A UKIRT WFCAM search for transits around M stars

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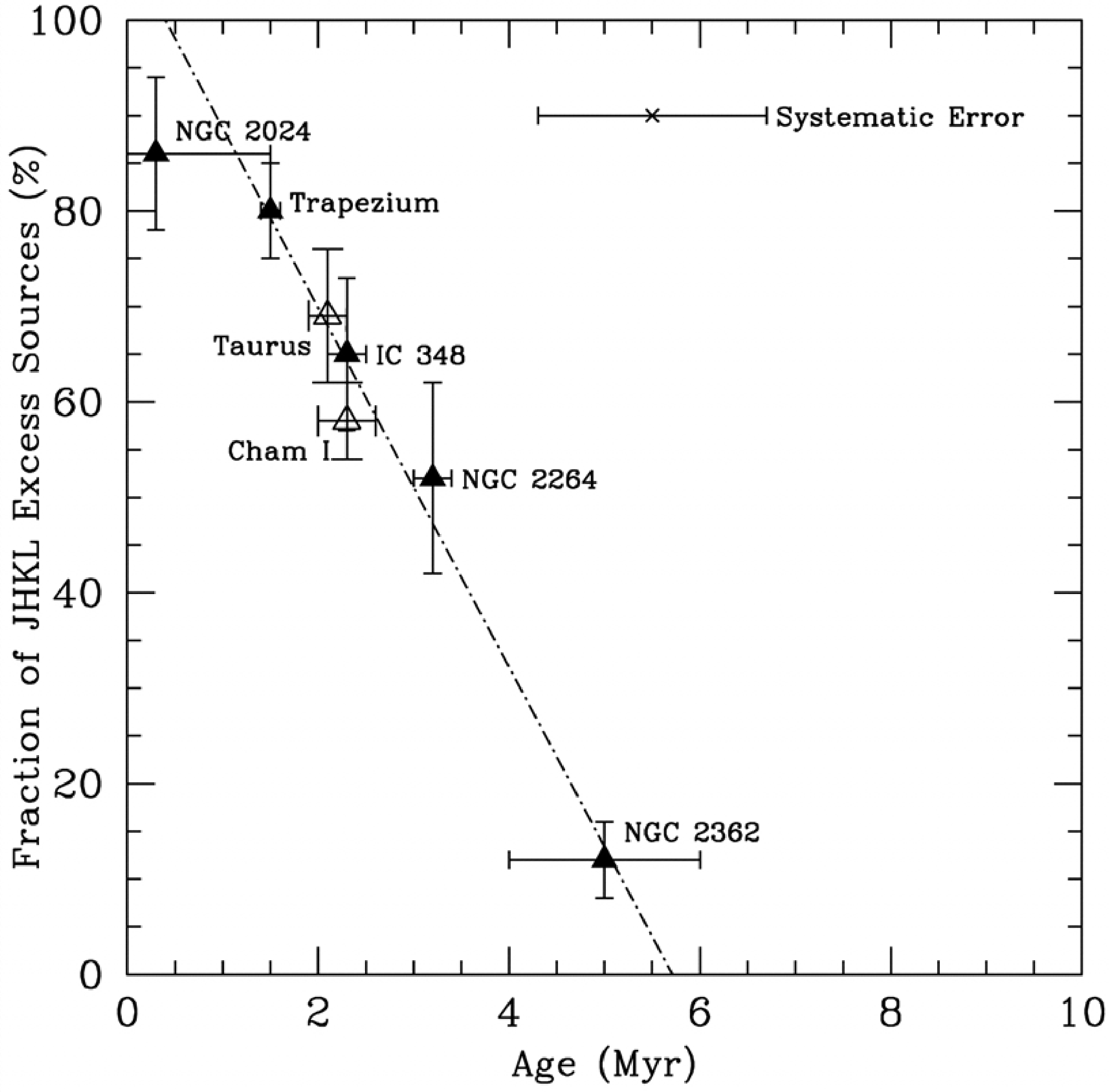
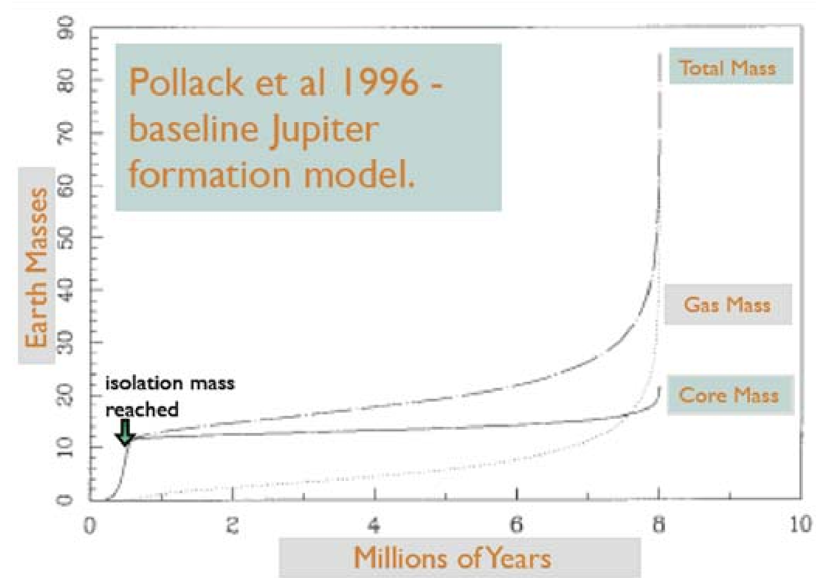
background

Core Accretion: standard model

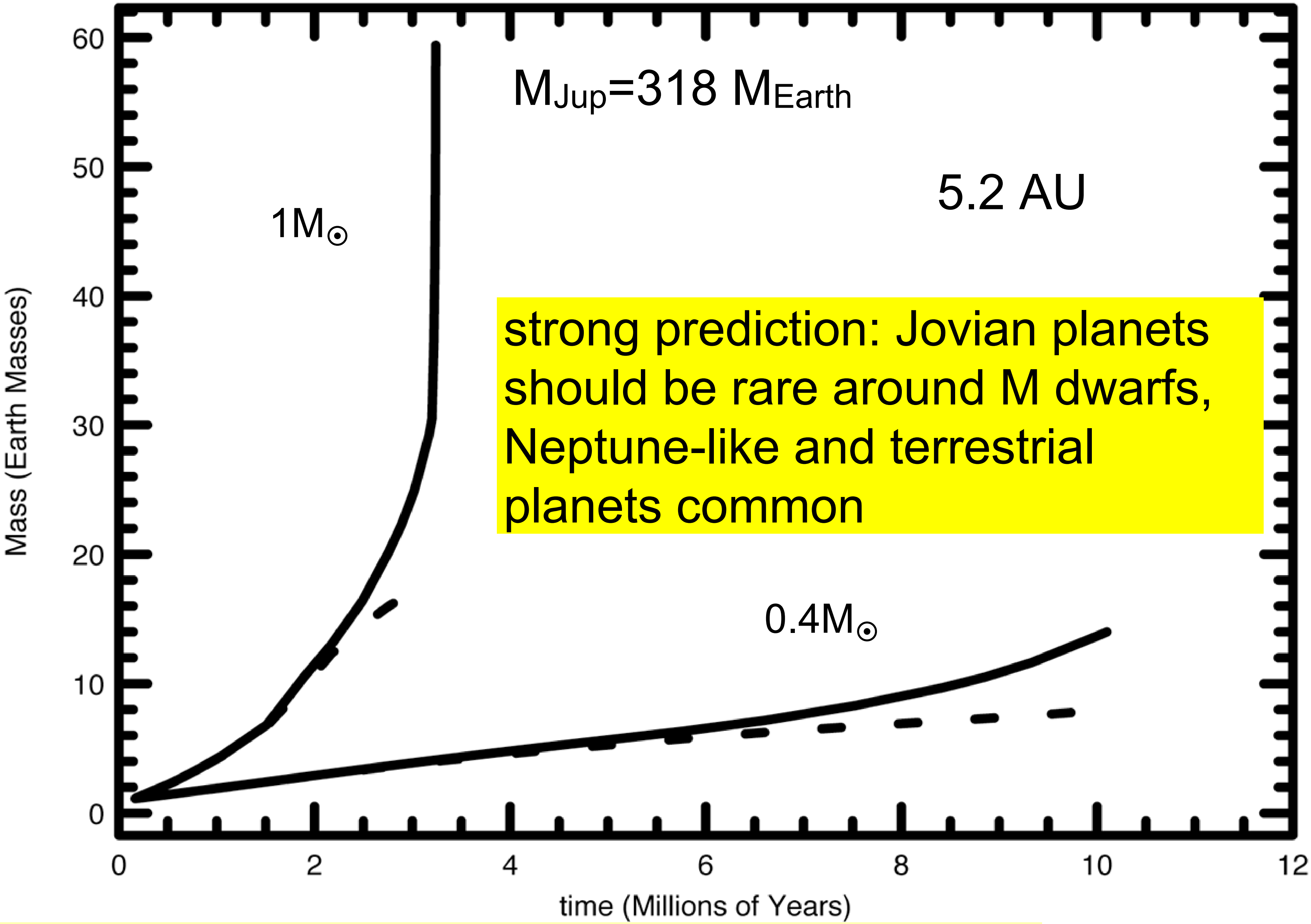




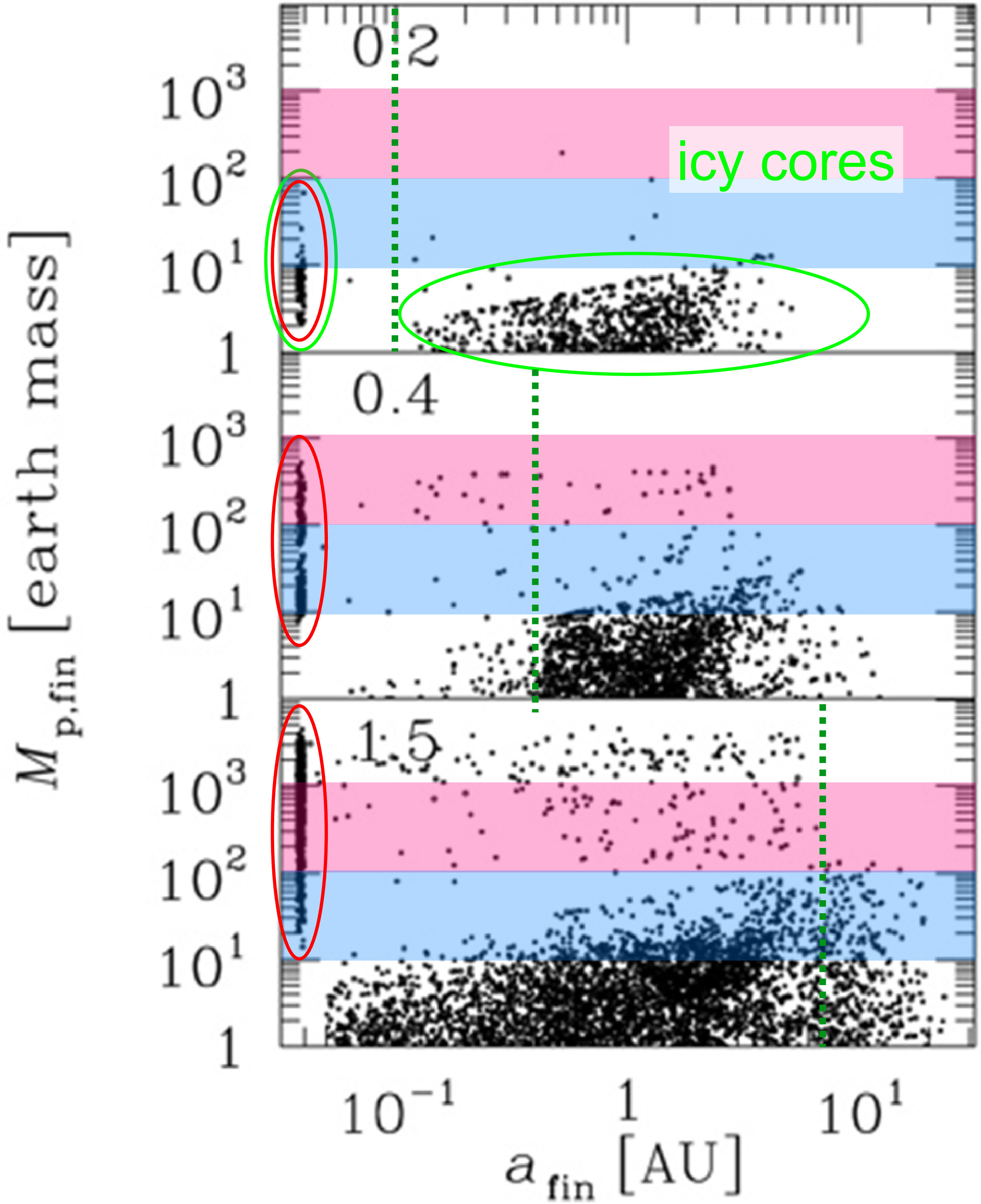
Timescales rather slow, but sensitive to: (i) assumed grain opacities and (ii) density of solids in the disk

slides from G. Laughlin (2005)

Figure 1 from Laughlin et al. 2004



Core-Accretion model predicts few Jovian-Planets Orbiting Red Dwarfs



Distributions of a and M of planets predicted by the Monte Carlo simulations of Ida & Lin (2005) for a range of primary masses (model includes migration and disk evolution).

Rocky planets are common around all spectral types, whilst gas giants are only predicted in large numbers around high mass stars.

(see also Lodato et al. 2006)

the picture painted by core accretion for low mass stars

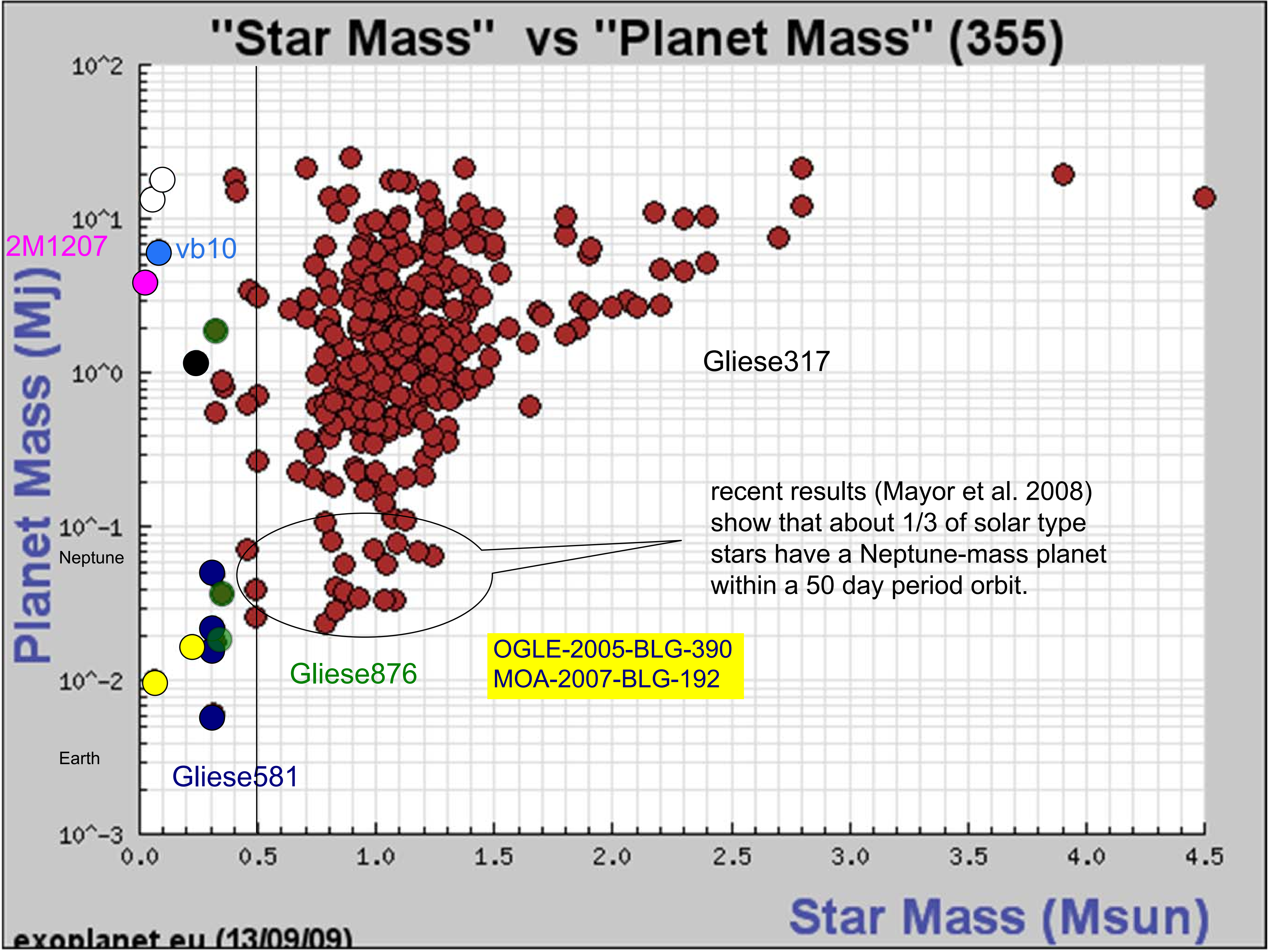
- low mass stars <=> low mass disks
- accretion of planetesimals proceeds more slowly
- low core mass leads to slow gas accretion
- migration proceeds more quickly than accretion
- planet population: few jupiters, lots of earths+neptunes

... so why look

- low-mass stars dominate the stellar population
- current surveys sample a narrow range of host star masses
- low primary mass: increased RV signature
- small stars: radii favour transits
- we are in fact sensitive to sub-Jupiters
- contrast favours direct imaging
- improve statistics on low mass close binaries

Alexander & Armitage 2009 ApJ (accepted)

Disks around low-mass stars and brown dwarfs are now commonly observed (e.g. Scholz et al. 2006), but our knowledge of their evolution is limited. Moreover, interpretation of the infrared spectral energy distributions of disks around low-mass (M-type) stars is fraught with difficulty (Ercolano et al. 2009a), and it is not at all clear whether such disks evolve in the same manner as their more massive counterparts. **Very little is known about disk lifetimes and masses in this regime, and the key physical processes (angular momentum transport, photoevaporation, planet formation) are essentially unconstrained.**

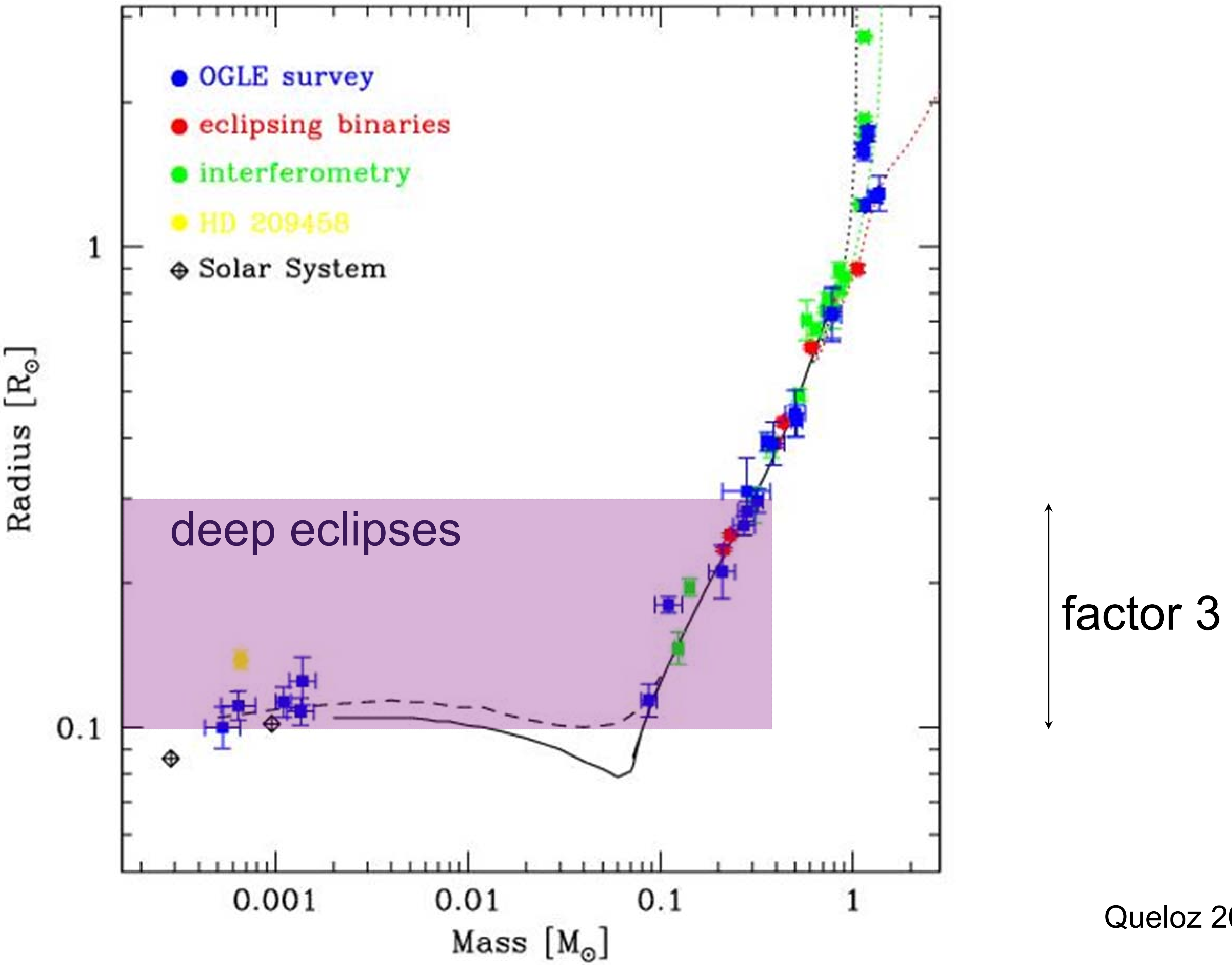

"Star Mass" vs "Planet Mass" (355)
10^2
10^1
10^0
10^-1
10^-2
10^-3
Planet Mass (Mj)
2M1207
vb10
Neptune
Earth
Gliese317
Gliese876
Gliese581
recent results (Mayor et al. 2008) show that about 1/3 of solar type stars have a Neptune-mass planet within a 50 day period orbit.
OGLE-2005-BLG-390
MOA-2007-BLG-192
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Star Mass (Msun)
exoplanet.eu (13/09/09)

transits

why transits (around red dwarfs) ?

- solve for the sin*i* degeneracy in planet mass
- solve for the planet radius : density
- transmission spectroscopy
- multiplicity

mass-radius relation



Queloz 2005

transit properties

$\otimes L / L = (R_p / R_*)^2$

	$1M_\odot$	$0.1M_\odot$
Jupiter	1%	100%
Neptune	0.1%	10%
Earth	0.01%	1%

$t = P (R_* \cos ™ + R_p) / □ a$

$t \sim 13 M_*^{-1/2} a^{1/2} R_*$ hours

Jupiter	t=25h	8h
Earth	t=13h	4h
Hot Jup	t=3 h	1h

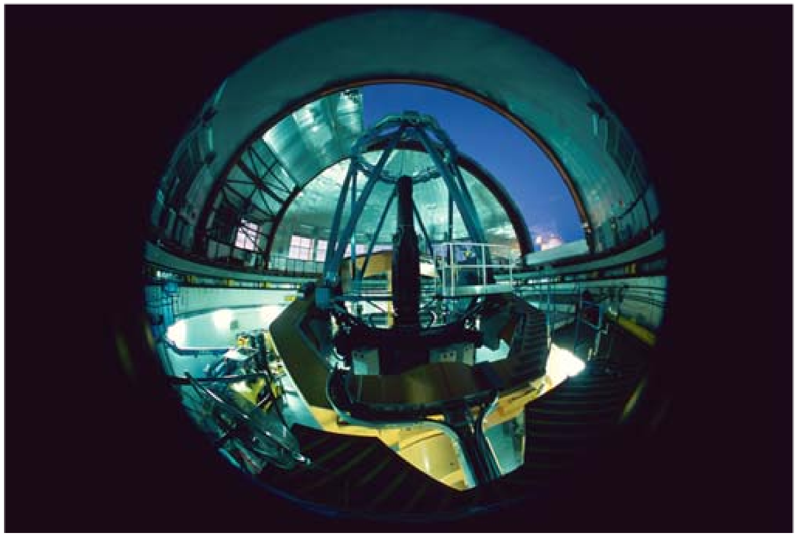
p(transit) = R_* / a

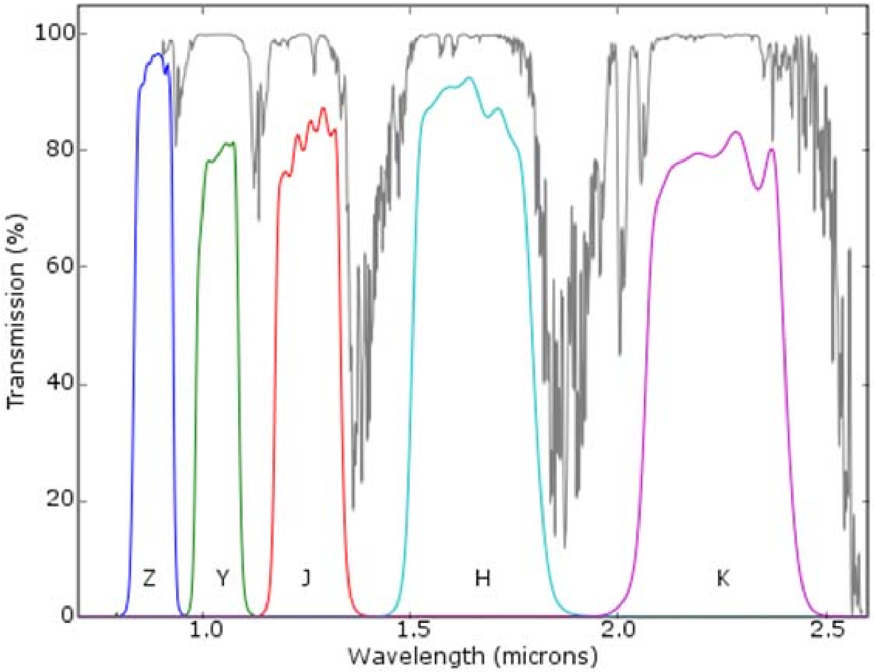
Hot Jup	10%	1%

Alignment probability recovered if planetary system scales with primary mass

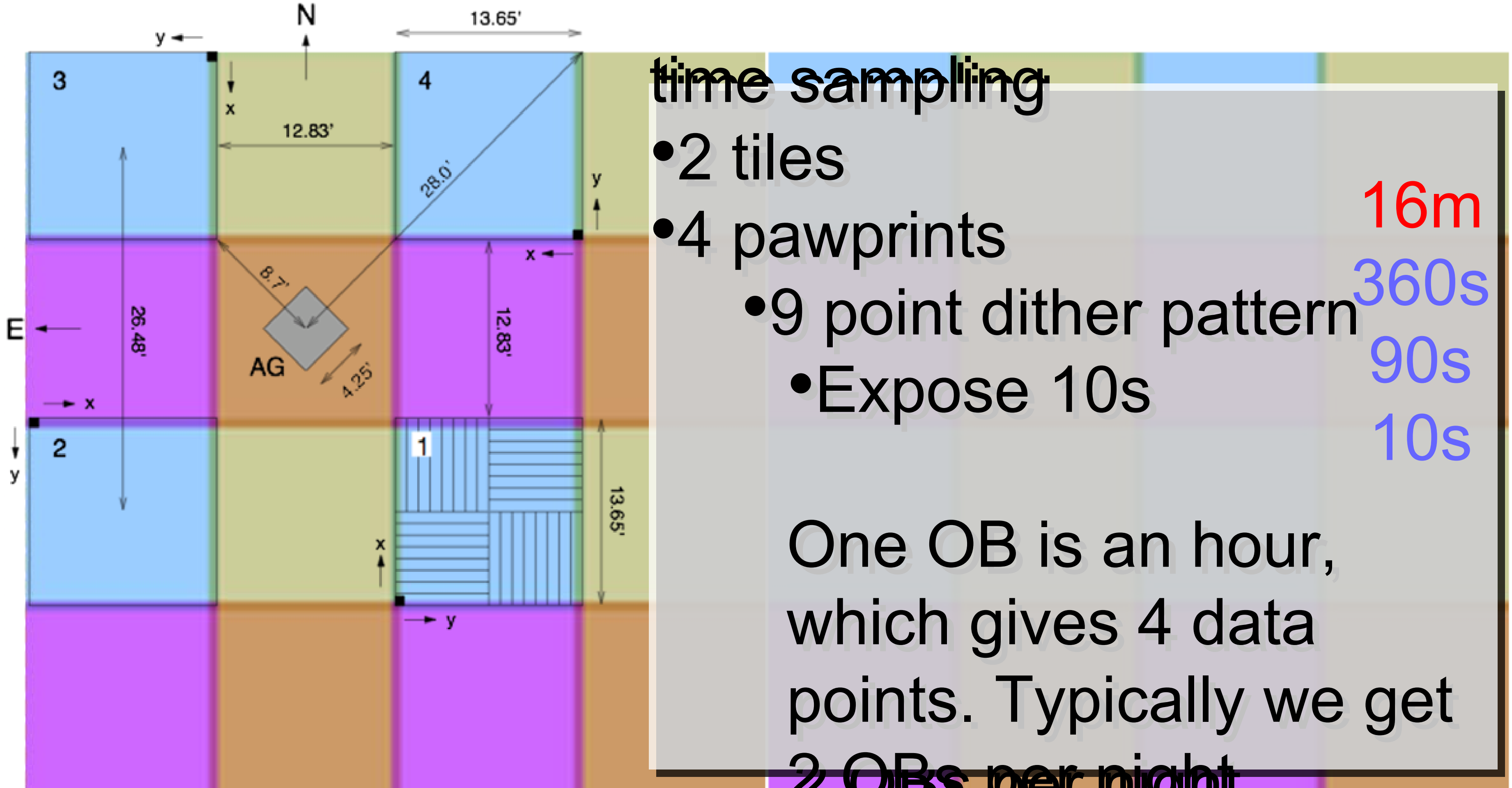
UKIRT+WFCAM

- **0.75** square degrees with **0.4** arcsecond pixels.
- **Queue scheduled**
- Now mounted 100% of the year
- We answered a call for campaign proposals released in Apr 2006
- We were awarded a total of 200 nights (2000 hours) with seeing>1.2 arcecs. 80 nights from 07B-09B
- Observations started summer 2007
- Extension proposal required for continuation beyond 09B





Pawprints, Tiles, Fields



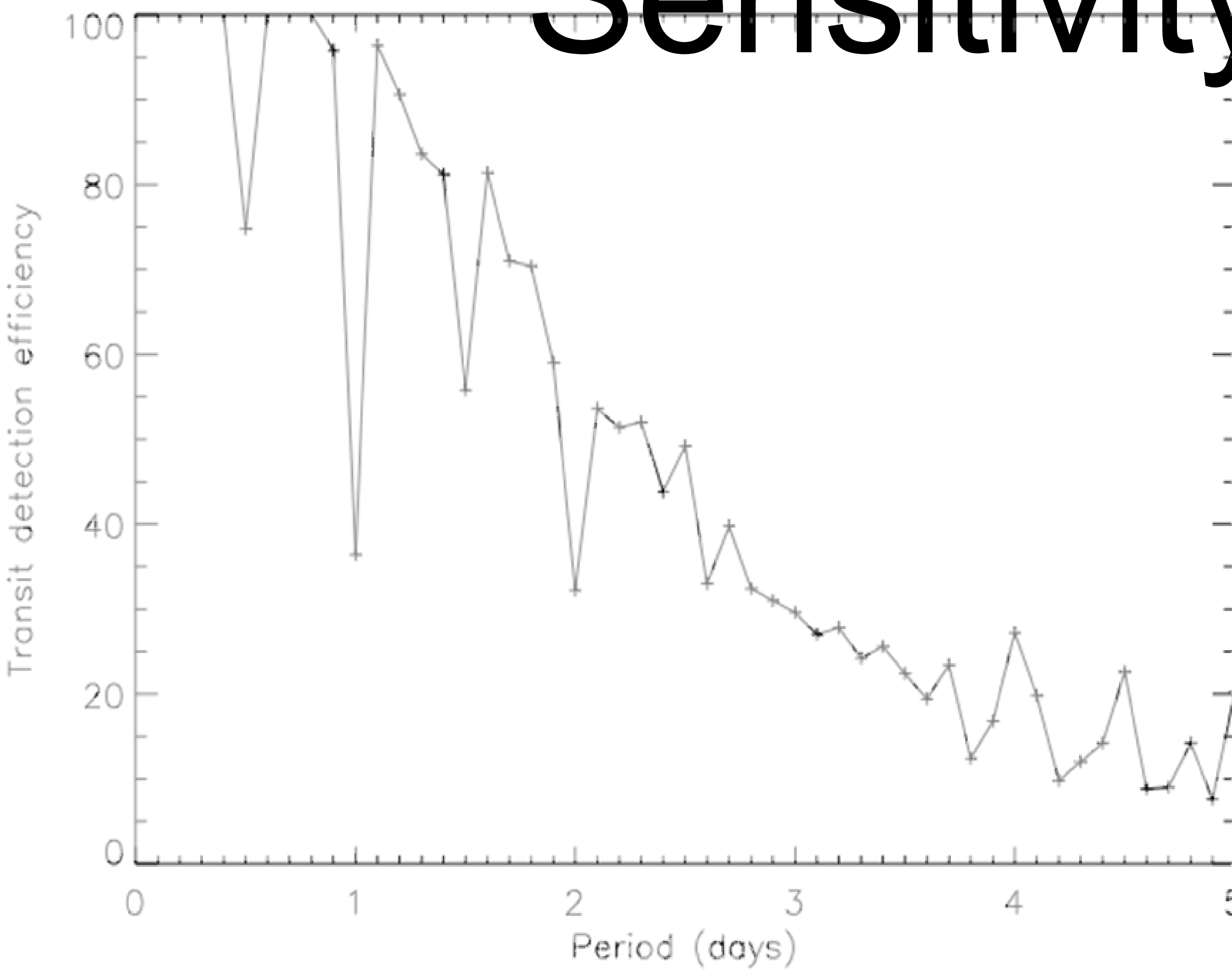
time sampling

- 2 tiles
- 4 pawprints
    - 9 point dither pattern
        - Expose 10s

16m
360s
90s
10s

One OB is an hour, which gives 4 data points. Typically we get 2 OBs per night.

WTS Survey Sensitivity

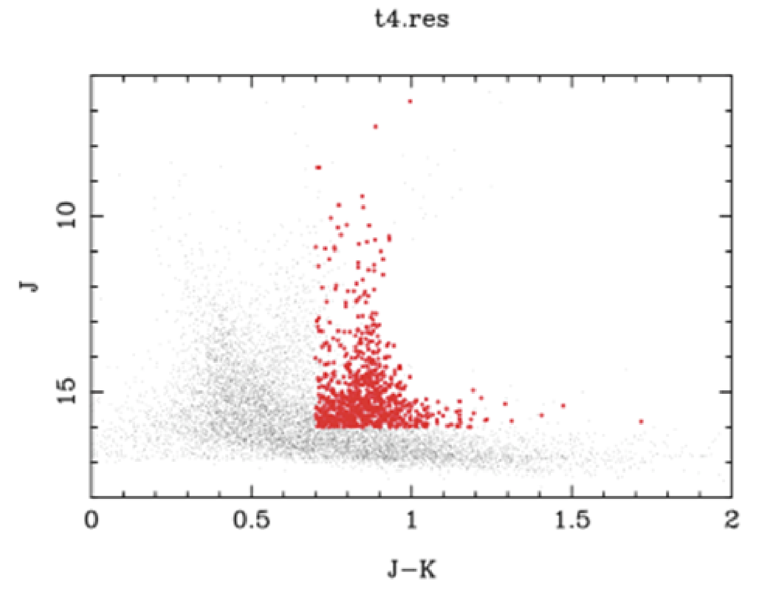


The **simulated** efficiency of the WTS transit detection for **200 hrs** on each region.
A confirmed transit detection requires that at least 4 separate transits are measured.

Planets	Radius (R_{Jup})	Transits found (PF=planet fraction)		
		PF=30%	PF=10%	PF=1%
Large rocky planets	0.10-0.25	~7	~2	–
Neptune-like	0.35	–	–	~4
Saturn-like	0.8	–	–	~10
Jupiter-like	1.0	–	–	~10

WTS Target Fields

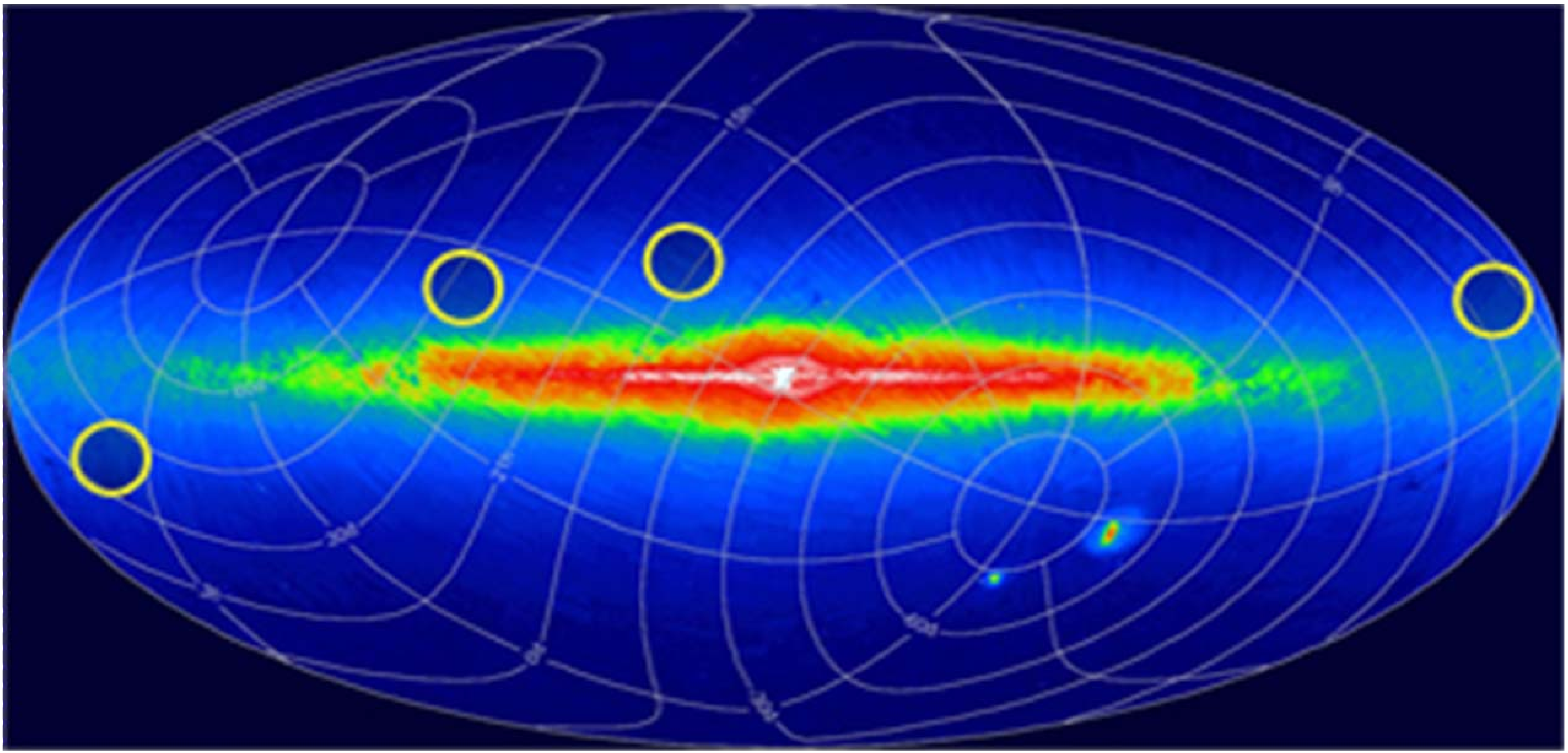
- We tried to select fields that:
  - maximized stellar density
  - avoided overcrowding
  - minimized giant contamination
  - kept reddening to an acceptable level (<0.1)
  - will pass within ~15 of degs of zenith
- Survey strategy should:
  - maximize areal coverage , while
  - maintaining sufficient cadence (<15 mins)



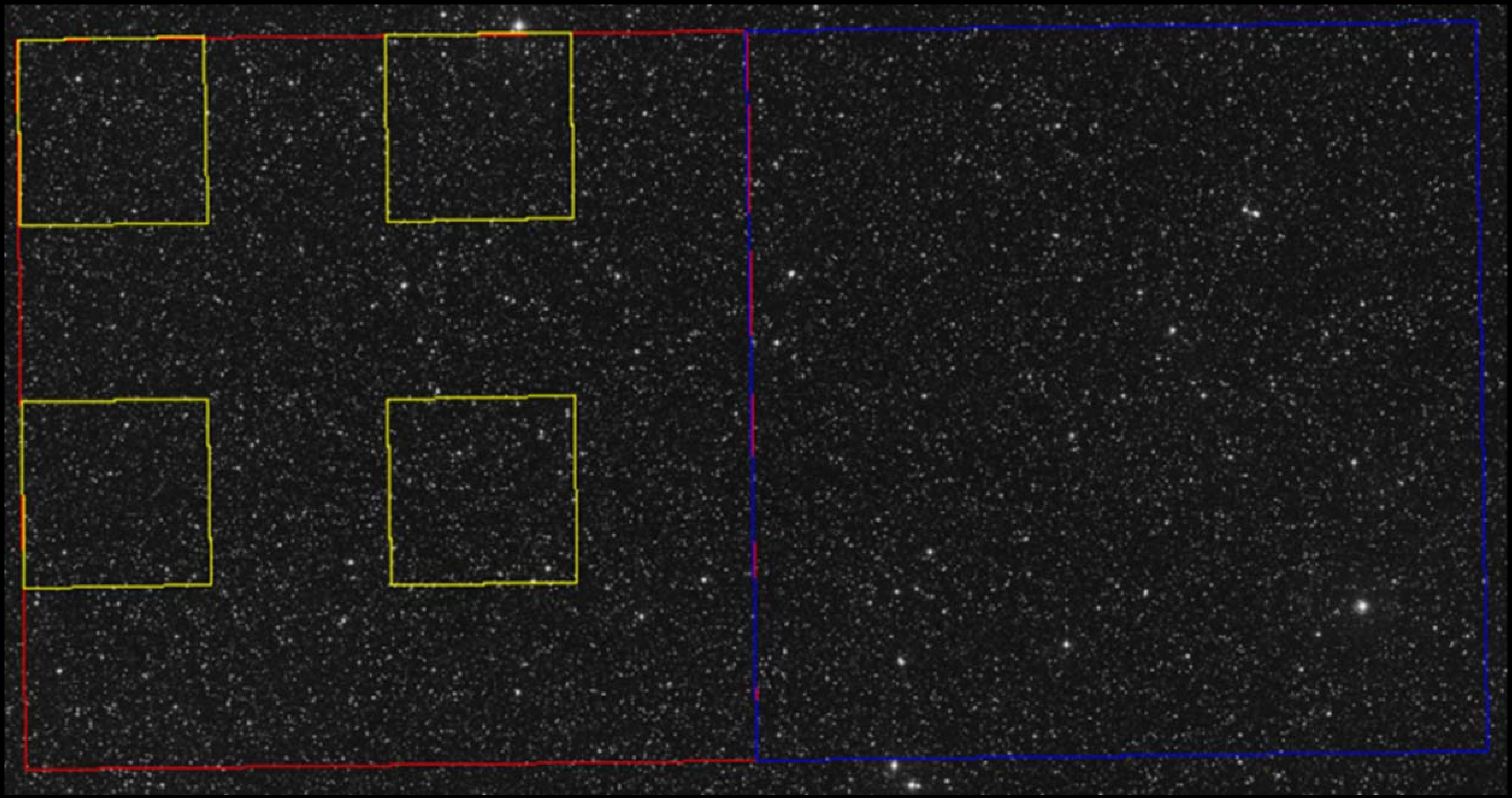
Around b=20, from 2MASS; expect:

- ~200 dM stars to J=16/pawprint
- ~800/tile
- ~6400 in 4 fields

WTS Fields on the 2MASS sky



SDSS overlap (2 fields)



Data Rate

First image: 5/8/2007

Field	b	Nobs (end 2008)	Nobs (Aug 2009)
3.6+39	-13	125	165
7.1+13	9	105	245
17.2+04	24	180	340
19.6+37	8	470	725
total		880(220 hrs)	1475 (370 hrs)

Processing steps

prepare - ingest, check MEF, check index, select, preview, process

linearity - dome sequences, non-linearity < 1%

dedark - combine darks, illumination-dependent reset anomaly

flatfield - weekly/monthly twilight flats, stable, internal gain corr

curtain - +/-5 ADUs, ~ 4-quadrant symmetry, bilinear removal

skysub - group master skys by time and MSB if possible

combine - interleaves, compute shifts and stack dithers

catalog - detect and parameterise objects

classify - morphological classification

astrom - astrometric calibration per detector

photom - photometric calibration per pointing

check - examine QC, reject bad products, random

Processing: locating the apertures

- the error in the photometry due to aperture placement goes as:

$\delta F/F \approx 0.119\Delta^2/\sigma^2 \approx$ mmag

(where Δ is the error in the position of the aperture and σ the s:n of the source, typically $\Delta \approx 0.1\sigma$)

- default placement using source centroid adds mmag jitter, plus additional blending issues.
- instead we measure the relative positions of the sources in a *master* frame, and compute the transformation to each separate observed field.
- more important in undersampled data.

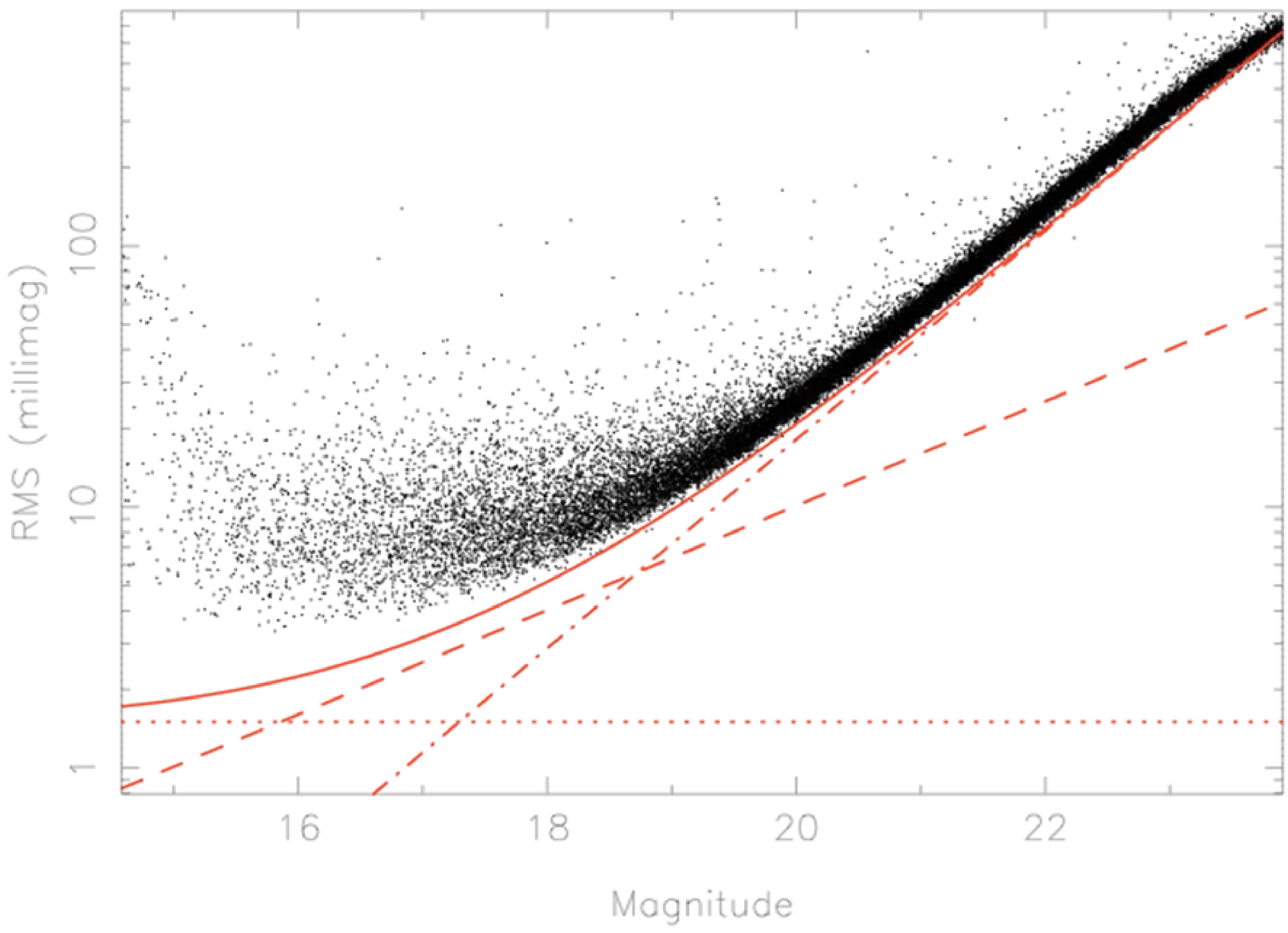
Processing: Forming the Master

- We stack around 20 of the best seeing frames to form a master image (per pawprint)
- We then generate a master catalogue
- And revise the astrometry and photometry
- This catalogue provides the source list for lightcurve generation
- Aperture photometry is measured for each source in each image

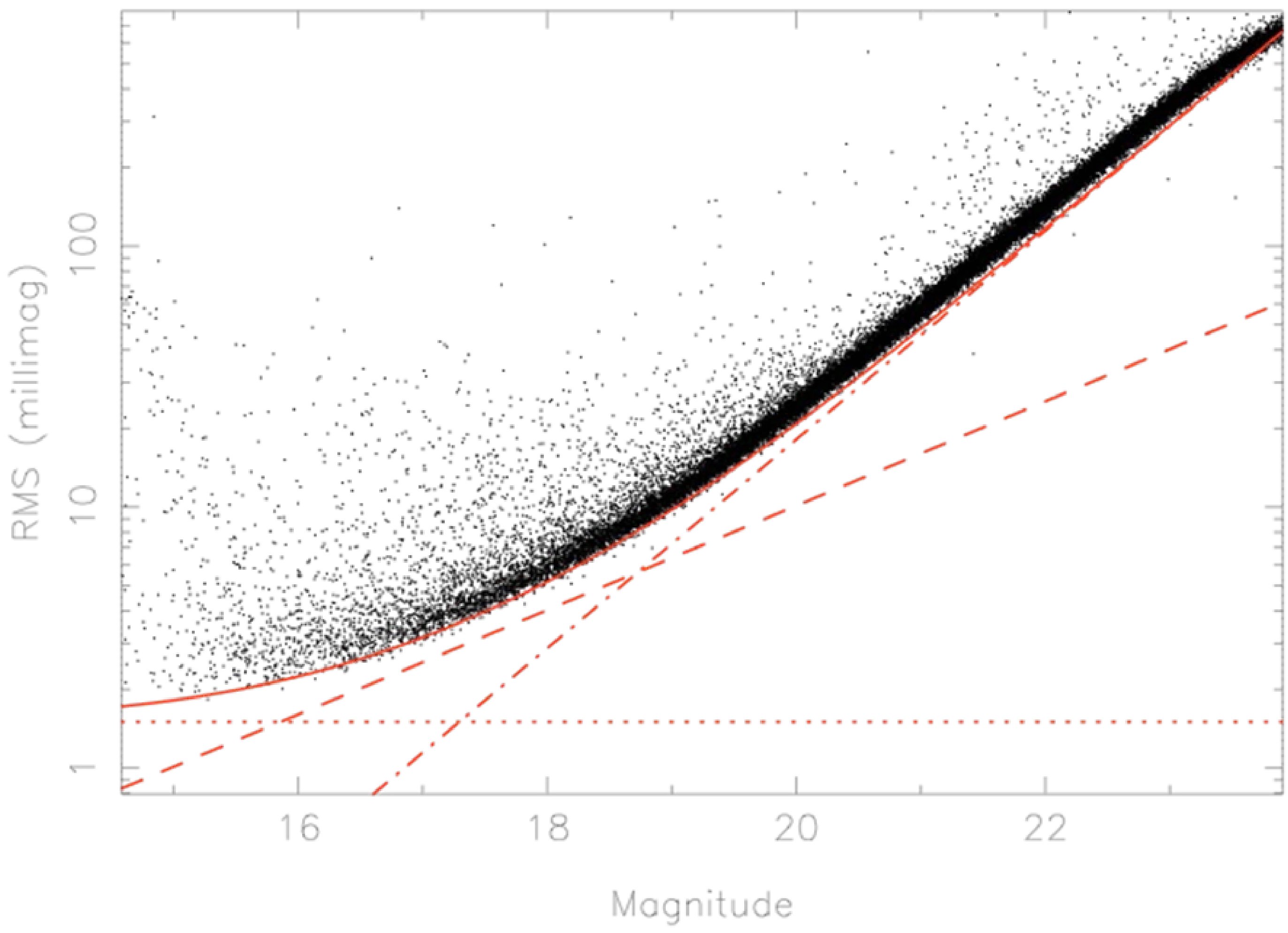
Photometry: size of the apertures

- Optimum signal-to-noise is achieved using the rule of thumb: that the aperture radius should match the stellar FWHM
- Complicated by:
  - if the aperture is too big, blending becomes an issue
  - bright stars can afford bigger apertures
- Best of both worlds solution is to use a variable aperture
- Modification is to use the aperture which minimises the rms on a per-source basis.

aperture: fixed



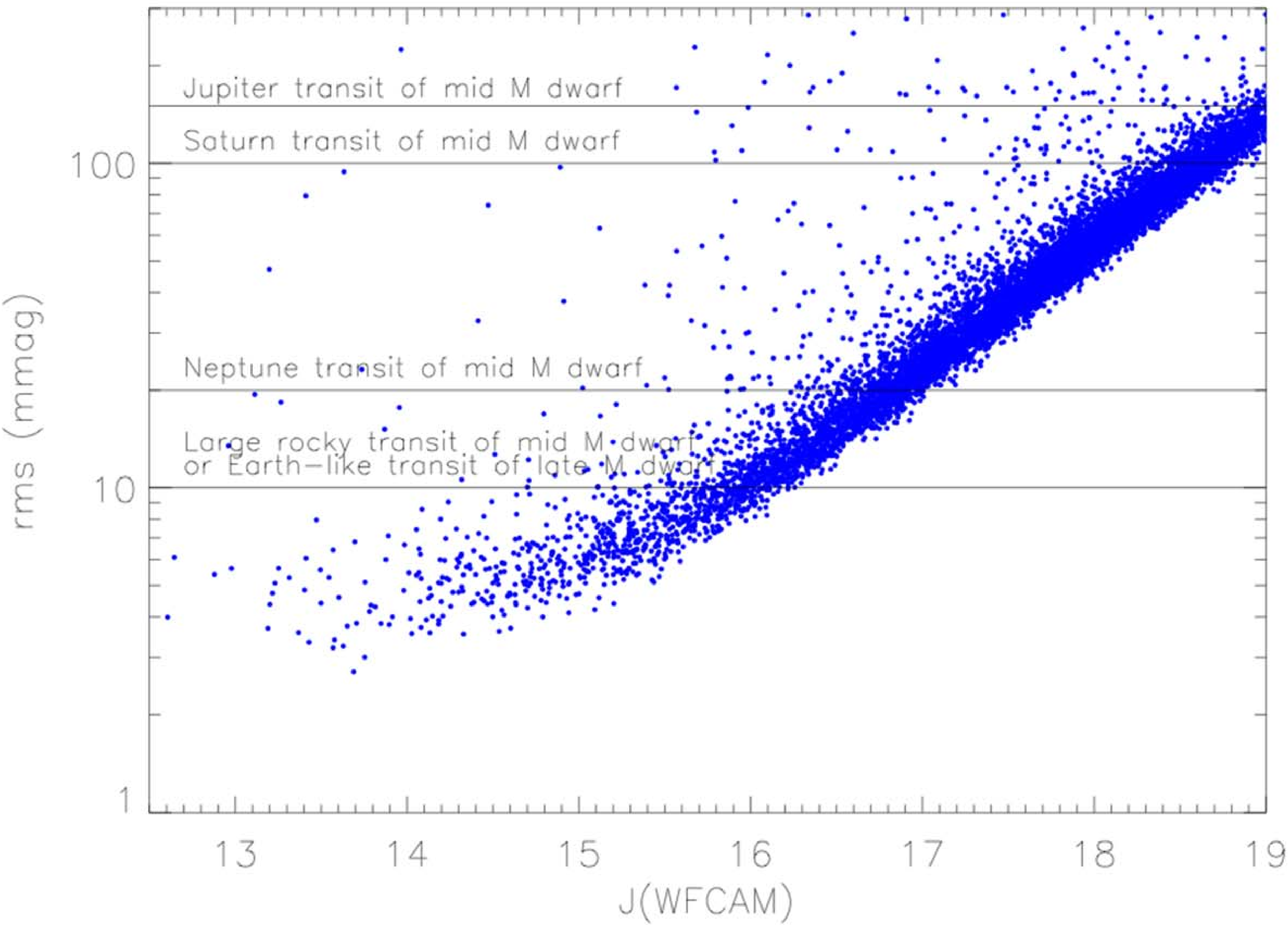
aperture: variable



Processing: Making the lightcurves

- The flux for a star in each frame needs to be normalized to account for variable extinction, instrument throughput and so on.
- simple case - use the median flux for selected stars as a linear offset
- modified to allow for a quadractic fit to the spatially resolved median flux (plenty stars)
- thus allow for differential extinction, varying pixel scale, intra-pixel sensitivity etc

WTS rms

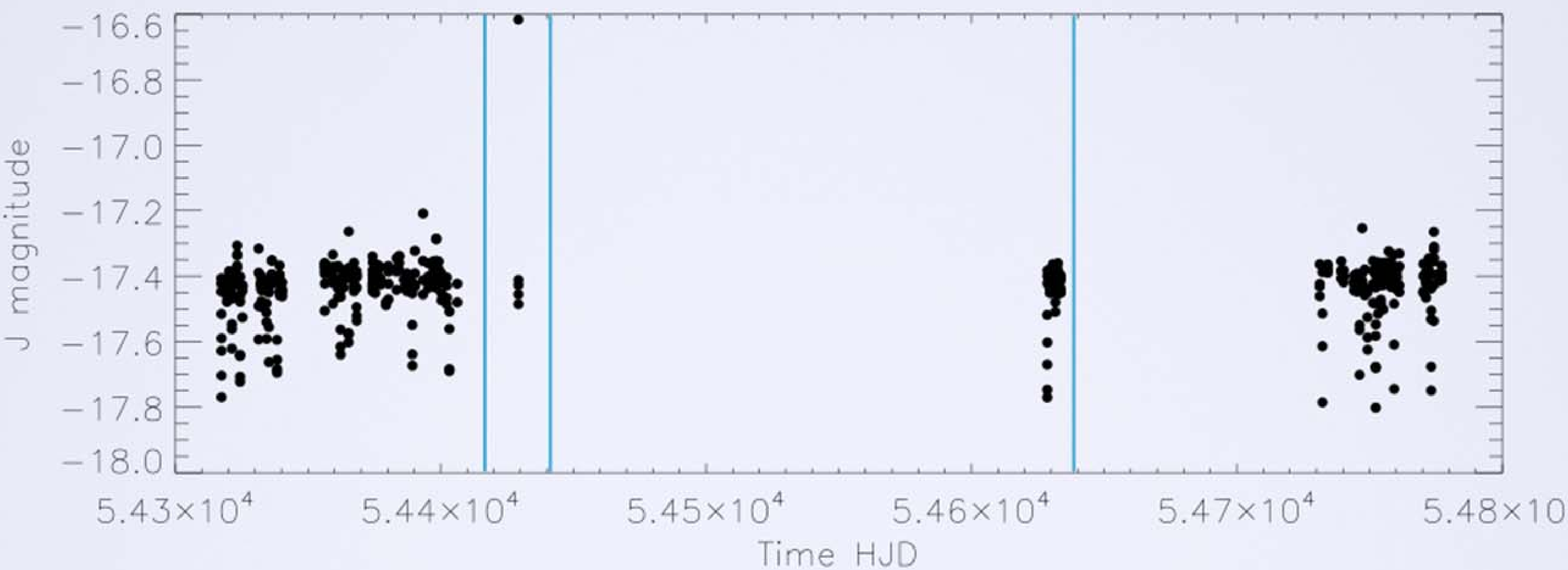


Jupiter transit of mid M dwarf
Saturn transit of mid M dwarf
Neptune transit of mid M dwarf
Large rocky transit of mid M dwarf
or Earth-like transit of late M dwarf
100
10
1
rms (mmag)
13
14
15
16
17
18
19
J(WFCAM)

Light Curves

- For one paw-print we observe ~20,000 stellar objects with J < 19.

Example light curve from WTS



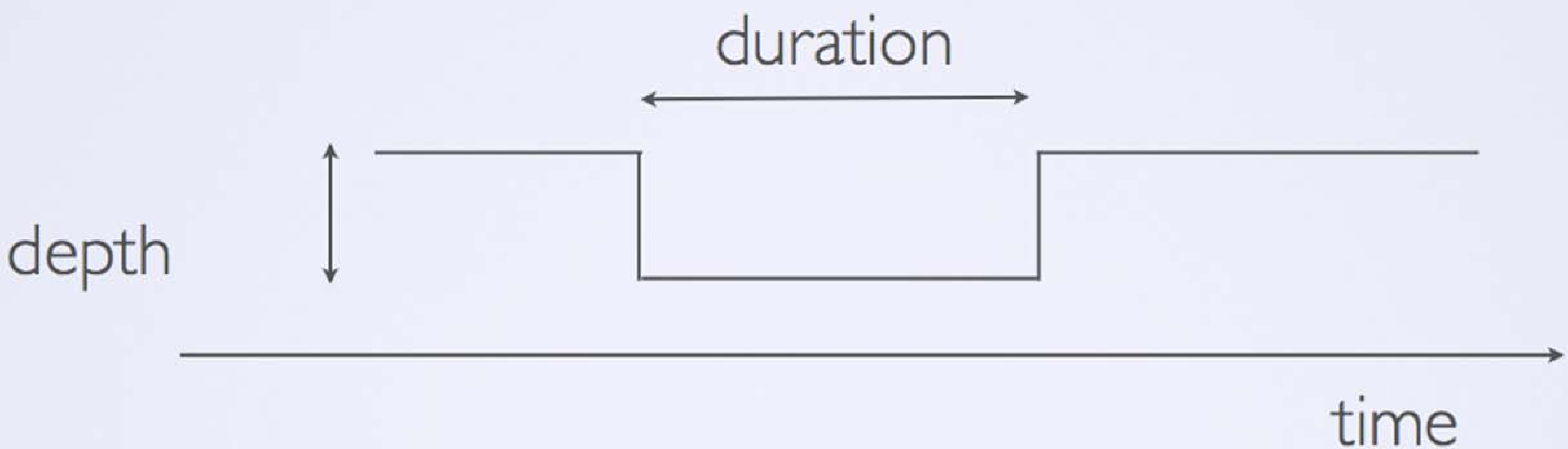
= New season

Aigrain & Irwin, 2004

Occfit: transit detection algorithm

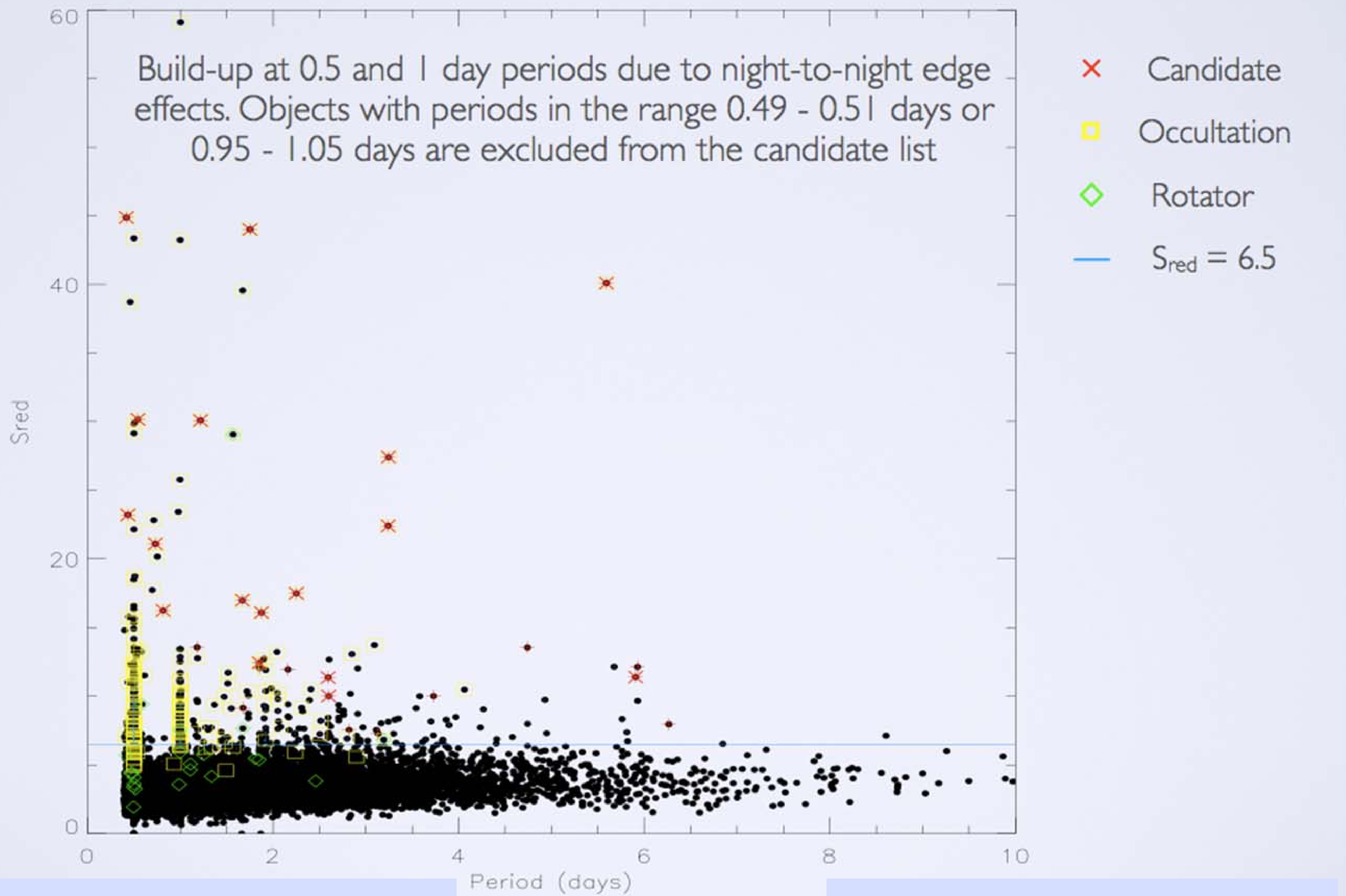
This is for occultation detection only. We distinguish between EBs and transits later by modelling.

Box-least-squares fitting algorithm

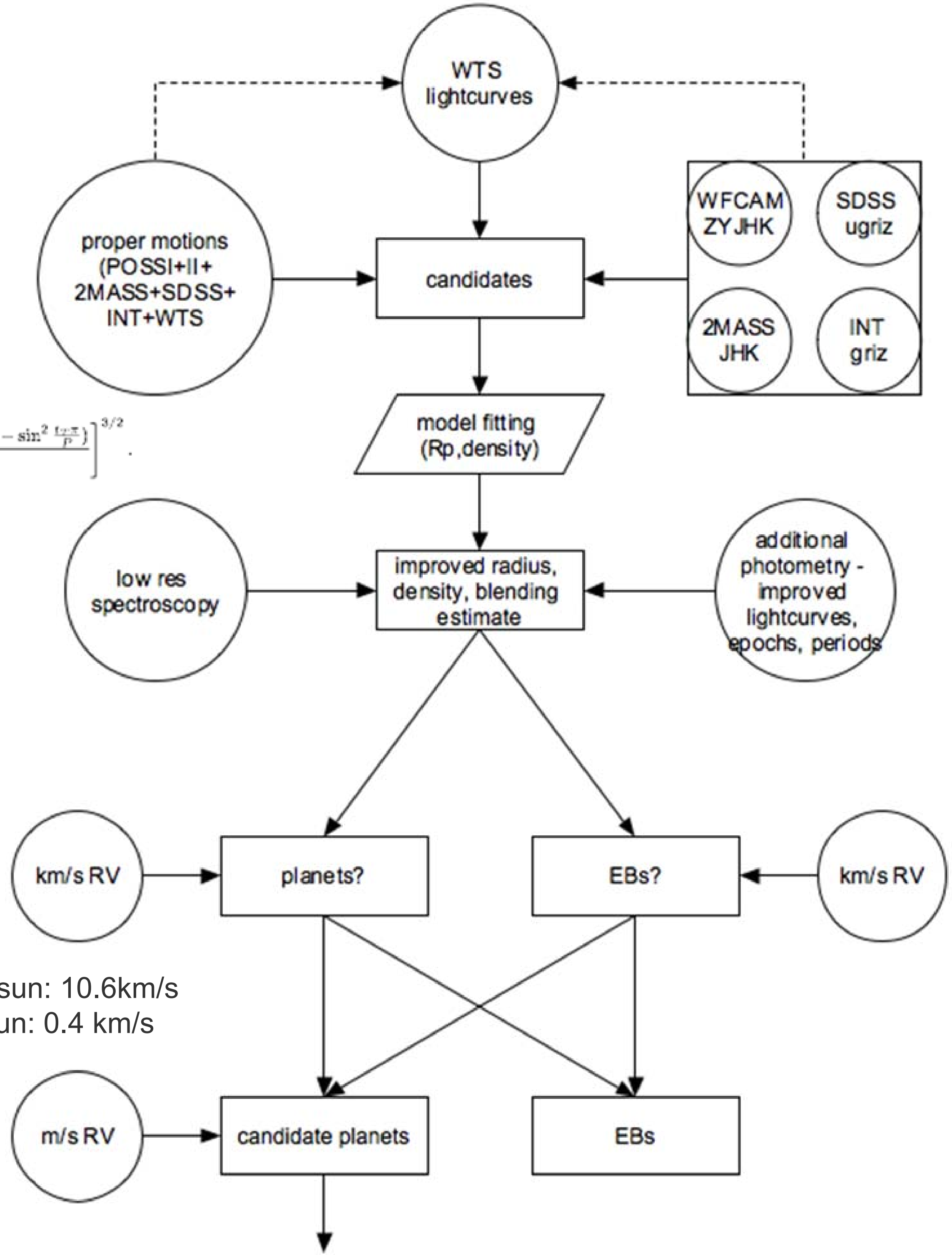


Input parameters i) Period 0.4 -10 days ii) parameter that keeps a physically plausible duration to period ratio (range 0.4-1.67)

SNR vs Period

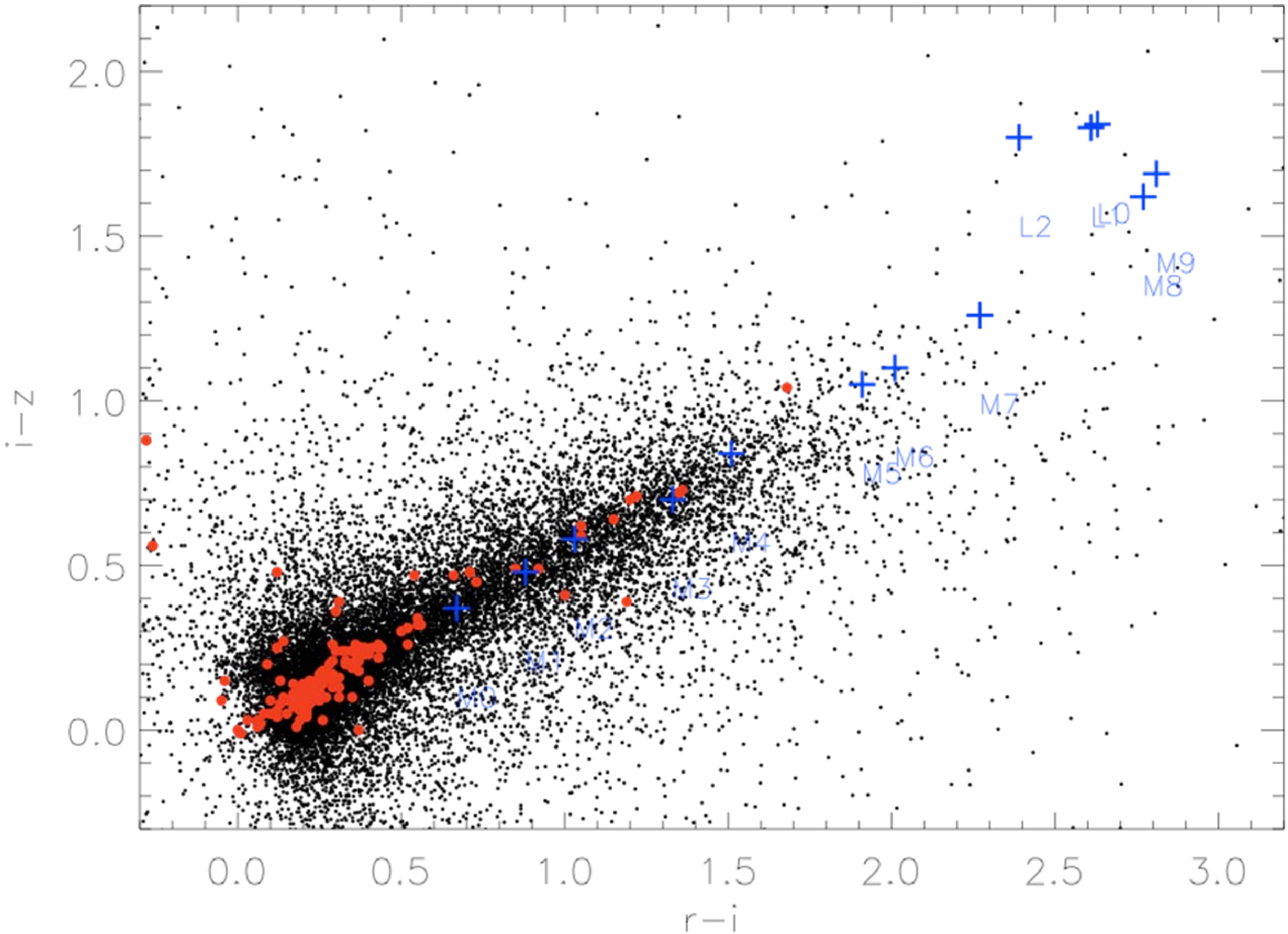


Follow up

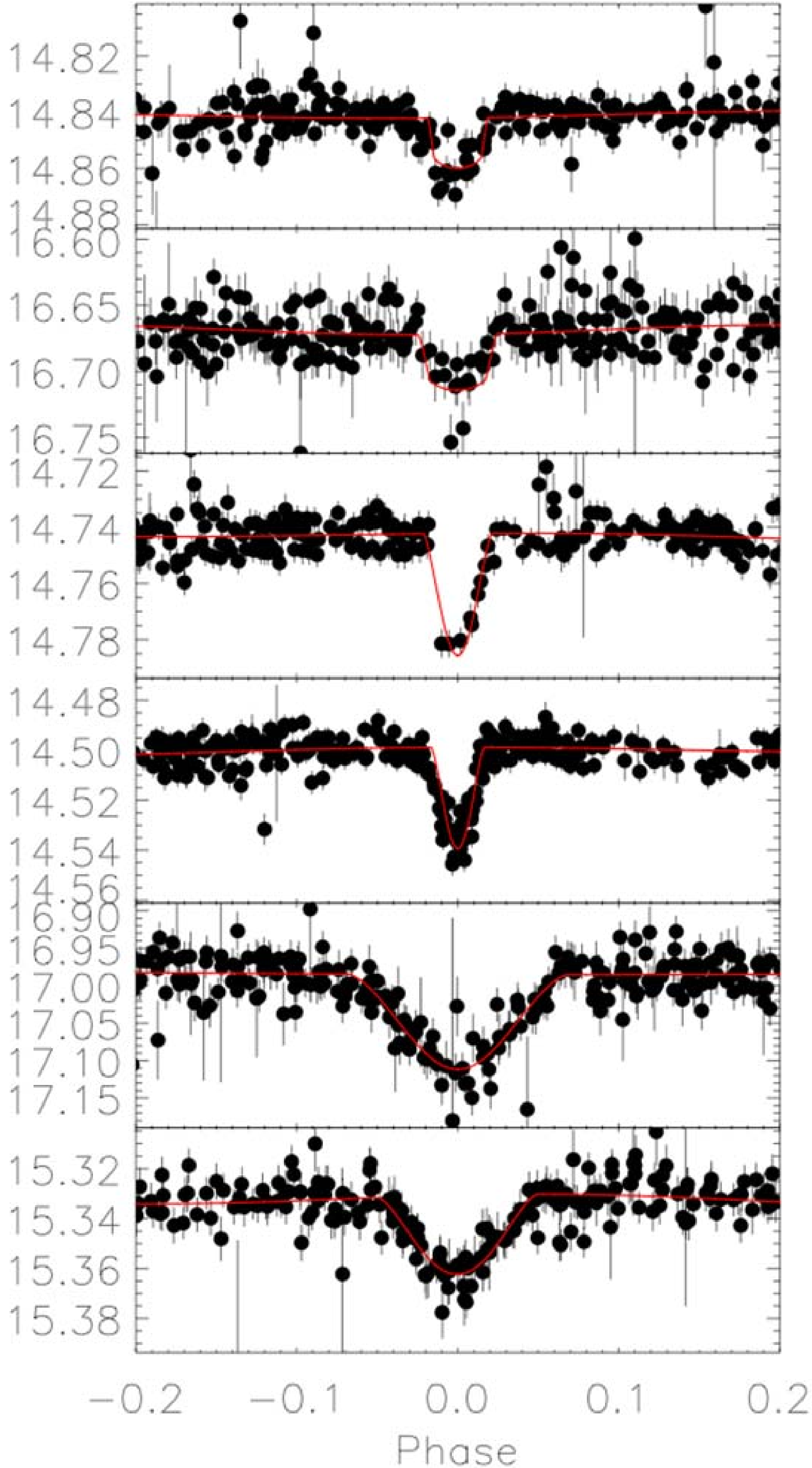


$$\frac{\rho_\star}{\rho_\odot} \equiv \frac{M_\star/M_\odot}{(R_\star/R_\odot)^3} = \left[\frac{4\pi^2}{P^2 G}\right] \left[\frac{(1+\sqrt{\Delta F})^2 - b^2(1-\sin^2 \frac{t_T \pi}{P})}{\sin^2 \frac{t_T \pi}{P}}\right]^{3/2}.$$

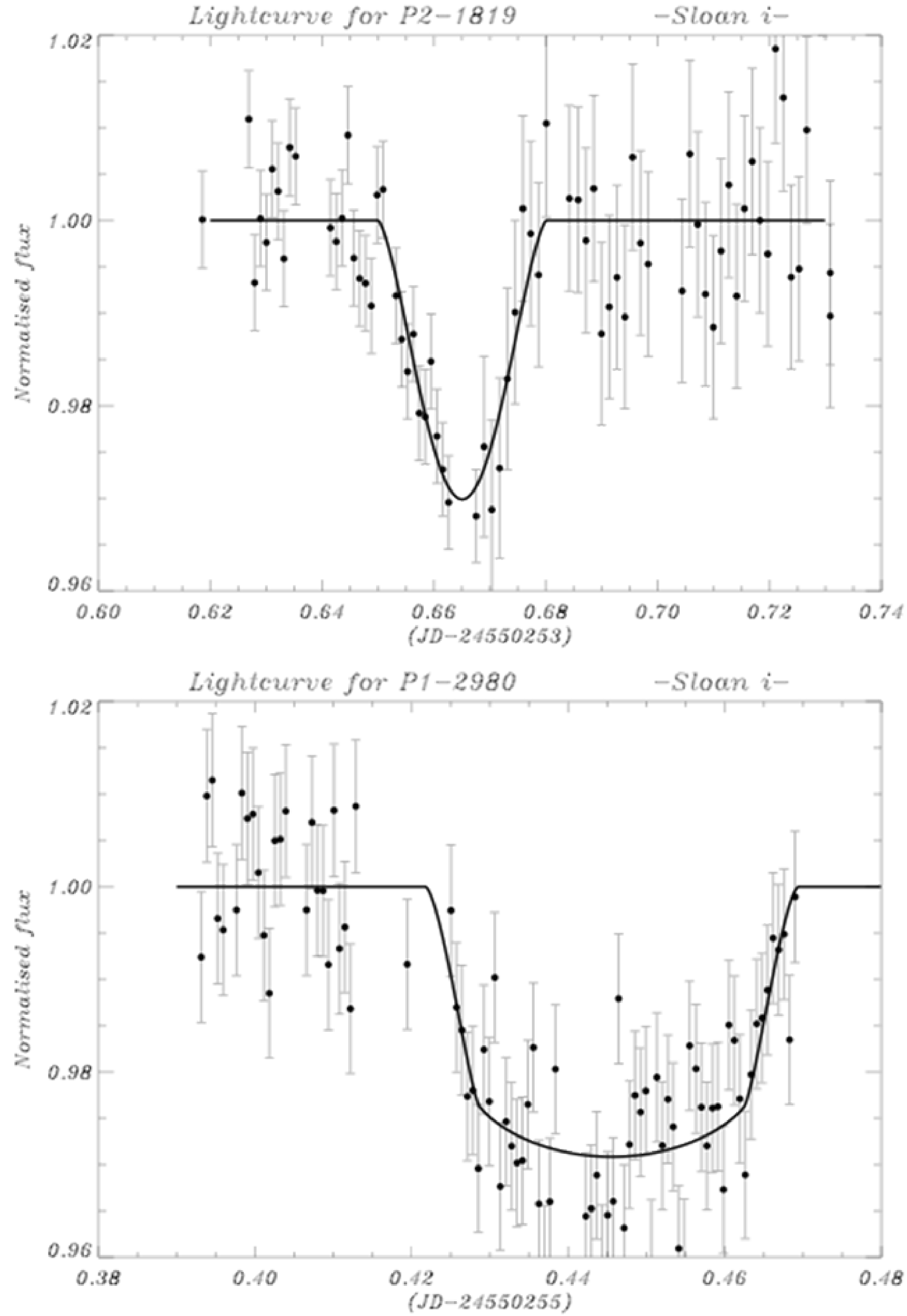
30Mj, 2dy period around a 0.3Msun: 10.6km/s
1Mj, 2dy period around a 0.3Msun: 0.4 km/s



2.0
1.5
1.0
0.5
0.0
i−z
0.0
0.5
1.0
1.5
2.0
2.5
3.0
r−i
M0
M1
M2
M3
M4
M5
M6
M7
M8
M9
L0
L2



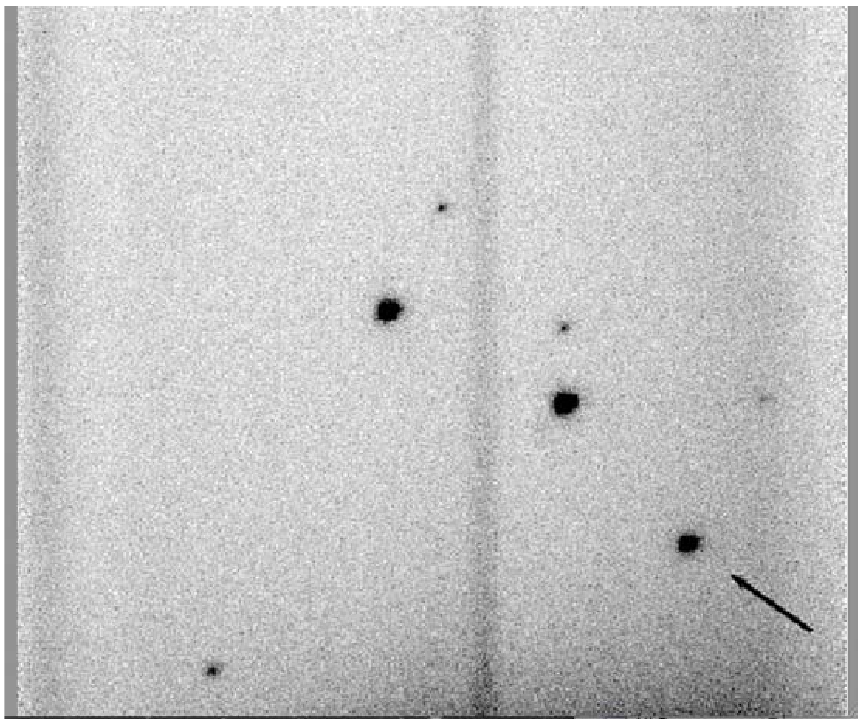
14.82
14.84
14.86
14.88
16.60
16.65
16.70
16.75
14.72
14.74
14.76
14.78
14.48
14.50
14.52
14.54
14.56
16.90
16.95
17.00
17.05
17.10
17.15
15.32
15.34
15.36
15.38
−0.2
−0.1
0.0
0.1
0.2
Phase



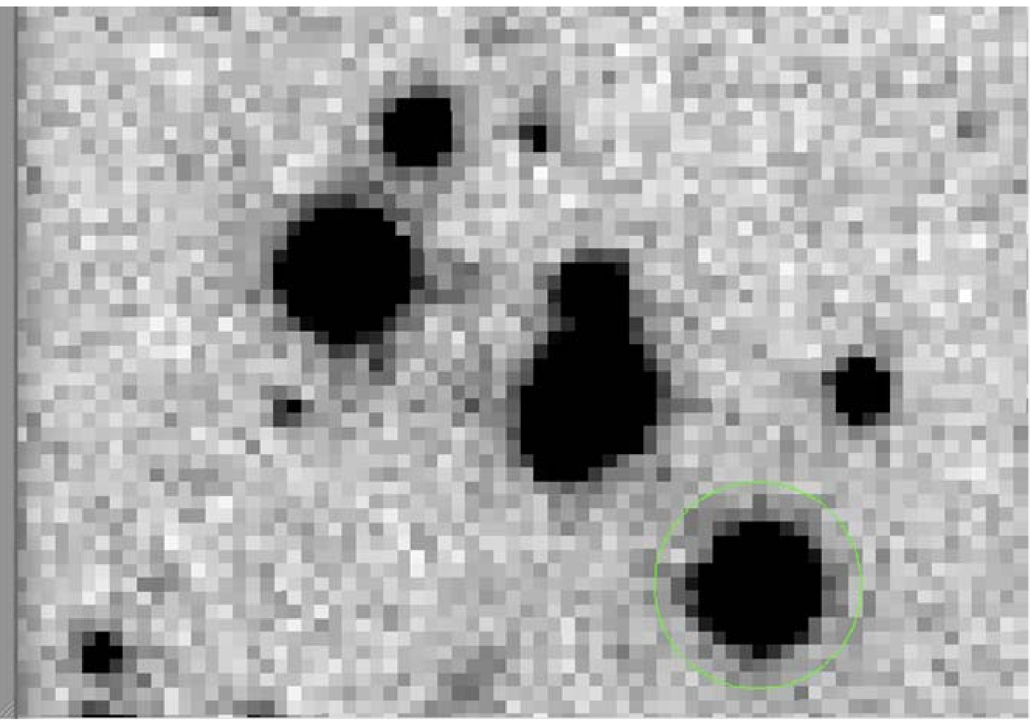
Lightcurve for P2-1819
-Sloan i-
Normalised flux
1.02
1.00
0.98
0.96
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
(JD-24550253)
Lightcurve for P1-2980
-Sloan i-
Normalised flux
0.38
0.40
0.42
0.44
0.46
0.48
(JD-24550255)

19h field:1_2980

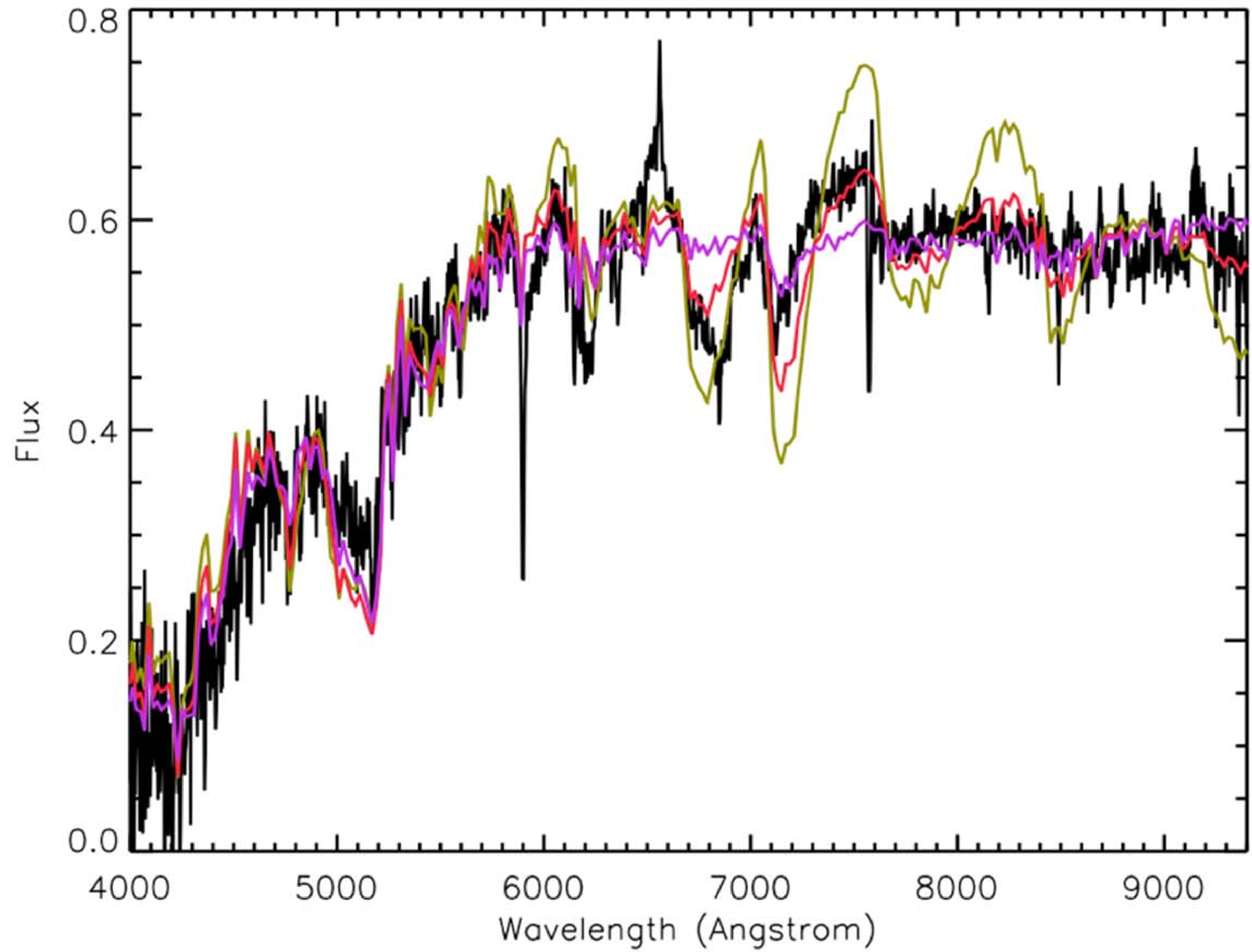
NOT+Lucky i’



UKIRT+WFCAM J



FWHM about 0.3" in 0.75" seeing. Approx 10 minute exposure, 10 percent selection. Pixels are about 0.0326".


0.8
0.6
0.4
0.2
0.0
Flux
4000
5000
6000
7000
8000
9000
Wavelength (Angstrom)

Safari File Edit View History Bookmarks Window Help

WTS Candidates

http://apm3.ast.cam.ac.uk/~sth/wts/candidates/candidates.html

Summary of candidates detected with occfit.

NB1: README for details of the data presented on this page.

NB2: Details of the source pages

NB3: Details of the ascii lightcurves

NB4: TODO list

For each source in the table below, there are links to (a) a summary page for the object including finding chart (form the WFCAM data) and occfit results, and (b) (under nmeas) a link to the ascii lightcurve for the source.

Name (field-chip_seq)	Ra (HMS)	Dec (DMS)	NMEAS	J(DC)	EPOCH	PERIOD	HW	DEPTH	SRED	ETAp	ETAs	J(2m)	H(2m)	K(2m)	Sep2m	u'	g'	r'	i'	z'	Class/Priority
19.53+36.60-1_2980	[illegible]	[illegible]	516	14.841	54318.15661	1.05178	0.031	0.010	7.0	0.71	0.78	14.90	14.21	13.97	0.07	21.34	18.73	17.26	16.53	16.08	P1
19.55+36.60-2_1819	[illegible]	[illegible]	508	15.375	54317.77497	0.82989	0.039	0.028	16.0	0.98	0.79	15.50	15.07	14.93	0.18	18.27	16.95	16.49	16.32	16.25	P2
19.55+36.60-3_5398	[illegible]	[illegible]	508	16.672	54317.45475	0.73369	0.044	0.028	7.8	1.02	0.83	nan	nan	nan	nan	20.85	18.55	17.74	17.41	17.17	P2
19.55+36.60-3_9004	[illegible]	[illegible]	508	14.744	54318.73554	2.44159	0.013	0.029	8.8	0.67	0.54	14.81	14.45	14.37	0.02	17.97	16.59	16.03	15.80	15.67	P2
19.55+36.60-4_4138	[illegible]	[illegible]	508	13.893	54317.59584	1.10663	0.029	0.021	13.7	0.82	0.73	13.89	13.49	13.43	0.06	17.04	15.70	15.18	14.95	14.86	P2
19.62+36.60-3_15172	[illegible]	[illegible]	573	14.459	54317.35413	1.74824	0.027	0.011	7.2	0.89	0.95	14.66	14.04	13.72	0.05	21.58	19.45	18.06	16.71	15.99	P2
19.62+36.60-3_7182	[illegible]	[illegible]	573	15.635	54317.52933	0.54464	0.073	0.062	39.4	1.64	1.06	15.68	15.61	15.29	0.31	17.71	16.48	16.41	16.40	16.41	P2
19.62+36.38-1_325	[illegible]	[illegible]	576	14.501	54317.76833	1.61540	0.020	0.020	13.1	0.72	0.65	14.53	14.00	13.98	0.09	19.55	17.18	16.19	15.84	15.60	P2
19.62+36.38-3_14283	[illegible]	[illegible]	576	16.990	54317.64618	0.68173	0.048	0.084	17.2	1.33	0.78	nan	nan	nan	nan	22.10	19.73	18.83	18.47	18.21	P2
19.62+36.38-4_9816	[illegible]	[illegible]	576	16.225	54317.99079	0.86506	0.038	0.060	16.9	1.15	0.75	16.25	15.68	15.49	0.10	20.11	18.39	17.80	17.45	17.26	P2
19.53+36.38-1_5755	[illegible]	[illegible]	512	15.334	54317.63693	0.77248	0.042	0.018	12.0	0.91	0.84	15.48	14.88	14.91	0.16	18.05	17.09	16.54	16.29	16.20	P2
19.53+36.60-1_10878	[illegible]	[illegible]	516	16.218	54317.46192	1.55495	0.021	0.194	24.2	1.16	0.54	16.23	15.92	15.34	0.37	24.48	20.68	19.17	18.12	17.53	B1
19.62+36.60-2_7671	[illegible]	[illegible]	573	15.860	54317.54140	0.44409	0.105	0.199	19.1	2.53	1.16	15.90	15.44	14.95	0.07	20.65	19.11	17.21	17.47	16.91	B1
19.62+36.38-2_357	[illegible]	[illegible]	576	15.448	54318.54676	1.75114	0.027	0.214	67.0	1.64	0.74	15.55	14.96	14.71	0.10	21.63	19.20	17.88	17.17	16.69	B1
19.62+36.38-3_14922	[illegible]	[illegible]	576	16.789	54317.43418	0.47740	0.097	0.043	8.3	1.85	1.33	nan	nan	nan	nan	24.69	23.24	21.16	19.48	18.44	B1
19.53+36.60-1_11106	[illegible]	[illegible]	516	14.903	54318.45201	2.34792	0.020	0.477	99.3	1.64	0.58	14.99	14.27	14.12	0.08	20.91	18.28	16.93	16.37	16.05	B2
19.53+36.60-1_4154	[illegible]	[illegible]	516	13.377	54318.78072	2.37530	0.014	0.129	23.0	0.96	0.50	13.48	13.17	13.11	0.14	16.59	15.14	14.60	14.42	14.41	B2
19.53+36.60-1_7470	[illegible]	[illegible]	516	13.931	54318.21322	1.20088	0.039	0.033	13.9	1.30	1.01	14.03	13.73	13.65	0.15	16.48	15.31	14.93	14.81	14.75	B2
19.53+36.60-1_8672	[illegible]	[illegible]	516	15.405	54317.49412	0.70147	0.066	0.246	28.5	2.23	0.96	15.47	15.21	15.17	0.15	17.84	16.58	16.30	16.24	16.23	B2
19.53+36.60-2_565	[illegible]	[illegible]	516	16.475	54318.02093	0.75205	0.043	0.334	47.1	1.58	0.62	16.80	15.73	15.86	0.62	21.22	19.33	18.33	17.90	17.65	B2
19.53+36.60-2_6413	[illegible]	[illegible]	516	13.816	54319.35837	3.58787	0.013	0.422	9.6	1.39	0.51	13.87	13.32	13.18	0.05	18.77	16.44	15.47	15.11	14.90	B2
19.53+36.60-3_5093	[illegible]	[illegible]	516	14.598	54318.22560	1.22789	0.032	0.060	12.9	1.23	0.80	14.61	14.24	14.23	0.08	17.20	15.97	15.67	15.57	15.48	B2
19.53+36.60-3_5976	[illegible]	[illegible]	516	12.556	54317.34098	0.59477	0.066	0.498	21.4	2.17	0.76	12.56	12.19	12.14	0.05	16.68	15.09	14.58	14.32	14.14	B2
19.53+36.60-3_6221	[illegible]	[illegible]	516	13.690	54318.30855	1.21898	0.027	0.124	29.0	1.18	0.62	13.77	13.19	13.12	0.03	18.69	16.51	15.54	15.11	14.85	B2
19.53+36.60-4_2732	[illegible]	[illegible]	516	16.813	54317.58365	1.70706	0.027	0.182	14.9	1.58	0.74	16.88	16.46	15.84	0.22	20.04	18.58	18.01	17.81	17.72	B2
19.53+36.60-4_3884	[illegible]	[illegible]	516	14.957	54317.53245	0.50494	0.064	0.131	16.1	1.57	0.81	15.05	14.44	14.30	0.04	19.74	17.63	16.79	16.44	16.25	B2
19.53+36.60-4_4542	[illegible]	[illegible]	516	16.083	54317.56501	0.44051	0.074	0.177	8.8	1.74	0.83	16.35	15.69	15.11	0.31	22.18	20.22	18.74	17.89	17.40	B2
19.53+36.60-4_4674	[illegible]	[illegible]	516	16.934	54317.80923	0.55623	0.059	0.257	21.2	1.72	0.73	16.86	16.54	16.84	0.10	21.92	20.03	18.97	18.47	18.17	B2
19.55+36.38-1_5249	[illegible]	[illegible]	512	16.237	54317.45032	0.46351	0.100	0.062	11.9	2.02	1.30	16.03	15.55	15.37	0.67	21.19	19.72	18.22	17.85	17.60	B2
19.55+36.38-1_7389	[illegible]	[illegible]	512	15.445	54317.30958	0.45397	0.072	0.120	8.7	1.62	0.86	15.43	14.93	14.66	0.32	20.91	18.69	17.46	16.94	16.68	B2
19.55+36.38-2_6766	[illegible]	[illegible]	512	12.210	54318.08803	1.90006	0.024	0.116	17.1	1.40	0.75	12.32	12.02	11.94	0.18	15.44	14.02	13.74	14.37	13.33	B2
19.55+36.38-2_7533	[illegible]	[illegible]	512	13.399	54318.87922	2.31926	0.017	0.135	42.7	1.16	0.60	13.46	13.19	13.07	0.10	16.42	15.02	14.49	14.36	14.28	B2
19.55+36.38-3_13260	[illegible]	[illegible]	511	14.075	54317.58056	0.65920	0.071	0.215	46.7	2.26	1.01	14.41	14.14	14.20	0.10	16.25	15.00	14.83	14.88	14.79	B2
19.55+36.38-4_1292	[illegible]	[illegible]	512	14.885	54319.71341	3.41540	0.014	0.203	12.5	1.32	0.60	15.19	14.61	14.61	0.05	19.54	17.59	16.70	16.33	16.11	B2
19.55+36.38-4_5194	[illegible]	[illegible]	512	15.925	54317.27390	0.41844	0.111	0.125	20.1	2.39	1.25	16.05	15.27	15.23	0.11	21.58	19.19	17.98	17.43	17.11	B2
19.55+36.38-4_6783	[illegible]	[illegible]	512	14.958	54317.49253	0.45572	0.087	0.319	65.1	2.28	0.91	15.03	14.81	14.73	0.04	17.81	16.61	16.36	16.29	16.27	B2
19.55+36.38-4_9917	[illegible]	[illegible]	512	14.392	54319.11406	2.48780	0.013	0.203	35.8	0.99	0.45	14.47	14.15	14.17	0.05	17.15	15.90	15.47	15.32	15.27	B2
19.55+36.60-1_1351	[illegible]	[illegible]	508	14.708	54317.54666	0.70412	0.066	0.028	10.8	1.48	1.20	14.80	14.53	14.40	0.20	17.26	16.06	15.73	15.63	15.58	B2
19.55+36.60-1_602	[illegible]	[illegible]	508	14.330	54317.76528	1.89954	0.021	0.405	61.9	1.47	0.55	14.37	13.98	14.11	0.27	17.61	16.13	15.56	15.37	15.29	B2
19.55+36.60-1_9155	[illegible]	[illegible]	508	15.696	54318.18742	1.42436	0.023	0.086	12.7	1.05	0.61	15.71	15.42	14.96	0.20	19.65	17.92	17.21	16.92	16.75	B2
19.55+36.60-2_10173	[illegible]	[illegible]	508	16.303	54317.37609	0.64189	0.051	0.068	11.2	1.30	0.82	nan	nan	nan	nan	24.07	19.96	18.59	17.93	17.46	B2
19.55+36.60-2_11585	[illegible]	[illegible]	508	12.349	54317.31603	0.52270	0.089	0.238	14.4	2.46	1.07	12.57	12.39	12.32	0.05	14.79	15.10	14.14	12.68	13.19	B2
19.55+36.60-2_11609	[illegible]	[illegible]	508	16.172	54317.41371	1.78090	0.026	0.309	47.1	1.68	0.68	16.23	15.56	15.56	0.96	21.20	18.87	17.89	17.77	17.29	B2
19.55+36.60-2_1387	[illegible]	[illegible]	508	14.647	54317.41678	0.74924	0.043	0.338	126.7	1.58	0.62	14.75	14.12	13.77	0.26	21.68	19.09	17.70	16.65	16.03	B2
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Proposal for extension of the WTS

False alarm rate - both international reviewers were concerned that the false alarm rate in this type of imaging survey would be prohibitive. The Board accepts this as a risk for the period to 2009, but expects to see hard evidence that the false positive rate is under control should the team propose an extension of the project.

1. Number of predicted transits - the Board recognise that there is a risk that no transits will be found. Before considering extending the WTS the Board will need observational evidence that the claimed sensitivity has been reached.

2. Additional time domain science goals - while not the primary goal of the WTS, including some indication of the additional science areas that can be addressed with the data would be helpful.

ue end sept 2009, currently reports sent every 6 month

RoPACS: Rocky Planets Around Cool Stars

A Marie Curie Initial Training Network

Kick-off Meeting

The kick-off meeting was held in Madrid between the 28th and 29th of January 2009, coinciding with the Madrid summer school. Visiting scientists were invited to participate with members of the RoPACS network to listen to a variety of introductory presentations.

The aim of the meeting was to cover the following points:

- Give a full presentation and agreement of the project, including overall work plan and specification of key deadlines and actions
- Provide basis for a detailed annual work plan
- Clarify methods of communication between partners
- Inform about administrative procedures, e.g. communication, reporting, financial issues
- Set up topical working groups
- Outline plans for research activities and present important updates on new results and facilities

Materials in support of the kick-off meeting

- Meeting Agenda - Timetable of presentations
- Annex I - Description of work

Presentations given at the kick-off meeting

Conclusions

- an M dwarf transit survey will enable stringent tests of planet formation scenarios (e.g frequency, mass function).
- even rocky/icy cores should be detectable
- spectroscopic follow-up ought to be viable in the infrared
- WTS is producing **beautiful data**, and hopefully some exciting results when we start follow-up in earnest next summer