Testing Low Mass Stellar Evolution Models with M-dwarf Eclipsing Binaries from the SDSS-II Supernova Survey

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Graduate Board Oral Exam
December 8, 2008

Outline

- Stellar populations and M-dwarfs
- Fundamental properties of stars and eclipsing binaries
- Disagreement between theory and observations
- How the SDSS-II Supernova Survey can help
- Future work
- Conclusions

Stellar Populations and M-dwarfs

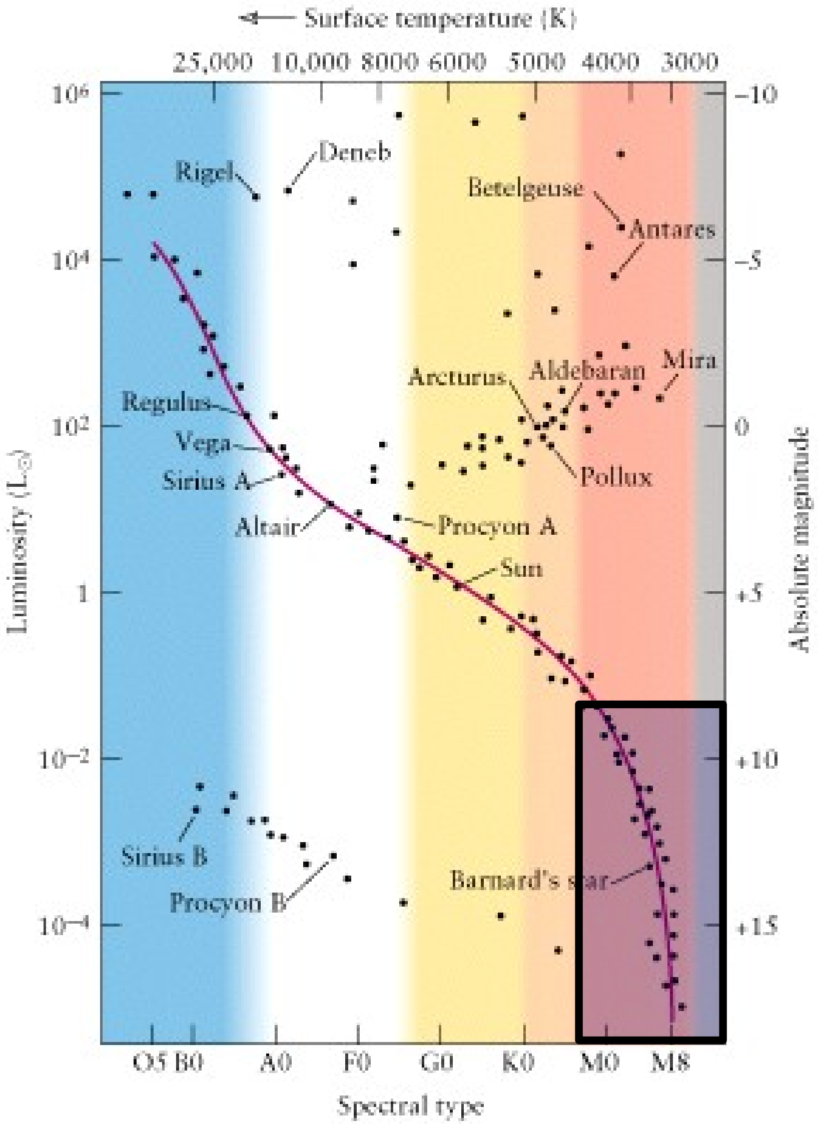
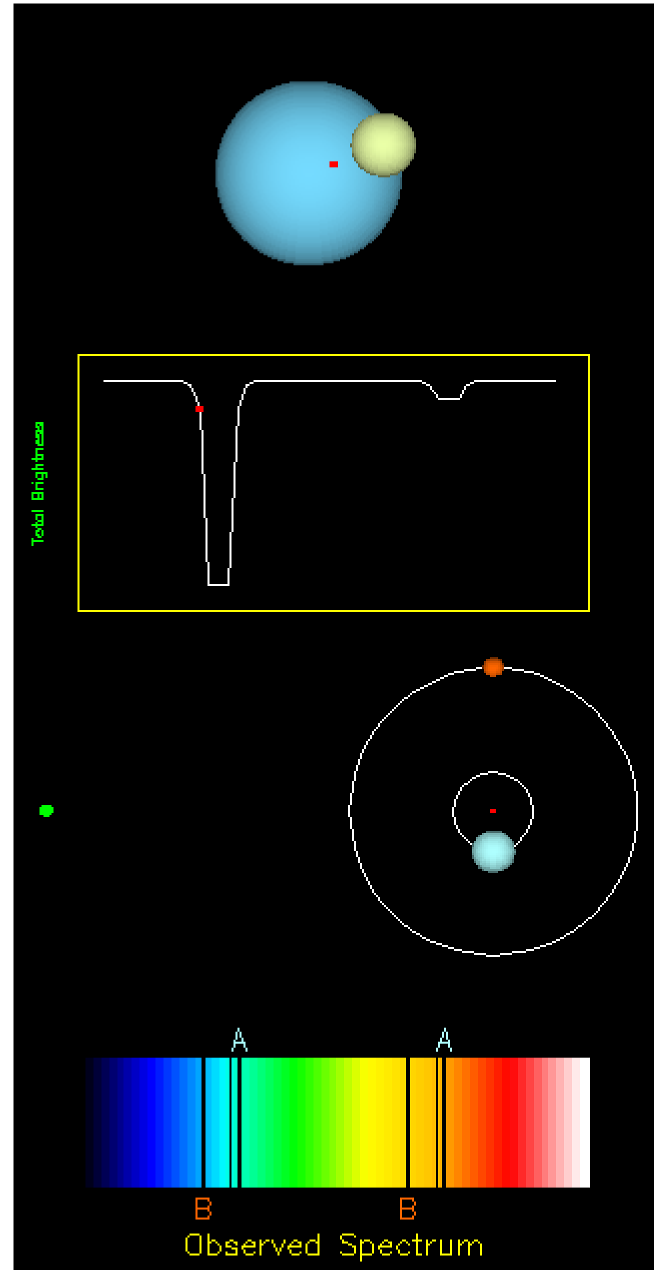


Figure from Kaufmann & Freedman, *Universe (6e)*, W.H. Freeman, 2001

- M-dwarfs
- Low mass stars (0.1-0.6 M_{sun})
  - low luminosities
  - low surface temperature
  - small radius
  - long life-time
- Most common type of star in the Galaxy (by number)
- Increasingly important because of connections to:
  - Brown dwarfs
  - Giant extrasolar planets

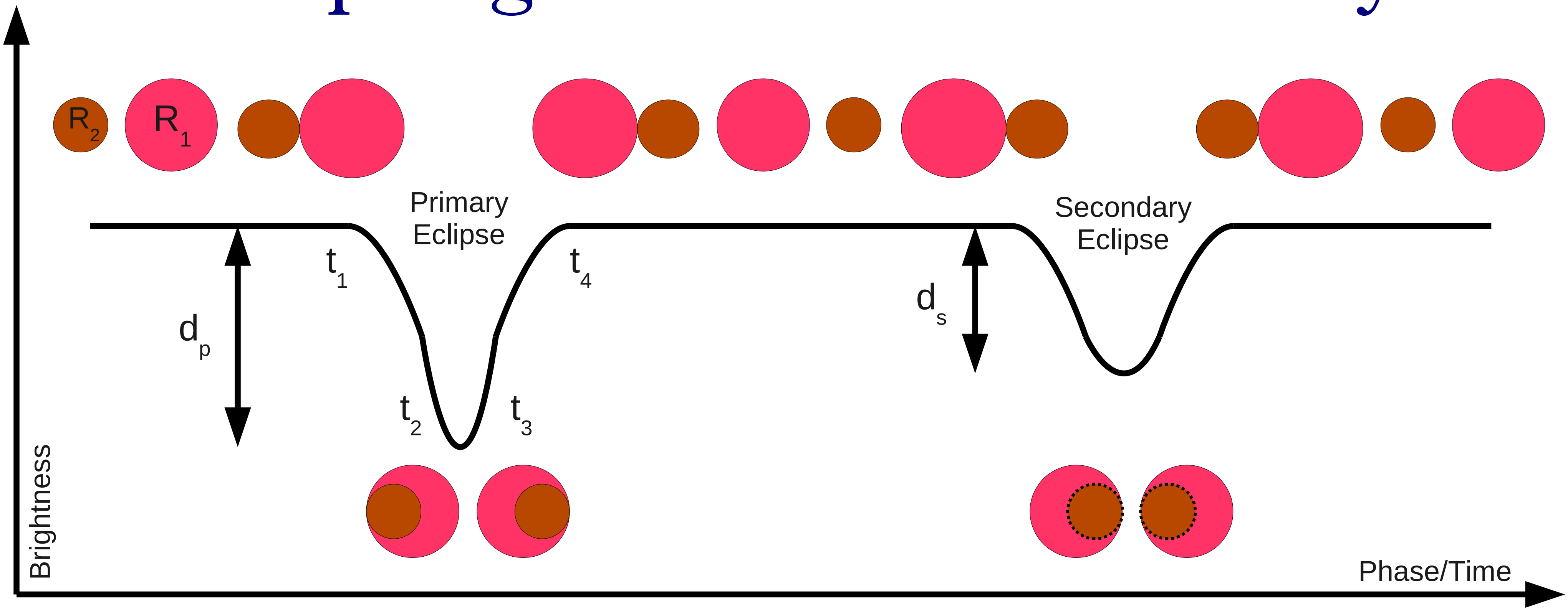
Eclipsing Binaries – Why Bother?

- Fundamental properties of stars:
  - Mass, chemical composition, age
  - Luminosity, radius, temperature
- Eclipsing binaries provide best estimates:
  - Measure relative radii, luminosities, temperatures from eclipses
  - Use spectra to get radial velocities, then use Kepler's 3rd Law for masses
  - Spectra also give direct measurements of other properties



Animations by R Pogge, OSU

Eclipsing Binaries – Photometry



Relative Radii:

$$t_2 - t_1 = t_4 - t_3 = 2R_2/(2\pi a)$$
$$t_3 - t_1 = t_4 - t_2 = 2R_1/(2\pi a)$$

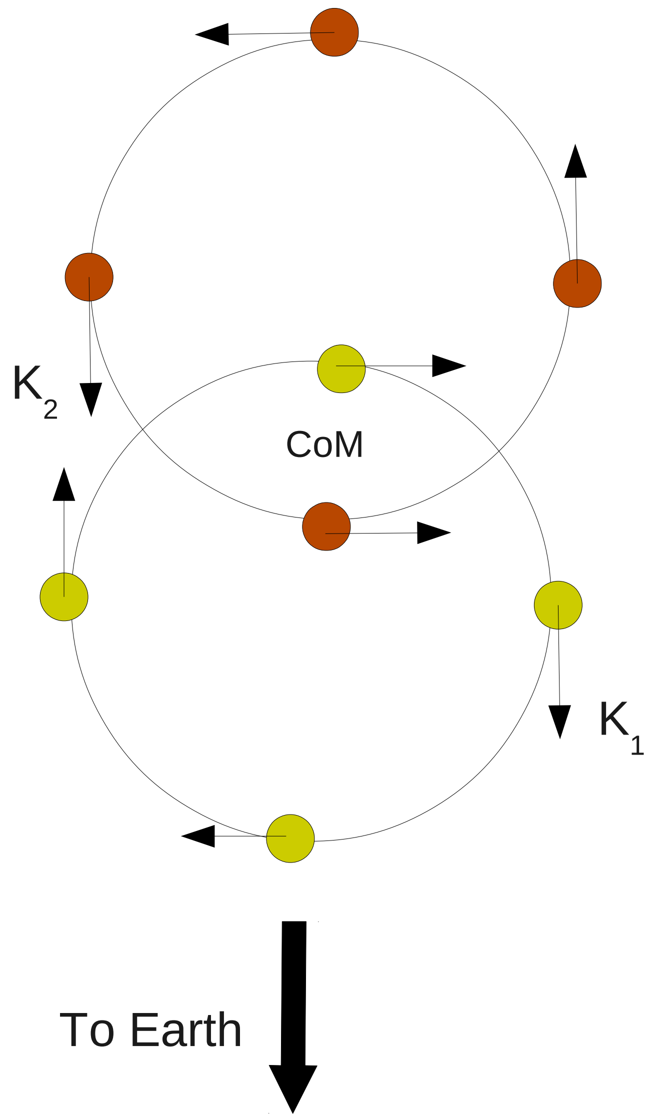
Relative Temperatures:

$$\left(\frac{T_1}{T_2}\right)^4 = \frac{F_1}{F_2} = \frac{d_p}{d_s}$$

Relative Luminosities:

$$\frac{L_1}{L_2} = \left(\frac{R_1}{R_2}\right)^2 \left(\frac{T_1}{T_2}\right)^4 = \left(\frac{R_1}{R_2}\right)^2 \left(\frac{d_p}{d_s}\right)^{1/4}$$

Eclipsing Binaries – Spectroscopy



Using Kepler's 3rd Law:

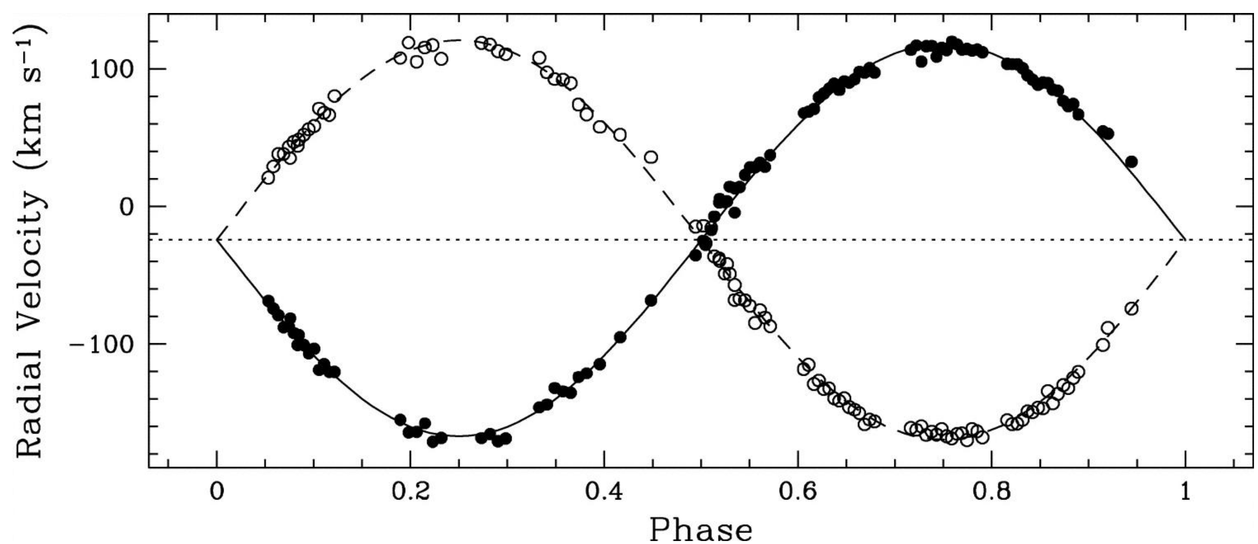
Semimajor axes of orbits in units of solar radii:

$$a_{1,2} = (1.9758 \times 10^4)(1 - e^2)^{1/2} K_{1,2} P$$

Masses of components in units of solar mass:

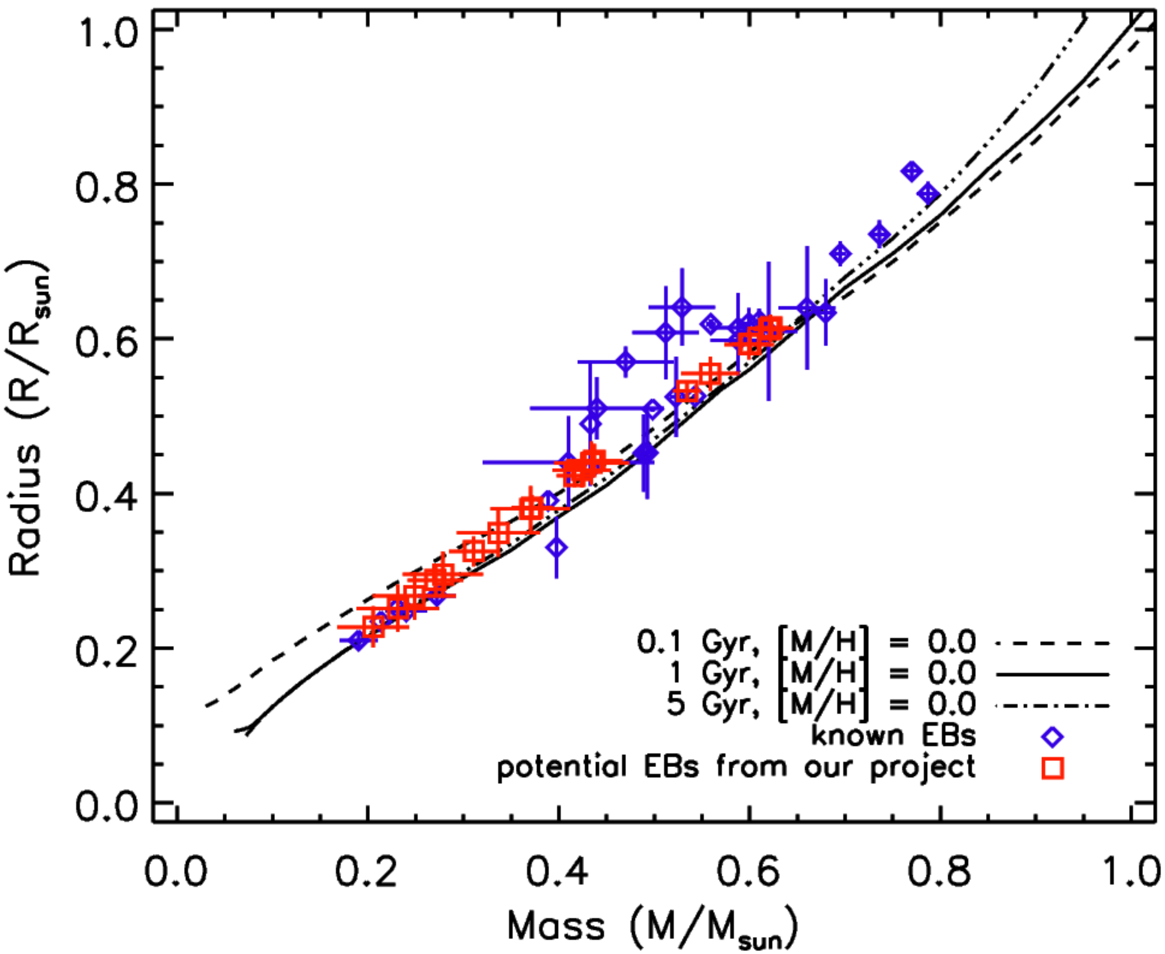
$$m_{1,2} \sin i = (1.0361 \times 10^{-7}(1 - e^2)^{3/2}(K_1 + K_2)^2 K_{2,1} P$$

Radial velocity curves for GU Bootis (from Lopez-Morales & Ribas 2005)



The Problem

- Only 16 known low-mass eclipsing binary systems (as of November 2008)
  - 2 K-dwarf, 14 M-dwarf
  - 0.2 M_{sun} < M < 0.8 M_{sun}
- Models don't agree with observations:
  - Under-predict radius by ~10%
  - Over-predict temperature by ~5%
- Why this disagreement?
- Are stars in binaries different from single stars?



32 known EB low mass stars (K/M-dwarfs)

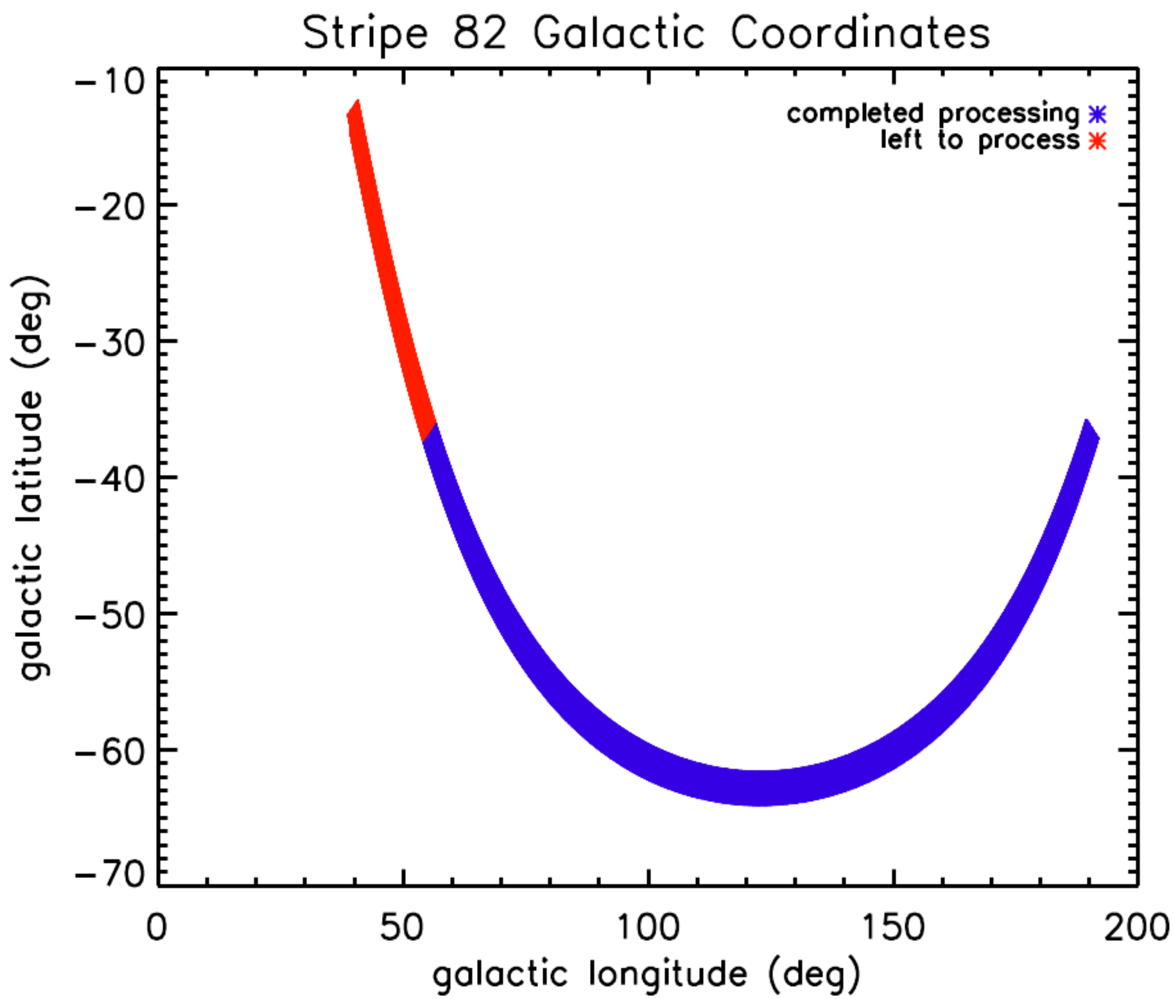
20 potential new EB low mass stars (M-dwarfs)

The Solution

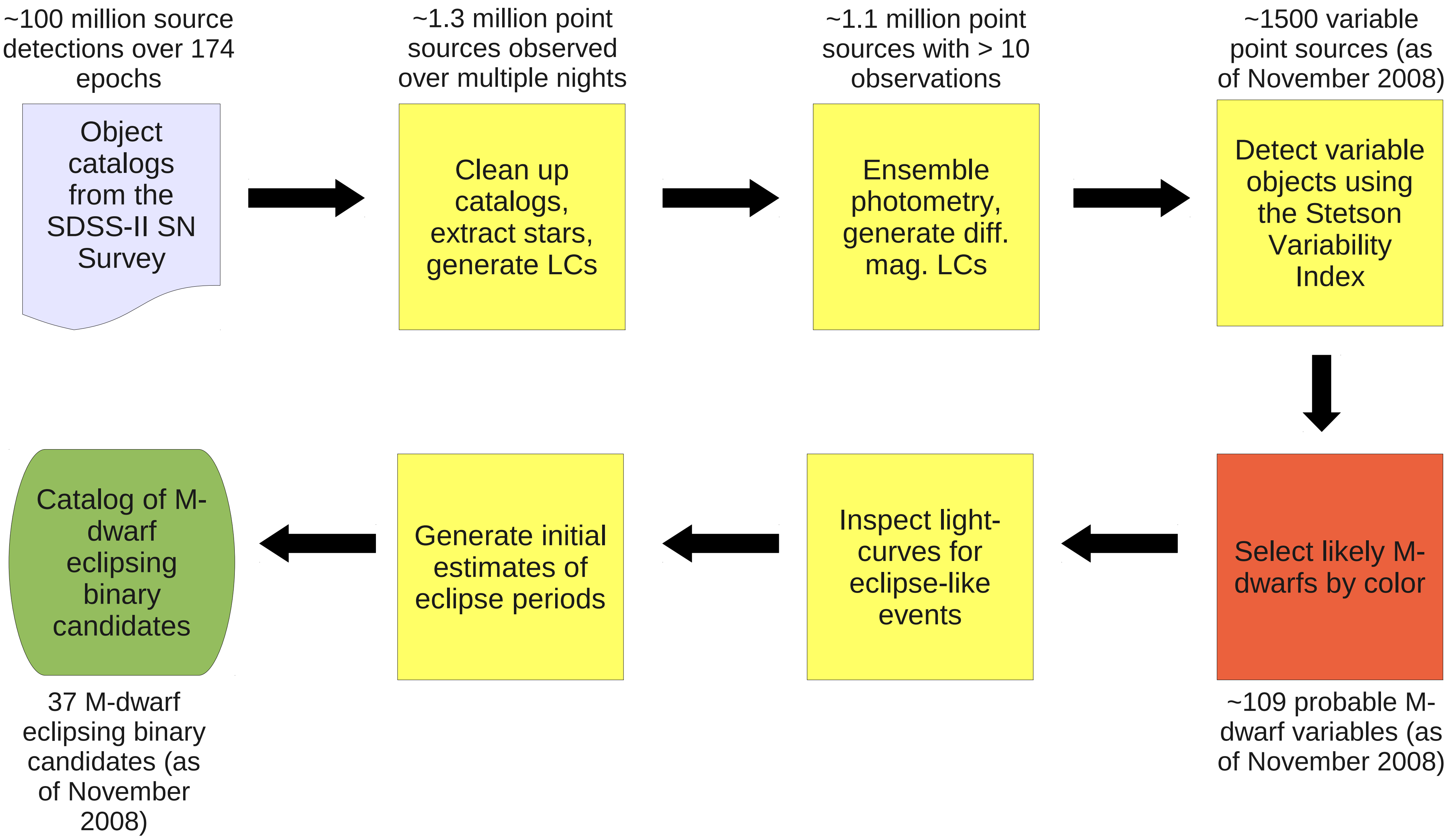
- Need more M-dwarf eclipsing binary systems
- The Plan:
  - Get candidates from the SDSS-II Supernova Survey
  - Generate initial eclipse periods from this data
  - Refine periods at a small telescope with lots of observations
  - Get high quality light-curves of best candidates with a bigger telescope
  - Take high resolution spectra using several big telescopes
  - Get masses, radii, luminosities, temperatures, etc.
  - Test the theoretical models

The SDSS-II Supernova Survey

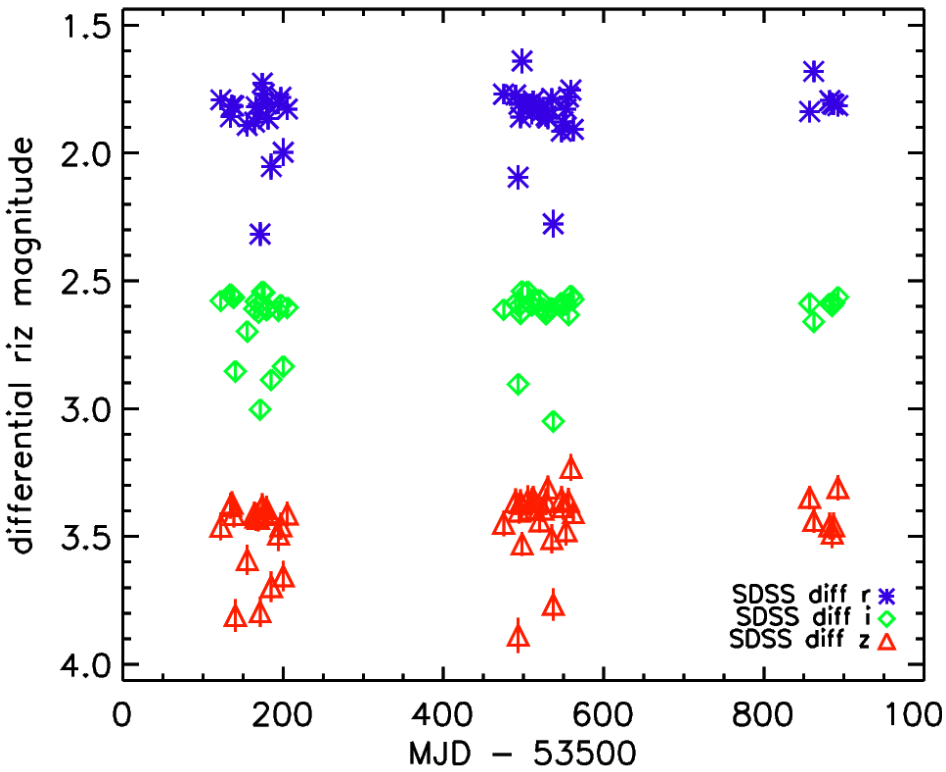
- Multi-epoch survey designed to search for supernovae Ia (2005-2007)
  - Monitored 300 sq deg of sky known as Stripe 82 during Sept – Dec
  - Full scan roughly every two nights
  - Five color photometry in *u, g, r, i, z* filters
  - Deep and uniform dataset
  - High Galactic latitude
- Calibrated object catalogs available for download
  - ~100 million total source detections over 174 total observation epochs



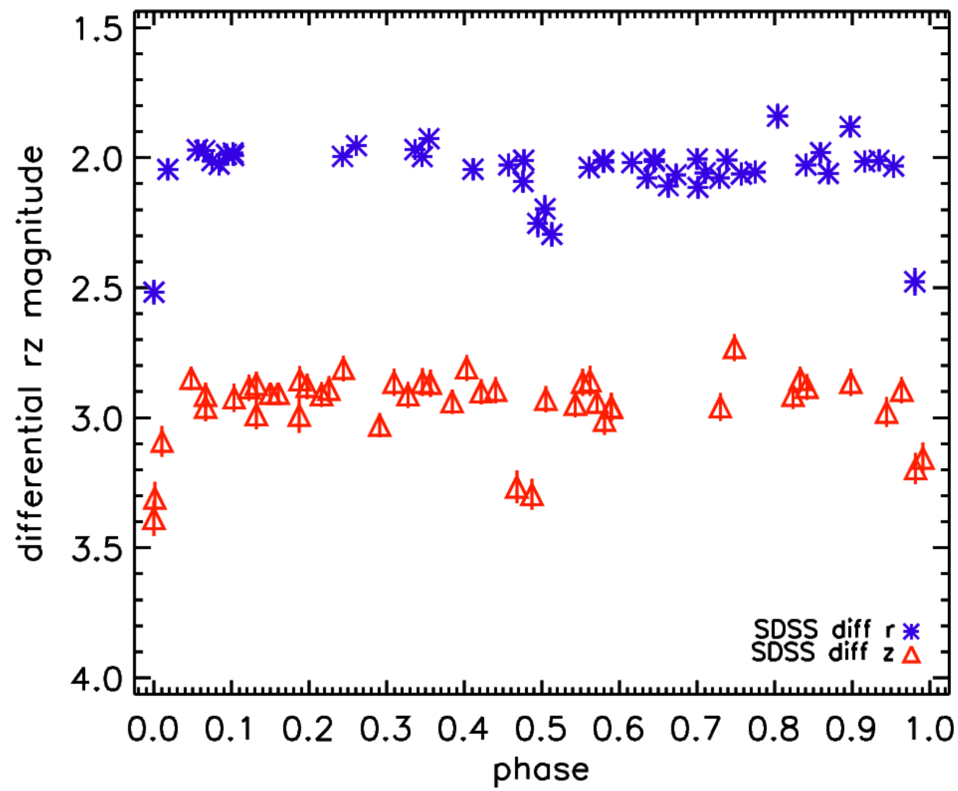
SN Survey: Data Reduction



SN Survey: M-dwarf Eclipsing Binaries



M-dwarf eclipsing binary candidate SDSS *J000557.61+005246.2* - M1 dwarf, 47 observations, *r ~ 20.2*, *i ~ 19.3, z ~ 18.8*



M-dwarf eclipsing binary candidate SDSS *J000557.61+005246.2 - r* and *z* light-curves phase-folded with period 2.14 days

SN Survey: Eclipsing Binary Candidates

- As of November 2008:
  - 37 M-dwarf eclipsing binary candidates
  - Expect ~50 in total
- Spectral type range M0 to M4
  - Masses between 0.6 and 0.2 M_{sun}
  - All relatively faint objects
    - SDSS *r* between 19.0 and 23.0
    - SDSS *i* between 18.5 and 21.2

Point sources with $\geq$ 10 detections	1,151,884
Other stars	455,983
M-dwarfs	695,901
M-dwarfs classified as possible variables	109
Unknown or wrongly classified as variable	32
Flare stars or non-eclipsing variables	40
Eclipsing binary candidates	37
Of type M0	8
Of type M1	8
Of type M2	7
Of type M3	7
Of type M4	6
Of type M5 and later	1

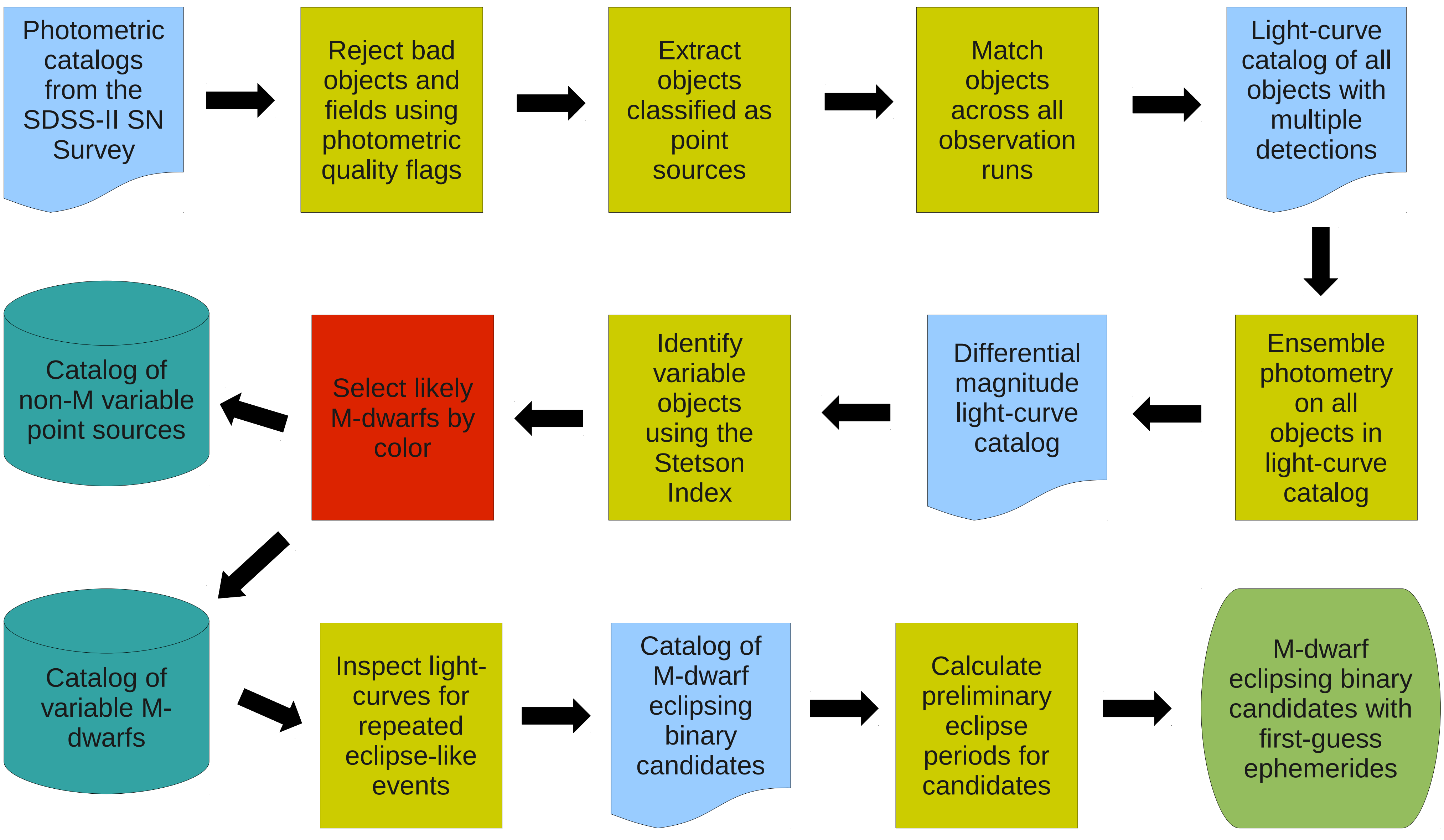
Photometric and Spectroscopic Followup

- Refine initial-guess periods for candidates using the Lowell Observatory 0.8-m telescope
- Use these periods to target brightest candidates for high time resolution observations with the APO 3.5-m telescope
  - Get high quality multi-color differential magnitude light-curves
  - Look at the colors of objects during and out of eclipse, the timing of primary and secondary eclipses, and the depths of the primary and secondary eclipses
- Use large telescopes (KPNO 4-m GC spectrograph, Gemini North 8-m GMOS, Keck 10-m HIRES) to obtain high SNR spectra
  - Measure radial velocities over several epochs to get masses
  - Measure other properties (temperature, surface gravity, chemical composition)

Conclusions

- Models of low-mass stars in binary systems do not agree with observations of their fundamental properties.
  - There are uncertainties in the mass-radius and the mass-temperature relations in particular.
  - More observations of these kinds of systems are needed.
- The SDSS-II Supernova Survey provides a unique opportunity to identify many candidate eclipsing binary systems (especially those consisting of M-dwarfs).
  - We have identified 37 candidates and expect about 50 in total.
  - We expect to precisely measure the masses, radii, and luminosities of at least 10 of these, yielding fundamental properties for ~20 stars.
- These systems will enable tests of low mass stellar structure and evolution models focusing primarily on the effects of large magnetic fields and star spots on stars in close binary systems.

SN Survey: Data Reduction

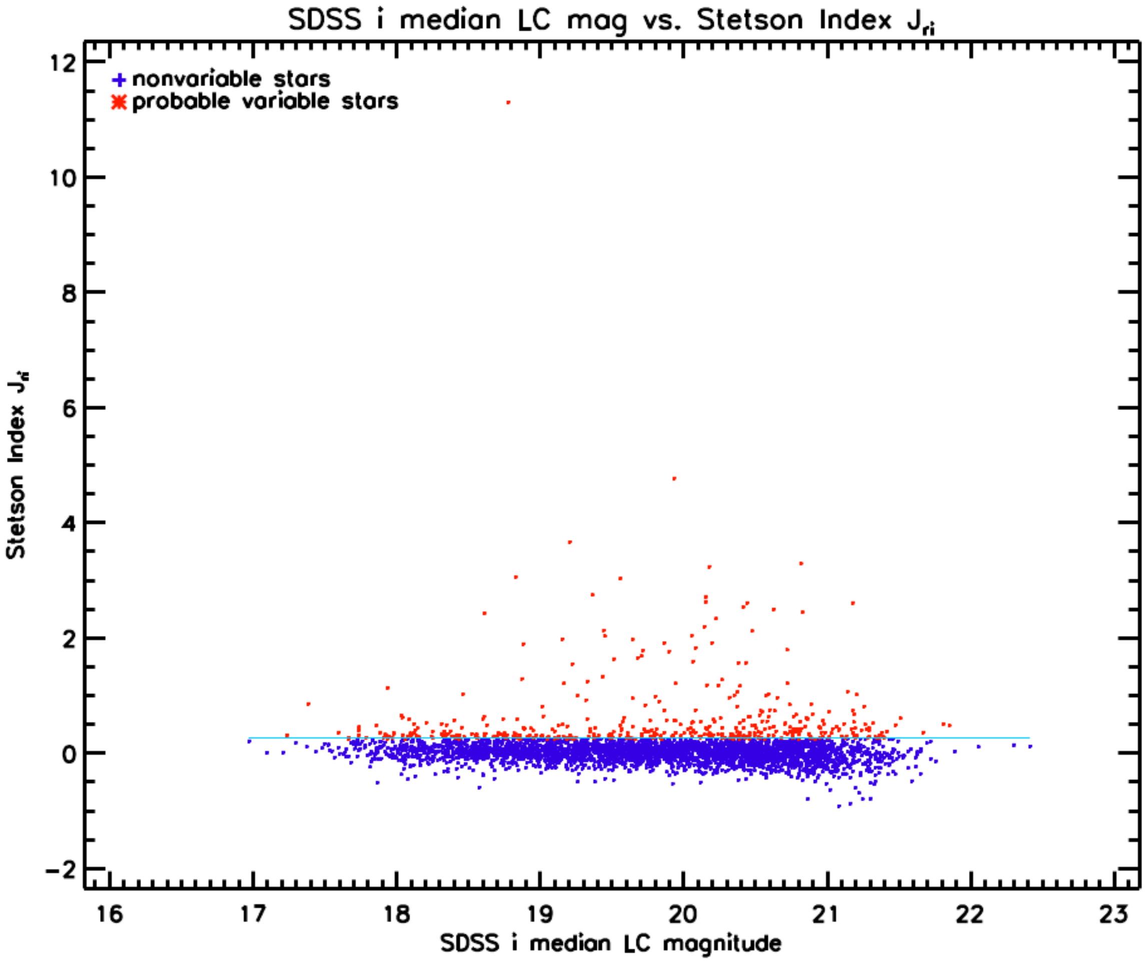


SN Survey: Ensemble Photometry

- Survey sacrifices photometric precision for temporal coverage
  - Observe during bad nights (i.e. high sky brightness due to the Moon, mild cloud cover, bad seeing, etc.)
  - Introduces systematic variability (for all objects on night) that can be confused for the real thing when looking at light-curves
- Ensemble photometry corrects for these night-to-night variations in photometric quality
  - Select an ensemble of neighbor stars around the target star
  - Calculate a weighted ensemble average magnitude
  - Subtract this from target star magnitude
  - Normalize to brightest star in ensemble
- Resulting differential magnitude is independent of systematic variations
- Improves photometric precision

SN Survey: Finding Variables

- Find variables in two steps:
  - Tag possible variables by looking at differential magnitude light-curve error vs. object median magnitude curves from ensemble photometry
    - These objects will have large LC errors
  - Use the Stetson Variability Index
    - A measure of correlated deviations in pairs of filters in a multi-color time-series of observations
    - Real variables have larger index values
    - Set a threshold index value and call all objects above that probable variables

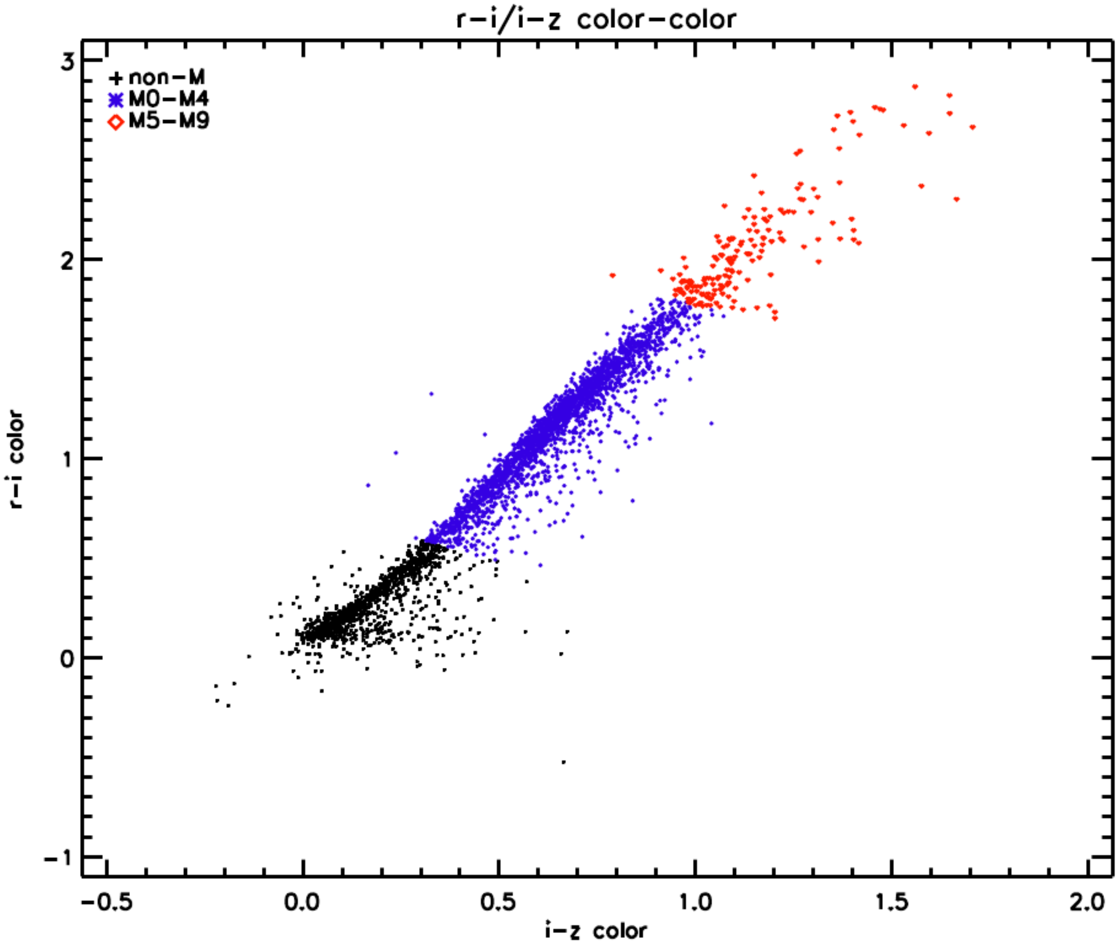


$$J_{\alpha\beta} = \frac{\sum_{k=1}^{n} w_k \, \mathrm{sgn}(P_k^{\alpha\beta}) \sqrt{|P_k^{\alpha\beta}|}}{\sum_{k=1}^{n} w_k}$$

$$P_k^{\alpha\beta} = \sqrt{\frac{n_\alpha}{n_\alpha - 1}} \sqrt{\frac{n_\beta}{n_\beta - 1}} \left(\frac{\alpha_k - \bar{\alpha}}{\sigma_{\alpha,k}}\right) \left(\frac{\beta_k - \bar{\beta}}{\sigma_{\beta,k}}\right)$$

SN Survey: Selecting M-dwarfs

- Select M-dwarfs by color
  - Use SDSS *r-i* and *i-z* color cuts from West et al. 2005
  - Reasonable guarantee that we are selecting dwarfs and not giants
- Select eclipsing binary candidates
  - Look for repeated eclipse-like events in *r*, *i*, and *z* differential magnitude light-curves
  - Demand at least 5 such events over 3 seasons



Mass-Temperature Relation