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UCRL-PROC-223125

The SuperMacho Project: Wide-field, Time-domain Survey of the Large Magellanic Cloud

K.H. Cook, M. Huber, S. Nikolaev, K. Olsen, A.R. Rest, R.C. Smith, A. Garg, C. Stubbs, A. Becker, D. Welch, A. Clocchiatti, D. Minniti

July 25, 2006

Stellar Pulsation and Evolution
Monte Porizo, Italy
June 19, 2005 through June 24, 2005

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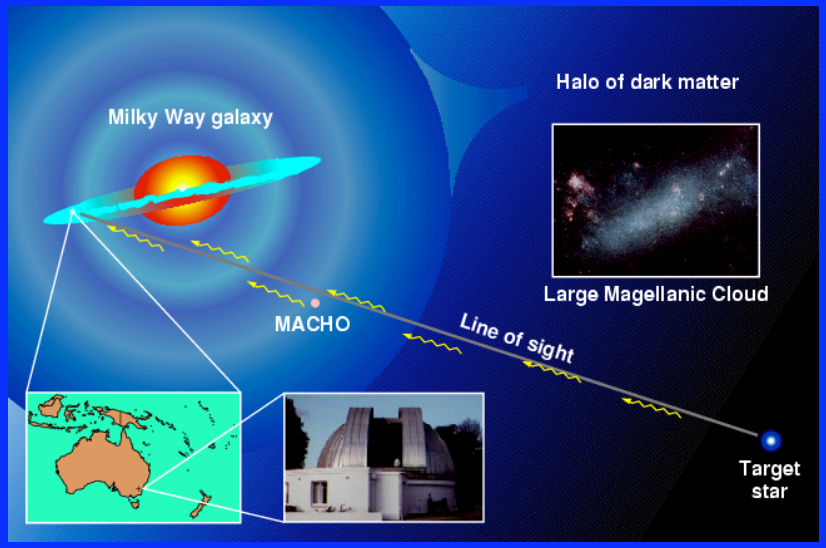
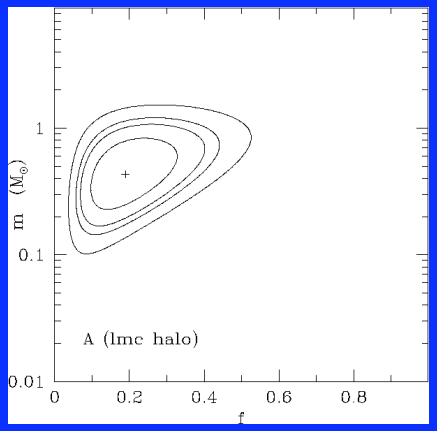
The SuperMacho Collaboration

Macho Project sought evidence for baryonic dark matter in the Milky Way Halo



MACHO found 20% of halo in 0.5 Msun objects



Macho Project sought evidence for MAssive Compact Halo Objects by surveying for the gravitational effect of the objects on light: microlensing

Macho Results:

- first microlensing detection
- no low mass (<0.1 Msun) lenses
- the Milky Way is a barred spiral
- 17 events detected toward the Large Magellanic Cloud (LMC)
  - too many for known populations

2 Major Dark Matter Results Common to MACHO, EROS, OGLE

Lack of LMC events of less than 20 days duration rules out low mass MACHOs

Rate of detected events exceeds that expected from known stellar backgrounds, and corresponds to a MACHO fraction of between 8% and 50% of the "standard" halo

(Alcock et al ApJ 542, 281 2000)

A Next Generation Microlensing Survey was Needed

Questions which need to be answered:

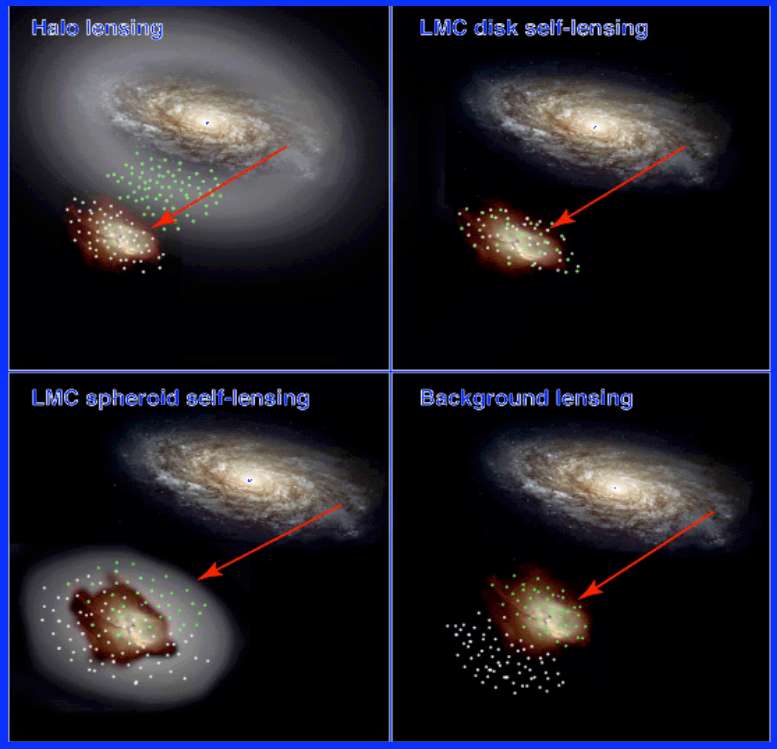
Where are lenses?
- Halo
- LMC
- Milky Way
- Unknown population/object

What are lenses?
- Mass
- Composition (baryonic?)

Characterizing Microlensing Populations

Spatial Distribution

- Distribution on the sky:
  - statistically significant number needed, too few from Macho
- Location along the line of sight:
  - The LMC is dusty
  - Can test where source stars are with respect to dust: weak result



Features of a Next Generation Microlensing Survey

The figure of merit (FOM) for a microlensing survey depends upon the number of sources which can be monitored in a given amount of time. Presented below is a table comparing the original MACHO survey with a survey using the Cerro Tololo Inter-american Observatory (CTIO) 4-m and prime focus mosaic CCD camera.

MACHO vs. 4 - m MOSAIC

	MACHO	CTIO 4-m	FOM gain
Seeing	2 arcsec	< 1 arcsec	>4
Aperture	1.27-m	4-m	9.9
CCD QE	~30%	~80%	2.7
Field	0.5 sq deg	0.36 sq deg	0.7
Sky brightness	bright	dark site	> 2
Nominal FOM gain			>150

A CTIO survey should detect an order of magnitude more events

A Next Generation Microlensing Survey: SuperMacho

SuperMacho became an NOAO survey 1991:
awarded 150 half nights on CTIO 4m

NOAO supporting project with hardware,
technical and scientific staff

Big aperture (4m)

Mosaic imager: 8kx8k, 0.35 square deg

Dark sky and good seeing

Custom broadband filter (5200A to 7300A)

68 fields, 24 sq deg.

Exposures optimized to maximize # of stars

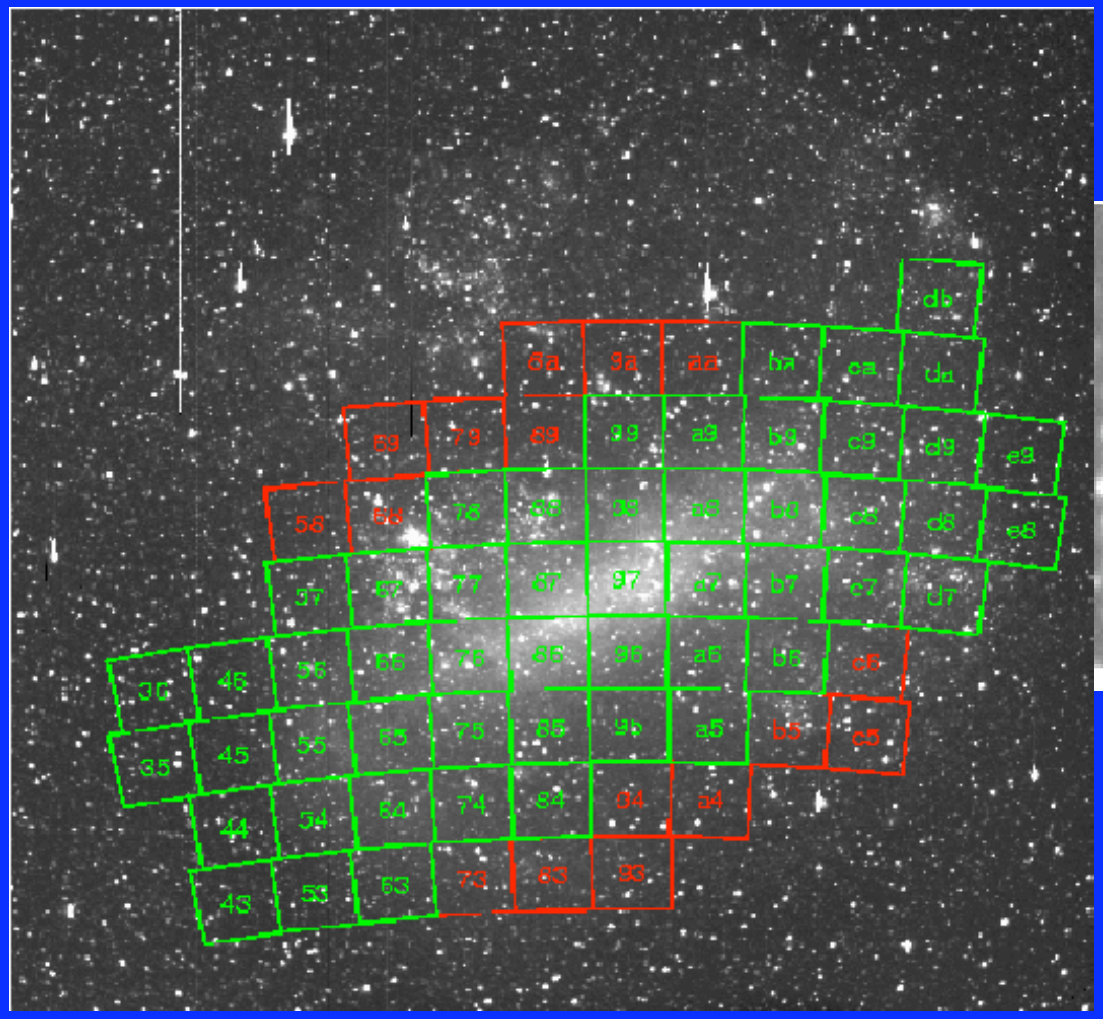
S/N = 0.1 mag at 23rd

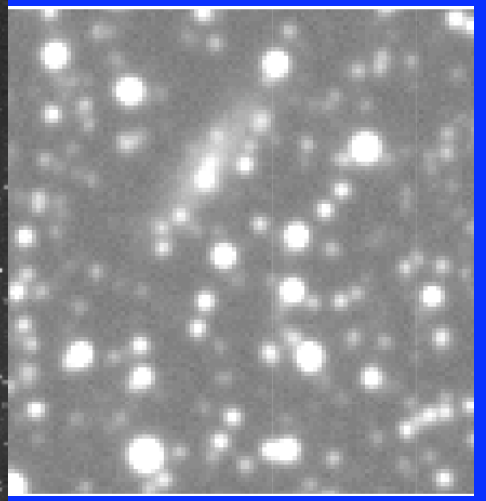
Goal is ~ 50 well-characterized events

Secondary Objectives

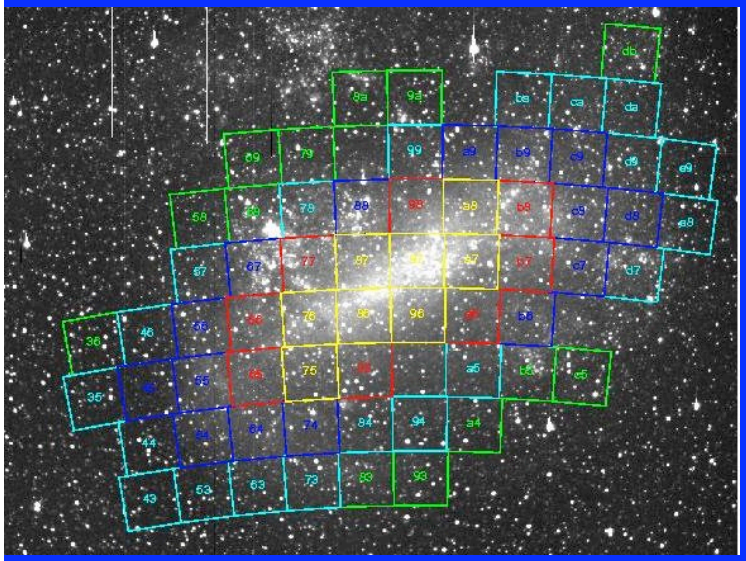
- Variable stars (instability strip @ MS in LMC)
- Solar System objects at ecliptic pole
- High Proper motion objects
- Super novae behind LMC
- LMC proper motion w.r.t. quasars
- Develop software for Large-aperture Synoptic Survey Telescope (LSST)

SuperMacho Field Centers and Image Data



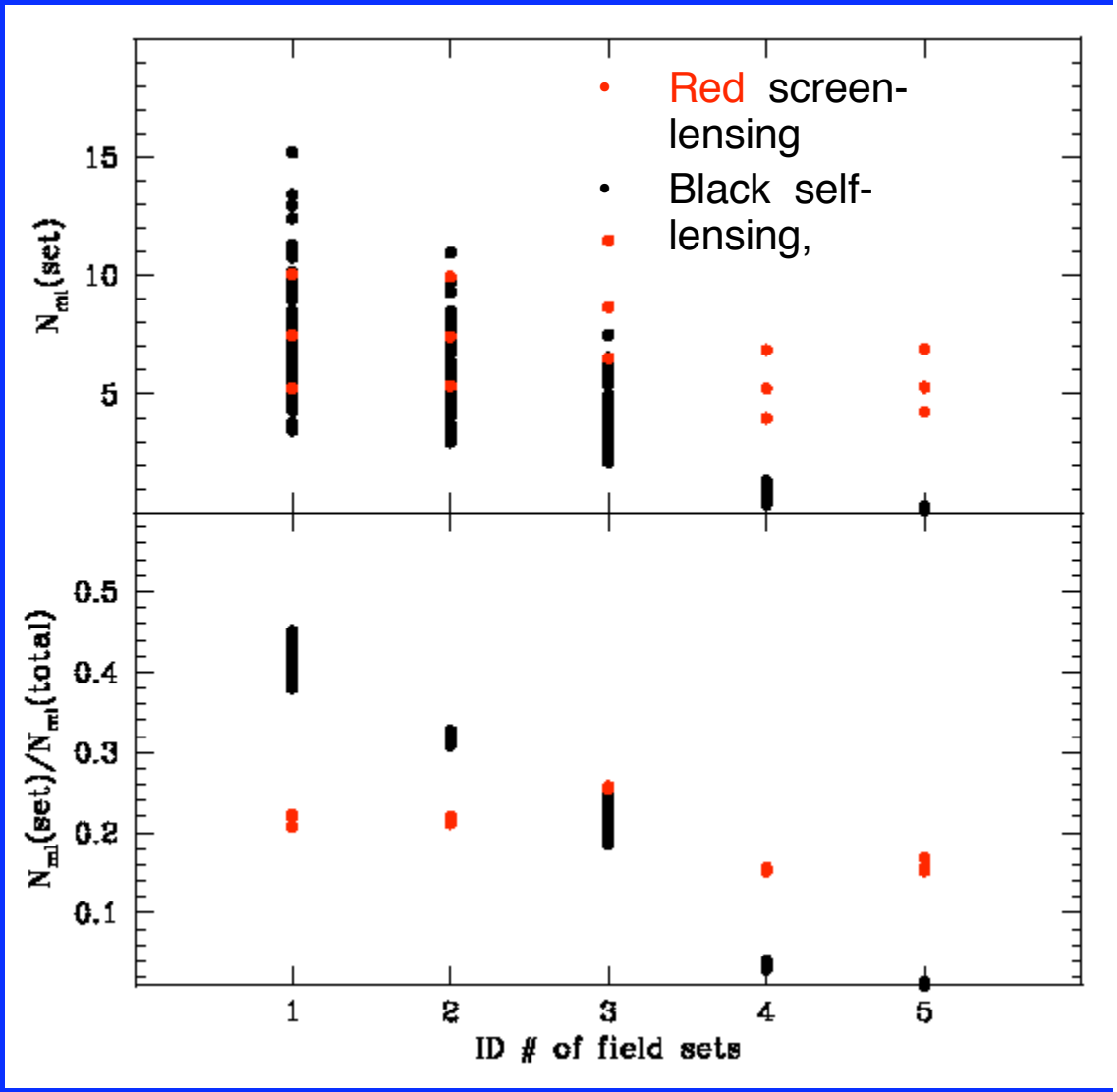


Discriminating self-lensing vs screen-lensing via spatial event distribution



$$N_{ml}(\mathrm{yrs}^{-1}) \approx N_{obs}\tau\varepsilon_t$$

Differential approach reduces sensitivity to LF, efficiencies, etc



SuperMacho Data "Reduction" Pipeline

Image Subtraction Analysis which is modular, flexible and almost real-time

- Make Flats and Bias Frames
- Cross-talk correct and WCS register
- Carve MultiFits 8K x 8K MOSAIC image into 1K x 4K amplifier images
- Flatten Images
- DoPhot reduction to obtain PSF and noise array
- Determine appropriate template by field and filter
- Register, convolve and subtract images
- Fixed-PSF, bipolar DoPhot on difference image
- Filter detections to reject artifacts, cosmic rays, etc.
- Upload observation and its detections to database
- SN & microlensing fits with visual interface to high-confidence detections for interactive classification by astronomers

The Data

- Survey data in wide VR filter (V + R)
- Variable exposure: ~ 60 - 100 sec
- Survey every other night for 20 nights per month for 3 months of LMC season
- ~ 30 epochs/field/year
- Extra nights for B & I colors: ~ 2 epochs/filter/field
- Microlensing alert fields get extra B & I during alert

Public Data Products

- Transient announcements
  - Email list (bidirectional!) & IAU Circulars
  - Finder charts, fits and spectra on web
- Images
  - Raw & Reduced (flat fielded) data
  - No proprietary period

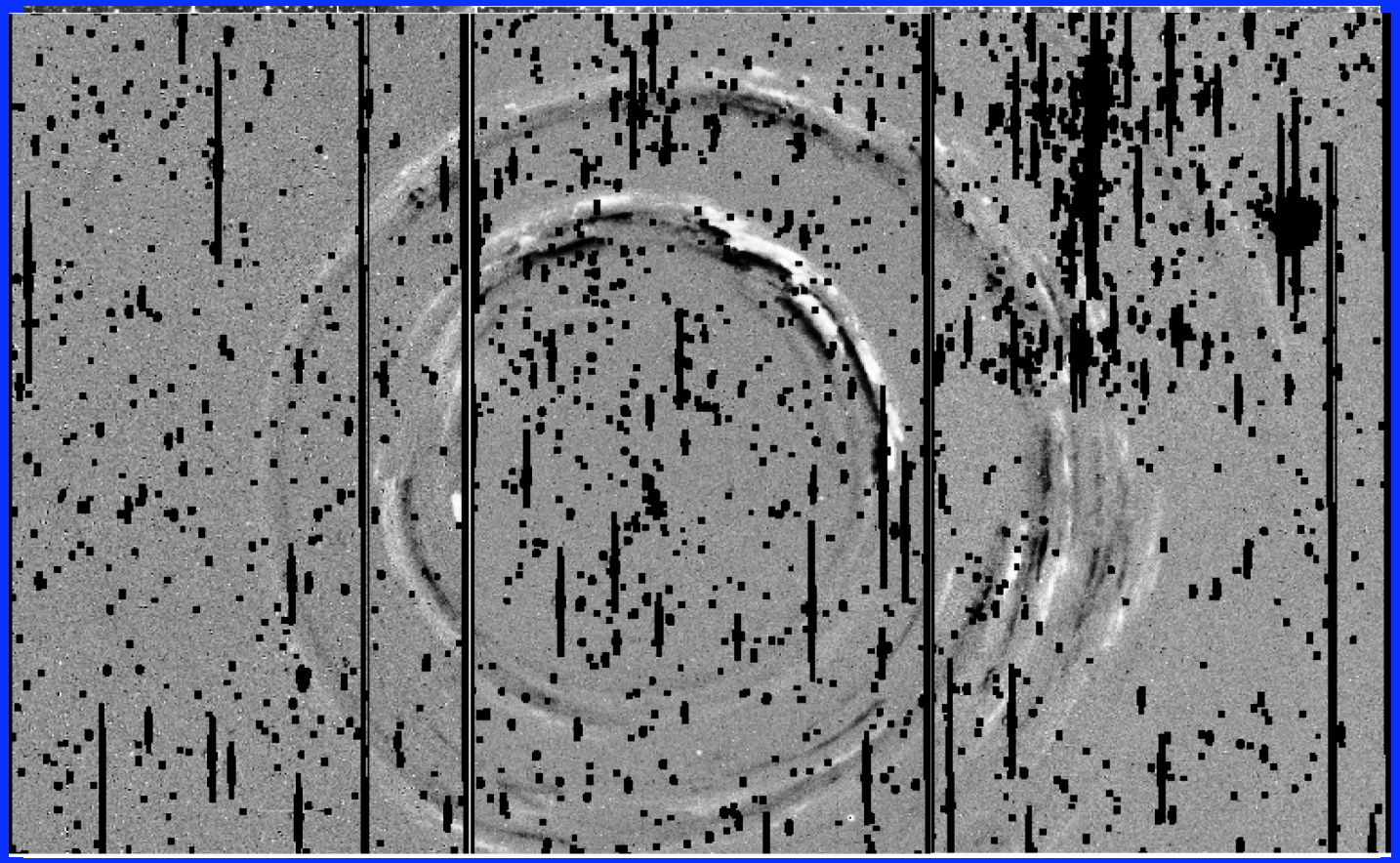
What have we found?

Lots of variables

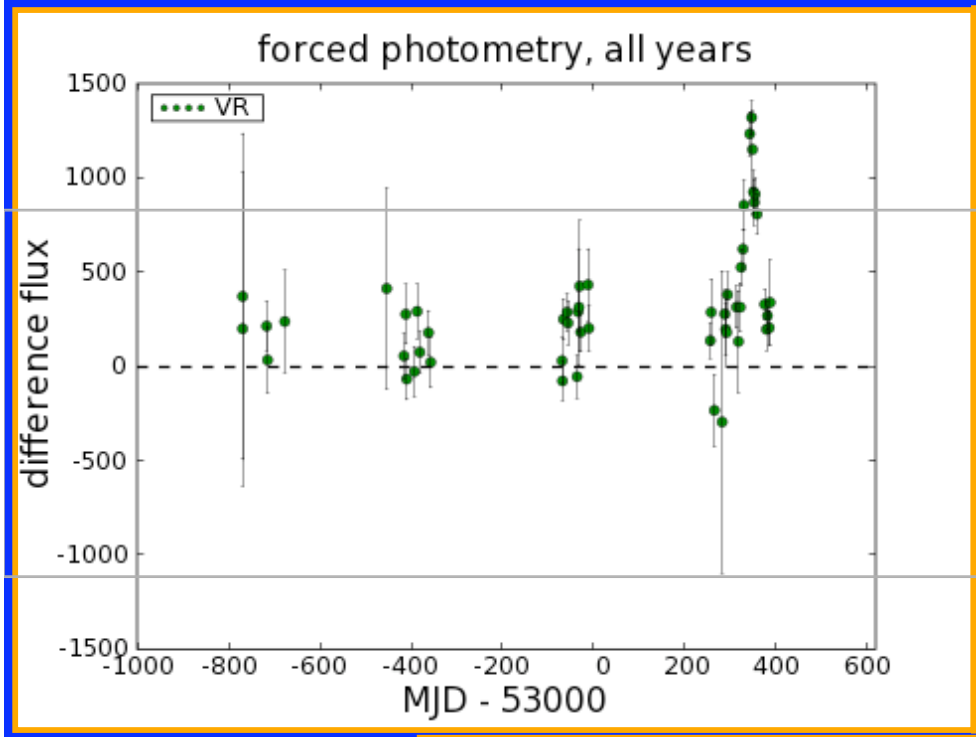
Lots of Supernovae ~10/month

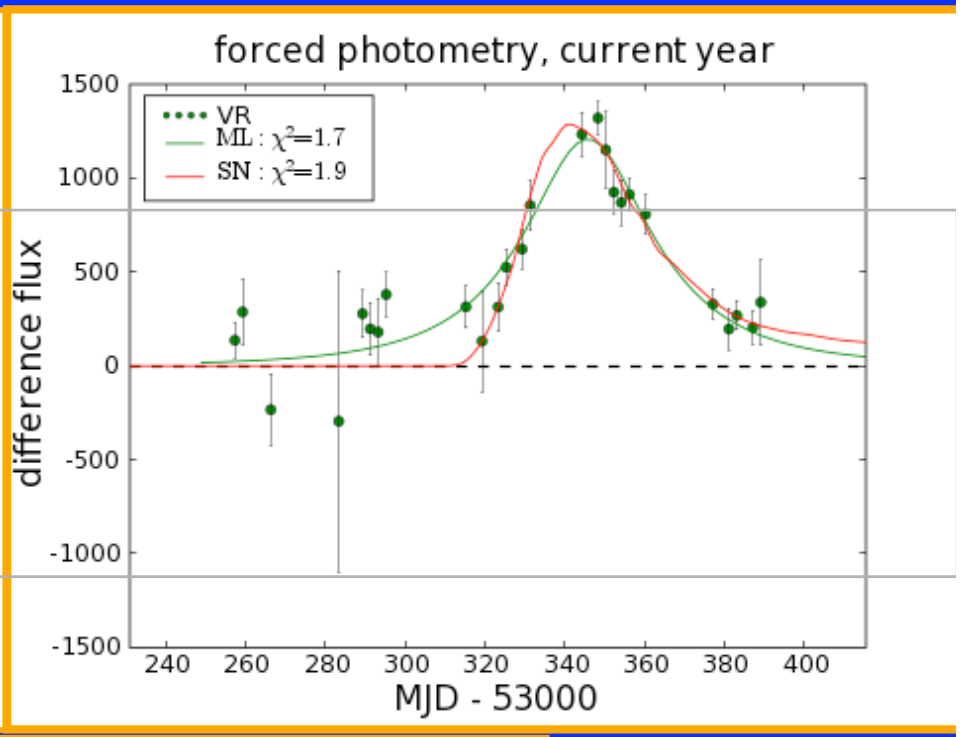
Lots of Microlensing ~11/month

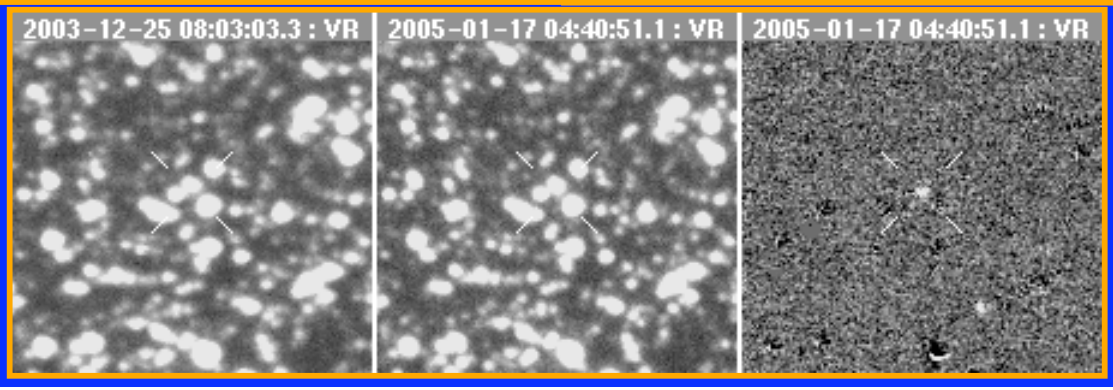
SN 1987a



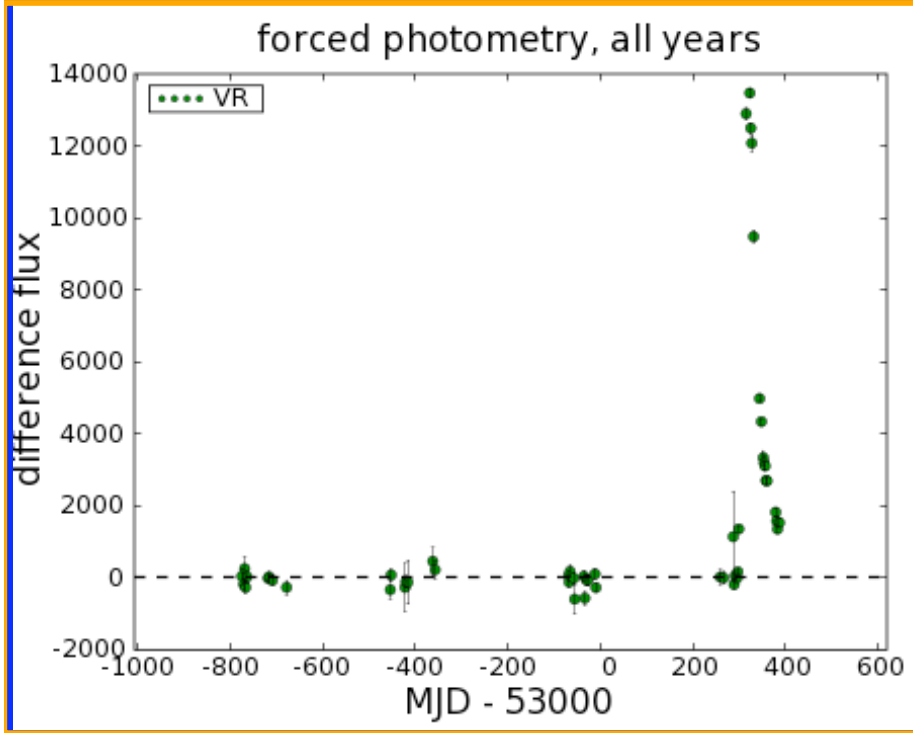
2004 LMC 958: Candidate microlensing event

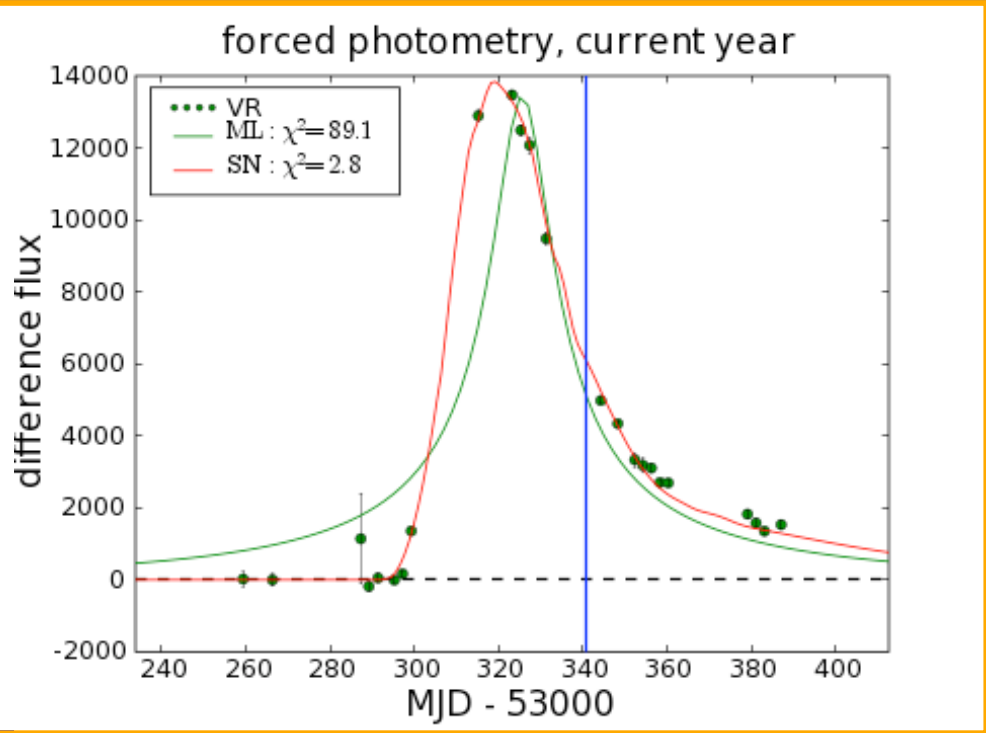


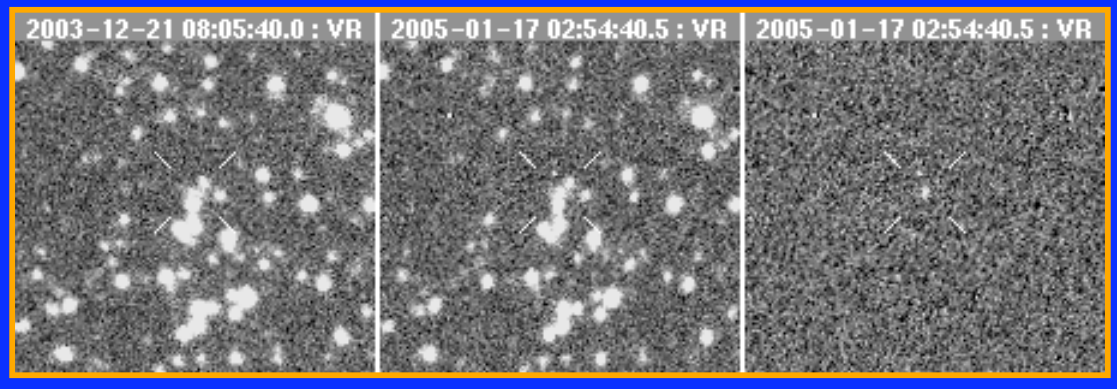




2004 LMC 797: z=0.15 type Ia SN







SuperMacho Status

Now entering 5th season of observations- requesting a 6th.

Microlensing science: ~70 SN and ~50 ML, pre-2004
13 ML and 7 confirmed SN in 2004.

No proprietary data period- raw and flat-fielded images available

Alerts available in real time: *http://darkstar.astro.washington.edu*

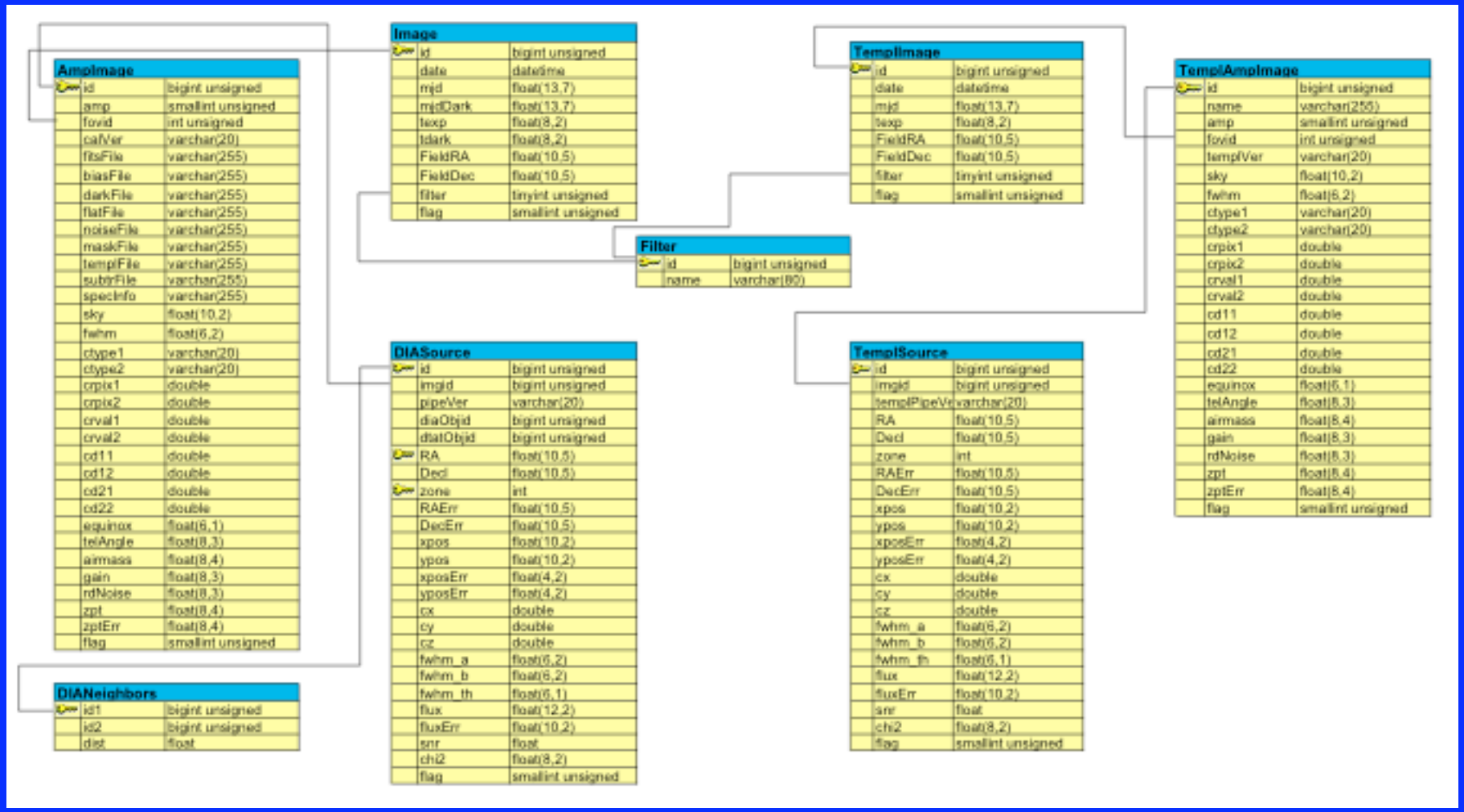
Real time followup imaging & spectroscopy for SN discrimination
Significant Magellan followup observations
HST time awarded: 32 orbits in cycle 14.

Starting to extract non-microlensing science.

Building Variable Light Curves

- ~ 20-30 images/field/year x 4 years
- 68 fields -> 16,465,672 ‘detections’
- Load into MySQL database
- Cluster with 1 arcsec radius
- Light curves extracted with > 20 points
- Center of cluster calculated, template flux extracted, light curve calibrated
- Light curves phased with SuperSmoother
- B and I magnitudes from object based photometry and match < 0.5 arcsec
- Fourier series fits and statistics calculated

SM Database Schema/Tables

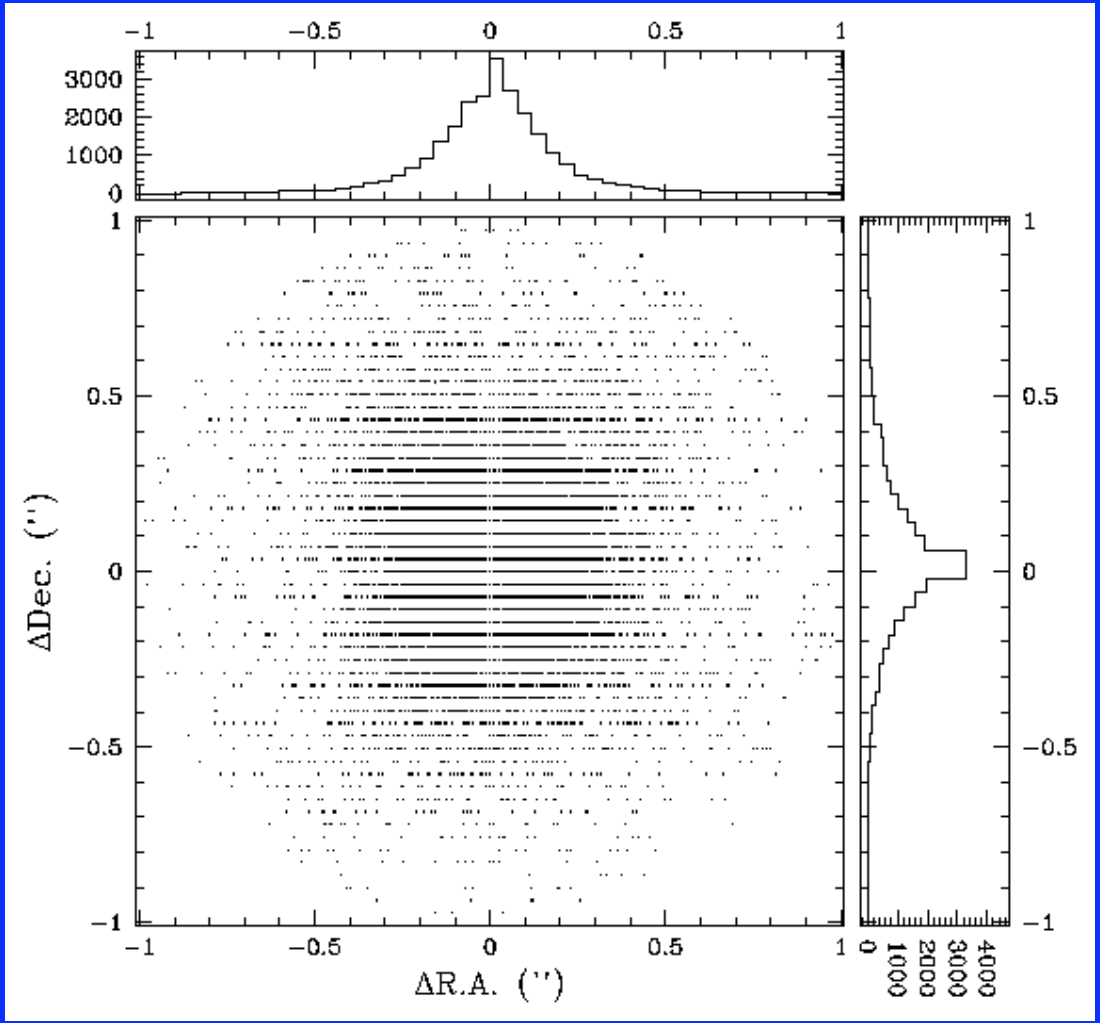


The Numbers

- ~ 2 TB of images
- 16,465,672 difference image detections
- 222,751,278 rows in DIANeighbors table
- 84,836 variables, 89650 light curves (overlap)
- 21,425 cross-id with MACHO
- 89,032 light curves with statistics

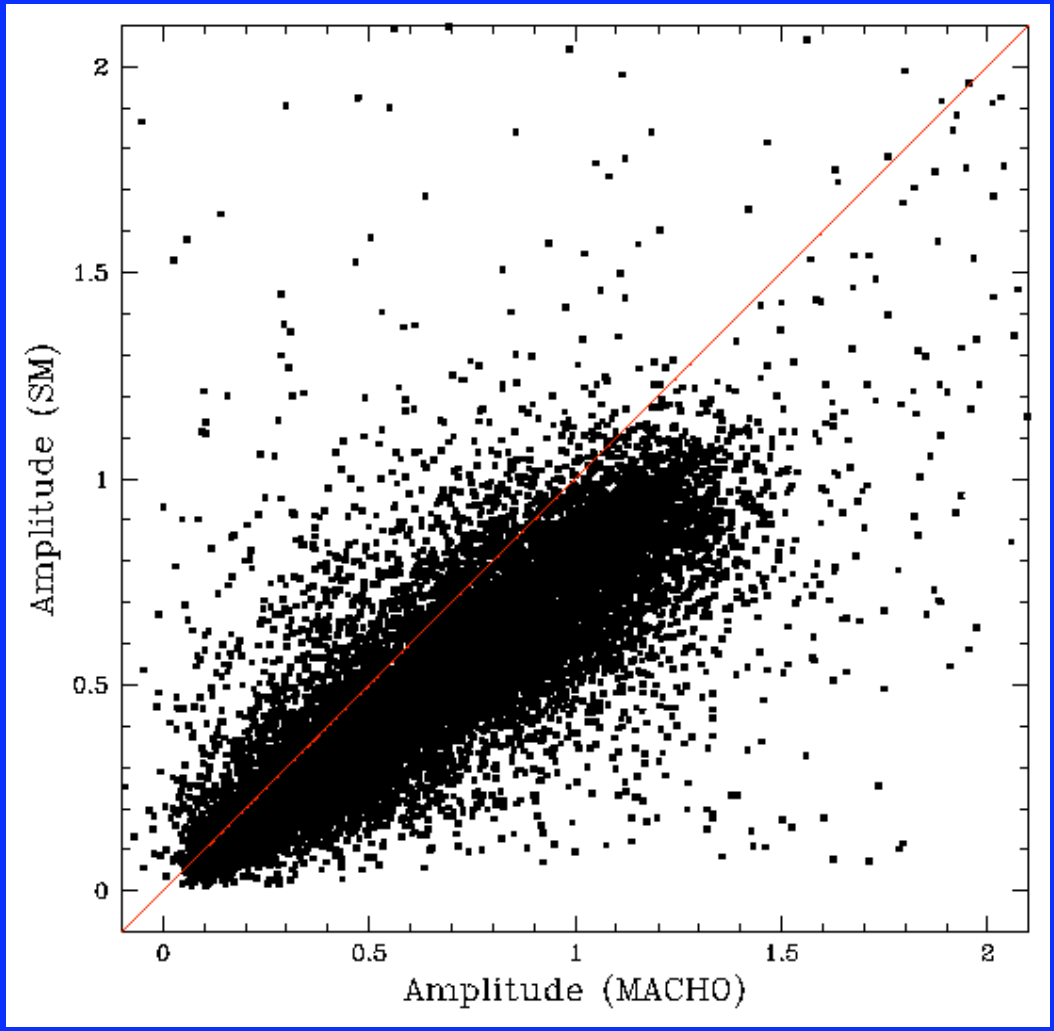
SuperMACHO positions compared to MACHO

Both use UCAC2 as astrometric system. Match at 1 arcsec radius yields standard deviation of 0.2 arcsec.

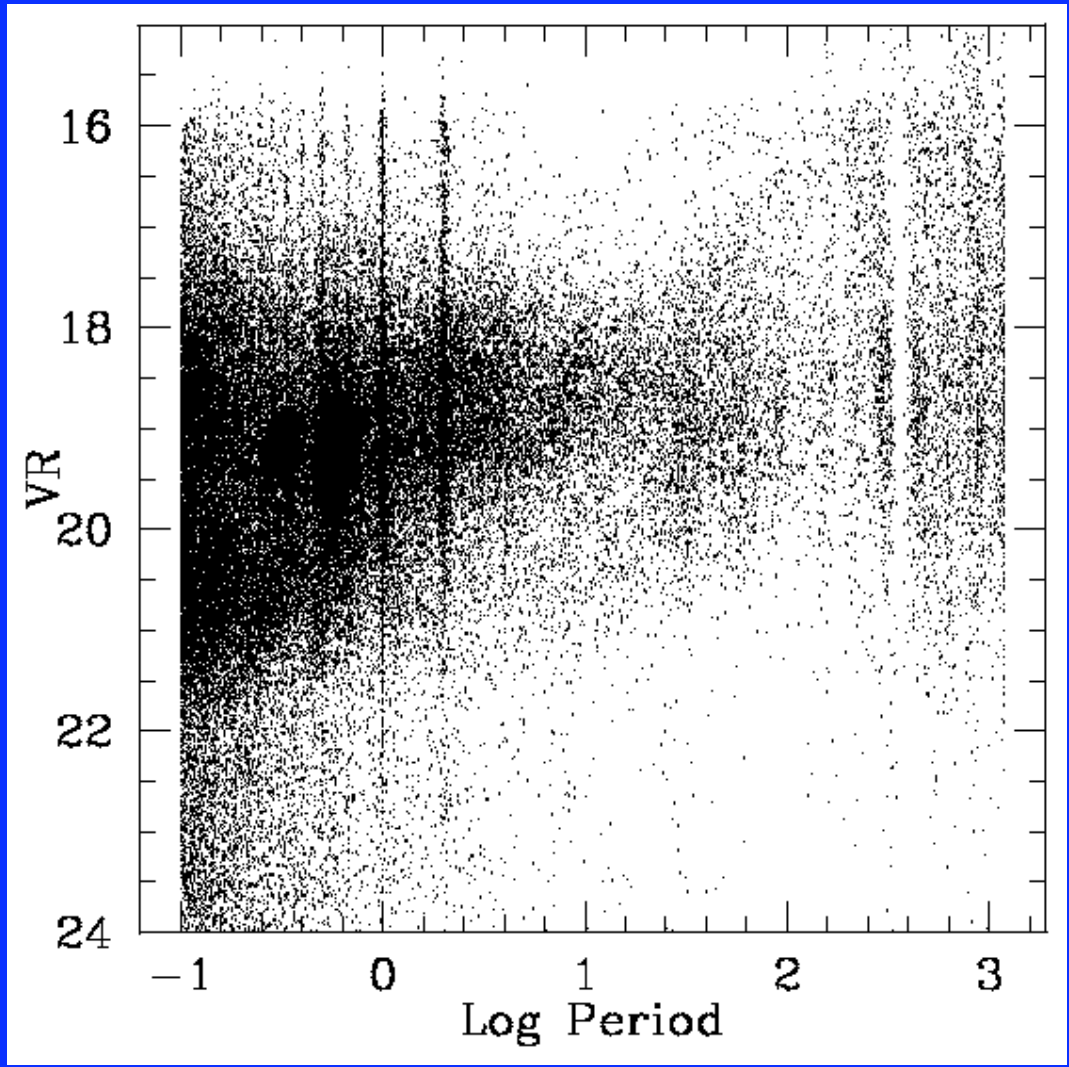


Amplitude comparison with Macho

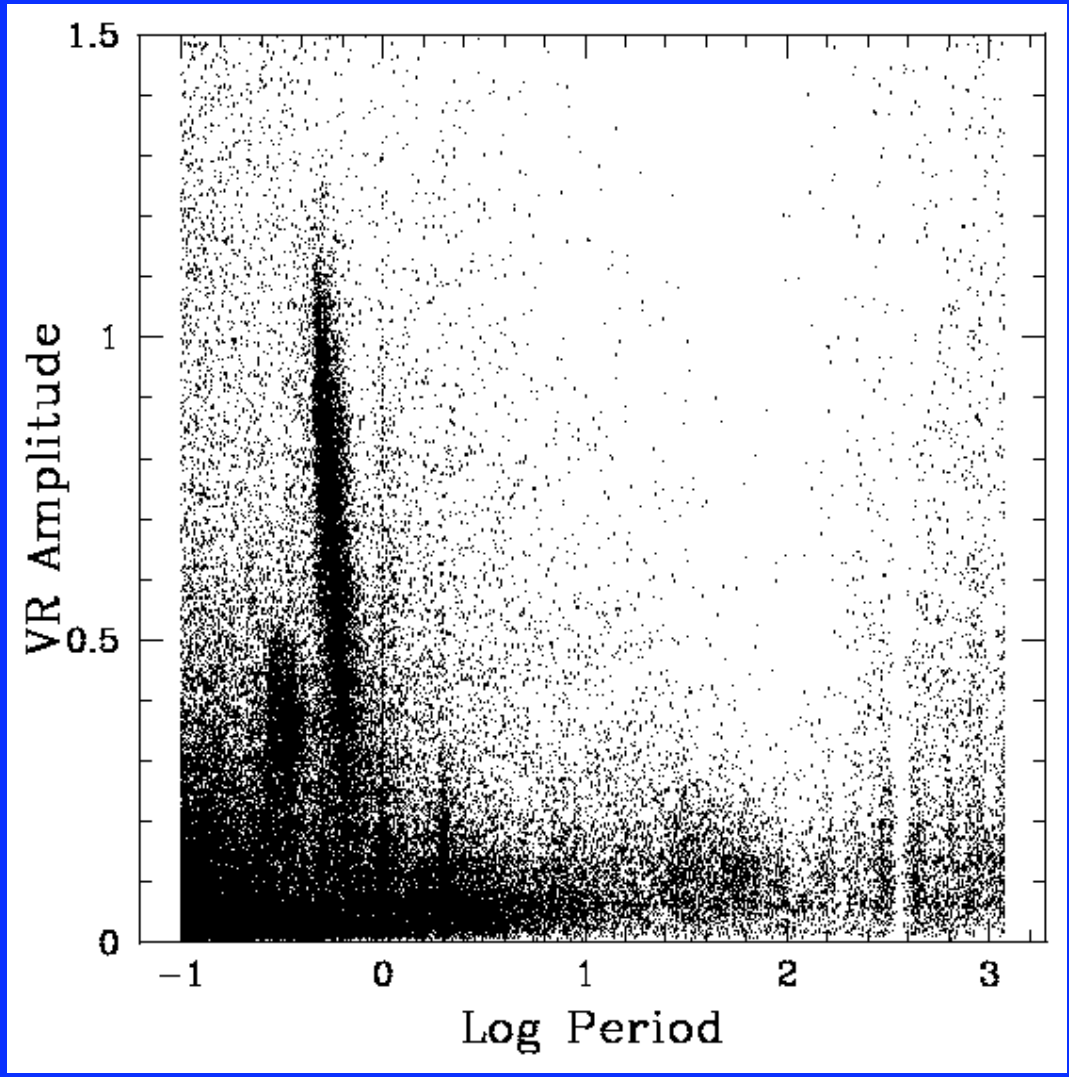
Fewer points for SM means that peak and minima may be missed, so systematically smaller amplitude



SM Period-'luminosity' distribution

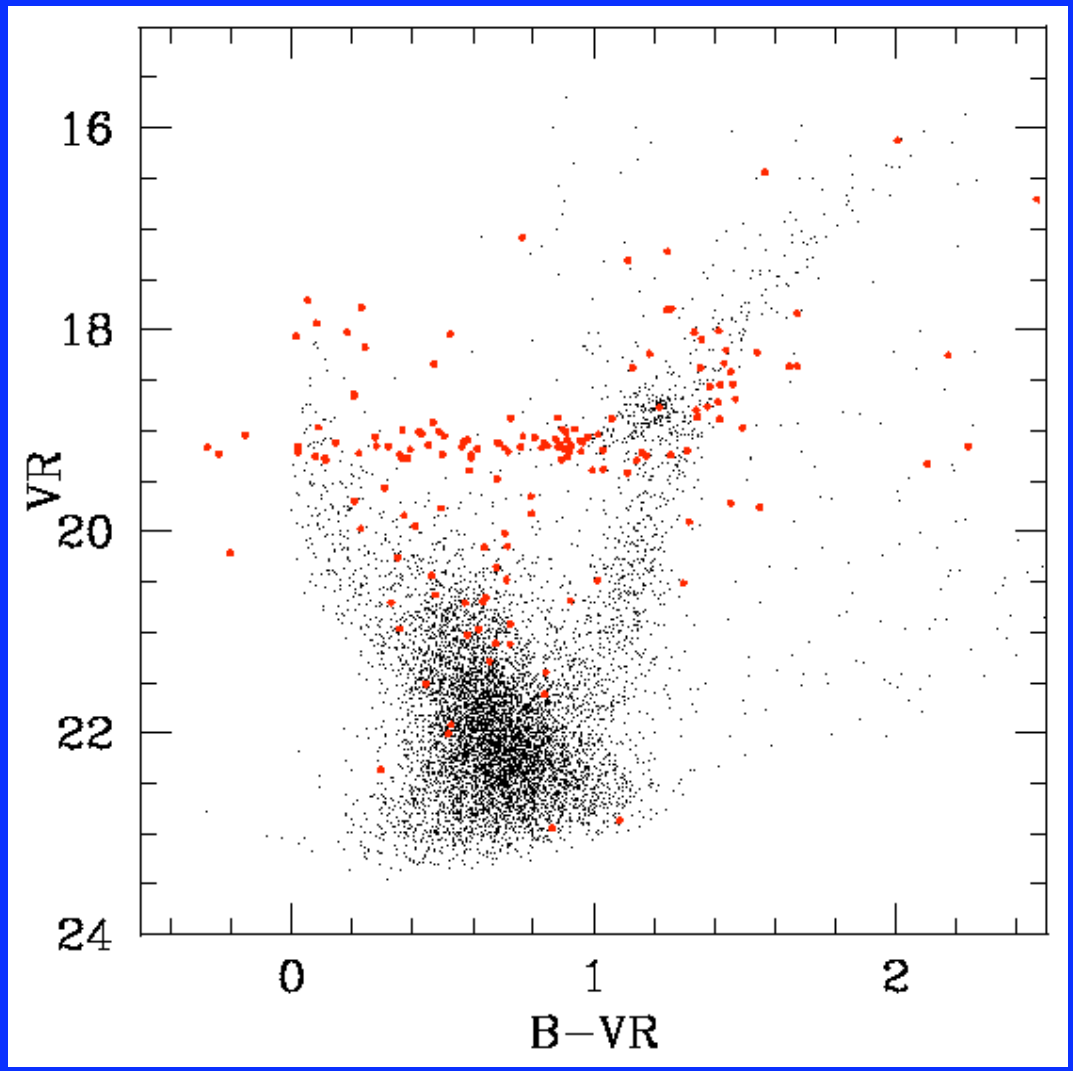


SM period-amplitude plot



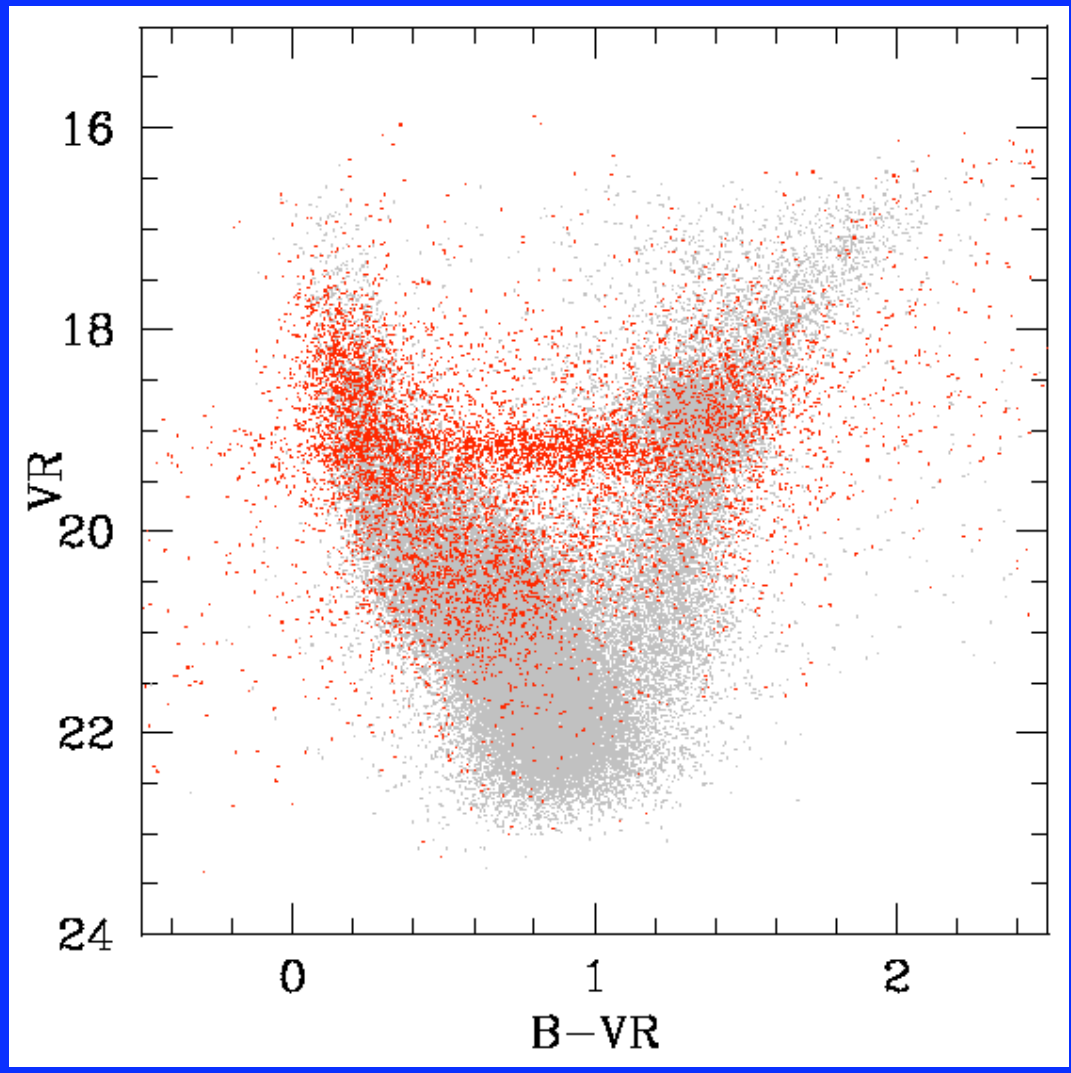
SM CMD with variables

CMD for one amplifier with variables plotted in red.



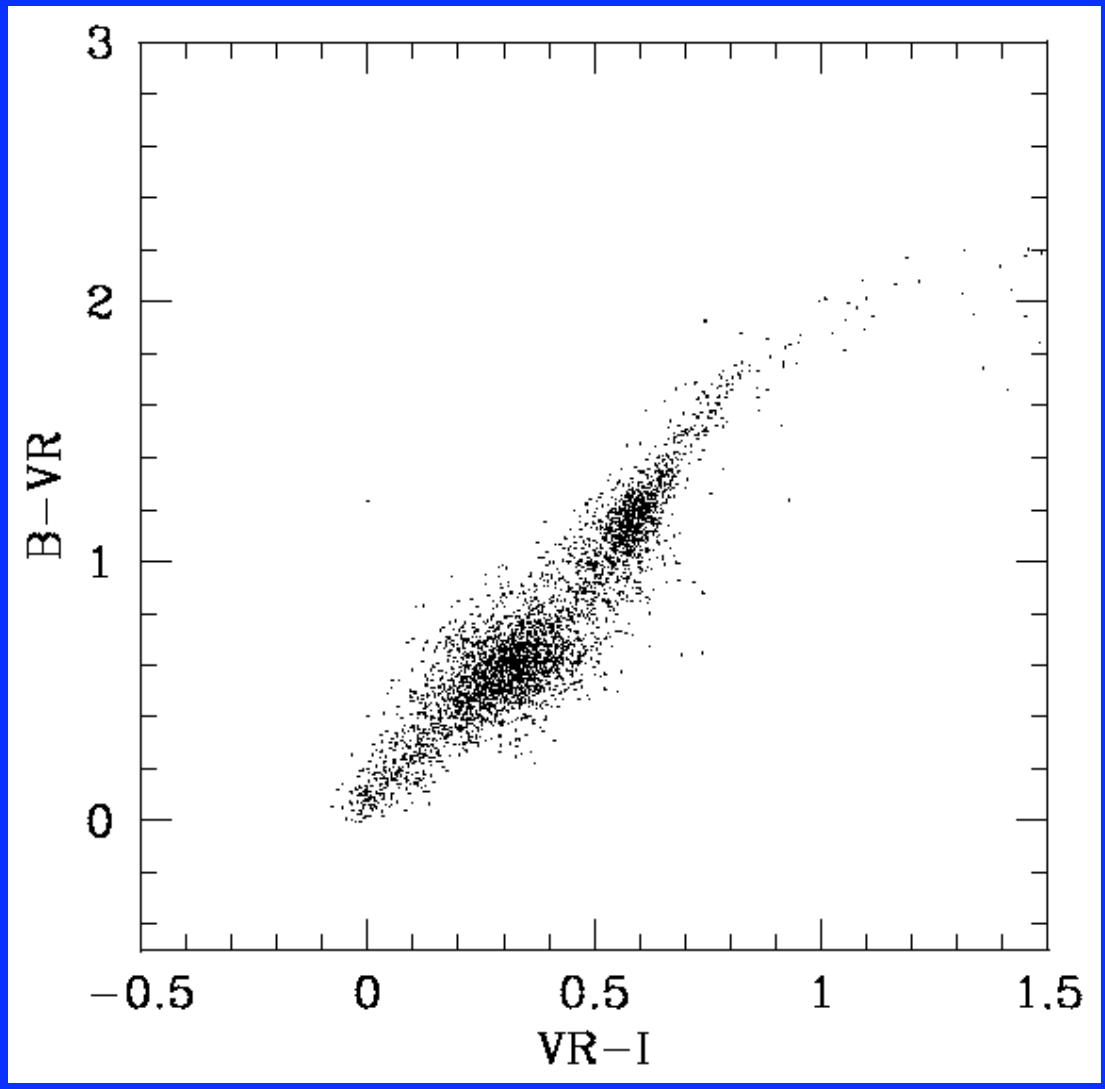
SM CMD, again

CMD for 7 SM fields with variables in red, showing spread in color due to needed B (and I) color terms.



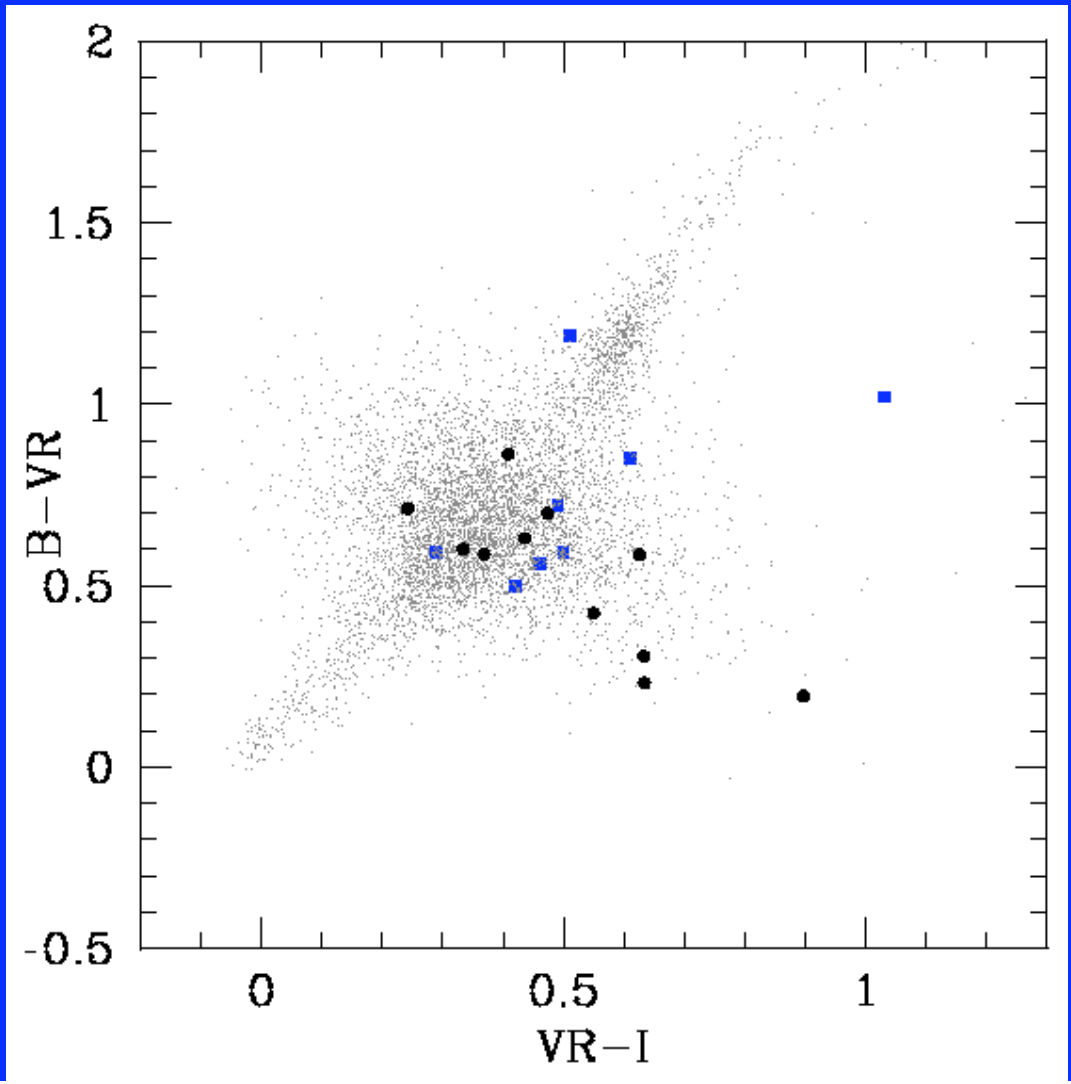
Color-color Diagram

Stellar locus helps distinguish SN and AGN from microlensing candidates.



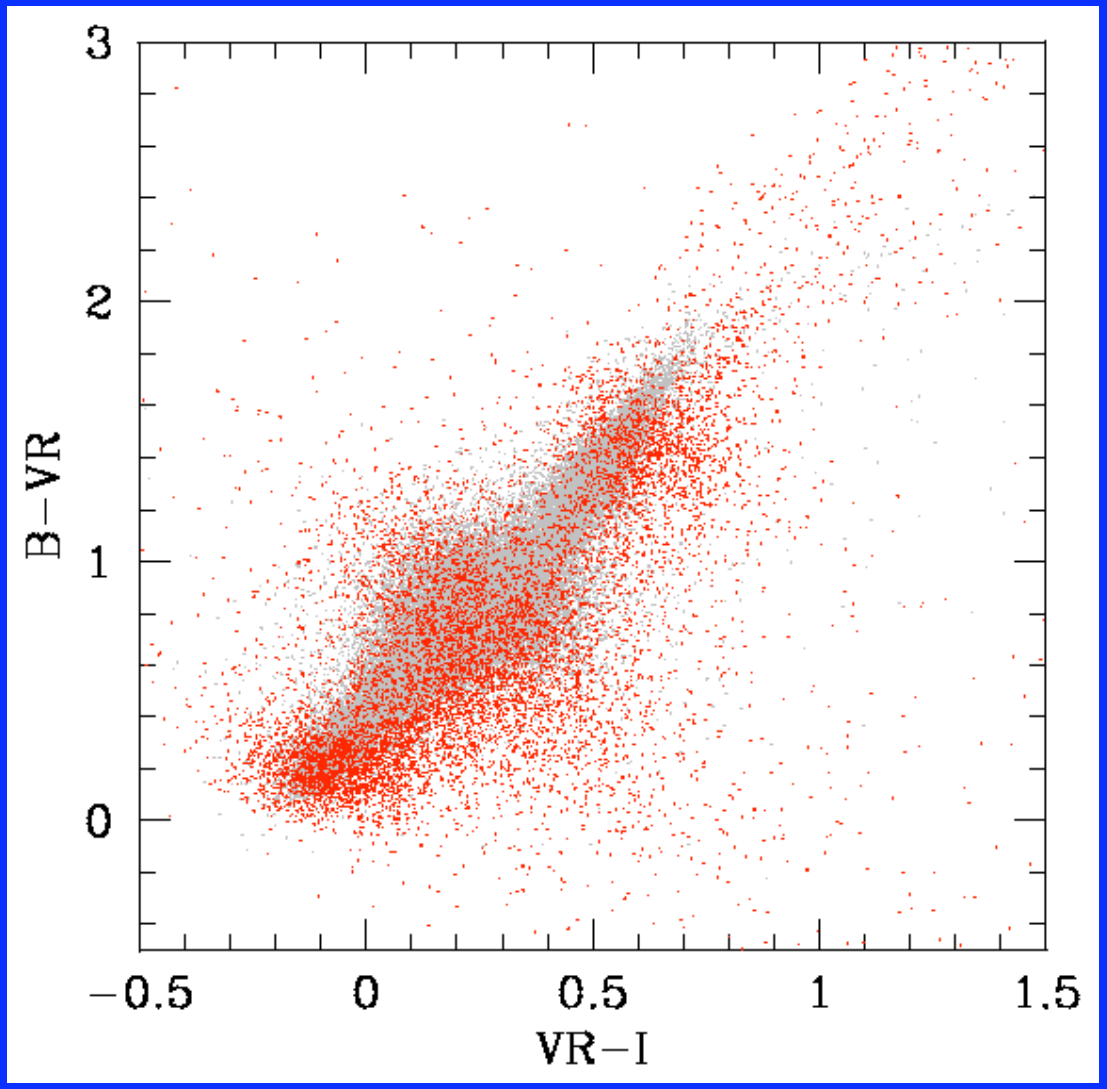
QSOs and AGN

Black points are QSOs from MACHO (Geha et al, 2003 AJ 125:1). Blue points are new, SM, AGN.



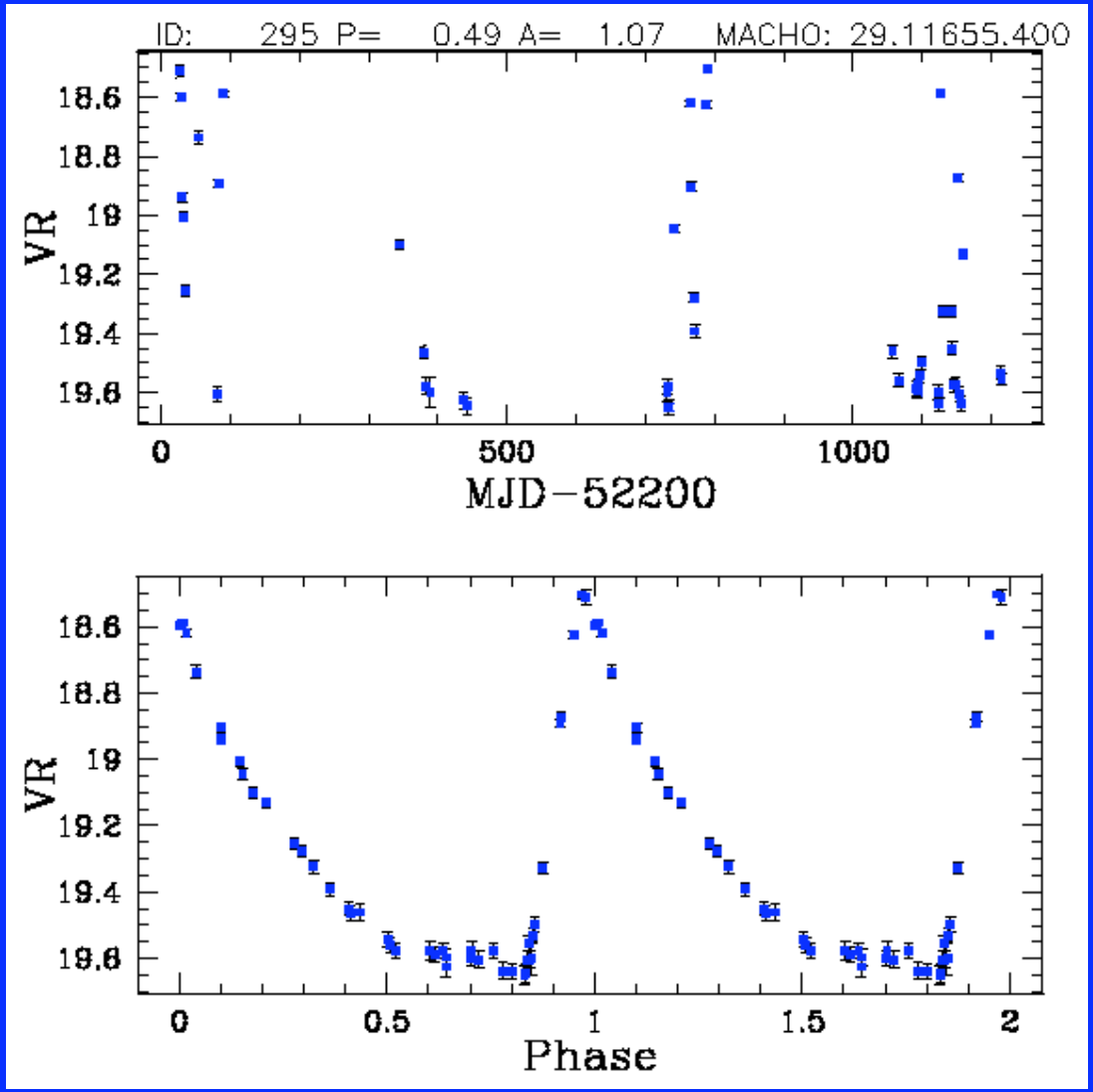
SM color-color plot

Color-color plot showing spread due to B and I transformations .

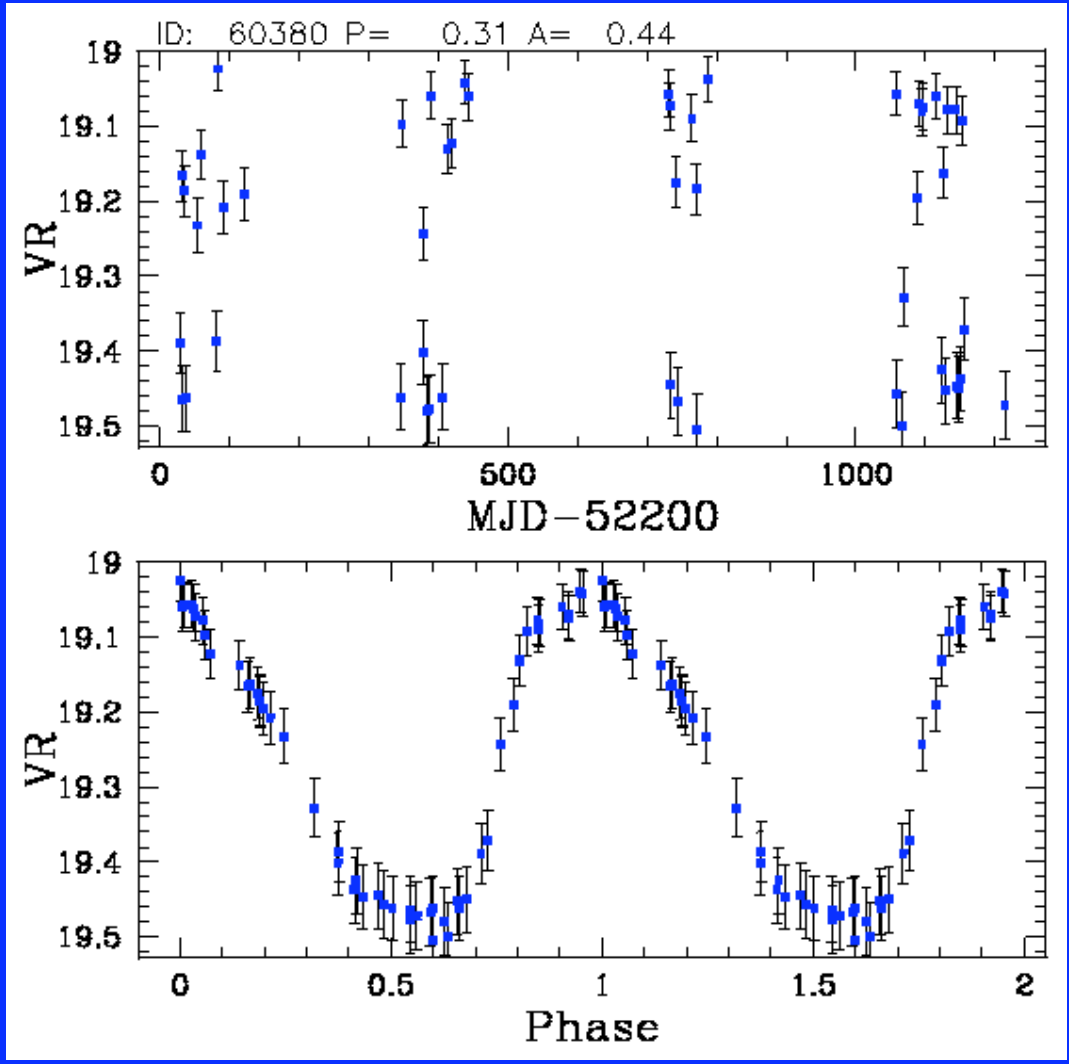


Example SuperMACHO (SM) light curves

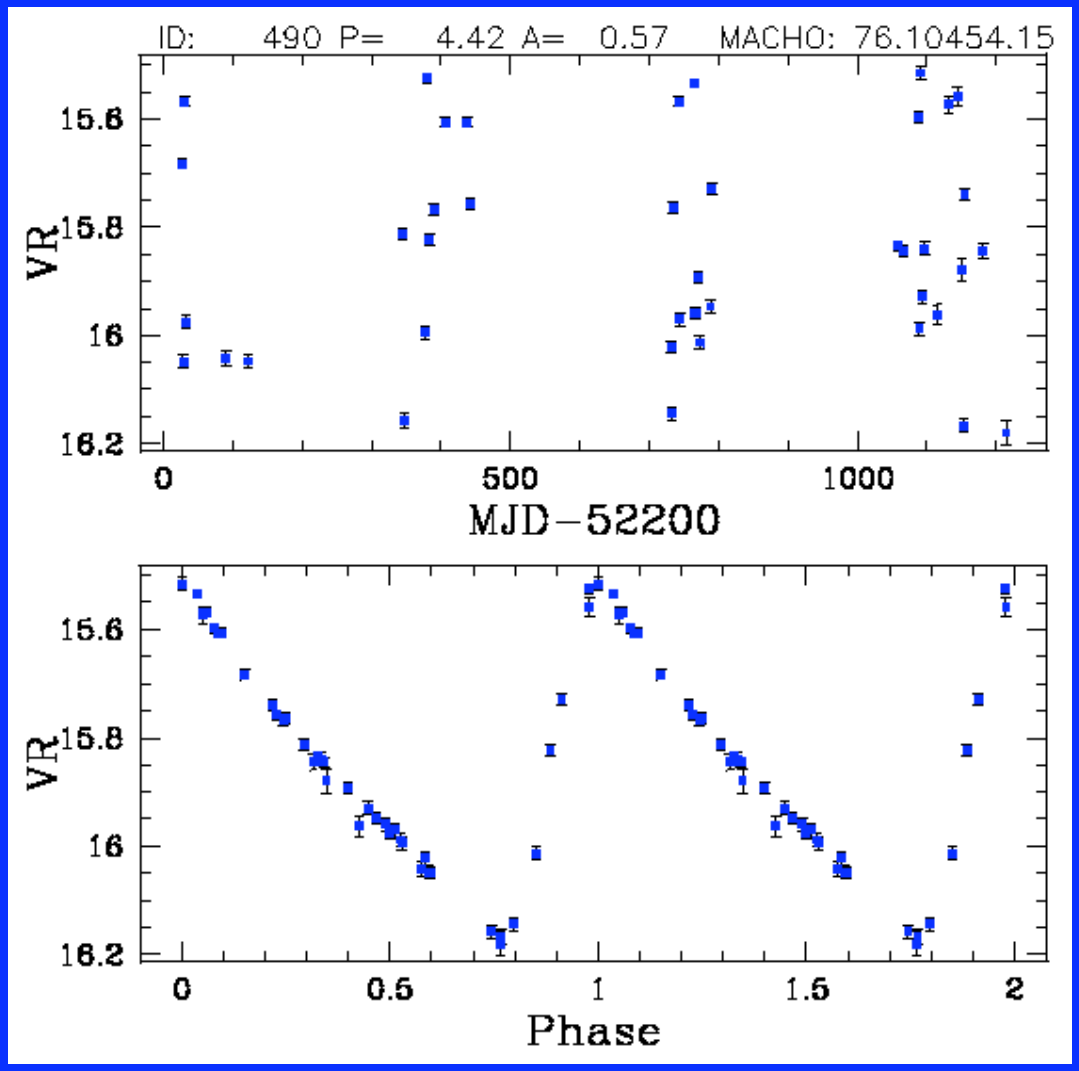
Example SM RR0



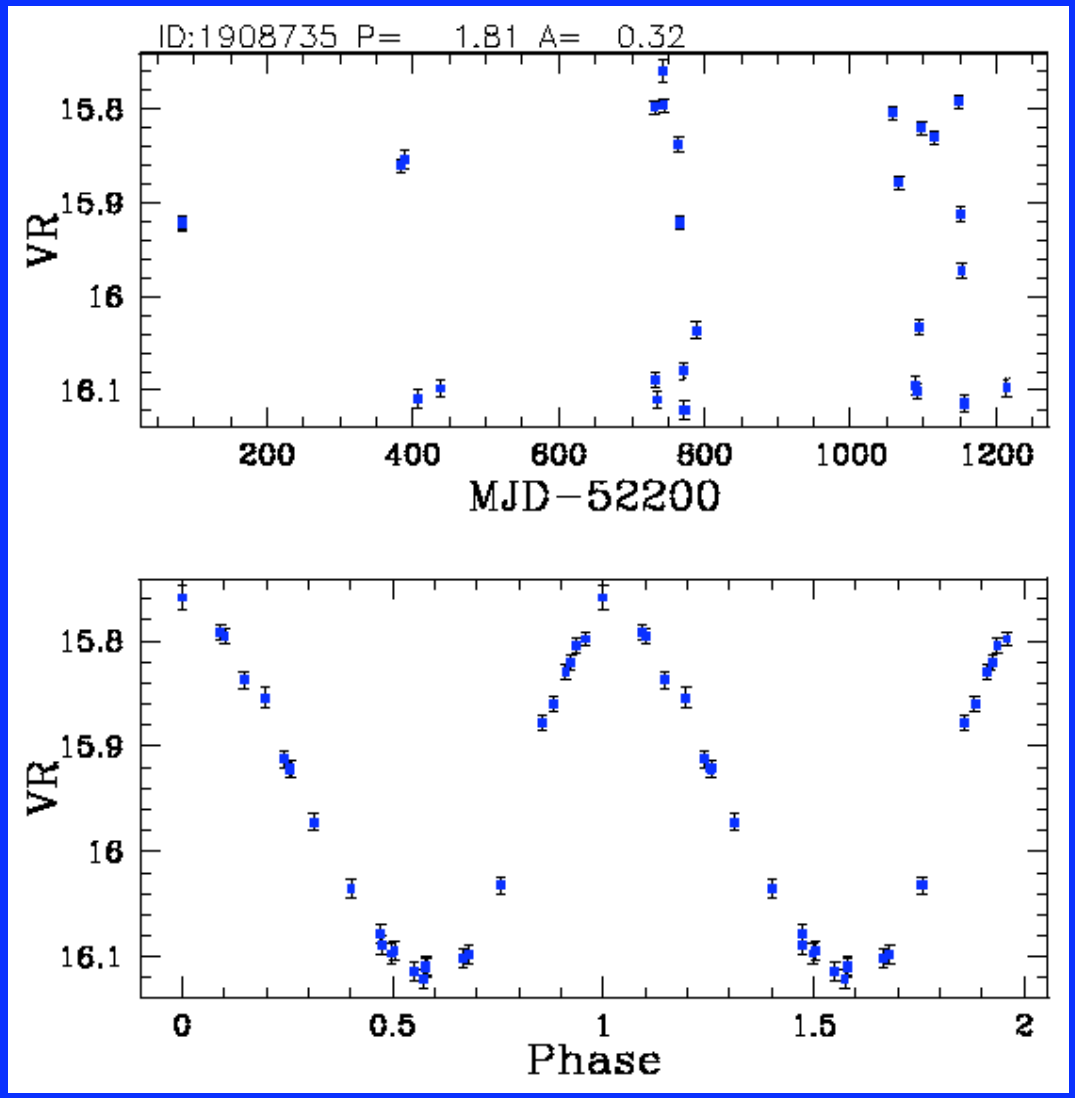
Example RR1


ID: 60380 P= 0.31 A= 0.44
VR
19
19.1
19.2
19.3
19.4
19.5
0
500
1000
MJD−52200
VR
19
19.1
19.2
19.3
19.4
19.5
0
0.5
1
1.5
2
Phase

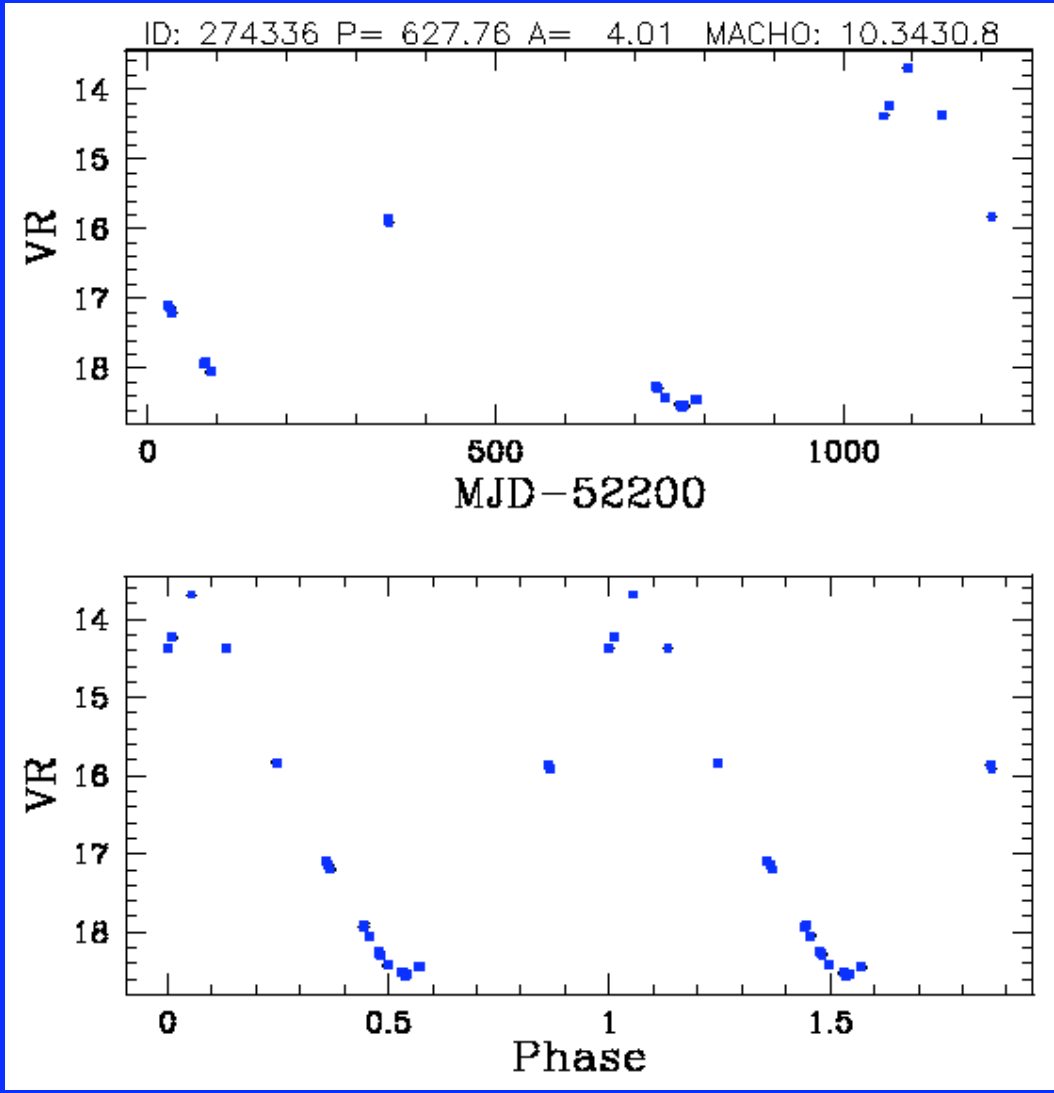
Example Fundamental Cepheid



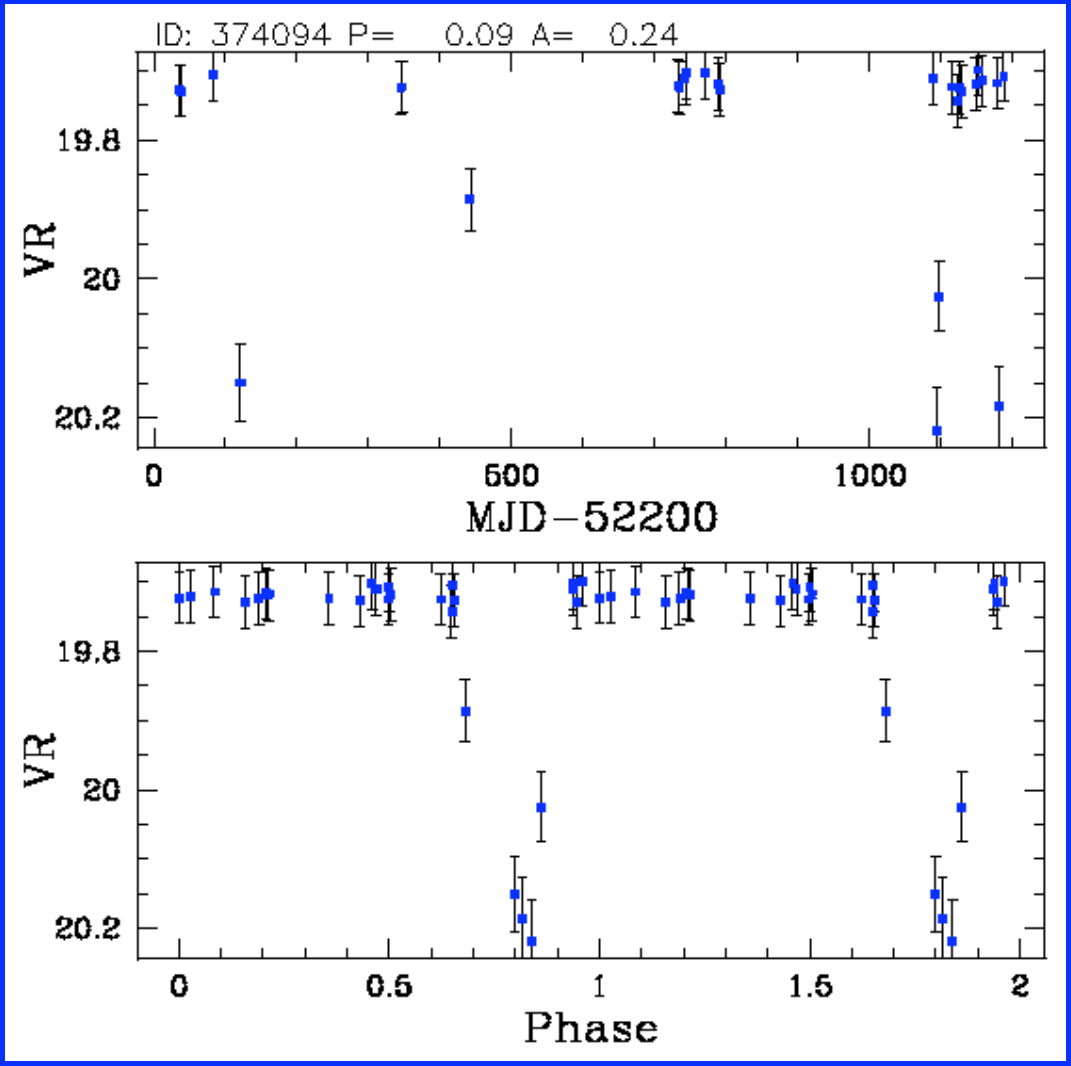
Example Overtone Cepheid



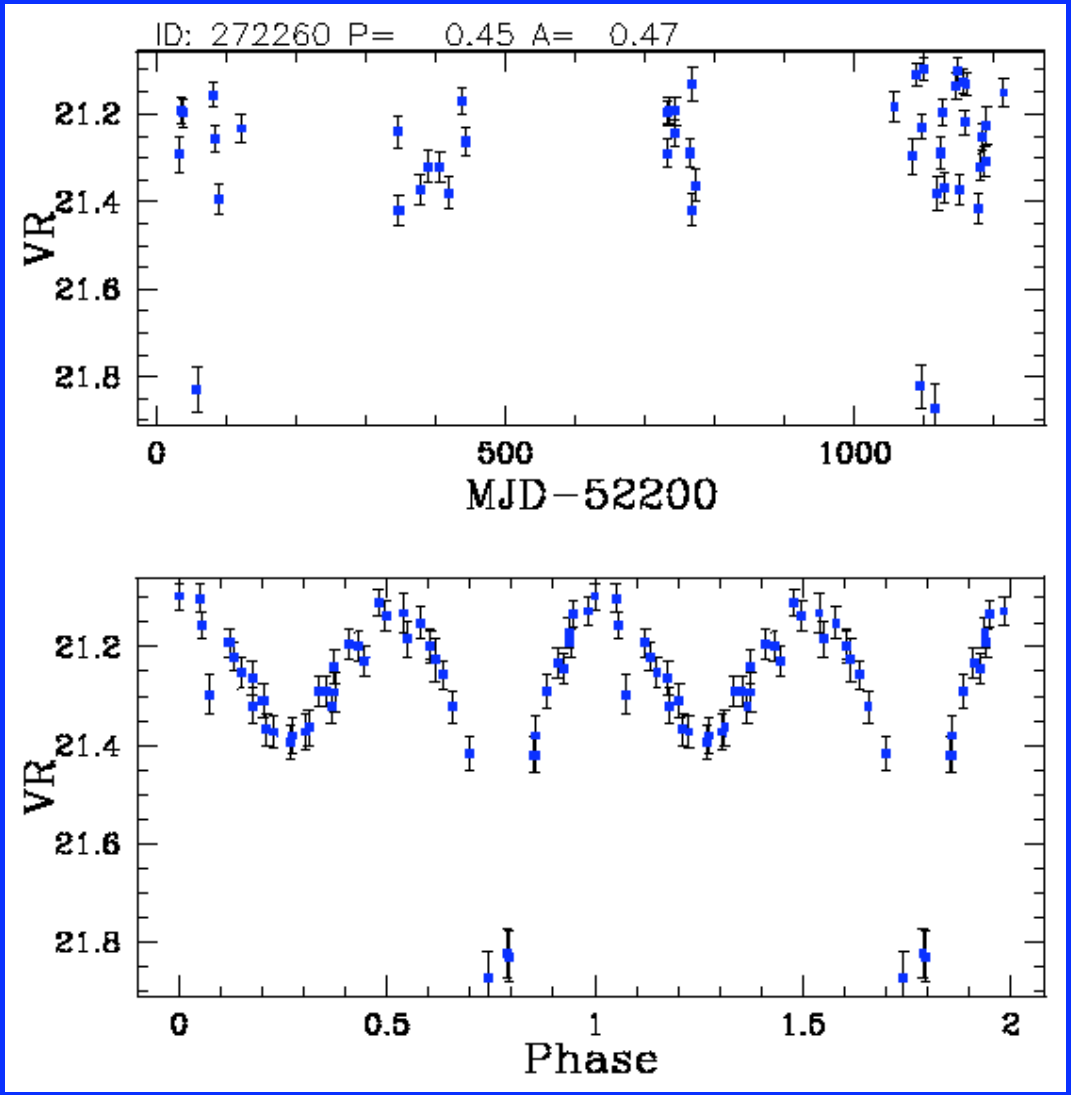
Example SM Mira



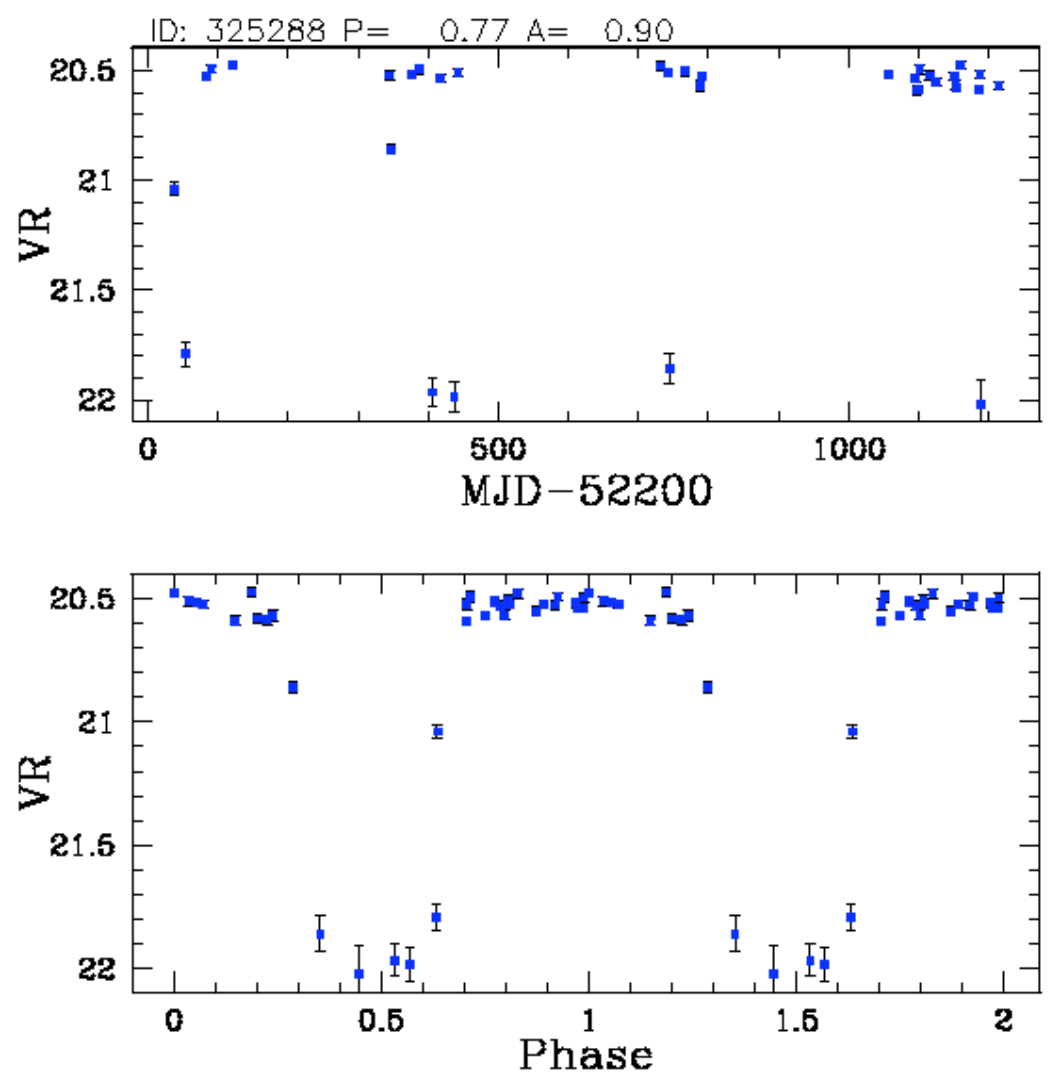
Example SM EB



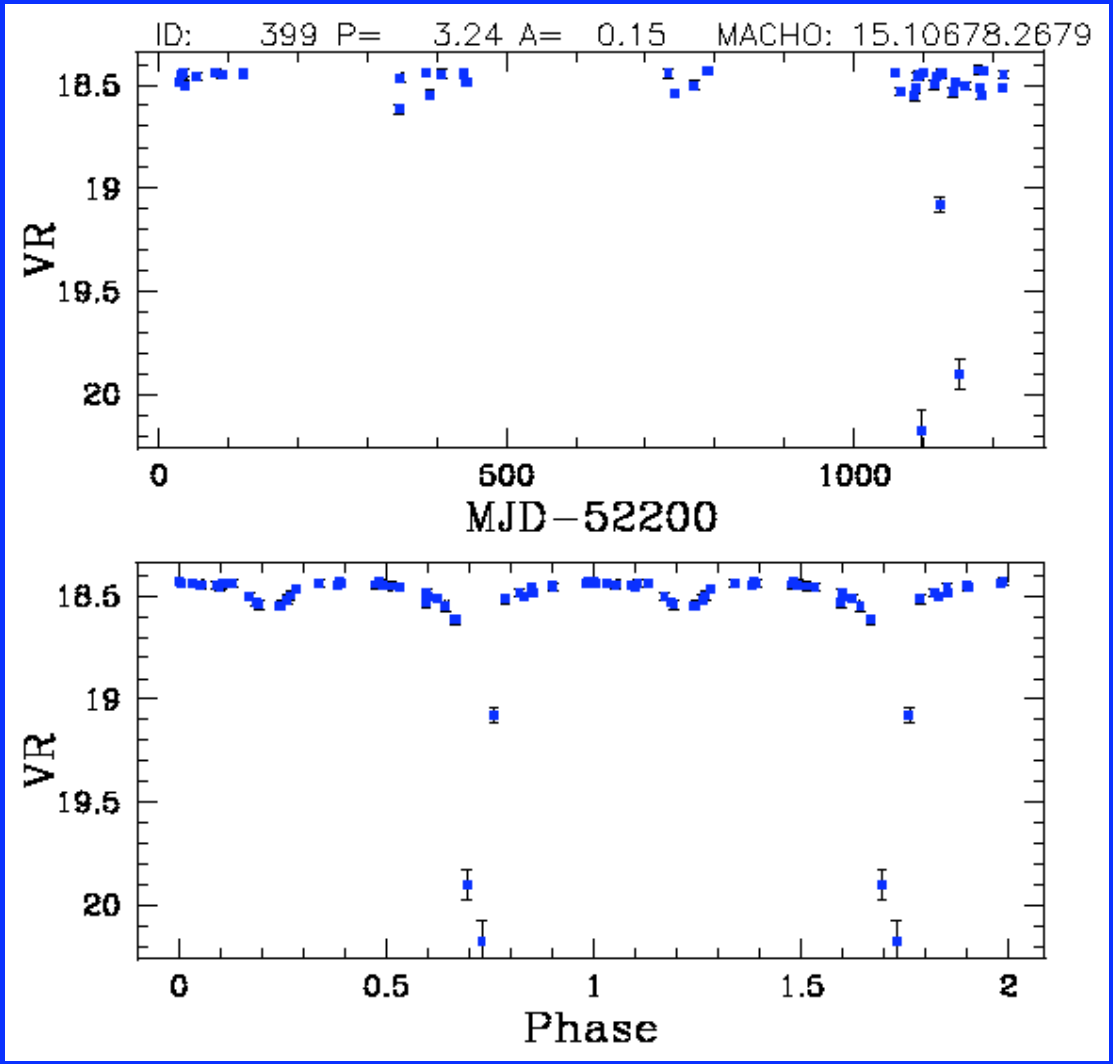
Example SM EB



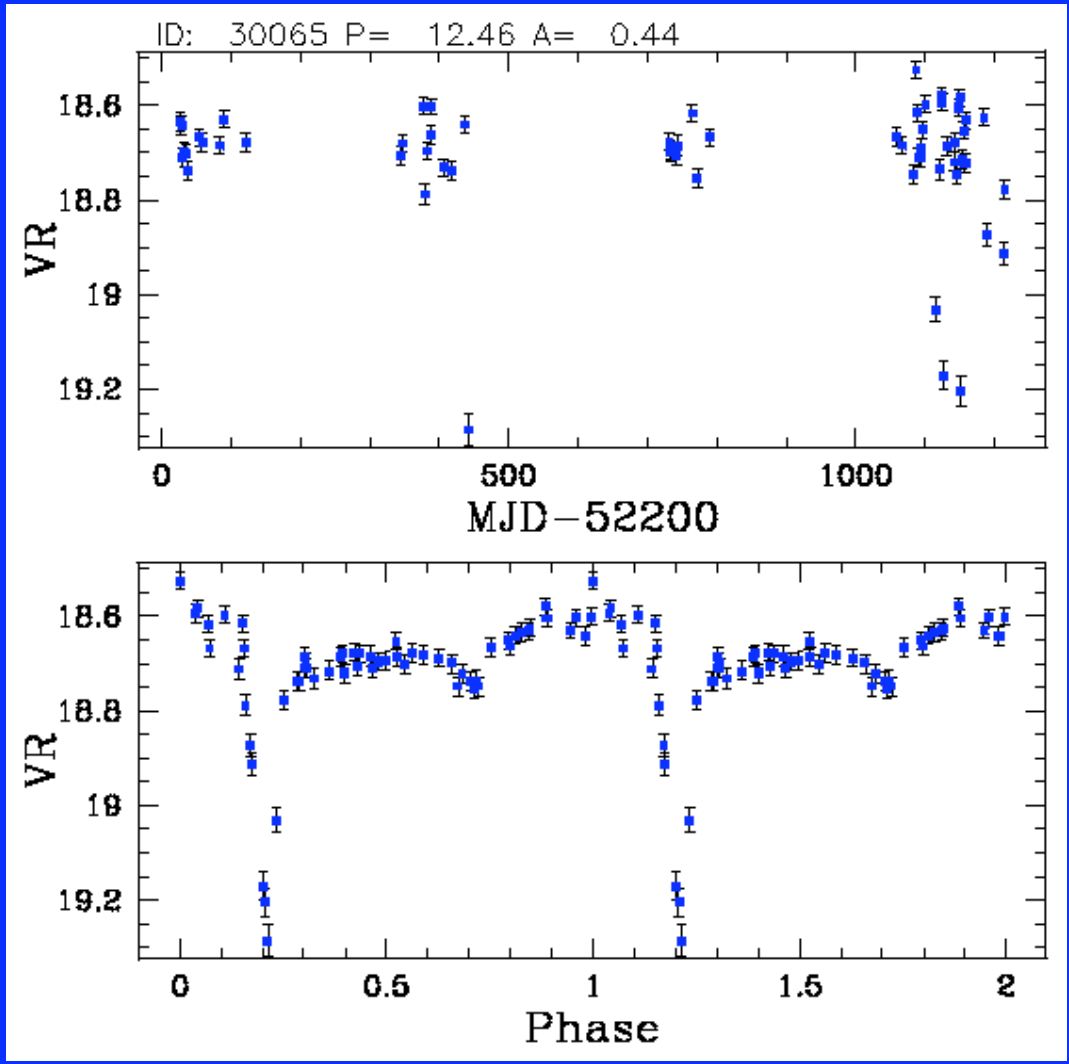
Example SM EB



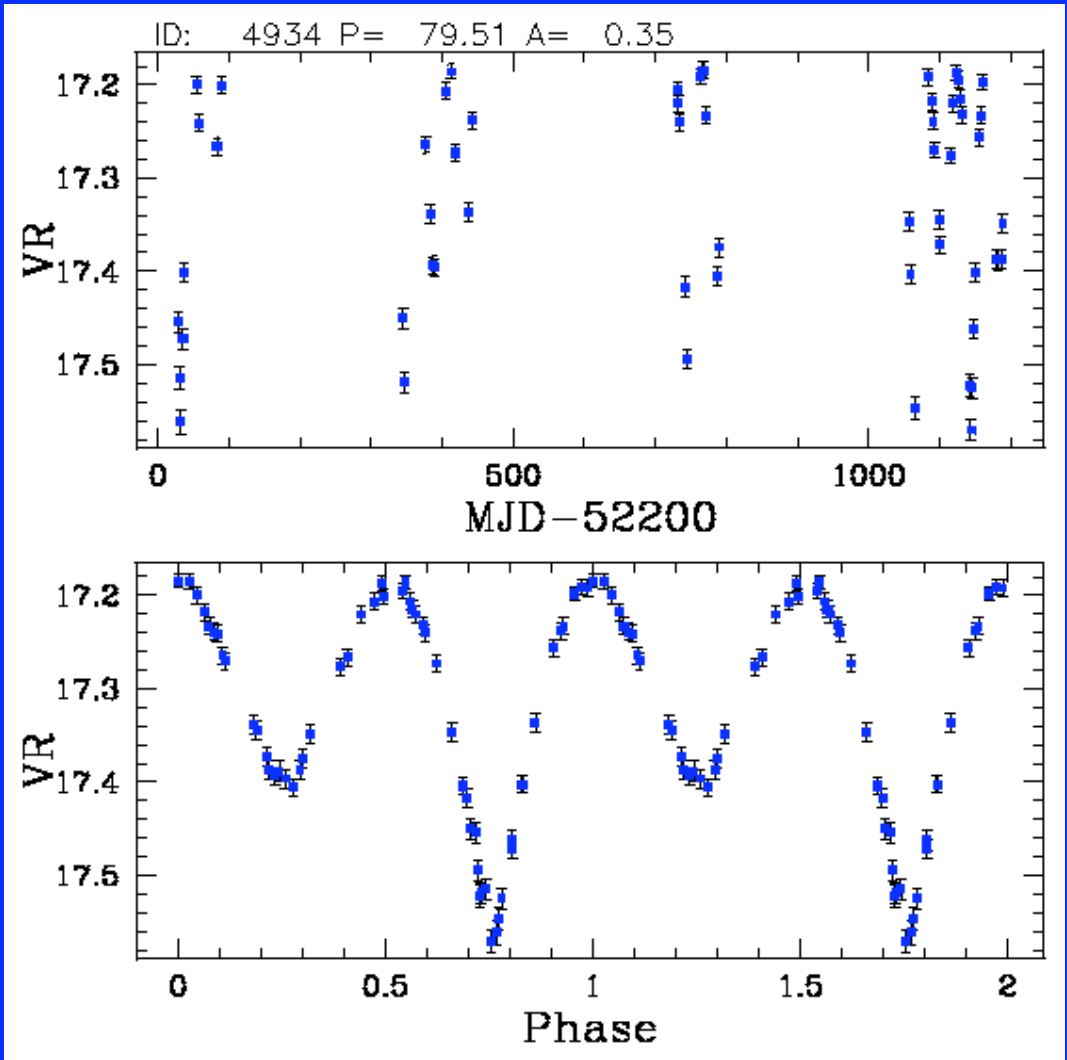
Example SM EB



Example SM EB



Example SM EB

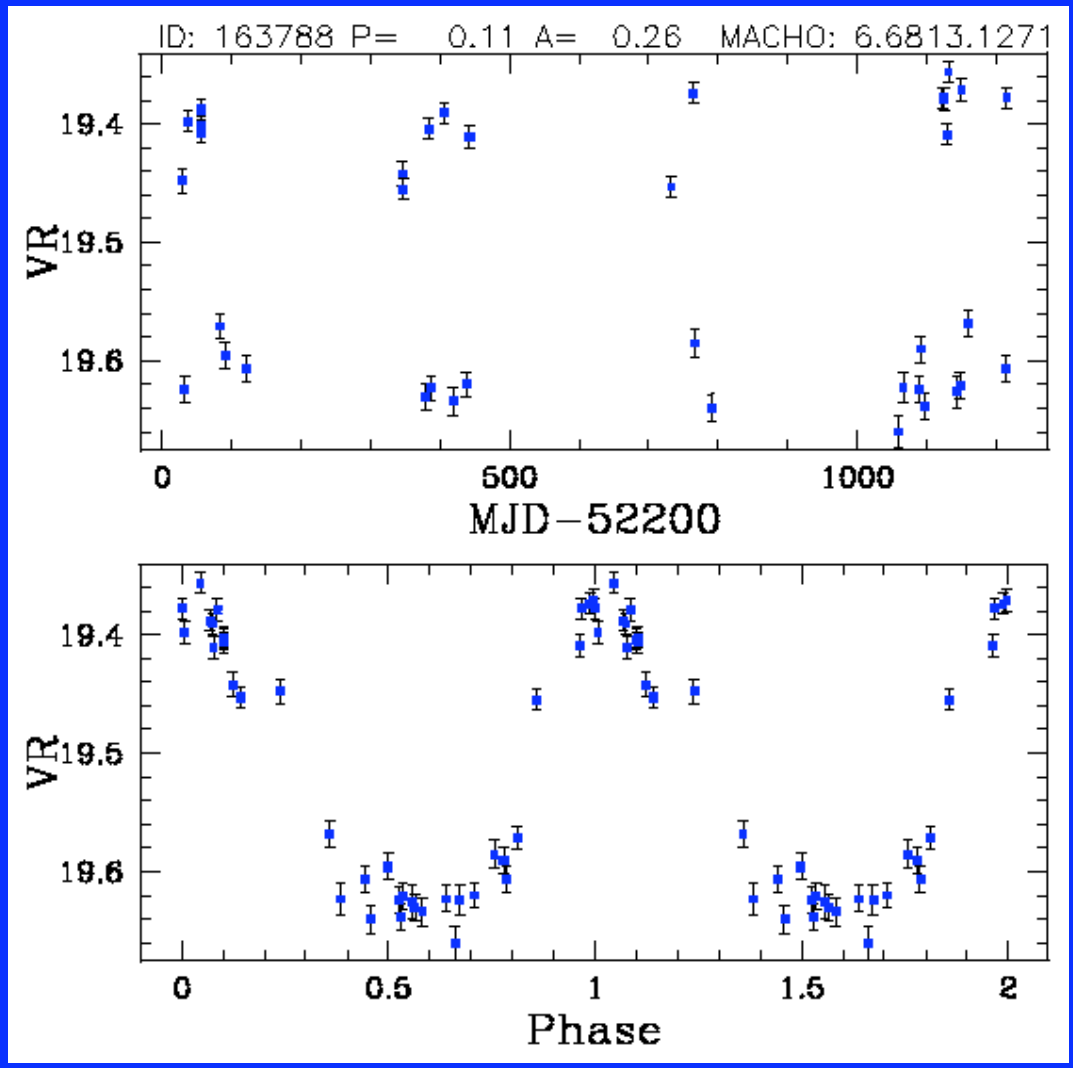


Beginnings of Variable Star Science

- Delta Scutis identified, analysis starting
- RR Lyrae behavior comparing with MACHO-period, phase evolution
- Fainter EB catalog on the way
- Cross correlating with 2MASS

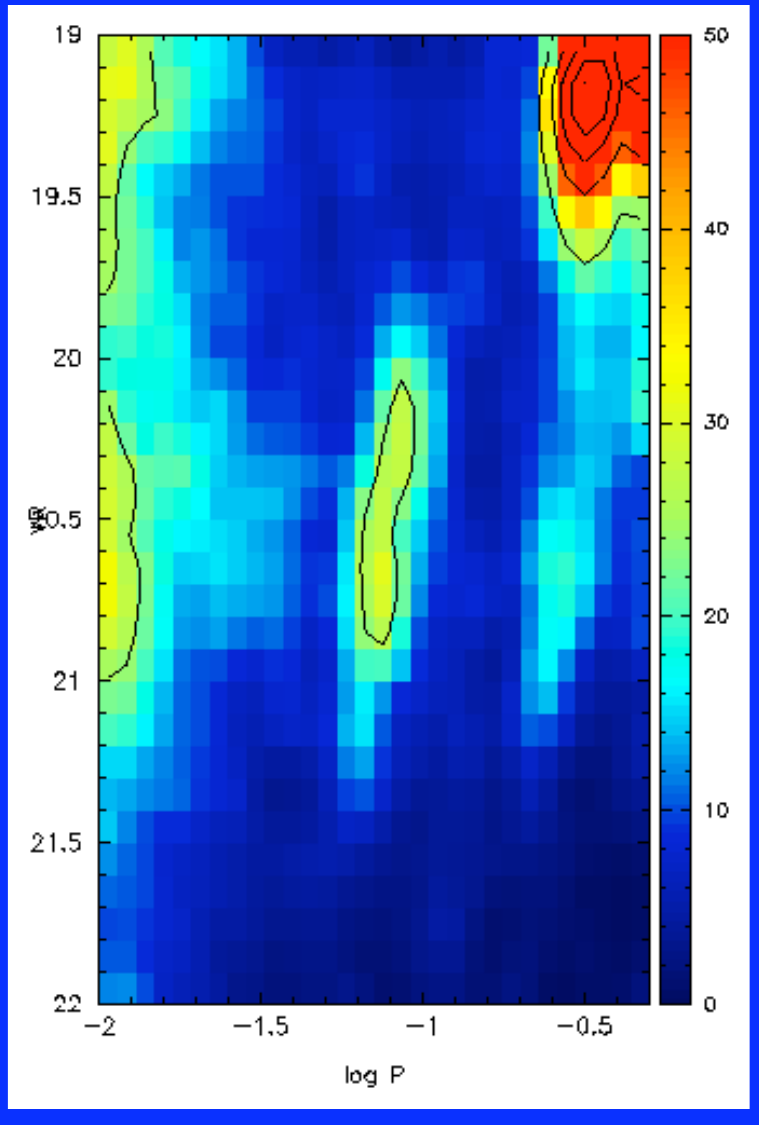
Delta Scuti in SM

Di Fabrizio *et al*, 2005 A&A 430:603 identified a Delta Scuti star in a MACHO field (their #28114). MACHO had phased it properly, but the light curve was EXTREMELY noisy. SM nails this object.

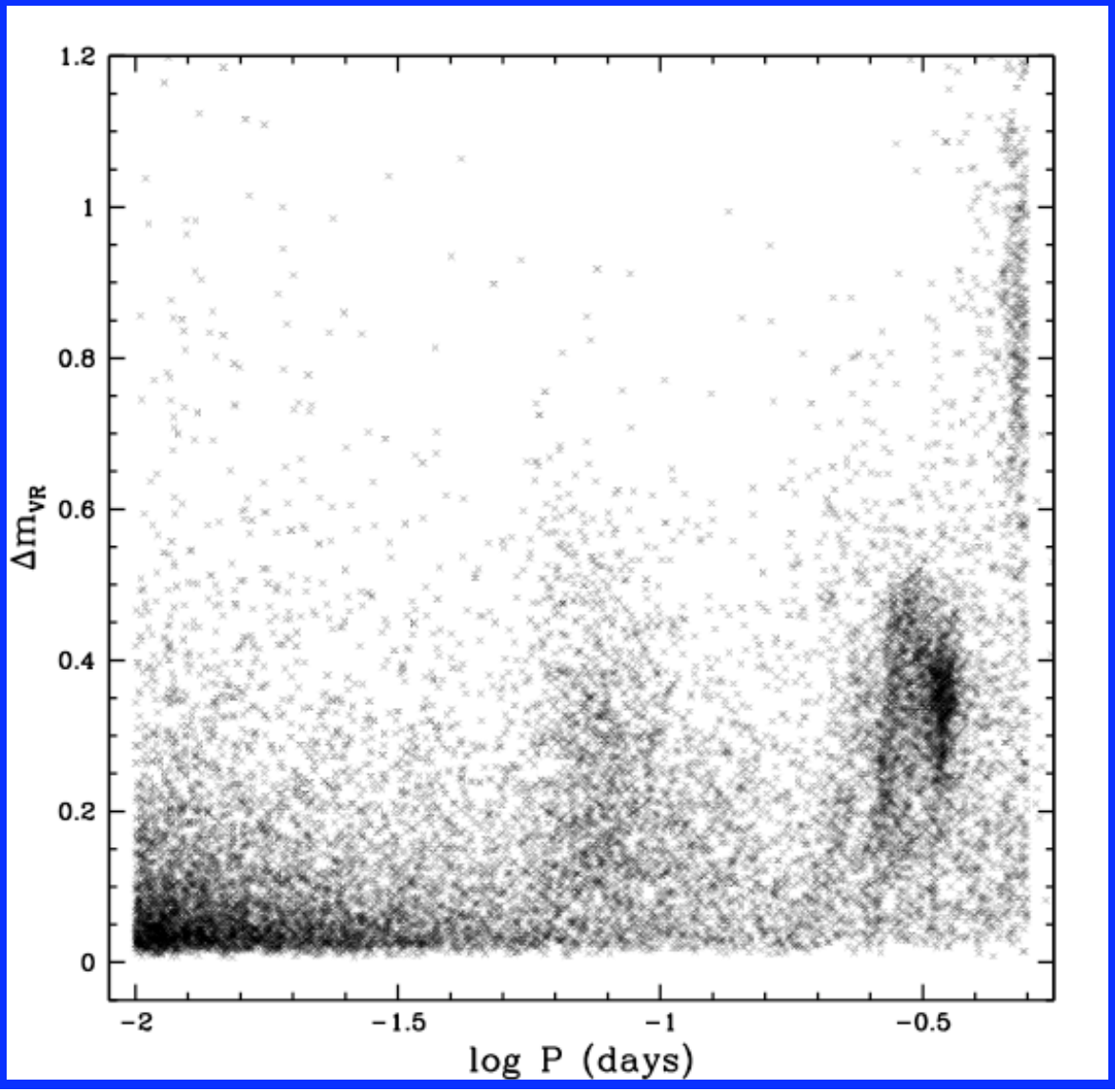


SM Delta Scuti region in PL

Contour plot of density of light curves in period-'luminosity' diagram showing large over density around 2 hours. Delta Scutis?

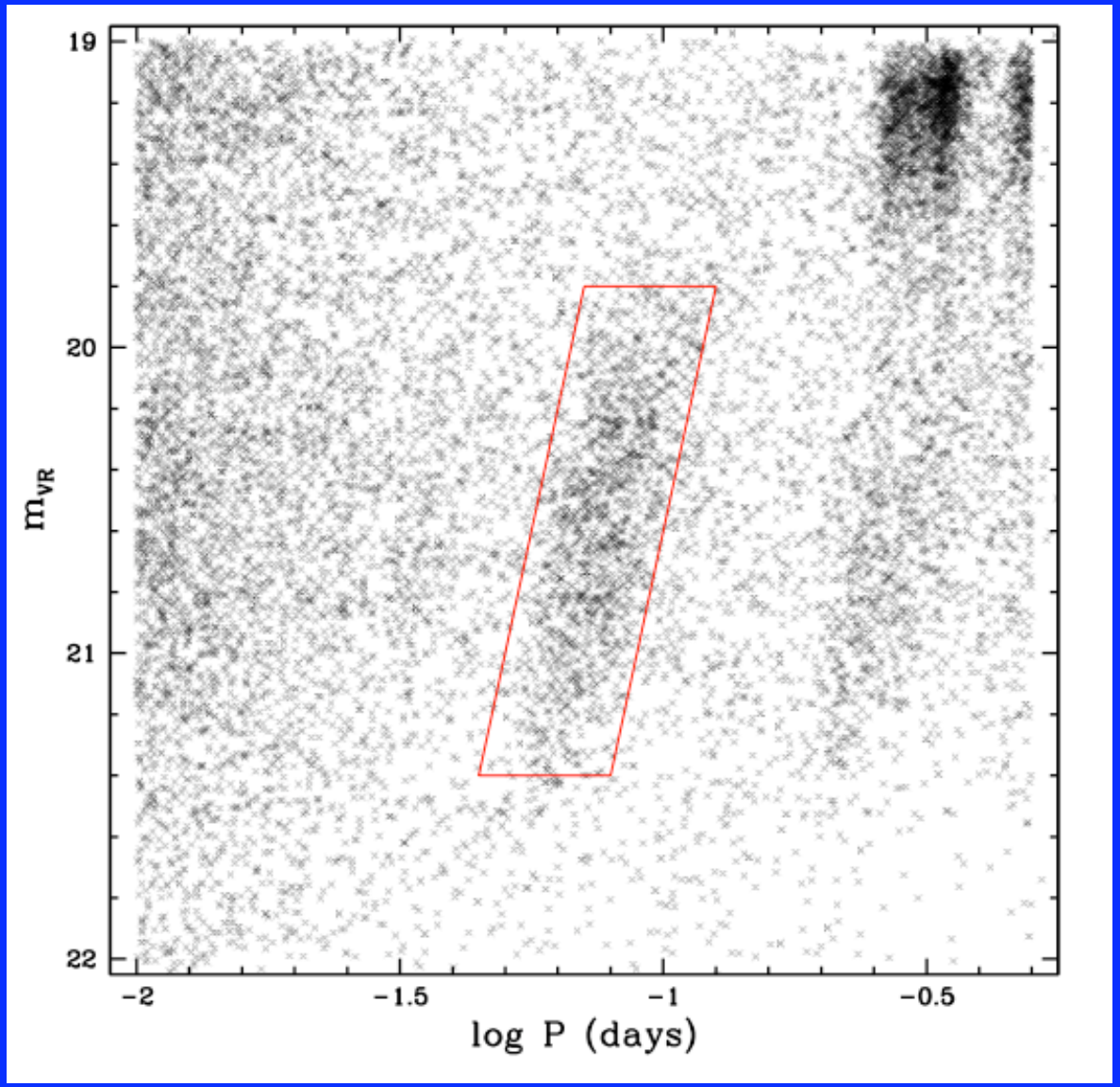


Period-amplitude region for Delta Scuti

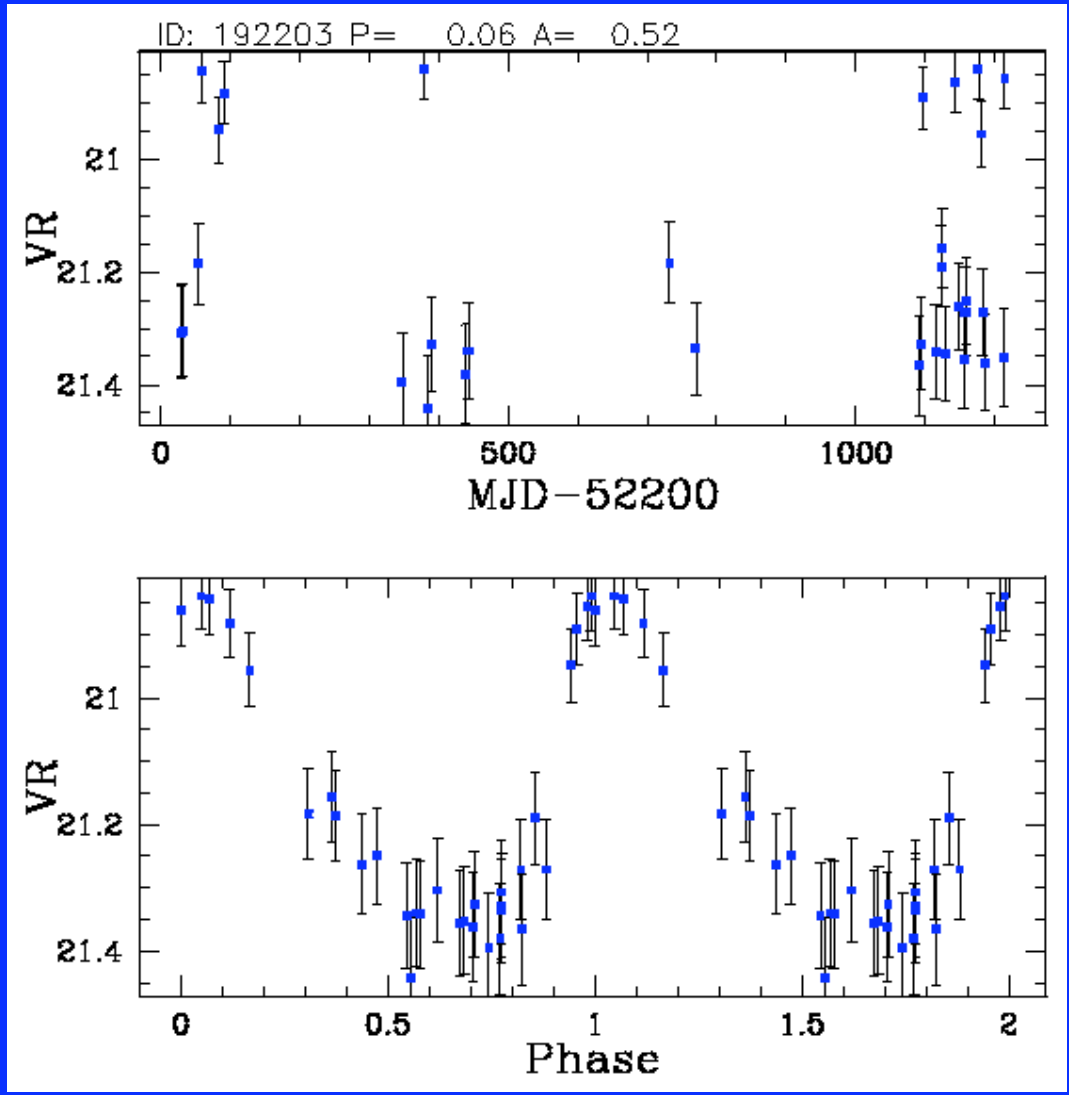


Delta Scuti region in P/L plane

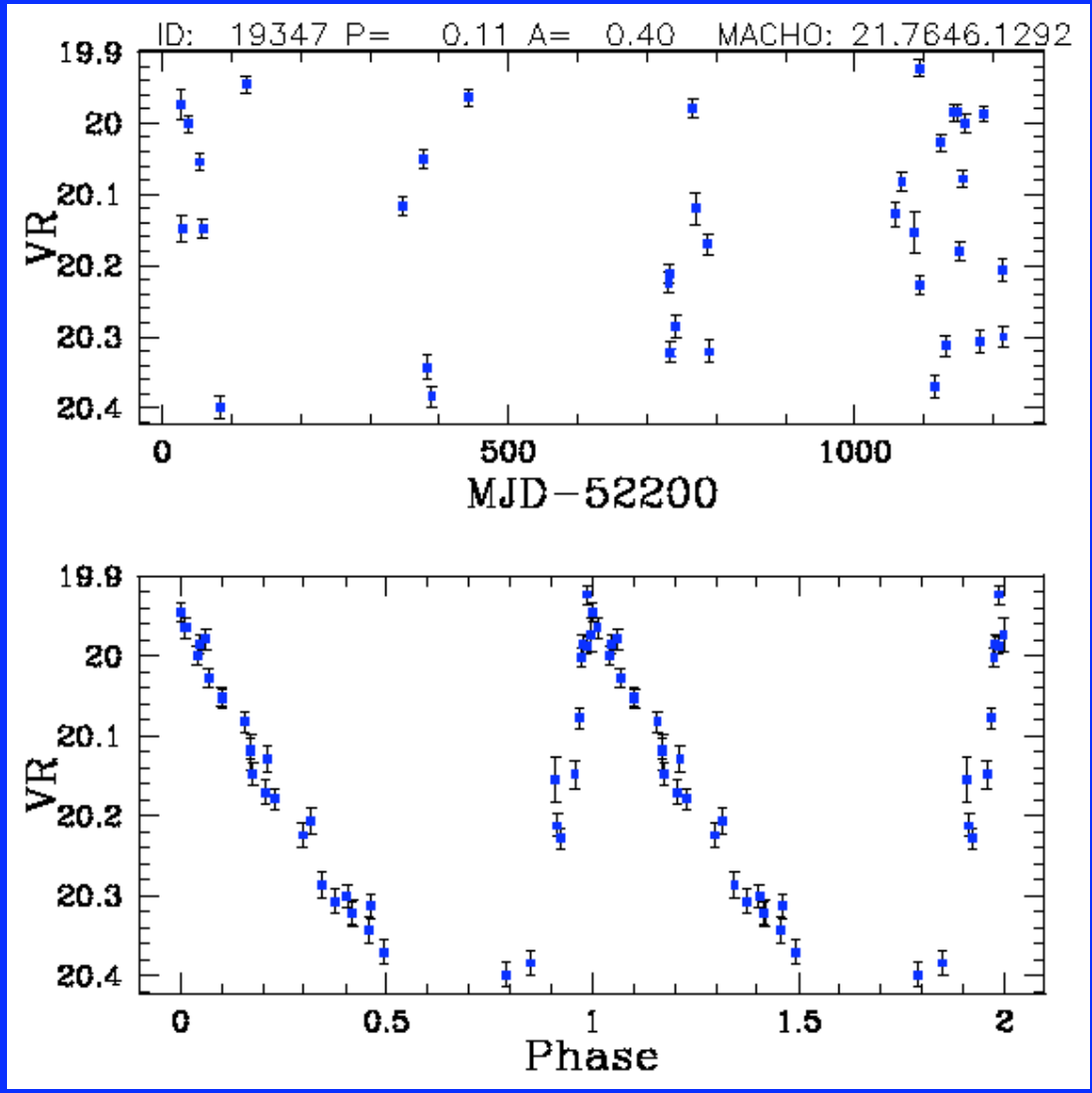
1629 light curves in potential Delta Scuti region. Examined by eye, selecting 785 reasonable candidates.



Delta Scuti examples

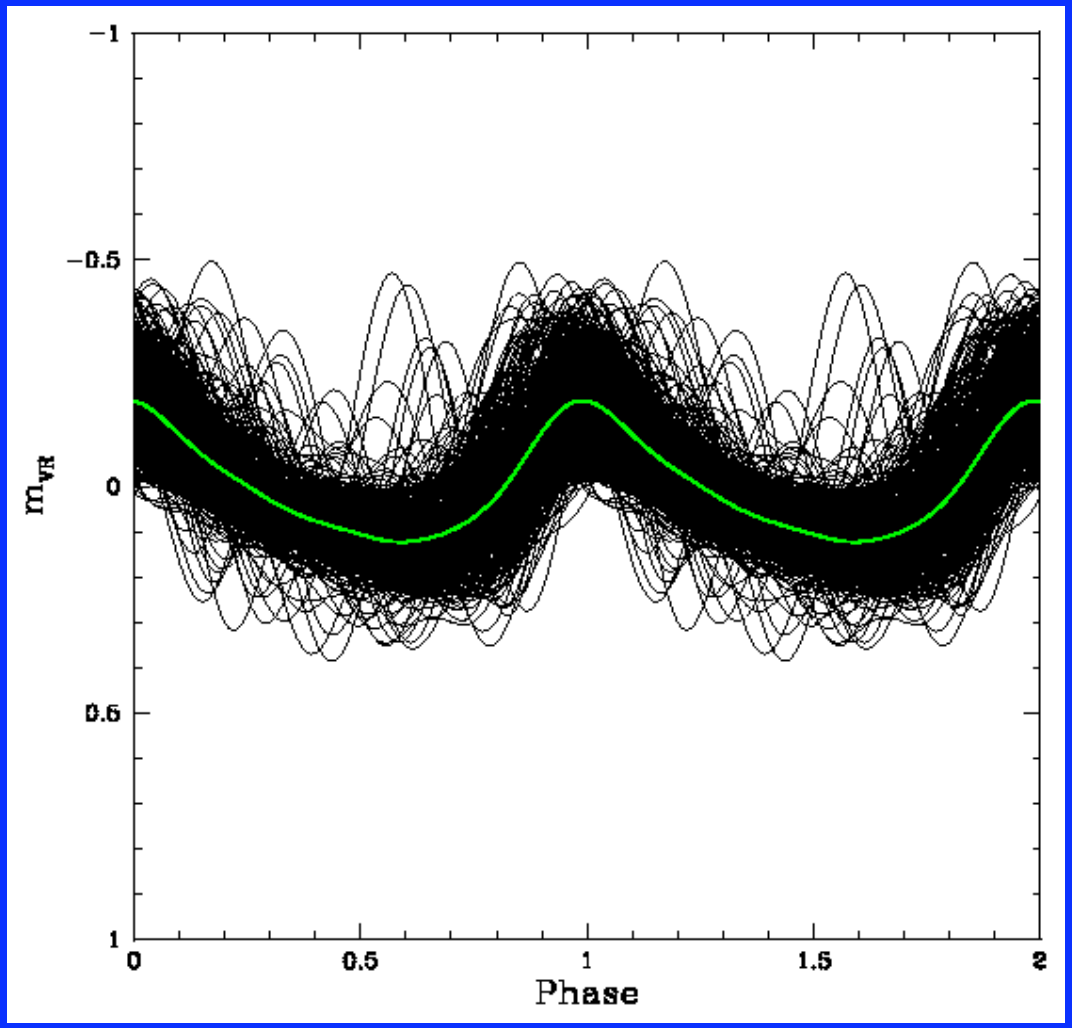


Delta Scuti examples

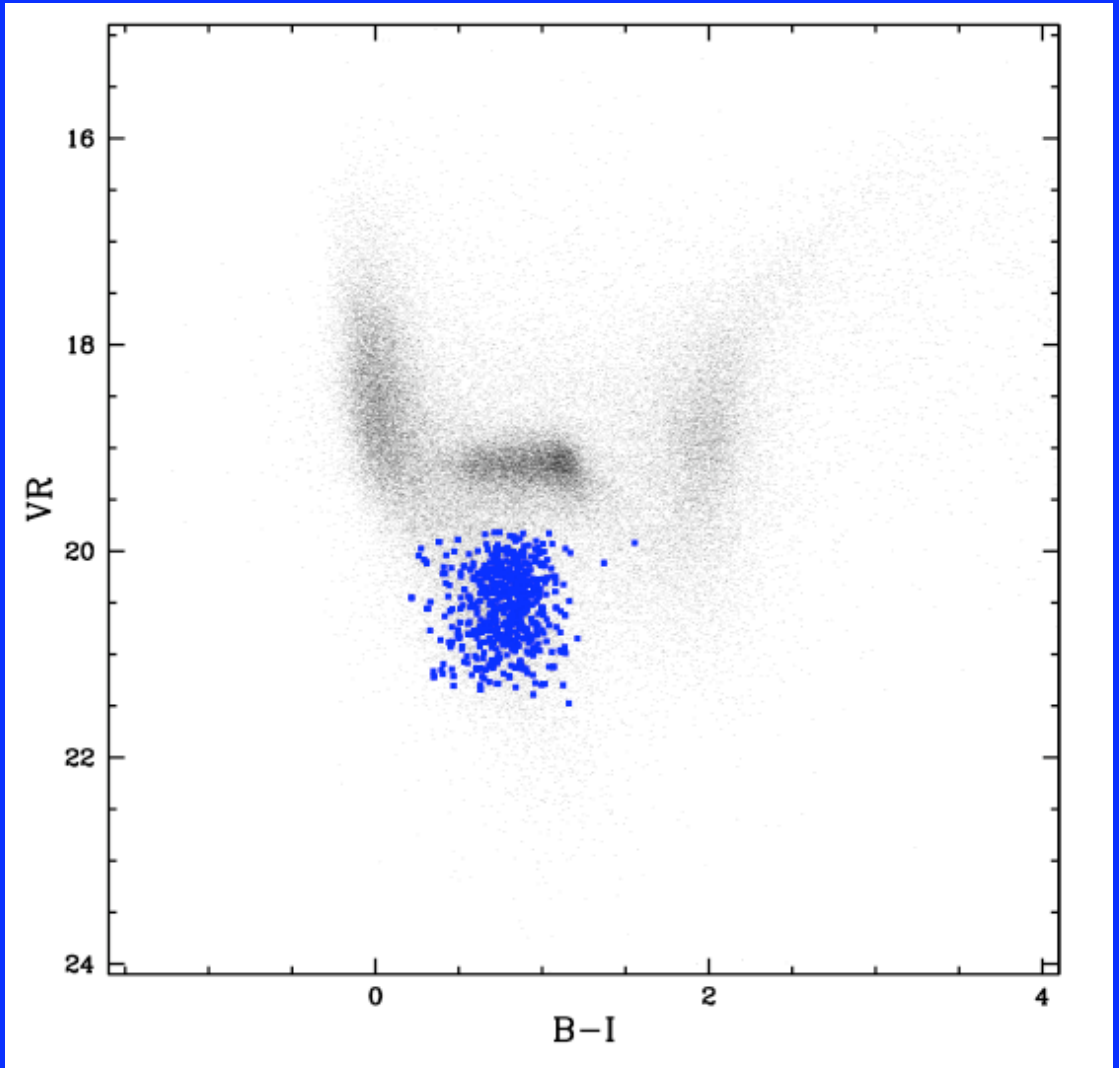


Delta Scuti template

Fourier coefficients for 785 candidates used to create template light curve, cut on amplitude of coefficients yielding 687 candidates of which 69 were in MACHO variable list.

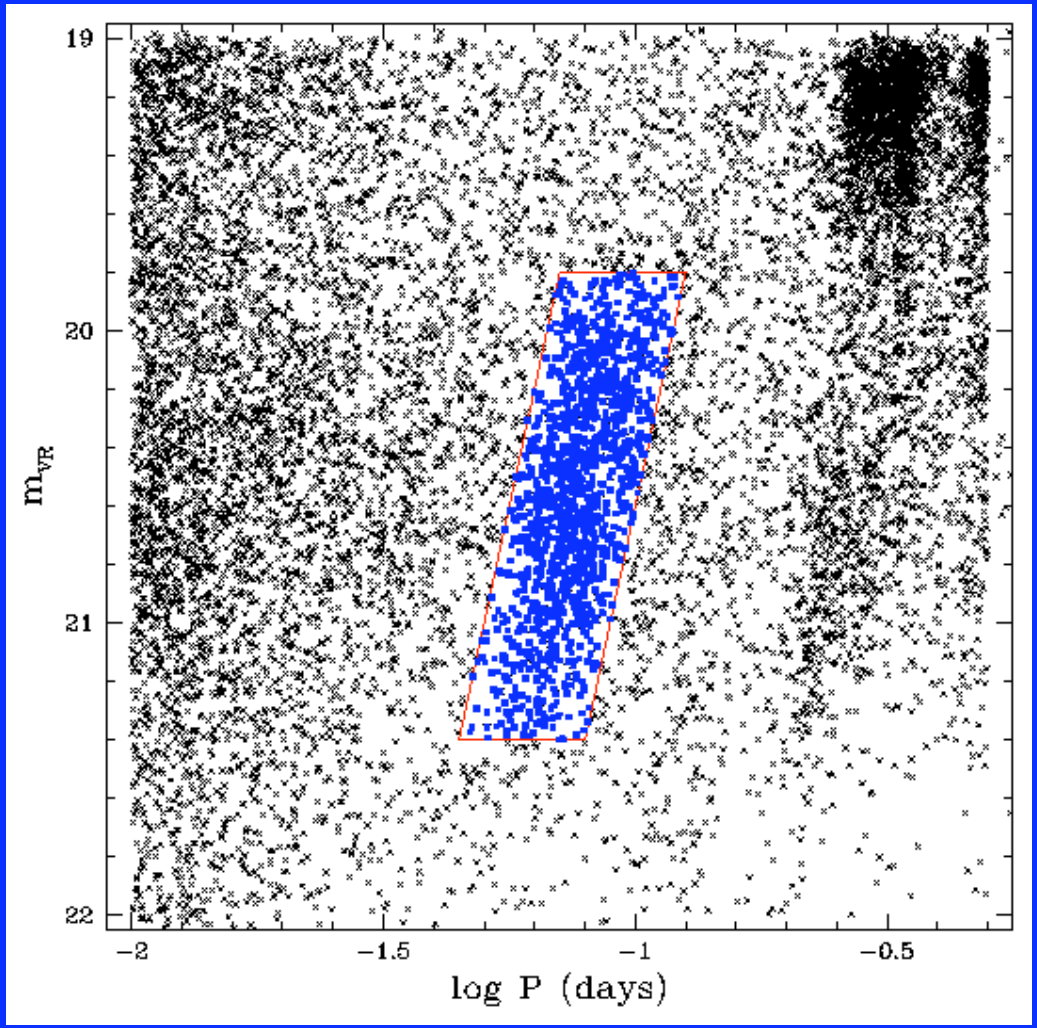


CMD of Delta Scuti Candidates and all variable stars

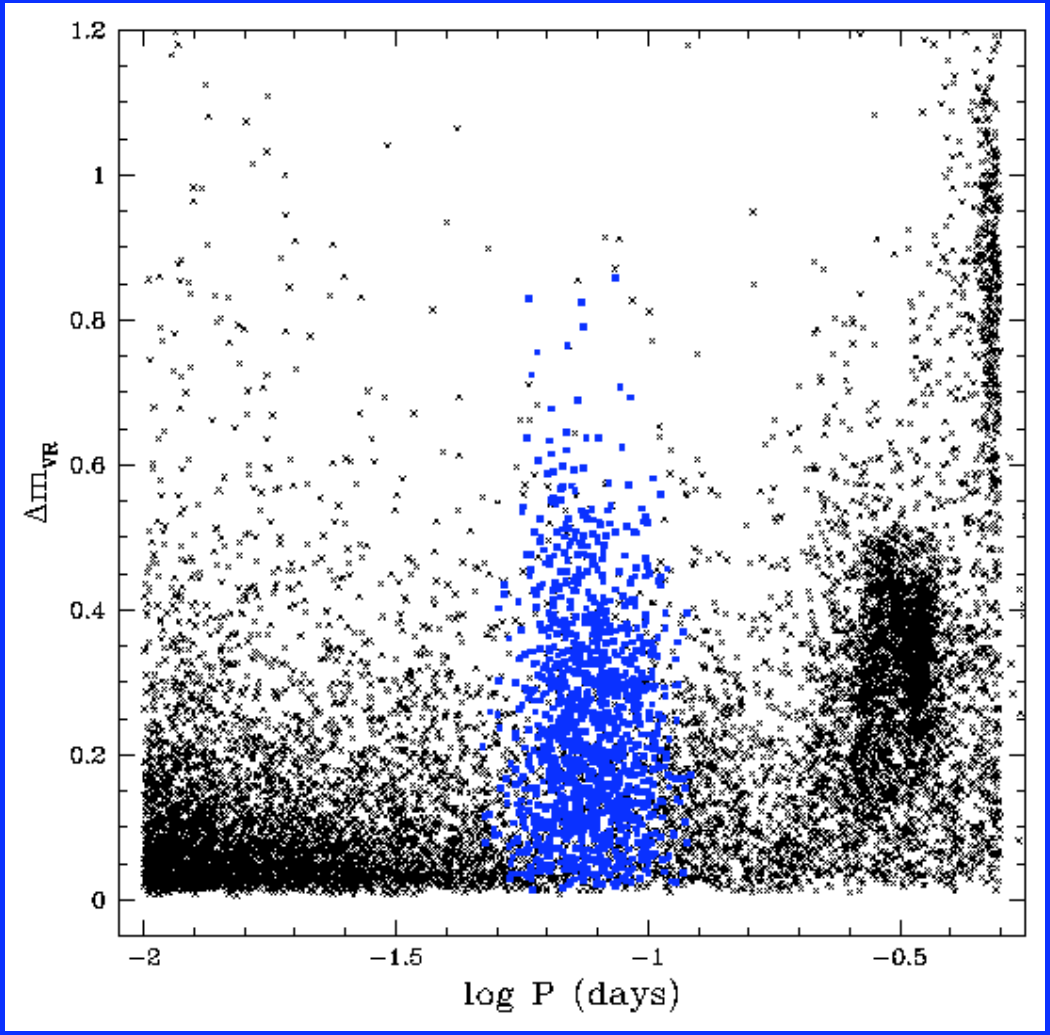


Fishing for LMC Delta Scutis

1629 light curves in potential Delta Scuti region. Examined by eye, selecting 785 reasonable candidates.

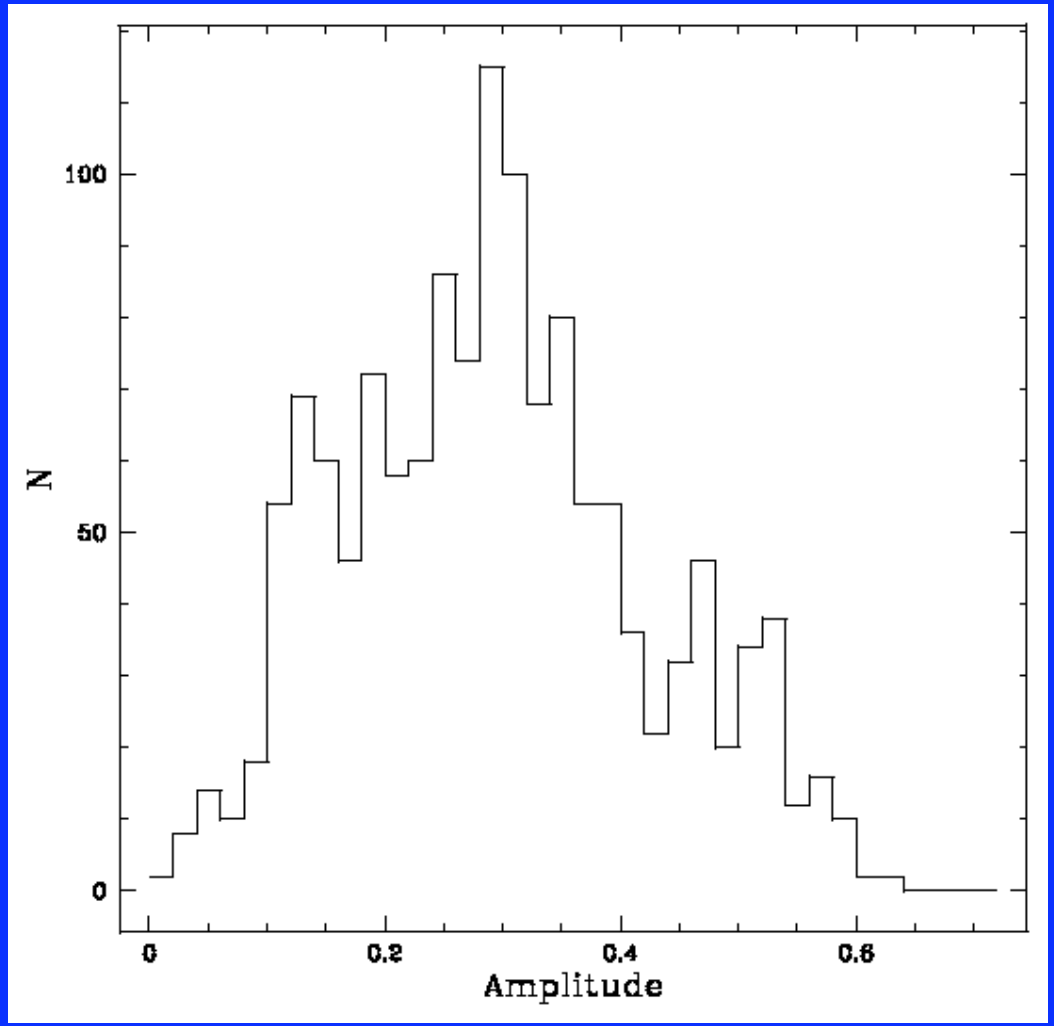


Period-amplitude distribution of Delta Scuti candidates



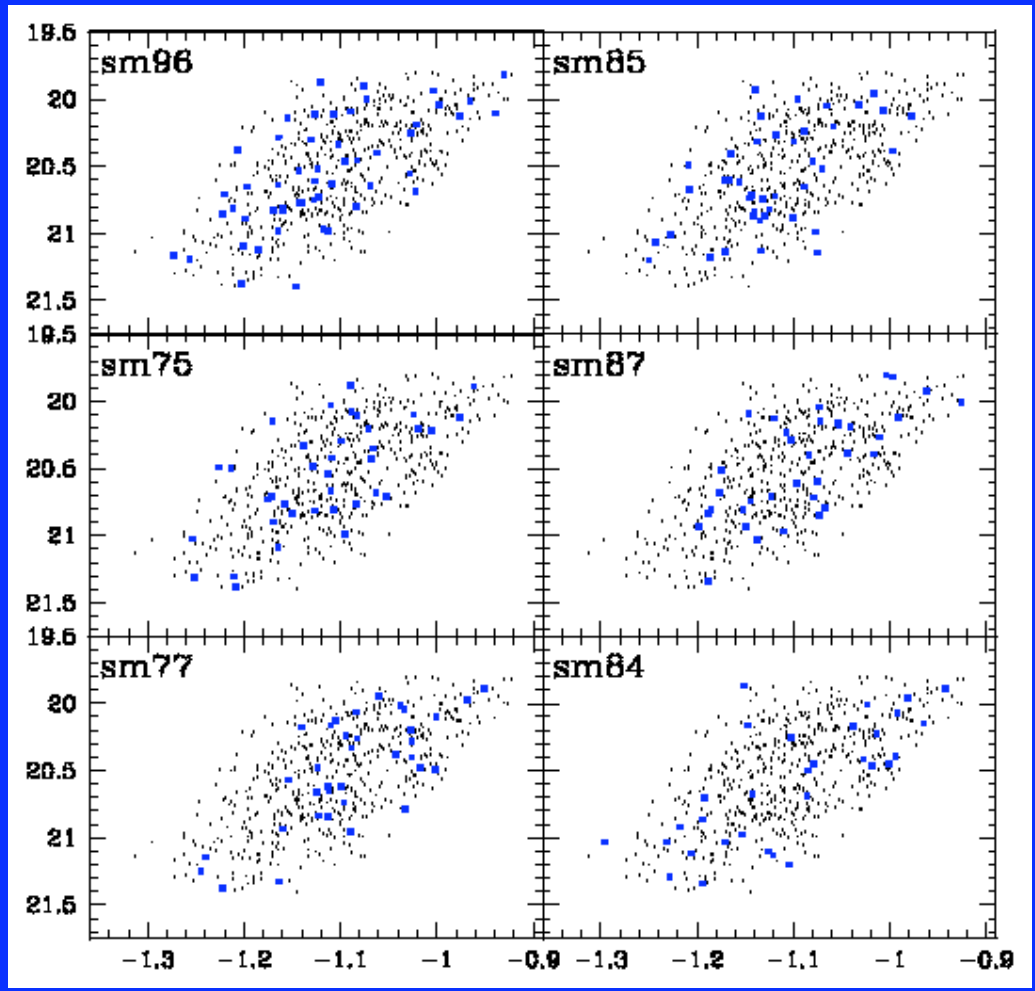
Amplitude distribution for Delta Scuti candidates

Amplitude distribution spans both low and high amplitude pulsations, but mostly high.



P/L relations for Delta Scutis in different SM fields

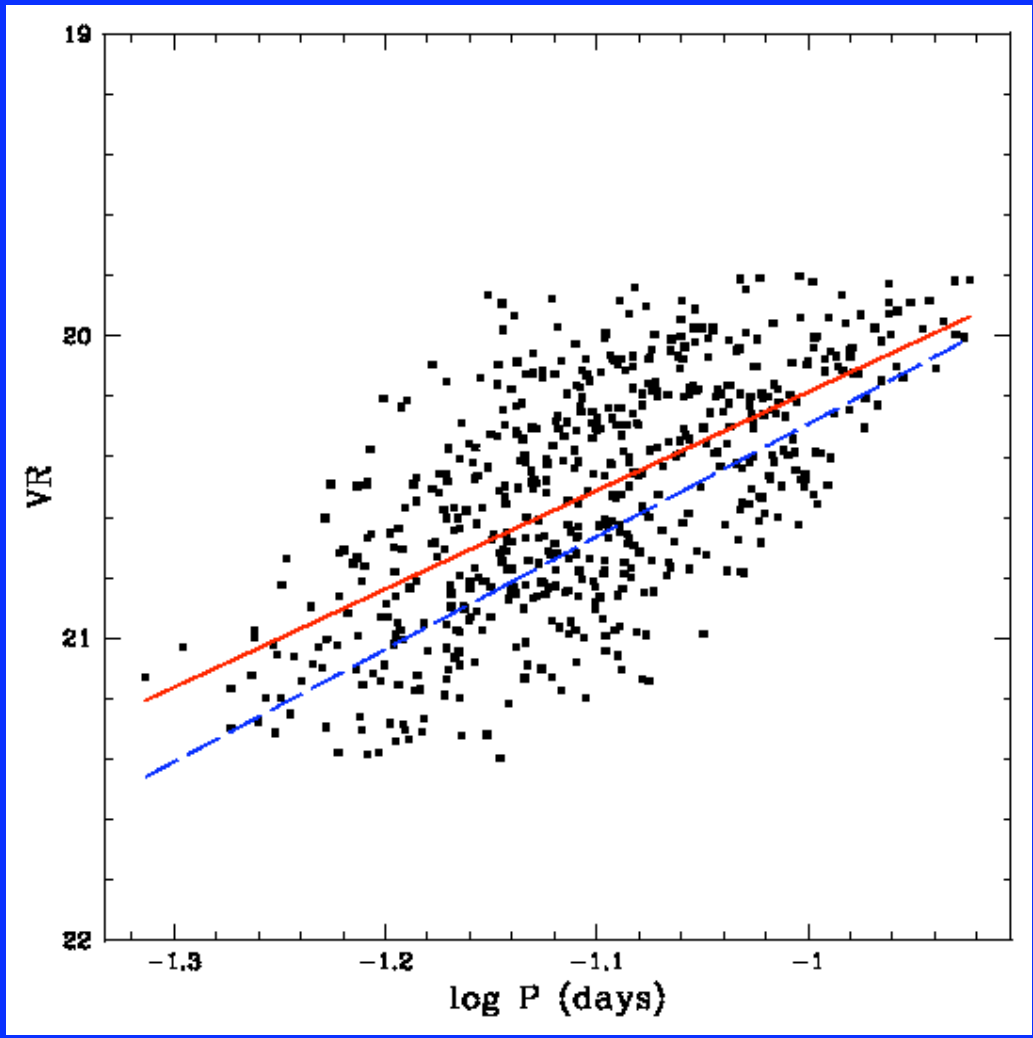
Broad dispersion of P/L relation not due to field-to-field zero point problems.



Preliminary SM Delta Scuti P/L realtion

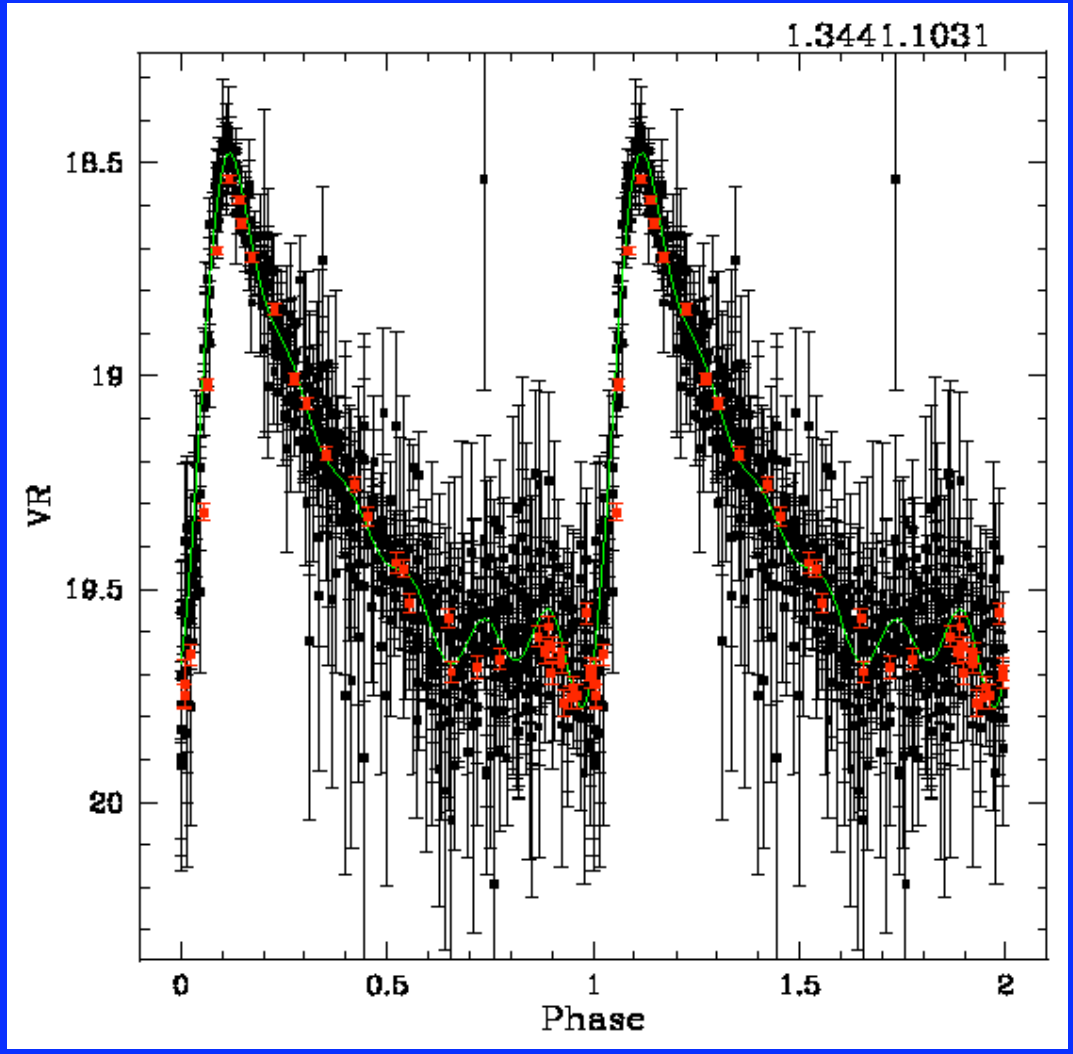
Blue, dashed line P/L relation of McNamara, 1997 PASP 109:1221: Mv ~ -3.725 logP.

Red line, SM fit: Mv ~ -3.26logP +/- 0.15



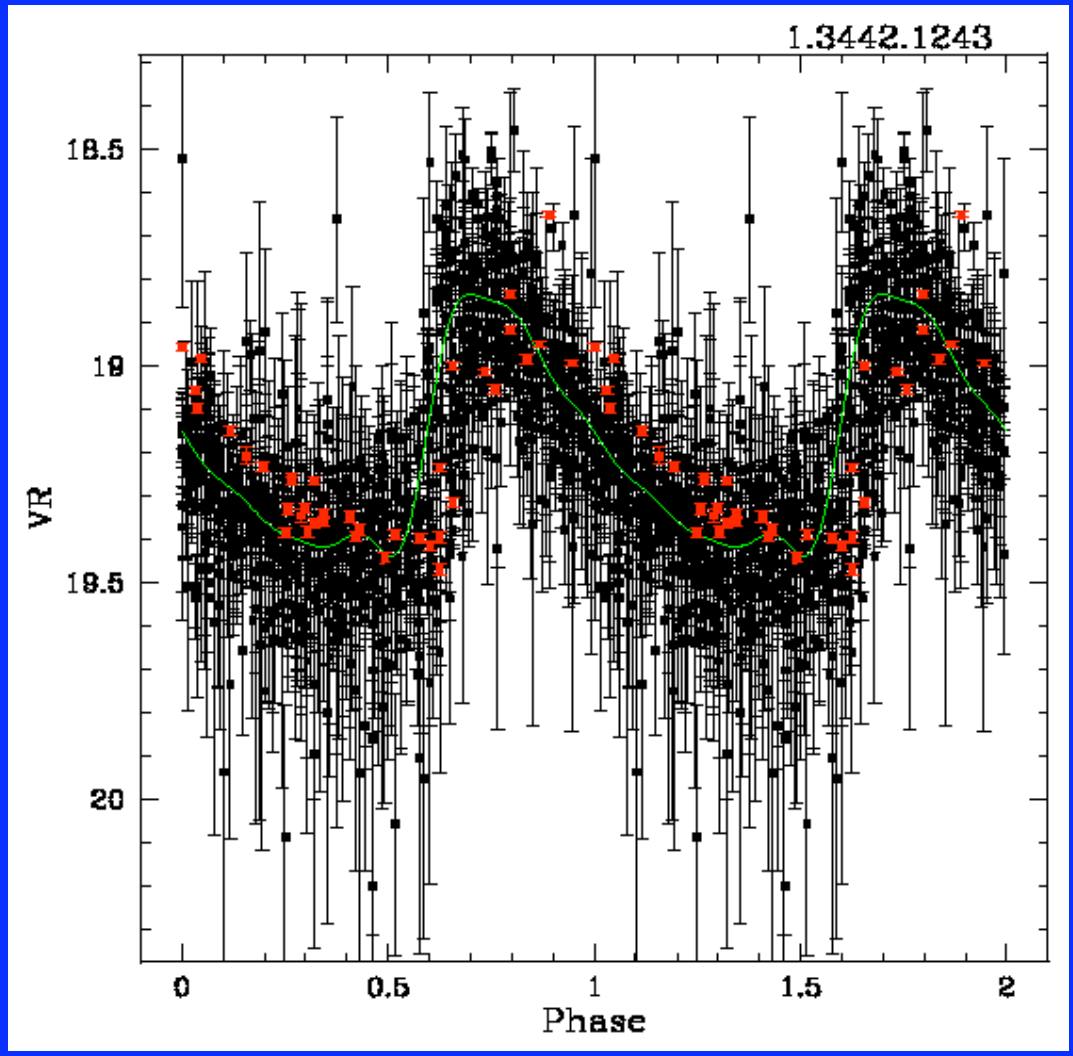
Comparing RR0 from SM and MACHO

MACHO data in black, SM data in red and green line is for 6th order Fourier fit to SM.



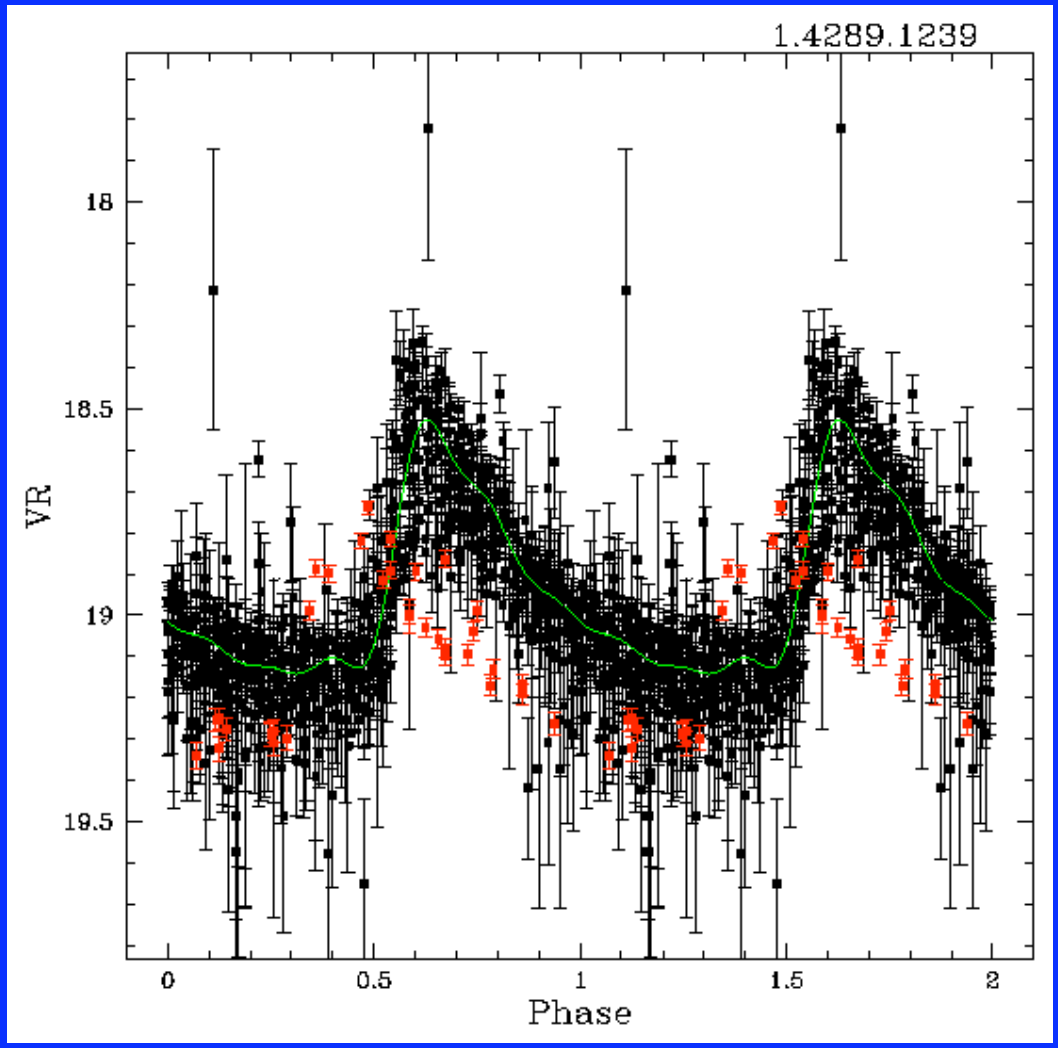
Blazko RR0

Blazhko RR0 with two side components, showing a phase or period shift between MACHO and SM.



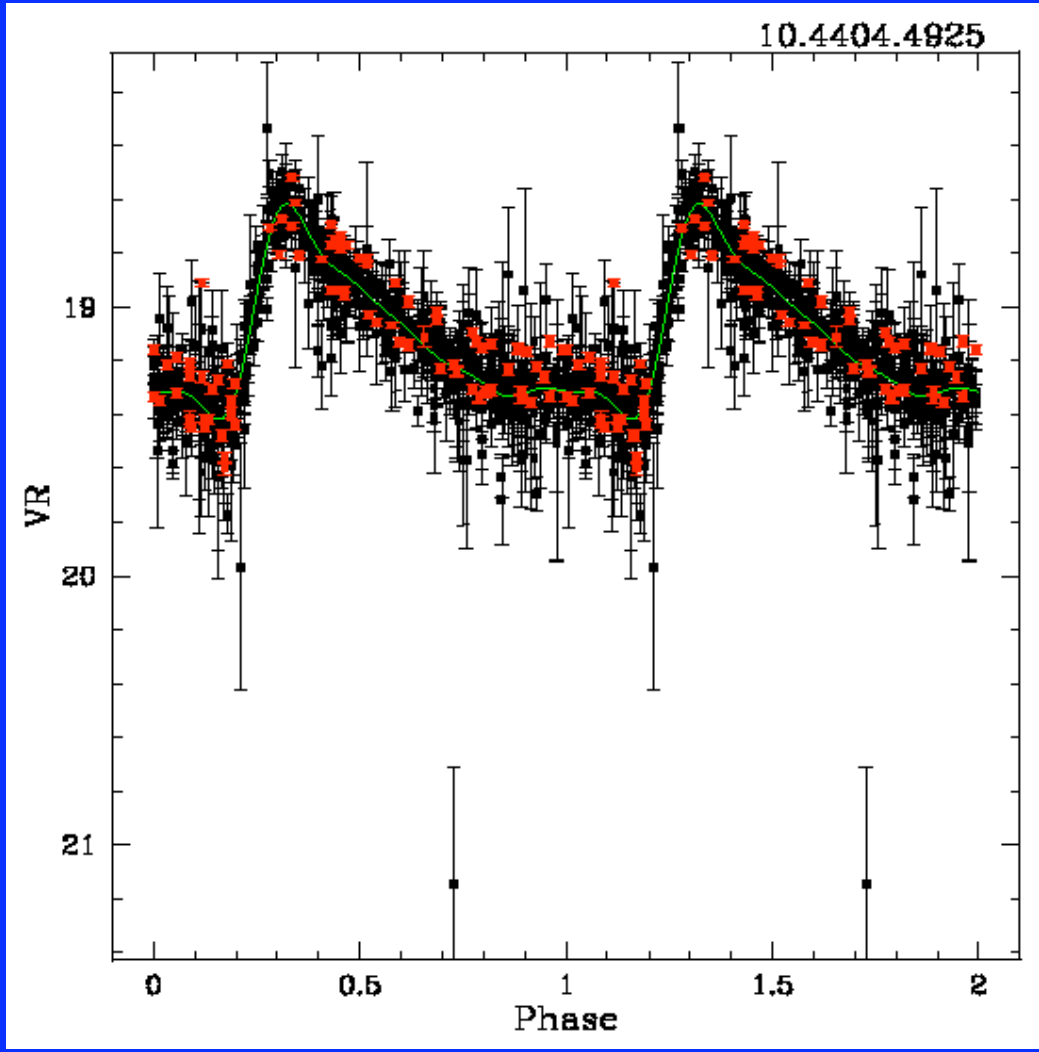
Blazhko RR0

Blazhko with one side component, showing phase or period shift and zero point problems with SM.



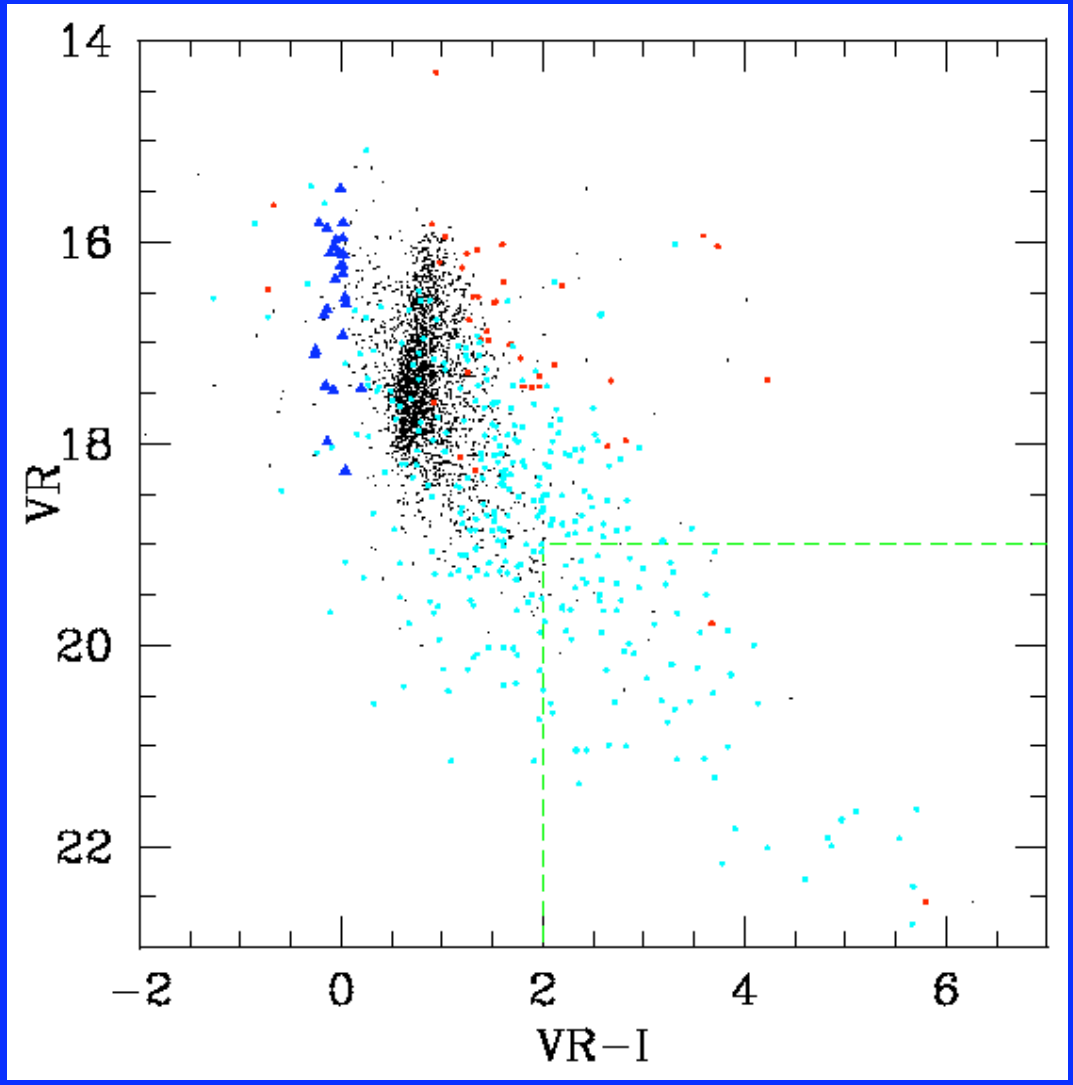
RR0 in SM field overlap

Edge of field in SM not well calibrated (yet) so zeropoints off by ~0.15 mag



Interesting variable matches to 2MASS sources

CMD for SM matches to 2MASS. Note blue sources (post-AGB stars?) and optically faint sources-- enshrouded AGB stars.



SuperMACHO in the future

- Microlensing distribution across LMC
- Rereduce MACHO with SM pipeline
  - 1.8x microlensing events, combine with SM
  - Better variable star light curves, clusters!
- SM variable star catalog
- Combined MACHO/SuperMACHO lightcurves

This work was performed under the auspices of the U.S. Department of Energy, National Nuclear Security Administration by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.