M Dwarf Eclipsing Binary Candidates from the SDSS-II Supernova Survey

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Collaborators and Co-conspirators

- Johns Hopkins University
  - Holland Ford
  - Justin Rogers
  - Emma Marcucci
- Space Telescope Science Institute
  - Larry Petro
- Rochester Institute of Technology
  - Michael Richmond
- Various unsuspecting ACS workstations I've run my pipeline on...

Outline

- Stellar Populations and M Dwarfs
- Eclipsing Binaries
- SDSS-II SN Survey
- Data Reduction
  - Cleanup
  - Selecting Targets
  - Problems
  - Ensemble Photometry
- Finding Variable Objects
- Identified M Dwarf Binary Candidates
- Work in Progress
- Future Work

M Dwarfs: Stellar Populations

- Stars classified by spectral features
  - Roughly by temperature
- On the main sequence (dwarf stars):
  - O & B stars: young, high mass stars, hot, blue
  - A & F stars: high mass, white stars
  - G & K stars: yellow, solar mass, solar age
  - M stars: red, low temperature, low mass, highly active, long-lived stars

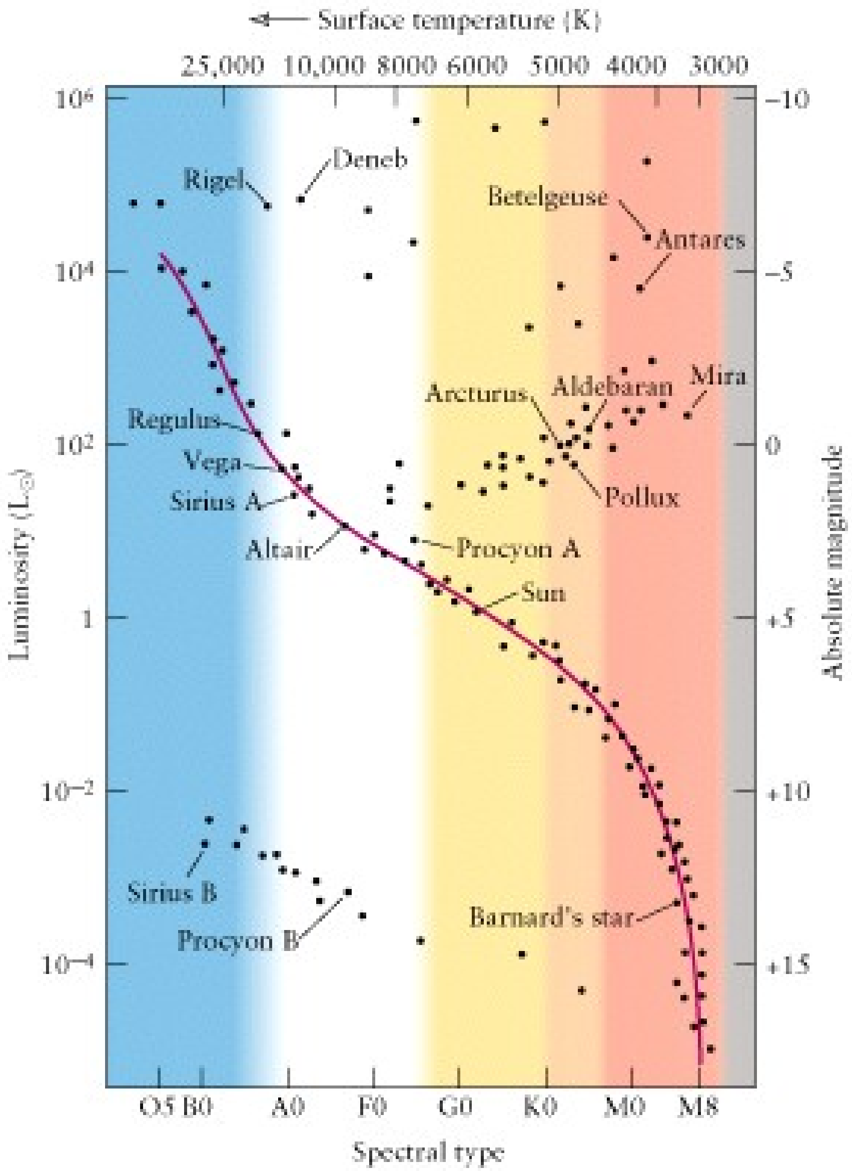

Figure from Kaufmann & Freedman, *Universe (6e)*, W. H. Freeman, 2001

M Dwarfs: Low Mass Stars

- Long lived stars
  - Take a long time to get to the main sequence (0.04 – 0.7 Gyr)
  - Burn H slowly: live on the main sequence practically forever
    - By number, most common type of star in the Galaxy
  - Low temperatures: 2,500 – 4,000 K (photosphere)
  - Low mass (0.1 – 0.6 Msun)
  - Small radius
    - Intrinsically faint
    - Hard to see

M Dwarfs: Theory vs. Observations

- Properties under study:
  - Mass, radius, luminosity
  - Temperature, metallicity, age
- Problems:
  - Underestimate radii by ~ 10% (obs err ~ 3%)
  - Overestimate temperature by ~ 5%
  - Mass-luminosity relation has high scatter
  - Need to explain high stellar activity

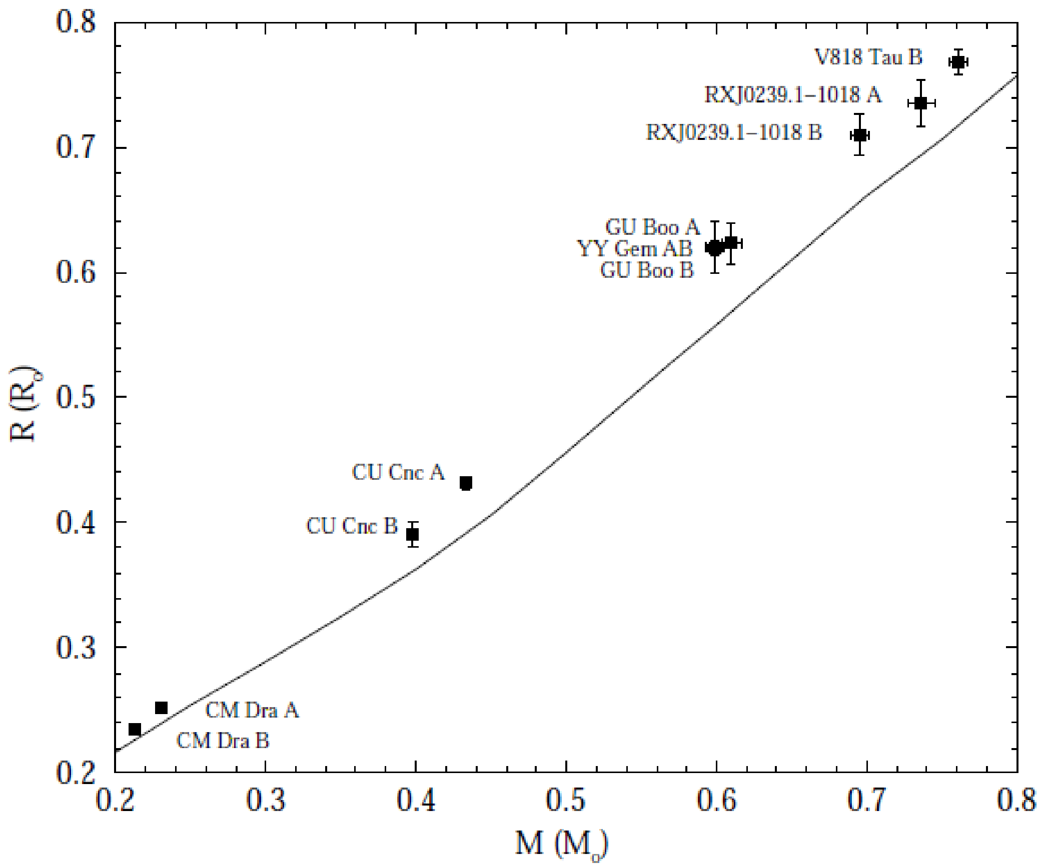

Figure from Ribas, 2006, ASP Conf. Ser., Vol. 999

Eclipsing Binaries: Why Bother?

- Observe via photometry and spectroscopy
- Photometric monitoring:
  - Gives relative radii of stars (primary & secondary eclipse)
  - Gives period of orbit
  - Gives relative luminosities, temperatures
- Spectroscopic observation:
  - Gives the period of the orbit, get semimajor axes
  - Gives masses of stars
  - Gives metallicity
  - Gives age and activity indicators

Eclipsing Binaries: Expected Numbers – I

- Expected number of detected M dwarf binaries is a function of:
  - Number of stars surveyed
  - Fraction of these that are M dwarfs
  - Fraction of these that are binary stars
  - Distribution of binary periods (and semimajor axes)
    - We're looking for short period binaries
  - Fraction of these binary systems that are geometrically favorable for eclipses
  - Fraction of these that can be detected given our temporal sampling
  - Fraction of these that are bright enough to be above our detection threshold and don't get lost somewhere in the data

$$N_{det} = N_{stars} f_{Mstars} f_{binary}(P) f_{geom} f_{window} f_{threshold}$$

Eclipsing Binaries: Expected Numbers – II

$$N_{det} = N_{stars} f_{Mstars} f_{binary}(P) f_{geom} f_{window} f_{threshold}$$

- Detailed Monte Carlo simulations give better estimates
  - We'll do a rough estimation instead (likely very optimistic)
- Nstars: estimate from number of stars we have in the survey
  - ~ 900,000 total stars
- Fraction of M stars: again, estimate from the survey
  - Color selection gives ~ 520,000 M stars = fraction = 0.59
- Total binary fraction: look at what people have found
  - ~ 35% of mid M dwarfs have binaries (Henry & McCarthy 1990)
  - ~ 10% of late M dwarfs have binaries (Bouy, Gizis 2003)
  - We'll say 25% of all M dwarfs have a binary companion
    - Need to modify this by looking at distribution with period

Eclipsing Binaries: Expected Numbers – III

$$N_{det} = N_{stars} f_{Mstars} \boxed{f_{binary}(P) f_{geom} f_{window} f_{threshold}}$$

- Distribution of binaries by period:
  - Surveys of clusters show more binaries at shorter periods (Yan & Mateo 2003)
  - Distribution follows: $\frac{df}{d(\log P)} = \beta_0$
  - Concentrate on binaries with periods of 2.5 days to 7 days
  - 2.2% of M dwarfs are binaries with these periods
    - Use this binary fraction
- Fraction of these binaries that are geometrically favorable for eclipses:
  - Combine with window function & do Monte Carlo simulations
    - ~ 7% of binaries with the above periods are favorable
- Say we can detect 10%

Expected # of M dwarf binaries ≈ 80

SDSS-II SN Survey: Overview

- Northern sky photometric (& spectroscopic) survey
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  - 2.5- ... Mexico
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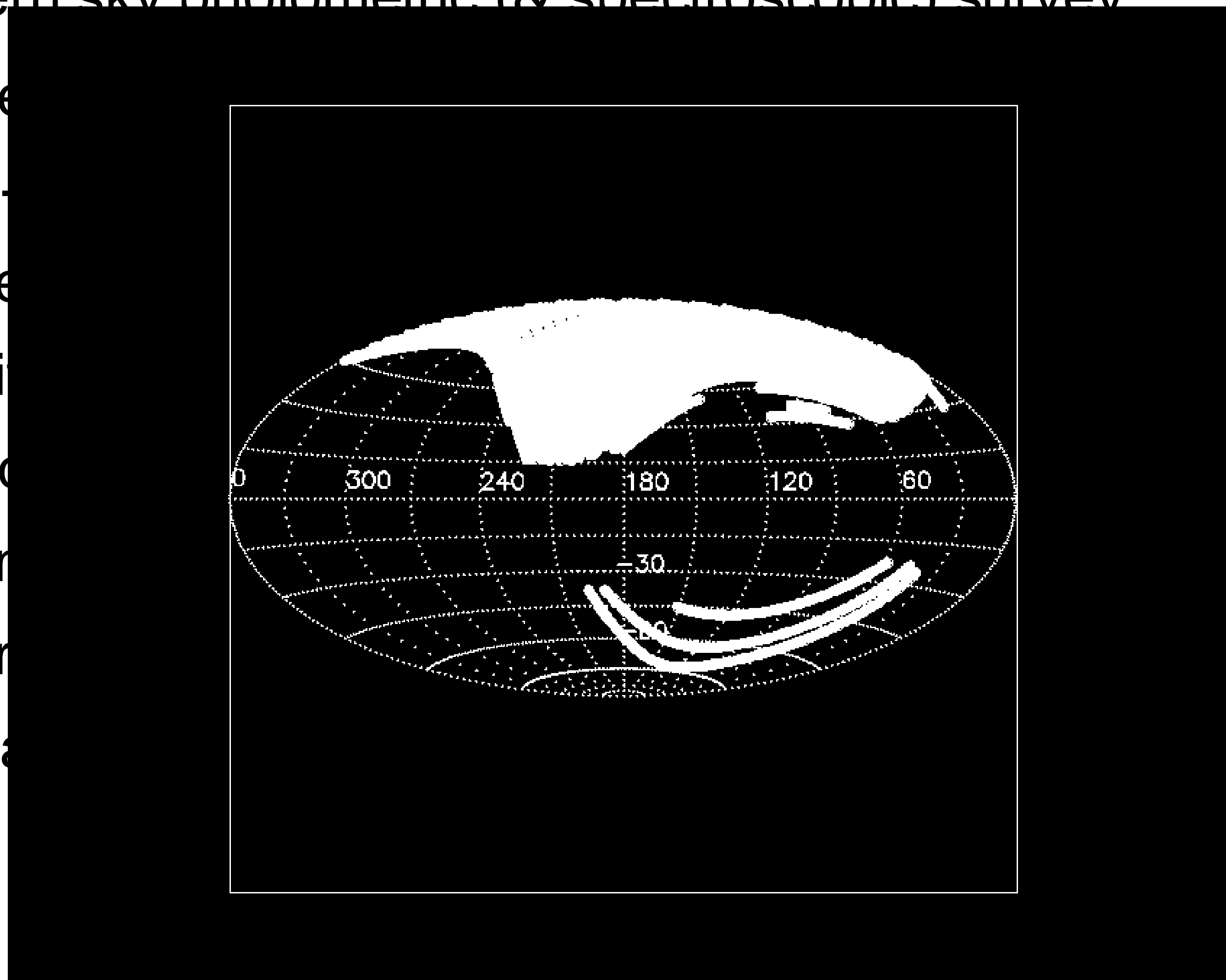
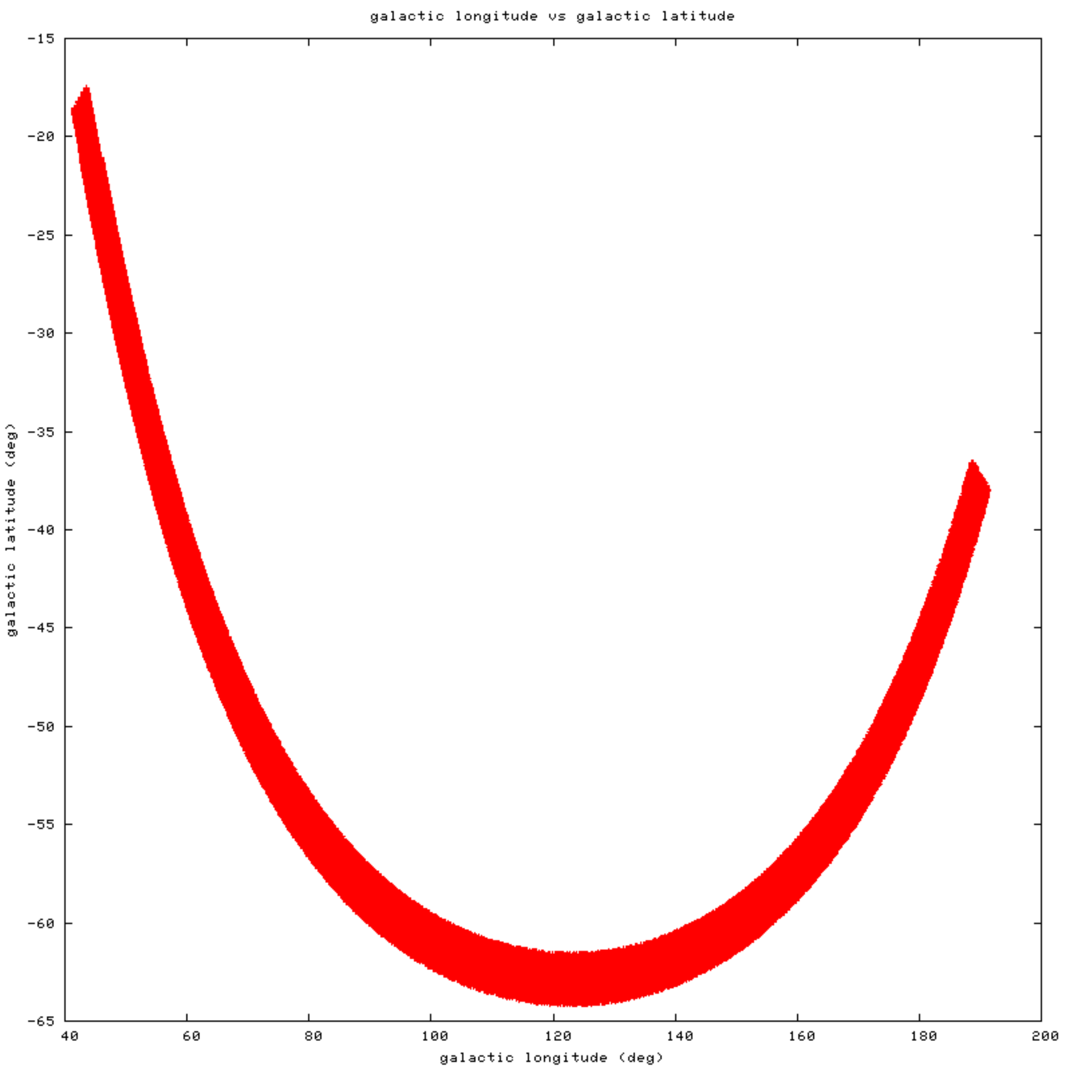
  - All a ... dss.org



Images from http://www.sdss.org/dr6/

SDSS-II SN Survey: Stripe 82

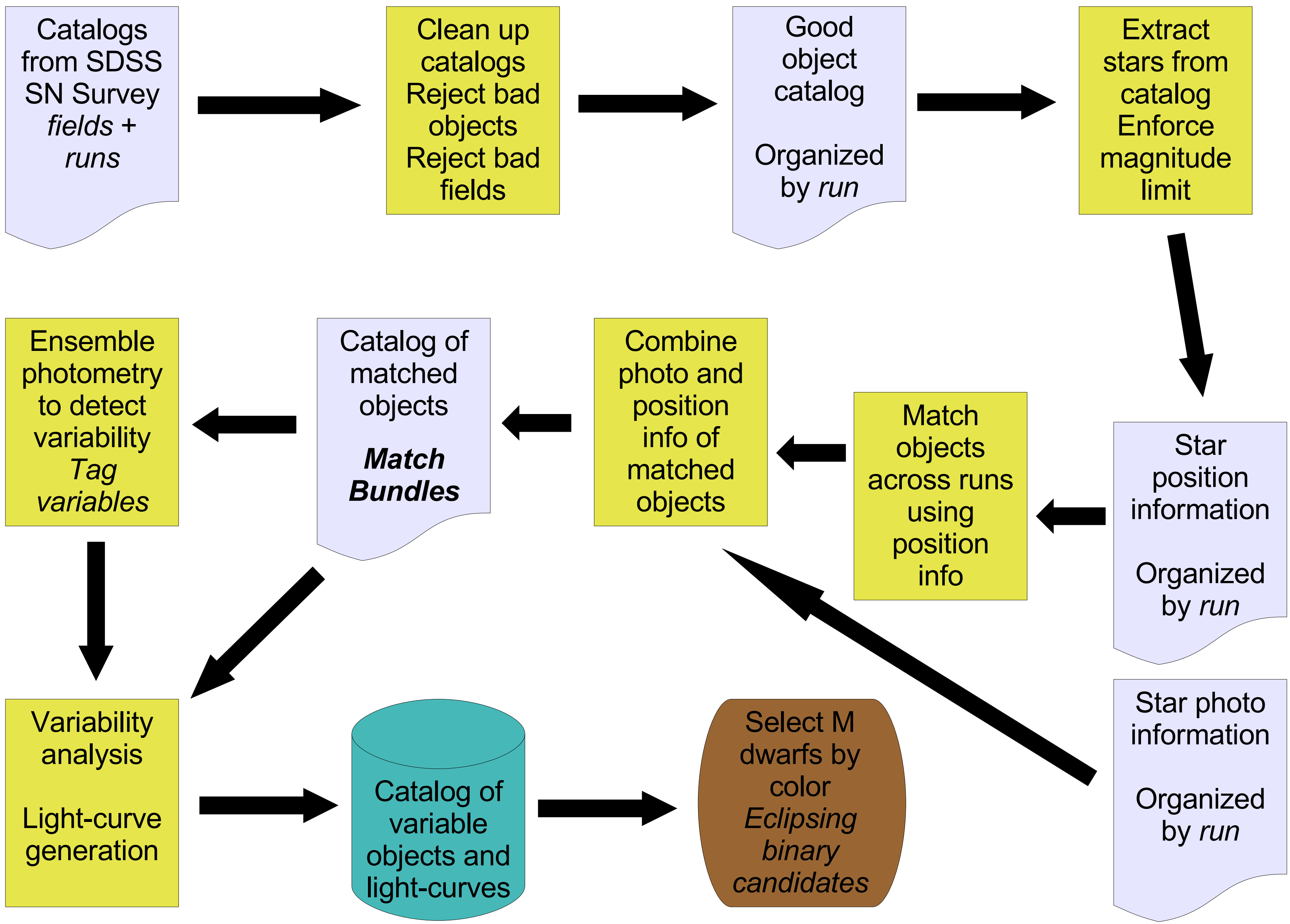
- SDSS catalogs are mostly single-epoch
  - Need time-series photometry for variability studies
- SDSS-II Supernova Survey (2004-2007)
  - Survey 300 sq deg of sky
  - Repeated scans
    - 3 seasons
    - ~ 60 nights per season
    - 2/3 nights between observations



The Data: SN Survey Products

- Supernova Survey data not accessible via the SDSS database server
  - Go to the source (FNAL) and download photometric catalogs
  - ~ 600 GB data per season
- Photometric catalogs in binary FITS tables:
  - One night of data = one *run*:
    - Continuous scan across the entire sky (sometimes partial)
    - Several hundred *fields* (13' x 10')
    - Each field has about 2,000 objects
    - Stars + galaxies + junk all included
  - Information for each object:
    - Position (ra, dec) + unique object identifiers
    - Photometry (magnitudes in all five bands)
    - Data quality flags + night photometric quality flags

The Data: Reduction Pipeline

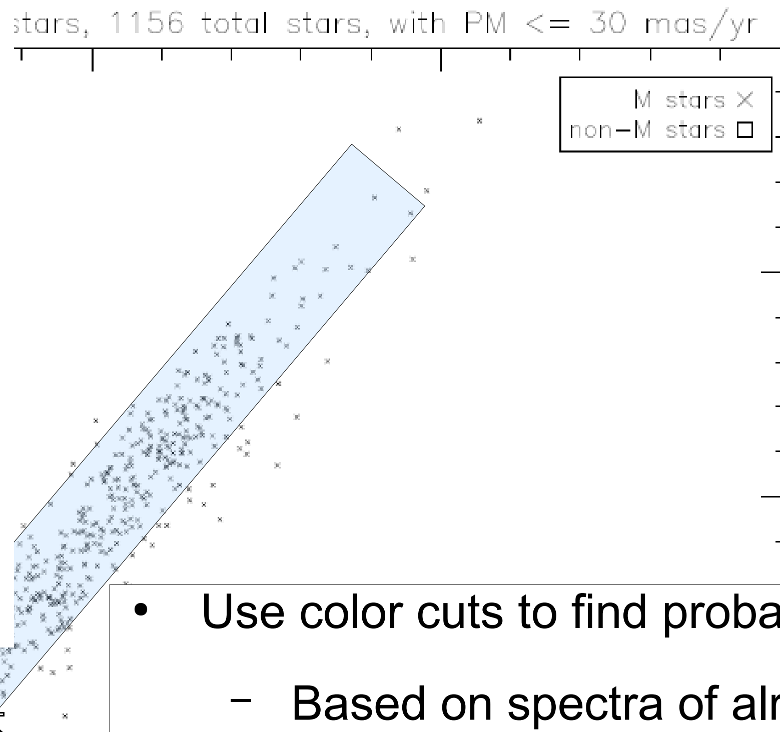


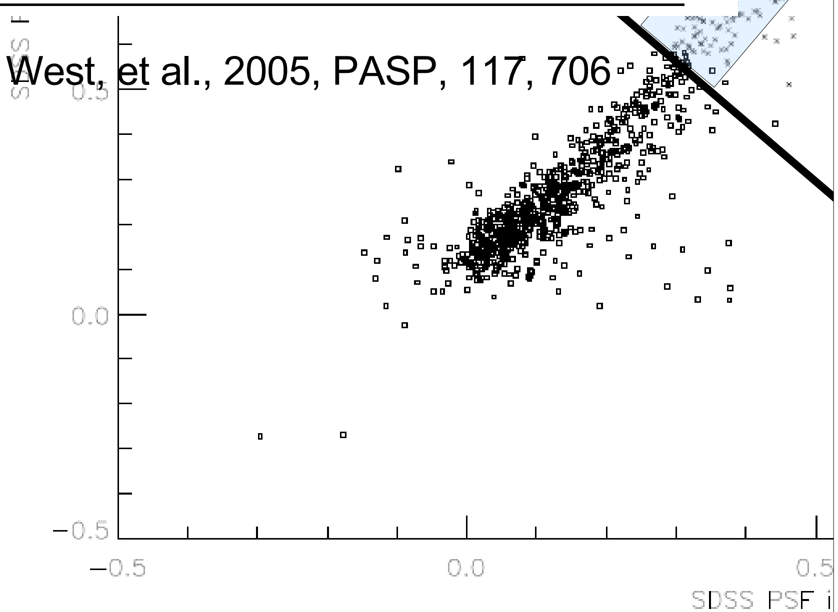
The Data: Selecting M Dwarfs

TABLE 1
AVERAGE COLOR BY SPECTRAL TYPE

Spectral Type	$r - i$	$i - z$	$z - J$	$i - J$	M_J
M0	0.67 (0.14)	0.37 (0.06)	1.45 (...)	1.92 (...)	6.45
M1	0.88 (0.15)	0.48 (0.13)	1.34 (0.09)	1.89 (0.05)	6.72
M2	1.03 (0.18)	0.58 (0.18)	1.45 (0.17)	2.10 (0.23)	6.98
M3	1.33 (0.30)	0.70 (0.31)	1.46 (0.15)	2.14 (0.15)	7.24
M4	1.51 (0.22)	0.84 (0.22)	1.57 (0.14)	2.47 (0.16)	8.34
M5	1.91 (0.14)	1.05 (0.09)	1.66 (0.09)	2.75 (0.12)	9.44
M6	2.01 (0.14)	1.10 (0.07)	1.76 (0.09)	3.02 (0.22)	10.18
M7	2.27 (0.20)	1.26 (0.12)	1.95 (0.15)	3.46 (0.24)	10.92
M8	2.77 (0.16)	1.62 (0.12)	2.05 (0.13)	3.71 (0.22)	11.14
M9	2.81 (0.28)	1.69 (0.07)	2.23 (0.09)	4.05 (0.13)	11.43
L0	2.63 (0.27)	1.84 (0.08)	2.28 (0.09)	4.24 (0.10)	11.72
L1	2.61 (0.27)	1.83 (0.09)	2.51 (...)	4.41 (...)	12.00
L2	2.39 (0.18)	1.80 (0.17)	2.57 (0.11)	4.43 (0.12)	12.29

Table from West, et al., 2005, PASP, 117, 706





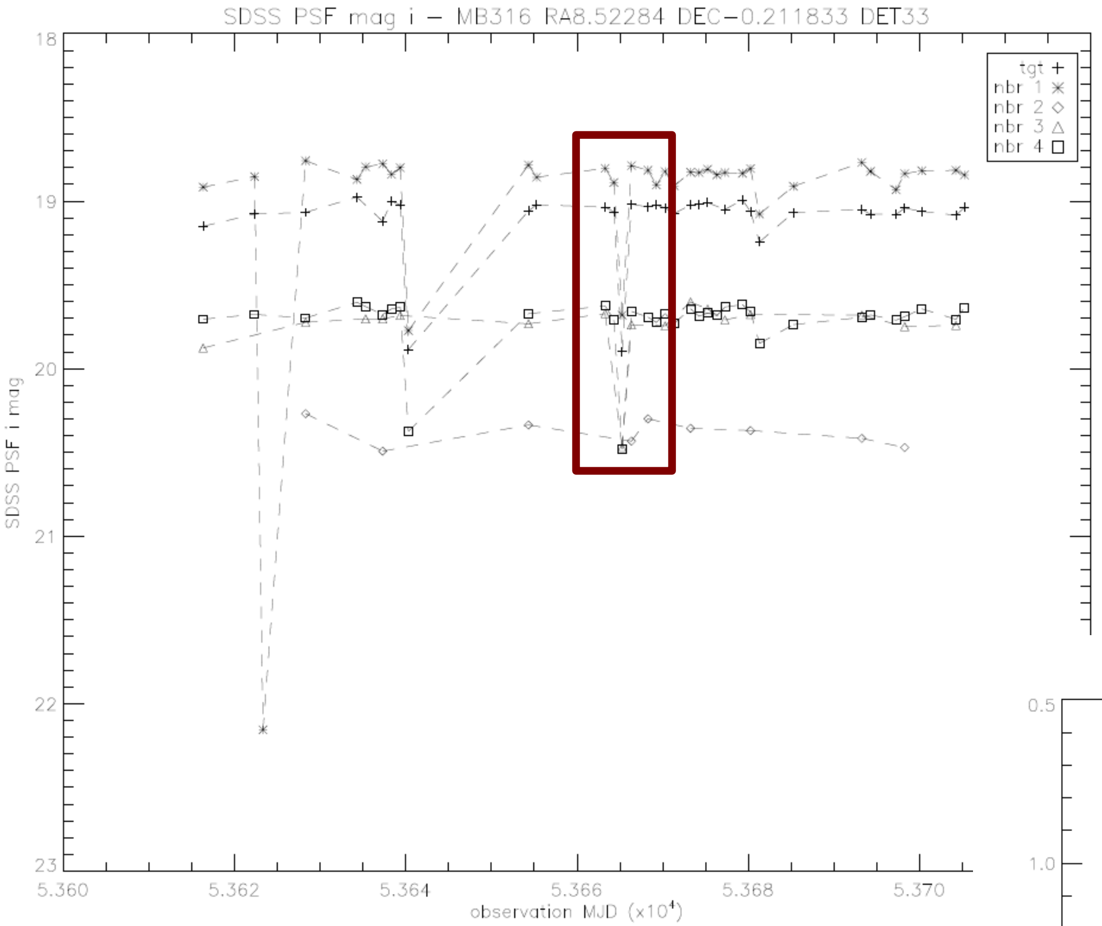
- Use color cuts to find probable M dwarfs
  - Based on spectra of already observed M dwarfs in the SDSS
  - Sloan *r-i* color and *i-z* color are good
- Anything redder than *r-i* = 0.67 and *i-z* = 0.37 is probably an M star
  - Enforce a bright limit to keep out nearby stars
  - Can also use proper motions to select foreground objects

The Data: Problems

- Photometric uniformity
  - Not as nice as we had hoped
  - Optimized for detection of SNe
    - Lowered standards for seeing, sky brightness
    - Hard to make light-curves out of raw SDSS measurements
    - Systematic effects over time
- Temporal uniformity
  - Inconsistent cadence
    - Return to each field every 2 or 3 nights (or a week later)
    - Continuous monitoring not possible
    - Hard to detect *periodic* variability over this kind of baseline

Ensemble Photometry – I

- Try to remove systematic variations from night to night
- Use ensemble photometry
  - Scaled up version of differential photometry
  - Uses many comparison stars
- Ensemble photometry
  - Pick a star and find all neighbors that were observed on the same night in the same field
  - Calculate an ensemble average magnitude using neighbors
    - Do this for each band separately
    - Try to select neighbors carefully
  - Subtract ensemble average from target magnitude
  - Resulting *differential* magnitude for target excludes systematic effects for the observed field



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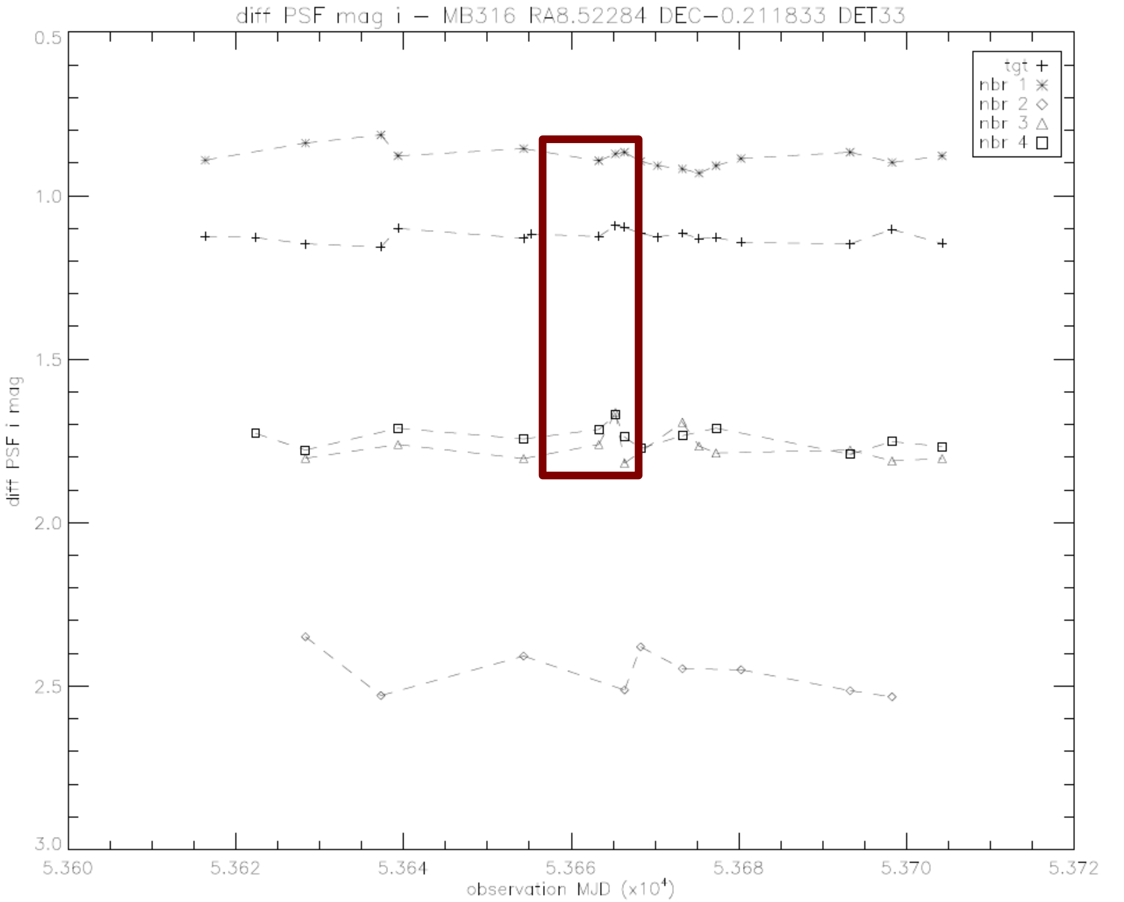
S light-curves



Variability: Stage 1

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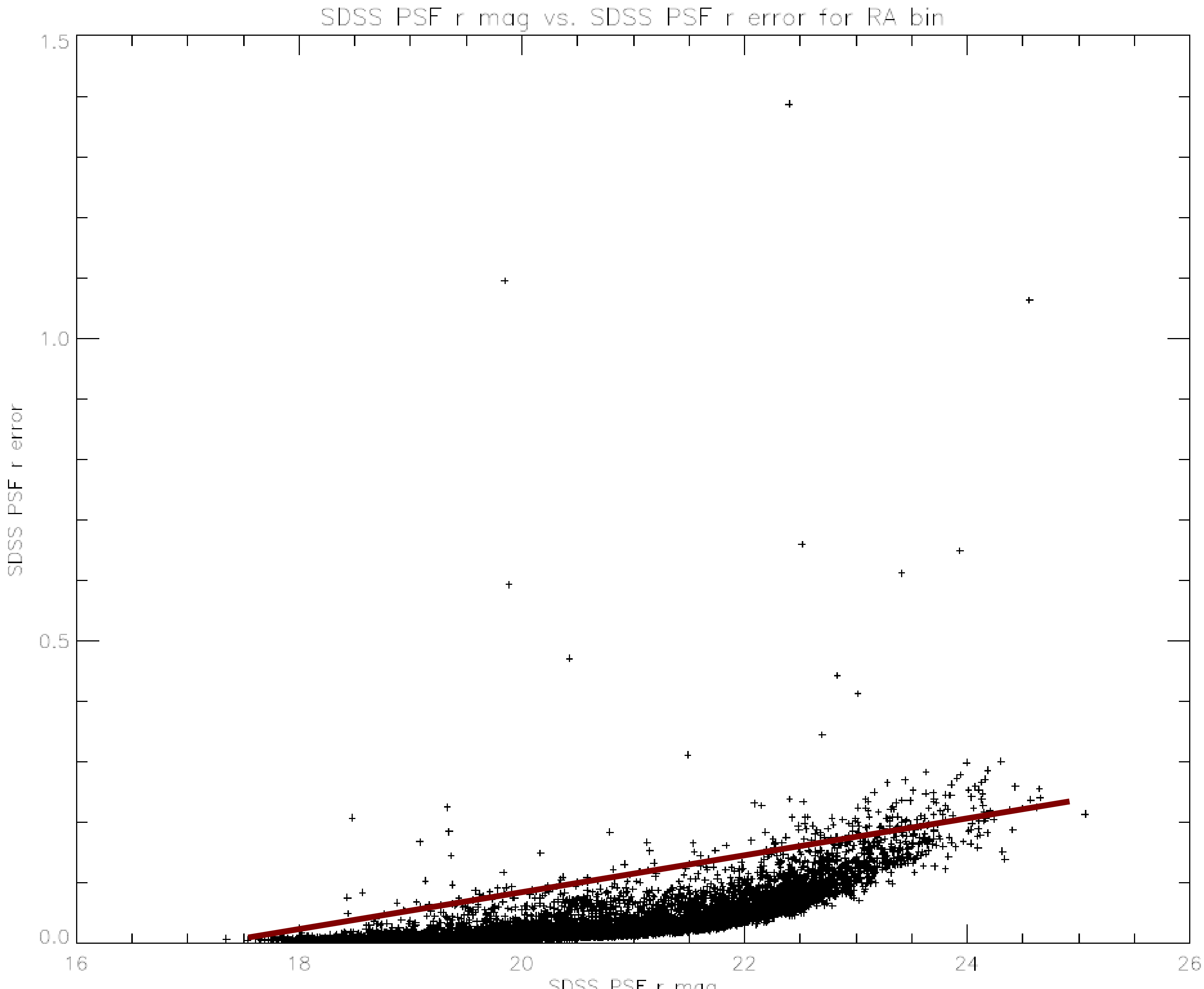
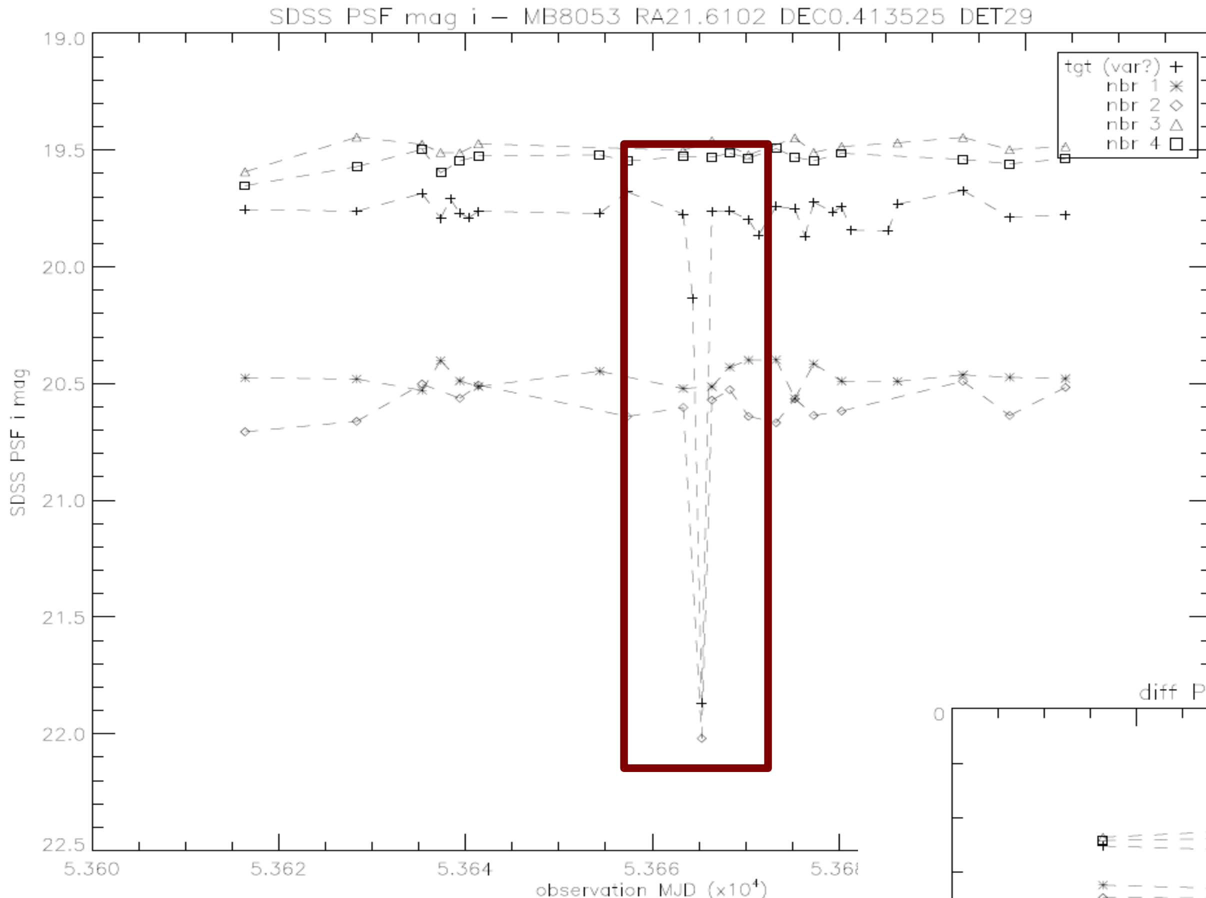


age 2

e photometry

2 sigma in the r, i, and z

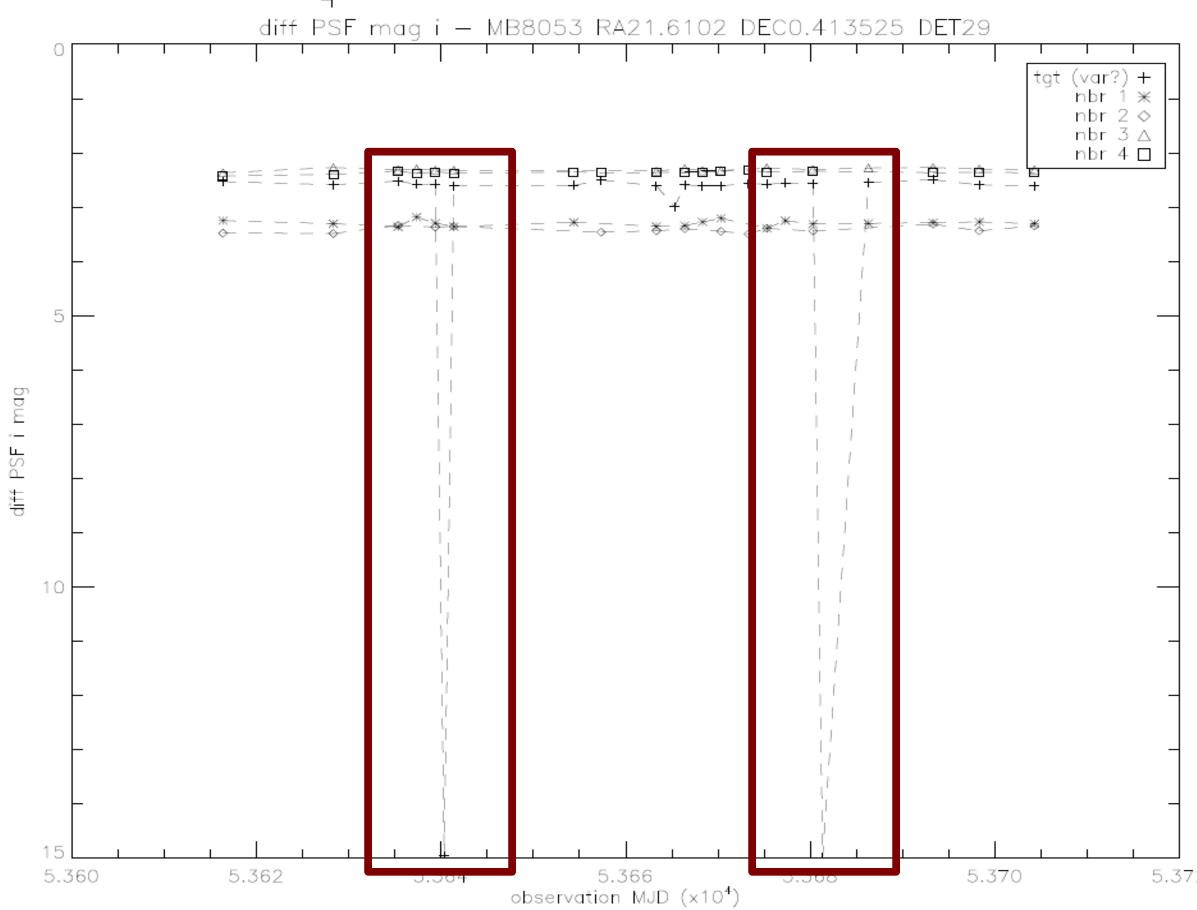
t a filter artifact



photometric noise f

– Sanity check neede

- See if ensemble st
- See if neighbors w

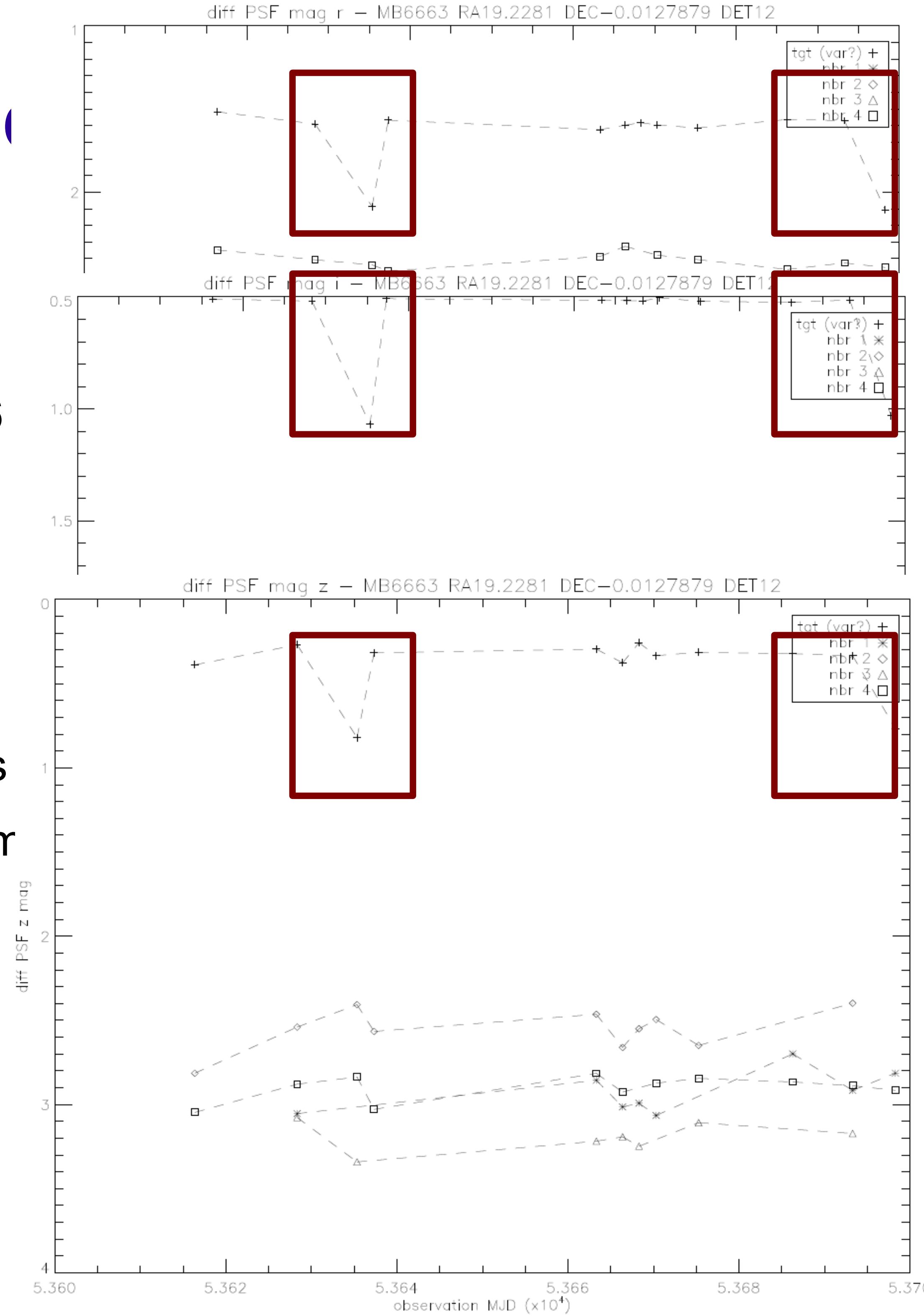


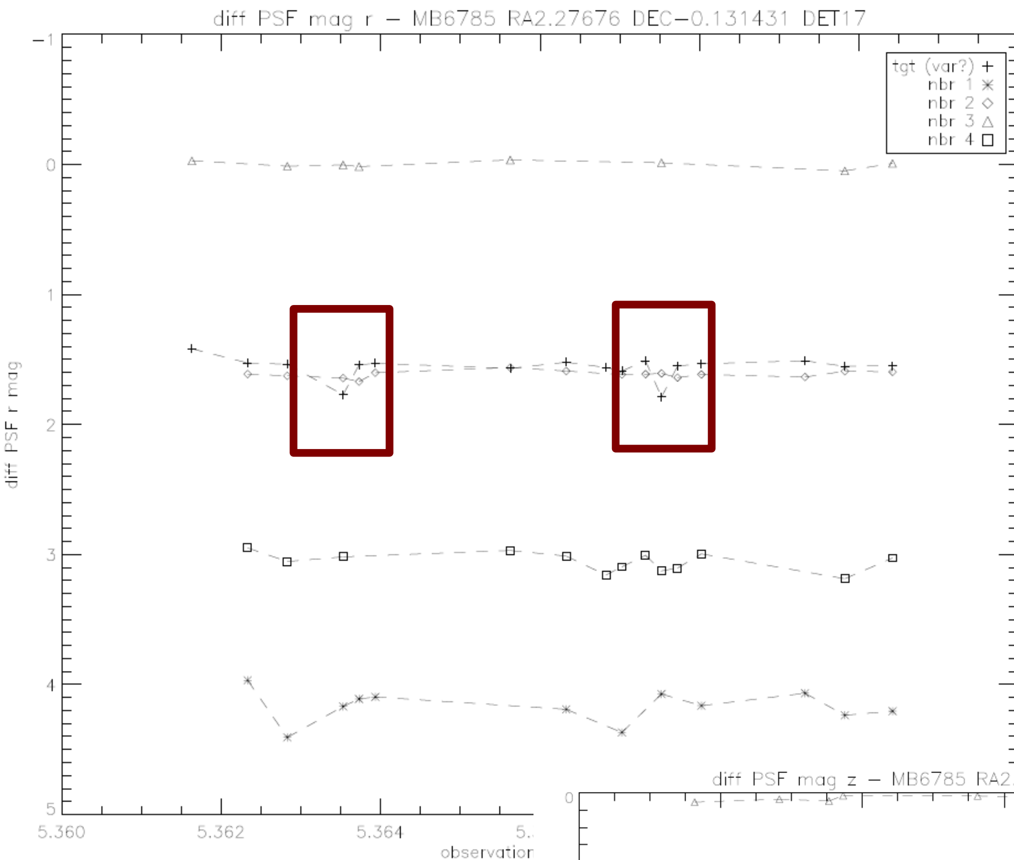
Variability: Stage 3

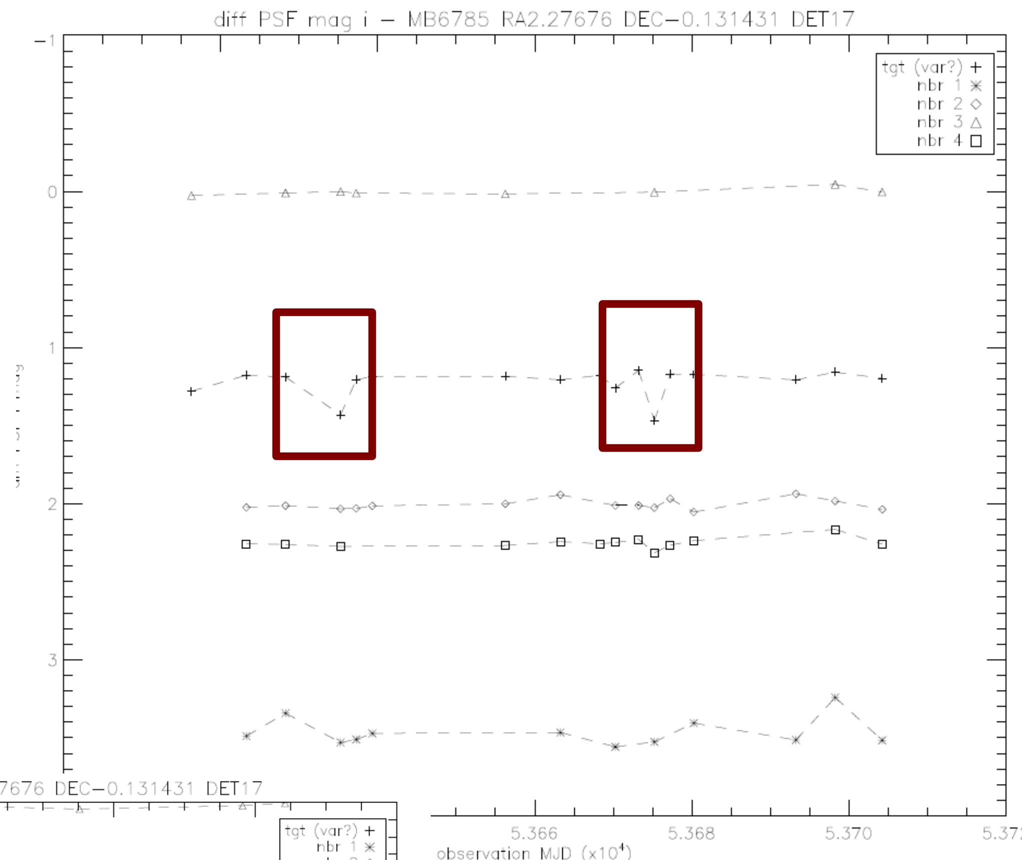
- Need to find *periodic* variables
  - Constrain periods from sparsely sampled light-curves
  - Unrealistic to expect many eclipsing events
- Require *three* eclipse events in a *differential* light-curve, seen simultaneously in *r*, *i*, and *z* band
  - Period constrained to the longest duration between two of these events
  - Better if three events with equal spacing in between
- These will be very rare

Candi

- MB6663
  - M3 dwarf
  - SDSS *g* average mag = 19.56
  - SDSS *z* average mag = 17.67
  - 12 observations
  - Tagged as variable by ensemble photo
  - 2 possible events, in *riz* bands
    - Need a third one to confirm variability





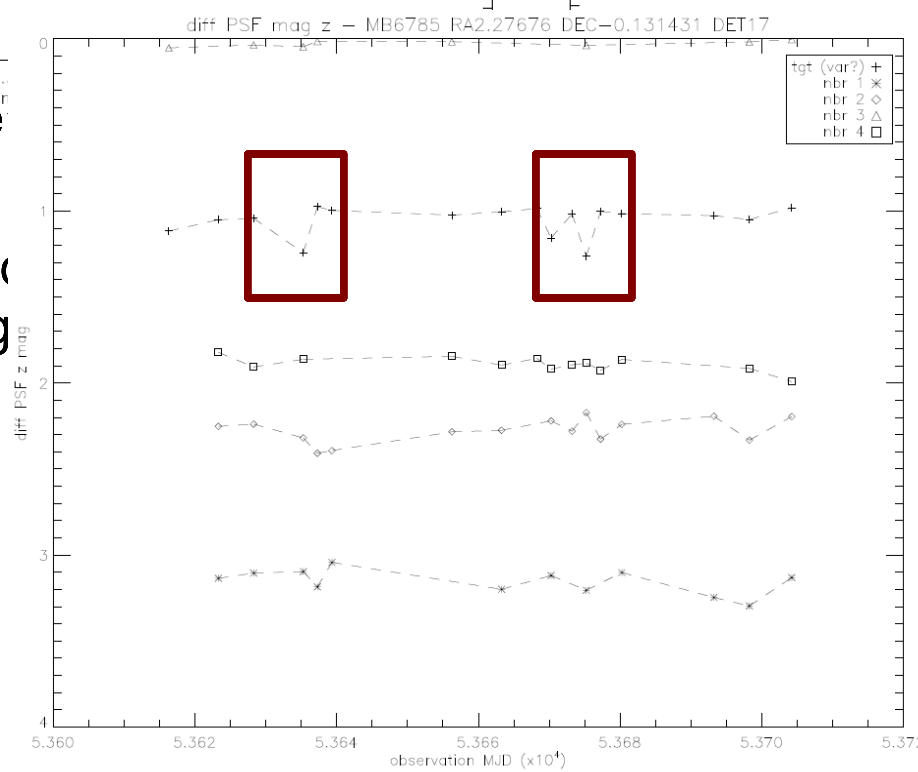


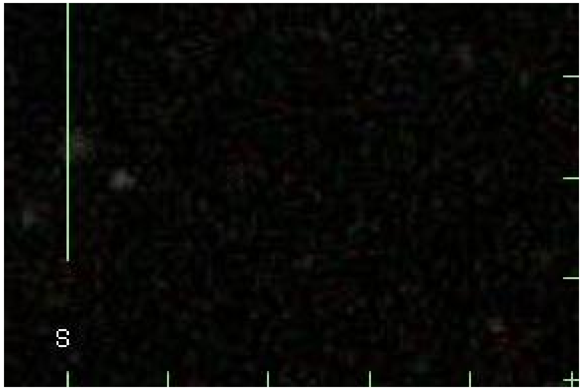
– 2 possible e

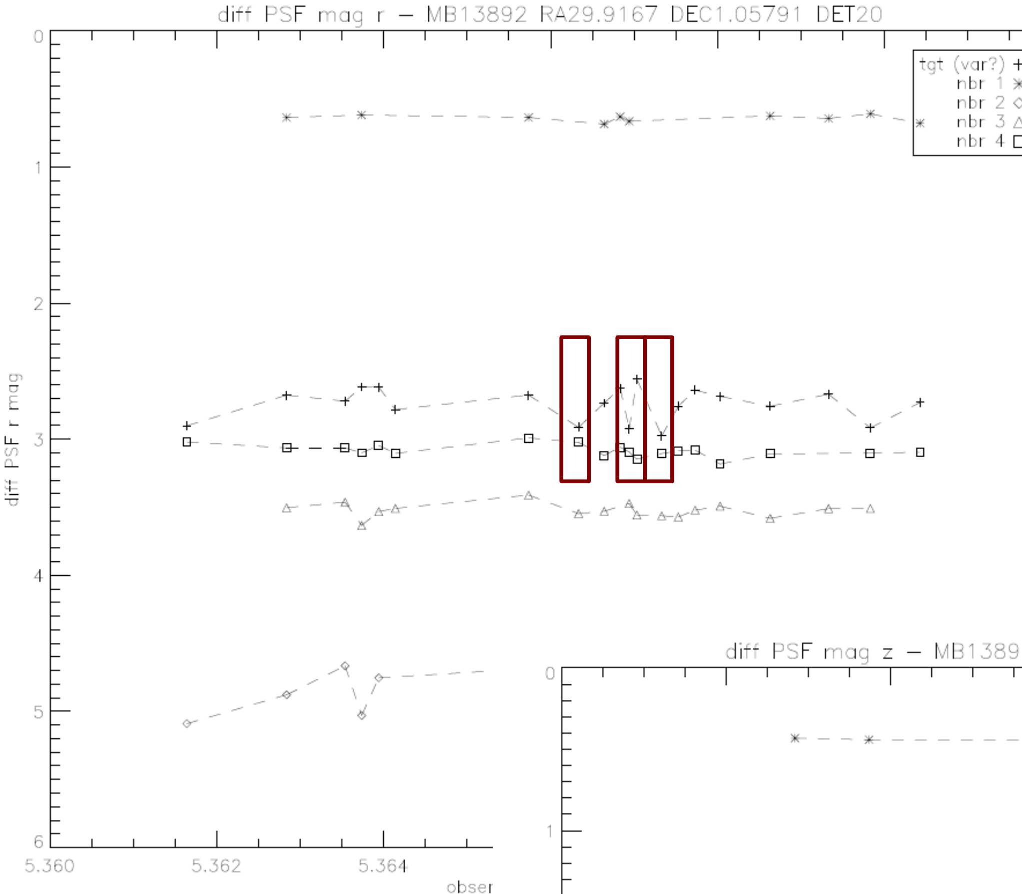
bands

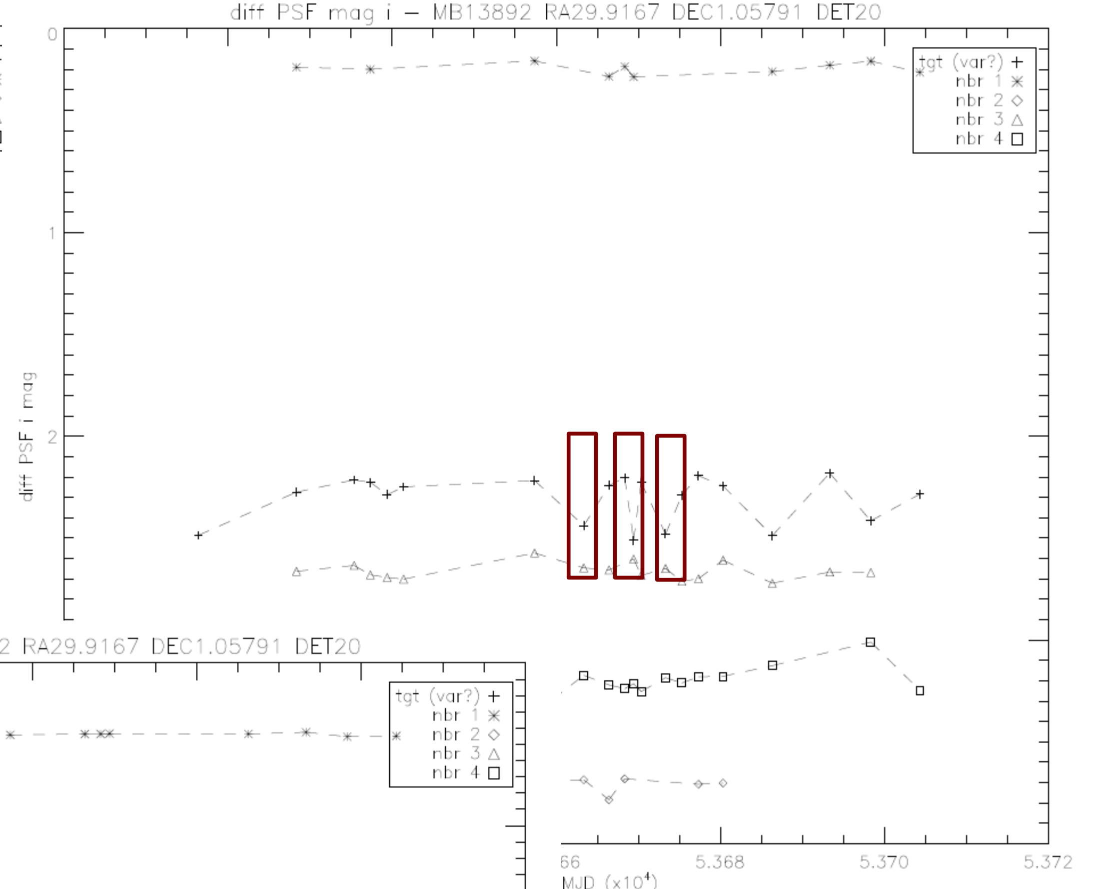
- Still need

anything









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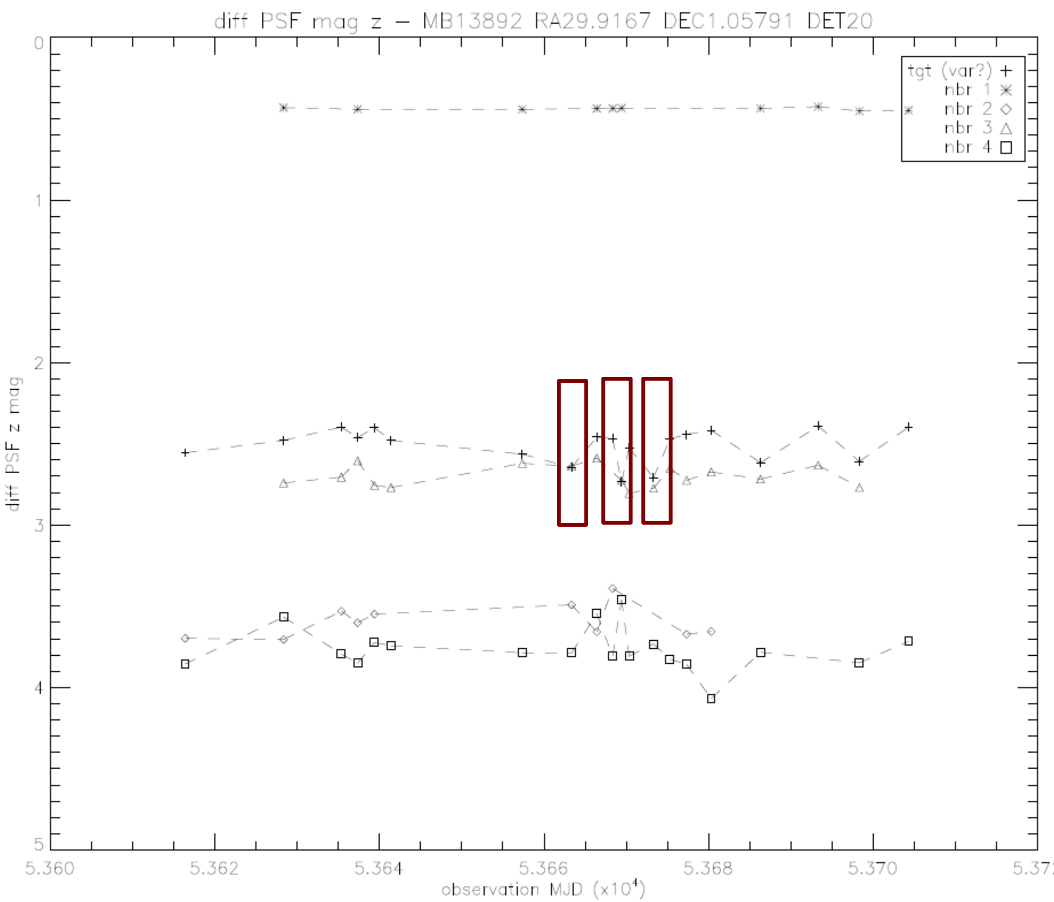

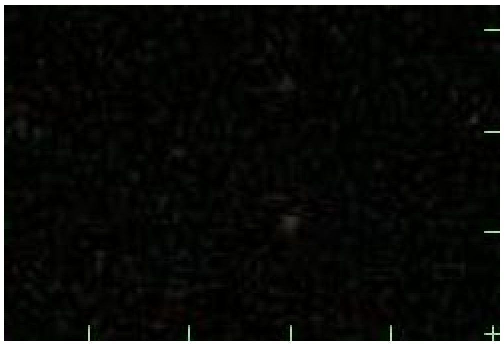

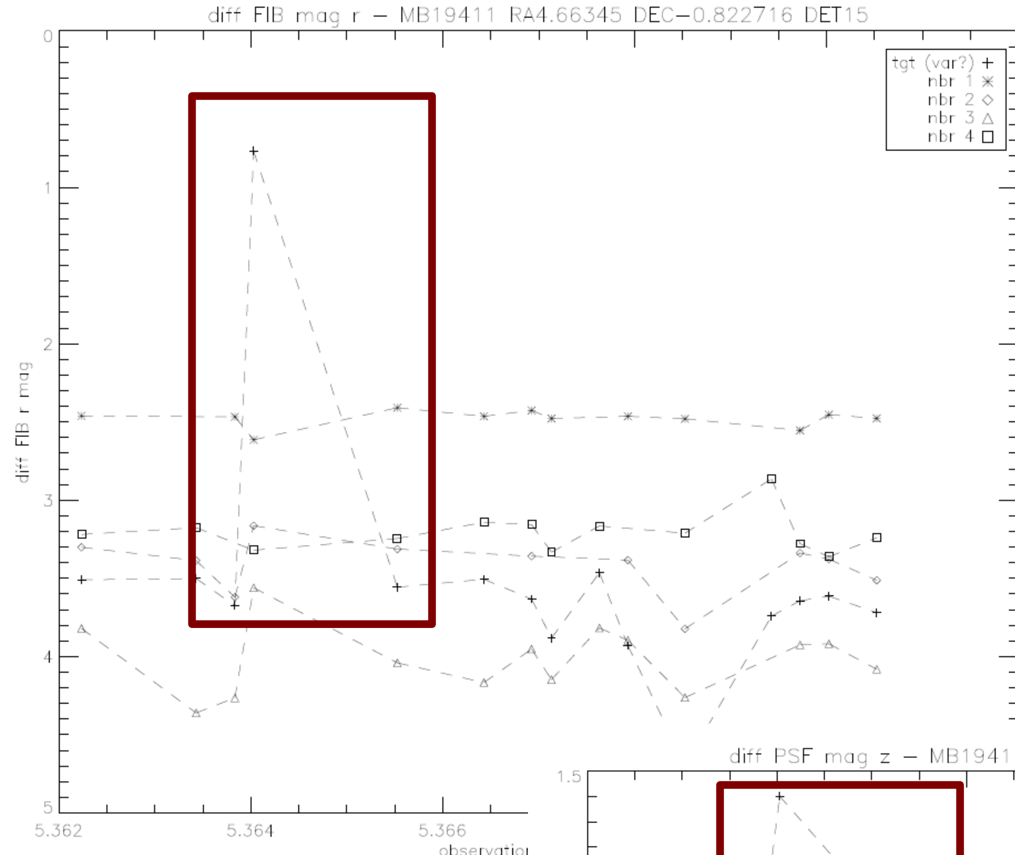

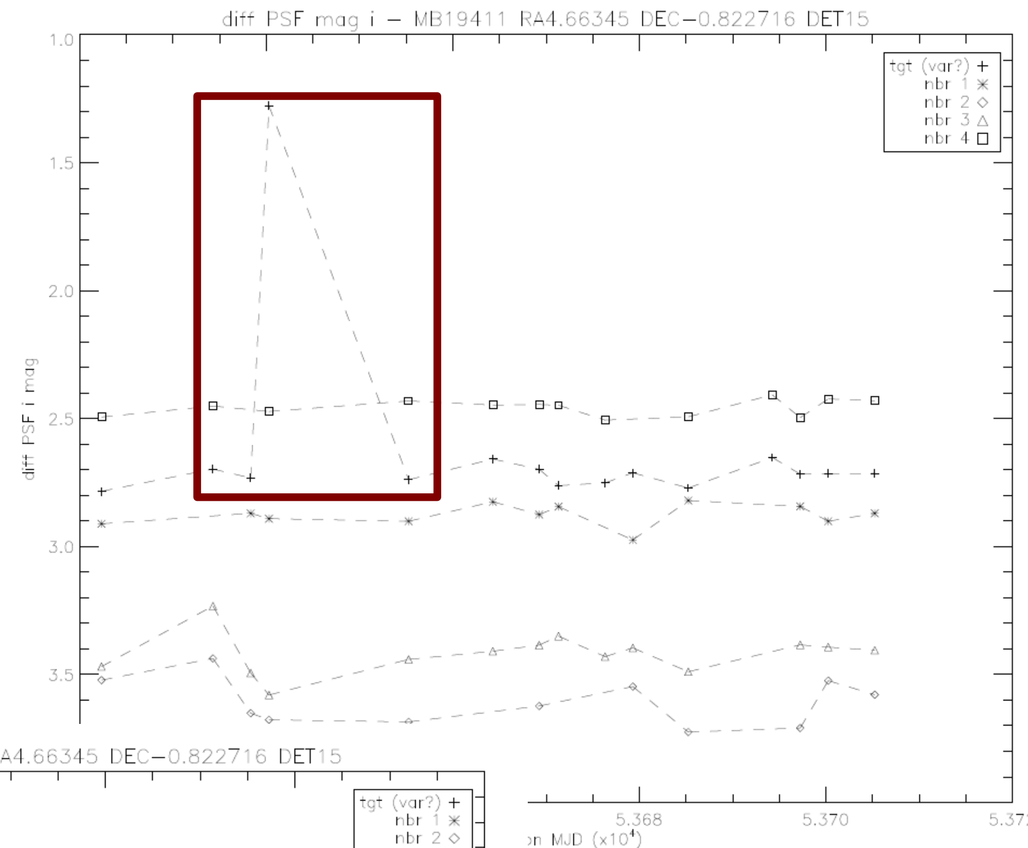

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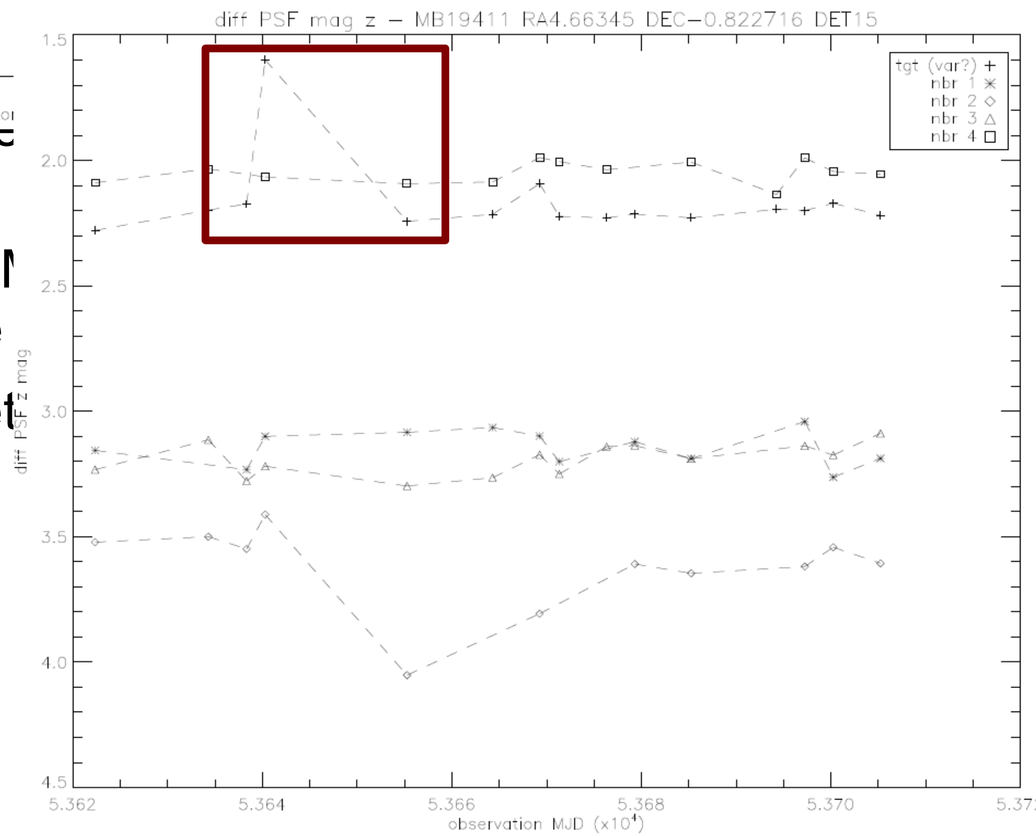

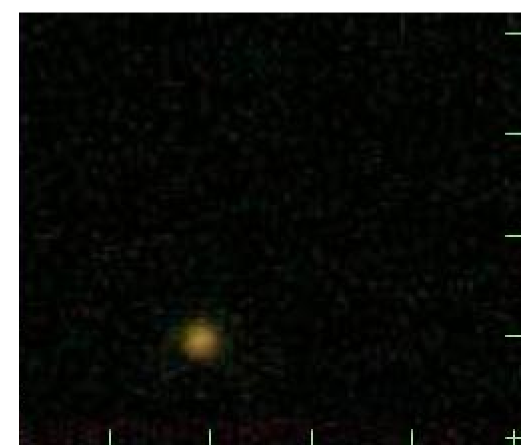

Work in Progress

- Understand the M dwarf binary fraction
  - Look at open clusters
  - Try to obtain the binary fraction in several clusters and nail down the expected value for stars in our survey
- Understand the window function
  - See how the time-sampling of observations affects our ability to detect transits
  - Monte Carlo simulations
- Figure out how many M dwarfs we expect
  - How does the number we have in our survey compare to predictions from Galaxy models?
- Understand our detection threshold
  - Given our photometric precision, can we expect to see anything at all?

Future Work

- Once we have several robust candidates:
  - Spectroscopic follow-up
    - Nails down period, type of variable, type of stars
    - Can derive masses
    - May be difficult for our fainter targets
  - Photometric monitoring
    - High cadence photometry gives detailed eclipse information
    - Obtain radii, luminosities, temperatures
- Connect these observed parameters to models
  - See if we can improve mass-radius, luminosity-mass relations

Yes, but what about those planets?!

- M dwarfs are low mass stars
  - Protoplanetary disk also has low mass
  - Forms giant planets with masses & radii << those of Jupiter, etc.
  - Expect more Neptune class planets around M dwarfs
- Jupiter transit depth around M4 dwarf ~ 8%
- Neptune transit depth around M4 dwarf ~ 1%
- 1% drop in flux from a star is hard to see using our survey data
- Numbers say there should be ~ 10 Jupiter class planets in our dataset
  - We're probably not good enough to get them
  - Need better calibrated photometry and a better time-sampling of observations
  - Still, worth a try (only after we've found M dwarf eclipsing binaries)

Conclusions

- Our knowledge of low mass stars, especially M dwarfs, can be improved by looking at eclipsing binaries.
- Using large sky surveys (like SDSS) gives us many targets to look at.
  - Needed because statistics don't favor detecting these systems.
- Going from detection to characterizing variability is hard.
  - Need multiple methods of confirming variability and periodicity.
  - Confirming periodic variables as eclipsing binaries requires photometric and spectroscopic follow-up.