Transiting planets and very low-mass EBs in young open clusters

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Outline

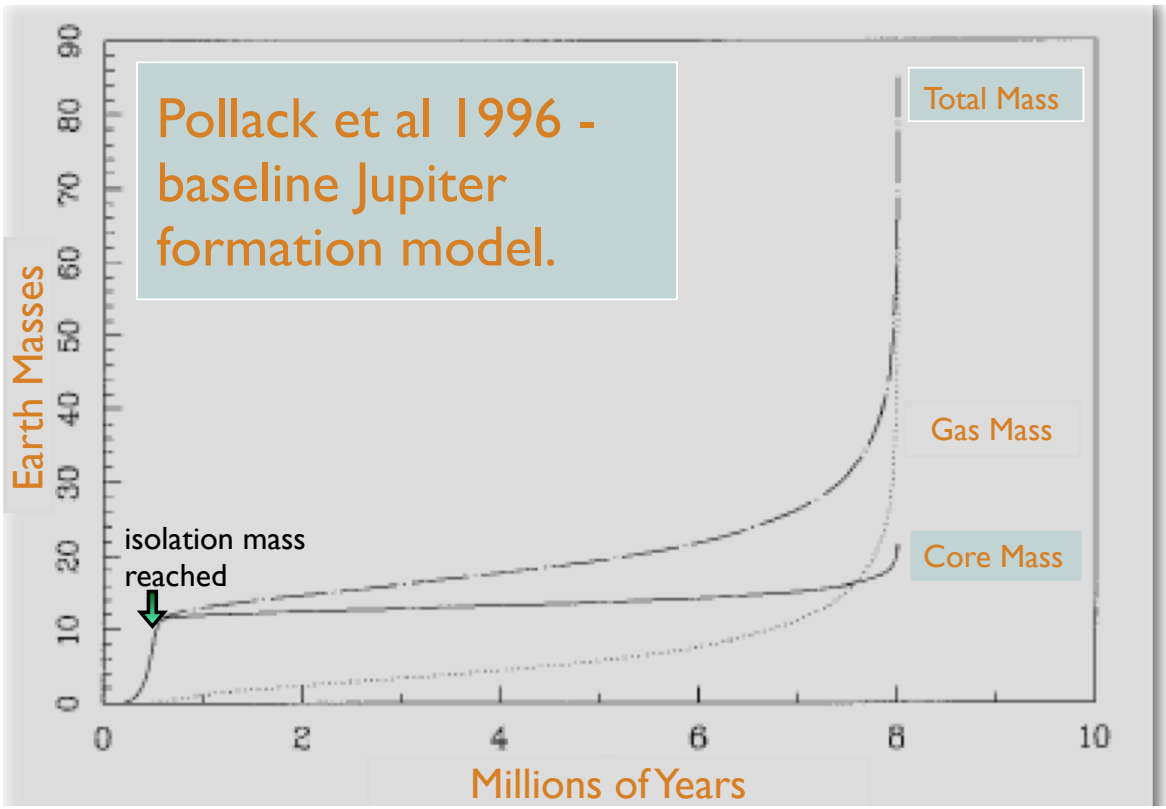
- The Monitor project
- Motivation
- Observations and data processing
- Transit / eclipse candidates
- Future prospects

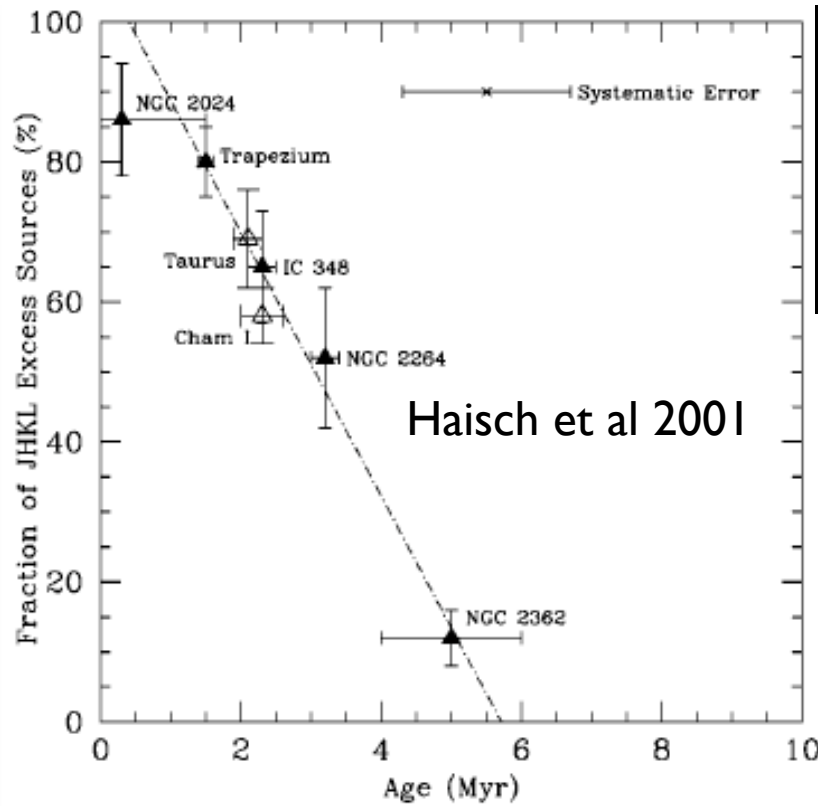
The Monitor Project

- Started 2004, co-PIs S. Hodgkin & S.A.
- Dozen open clusters aged 1-200 Myr
- Photometric monitoring from 4 telescopes 2-4m (INT, ESO 2.2m, CFHT, CTIO 4m)
- Primary goal eclipses/transits
- Secondary goal rotation studies, plus flaring, acrretion, etc...

Motivation - I

Can planets form as fast as disks evaporate?



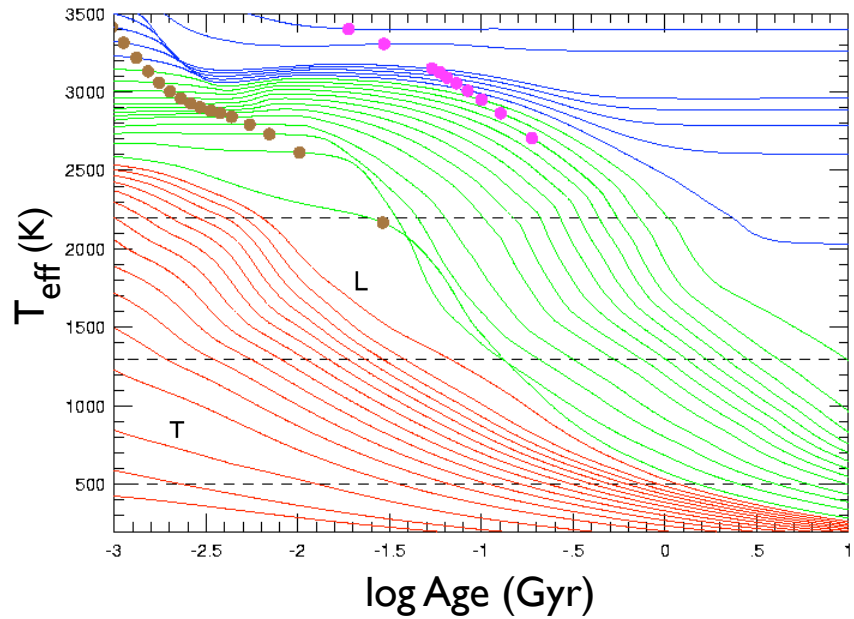


slides from G. Laughlin (2005)

Motivation - 2

How bright & large are young brown dwarfs and planets?

- Evolutionary models
  - Baraffe et al. 98
  - Chabrier et al. 00
  - Burrows et al. 97



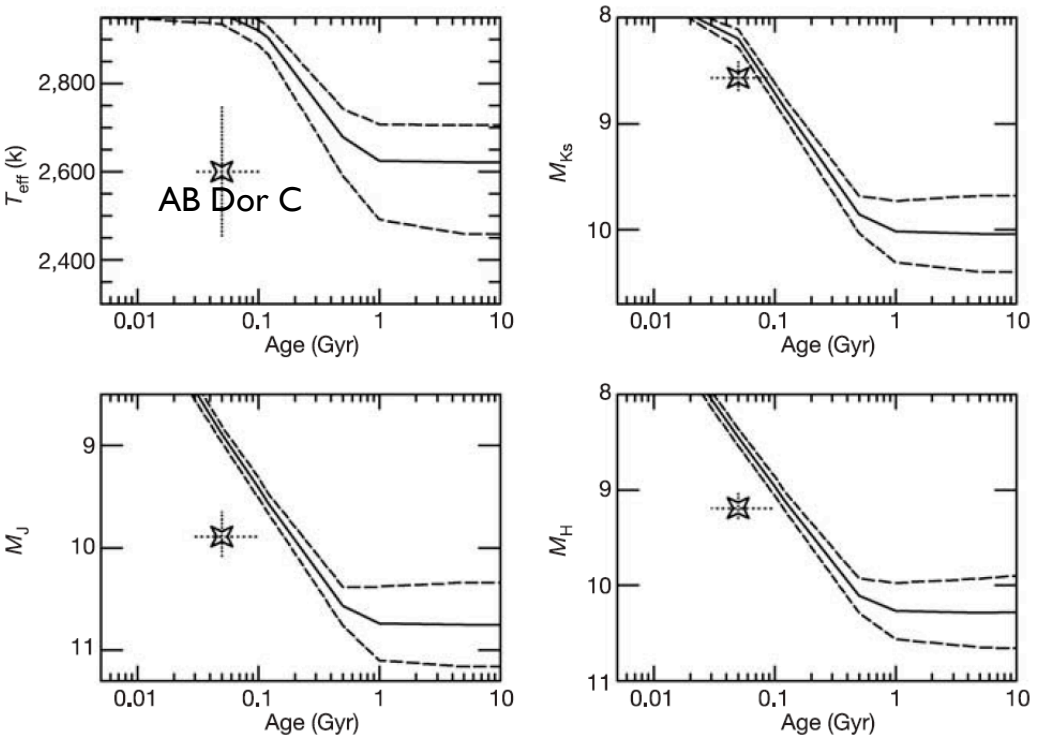
Burrows et al. 1997

- Initial conditions?
- High uncertainties at early ages (Baraffe et al. 2003, Marley et al 2005)

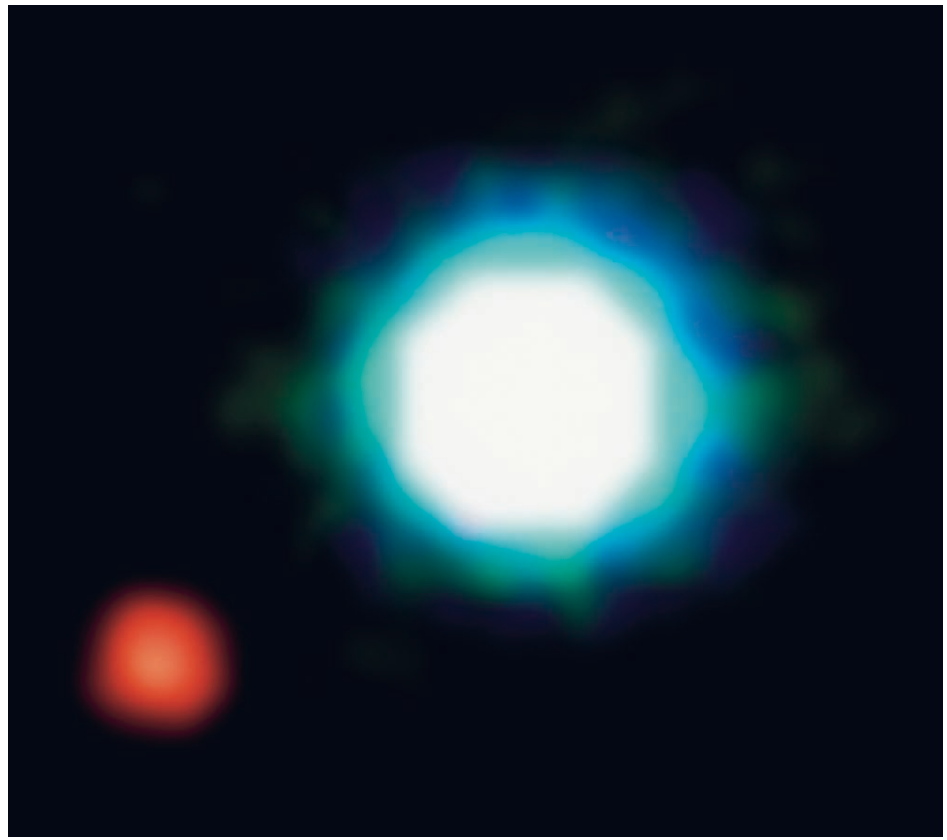
Motivation - 2

How bright are young brown dwarfs and planets?

Close et al. 2005



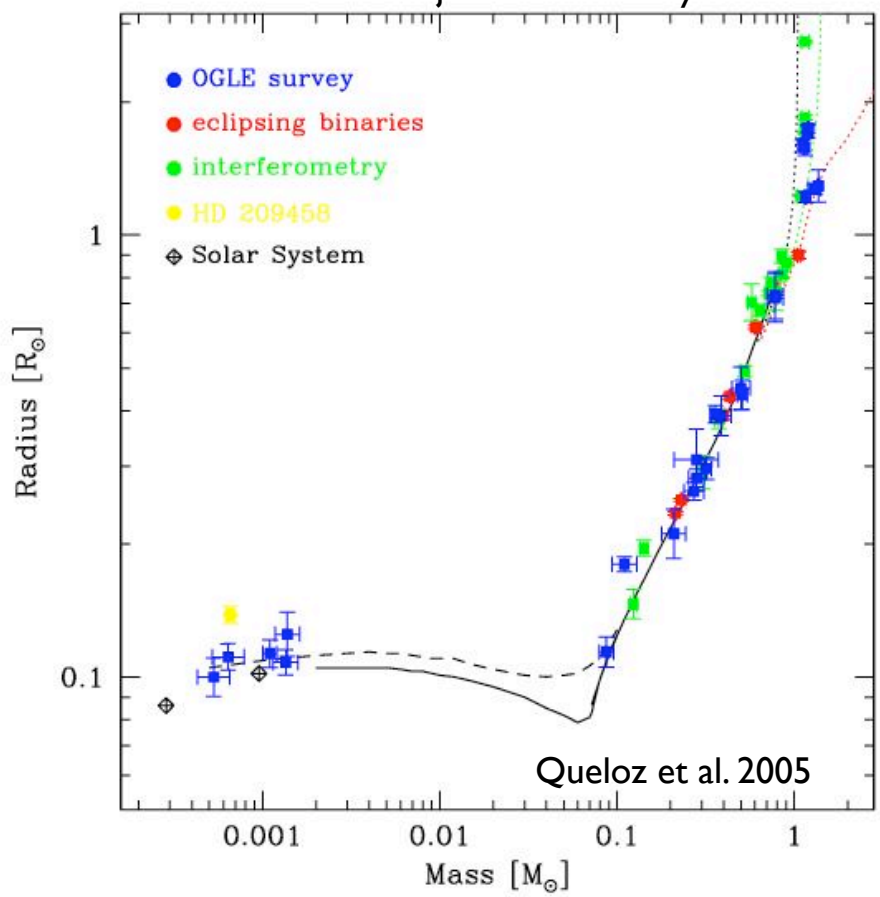
Chauvin et al. 2005a,b



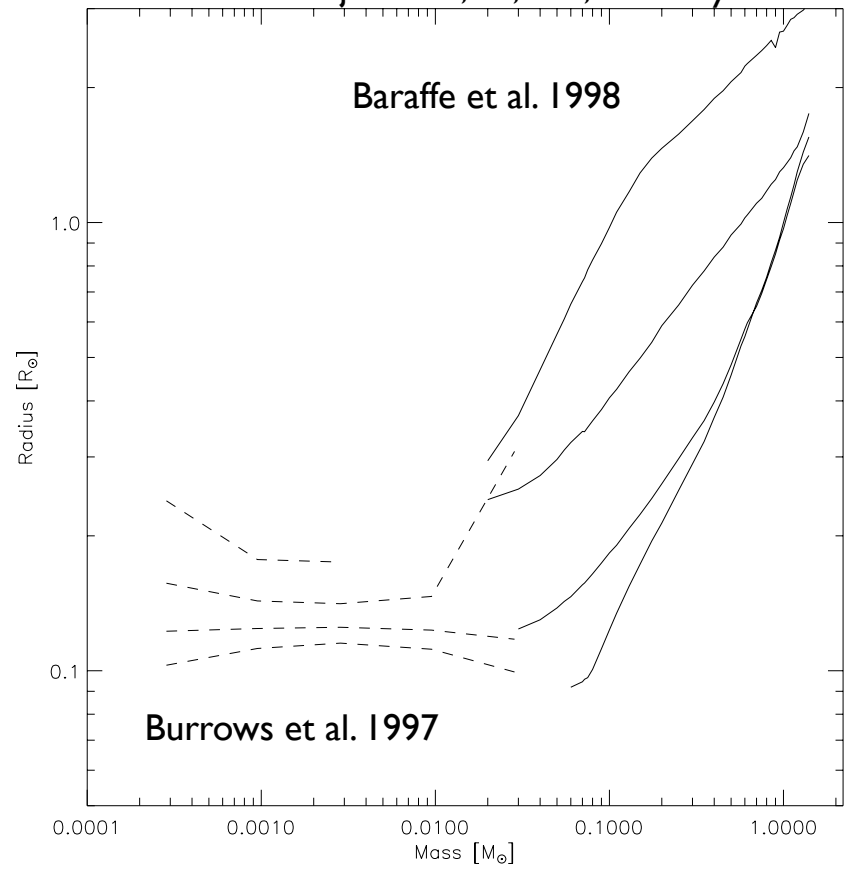
Motivation - 2

How large are young brown dwarfs and planets?

Field objects - several Gyr



PMS objects - 1, 10, 100, 1000 Myr



Motivation - 3

A crucial and unchartered area of parameter space

- ~ 154 known exoplanets, mostly from RV surveys, 9 that transit:
  - HD 209458b, 189733b, 149026b,
  - OGLE-TR-10, 56, 111, 113, 132, TrES-1
- Few K & M eclipsing binaries
- But all orbit main sequence stars with ill-known ages
- Only 2 known PMS EBs with both components < $1M_{\odot}$ (Stassun et al. 2004, 2006)

Transits...

- Simultaneously survey 1000's of stars
- With RV follow-up, constrain companion radius & mass
  - In EB case, contrain T_{eff} & luminosity to few %
- Potential for follow-up:
  - Transit spectroscopy
  - Secondary eclipse searches

...in young open clusters

- Known ages (& metallicities)
- Increased alignment probabilities (bloated primaries)
- Luminous BDs & planets - enhanced follow-up potential
- Observations tailored for low and very low mass primaries
  - Unchartered region of parameter space
  - Deeper transits
  - Larger RV amplitude: easier confirmation

but...

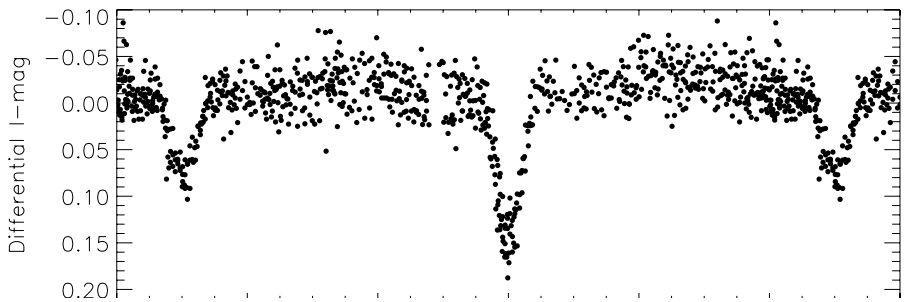
- Strong bias towards short periods (Queloz et al. 2005, Gaudi et al 2005)
- Need many observations per field (Pepper & Gaudi 2005, Pont et al. 2006)
- Activity and accretion related variability may impede transit detection
  - variability filters
  - simultaneous V & i monitoring for the youngest targets
- Faint targets + activity induced jitter may impede RV follow-up?
  - expect jitter ~ 60 m/s at 3 Myr
  - 0.03$M_\odot$ BD in 3d orbit around 1$M_\odot$ star: RV amplitude 3 km/s
  - 1 M_{Jup} planet in 3 d orbit around 1$M_\odot$ star: RV amplitude 140 m/s
- For high mass ratio systems, have to rely on models for primary mass and radius estimate

Open cluster transit searches

- EXPLORE-OC (von Braun et al. 2004)
- St Andrews Open Cluster Planet Search (Street et al. 2003, Bramich et al. 2005)
- PISCES (Mochejska et al 2002, 2004, 2005)
- Older open clusters (1 to a few Gyr)
- No detections so far (some viable candidates)
- Pepper et al (2005) show absence of detections consistent with results of RV searches

Open cluster EB searches

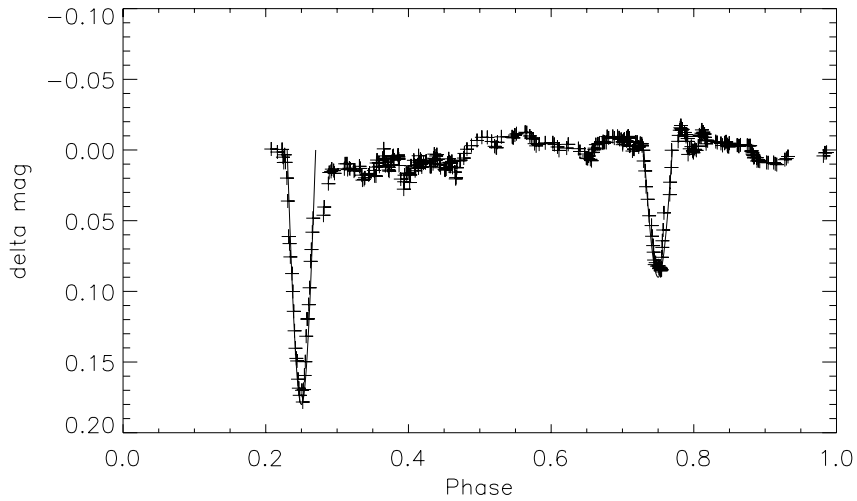
Survey of middle aged open clusters to search for VLM EBs (Hebb et al. 2004)



New dM EB in NGC1647
(Hebb et al. 2006)

Candidate in M35

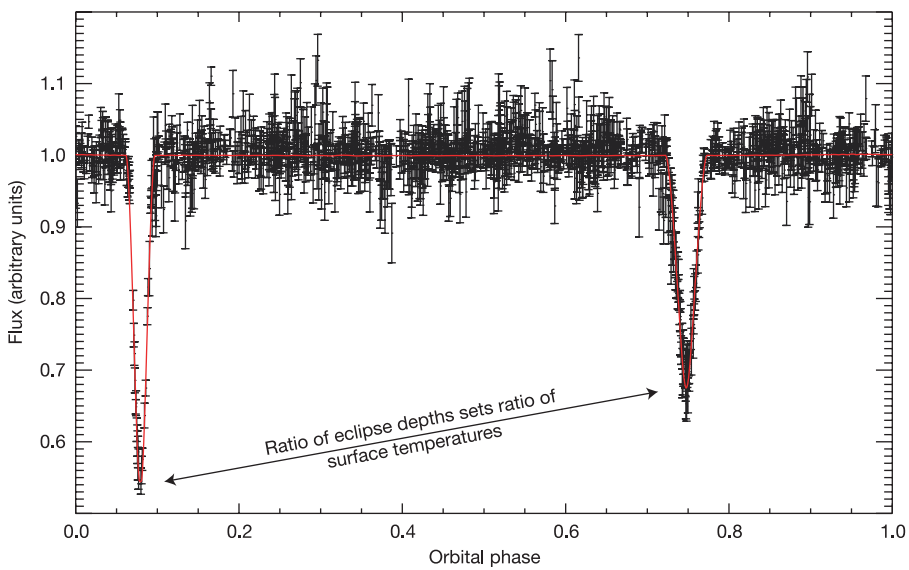
Secondary eclipse detected during main survey, primary detected during a Monitor run



Low mass EBs in ONC

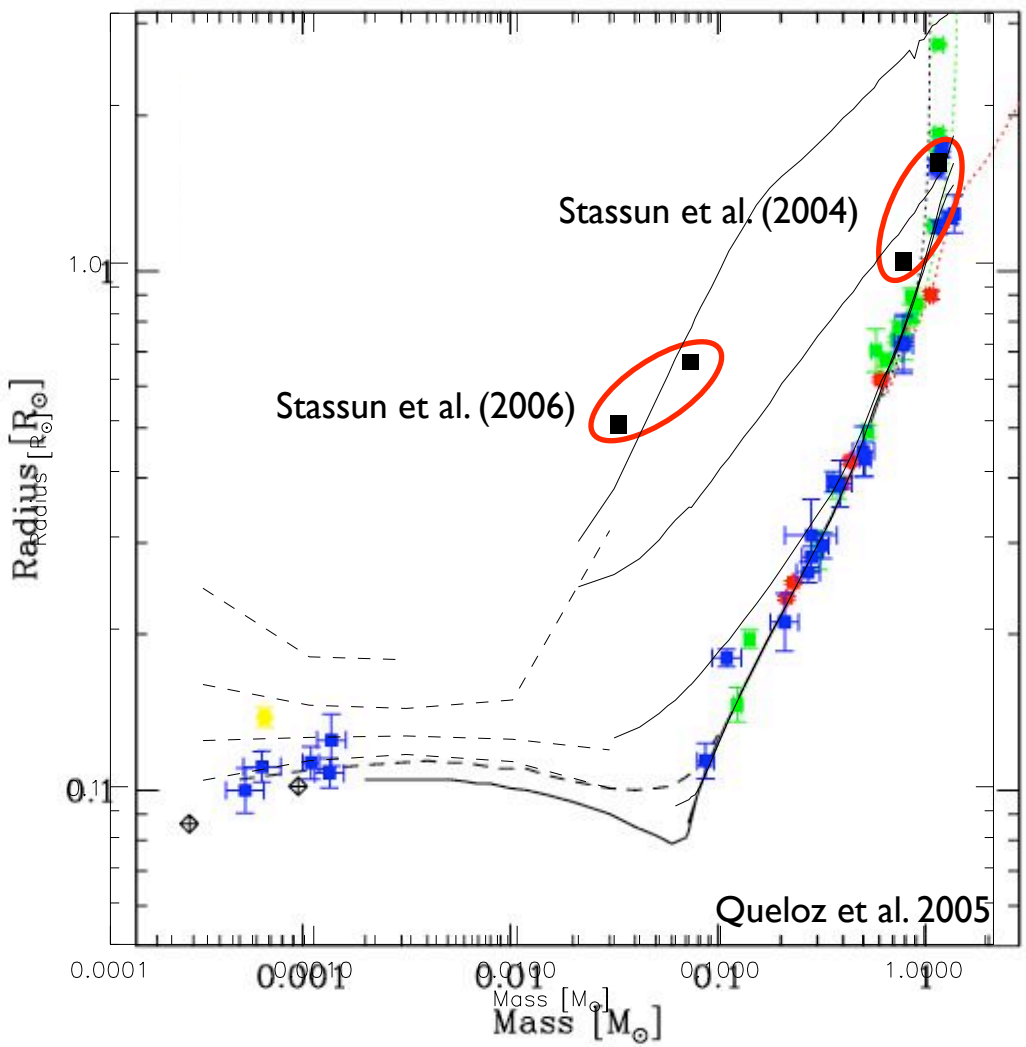
0.7+1.0 M EB ins ONC (Stassun et al. 2004)

BD-BD EB in ONC (Stassun et al. 2006)



Only 2 low mass PMS EBs known so far

Our preliminary detection rate estimates (Aigrain et al. in prep.) show Monitor should find TENS of PMS EBs



Monitor targets

Name	RA (hh~mm)	Dec (dd~mm)	Age (Myr)	(M-m)_0 (mag)	E(B-V) (mag)	I(HBL) (mag,a)	M(I=20) (M_Sun,b)
ONC	05 35	-05 23	1	8.16	0.05	16.6	0.02
NGC~2362	07 19	-24 57	7	11.0	0.10	20.5	0.09
h/χ~Per	02 20	+57 08	13	11.85	0.56	22.0	0.22
NGC~2547	08 10	-49 10	30	8.4	0.06	19.2	0.05
Blanco~1	00 04	-29 56	100	7.1	0.01	19.2	0.06
M50	07 02	-08 23	130	10.0	0.22	22.6	0.25
NGC~2516	07 58	-60 52	150	7.7	0.10	20.0	0.08
M34	02 42	+42 47	200	8.7	0.07	21.7	0.11

We are currently surveying the PMS population of a number of additional potential targets

Photometric monitoring to date

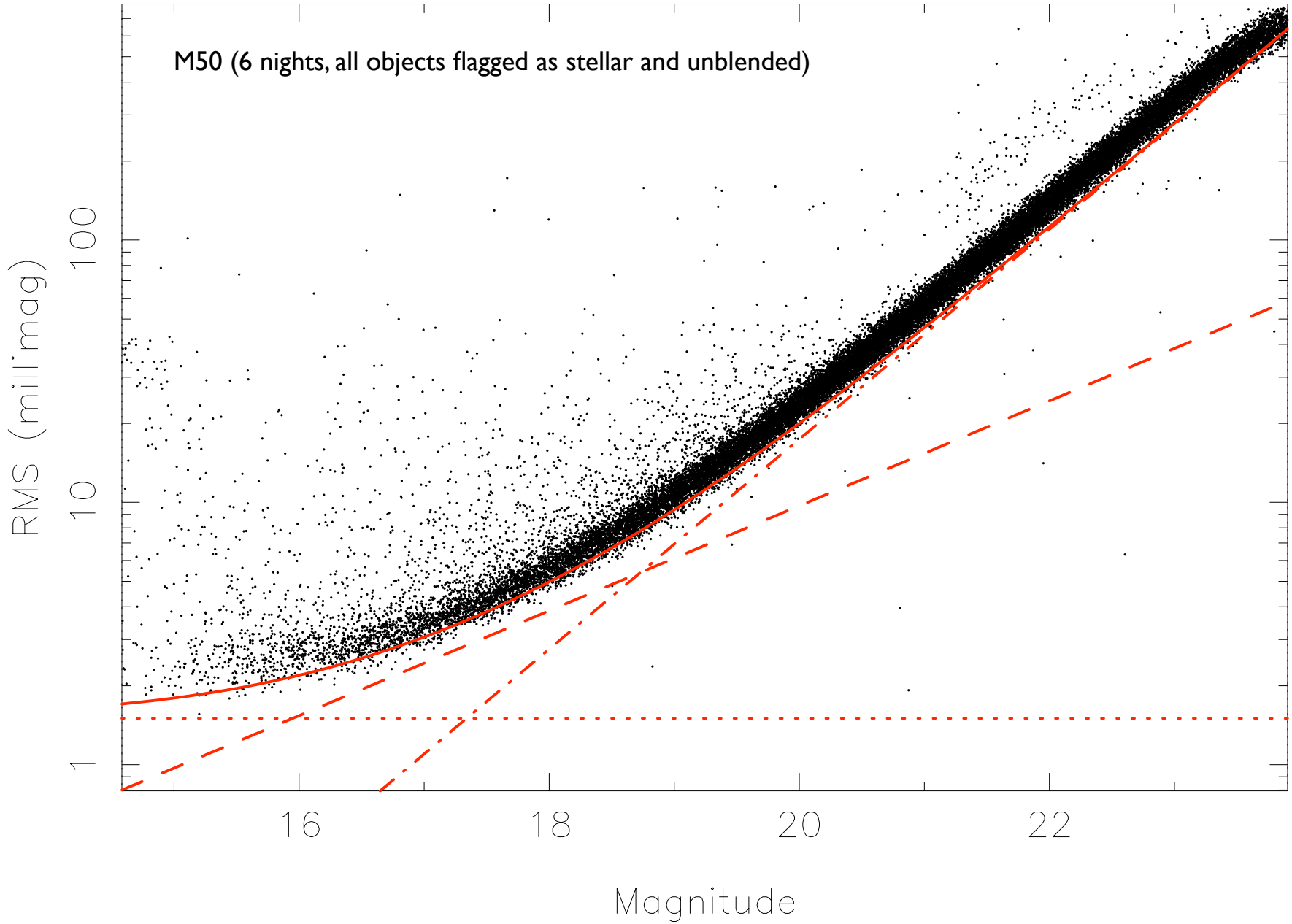
Telescope	Instrument	Semester	Targets	Nights / hours	Status
INT 2.5m	WFC	2004B, 2005B	ONC, M34	3 x 10 nights (~10 clear)	fully processed M34 fully analysed ONC under analysis
CTIO 4m	Mosaic2	2005A, 2005B, 2006A	NGC 2362, M50, NGC 2516	6 + 8 + 8 nights mostly clear	fully processed under analysis
ESO 2.2m	WFI	P75, P76, P77	Blanco 1, NGC 2457	2 x 100h	awaiting data
CFHT 3.6m	MegaCAM	2005A, 2005B	IC 4665 M34, h & X Per	2 x 40h	2005A not enough data 2005B awaiting data

Data reduction & light curves

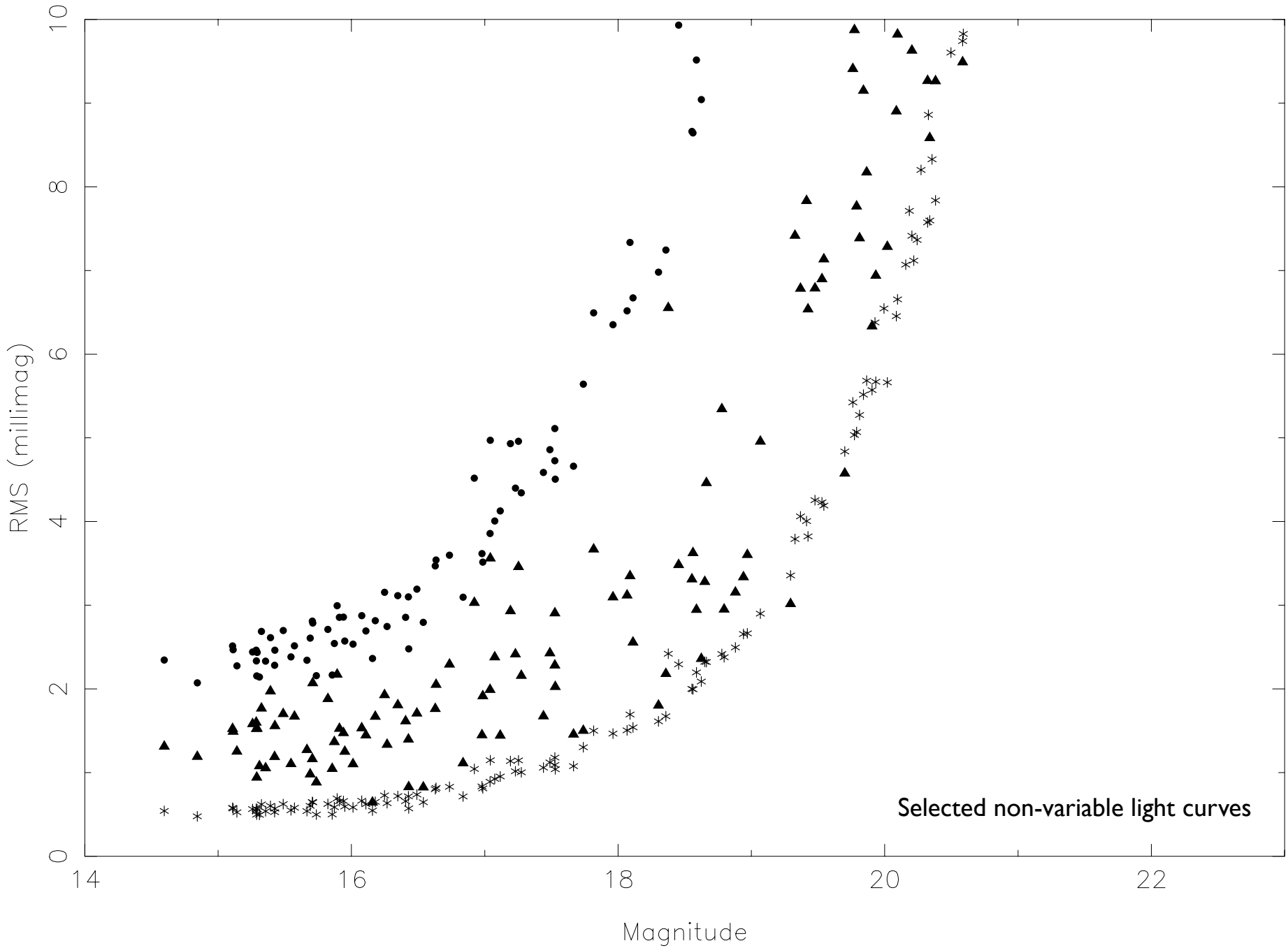
(Irwin et al. in prep.)

- Reduction and calibration: INT Wide Field Survey (WFS) pipeline developed by the Cambridge Astronomy Survey Unit (Irwin & Lewis 2001)
- Co-located aperture photometry:
  - Refine astrometric solution to 0.1" accuracy
  - Generate master catalogue 'noise free' stacked master frame, flagging likely blends and non-stellar objects
  - Perform aperture photometry at master catalogue position on each frame, choosing from a range of aperture sizes to maximise SNR in aperture
  - Background estimated by interpolating across grid of 64x64 pixel bins
- Fit 2-D polynomial surface to map of light curve residuals versus x-y position to remove systematics that vary temporally as a function of position

Frame-to-frame RMS



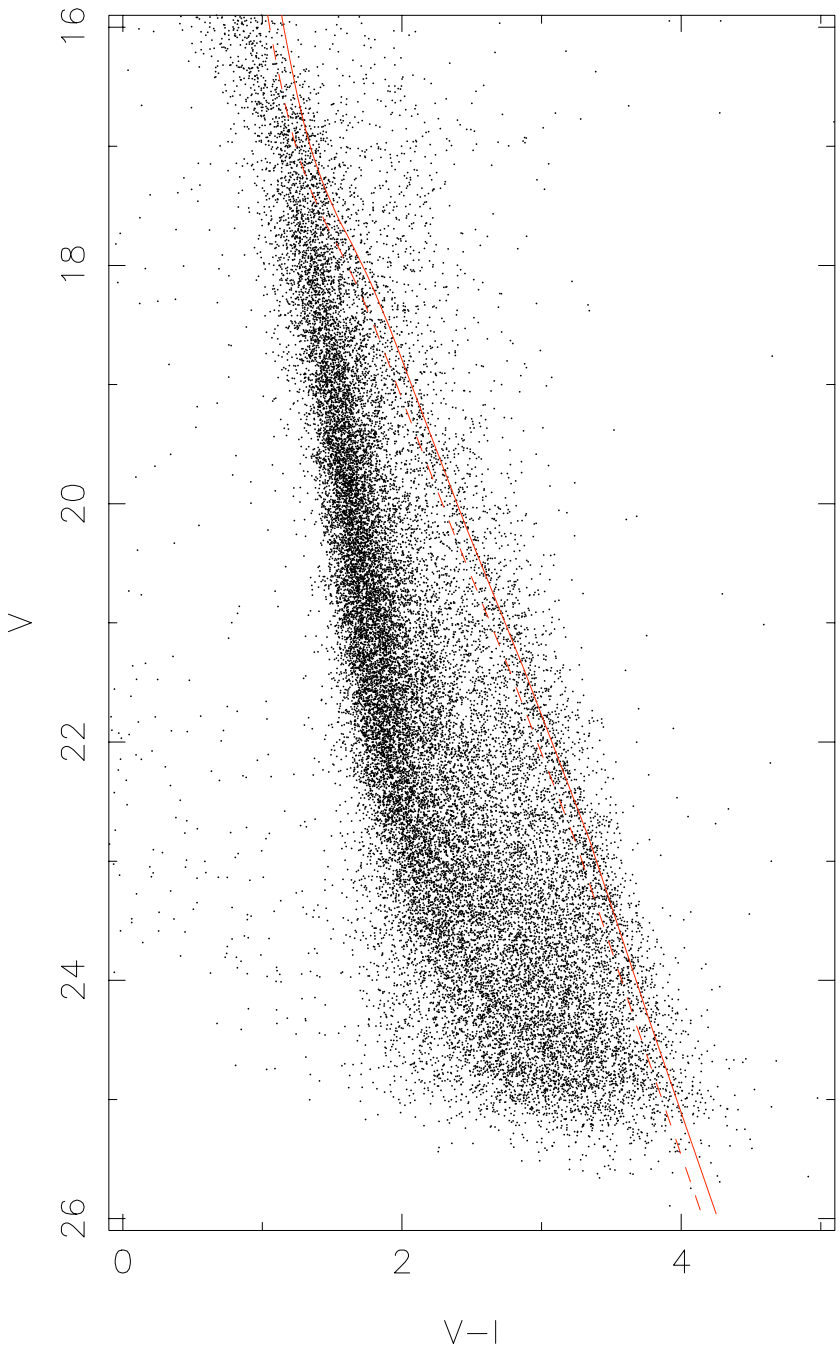
RMS over transit timescale

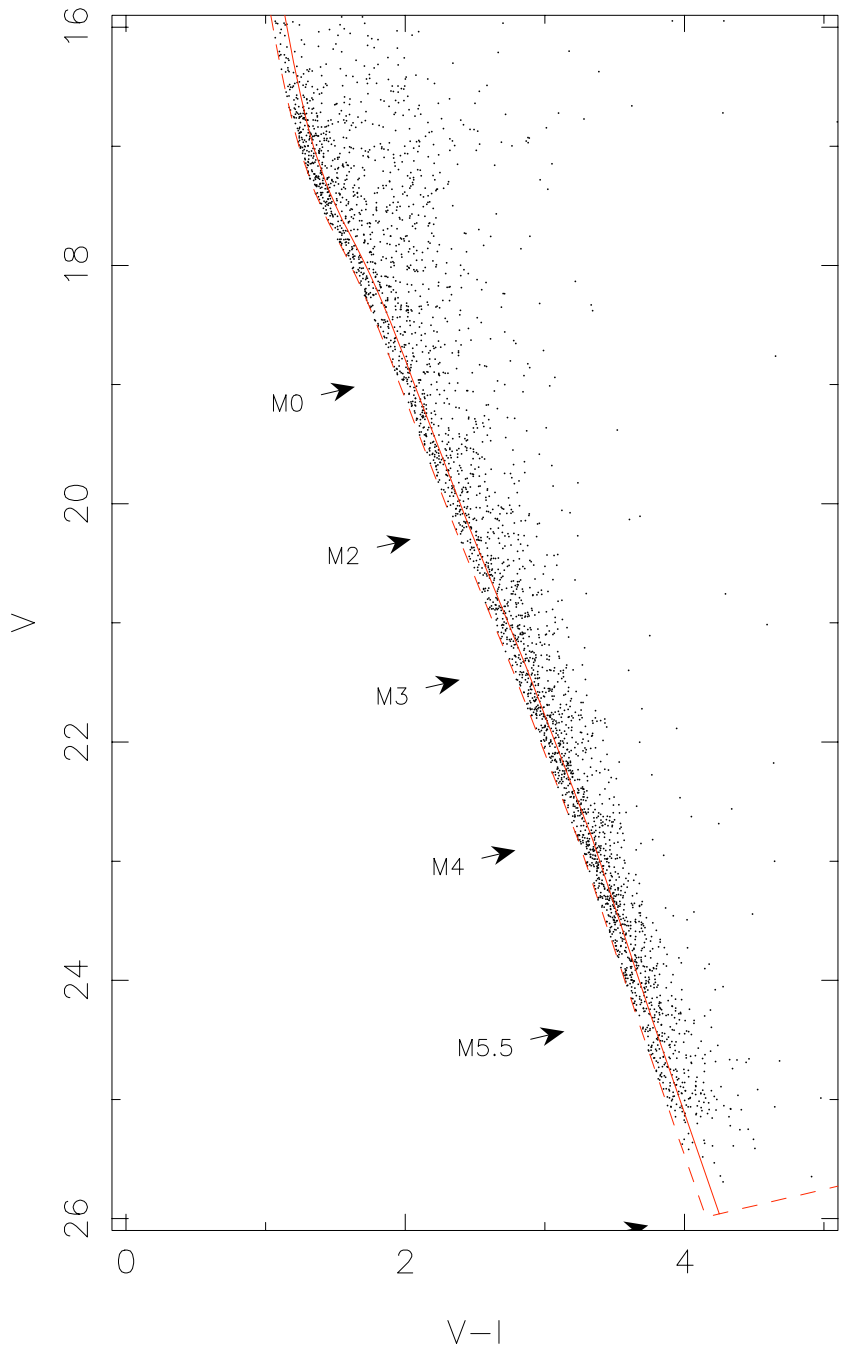


Transit / eclipse detection

- Membership selection from V, V-I CMD using empirical sequence
- Transit search algorithm (Aigrain & Irwin 2005) for box-shaped transits (good enough approximation for most eclipses)
- Currently, correlated noise implies we have to set relatively high detection threshold - all our candidates were independently identified by eye
- Recently implemented a modification of algorithm to account for correlated noise, following Zucker & Pont (in prep.). This should lead to further detections.
- Require >=3 observed eclipses to trigger follow-up

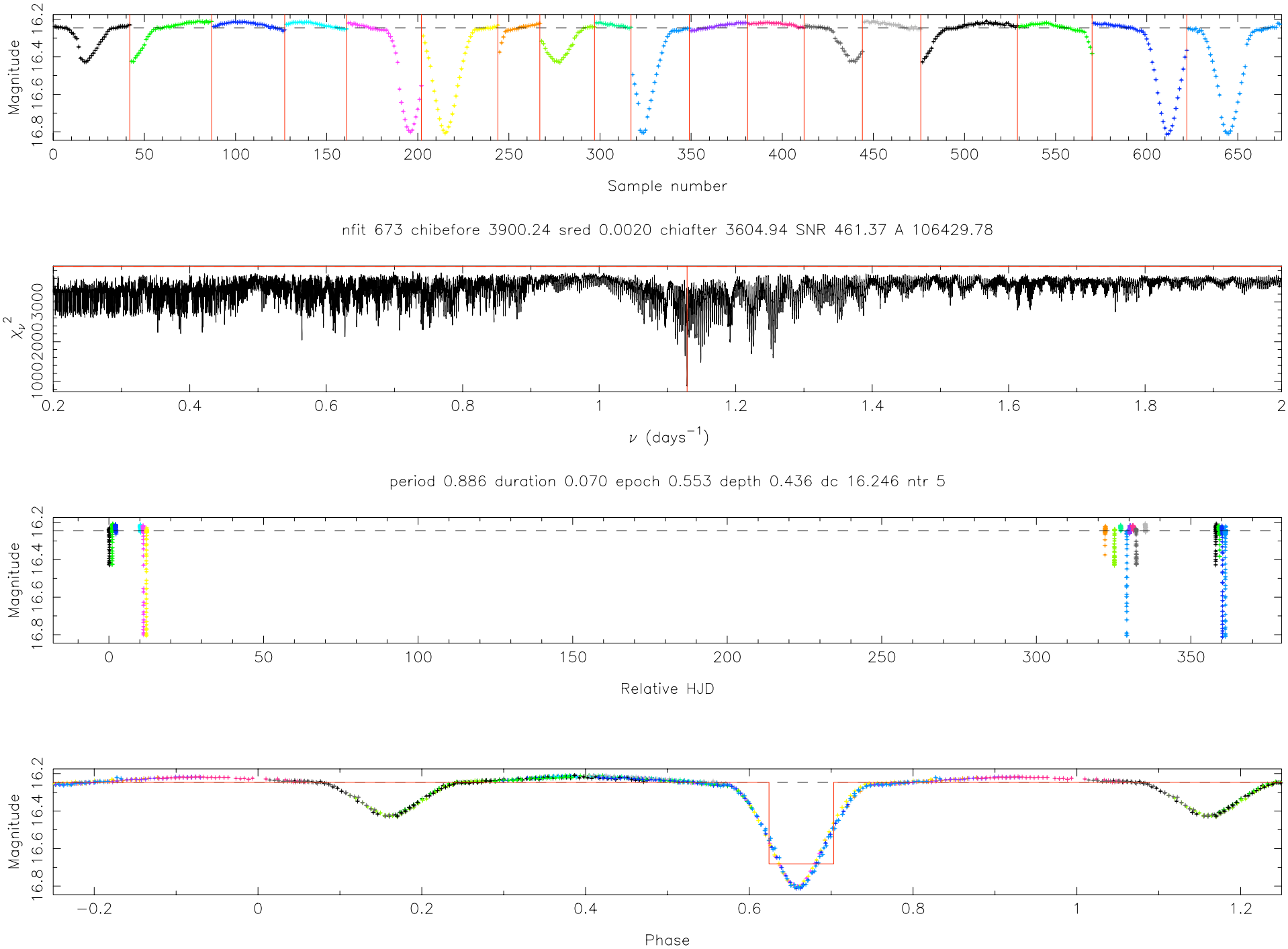
Cluster sequence definition: M50



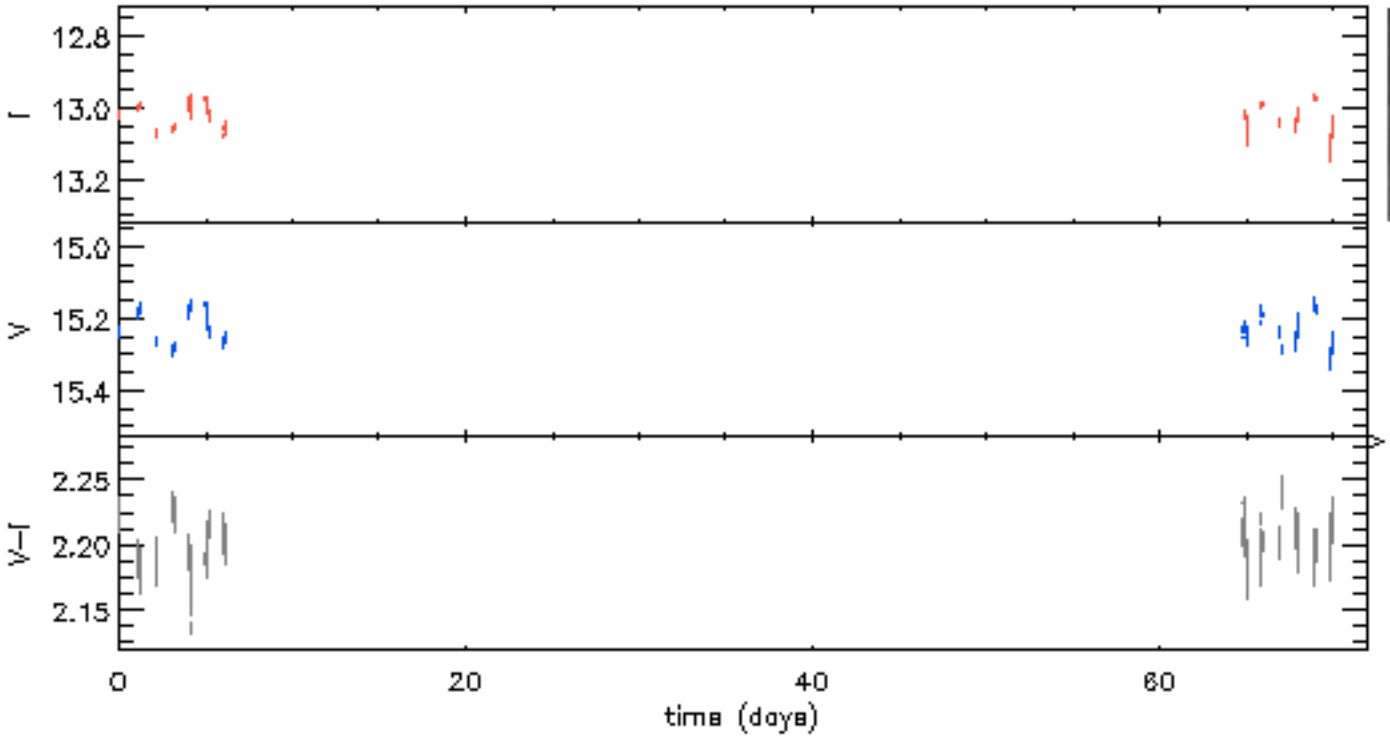


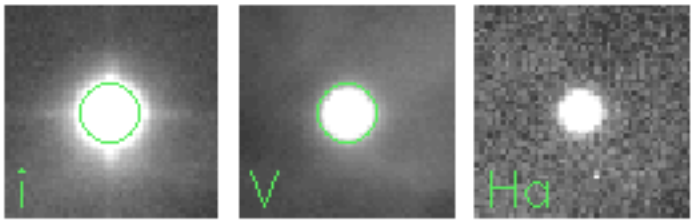
Contamination estimated 50 to 80% depending on magnitude. Less contamination in other clusters.

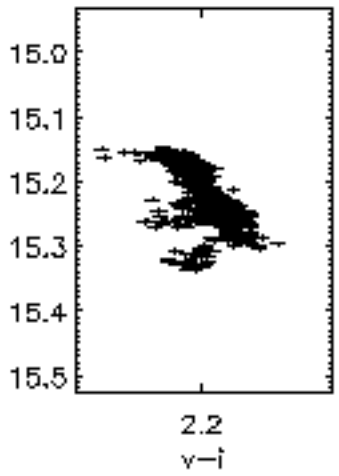
Eclipse search: example in M50

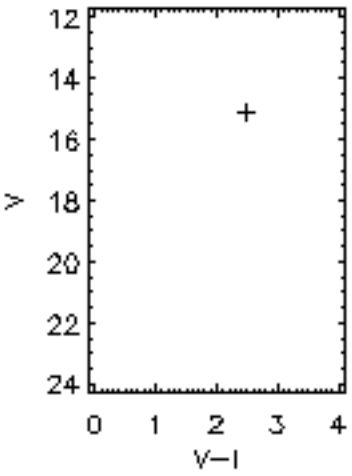


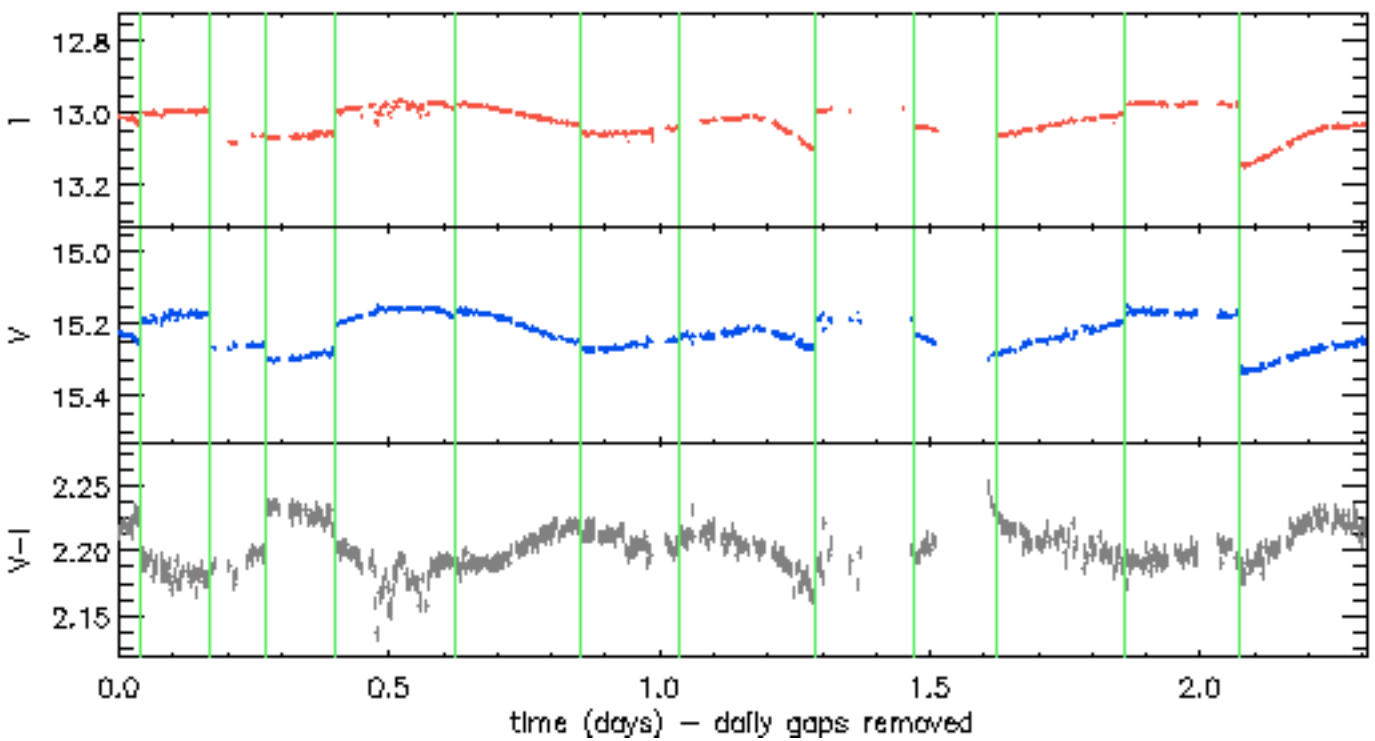
Monitor Project Light Curve Atlas





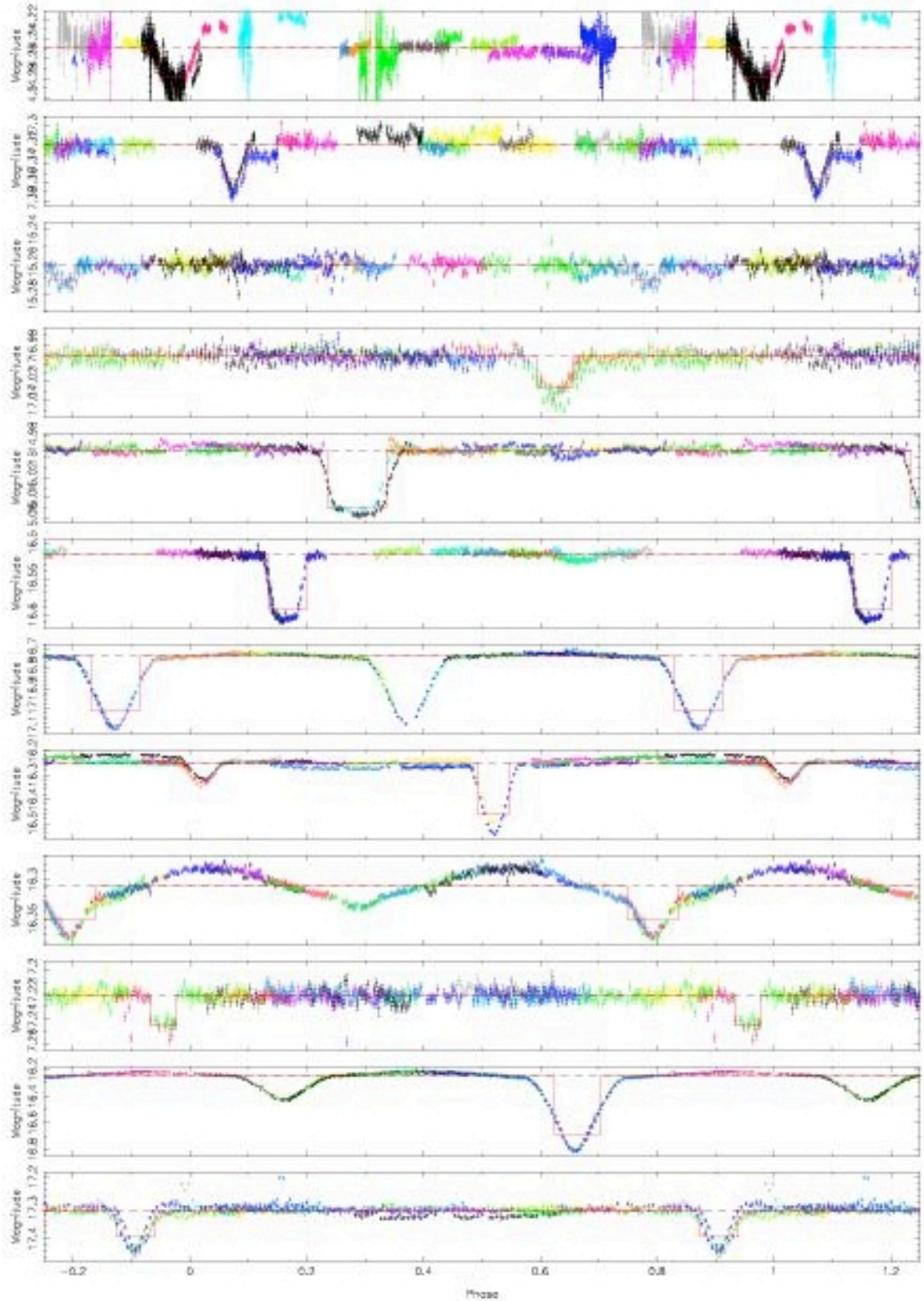






field = ONC
ccd = 1
star = 295
RA = 05 35 11.14
Dec = −05 36 51.2
V = 15.12
I = 12.65
cls = −1
bfl = 0
cfl = 0
σ_I = 0.048
σ_V = 0.060
Hα = 15.43

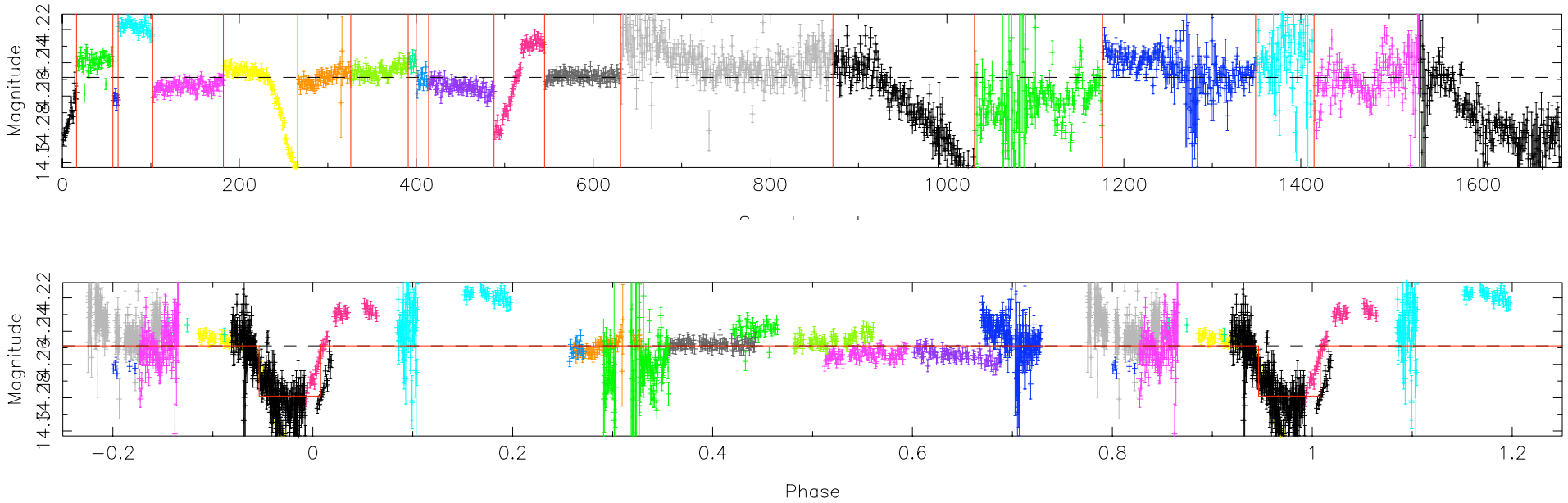
J = 11.12
H = 10.27
K = 9.94
H97_ID = 363
H97_MP = 0.98
H97_A_V = 0.72
H97_log(T_{eff}) = 3.544
H97_log(L) = 0.120
H97_R = 3.13
H97_M = 0.20
H97_log(t) = 4.27
H97_Δ(I−K) = 0.40
vsini = 33.40



Candidates

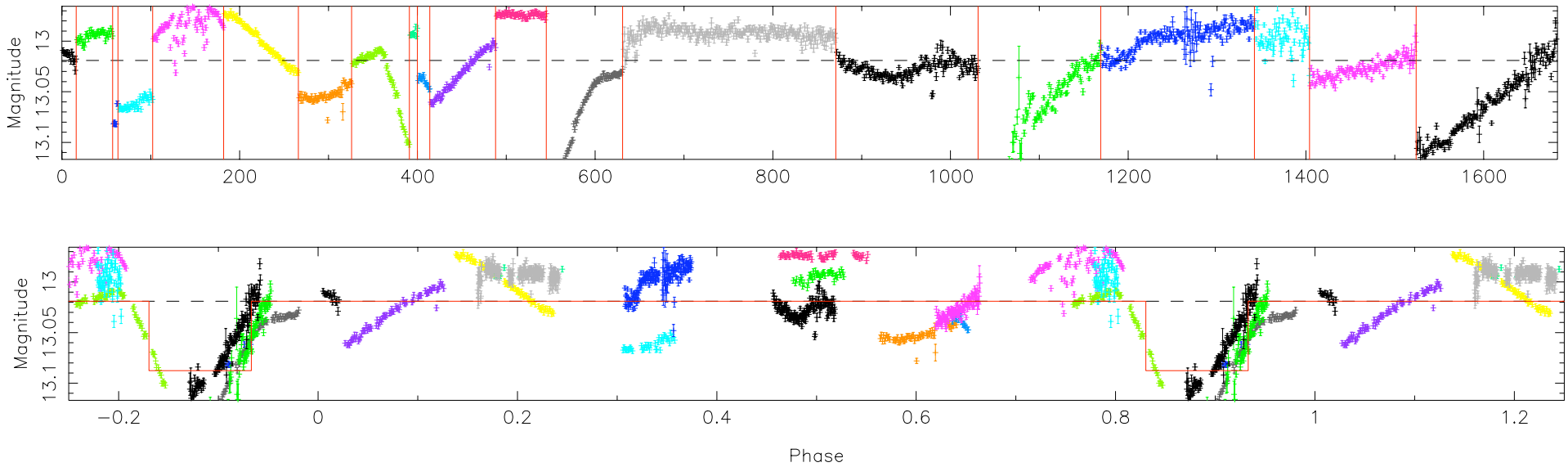
- 25 priority 1 candidates in 4 clusters so far
- ages 1 - 130 Myr
- 10 with depths compatible with planet
- completely unprecedented sample
- spectroscopy needed to
  - confirm cluster membership
  - measure companion masses

ONC 1-290



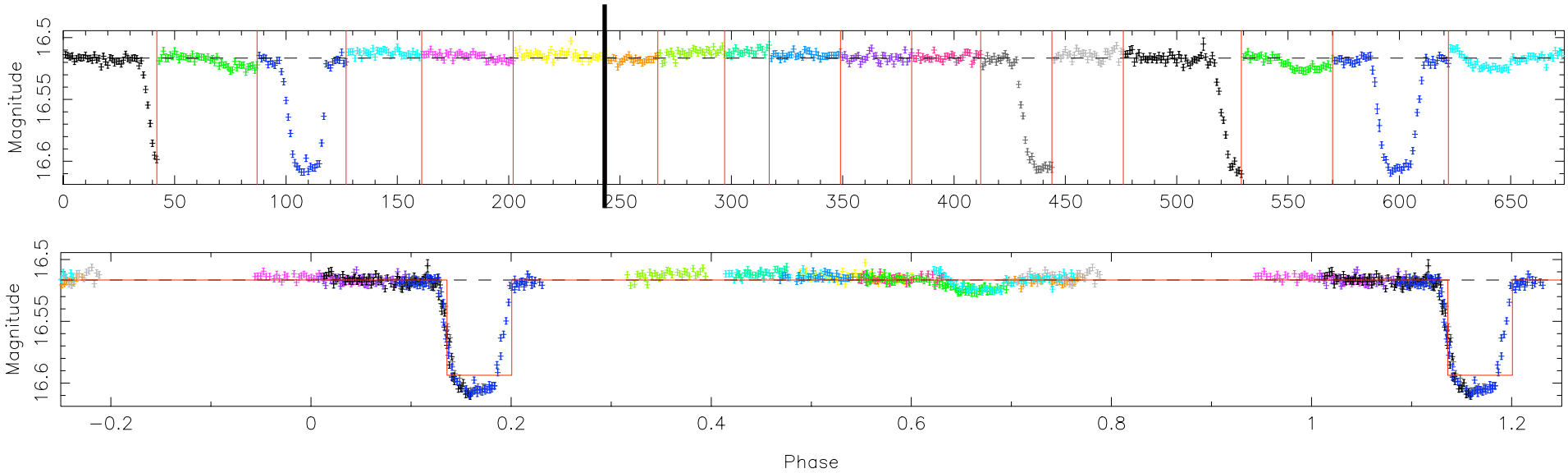
- 3 partial eclipses observed in 2004B INT data
- I = 13.82, V = 16.92, P = 2.65 days, dur = 0.2 days, depth = 6%
- Membership probability 99% (Hillenbrand 1997)
- Light curve displays out of eclipse variability typical of weak-line TTS
- One year later, follow-up photometry from NMSU 1m (courtesy J. Holzman) confirmed eclipses occurred at predicted times

ONC 1-295



- 2 partial eclipses observed in 2004B INT data
- I = 12.65, V = 15.12, P = 2.34 days, dur = 0.24 days, depth = 10%
- Membership probability 98%, SPT M2V, M ~0.2 $M_{\odot}$ (Hillebrand 1997)
- Light curve displays out of eclipse variability typical of weak-line TTS
- NMSU photometry confirmed eclipses occurred at predicted times

M50 2-3089



- 1 partial and 1 full eclipses observed in 2005A CTIO data
- Secondary eclipse (as well as more primaries) seen in second season
- I = 16.41, V = 17.64, P = 1.350 days, dur = 0.09 days, depths = 9 / 1.5%
- First guess at component masses from relative eclipse depths and apparent magnitudes: M_1~0.7 $M_\odot$, M_2~0.2 $M_\odot$ (Baraffe et al. 1998, 130 Myr).
- That would lead to K ~ 41 km/s.

Spectroscopy to date

Tel	Inst	Date	Region	Thanks	Object	No	Status
WHT	ISIS	11/05	Ca II IRT		ONC-1-290	2	reduced, RVs measured
					ONC-1-295	2	
					M50-2-3089	1	
Keck	NIRSPEC	01/06	J	E. Martin	ONC-1-290	1	reduced but no RV standards
VLT	ISAAC	02/06	J	G. Meeus M. McCaughrean	ONC-1-290	3	reduced, RVs measured
					ONC-1-295	2	
WHT	ISIS	02/06	Ca II IRT		ONC-1-290	1	reduced, RVs measured
					M50-2-3089	1	
Magellan	MIKE	02/06	Ca II IRT	A. Brandeker R. Jayawardhana	ONC-1-295	3	reduction in progress
					M50-2-3089	3	

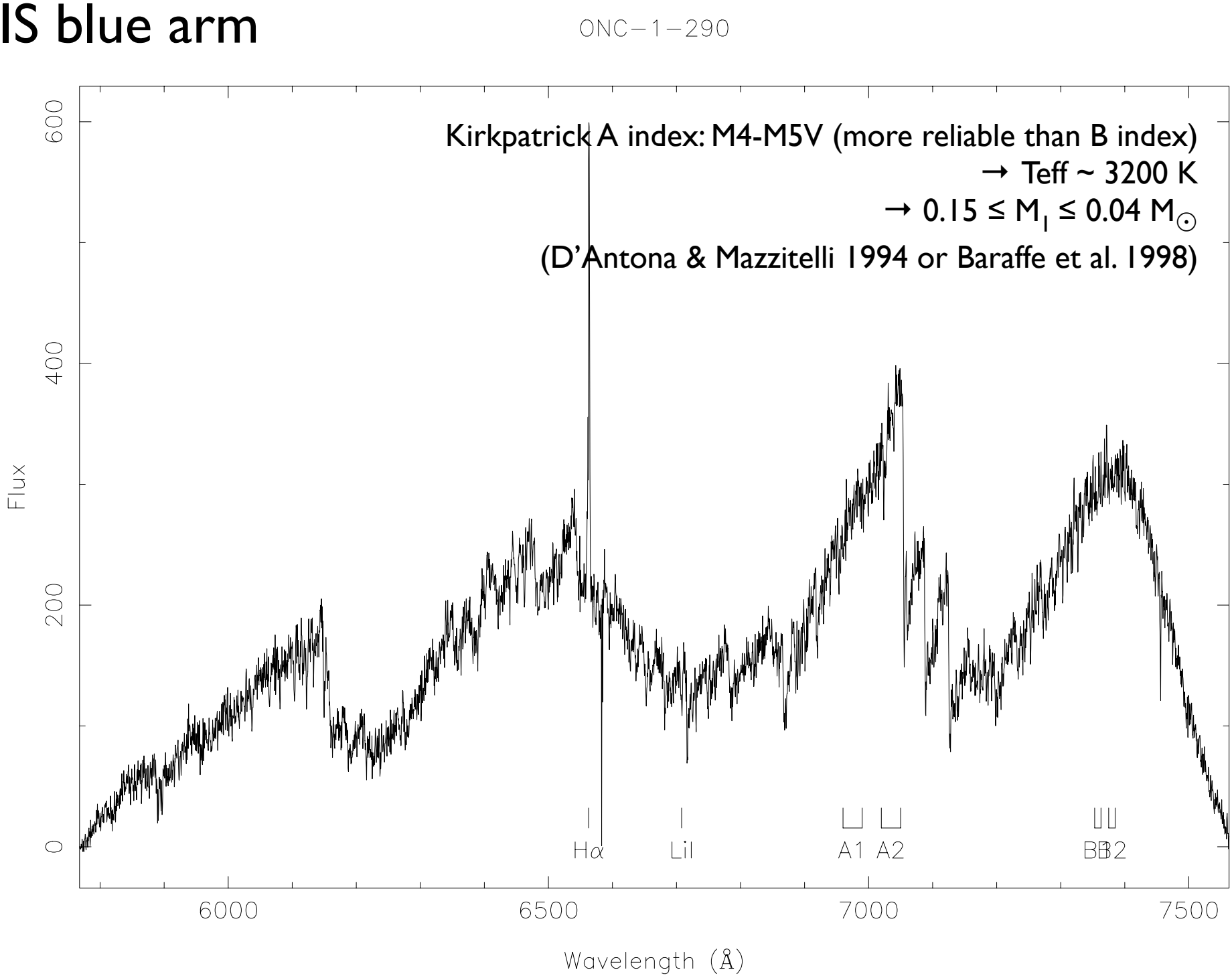
ISIS spectroscopy

- Red arm 8085-8075 A, R~5000
  - RV by cross-correlation across Ca II IRT region
  - Expect RV accuracy ~ 4 km/s for SNR~10
- Blue arm 5950-7350 A, R~2000
  - Youth indicators (Hα, Li I)
  - Kirkpatrick (1991) relative flux indices A & B → spectral classification to 0.5 spectral subclasses
- Data taken in poor conditions in both runs (seeing > 2", partial cloud cover)
- Arc and flat immediately after each science frame to minimise impact of flexure and fringing
- RV standards of similar spectral type to targets (early to mid M) observed in the same conditions in the same nights
- Reduction and RV measurements using standard IRAF tasks

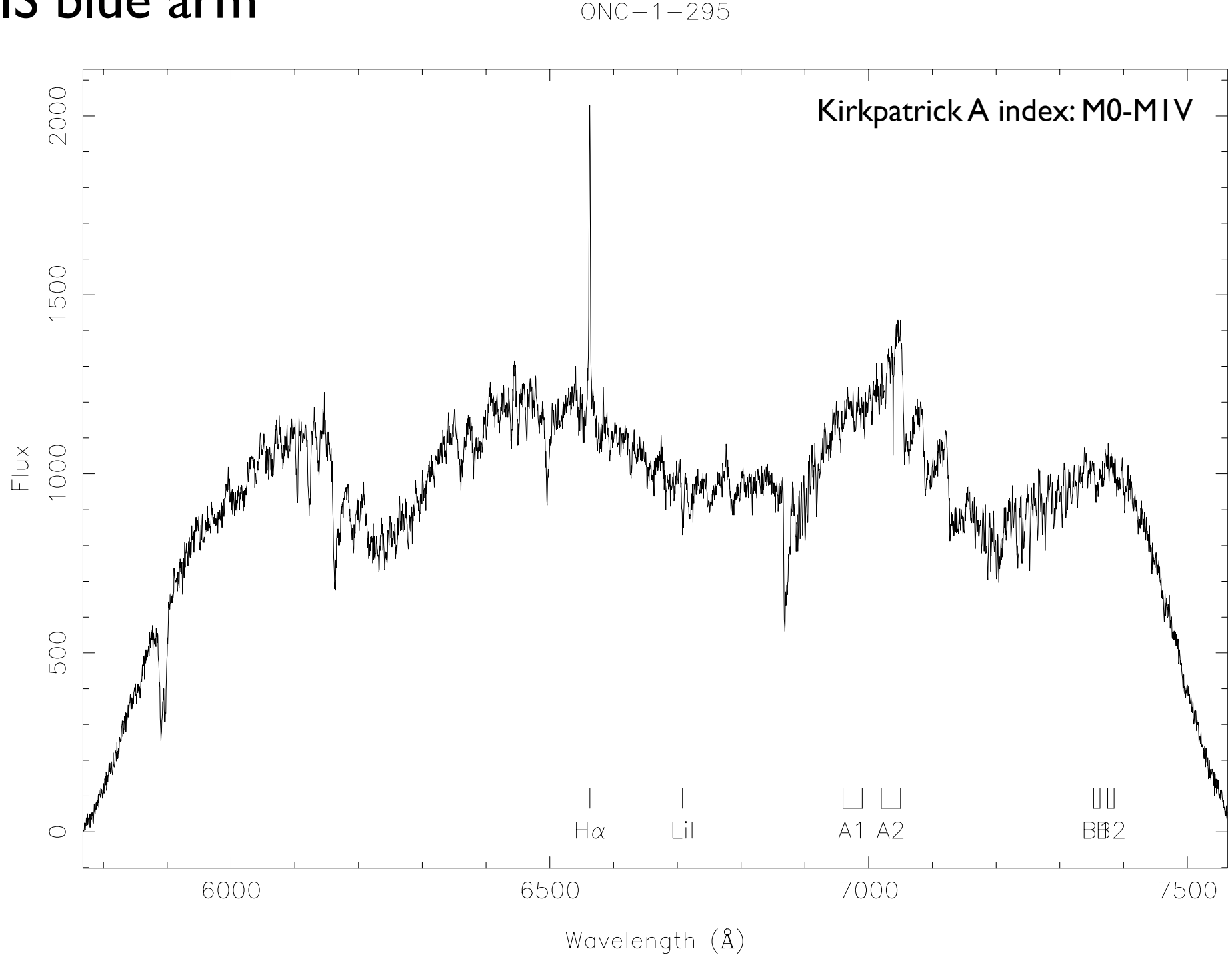
ISAAC spectroscopy

- Backup programme to spectroscopy of much fainter ONC objects
- Wavelength range 1.1293 - 1.1905 μm (telluric line contaminated)
- Resolution R~3500
- Observations taken in variable seeing
- RV by cross-correlation with simultaneously observed M-type RV standard
- Reduction and RV measurements using standard IRAF tasks

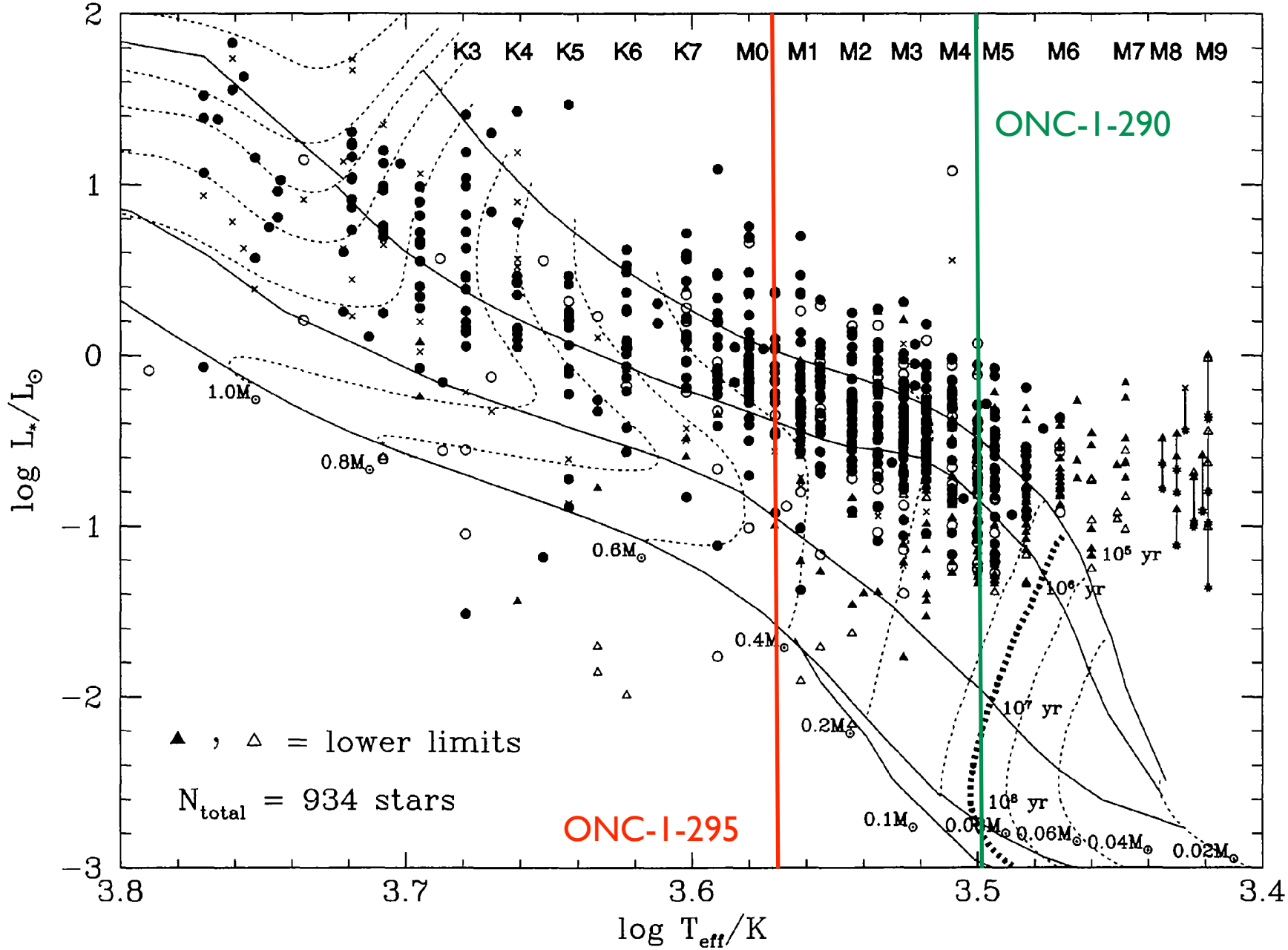
ISIS blue arm



ISIS blue arm



Hillenbrand (1997) HR diagram for the ONC, with
D'Antonella & Mazzitelli (1994) models

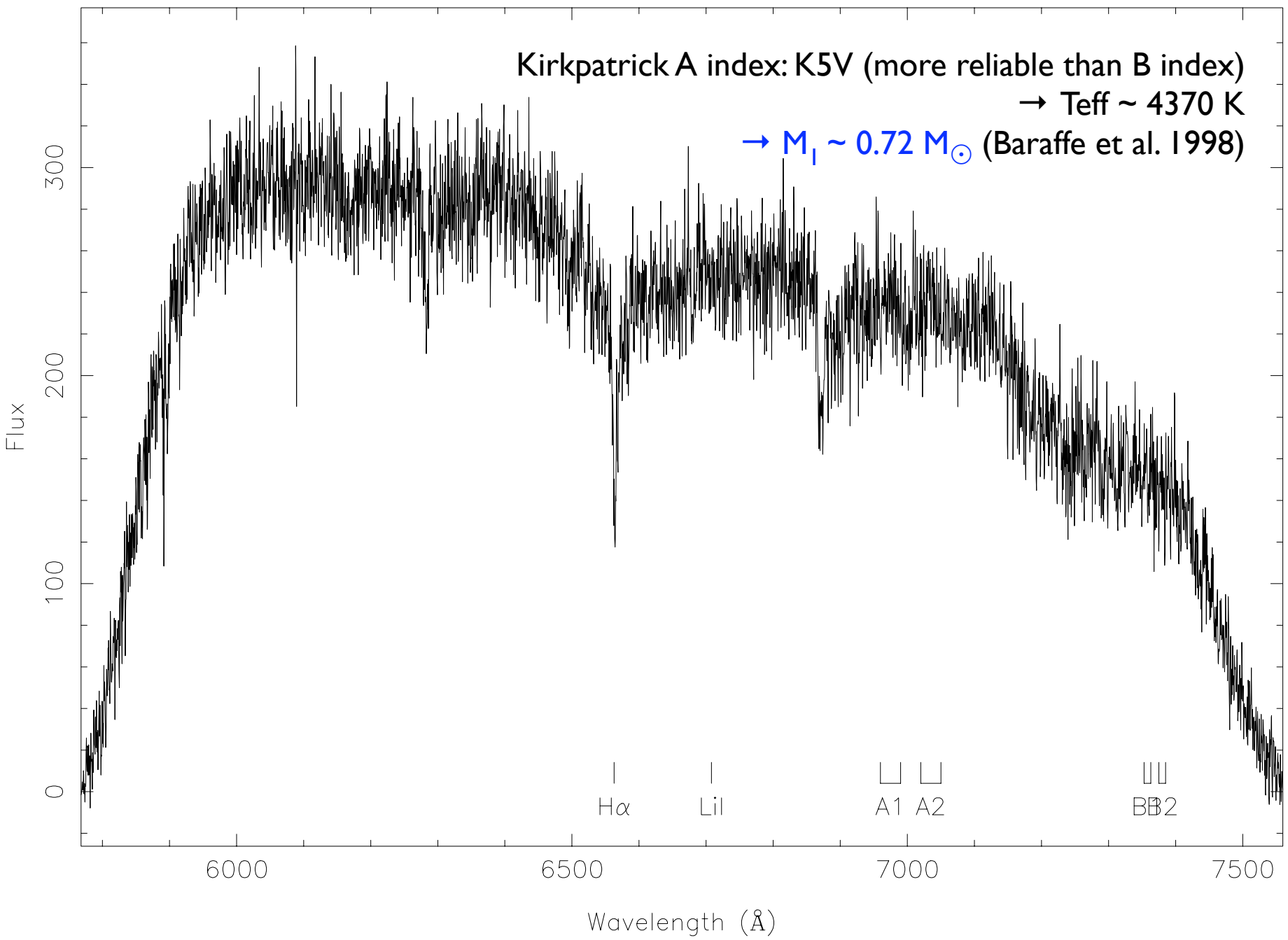


Bracket mass estimates between D'Antonella & Mazzitelli (1994) and Baraffe et al (1998) models

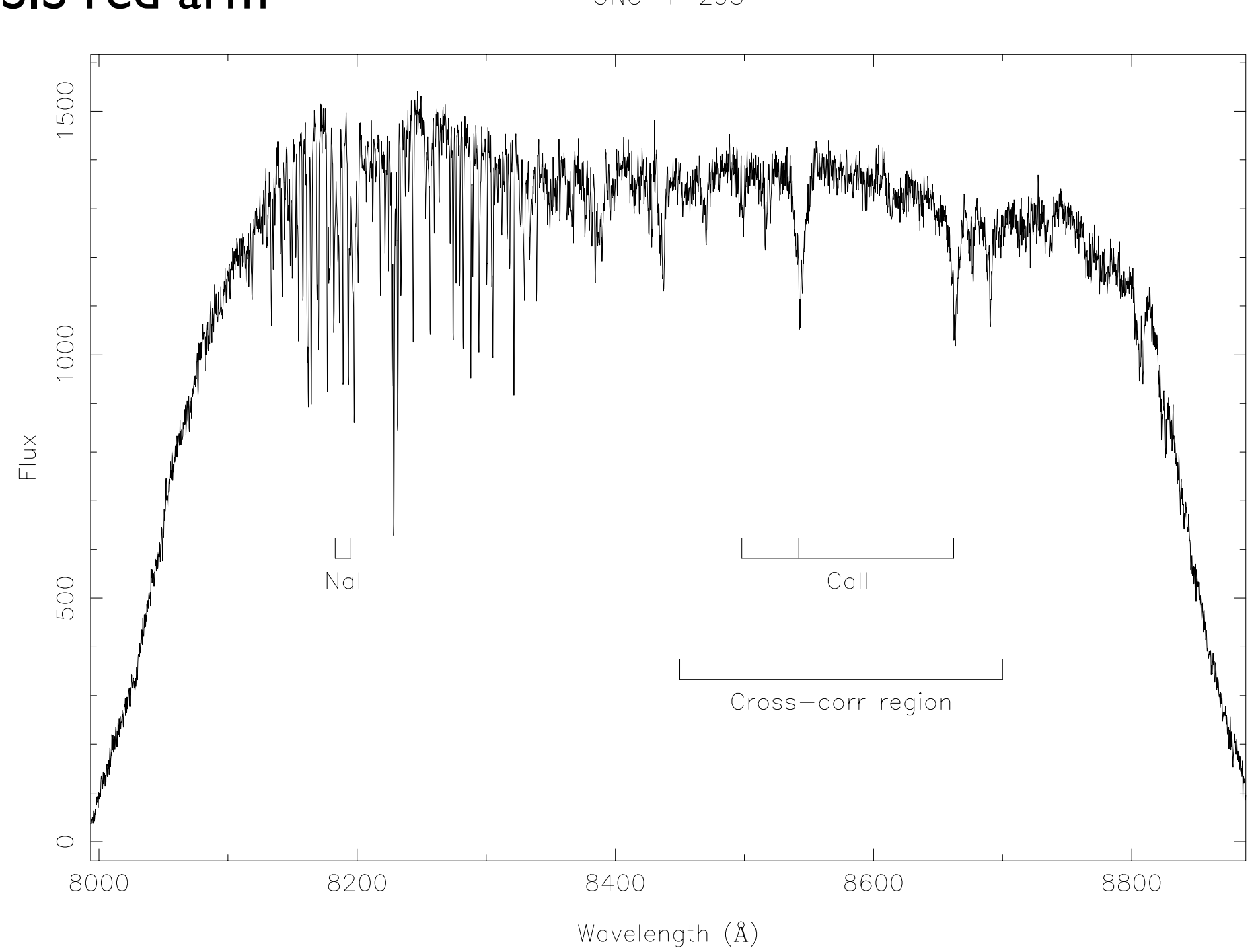
ONC-1-290: $0.15 \leq M_{\odot} \leq 0.25\ M_{\odot}$

ONC-1-295: $0.35 \leq M_{\odot} \leq 0.9\ M_{\odot}$

ISIS blue arm

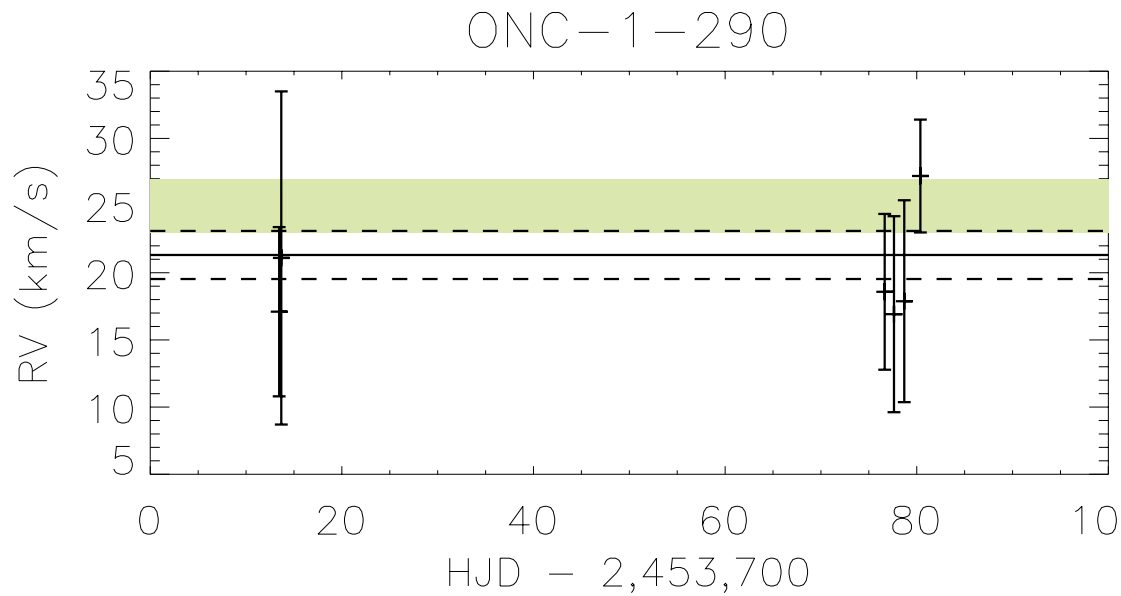


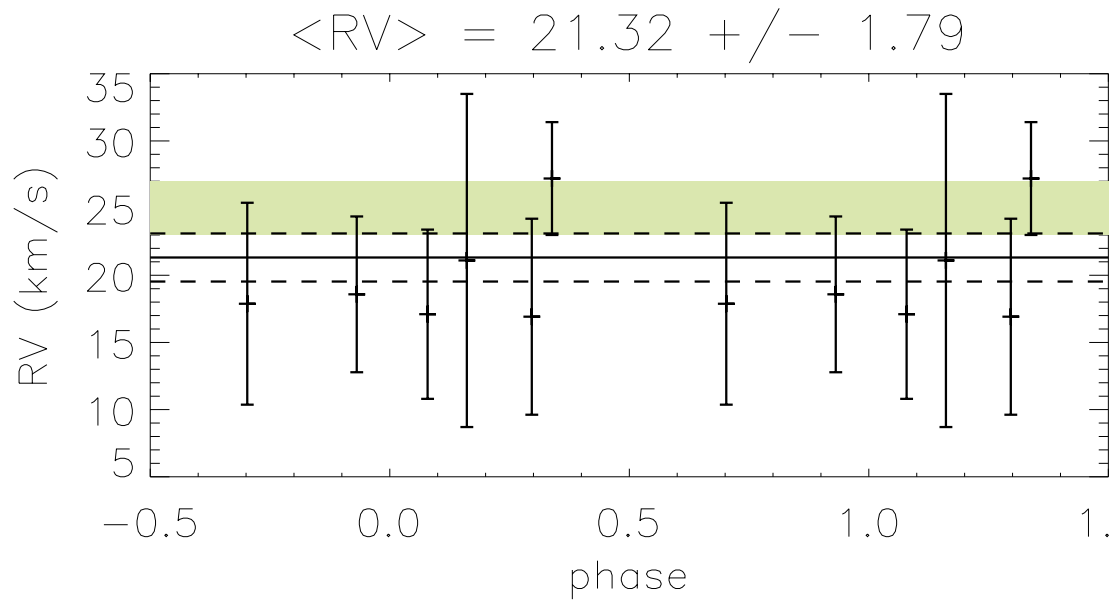
ISIS red arm


ONC−1−295
Flux
0
500
1000
1500
8000
8200
8400
8600
8800
Wavelength (Å)
NaI
CaII
Cross−corr region

ONC-1- 290 radial velocities

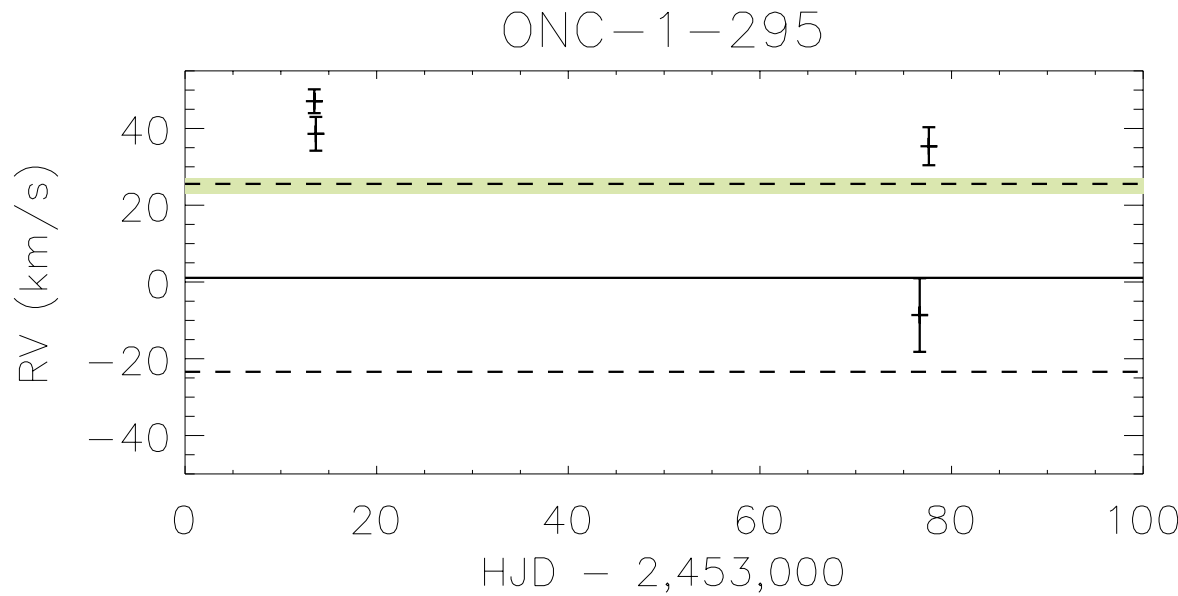
- No significant RV variations detected at the few km/s level
- Mean RV consistent with cluster RV of 25 ± 2 km/s (Sicilia-Aguilar 2005)
- If K ≤ 3 km/s then $M_2 \leq 0.04\ M_\odot$
- Companion is very likely a brown dwarf or planet
- Higher precision RV measurements are needed to constraint K and hence companion mass
- Dominant source of uncertainty may remain primary mass and radius

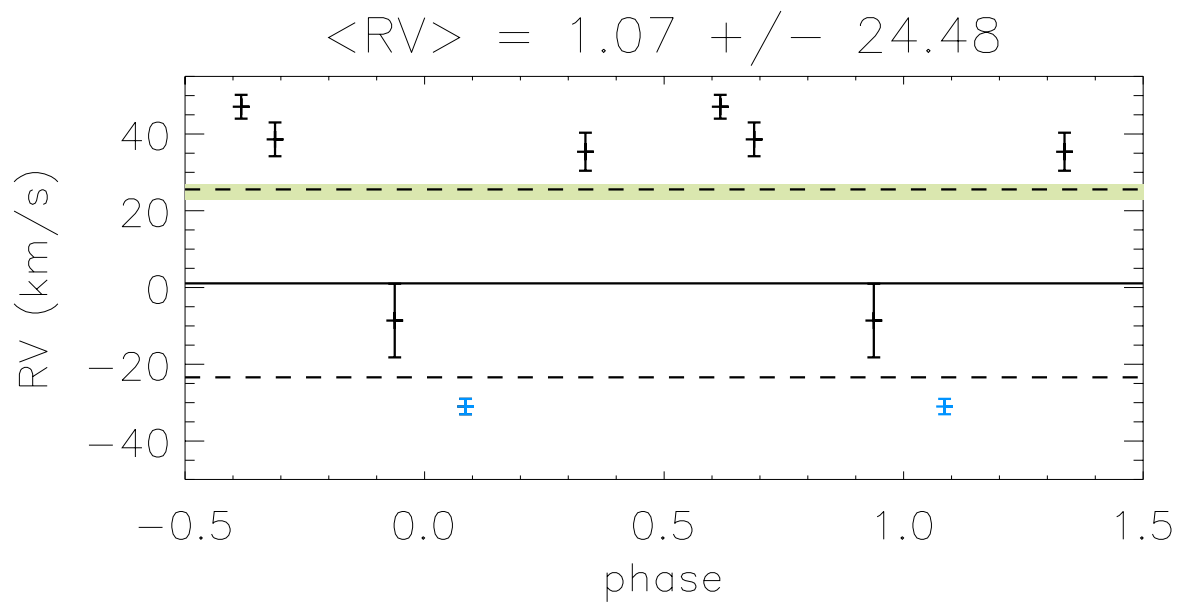




ONC-1-295 radial velocities

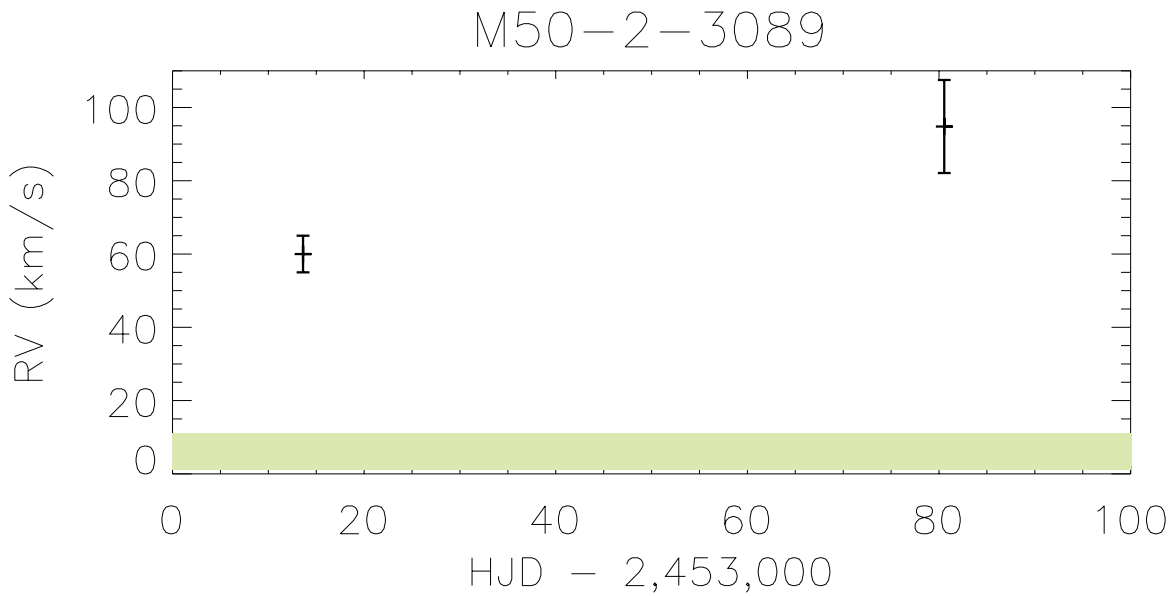
- 1 prior RV epoch from Sicilia-Aguilar (2005) for which we had to guestimate HJD
- Clear RV variations, K ≥ 40 km/s (27 without Sicilia-Aguilar data point)
- Companion is very likely an M dwarf
- To solve for both masses we would need:
  - Higher resolution spectra to separate the two sets of lines and dynamically constrain the masses
  - Observations of the secondary eclipses to measure relative surface brightness





M50-2-3089 radial velocities

- Only two data points, but significant RV variations already clearly detected
- Mean RV marginally consistent with cluster RV of 6 ± 5 km/s
- Need K ≥ 40 km/s for consistency with cluster RV
- Consistent with 0.7 + 0.2 $M_{\odot}$ system
- More data points needed

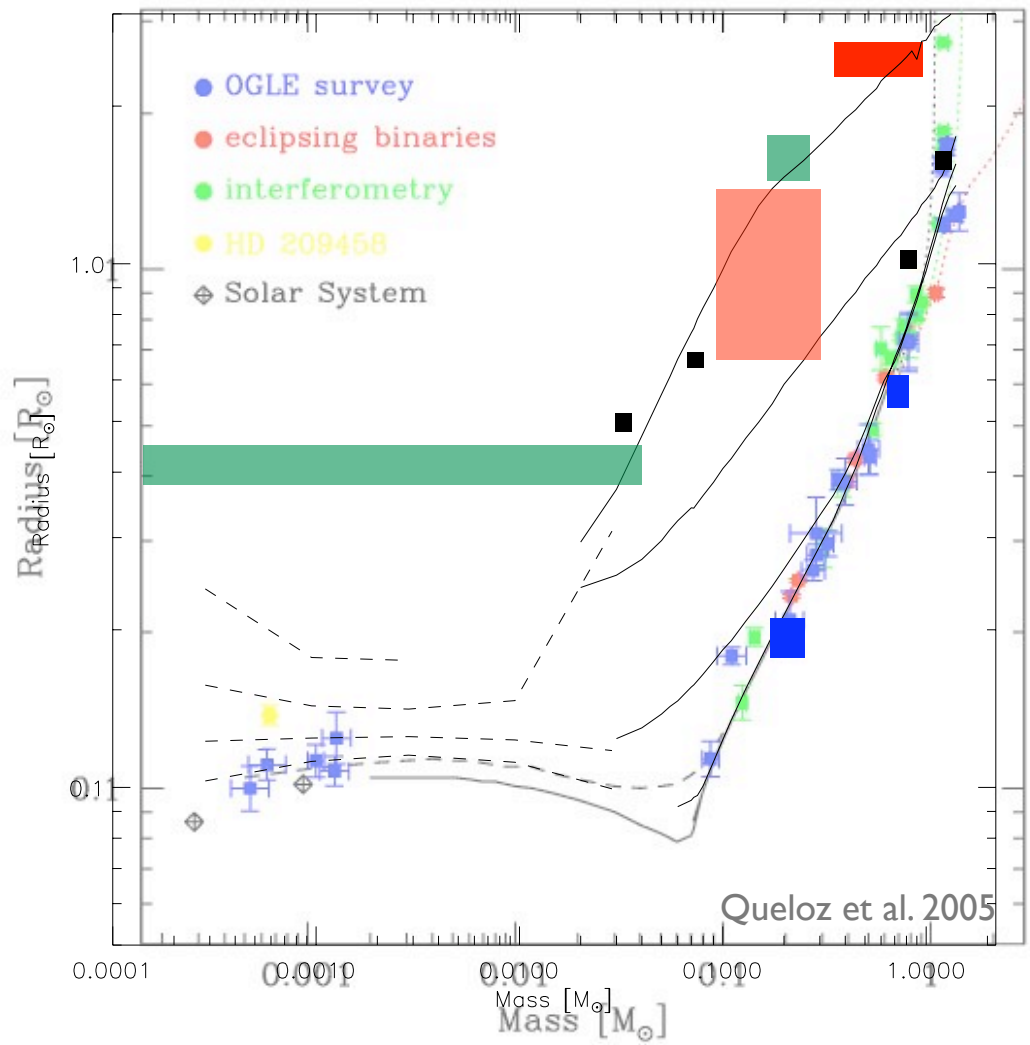


What can we say already?

- ONC-1-290
  - $0.15 \leq M_1 \leq 0.25\ M_\odot$
  - $1.6 \leq R_1 \leq 1.8\ R_\odot$ (from T_{eff} & L)
  - $M_2 \leq 0.04\ M_\odot$
  - $0.39 \leq R_2 \leq 0.44\ R_\odot$

- ONC-1-295
  - $0.35 \leq M_1 \leq 0.9\ M_\odot$
  - $2.3 \leq R_1 \leq 2.6\ R_\odot$
  - $M_2 \geq 0.1\ M_\odot$
  - $R_2 \geq 0.7\ R_\odot$

- M50-2-3089
  - $M_1 \sim 0.7\ M_\odot$
  - $R_1 \sim 0.6\ R_\odot$
  - $M_2 \sim 0.2\ M_\odot$
  - $R_2 \sim 0.18\ R_\odot$



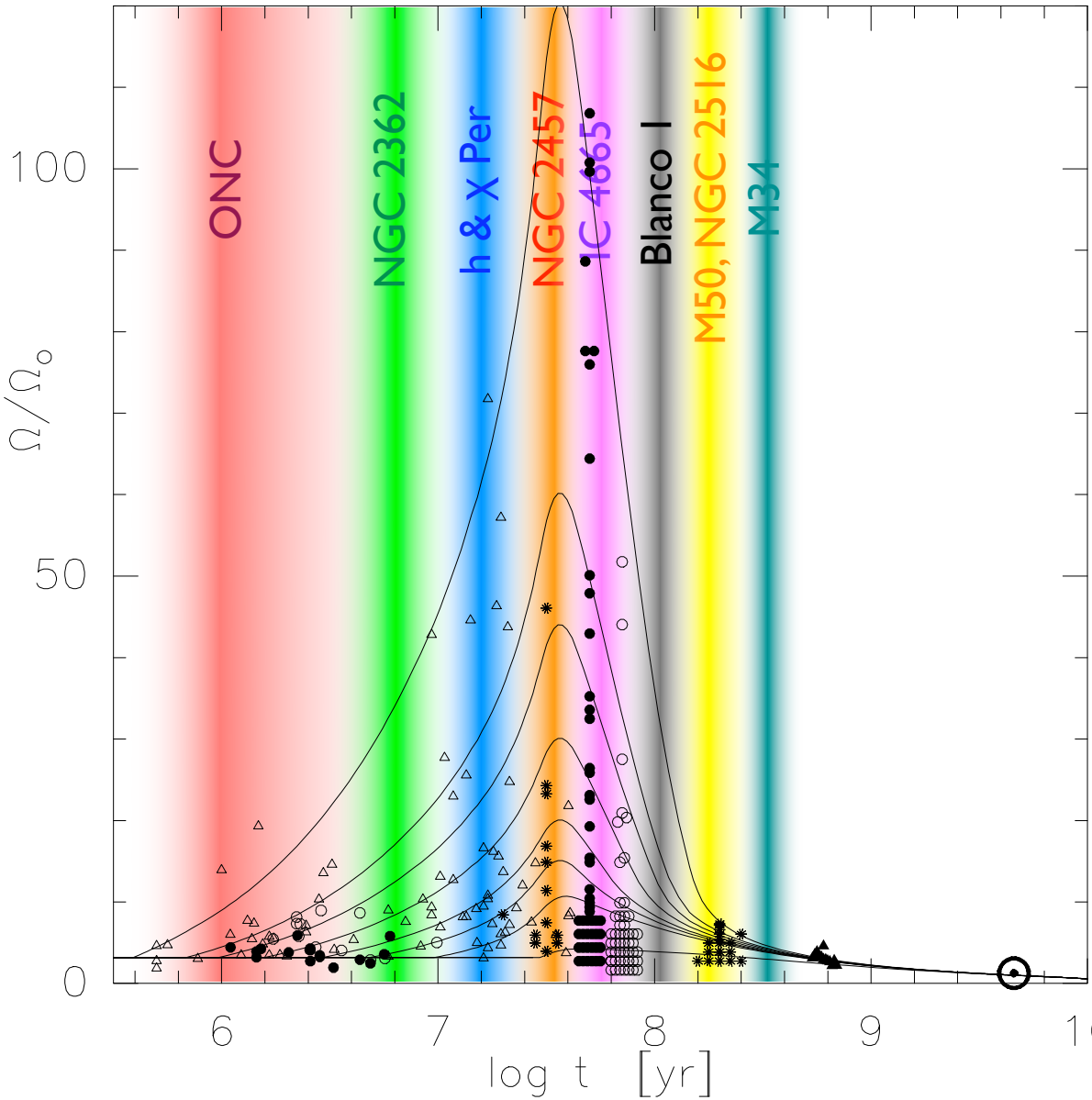
Eclipse candidates - the future

- Magellan data under reduction
- Simultaneous fit to light curve and RV curve under development
- Applied for medium- and high-dispersion spectroscopy in 2006B to follow-up existing set of candidates
- Additional photometric data recently obtained or soon to come on 4 more clusters
    - expect about same number of candidates again
- Will perform a-posteriori evaluation of detection limits for each cluster by injecting fake events into real light curves
    - deduce (limits on) companion incidence

Summary

- Monitor is the first dedicated transit survey in young open clusters. It will
  - measure the PMS mass-radius relation from M dwarfs to exoplanets
  - (hopefully) provide constraints on planet formation and migration timescales
- Well honed data reduction and analysis pipeline in place, though further improvements may be made (e.g. DIA)
- 25 candidates are currently under follow-up, more to come
- Early results can already be compared to theory, though more data is needed for firm constraints

Rotation periods



Monitor target clusters cover the entire evolutionary sequence up to the early MS

In the TTauri phase, examine link between rotation and presence of disks

Will also reach down to the BD regime, where the star-disk connection may be altered

Will cover in detail the ZAMS phase, which is crucial for constraining spin-down models

First rotation analysis, in M34, completed: 104 periods detected (Irwin et al., submitted to MNRAS)