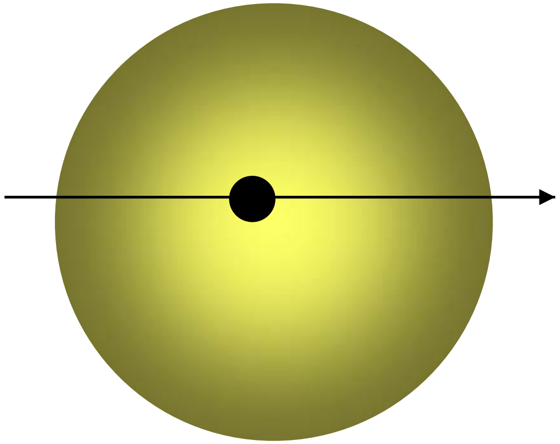
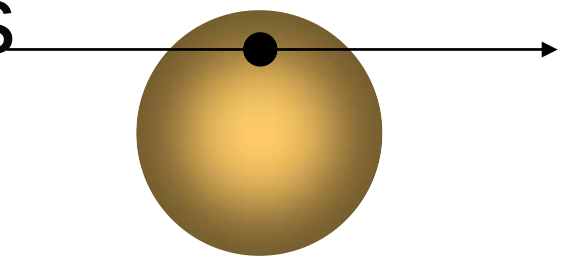
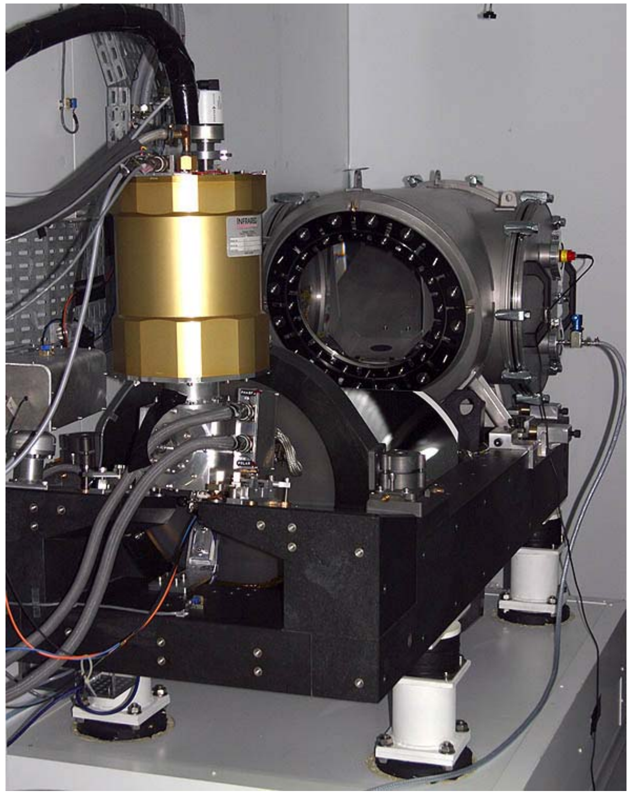


Detection of extra-solar planets in wide-field surveys



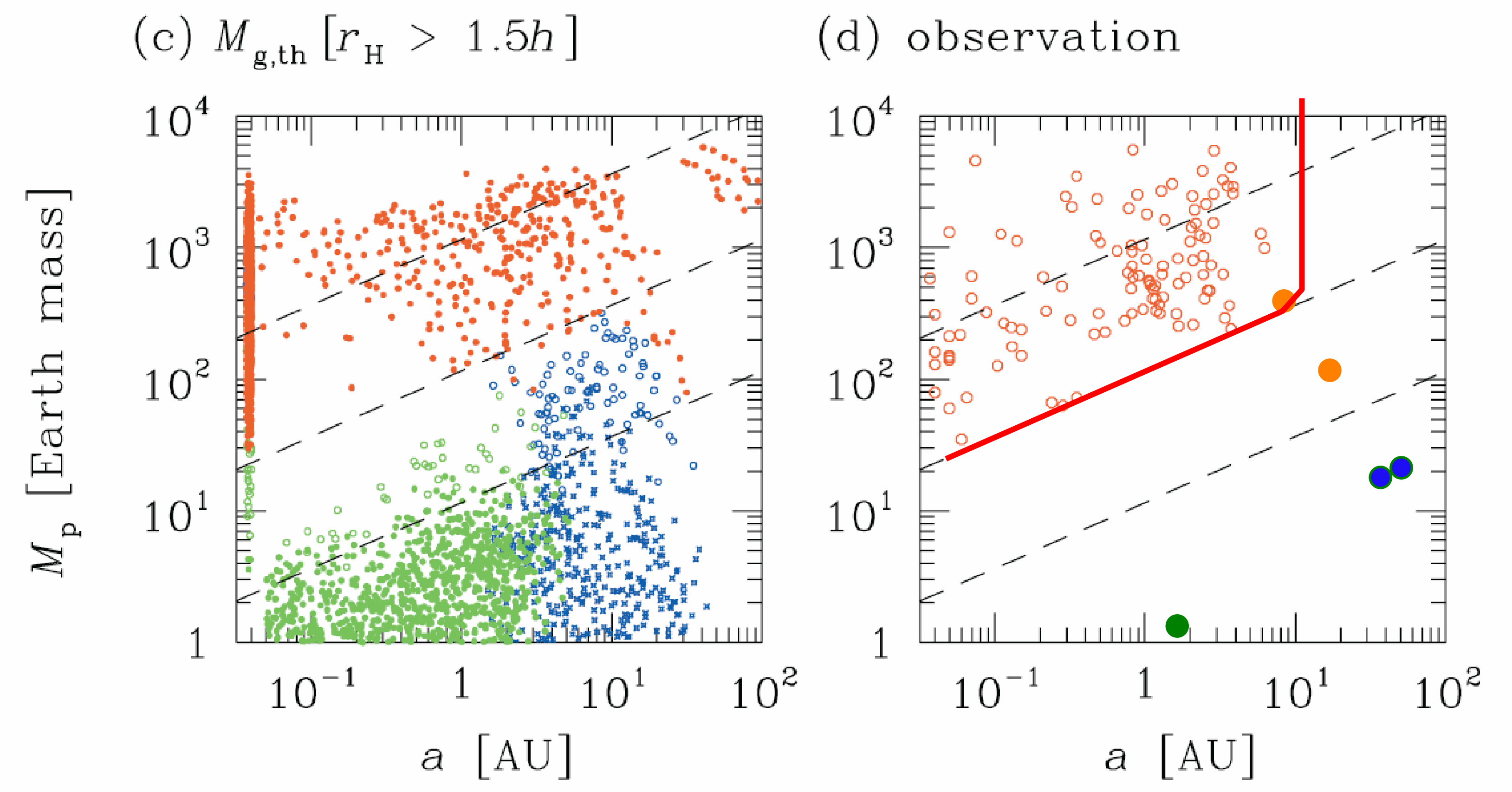
Andrew Collier Cameron

University of St Andrews

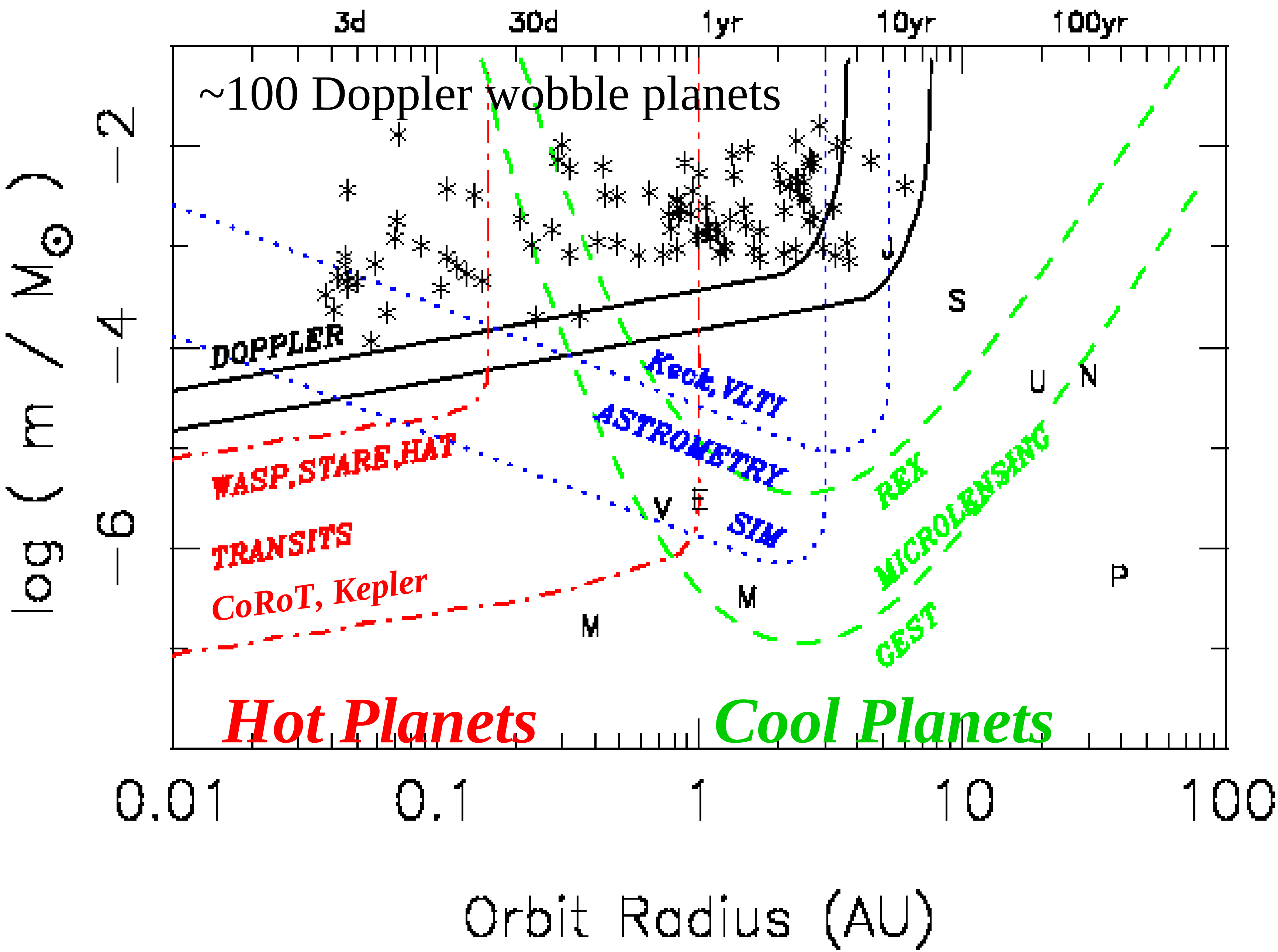


Tip of the iceberg?

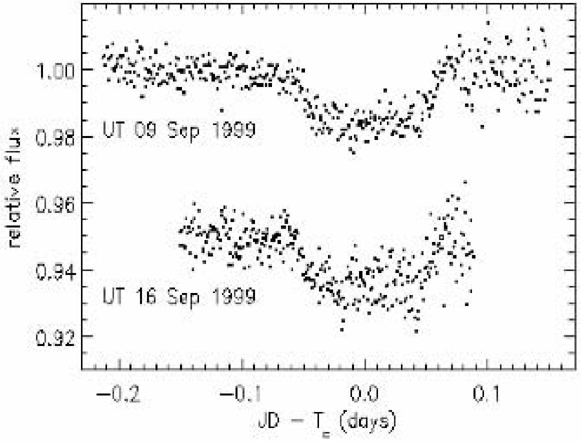
- Left panel: Core accretion+migration simulation by Ida & Lin (2004), showing gas giants, ice giants, rocky planets.
- Right panel: Radial-velocity discoveries so far.



Exoplanet "Discovery Space"

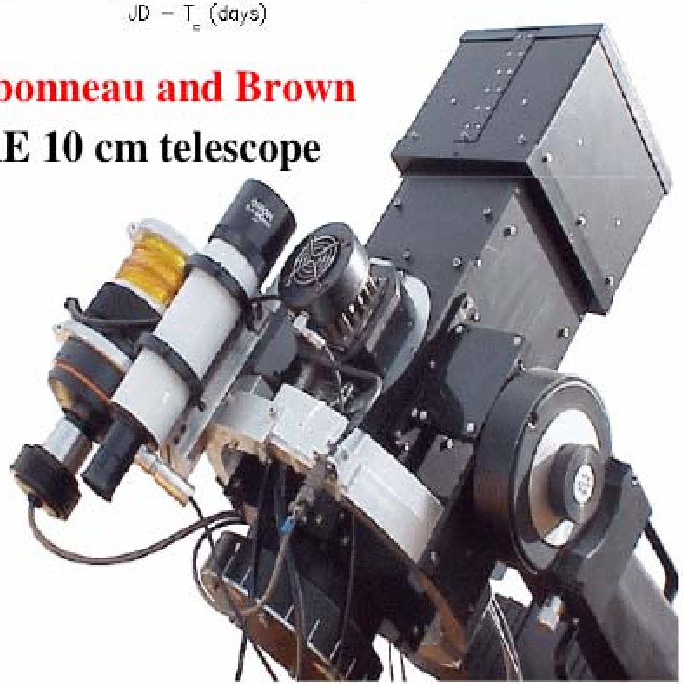


1999 First Planet Transits

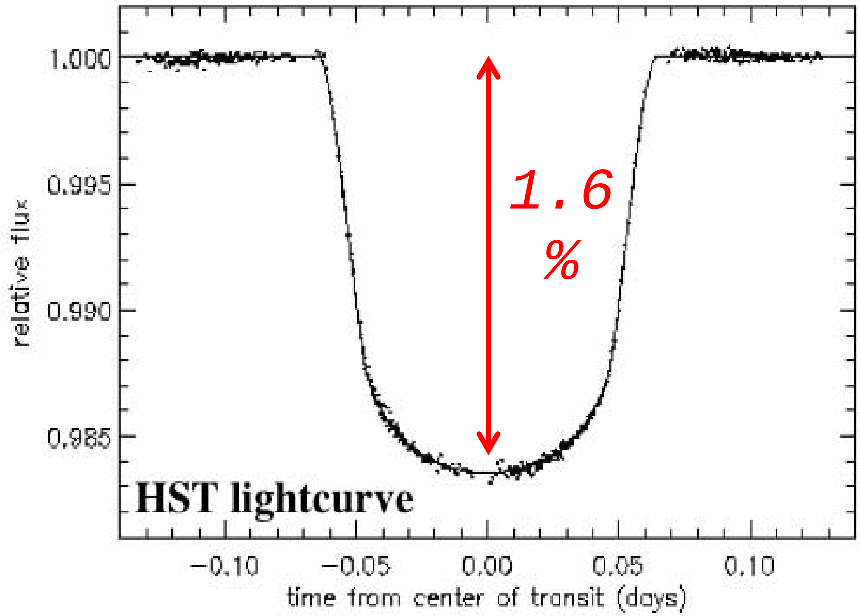


1.6% "winks"
last 3 hours
repeat every
3.5 days.

Charbonneau and Brown
STARE 10 cm telescope



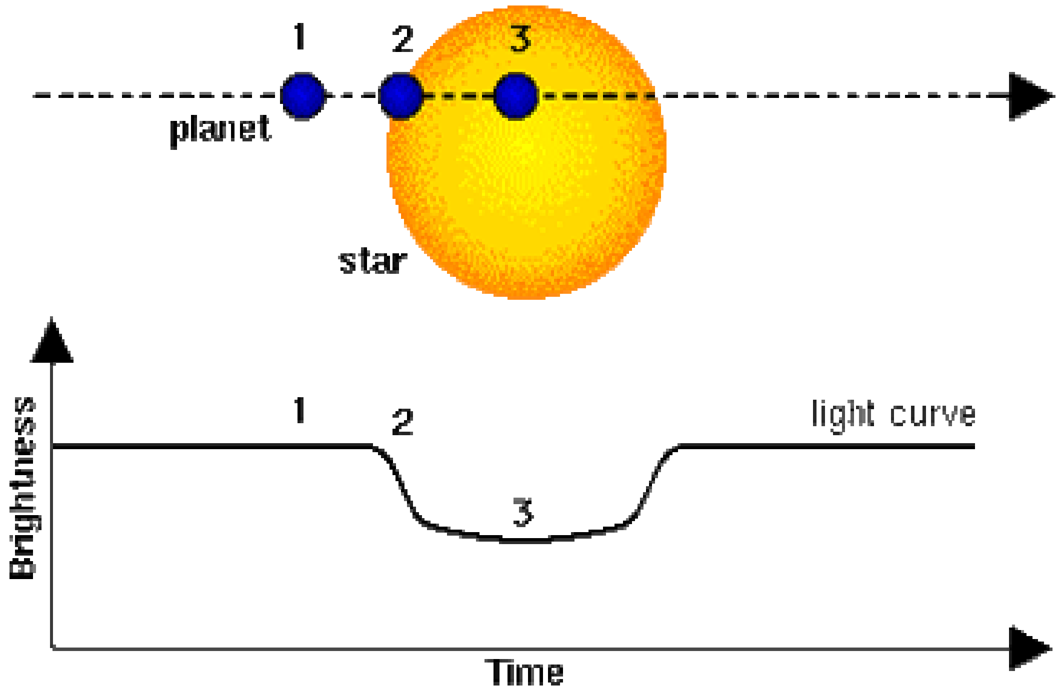
HD 209458
The First Transiting Planet



Diameter = 1.3 x Jupiter
Mass = 0.6 x Jupiter
Temp = 2000 Centigrade

This "Hot Jupiter" is a Gas Giant.

Transit Lightcurves



$$r_{Jup} \approx 0.1\, R_{Sun}$$

Depth:

$$\frac{\Delta f}{f} \approx 1\% \left(\frac{r_p}{r_{Jup}}\right)^2 \left(\frac{R_*}{R_{Sun}}\right)^{-2}$$

Duration:

$$\Delta t \approx 3h \left(\frac{M_*}{M_{Sun}}\right)^{2/3} \left(\frac{P}{4d}\right)^{1/3}$$

Probability:

$$P_t \approx 10\% \left(\frac{R_*}{R_{Sun}}\right)\left(\frac{M_*}{M_{Sun}}\right)^{-1/3} \left(\frac{P}{4d}\right)^{-2/3}$$

Wide-field transit surveys

- **OGLE-III**
  - **1.3-m aperture, Las Campanas**
  - **5 transiting planets found**
- **TrES**
  - **10-cm apertures**
  - **Palomar, Lowell Obs (Arizona), Tenerife**
  - **3 transiting planets found**
- **HAT**
  - **11-cm aperture, f=200mm**
  - **F L Whipple Obs (Arizona), Mauna Kea (Hawaii)**
  - **2 transiting planets found**
- **XO**
  - **11-cm aperture, f=200mm**
  - **Haleakala (Hawaii)**
  - **2 transiting planets found**
- **SuperWASP**
  - **11-cm aperture, f=200mm**
  - **La Palma (Canaries), Sutherland (South Africa)**
  - **2 transiting planets found**

Mass-radius relation for hot Jupiters 01-Sep-06

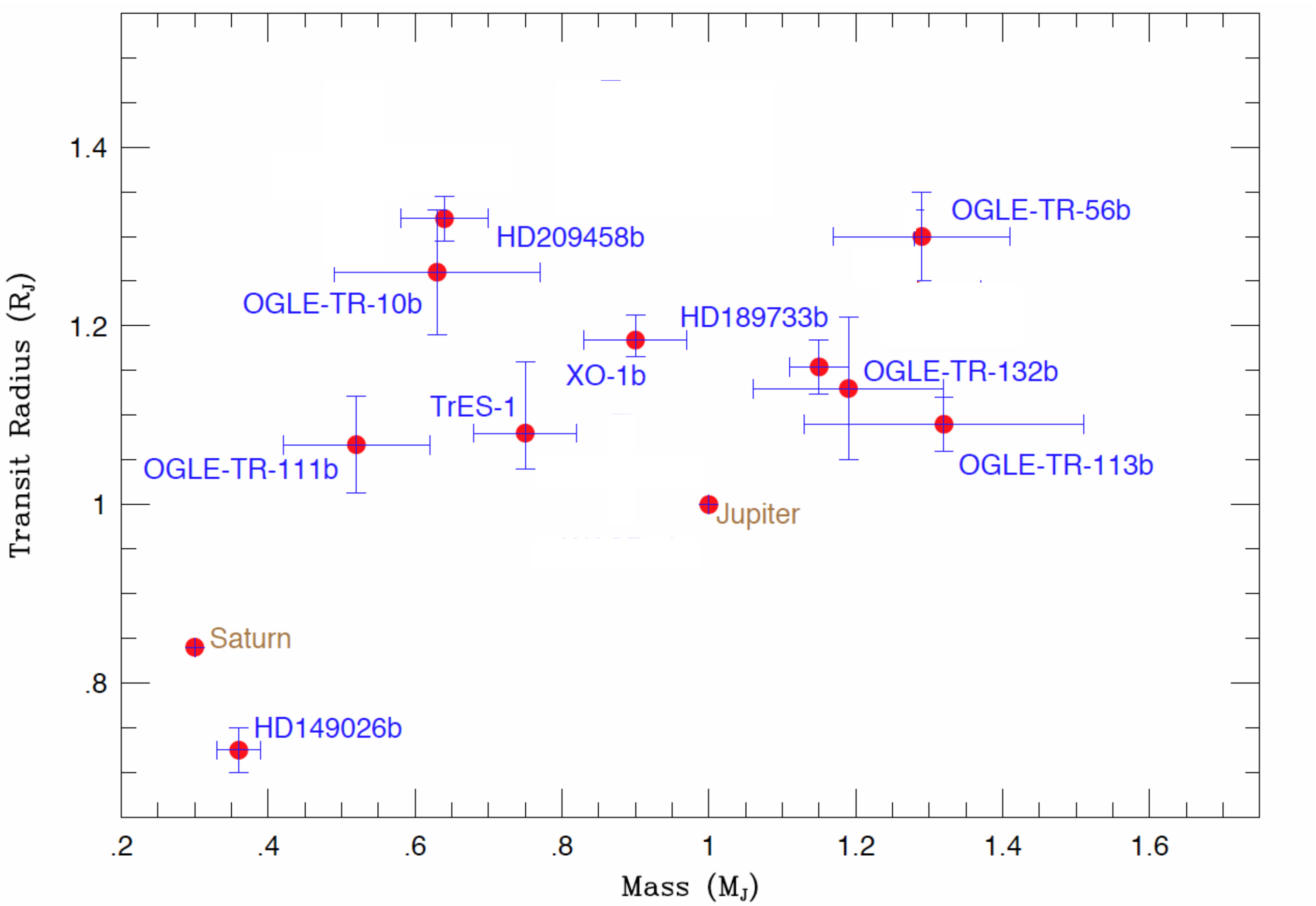


FIG. 1.— Transit radii (R_p, in R_J) of all of the irradiated EGPs listed in Table 1 versus planet mass (M_p, in M_J), along with published $1-\sigma$ error bars for each quantity. For comparison, points for Jupiter and Saturn themselves are also shown.

Mass-radius relation for hot Jupiters 08-Sep-06

- **TrES-2b, O'Donovan et al 2006 ApJ 651, 61**

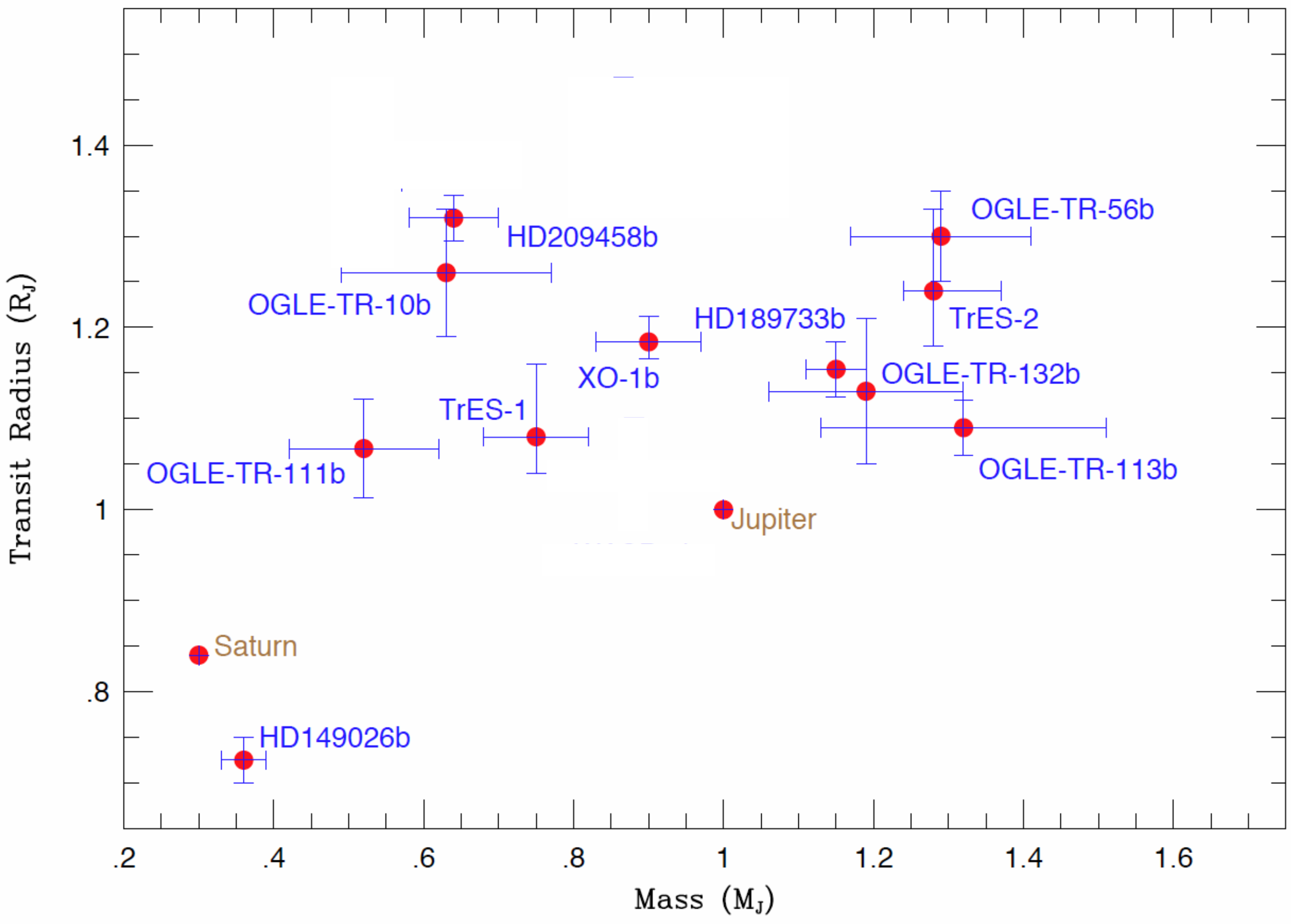


FIG. 1.— Transit radii (R_p, in R_J) of all of the irradiated EGPs listed in Table 1 versus planet mass (M_p, in M_J), along with publishec 1−σ error bars for each quantity. For comparison, points for Jupiter and Saturn themselves are also shown.

Mass-radius relation for hot Jupiters 15-Sep-06

- **HAT-P-1b, Bakos et al 2006 astro-ph/0609369**

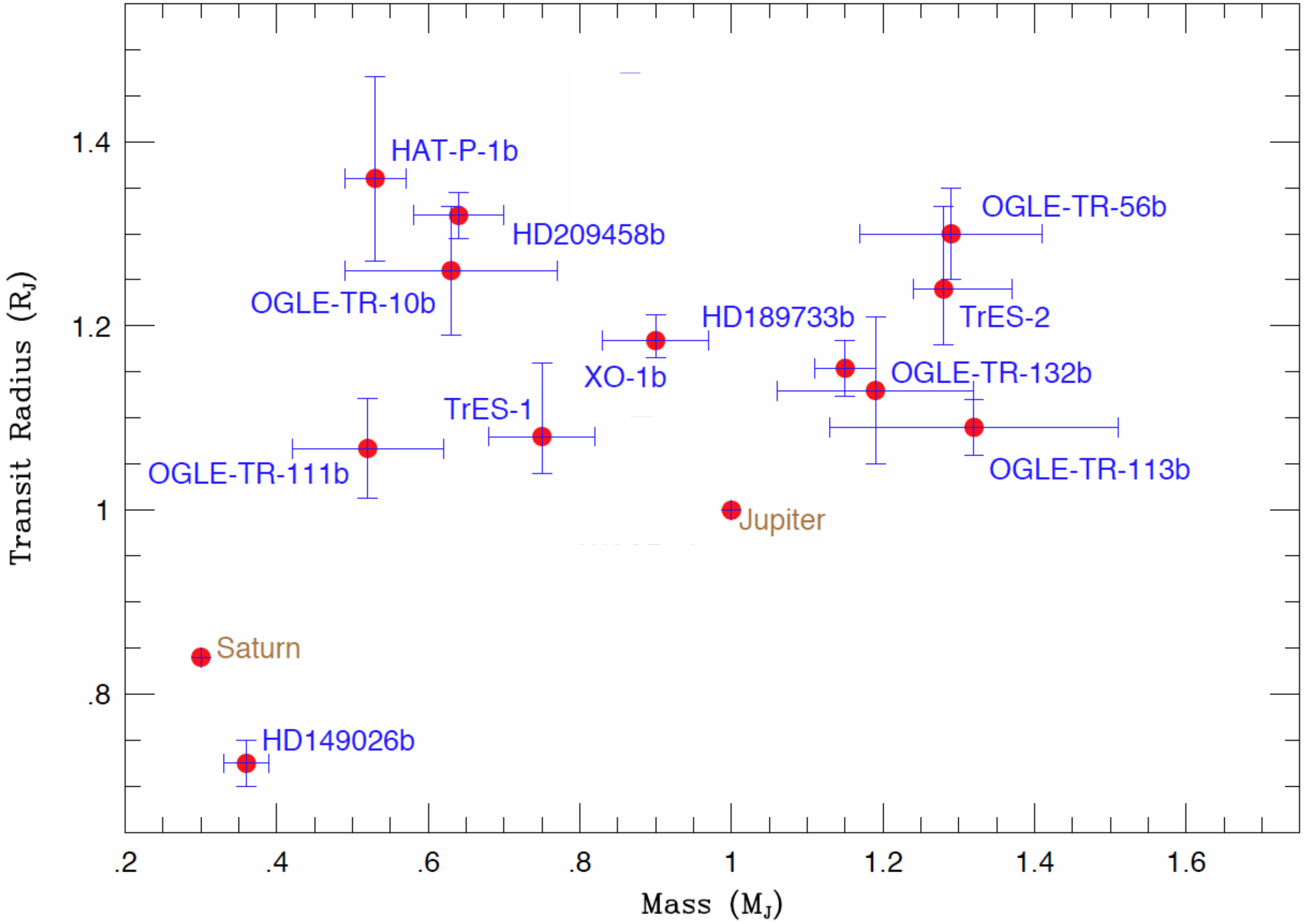
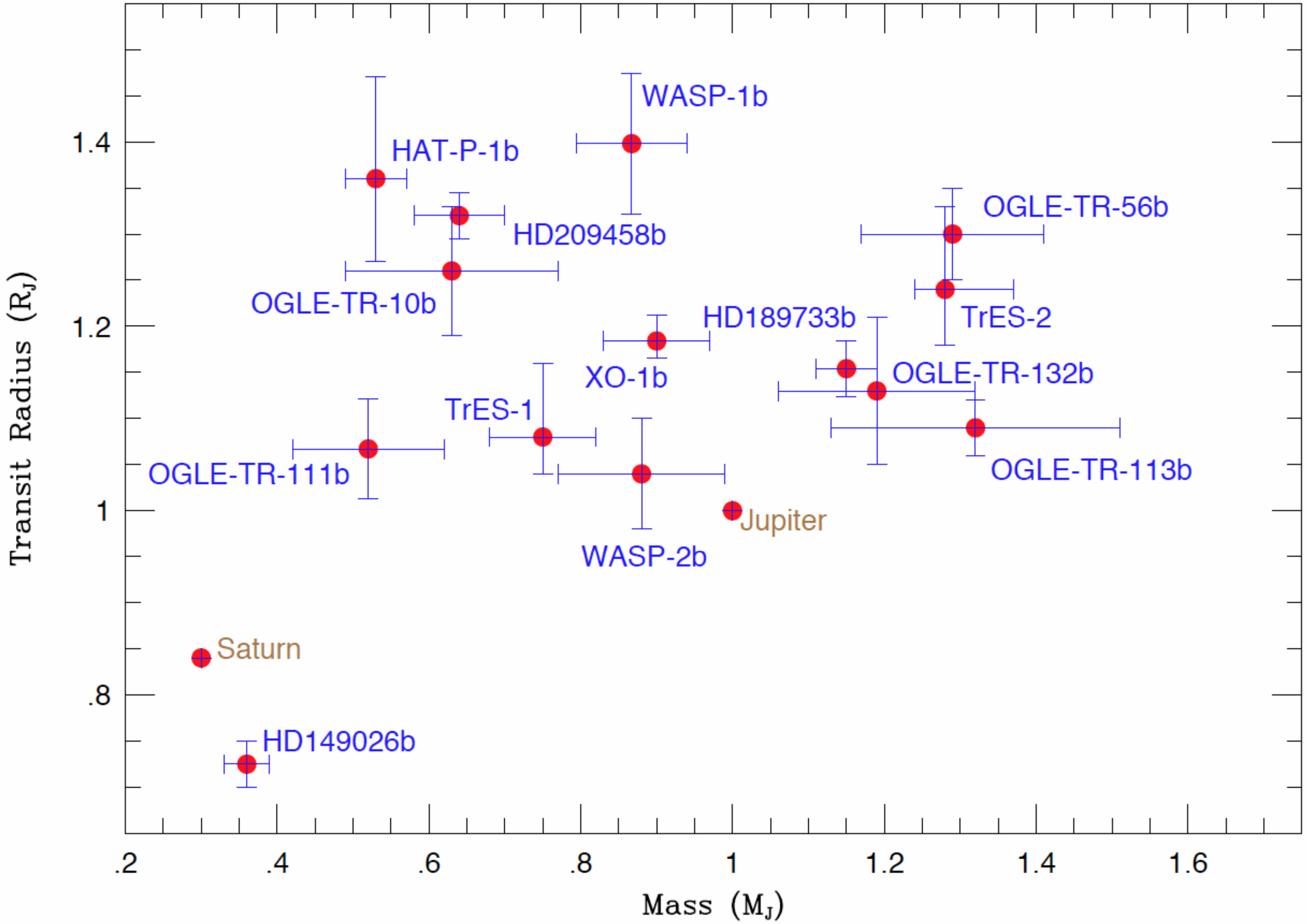


FIG. 1.— Transit radii (R_p, in R_J) of all of the irradiated EGPs listed in Table 1 versus planet mass (M_p, in M_J), along with published $1-\sigma$ error bars for each quantity. For comparison, points for Jupiter and Saturn themselves are also shown.

Mass-radius relation for hot Jupiters 25-Sep-06

- **WASP-1b,-2b: Cameron et al 2007, astro-ph/0609688**

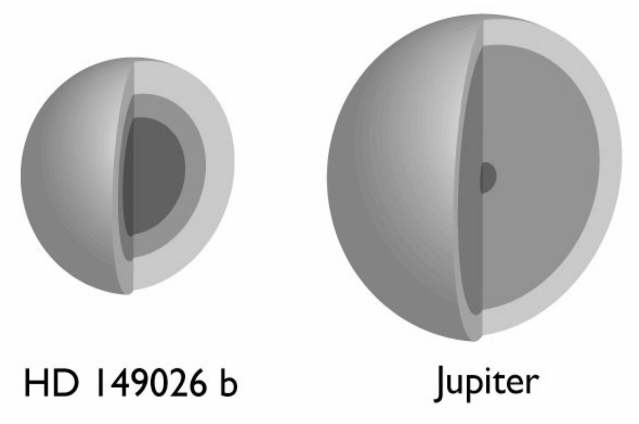


(+ XO-2b, HAT-P-2b, TrES-3, CoRoT-EXO-1b, Gl 436b since 2007 May 1)

FIG. 1.— Transit radii (R_p, in R_J) of all of the irradiated EGPs listed in Table 1 versus planet mass (M_p, in M_J), along with publishe 1$-\sigma$ error bars for each quantity. For comparison, points for Jupiter and Saturn themselves are also shown.

Why we need many more …

- **How does planet radius scale with**
  - **Planet mass? (Fortney et al 2007)**
  - **Planet age? (Many!)**
  - **Metallicity/opacity? (Burrows et al 2007, Guillot et al 2006)**
  - **Existence/size of core? (Guillot et al 2006)**
  - **Proximity to host star? (Fortney et al 2007)**
  - **Migration history?**
  - **?**



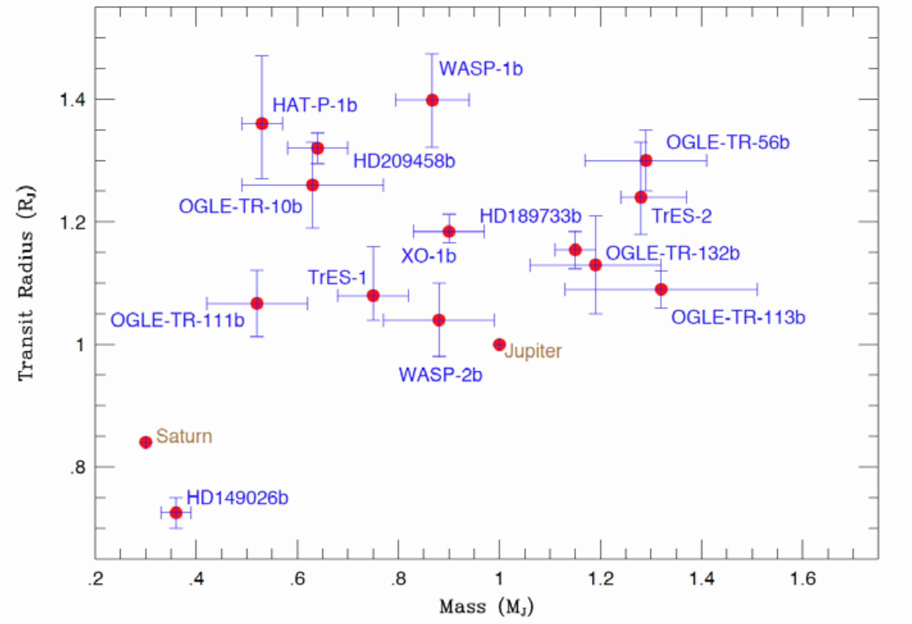
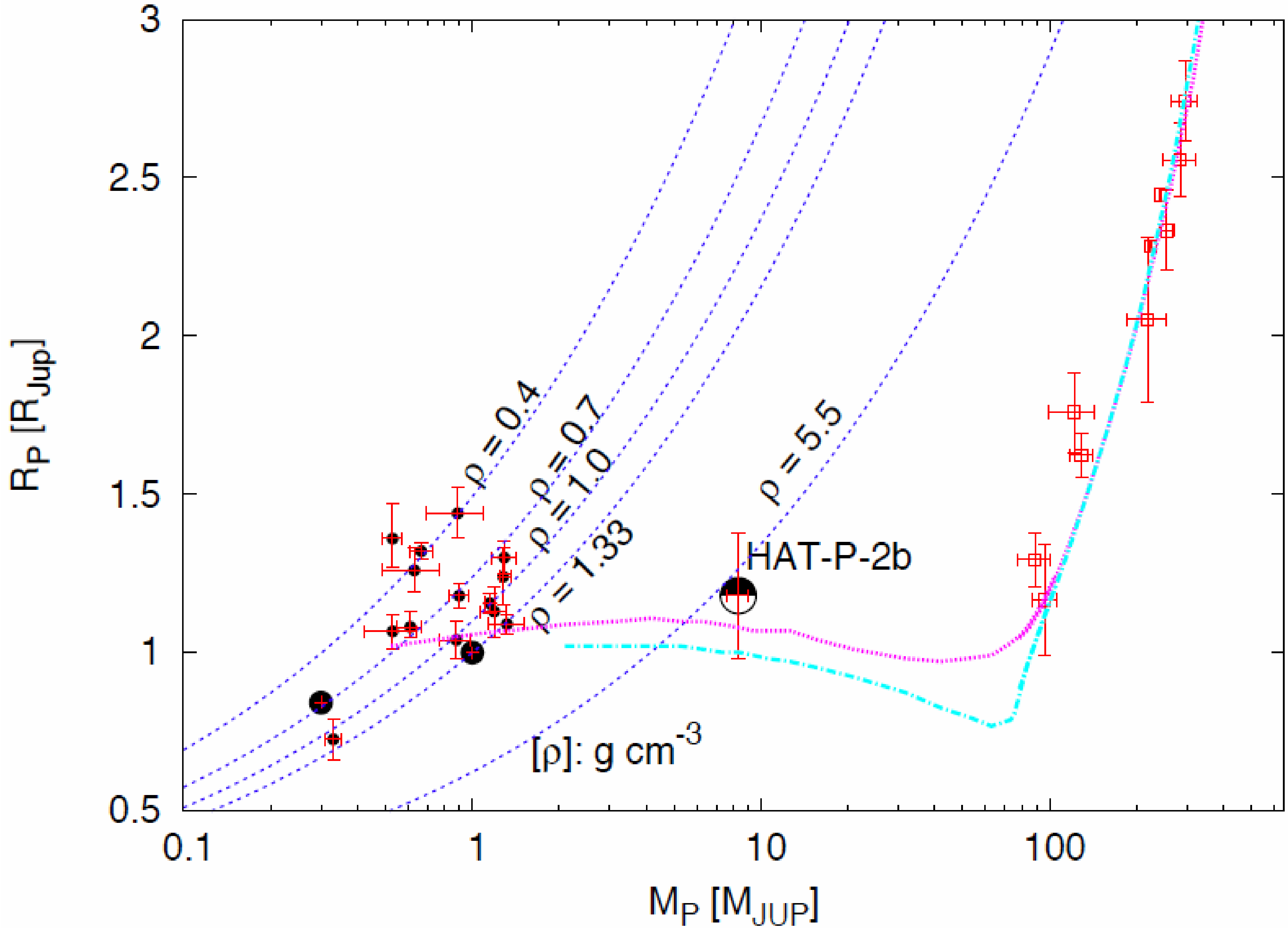


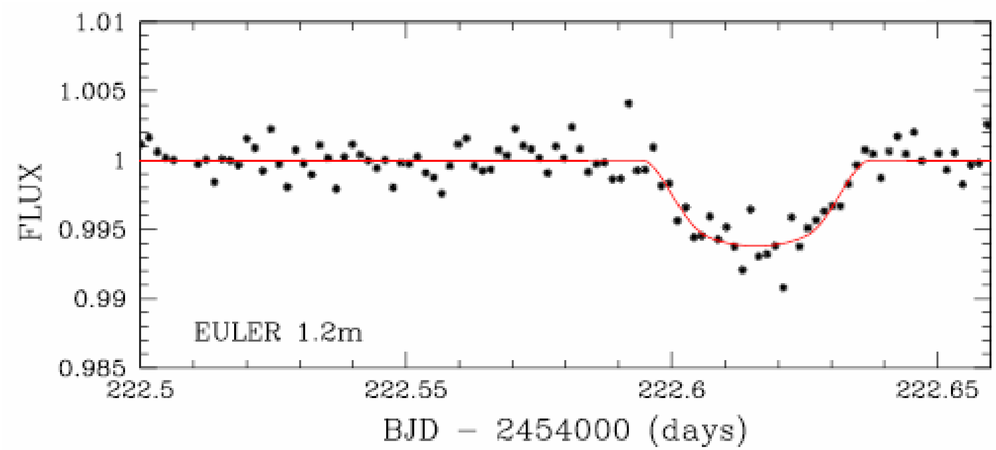
Fig. 1.— Transit radii (R_p, in R_J) of all of the irradiated EGPs listed in Table 1 versus planet mass (M_p, in M_J), along with publishe 1−σ error bars for each quantity. For comparison, points for Jupiter and Saturn themselves are also shown.

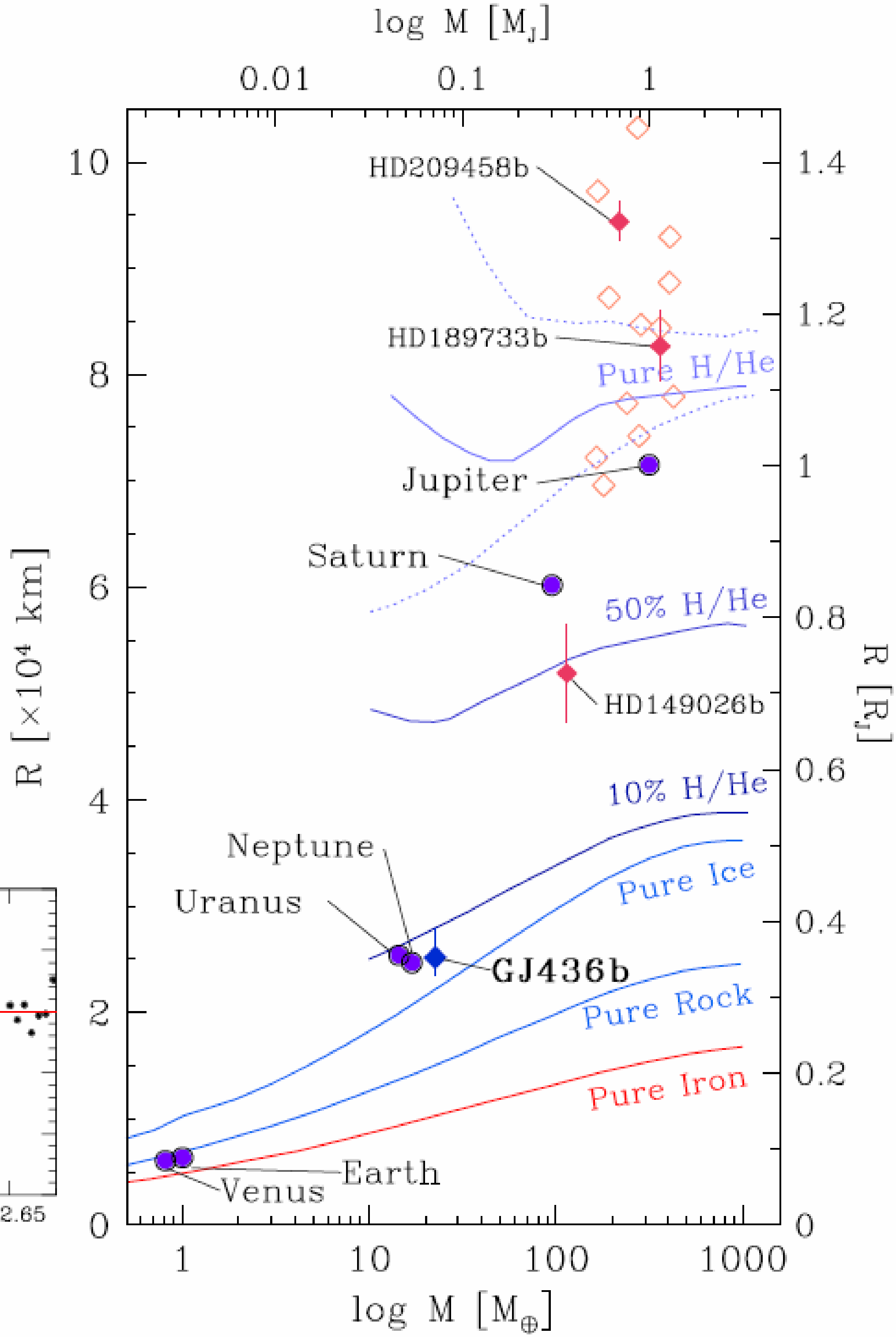
Substellar mass-radius relation



GJ 436 b

- **Gillon et al 2007 May 17, astro-ph/0705.2219**
- **Neptune-mass planet**
- **Neptune-like radius**
- **Radius depends strongly on composition (cf. Fortney et al 2007, astro-ph/0612671)**
- **Ice-giant structure.**





Skye, May 2007

Super**WASP**

Wide Angle Search for Planets

S. Aigrain (Cambridge)
D.J. Christian (Belfast)
W.I. Clarkson (Open University)
A. Collier Cameron (St Andrews)
B. Enoch (Open University)
N.A. Evans (Keele)
A. Fitzsimmons (Belfast)
C.A. Haswell (Open University)
L. Hebb (St Andrews)
C. Hellier (Keele)
S.T. Hodgkin (Cambridge)
K. Horne (St Andrews)
J. Irwin (Cambridge)
S.R. Kane (St Andrews)
F.P. Keenan (Belfast)
T.A. Lister (St Andrews/Keele)
P Maxted (Keele)
A.J. Norton (Open University)
J. Osborne (Leicester)
N. Parley (Open University)
D. Pollacco (Belfast)
R. Ryans (Belfast)
I. Skillen (ING)
R.A. Street (Belfast)
A.M.H.J. Triaud (St Andrews)
R.G. West (Leicester)
D.M. Wilson (Keele)
P.J. Wheatley (Leicester)

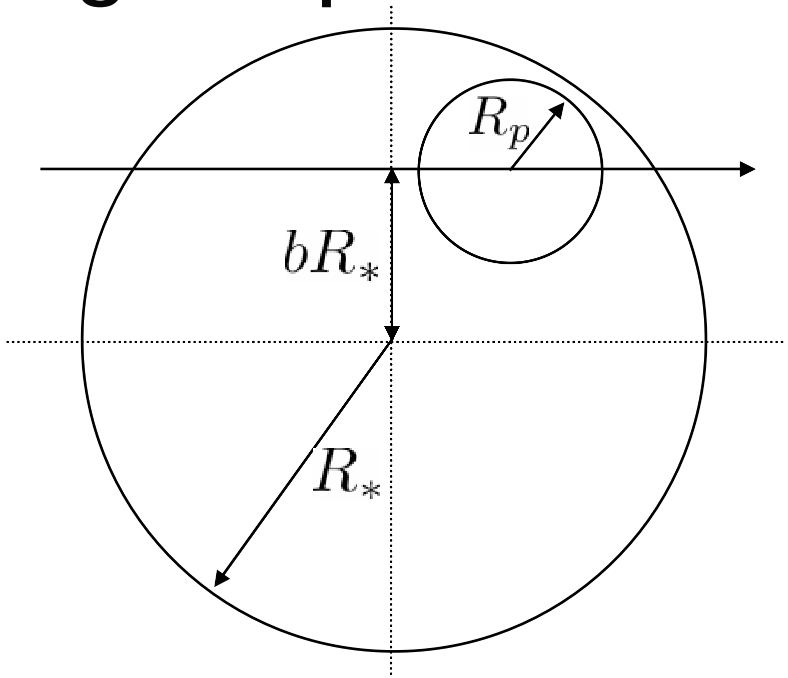
With:
F Bouchy (Geneva)
G Hébrard (IAP)
F Pont (Geneva)
B Loeillet (Marseille)
M Gillon (Geneva)
M Mayor (Geneva)
C Moutou (Marseille)
D Queloz (Geneva)
S Udry (Geneva)

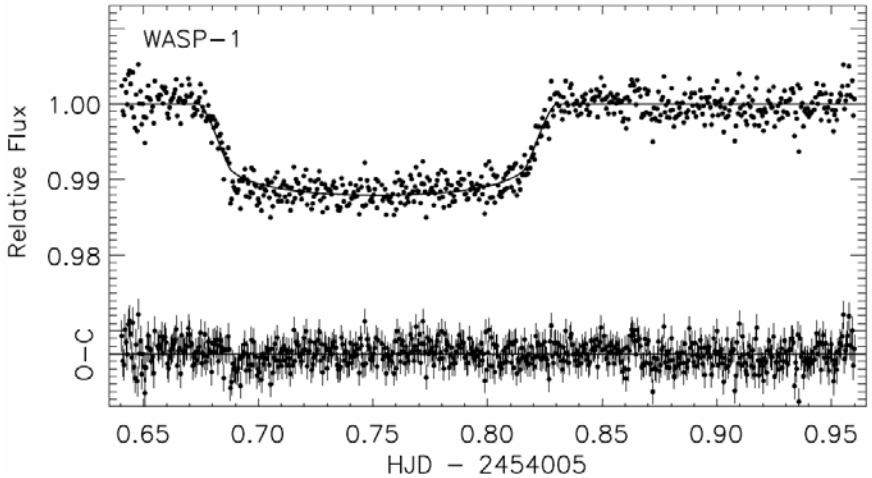
SuperWASP North and South

- **8-camera configuration**

Transiting extrasolar giant planets

- **19 examples known.**
- **Stellar mass and period yield orbital separation *a*.**
- **Transit shape yields**
  - **impact parameter** $b = \frac{a \cos i}{R_*}$
  - **stellar radius** R_*/a
- **Transit depth yields ratio of radii** R_p/R_*
- **Hence get *direct measure of planetary density.***





Example: 2004 SuperWASP season

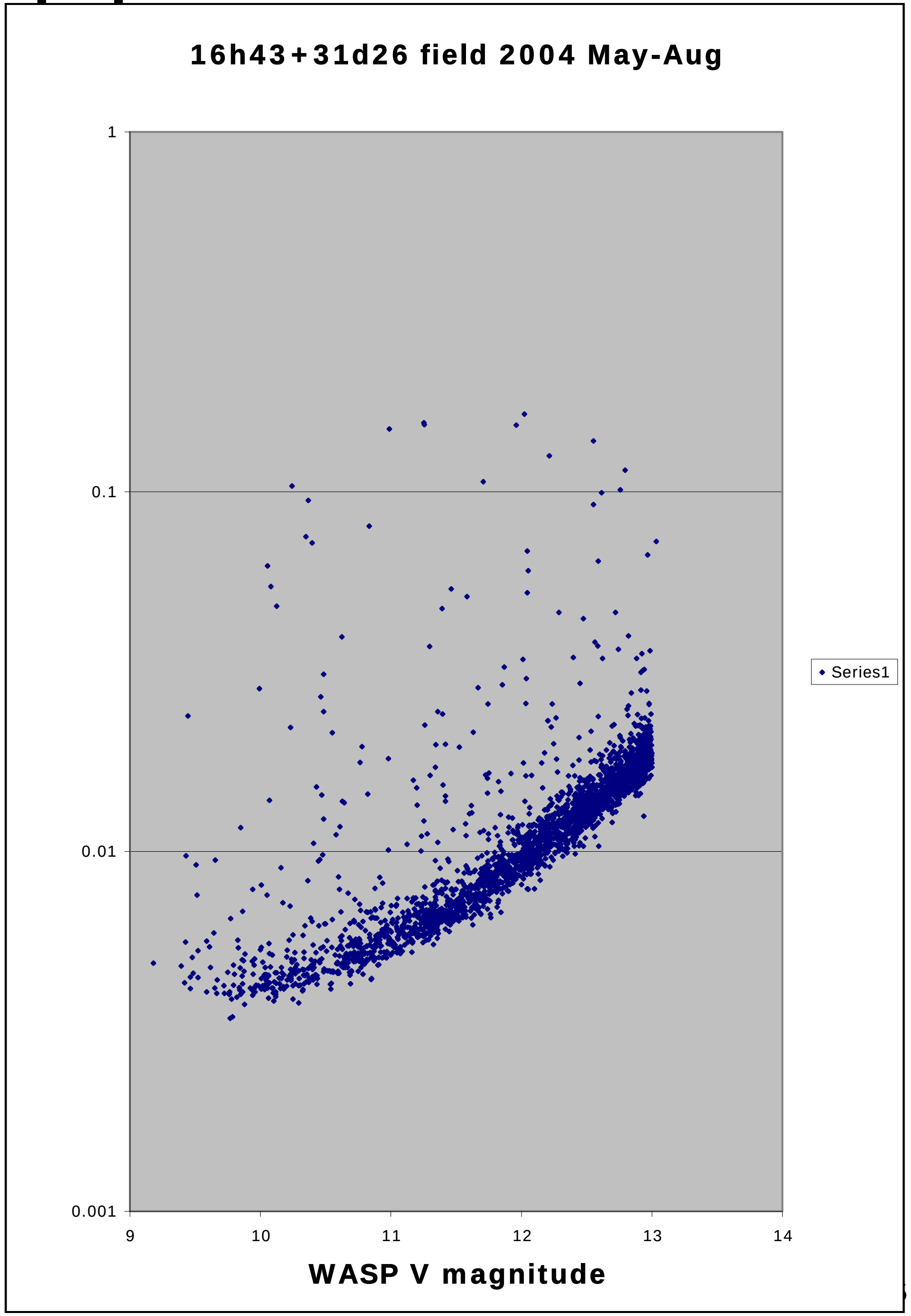
- **Light curves secured for 1.1×10^6 stars with $8 < V < 13$**
- **Average ~3000 measurements per star spanning ~120d.**
- **Transit candidate detection and selection methodology:**
  - **Collier Cameron et al 2006, MNRAS 373, 799**
- **Long-list of 109 transit candidates identified**
  - **Christian et al 2006, MNRAS 372, 1117**
  - **Other papers to follow**
- **Short-list of 25 candidates identified for spectroscopic followup on OHP 1.93-m telescope 2006 Aug/Sep.**
- **2 planets discovered**
  - **Collier Cameron et al 2007, MNRAS 375, 951**

SuperWASP hardware

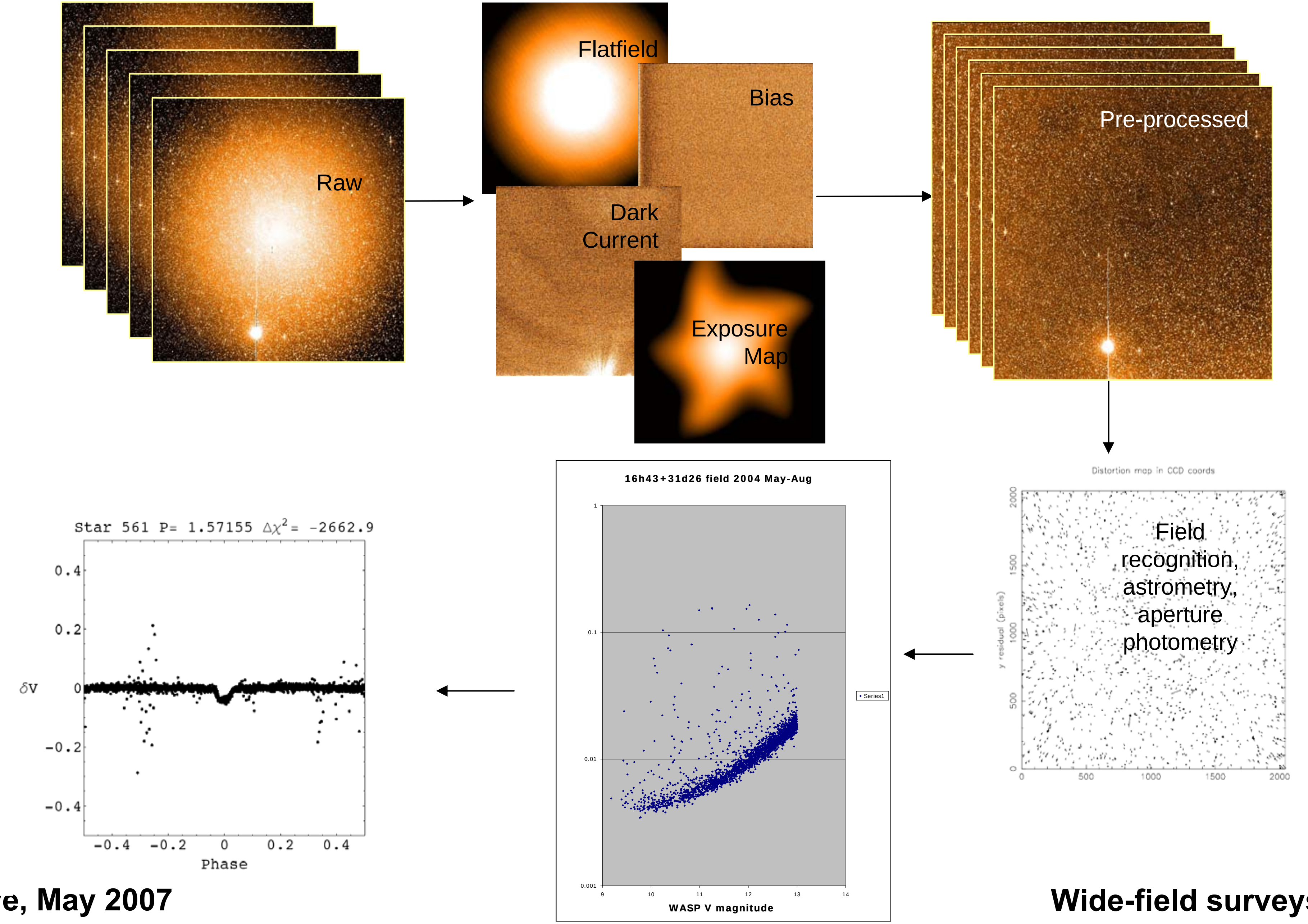
- Pollacco et al 2006, PASP 118, 1407
- Lenses
  - Canon 200mm f/1.8
  - Aperture 11.1 cm
- CCD Detector
  - 2048 x 2048 thinned e2v (Andor, Belfast)
  - 13.5x13.5 micron pixels
- Field of View
  - 7.8 x 7.8 degrees
  - 13.7 arcsec/pixel
- Mount
  - OMI/Torus robotic mount
- Operating Temperature
  - −50 °C
  - 3-stage Peltier Cooling

WASP data pipeline

- **Pollacco et al 2006, PASP 118, 1407**
- **Continuous unattended operation.**
  - Creates, applies master calibration frames
  - Field recognition, astrometry
  - Aperture photometry, blend analysis
  - Extinction, colour, zero-point calibration
  - 90s/frame for up to 170,000 stars
  - 1 night's data for 1 camera takes ~12 hours to process
- **Precision and long-term stability**
  - 0.004 mag at V~9.5,
  - 0.010 mag at V~12.0
  - Night-to-night RMS error <2 millimag.



WASP data reduction pipeline



Skye, May 2007

Wide-field surveys

Correlated systematic errors

- **Nightly zero-point calibration**
- **Secondary extinction**
- **Imperfect flat fielding/vignetting corrections**
- **Thermal drift in camera focus**
- **Etc…**
- **Use SysRem algorithm (Tamuz et al 2005):**
  - **Minimize**

$$\chi^2 = \sum_{ij} \frac{m_{ij} - c_i a_j}{\sigma_{ij}^2}$$

  - **With respect to c_i, a_j alternately, iterating to convergence**
  - **Similar to principal component analysis, but inverse variance weighted.**

Computation of SysRem components

$$c_i = \frac{\sum_j m_{ij} a_j / \sigma_{ij}^2}{\sum_j a_j^2 / \sigma_{ij}^2}$$

$$a_j = \frac{\sum_i m_{ij} c_i / \sigma_{ij}^2}{\sum_i c_i^2 / \sigma_{ij}^2}$$

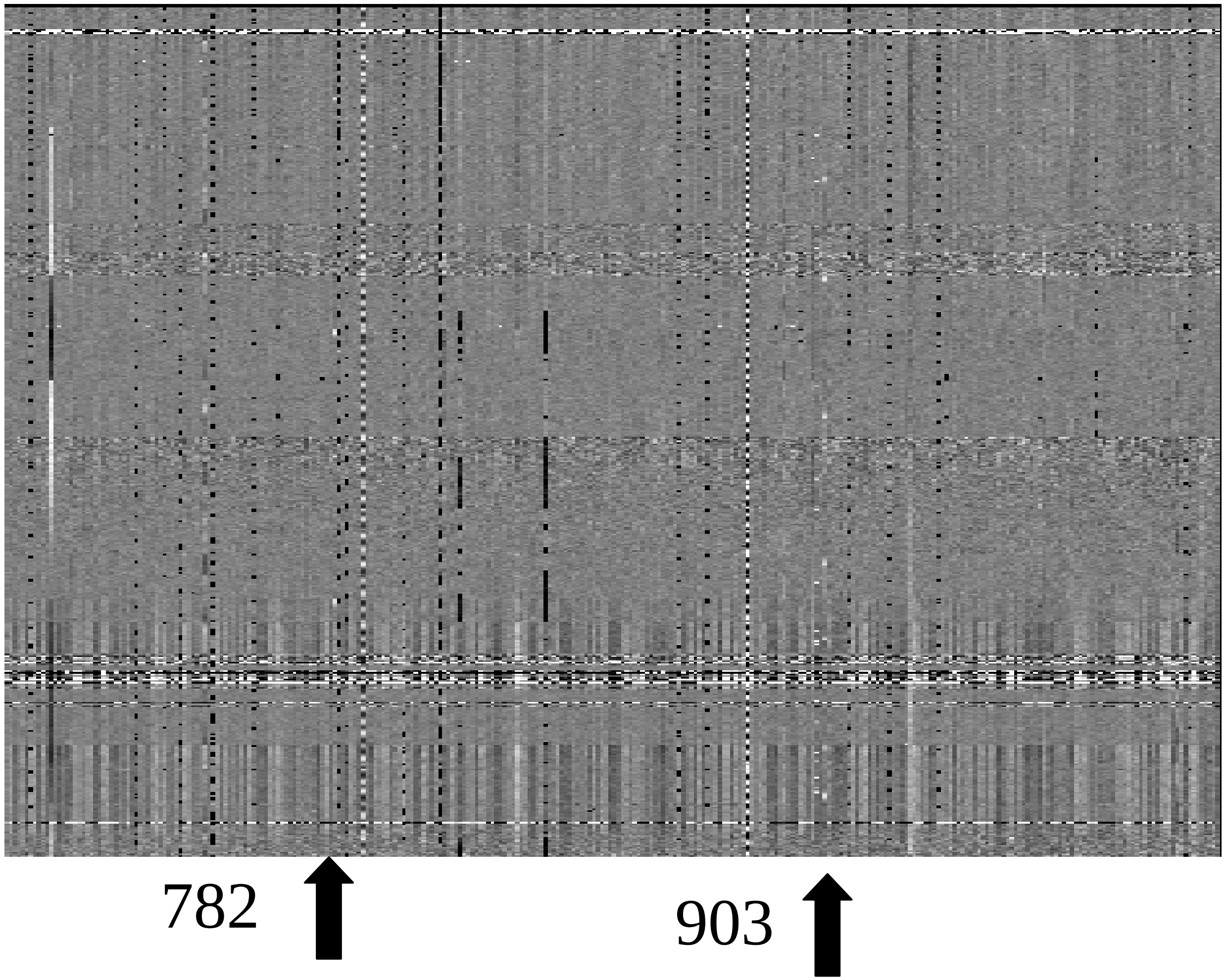
- **Iterate to convergence, then remove:**

$$^{(1)}m_{ij} = m_{ij} -^{(1)} a_i^{(1)} c_j$$

Decorrelation/ systematics removal

Tamuz et al 2005

16h30+28 field
300 stars
2549 observations
100 days



Decorrelation/ systematics removal

Tamuz et al 2005

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300 stars
2549 observations
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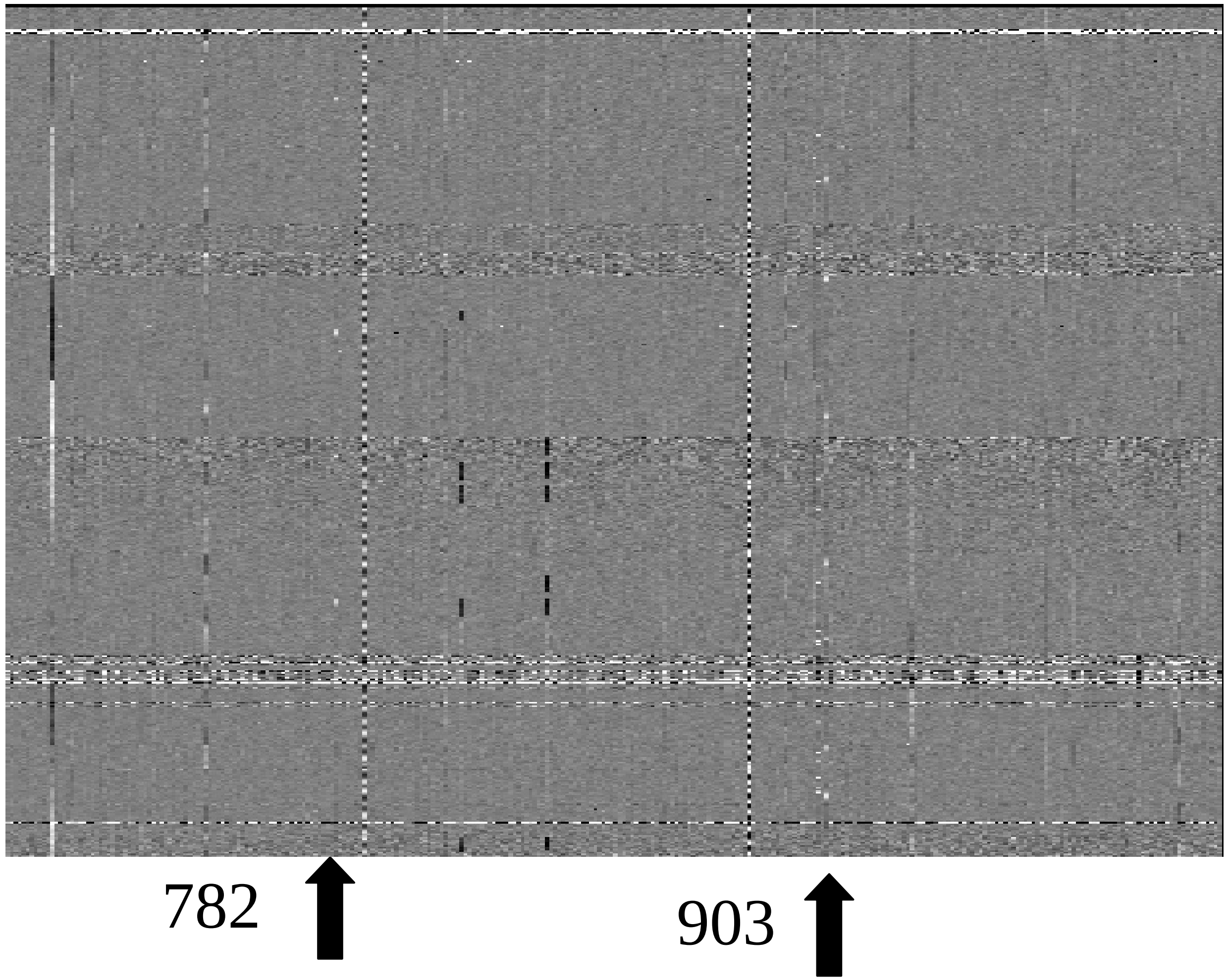


Systematic errors

- **Systematic errors tend to be correlated.**
  - **"Red noise"**
  - **Pont, F., et al 2006, MNRAS 373, 231.**

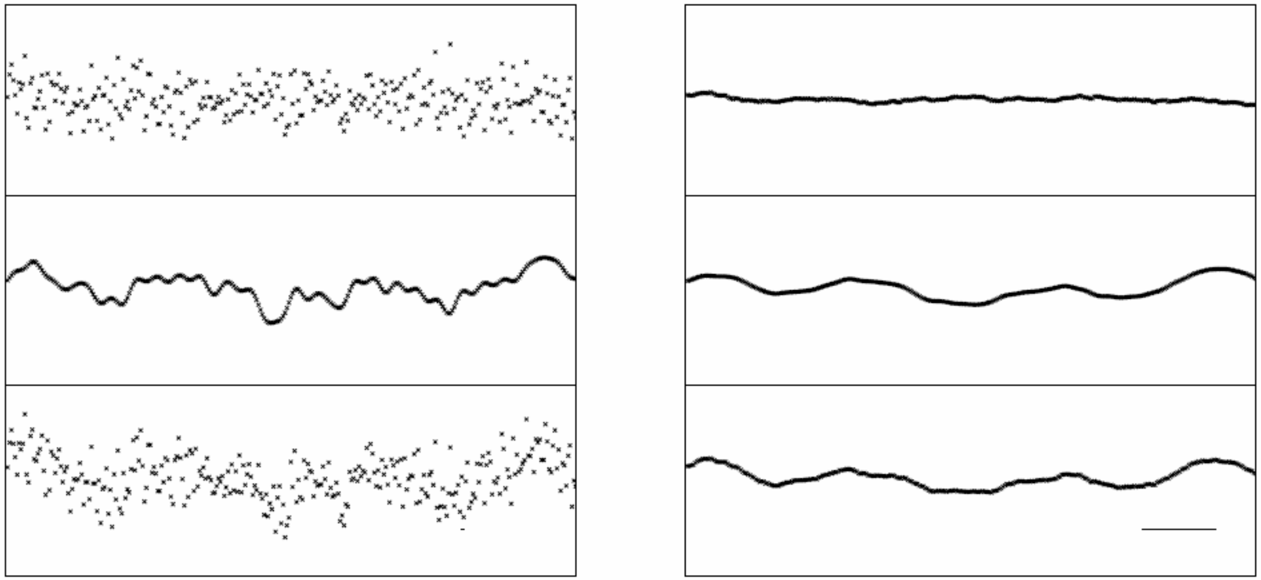


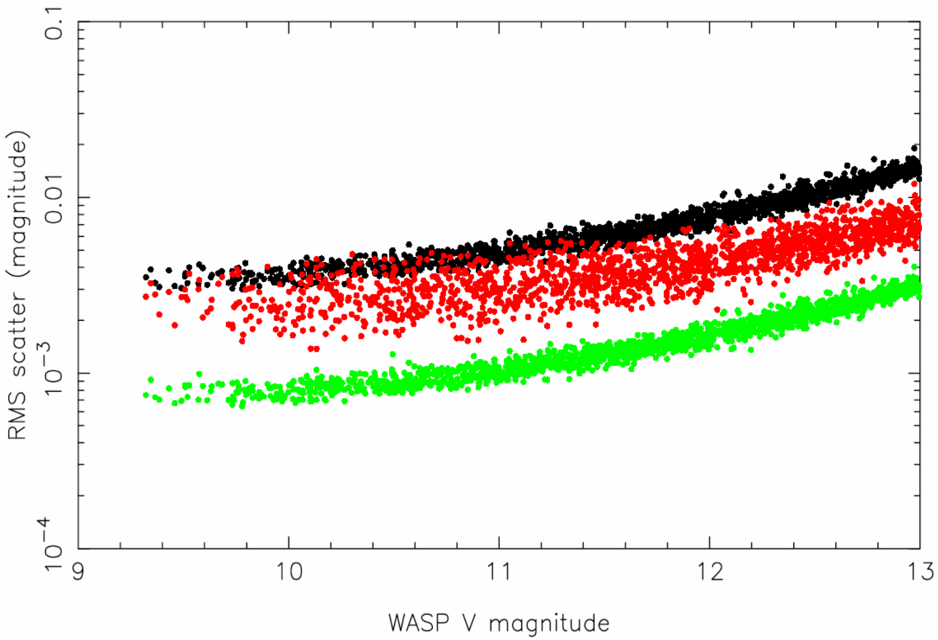
Figure 3.: **Left:** *A photometric time series with white, red or pink noise. The global dispersion is the same for the three curves.* **Right:** *the same series averaged over a transit duration (the transit duration is shown by the bar at the bottom right).*

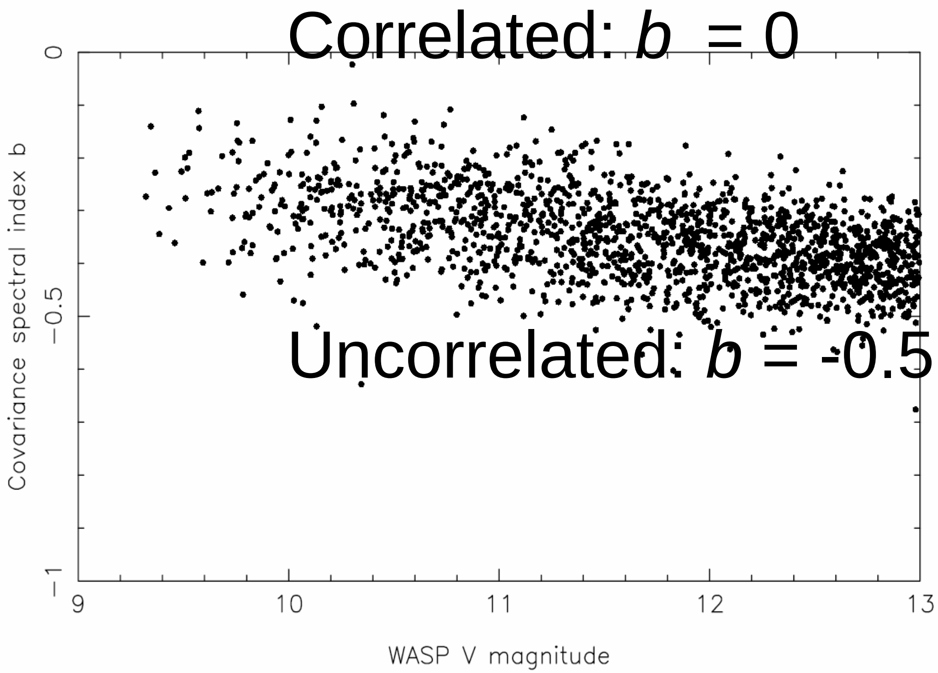
Red noise

- **Upper:**
  - **RMS scatter per observation**
  - **RMS scatter in 2.5-hr moving average**
  - **RMS scatter/√22**
- **Lower:**
  - **Covariance spectral index *b*:**

$$\sigma_{\text{binned}} = \sigma_{\text{unbinned}} L^b$$

  - **Where *L* = no of points in boxcar smoothing interval.**
  - **Cf. Pont et al (2006)**





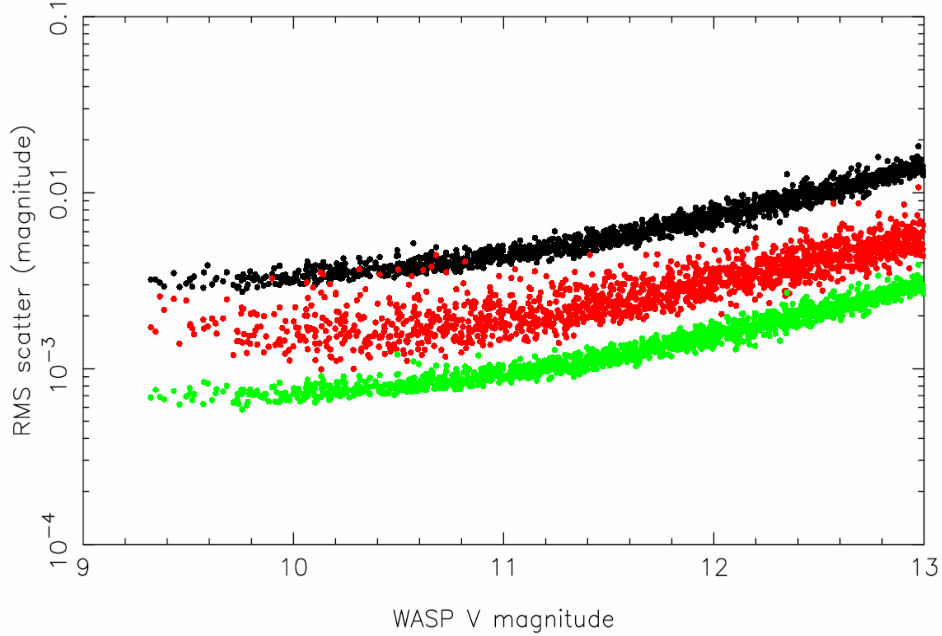
Skye, May 2007

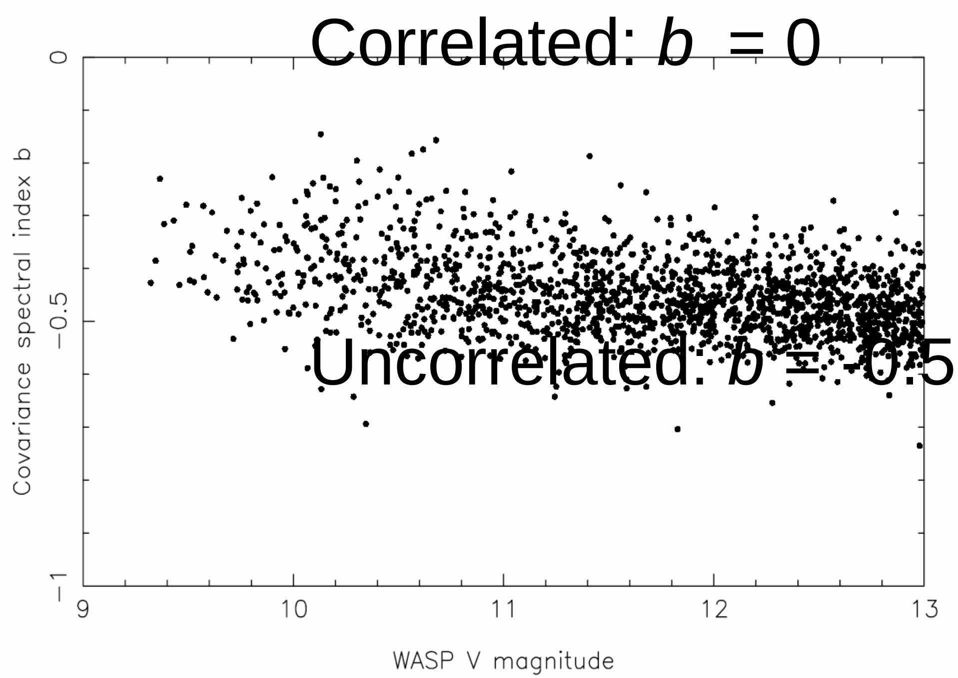
Post-SysRem

- **Upper:**
  - **RMS scatter per observation**
  - **RMS scatter in 2.5-hr moving average**
  - **RMS scatter/√22**
- **Lower:**
  - **Covariance spectral index *b*:**

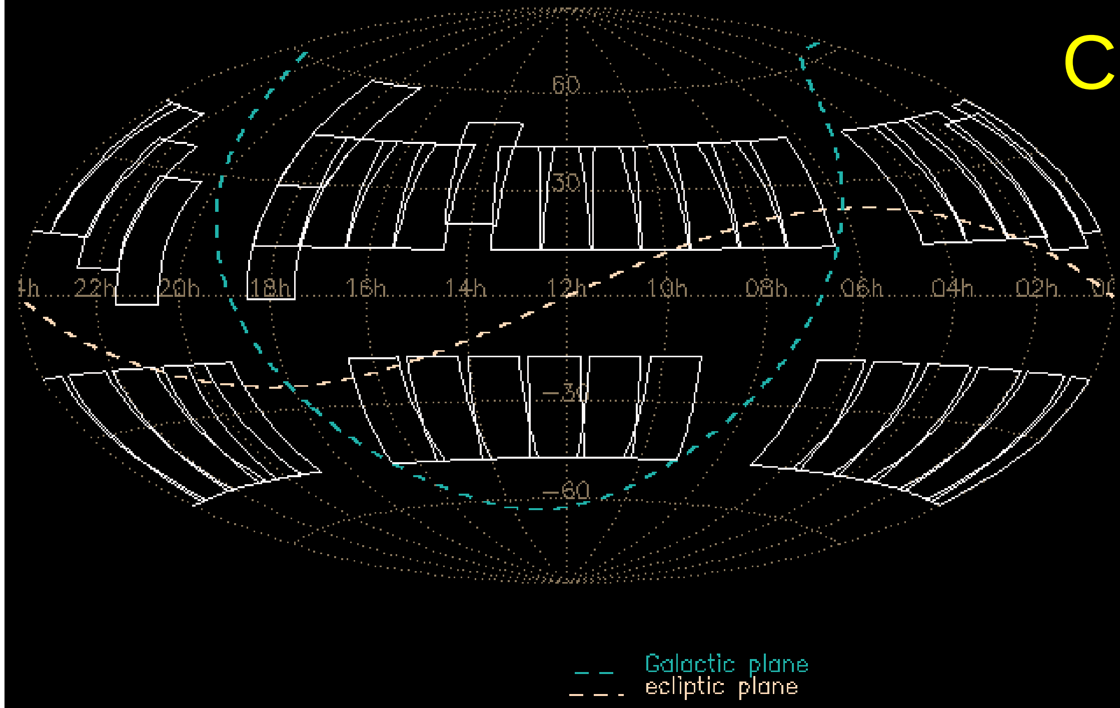
$$\sigma_{\text{binned}} = \sigma_{\text{unbinned}} L^{b}$$

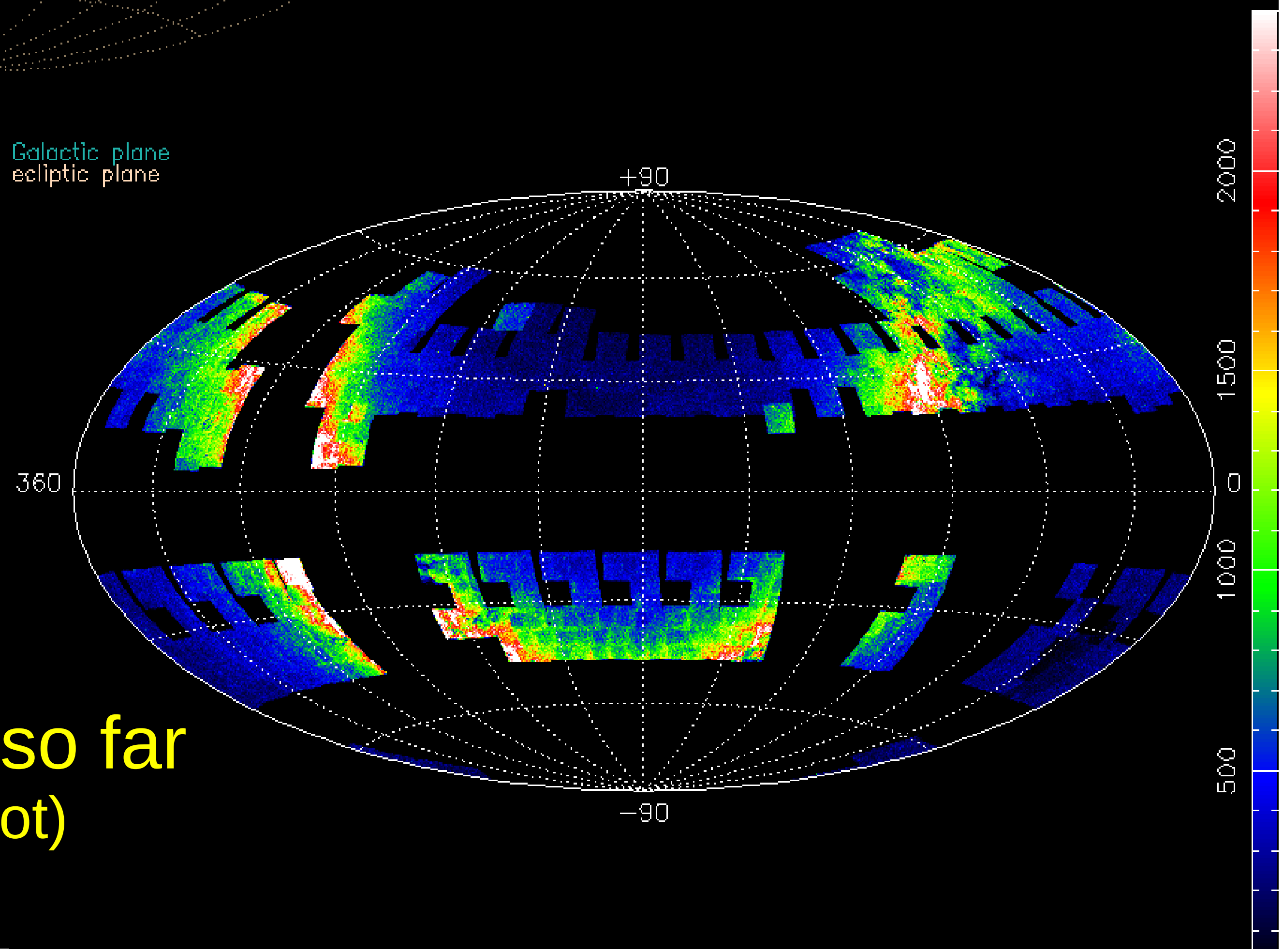
  - **Where *L* = no of points in boxcar smoothing interval.**
  - **Cf. Pont et al (2006)**





Current Observing fields





Data processed so far

(stellar density plot)

Lecture 2

- **How to detect transits in noisy data**
- **Measurement of stellar and planetary dimensions**
- **How to decide which ones to throw away**

The BLS (box least-squares) transit-search algorithm - I

- Kovacs et al 2002 A&A 391, 369
- Aigrain & Irwin 2004, MNRAS 350, 331
- Burke et al 2006 AJ 132, 210

- Observations (magnitudes) $\tilde{x}_i$
- Variances σ_i^2
- Inverse-variance weights $w_i = 1/\sigma_i^2$
- Subtract optimal average to get differential magnitudes

$$x_i = \tilde{x}_i - \frac{\sum \tilde{x}_i w_i}{\sum w_i}$$

The BLS algorithm - II

- **Define** $t = \sum_i w_i, \ \ \chi_0^2 = \sum_i x_i^2 w_i$
- **For each period P and epoch T0:**
  - Determine transit duration
  - Partition the data into a subset ℓ of low points in transit
  - Define

$$s = \sum_{i \in \ell} x_i w_i, \ \ r = \sum_{i \in \ell} w_i, \ \ q = \sum_{i \in \ell} x_i^2 w_i.$$

- **Mean mag inside (L) and outside (H) transit:**

$$L = \frac{s}{r}, H = \frac{-s}{t-r}$$

$$\mathrm{Var}(L) = \frac{1}{r}, \ \ \mathrm{Var}(H) = \frac{1}{t-r}.$$

The BLS algorithm - III

- **Fitted transit depth:**

$$\delta = L - H = \frac{st}{r(t-r)}, \quad \mathrm{Var}(\delta) = \frac{t}{r(t-r)},$$

- **Signal-to-noise ratio (SNR) of transit depth:**

$$\mathrm{SNR} = \frac{\delta}{\sqrt{\mathrm{Var}(\delta)}} = s\sqrt{\frac{t}{r(t-r)}}$$

- **Badness of fit and improvement relative to no transit:**

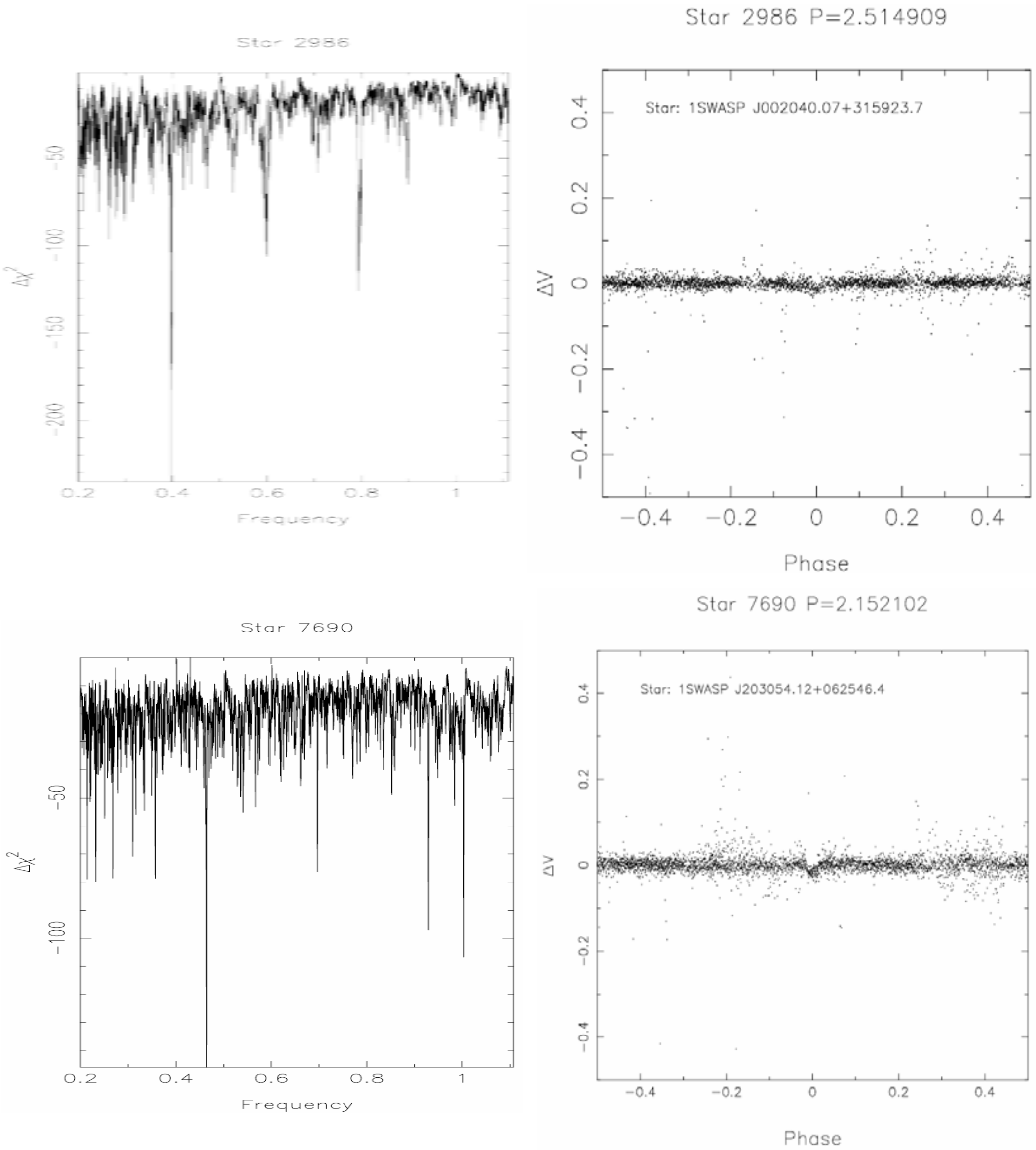
$$\chi^2 = \chi_0^2 - \Delta\chi^2 \qquad \Delta\chi^2 = \frac{s^2 t}{r(t-r)} = s\delta = (SNR)^2$$

- **Goodness of fit outwith transit (where light curve is supposed to be flat!):**

$$\chi_h^2 = \chi_0^2 - \frac{s^2}{(t-r)} - q$$

Accelerated BLS method

- **Collier Cameron et al 2006, MNRAS 373, 799**
  - **Coarse search, ~10x faster than Kovacs (2002) code**
    - » **Period range 1 - 5 days**
    - » **Precompute transit duration for each period**
    - » **Least-squares fit to box-shaped transit**
  - **Linearised parameter refinement around periodogram peaks**
  - **(cf. Protopapas et al 2005. MNRAS 462, 360)**
  - **Yields epoch, period, transit duration, transit depth**



Candidate selection

- **Christian et al 2006, MNRAS 372,1117**
- **Cameron et al 2007, MNRAS (submitted)**
- **Require**
  - **N > 2 transits**
  - **Post-fit $\chi^2 < 3.5 N_{obs}$**
  - **Signal-to-red-noise ratio > 5 (Pont et al 2006)**
  - **"Anti-transit ratio" $\Delta\chi^2/\Delta\chi^2_{-} > 1.5$ (Burke et al 2005)**
- **Astrophysical false positives (Pont et al 2005):**
  - **Grazing stellar binaries.**
  - **Bright stars blended with ecipsing binaries**
  - **Binaries with planet-sized stellar-mass secondaries**
- **Two important questions:**
  - **Is the primary on the main sequence?**
  - **Is the secondary planet-sized?**

M-S temperature and radius from *J-H*

$$T_{eff} = -4369.5(J-H) + 7188.2, 4000 < T_{eff} < 7000$$

- **Calibration sample: Ammons et al 2006**

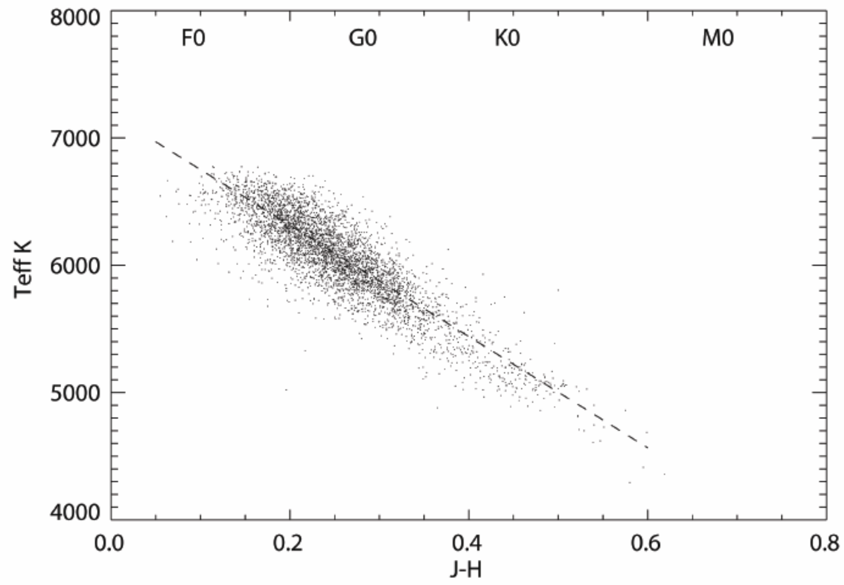


Figure B1. $J-H$ colour index against temperature for FGK dwarfs from the Tycho-2 catalogue (only 1/15 datapoints are shown for clarity).

- **Polynomial fit to temp-radius tabulation of Gray (1992)**

$$\frac{R_*}{R_\odot} = -3.925 \times 10^{-14}(T_{\rm eff})^4 + 8.3909 \times 10^{-10}(T_{\rm eff})^3 - 6.555 \times 10^{-6}(T_{\rm eff})^2 + 0.02245(T_{\rm eff}) - 27.9788.$$

Dwarf-giant separation

- **Reduced proper motion**
  - **Using 2MASS J magnitude**
- **Calibration stars from**
  - **Valenti & Fischer 2005**
  - **Cayrel de Strobel 2001**
- **Catalogue mining:**
  - **2MASS J, H**
  - **NOMAD proper motions**
- **Indicative rather than conclusive.**

$$\mathrm{H_J} = J + 5\log(\mu)$$

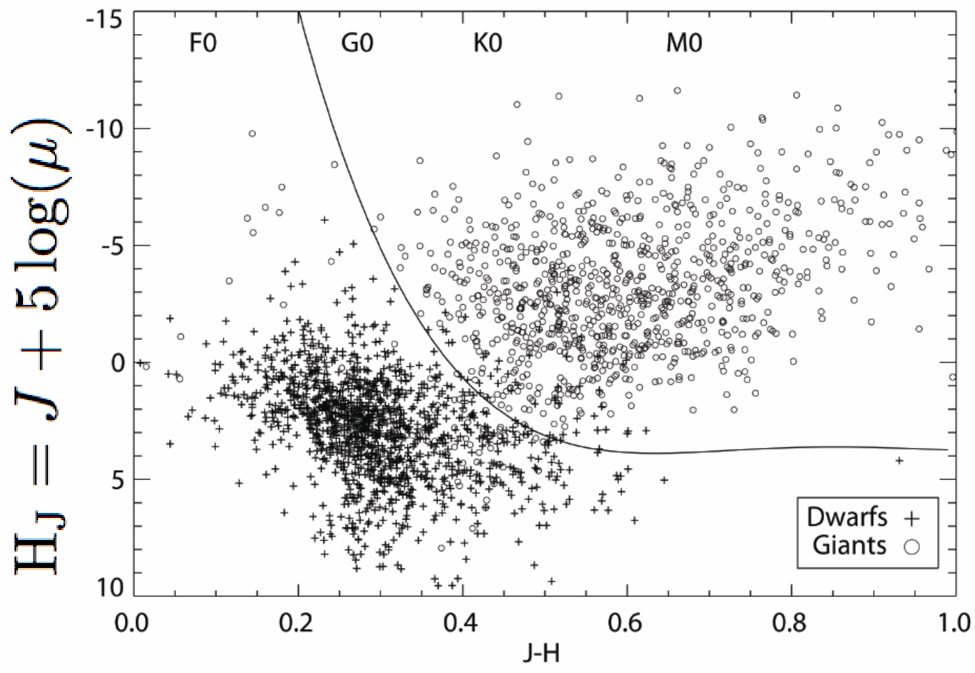


Figure 8. Reduced proper motion against $J - H$ for dwarfs (log g $\geqslant 4.0$) and giants (log $\leqslant 3.0$).

Stellar and planetary parameters

- **Analytic light curve model**
  - Mandel & Agol 2002, ApJ 580, L171
- **Linear, quadratic or 4-coeff limb darkening.**
- **Orbital and geometrical parameters:**
  - Epoch T_0
  - Period P
  - Impact parameter $b = \frac{a \cos i}{R_*}$
  - Companion radius / primary radius R_2/R_*
  - Stellar radius / orbital separation R_*/a
  - Stellar mass M_*
- **Compute model** $\mu(T_0, P, R_2/R_*, R_*/a, b, M_*)$
- **Evaluate** $\chi^2 = \sum_j \frac{(m_j - \mu_j - \Delta m)^2}{\sigma_j^2}$

$$\Delta m = \frac{\sum_j (m_j - \mu_j) w_j}{\sum_j w_j}$$

Physical vs observable parameters

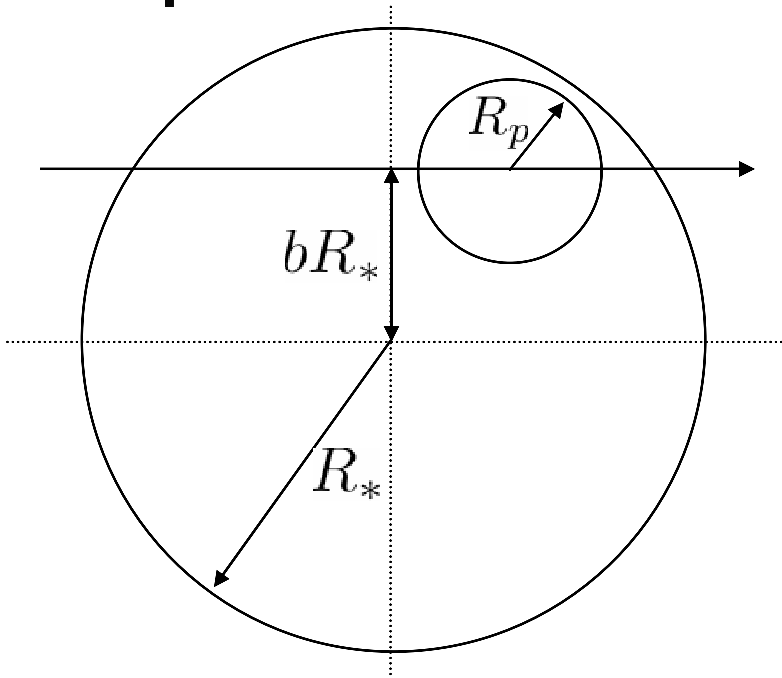
- **Seager et al (2003)**
- **Define a quantity akin to transit depth:**

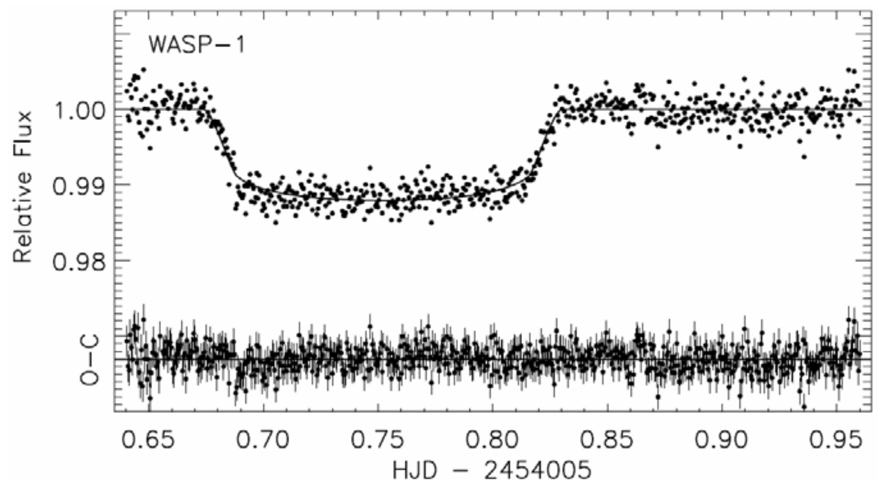
$$\Delta F = (R_2/R_*)^2$$

- **For $R_p+R_* \ll a$, total transit duration from first to last contact is:**

$$\frac{t_T}{P} = \frac{R_*}{a}\frac{(1+\sqrt{\Delta F})^2 - b^2}{\pi}$$

- **t_T and ΔF are constrained by observation, giving an ambiguity between b and R_* /a**





Prior knowledge is useful!

- **Likelihood of getting data *D* given model parameters:**

$$\mathcal{P}(D|T_0, P, \Delta F, t_T, b, M_*) = \exp\left(-\chi^2/2\right)$$

- **Prior probability for stellar mass and radius:**

$$\mathcal{P}(M_{*,i}, R_{*,i}) = \exp\left(-\frac{(M_{*,i}-M_0)^2}{2\sigma_M^2} - \frac{(R_{*,i}-R_0)^2}{2\sigma_R^2}\right)$$

- **For simplicity derive R_0 from *J-H* and M_0 from mass-radius relation**

$$\frac{M_0}{M_\odot} \simeq \left(\frac{R_0}{R_\odot}\right)^{1.25}$$

Constrained optimisation

- **Bayes' Theorem: Posterior probability is proportional to product prior x likelihood:**

$$\mathcal{P}(M_*, R_*) \exp(-\chi^2/2)$$

- **Use prior estimate of the stellar mass and radius (from *J-H*) to constrain solution by minimising**

$$Q \equiv \chi^2 + \frac{(M_* - M_0)^2}{\sigma_M^2} + \frac{(R_* - R_0)^2}{\sigma_R^2}$$

- **Use Markov-Chain Monte Carlo (MCMC) method to get posterior probability distributions of system parameters:**

$$\{T_0, P, \Delta F, t_T, b, M_*\}$$

- **And hence, also** $\{R_p, R_*\}$

A crash course in MCMC - I

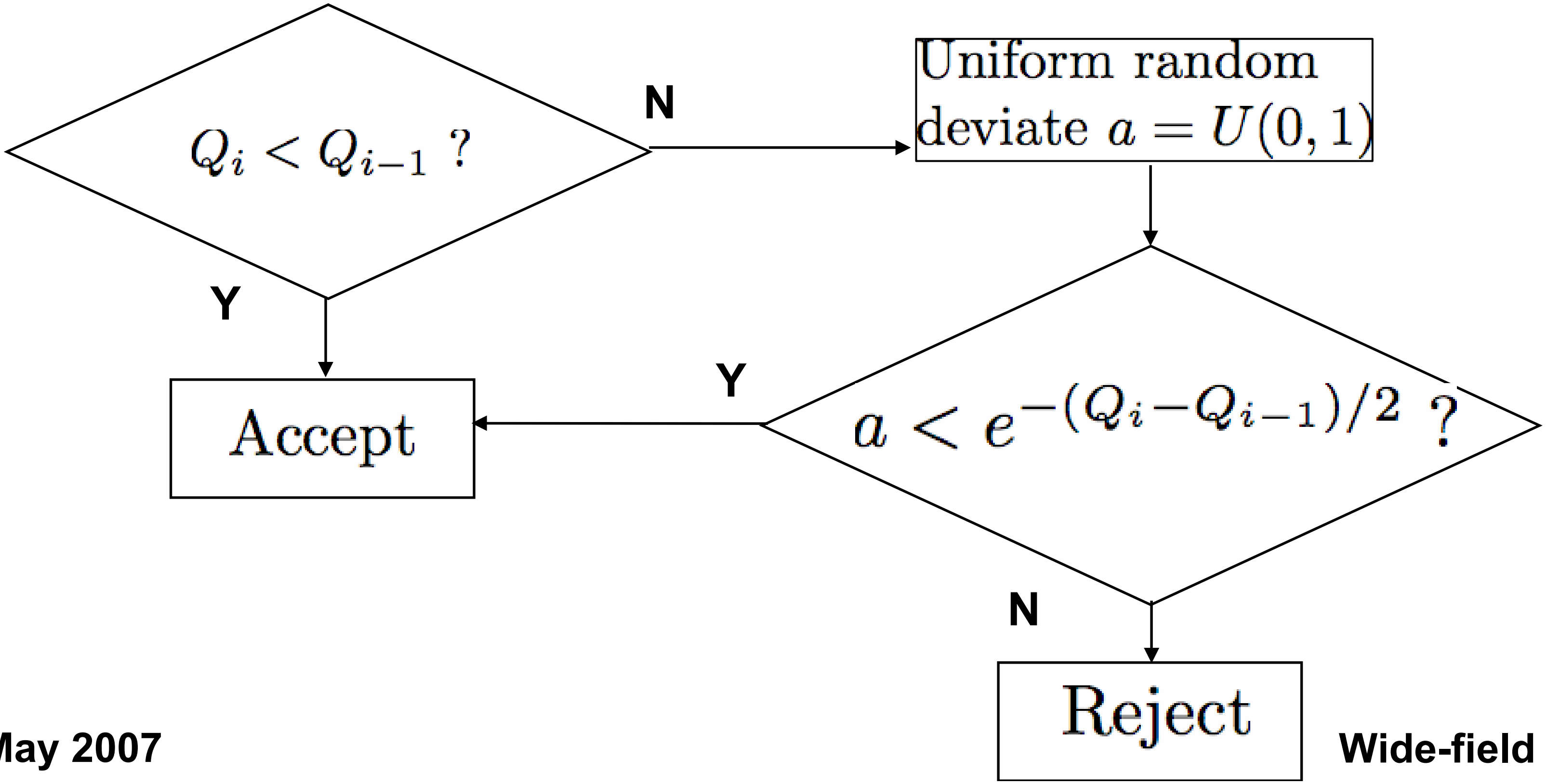
- **Generate a sequence of random steps in parameter space:**

$$
\begin{aligned}
T_{0,i} &= T_{0,i-1} + \sigma_{T_0} G(0,1) f \\
P_i &= P_{i-1} + \sigma_P G(0,1) f \\
\Delta F_i &= \Delta F_{i-1} + \sigma_{\Delta F} G(0,1) f \\
t_{T,i} &= t_{T,i-1} + \sigma_{t_T} G(0,1) f \\
b_i &= T_{0,i-1} + \sigma_b G(0,1) f \\
M_{*,i} &= M_{*,i-1} + \sigma_M G(0,1) f
\end{aligned}
$$

- **Random Gaussian deviate** $G(0,1)$
- **Adaptive stepsize controller** $0.5 < f < 1.0$

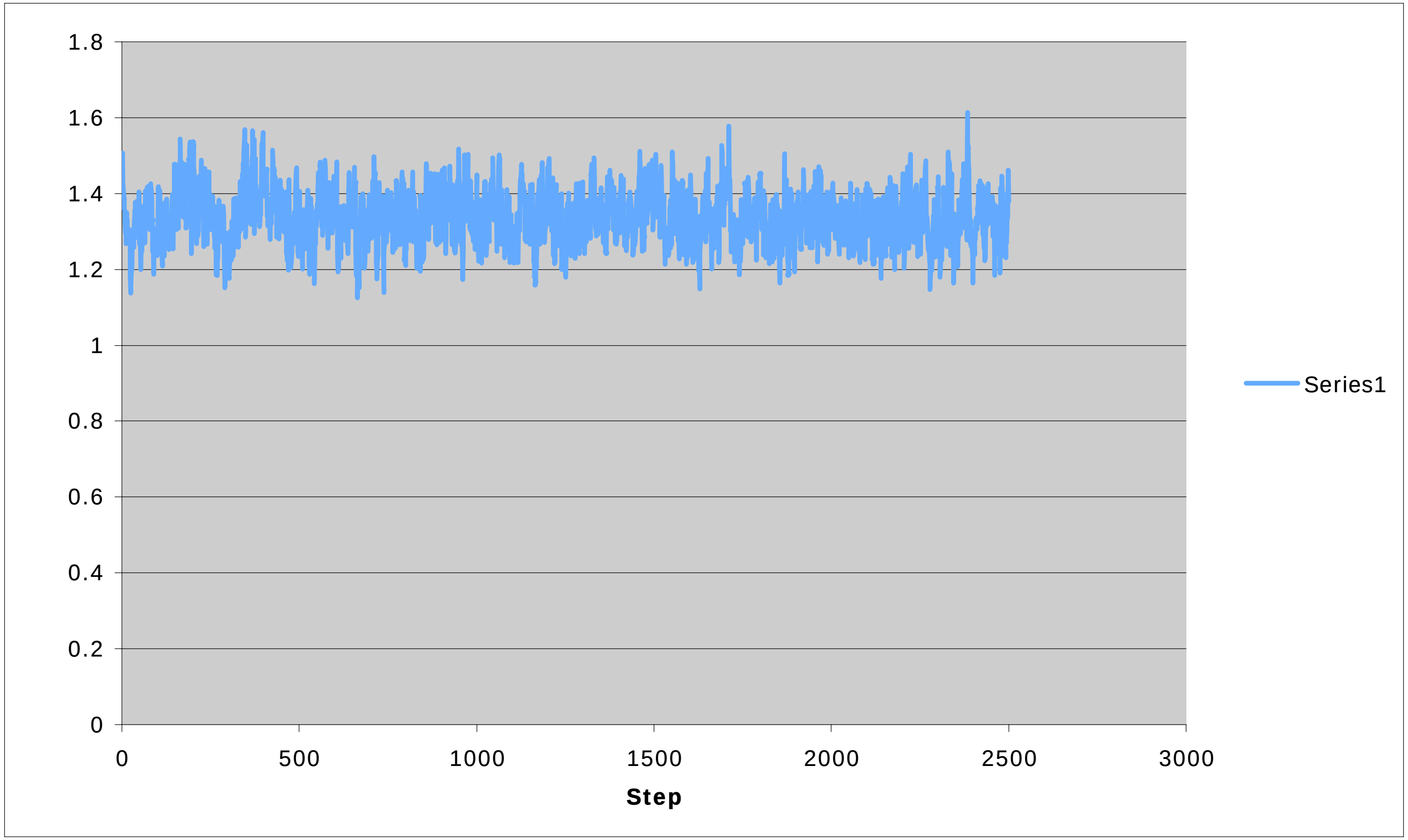
A crash course in MCMC - II

- **Compute model light curve using new parameters**
- **Compute** $Q_i \equiv \chi_i^2 + \frac{(M_{*,i} - M_0)^2}{\sigma_M^2} + \frac{(R_{*,i} - R_0)^2}{\sigma_R^2}$
- **Apply *Metropolis-Hastings test* to decide whether to accept or reject new set:**

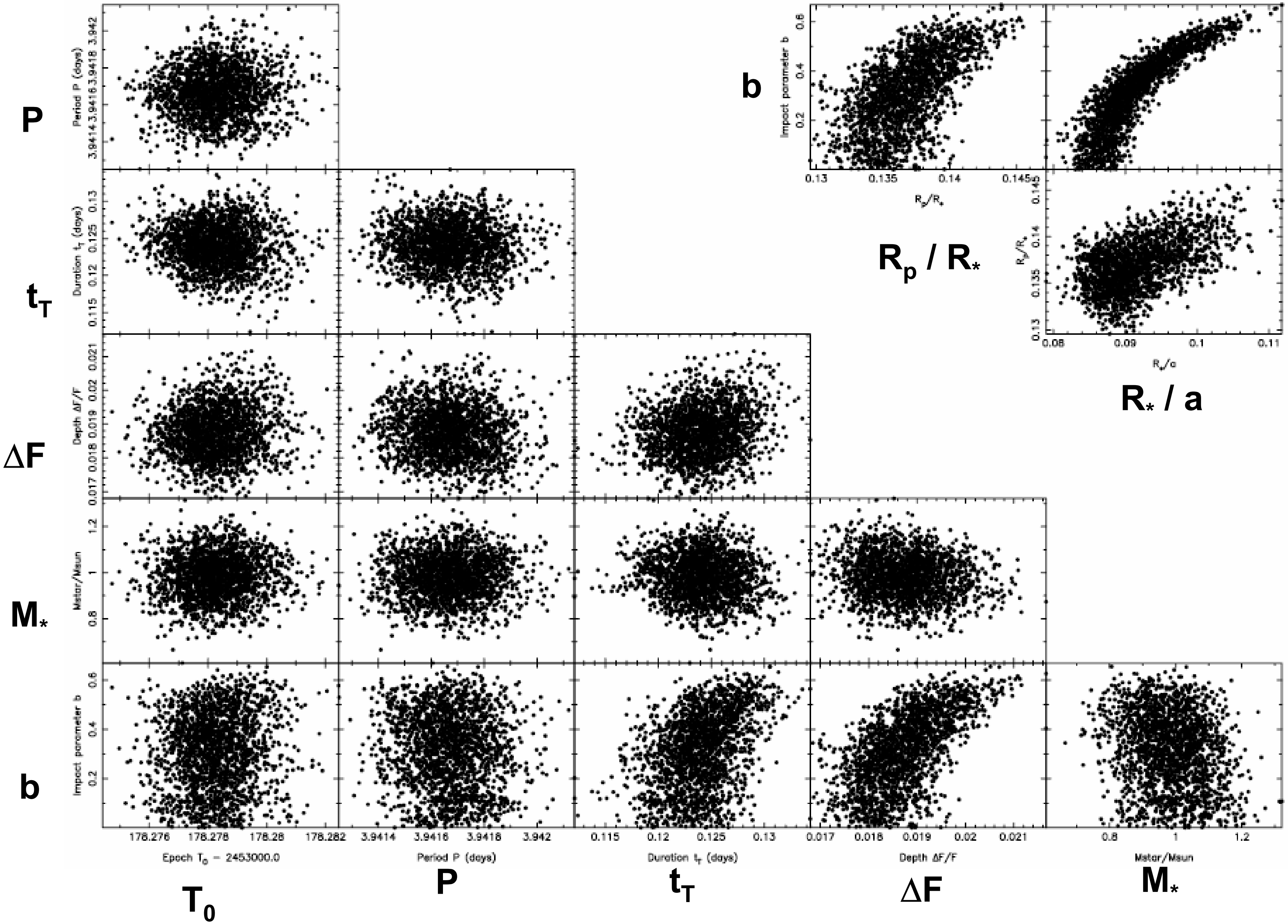


Burn-in

- **After initial settling-down phase, estimate σ from Markov chain itself:**

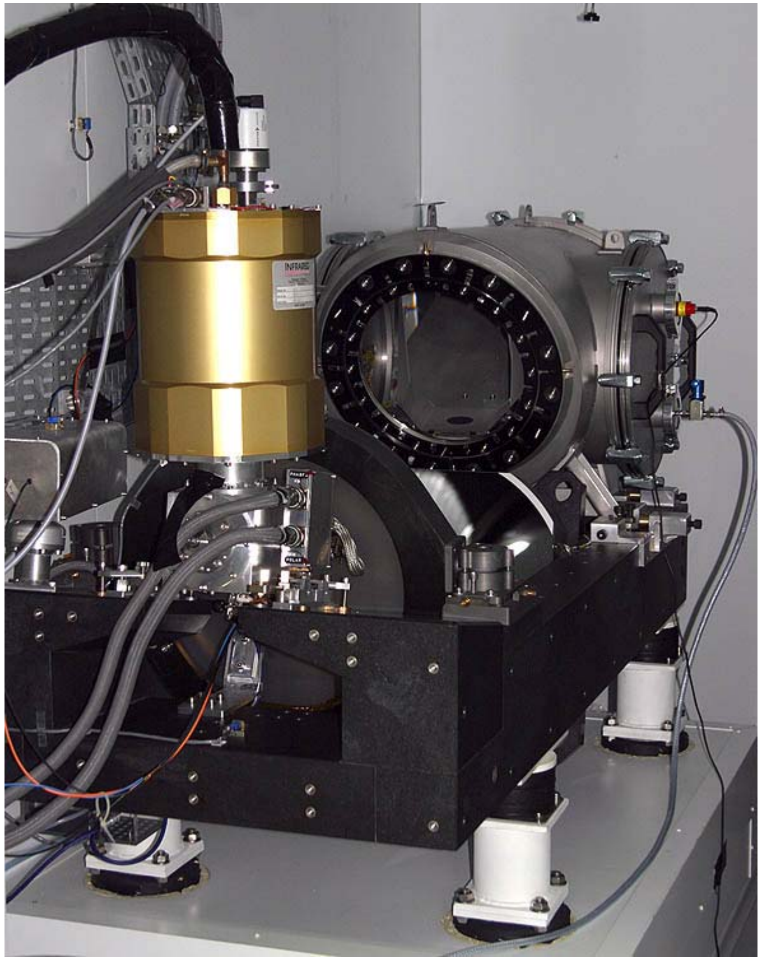


A crash course in MCMC - III



Targets observed at OHP 1.93-m

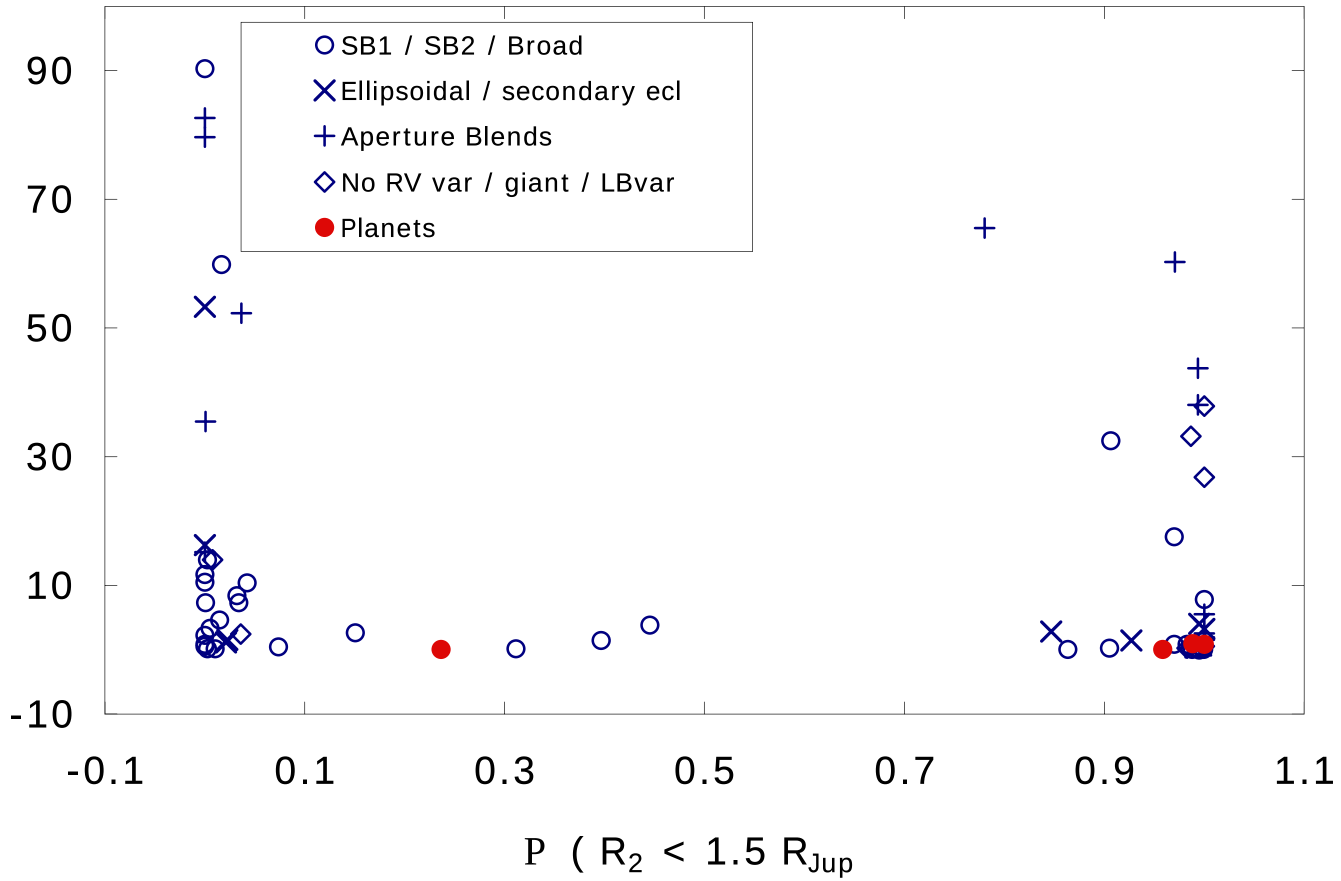
- **25 targets observed in 4 nights, 2006 Aug 31-Sep 3.**
- **15 single-epoch rejects:**
  - 8 exhibited multiple spectra
  - 3 showed single CCF peaks strongly broadened by rotation.
  - 4 were giants
- **2 second-epoch rejects:**
  - 2 narrow-lined SB1s, km/sec amplitude
- **5 third-epoch rejects:**
  - 5 showed no significant RV variation
- **3 candidates with significant RV variability less than a few hundred m/sec.**
  - 1 eliminated as a blend (variable line-profile asymmetry)
  - 2 planets



SOPHIE spectrograph (Bouchy et al 2006)

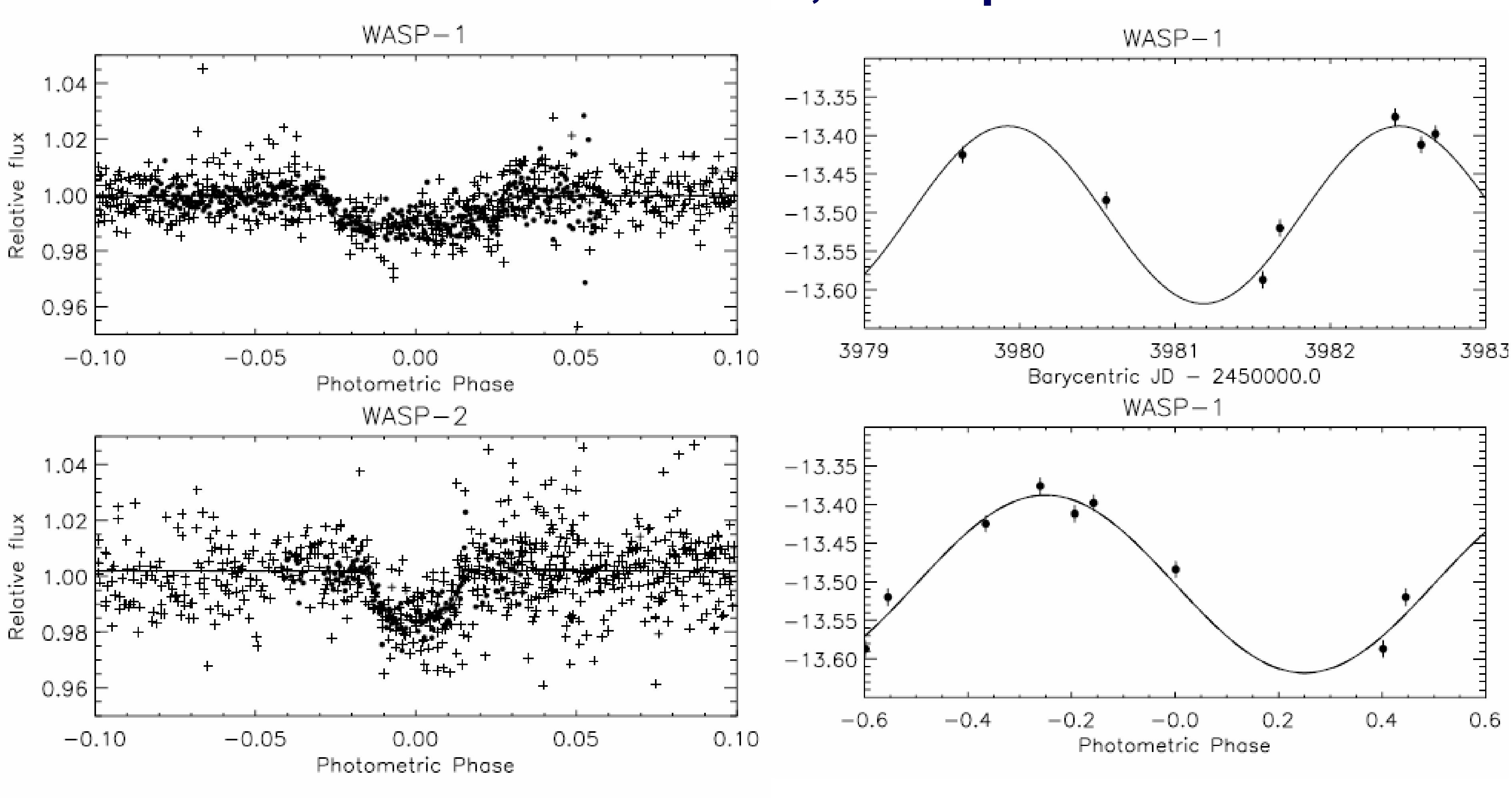
Candidate identification

- **Is the primary on the main sequence?**
  - **Use prior at optimal solution**
- **Is the secondary planet-sized?**

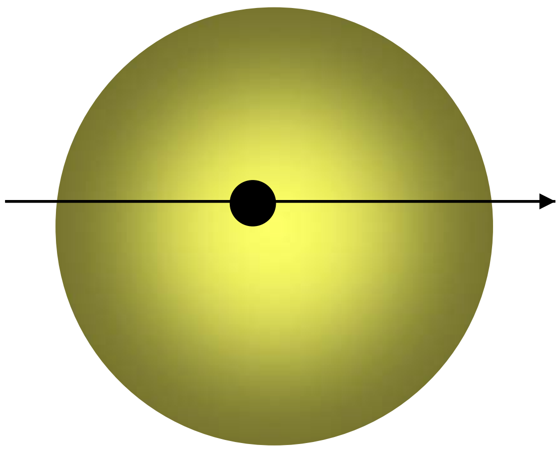


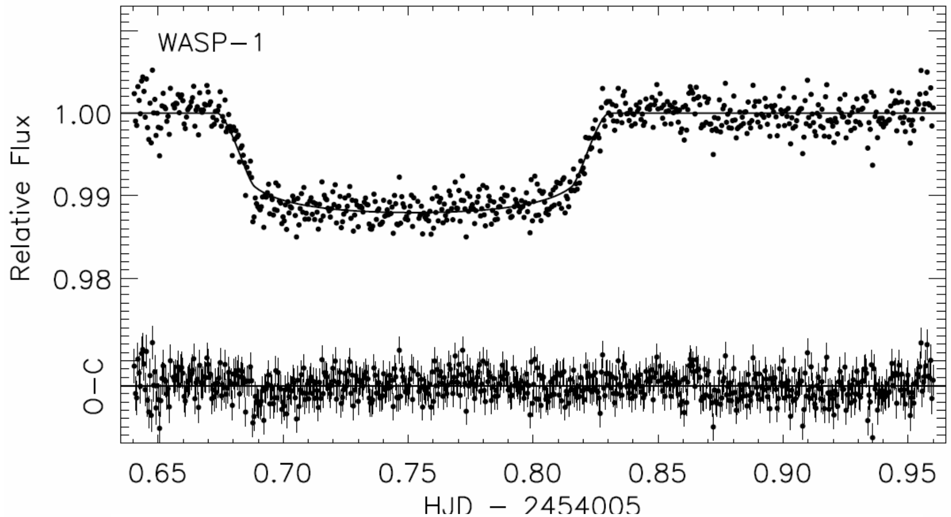
Transit profiles and RV orbits

- **Collier Cameron et al 2007, astro-ph/0609688**



WASP-1: physical parameters





Star

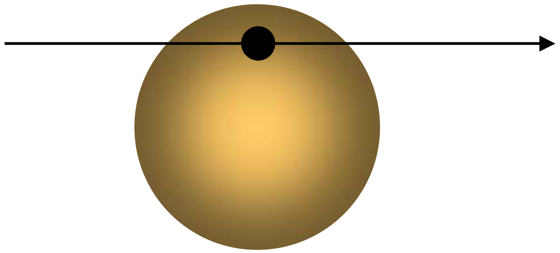
Parameter	WASP-1
GSC	02265-00107
WASP V (mag)	11.79
Spectral type	F7V
$T_{\rm eff}$ (K)	6200 ± 200
$\log g$	4.3 ± 0.3
M_V (mag)	3.9 ± 0.4
$M_*/M_\odot$	$1.15^{+0.24}_{-0.09}$
$R_*/R_\odot$	$1.24^{+0.68}_{-0.20}$

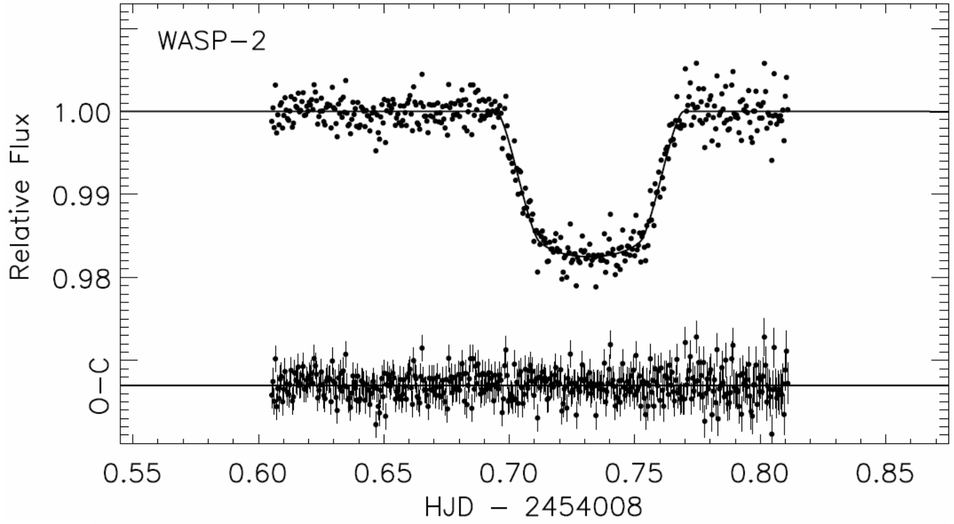
Planet

Parameter	Value	Uncertainty
$R_\star/R_\odot$	1.453	0.032
$R_p/R_{\rm J}$	1.443	0.039
$R_p/R_\star$	0.10189	0.00093
i [deg]	$> 86.^\circ1$	(95% conf.)
b	< 0.336	(95% conf.)
$t_{\rm IV} - t_{\rm I}$ [hr]	3.773	0.031
$t_{\rm II} - t_{\rm I}$ [min]	21.5	1.1
T_c [HJD]	2454005.75196	0.00045

Cameron et al 2007, astro-ph/0609688 **Charbonneau et al 2007, astro-ph/0610589**

WASP-2: physical parameters





Star

Parameter	WASP-2
GSC	00522-01199
WASP V (mag)	11.98
Spectral type	K1V
$T_{\rm eff}$ (K)	5200 ± 200
$\log g$	4.3 ± 0.3
M_V (mag)	6.2 ± 0.5
$M_*/M_\odot$	$0.79^{+0.15}_{-0.04}$
$R_*/R_\odot$	0.78 ± 0.06

Planet

Parameter	Value	Uncertainty
$R_\star/R_\odot$	0.813	0.032
$R_p/R_{\rm J}$	1.038	0.050
$R_p/R_\star$	0.1309	0.0015
i [deg]	84.74	0.39
b	0.731	0.026
$t_{\rm IV} - t_{\rm I}$ [hr]	1.799	0.035
$t_{\rm II} - t_{\rm I}$ [min]	24.6	2.4
T_c [HJD]	2454008.73205	0.00028

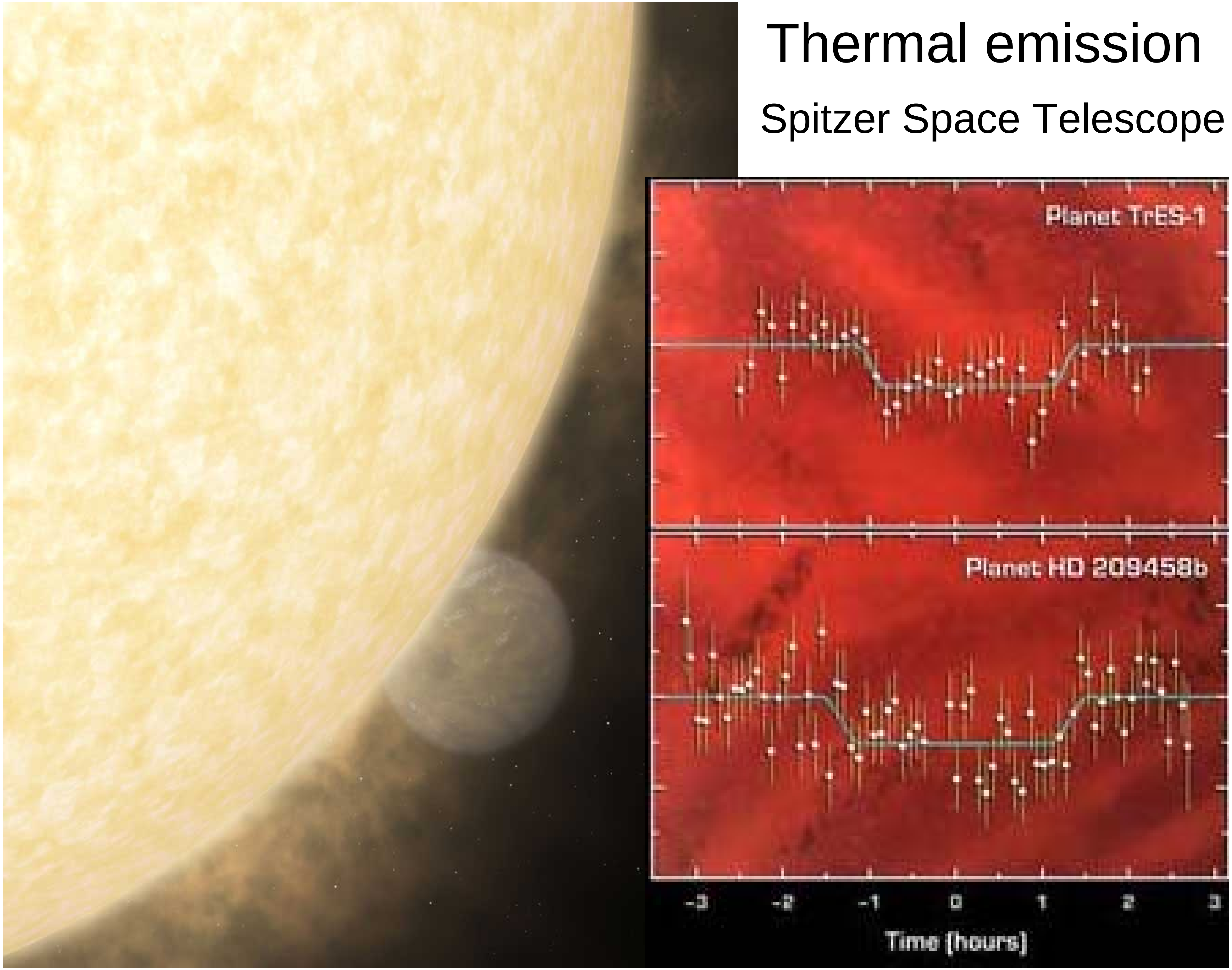
Cameron et al 2007, astro-ph/0609688 **Charbonneau et al 2007, astro-ph/0610589**

Summary and prospects

- **2 new transiting exoplanets detected in 2004 SuperWASP season data**
  - **19 such objects now known**
  - **WASP-1b: one of 3 "bloated" hot Jupiters discovered to date**
  - **Challenge to theories of formation, structure and evolution**
  - **Several strong 2004 candidates await RV followup in 2007.**
- **Ground-based followup photometry yields useful radius estimates.**
- ***HST/ACS* and *Spitzer/IRAC* DDT awarded to refine radii and measure T_{eff} of WASP-1b, WASP-2b.**
- **16 cameras operating since May 2006 (8N + 8S).**
- **More than 6 planets/year/hemisphere anticipated from 2006 on:**
  - **Northern hemisphere RV followup with OHP 1.93-m+SOPHIE**
  - **Southern hemisphere RV followup with CORALIE at La Silla**
  - **Improved light-curve analysis and selection procedures yield 1-in-5 hit rate for 2004 sample.**
- **Excellent prospects for defining hot Jupiter mass-radius relation.**

Thermal emission

Spitzer Space Telescope



HST+Spitzer followup (DDT)

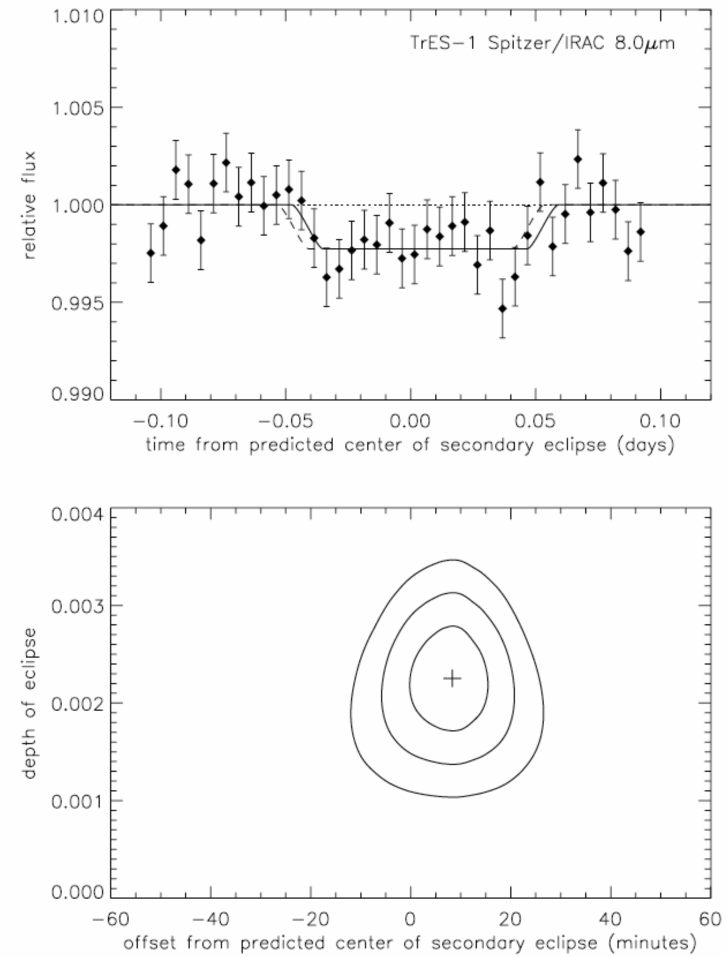


FIG. 1.—*Top:* Binned 8.0 μm time series. The best-fit model eclipse curve has a depth of $\Delta F_{\rm II} = 0.00225$ and a timing offset of $\Delta t_{\rm II} = +8.3$ minutes and is plotted as the solid line. A model of the same depth but $\Delta t_{\rm II} = 0$ is shown as the dashed line. *Bottom:* The 1, 2, and 3 σ confidence ellipses on the eclipse depth and timing offset.

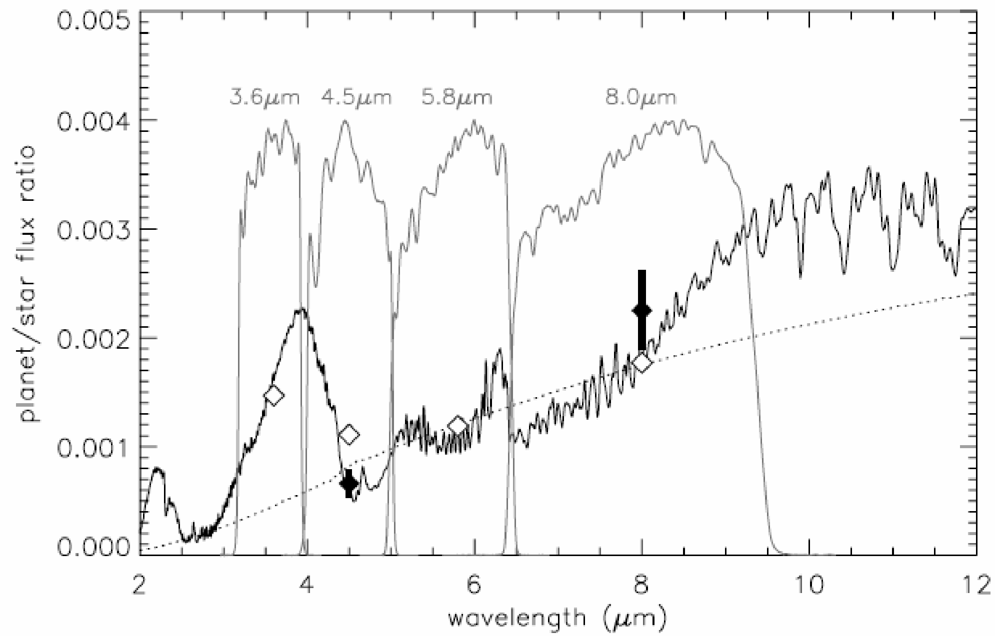


FIG. 3.—Solid black line shows the Sudarsky et al. (2003) model hot Jupiter spectrum divided by the stellar model spectrum (see text for details). The open diamonds show the predicted flux ratios for this model integrated over the four IRAC bandpasses (which are shown in gray and renormalized for clarity). The observed eclipse depths at 4.5 and 8.0 μm are overplotted as black diamonds. No parameters have been adjusted to the model to improve the fit. The dotted line shows the best-fit blackbody spectrum (corresponding to a temperature of 1060 K), divided by the model stellar spectrum. Although the Sudarsky et al. (2003) model prediction is roughly consistent with the observations at 8.0 μm, the model overpredicts the planetary flux at 4.5 μm. The prediction of a relatively large flux ratio at 3.6 μm should be readily testable with additional IRAC observations.

Charbonneau et al 2005

WASP-1 with Spitzer

T~2000K