M31 Pixel Lensing, PLAN @ OAB and beyond…

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Layout

- Framework: microlensing and the search of MACHOs
- M31 pixel lensing
  - The expected signal
  - PLAN@OAB: the 2006-2010 campaign
  - What next? **L**arge **B**inocular **T**elescope !!
- Conclusions

Compact halo objects as dark matter candidates at the galactic scale

LMC and SMC

- $\mathrm{M} < 10^{-1}\ M_{sun}: f < 10\%$ (MACHO, EROS, OGLE)
- (0.1-1) M_{sun} (the same mass range for lensing by stars!)
    - $f \sim 20\%$ (MACHO 2000, Bennett 2005)
    - self lensing (EROS 2007, OGLE II-III, 2009-2011)

M31 (Andromeda)

- «evidence» for a MACHO signal (POINT-AGAPE 2005)
- Self lensing and upper limit for f (MEGA 2006)

} *The same data set!*

- PA-S3/GL1: a bright candidate attributed to MACHO lensing (WeCAPP 2008)
- OAB-N2: lens proper motion analysis favors MACHO lensing over self lensing (PLAN 2010)

even a (relatively) small, still sizeable, fraction f would constitute a challenge to our understanding of galactic astrophysics , which is well worth a further effort…

M31 Pixel lensing (D=770 kpc)

Looking for flux variations of *unresolved* sources

Large number of potential sources *per pixel*

Additional **degeneracy** in the lensing parameter space

$$t_{1/2} = t_E \cdot f(u_0)$$
$$\Delta\Phi = \phi_* \cdot A(u_0)$$

The **noise** level is set by the surface brightness M31 profile

bonus

We can probe the full M31 own dark matter halo
(about 1/3 of the MACHO lensing expected from the MW halo)

How to get to an accurate estimate of the expected signal

- number of events
- characteristics

Astrophysical model
Magnification model

→ the microlensing rate, $d\Gamma$

in the «classical» microlensing regime (with the caveat of *blending*)

$$dN_{exp} = N_{sources} \cdot T_{obs} \cdot u_{max} \cdot d\Gamma \cdot \varepsilon(t_E)$$

the same holds for pixel lensing but …

$$\varepsilon = \varepsilon(\phi_*, u_0, t_E) \rightarrow \varepsilon(t_{1/2}, \Delta\Phi)$$

so that we end up with

$$N^{(M31)}{}_{exp} = N_{sources}(\mathcal{M} < \mathcal{M}_{th}) \cdot T_{obs} \cdot u_{th} \cdot \int_{\mathcal{M}<\mathcal{M}_{th}, u<u_{th}} d\Gamma \; \varepsilon\left(t_{1/2}, \Delta\Phi\right)$$

namely we have to integrate out the following

$$dN_{exp} = dN_{exp}(\alpha, \delta;\; D_l, D_s, \mu, \phi_*, v, \theta, u_0, t_0, \ldots)$$

How do we carry out the dN_{exp} integration ?

$N_{exp} = \iiint dN_{exp}$ (eg «Vegas» NR routine)

Monte Carlo simulation: we draw each parameter according to its parent distribution, so that we associate to each simulated event a *weight,* $w \propto d\Gamma$*,* so that we have

$$N_{exp} = \sum_i w_i \cdot \varepsilon_i , \qquad \varepsilon_i = 0, 1$$

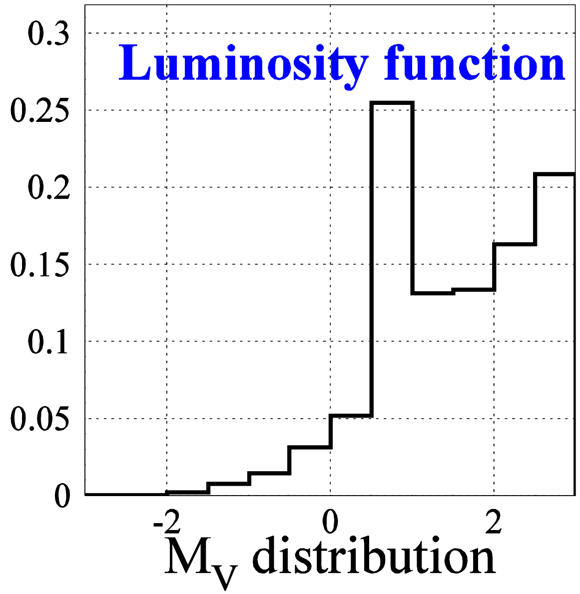
The MC is our workhorse in the analysis, as a test we have verified that, following either of the two approaches, we get to the same results within the numerical error fixed below the 1% level

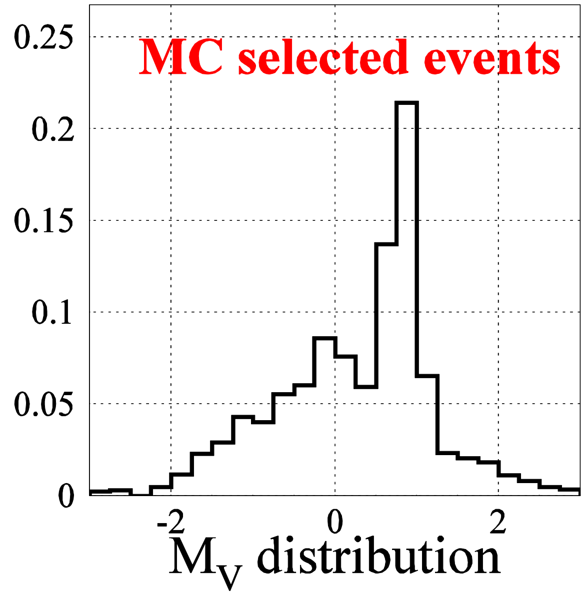
within this framework one can, at best, probe ε due to the statistical noise level, whereas a given pipeline has to deal with **data** (namely, with images): this introduces additional ingredients one is supposed to properly take into account such as effects due to *crowding, seeing, ….*

Vegas is fast, however…

The bonus of the Monte Carlo approach

1) together with N_{exp} we get, for free and in a single shot, the expected distributions for all the parameters





2) we can easily introduce additional lensing parameters (eg the stellar radius)

3) we can simulate the events *selected* within the MC on the (real) images, run from scratch the full selection pipeline (which must be *fully automated!)* so to properly evaluate the efficiency of the pipeline

$$\varepsilon_{pipeline} = \frac{\sum_i w_i \cdot \eta_i}{\sum_i w_i}, \quad \eta_i = 0,1$$

The M31 pixel lensing **PLAN** observational campaign

Salerno Univ.
Salento Univ.
INAF
M. Dominik, Ph. Jetzer, A. Gould

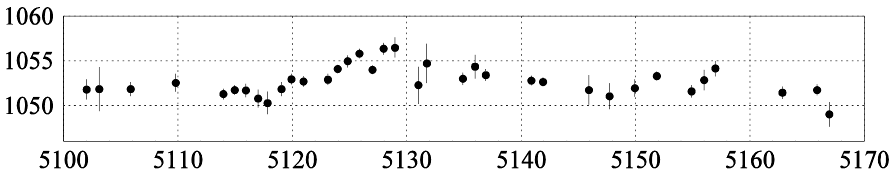
1.5 m Cassini telescope (OAB)
CCD fov: 13’ X 12.6’
we monitor 2 fields, North and South M31 center
Observations in R and I broad band filters
«superpixel» (AGAPE) photometry

Year	# good/allocated nights	# number of useful hrs/(good) night
2006	8/11 (73%)	4.2
2007	31/50 (62%)	3.8
2008	38/65 (58%)	4.6
2009	25/36 (69%)	5,5
2010	20/41 (49%)	4.6
Tot	122/203 (60%)	4.5

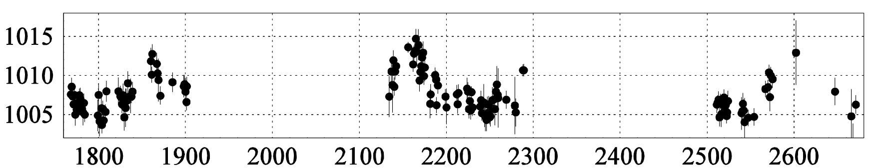
M31 is observable up to 8 hr/night below 1.5 airmass: overall the fraction of usuable hours over the allocated ones is barely above 30%.....

The *fully automated* selection pipeline

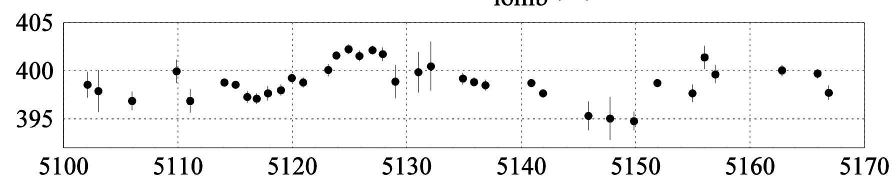
- Selection of flux variations
- PSF analysis of the bump (to exclude artefacts)
- Shape analysis: R&I Paczinski fit
- Unicity test along INT baseline (analysis based on the Lomb periodogram)



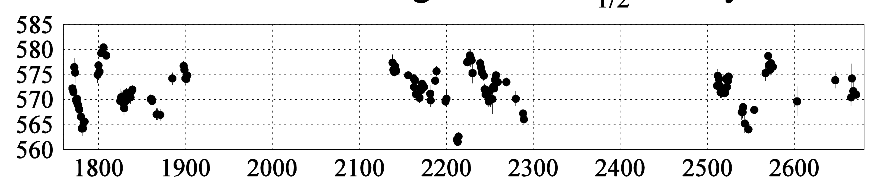
OAB selected light curve - $t_{1/2}$=12 days



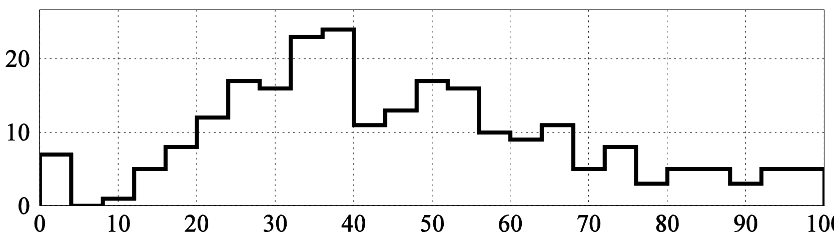
INT extension - $P_{lomb}(R)$ = 31.8



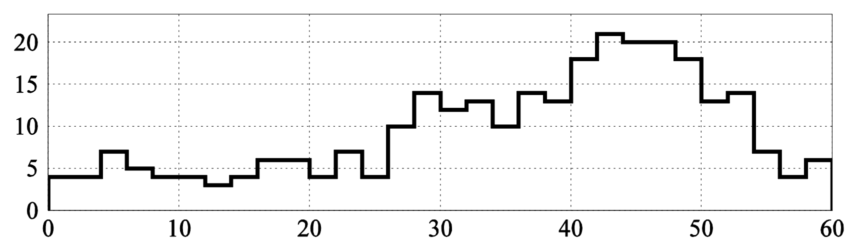
OAB selected light curve - $t_{1/2}$= 6 days



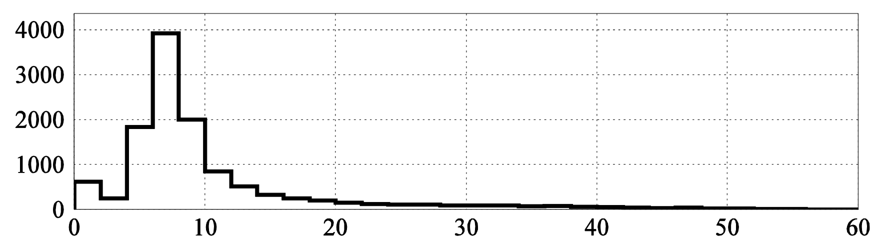
INT extension - $P_{lomb}(R)$ = 43.4



OAB: $t_{1/2}$ (days) - OAB pipeline selected light curves



INT: $P_{lomb}(R)$ - OAB pipeline selected light curves



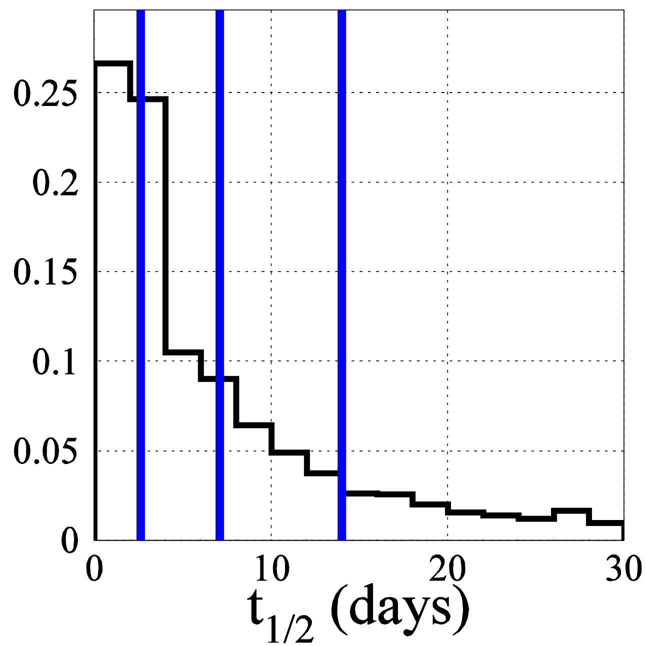
INT: $P_{lomb}(R)$ - random light curves

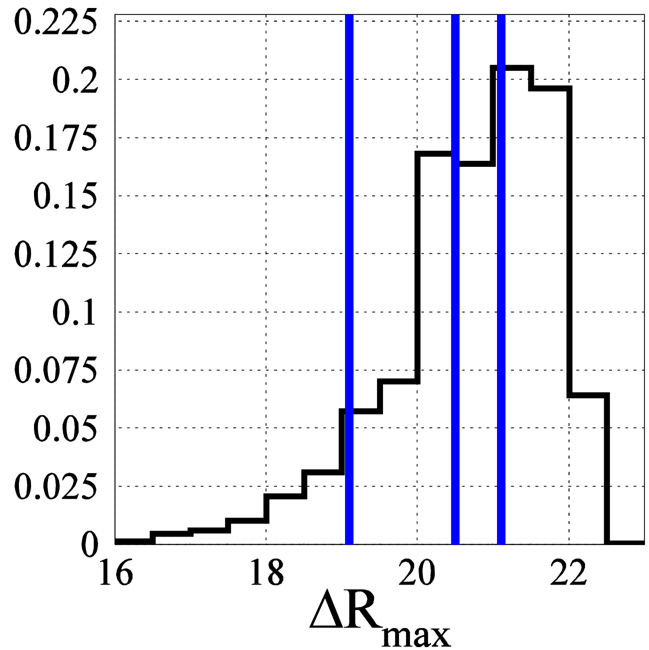
Results: the microlensing candidates

Name	$t_{\frac{1}{2}}(d)$	ΔR_{max}	$R-I$	$\Delta M31\ (')$
OAB-07-N1	7.1	21.1	1.0	7.1
OAB-07-N2	2.6	19.1	1.1	2.8
OAB-10-S3/ Pand-4(*)	14	20.5	0.3	5.9

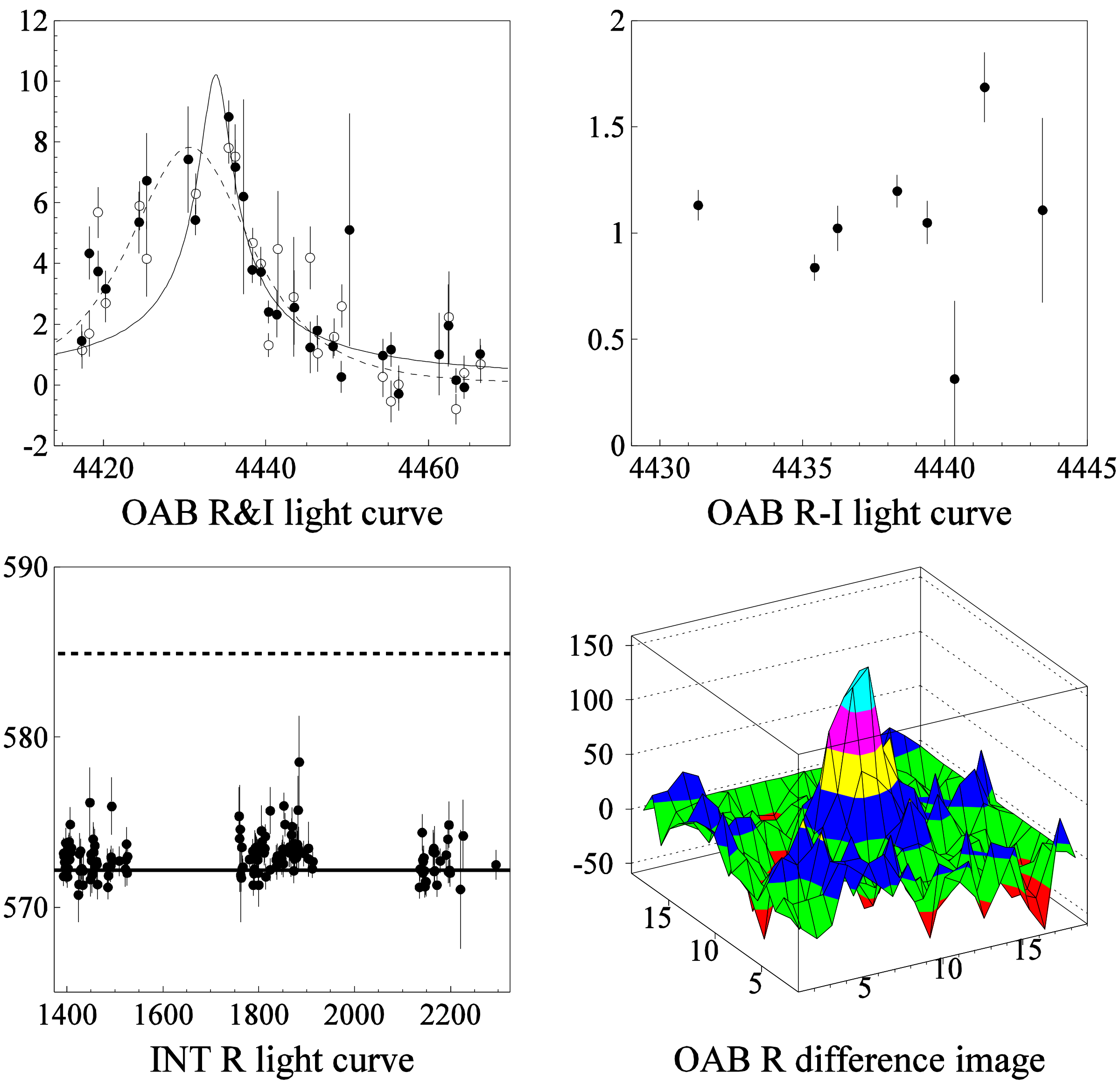
(*) Lee et al, AJ 2012, The PANDROMEDA PS1 campaign

The observed lensing parameters match well the expected ones



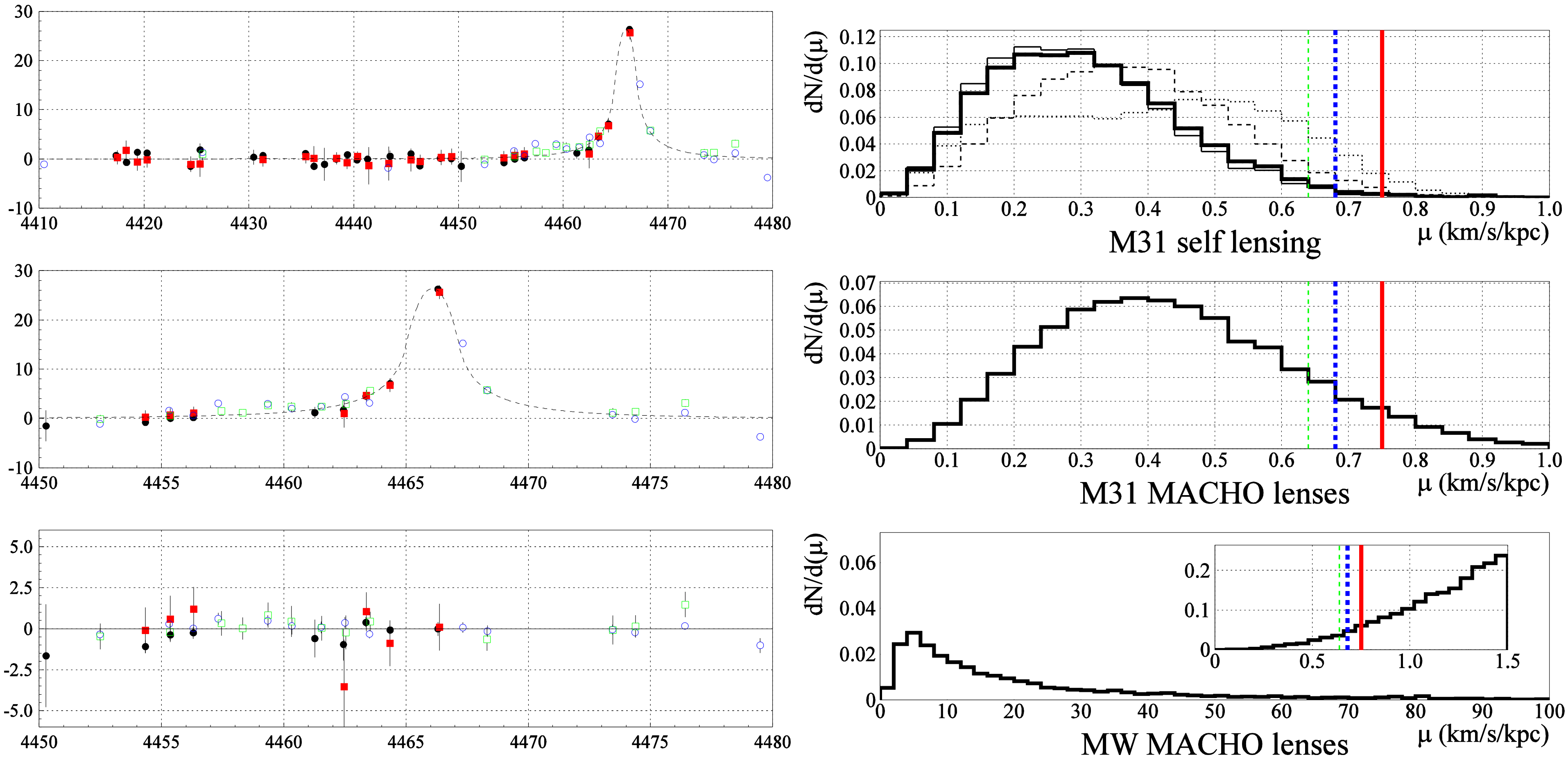


OAB-N1 microlensing candidate

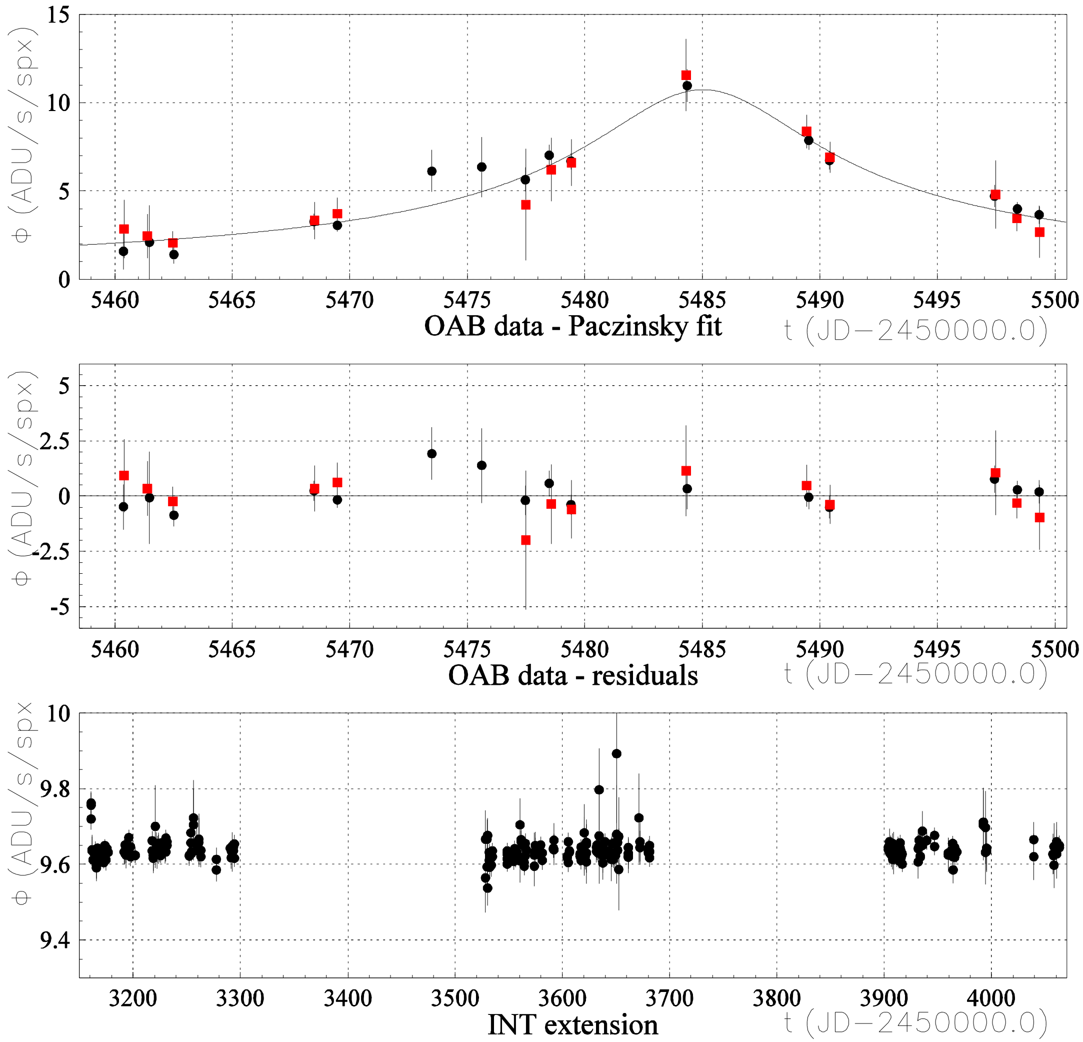


OAB-N2 microlensing candidate

- sampling nicely completed by WeCAPP data: microlensing nature confirmed
- *lens proper motion* analysis: the lens is more likely to be attributed to a MACHO



OAB-S3 / PAnd-4 microlensing candidate



The expected signal (vs $n_{obs} = 3$)

- Self lensing: **3 events** (a rather *fat* M31 bulge)
- MACHO lensing: **5 events** (full halo, 0.5 solar mass MACHOs)

(preliminary) conclusions:

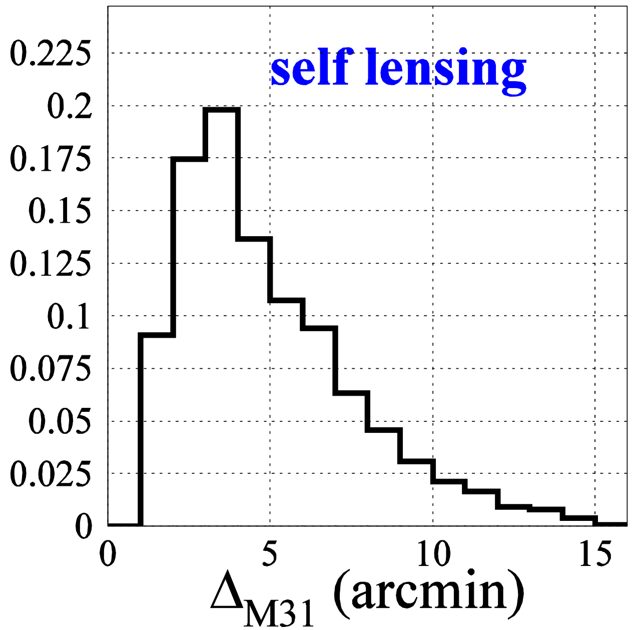
- *the observed rate matches well the expected SL one*
- *the expected MACHO lensing is relatively small compared to SL (a big difference vs the LMC/SMC case)*
    - *based on this analysis one can not draw strong conclusions on MACHO lensing*
    - *the thorough characterization of single events (MACHO or self lensing ?) becomes essential*

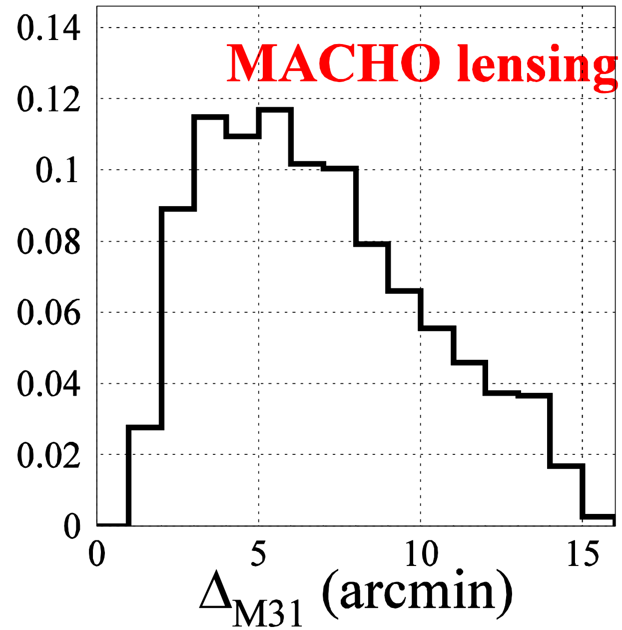
MACHO or self lensing ?

$t_{1/2}$ and $\Delta\phi_{max}$ are not useful to this purpose

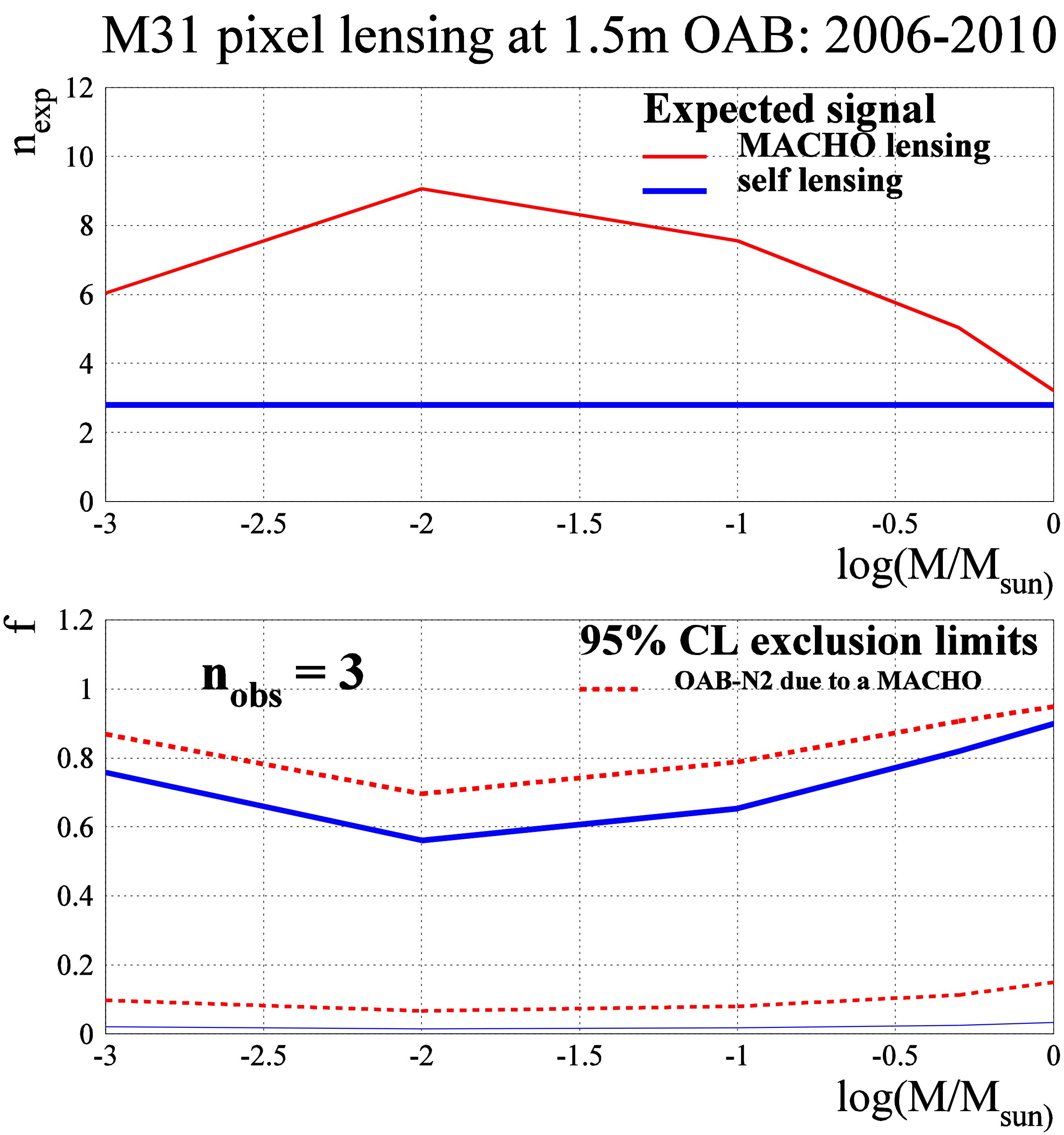
The distance from the M31 center as a useful statistics to approach this issue

An expected (2° order) effect is the asymmetry in the spatial distribution of M31 MACHO lensing – for this a larger statistics is needed and a caveat is M31 differential extinction





Likelihood analysis (2' bin in distance from the M31 center)

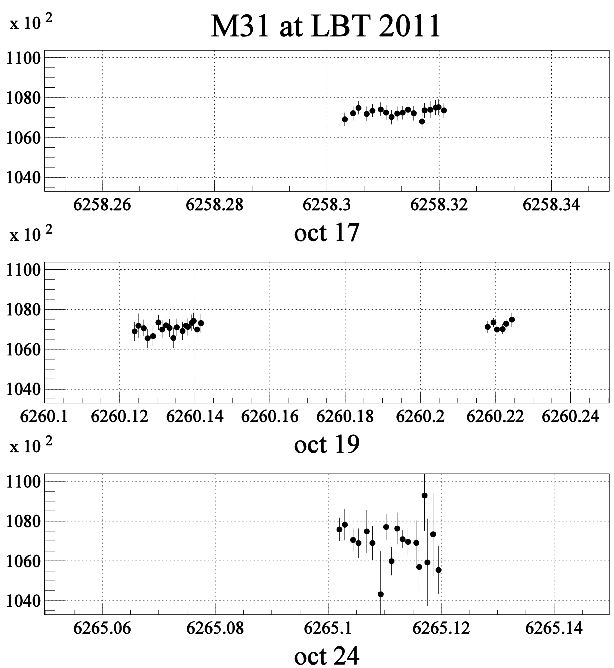


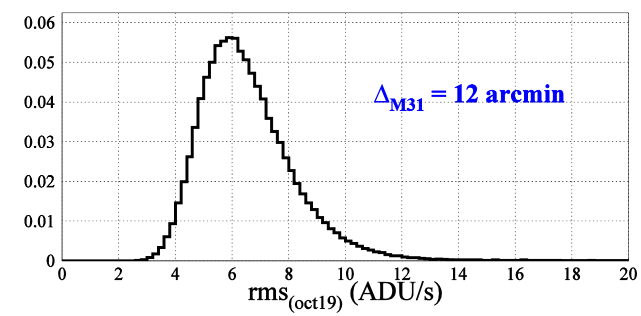
Moving beyond …… M31 pixel lensing with LBC @ LBT !!

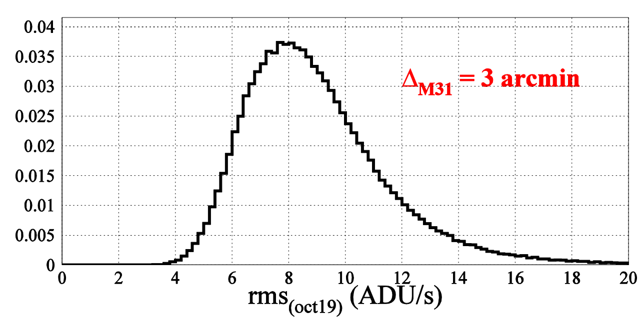
The ideal experimental set up (can get to very large S/N with very short integration times)

- 8m class telescope
- Binocular (simultaneous V and R broad band observations)
- LBC: Large field of view 4x (7.8’ x 17.6’): 23’ x 25’
- LBC: Pixel scale: 0.2255’’/pixel with typical seeing below 1’’

3 epochs pilot campaign on OSURC time (A.Gould, SCN)
on October 2011 (15 minutes integrated exposure time / night):
at glance, the results are very encouraging…. let’s hope for new data!!!







$ZP = 28$

Sensitivity down to
$\Delta R_{max} \gtrsim 24$
for $t_{exp} = 60\ sec$

SUMMARY

- Microlensing as a tool to look for dark matter in form of MACHOs
- The expected signal: the case for M31 pixel lensing
- The PLAN M31 pixel lensing observational campaign at OAB
  - Selection pipeline: 3 candidate microlensing events
  - The observed rate matches well the expected SL signal
  - Expected MACHO lensing signal «small» with respect to SL
  - Complementary information suggest OAB-N2 due to MACHO lensing
- M31 pixel lensing at LBT: the 2011 pilot campaign