PAndromeda

- A dedicated M31 survey with Pan-STARRS 1 -

PIs: Stella Seitz, Ralf Bender

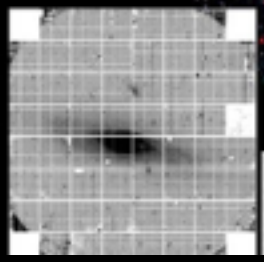
Team Members:
Arno Riffeser, Mihael Kodric,
Johannes Koppenhoefer, Ulrich Hopp,
Jan Snigula, Claus Goessl
& PS1 Science Consortium

Chien-Hsiu Lee 2015 August 20
@ Subaru Seminar

The Andromeda Galaxy Observed by Pan-STARRS 1

This full-color image of the Andromeda Galaxy was constructed from a series of *g*, *r*, *i* images obtained 2007.12.02 during the second PS1 commissioning run. Twelve images were obtained in each filter at dithered offset positions.

The images were warped into a regular pixel grid aligned with the celestial coordinates. The raw 0.26 arcsec GPC1 pixels were re-sampled to 0.33 arcseconds, and binned 2x2 for this image.



One of the individual *i*-band images used to build the full-color image. This image has been dark and flat-corrected, and illustrates the layout of the 60 GPC1 CCDs and the

Pan-STARRS

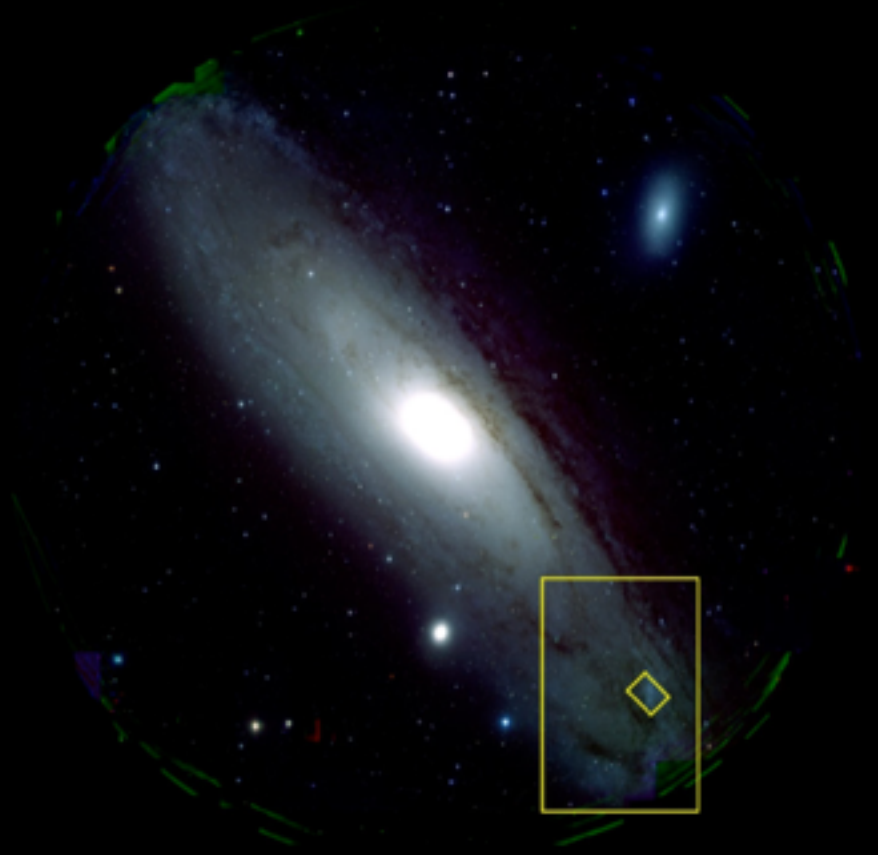
Pan-STARRS 1 Commissioning Observations 2007.12.02

Eugene A. Magnier, Kenneth C. Chambers, Jeffery Morgan, Nick Kaiser, John Tonry, William Burgett and

満月の典型的な
見かけの大きさ
(視直径 0.5 度角)

Suprime-Cam
ファーストライト
(1999年1月公開)

Suprime-Cam
(2001年9月公開)



Hyper Suprime-Cam
(2013年7月公開)

The PAndromeda Team

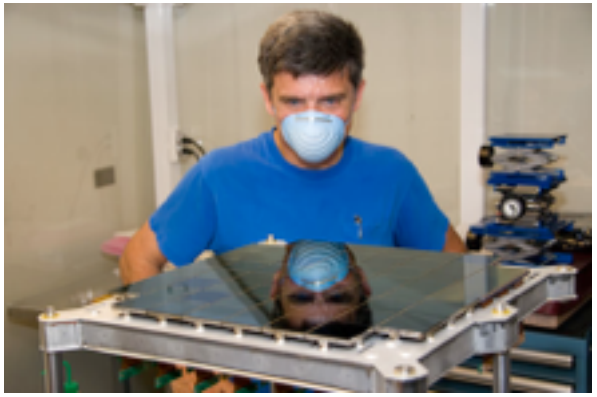
Pan-STARRS 1

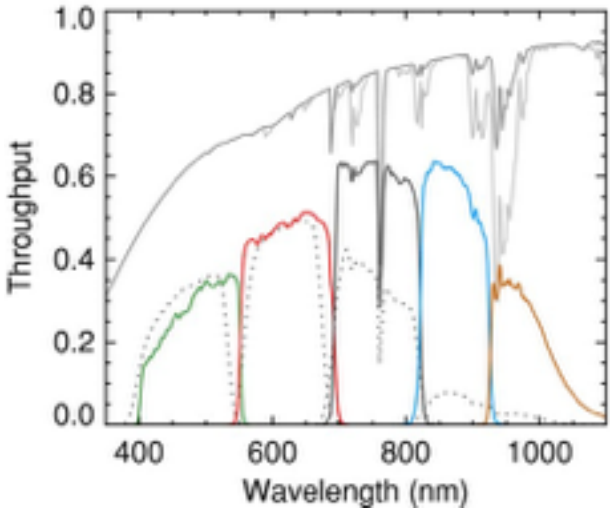
- Panoramic Survey Telescope And Rapid Response System (Pan-STARRS)

- Wide-field imager, 1.4 Giga pixel, ~7 deg^2 F.O.V with 0.25"/pixel

- 3Pi survey (Dec>-30 deg): 30,000 squared degrees in g, r, i, z, and y, about 1 mag deeper than SDSS

- Plus selected deep fields for SNe, planets, M31





Dupuy & Liu 2009

PAndromeda in a nutshell

- Observed M31 in 2010-2012, from July to Dec.

- 2% of the 3yrs PS1 observing time (including overheads)

- 1.8m PS1 telescope, ~7 deg2 F.O.V., 0.25"/pixel

- r_{PS} and i_{PS} : up to 2 visits per night

- g_{PS}, z_{PS}, y_{PS} : sparse exposures in 3 yrs

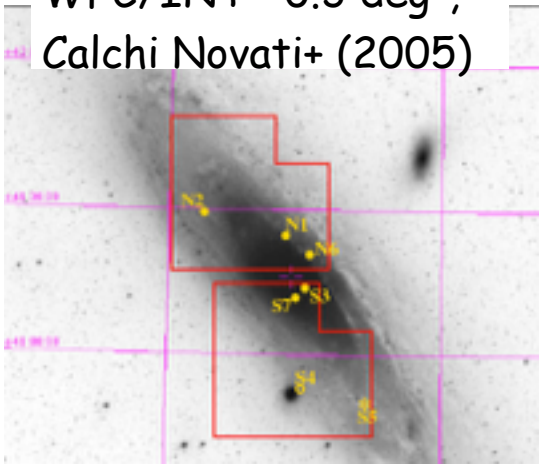
Main goals:

- Constraining the compact matter fraction in the M31/MW halos

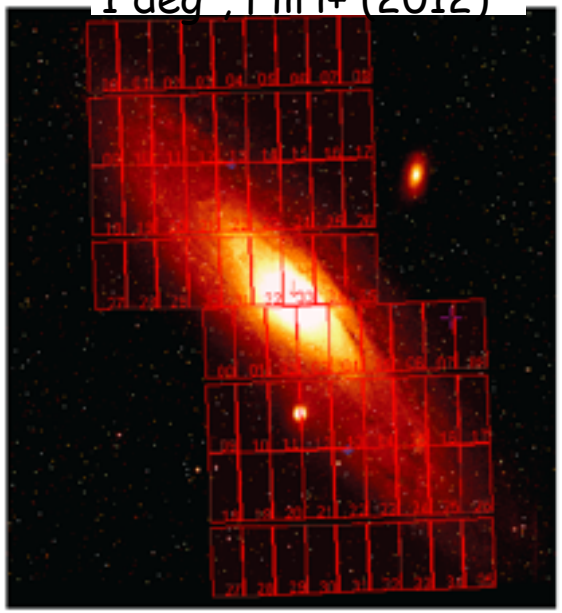
- Inventory of variables in M31, including Cepheids, binaries, long-period variables

PAndromeda footprint

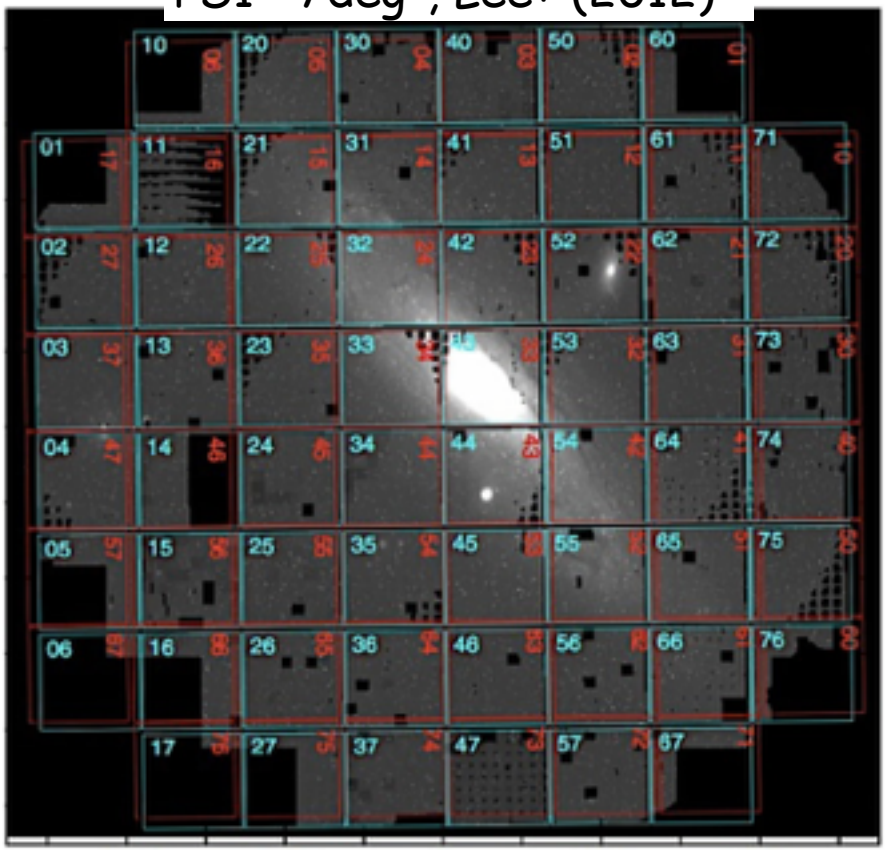
WFC/INT ~0.3 deg^2,
Calchi Novati+ (2005)



MegaCAM/CFHT
1 deg^2, Fliri+ (2012)



PS1 ~7deg^2, Lee+ (2012)



Observation Cadence

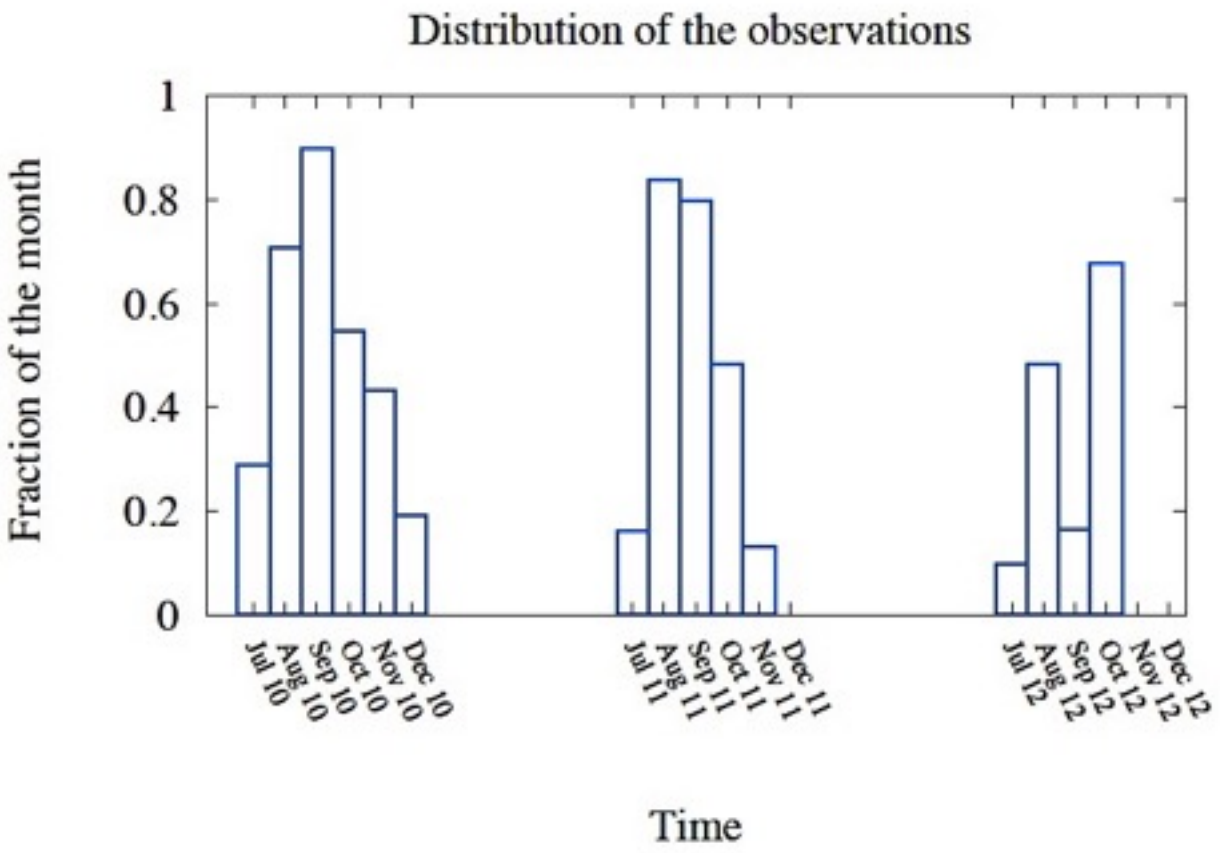
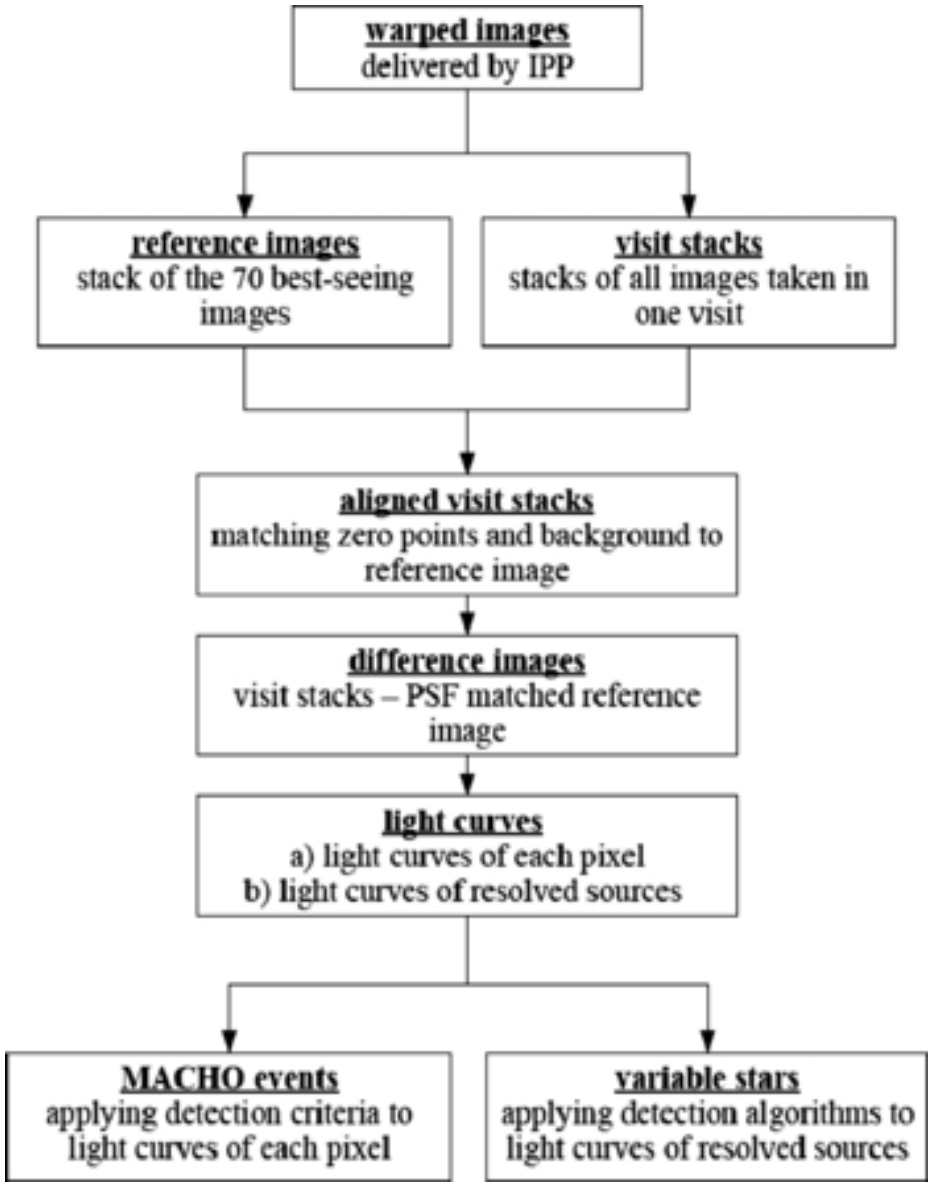


Fig. 1.— The distribution of the observations of PS1 towards M31. We plot the monthly fraction of nights in the r_{P1}-filter during the 2010, 2011 and 2012 seasons. In general, the observations cover most of the time in the second half of each year.

Lee et al. (2014)

Data Analysis



Use our own image subtraction software mupipe (Goessl & Riffeser 2002) and MDia (Koppenhoefer 2013) to obtain high quality lightcurves in crowd fields

Kodric et al. (2013)

Microlensing – Event position

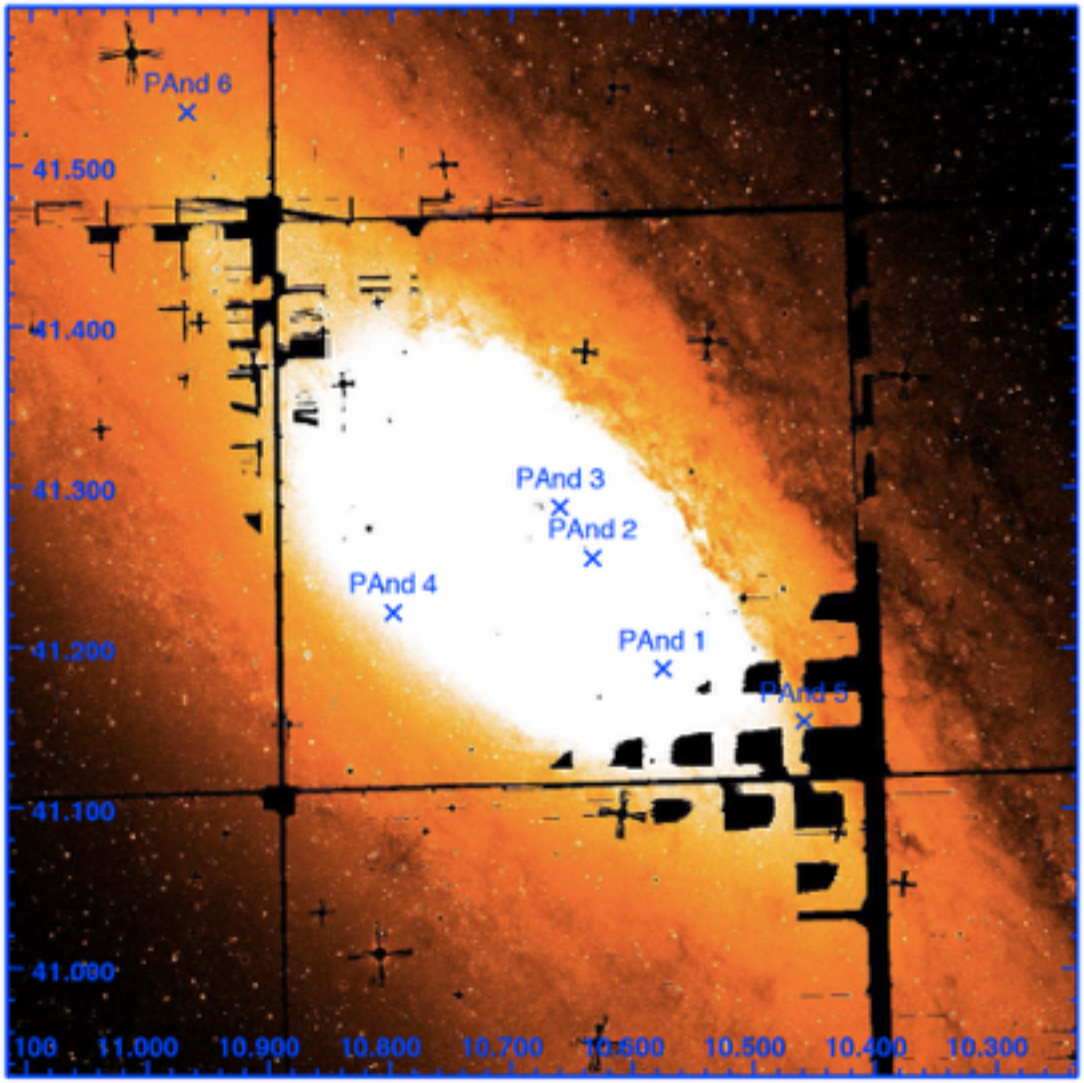
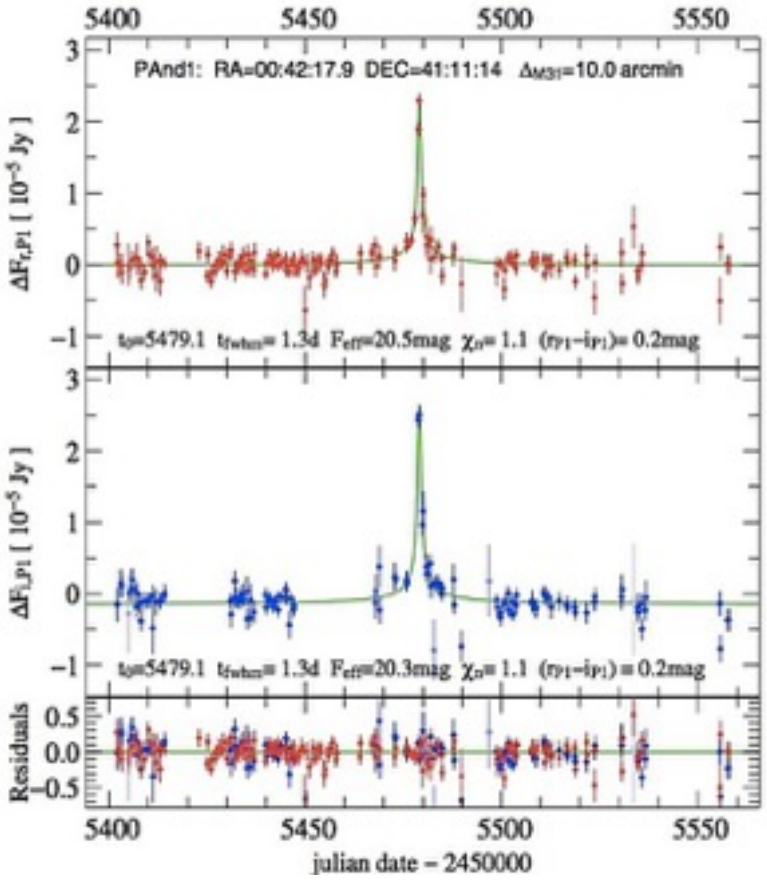
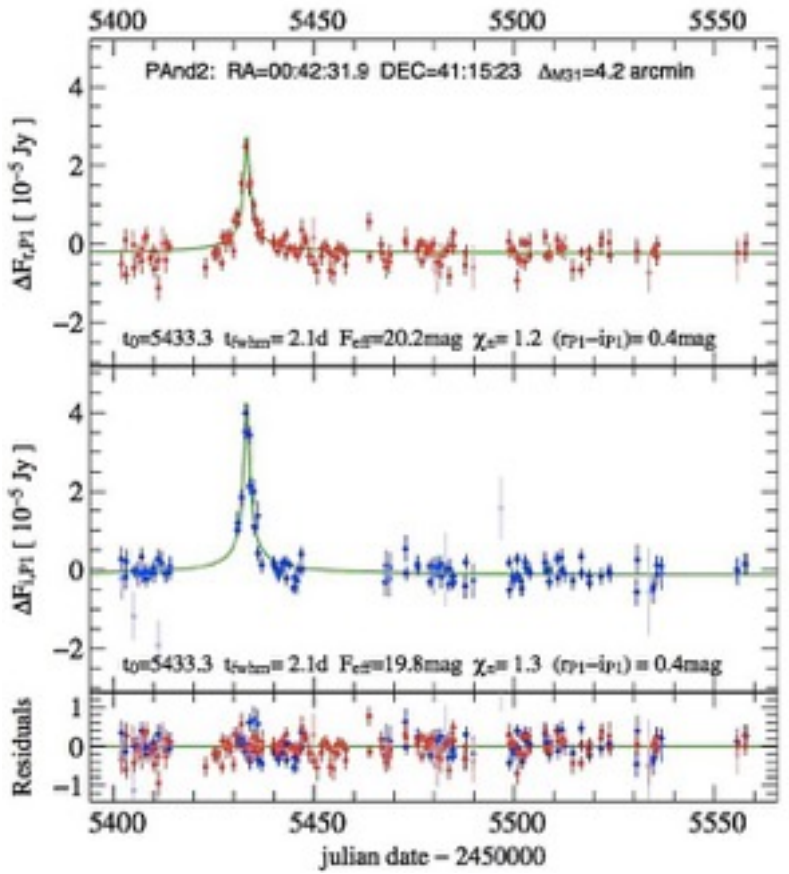


Fig. 14.— Position of the six microlensing event candidates detected in the central $40' \times 40'$ region of M31 from PAndromeda. The coordinates, RA (J2000) in hour and Dec (J2000) in degree are also shown in the figure. The FOV of this image is $40' \times 40'$. Lee et al. (2012)

Microlensing – Lightcurve examples



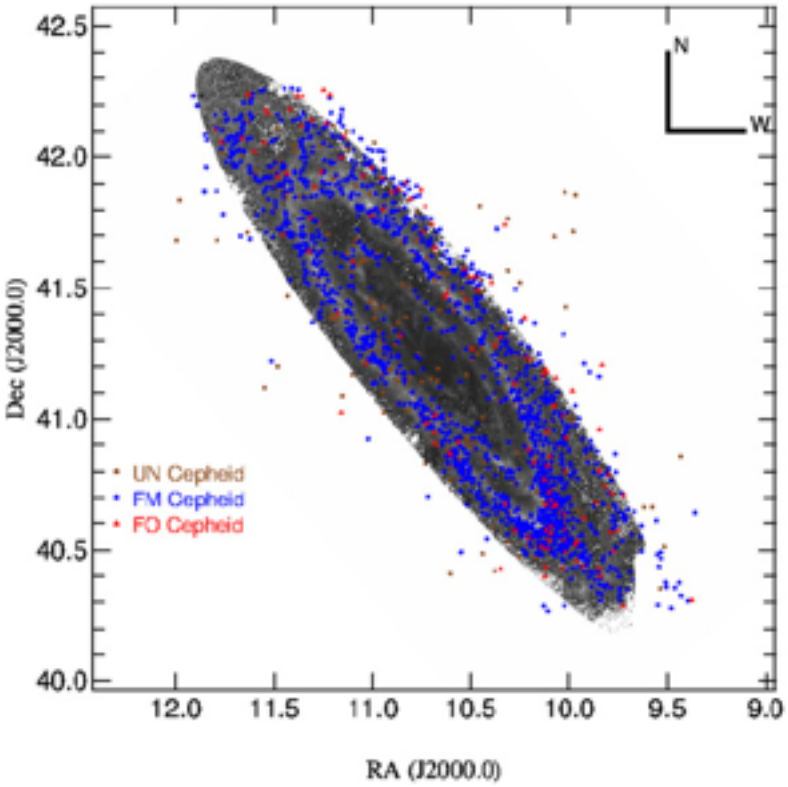


6 short duration events, Lee et al. (2012)

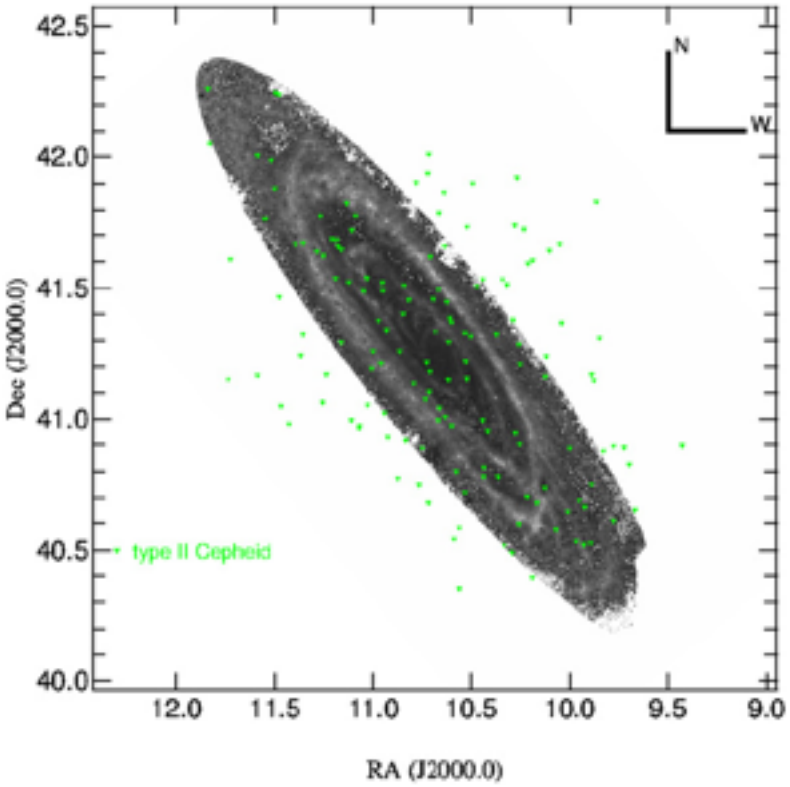
2009 Cepheids

– Largest published sample to-date

Type I Cepheids trace the spiral arms

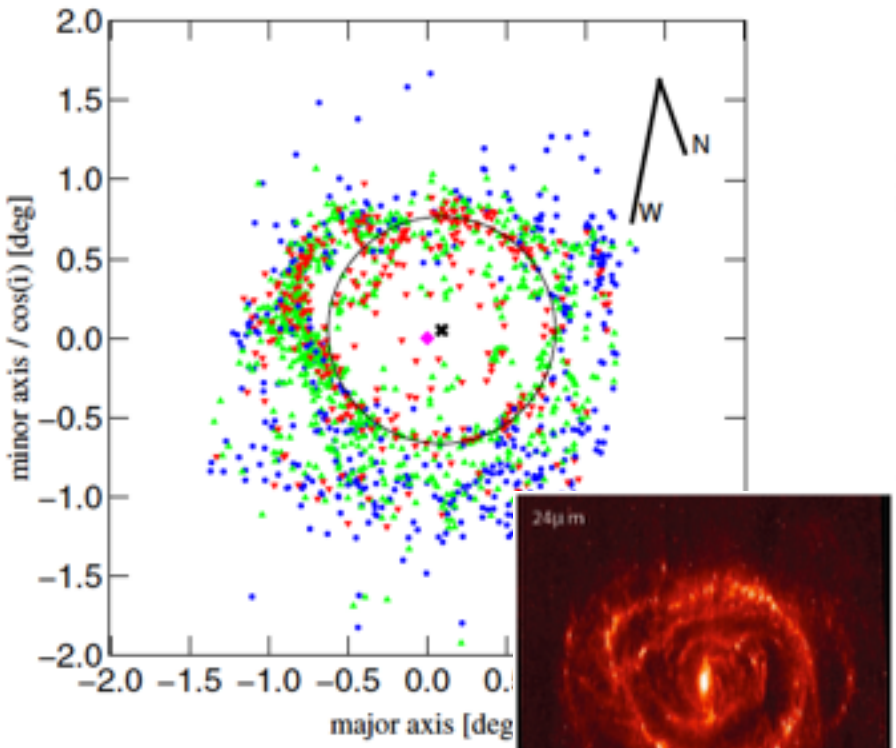


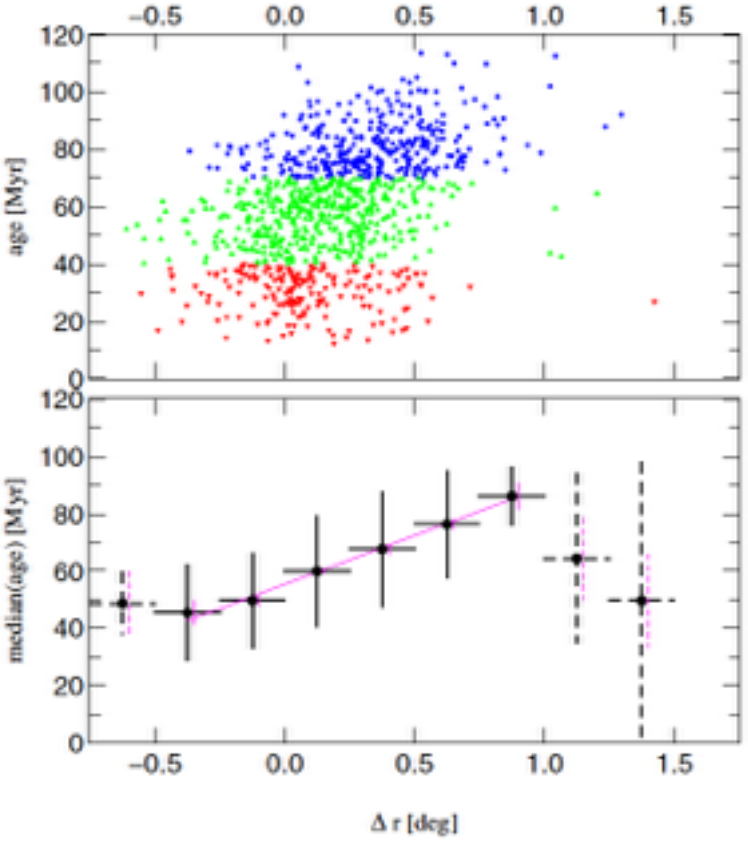
Type II Cepheids trace M31 halo



Kodric et al. (2013)

Cepheids
– Age distribution





t>70 Myr

70>t>40Myr

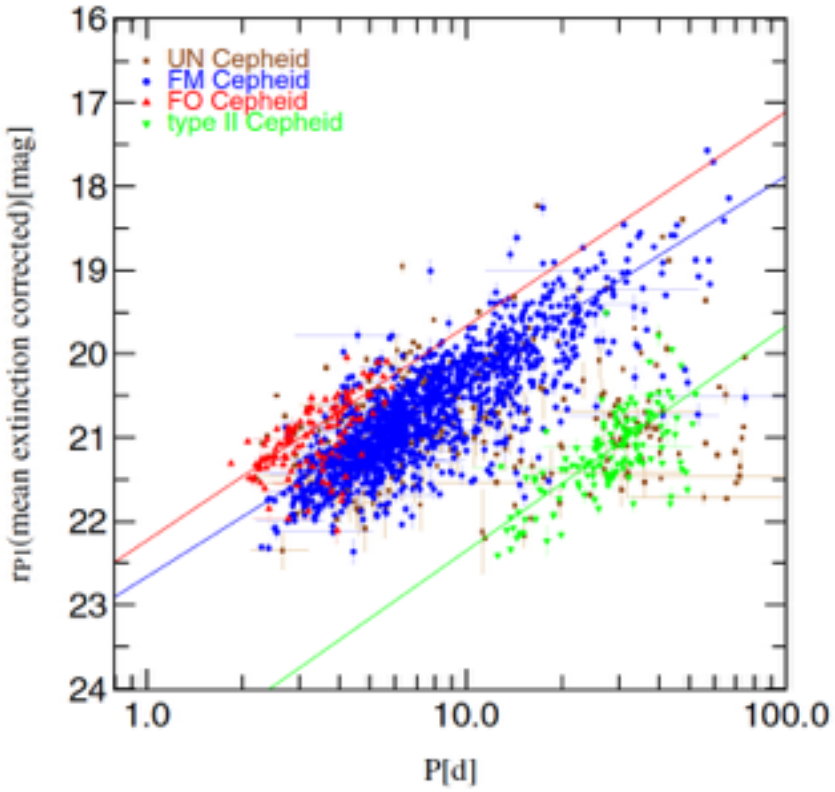
t<40 Myr

Star formation ring at 10 kpc

Kodric et al. (2013)

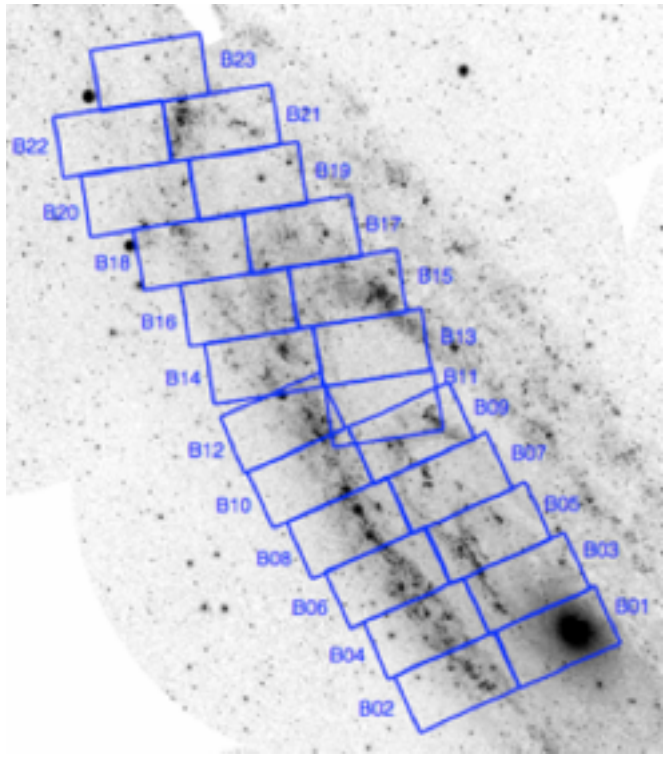
Cepheids
– PL relation

PS1 optical photometry



Kodric et al. (2013)

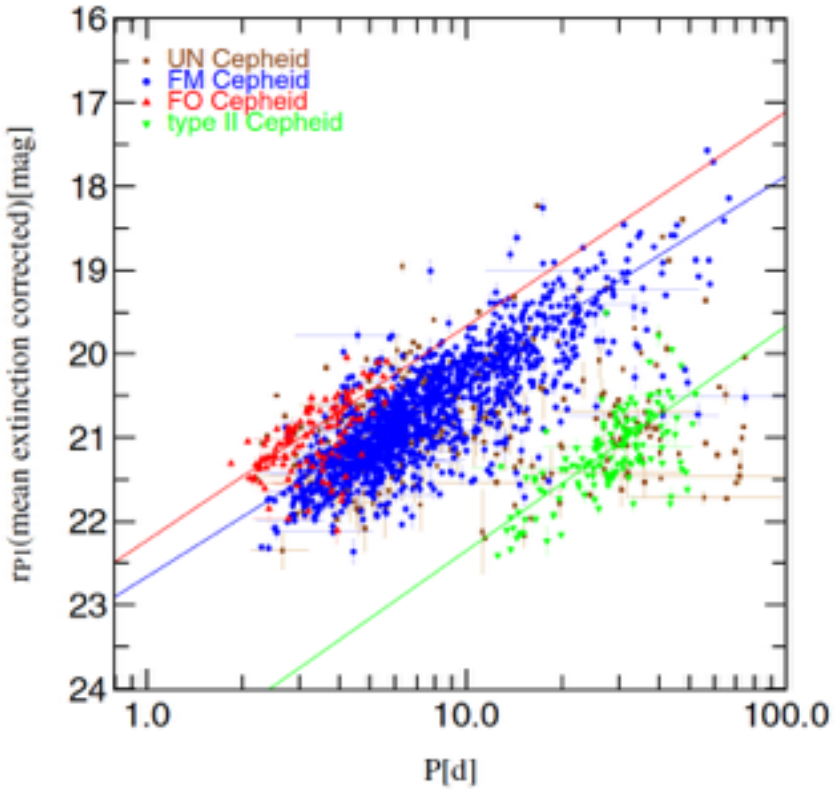
Pan-chromatic Hubble Andromeda Treasury (PHAT)



Dalcanton et al. (2012)

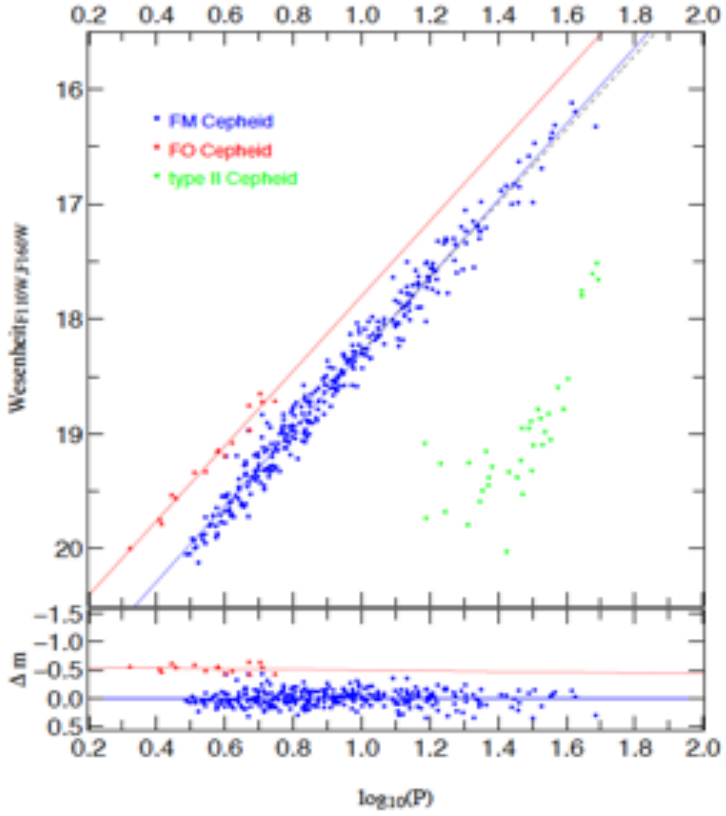
Cepheids
– PL relation

PS1 optical photometry



Kodric et al. (2013)

HST IR photometry



Kodric et al. (2014)

Beat Cepheid – Metallicity Tracer

- Cepheids pulsate at two radial modes simultaneously

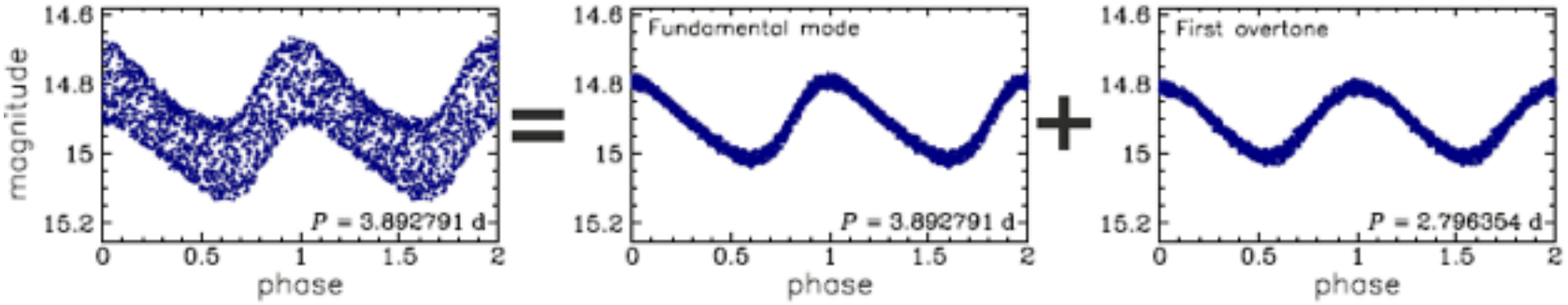
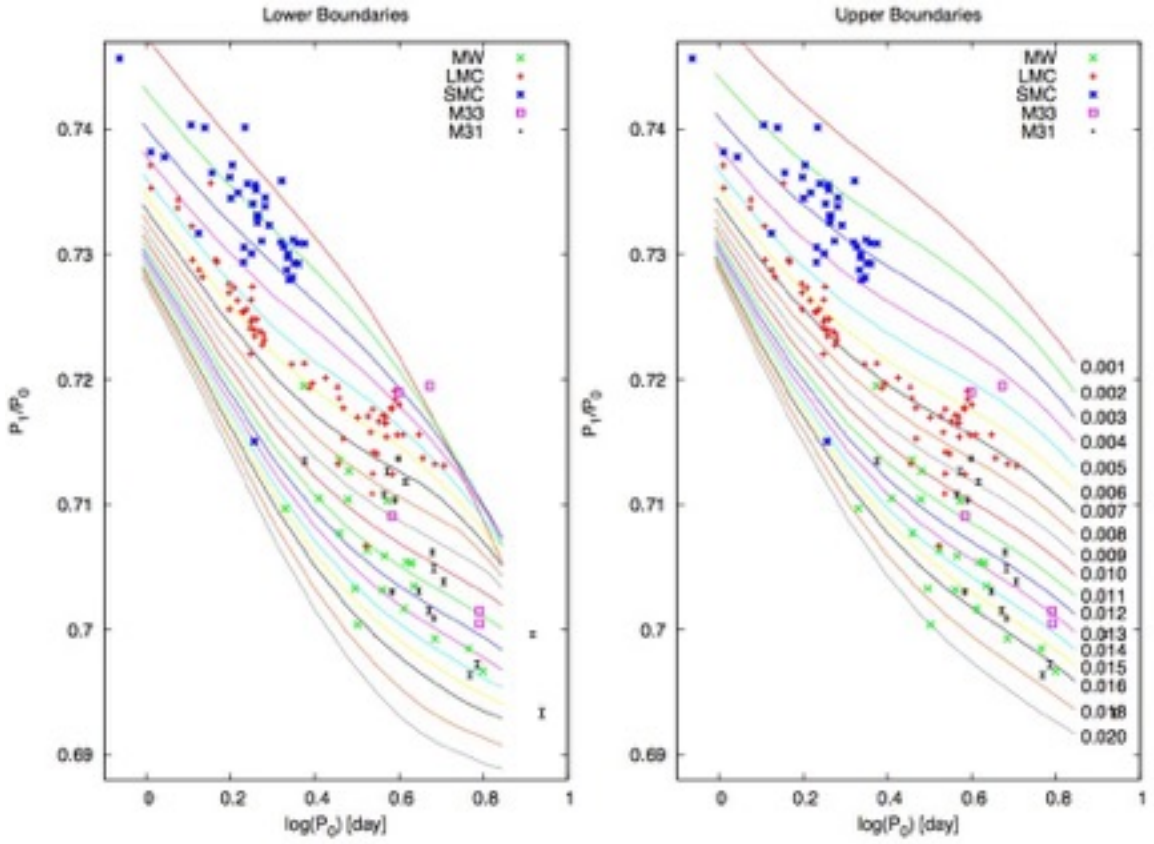


Image Credit: OGLE team

- 17 beat Cepheids in PAndromeda sample

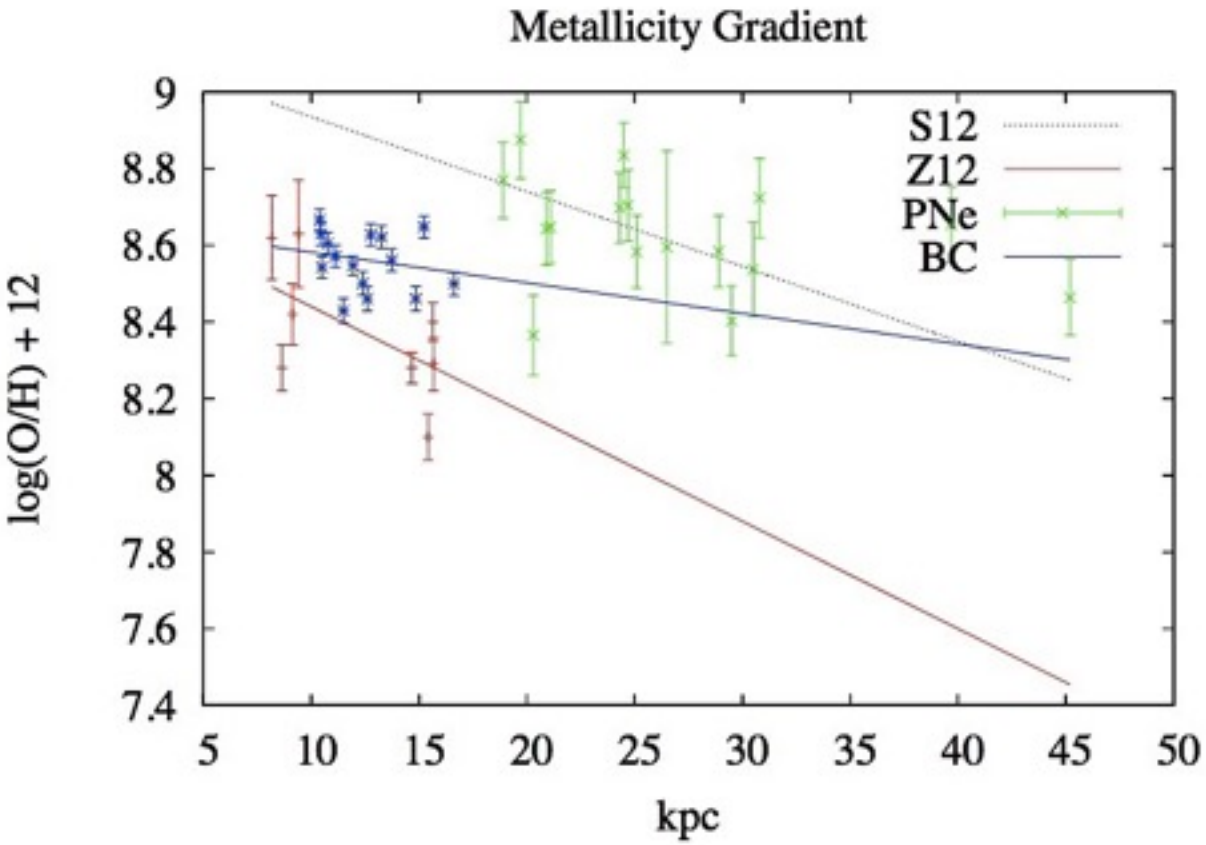
Z from Petersen diagram

- Isometallicity tracks from Buchler & Szabo (2007)



Lee et al. (2013)

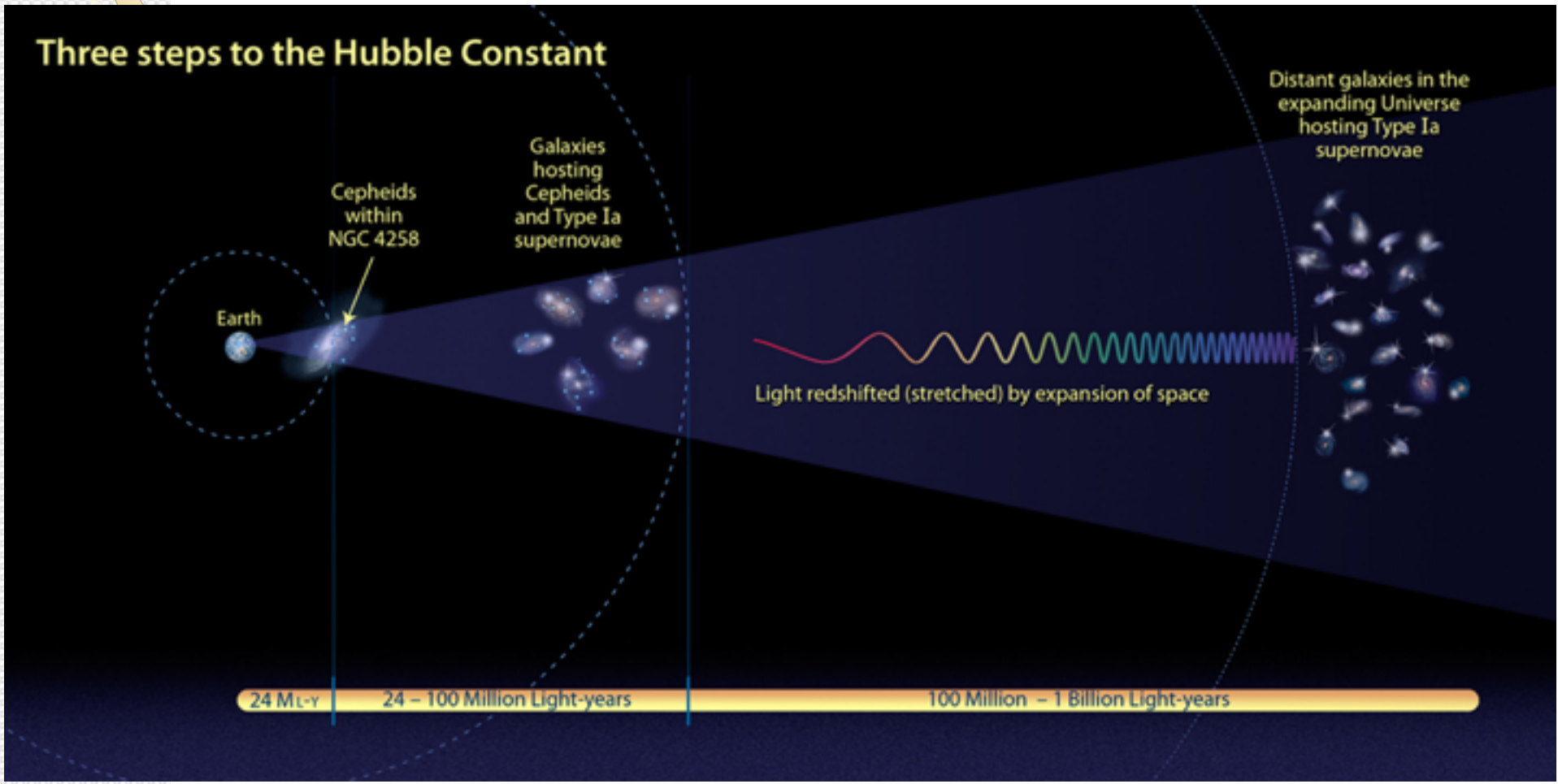
M31 Metallicity Gradient



Lee et al. (2013)

Metallicities of Beat cepheids have small errors.
Metallicities are subsolar similar to those from HII regions (Z12).
Beat Cepheid metallicities in the inner disk are smaller than those for PNe from the outer disk

Eclipsing binary
- M31 as a distance anchor



Credit: NASA, ESA, and A. Feild (STScI)

Eclipsing binary
- M31 as a distance anchor

- H_0 error budget (Riess et al. 2011)

Table 5
H_0 Error Budget for Cepheid and SN Ia Distance Ladders[a]

Term	Description	Previous LMC	R09 N4258	Here N4258	Here All Three[b]
σ_{anchor}	Anchor distance	5%	3%	3%	1.3%
$\sigma_{anchor-PL}$	Mean of P–L in anchor	2.5%	1.5%	1.4%	0.7%
$\sigma_{host-PL}/\sqrt{n}$	Mean of P–L values in SN hosts	1.5%	1.5%	0.6 %	0.6%
$\sigma_{SN}/\sqrt{n}$	Mean of SN Ia calibrators	2.5%	2.5%	1.9%	1.9%
σ_{m-z}	SN Ia m–z relation	1%	0.5%	0.5%	0.5%
$R\sigma_{\lambda,1,2}$	Cepheid reddening, zero points, anchor-to-hosts	4.5%	0.3%	0.0%	1.4%
σ_Z	Cepheid metallicity, anchor-to-hosts	3%	1.1%	0.6 %	1.0%
σ_{PL}	P–L slope, $\Delta\log P$, anchor-to-hosts	4%	0.5%	0.4%	0.6%
σ_{WFPC2}	WFPC2 CTE, long-short	3%	0%	0%	0%
Subtotal, σ_{H_0}		10%	4.7 %	4.0%	2.9%
Analysis systematics		NA	1.3%	1.0%	1.0%
Total, σ_{H_0}		10%	4.8 %	4.1%	3.1%

Notes.
[a] Derived from diagonal elements of the covariance matrix propagated via the error matrices associated with Equations (1), (3), (7), and (8).
[b] Using the combination of all three calibrations of the Cepheid distance scale, LMC, MW parallaxes, and NGC 4258.
[c] For MW parallax, this term is already included with the term above.

3 Anchors:
- MW Cepheids
- LMC
- NGC4258

- M31?

Riess et al. 2011

Exquisite photometry from HST

- Cepheid PL relation (Kodric et al. 2014)

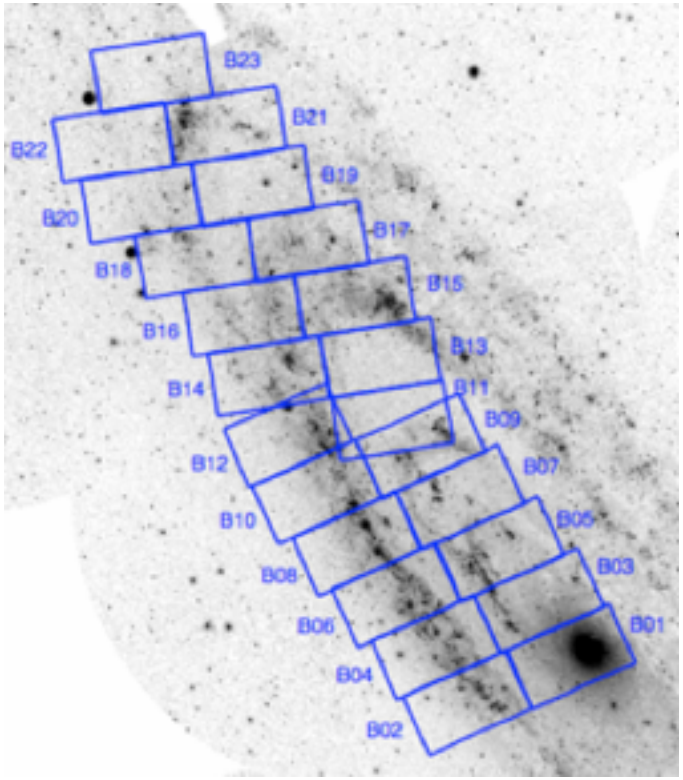
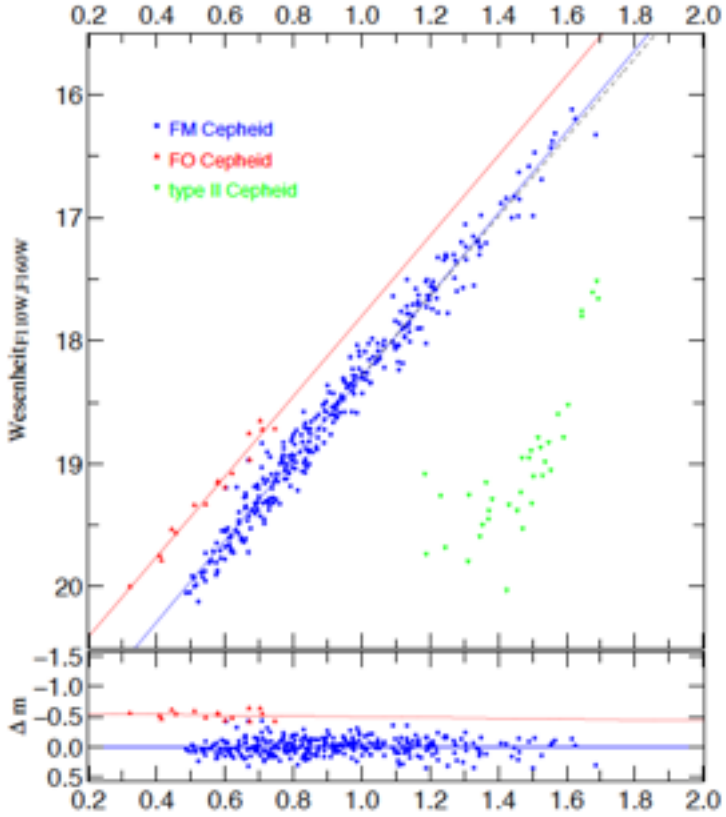


Image Courtesy: PHAT team



Kodric et al. 2014

Distance estimate with binaries

Detached eclipsing binaries as primary distance and age indicators †

By BOHDAN PACZYŃSKI

Princeton University Observatory, 124 Peyton Hall, Princeton, NJ 08544-1001, USA

Detached eclipsing double line spectroscopic binaries offer an opportunity to measure directly stellar parameters: mass, luminosity, radius, as well as the distance. The only non-trivial step is the need to determine surface brightness of each component on the basis of something measurable, like the color or the line ratios. Modern model atmospheres provide a fairly good calibration of that relation, but empirical verification is possible, and it is needed to achieve the highest accuracy. When this approach is fully developed the detached eclipsing binaries should provide direct (single step) distances with $\sim 1\%$ accuracy to all galaxies in the Local Group.

$$f_\lambda = \frac{1}{d^2}\left(R_1^2\, F_{1,\lambda} + R_2^2\, F_{2,\lambda}\right) \times 10^{-0.4\, A(\lambda)}$$

$$A\,(\lambda) = E\,(B-V)\,[k\,(\lambda - V) + R_V]$$

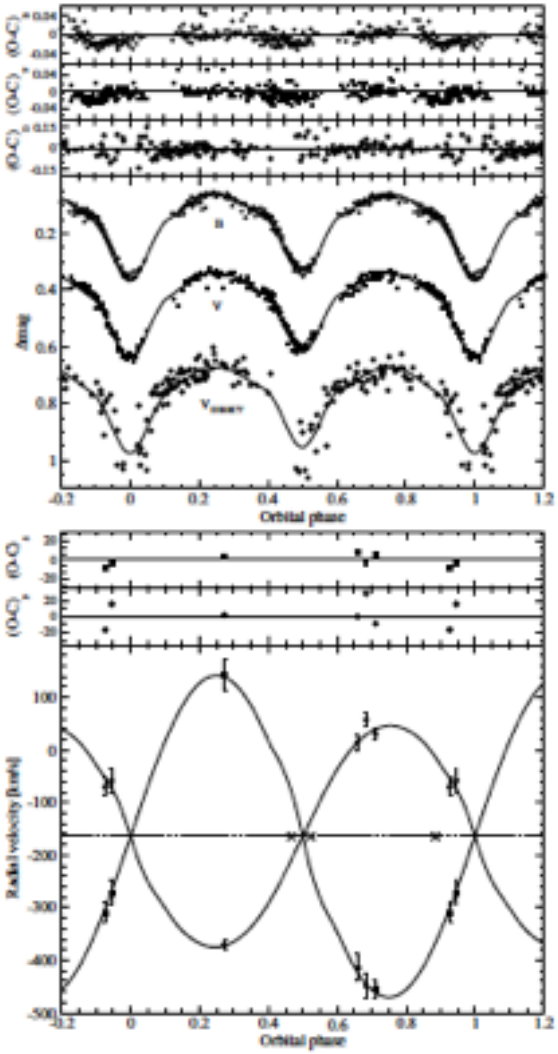
Bonanos et al. 2006

Information from LC and Spec.

- Light curve:
  - period (P)
  - inclination (i)
  - eccentricity (e)
  - fractional radii (Rp/a, Rs/a)
  - 3rd light ratio (blending)

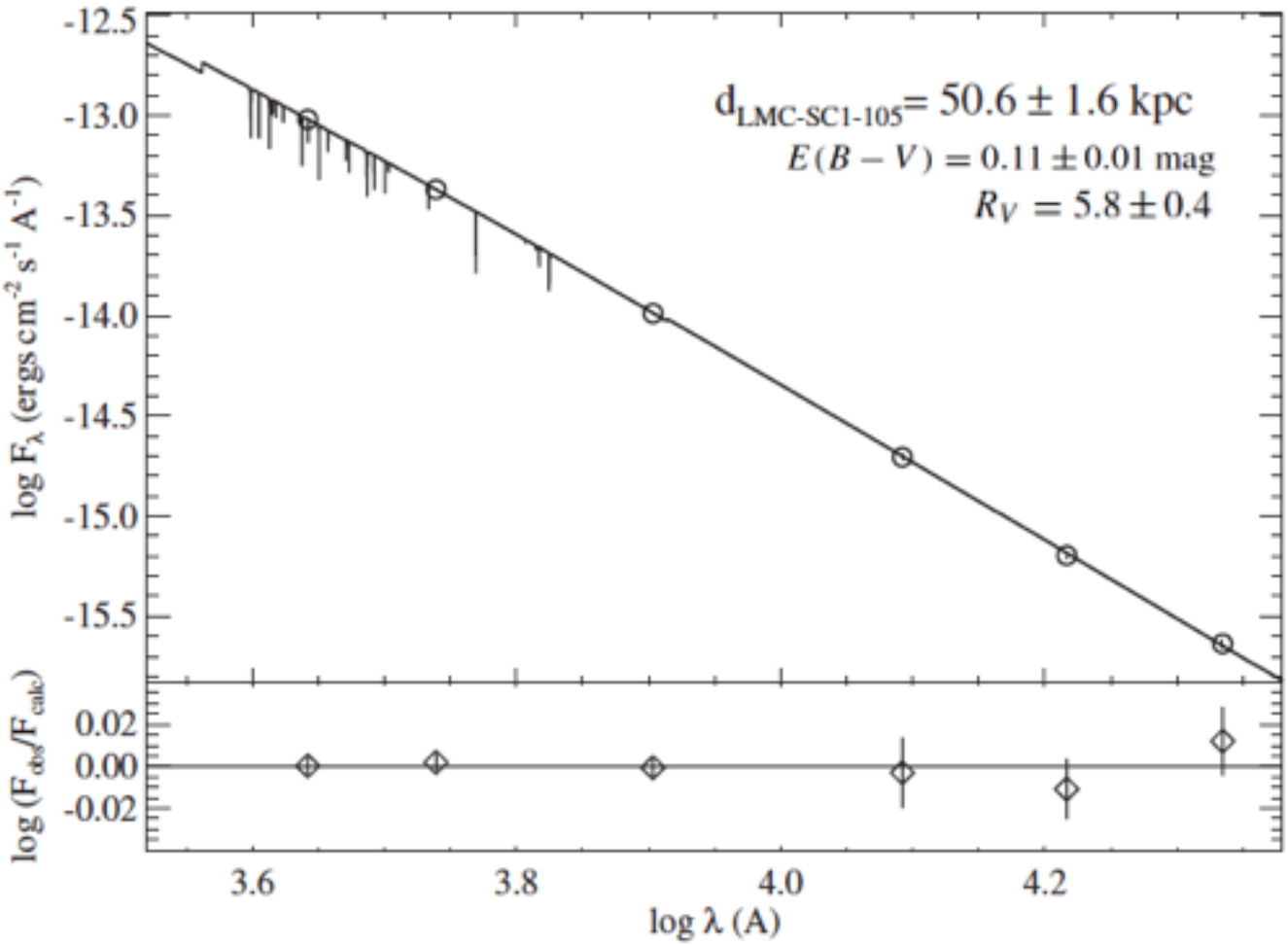
- Spectra:
  - temperature
  - semi-amplitudes (Kp, Ks)

$$a \sin i = \frac{P(K_P + K_S)\sqrt{1 - e^2}}{2\pi}$$



Vilardell et al. 2010

Reddening

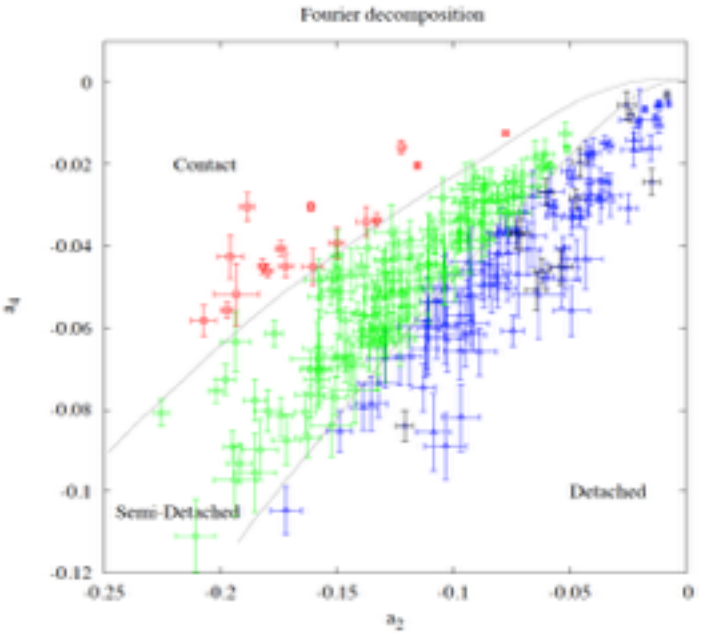


Bonanos et al. 2011

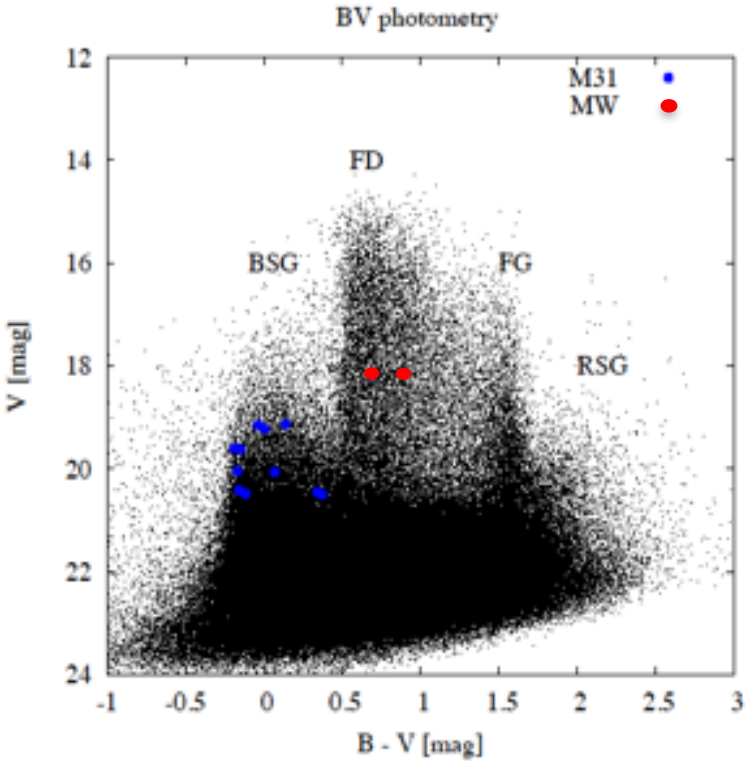
298 Eclipsing binaries

- Classification (Rucinski 93, Pojmanski 02):

$$f(\phi) = \Sigma_{i=1}^{4} a_i cos(2\pi i\phi) + b_i sin(2\pi i\phi)$$

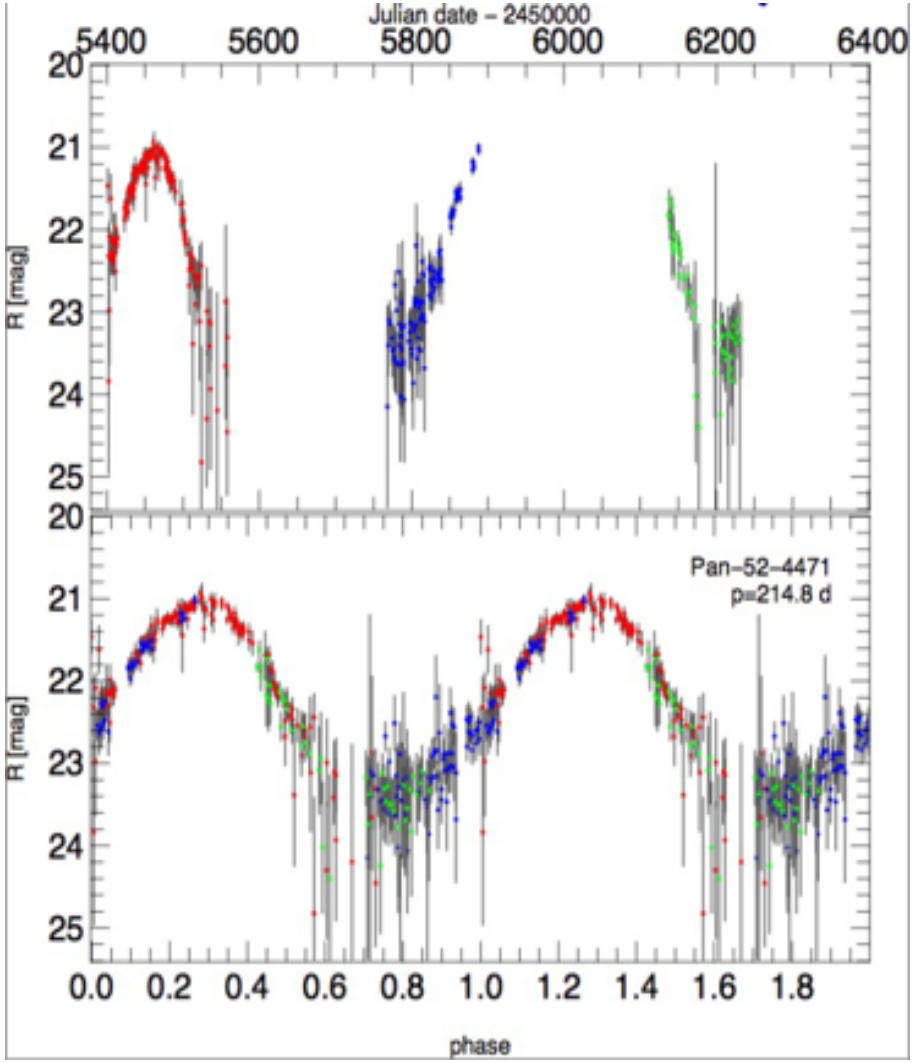


- Select bright detached systems for spec. follow-up:



Lee et al. 2014

Long-period variables



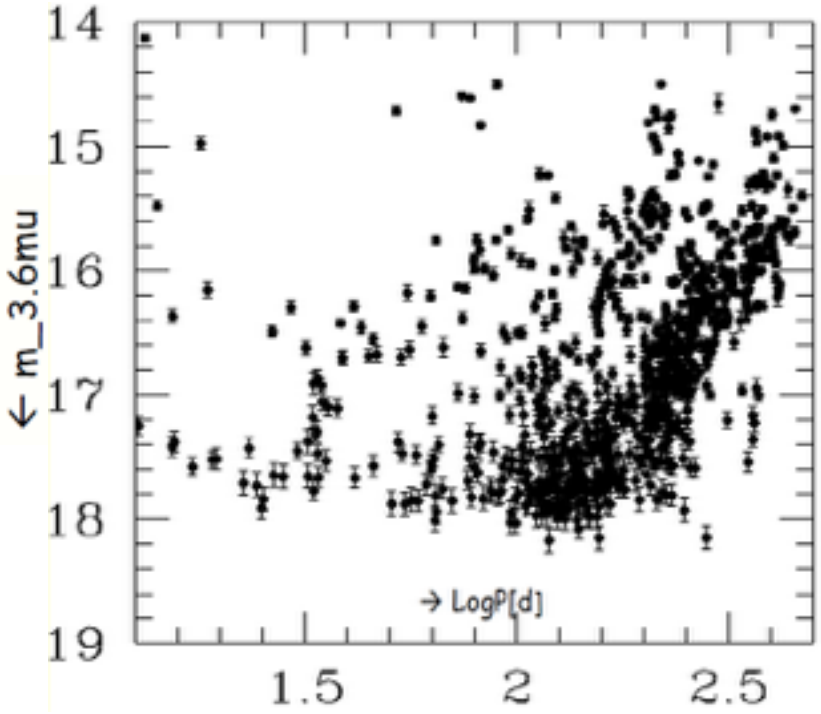
We found 5900 LPVs, among them 3800 with P>100d (mainly Miras)

600 semi-regular variables (SRVs)

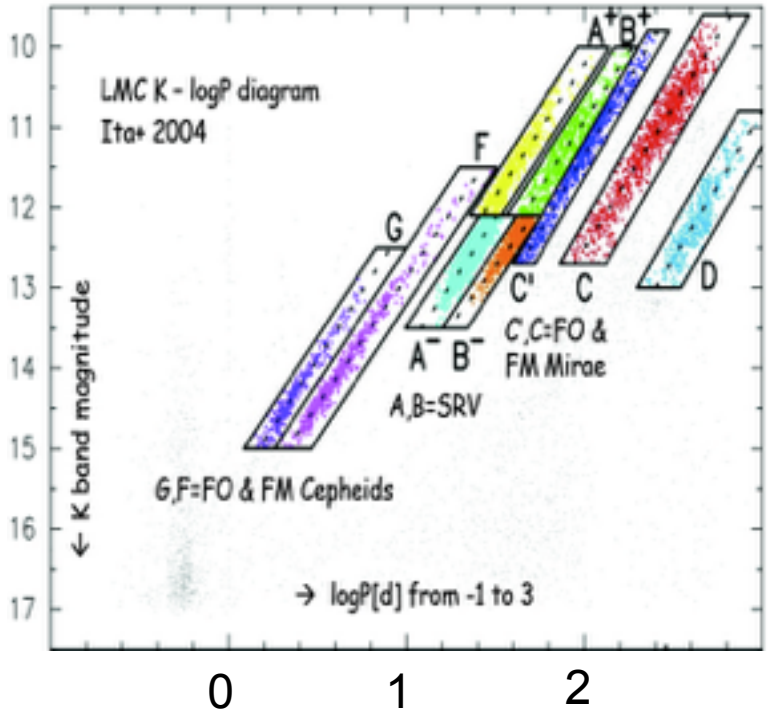
Snigula et al. (in prep.)

Long-period variables - IR P-L relation

M31 3.6 um – log P



LMC K – log P



Summary

- PAndromeda provides a wide, high-cadence view of M31.

- With image subtraction method, we are able to detect microlensing events and identify different classes of variables.

- The 3-year light curves, as well as classification of variables, will be released to the public.