Low-mass Stars in Synoptic Surveys

www.sdss3.org

RHK Conference

Cullen Blake

Outline

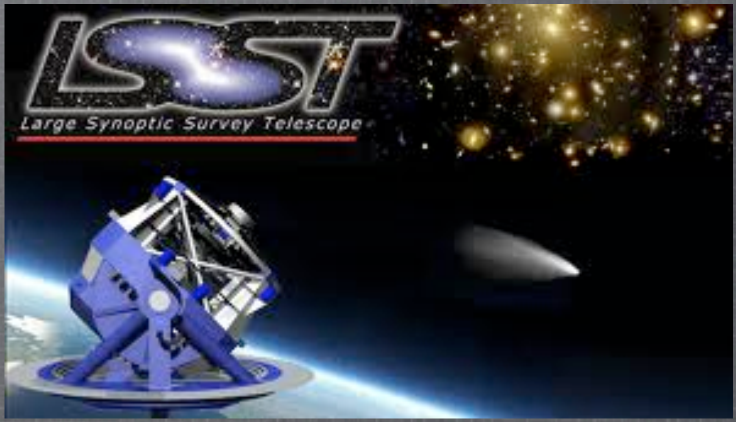
time domain Data:
A powerful tool for studying low-mass stars

- Double-lined Eclipsing Binaries
  - Stellar Masses and Radii
- Statistical Properties of Binaries
  - Formation history

Synoptic Surveys:
Astronomy in the time Domain

Pan-STARRS

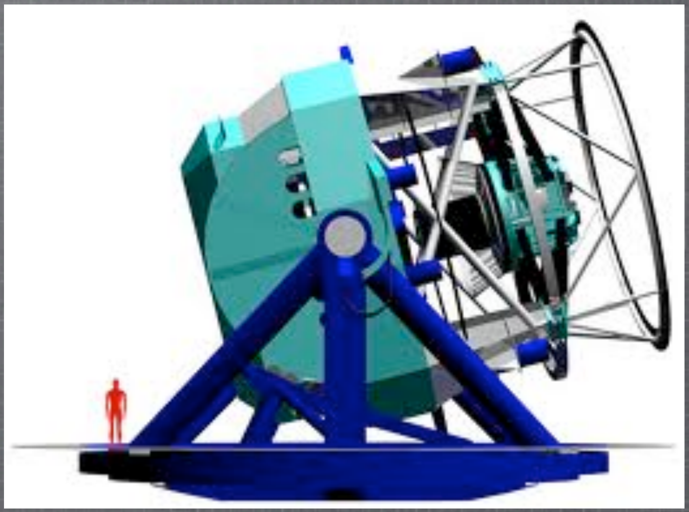
Imaging:
2 TB/night of data
g,r,i,z,y filters
30,000 □°
10 visits/filter
r<22



Imaging:
10 TB/night of data
u,g,r,i,z,y filters
18,000 □°
200 visits/filter
r<24.5

Wide-Ranging Science

LSST



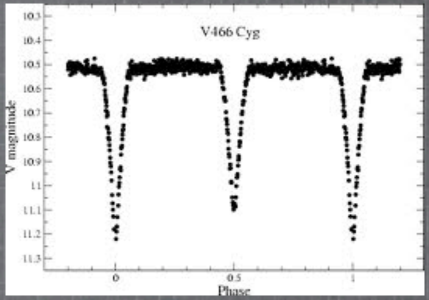
- Solar System Objects
- Active Galactic Nuclei
- Gamma Ray Bursts
- Supernovae
- Micro, Weak, and Strong Lensing
- Exotic Phenomena (we haven't thought of yet!)
- Stellar Variability

Astro-2010 Report

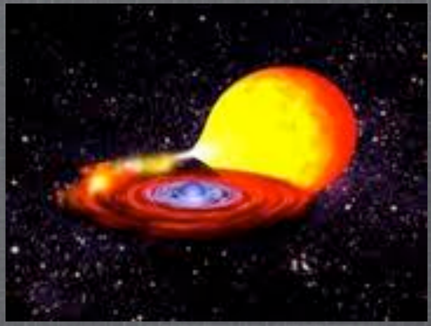
Large-Scale Ground-Based Initiatives		
Priority	Recommendation	Description
1	Large Synoptic Survey Telescope (LSST)	A wide-field optical survey telescope that will transform our observation of the variable universe and will address broad questions from indicating the nature of dark energy to determining whether there are objects that may collide with Earth.

Stellar Variability

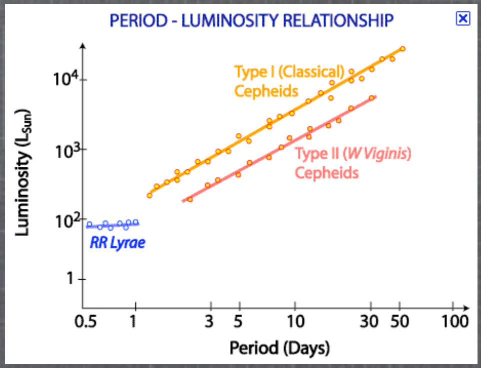
- Stellar Astrophysics:
  - Activity, Pulsations, Binary Stars



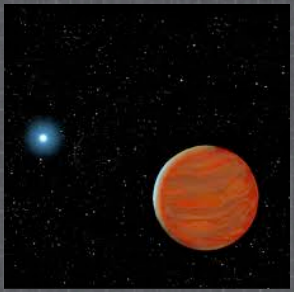
- Accretion Physics and Compact Objects:
  - Dwarf Novae, CVs



- Galactic Structure:
  - RR Lyrae, Cepheids



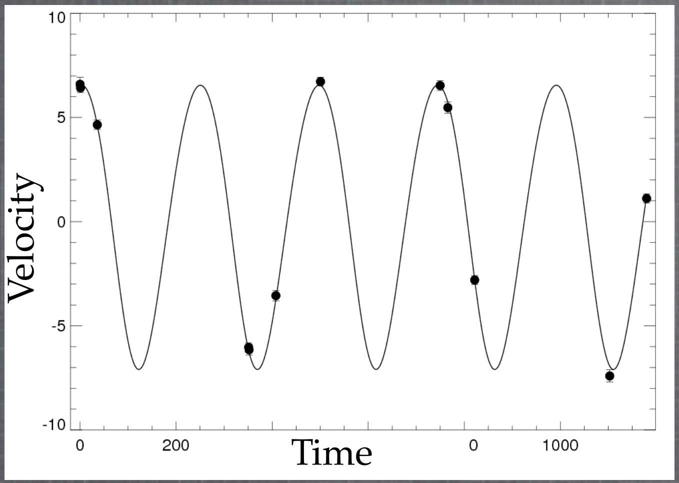
- Nearby Objects:
  - Brown Dwarfs, White Dwarfs



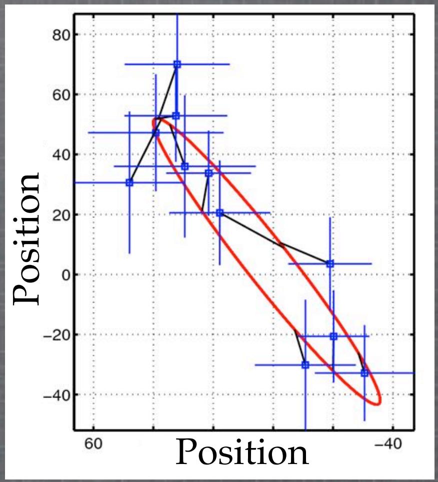
Stellar Astrophysics

Binary systems enable direct measurements of the physical properties of stars

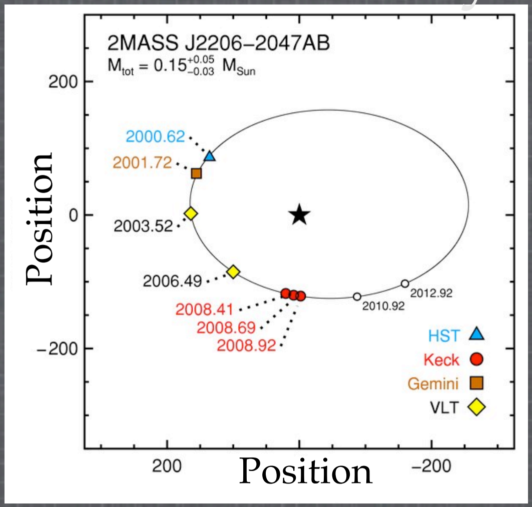
Spectroscopic Binary



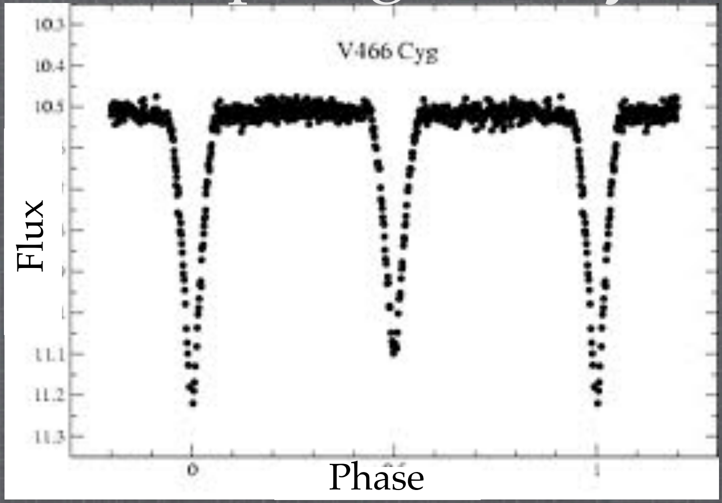
Astrometric Binary



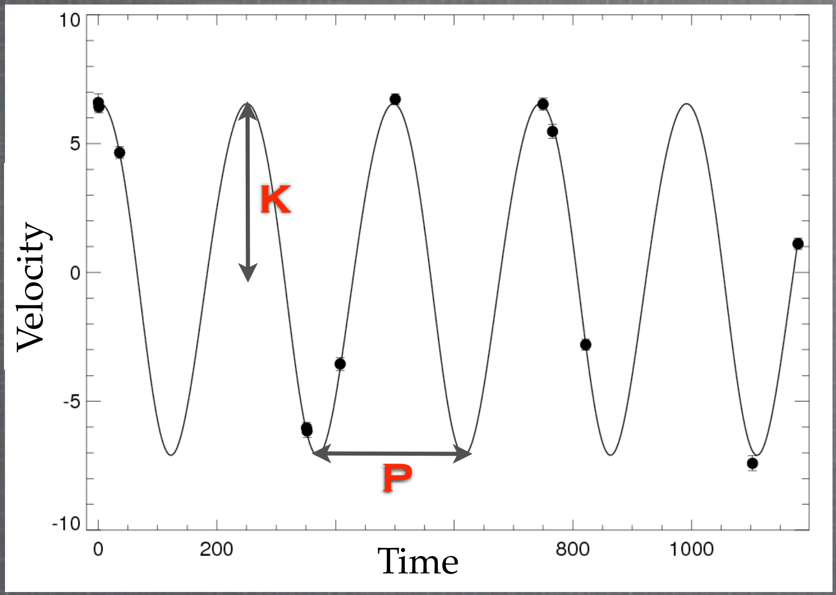
Visual Binary



Eclipsing Binary



Spectroscopic Binary Stars



Kepler's law

$$\left(\frac{2\pi}{P}\right)^2 a_1^{\ 3} = \frac{M_2^{\ 3}}{(M_1 + M_2)^2}$$

Momentum conservation

$$K_1 = \frac{2\pi a_1 \sin(i)}{P\sqrt{1-e^2}}$$

Single-Lined (SB1): Mass function

$$M_2 \sin(i) = C \times (M_1 + M_2)^{2/3}$$

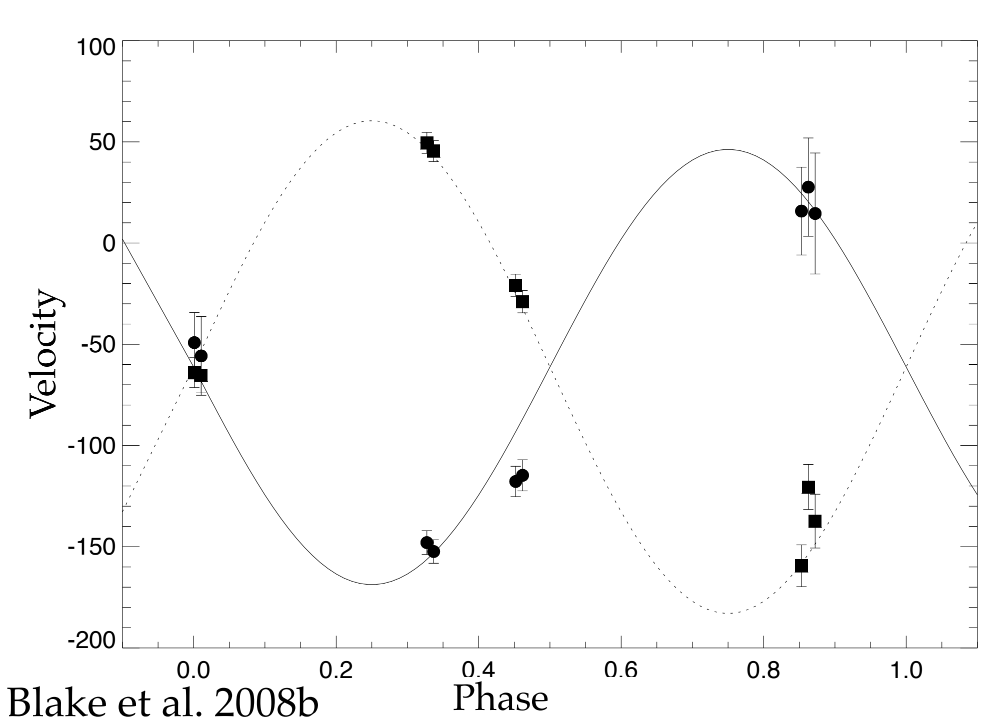
Double-Lined (SB2): Mass + Luminosity ratios

$$M_1 \sin(i)^3 = C \times PK_2\left(1-e^2\right)^{3/2}\left(K_1 + K_2\right)^2$$

$$\frac{M_1}{M_2} = \frac{K_2}{K_1}$$

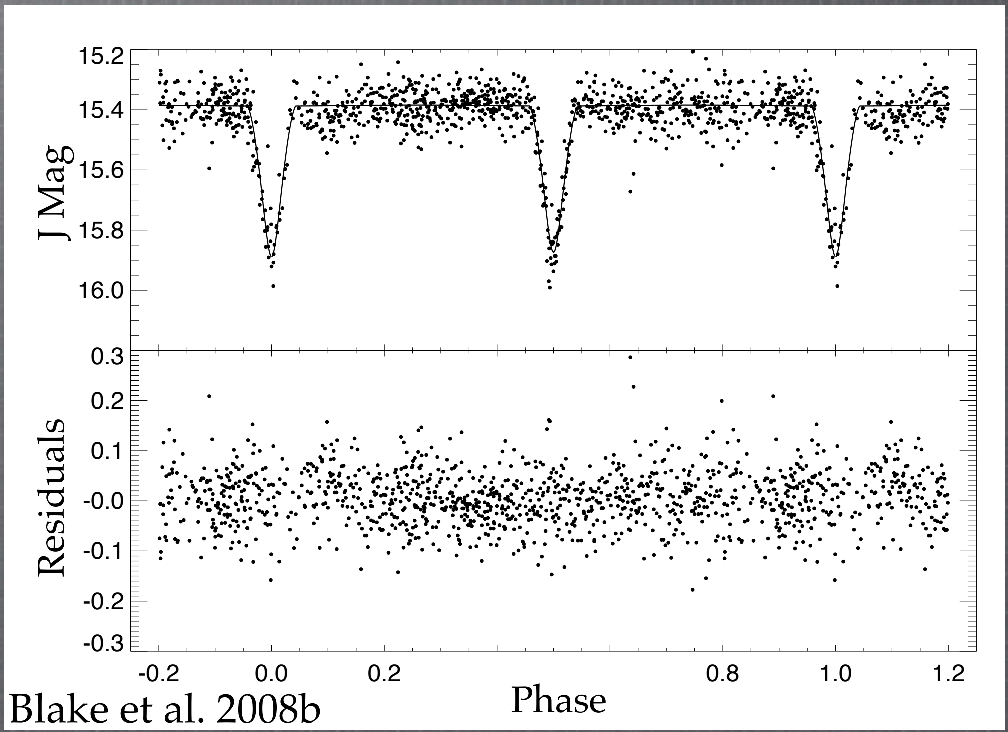
Double-Lined Eclipsing Binaries

Spectroscopy



Velocities of both stars

Photometry



Inclination and Radii

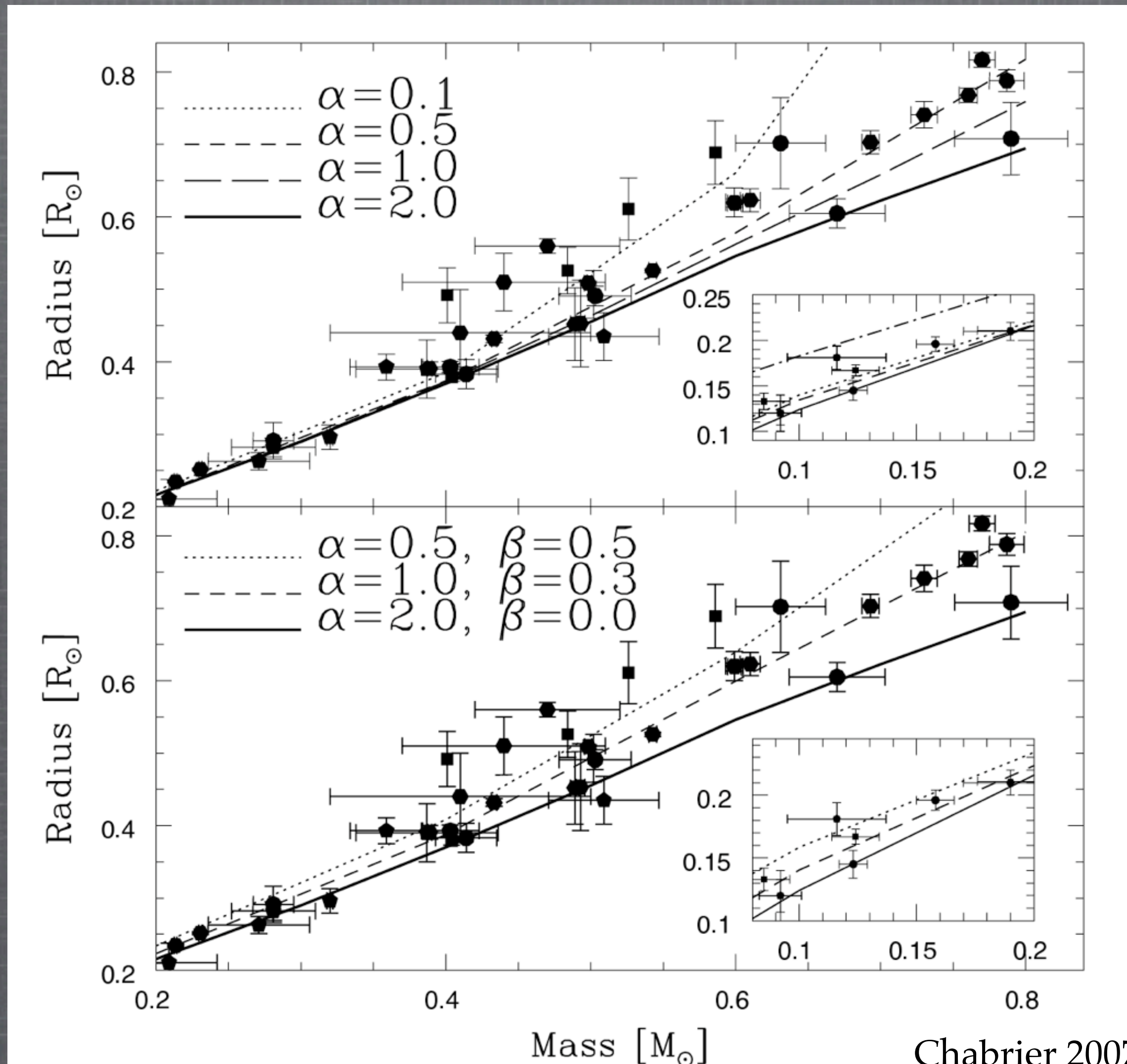
<u>when Combined: Masses and Radii</u>

bedrock of stellar astrophysics!

Theoretical Expectations: Missing Physics?

α: mixing length

β: spot coverage



Chabrier 2007

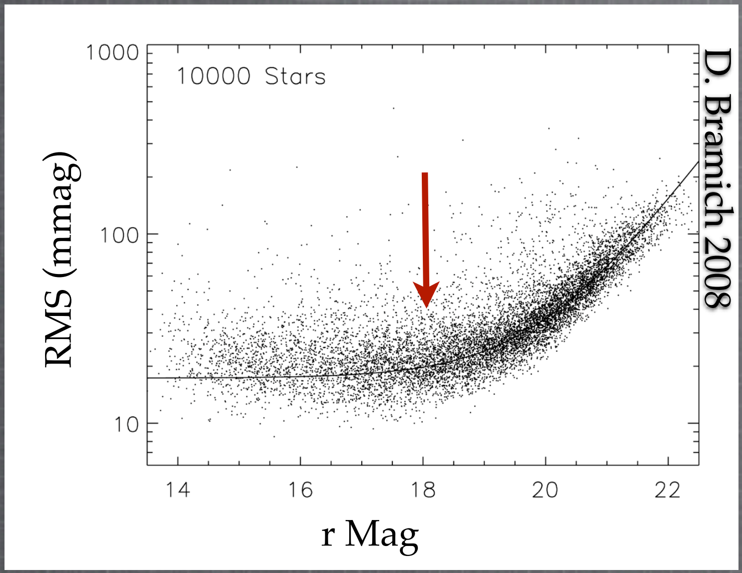
significant scatter in observed M-R relation

Synoptic Surveys to the Rescue

- Problem 1: Do stellar interactions bias radii?
  - Probability of eclipse $\propto 1/a$
  - If $\Delta R \propto 1/a^N \rightarrow$ biased toward big stars
- Solution: Find long-period eclipsing Systems
- Problem 2: Small number of M and R measurements
- Solution: Monitor large number of stars!

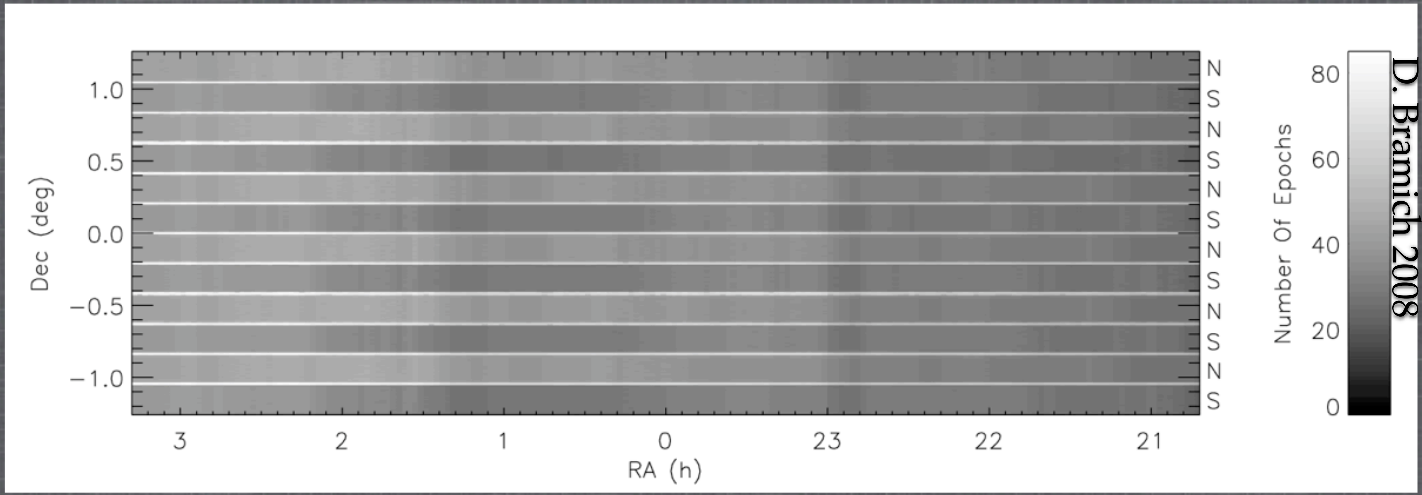
Surveys like LSST address both issues

SDSS Stripe 82 - A Testbed



- 250 square degrees
- up to 100 visits over 9 years
- Near-simultaneous *u,g,r,i,z*
- +/- 0.02 mag at *r*=18
- 4 million objects

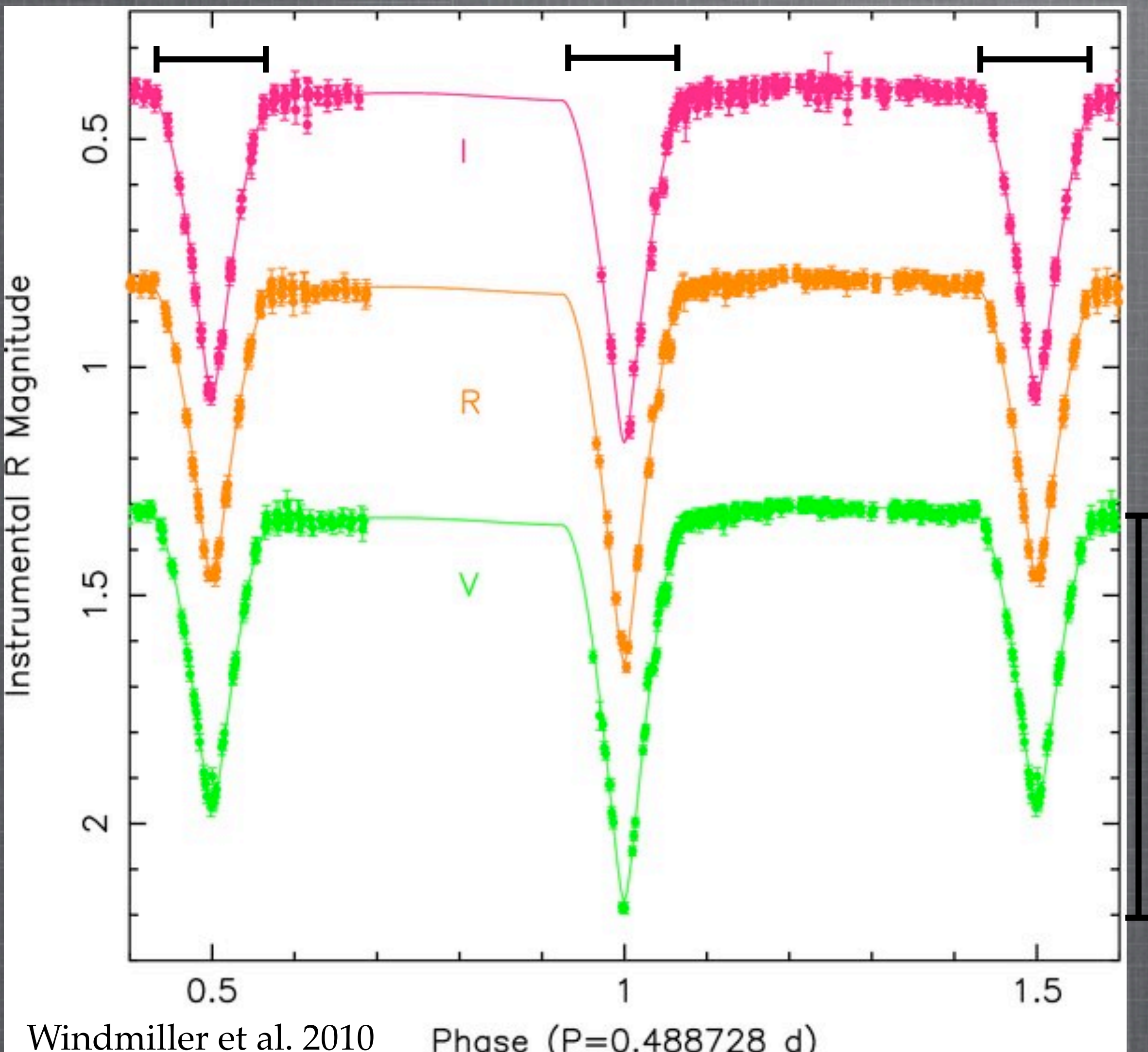
S82 Coverage



See: Ivezić et al. (2007), Bramich et al. (2008), Sako et al. (2008)

Big signals, Sparse Data

Typical Eclipsing Binary



Windmiller et al. 2010

Eclipse Duty Cycle:

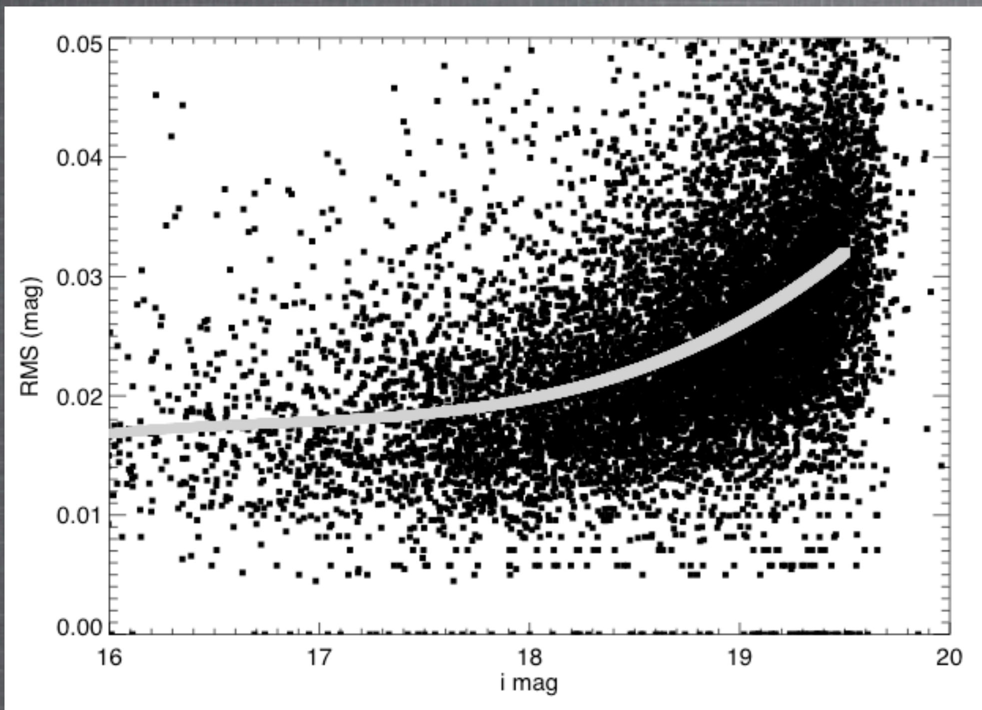
up to few 10s of %

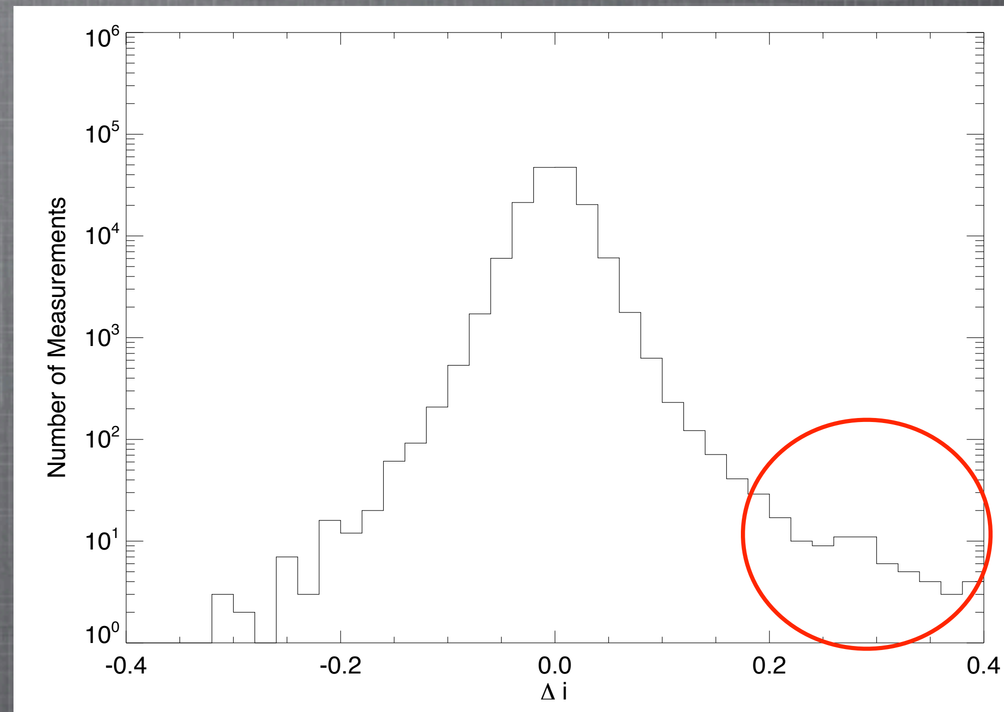
Eclipse Amplitude:

up to 0.75 mag

candidates identifiable with just a few observations?

Relative Photometry





$\sigma(i)$=25 mmag at i=19

Non-Gaussian Tails

11,000 mid- to late-M stars

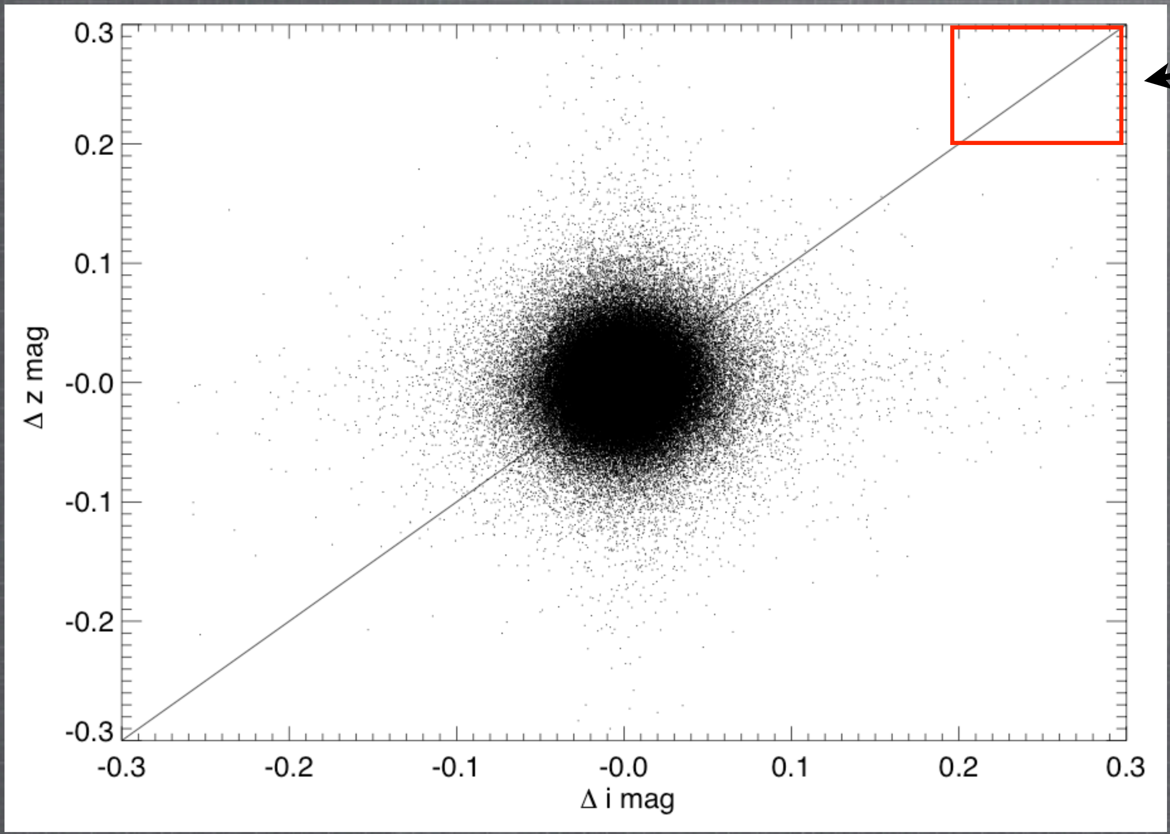
False Alarm Probability of $\Delta i > 0.2$: ~10^{-3}

Expected rate of eclipsing systems: 10^{-4}

Eclipse Signals

- Eclipses are achromatic: $\Delta z \sim \Delta i \sim \Delta r$

Eclipse Candidates



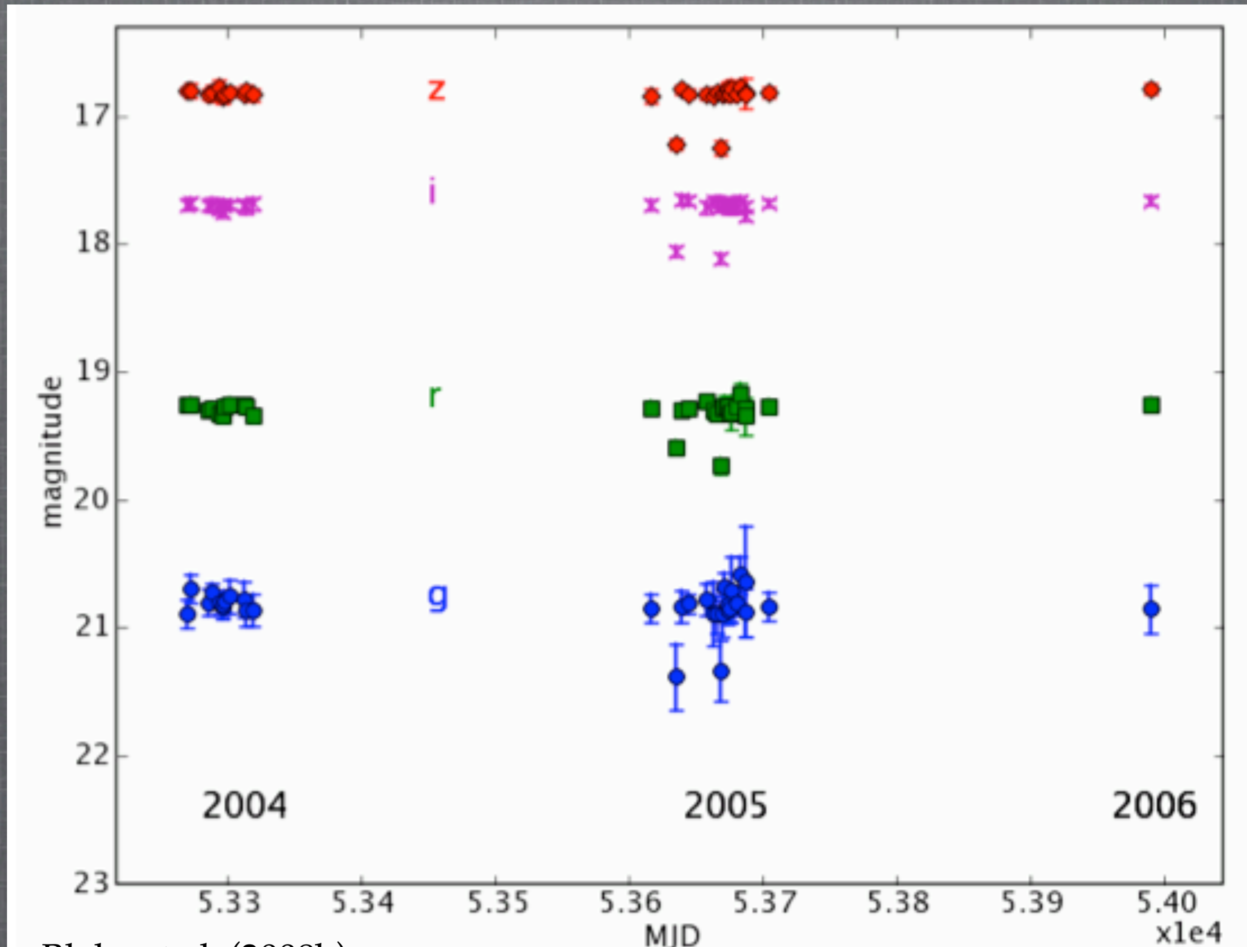
<u>Using All Three Bands</u>

FAP<10^{-9}?

Δi vs. Δz correlation

Candidate Selection

SDSS-MEB-1



Blake et al. (2008b)

0.4 mag

Simple Selection Criteria: $\Delta z \sim \Delta i \sim \Delta r > 0.2$ mag

See also Becker et al. (2008,2011); Bhatti et al. (2010)

Followup Challenge

Masses and Radii at i=18:
Expensive photometry+spectroscopy

- 100 1% photometric points:
  - 25 hours on 1-2 m telescope

- 10 moderate-resolution spectra:
  - 10 hours on 8 meter telescope

PAIRITEL
PETERS AUTOMATED INFRARED IMAGING TELESCOPE

- Former 2MASS telescope
- Mt. Hopkins, AZ
- 1.3 m - fully robotic
- Simultaneous JHK imaging
- PAIRITEL Automation Team:
  - J. Bloom (PI)
  - C. Blake
  - D. Starr
  - W. Peters

CfA

VE RI TAS HARVARD

UNIVERSITY OF CALIFORNIA, BERKELEY Cal

Real-Time Scheduling

MySQL Database

1000s of observations
100s of objects
10s of projects

Scheduling Algorithm

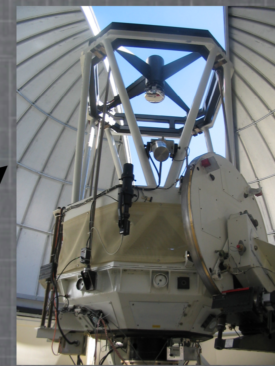
airmass **priority**
weather
moon
ephemeris

Control PC

Weather/clouds

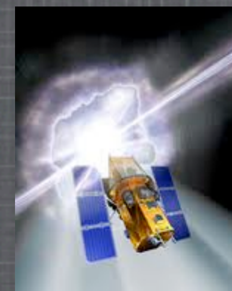
VAISALA

PAIRITEL



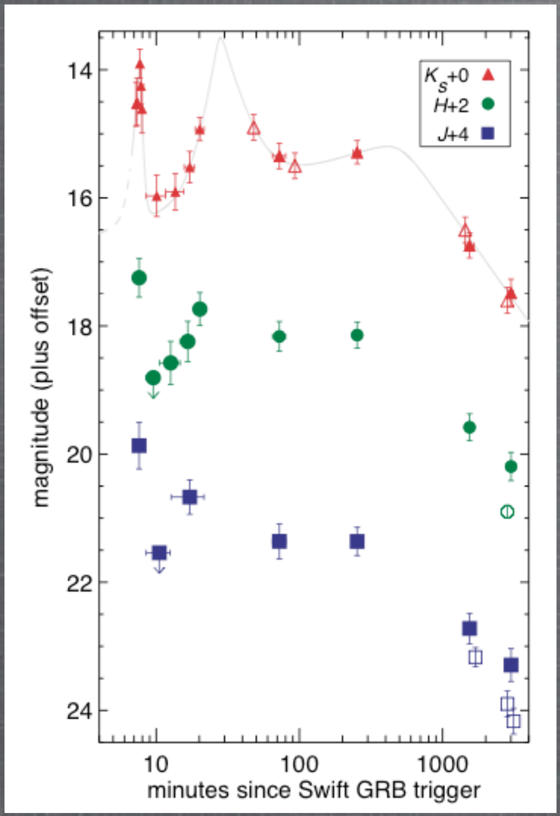
Data Reduction

GRB Alerts



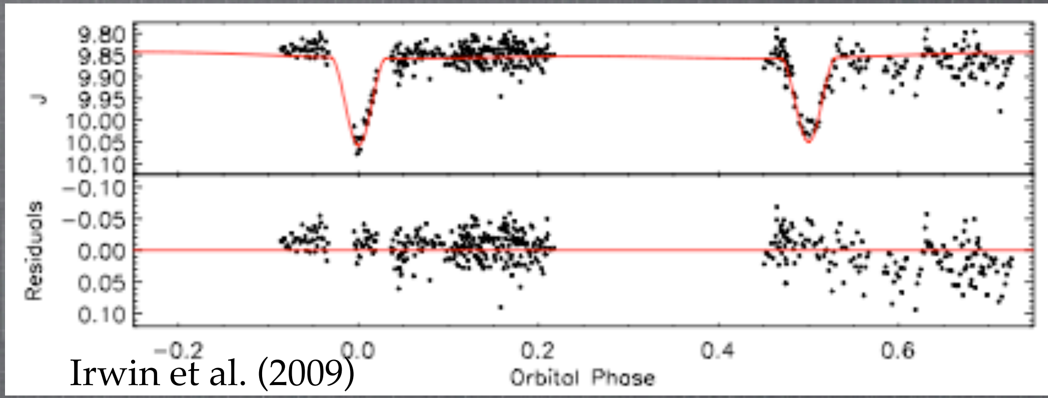
PAIRITEL Science

GRBs



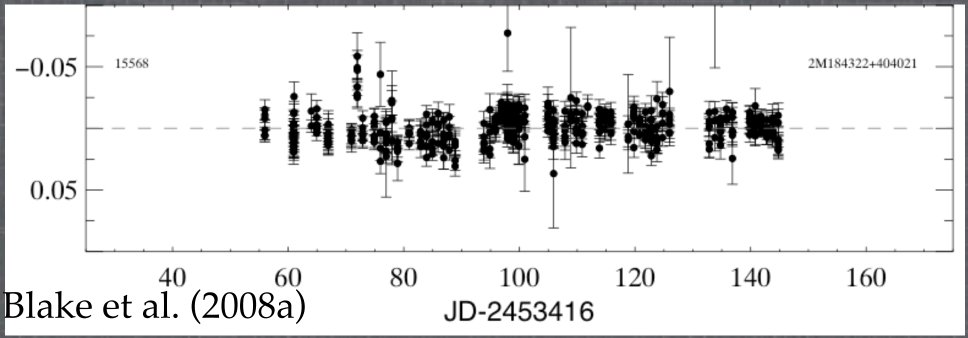
Blake et al. *Nature* (2005)

Eclipsing Binaries



Irwin et al. (2009)

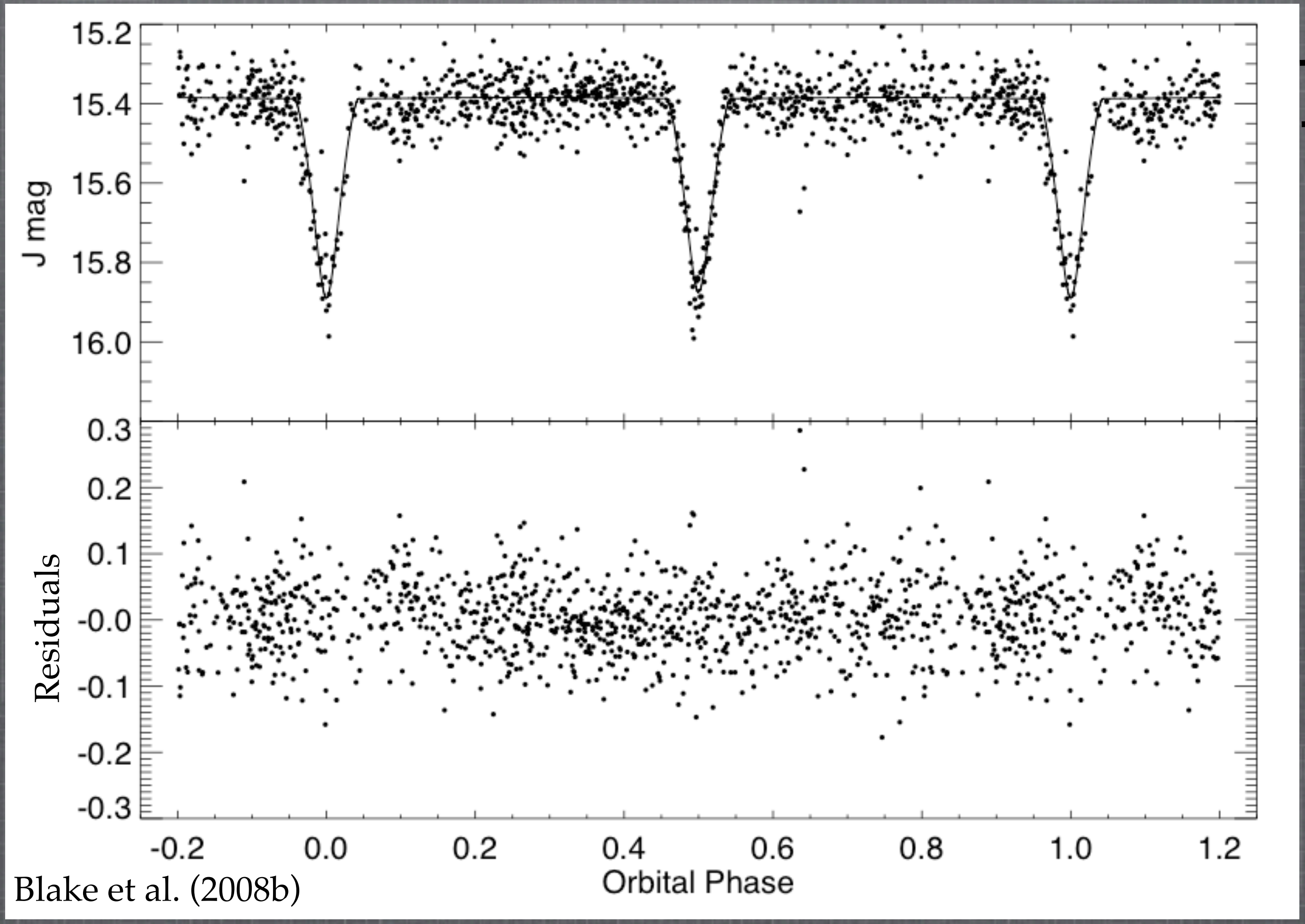
L Dwarf Transit Search



Blake et al. (2008a)

PAIRITEL Photometry

SDSS-MEB-1

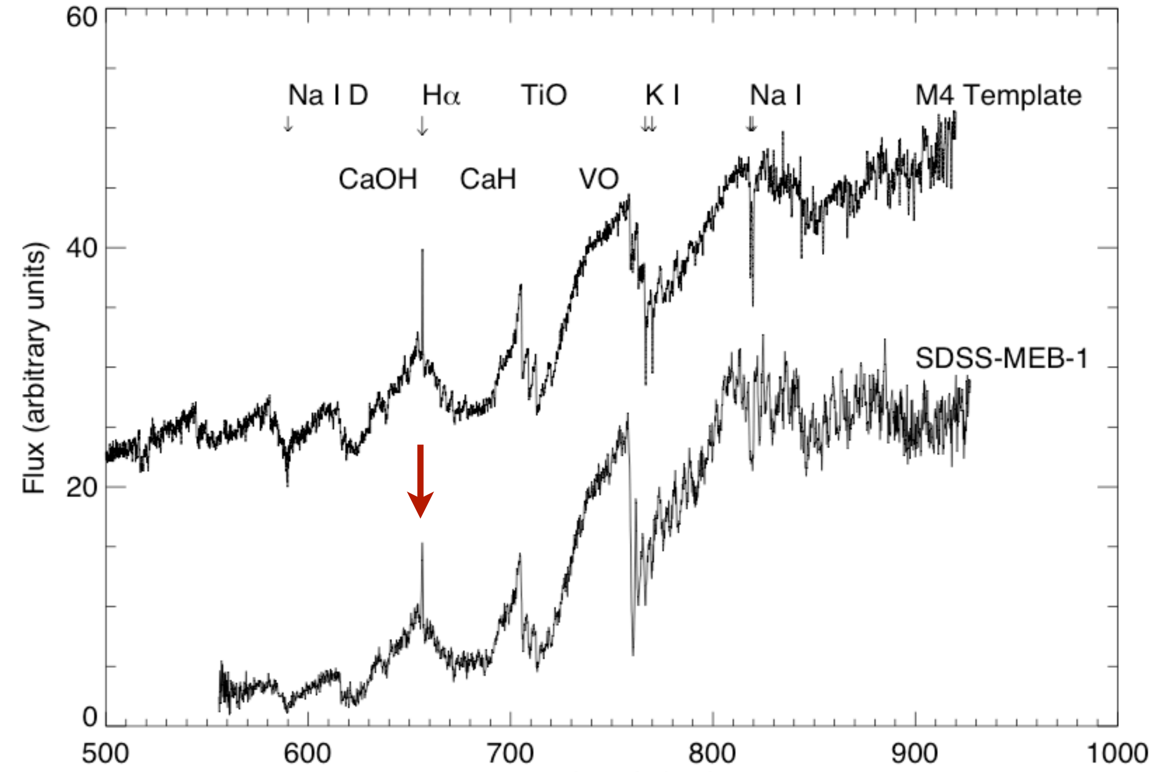


- 1000 individual observations over 30 days
- Period = 0.41 days

Radial Velocities

Radial Velocities required to get masses

Resolving lines of both stars challenging

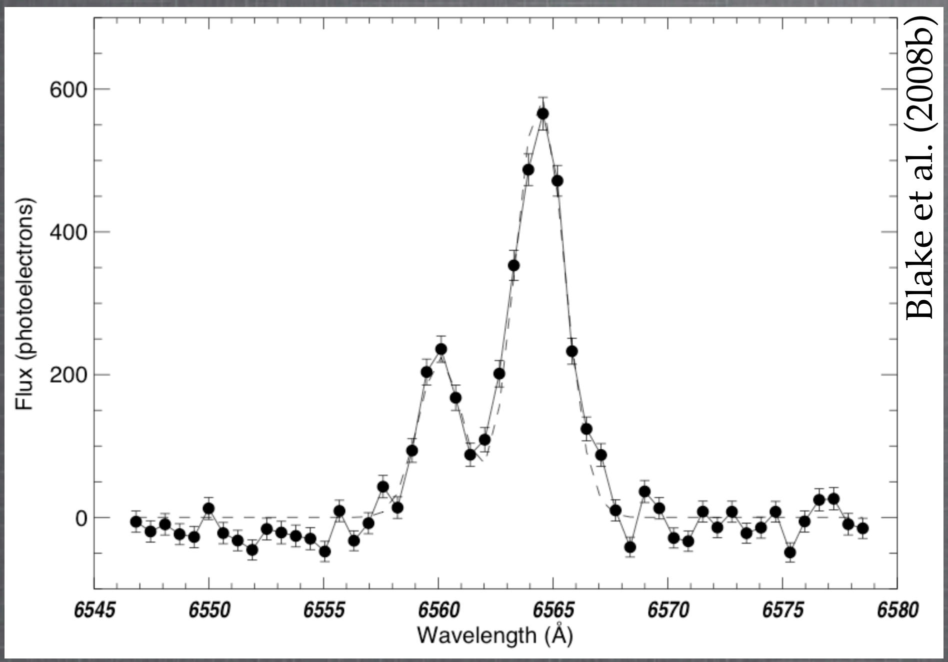


Blake et al. (2008b)

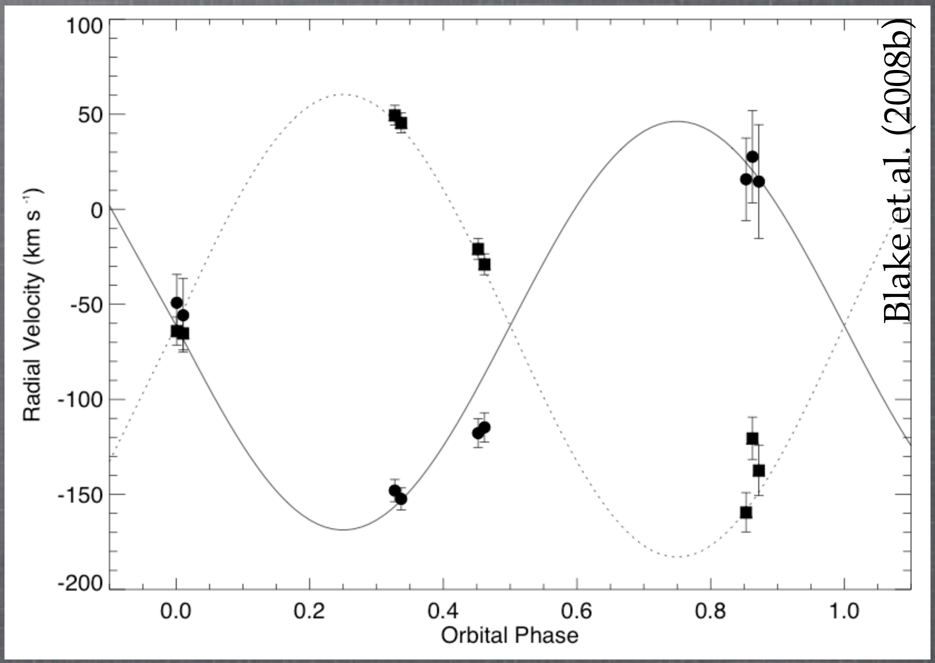
SDSS-MEB-1 Spectrum

Radial Velocities

- Keck+LRIS: 10 spectra at R~3500, 600s exposures

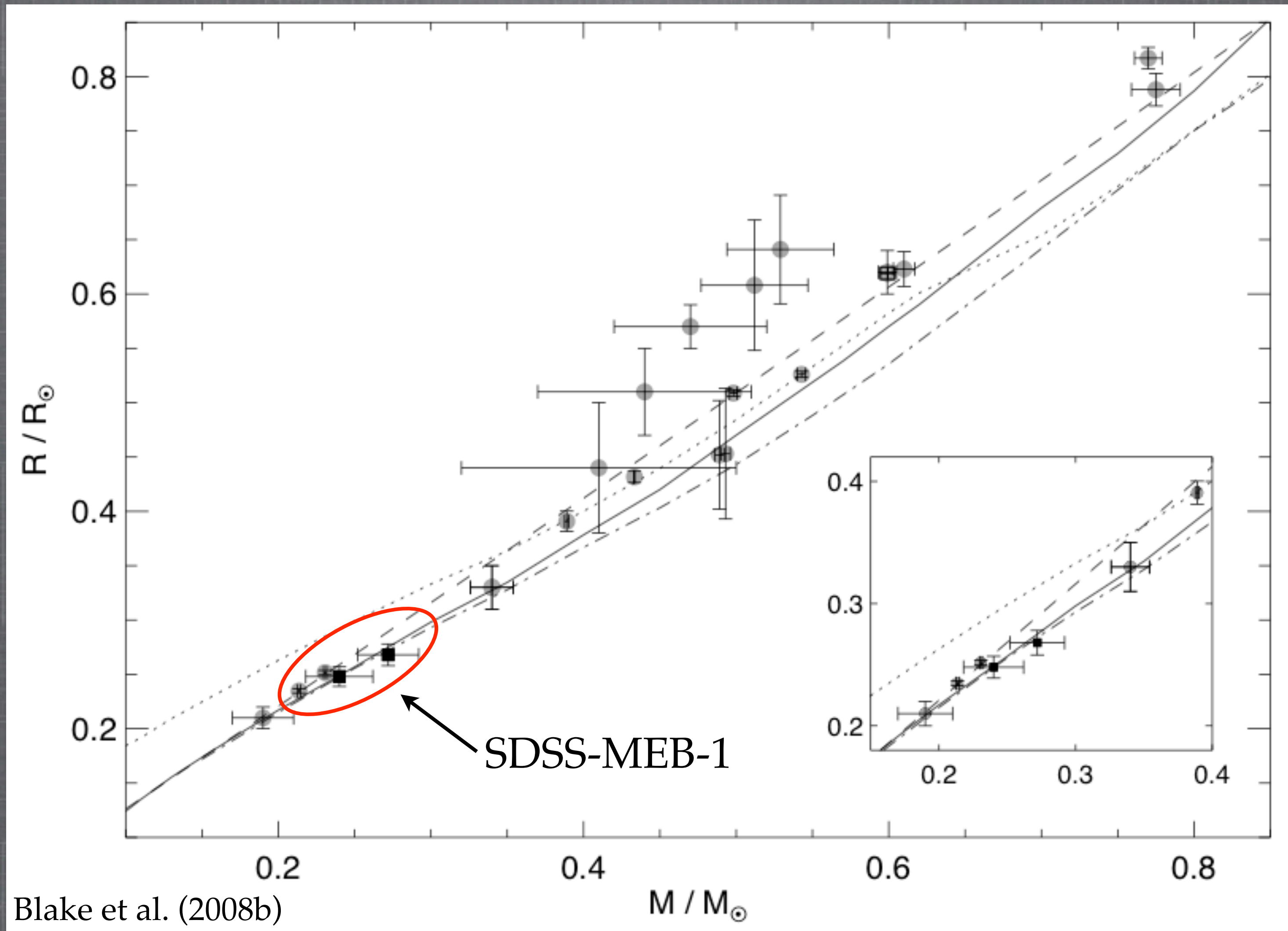


Hα lines: σ~10 km/s



K1=108 km/s   K2=122 km/s

Known Period



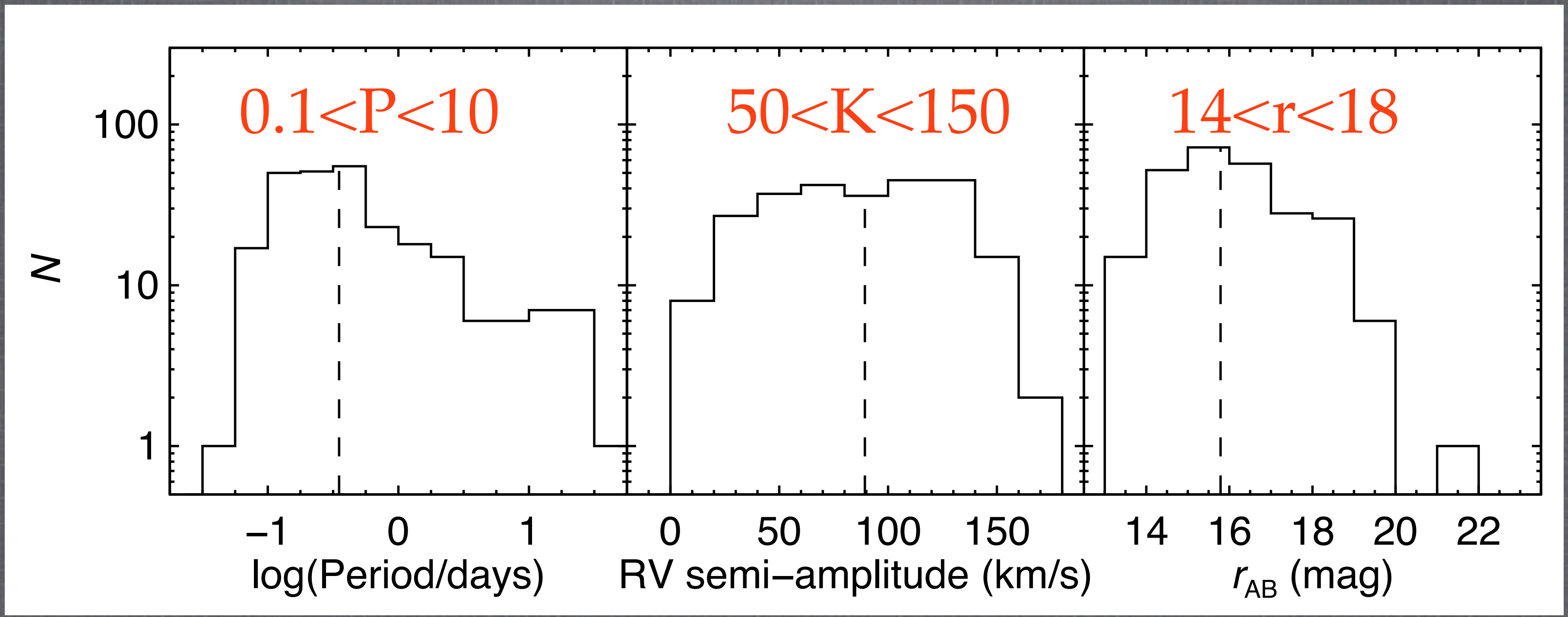
Two of the smallest stars with mass and radius measurements

Parameter	Value
M_1 ($M_\odot$)	0.272±0.020
M_2 ($M_\odot$)	0.240±0.022
$a(R_\odot)$	1.850±0.047
R_1 ($R_\odot$)	0.268±0.0090
R_2 ($R_\odot$)	0.248±0.0084

Pan-STARRS Simulations

Dupuy and Liu (2009, ApJ, 704,1519)

Prediction: ~200 EBs in Pan-STARRS "3π Survey"

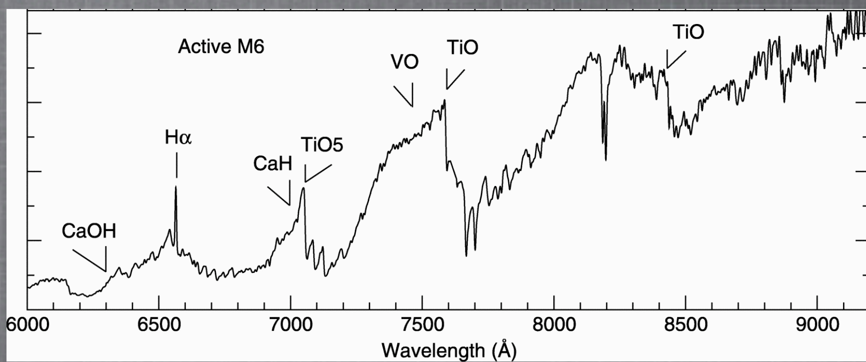


Photometry: 3000 m^2-hours of telescope time

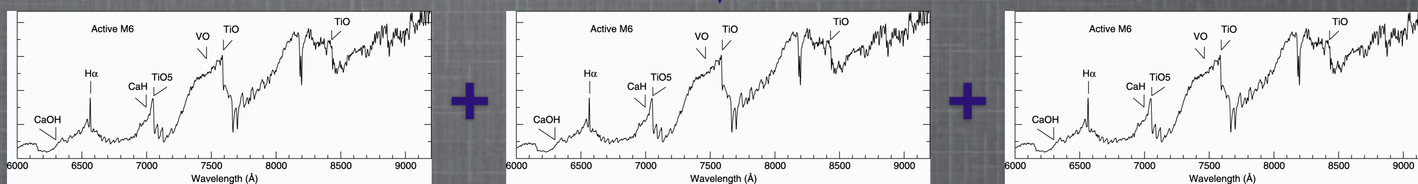
Spectroscopy: 7000 m^2-hours of telescope time

SDSS Spectroscopy

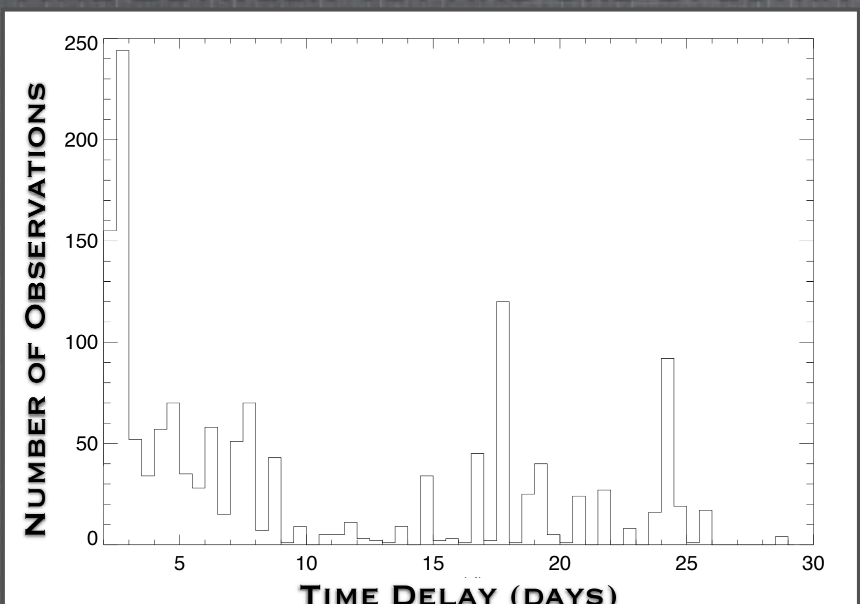
R~2000
380 to 920 nm
84,000 M stars



Bochanski et al. 2007



Time Between 1st and 3rd Spectra



Can the SDSS spectra be used to constrain the statistical properties of short-period binaries?

Spectroscopic Binaries in SDSS

M Star

a=0.2 AU

P~40 days

ΔRV~20 km/s

M Star

σ~4 km/s ~8000 M stars

Detectable Even With Only Three Spectra?

The Close Binary Fraction of Dwarf M Stars

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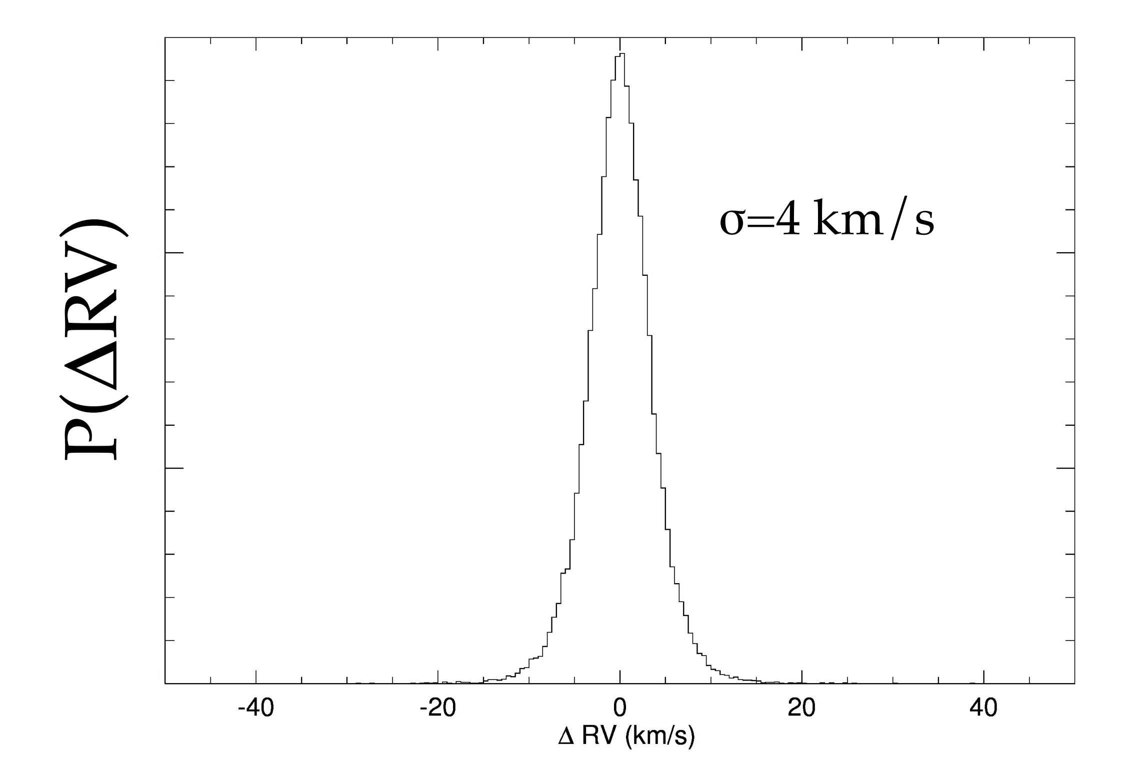
RV Control Sample

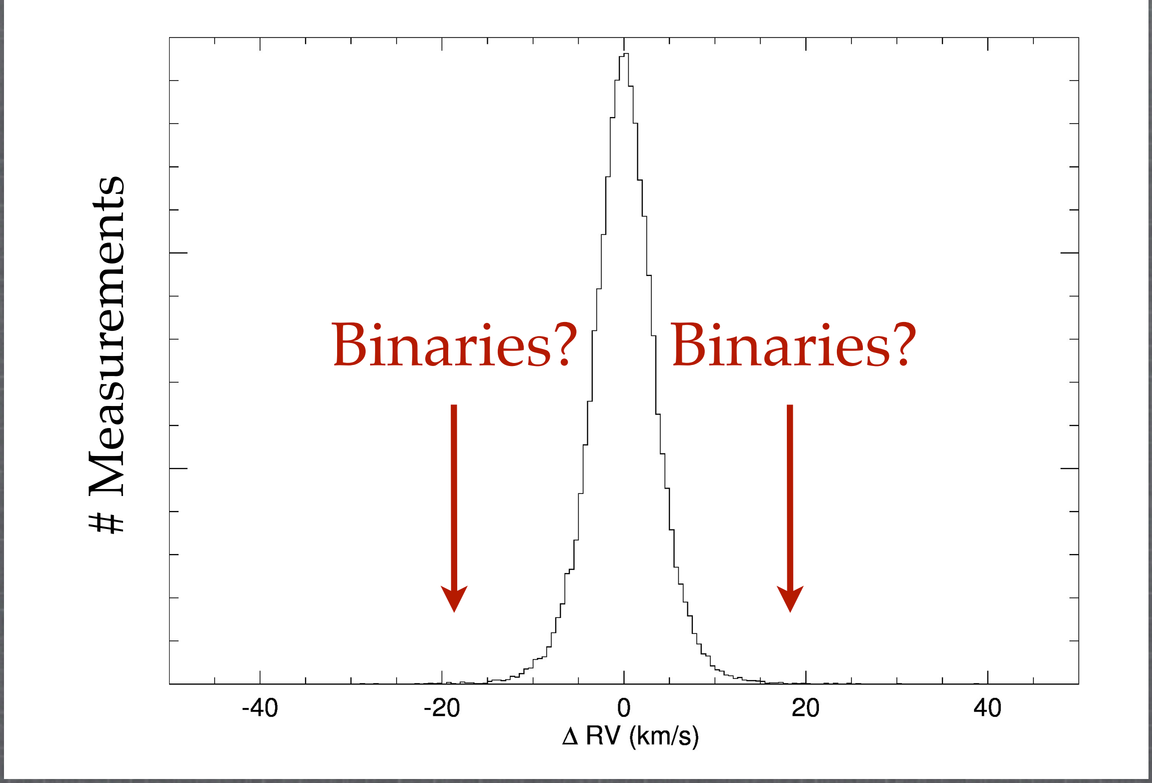
- Time between observations: $\Delta t<2$ hours
- 7,000 M dwarfs ($16<i<20.5$; $i-z > 0.3$)
- Spectra visually inspected

Empirical RV Error Distribution



Experimental Sample

- Time between observations: 2<Δt<30 days
- 1,700 M dwarfs (16<i<20.5; i-z > 0.3)
- Spectra visually inspected



monte Carlo Simulations

<u>What is N, the Binary Fraction at *a*<0.4 AU?</u>

P(N) Given RV and P(ΔRV) ← Empirical Error Distribution (control sample)

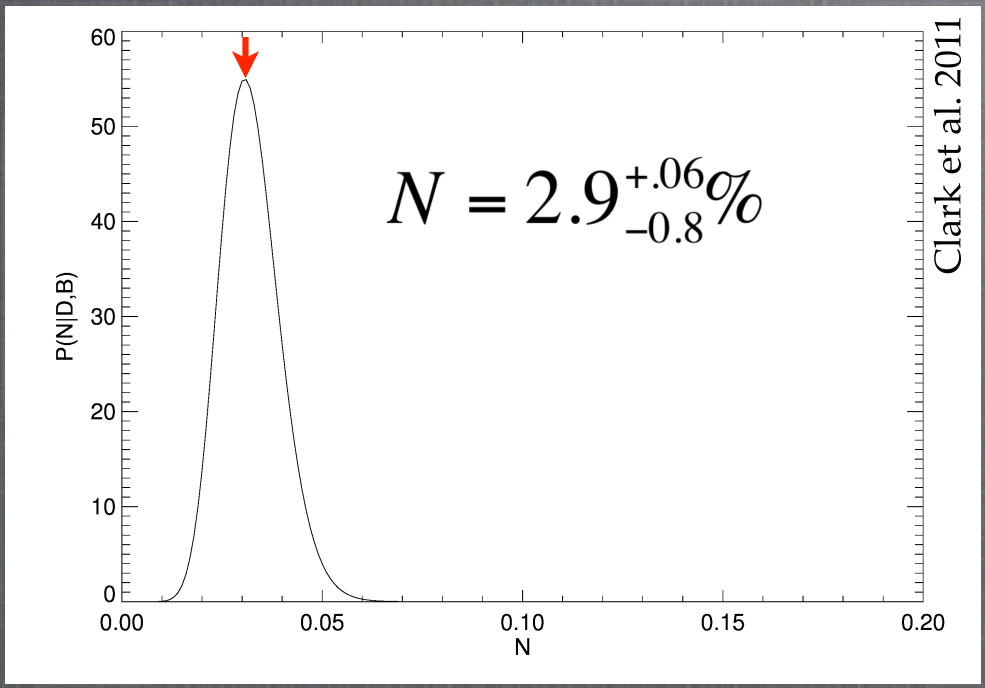
↑ Binary Fraction

↑ Experimental sample (6000 RVs)

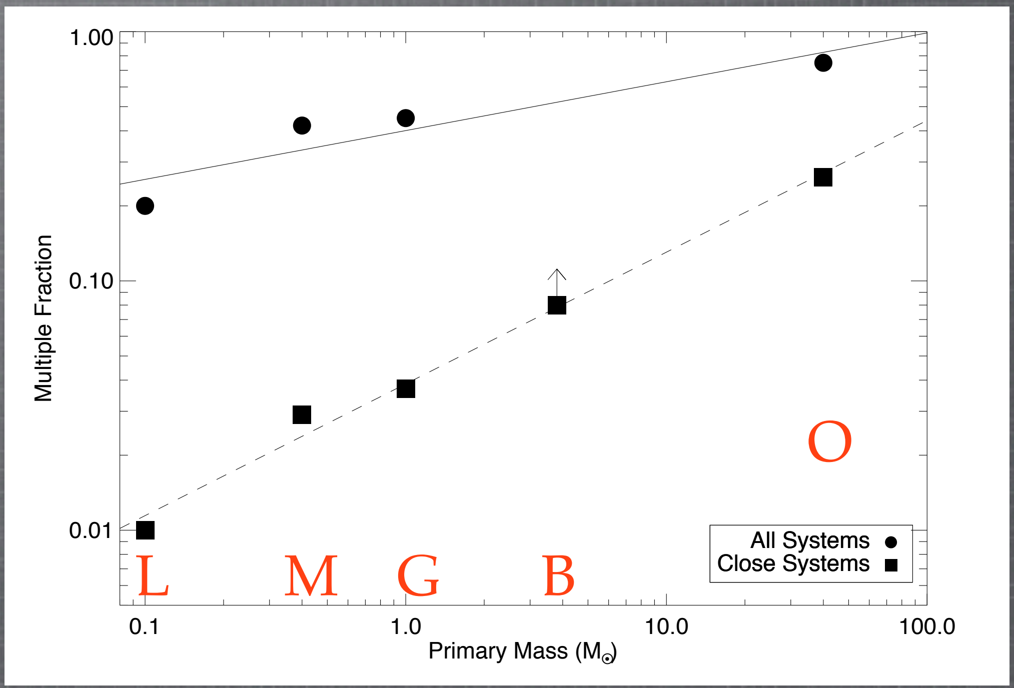
1. How many binaries detected given P(ΔRV) ?
2. Given N, how many binaries should be detected given the <u>detection efficiency</u>?

CPU Month

Close Binary Fraction



Posterior Distribution for N



N vs. Primary Mass

Binary Fraction: function of Stellar Mass

See also Fischer & Marcy (1992); Lada (2006); Raghavan et al. (2010)

Conclusions

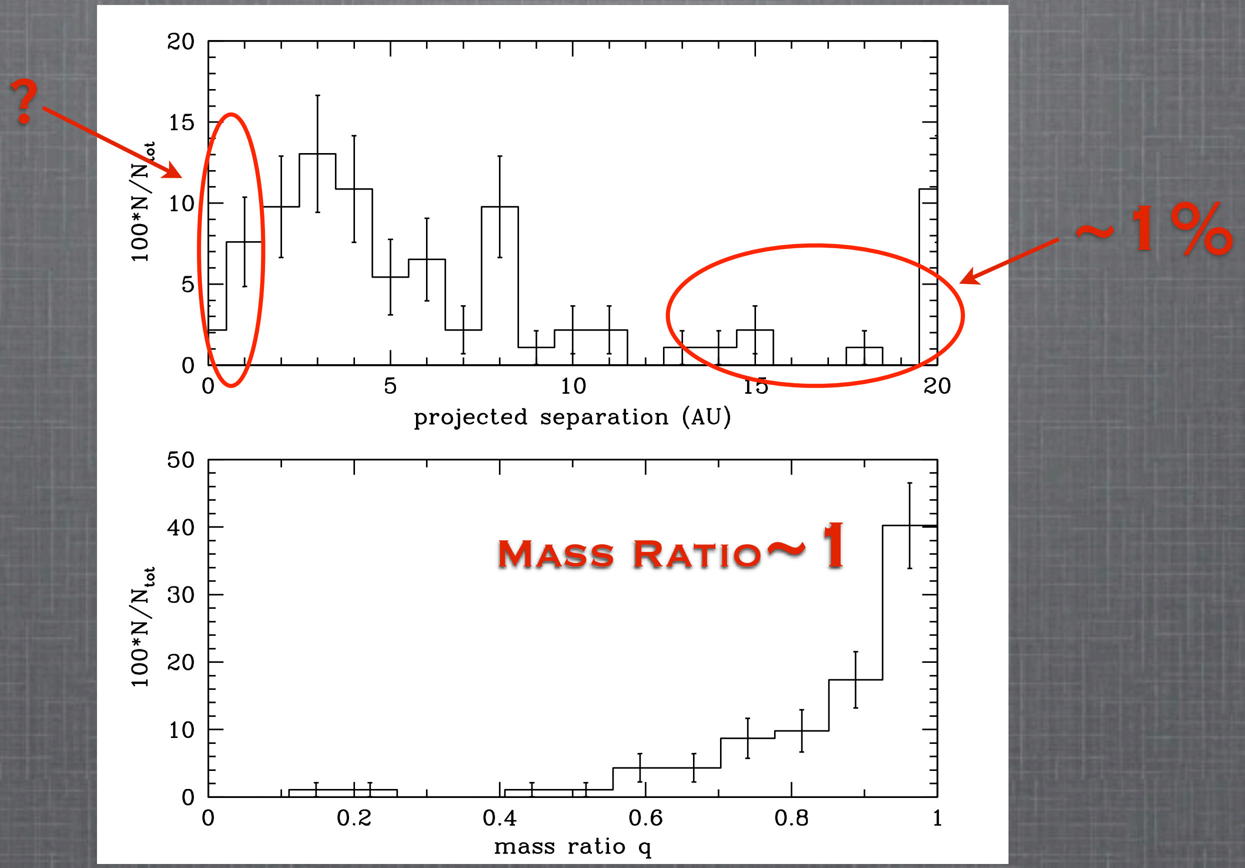
Synoptic surveys: Rich with low-mass star science

- Eclipsing Binary Stars:
  - Test models for bottom of main sequence
- Binary Statistics:
  - Piece of the formation-history puzzle

Challenge: Heavy Burden on Followup Observations

Low-Mass Star Formation

Observed Binary Properties

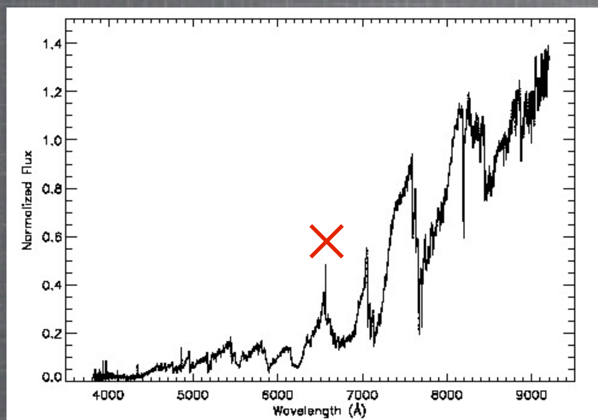


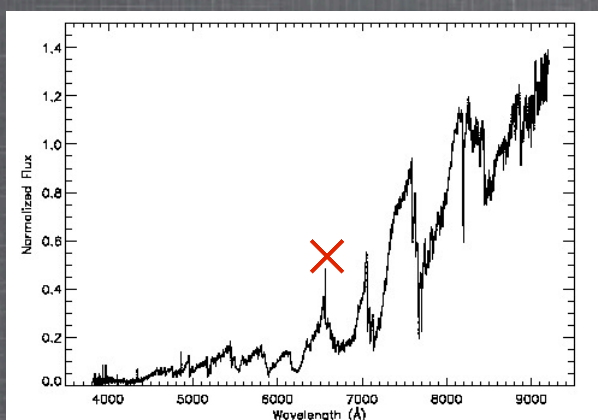
Theoretical Predictions:

1. Mass Ratios~1 ✔
2. Binary Fraction~40% ✔
3. small a > large a

RV Estimation

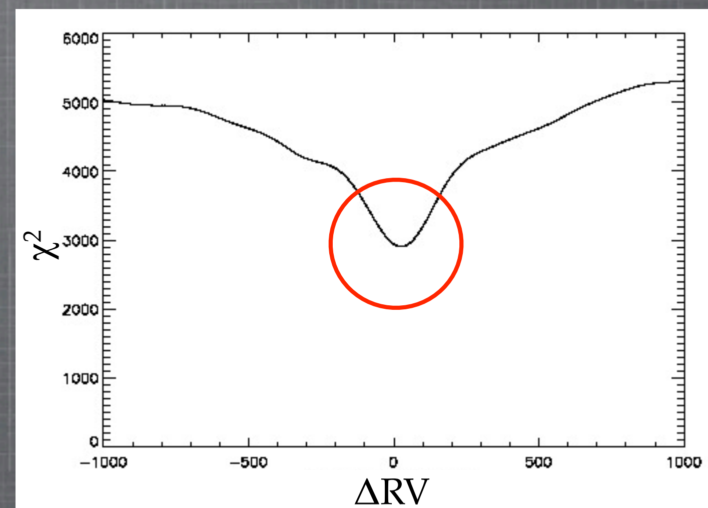
15-minute Spectrum

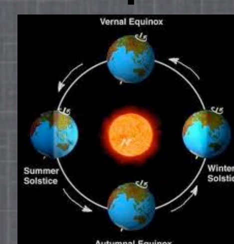




Spectral Template From Bochanski

Cross Correlation

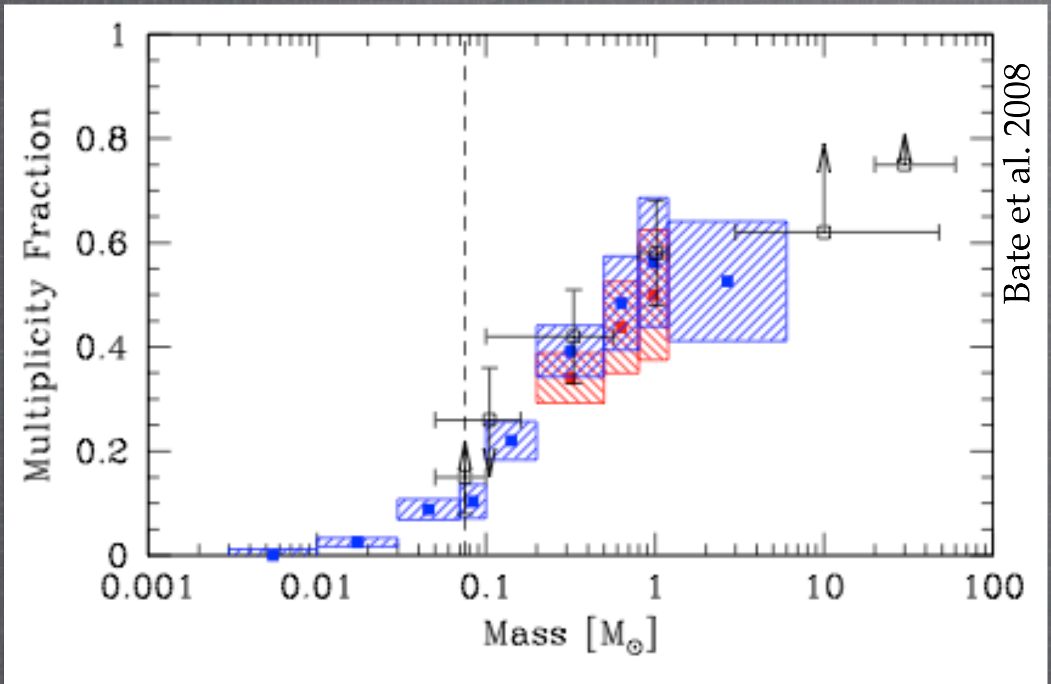




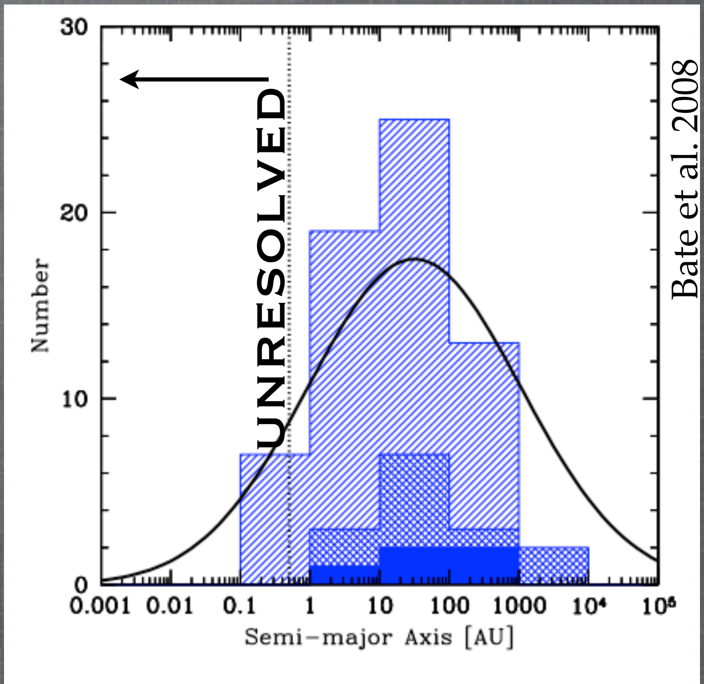
Barycentric Motion

Star Formation

Total Binary Fraction



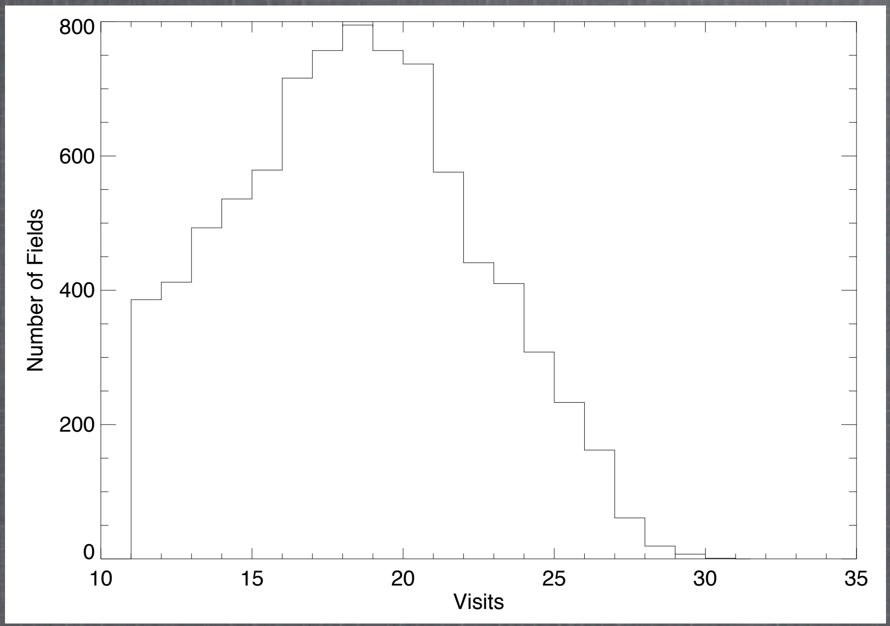
Separation Distribution



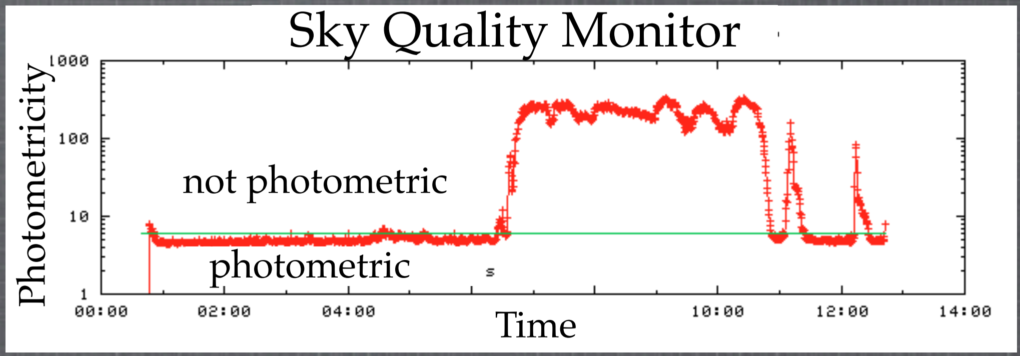
Results of SPH Simulations

S82 M Dwarf Light Curves

- 11,000 M stars, M4 and later, $i<20$
- New pipeline to generate <u>relative</u> photometry:
    - ensemble of nearby reference stars



Number of Visits



Photometric recalibration

monte Carlo Simulations

What is N, the Binary Fraction at *a*<0.4 AU?

Posterior Distribution — Survey Sensitivity — Prior

$$P\left(N \mid RV, P(\Delta RV)\right) \propto P\left(RV \mid N, P(\Delta RV)\right) \cdot P(N)$$

Binary Fraction

Experimental sample (6000 RVs)

Empirical Error Distribution (control sample)

CPU Month

Assumed Binary Properties

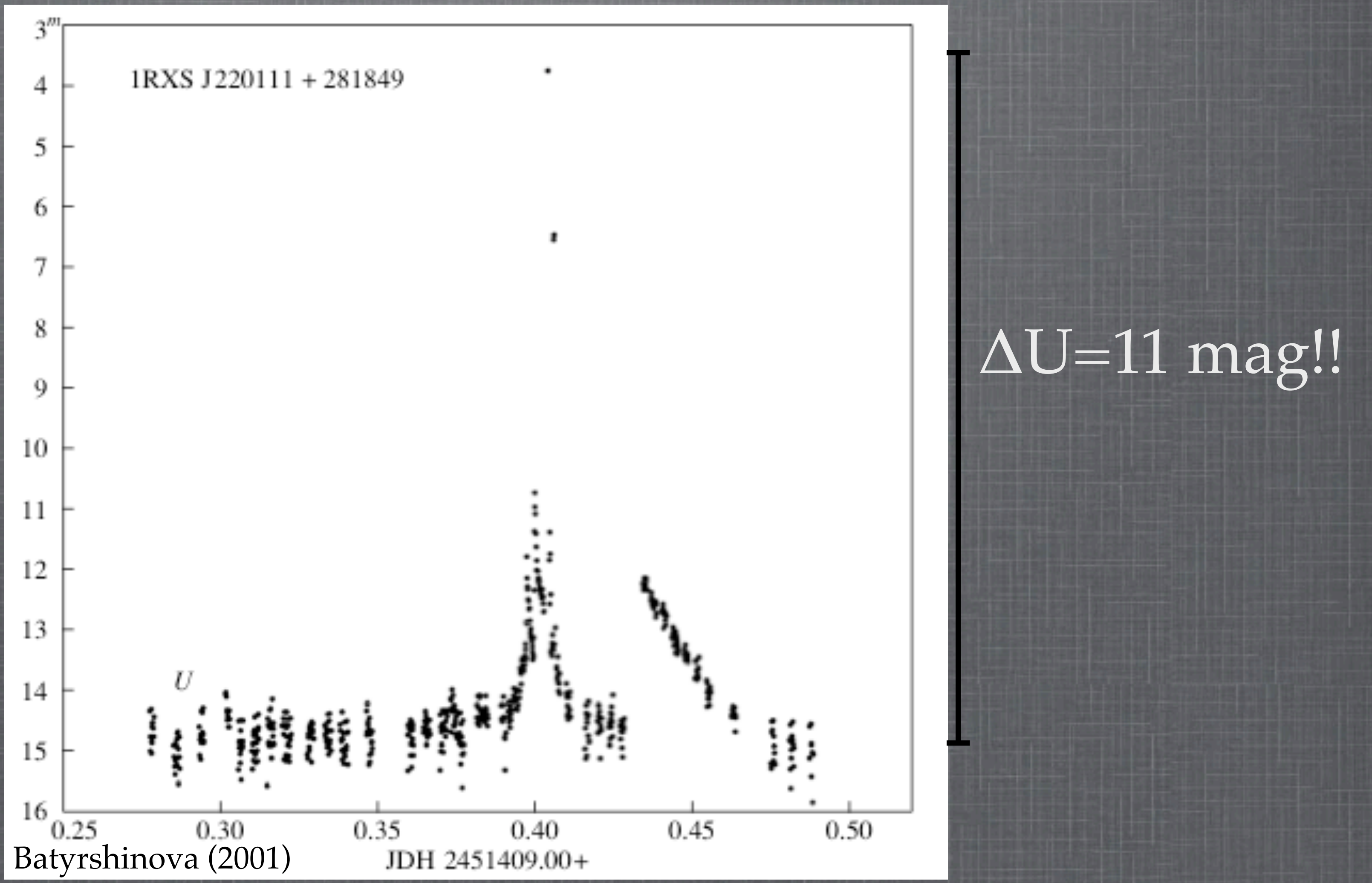
e=0

a: uniform

q: power-law

i: random

Stellar Activity: M Dwarfs

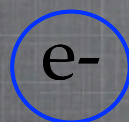


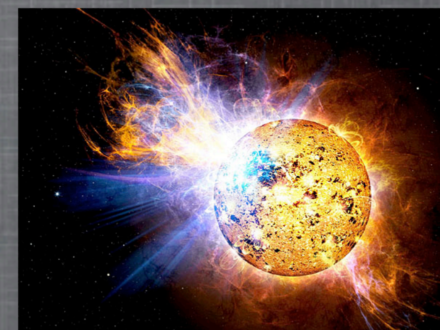
Foreground Fog for cosmological transients?

Goal: the overall statistical properties of flares

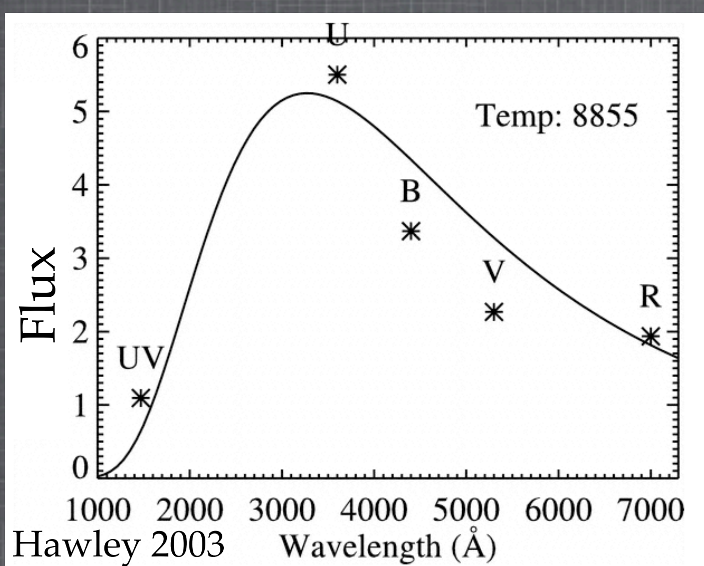
Stellar Flares

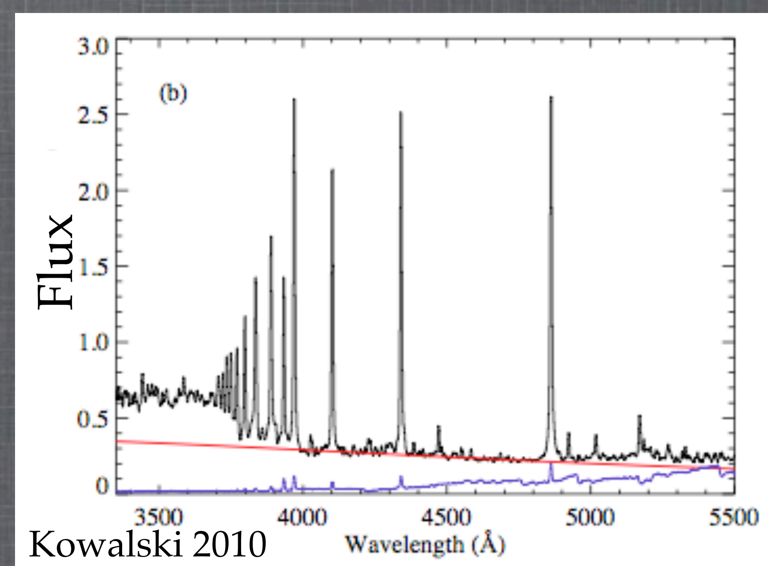
- complex, poorly-understood phenomena

Emission from radio to xray

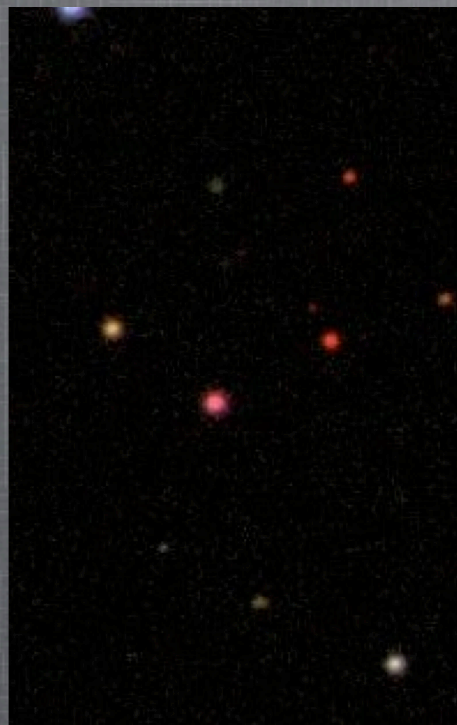




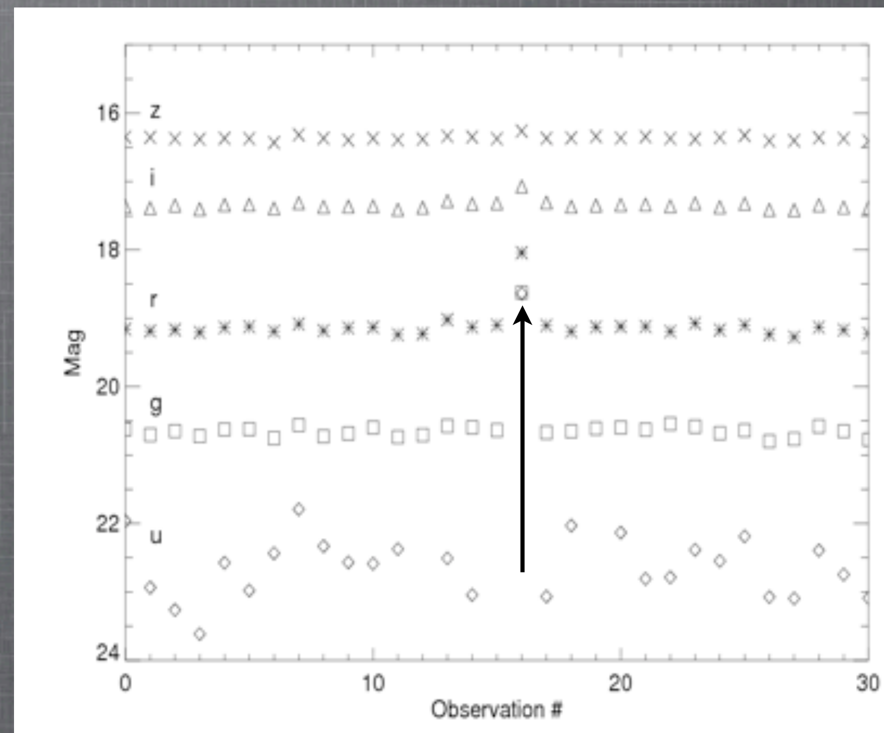
Flares in Stripe 82

Quiet

Flaring



Δu=4 mag



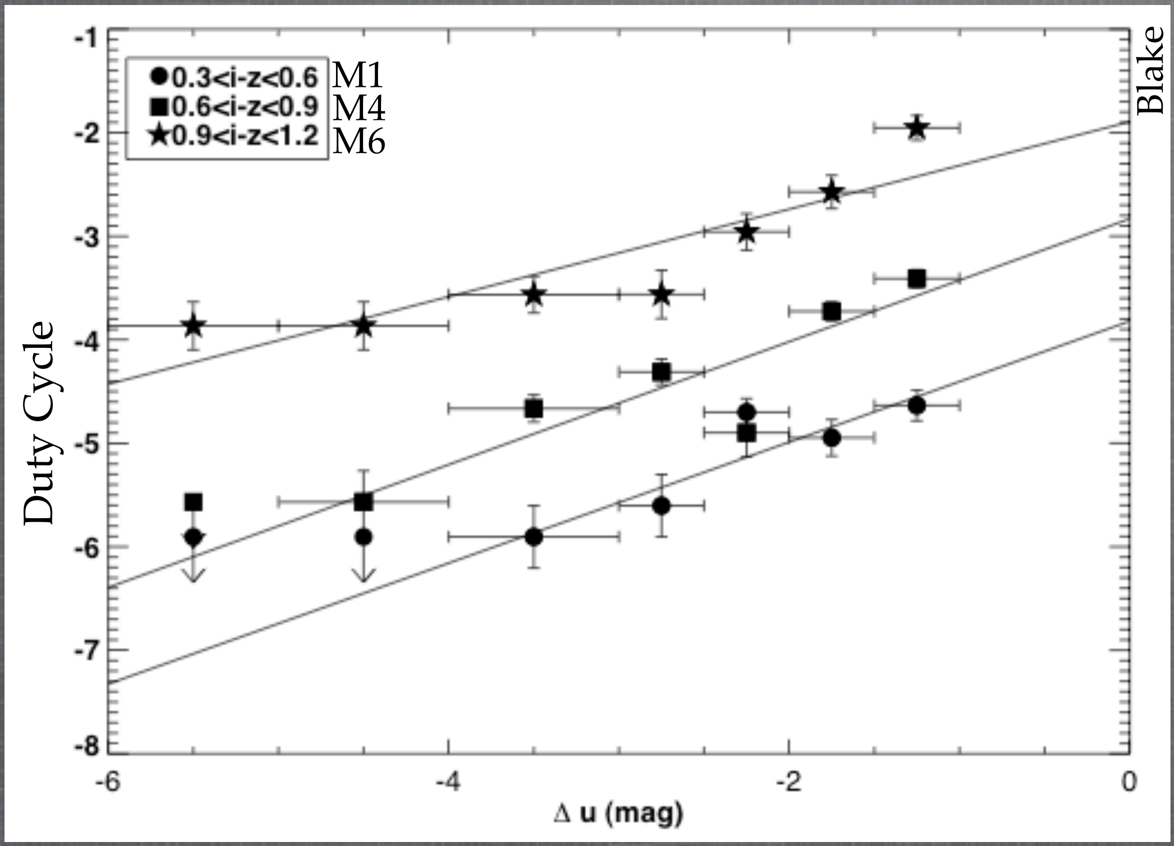
- 40,000 M stars, 1.6x10^6 observations
- More than 100 $\Delta u > 1.0$ mag events

u Band Movies





Flare Duty Cycle



Overall Duty Cycle:

Δu>1.0 mag:

M1 ~ 5×10^{-5}

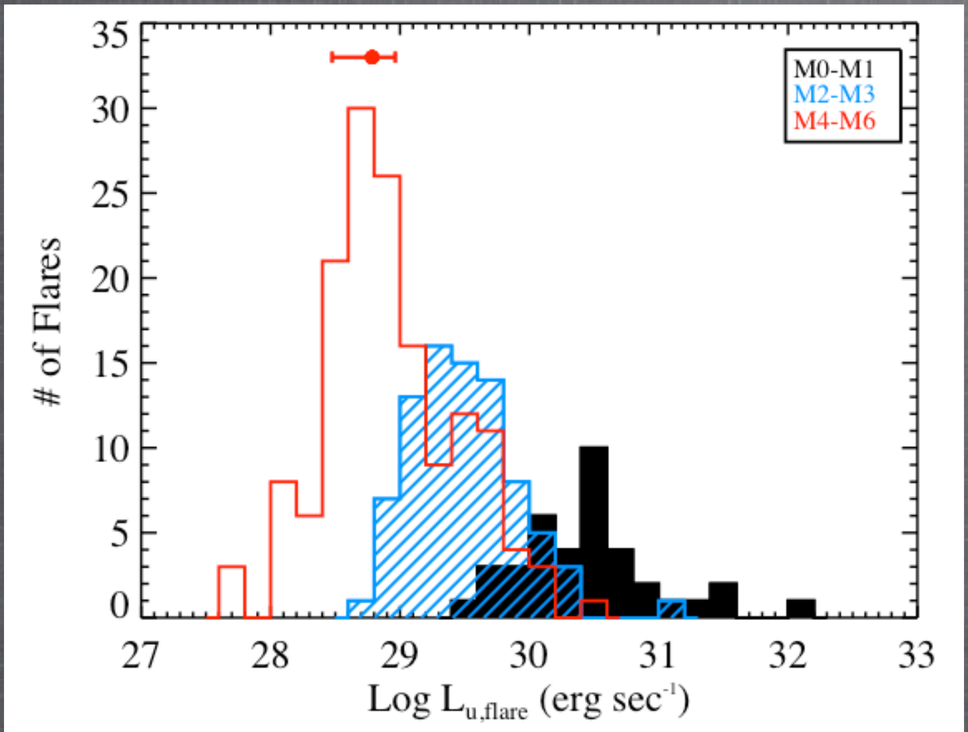
M4 ~ 8×10^{-4}

M6 ~ 1×10^{-2}

- Redder stars: more and larger flares
- ~1 flare/hour/□° in stripe 82 (u<21)

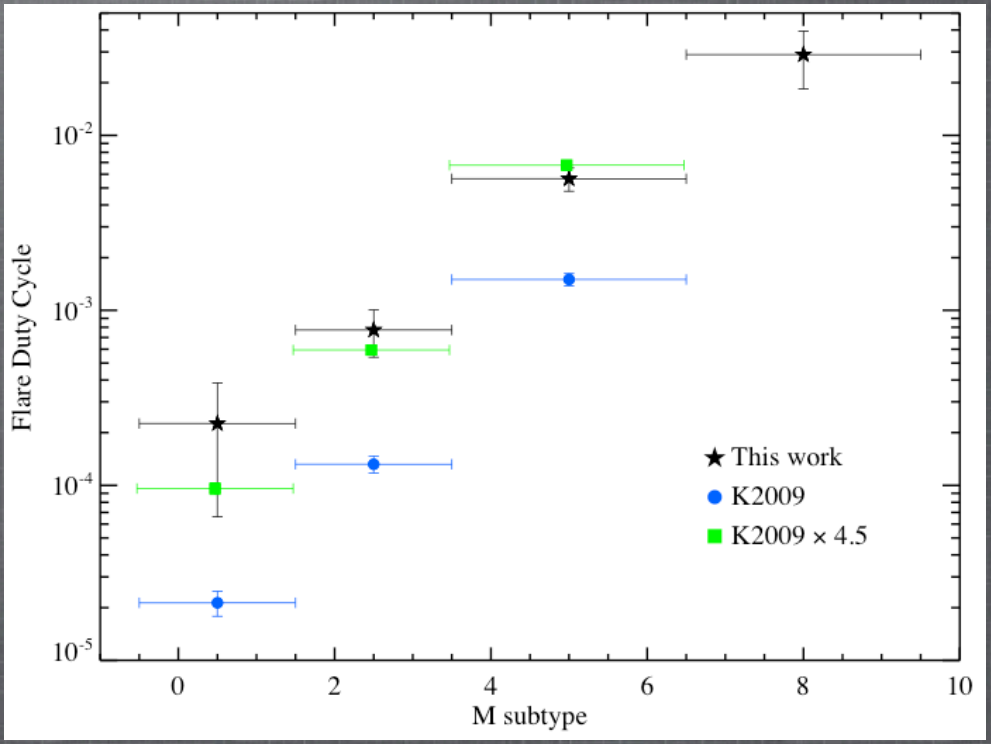
Flare Energies and Rates

Kowalski et al. (2009)



Flare Energy

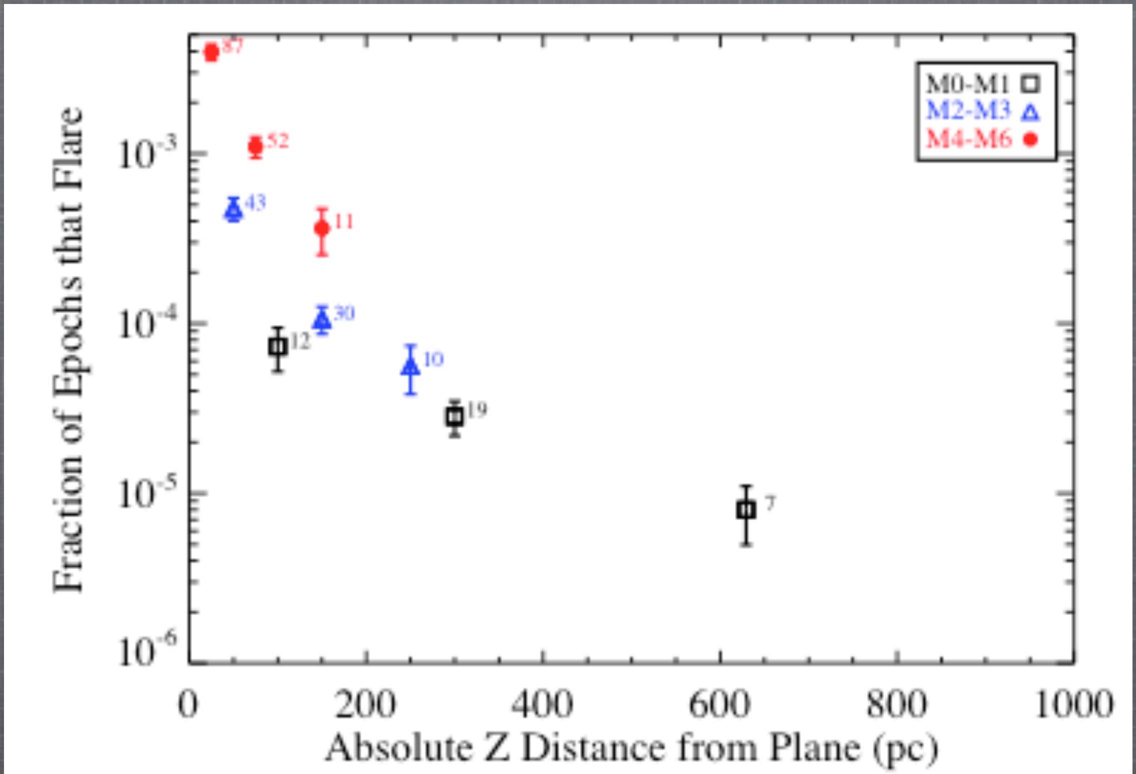
Hilton et al. (2010)



Flare Duty Cycle

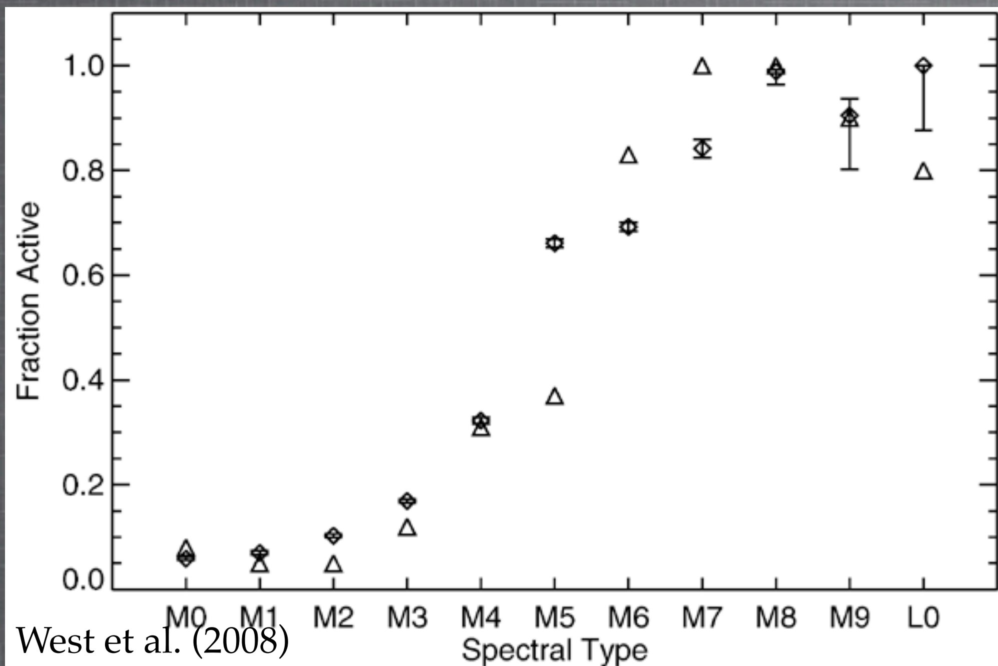
Flare Rates

Kowalski et al. 2009



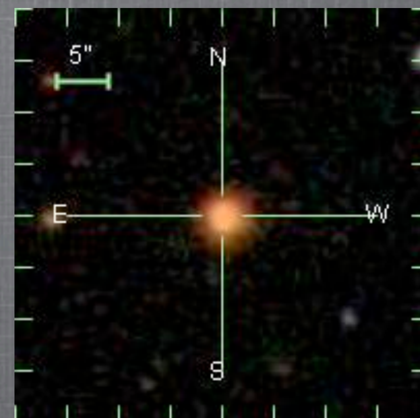
Flare rate decreases with stellar age

Flare Rates



Hα Activity Fraction

M1 u=19.0 <u>L_u=10^{29} erg/s</u>



Δu=0.2 mag

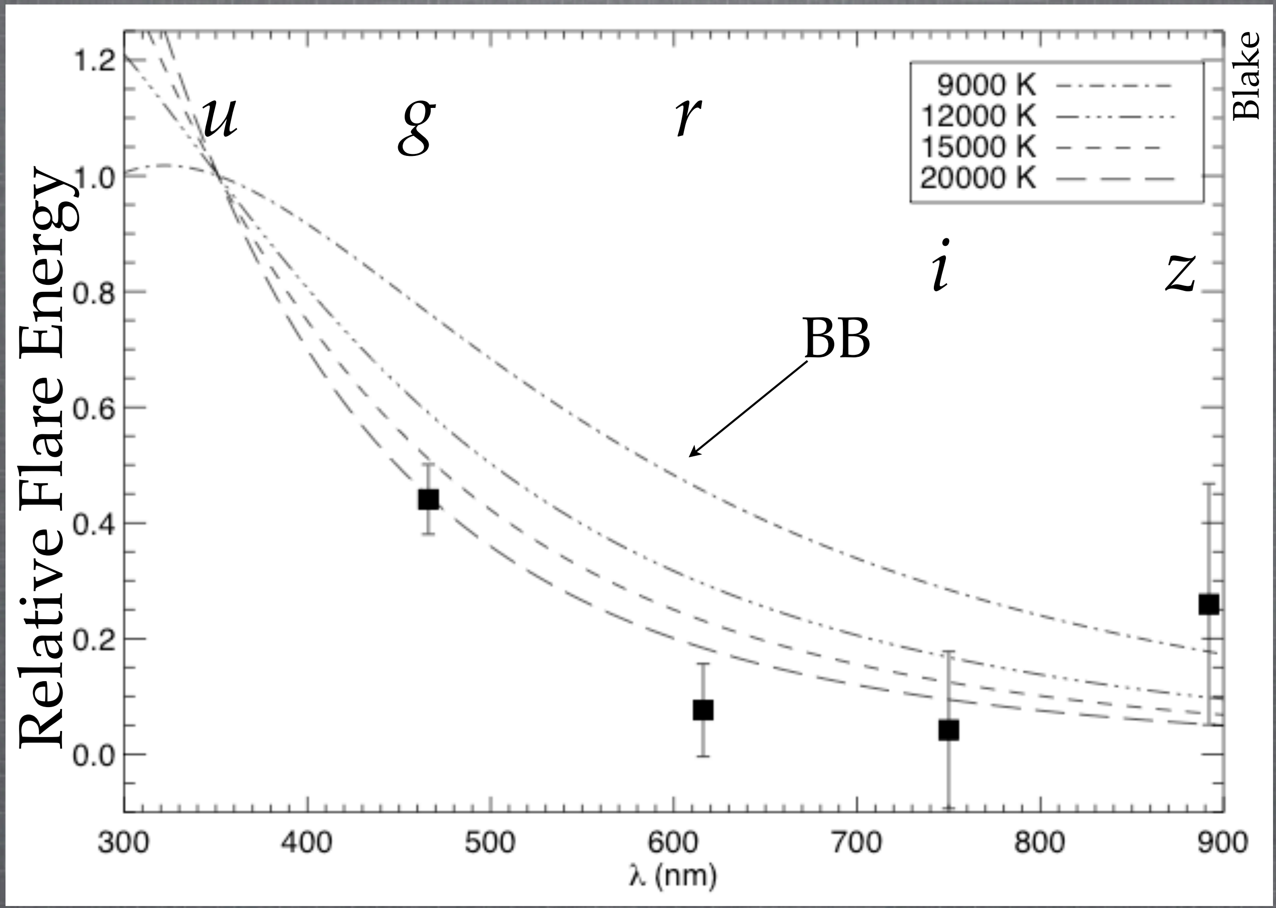
M4 u=22

Δu=2.2 mag

Flare Luminosity at d=200 pc

Flare Colors

Flares are Very Blue

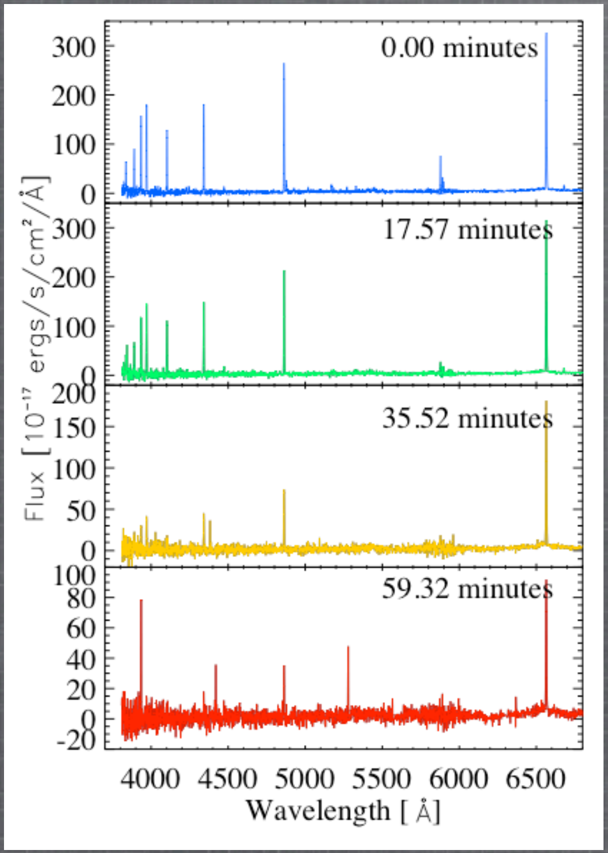


Important Caveats:

- ➔ *u* filter has red leak
- ➔ ~2 minutes between *u* and *g* (drift scan)

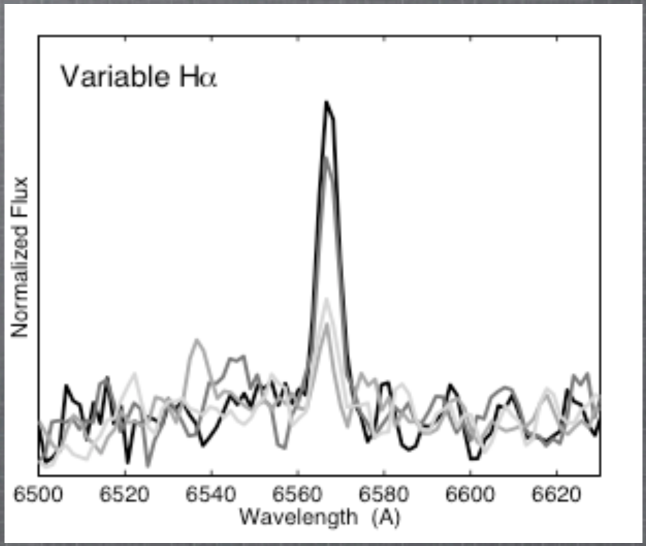
SDSS Spectroscopy: the Time Domain

Flare Spectra



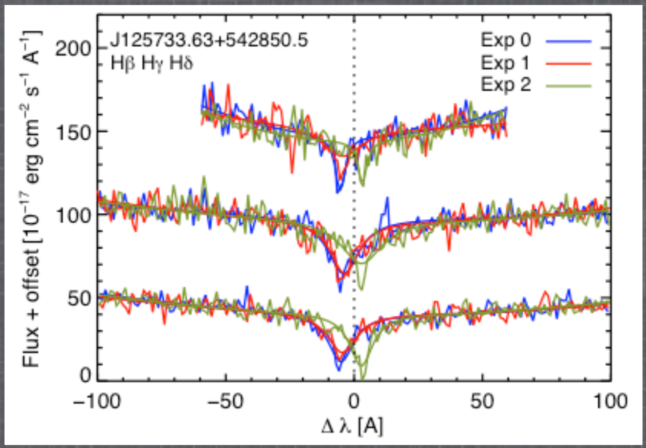
Hilton et al. (2010)

Line Flickering



Kruse et al. (2010)

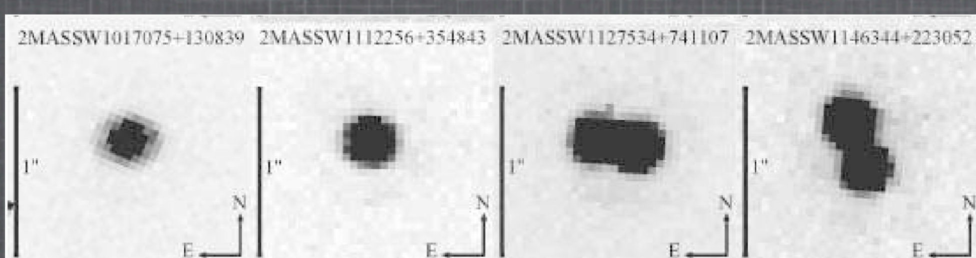
RV Shifts



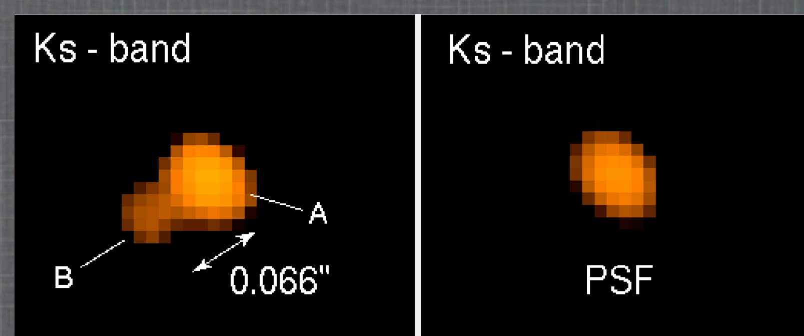
Bendes et al. (2009)

Low-mass Binaries

	Low-mass Stars	G Stars
1] Mass ratios:	q~1	q~0.3
2] Avg. Separation:	7 AU	30 AU
3] a>50 AU systems:	No	Yes
4] Total Fraction:	~20%	60%



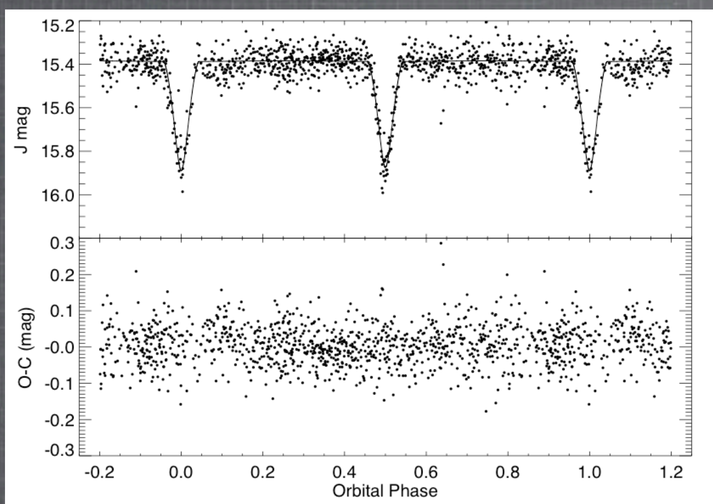
HST (~100 mas; Bouy 2003)



LGSAO (~60 mas)
Siegler et al 2007

Low-mass Stars in the Time Domain

Stellar Structure, Evolution, and Formation



Koch Conference

Cullen Blake