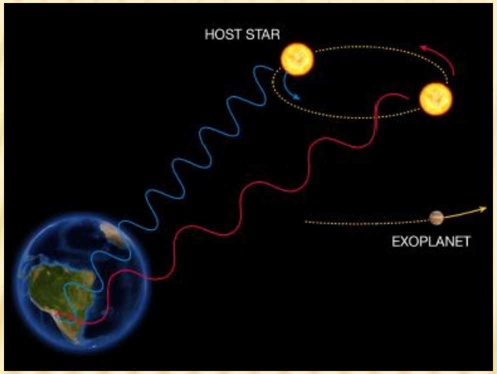
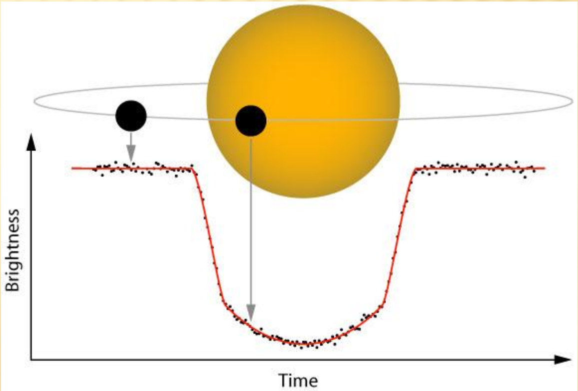
M. Barnum, L. Childers, C. Bilinski, K. Newman

TORT: TRANSIT OBSERVATION ON RV TARGETS

INTRODUCTION

Goal: Use existing database of 387 known planets with only Radial Velocity (RV) data to observe transits





Orbital Period

$M_{planet} * \sin(i)$

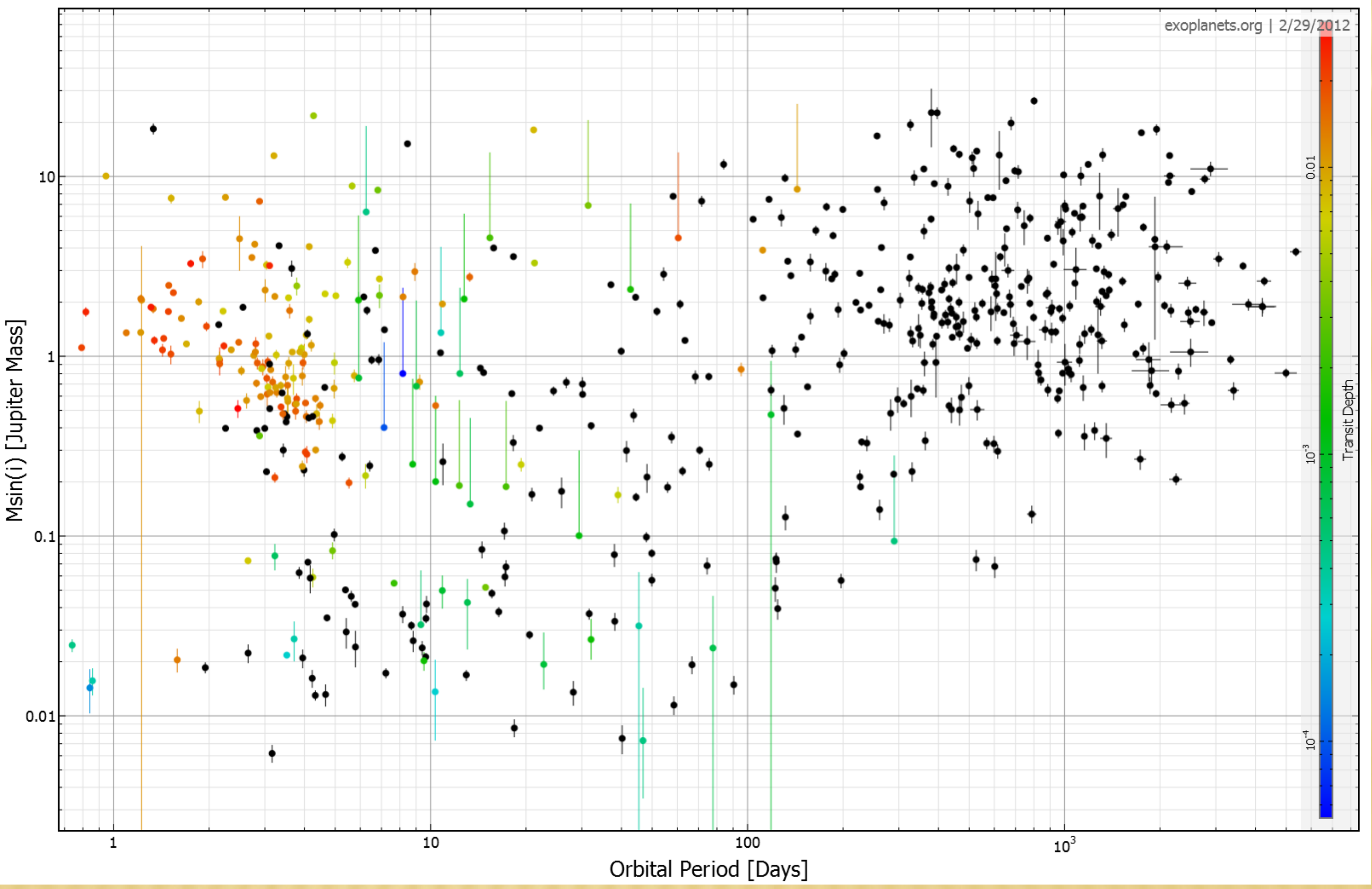
Orbit Inclination???

Radius of Planet

Orbit Inclination

Planet Mass

CONFIRMED EXOPLANETS

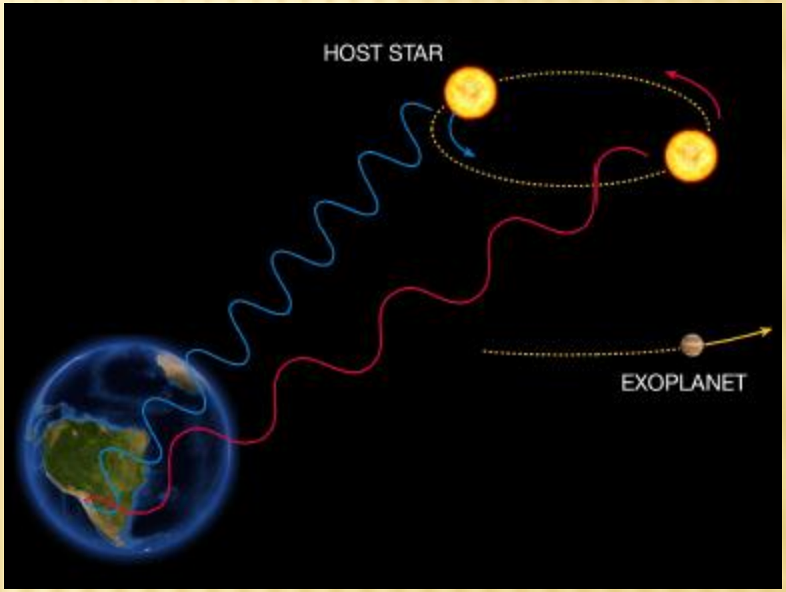


OUTLINE

1. Radial velocity and transit method overview
2. Prediction of transits
3. Estimation of transit depths
4. Noise constraints
5. Observation Plan
6. Current projects

RADIAL VELOCITY

- Star and planet orbit around a common center of mass
- Change in star velocity causes a change in its spectrum as observed from Earth
  - Doppler Effect
- Search for planets by looking for periodic shifts in stellar spectra



INFORMATION FROM RV

1. Radial Velocity formula:

$$V_{star} = \frac{V_{planet} * M_{planet}}{M_{star}}$$

2. Observed quantity is:
   + We do NOT know the orbit inclination

$$V_{star} * \sin(i)$$

3. Orbital period known from several RV measurements

$$\alpha = \sqrt[3]{\frac{P^2 G M_t}{4\pi^2}}$$

P is orbital period
M_t is combined mass of planet and star
G is gravitational constant
α is semi-major axis of orbit

4. Use Kepler's third law to determine semi-major axis of orbit

5. Then determine velocity of the planet

$$V_{planet} = \frac{2\pi\alpha}{P}$$

6. We have an estimate for planet mass as a function of orbit inclination

$$M_{planet} * \sin(i)$$

$$V_{star} * \sin(i)\,, V_{planet} \rightarrow \; M_{planet} * \sin(i)$$

GAINS ON INFO FROM TRANSIT

1. Radius of planet determined by ratio of flux inside and outside of transit

$$\frac{\Delta F}{F_o} = \left(\frac{R_{planet}}{R_{star}}\right)^2$$

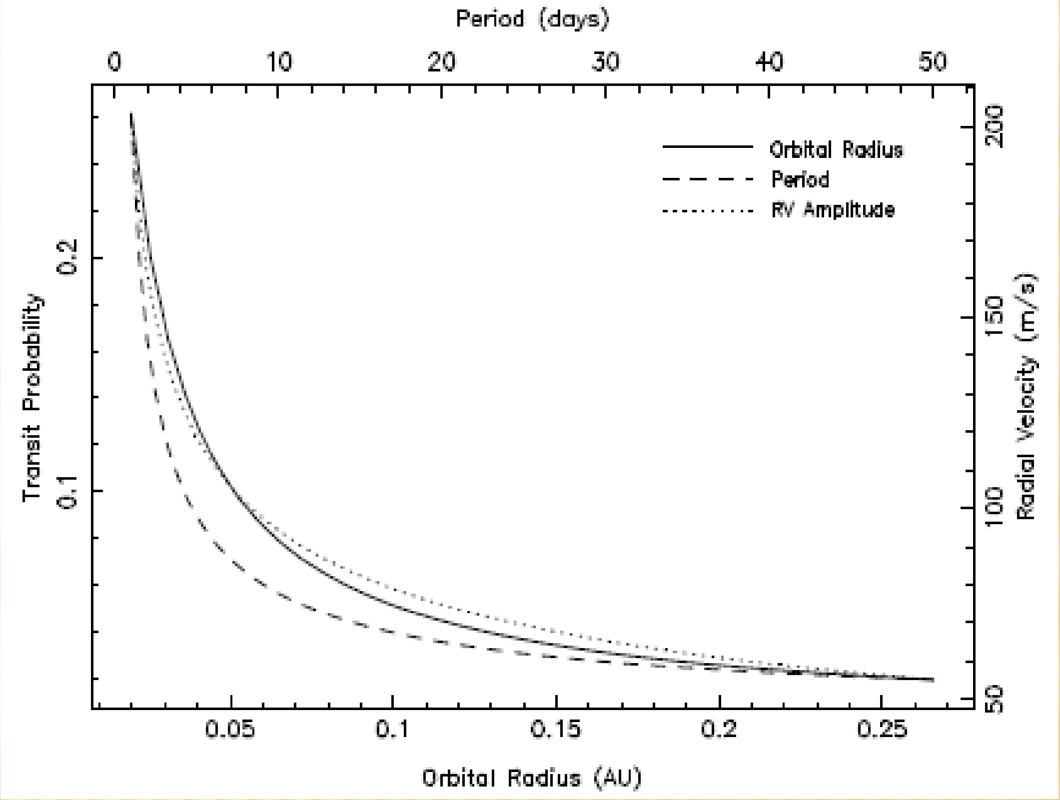
2. Inclination of the orbit determined from transit duration

$$t_d = \frac{P}{\pi}\arcsin\left(\sqrt{\frac{\left(R_p + R_*\right)^2 - (acosi)^2}{a}}\right)$$

3. Then solve for mass of planet using $M_{planet} * \sin(i)$ information from RV measurement

TRANSIT PROBABILITY FROM RV DATA

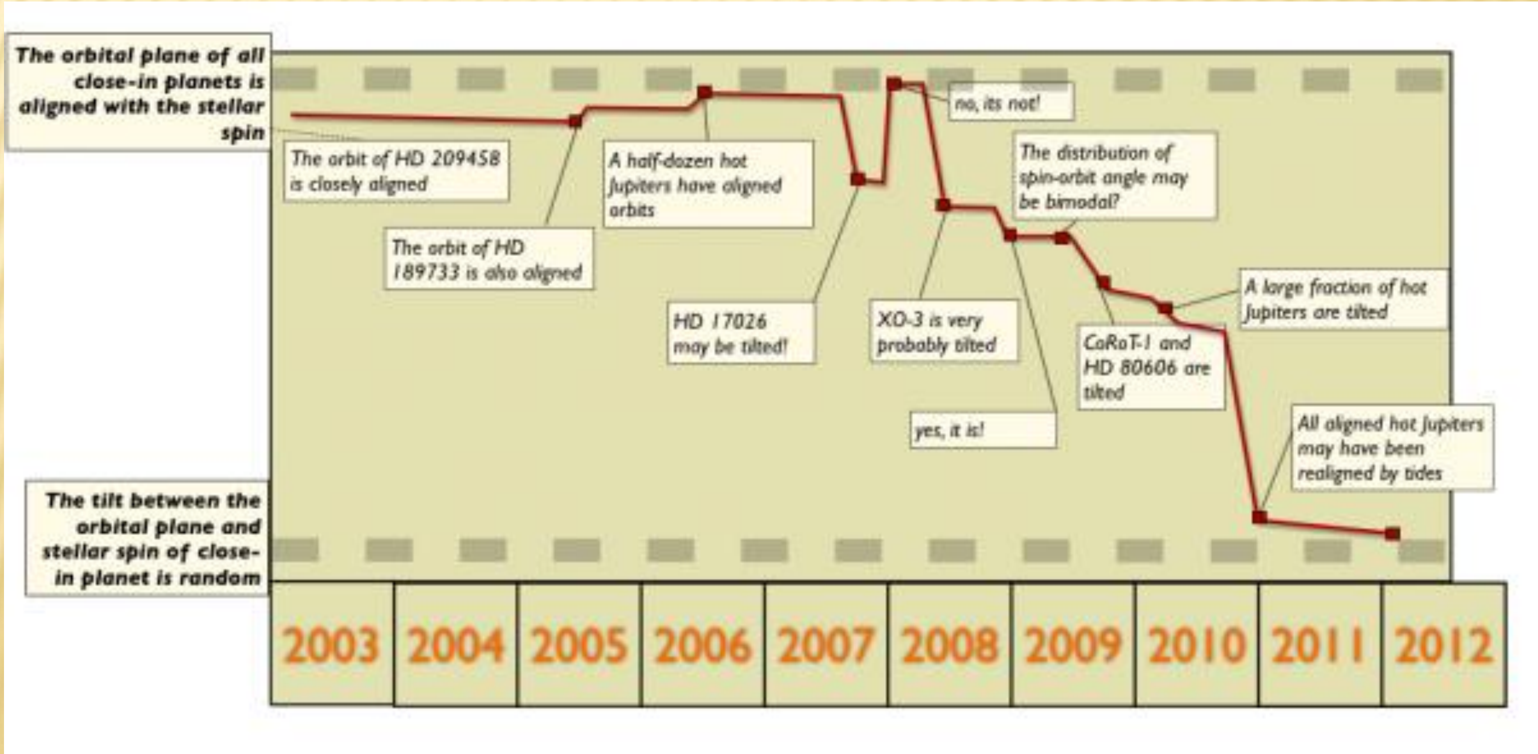
- Inclination of the orbit must be within range to observe transit
- Probability of transit mainly dependent on size of star and orbital radius
- Transit method is best for large planets orbiting at small orbital radii: “hot Jupiters”
- ~10% of hot Jupiters will transit their stars



$$P_t = \frac{(R_p + R_*)}{a(1 - e cos E)} \approx \frac{R_*}{a(1 - e cos E)}$$

SPIN-ORBIT RELATIONSHIP

- If there is a relationship between stellar spin and planetary orbit inclination, it could help us confine the probability of transit!
- Spin-Orbit relationships also provide evidence for planet migration theories!
  - Do disk-planet interactions, or planet-planet interactions, cause the migration of large planets towards their stars?

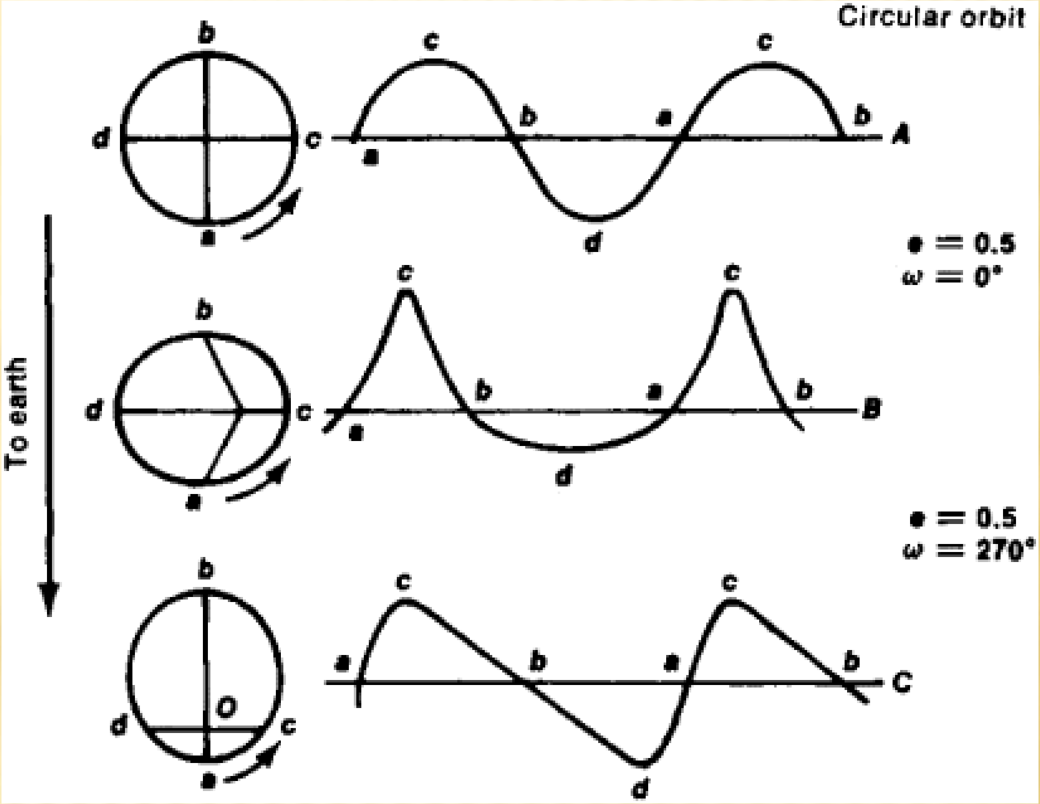


SPIN-ORBIT RELATIONSHIP

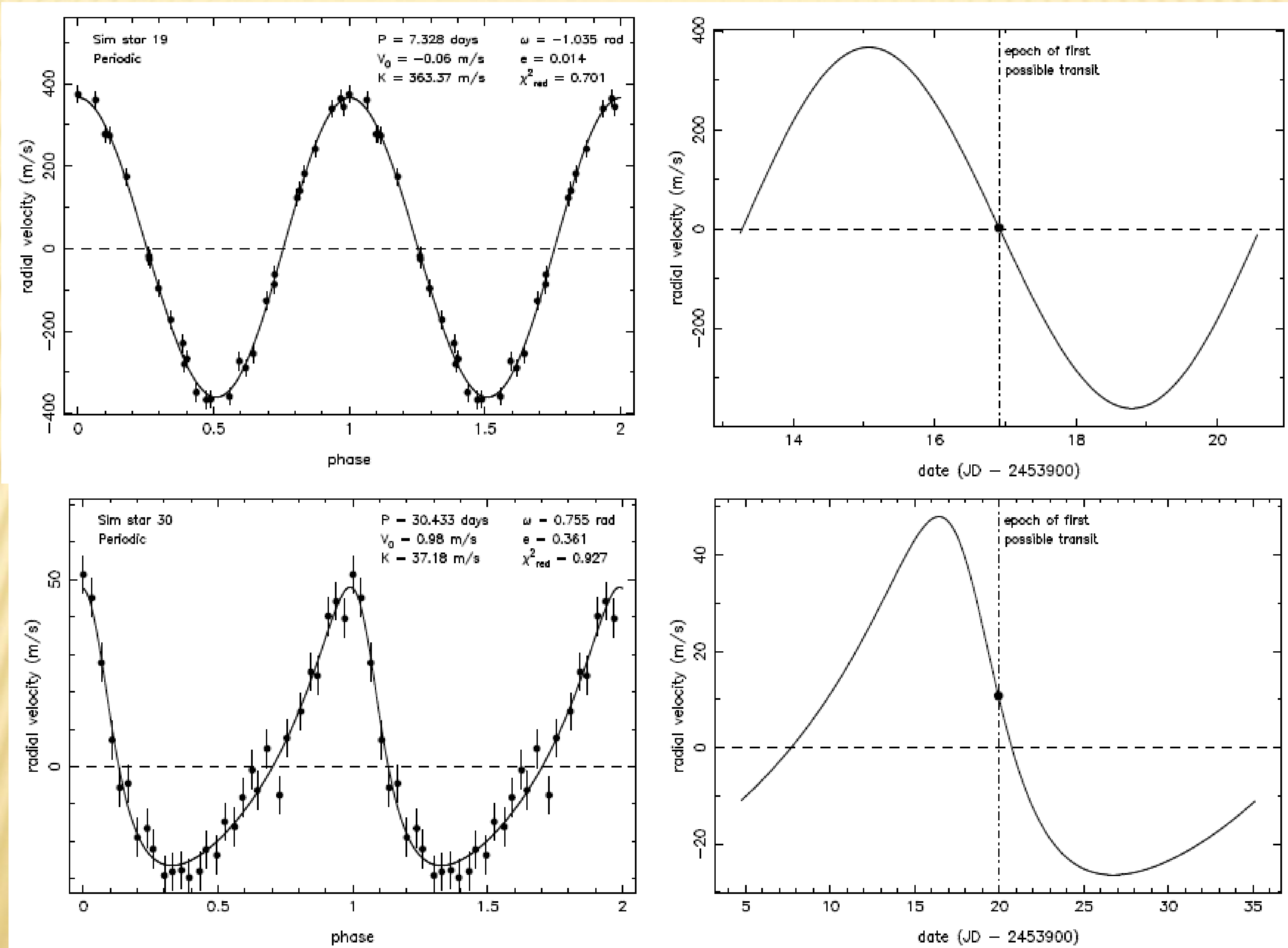
- Initial data from Rossiter-McLaughlin measurements showed a few hot Jupiter orbits aligned with stellar spin
- More recent measurements have a trend in favor of spin-orbit misalignment. If this is true, there could be a greater probability for transit if the stellar spin axis is perpendicular to our line of sight.
- There is not enough evidence to show a strong relationship, so it will not affect our follow-up observations. If there were a strong relationship, there would still be some probability for transit around any star.

EPOCH OF TRANSIT

- For purely circular orbit, transit is predicted when radial velocity of star is zero and decreasing
- Usually good approximation; hot Jupiters tend to have orbits with near-zero eccentricity due to effects of tidal circularization



EPOCH OF TRANSIT



EPOCH OF TRANSIT

- The error in estimating the epoch of transit is based on the error in the period and the number of elapsed orbits since the last RV measurement
- For a Jupiter-size planet with a 4 day period and a 10° uncertainty in the argument of periastron, the predicted epoch of transit can be off by as much as three hours
- Can estimate transit duration based on RV data

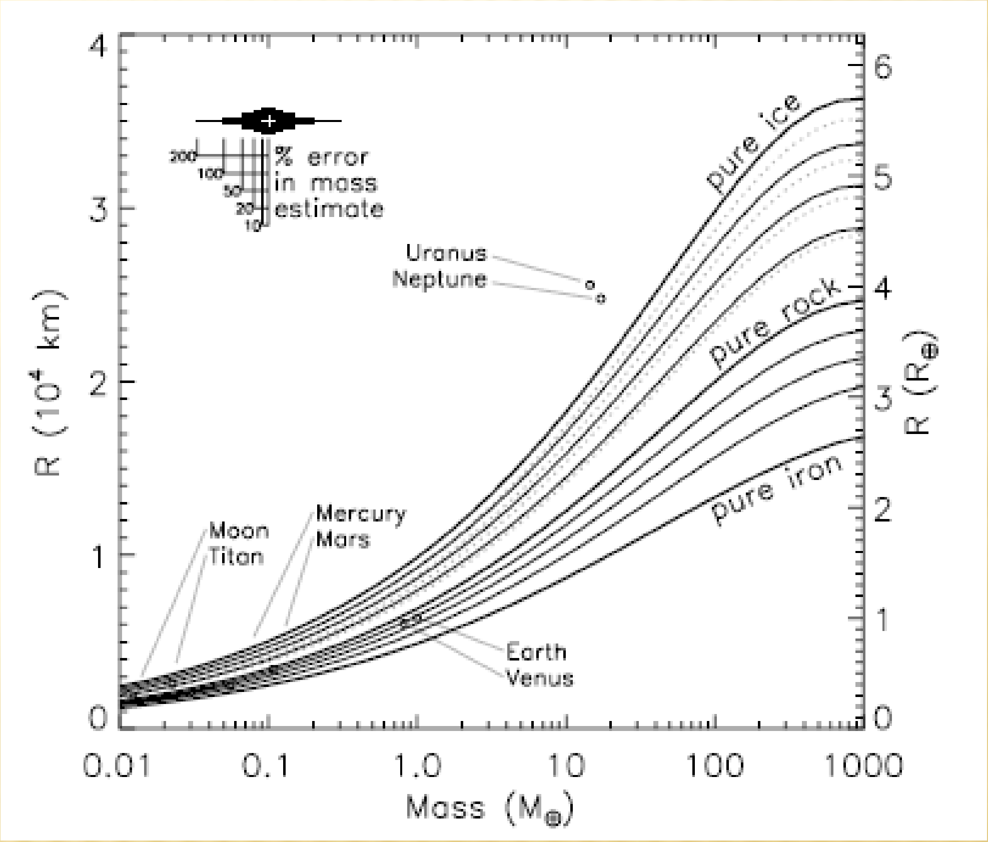
EXPECTED TRANSIT DEPTH

- Obtaining transit depth estimates boils down to making radial estimates of observable planets
  - $transit\ depth = \left(R_{planet}/R_{star}\right)^2$

- Planetary Radii depends on multiple factors:
  - Mass
  - Composition
  - Age of parent star
  - Presence of Core (or lack thereof)
  - Stellar Irradiation (Hot Jupiters)

LOW MASS PLANET ASSUMPTIONS

- Assumption #1 – Assume there's a transit for a particular RV measurement
  - $Msin(i)$ reduces to M
- Assumption #2 – Planet composition ~33% iron, 67% rock
  - Similar to Earth composition
  - Good up to $\sim 15 M_{\oplus}$



LOW MASS PLANET ASSUMPTIONS

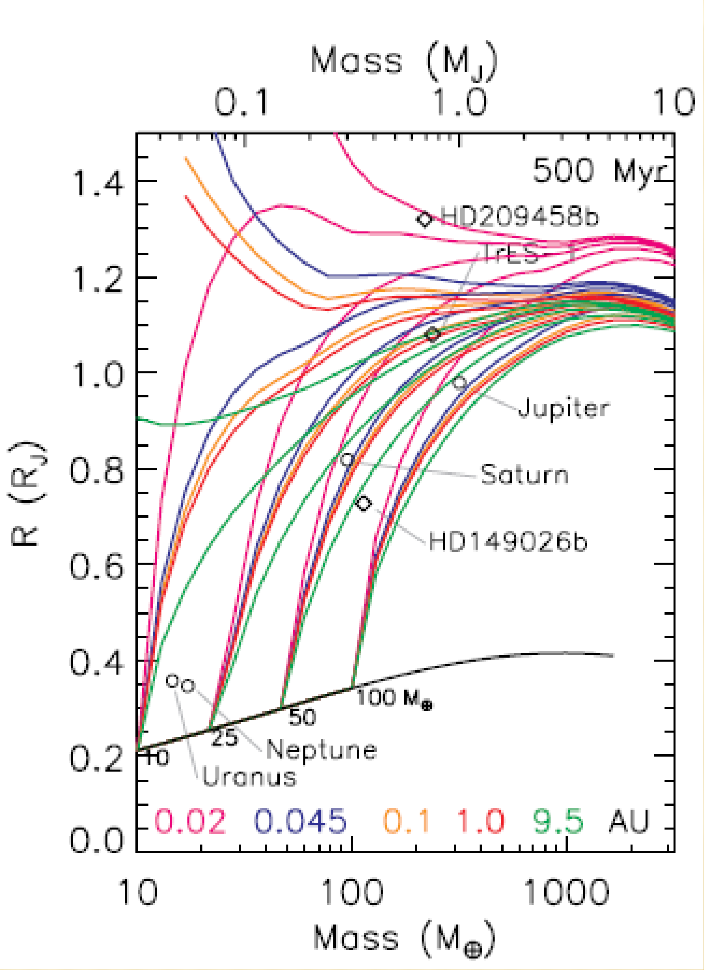
- Ice/Rock Composites
  - $R = (0.0912imf + 0.1603)(logM)^2 + (0.3330imf + 0.7387)logM + (0.4639imf + 1.1193)$

- Rock/Iron Composites
  - $R = (0.0592imf + 0.0975)(logM)^2 + (0.2337imf + 0.4938)logM + (0.3102imf + 0.7932)$

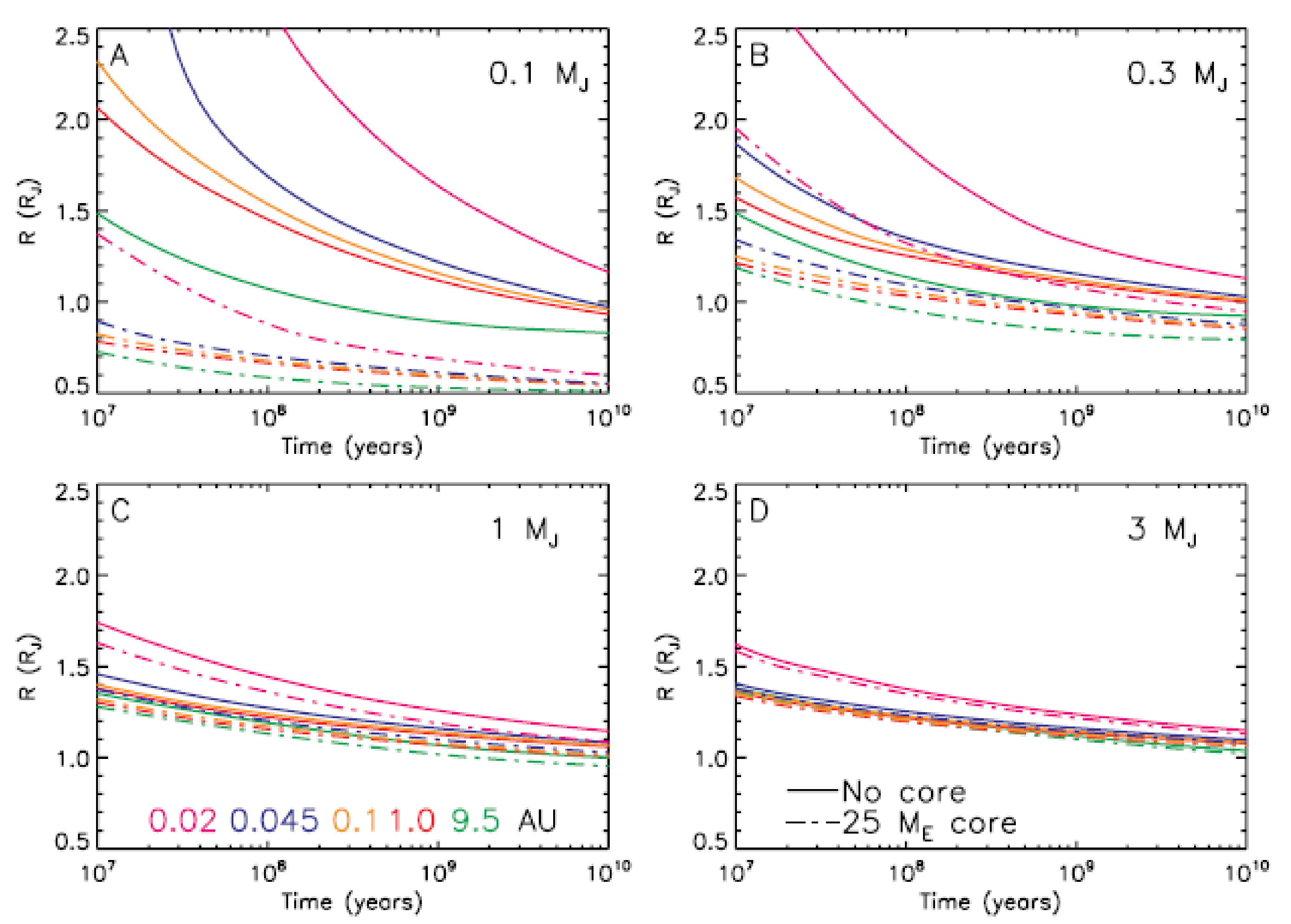
HIGH MASS PLANET ASSUMPTIONS

- Assumption #1 – Above $\sim 50 M_{\oplus}$, planet radii stagnate at $\sim 1 R_J$

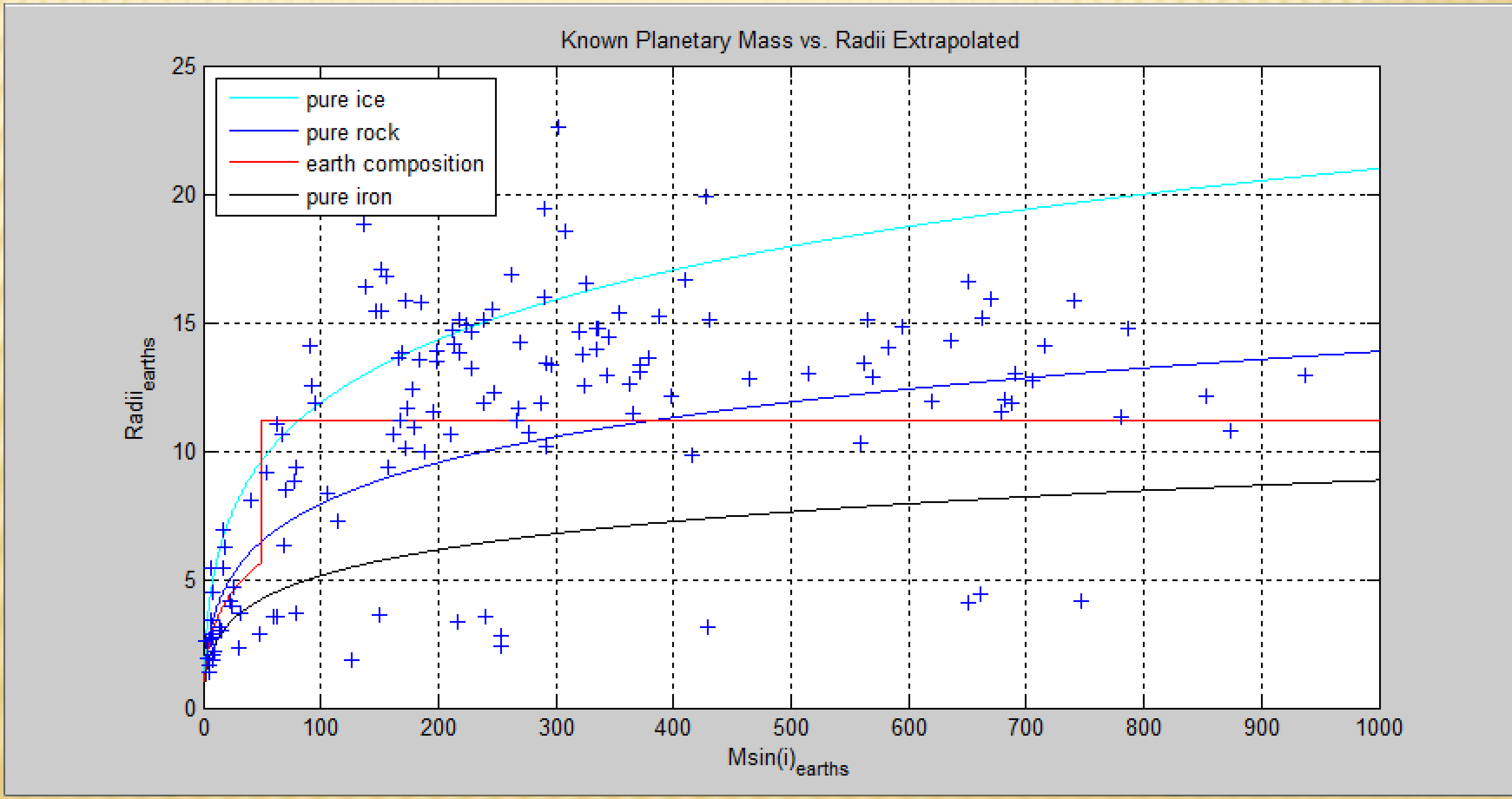
- Factors to Consider
  - Core Size
  - Stellar Irradiation
  - Orbital Size
  - Parent Star



PARENT STAR CONSIDERATIONS



Extrapolated Data



LIMITING FACTORS ON TRANSIT DETECTION

- Multiple sources of error exist, including photon noise, scintillation, tracking errors, differential tip-tilt, PSF variations, source bending, and more
- The photon and scintillation noise are the dominant concerns for our project

PHOTON NOISE

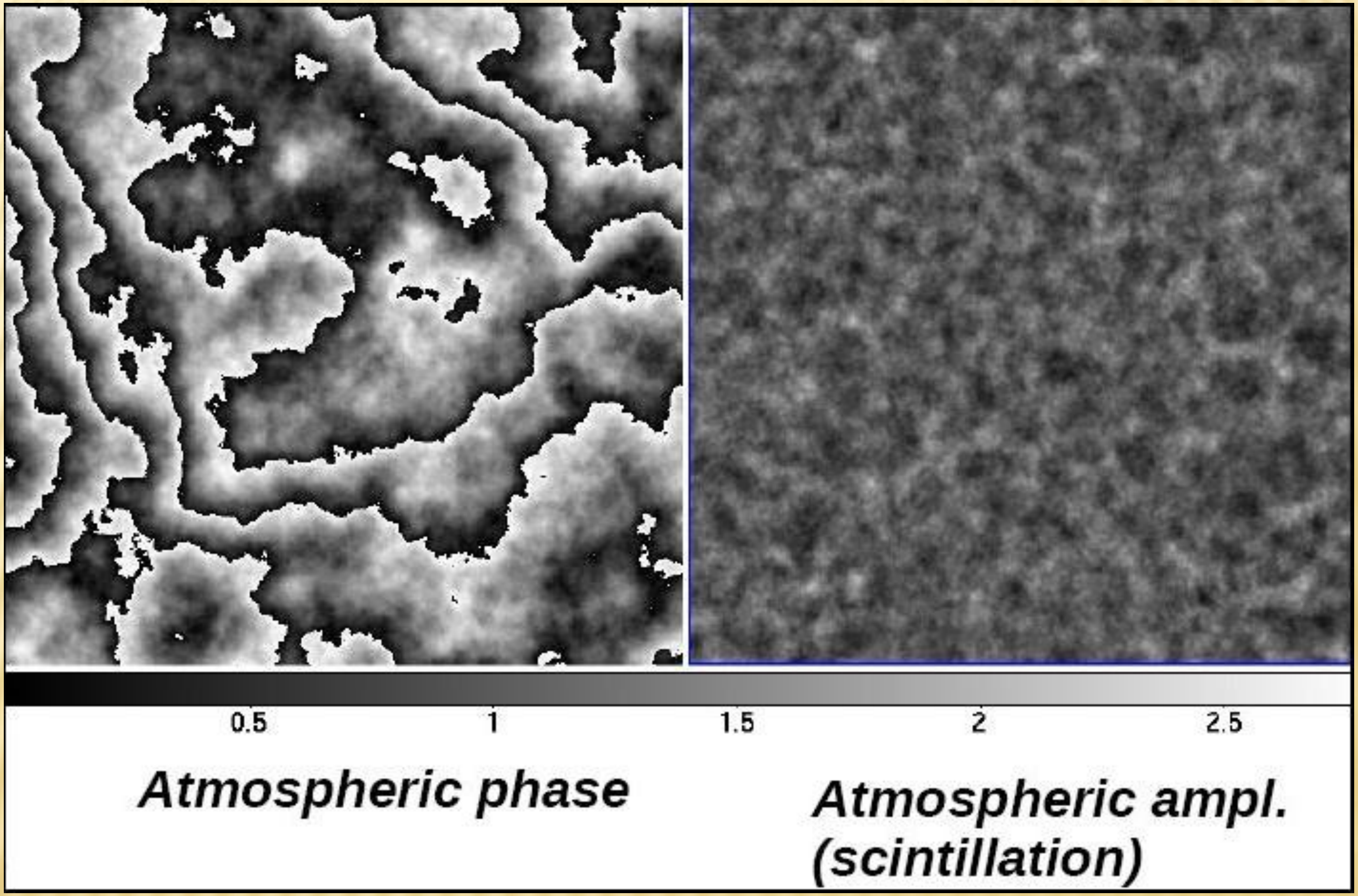
- Caused by variation of the incident photon flux
- The photons have a Poisson distribution
- Photon noise is calculated by taking the square root of the number of photons (assuming no additional instrument noise)
- In other words, the expected difference between the number of photons collected and the average is equal to the square root of the average number of photons
- To correct, must have large etendue and/or small PSF

EXAMPLE OF IMAGES WITH PHOTON NOISE

SCINTILLATION NOISE

- Caused by variations of the atmosphere's refractive index
- Wind will move these variations across the viewer's line of sight, causing intensity to change
- The most common example is of stars "twinkling"
- Can be corrected with large etendue, using multiple imaging systems, and/or multicolor imaging

EXAMPLE OF IMAGES WITH SCINTILLATION NOISE



PHOTON AND SCINTILLATION NOISE OVERVIEW

	Photon Noise	Scintillation Noise
Causes	Background and light from occulted star (moonlight scatter)	Atmospheric inconsistencies (refractive index, wavelength, etc)
Relevance	Faint Stars	Constant for all magnitudes
Corrective Action	Pixel size matched to the seeing, small PSF, large Etendue	Using large aperture, multiple observing units, increase integration time, lower airmass

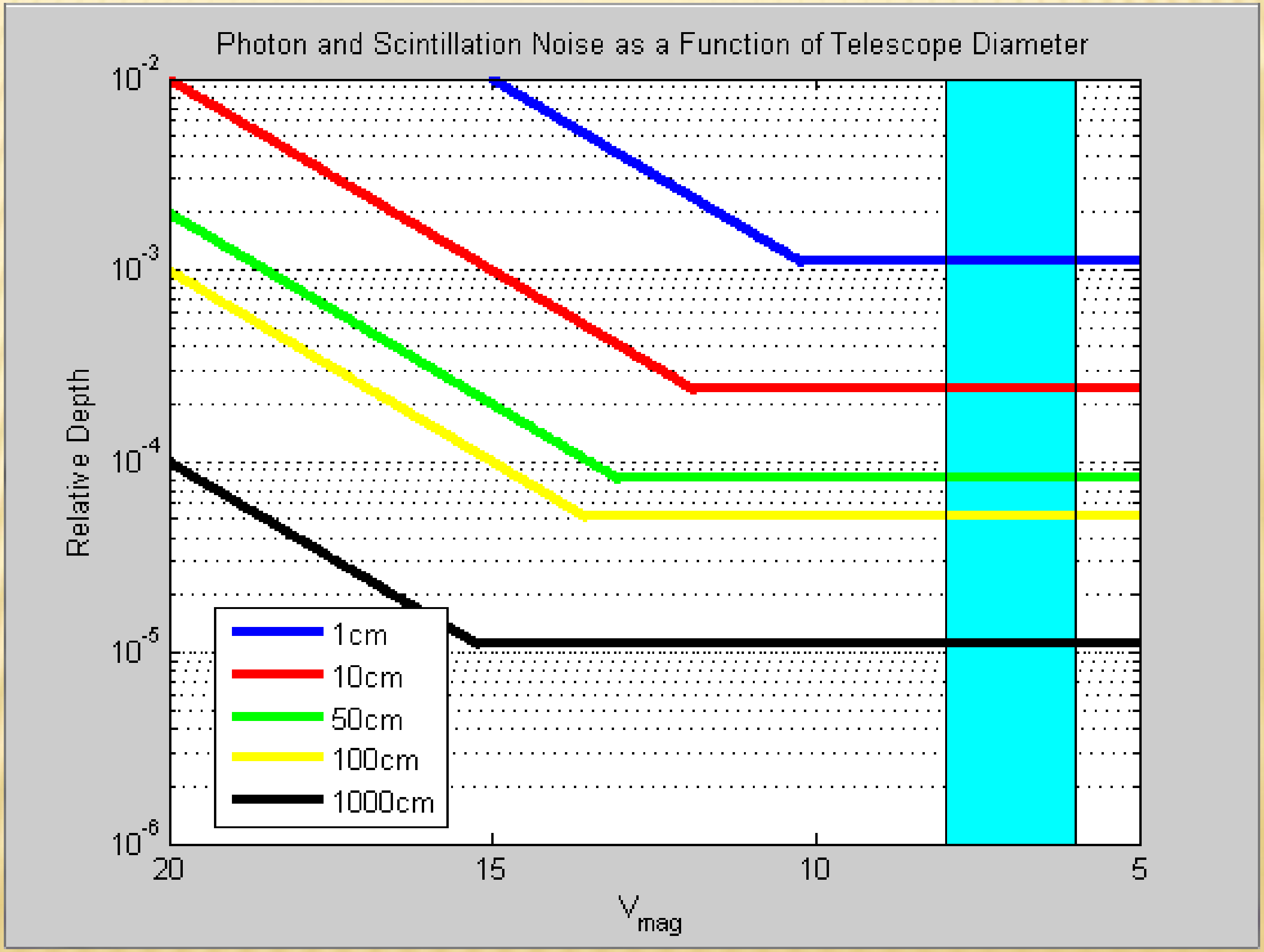
PHOTON NOISE

- $\sigma_{Photon} = \sqrt{N_{photon}} = 10^{11} * 10^{\left(-\frac{Vmag}{2.5}\right)} \pi R^2 t B$ in counts
- $R \equiv Radius\ of\ Telescope{\sim}5cm$
- $t \equiv Integration\ Time{\sim}1hour$
- $B \equiv Bandwidth = 0.088\mu m$
- Relative error of $\sim 5 * 10^{-5}$ for 10cm diameter telescope with $Vmag{\sim}7$

SCINTILLATION NOISE

- $\varepsilon = 90 * 10^{-3} \frac{X^{7/4}}{D^{2/3}\sqrt{2t}} \left(\frac{\lambda}{550}\right)^{-7/12} e^{\frac{-h}{8000}}$ in mags
- $X \equiv Airmass{\sim}1.5$
- $D \equiv Diameter\ of\ Telescope{\sim}10cm$
- $t \equiv Integration\ Time{\sim}1hour$
- $\lambda \equiv Wavelength{\sim}551nm$
- $h \equiv elevation{\sim}1000m$
- Relative error of $3.77 * 10^{-4}$ for 10cm diameter telescope

PHOTON AND SCINTILLATION NOISE



DETERMINING THE DIAMETER

- Assume a limiting relative noise that is $\frac{1}{3}$ the predicted transit depth (SNR=3)
- Determine telescope size needed to achieve this limiting condition.
  - $D = \left(90\frac{10^{-3}X^{\frac{7}{4}}}{\varepsilon\sqrt{2t}}\left(\frac{\lambda}{550}\right)^{-\frac{7}{12}}e^{\frac{-h}{8000}}\right)^{3/2}$ in cm

OBSERVATION PLAN

Diameter	Targets Achievable	Percentage	Targets Remaining
< 2 cm	257	72.2%	99
< 10 cm	290	81.5%	66
< 25 cm	308	86.5%	48
< 50 cm	314	88.2%	42
< 1 m	326	91.6%	30
< 2.5 m	331	93.0%	25
< 5 m	335	94.1%	21
< 10 m	340	95.5%	16

Measurements in Johnson V-band, centered at 551nm with FWHM of 88nm

FIELD OF VIEW LIMITATIONS

- Desire ~10 stars of similar magnitude in the field of view for calibration
  - 129889 stars in the magnitude range 5-10 for V band according to SIMBAD.
  - 41253 square degrees in the sky
  - $\frac{\sim 3.2 stars}{sq.degrees} \Rightarrow$ hope for Field of View~3sq. degrees

FIELD OF VIEW LIMITATIONS

- Small Telescopes generally have a rather large apparent field of view
  - Don't need to worry about eyepiece field of view restrictions (not using an eyepiece for imaging)
  - Detector size potentially an issue to address:
  - $FOV = \frac{w_D}{D_T f\#} \approx 0.57°$
    - $w_D = detector\ width\ (\sim 5mm)$
    - $D_T = diameter\ of\ telescope\ (\sim 10cm)$
    - $f\# = focal\ ratio\ (\sim 5)$
  - Need fast (small $f\#$) and small diameter telescopes and larger detectors or we will have to work with fewer than optimal amounts of calibrators in the FOV

AMATEUR ASTRONOMY APPROACH-PROBLEMS AND CHALLENGES

- Amateur astronomers with access to a plethora of small telescopes may not be set up for precision photometry, requiring:
  - Careful data analysis
  - Custom algorithms
- An array of unique telescopes are being used
  - Unique errors may arise from each telescope
  - Locations of observation will vary, therefore atmospheric conditions may not be ideal

AMATEUR ASTRONOMY APPROACH-POSSIBLE SOLUTIONS

- Outsourcing
  - Provide easy access tutorials
  - Provide algorithms and pipelines amateurs may utilize to process their own data
  - Provide contact (email) service for aid
  - Provide an open conference for amateur astronomers to attend (physically or remotely)
- Amateurs may upload to an online database
  - Further analyze objects of interest more carefully ourselves to verify results
  - Database not too large so we could keep it online and do our own verification without too much trouble

PESKY PLANETS

- 8.4% of planets would be difficult for amateurs to observe
- Need larger (>1m), higher power telescopes to make observations
- Request time on existing telescopes

SECONDARY OCCULTATIONS

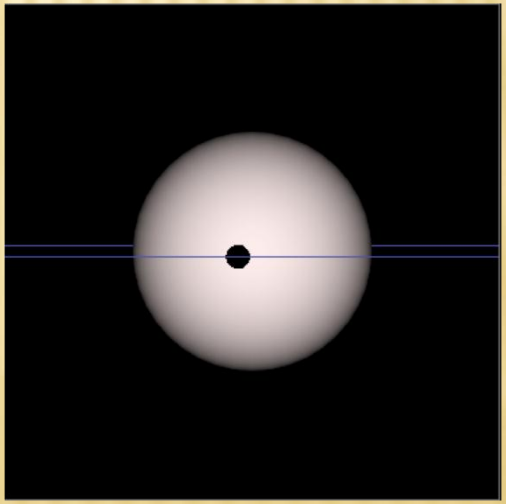
- Rowe et. al. 2008 show:
  $$\frac{F_p}{F_*} \approx A_g \left(\frac{R_p}{R_J}\right)^2 \left(\frac{a}{0.05AU}\right)^{-2} 100ppm$$
- For a Jupiter radius planet orbiting at $0.05AU$ with a 10% albedo, we can expect a 10ppm secondary occultation
- $10ppm \sim 10^{-5}$, whereas with a 10m telescope $\sigma_{scint} \sim 1.75 * 10^{-5}$ so these would be very difficult to observe

SIMILAR PROJECT - WASP

- Wide Angle Search for Planets
- Monitor 5,000 – 10,000 stars per 9.5x9.5 degree field, 5 fields
- 5 fields observed over ~2 months
- Magnitude range: 7 – 13
- 200 mm, F/1.8
- 65+ planets discovered

OTHER INFO WE COULD GET FROM OBSERVATIONS

- Using color bands to get transmission spectrum of the planet’s atmosphere
  - What would this tell us about the planet?
  - Could provide information about the temperature and atmospheric composition



Thank you for your attention!

Are there any questions?

REFERENCES

- A. Richichi , *Lunar Occulations of Stars with Exoplanet Candidates*, www.eso.org/~arichichi
- S. Kane, *Detectability of Exoplanetary Transits from Radial Velocity Surveys*
- R. A. Street, *SuperWASP: Wide Angle Search for Planets*
- Rowe et. al. 2008, Towards the Albedo of an Exoplanet: MOST Satellite Observations of Bright Transiting Exoplanetary Systems
- *Exoplanets.org*
- J. Fortney et. al, Planetary Radii Across Five Orders of Magnitude in Mass and Stellar Insolation: Application to Transits
- J. Barnes, *Transit Lightcurves of Extrasolar Planets Orbiting Rapidly Rotating Stars*
- http://www.exoclimes.com/topics/changing-views-on-spin-orbit-alignment/
- NAOJ, *Inclined Orbits Prevail in Exoplanetary Systems*
- http://www.naoj.org/
- http://en.wikipedia.org/wiki/File:Photon-noise.jpg
- http://simbad.harvard.edu/simbad/
- http://www.chiandh.me.uk/p/Webcam_amateur_astronomy:_detector
- Course Lecture Slides