{\text{planet}}$$



Non-standard methods for measuring RVs.

“Grand Solution” Style (Jeff Valenti)

- Jeff Valenti and BJ Fulton on HIRES data
- Gao et al. 2016 for CSHELL and iSHELL on IRTF
- *wobble*, Bedell et al. 2019

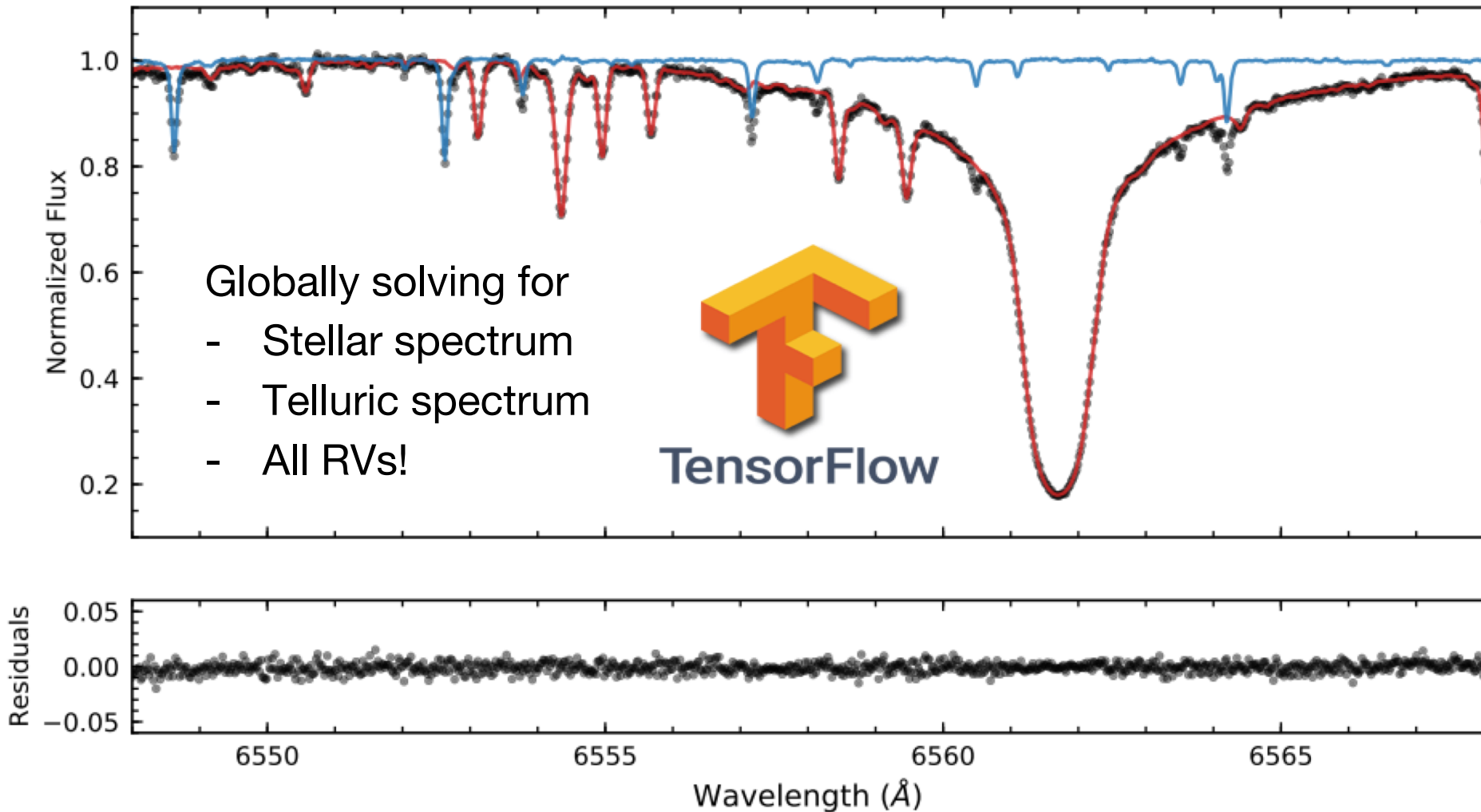
Gaussian Process

- PSOAP, Czekala et al. 2017
- Rajpaul et al. 2020

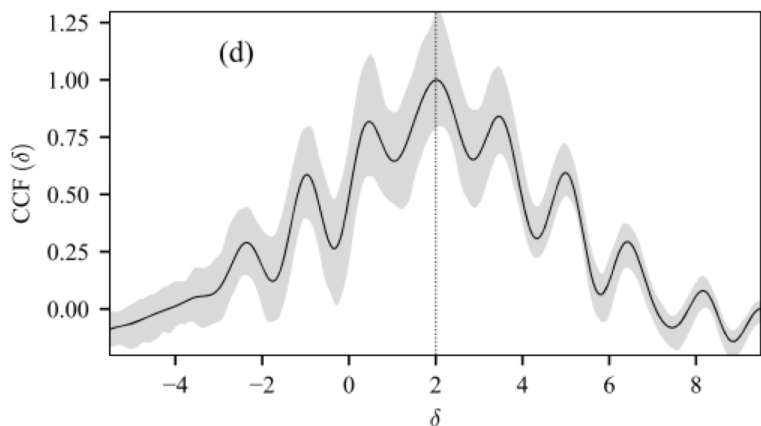
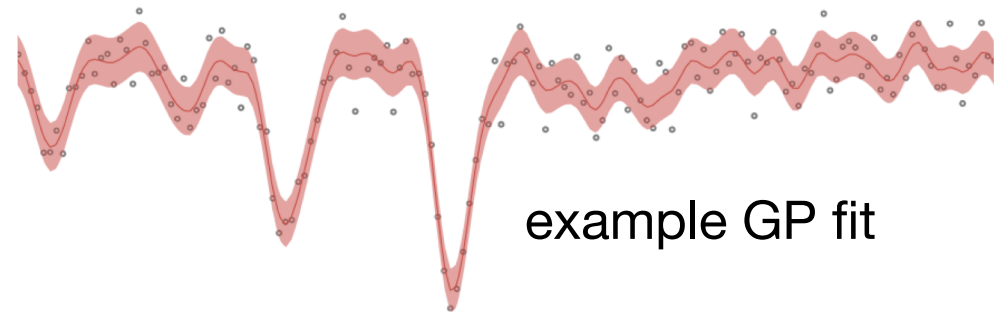
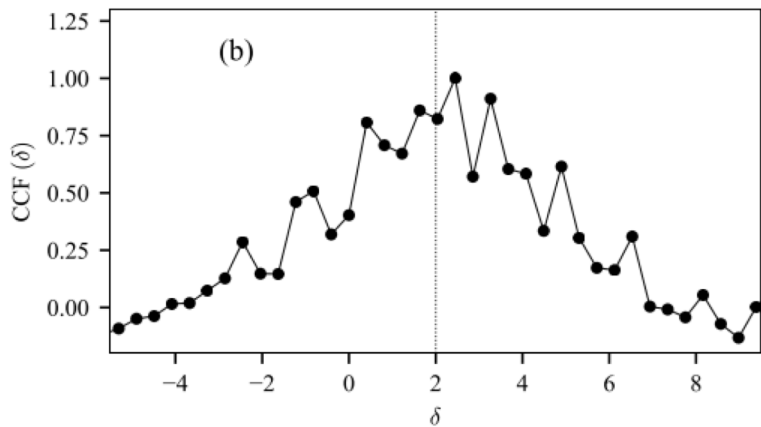
Others

- Machine learning (Davis+2017), neural network?
- Other statistical/numerical method teasing out *only* Doppler shifts

No prior knowledge required.



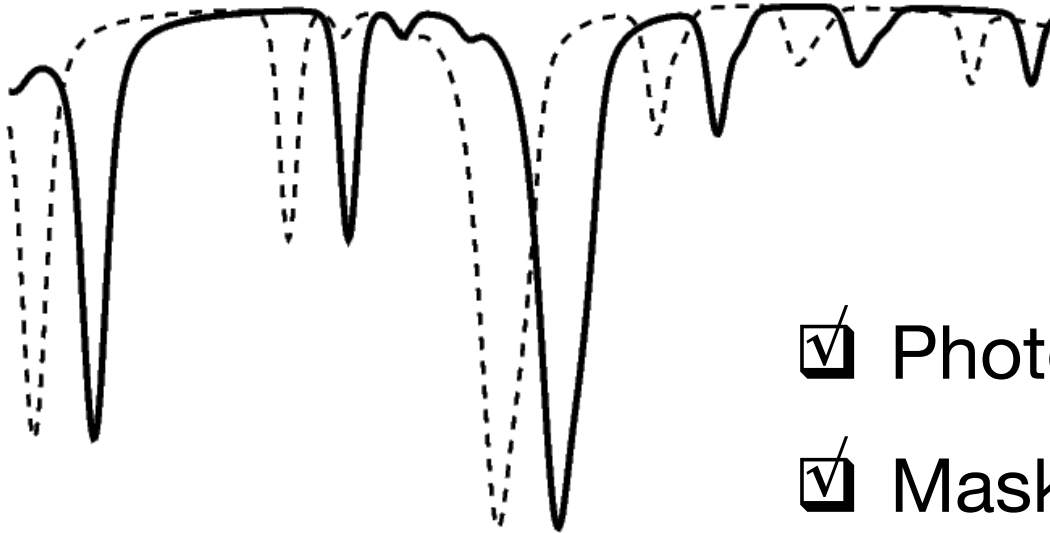
Pair-wise extraction of RVs with GP regression



CCF is continuous!

- RVs from each pair of spectral orders within a pair of observations
- Determine the “contaminated” orders post extraction
- Rejecting “contaminated” orders

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Thank You

& questions welcome

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