Lecture 5: Candidate validation and false-positive winnowing

Astrophysical confusing signals: activity and pulsation

Astrophysical false positives

Dwarf-giant separation

Using the main-sequence mass-radius relation

Statistical validation

Dealing with rapid rotators

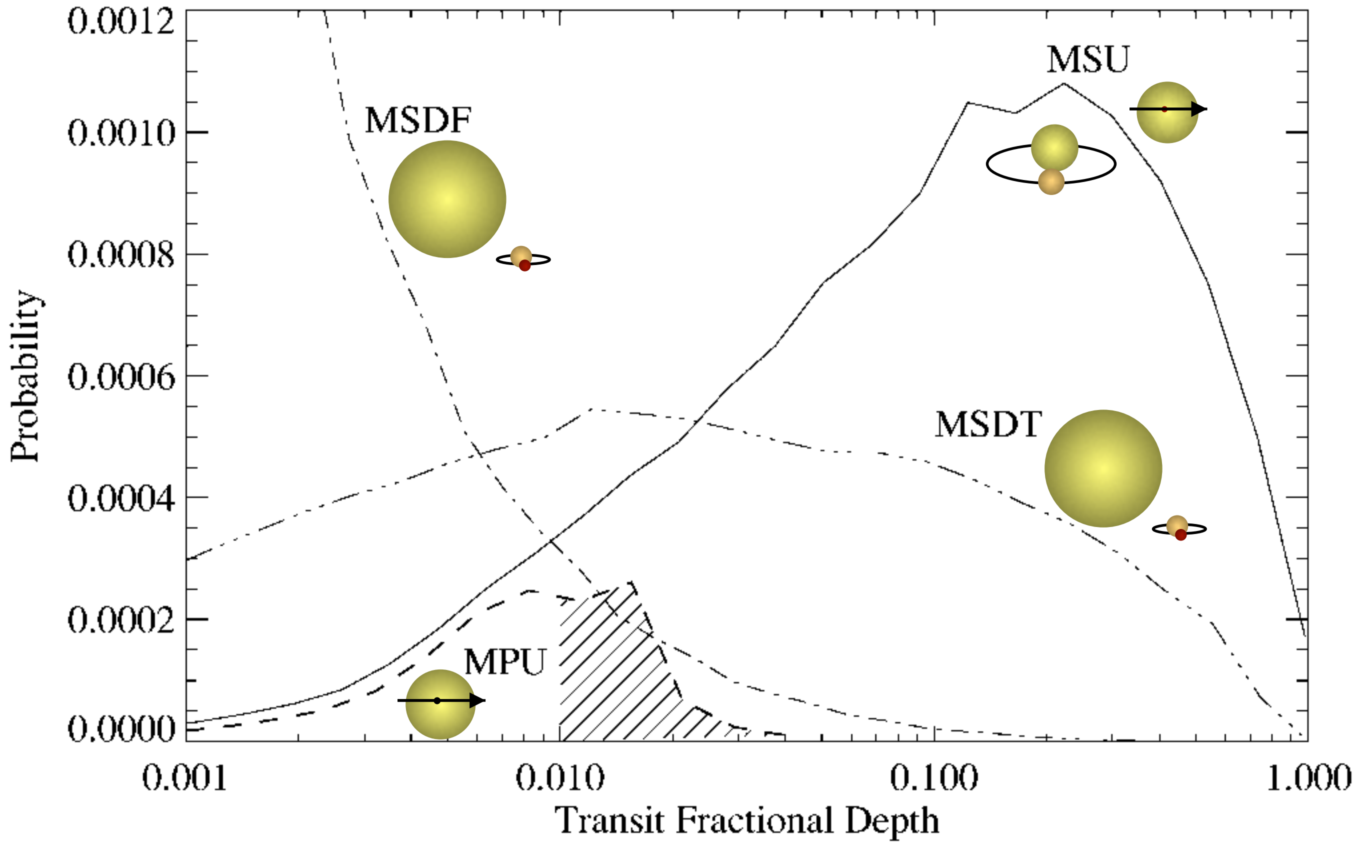
Two motivations

- **Ground-based surveys: time=money**
  - **Radial velocity followup is expensive**
  - **Can we identify and reject false positives from transit survey data and catalogue data alone?**
  - **Huge savings in telescope time requirements**

- **Space-based surveys (Kepler): lies, damned lies and statistics**
  - **What is the influence of false positives on occurrence statistics?**
  - **Validation: Is P(planet) >> P(false positive)?**
  - **No need for RV followup?**

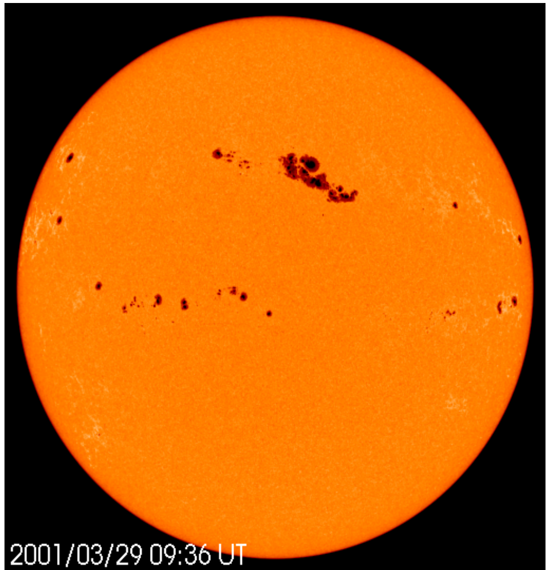
Astrophysical false positives

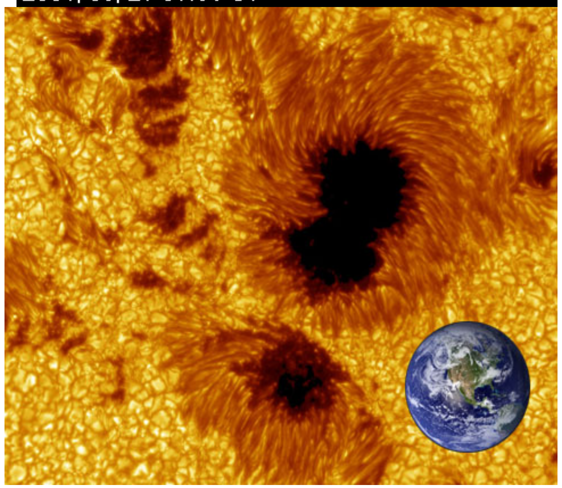
- **Brown (2003): 5 main classes**
  - **MPU = Main-sequence star + planet, undiluted**
  - **MSU = Main-sequence binary, undiluted**
  - **MSDF = Main-sequence binary diluted by foreground star**
  - **MSDT = Main-sequence binary diluted by associated tertiary**
  - **GSU = Giant primary with MS companion**

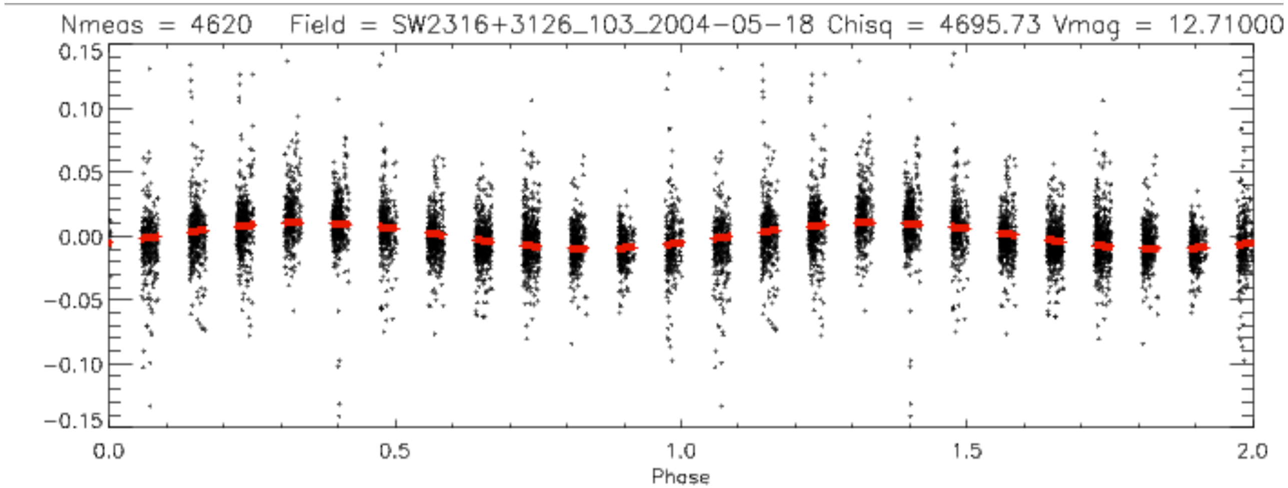


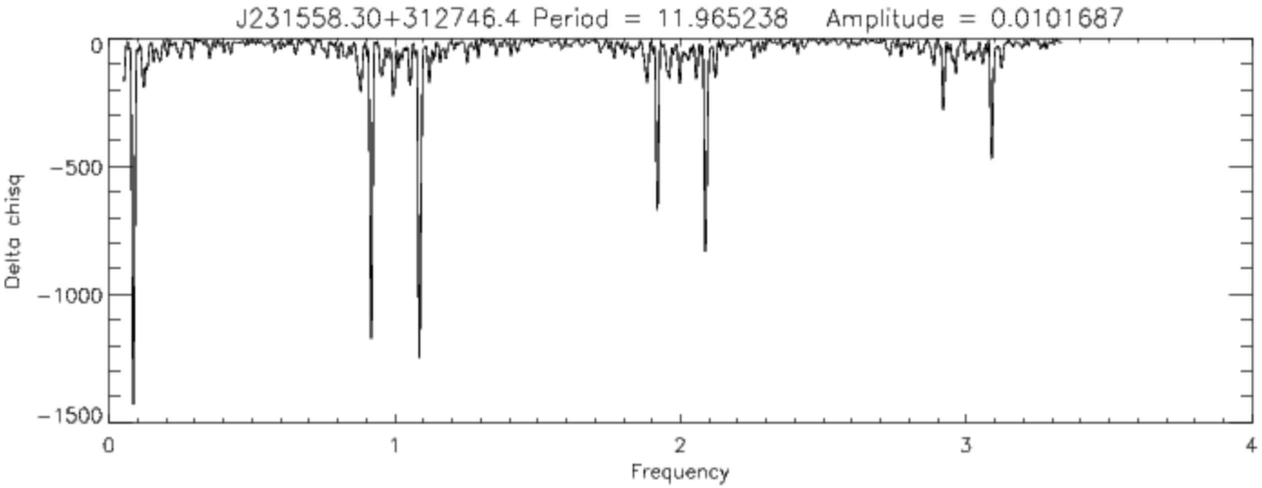
Star Spots

Multiple starspots tend to cause sine-like variations, not dips.
Starspots come and go, transiting planets are always there.



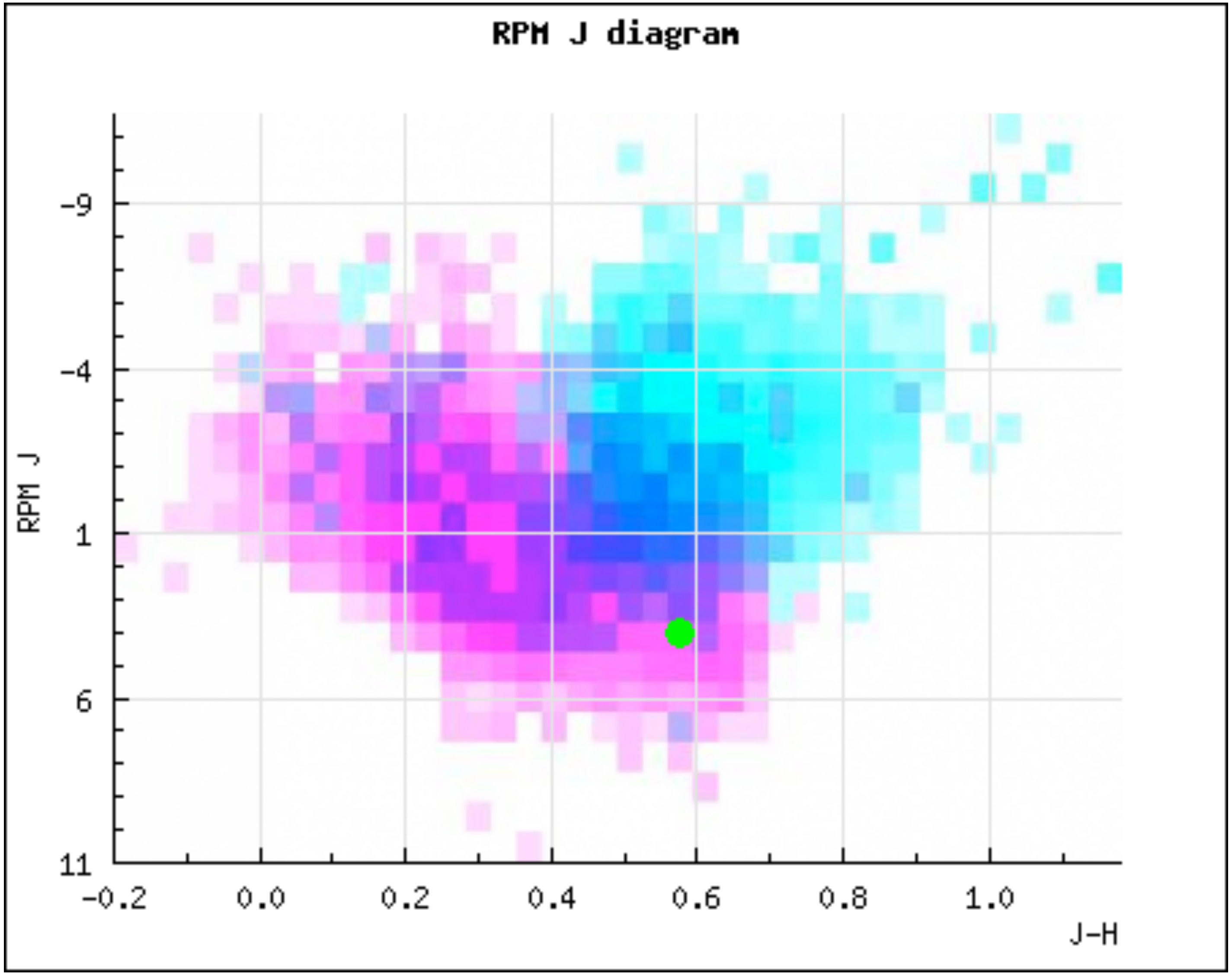






Makes detection of Earth sized planets more difficult

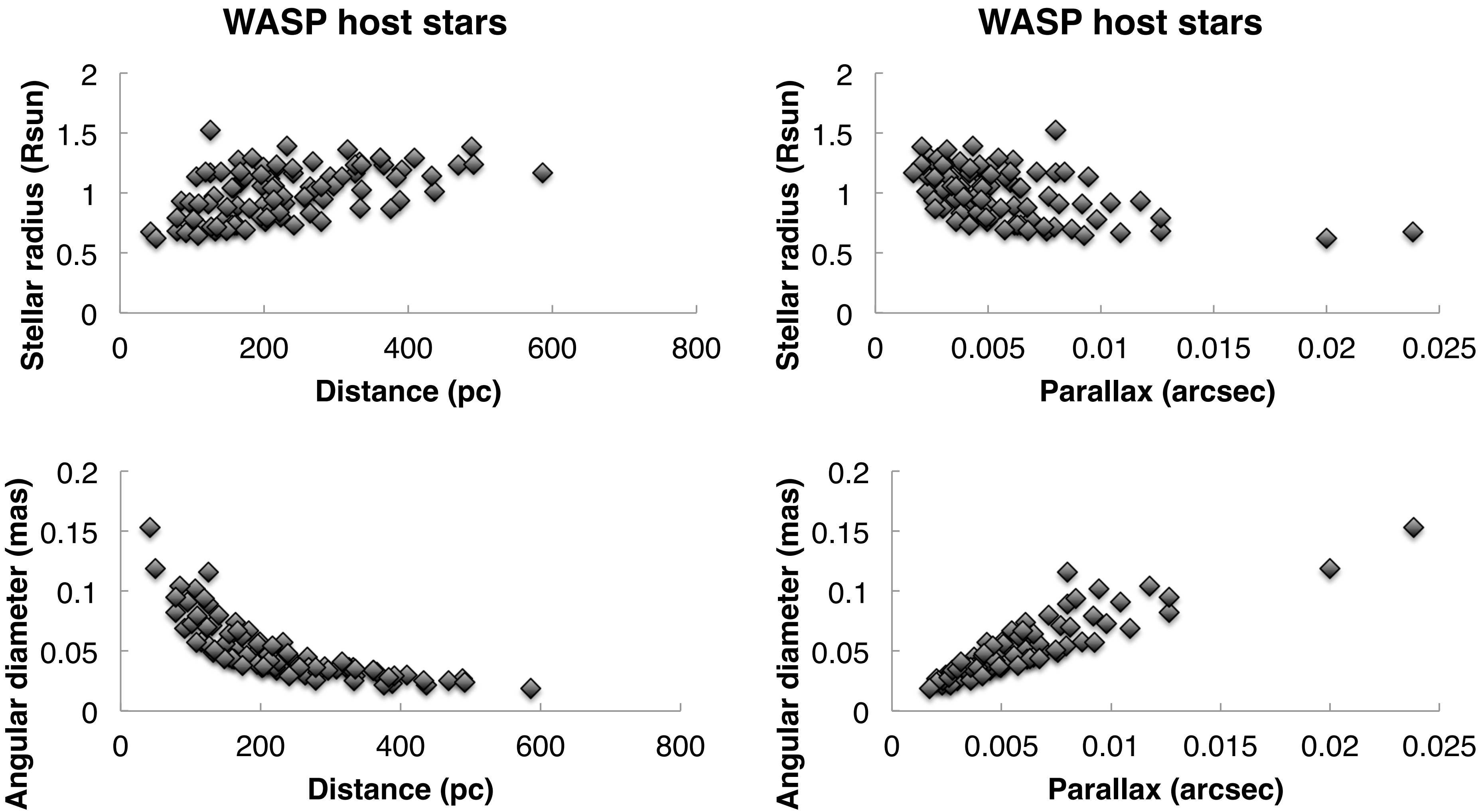
Late-type dwarf or giant?



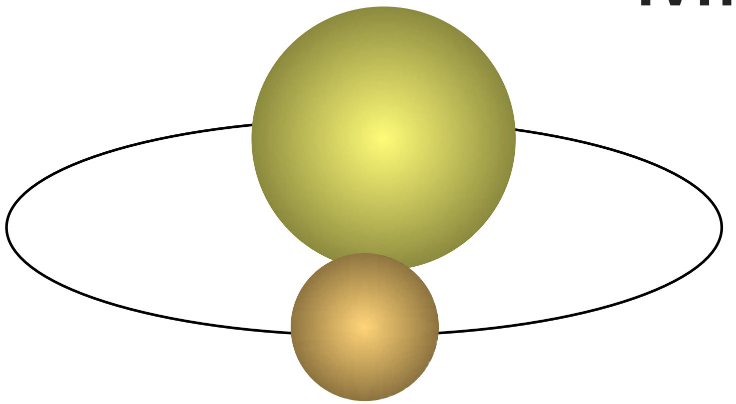
RPM = J + 5 + 5 log μ

Parallaxes and radii of WASP stars

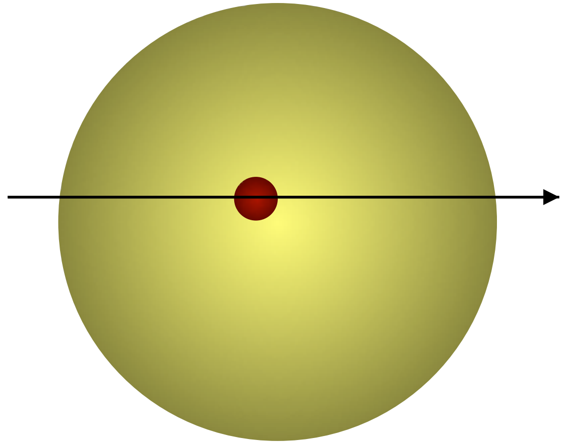
GAIA parallax precision ~ 8 μas at V<13



Mimics

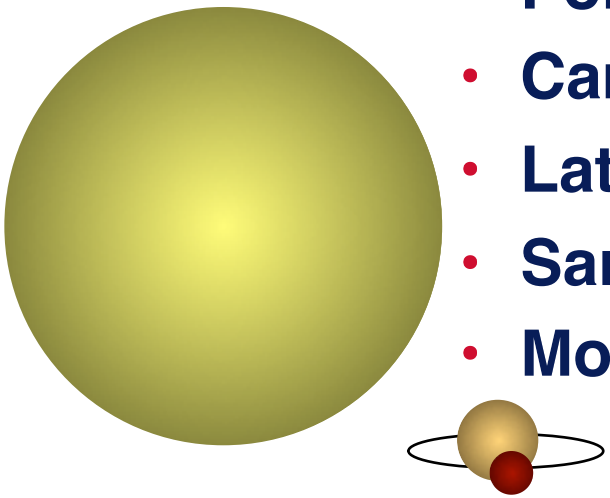


Grazing stellar binaries

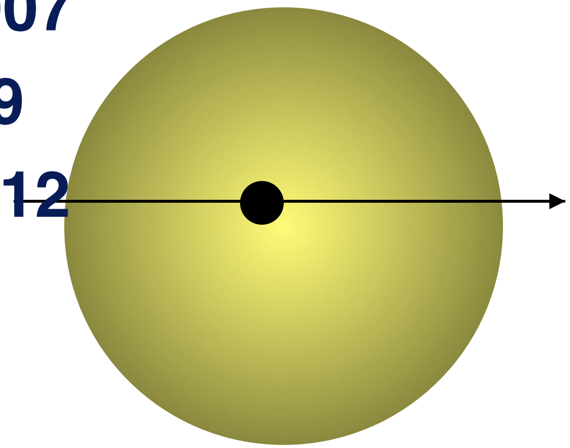


Transiting red/brown dwarfs

- Pont et al 2005
- Cameron et al 2007
- Latham et al 2009
- Santerne et al 2012
- Morton 2012

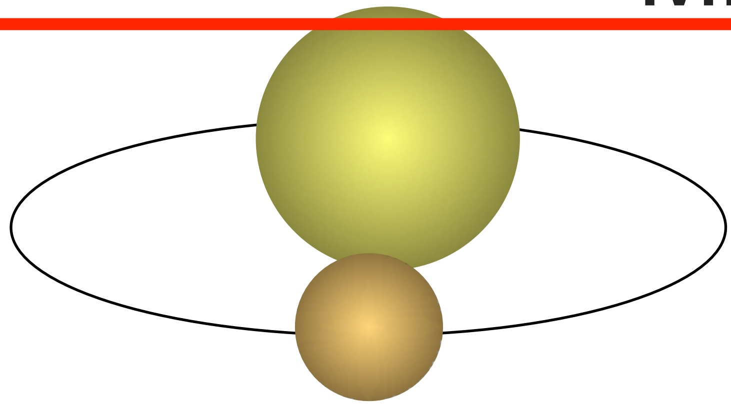


Blended stellar binaries



Planets

Mimics



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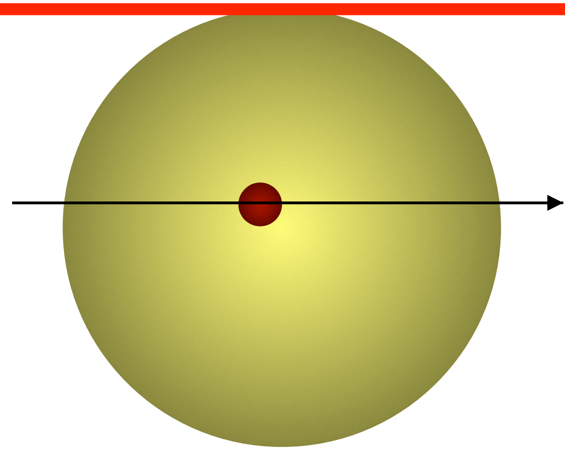

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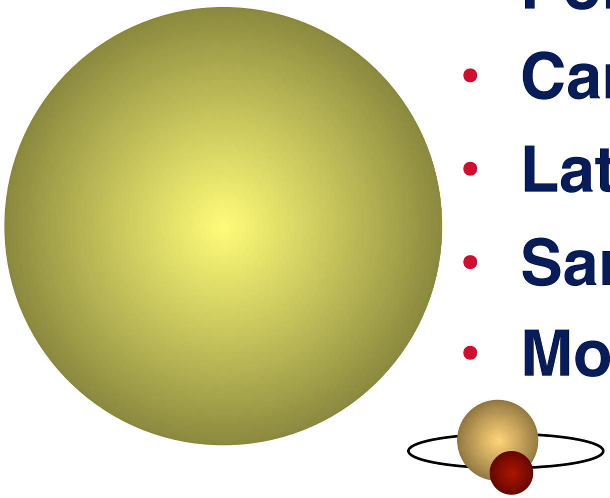

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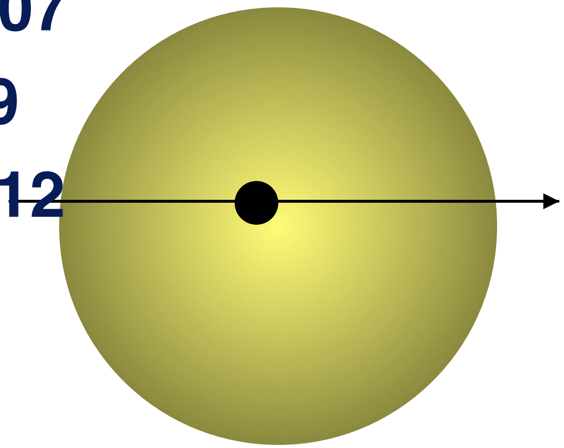
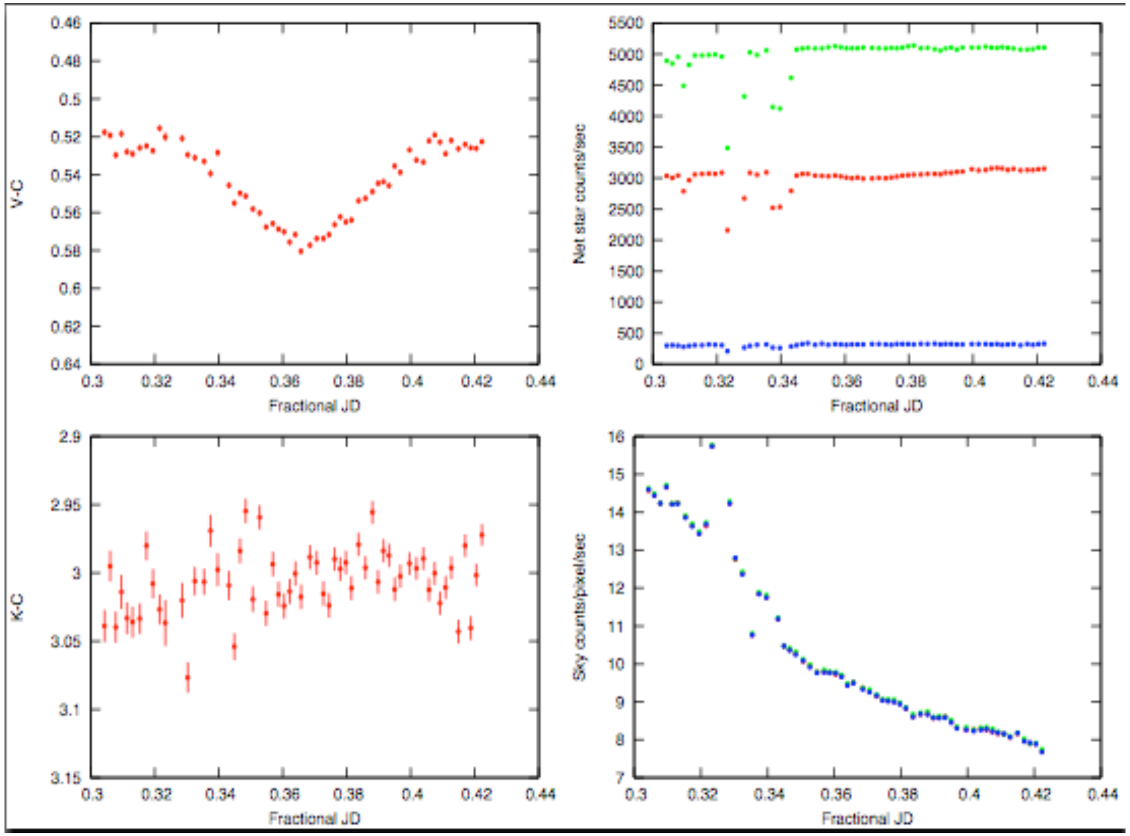


Planets

Grazing binary

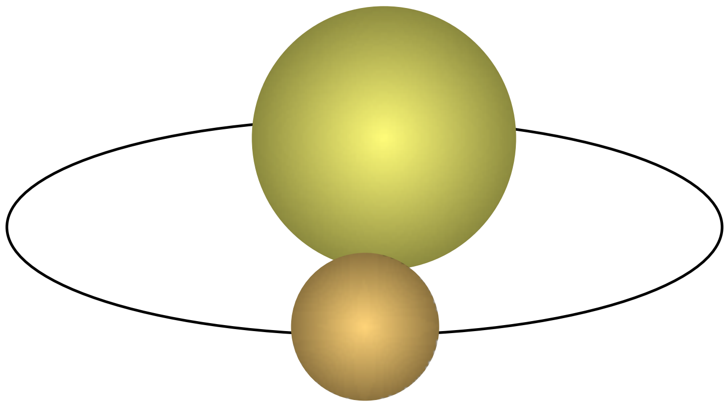
**2 equal mass, equal size stars that just barely eclipse eachother.
This causes a small dip in brightness which is approximately planet sized.
However, the transit is V-shaped.**



Observations taken with the JGT in St Andrews

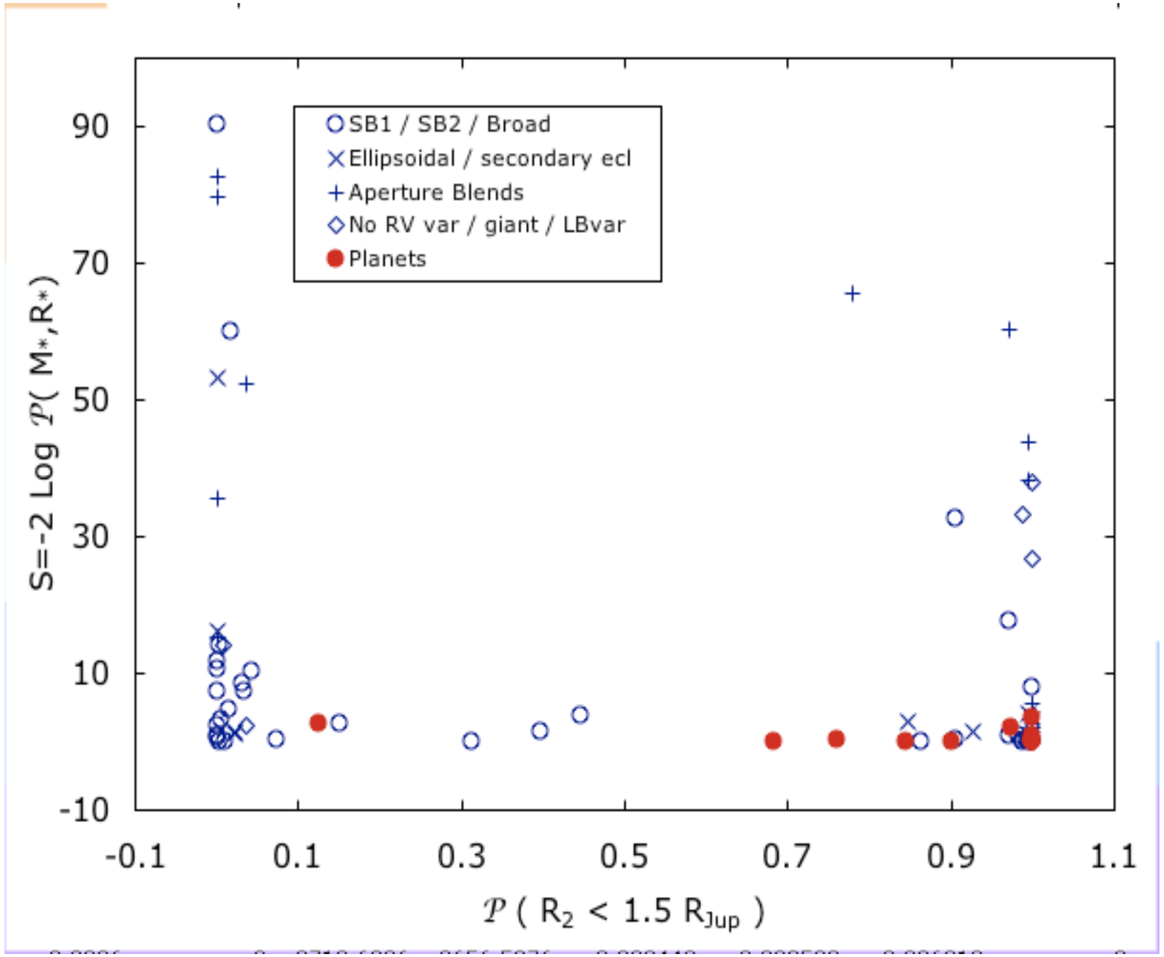
Grazing binary symptoms

- **Inconsistent 2MASS, optical colours**
- **High impact parameter**
- **Inconsistent stellar radius from MCMC**
  - **abnormally low stellar density given Teff**
- **Colour-dependent eclipse depth**
  - **needs photometric followup**



False-positive winnowing

- **E.g. Cameron et al 2007, MNRAS 380, 1230**
  - Markov-chain Monte-Carlo modelling of stellar parameters
  - M-R relation used as Bayesian prior
  - Selection criteria:
    - Pr(Mp < 1.5 M_{jup})
    - Departure of (M_*,R_*) from main-sequence

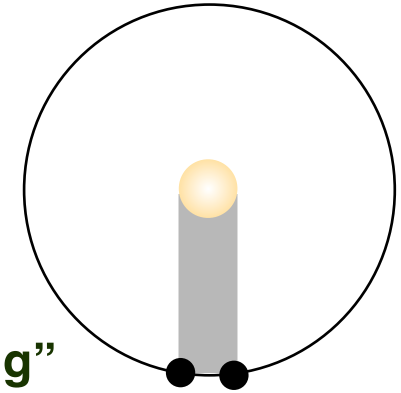


- **Photometry**
  - On-off photometry to eliminate faint blended and grazing EBs

Using the MS mass-density relation

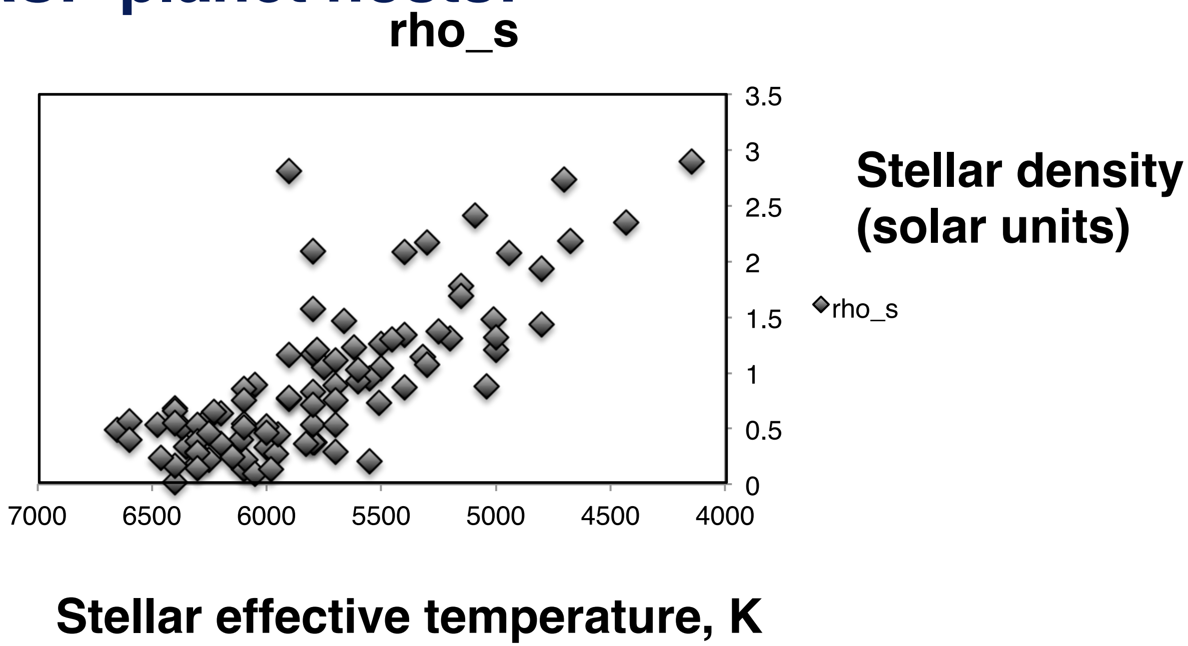
- **Transit duration gives fundamental measure of stellar density**

$$\frac{T_{tr}}{P} \approx \frac{2R_*}{2\pi a} = \left(\frac{4R_*^3}{\pi G P^2 M_*} \right)^{1/3} = \left(\frac{3}{\pi^2 G P^2 \rho_*} \right)^{1/3}$$

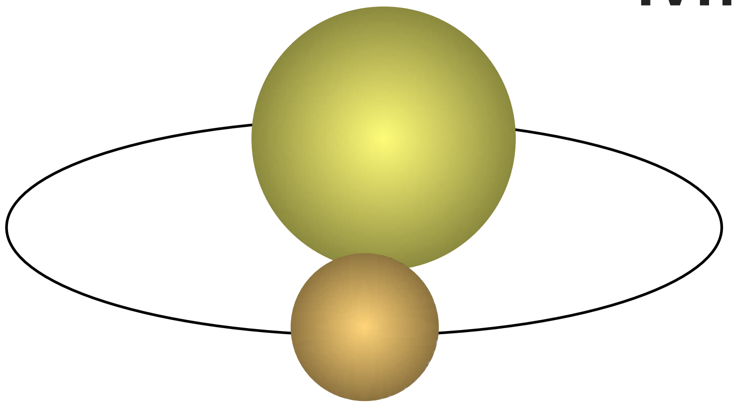


  – **See poster by D. Sliski "Asterodensity profiling"**

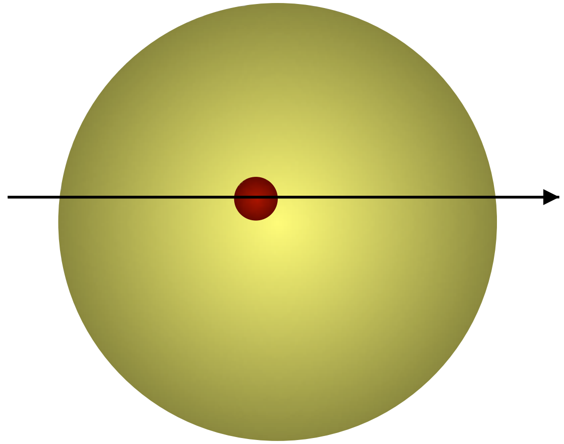
- **e.g. WASP planet hosts:**



Mimics



Grazing stellar binaries



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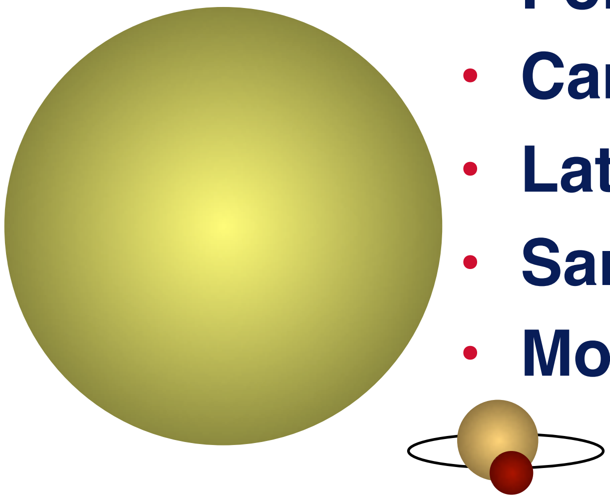
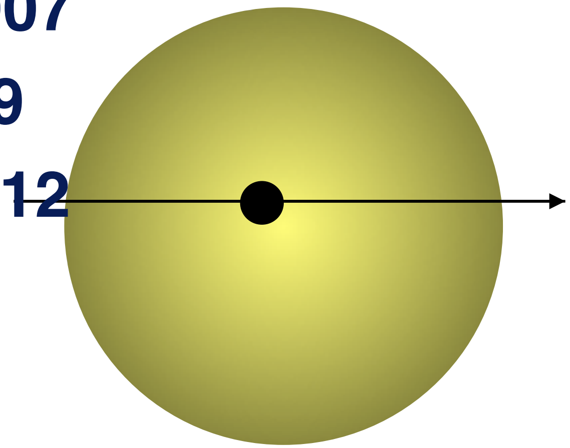


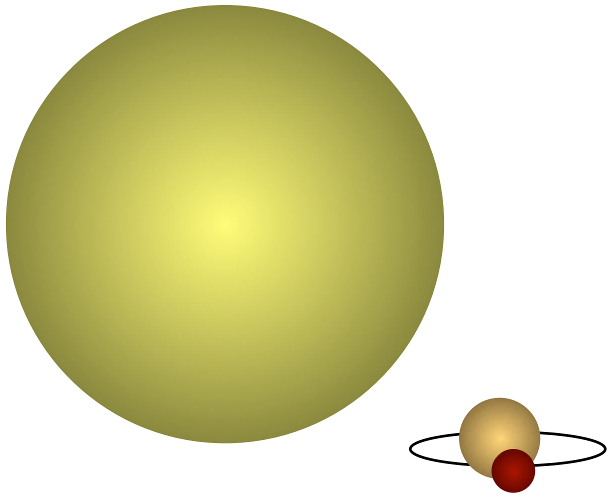
Blended stellar binaries



Planets

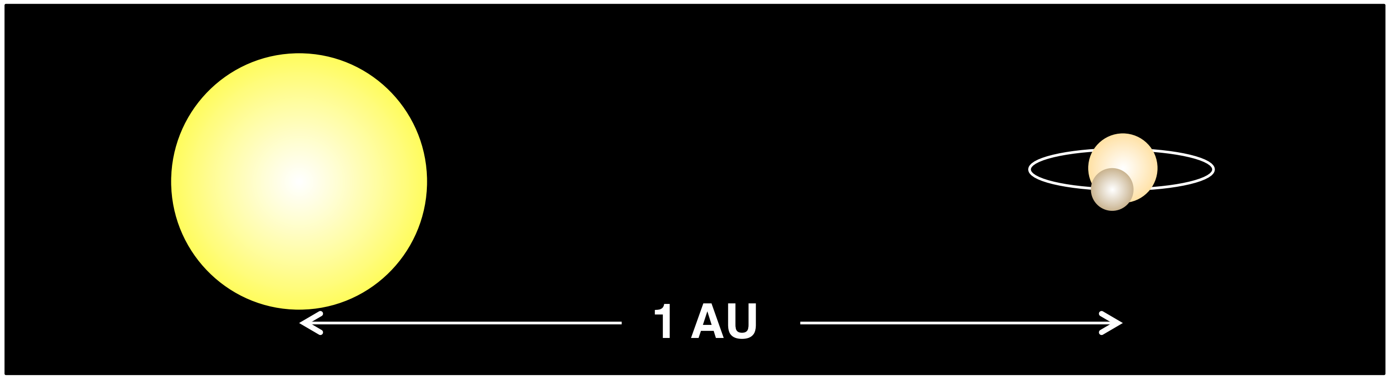
Background/hierarchical binaries

- **Astrometric shift during transit (Kepler)**
- **Inconsistent 2MASS, optical colours**
- **Inconsistent stellar radius from MCMC**
  - **abnormal stellar density given Teff**
- **Colour-dependent eclipse depth**
  - **needs photometric followup**



Example: Hierarchical triple

- **0.5-mag eclipsing binary at 1 AU separation**
- **5 magnitudes fainter**
- **=> Apparent transit depth 0.005 magnitude**
- **Distance to system = 250 pc**
- **=> Angular separation = 4 mas**
- **=> Centroid shift = 19.5 μas towards A in eclipse**
- **cf. Single-measurement precision 30 μas (V<12)**



A **B+C**

Kepler “rain plots”

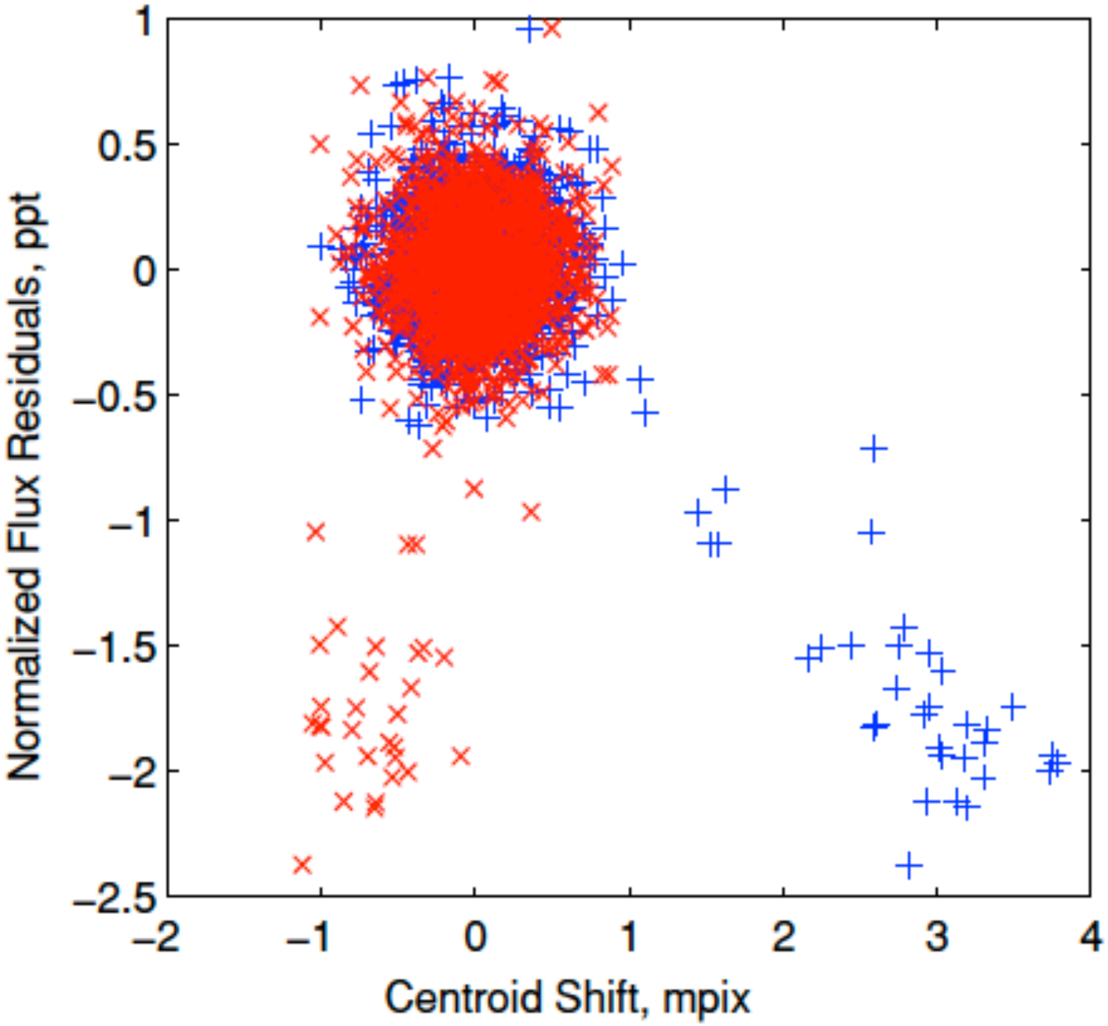


Figure 4. Flux versus residual row (×) and column (+) centroids for KOI-140.

3000 μpix = 12000 μas

BLENDER, PASTIS

- **BLENDER: Fressin et al 2013, ApJ 76, 18**
- **PASTIS: Diaz et al 2014, MNRAS 441, 983**
- **Simulate populations of**
  - **background eclipsing binaries**
  - **bound eclipsing binaries (hierarchical triples)**
  - **Main goal: statistical occurrence in Kepler sample**
- **False positive occurrence rates for Kepler:**
  - **Giant planets (6-22 REarth) 17.7%**
  - **Neptunes (2-4 REarth) 6.7%**
  - **Earth-size planets (0.8-1.25 REarth) 12.3%**

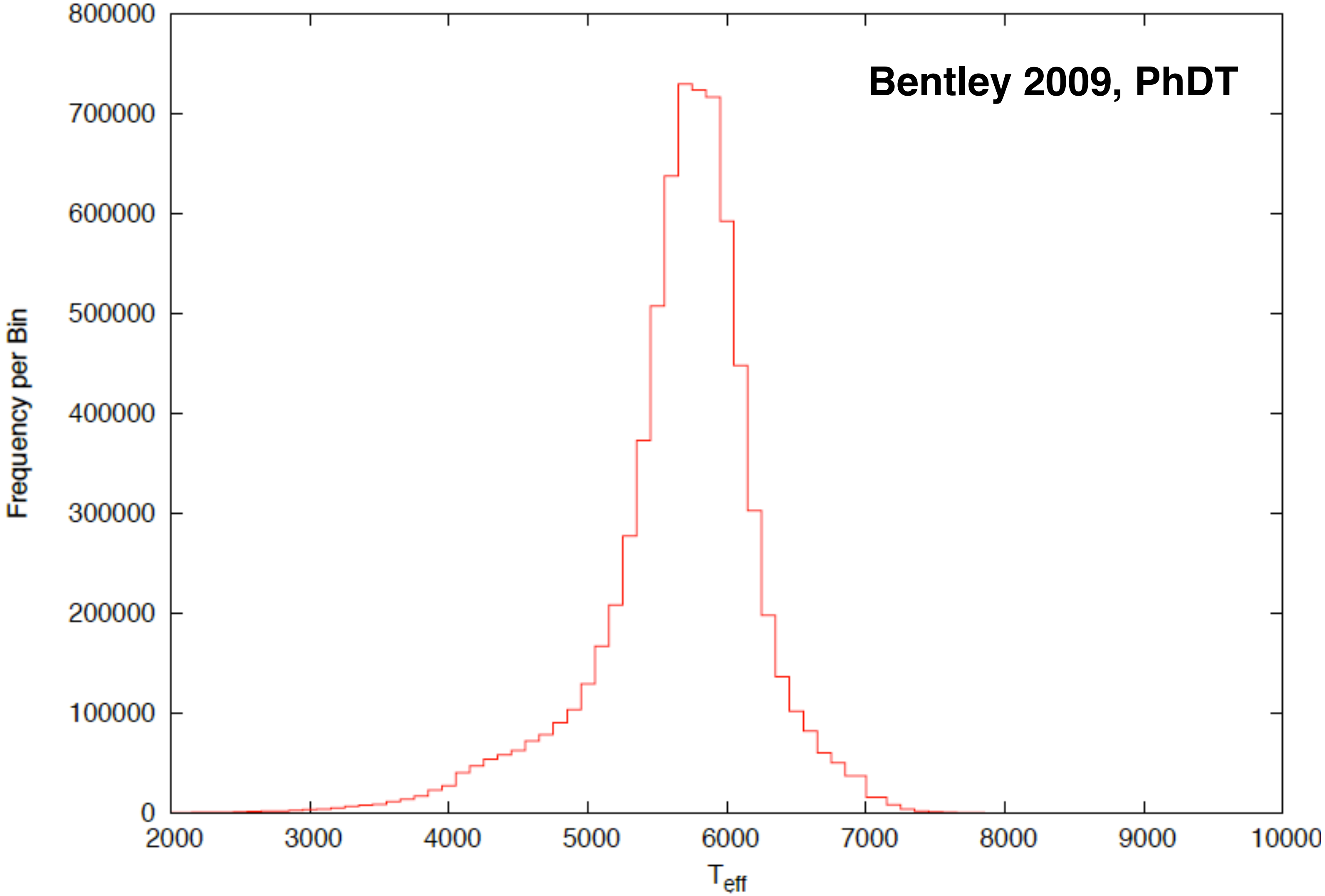
Multiple transiting planets

> To lose one parent may be regarded as a misfortune; to lose both looks like carelessness.
>
> Oscar Wilde

- **How many chance alignments of distant eclipsing binaries do we expect in Kepler's photometric aperture?**
  - **Lissauer et al 2014, ApJ 744, 44**
  - **Rowe et al 2014, ApJ** $E(j) = \lambda^j e^{-\lambda}$
- **Assume:**
  - **False positives (FPs) are randomly distributed among targets**
  - **No correlation between probability that a star hosts one or more planets, and to display FPs.**
- **Result: nearly 1000 validated Kepler planets.**

WASP archive: main-sequence stars

- **Frequency of dwarf stars by effective temperature**



The elusive mass of WASP-33b

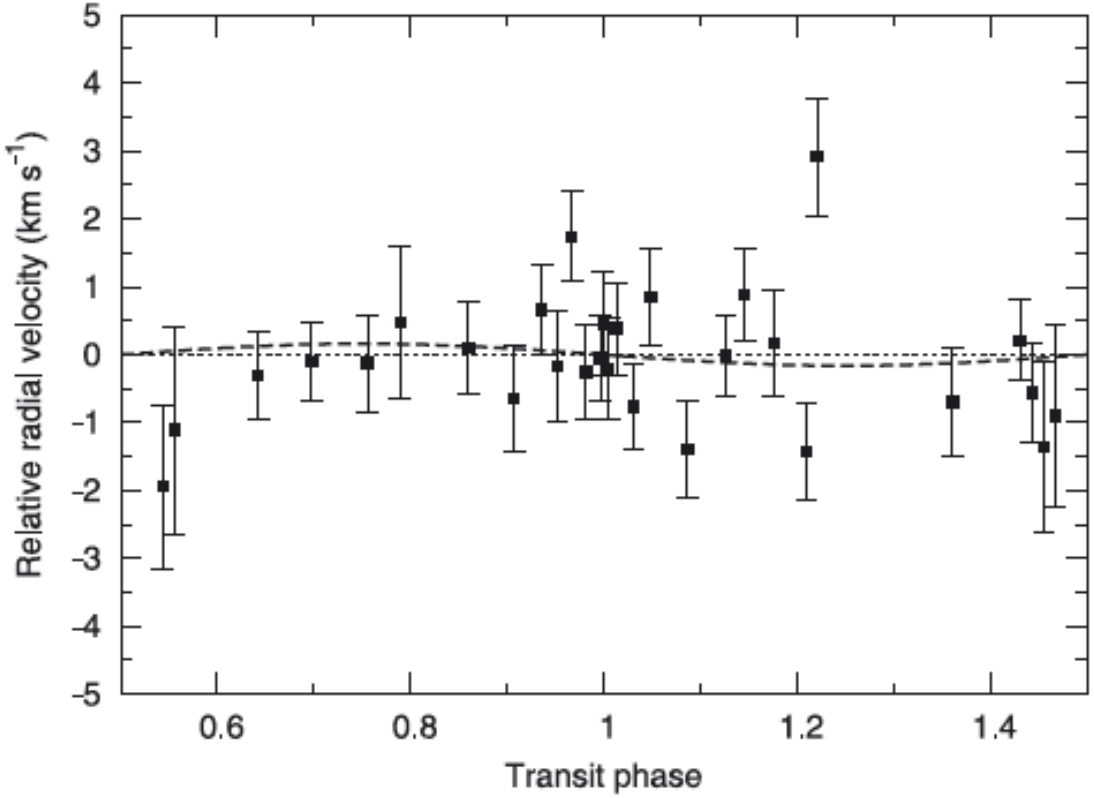
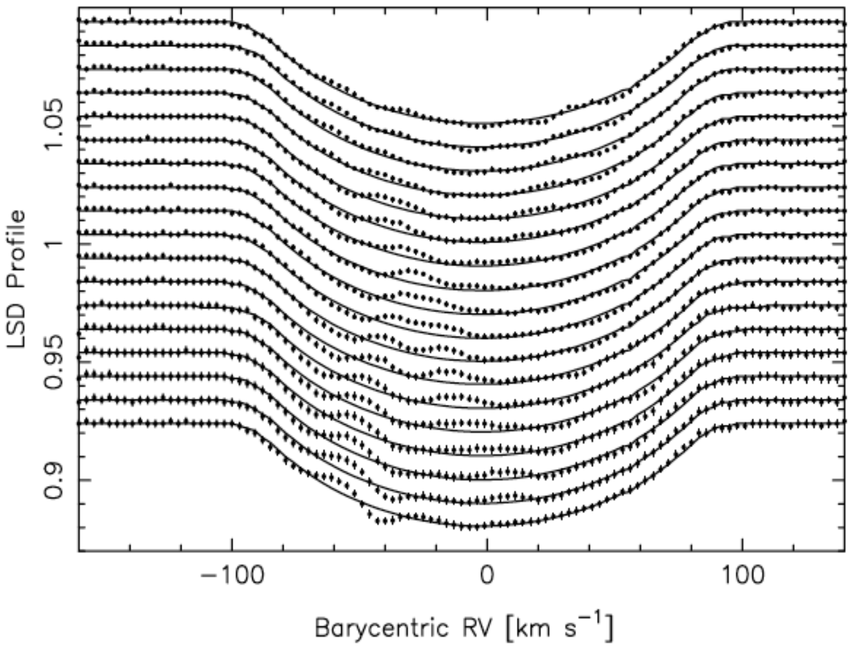


Figure 2. RV curve of HD 15082 obtained with the iodine cell at Tautenburg. The upper panel shows the long-term radial acceleration. The lower panel shows the phased RVs with a linear trend of 0.018 km s^{-1} d^{-1} subtracted. The dashed curve represents the best-fitting circular-orbit solution. The zero-point of the RV scale is arbitrary.

Collier Cameron et al 2010 MNRAS 407, 507

A fast rotator – with pulsations



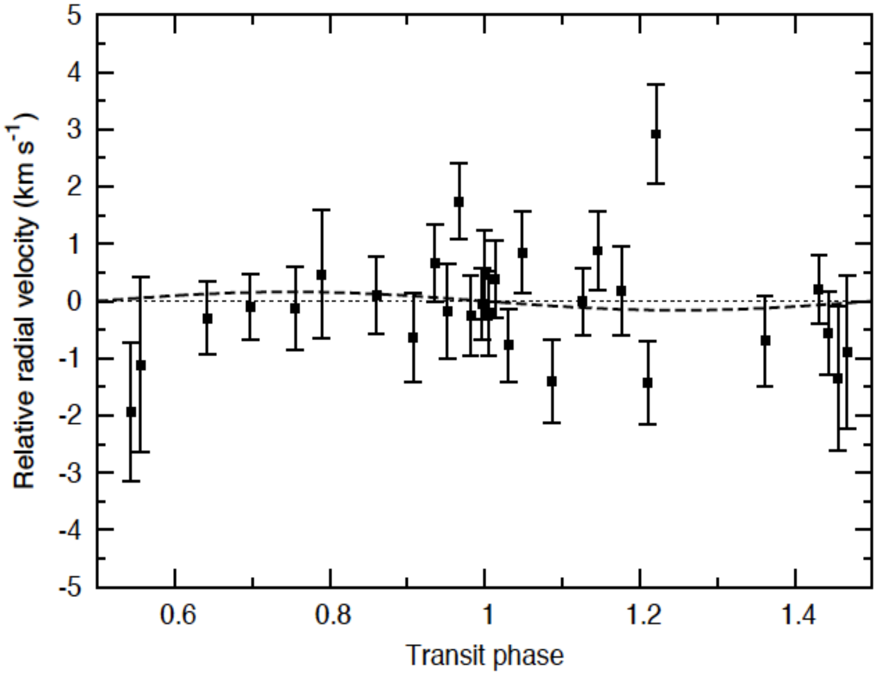


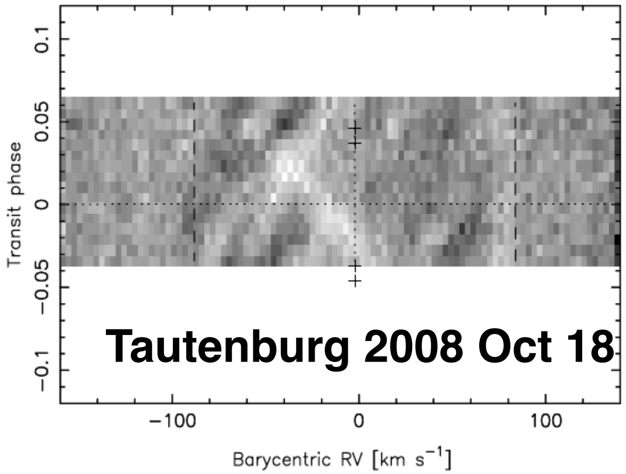
Figure 2. Radial-velocity curve of HD 15082 obtained with the iodine cell at Tautenburg. The upper panel shows the long-term radial acceleration. The lower panel shows the phased radial velocities with a linear trend of 0.018 km s^{-1} d^{-1} subtracted. The dashed curve represents the best-fitting circular-orbit solution. The zero-point of the radial-velocity scale is arbitrary.

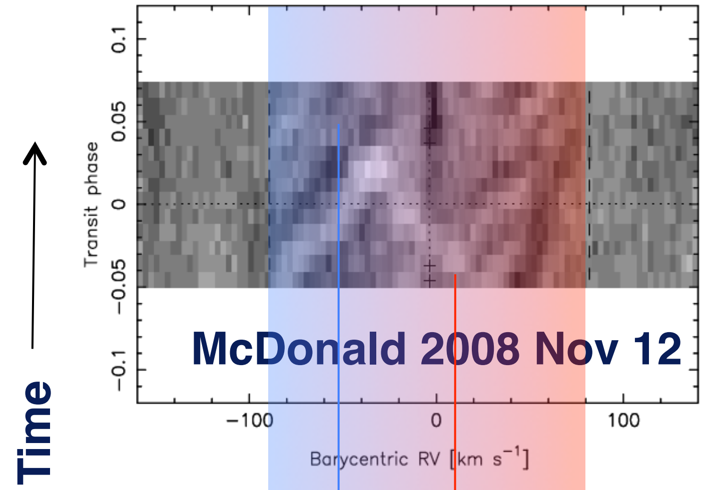
Collier Cameron et al 2010, MNRAS 407, 507

$v \sin i = 86$ **km/sec**

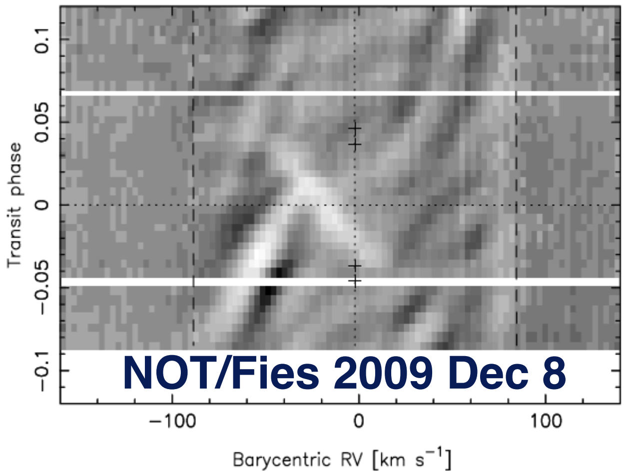
$M_p < 4\ M_{jup}$

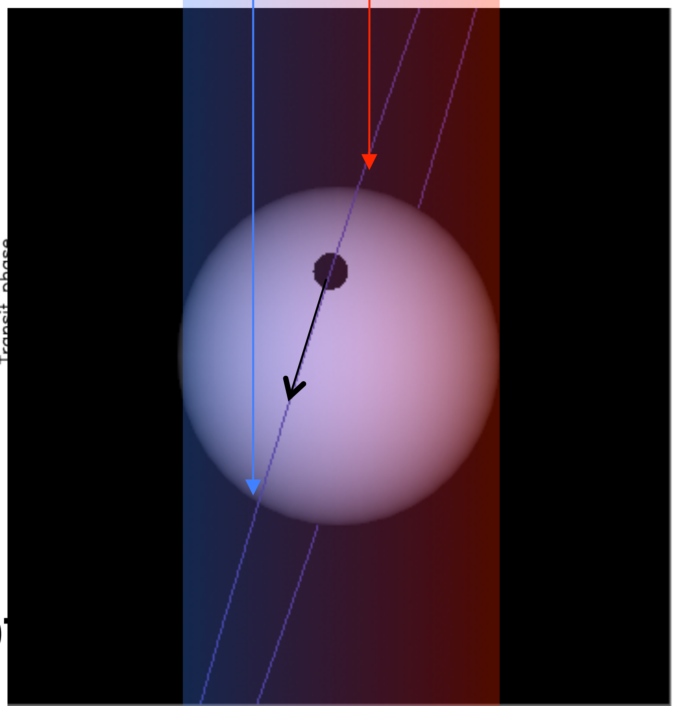
Transit tomography of WASP-33b





Velocity

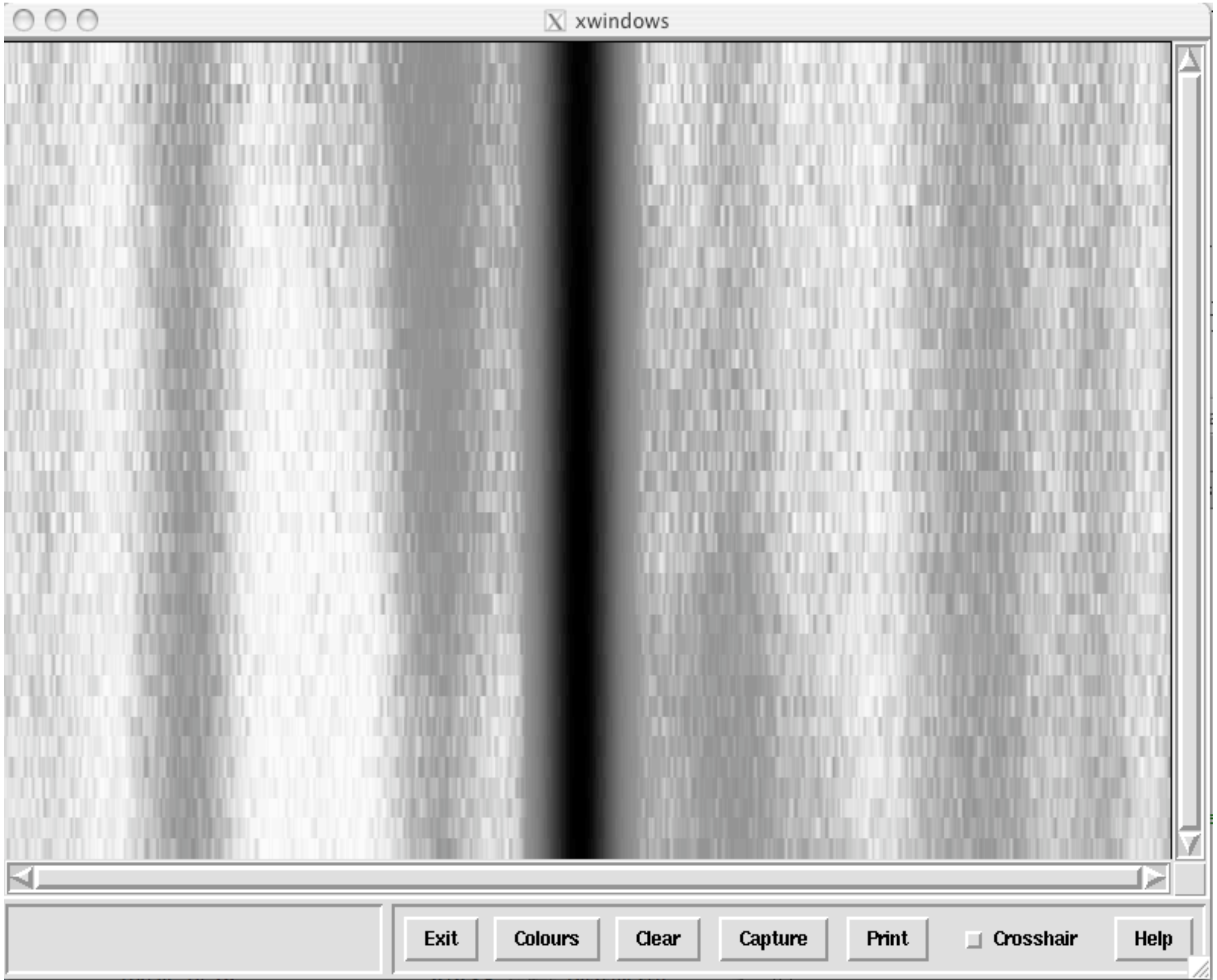




Collier Cameron et al 2010, MNRAS 40

The cautionary tale of WASP-9

- **Ségransan et al, in prep**



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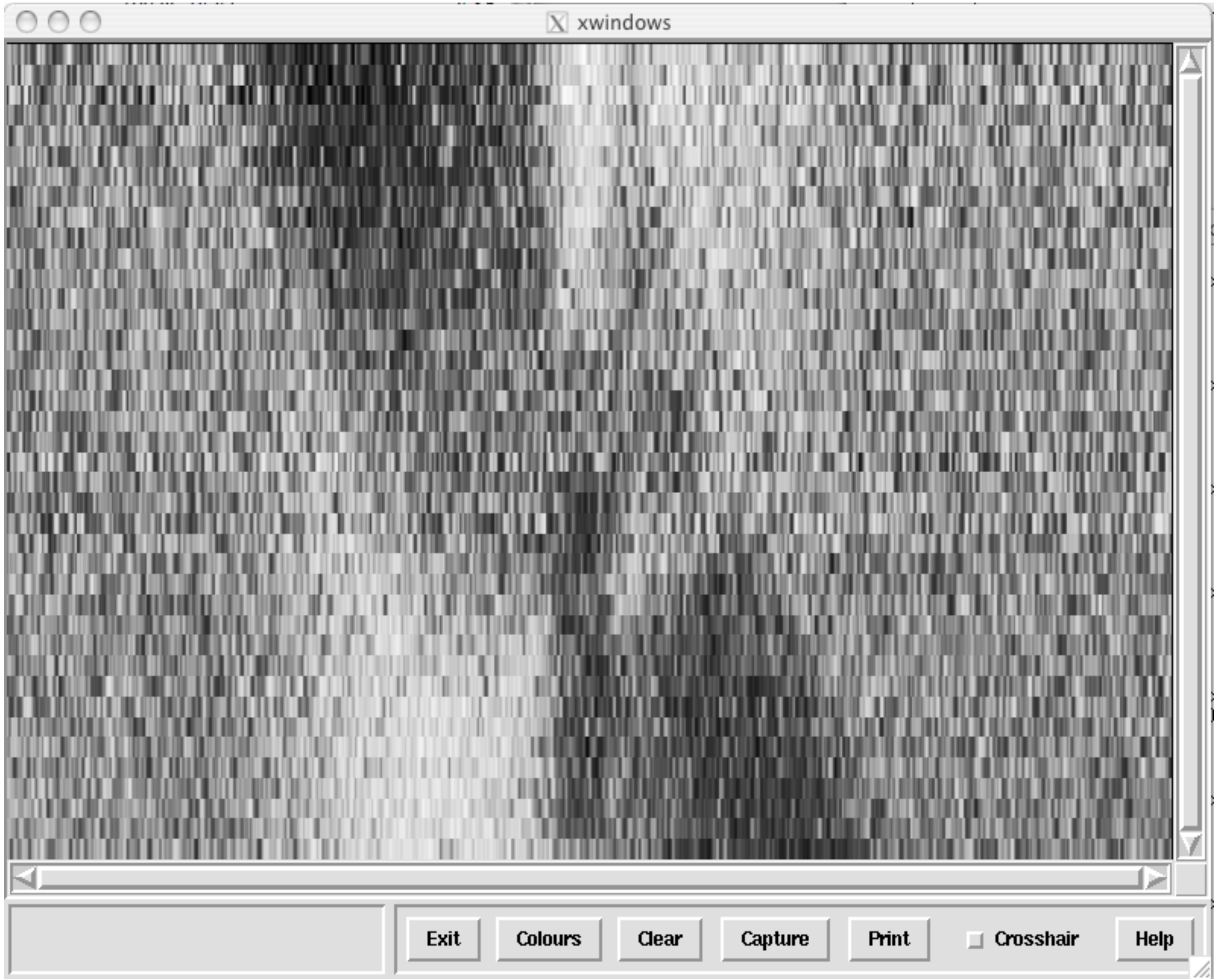

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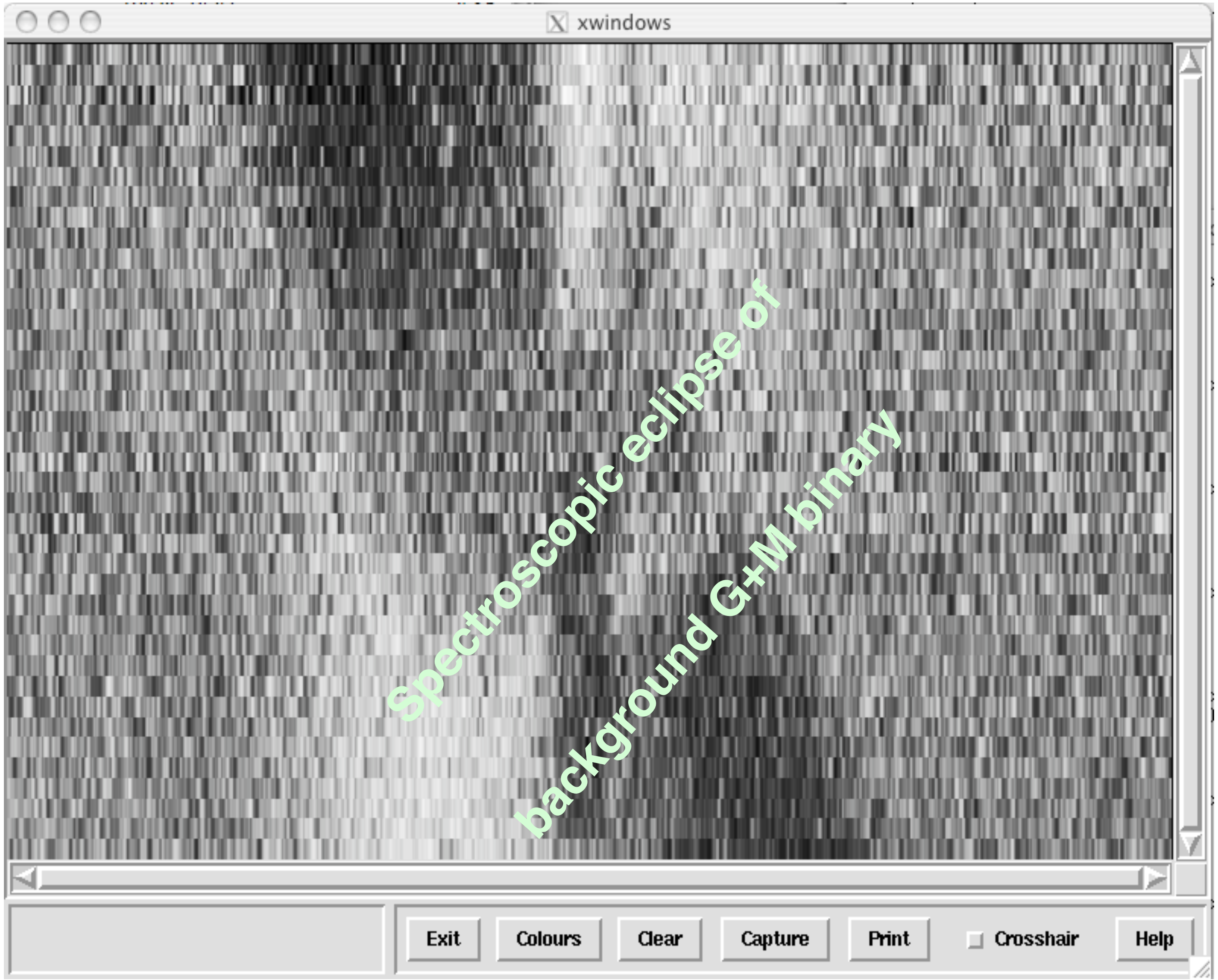
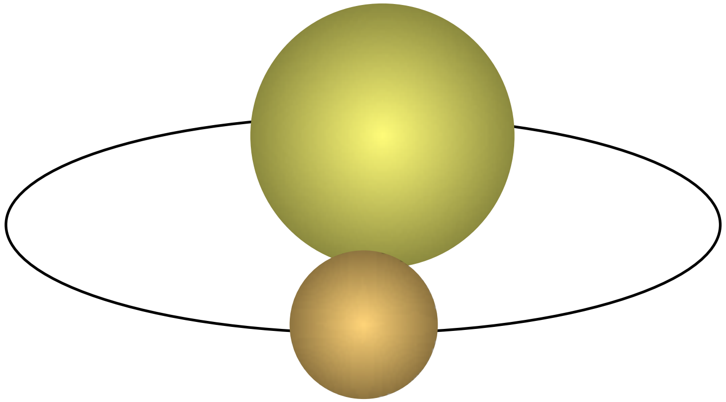
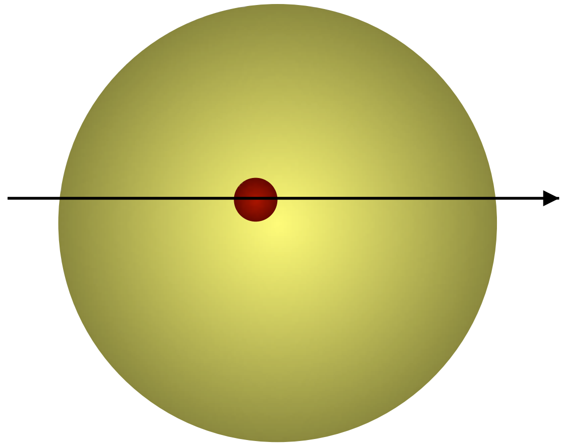


Astrophysical False Positives

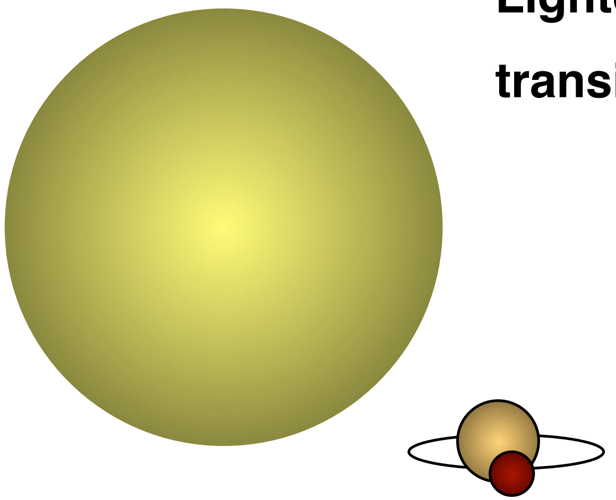


Grazing stellar binaries



Transiting red/brown dwarfs

Lightcurves mimic those of transiting planets.



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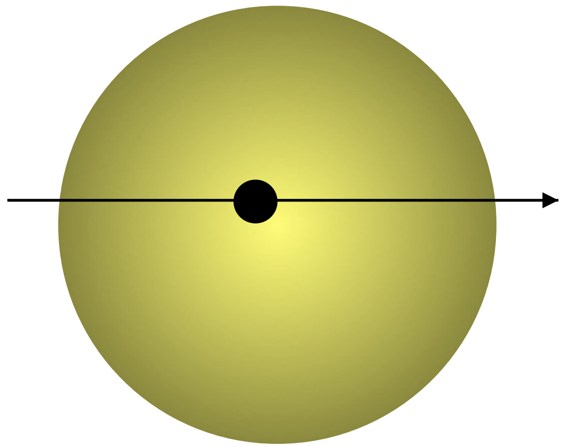

Planets

Summary: sources of confusion

- *Giant stars* showing dips in brightness. Secondary object would not be planet sized. Colours and proper motion of the star can distinguish giants from main sequence stars
- A *stellar binary* can have an inclination such that the eclipsing secondary grazes the primary causing photometric dips very similar to those expected from planetary transits.
  - Inconsistent stellar density
  - Identify with multi-colour photometry and spectroscopy.
- *Line-of-sight blending* with an eclipsing binary
  - blending due to large pixel of survey telescope can be resolved with followup photometry at large separations
  - astrometric shift during eclipse at small separations (Kepler)
  - Blend probability assessment is time-consuming: BLENDER, PASTIS
  - unresolved blends require RV measurements and show variations with the "line-bisector"
- *Stellar spots* – initially confusing but not permanent, different shape than a transit.
- Massive *M-dwarf secondary*, rather than a planet mass secondary.