Spectroscopic follow-up of Hot Jupiters

Research workshop on evolved stars

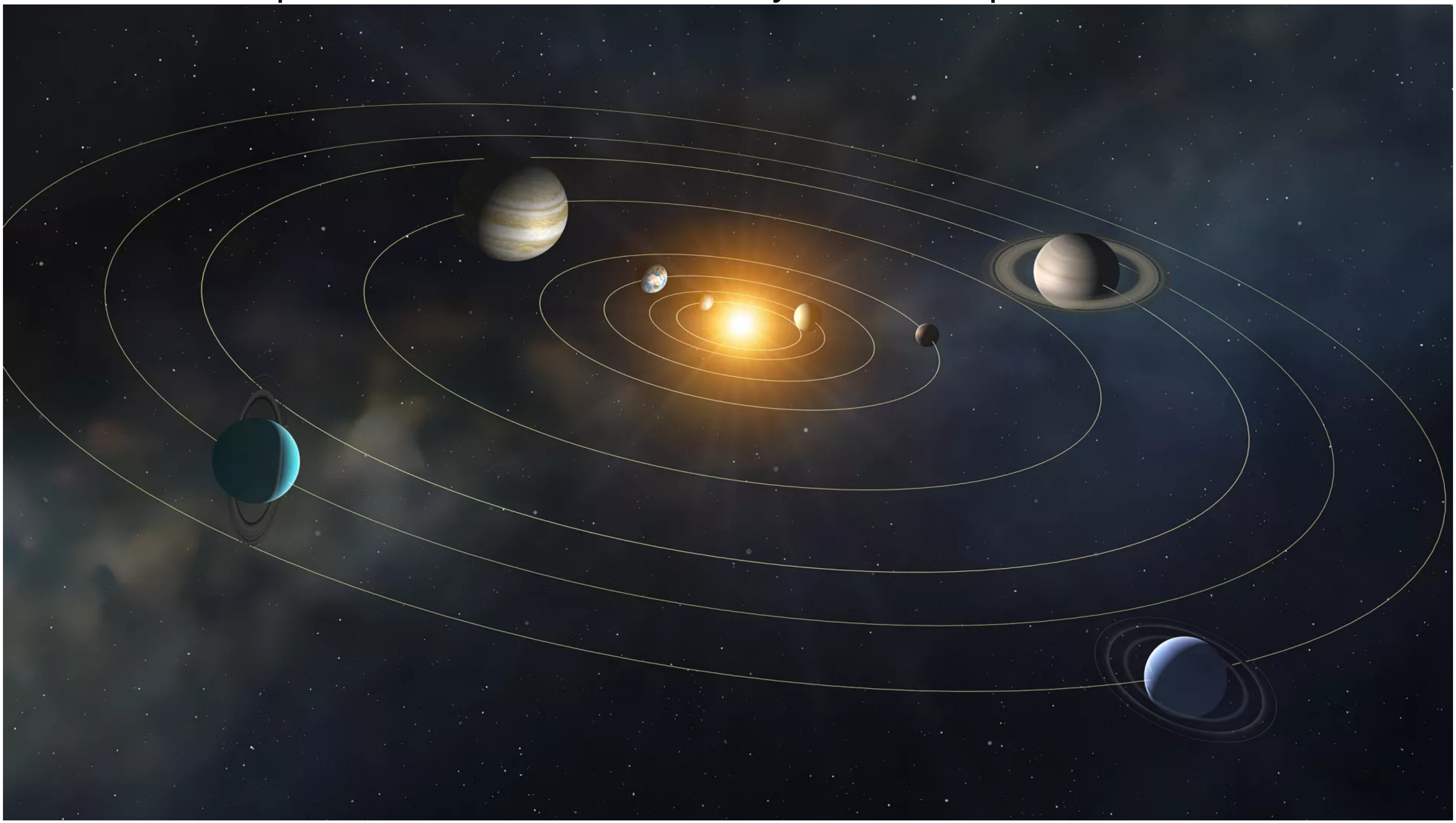
Veronika Schaffenroth

27.08.2024

Thüringer Landessternwarte
Email: schaffenroth@tls-tautenburg.de

Expectations for exoplanet systems

Before 1995 expectations based on solar system example



Expectations for Exoplanetary Systems

1. Planets in circular orbits
2. Planets in prograde orbits (same direction as star rotates)
3. Planet orbits are in the same plane
4. Giant planets in the outer parts
5. Rocky planets in the inner parts
6. No giant planets beyond 30 AU
7. No rocky planets inside 0.4 AU
8. Satellites should be common, especially for giant planets
9. Rings around Giant planets should be common

Why search for extrasolar planets?

It is dangerous to base a theory on one example:

- Ptolemaic system could explain the motions of the planets better than Copernicus (who only used circular orbits) but it was wrong
- Limited parameter space can give you the wrong impression

Main questions:

- How do planetary systems form?
- How many planets are there in our Galaxy? (common or an infrequent event)
- How unique are the properties of our own solar system? (Does the Earth have life because of the unique properties of our solar system?)
- How diverse are planets? (Do planetary systems all look the same, or are they like people, very diverse.)

IAU Working Definition of Exoplanet

1. *Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars, brown dwarfs or stellar remnants and that have a mass ratio with the central object below the L_4/L_5 instability ($M/M_{\mathrm{central}} < 2/(25+\sqrt{621}) \approx 1/25$) are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.*
2. *Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.*
3. *Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).*

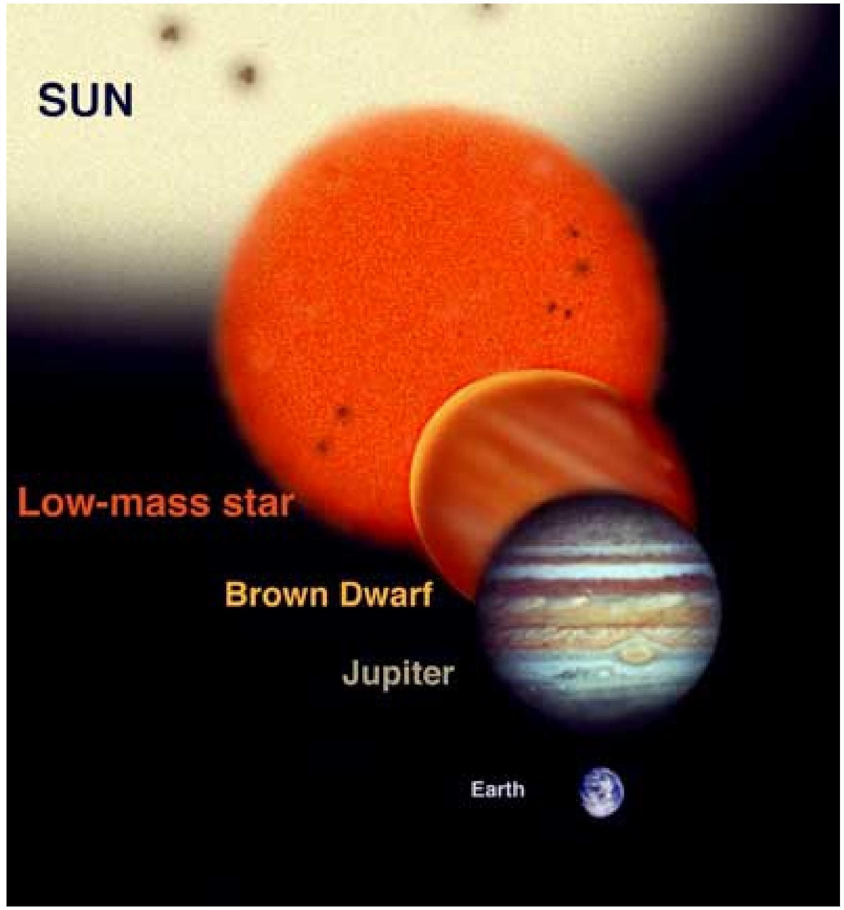
"A non-fusor in orbit around a fusor"

$\rightarrow$ sub-brown dwarfs usually called free-floating planetary mass objects

$\rightarrow$ deuterium-burning limit is for solar metallicity

$\rightarrow$ question of lower mass limit still open: exocomets and asteroids observed

Mass as the defining characteristic



Giant Planet

CoRoT-1b

Mass = 1 $M_{♃}$

Radius = 1.5 $R_{♃}$

Brown Dwarf

CoRoT-3b

Mass = 26 $M_{♃}$

Radius = 1 $R_{♃}$

Star (M dwarf)

OGLE-TR-133b

Mass = 85 $M_{♃}$

Radius = 1.33 $R_{♃}$

Mass as the defining characteristic

Star: Has sufficient mass to fuse hydrogen to helium.

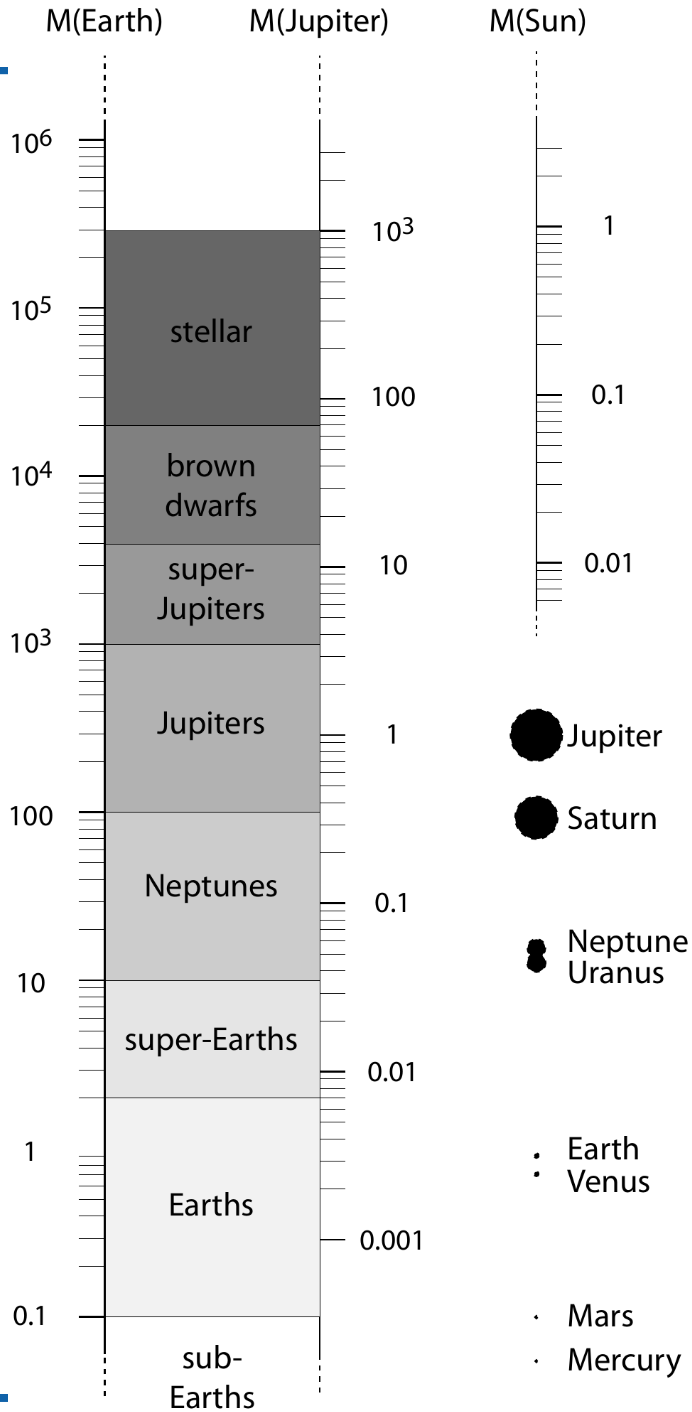
$$M \gtrsim 80\,\mathrm{M}_{♃}$$

Brown Dwarf: Has sufficient mass to fuse hydrogen to helium.

$$13\,\mathrm{M}_{♃} \lesssim M \lesssim 80\,\mathrm{M}_{♃}$$

Planet: Has sufficient mass to fuse hydrogen to helium.

$$M \lesssim 13\,\mathrm{M}_{♃}$$



Classes of planet

Classification by Planet size:

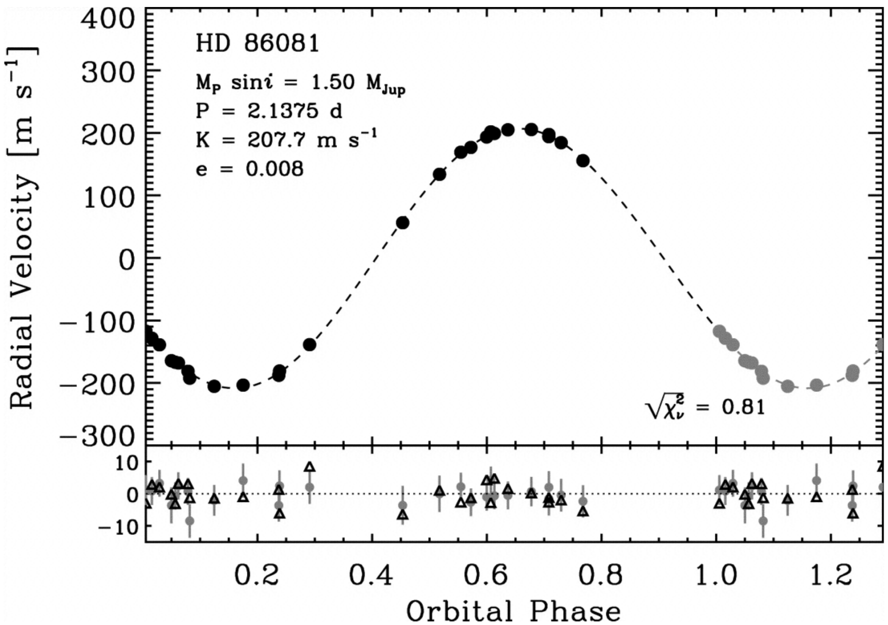
- Earth-size, or terrestrial planets ($< 1.25\,R_\oplus$),
- super-Earth-size ($1.25 - 2\,R_\oplus$),
- Neptune-size ($2 - 6\,R_\oplus$),
- Jupiter-size ($6 - 15\,R_\oplus$).

Classification by Planet mass:

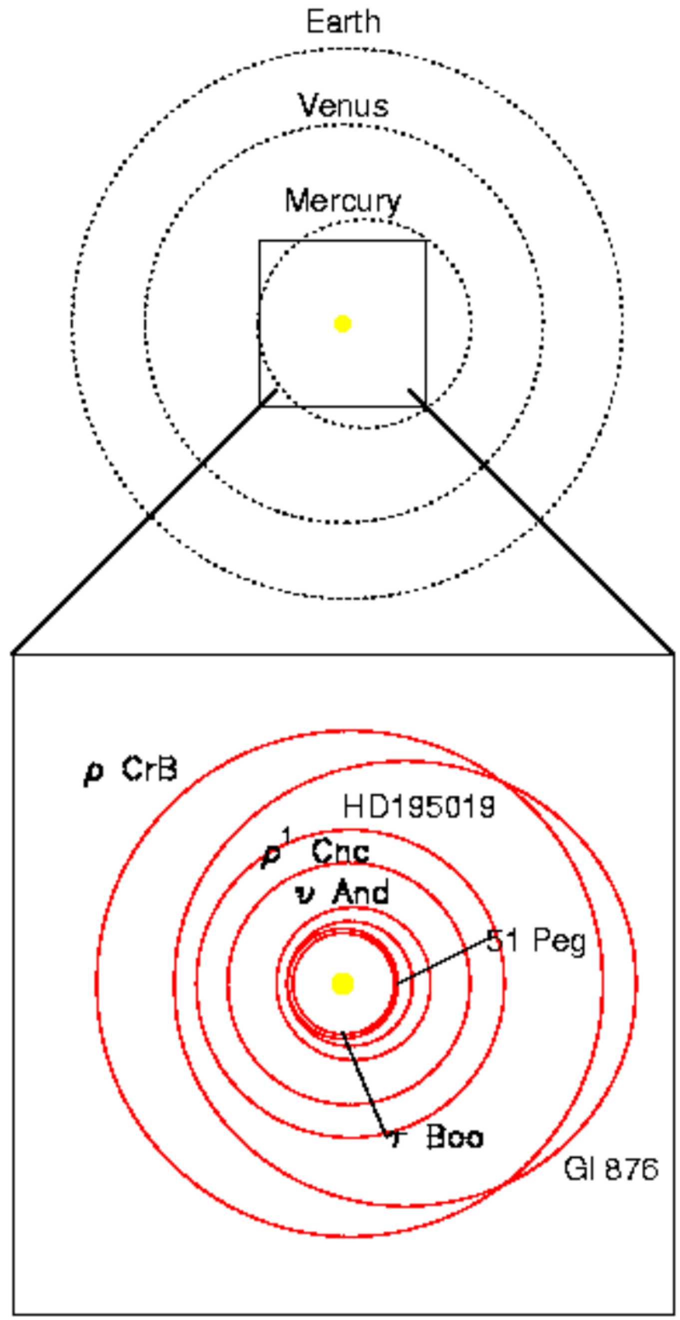
- sub-Earths ($10^{-8} - 0.1\,M_\oplus$),
- Earths ($0.1 - 2\,M_\oplus$),
- super-Earths ($2 - 10\,M_\oplus$),
- Neptunes ($10 - 100\,M_\oplus$),
- Jupiters ($100 - 1000\,M_\oplus$),
- super-Jupiters ($1000\,M_\oplus - 13\,M_{♃}$),
- brown dwarfs ($13\,M_{♃} - 0.07\,M_\odot$).

not universally-accepted "definitions", other boundaries have also been adopted

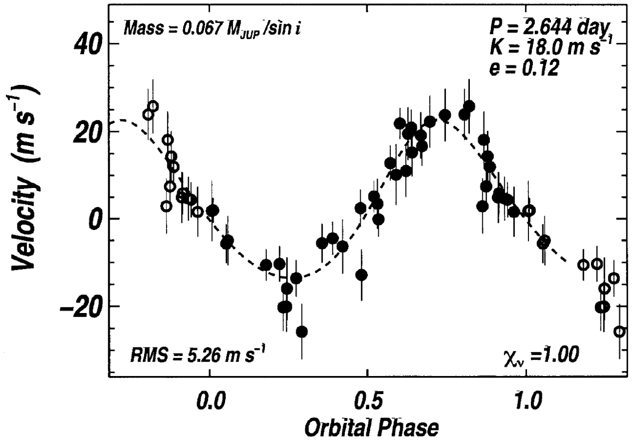
Classes of planets: Jupiter mass planets in short orbits



- hot Jupiters ($a \lesssim 0.1$ au, $P = 3 - 9$ d)
- very hot Jupiters ($P < 3$ d)
- ultra-short-period hot Jupiters ($P < 1$ d)
- warm Jupiters ($a \sim 0.1 - 1$ au, $P \gtrsim 10$ d)



Classes of planets: "Hot" planets at all masses

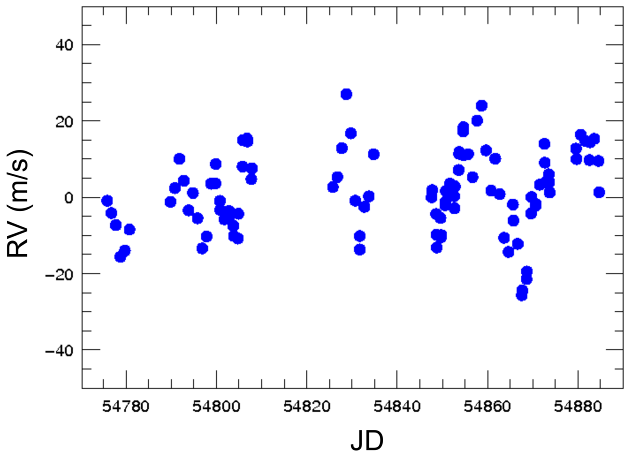


Hot Neptune

GJ486

Mass = 21 $M_\oplus$

P = 2.6 d



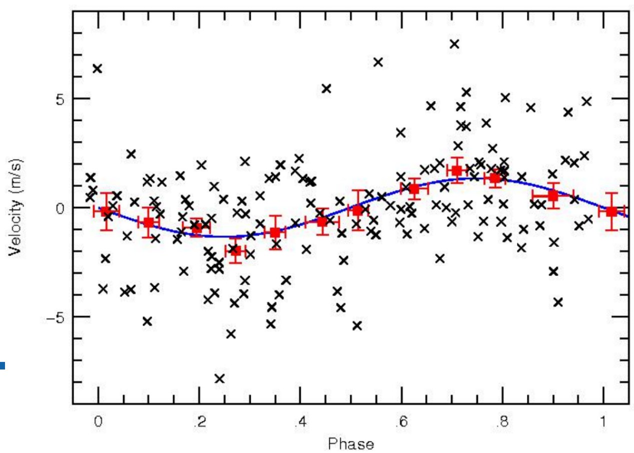
Hot Super-Earth

CoRoT-7b

Mass = 7.4 $M_\oplus$

P = 0.85 d

(transit discovery)



Hot Earth

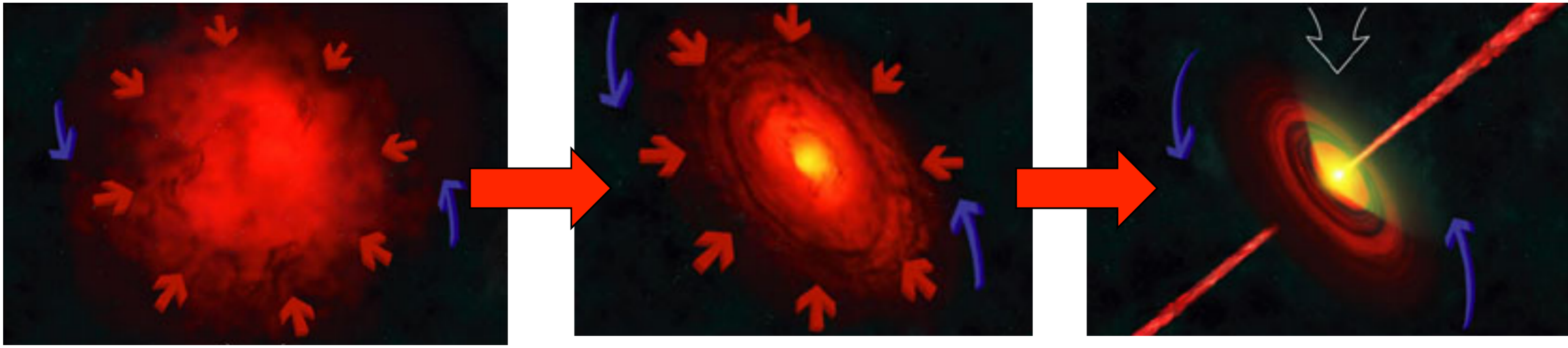
Kepler 78b

Mass = 1.3 $M_\oplus$

P = 0.35 d

(transit discovery)

Standard model for Formation of the Solar System



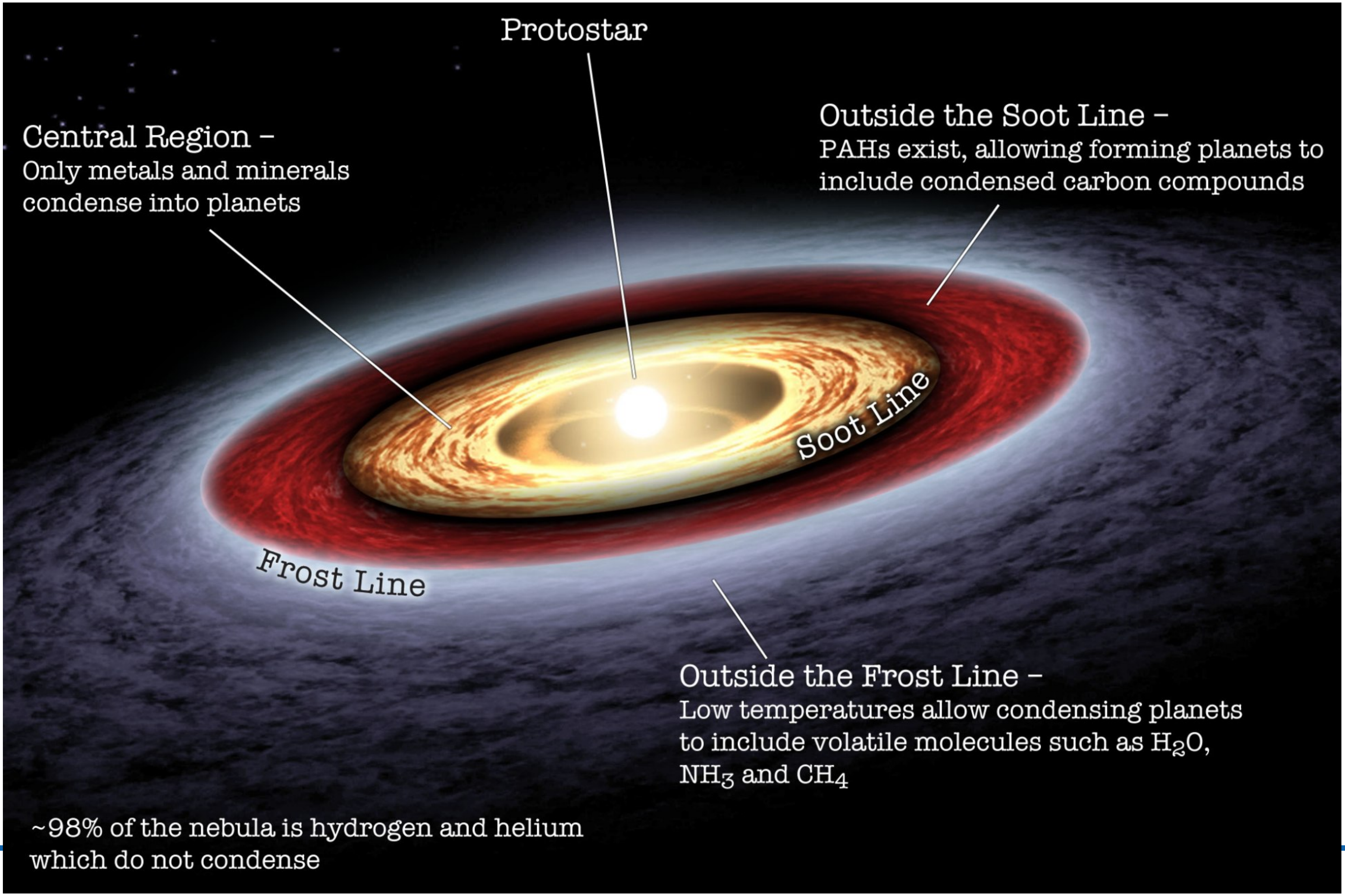
A star (sun) forms from a proto-cloud collapsing due to gravity

The cloud rotates so it collapses into a disk

To collapse the cloud must lose angular momentum, carried away via jets

Standard model for Formation of the Solar System

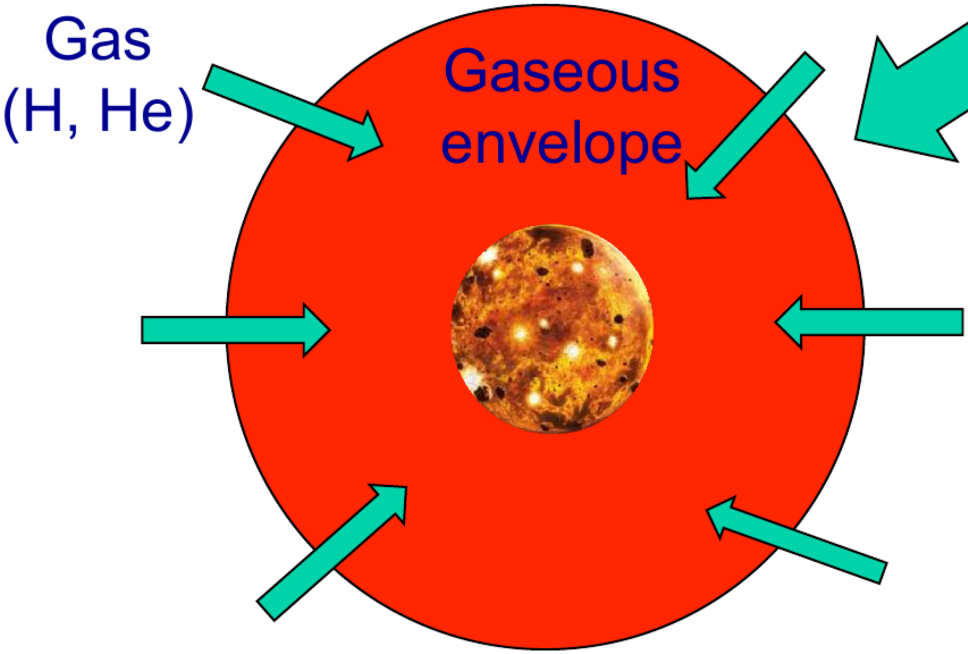
protoplanetary disk out of which planets form:



Formation of giant planets: Core accretion

Planetesimals collide and form a core

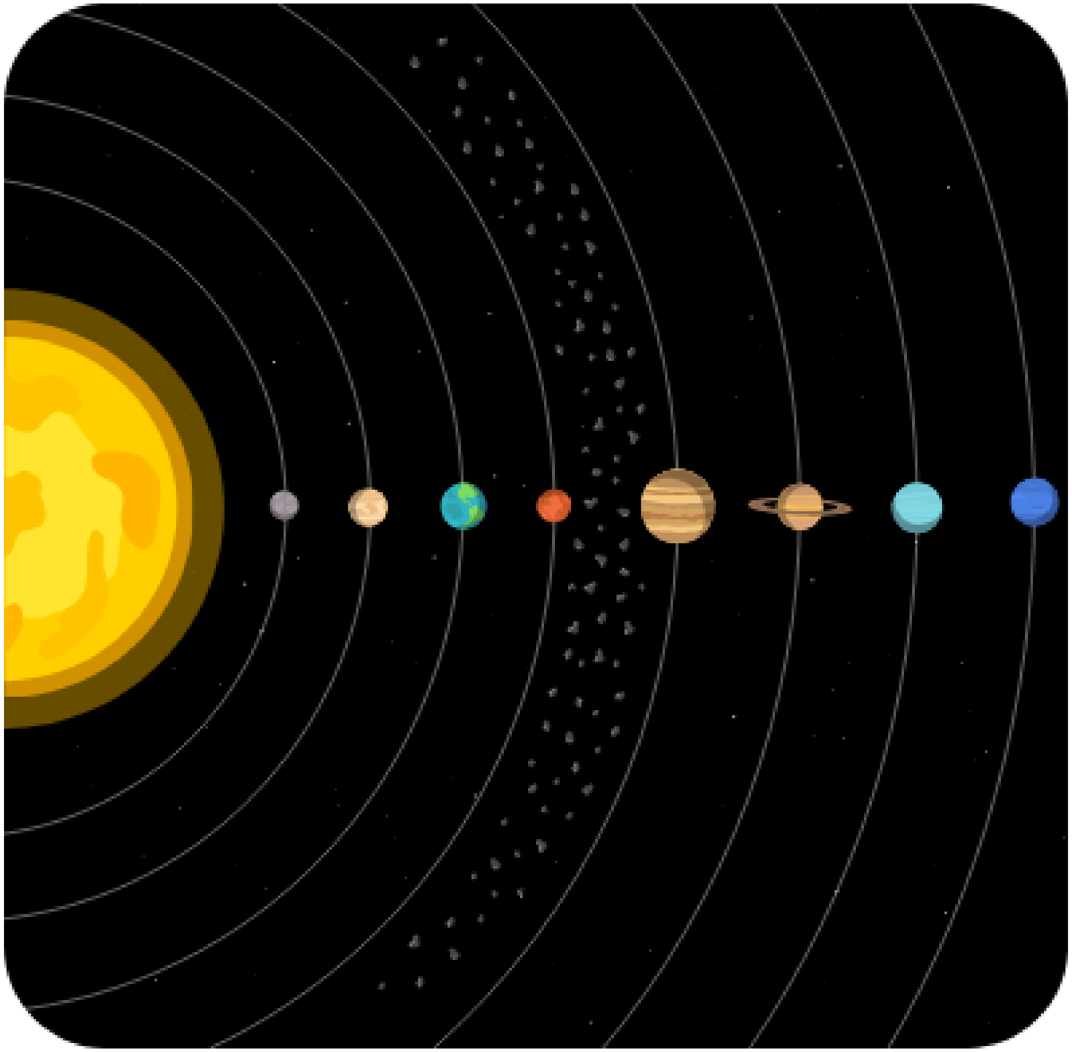
And you form a core



When the core reaches a mass of ~ 10 M_{earth} its gravity can start to accrete gas (H, He)

Formation of giant planets: Core accretion

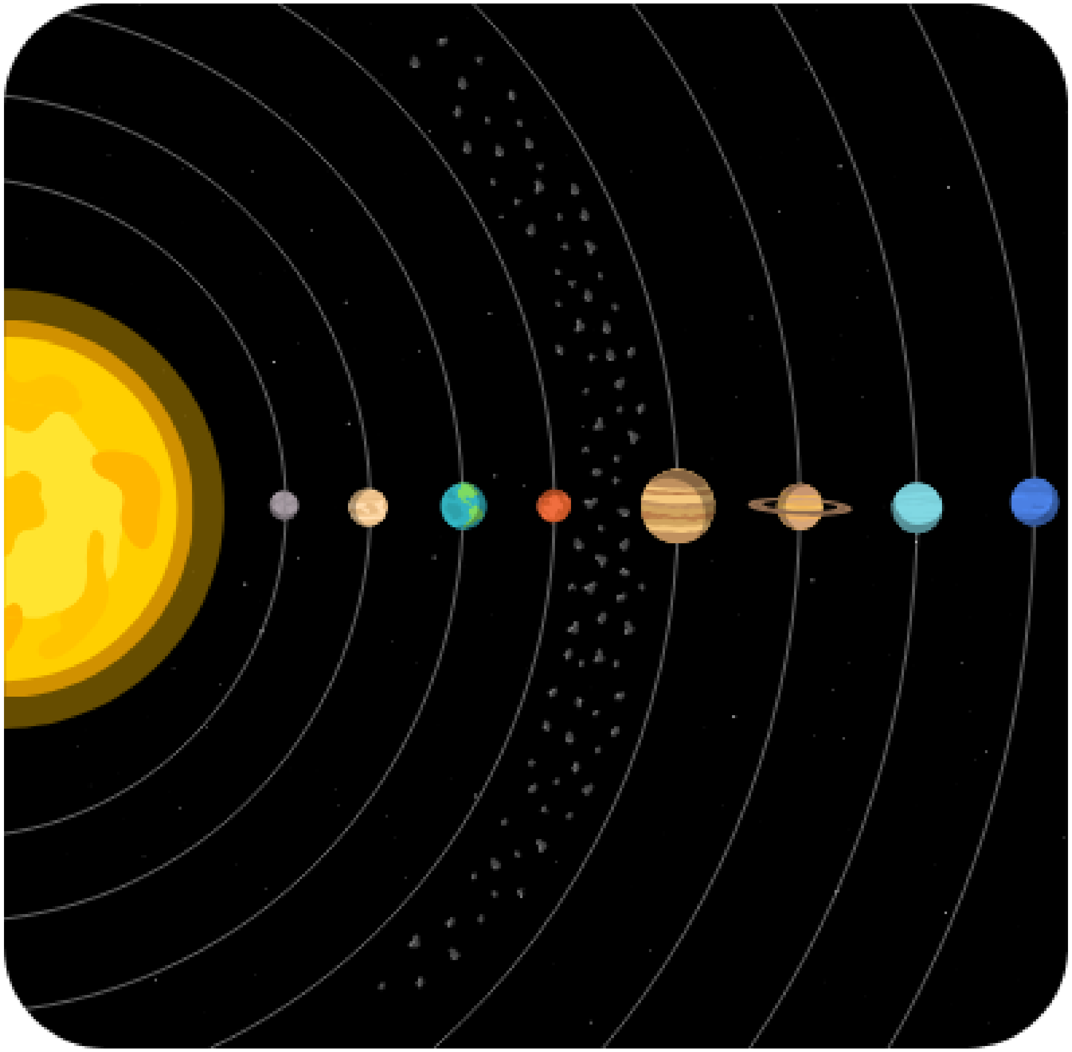
outside ice line at ~ 3 AU



Cool disk, lots of ices and solid particles, easy to form a 10 $M_\oplus$ core. Lots of gas, easy to form a gaseous envelope: giant planets

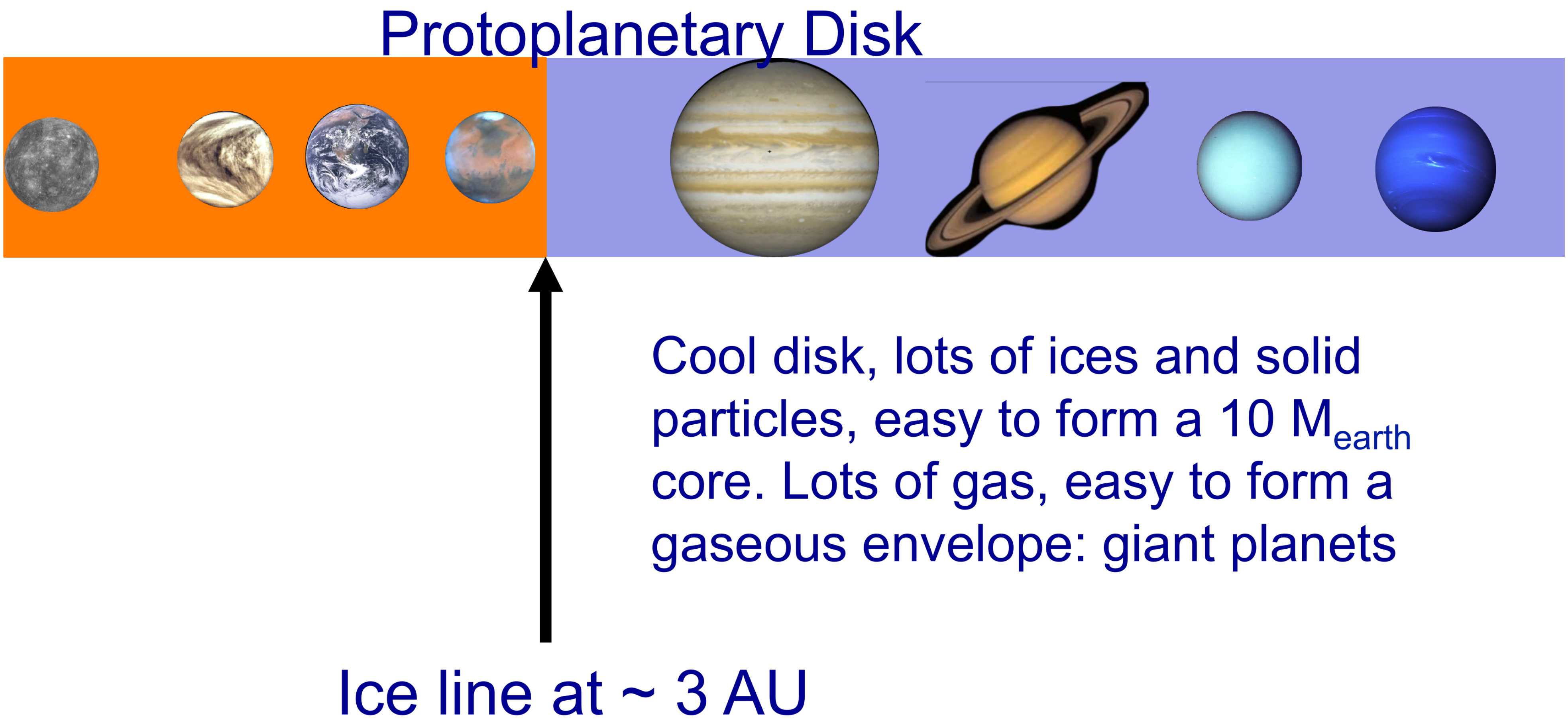
Formation of rocky planets

inside ice line at $\sim$ 3 AU



Hot disk, only solid materials with high melting points (fewer planetesimals), little gas. Can only form small, rocky planets

Formation of hot Jupiters



giant planets are formed beyond the ice line in the protoplanetary disk at $\sim$ 3 AU where there is enough solid material to form a $13M_{\oplus}$ core which can accrete H and He gas

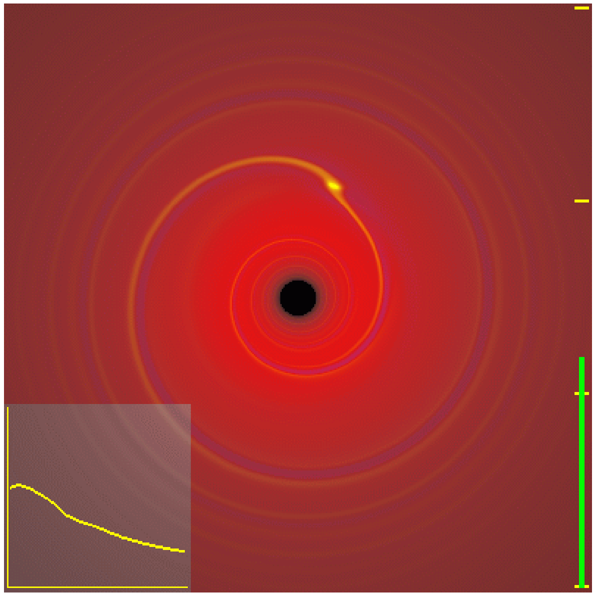
Orbital Migration

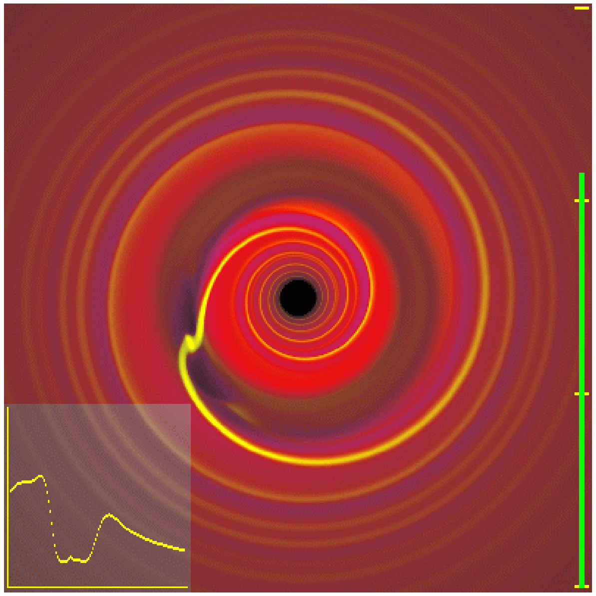
(forming) planets interact gravitationally with the disk (and other planets), and may move from where they form(ed), sometimes a lot

(1) type I migration: relatively low-mass planets (e.g. $\sim$ 1 $M_\oplus$) do not significantly alter surface density profile $\Sigma(R)$ but material concentrates asymmetrically in resonances and exerts torque causing migration

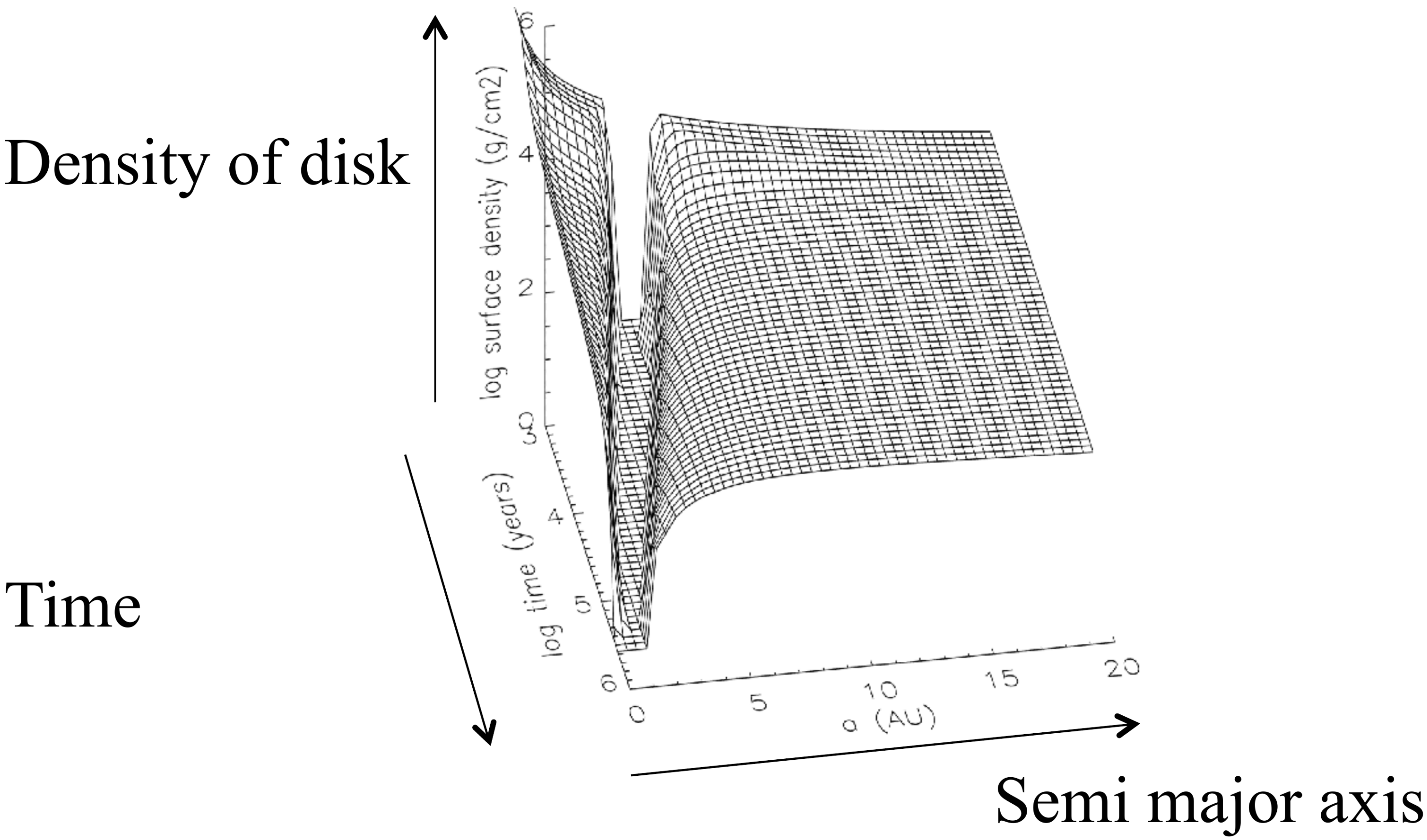
(2) type II migration: high-mass planets ($\sim$ 1 $M_{♃}$) open gaps and launch strong spiral arms that exert torque.

(3) Planet-planet interaction can significantly alter orbits of planets on timescales of $\gg$ 1 orbit





Formation of hot Jupiters: Migration



Once the giant planet at ~ 5 AU forms, it opens a gap in the protoplanetary disk (above). Tidal interactions causes the planet to lose angular momentum and spiral into the star.

New problems: What stops the migration and why did our own Jupiter stay where it formed?

How to search for Exoplanets

Indirect Techniques

- Radial Velocity (Doppler Method)
- Astrometry
- Transits
- Microlensing

Direct Techniques

- Spectroscopy/Photometry: Reflected or Radiated light
- Imaging

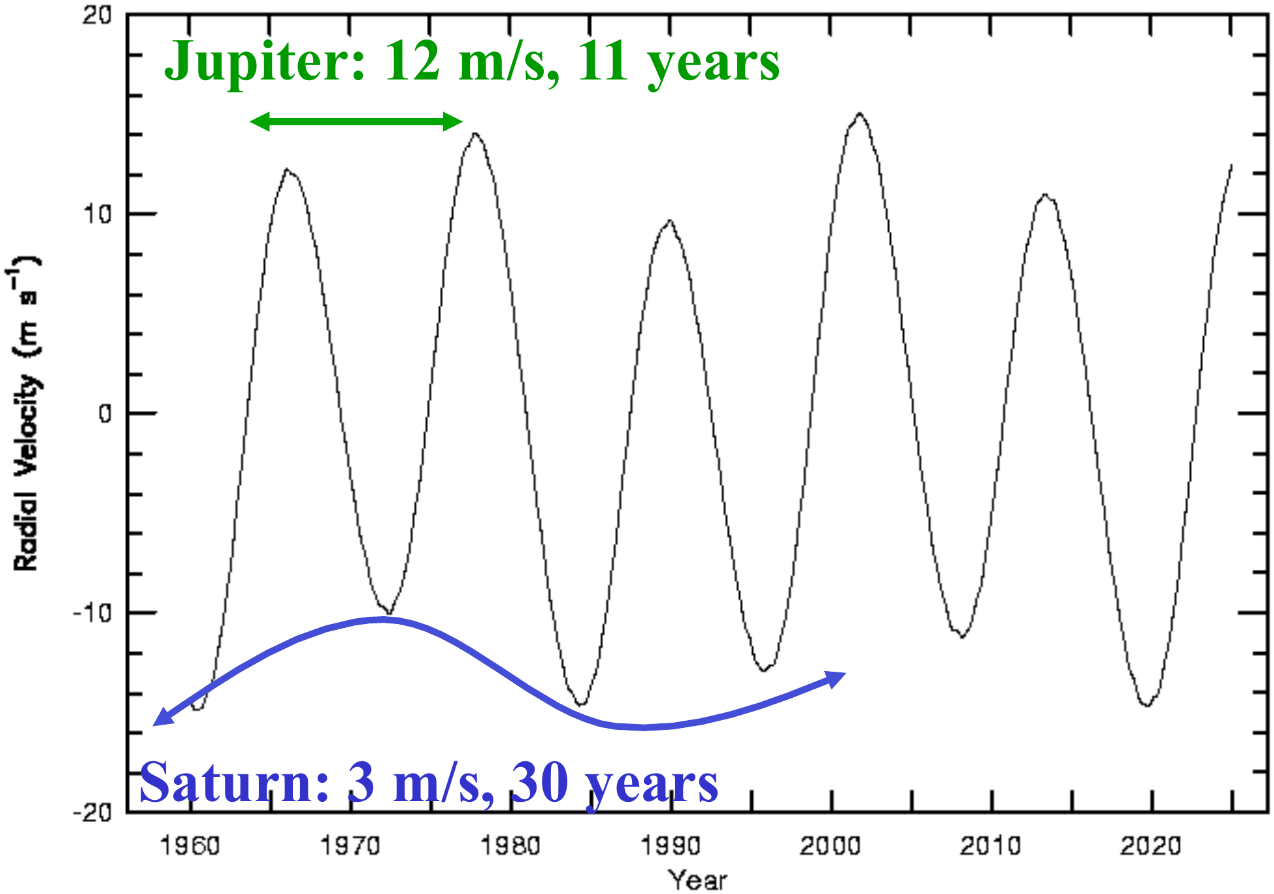
All of these techniques have successfully discovered a planet, or detected a known plane

How to search for Exoplanets – Radial velocity measurements

$$f(m) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{PK_1^3}{2\pi G} \qquad \frac{\Delta\lambda}{\lambda} = \frac{v_{\rm rad}}{c}$$

How to search for Exoplanets – Radial velocity measurements

RV method measures the mass of the exoplanet

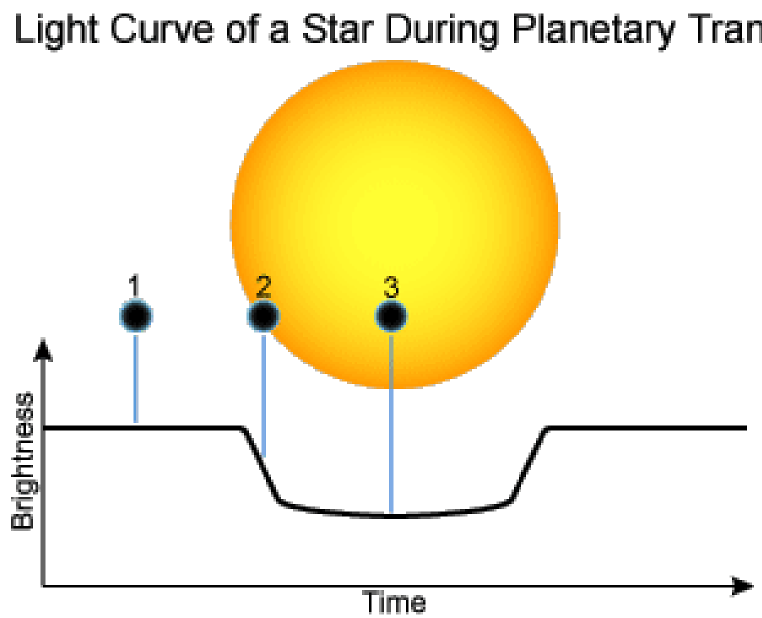


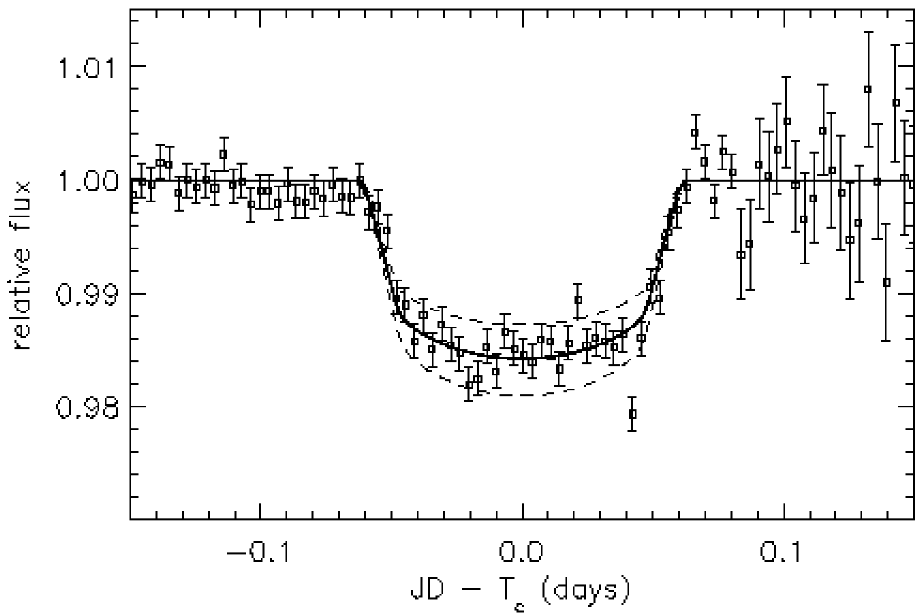
Requirements:

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

How to search for Exoplanets – Transit search

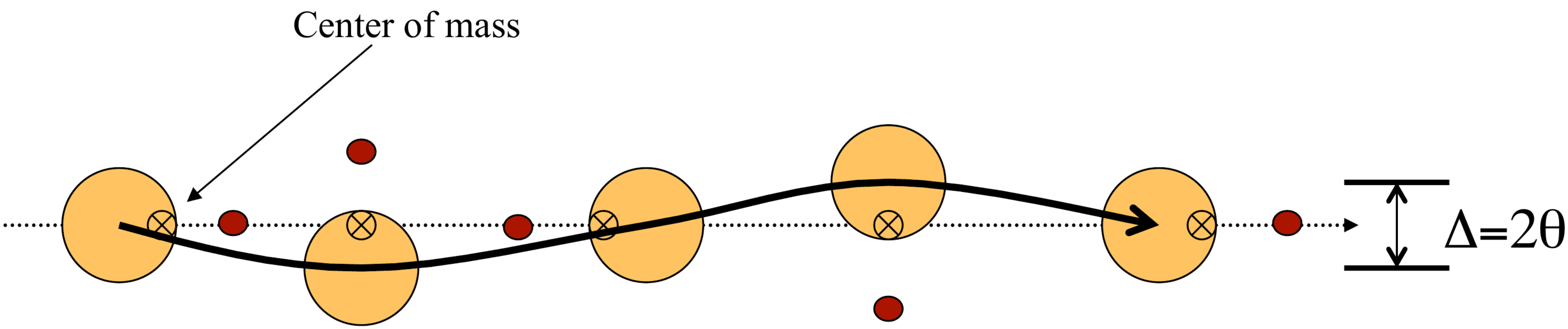
transit method measures the radius of the exoplanet





How to search for Exoplanets – Astrometric measurements

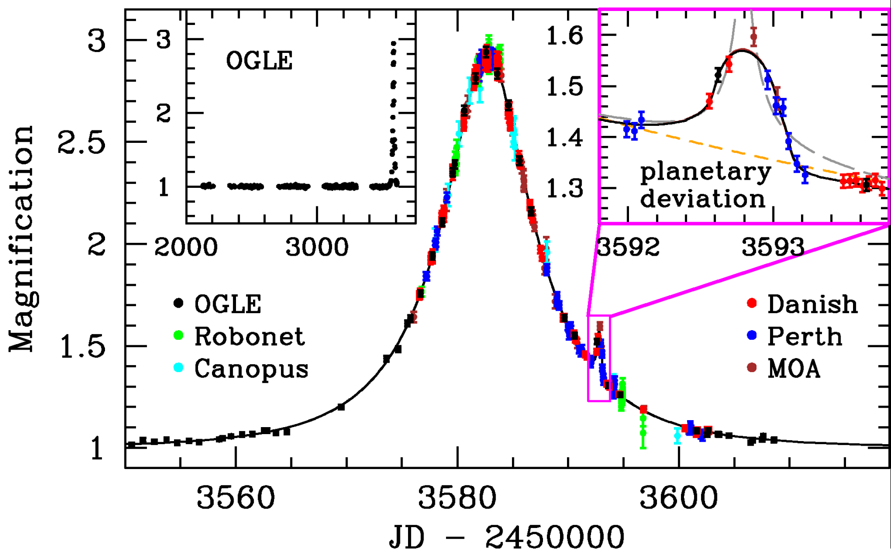
Astrometric method measures true mass of the exoplanet

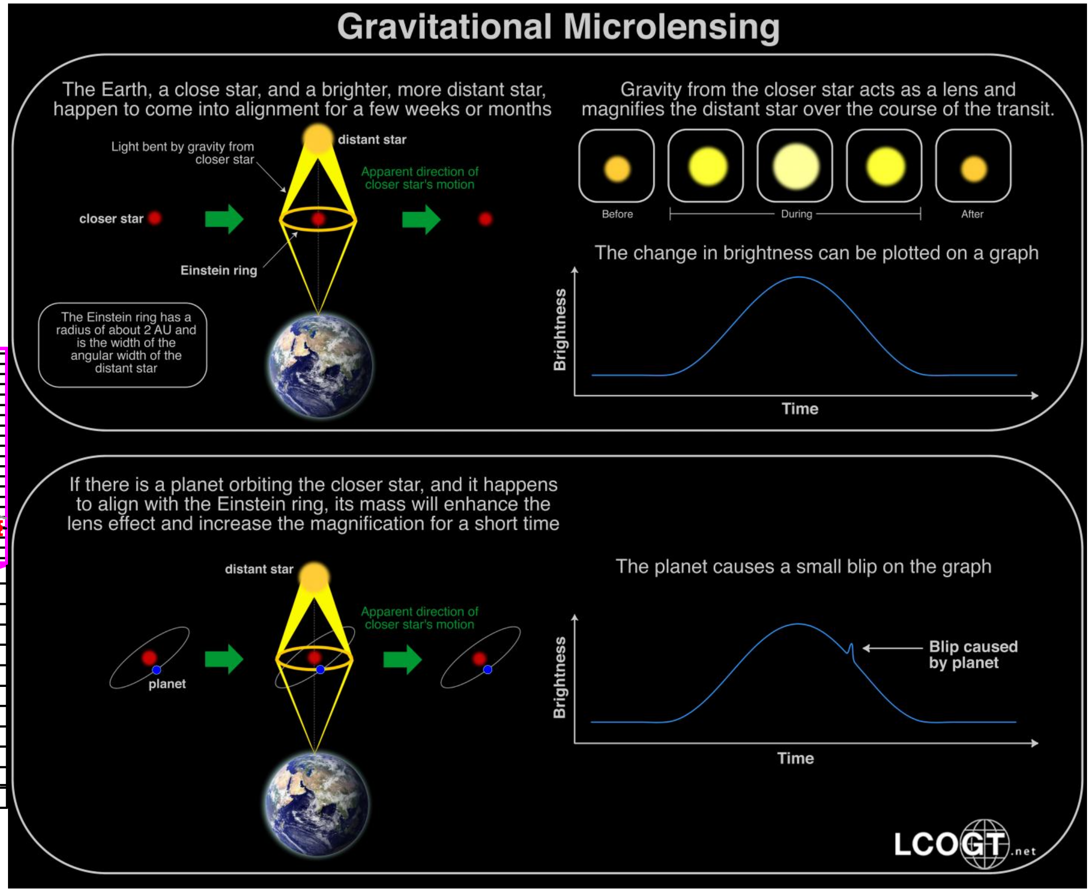


→ $\Delta \sim 1/D$ with D the distance to the star

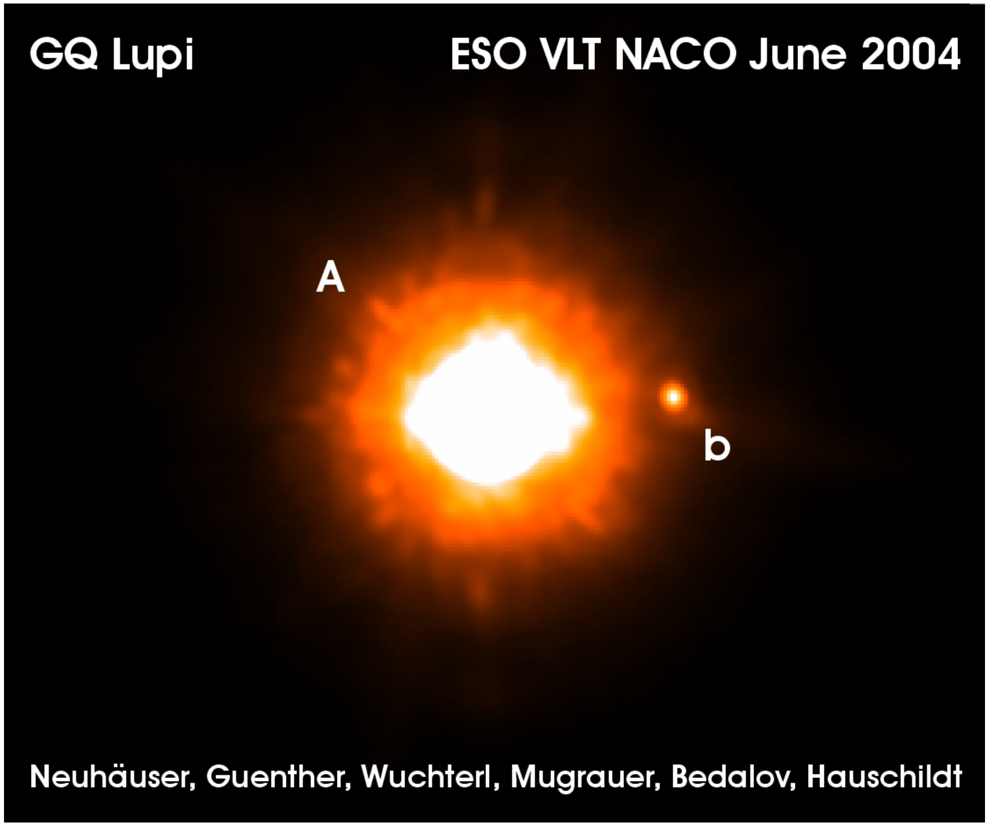
→ only possible for nearby stars (8 mas for Jupiter around α Cen)

How to search for Exoplanets – Microlensing



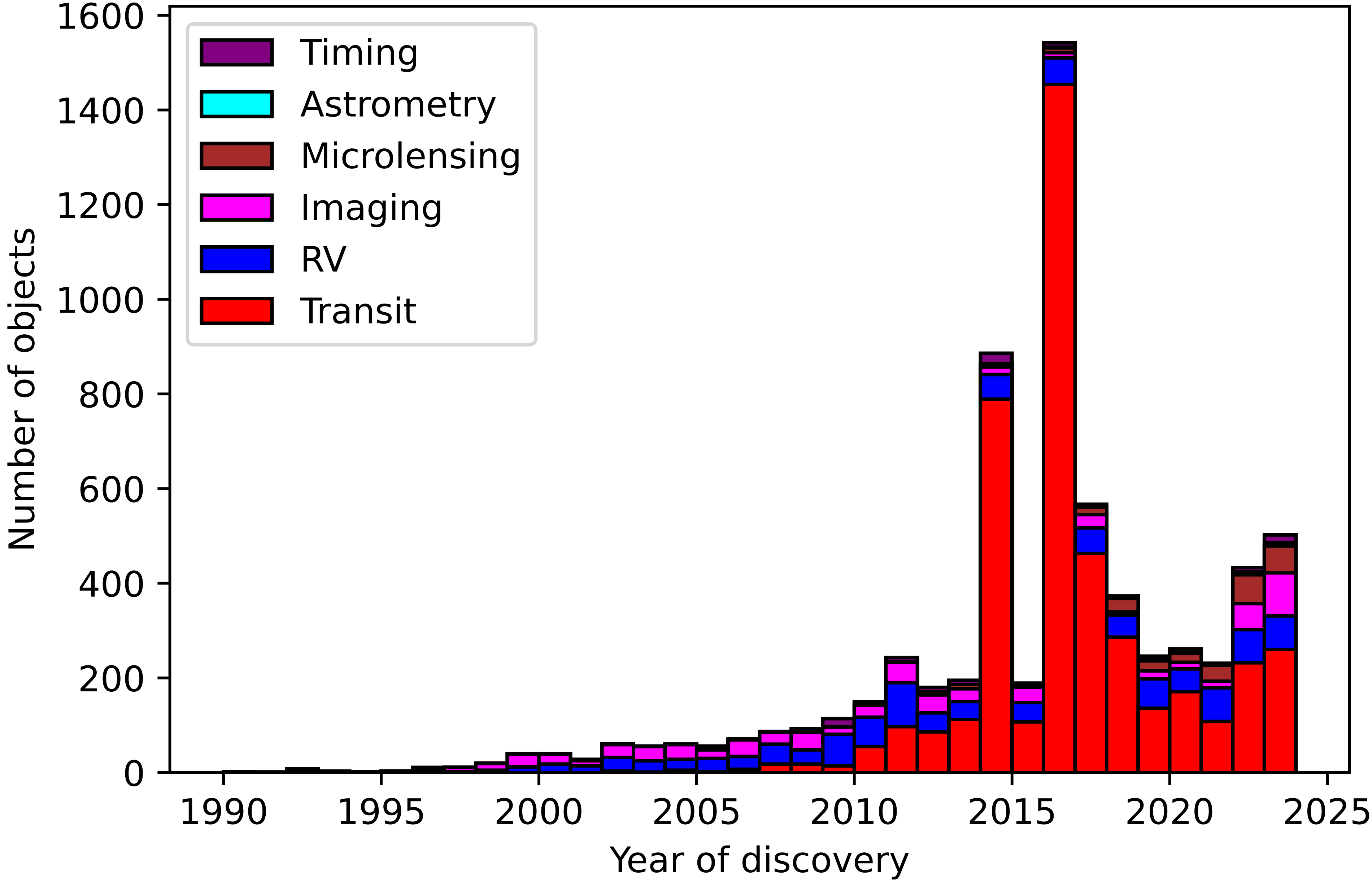


How to search for Exoplanets – Direct Imaging

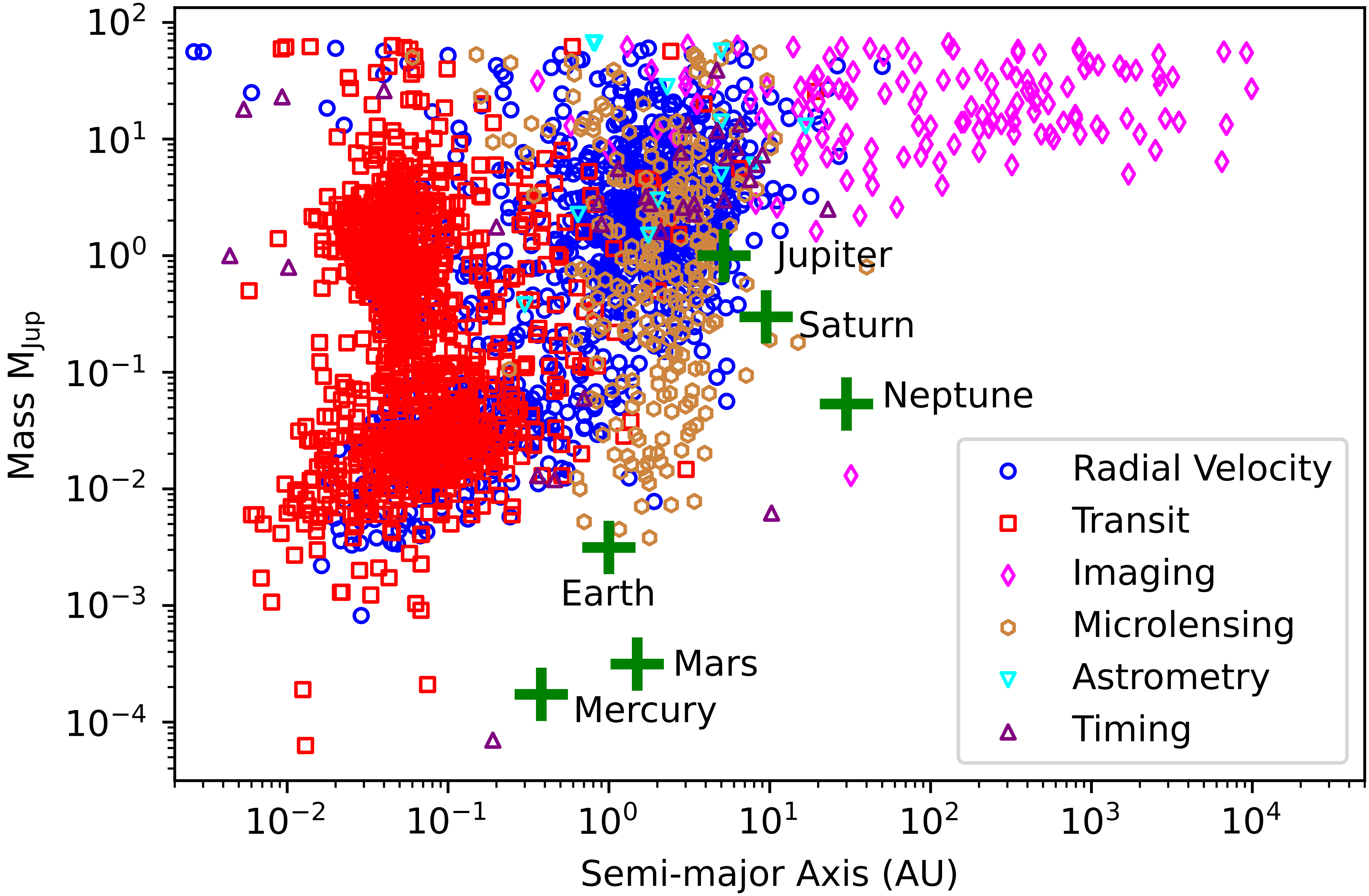


$\rightarrow$ planet 1,000,000 times fainter, separation $\sim$ arcsec
$\rightarrow$ easier for large orbital radii and massive planets

Exoplanet Discovery Space



Exoplanet Discovery Space



Mass determination in binaries

To determine stellar (or planetary) masses, use Kepler's 3rd law:

$$\frac{(a_1 + a_2)^3}{P^2} = \frac{G}{4\pi^2}(m_1 + m_2)$$

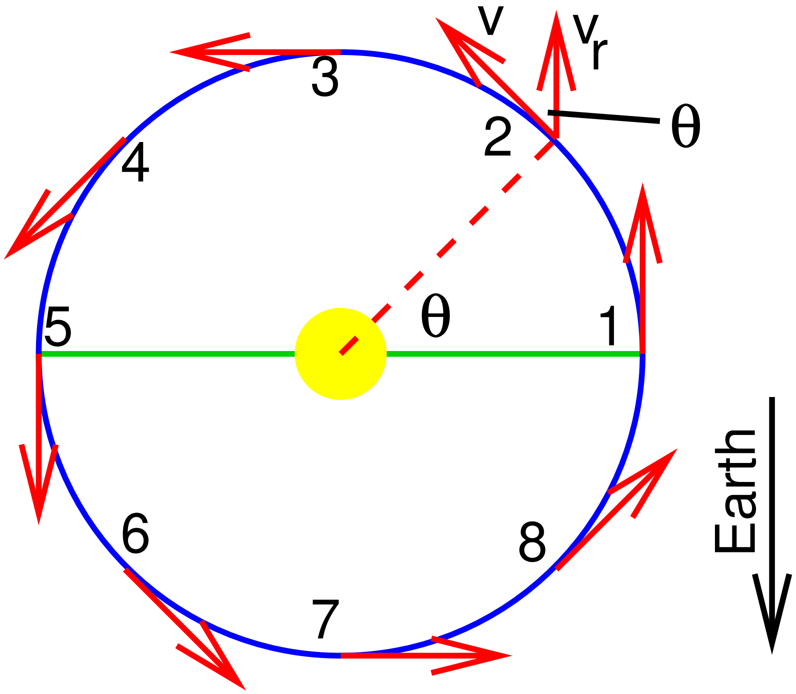
where

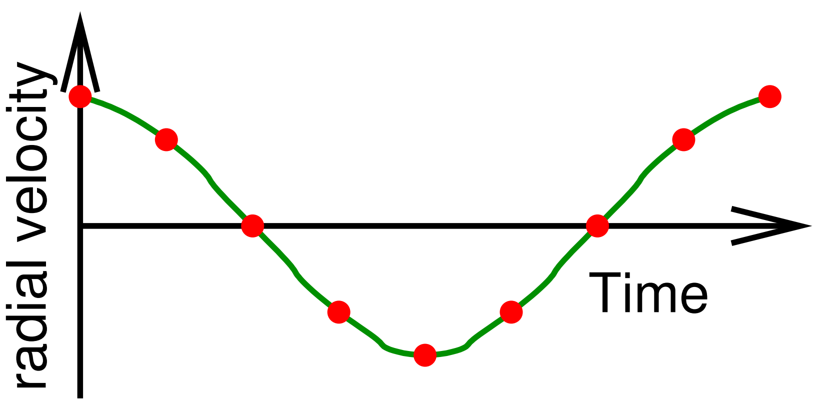
- $M_{1,2}$: masses
- P: period
- $a_{1,2}$ semimajor axis

Observational quantities:

- P – directly measurable
- a – measurable from image *if and only if* distance to binary and the inclination are known

Spectroscopic binaries





For spectroscopic binaries: can only measure radial velocity along line of sight

For circular orbit, angle θ on orbit:

$$\theta = \omega t$$

where $\omega = 2\pi/P$.

Observed radial velocity:

$$v_r = v\cos(\omega t)$$

If orbit has inclination i, then

$$v_r(t) = v\sin i\cos(\omega t) = K\cos(\omega t)$$

From observation of $v_r(t) \Longrightarrow v\sin i = K$.

(“velocity amplitude”)

Spectroscopic binaries

Double-lined spectra, case SB2

Assume circular orbit ($e = 0$)

K_1, K_2	velocity half amplitudes of components 1 & 2
P	orbital period
$2\pi a_{1/2}$	orbital radii of components 1 & 2

$$K_{1/2} = \frac{2\pi a_{1/2}}{P} \sin i$$

$$\Longrightarrow a_{1/2} \sin i = \frac{P}{2\pi} K_{1/2}$$

again sin *i* remains in-determined

Spectroscopic binaries

centre of mass law:

$$\frac{M_1}{M_2} = \frac{a_2}{a_1} = \frac{K_2}{K_1}$$

Kepler's third law:

$$M_1 + M_2 = \frac{4\pi^2}{G\,P^2} a^3,$$
$$a = a_1 + a_2 = \frac{P}{2\pi}(K_1 + K_2)/\sin i$$

$$\Longrightarrow M_1 + M_2 = \frac{4\pi^2}{G\,P^2}\frac{P^3}{(2\pi)^3}\frac{(K_1+K_2)^3}{(\sin i)^3}(\star)$$

$$\Longrightarrow M_1 + M_2 = \frac{P}{2\pi G}\frac{(K_1+K_2)^3}{(\sin i)^3}$$

$$(M_1 + M_2)(\sin i)^3 = \frac{P}{2\pi G}(K_1 + K_2)^3$$

$\Longrightarrow$ two equations for three unknowns ($M_1 + M_2$, $\sin i$),
$\sin i$ can only be determined for eclipsing binaries

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:

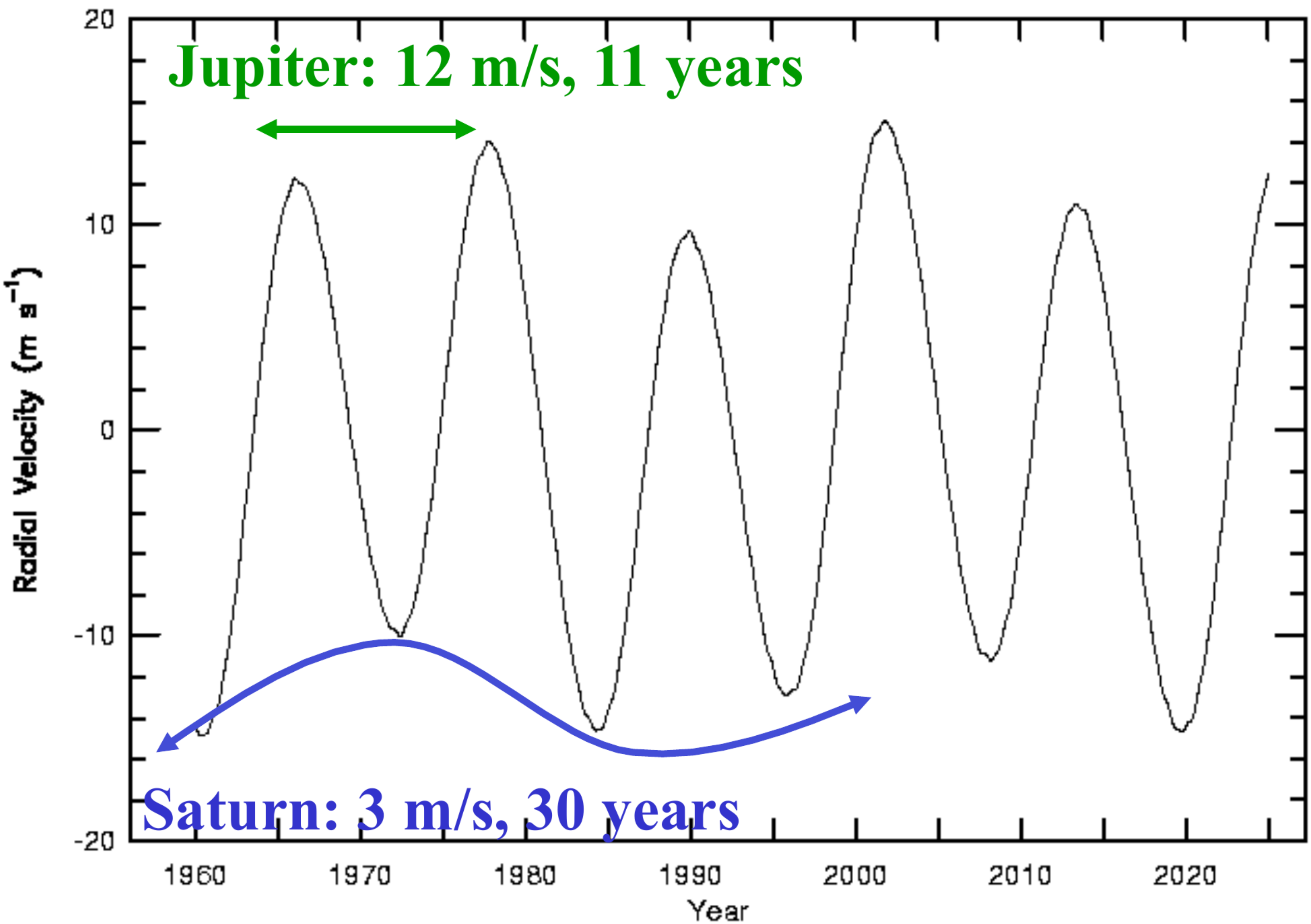
- Circular Orbit
- Star is much more massive than the planet

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

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

Exercise for the reader: Derive this!

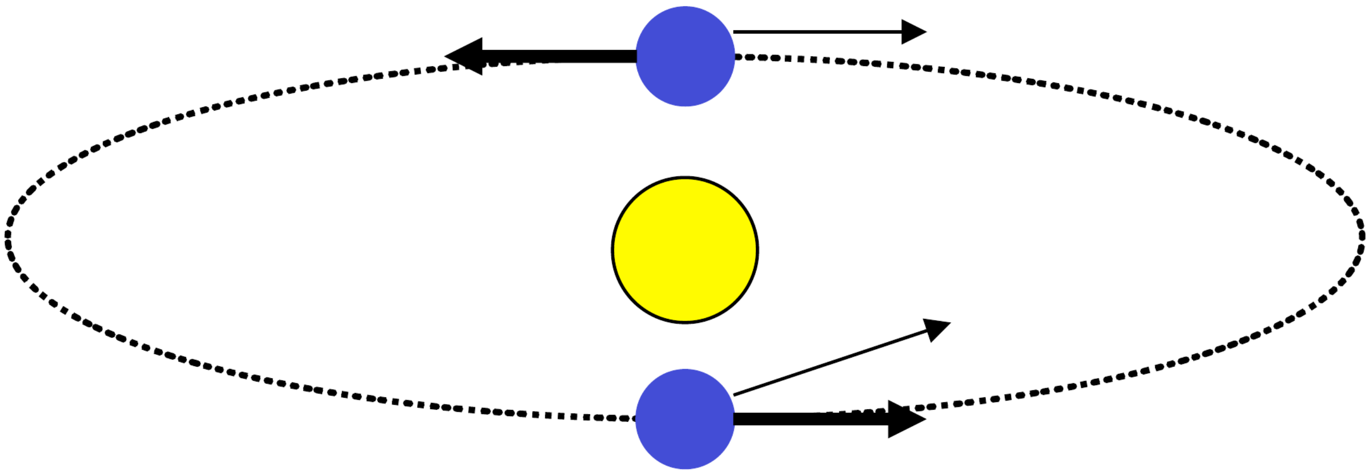
Velocity of the Sun around the Solar System Barycenter



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

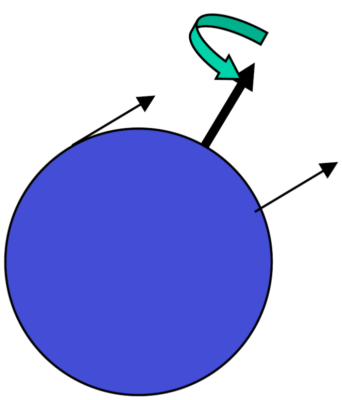
Barycentric correction



Need to know:

- Position of star
- Earth's orbit
- Exact time

Earth's orbital motion can contribute $\pm$30 km/s (maximum)



Need to know:

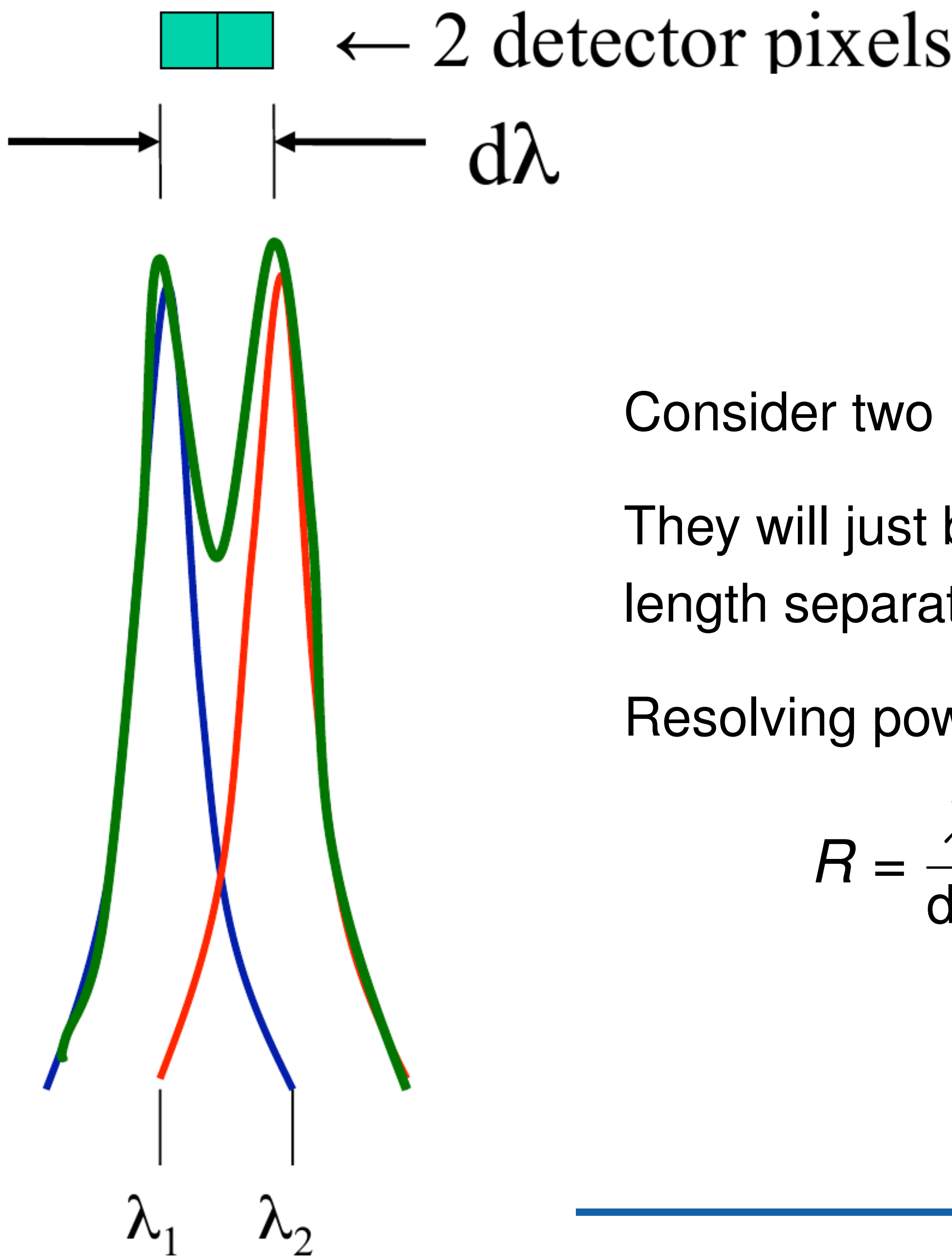
- Latitude and longitude of observatory
- Height above sea level

Earth's rotation can contribute $\pm$460 m/s (maximum)

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

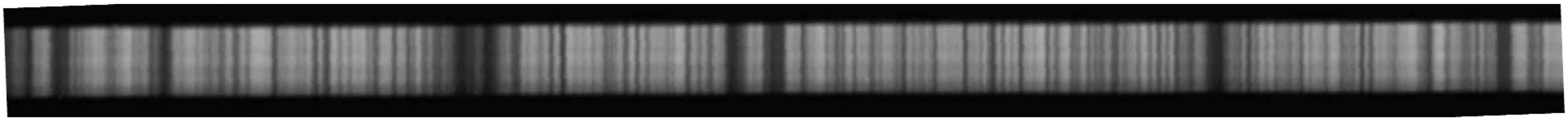
They will just be resolved when they have a wavelength separation of $d\lambda$

Resolving power:

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

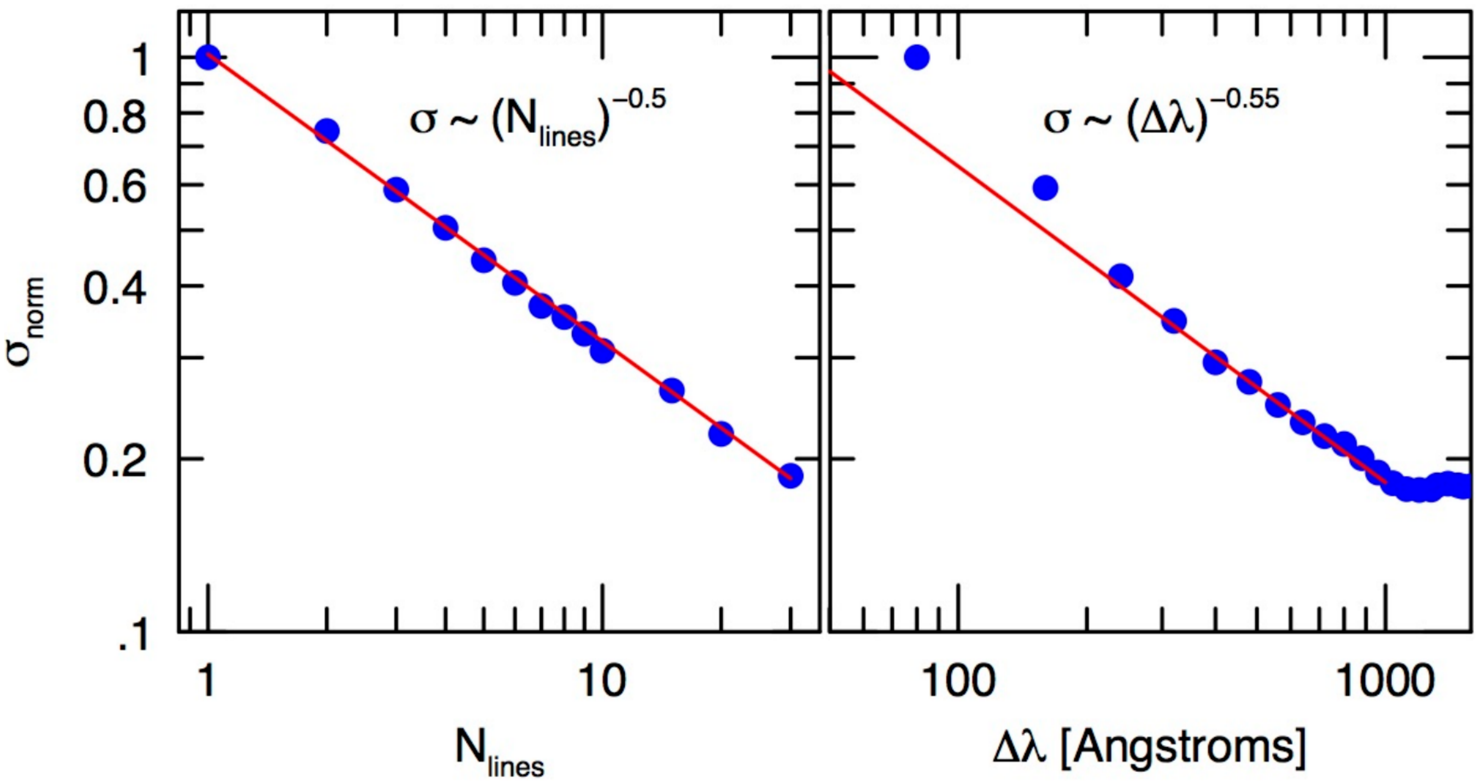
$d\lambda$ = full width of half maximum of calibration lamp emission lines

Large Wavelength Coverage

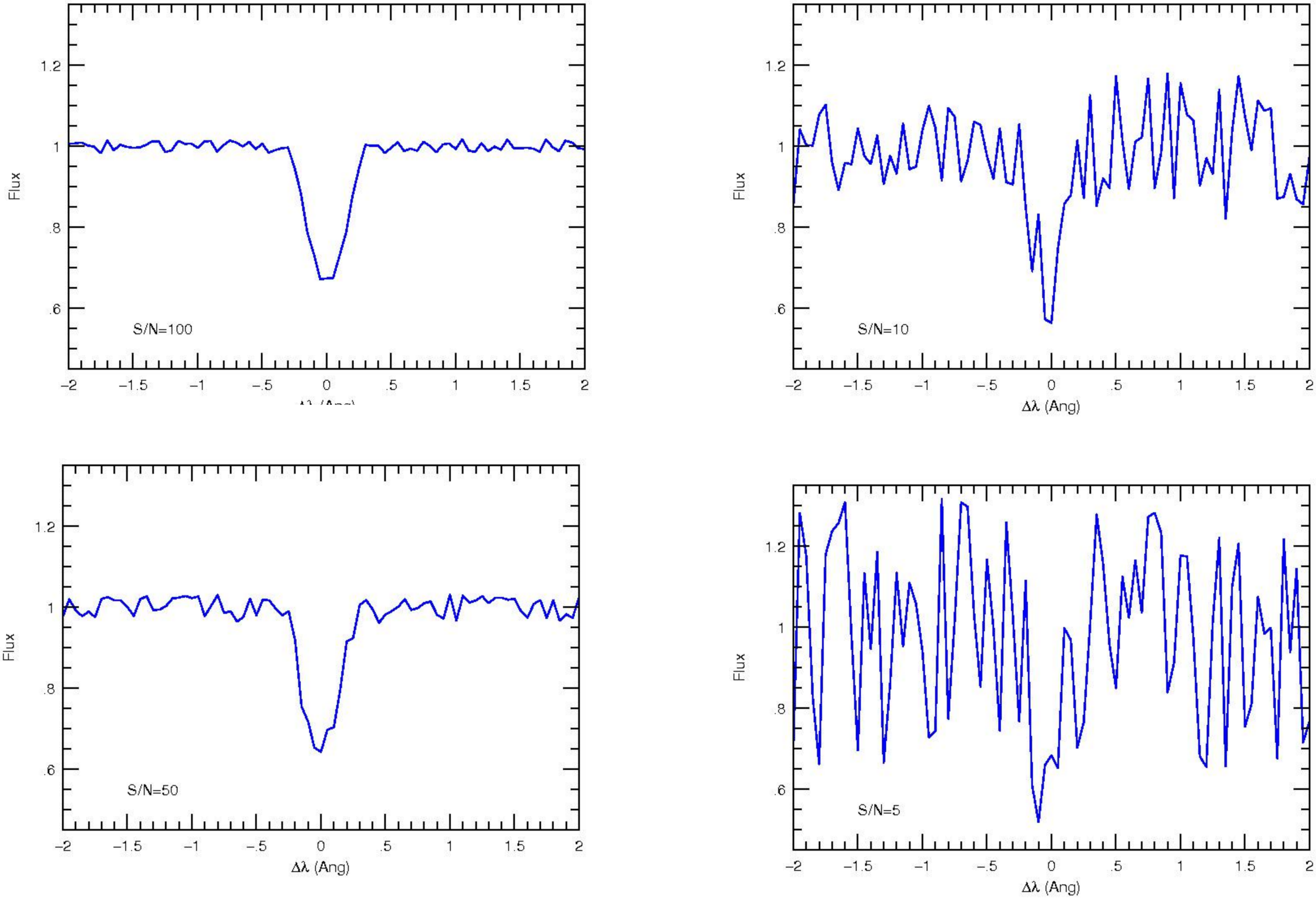


- Each line gives you a measurement of the Doppler shift with an error
- Use 100 lines and your error is 10 times lower

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

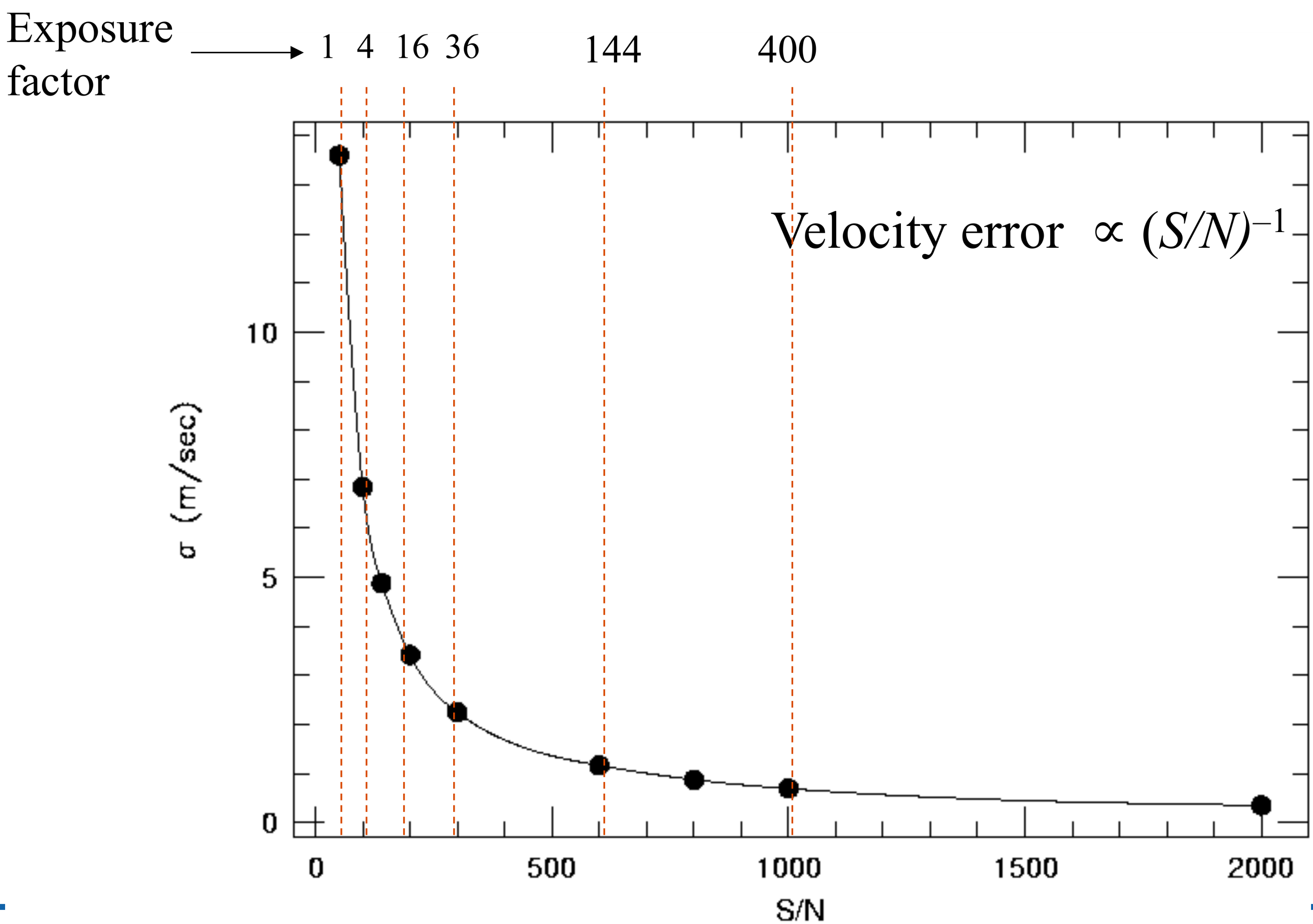


Influence of the noise



Influence of the noise

Velocity error as a function of S/N



Price: $S/N \propto t_{exposure}^{1/2}$

$Photons \propto t_{exposure}$

Influence of the noise

How does the radial velocity precision depend on all parameters?

$$\sigma(\text{m/s}) = \text{Constant} \times (S/N)^{-1} R^{-1.2} (\Delta\lambda)^{-1/2}$$

σ: error

R: spectral resolving power

S/N: signal to noise ratio

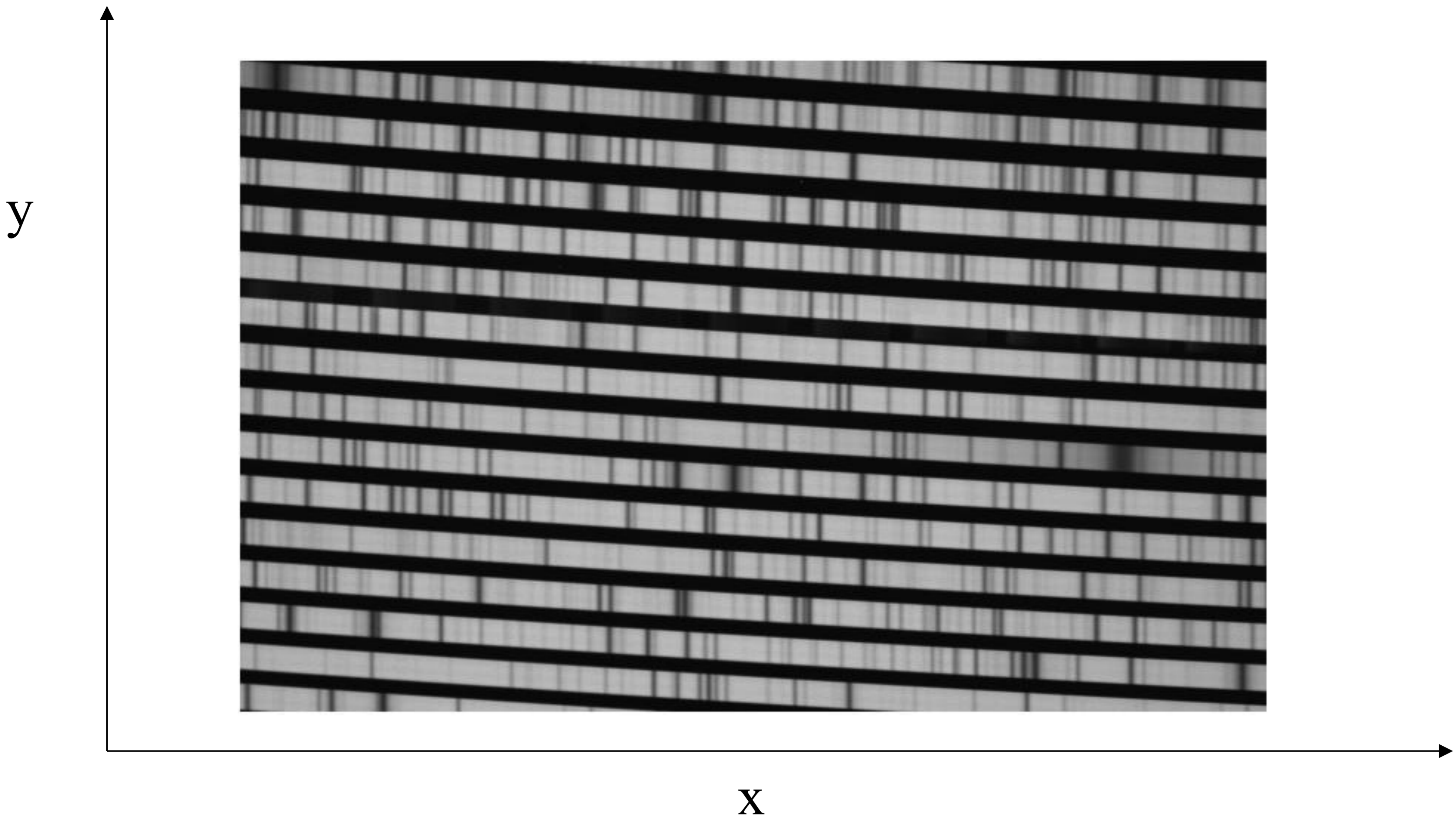
$\Delta\lambda$ wavelength coverage of spectrograph in Angstroms

$C \approx 8.2 \times 10^9$

TLS Echelle Spectrograph:
2m telescope
$R = 67,000$
$\Delta\lambda = 5000$
S/N = 200
$\sigma \approx 3$ m/s

Pucheros Spectrograph:
1.52m telescope
$R = 15,000$
$\Delta\lambda = 3500$
S/N = 200
$\sigma \approx ?$ m/s

Wavelength calibration

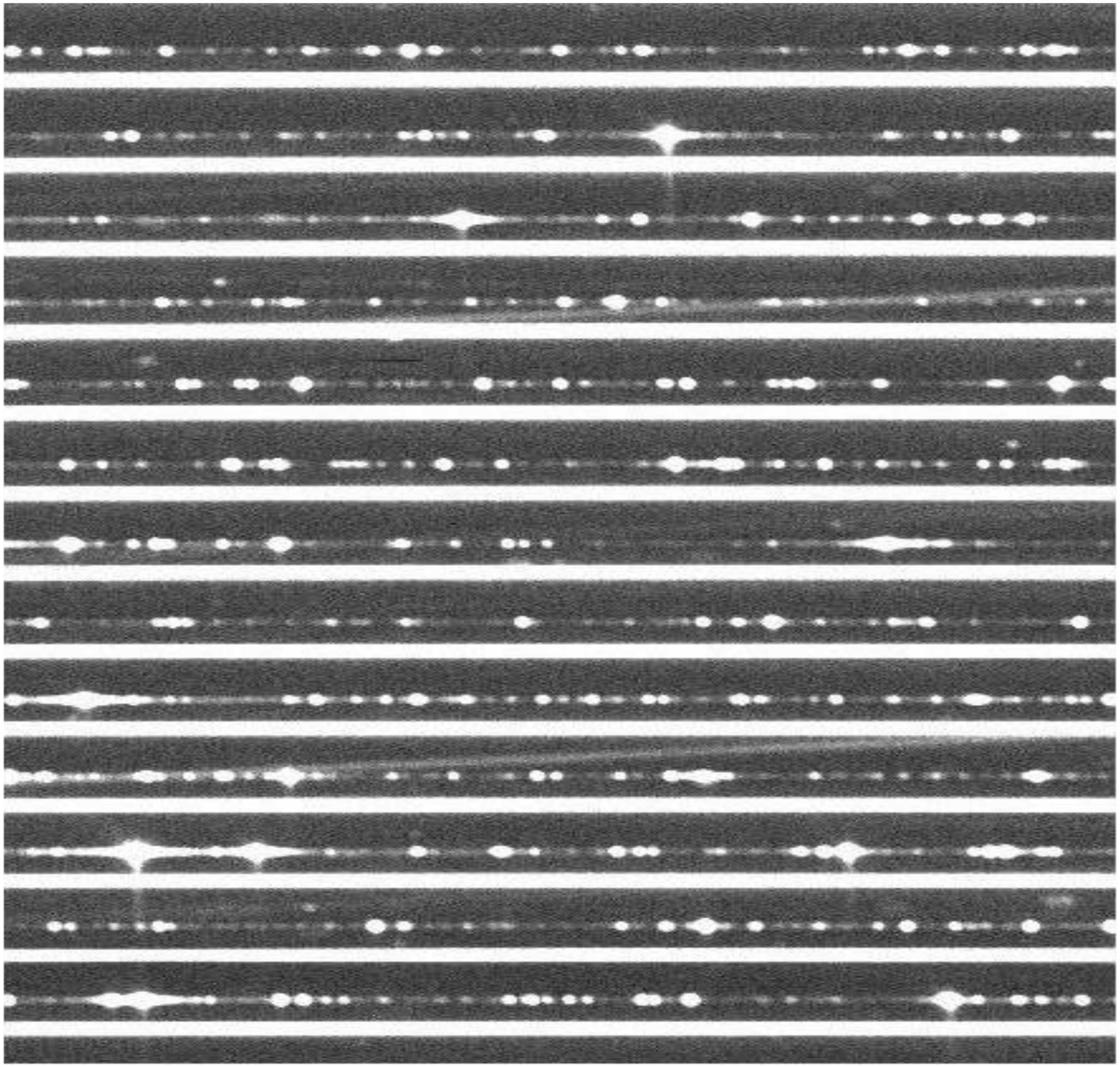


On a detector we only measure x- and y- positions, there is no information about wavelength. For this we need a calibration source

Solution 1: simultaneous observation of calibration source (Th-Ar)

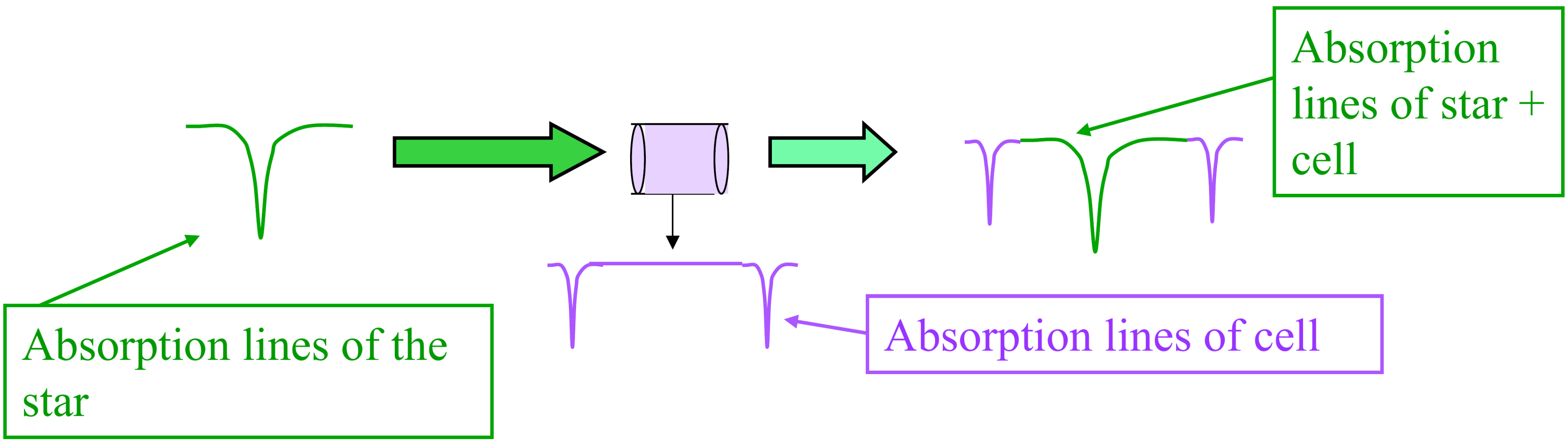
Stellar spectrum→

Thorium-Argon calibration→



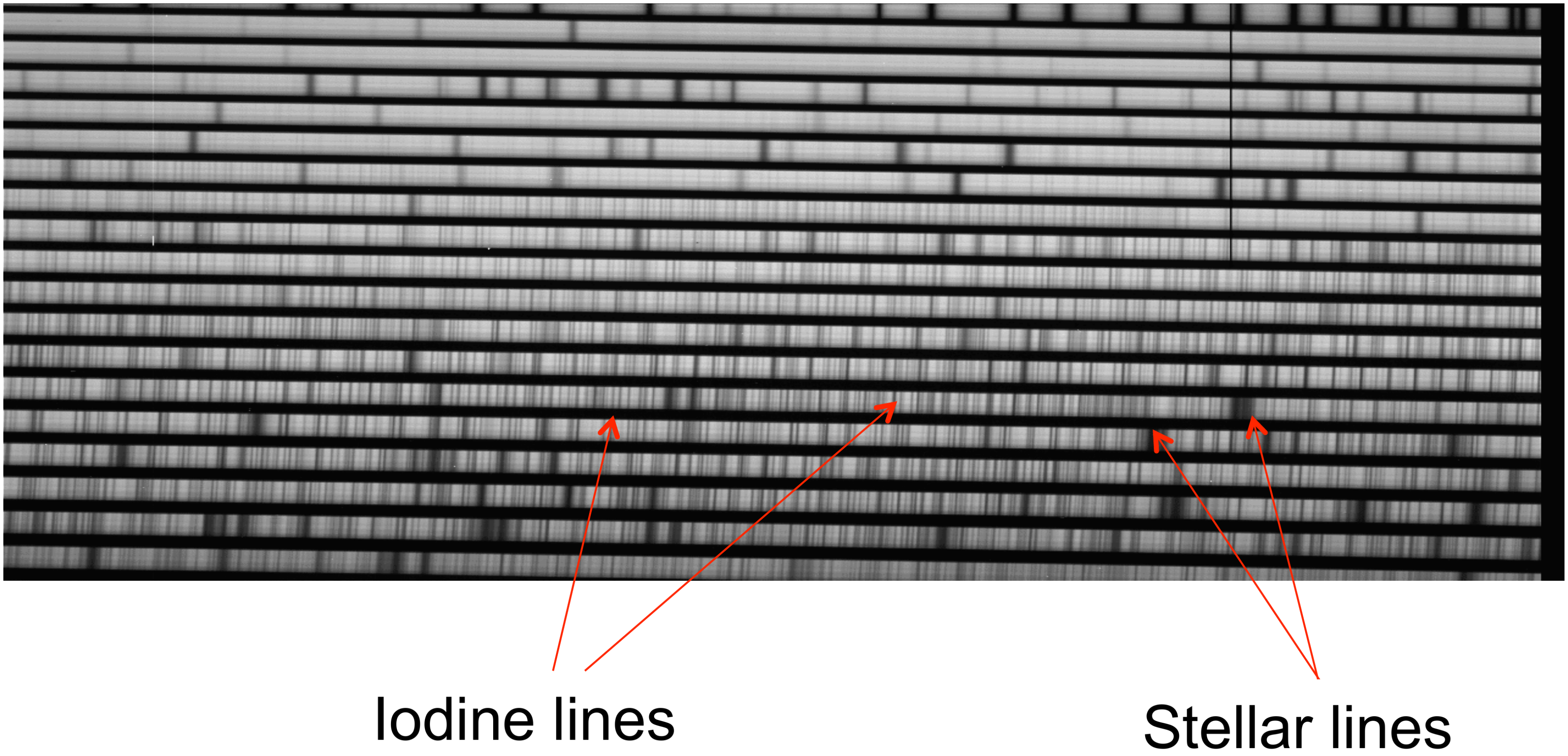
Spectrographs: CORALIE, ELODIE, HARPS

Solution 2: Gas Absorption Cells



Solution 2: Gas Absorption Cells – Iodine

Star observed through an Iodine cell

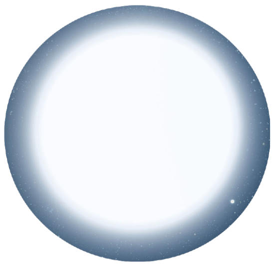


one high S/N spectrum without Iodine cell necessary for comparison, rest of measurements through Iodine cell → more details in Jana's talk about VIPER

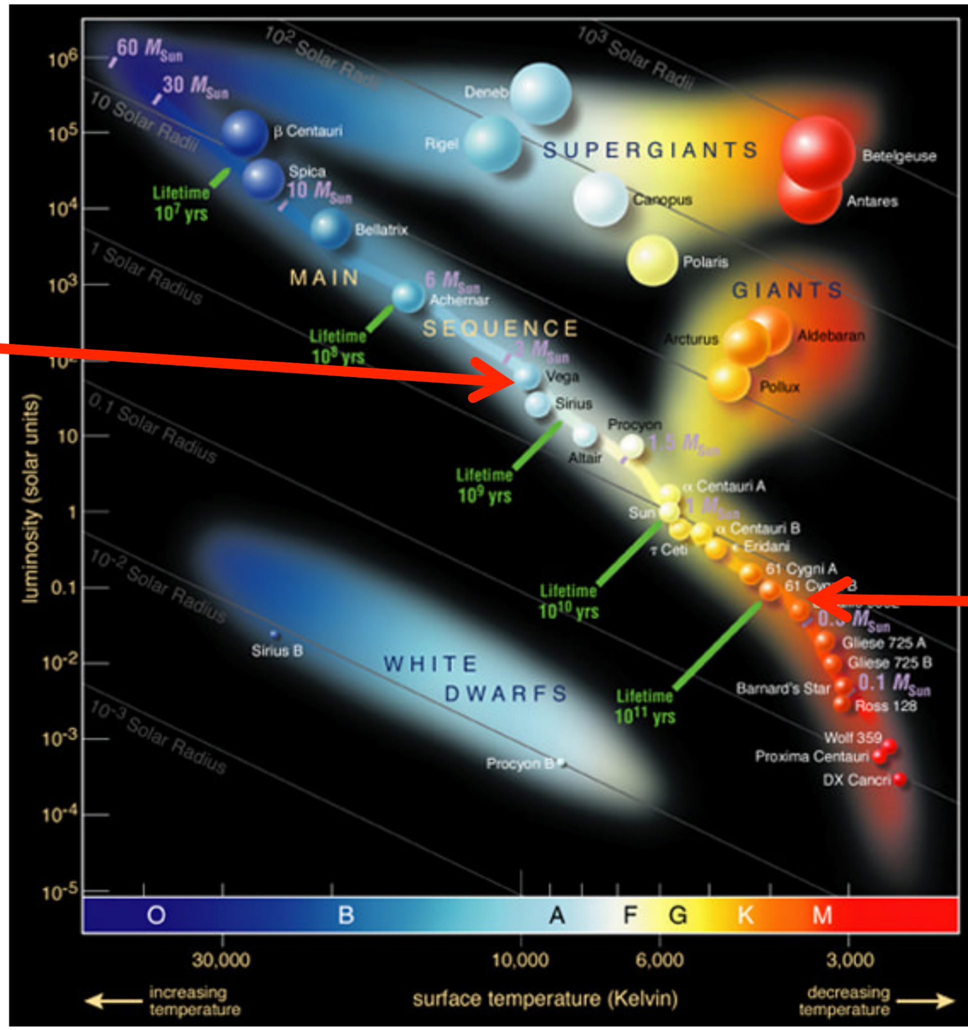
Radial velocity accuracy for different kind of stars

With different kind of stars you can reach different RV accuracy

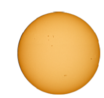
A-type



T = 10000 K
Rotational velocity ~ 200 km/s



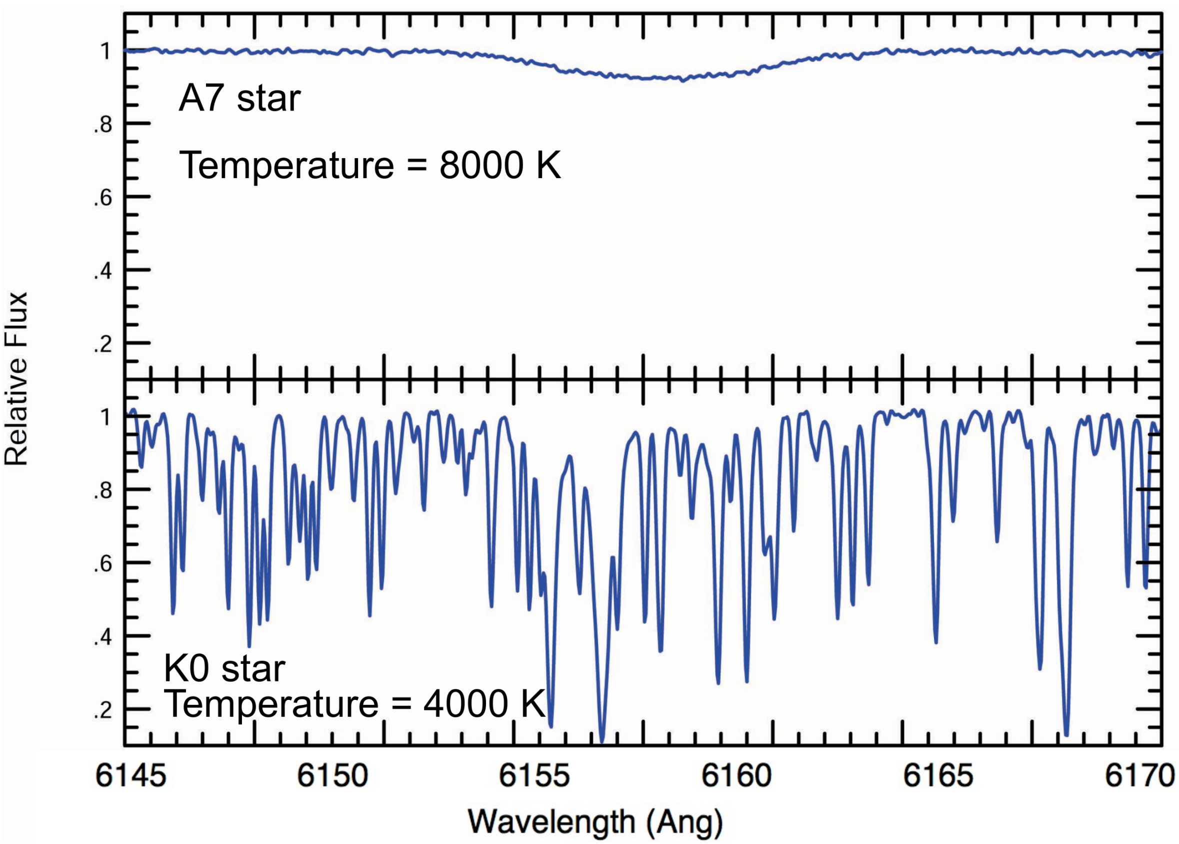
K-type



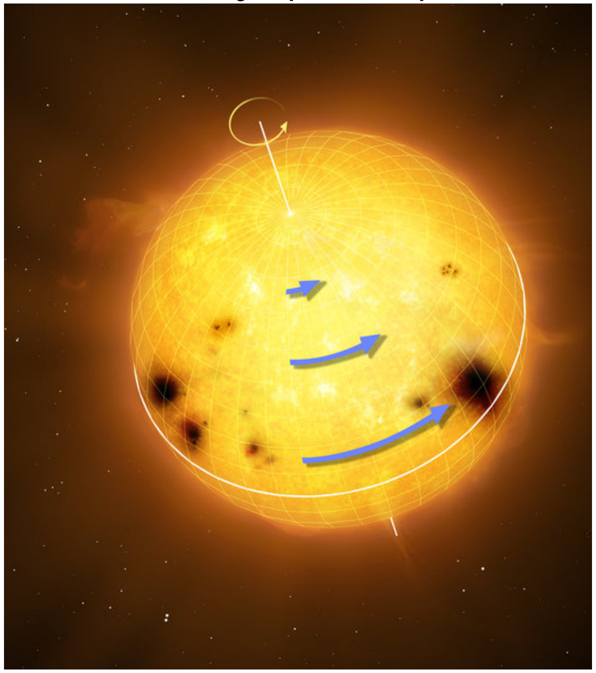
T = 4500 K
Rotational Velocity ~ 3 km/s

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)

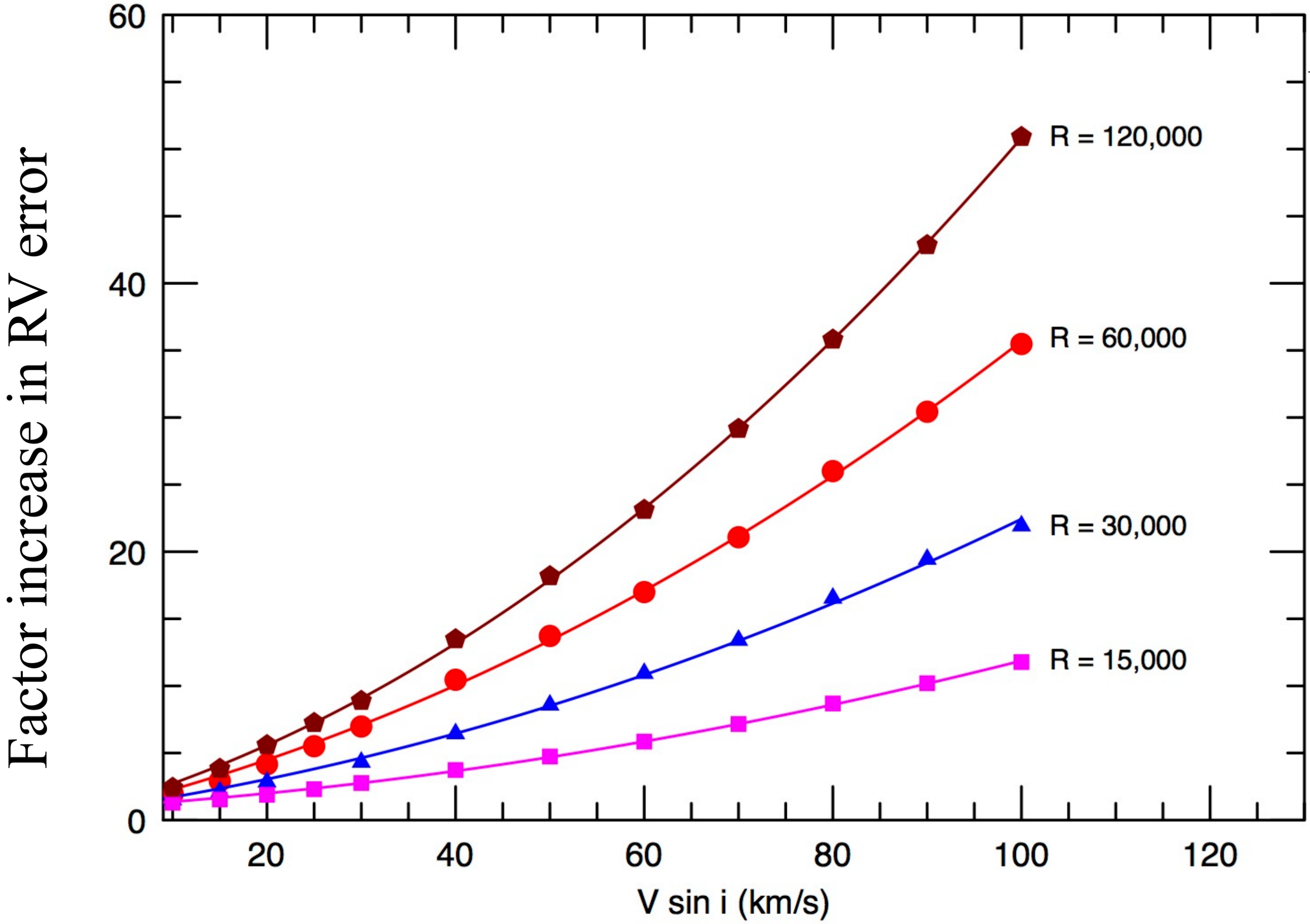


Projected rotational velocity = $v_{rot} \times \sin i$

(spin axes of star)

Radial velocity accuracy for different kind of stars

Increase in Error with Stellar Rotation (v sin i)

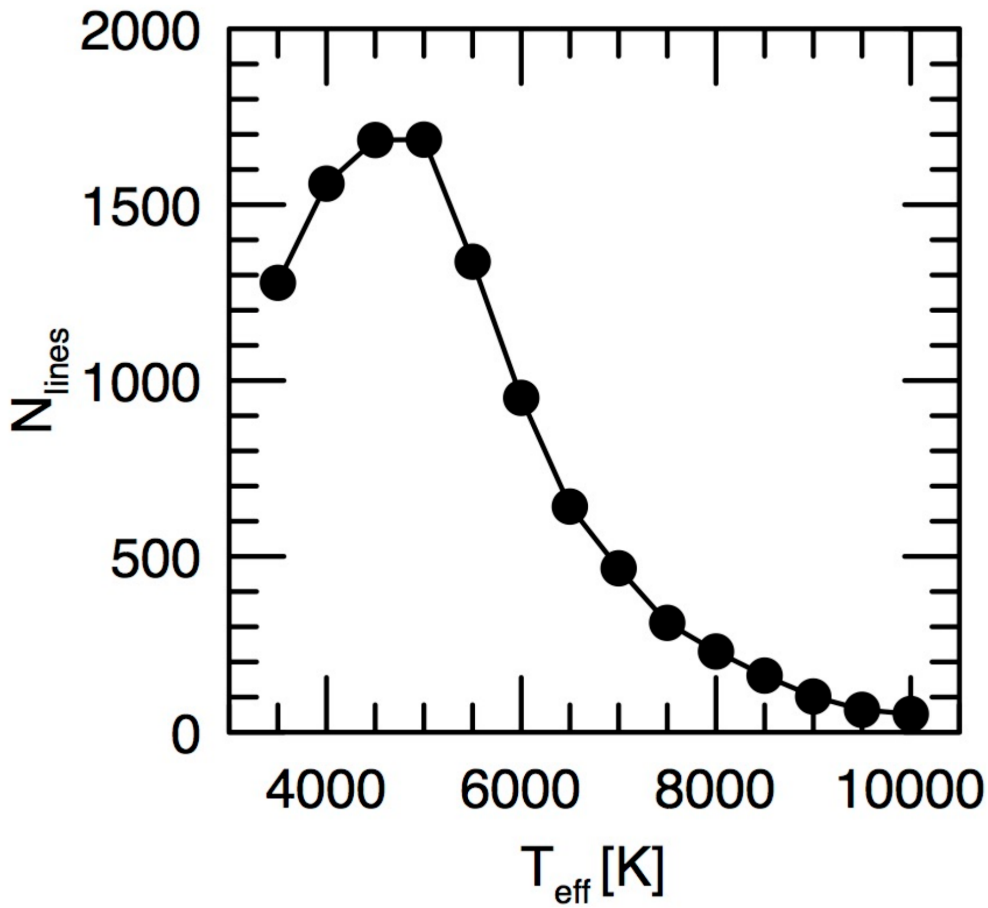


Using R = 60,000 for two stars with the same temperature: One rotating at 100 km/s will have an error 35 times greater than a star rotating at 2 km/s

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 $T_{\text{eff}} = 8000$ K will have nearly 9 times less useful spectral lines than a star at $T_{\text{eff}} = 5000$ 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

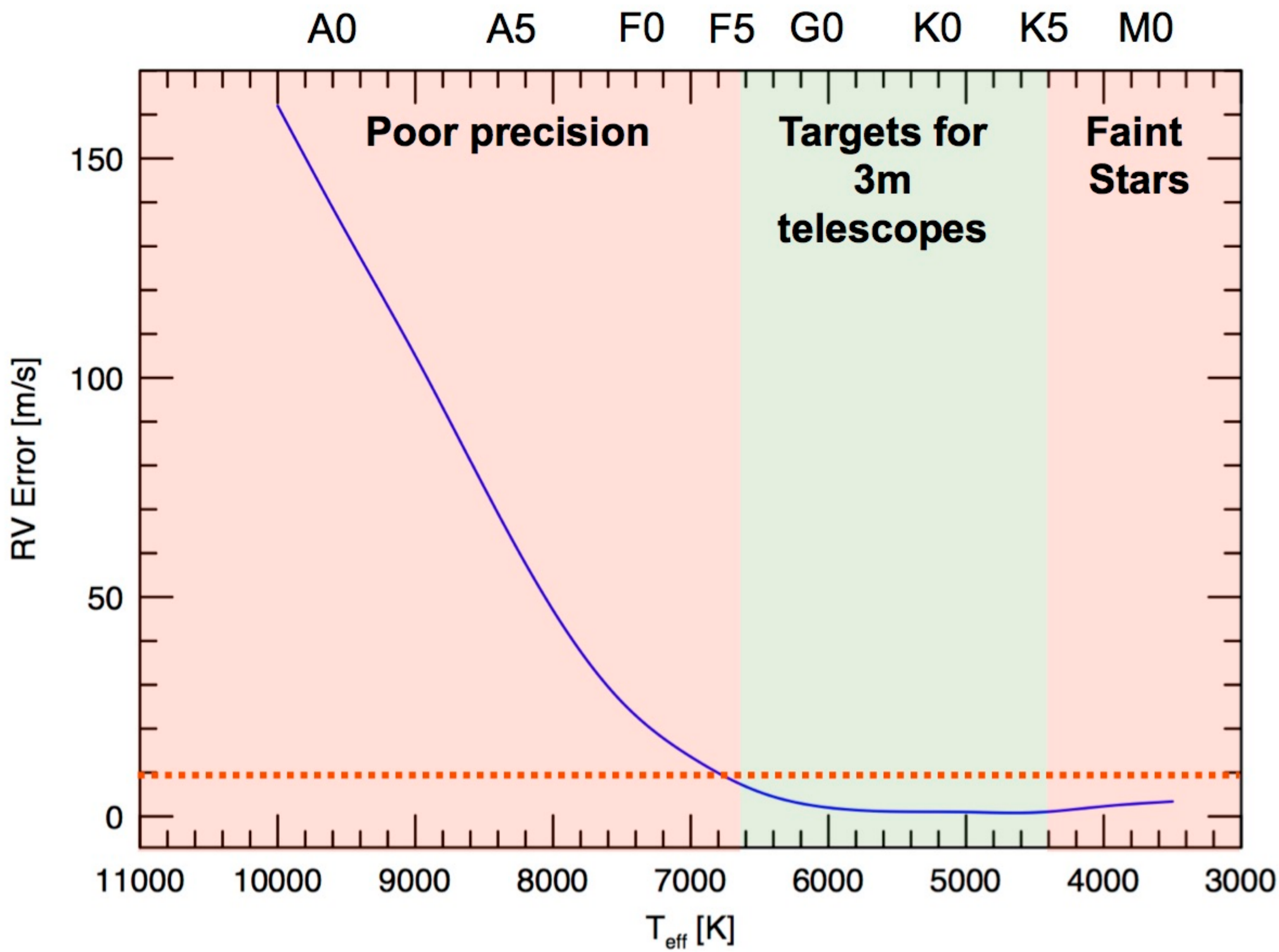
$f(V) = 0.62 + (0.21 \log R - 0.86)V + (0.00260 - 0.0103)V^2$

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

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

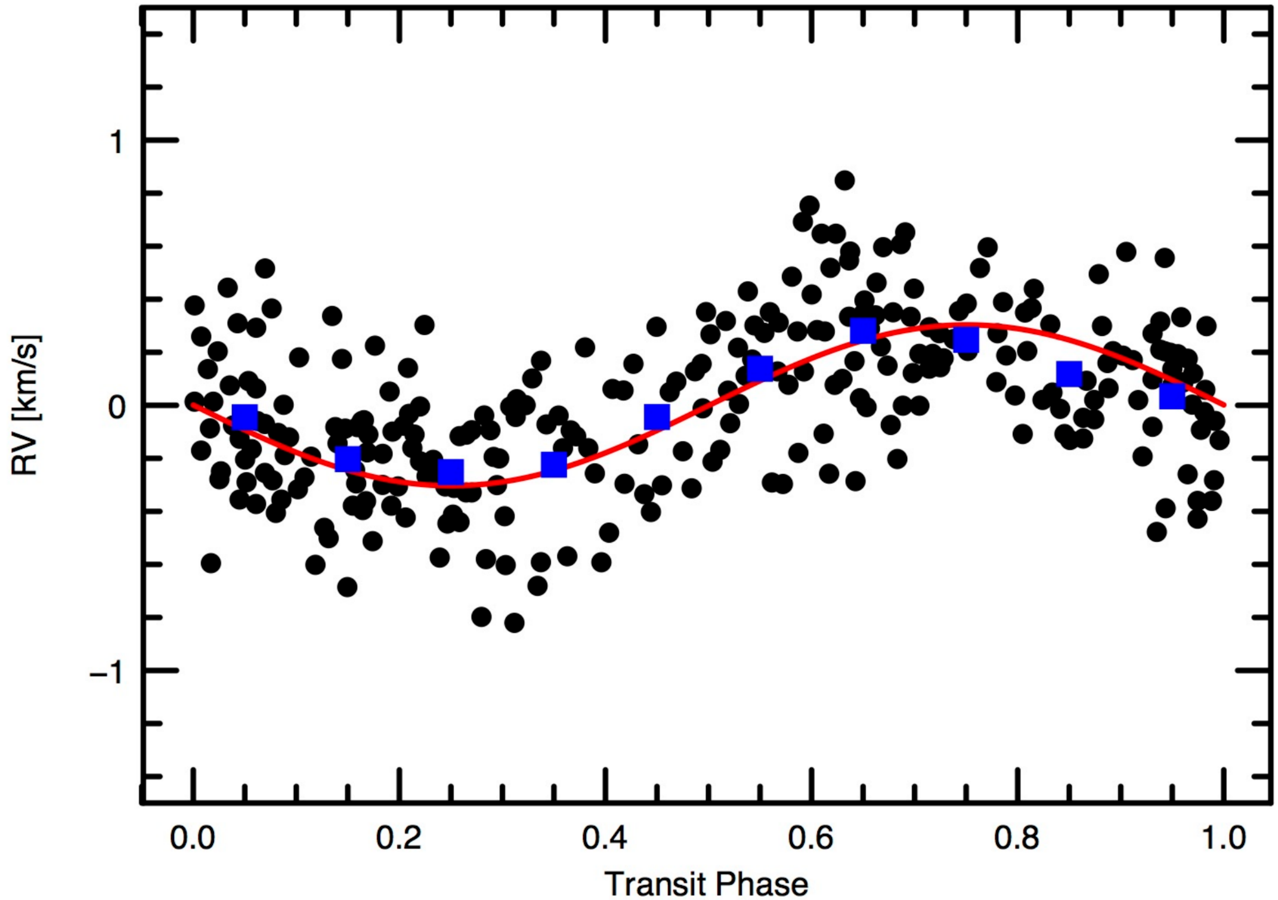
T = effective temperature of the star

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
  $\rightarrow$ stellar magnitude (< 11 mag)
  $\rightarrow$ orbital period
  $\rightarrow$ accuracy of spectrograph
  $\rightarrow$ RV amplitude
- important to cover the orbital period with enough data points

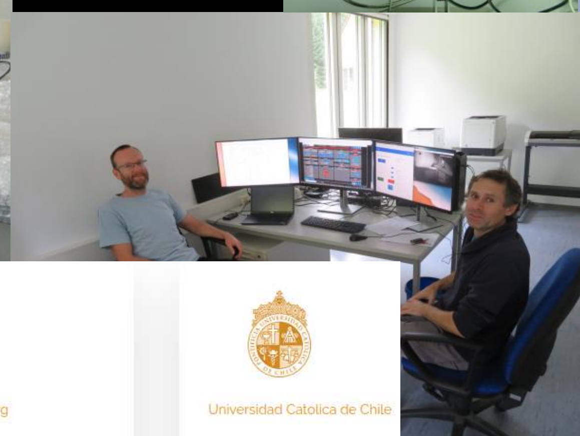
Project:

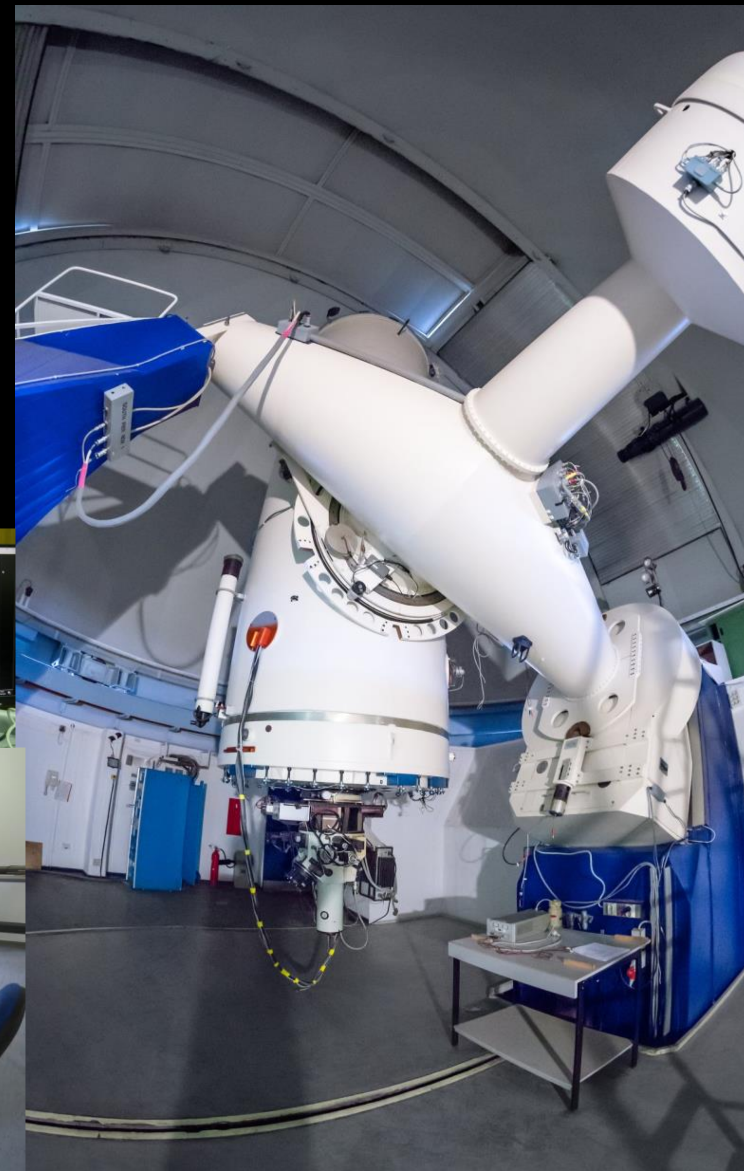
$\Rightarrow$ Do spectral follow-up of a hot Jupiter using Pucheros at the E152m telescope in La Silla with an Iodine cell
$\Rightarrow$ Determine RVs
$\Rightarrow$ Fit RV curve
$\Rightarrow$ Derive stellar parameters/ mass
$\Rightarrow$ Determine (minimum) planet mass

PUCHEROS@ESO 1.52-m

Fibre-fed Echelle-spectrograph
Wavelength range: 390-740nm
Resolution: 15000
Calibration with ThAr lamp, not simultaneously,
since a few months additonally with Iodine cell
maximum RV-accuracy: 50 m/s with only ThAr
10-20 m/s with iodine cell

Remote operation, later robotic.
80% observing time goes to the consortium.





asu
Astronomical Institute
of the Czech Academy of Sciences

TLS
Thüringer Landessternwarte Tautenburg

Universidad Catolica de Chile

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