HELIOPHYSICS

# I. Characteristics of Planetary Systems

## II. Insights into Formation


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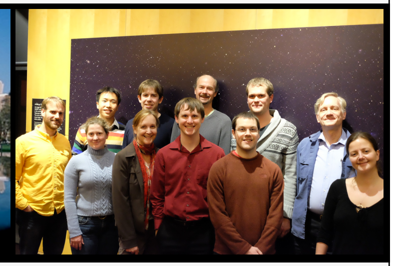


## Review of observational techniques:

Understanding exoplanet statistics requires an understanding of sample biases and observational incompleteness.

- Doppler technique
- Transit technique
- Direct imaging
- Microlensing
- Astrometry

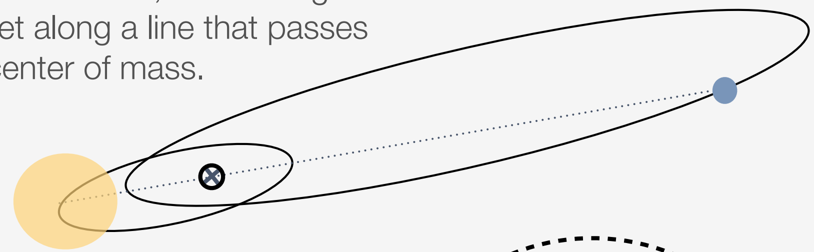
Your HW problem: sketch a plot (planet mass vs orbital period) that shows the parameter space where each of these techniques are sensitive to exoplanets.

It is not possible to understand the ensemble of exoplanets without understanding the observational biases and incompleteness. Might seem fundamental, but need the foundation to back into the important question of how to get around the stellar noise.

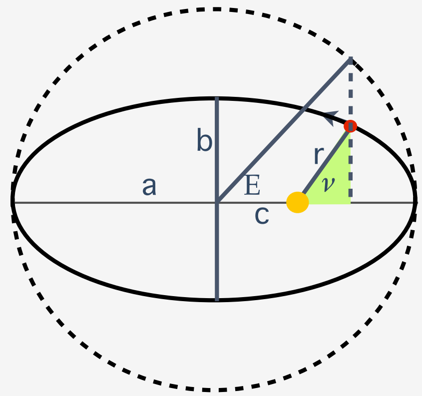
When you see Sherlock...

This is your clue that there is a question to be answered!

Gravity is a central force, connecting the star and planet along a line that passes through the center of mass.



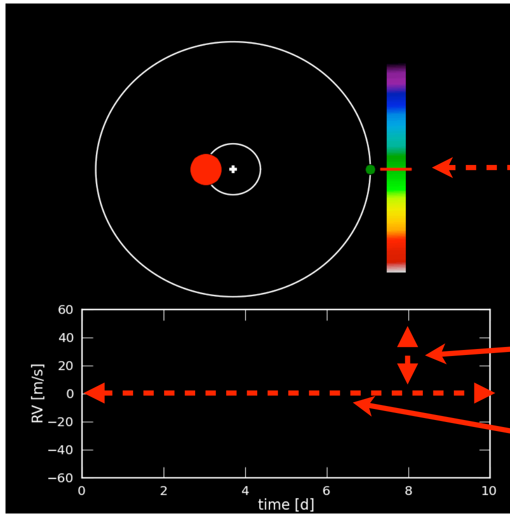
Kepler's Laws:
1. star is at the focus of an ellipse
2. equal angles in equal time intervals
3. $P^2 \propto a^3$



## The Doppler Technique

Radial velocity equation

$$K_1 = \frac{8.95 cm s^{-1}}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_\oplus} \left( \frac{M_* + m_p}{M_\odot} \right)^{-2/3} \left( \frac{P}{yr} \right)^{-1/3}$$




$$\sim \frac{M_{pl} \sin i}{M_\star^{2/3}}$$

$P_{pl}$

*animation credit: Xavier Dumusque*

Msini, so there is a limit on inclination, but not as severe as for transits.
For nearby stars, this gives us access to more planets around closer stars, and with time, access to wider orbital radii.

## Doppler Method:

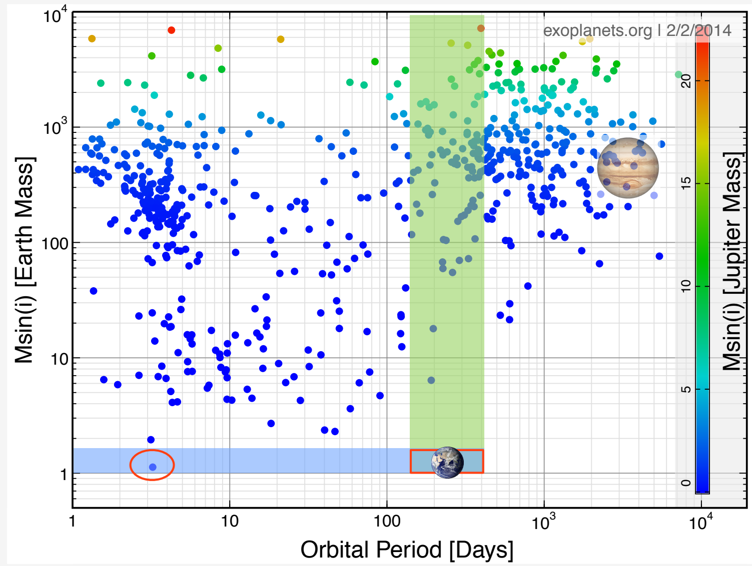
Detection of exoplanets requires extremely high precision measurements.

Jupiter: 12 m/s reflex velocity in the Sun; P =12 years
Earth: 0.1 m/s reflex velocity of the Sun; P = 1 year

The Doppler method measures line-of-site velocity component only.... the “radial” velocity (RV).

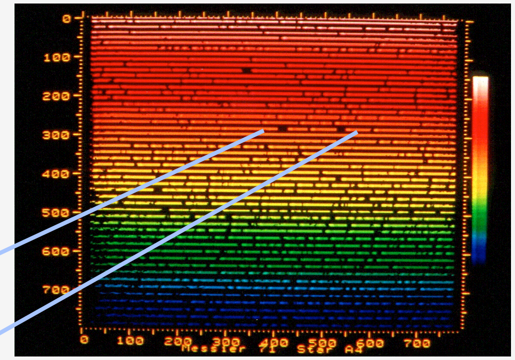
1. circular orbits produce a sinusoidal variation
2. if orbit is inclined, the RV amplitude is reduced by sin(incl)
3. need at least one full orbit to model

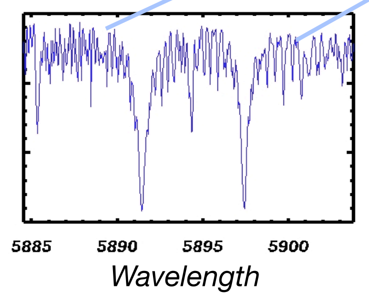
# Current Doppler detections



## Doppler Method:

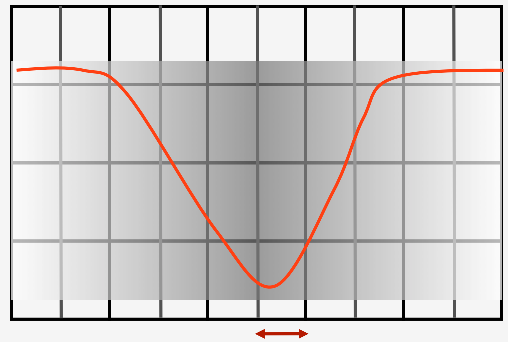
An Echelle spectrometer disperses wavelengths and records the high resolution spectrum on a CCD. We extract the 2-d data into a 1-d spectrum (intensity vs. wavelength).



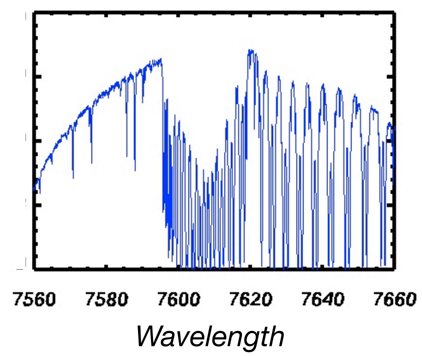


## Doppler Method

An RV precision of 1 m/s (the current state-of-the-art) requires measurement of the spectral line centroid to 1/2000$^{th}$ of a pixel.




Physical dimension: 15 $\mu$
Dispersion ($\lambda$): 0.05 A
Velocity: 2000 m/s

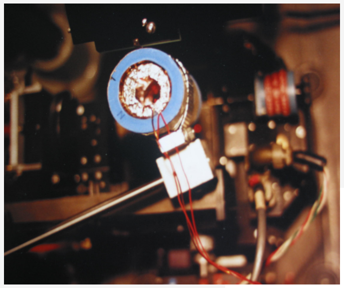



## How to measure $\delta\lambda$?

In the beginning, spectral line shifts were measured relative to telluric lines from Earth atmosphere (OH, $O_2$, $H_2O$).

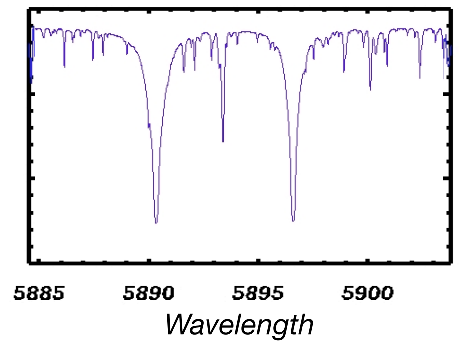
Doppler shifts relative to telluric lines are accurate to ~1/2 pixel.

What RV precision would 1/2 pixel shifts yield?
How does this compare to the precision needed for exoplanet detections?



## We impose our own reference spectrum.

Measure Doppler shifts ($\delta\lambda$) relative to the iodine absorption spectrum.

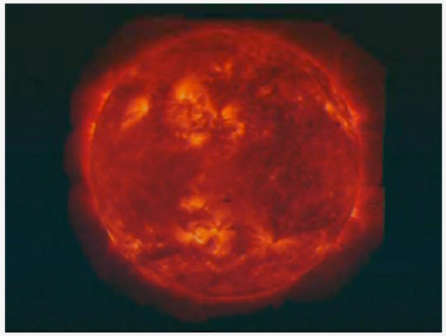


## Obstacles to higher precision:

1. Instrumental stability
   - [x] temperature, pressure
   - [x] detectors
   - [x] uniform illumination of optics
2. Information content
   - [x] SNR, spectral resolution and sampling
3. Analysis errors
   - [x] wavelength calibration (eliminate iodine)
   - [x] psf modeling
   - [x] data analysis
4. Astrophysical noise
   - [ ] pulsation, granulation, spots, activity cycles

*How do we address the astrophysical signals?*

## Astrophysical "noise"

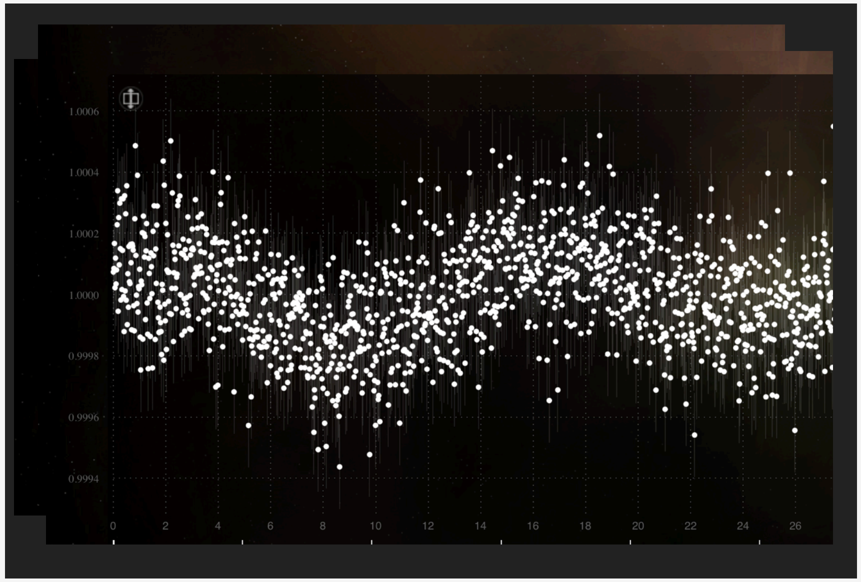


Spots, flares, meridional flows have ~km/s outflow velocities producing convective blueshifts in spectral line profiles.

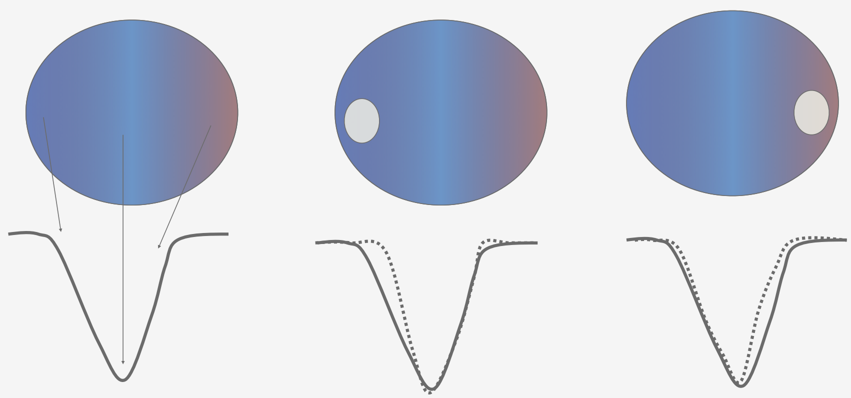
These arise from the photosphere and are not dynamical Doppler shifts.

Can we distinguish photospheric from Doppler signals?

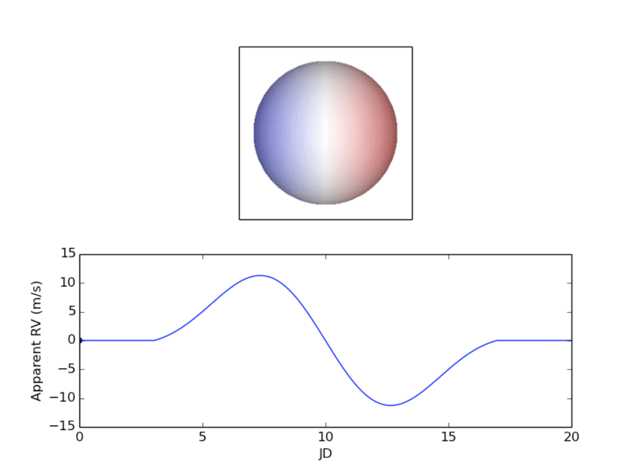
We know from *Kepler* mission that many stars are more active than the Sun.



**Star spots** are one of the most serious photospheric noise sources for exoplanet detections (similar periodicity to planets). As star spots rotate across the star, the line centroid shifts - producing a spurious Doppler shift in our model.

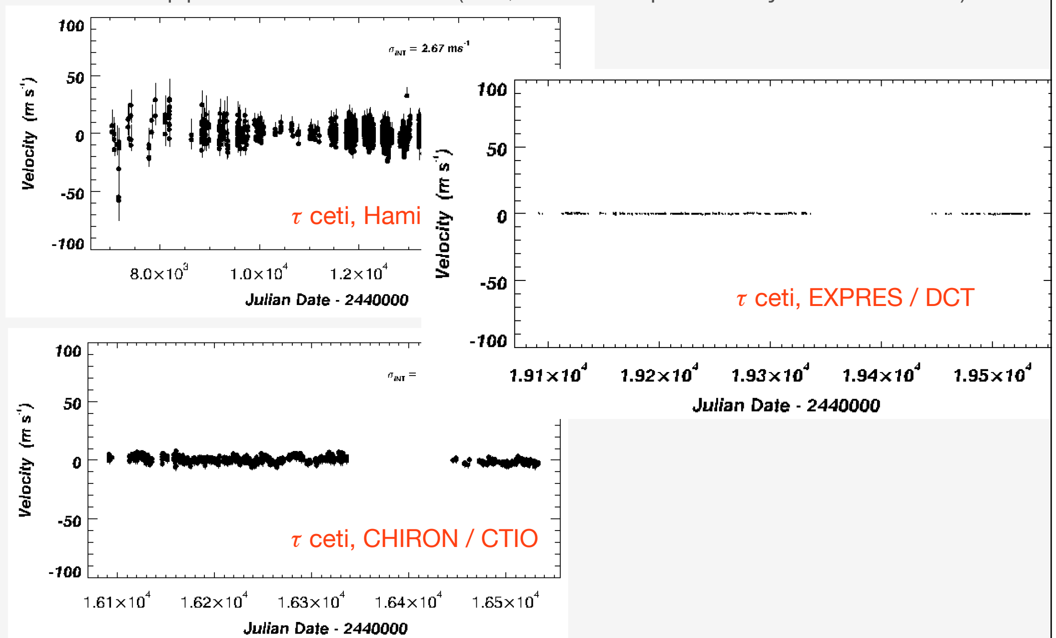


We model intensity-weighted and disk-integrated velocity perturbations from star spots on a spherical grid. Note that RV excursions are only seen during ingress / egress of the spot (this signal is found in the wings of a spectral line).

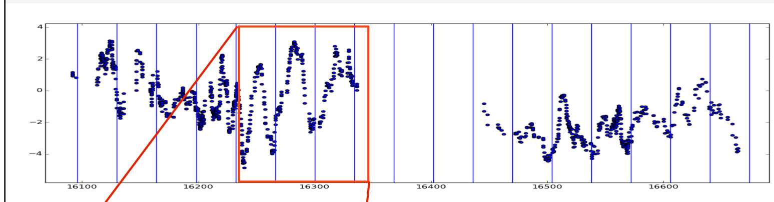



*Simulation:*
*Matt Giguere, Aida Behmard, Cyril Zhang*

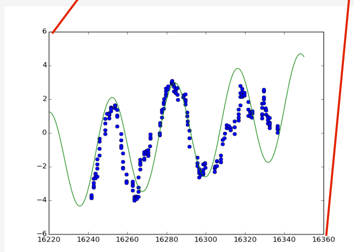
Actual Doppler data for $\tau$ Ceti (old, chromospherically inactive star).



Actual Doppler data for $\tau$ Ceti (CHIRON / CTIO). We measure the RV perturbations, but cannot resolve the stellar "noise" in the spectra.




*Periodicity = 33d (rotation period of star)*



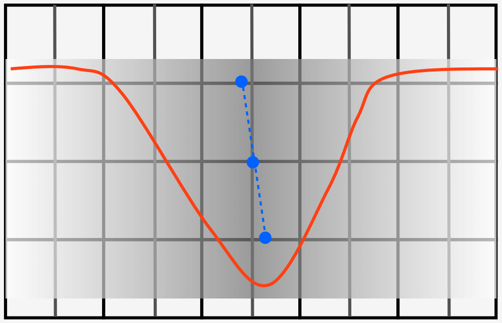

Does this look like a signal from photospheric processes? exoplanets? instrumental noise?

*Simulation:*
*Matt Giguere, Aida Behmard, Cyril Zhang*

## Solution:

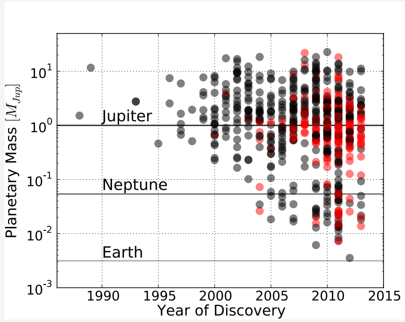
Ultimately, we need to build instruments that can resolve the stellar signals, not instruments to measure Doppler shifts.

We expect that stellar noise should be distinguishable from Doppler shifts.



# Doppler Detections

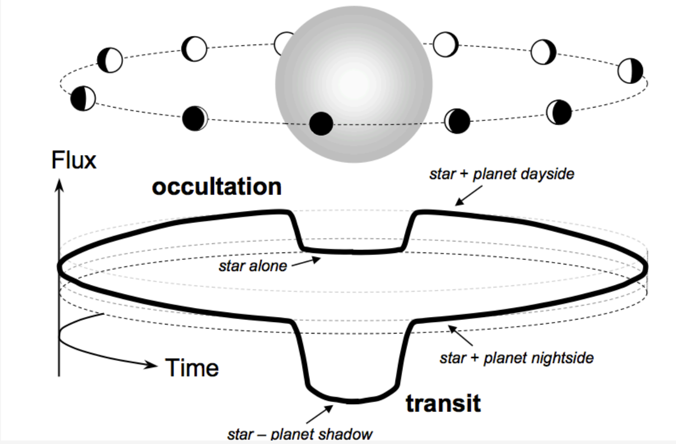
- Doppler observations favor the detection of more massive exoplanets (> $M_{Neptune}$) in closer orbits (< few AU).
- RV amplitudes are reduced by inclination, but the constraint on inclination is not very strong (i > 13° means Msini < 2 x $M_{true}$)
- At least one full orbit is required for detection.
- Current precision (1 m/s) is not sufficient to detect Earth analogs.
- Stellar "noise" limits precision with current instruments.
- More than 500 planets have been detected in the past 20 years with this technique




*RV precision has improved over time, but we need another factor of ten improvement in precision to detect Earth analogs.*

# The Transit Technique

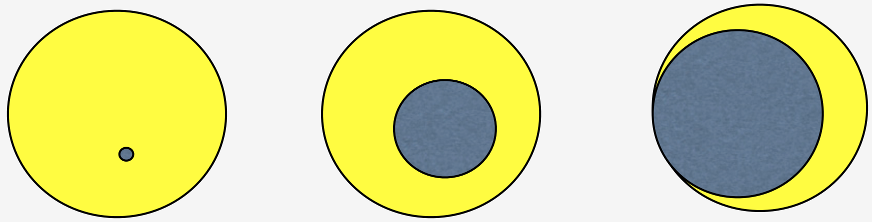
Measure the brightness of star (photometry) over time, relative to other stars.



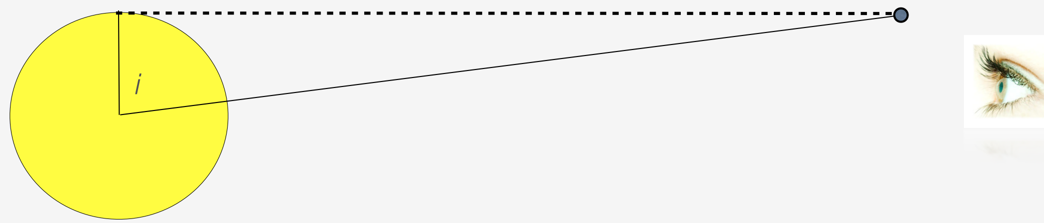

*Winn: Exoplanet Transits and Occultations, Fig 1*

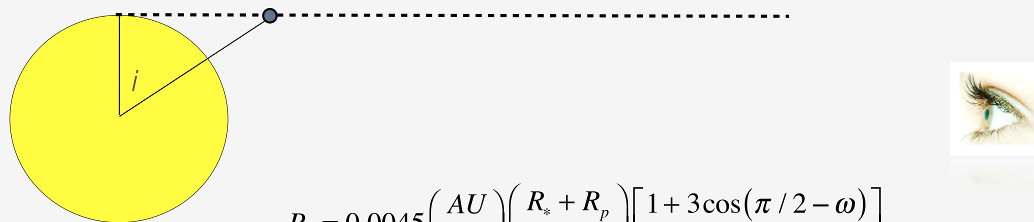
Transit depth is ~ dependent on the ratio of the planet-to-star radius.

- transits only reveal the radius of the planet (not mass)
- $R_{pl}$ depends on knowing the stellar radius accurately

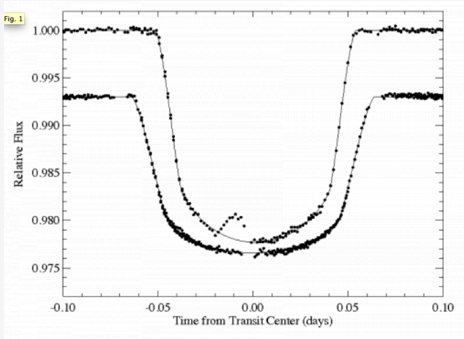


**Transit detection** is most favorable for close-in orbits. For planets in wider orbits, the inclination is highly constrained to be close to 90 degrees




$$P_{tr} = 0.0045\left(\frac{AU}{a}\right)\left(\frac{R_* + R_p}{R_\odot}\right)\left[\frac{1+3\cos(\pi/2-\omega)}{1-e^2}\right]$$




*TrES-1 (with a starspot crossing!)*

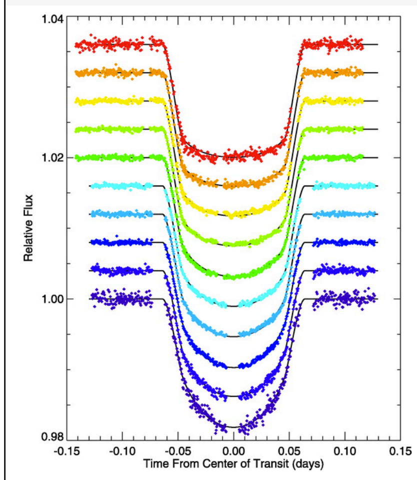
*HD209458*

*Winn 2010, Seager & Mallen-Ornelas (2003)*

The following parameters can be determined from a light curve with two or more eclipses:

$M_{star}$, $R_{star}$, $R_{pl}$, a, i

Stellar variability limits photometric precision - important for smaller planets with comparable photometric depths as the spot signals.



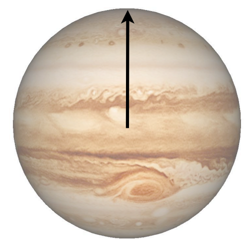

922 - 1019 nm
825 - 922 nm
727 - 824 nm
629 - 726 nm
532 - 629 nm
512 - 567 nm
458 - 512 nm
403 - 512 nm
348 - 402 nm
293 - 347 nm

*Knutson et al. (2007) HST multi-band observations of HD 209458.*

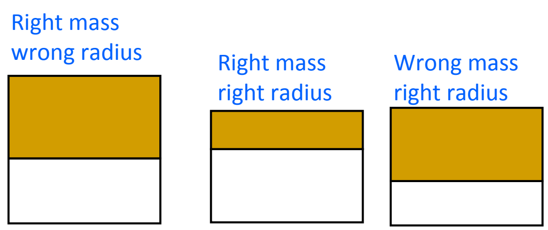
Why do these HST transit curves of HD 209458 have a different shape at different wavelengths?

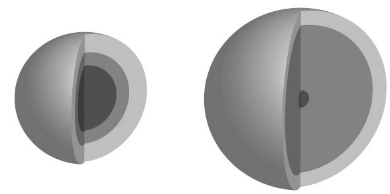
At red wavelengths, the star is a uniform disk; at blue wavelengths limb darkening decreases flux at edges so transit appears more gradual.

Planet radius (transits) + planet mass (Doppler measurements) reveal the density of the exoplanet.



For each assumption of core and mantle composition, the mass and radius constraints provide a unique interior model.



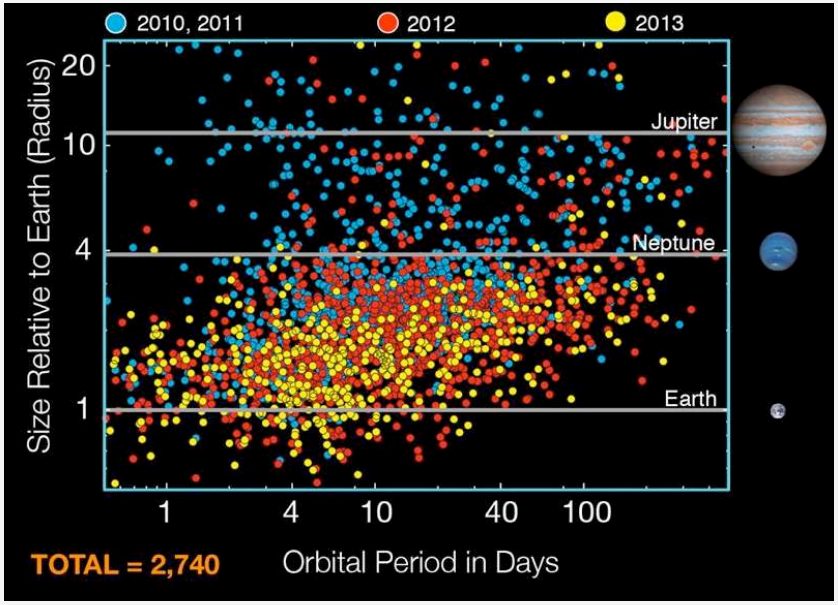
How would orbital eccentricity and orbit orientation affect the transit duration and the probability of detecting a transit?

Could atmospheric circulation in the planet affect the transit light curve?

How do star spots affect the transit light curve?

How would limb darkening affect the transit light curve?

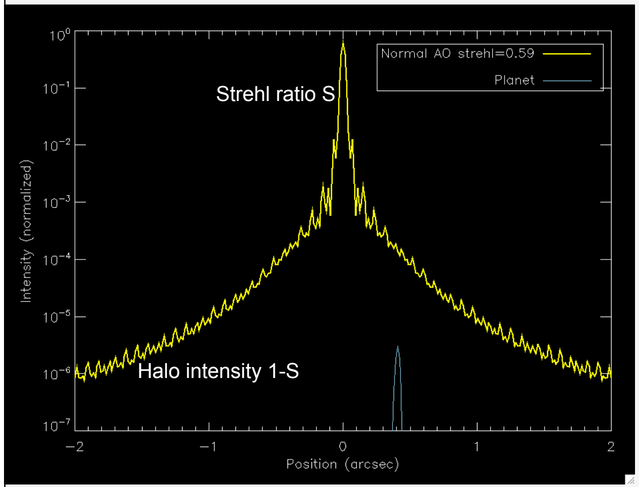
1. gets planet closer to star if omega is right. 2. good circulation – decreases the transit depth and makes the planet look smaller. 3. add noise – can be used to deduce coplanarity w/o RV. 4. rounds the curve for blue wavelengths


2010, 2011
2012
2013
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
TOTAL = 2,740
Orbital Period in Days

## Transit Detections

- Transit observations favor the detection of larger exoplanets in closer orbits.
- The constraint on sin(inclination) is very strong ($i > 86^o$).
- At least three orbits are generally required for detection.
- Current precision is not sufficient to detect Earth analogs.
- Stellar “noise” limits precision even with Kepler to $R > 2R_E$.
- The combination of RV measurements + photometry yield density - a very powerful combination.
- A few hundred transiting planets have been found with 15 years of ground-based searches and ~1000 were found with 4 years of Kepler data.

**Direct Imaging Technique:** suppress the light of the star to image the faint orbiting planets.




This is a simulation of a generic AO system. Currently with adaptive optics systems, while some of the light is concentrated into a nice PSF core, the remainder is scattered into a broad halo.

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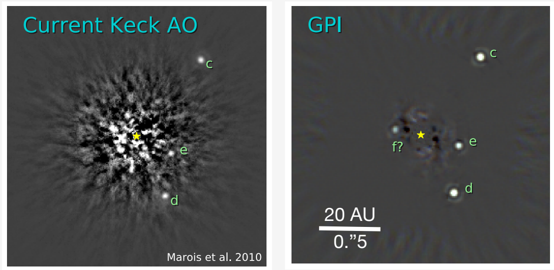
HR8799 system (simulation)

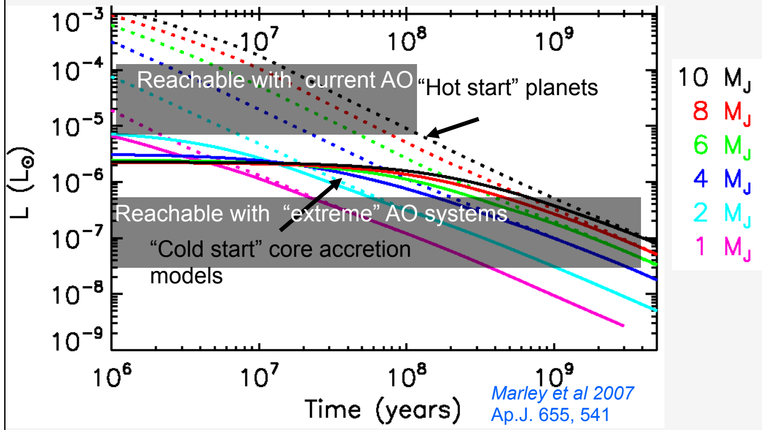



*Macintosh et al 2012 Proc. SPIE 8446*

Distances determined by parallax, then the physical separation is the angular separation times distance.

$$\alpha = \frac{a\ [AU]}{d\ [pc]}$$

Need bright exoplanets (gas giants) separated by 0."2 - 2".

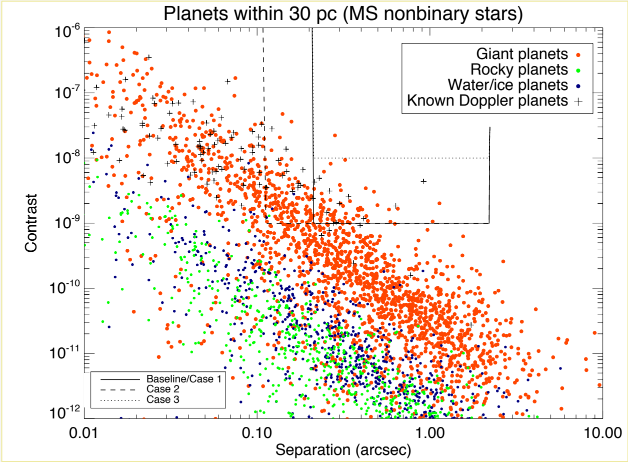



The curves show luminosity vs time for planets of various masses (solid and dashed represent different initial conditions).

At the $10^5$ level, we can only planets < 100 Myr or so.

Next-generation "extreme" AO systems like SPHERE and GPI will reach contrasts of $10^7$, opening up more targets and allowing even lower-mass planets to be seen.

*A simulation of possible coronagraphs on the WFIRST 2.4-telescope*




*Spergel et al. 2013, "What every astronomer needs to know about WFIRST" arXiv 1305-5425*

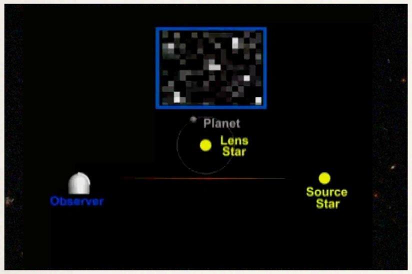
Mature planets are only visible in reflected light and are much fainter than young planets.

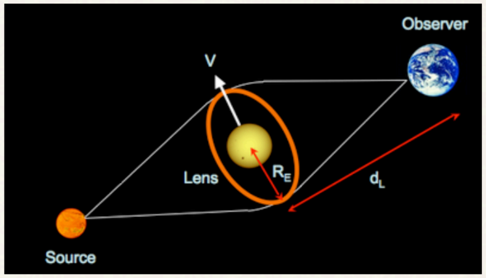
This shows a simulated population of planets in the solar neighborhood, as well as the contrast of some known Doppler planets.

## Direct Imaging Detections

- Direct imaging favors detection of younger planets.
- Star-planet separations 0."2 - 2" can be detected (2 - 20 AU for stars at 10 pc or 20 - 200 AU for stars at 100 pc).
- Common proper motion (~ few years) required for confirmation.
- Current sensitivity is to young gas giant planets.
- ~ a dozen gas giant planet candidates have been detected with orbital radii of 10-100 AU.

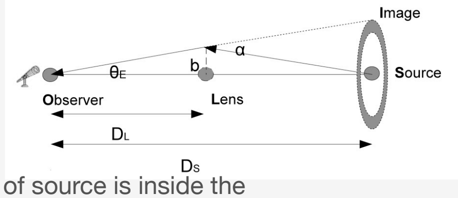
## **Microlensing Technique:** serendipitous alignment of foreground lensing star and background source star.



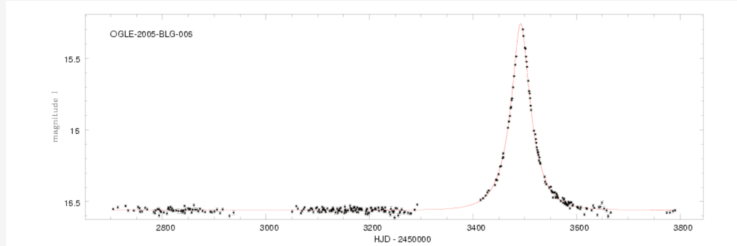




$$\alpha = \frac{4GM}{bc^2}$$

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_s}}$$




$\Theta_E$ of star is given in radians.
M = Mass of lens
As long as the angular projection of source is inside the Einstein ring of the lens, a brightening will be observed.

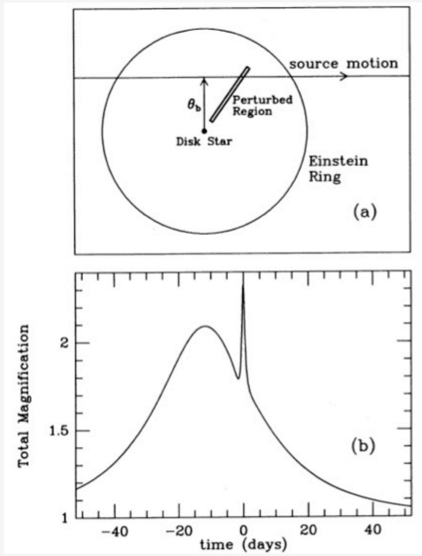



Microlensing was developed as a technique to search for dark matter.
Three model parameters: amplitude, $t_{max}$, lensing duration.

The lensing duration scales with the mass of the lens.

$$t_E = \frac{R_E}{V} = 21\sqrt{\frac{M}{0.3M_\odot}}\sqrt{\frac{D}{2kpc}}\left(\frac{200km\ s^{-1}}{V_t}\right)$$

What parameter do you think might affect the brightening (lensing) amplitude?

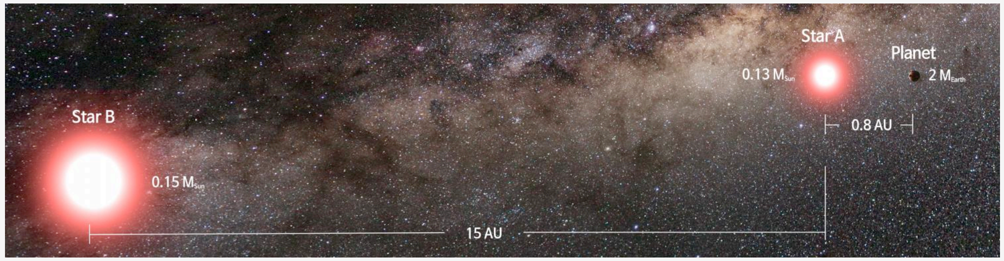



The amplitude of brightening is inversely proportional to the impact (crossing) parameter.

Not very sensitive to size or mass of the lens, so that even rocky planets can give strong brightening if fortuitous alignment; even moons might be observable!

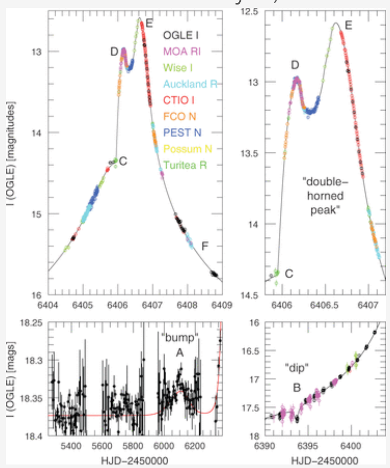
Microlensing is most sensitive to planets beyond the ice ring; limited by photometric precision of ground-based surveys.

In the news.... July 3, 2014

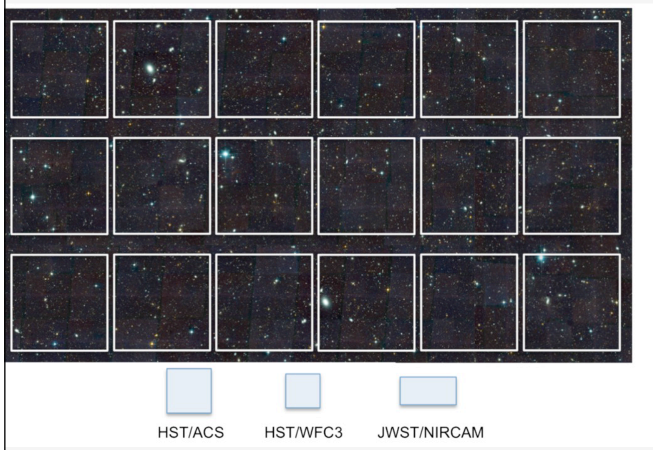


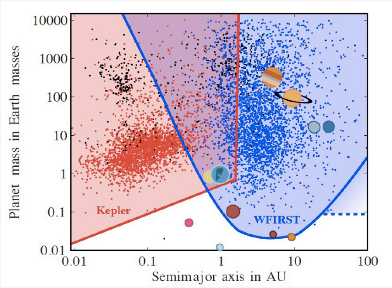

These were three lensing objects: Star A, Star B, and a 2 $M_{Earth}$ planet.
The stars are 3 kpc distant.

In the news.... July 3, 2014




Coordinated effort as observatories at different longitudes followed the microlensing event.



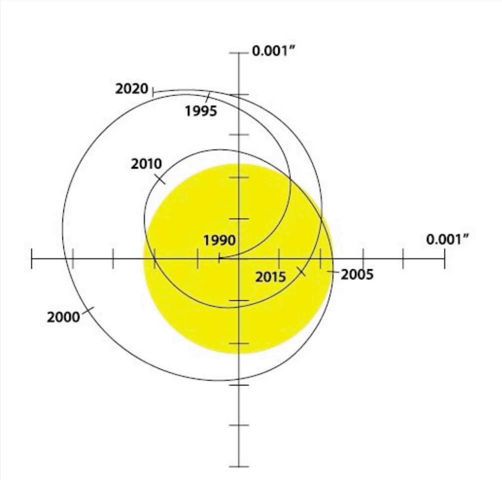

*Spergel et al. 2013,*
*"What every astronomer needs to know about WFIRST"*
*arXiv 1305-5425*

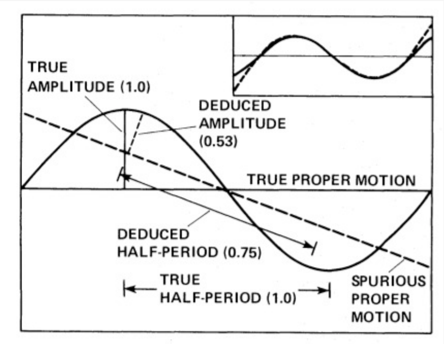
WFIRST now in the NASA plan for a launch in 202x.

## Microlensing Detections

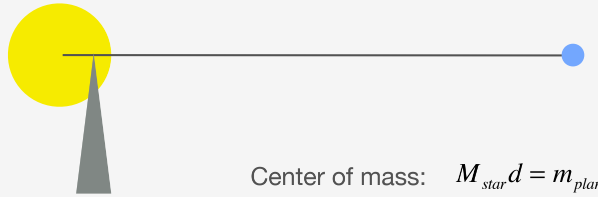
- Microlensing can detect low mass planets (little sensitivity to mass as long as the lens-source alignment is excellent).
- Often difficult (not impossible) to follow up on the lens star.
- Most sensitive to planets beyond 2 AU, so complementary to Doppler and transit observations.
- WFIRST will detect hundreds of exoplanet candidates (enormous field of view)
- ~ a dozen exoplanet candidates have been detected with microlensing.

**Astrometric Technique:** measures motion of nearby stars relative to background stars.




Need to observe at least one full period to derive the orbit.



Center of mass: $M_{star} d = m_{planet} a$

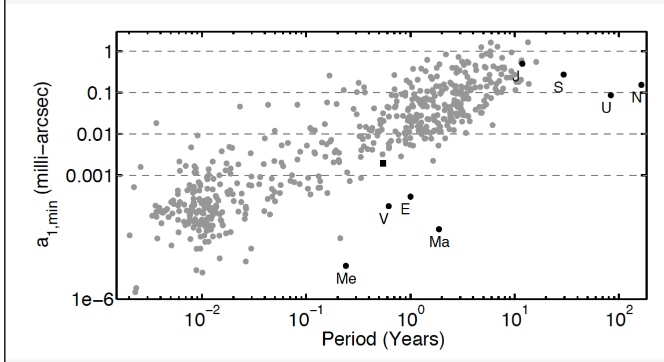
Kepler's Law: $\theta = \frac{m_{planet} a}{M_{star} d} = \left(\frac{G}{4\pi}\right)^{1/3} \frac{m_{planet} P^{2/3}}{M_{star}^{2/3} d}$

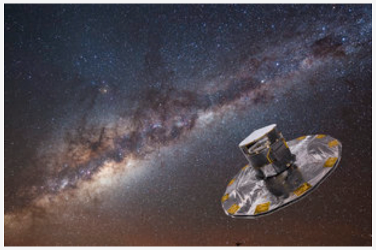
Distance matters: (angular separations $\theta = 3\mu as \frac{m_{planet}}{m_{\oplus}} \left(\frac{M_{star}}{M_{\odot}}\right)^{-2/3} \left(\frac{P}{yr}\right)^{2/3} \left(\frac{d}{pc}\right)^{-1}$

Astrometry most sensitive to long-period orbits (and need to observe at least one full period).

Astrometric orbits are 2-d. No ambiguity about orbital inclination.

Current ground-based precision: about 1 mas



Gaia: new game in town!

Launched by ESA, Gaia will measure $10^8$ stars 70 times over a 5-year period.

## Astrometric Detections

- Favor the detection of long period and massive planets (largest COM displacement of the star)
- Space-based observations needed for significant precision and sensitivity.
- no planet candidates have been detected (yet) with this technique.