Generating Precise Radial Velocities

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Outline

- What is radial velocity? What are we measuring?
- What to expect when you work with RV data?
- How exactly do we get RVs from data?

Prelim

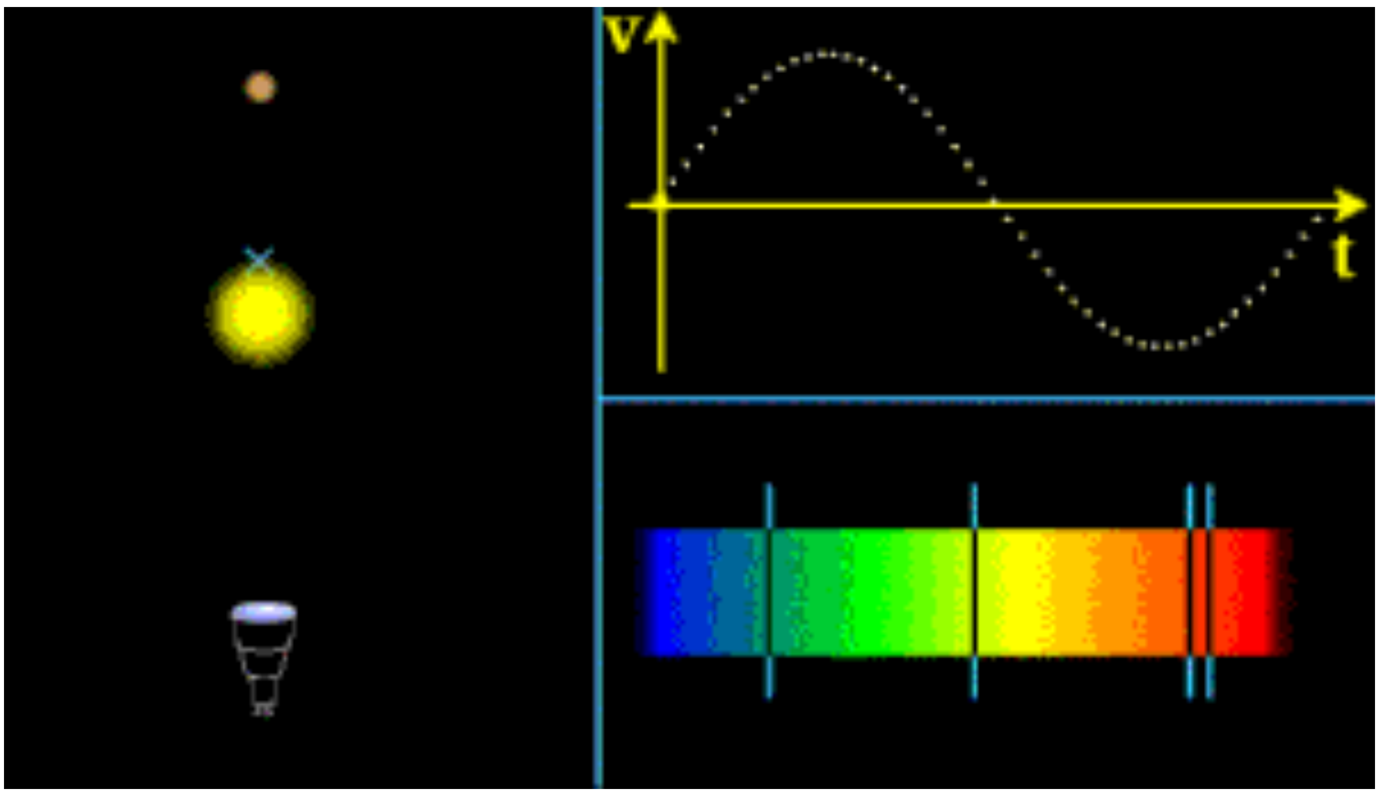
- Some slides are dense – focus on larger words.

- Focus on overview and practical use.

- Will have references for going in-depth on some topics at the end.

Velocity along line of sight

positive = redshifted = going away



RV Components

Reference frame: your spectrograph

- Relative velocity between the star and solar system

RV Components

Reference frame: your spectrograph

- Relative velocity between the star and solar system
- Relative velocity between the Earth and the barycenter

RV Components

Reference frame: your spectrograph

- Relative velocity between the star and solar system
- Relative velocity between the Earth and the barycenter
- Rotation of the Earth

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Reference frame: the **barycenter** of solar system

RV Components

Reference frame: your spectrograph

- Relative velocity between the star and solar system
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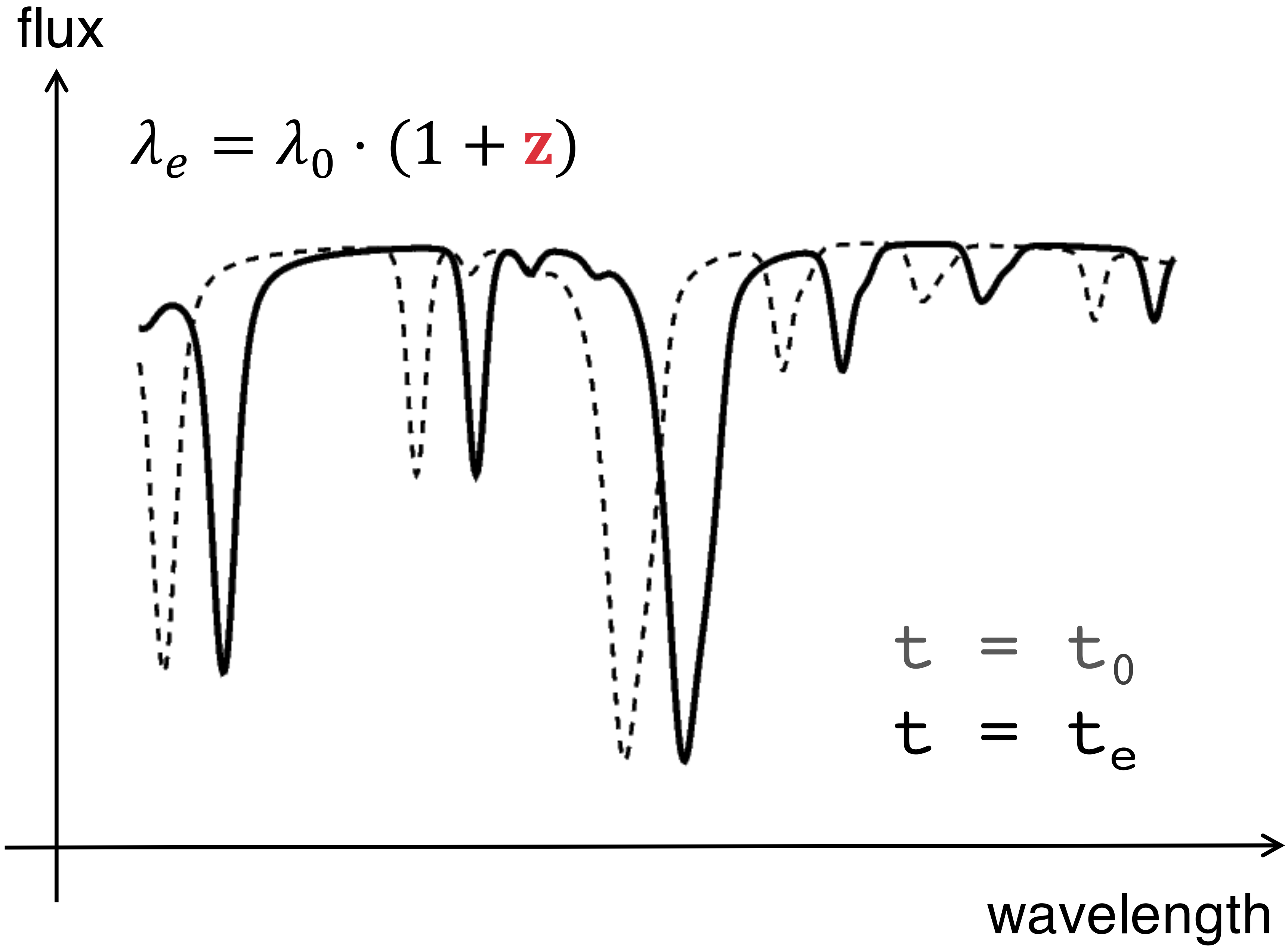
Reference frame: the **barycenter** of solar system

- Relative velocity between the star and solar system
  - Systemic velocity of the star
  - Velocity of the star around the barycenter of its system (companions including planets)


flux
$\lambda_e = \lambda_0 \cdot (1 + \mathbf{z})$
$t = t_0$
$t = t_e$
wavelength

In reality,

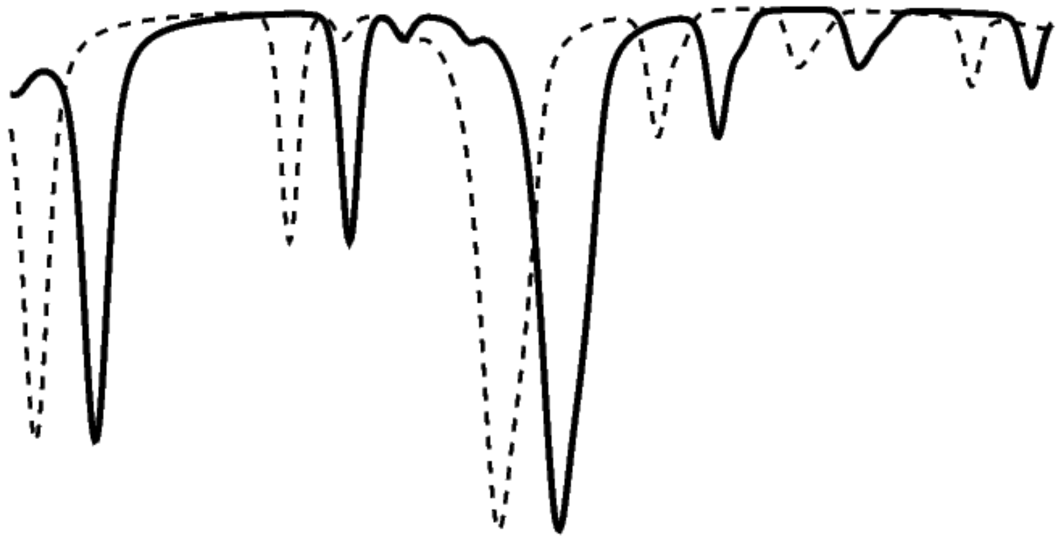
we are measuring **ΔRV** in the **lab frame**.

RV ***change*** of the star w.r.t.
an arbitrary time frame

=> **arbitrary RV offset**

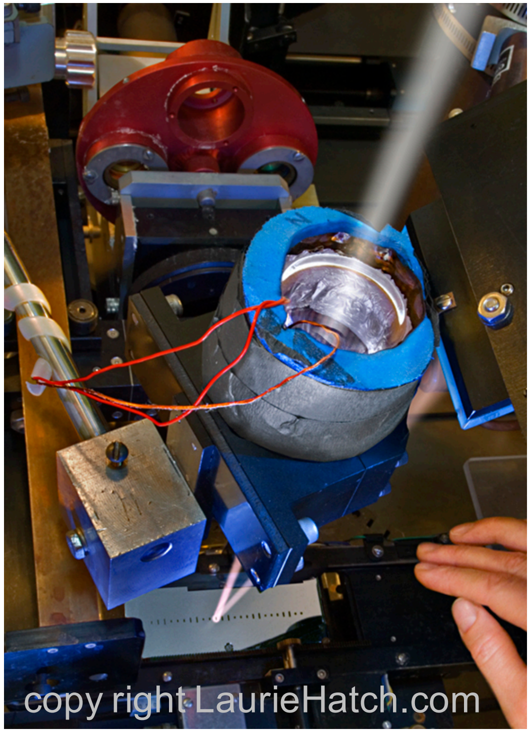
Need to ***translate*** into
barycentric frame.

=> barycentric correction



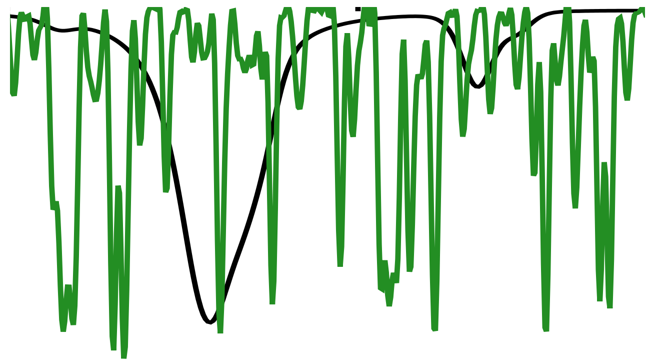
What do we actually measure?

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



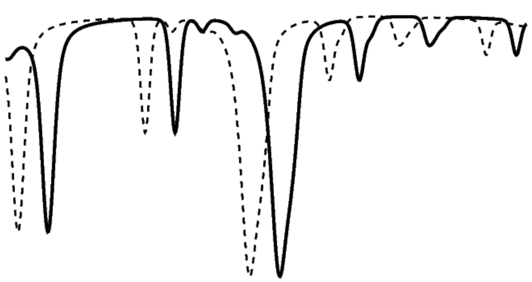
Iodine Cell Calibrated

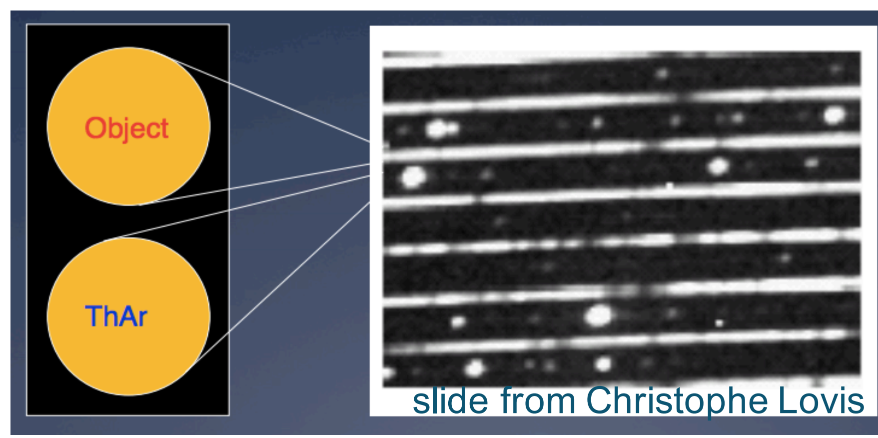
e.g. Keck/HIRES

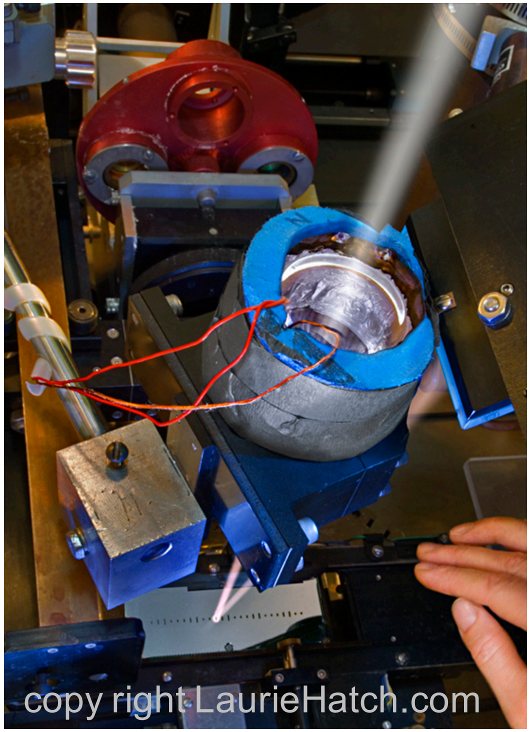


ThAr Calibrated

e.g. HAPRS

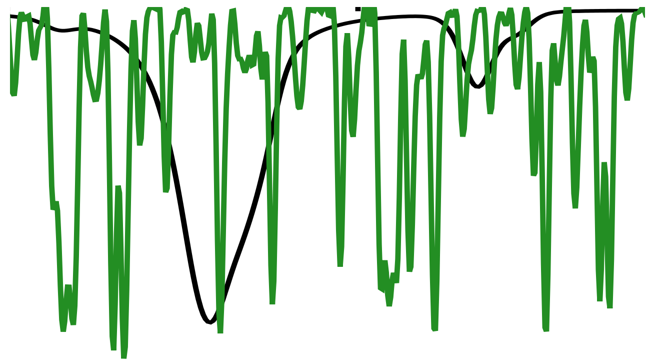






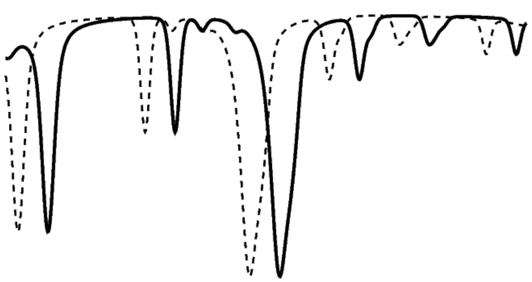
Absorption Cell Calibrated

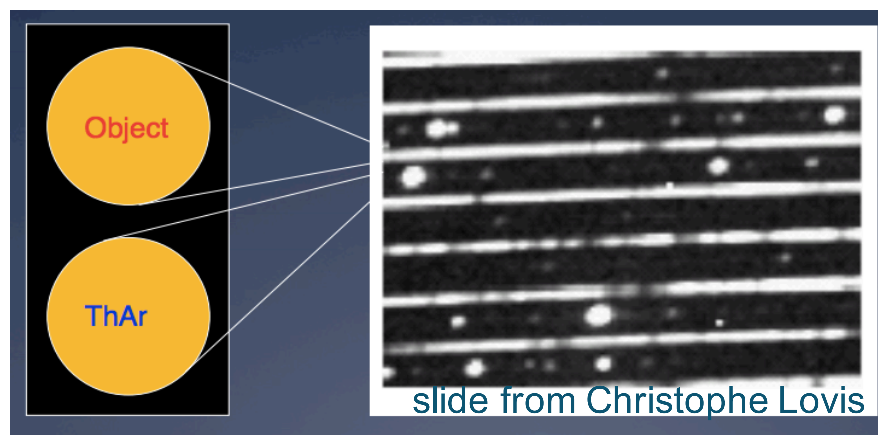
e.g. Keck/HIRES



Simultaneous Reference

e.g. HAPRS





How do we get RVs out?

Cross Correlation Function (CCF)

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

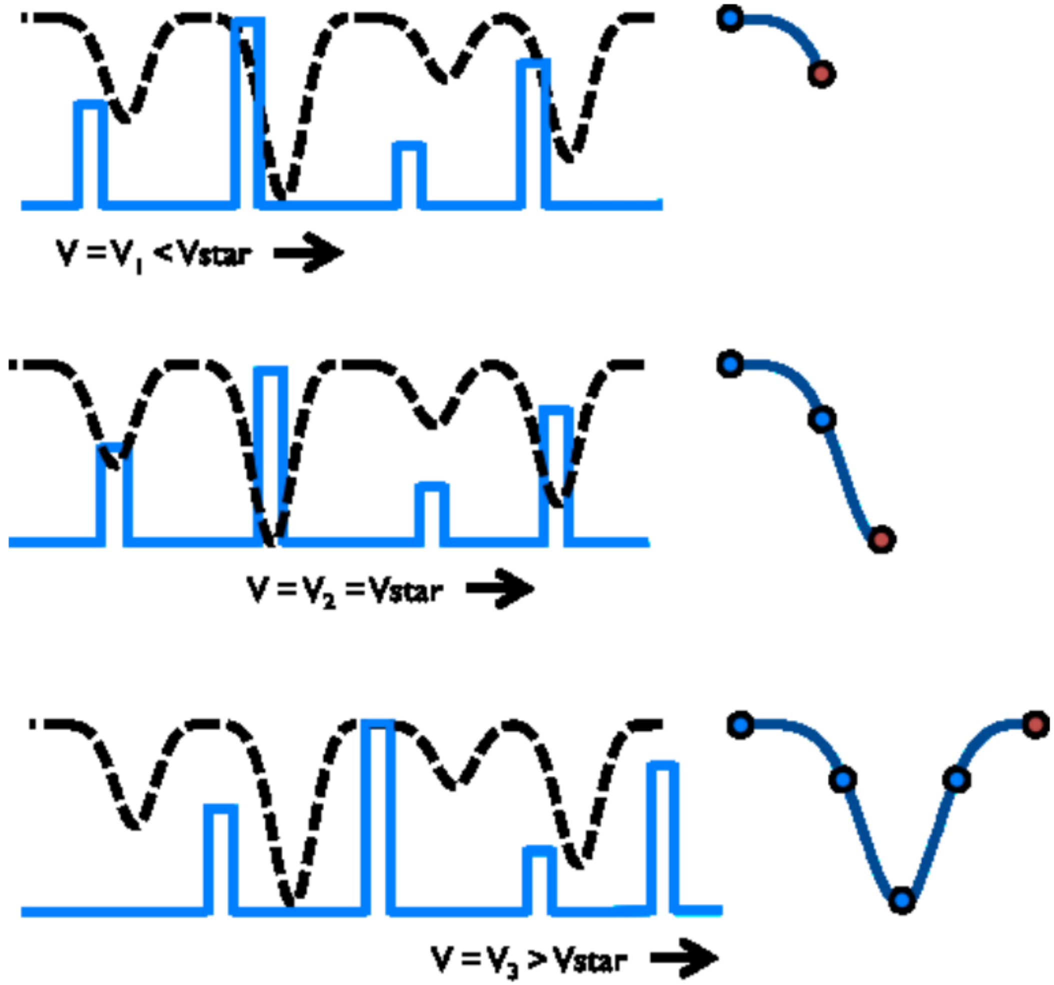
Baranne et al. 1996

Forward Modeling

used for both calibration methods.

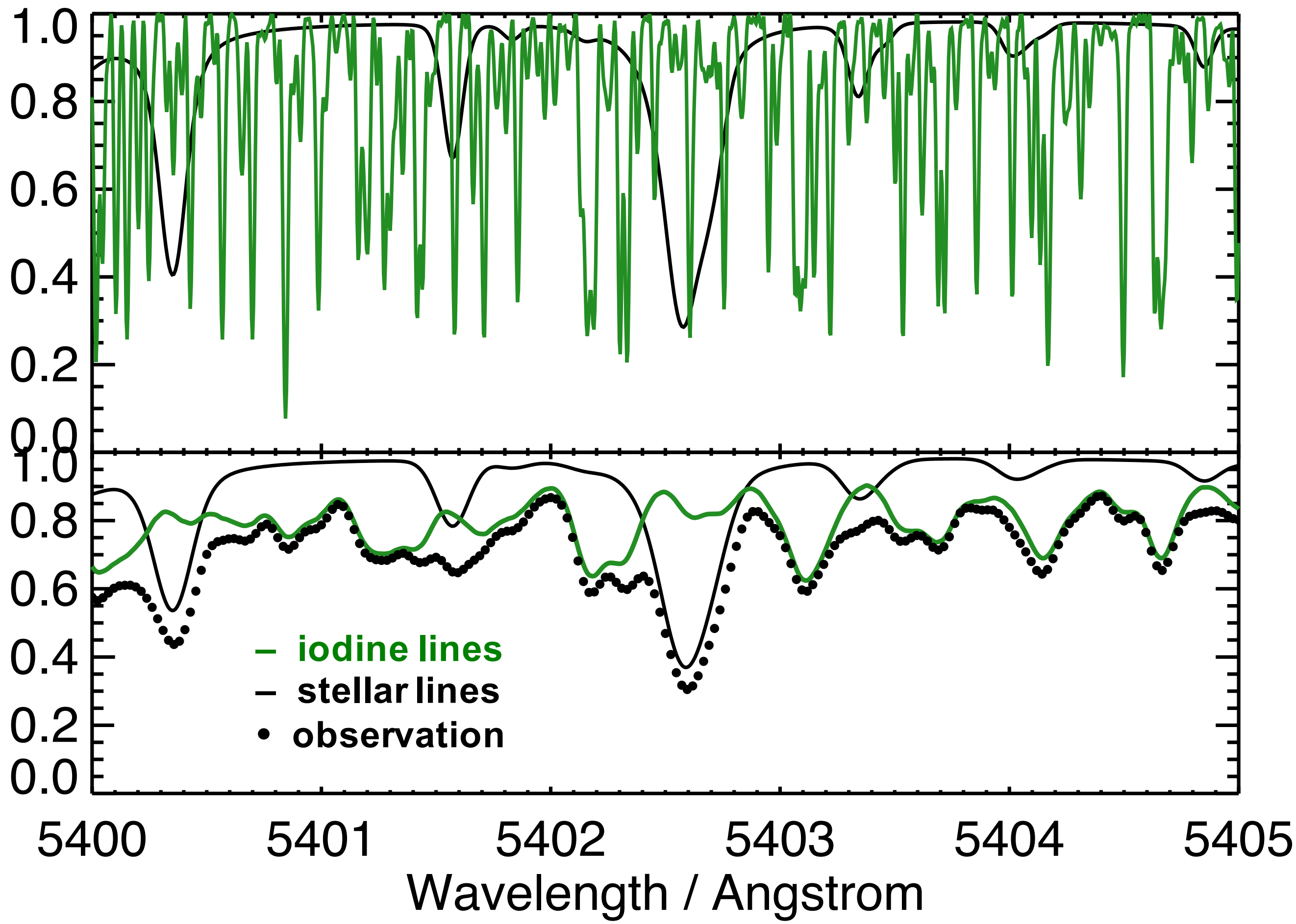
Butler et al. 1996

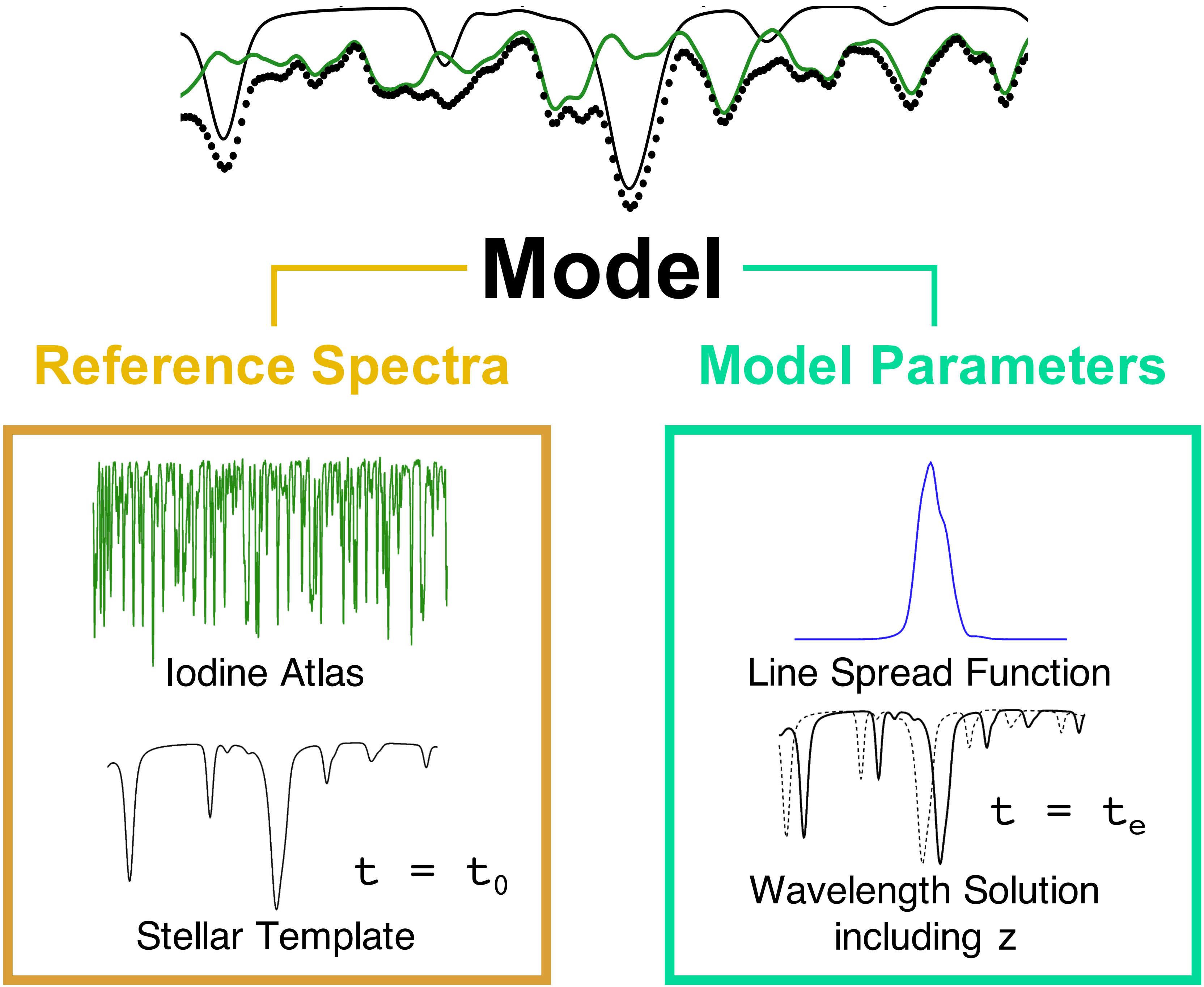
CCF



See Arpita Roy’s talk; Roy et al. 2016

Forward Modeling




Model
Reference Spectra
Model Parameters
Iodine Atlas
Stellar Template
t = t0
Line Spread Function
Wavelength Solution including z
t = te

About the **stellar reference** spectrum…

(or the stellar template, in some cases)

- They are typically empirically derived.
    - Deconvolution, Butler et al .1996
    - Customized masks for the CCF method, Baranne et al. 1996
    - Shift and stack many frames, Anglada-Escudé & Butler 2012

- You don’t absolutely need them, actually.
    - “The grand solution” (Jeff Valenti), Gao et al. 2016 for CSHELL
    - PSOAP, Czekala et al. 2017

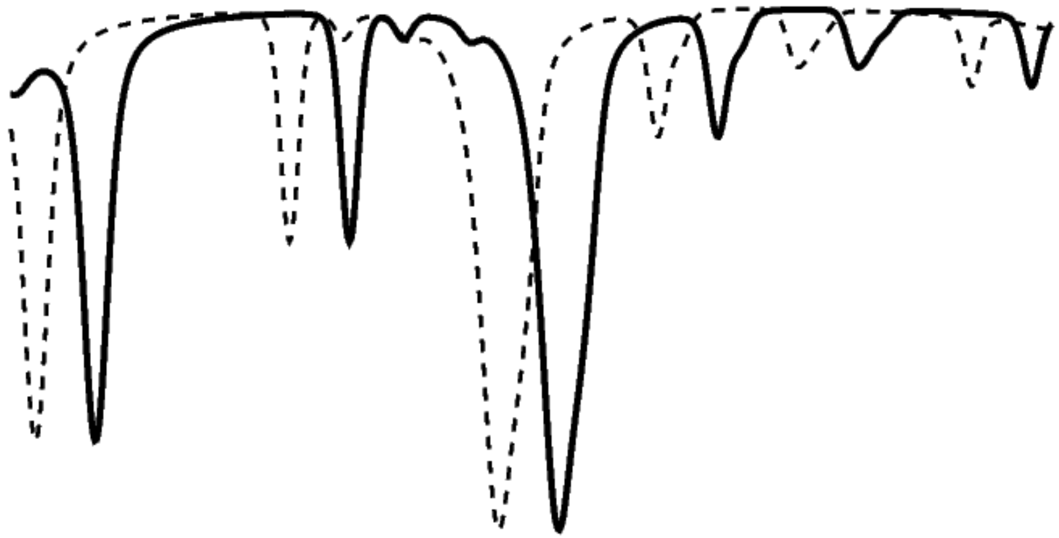
How do we get RVs out?

Cross Correlation Function (CCF)

Pro: quick and simple.
Con: relies on stabilized spectrograph; hard to deal with tellurics or variations in spectral PSF.

Forward Modeling

Pro: versatile – can add component and deal with changing PSF.
Con: algorithmically and computationally more challenging.



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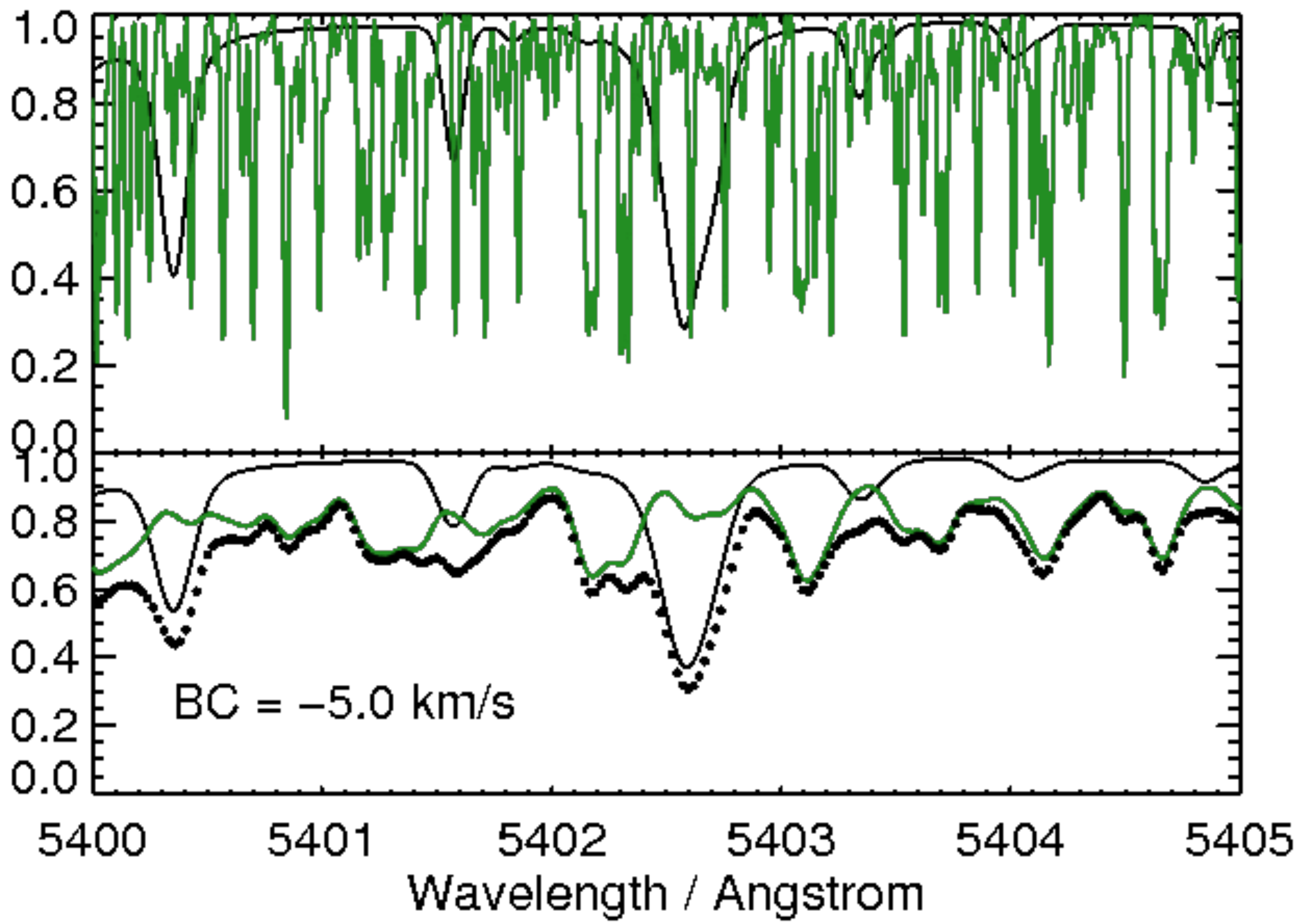
1 m/s ~ 1/1000th pixel

… and the largest component in your signal comes from the Earth!



Quick manual for using typical RV products

Time / **B**JD	RVs	Errors
2459999.12345	21316.78	1.23

Do not be alarmed if you RVs have an arbitrary constant offset (which could be a pretty large number sometimes).

The errors on the RVs are the “internal” errors reported from the data analysis for a single epoch. Typically representing the photon-limited precision. Quite often underestimated due to omitted instrumental and stellar jitter.

What is the “RV precision” ?

Photon-limited RV precision: (your typical “error bar”)

Instrument RV precision:

On-target RV precision:

What is the "RV precision" ?

Photon-limited RV precision: (your typical "error bar")

The best you will ever get because of information content of the stellar spectrum, amount of photons you get, and your calibration method.

Instrument RV precision:

On-target RV precision:

What is the "RV precision" ?

Photon-limited RV precision: (your typical "error bar")

The best you will ever get because of information content of the stellar spectrum, amount of photons you get, and your calibration method.

Instrument RV precision:

What your instrument is capable of, set by the intrinsic stability of the instrument and your calibration method (and even data analysis method). Often quoted as "goals" for new instruments.

On-target RV precision:

What is the "RV precision" ?

Photon-limited RV precision: (your typical "error bar")

The best you will ever get because of information content of the stellar spectrum, amount of photons you get, and your calibration method.

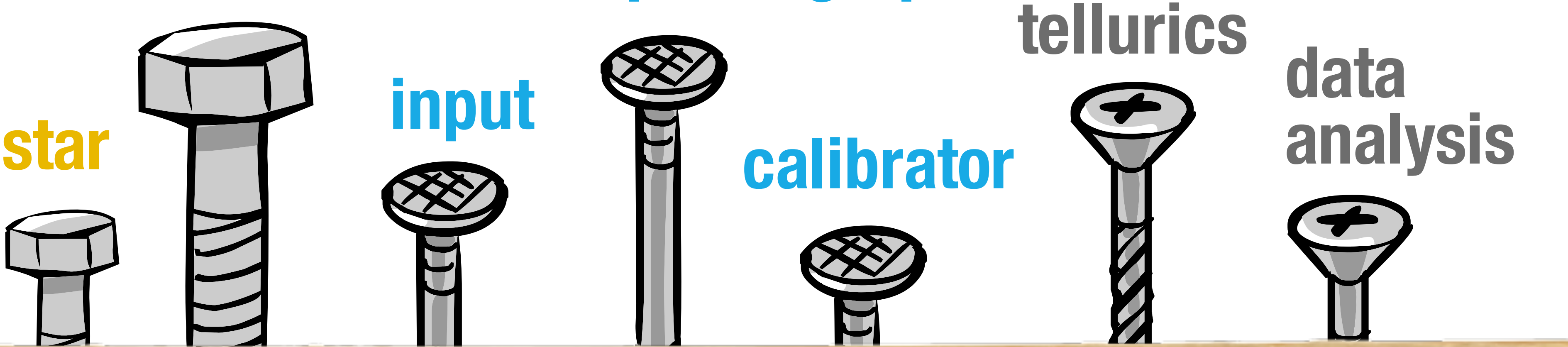
Instrument RV precision:

What your instrument is capable of, set by the intrinsic stability of the instrument and your calibration method (and even data analysis method). Often quoted as "goals" for new instruments.

On-target RV precision:

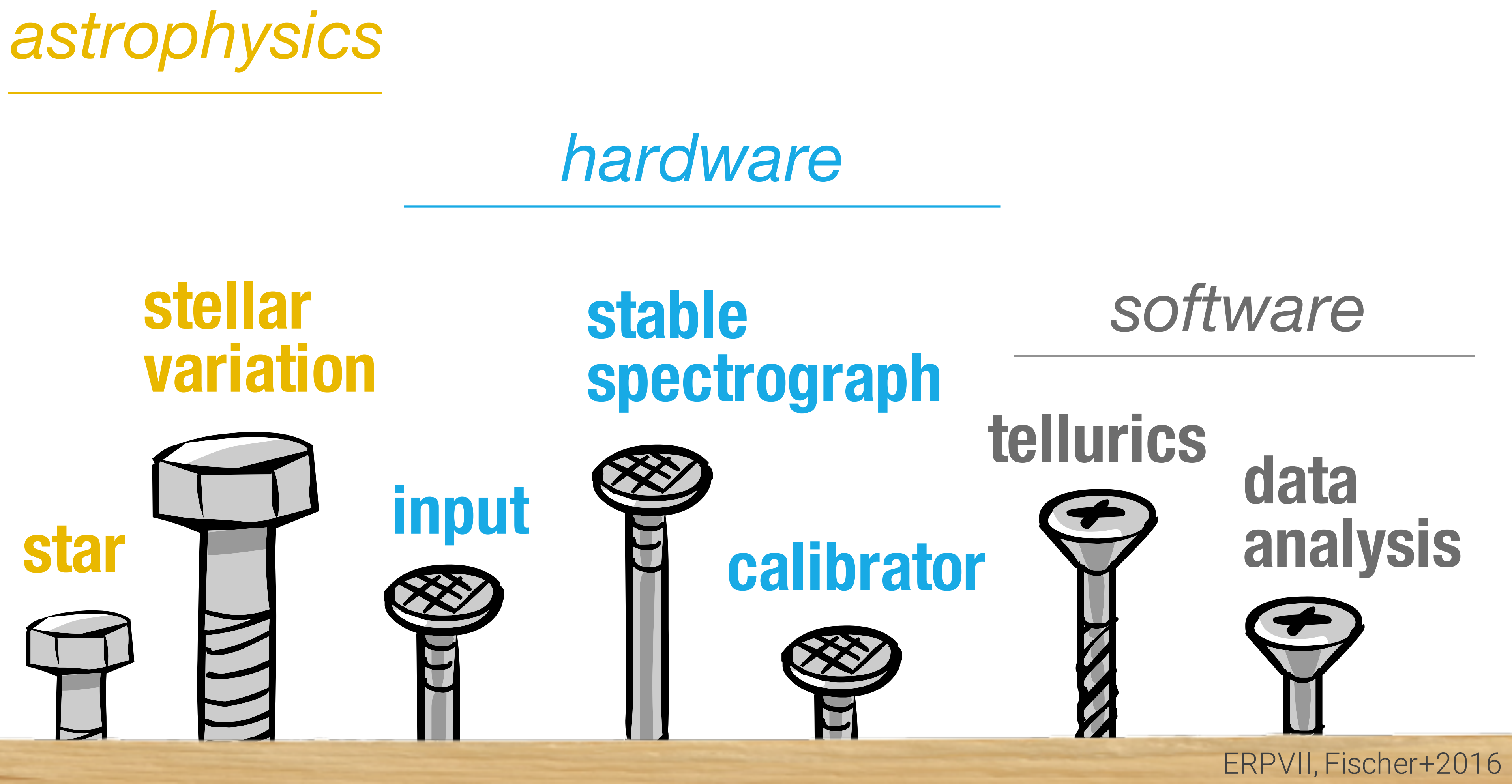
Set by the two terms above, plus stellar jitter and stellar activity. Often we try to estimate the best performance possible for an instrument by observing RV standard stars (quiet and no planet).

the 7 components of precise RV

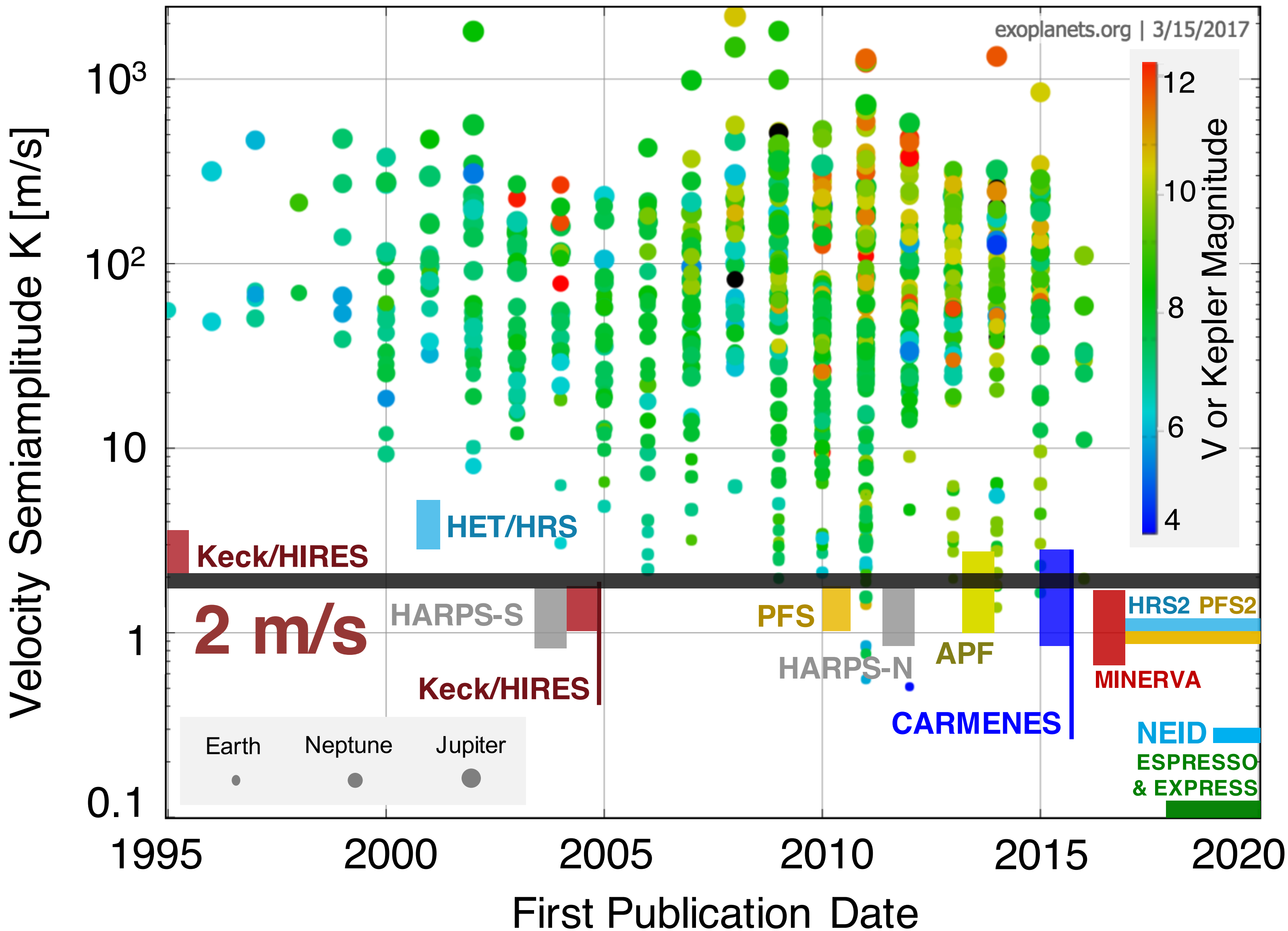


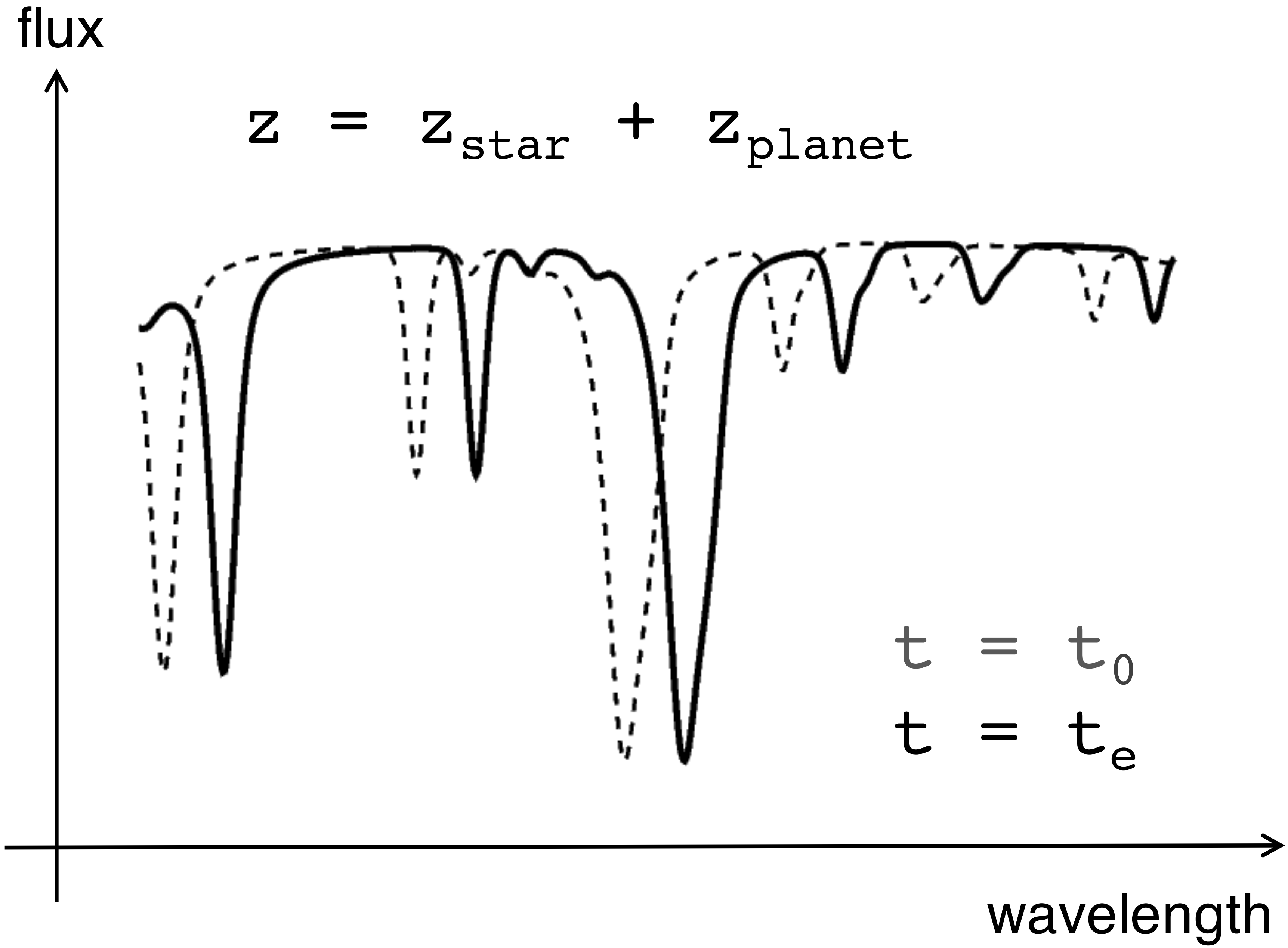
ERPVII, Fischer+2016

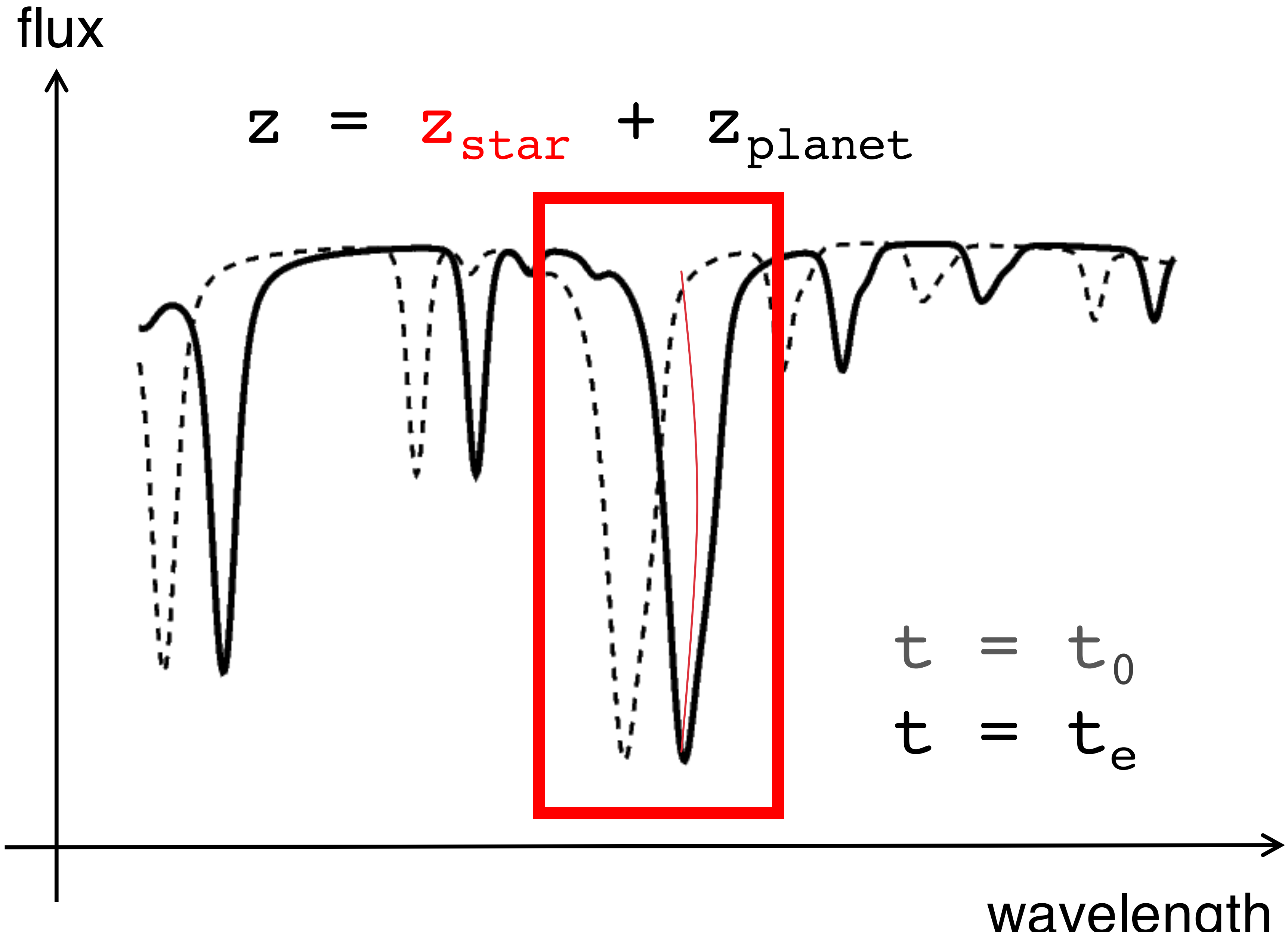
the 7 components of precise RV



Breaking the 1 m/s barrier in the near future.




flux
z = z_star + z_planet
t = t_0
t = t_e
wavelength



Disentangle these? See, e.g., Davis et al. 2017

Thank You
& questions welcome

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Overall introduction to the RV technique and the field:

Radial Velocity as an Exoplanet Discovery Method, Wright
https://arxiv.org/abs/1707.07983
Radial Velocity Techniques for Exoplanets, Lovis & Fischer
http://exoplanets.astro.yale.edu/workshop/EPRV/Bibliography_files/Radial_Velocity.pdf
Status of the Field, Fischer et al EPRV2, 2016
https://arxiv.org/abs/1602.07939

A Tally Sheet for RV Instruments:

Compiled by CARMENES group (last updated ~2016?):
http://carmenes.caha.es/ext/instrument/index.html
New and commissioning RV instruments, 2017, EPRV3 meeting:
https://arxiv.org/abs/1801.05383

Citations in this presentation:

Butler et al. 1996:
http://adsabs.harvard.edu/abs/1996PASP..108..500B
Baranne et al. 1996
http://adsabs.harvard.edu/abs/1996A%26AS..119..373B
Anglada-Escude & Butler 2012
https://arxiv.org/abs/1202.2570
Gao et al. 2016
http://adsabs.harvard.edu/abs/2016PASP..128j4501G
Davis et al. 2017
http://adsabs.harvard.edu/cgi-bin/bib_query?arXiv:1708.00491
Czekala et al. 2017
http://adsabs.harvard.edu/abs/2017ApJ...840...49C
Roy et al. 2016
https://arxiv.org/abs/1607.06485

Note:
There are RV extraction codes that are “publicly available”.
Email me if you’d like to learn more.