Spectroscopic follow-up of Hot Jupiters

Research workshop on evolved stars

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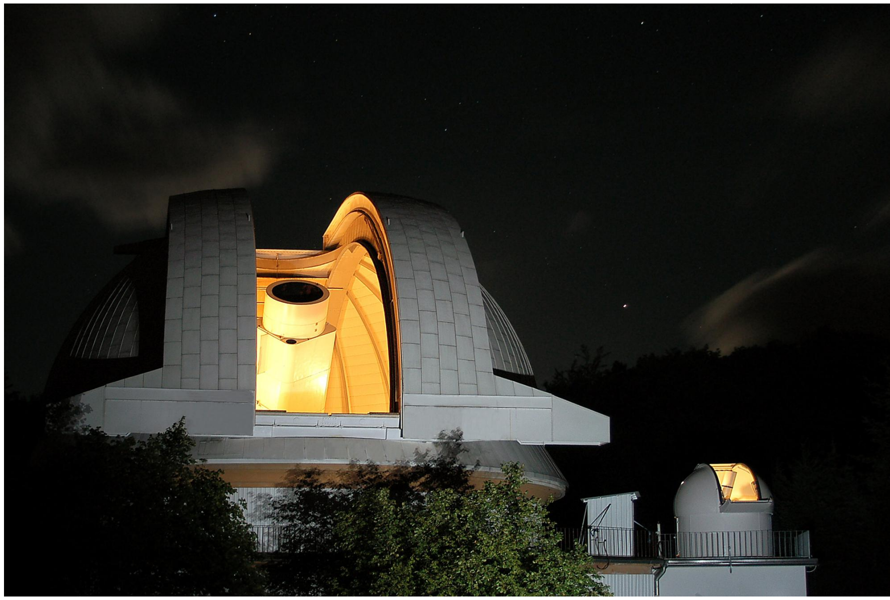
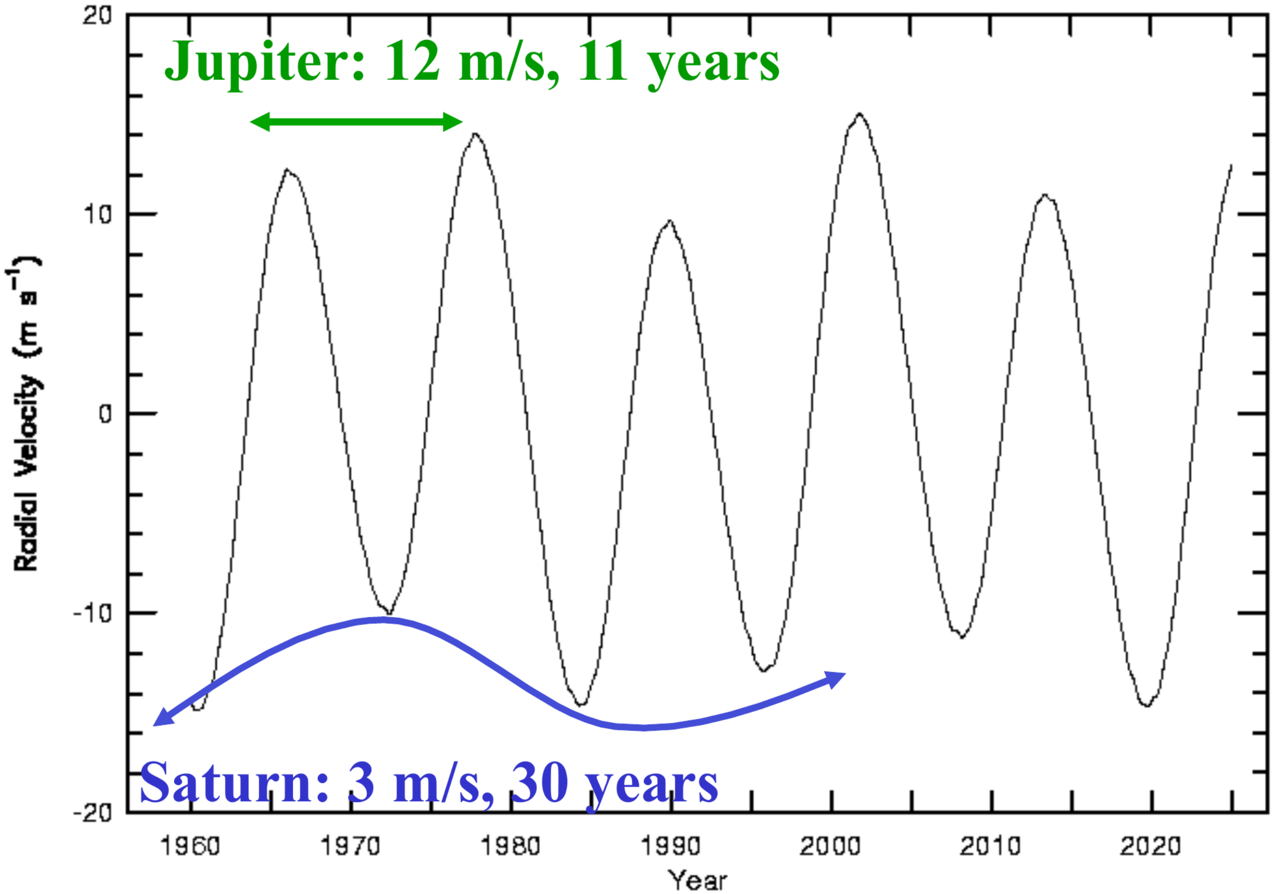



RV method

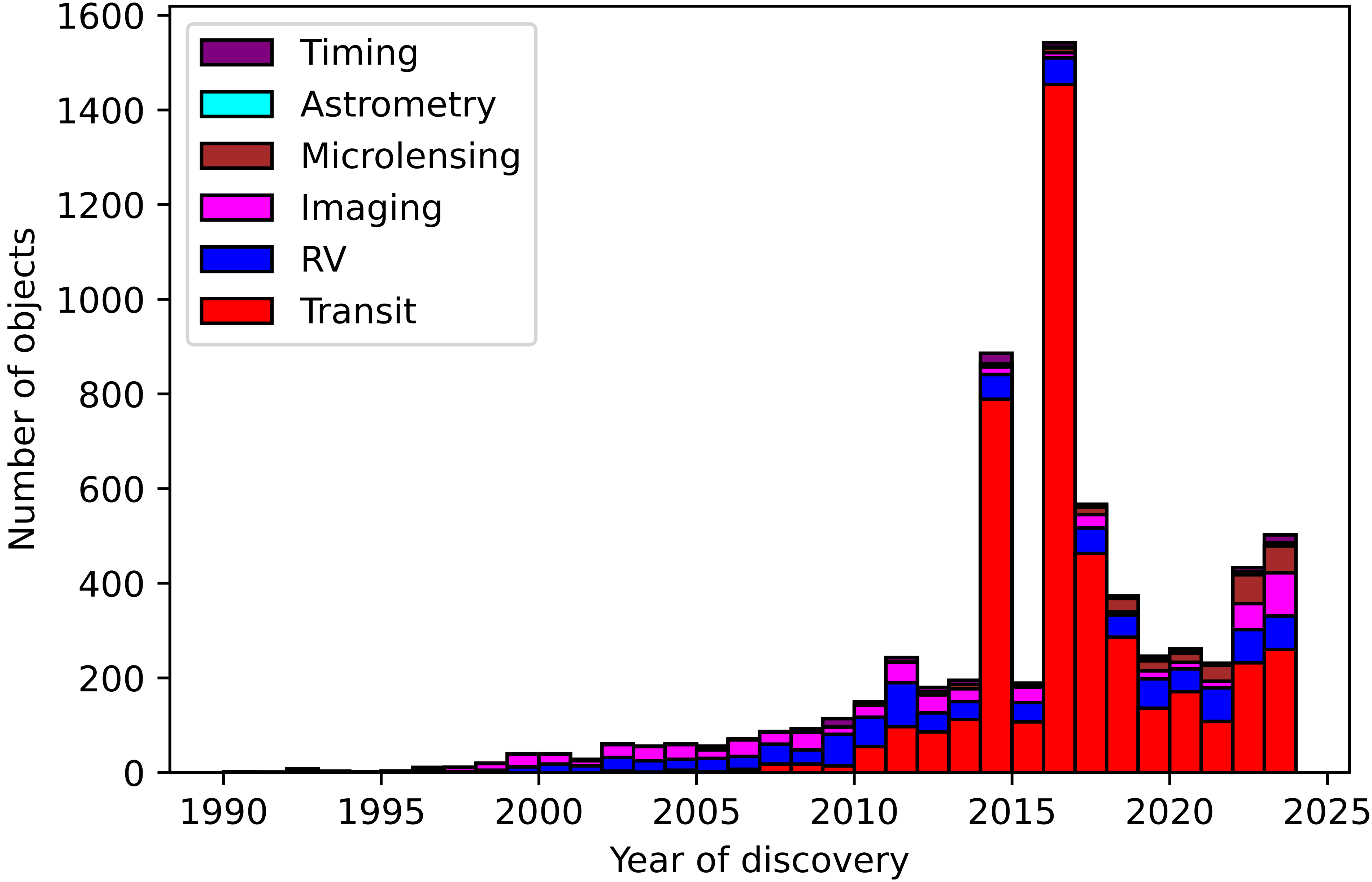
RV method measures the mass of the exoplanet



Requirements:

- Accuracy of better than 10 m/s
- Stability for at least 10 Years

Exoplanet Discovery Space



Mass determination of a planet in an (exo-)planetary system

planet is invisible, so we can only measure the velocity of the star about the center of mass of the system

Using:

- Circular Orbit
- Star is much more massive than the planet

$$v_{\mathrm{obs}} = \frac{28.4 m_{\mathrm{p}} \sin i}{P^{1/3} m_{\mathrm{s}}^{2/3}}$$

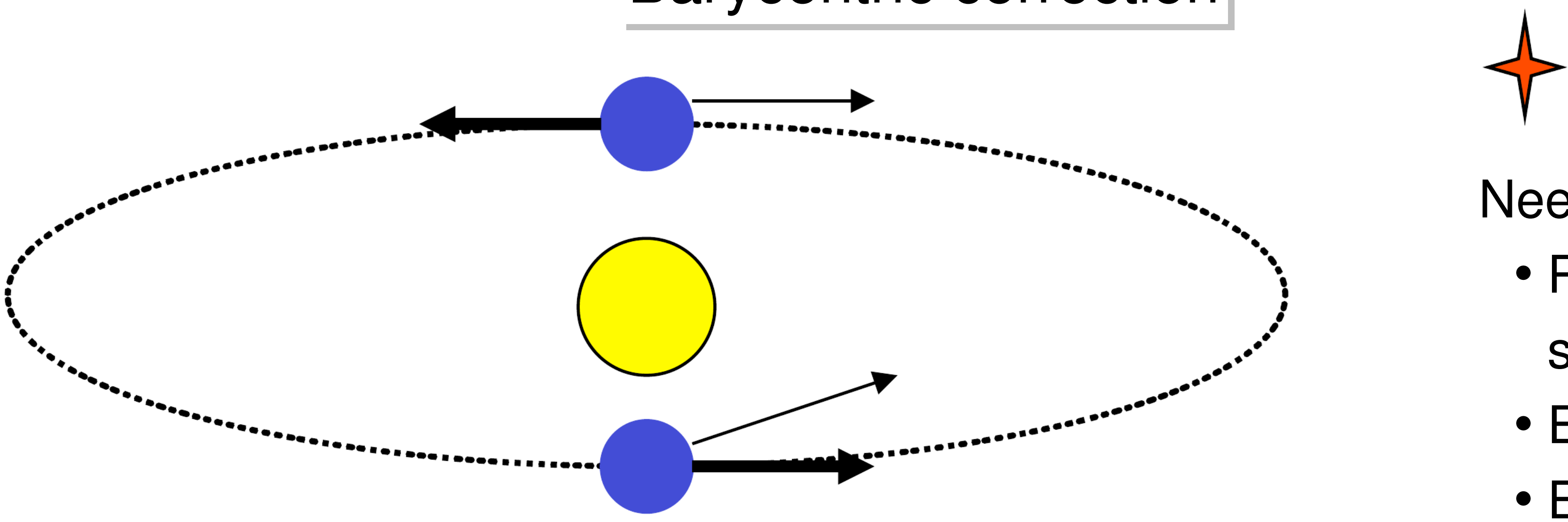
m_{p} in Jupiter masses, m_{s} in solar masses, P in years, V in m/s

Exercise for the reader: Derive this!

Radial Velocity Amplitude of Sun due to Planets in the Solar System

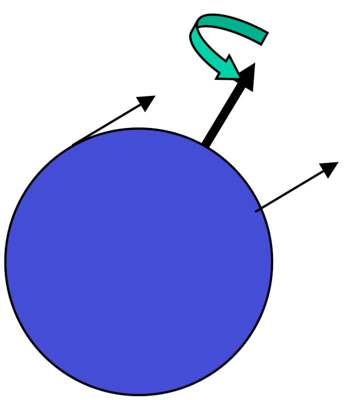
Planet	Mass (M_J)	V (m/s)
Mercury	1.74×10^{-4}	0.008
Venus	2.56×10^{-3}	0.086
Earth	3.15×10^{-3}	0.089
Mars	3.38×10^{-4}	0.008
Jupiter	1.0	12.4
Saturn	0.299	2.75
Uranus	0.046	0.297
Neptune	0.054	0.281

Barycentric correction



Earth's orbital motion can contribute ±30 km/s (maximum)

Need to know:
- Position of star
- Earth's orbit
- Exact time



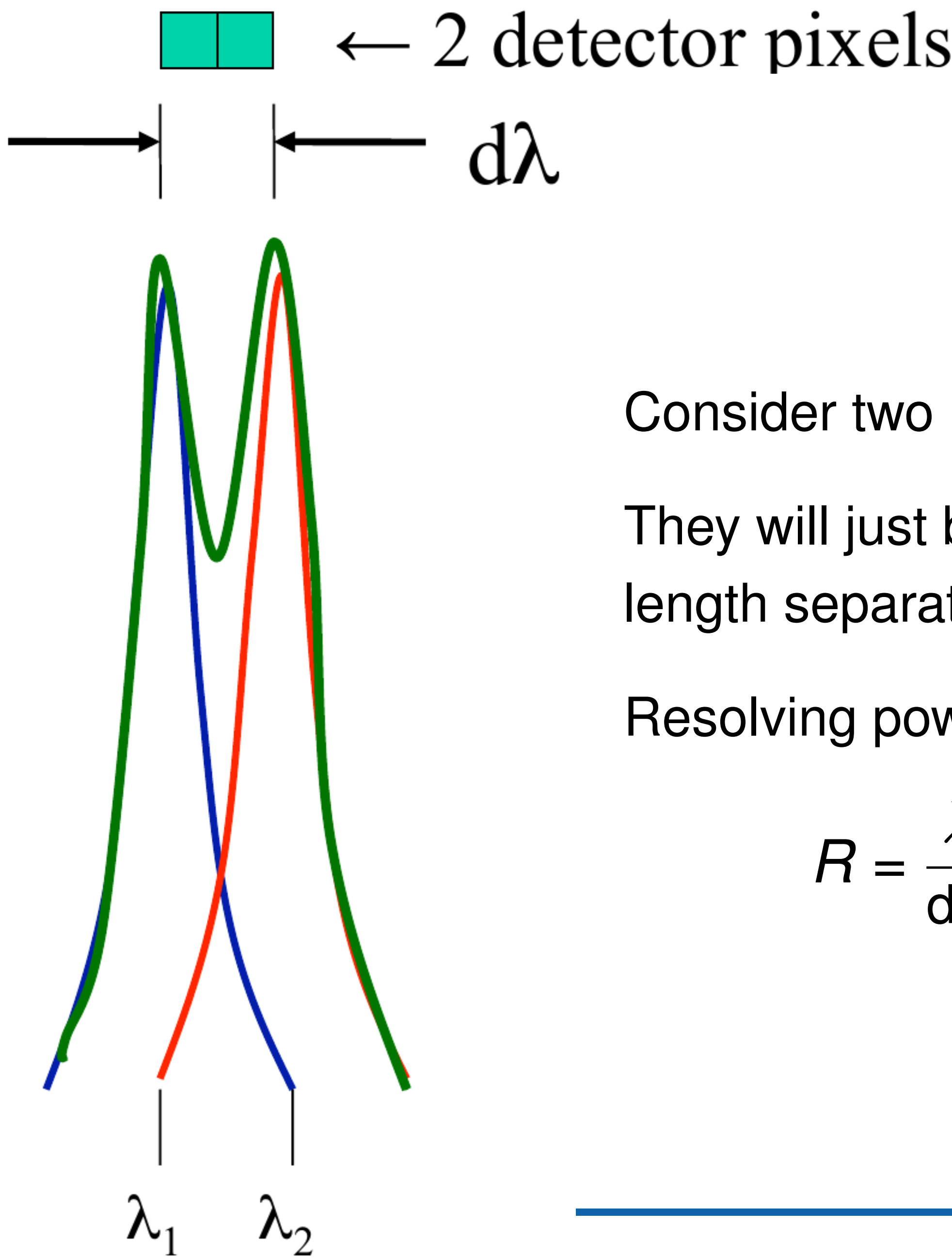
Earth's rotation can contribute ±460 m/s (maximum)

Need to know:
- Latitude and longitude of observatory
- Height above sea level

Ingredients for Precision Radial Velocities

1. High spectral resolution
   – Easier to detect a Doppler Shift
2. Large wavelength coverage
   – More spectral lines for a measurement
3. High Signal-to-noise ratio data
   – High quality data
4. Simultaneous wavelength calibration
   – Eliminating instrumental shifts

High spectral resolution



Consider two monochromatic beams

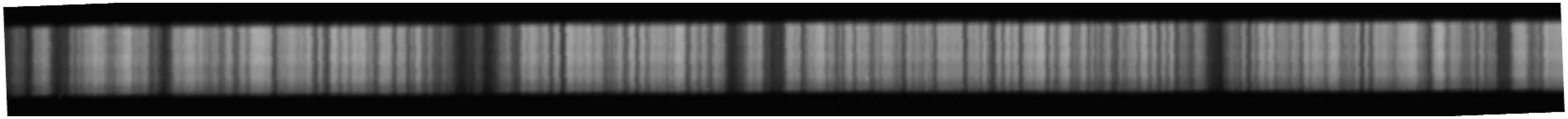
They will just be resolved when they have a wavelength separation of $d\lambda$

Resolving power:

$$R = \frac{\lambda}{d\lambda}$$

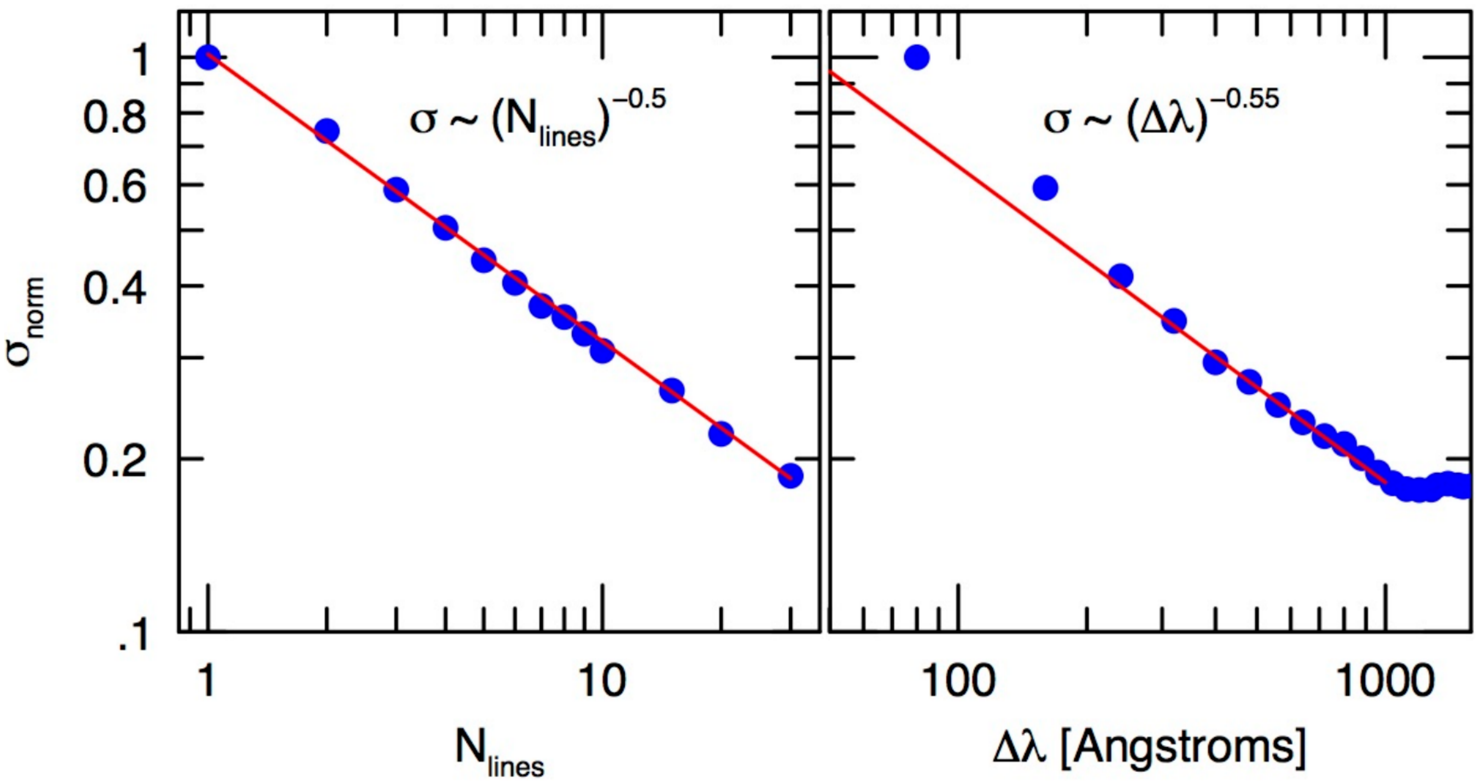
$d\lambda$ = full width of half maximum of calibration lamp emission lines

Large Wavelength Coverage

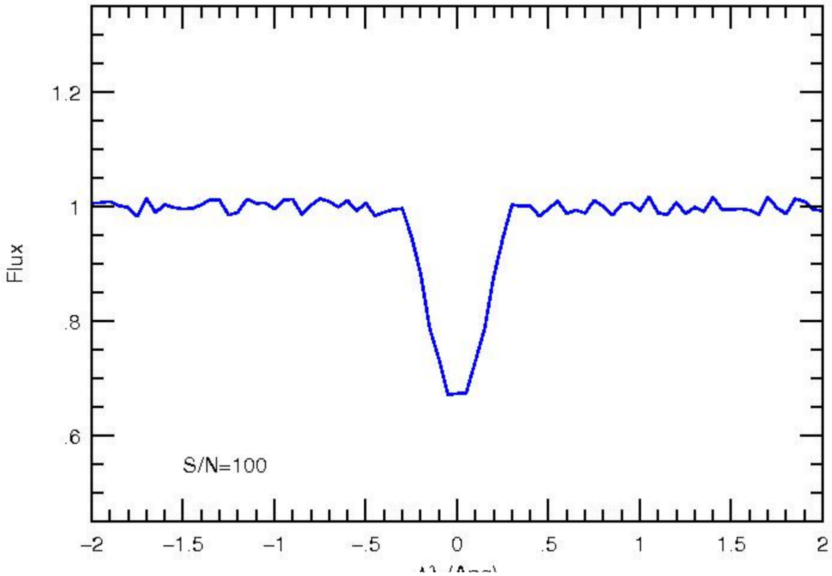


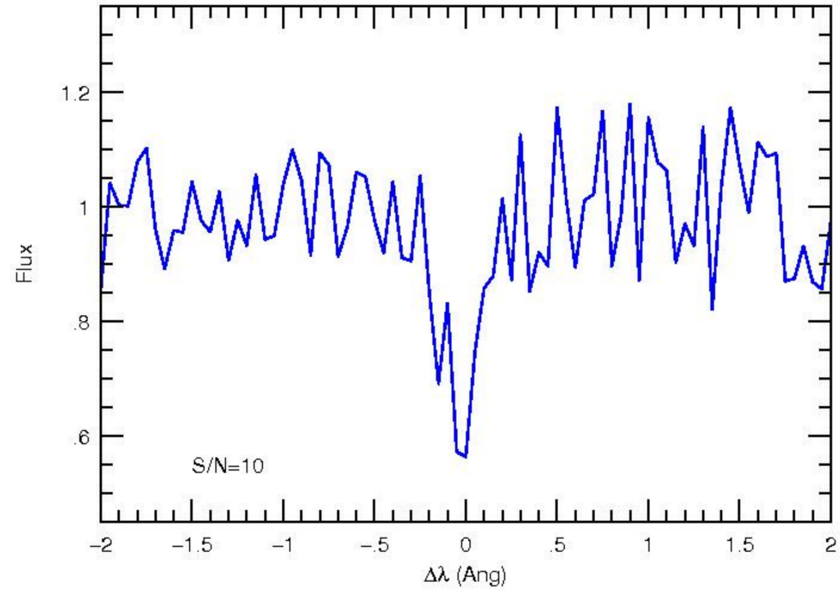
- Each line gives you a measurement of the Doppler shift with an error
- Use 100 lines and your error is 10 times lower

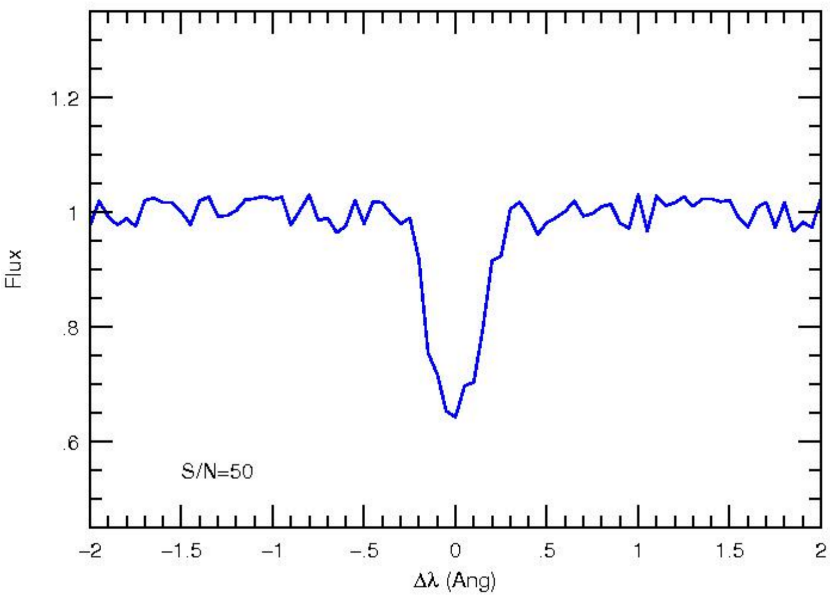
  RV error is proportional to $1/\sqrt{N_{\text{lines}}}$

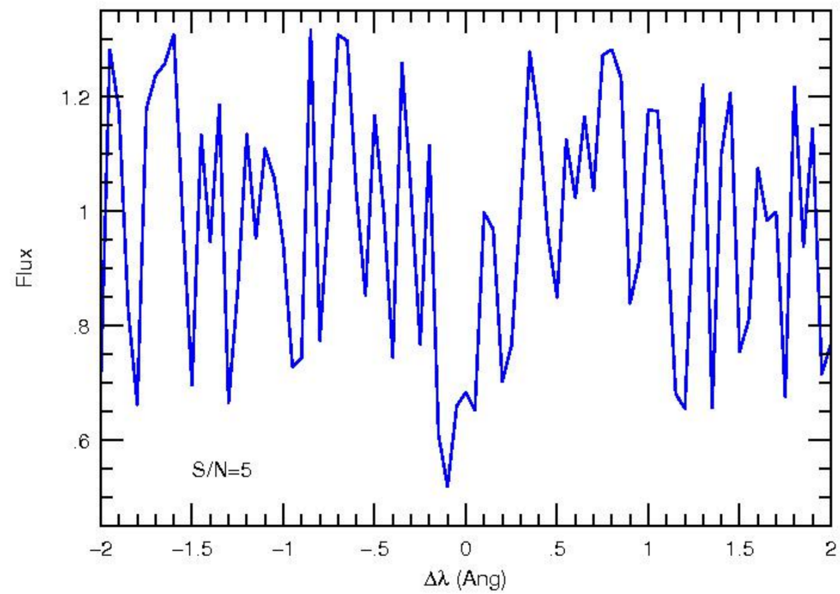


Influence of the noise

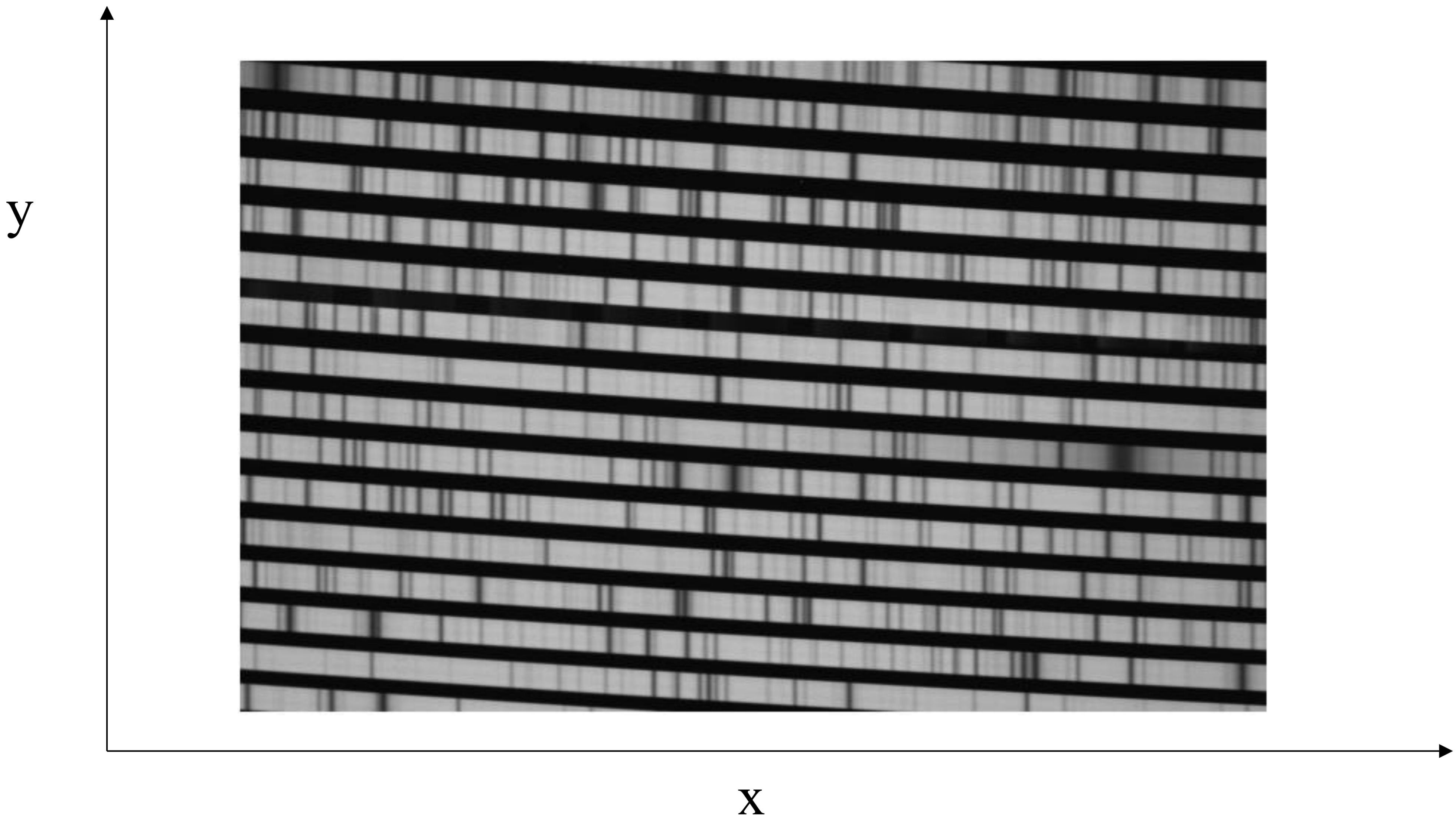






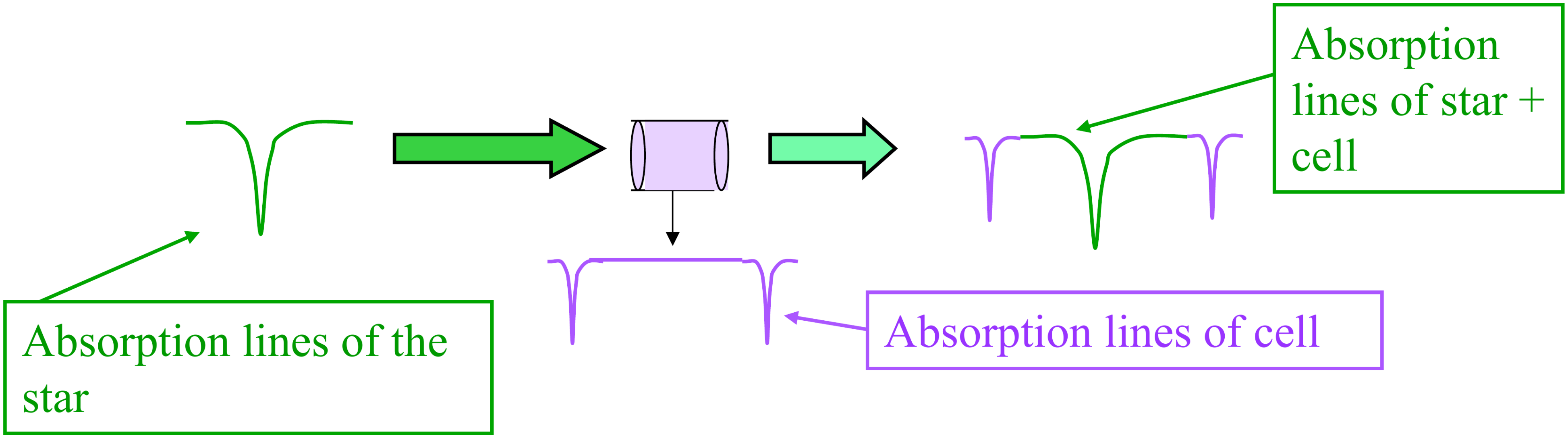


Wavelength calibration



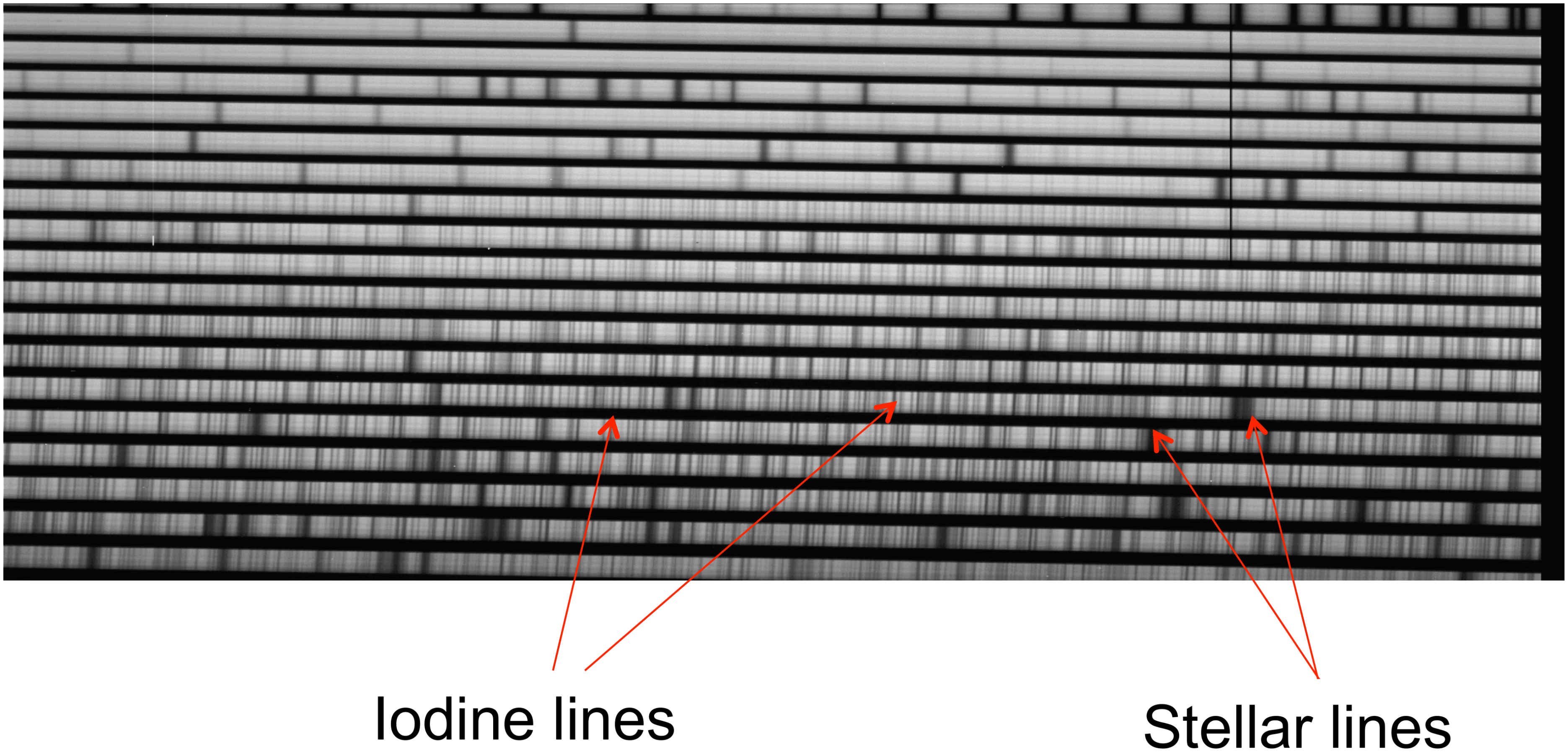
On a detector we only measure x- and y- positions, there is no information about wavelength. For this we need a calibration source

Solution 2: Gas Absorption Cells



Solution 2: Gas Absorption Cells – Iodine

Star observed through an Iodine cell

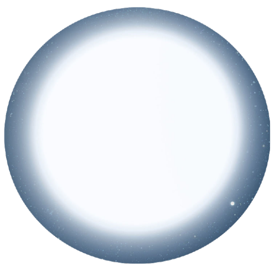


one high S/N spectrum without Iodine cell necessary for comparison, rest of measurements through Iodine cell $\rightarrow$ more details in Jana's talk about VIPER

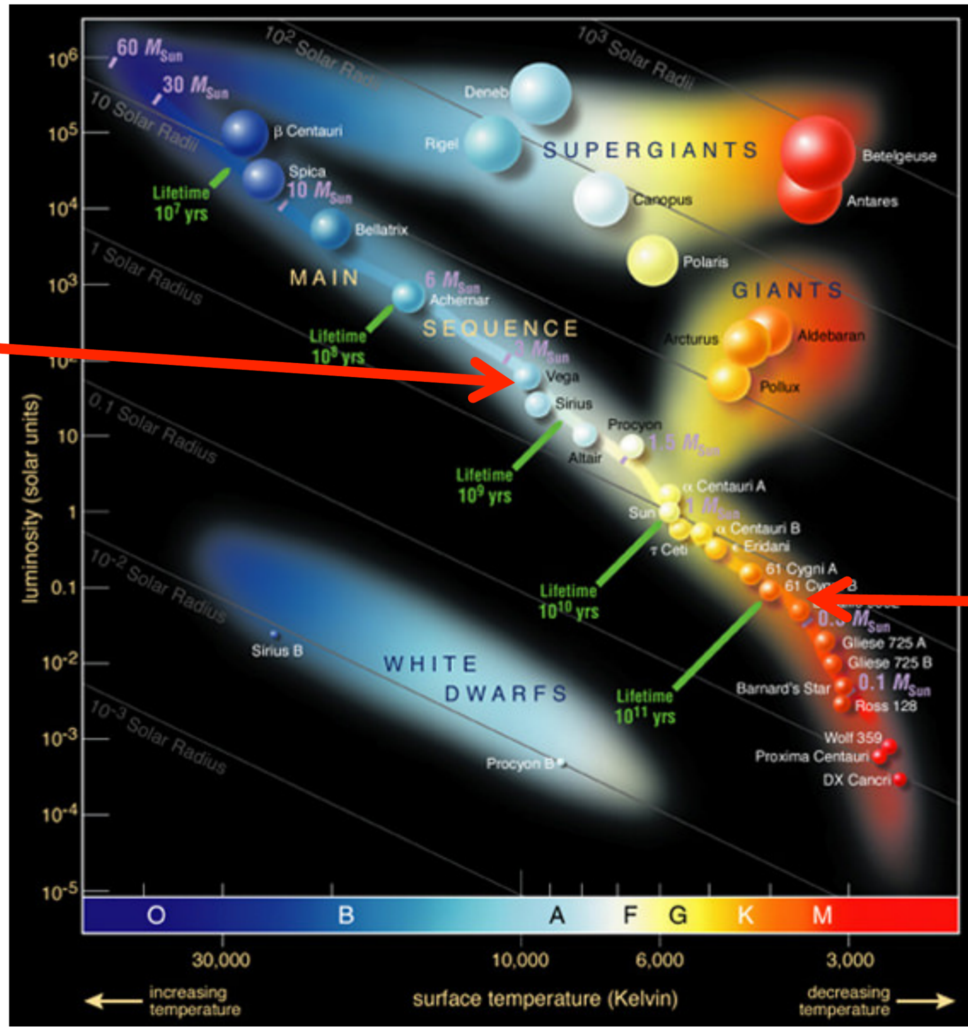
Radial velocity accuracy for different kind of stars

With different kind of stars you can reach different RV accuracy

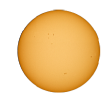
A-type



T = 10000 K
Rotational velocity ~ 200 km/s



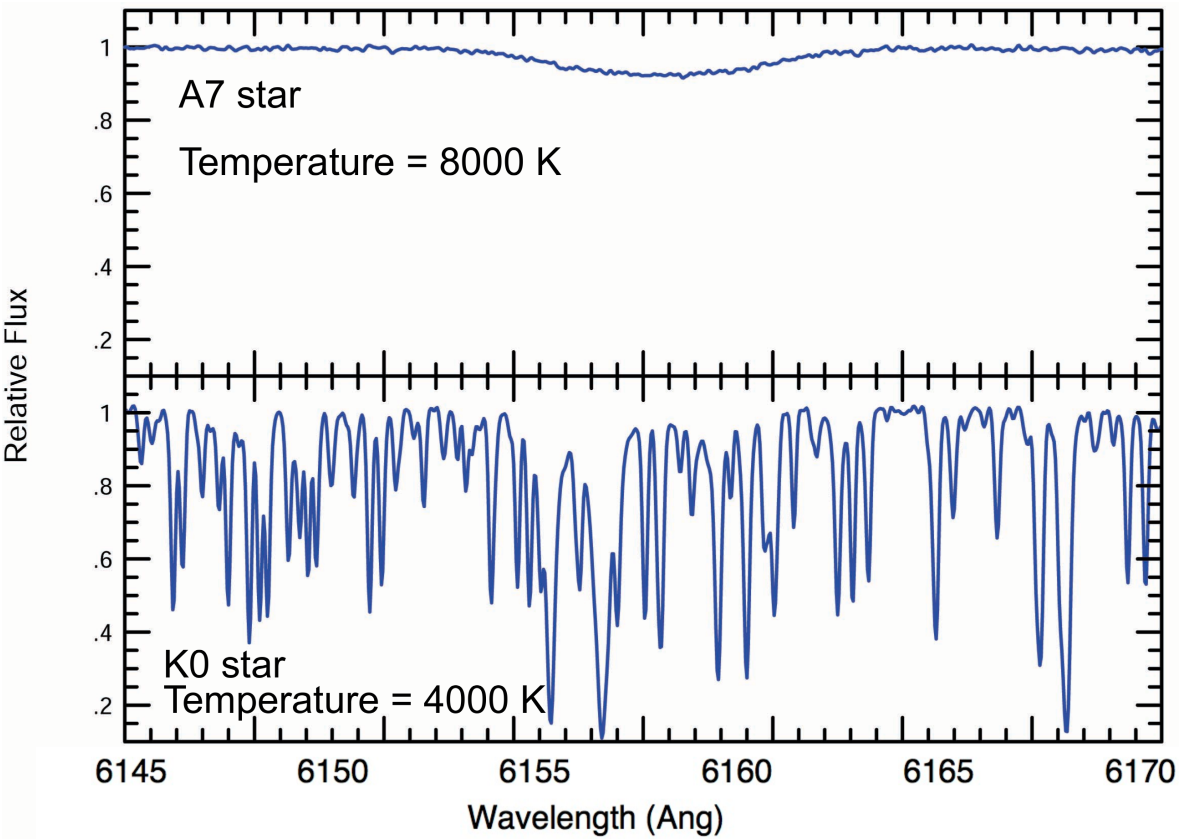
K-type



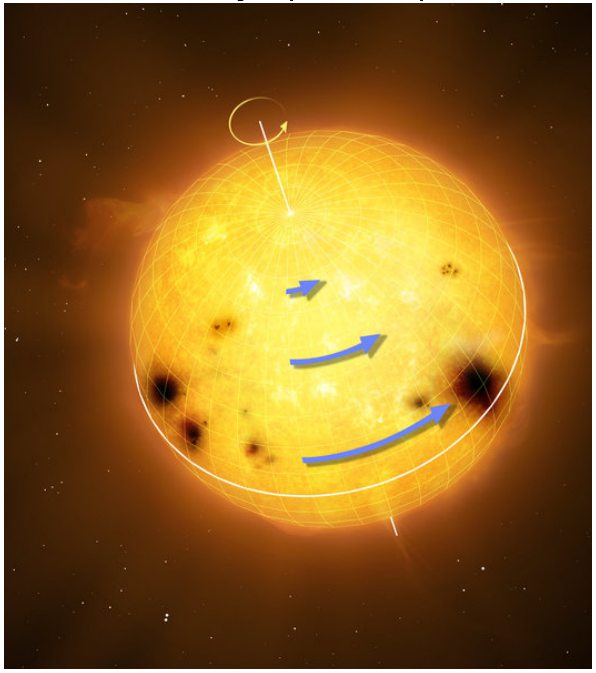
T = 4500 K
Rotational Velocity ~ 3 km/s

Radial velocity accuracy for different kind of stars

Early-type stars have few spectral lines (high effective temperatures) and high rotation rates.



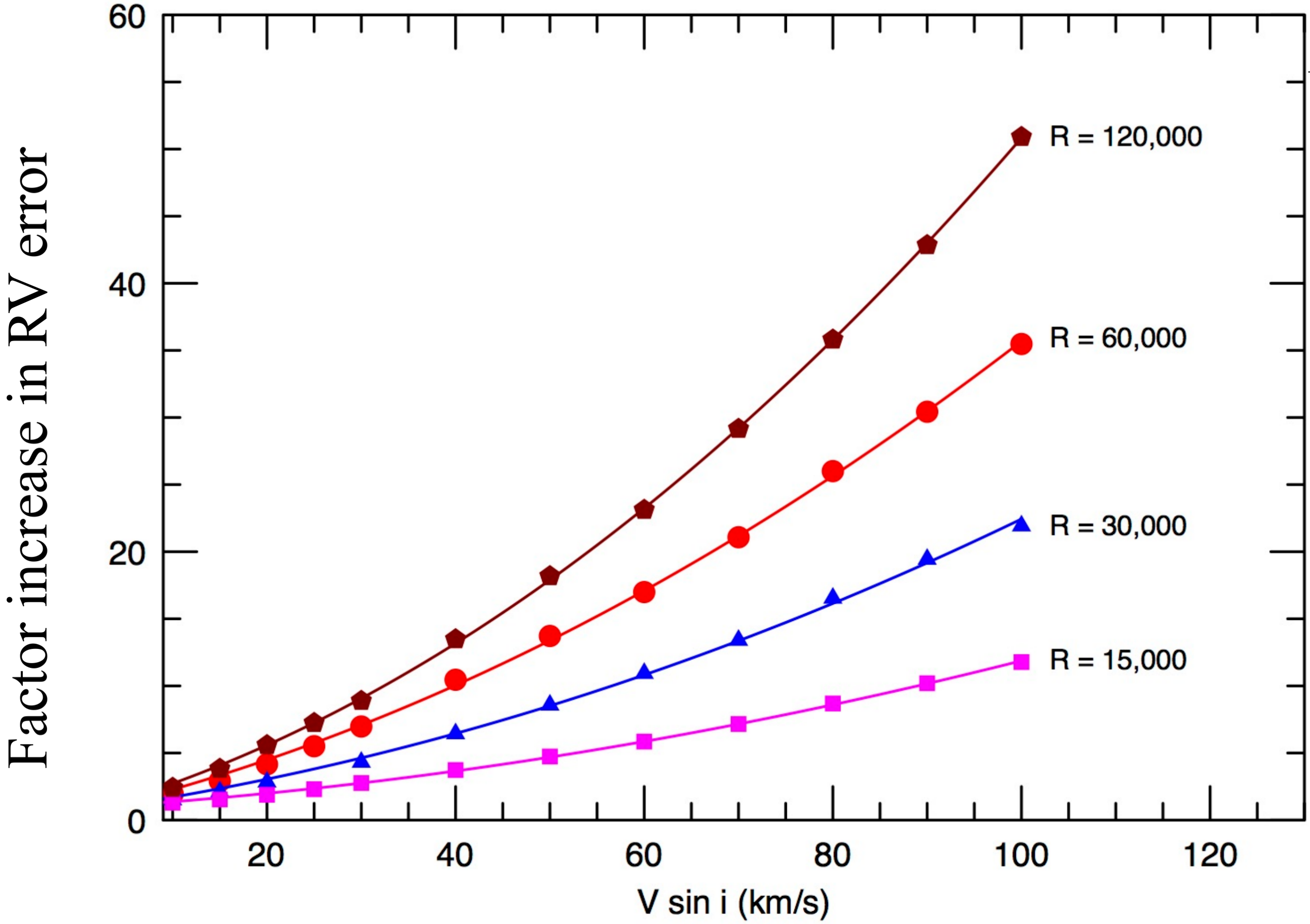
From Gray (1982)



Projected rotational velocity = $v_{rot} \times \sin i$ (spin axes of star)

Radial velocity accuracy for different kind of stars

Increase in Error with Stellar Rotation (v sin i)

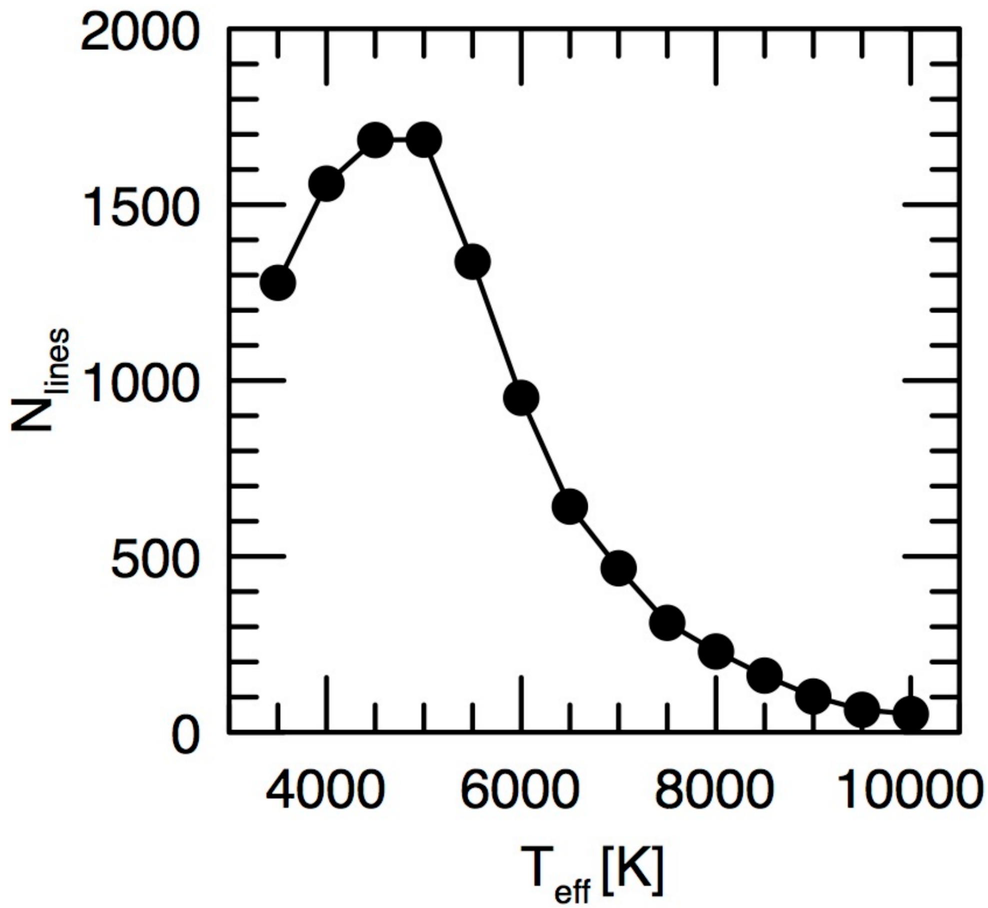


Using R = 60,000 for two stars with the same temperature: One rotating at 100 km/s will have an error 35 times greater than a star rotating at 2 km/s

Spectral type	Rotational velocity [km/s]
O4	110
O9	105
B5	108
A0	82
A5	80
F0	44
F5	11
G0	4
G5	3
K0	3
K5	2
M0	10
M4	16
M9	10

Radial velocity accuracy for different kind of stars

Decrease in number of (useful) lines with Effective Temperature



A star with $T_{\rm eff} = 8000$ K will have nearly 9 times less useful spectral lines than a star at $T_{\rm eff} = 5000$ K. The RV measurement error for the hot star will be ~ 3 times greater

Radial velocity accuracy for different kind of stars

Including dependence on stellar parameters

$$\sigma(\mathrm{m/s}) = 8.2 \times 10^9 \times (S/N)^{-1} \mathrm{R}^{-1.2} (\Delta\lambda)^{-1/2}\, \mathrm{f(V)}\, \mathrm{g(T)}$$

f(V) and g(T) are the effects due to the star

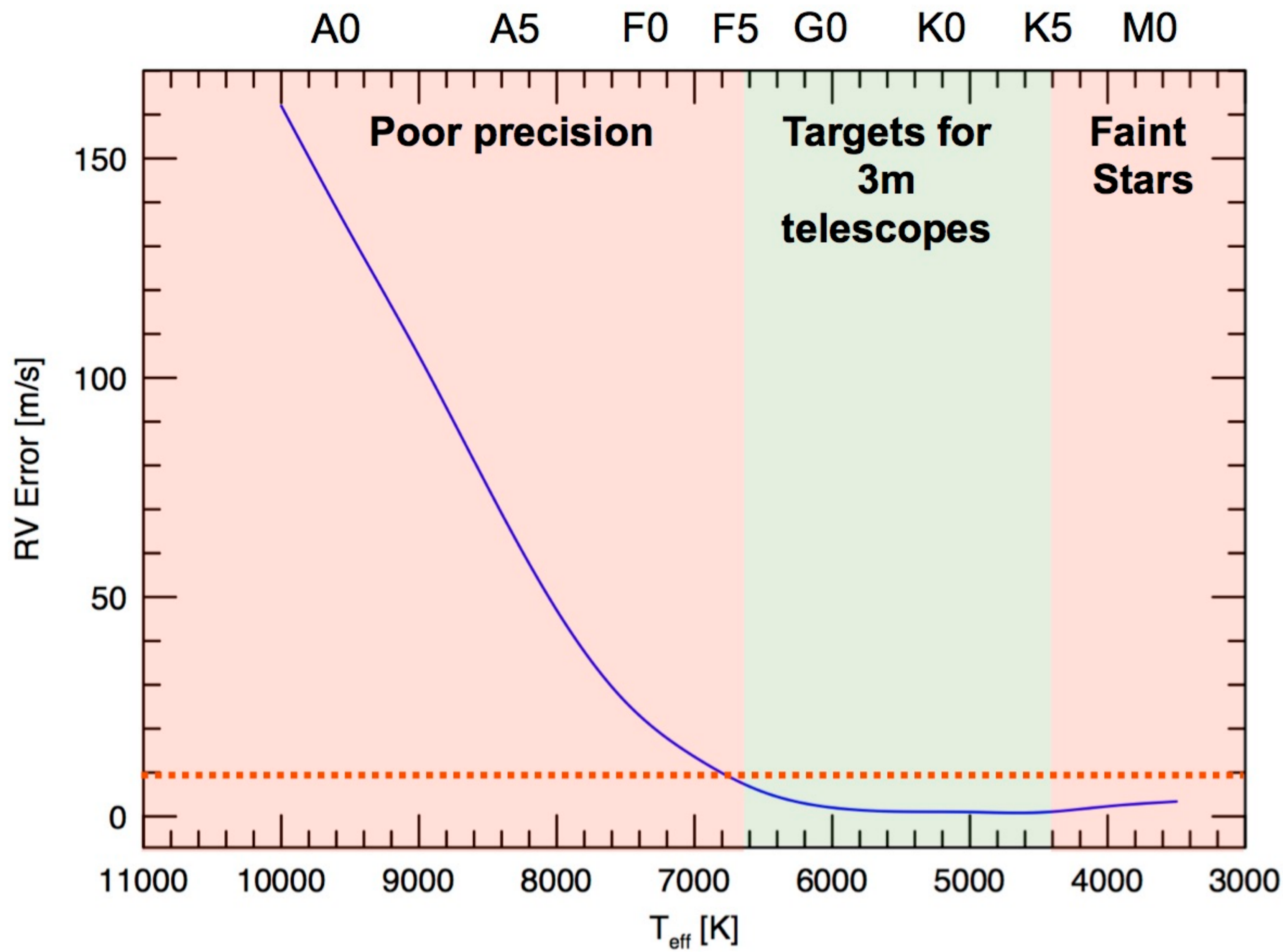
$\mathrm{f(V)} = 0.62 + (0.21 \log \mathrm{R} - 0.86)\mathrm{V} + (0.00260 - 0.0103)\mathrm{V}^2$

With R = resolving power of spectrograph and V = rotational velocity of the star (v sin i) in km/s

$\mathrm{g(T)} = 0.16e^{1.79(\mathrm{T}/5000)}$

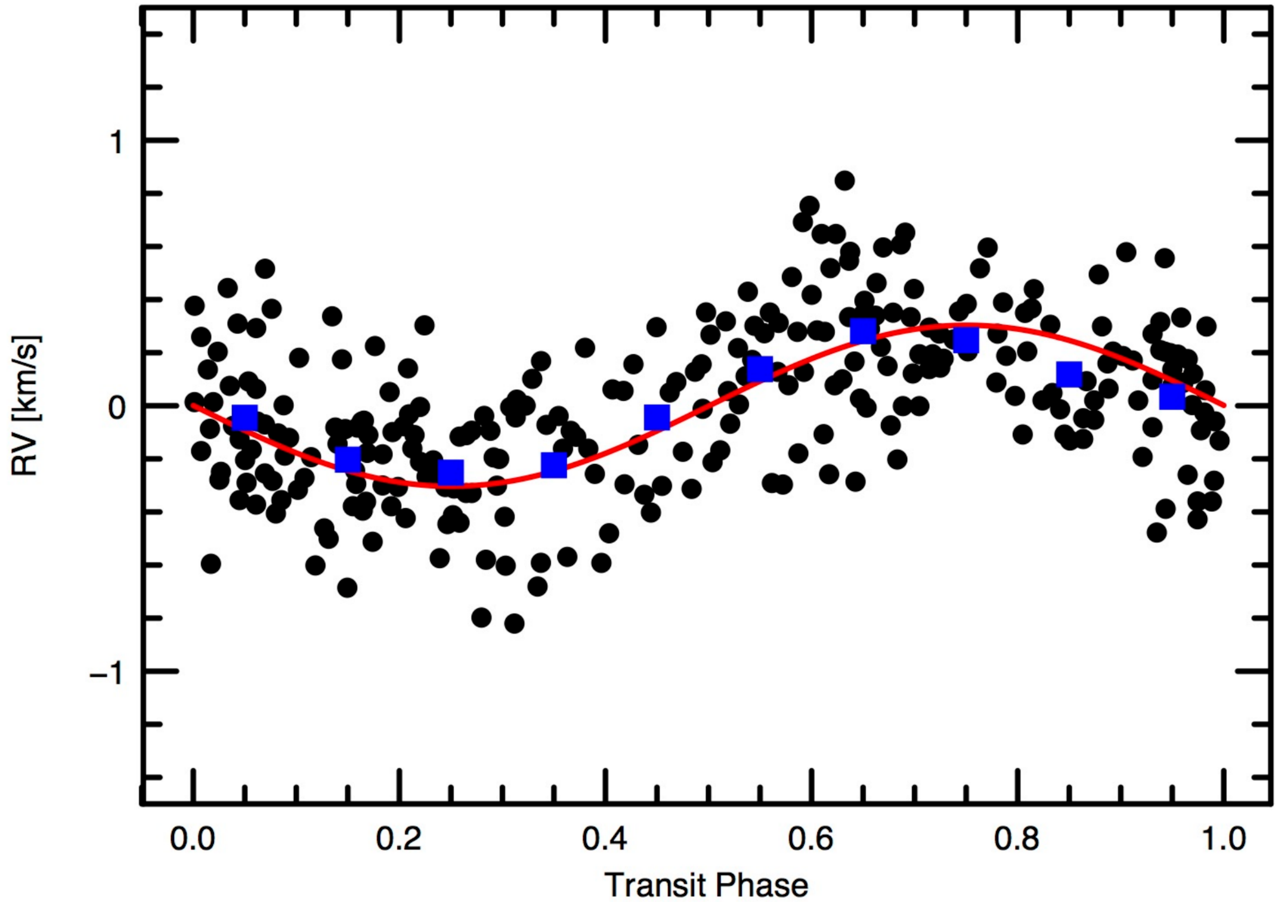
T = effective temperature of the star

The "sweet spot" for RV measurements



Increase accuracy of RV measurements

Just take lots of measurements!



WASP-33b:

- Transiting Planet
- A5 Star
- T = 8100 K, v_{rot} = 90 km/s

Follow-up of exoplanets

7047 confirmed planets:

- spectroscopic follow-up to determine/improve mass determination of the exoplanet
- strategy to find best targets (from `www.exoplanet.eu`)
  $\rightarrow$ stellar magnitude ($<$ 11 mag)
  $\rightarrow$ orbital period
  $\rightarrow$ accuracy of spectrograph
  $\rightarrow$ RV amplitude
  $\rightarrow$ Visibility: observations from 3 UT (5 am)
- important to cover the orbital period with enough data points

Project:

$\Rightarrow$ Do spectral follow-up of a hot Jupiter using Platospec at the E152m telescope in La Silla with an Iodine cell (> 3-5 m/s accuracy)

$\Rightarrow$ Determine RVs

$\Rightarrow$ Fit RV curve

$\Rightarrow$ Derive stellar parameters/ mass

$\Rightarrow$ Determine (minimum) planet mass

Determining periods - Fourier transformation

```
import matplotlib.pyplot as plt
import numpy as np
import math
#you'll probably need to install the following two packages
#e.g. with "pip3 install astropy"
import astropy
import lightkurve as lk

#read-in data and convert to lightkurve format
data=np.loadtxt('data.txt')
lc=lk.LightCurve(time=data[:,0],flux=data[:,1],
flux_err=data[:,2])

#Lomb-Scargle periodogram to determine most likely period
pg=lc.to_periodogram(oversample_factor=100,minimum_period=0.1,
maximum_period=10,normalization='amplitude',ls_method='auto')
```

Determining periods - Fourier transformation

```
ax1=pg.plot(view='period')
print('period:',pg.period_at_max_power.value)

#Phase-fold RV curve
period=pg.period_at_max_power.value
#period from highest peak in Lomb-Scargle
lc_fold=lc.fold(period,epoch_time=0.0)

#save phase-folded RV curve
x=lc_fold.time.value/period
y=lc_fold.flux
yerr=lc_fold.flux_err
```

Fitting RVs using RadVel

RadVEl – The Radial Velocity Fitting Toolkit (example control file, data)

Parameters:

- *starname* – name of star
- *nplanets* – Number of planets
- *instnames* – list of instruments
- *per*n – orbital period of nth planet
- *tc*n – time of inferior conjunction
- *e*n – eccentricity
- *w*n – argument of periastron
- *k*n – velocity semi-amplitude
- *gamma*_x – velocity zero-point for instrument x
- *jit*_x – jitter for instrument x
- params["param"].vary = False – keep parameter fixed while fitting
- *priors* – set limits for parameters
- stellar = dict(mstar=1.12, mstar_err= 0.05) – stellar mass

Fitting RVs using RadVel

- maximum-likelihood fit
  radvel fit -s control_file.py
- plot best-fit solution
  radvel plot -t rv -s control_file.py
- perform Markov-Chain Monte Carlo (MCMC) exploration to assess parameter uncertainties
  radvel mcmc -s control_file.py
- update plot with MCMC results
  radvel plot -t rv corner trend -s control_file.py
- combine fit of RV time-series with properties of host star
  radvel derive -s control_file.py
- plot of derived parameters
  radvel ic -t nplanets e trend -s control_file.py

Modeling the Rossitter-McLaughlin Effect

starry: `https://starry.readthedocs.io`