

Time-domain Studies of M31

- Through the eye of Pan-STARRS 1 -

李見修 (Lee, Chien-Hsiu)

Subaru Telescope, NAOJ

APRIM, 2017 July 5th @ Taipei, Taiwan

1. **Project overview**: Lee et al. 2012, AJ, 143, 89
2. **Cepheids**: Kodric et al. 2013, AJ, 145, 106
3. **Beat Cepheids**: Lee et al. 2013, ApJ, 777, 35
4. **Luminous blue variables**: Lee et al. 2014, ApJ, 785, 11
5. **Eclipsing binaries**: Lee et al. 2014, ApJ, 797, 22
6. **PS1 + HST = Cepheid IR PL**: Kodric et al. 2015, ApJ, 799, 144

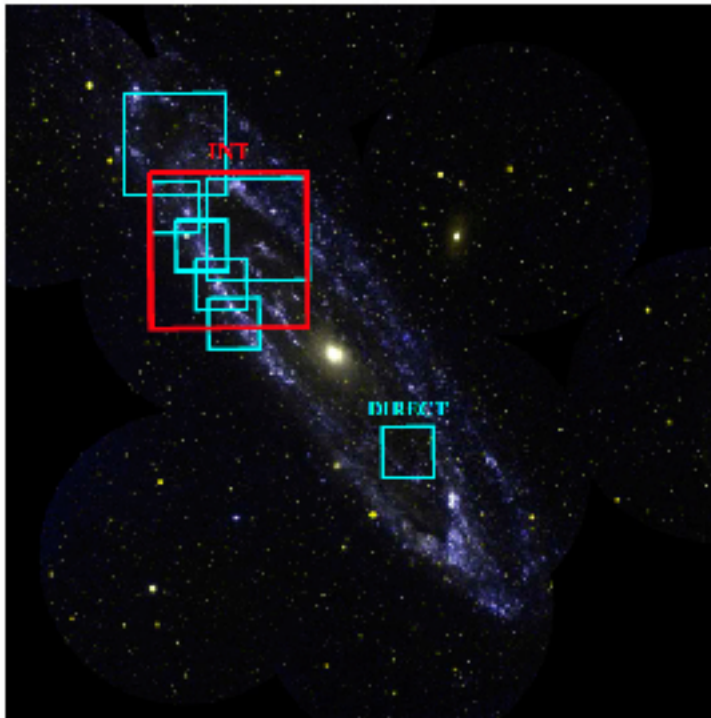
... and many more! All summarized in:

Lee, 2017, “Time-domain Studies of M31”,
Astronomical Review (open access)

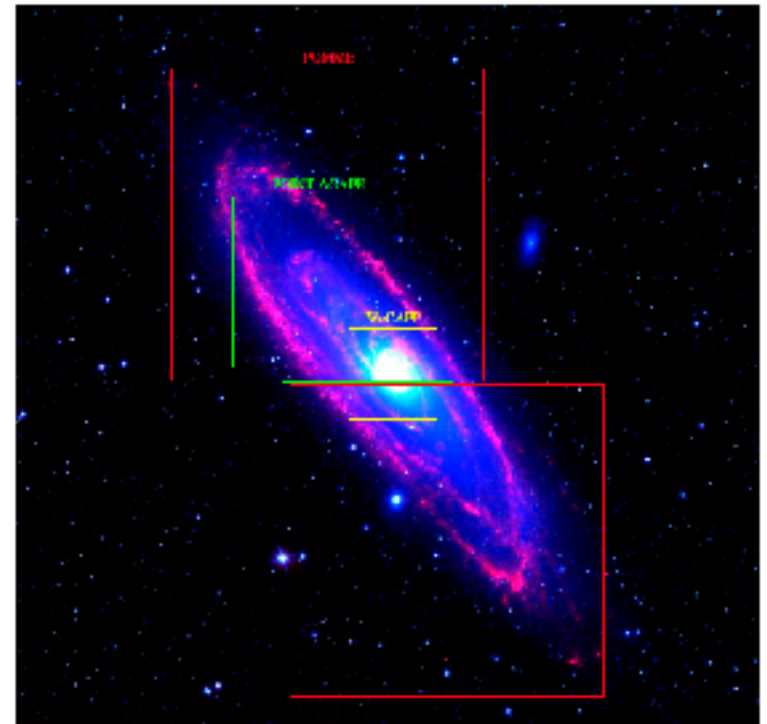
M31 - the closest spiral galaxy

1. Complete view of M31 vs. partial/limited sight-lines of Milky Way
2. Simple geometry, all sources at same distance (770 kpc)
3. Variables and transients bright enough/to be resolved
4. Metal rich (compared to LMC and SMC)

1st wave: Distance indicator surveys



2nd wave: Microlensing surveys



Lee (2017)

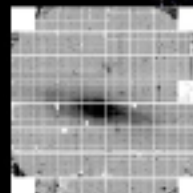
3rd wave: ultra-wide CCD surveys



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 2007-2008 during the second PS1 commissioning run. Twelve images were obtained at each filter at dithered observation positions.

The images were then aligned to a regular grid and aligned with the optical axis. The 0.25 arcsec PSF1 pixels were re-sampled to 0.30 arcseconds, and dither 3G for this image.



One of the individual observed images used to build the full-color image. This image has been dithered 3G and has a PSF of 0.25 arcseconds and has been re-sampled to 0.30 arcseconds.



Pan-STARRS 1
Commissioning
Observations
2007-2008

Robert A. Magnier, Kenneth C. Chambers, Jeffrey Wang, Steve Kenner, John J. Zaritsky, and the PS1 team



The PAndromeda Team



PIs: Ralf Bender Stella Seitz



PAndromeda in a nutshell

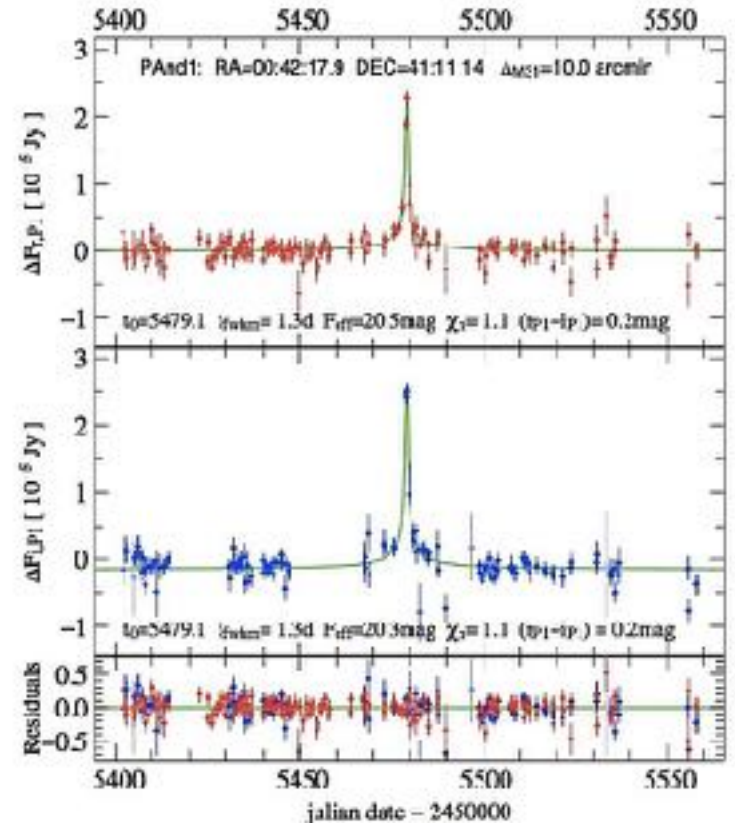
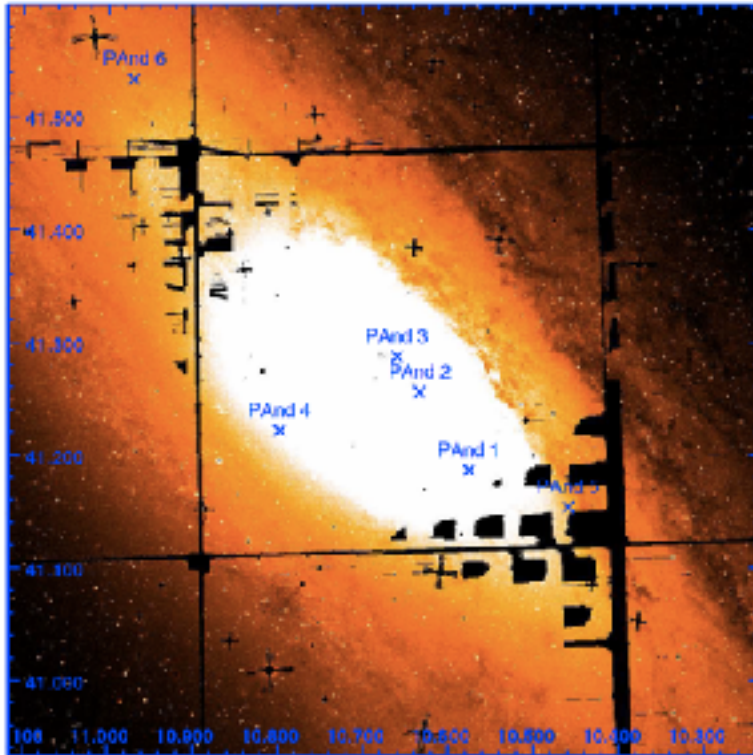
Scientific drivers

- - Constraining the compact matter fraction in the M31/MW halos
- Inventory of variables in M31, including Cepheids, binaries, long-period variables

Observation strategy

- 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

Result 1: Microlensing

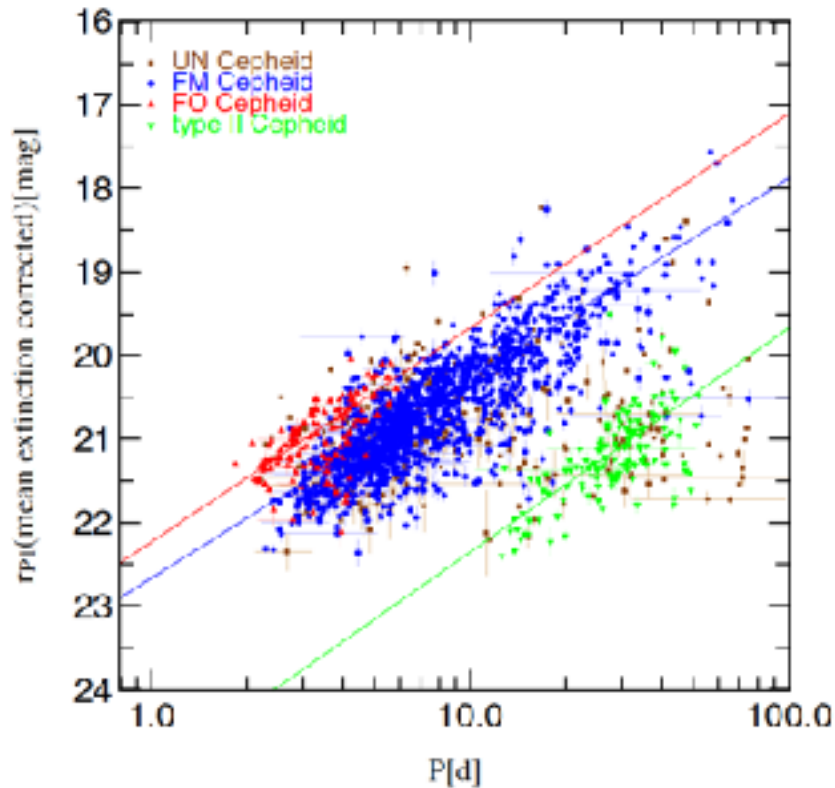


Lee et al. (2012)

Result 2: 2009 Cepheids

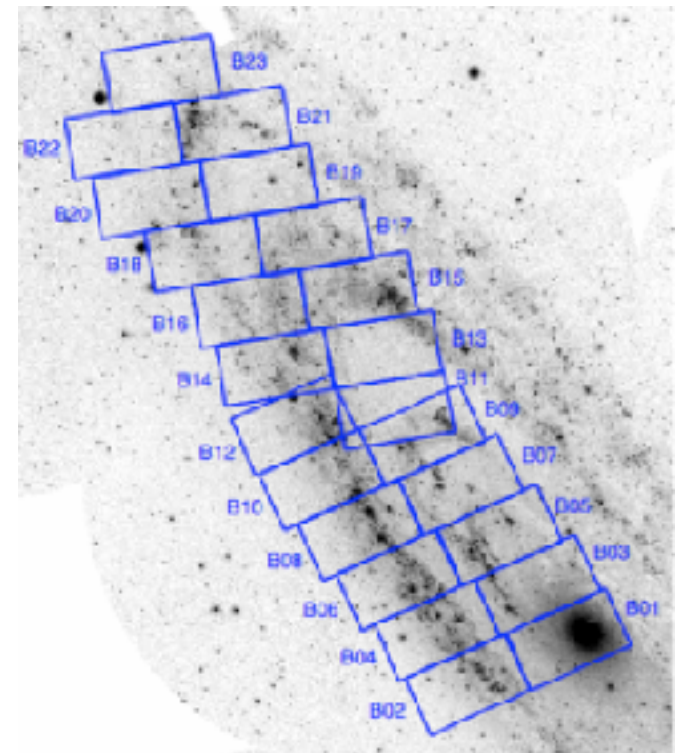
- Largest published sample to-date

PS1 optical photometry



Kodric et al. (2013)

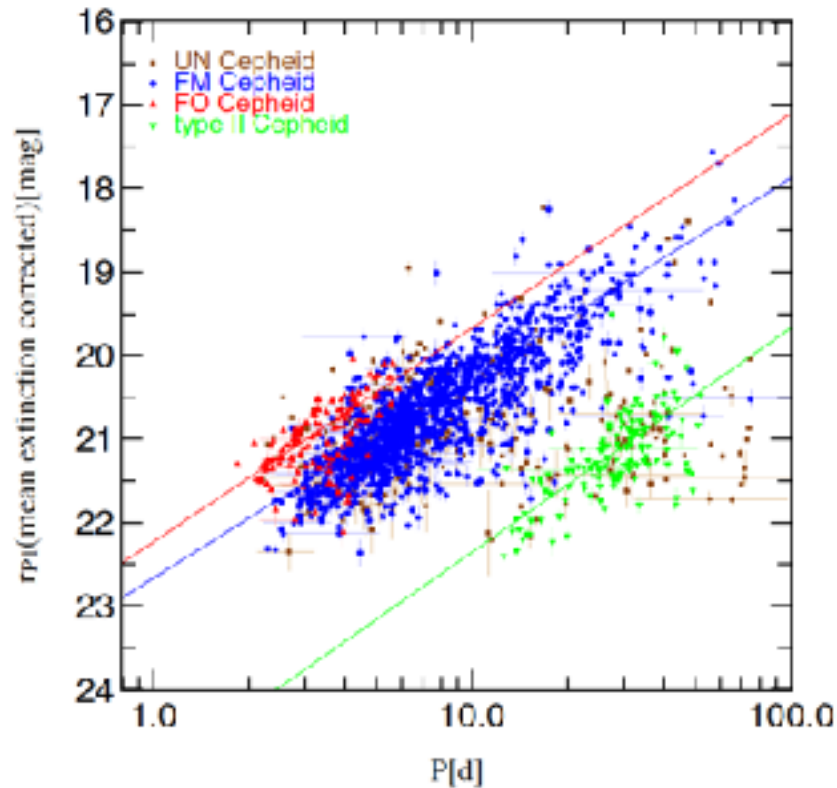
Pan-chromatic Hubble
Andromeda Treasury (PHAT)



Dalcanton et al. (2012)

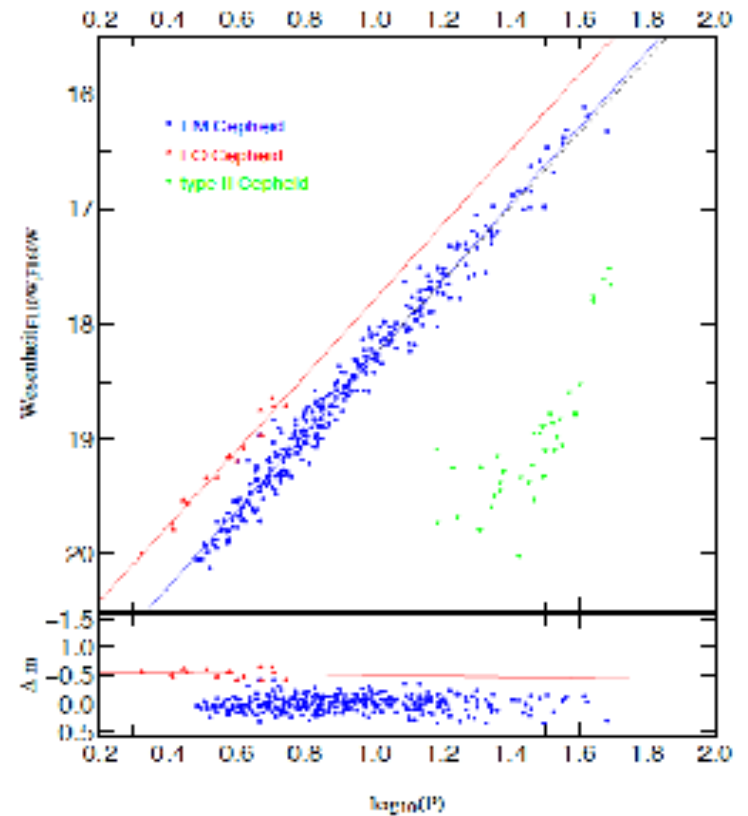
Cepheids - PL relation

PS1 optical photometry



Kodric et al. (2013)

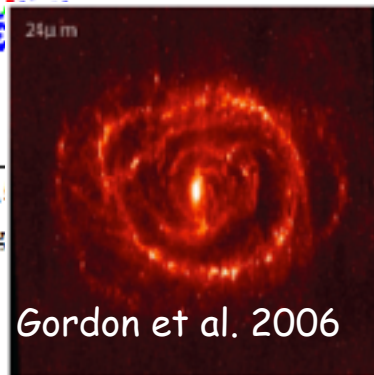
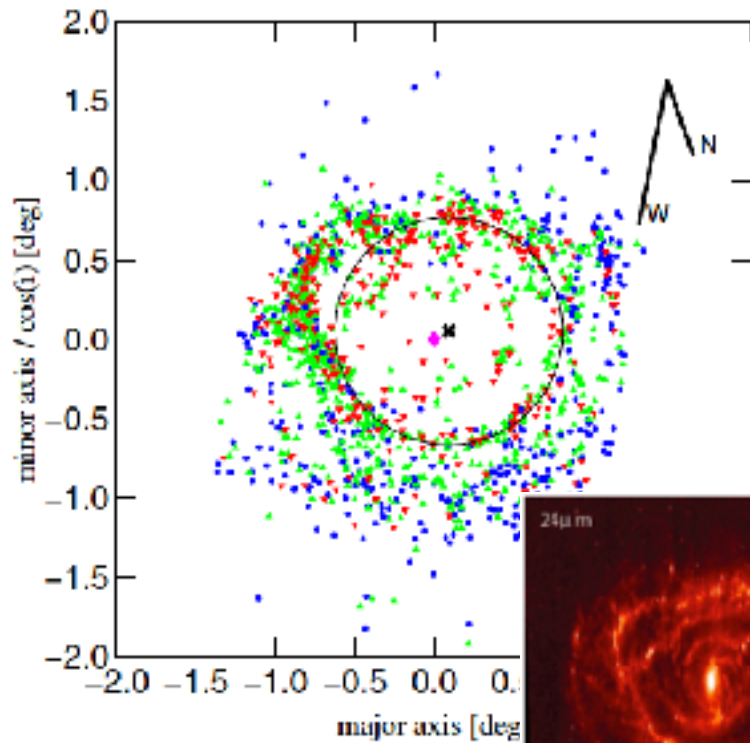
HST IR photometry



Kodric et al. (2015)

Cepheids

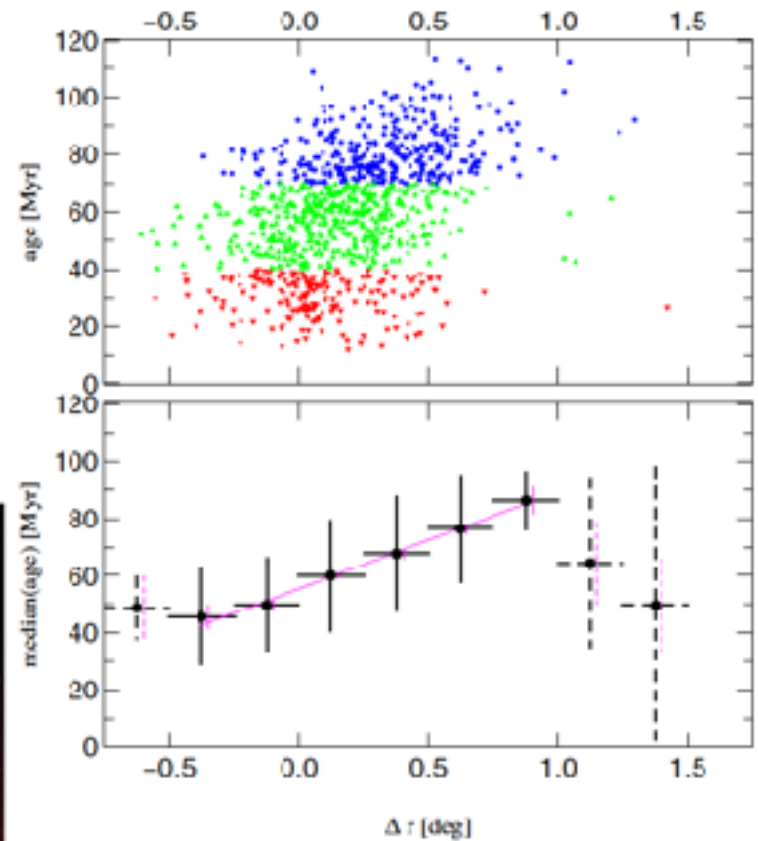
- Age distribution



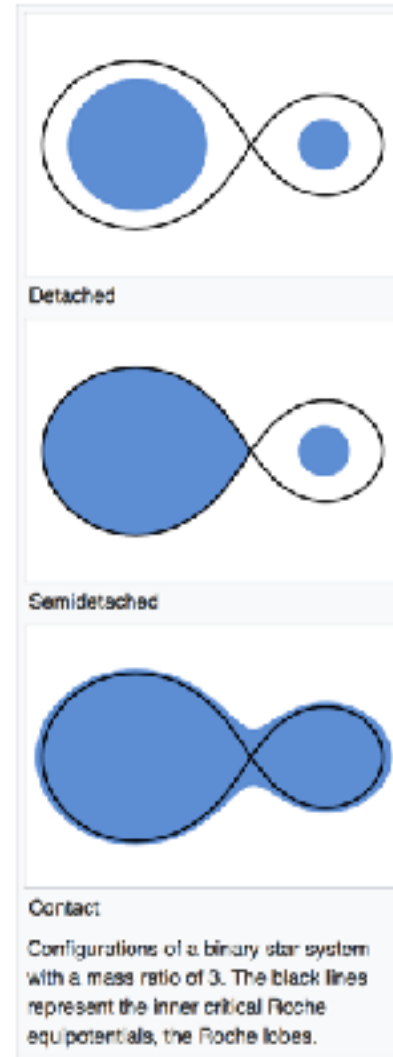
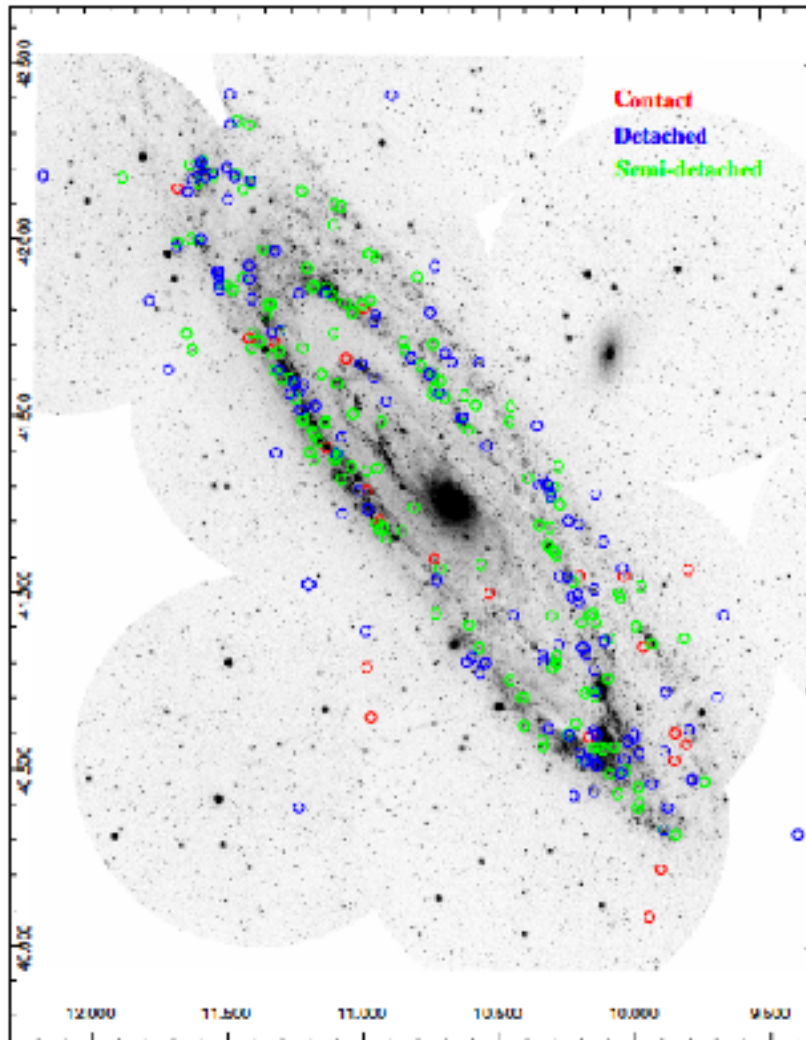
Gordon et al. 2006

Star formation ring at 10 kpc

$t > 70$ Myr
 $70 > t > 40$ Myr
 $t < 40$ Myr



Result 3: 298 Eclipsing binaries



Eclipsing binary

- M31 as a distance anchor

- H_0 error budget (2.4%, Riess et al. 2016)

Term	Description	Prev. LMC	R09 N4258	R11 All 3	This work	
					N4258	All 3
σ_{anchor}	Anchor distance, mean	5%	3%	1.3%	2.6%	1.3%
$\sigma_{\text{anchorPL}}^*$	Mean of $P-L$ in anchor	2.5%	1.5%	0.8%	1.2%	0.7%
$\sigma_{\text{hostPL}/\sqrt{n}}$	Mean of $P-L$ values in SN Ia hosts	1.5%	1.5%	0.6%	0.4%	0.4%
$\sigma_{\text{SN}}/\sqrt{n}$	Mean of SN Ia calibrators	2.5%	2.5%	1.9%	1.2%	1.2%
σ_{m-z}	SN Ia $m-z$ relation	1%	0.5%	0.5%	0.4%	0.4%
$R\sigma_{sp}$	Cepheid reddening & colors, anchor-to-hosts	4.5%	0.3%	1.4%	0%	0.3%
σ_Z	Cepheid metallicity, anchor-to-hosts	3%	1.1%	1.0%	0.0%	0.5%
σ_{PL}	$P-L$ slope, A log P , anchor-to-hosts	4%	0.5%	0.6%	0.2%	0.5%
σ_{WFPC2}	WFPC2 CTE, long-short	3%	N/A	N/A	N/A	N/A
subtotal, $\sigma_{H_0}^b$		10%	4.7%	2.9%	3.3% ^c	2.2%
Analysis Systematics		N/A	1.3%	1.0%	1.2%	1.0%
Total, σ_{H_0}		10%	4.8%	3.3%	3.5%	2.4%

- 3 Anchors:
- MW Cepheids
 - LMC
 - NGC4258
 - M31?

Riess et al. 2016

Making data public!

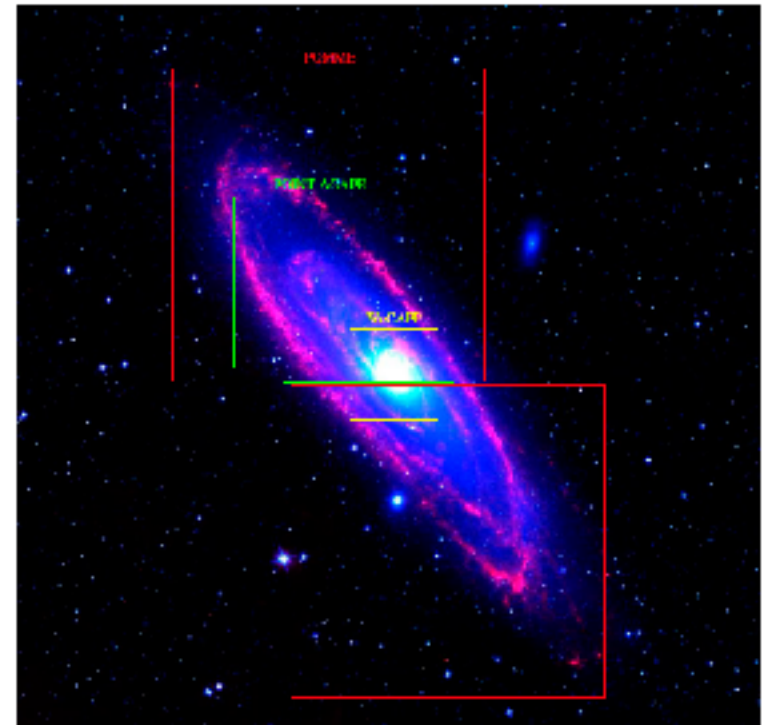
The only way to realize the full scientific benefit of our observation is to share the data with our competition.

—Bohdan Paczynski

Andromeda Real-Time Inspection System (ARTIS)

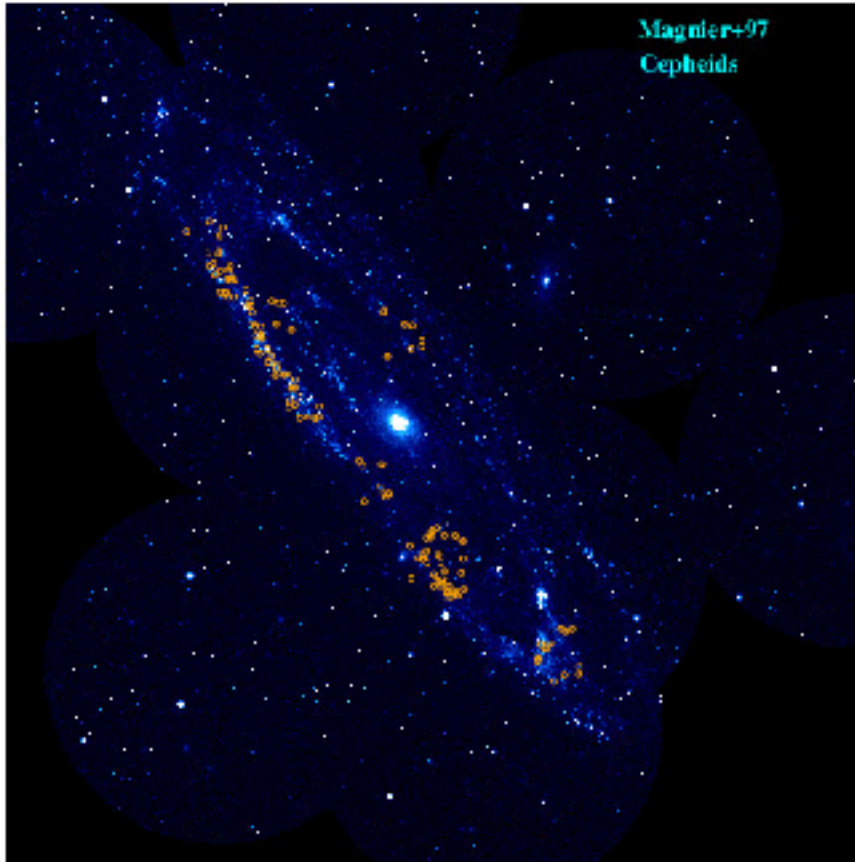


1. Catalog & light curves from literature
2. Deep M31 Atlas: PHAT (1/4 M31 disk from **HST**), LGS (deep optical imaging from **KPNO**), ANDROIDS (optical+NIR from **CFHT**), etc.
3. Reprocessing archival data (INT/WFCAM 1999-2002, CFHT/MegaCAM 2004-2005, PS1 2010-2012), providing long-term g, r, i light curves **in a consistent manner**
4. Online query system of **difference imaging analysis light curves** at any given position



Online data-base (work in progress)

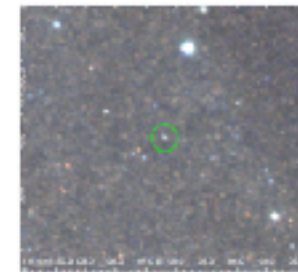
1. Query by catalog



2. Query by position

M31I004506.39+414141.5

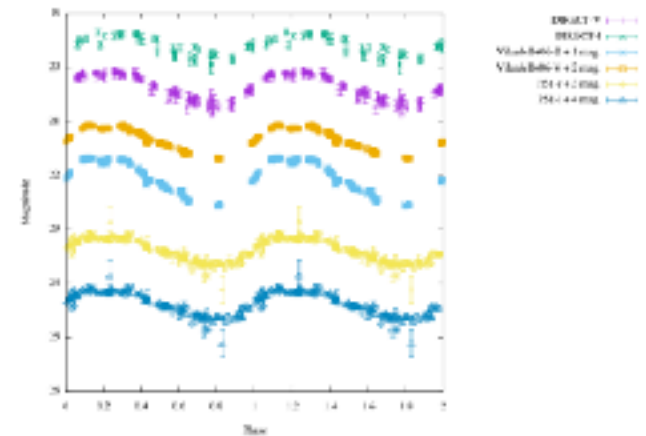
Imaging (from LEGS)



Photometry

Filter	Magnitude	Mag. error
U	20.657	0.025
B	20.557	0.021
V	20.254	0.011
R	19.878	0.013
I	19.377	0.008

Light curve



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