Bamberg 12 March 2019

M31 surveys
at the University Observatory Munich

Arno Riffeser

Ralf Bender
Stella Seitz
Ulrich Hopp
Claus Gössl

University Observatory Munich
Universitäts-Sternwarte München
Ludwig-Maximilians-Universität München

M31 surveys at University Observatory Munich

- **WeCAPP** *1998 – 2008* ➔ 0.08 deg^2

  (Wendelstein Calar Alto Pixellensing Project)

  - 0.8 m at Mount Wendelstein (Bavaria)
  - 1.23 m at Calar Alto (Spain)
- **PAndromeda** *2009 – 2012* ➔ 7 deg^2

  (Pan-STARRS Andromeda survey)

  - 1.8 m PS1 (Maui)
- **WST2M31** *2014 – 2018* ➔ 1 deg^2

  (Wendelstein 2m M31 survey)

  - 2.0 m Fraunhofer (Bavaria)

M31 surveys at University Observatory Munich

- **WeCAPP** *1998 – 2008* ➔ 0.08 deg^2

  (Wendelstein Calar Alto Pixellensing Project)

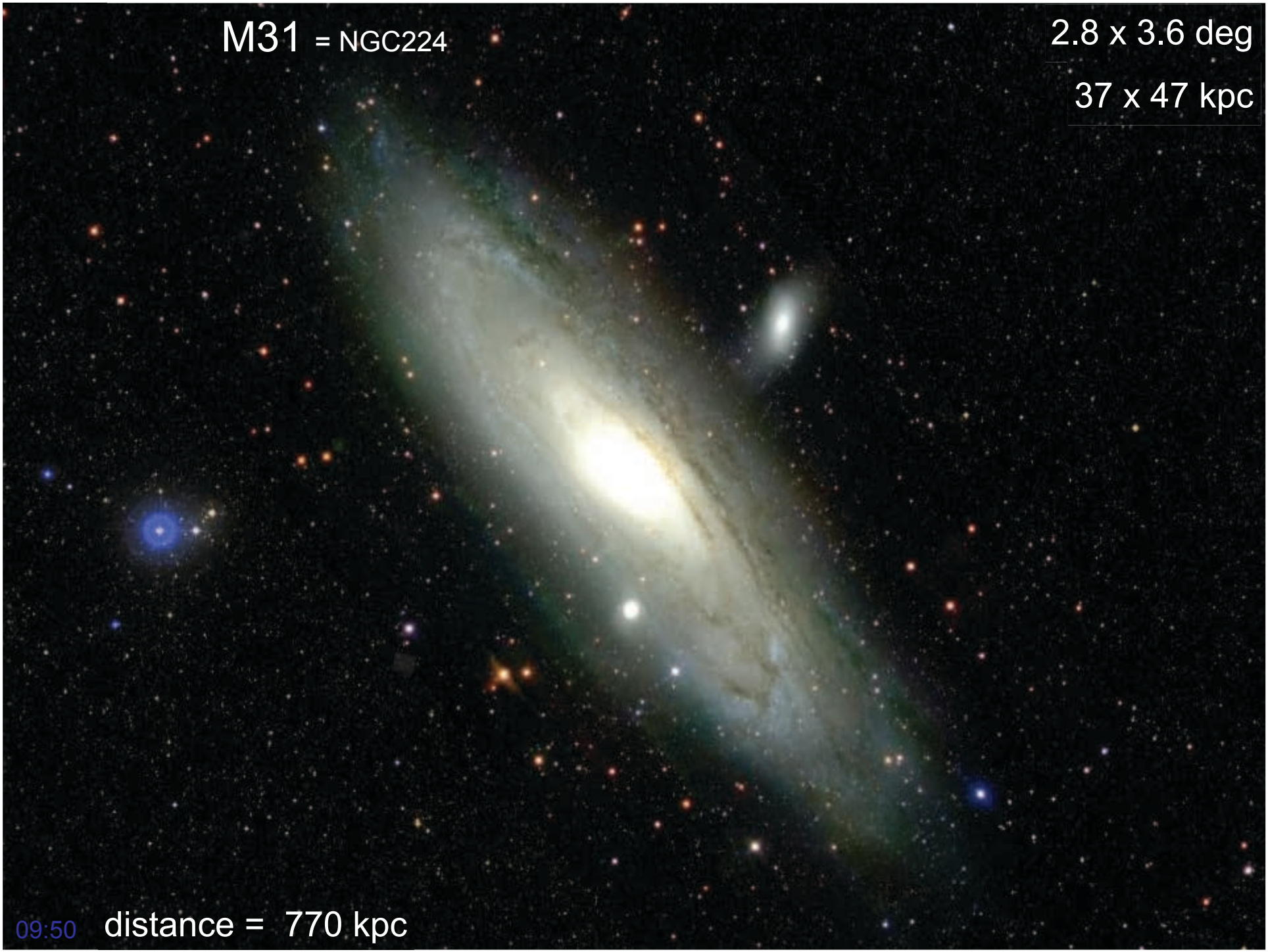
  - 0.8 m at Mount Wendelstein (Bavaria)
  - 1.23 m at Calar Alto (Spain)
- **PAndromeda** *2009 – 2012* ➔ 7 deg^2

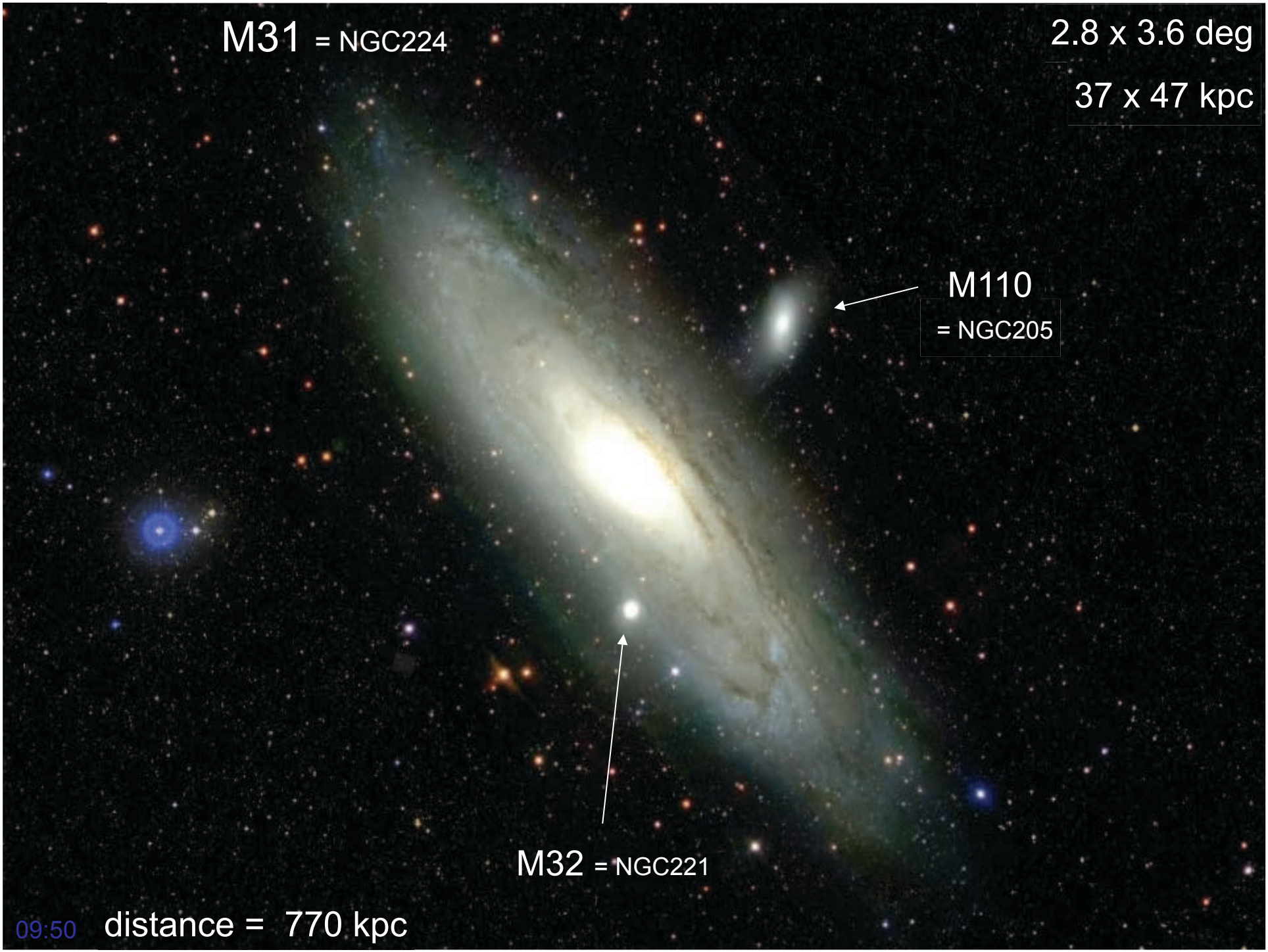
  (Pan-STARRS Andromeda survey)

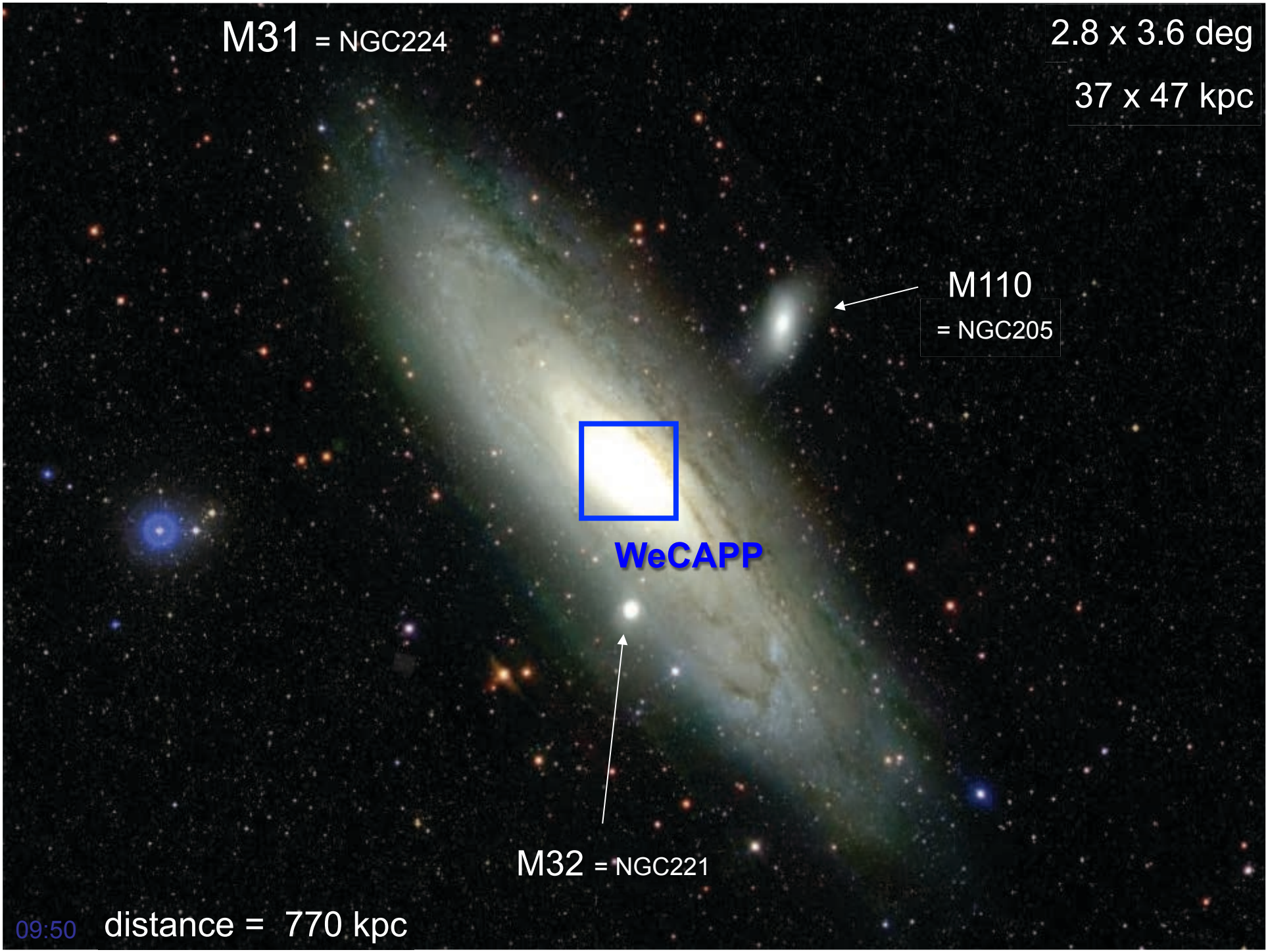
  - 1.8 m PS1 (Maui)
- **WST2M31** *2014 – 2018* ➔ 1 deg^2

  (Wendelstein 2m M31 survey)

  - 2.0 m Fraunhofer (Bavaria)


M31 = NGC224
2.8 x 3.6 deg
37 x 47 kpc
09:50
distance = 770 kpc


M31 = NGC224
2.8 x 3.6 deg
37 x 47 kpc
M110
= NGC205
M32 = NGC221
09:50 distance = 770 kpc


M31 = NGC224
2.8 x 3.6 deg
37 x 47 kpc
M110
= NGC205
WeCAPP
M32 = NGC221
09:50
distance = 770 kpc

WeCAPP: Lee, Riffeser *et al.* (2015ApJ...806..161L)

Season	Observatory	*R* or *I*-band	
		F1 or F2 or F3 or F4	
1997–1998	WS	38	
1998–1999	WS	33	
1999–2000	WS or CA	134	
2000–2001	WS or CA	154	
2001–2002	WS or CA	201	
2002–2003	WS or CA	52	
2003–2004	WS	69	
2004–2005	WS	47	
2005–2006	WS	71	
2006–2007	WS	124	
2007–2008	WS	92	
Total	WS	765	
Total	CA	346	
Total	WS or CA	1015	nights

WeCAPP: Lee, Riffeser *et al.* (2015ApJ...806..161L)

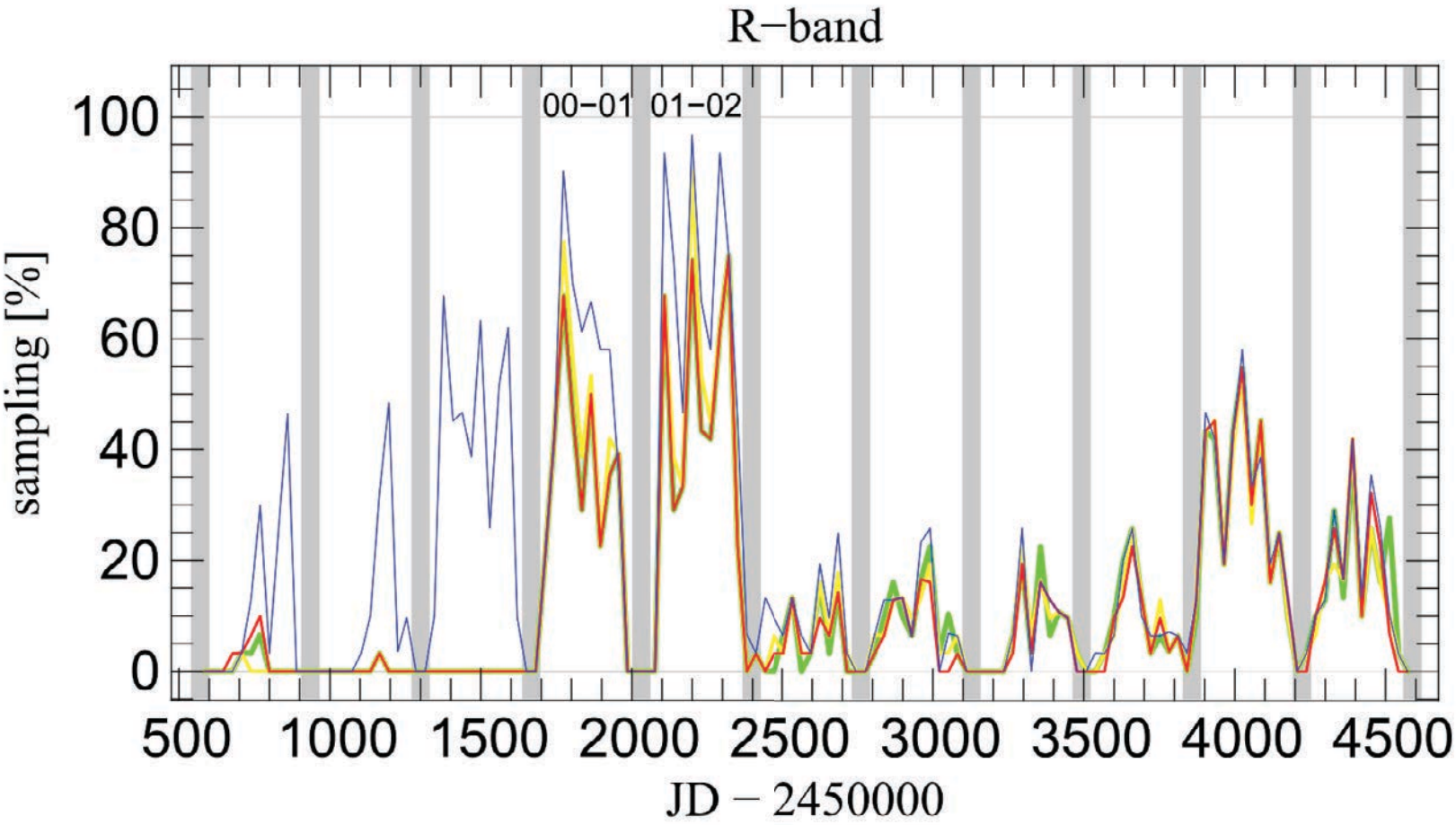
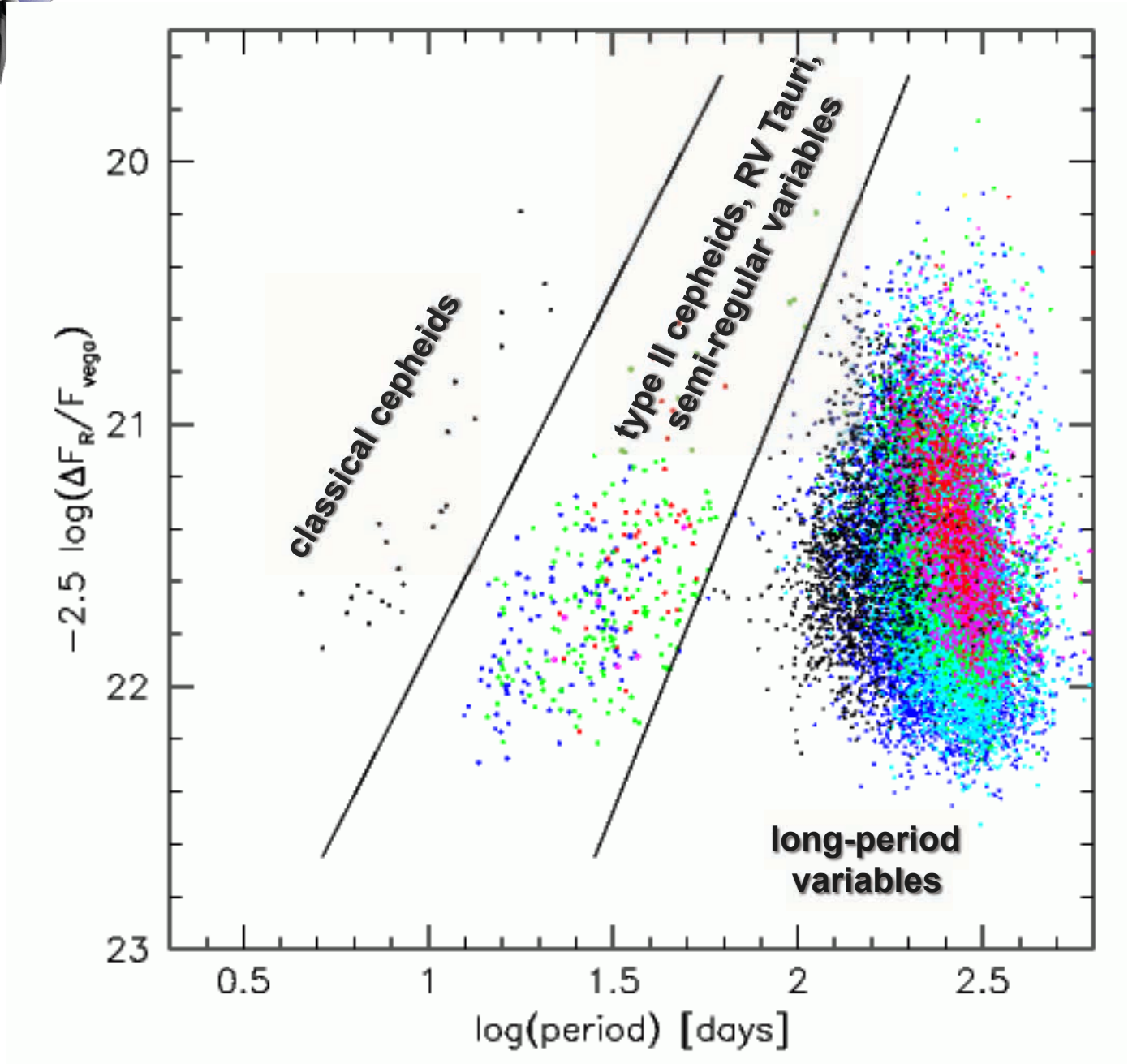


Figure 3. Daily samplings of the four different fields F1, F2, F3, and F4 are colored in blue, red, yellow and green, respectively. Periods marked in gray show the 61 days (from April 1 to May 31) during which M31 can hardly be observed. See also Table 1. The two seasons with the highest sampling are 2000/2001 and 2001/2002, i.e., those seasons where we could combine Wendelstein with Calar Alto data.

WeCAPP variables: Fliri, Riffeser *et al.* 2006A+A...445..423F)



25 571 variable point sources in a 16.1′ × 16.6′

Period-amplitude relation of variables in inner 4 kpc of M 31.

WeCAPP Novae: Lee, Riffeser *et al.* (2012A+A...537A..43L)

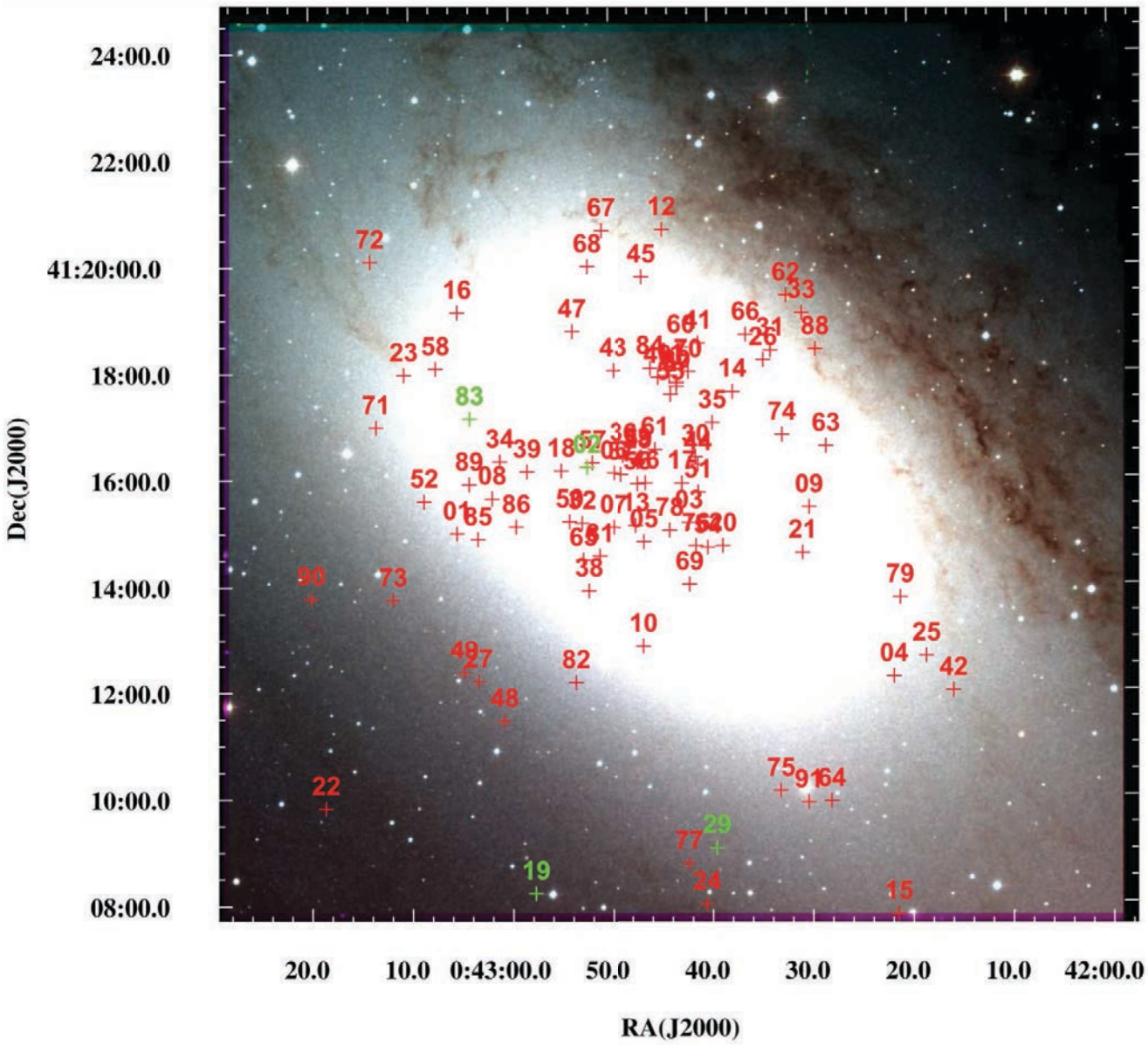
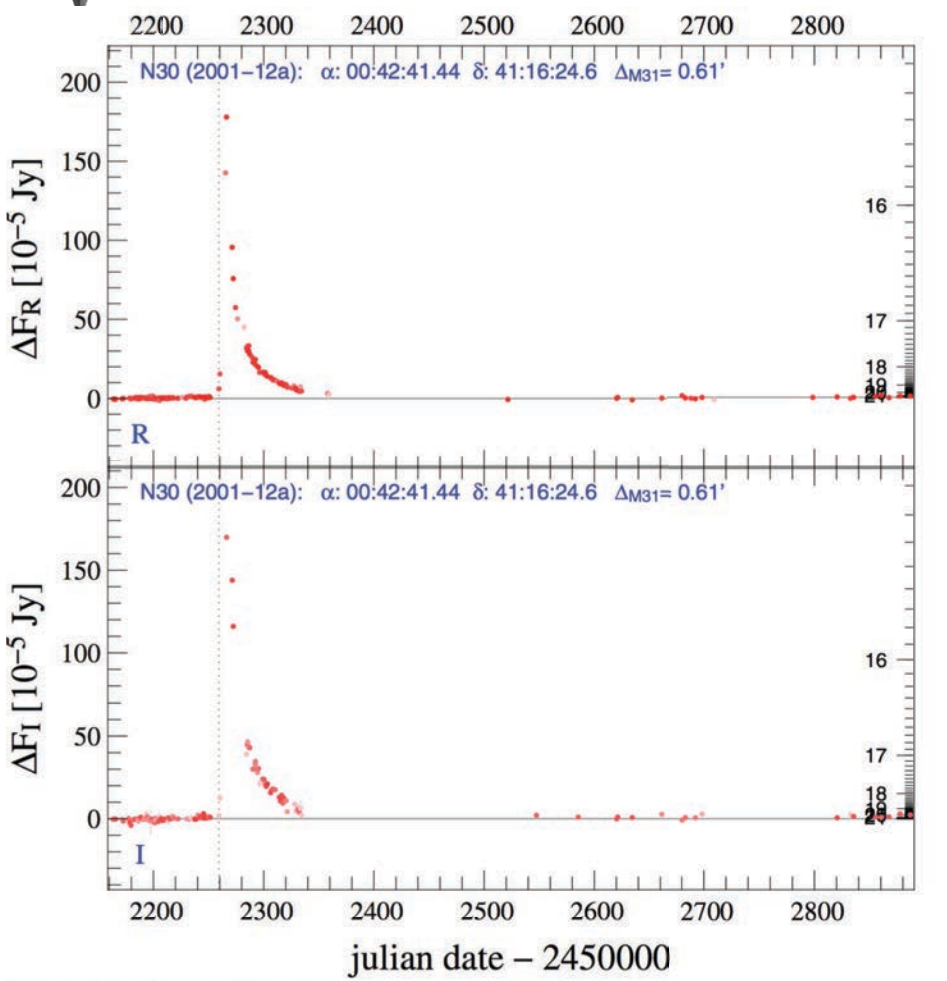
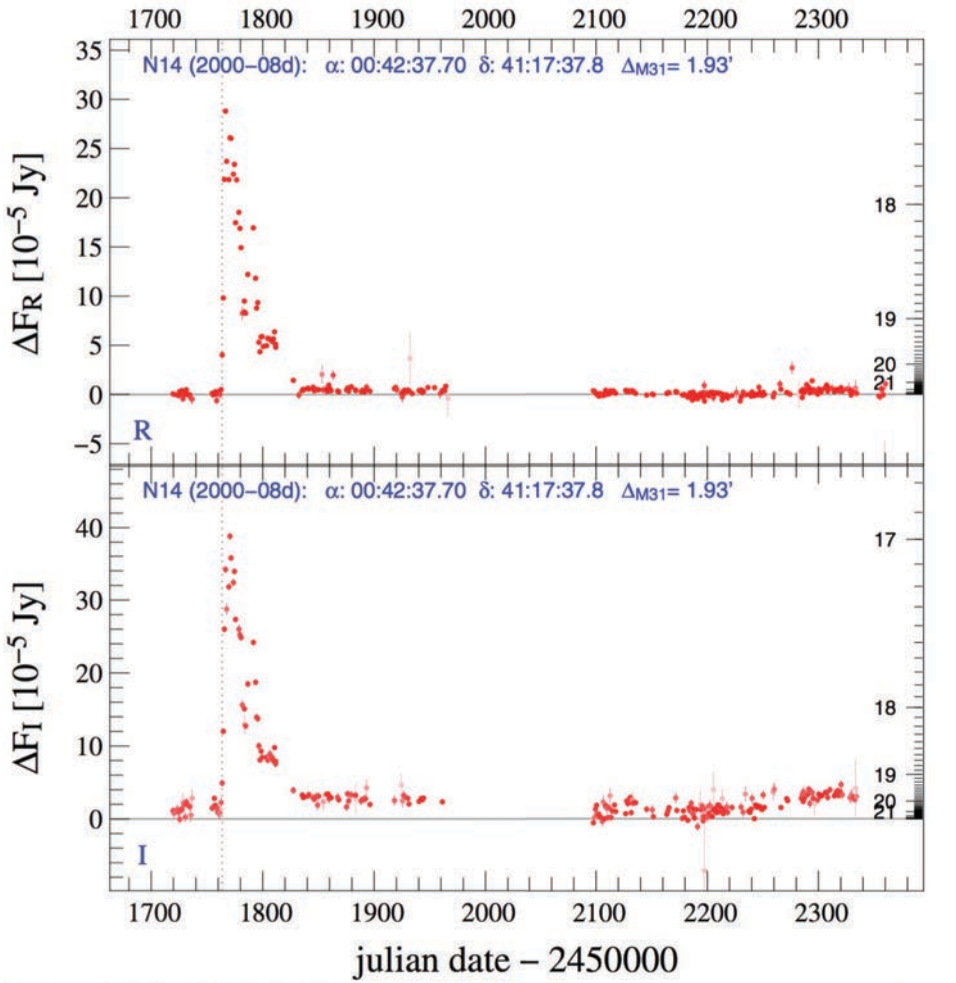
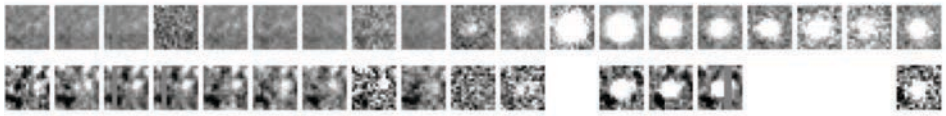


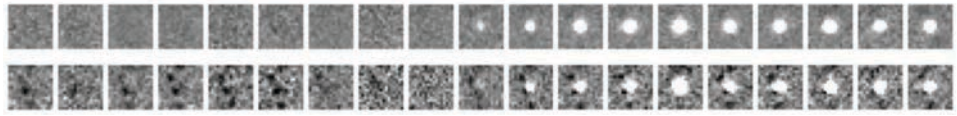
Fig. 4. Distribution of the WeCAPP nova candidates. The recurrent nova candidates (see Sect. 5) are marked in green. The overlaying image is a three-colour-combined image using the observations obtained from Calar Alto observatories in *V*, *R*, and *I*-band. The image has a size of 17.′2 × 17.′2.

WeCAPP Novae: Lee, Riffeser *et al.* (2012A+A...537A..43L)



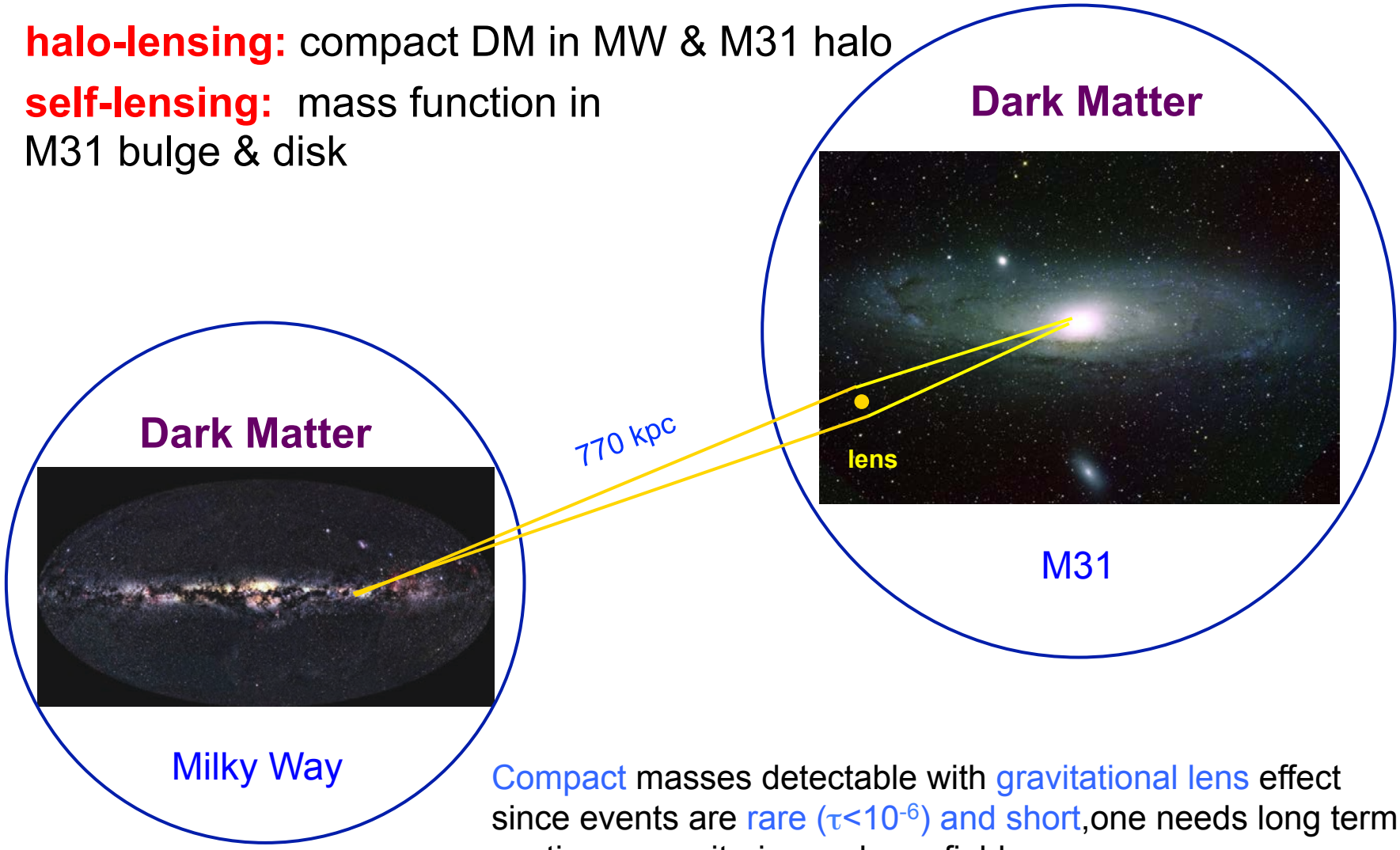






Microlensing in M31

- **halo-lensing:** compact DM in MW & M31 halo
- **self-lensing:** mass function in M31 bulge & disk

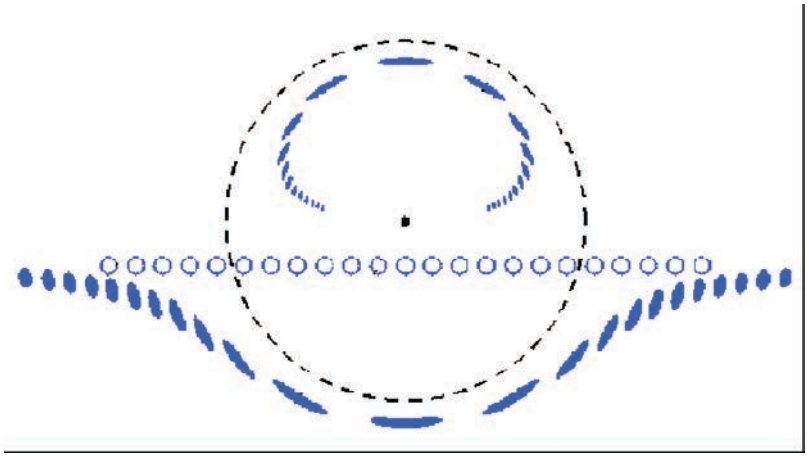


Compact masses detectable with gravitational lens effect since events are rare ($\tau<10^{-6}$) and short,one needs long term, continous monitoring on large fields

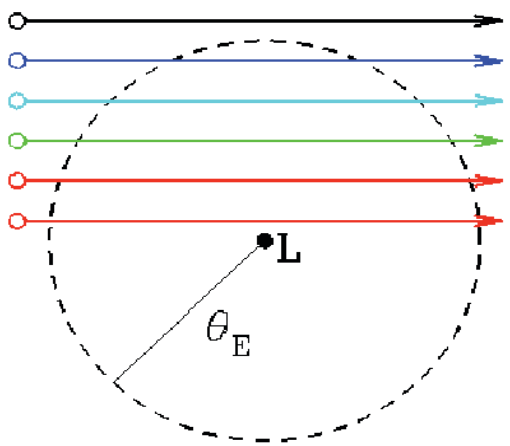
Large field also helps discriminating self- vs. halo-lensing

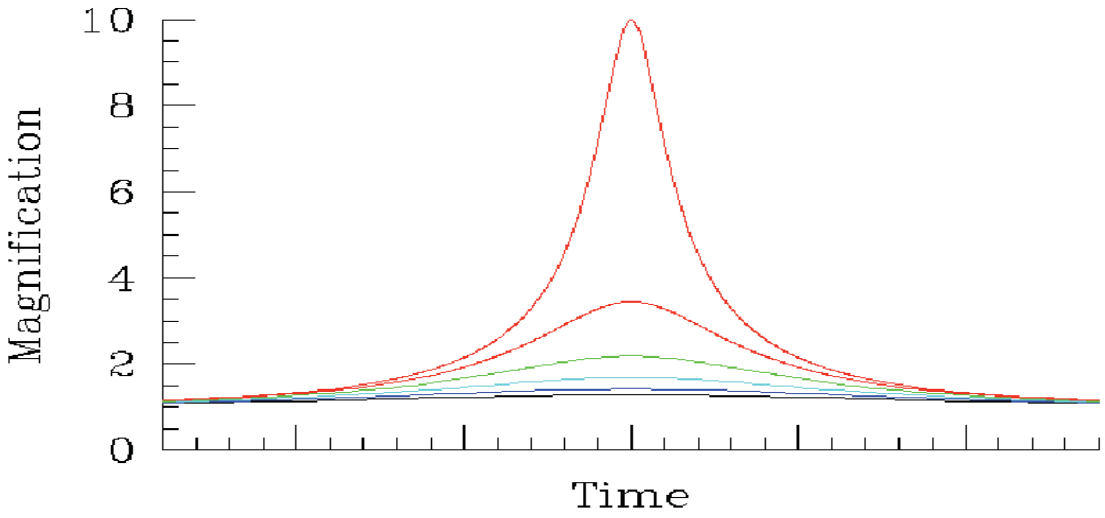
gravitational microlensing (ML) of a point mass
Paczynski (1986)

$$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \qquad u(t) = \sqrt{u_{min}^2 + (\frac{t - t_0}{t_E})^2}$$



1. for solar mass objects, image splitting is sub-milli-arcsec's and can not be resolved
2. light curve is symmetric and achromatic
3. maximum magnification depends on impact parameter $u_{\rm min}$
4. timescale of the event $t_{\rm E} = R_{\rm E}(M) / v_{\rm t}$





WeCAPP ML: Lee, Riffeser *et al.* (2015ApJ...806..161L)

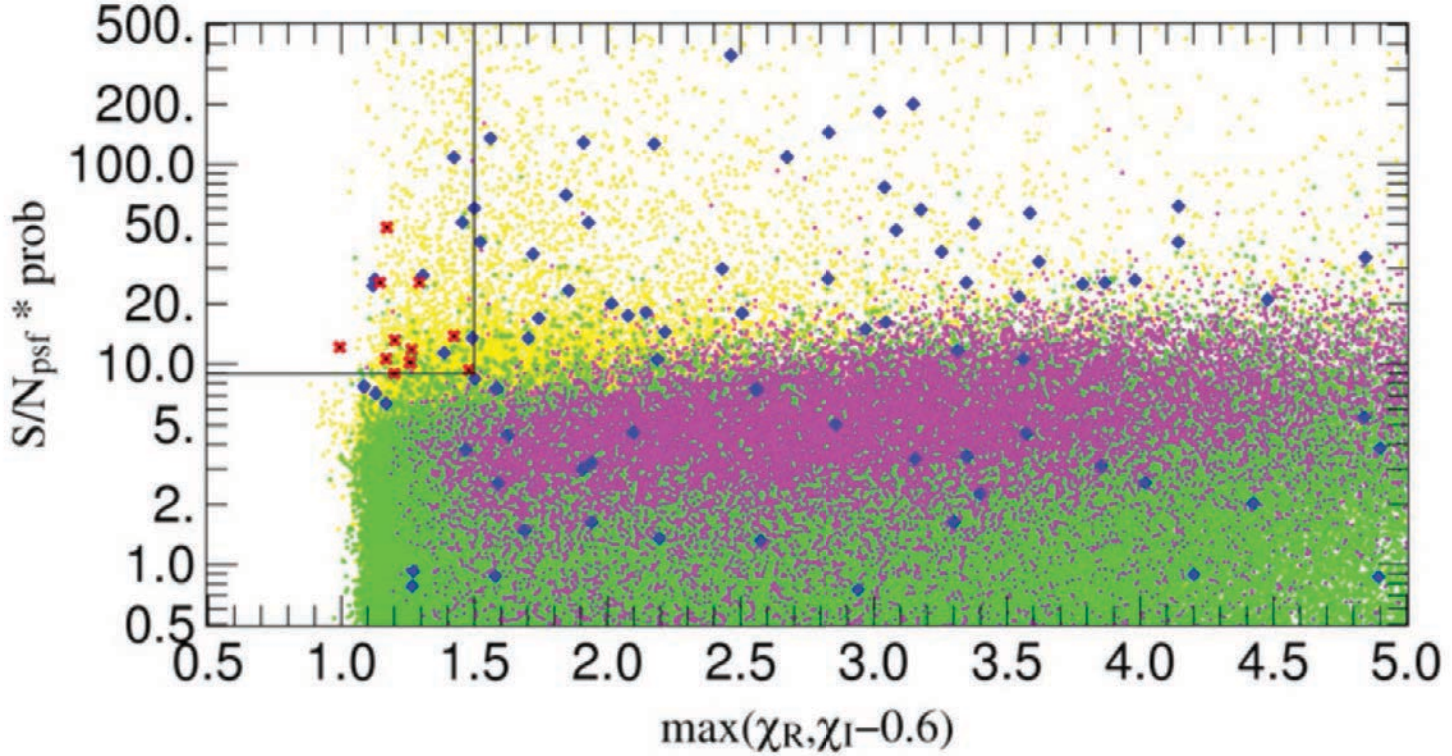
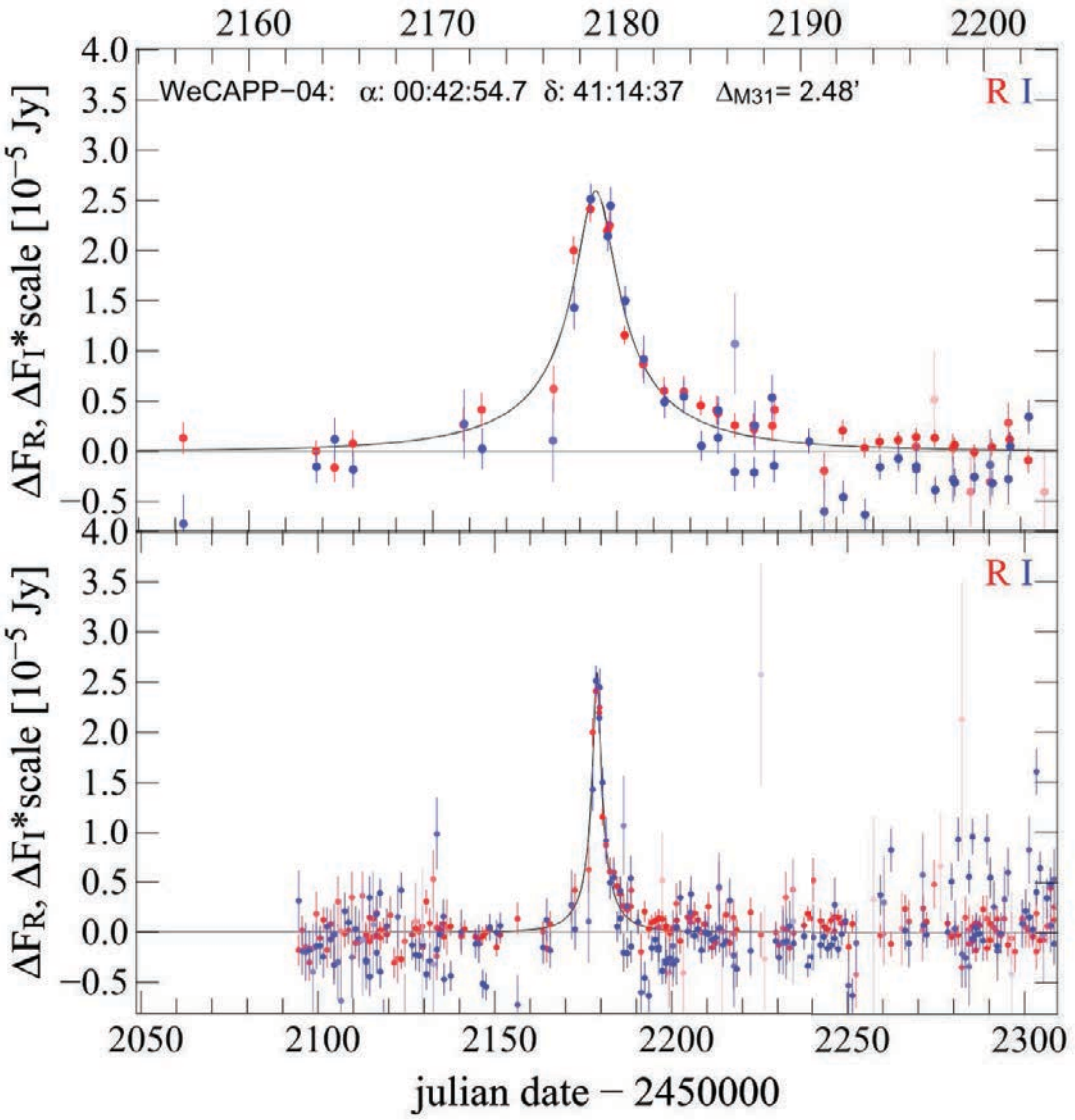


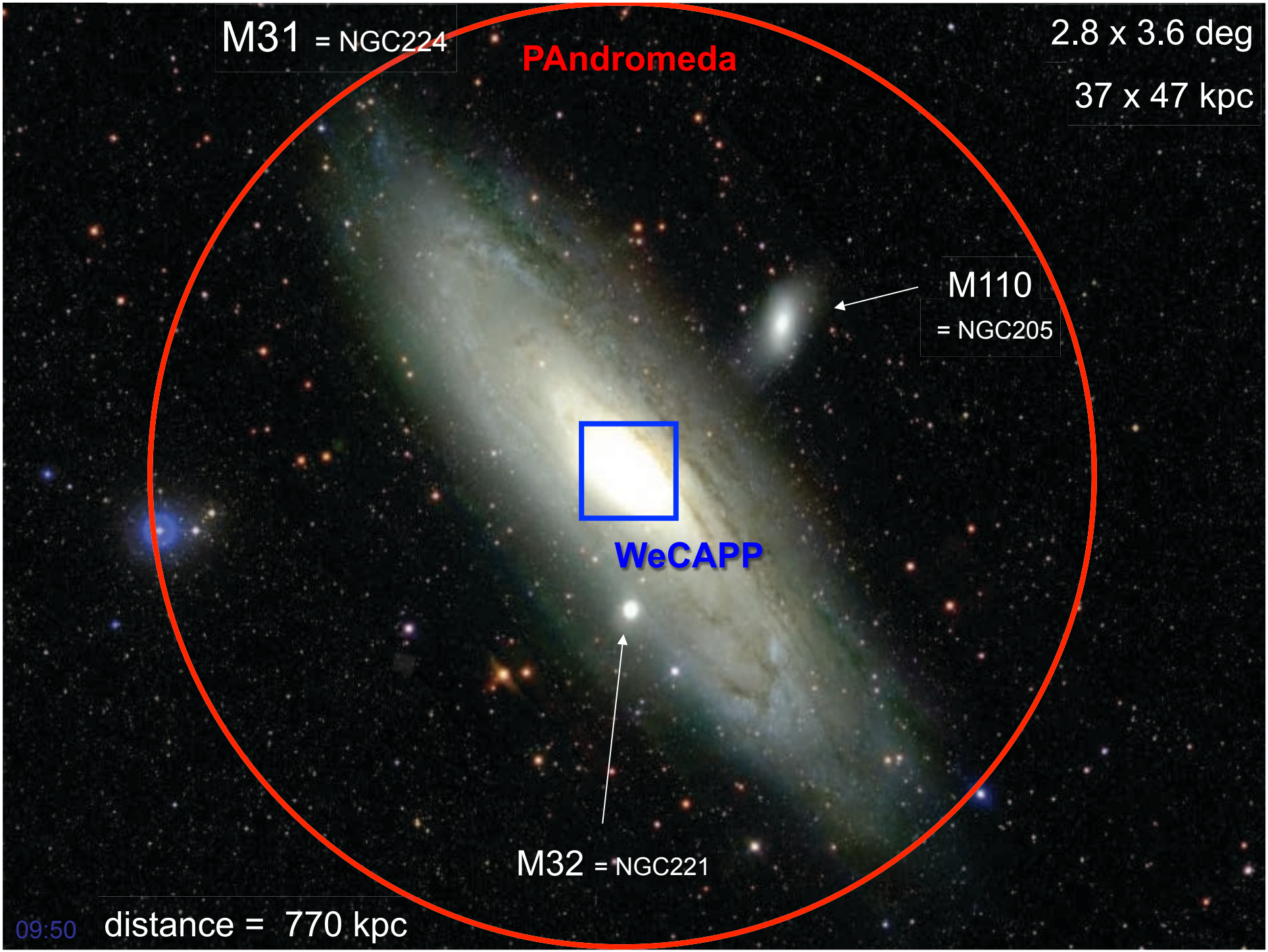
Figure 7. Criteria III and IV reduce the light curves from 719,628 (green) to 2247, as shown in the box on the upper left side. The light curves that do not pass criterion VI are marked in yellow. We show the 23,001 variables published in the WeCAPP variable star catalog from Fliri et al. (2006) in magenta, as well as the 91 novae from Lee et al. (2012) in blue. The final 12 microlensing events are shown in red. We note that the declining parts of nova light curves resemble microlensing events and often make short-timescale novae the major contamination in microlensing detections. In this regard, we show that criteria III and IV can efficiently discriminate microlensing events from novae, and hence remove their contamination.

WeCAPP ML: Lee, Riffeser *et al.* (2015ApJ...806..161L)



M31 surveys at University Observatory Munich

- **WeCAPP** *1998 – 2008* ➔ 0.08 deg^2
  (Wendelstein Calar Alto Pixellensing Project)
  - 0.8 m at Mount Wendelstein (Bavaria)
  - 1.23 m at Calar Alto (Spain)
- **PAndromeda** *2009 – 2012* ➔ 7 deg^2
  (Pan-STARRS Andromeda survey)
  - 1.8 m PS1 (Maui)
- **WST2M31** *2014 – 2018* ➔ 1 deg^2
  (Wendelstein 2m M31 survey)
  - 2.0 m Fraunhofer (Bavaria)


M31 = NGC224
PAndromeda
2.8 x 3.6 deg
37 x 47 kpc
M110
= NGC205
WeCAPP
M32 = NGC221
09:50
distance = 770 kpc

PAndromeda Cepheids: Kodric, Riffeser *et al.* (2018AJ....156..130K)

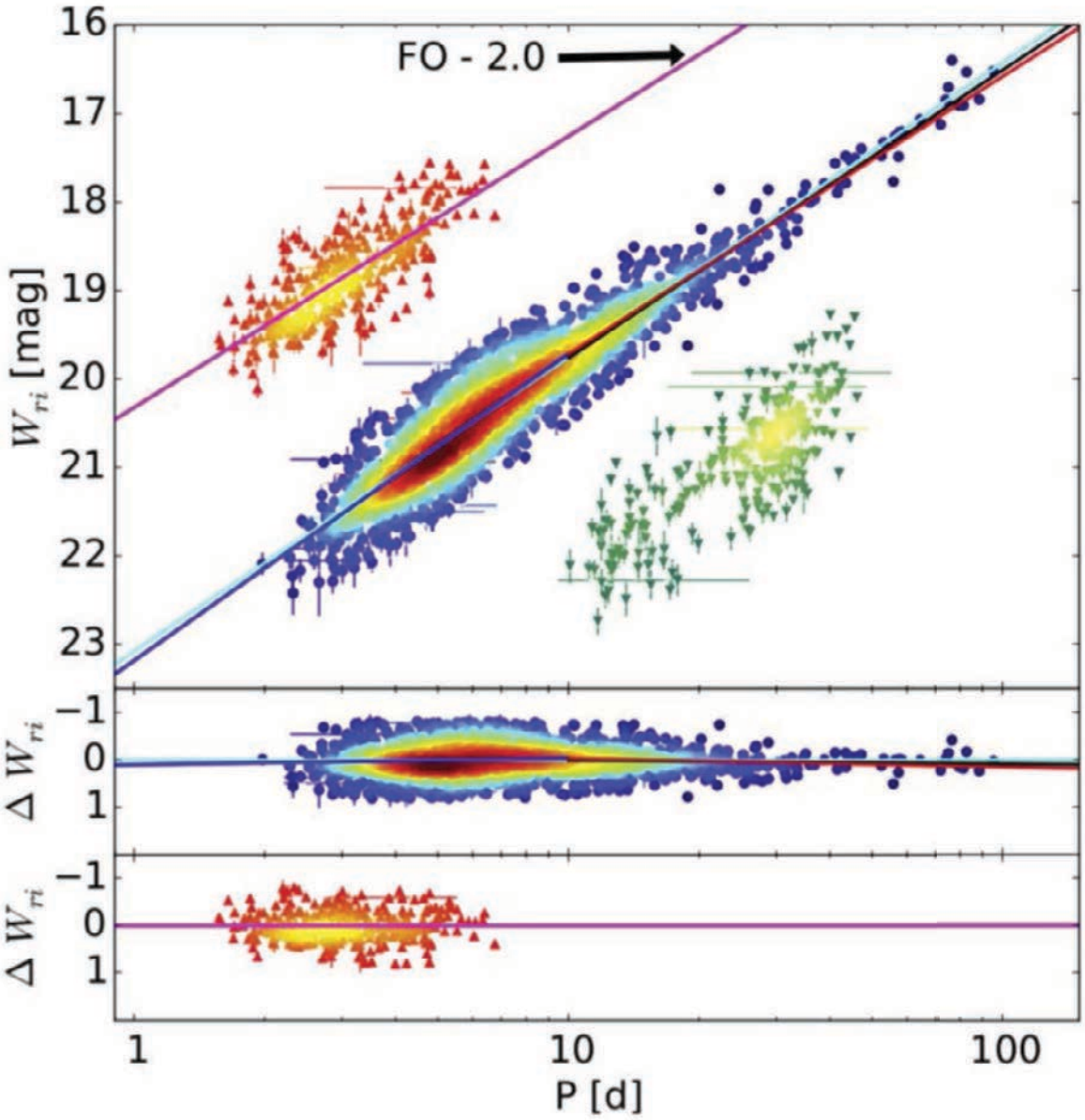


Figure 19. Period Wesenheit diagram. In total, there are 1662 FM Cepheids, 307 FO Cepheids, and 278 T2 Cepheids. In the top panel, the FO Cepheids

PAndromeda Cepheids: Kodric, Riffeser *et al.* (2018AJ....156..130K)

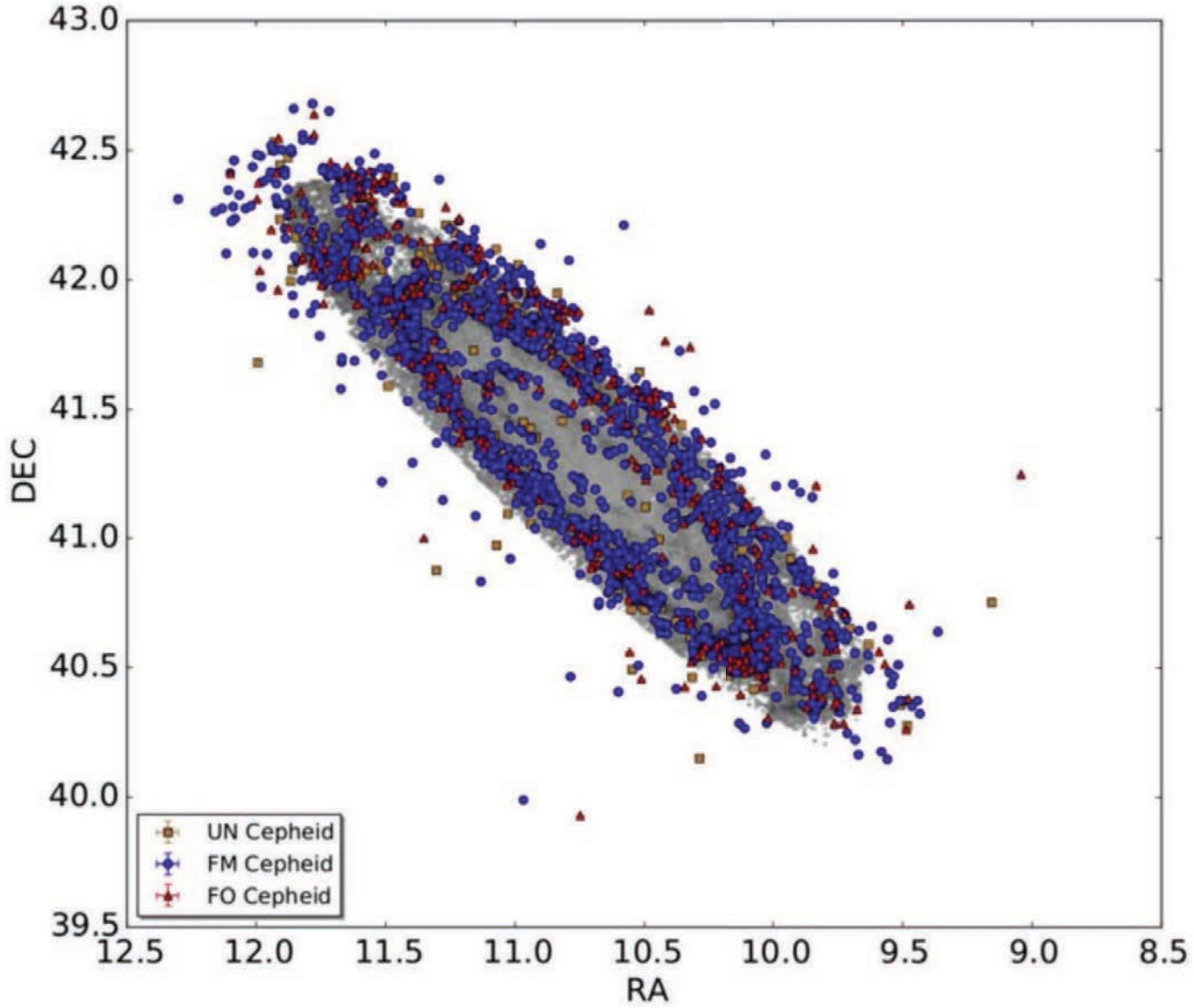


Figure 17. Spatial distribution of FM and FO Cepheids of the PAndromeda Cepheid catalog. The Cepheids are plotted over the $E(B-V)$ map of Montalto et al. (2009), and they follow the ring structure of M31.

PAndromeda Cepheids: Kodric, Riffeser *et al.* (2018AJ....156..130K)

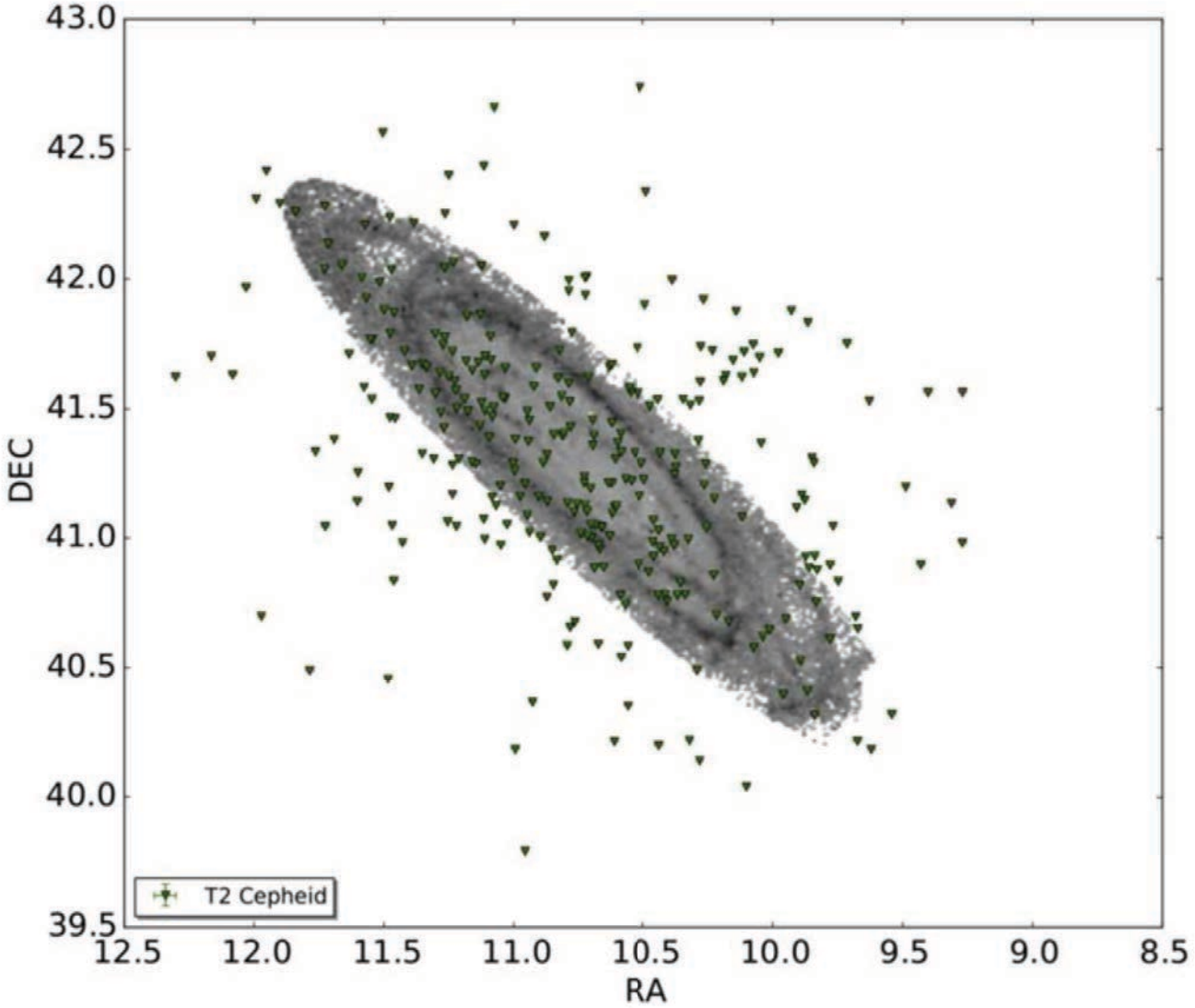


Figure 18. Spatial distribution of T2 Cepheids of the PAndromeda Cepheid catalog. As in Figure 17, the Cepheids are plotted over the Montalto et al. (2009) $E(B-V)$ map. In contrast to the FM and FO Cepheids, the T2 Cepheids follow the M31 halo.

PAndromeda ML: Lee, Riffeser *et al.* (2012AJ....143...89L)

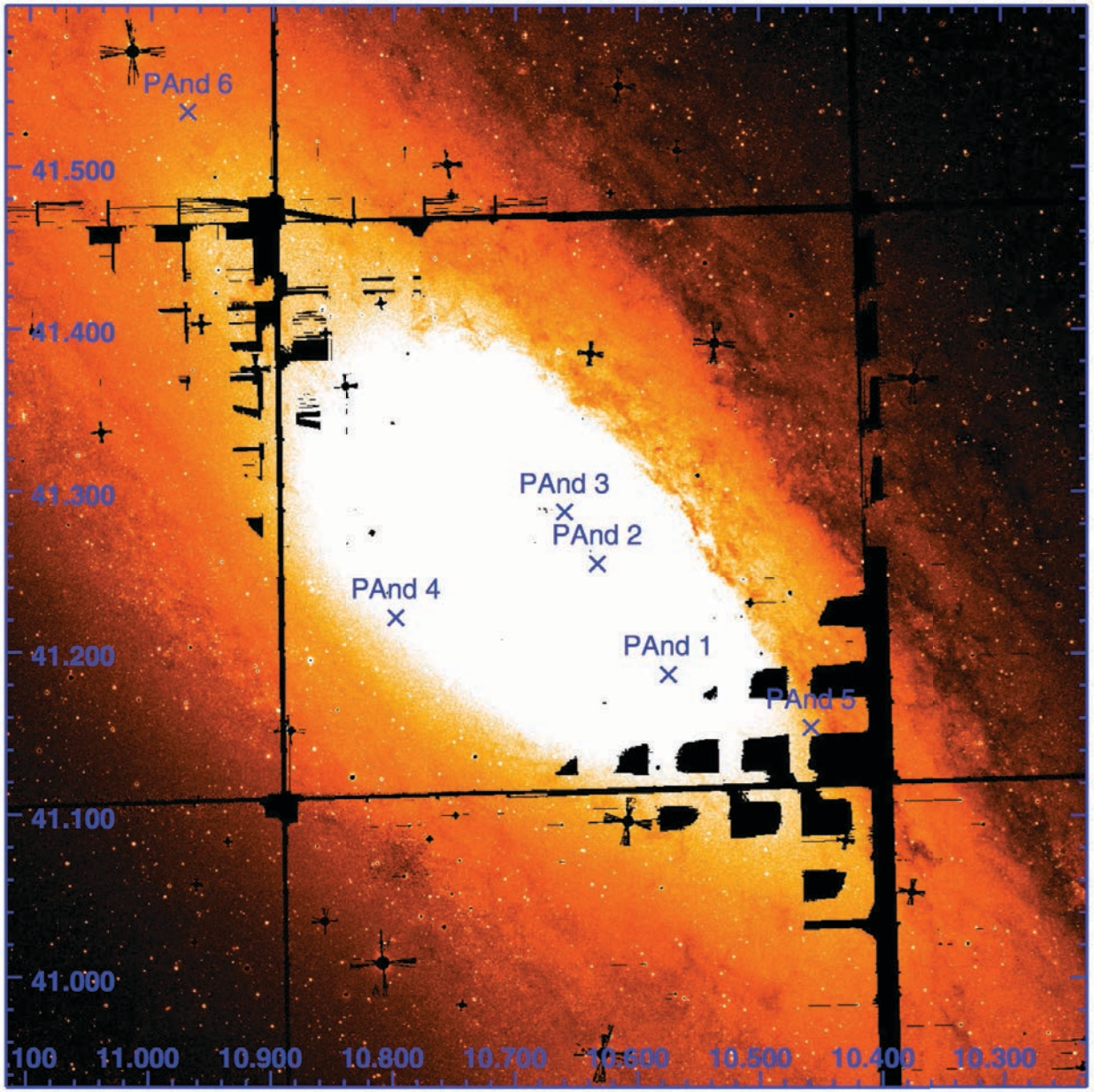
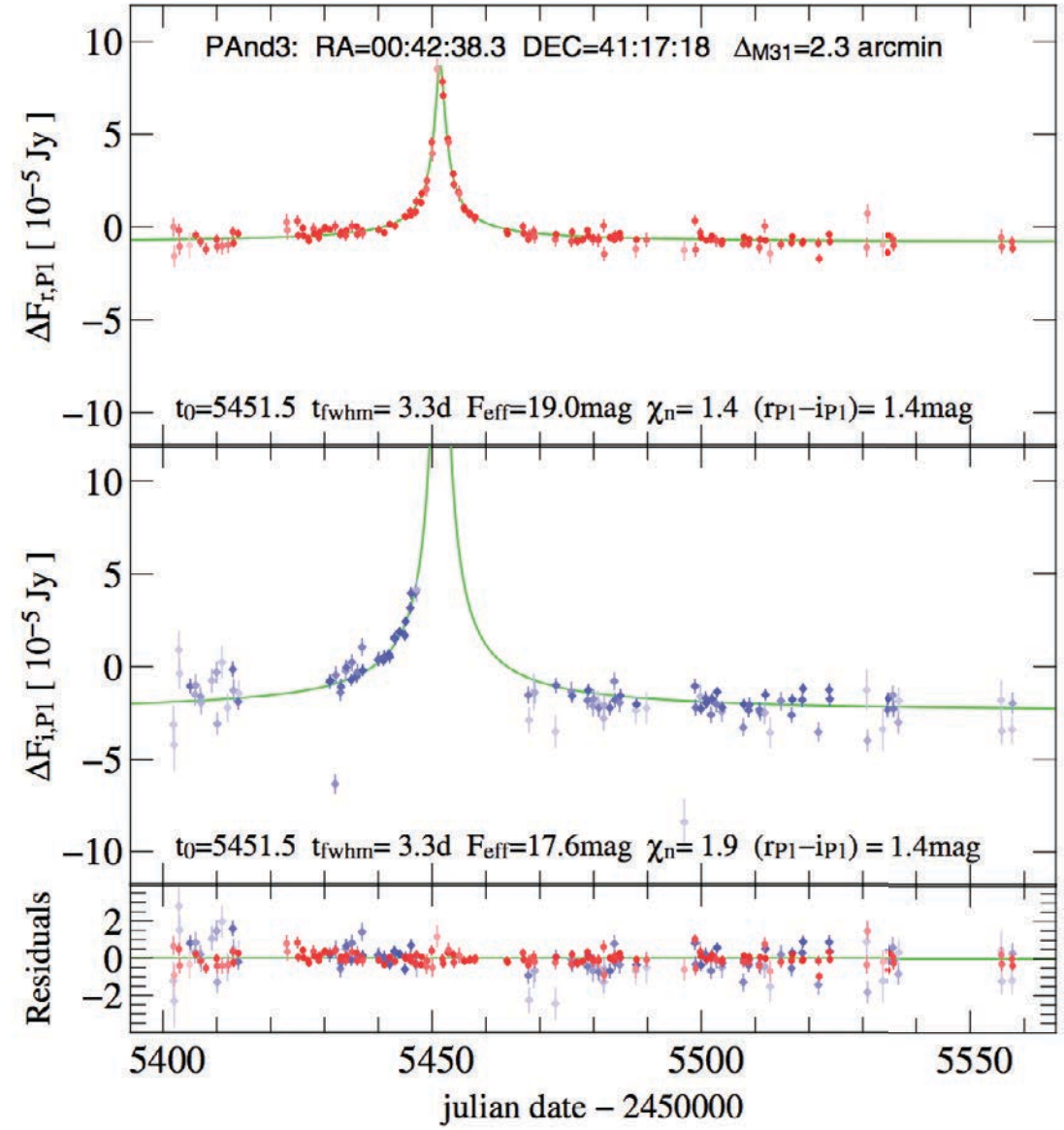


Figure 14. Position of the six microlensing event candidates detected in the central 40′ × 40′ region of M31 from PAndromeda. The coordinates, R.A. (J2000) in hour and decl. (J2000) in degree, are also shown in the figure. The FOV of this image is 40′ × 40′.

PAndromeda ML: Lee, Riffeser *et al.* (2012AJ....143...89L)

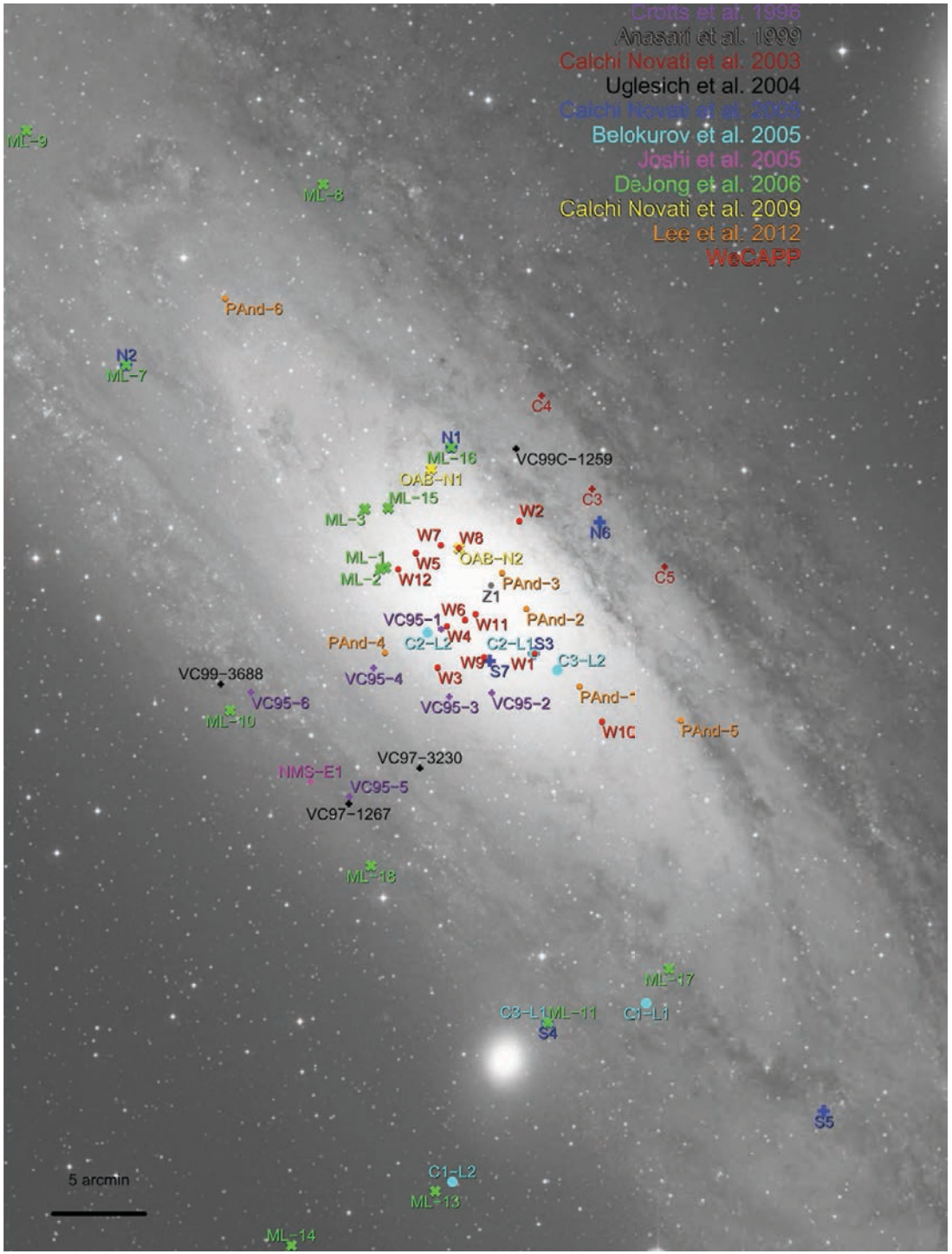


←19 mag

WeCAPP ML:

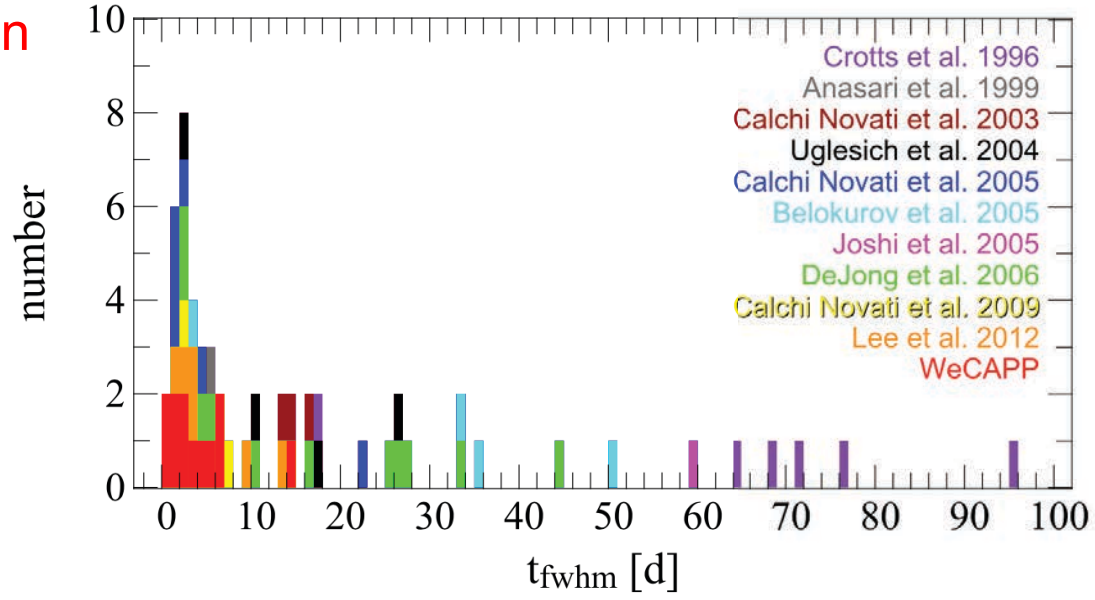
Lee, Riffeser *et al.* (2015ApJ...806..161L)

56 ML events in M31



WeCAPP ML: Lee, Riffeser *et al.* (2015ApJ...806..161L)

time scale distribution



brightness distribution

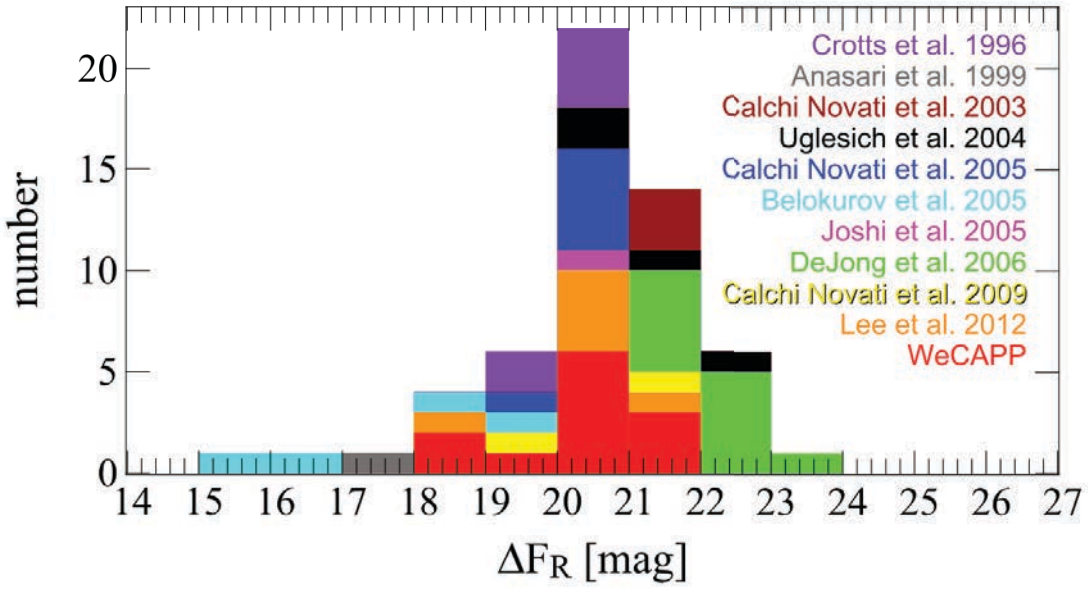
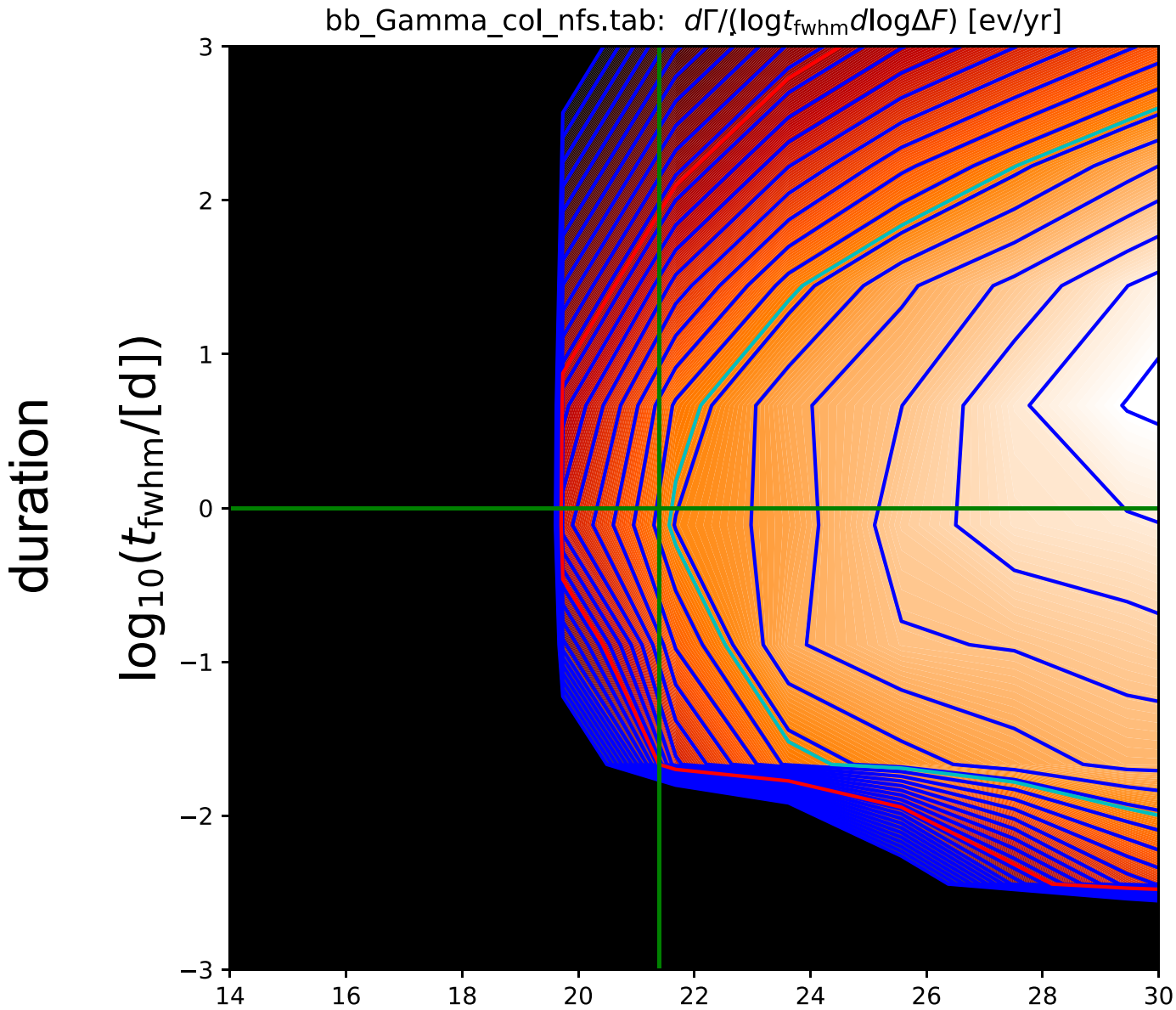


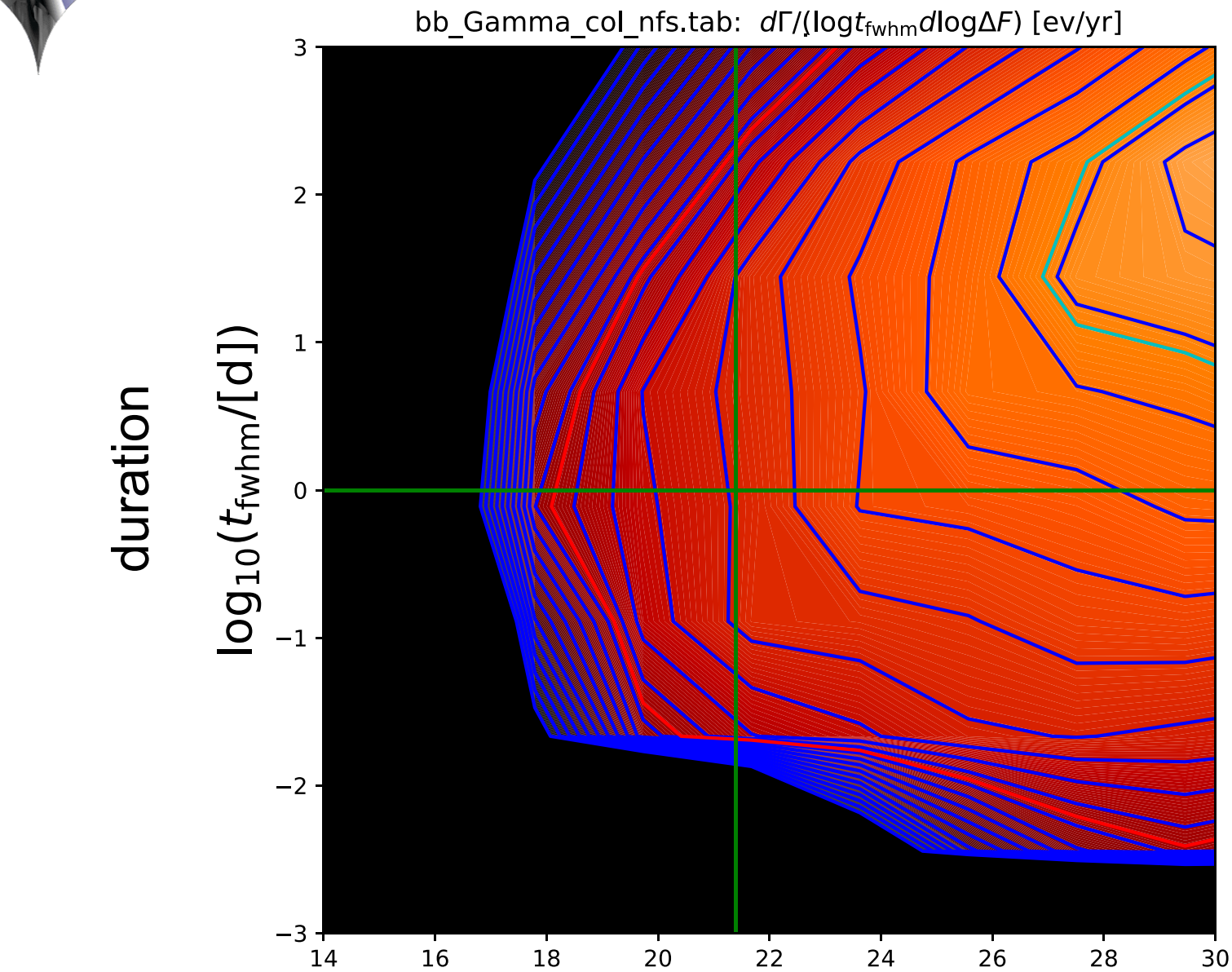
Figure 13. t_0, t_{FWHM}, and Δ_{F_R} distribution of all microlensing events in M31

star-bulge self lensing: no remnants



Riffeser *et al.*
2006ApJS..163..225R

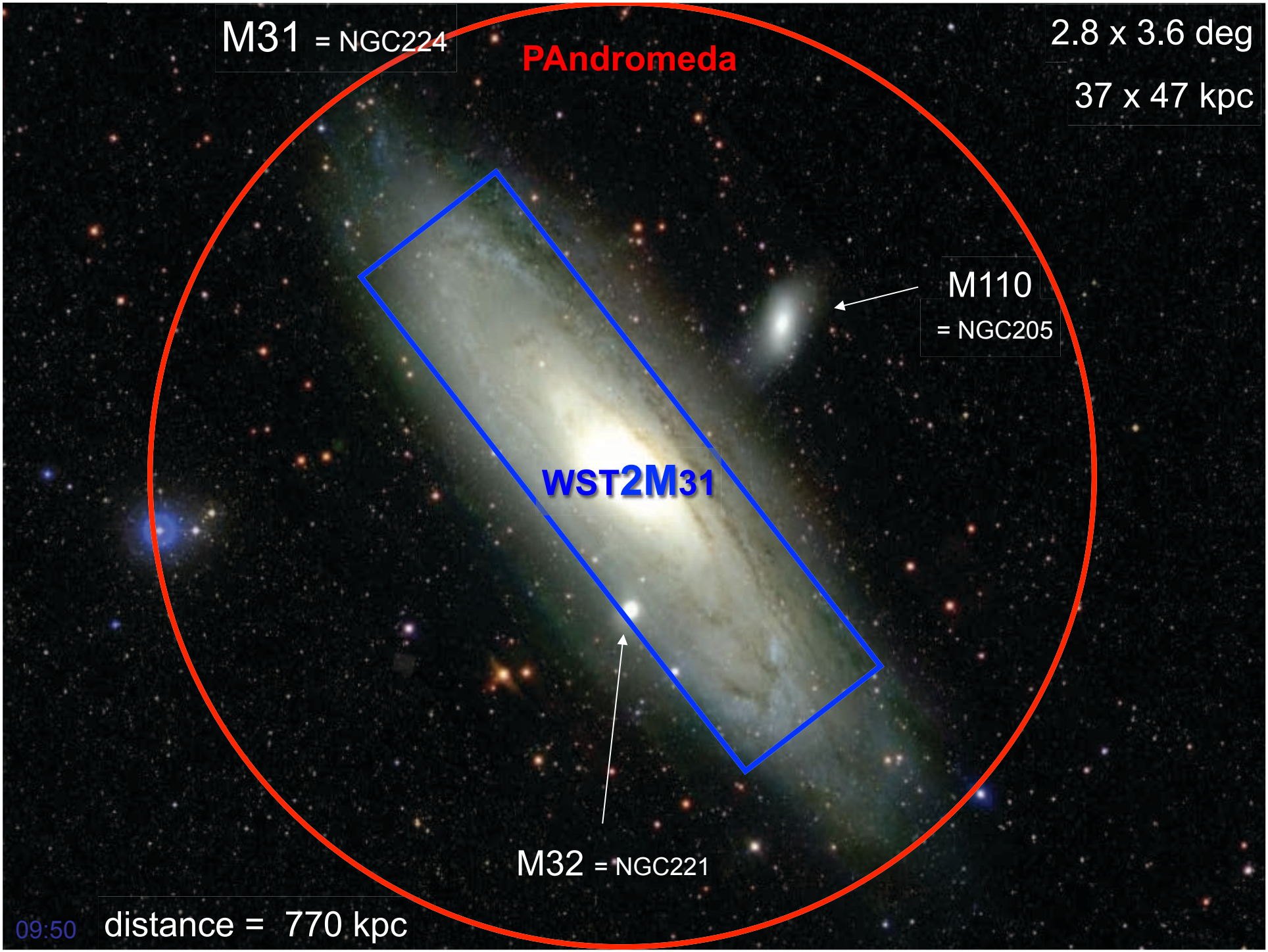
BH-bulge lensing: only BH remnants as lenses



Riffeser *et al.*
2006ApJS..163..225R

M31 surveys at University Observatory Munich

- **WeCAPP** *1998 – 2008* ➔ 0.08 deg^2
  (Wendelstein Calar Alto Pixellensing Project)
  - 0.8 m at Mount Wendelstein (Bavaria)
  - 1.23 m at Calar Alto (Spain)
- **Pandromeda** *2009 – 2012* ➔ 7 deg^2
  (Pan-STARRS Andromeda survey)
  - 1.8 m PS1 (Maui)
- **WST2M31** *2014 – 2018* ➔ 1 deg^2
  (Wendelstein 2m M31 survey)
  - 2.0 m Fraunhofer (Bavaria)


M31 = NGC224
PAndromeda
2.8 x 3.6 deg
37 x 47 kpc
M110
= NGC205
WST2M31
M32 = NGC221
09:50
distance = 770 kpc

WST2M31 survey

nights 14/12/05 - 18/08/26 (3.75 yrs)

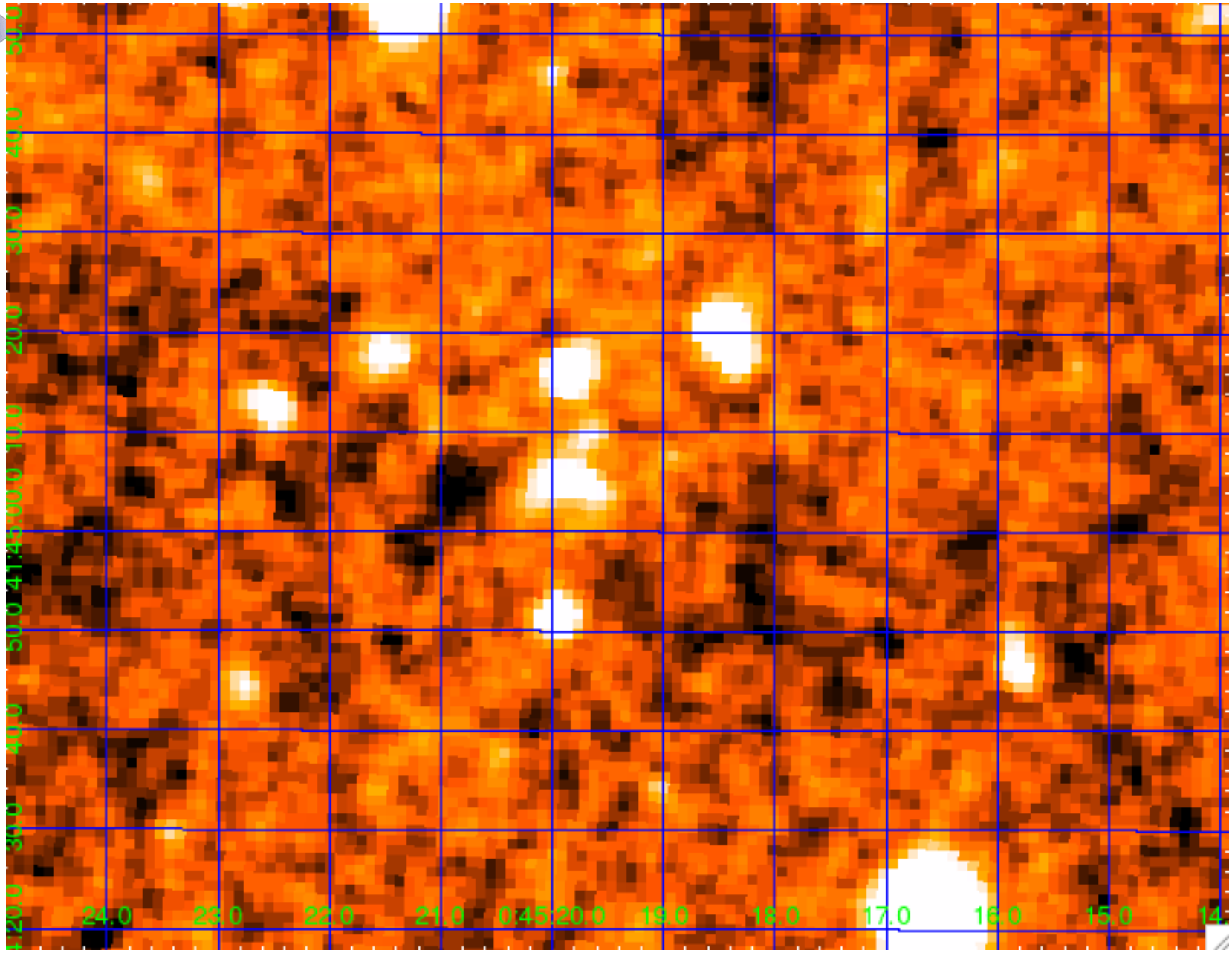
4 fields

	r	i	g
F1	180	164	2
F2	155	145	2
F3	150	142	1
F4	130	124	2

~ 21 000 **frames** (2.6 TB raw data)

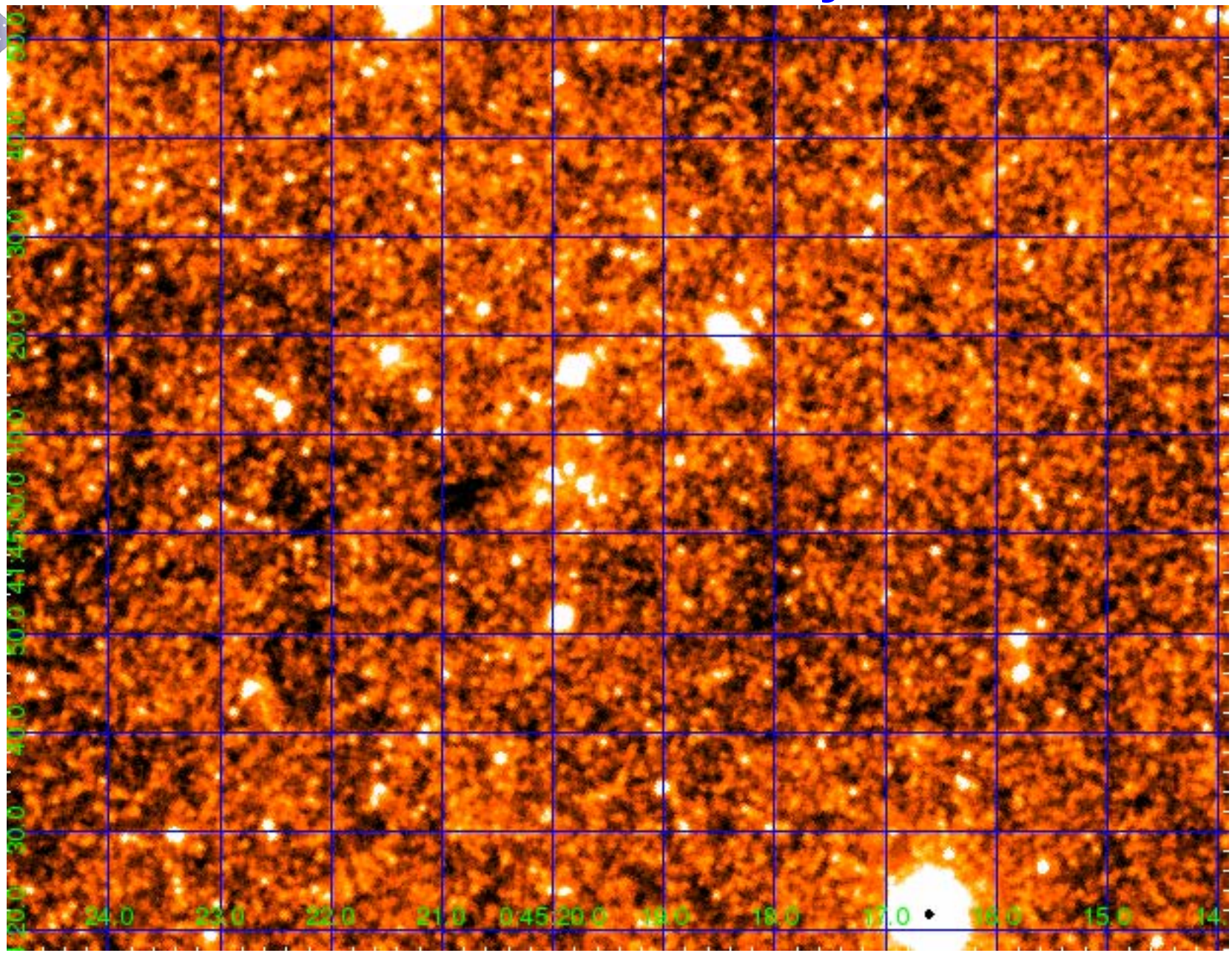
	r	i
F1	5586	2757
F2	2220	2147
F3	2205	2114
F4	1901	1841
	11912	**8859**

ESO Digitized Sky Survey



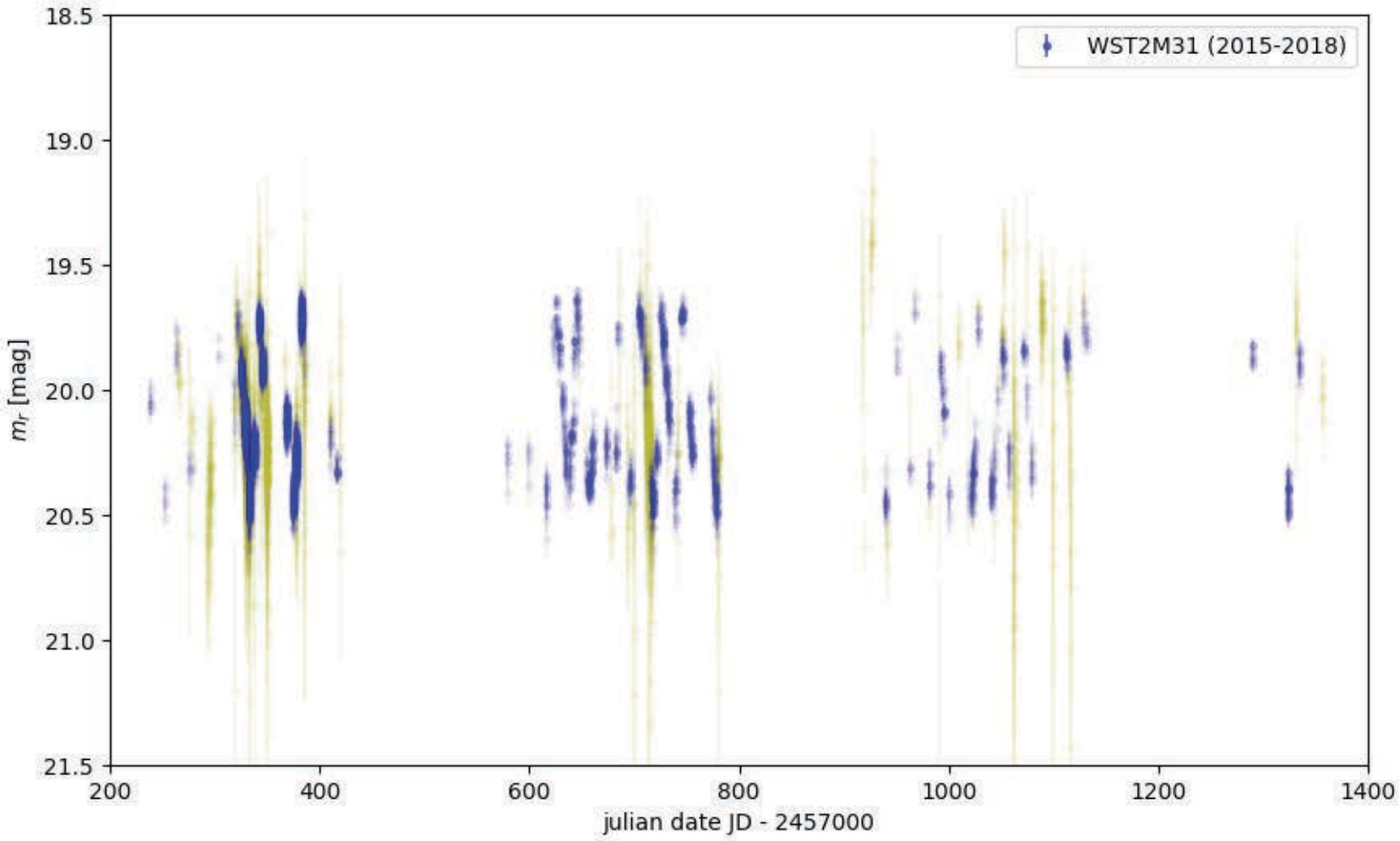
px-scale = 1 arcsec/px

WST2M31 survey

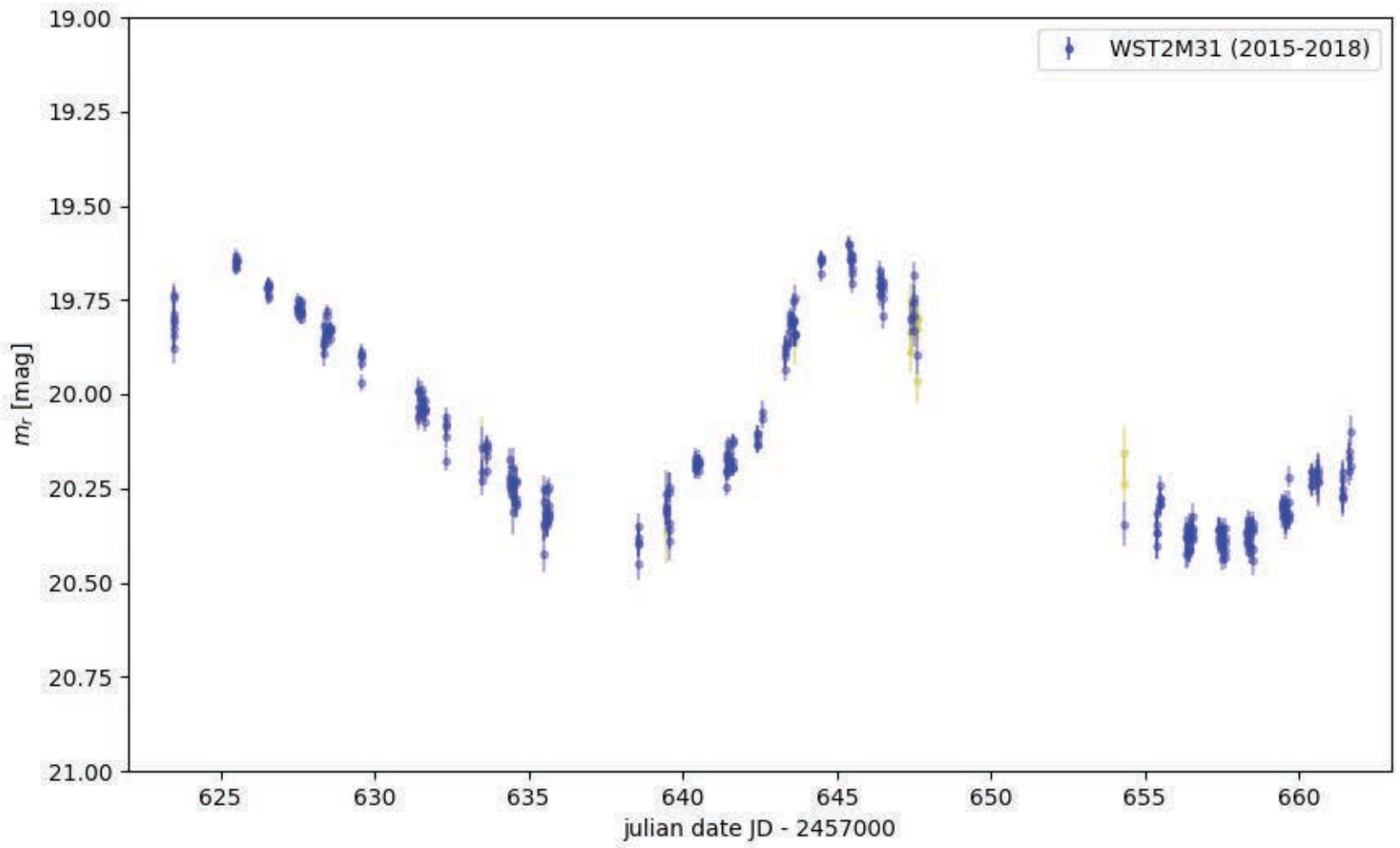


px-scale = 0.2 arcsec/px

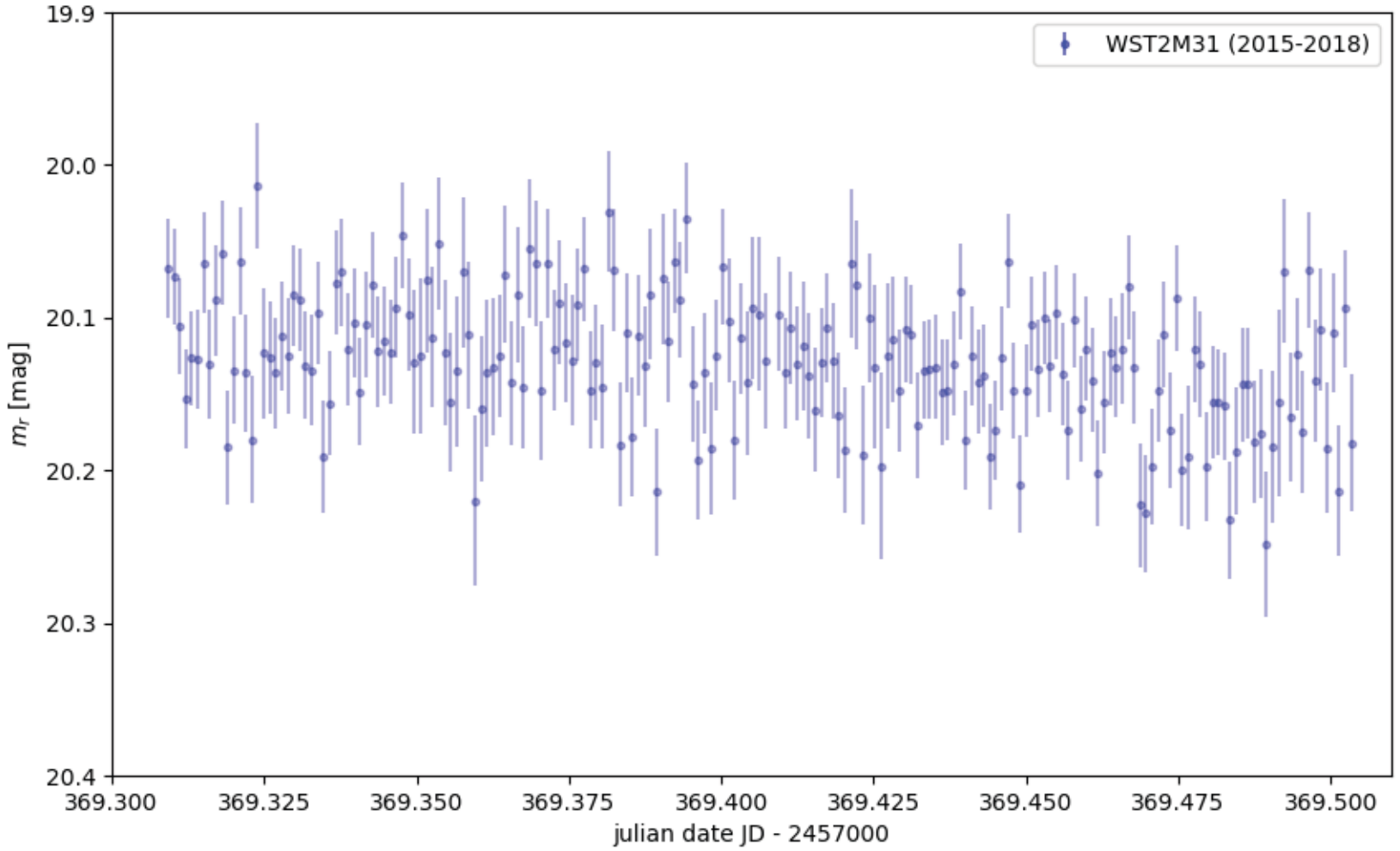
WST2M31 survey
3.5 years
5000 x 60 sec images



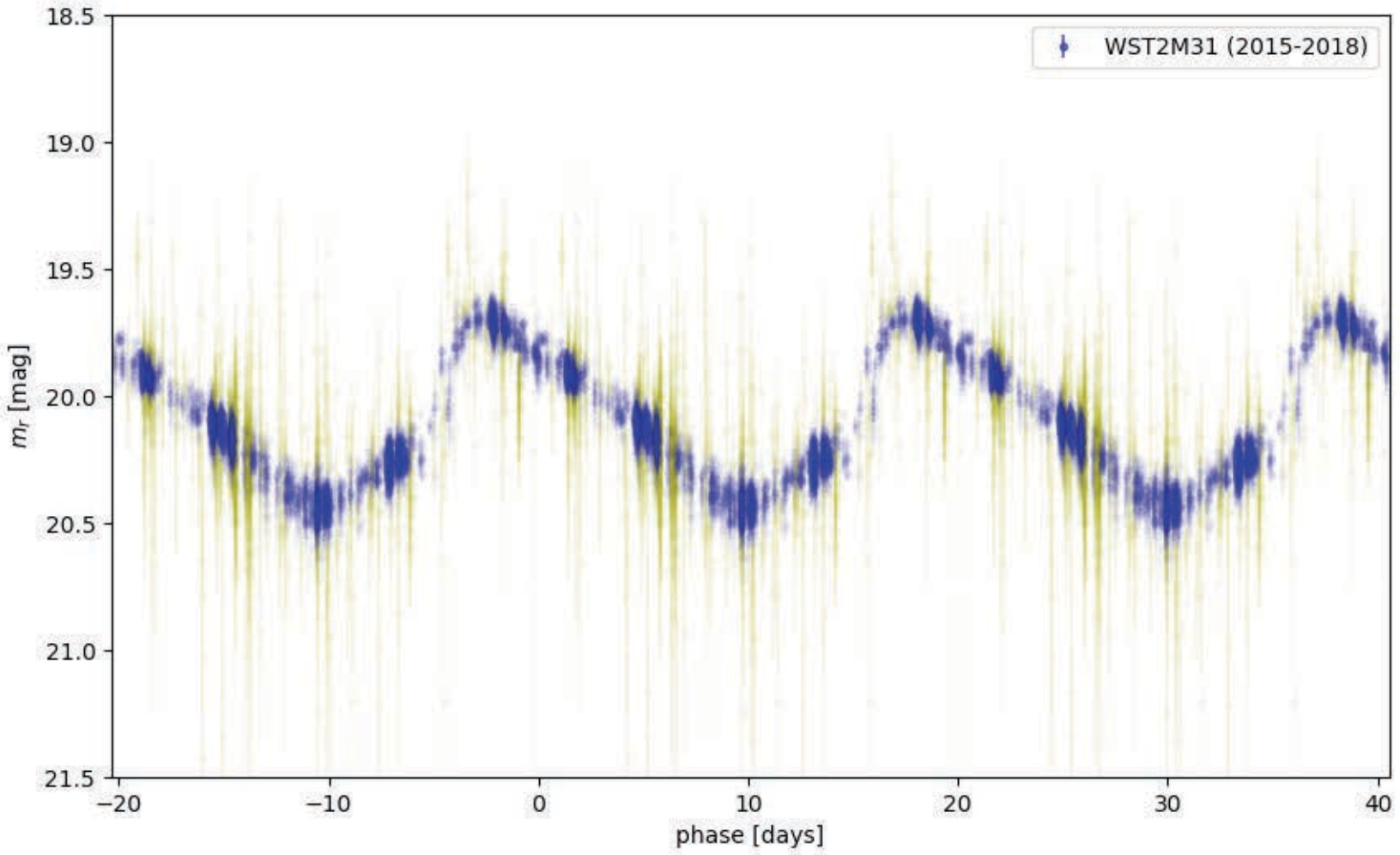
WST2M31 survey
40 nights
60 sec images



WST2M31 survey
1 night
195 x 60 sec images



WST2M31 survey
cepheid with period 20.23 days
5000 x 60 sec images



M31 surveys at University Observatory Munich

- **WeCAPP** *1998 – 2008* ➔ 0.08 deg^2

  (Wendelstein Calar Alto Pixellensing Project)

  - 0.8 m at Mount Wendelstein (Bavaria)
  - 1.23 m at Calar Alto (Spain)
- **PAndromeda** *2009 – 2012* ➔ 7 deg^2

  (Pan-STARRS Andromeda survey)

  - 1.8 m PS1 (Maui)
- **WST2M31** *2014 – 2018* ➔ 1 deg^2

  (Wendelstein 2m M31 survey)

  - 2.0 m Fraunhofer (Bavaria)