Search for intermediate mass black holes as dark matter using gravitational microlensing

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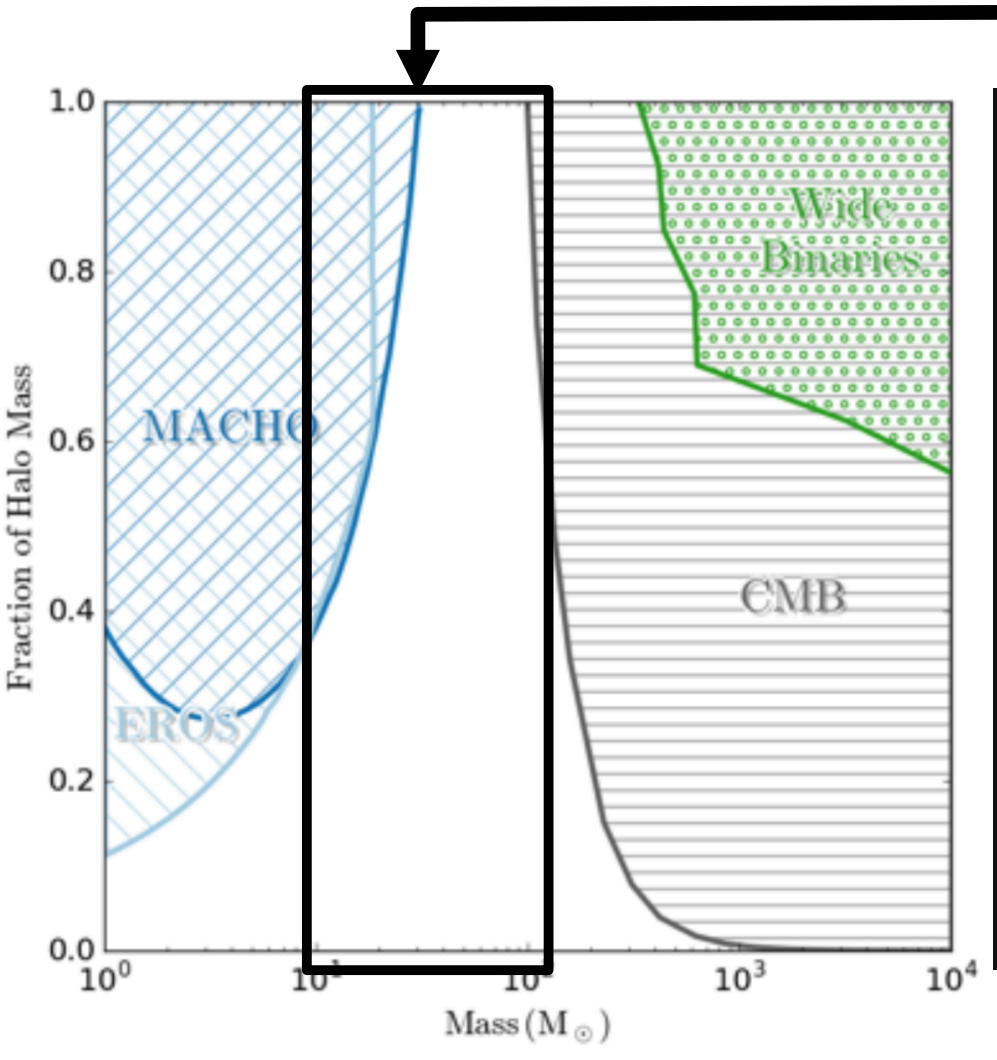
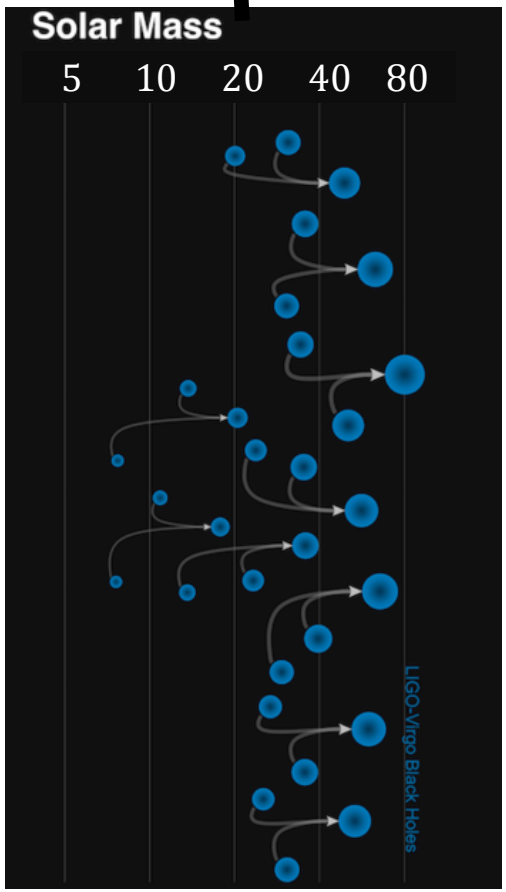
IJCLab, IN2P3, CNRS

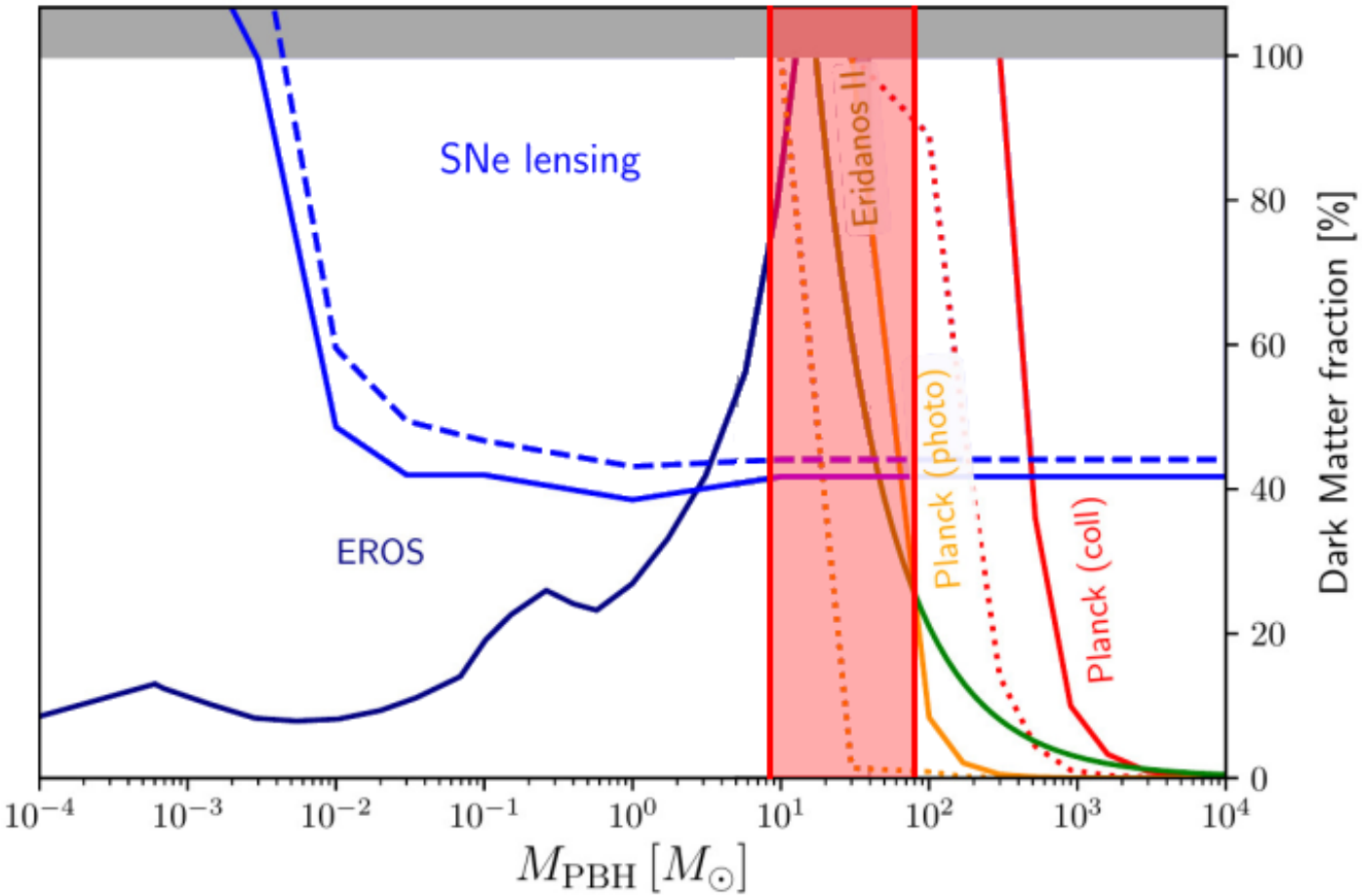
LSST France, February 5th, 2020





LIGO/Virgo Black holes

Constraints weaken between ~ 10 and $\sim 100 M_\odot$.
Coincidentally LIGO/Virgo discovered black holes in this mass range.



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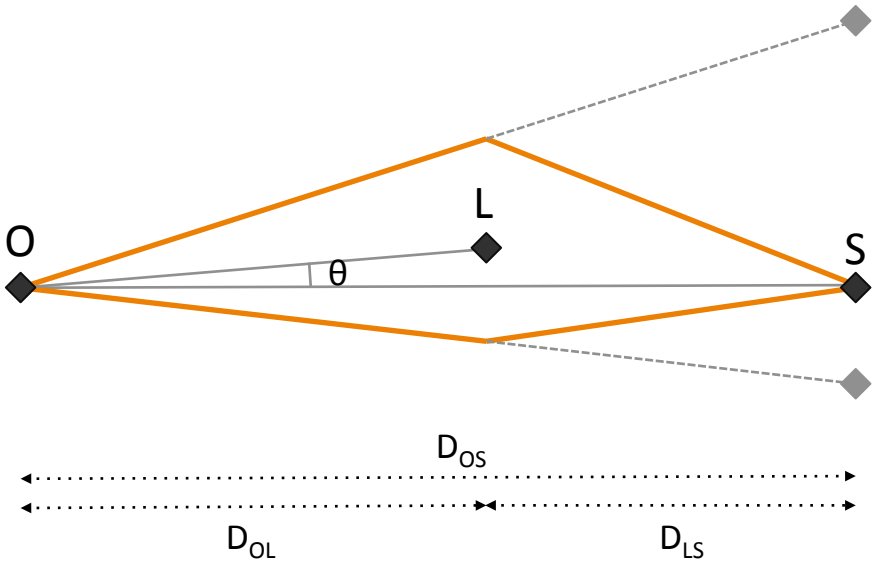
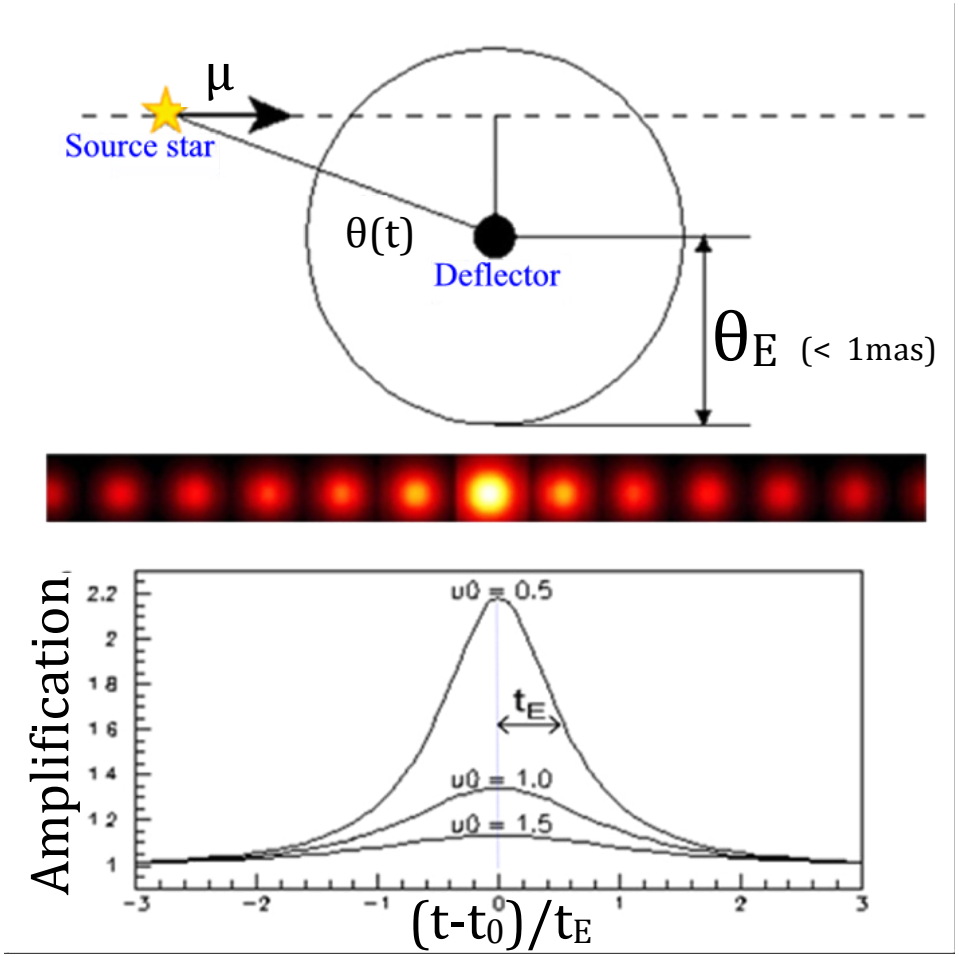
Coincidentally LIGO/Virgo discovered black holes in this mass range.
Great interest in exploring this mass interval since those discoveries.

Microlensing : gravitational lensing but only the **magnification** is significant.

The magnification depends on the normalized distance $u(t) = \frac{\theta(t)}{\theta_E}$ between the source and the lens and is **time-dependent**.

The Einstein time is the characteristic time : $t_E = \frac{\theta_E}{\mu} \propto \sqrt{M_L}$
(μ is the relative angular speed between the source and the lens).





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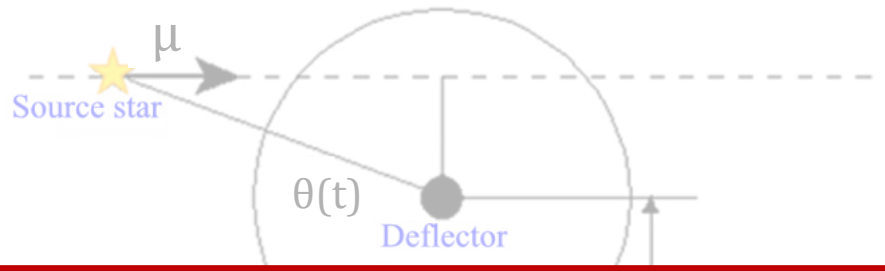
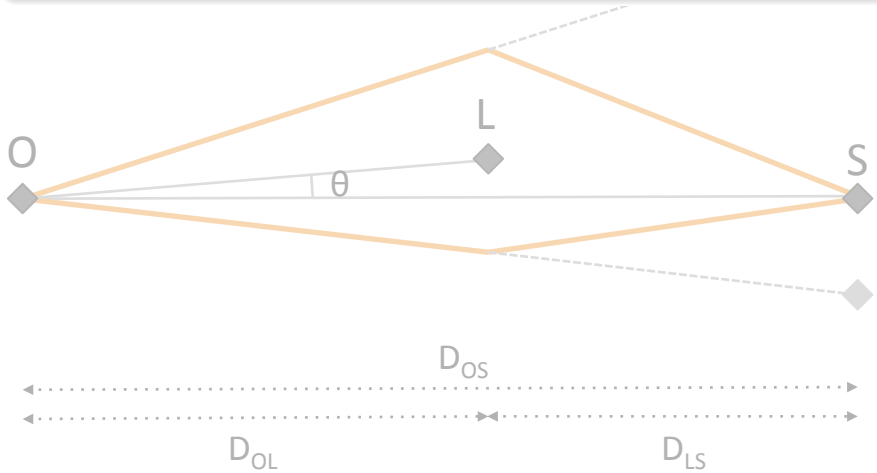
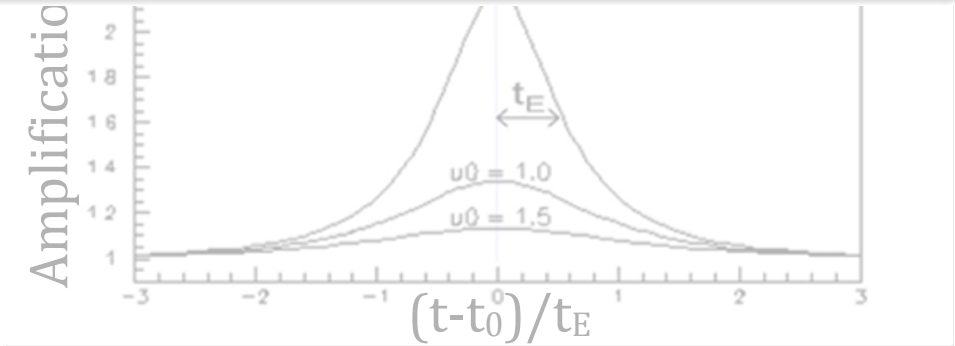


Important

Standard microlensing event light curves are **symmetric** and **achromatic**.
Microlensing events are **rare** (< 1 evt/10^6 stars toward LMC for halo compact objects).
$t_E \propto \sqrt{M_L} \implies$ need to monitor sources long enough.





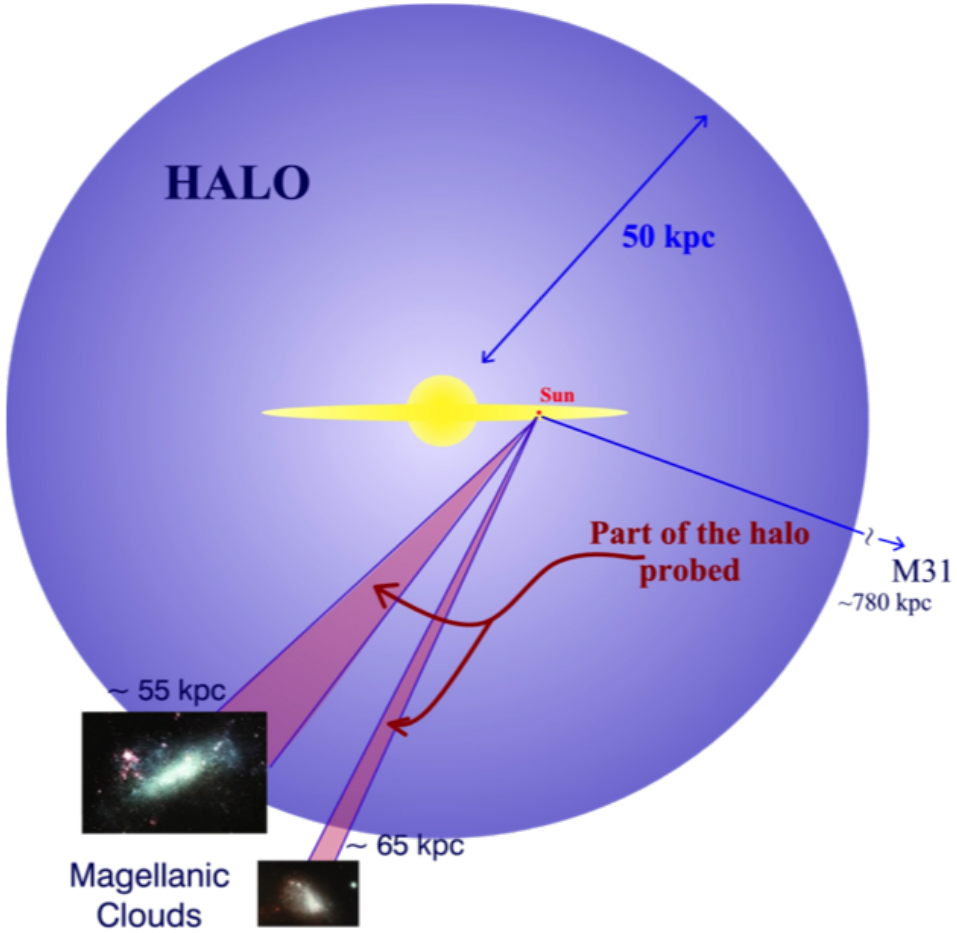
Dark matter search : How to use microlensing ?

The galactic dark matter halo could be composed of **massive compact objects**, too faint to be seen directly or invisible (free floating exoplanets, brown dwarves, black holes, accreted non-baryonic particles...).

Microlensing is used to search for **lenses too faint** to be seen directly.

Monitoring of the **Magellanic Clouds** stars proposed in the end of the 1980's.

Main searches during 1990's-2000's (MACHO, EROS, OGLE, ...).



Dark matter search : Current microlensing constraints

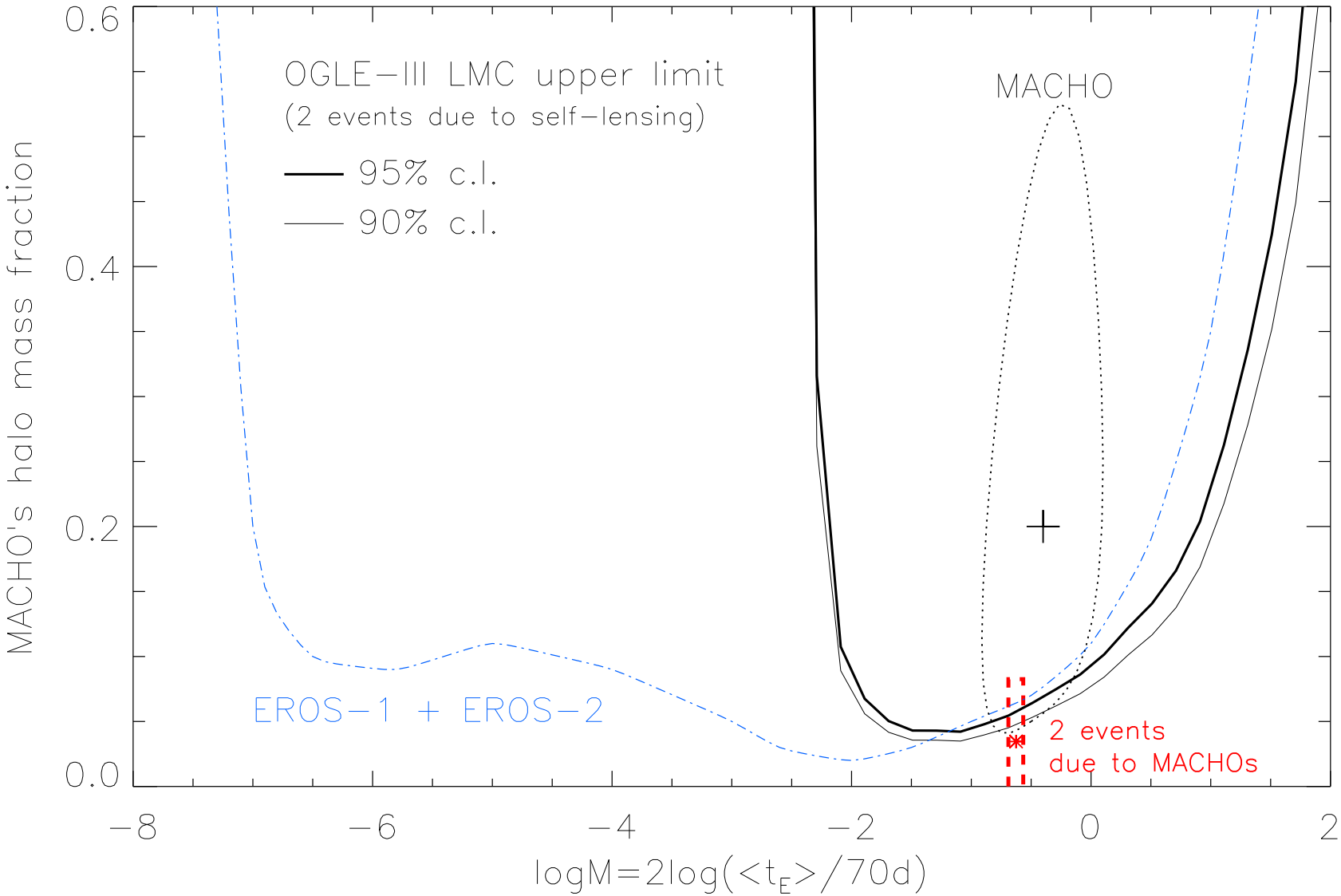
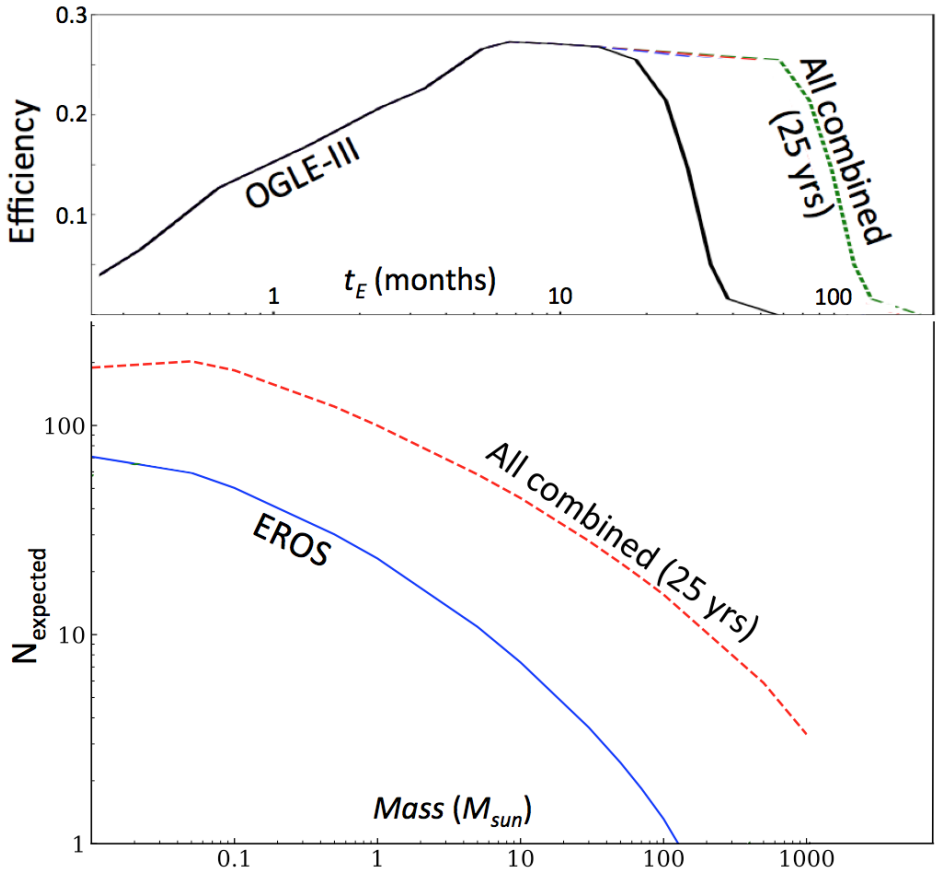


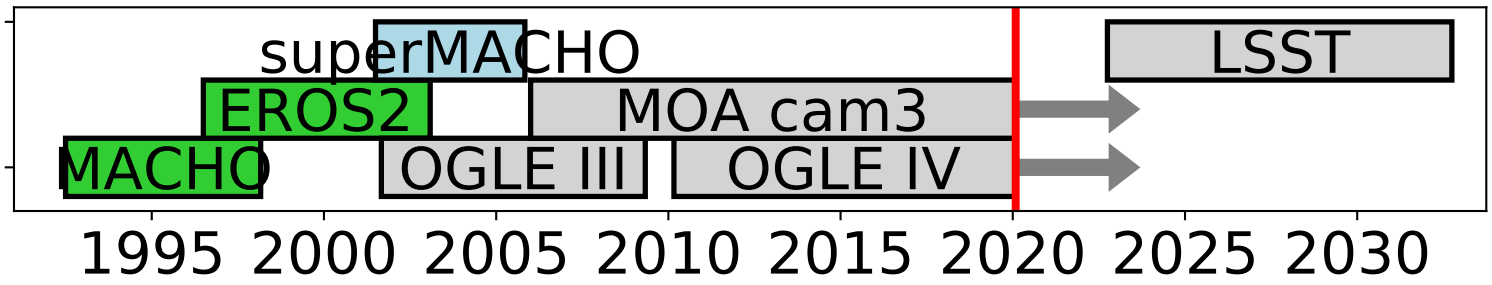
Figure from Wyrzykowski+2010



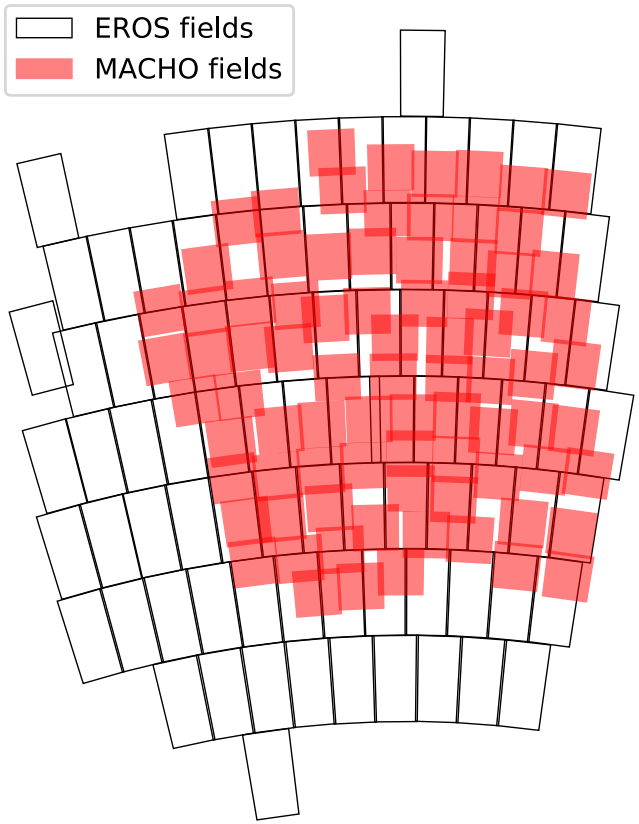
Adapted from Mirhosseini & Moniez 2018

$$\langle t_E \rangle = 70\text{d} \times \sqrt{\frac{M_L}{1 M_\odot}}$$

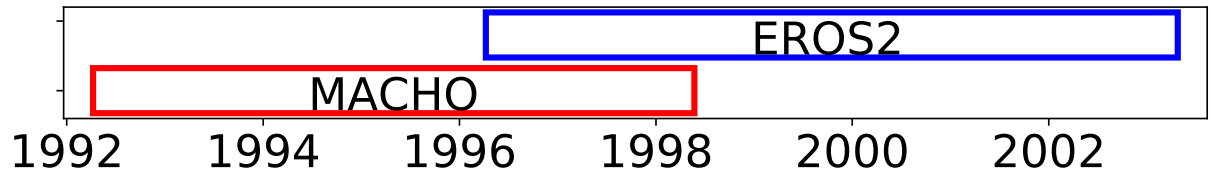
Past surveys had their efficiency limited by their duration.
We can merge them to extend the total time span.
Efficiency of merging existing catalogues has been estimated (MACHO, EROS2, OGLE-III and OGLE-IV).
Sensitivity up to $\sim$ 1000 $M_\odot$.



Catalogue merging : EROS2 and MACHO



We currently have only access to the MACHO and EROS2 databases.
Search for microlensing over **10.6 years** in a combined catalogue of **14.10^6 light curves.**
Each survey uses 2 non standard filters.
($\sim$ 1700 measures for each star, $\sim$ 700Go photometric database).
Combination using astrometry.



Survey	Dates	Duration (year)	Sky coverage (deg^2)	Number of stars ($x10^6$)
MACHO	07/92 - 01/00	5.7	40	22.3
EROS2	07/96 - 02/03	6.7	84	28.8
EROS2+MACHO	**07/92 - 02/03**	**10.6**	**$\sim$40**	**$\sim$14**

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7 parameters to fit :

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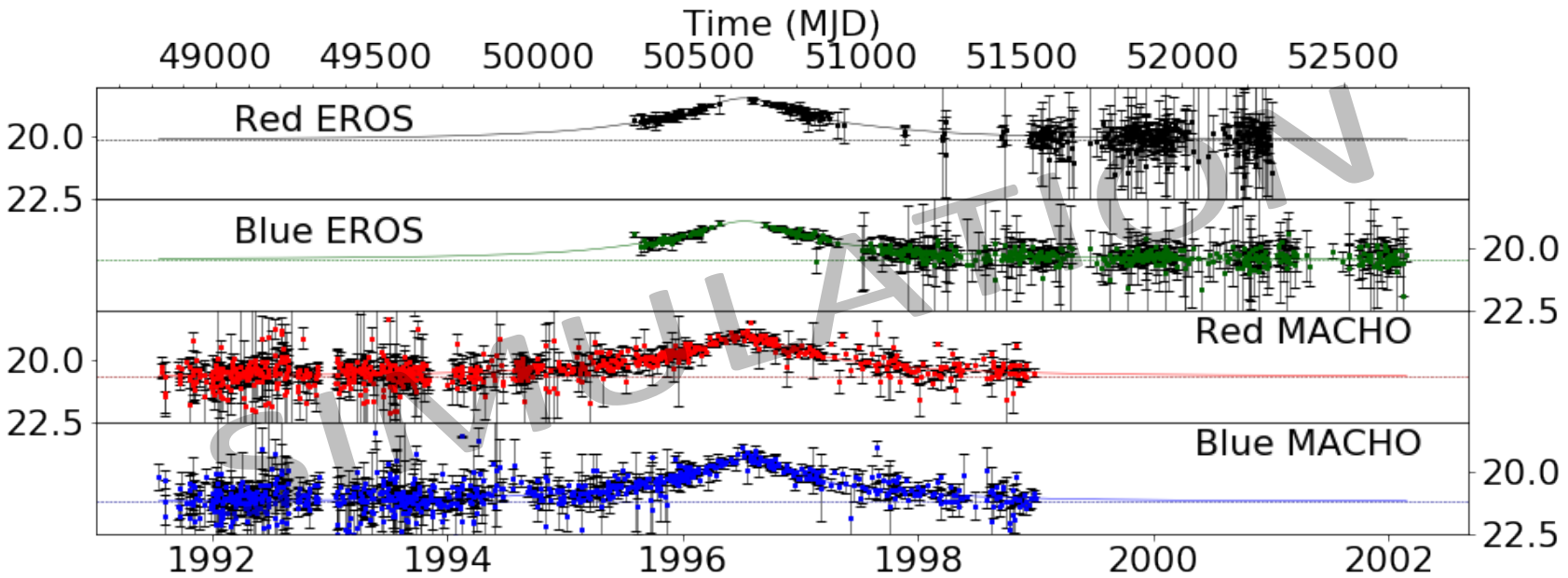
- 4 flux parameters for the source, one for each filter color.



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The fit improvement is quantified by :

$$\Delta\chi^2 = \frac{\chi^2_{\text{flat}} - \chi^2_{\text{ml}}}{\chi^2_{\text{ml}}/N_{\text{dof}}} \frac{1}{\sqrt{2N_{\text{dof}}}}$$

Preliminary analysis : Event selection

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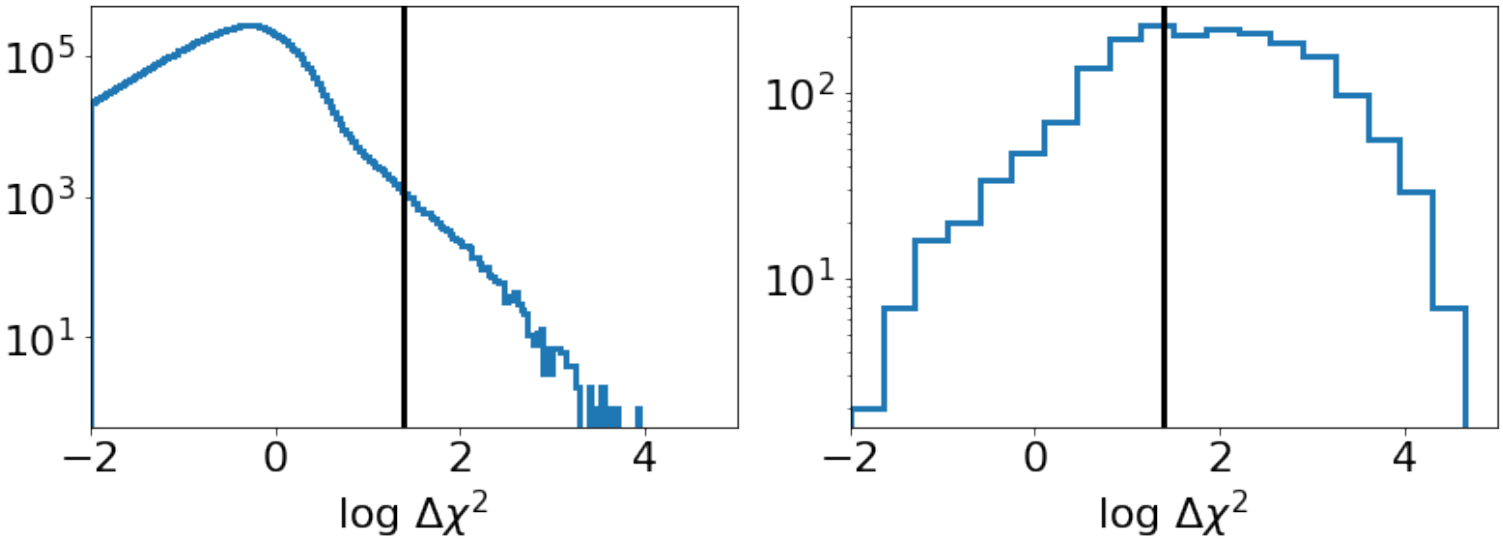
- Improvement between microlens fit and flat fit $\Delta\chi^2 > 25$ (black line)



(a) Real data

(b) Simulated microlensing light curves

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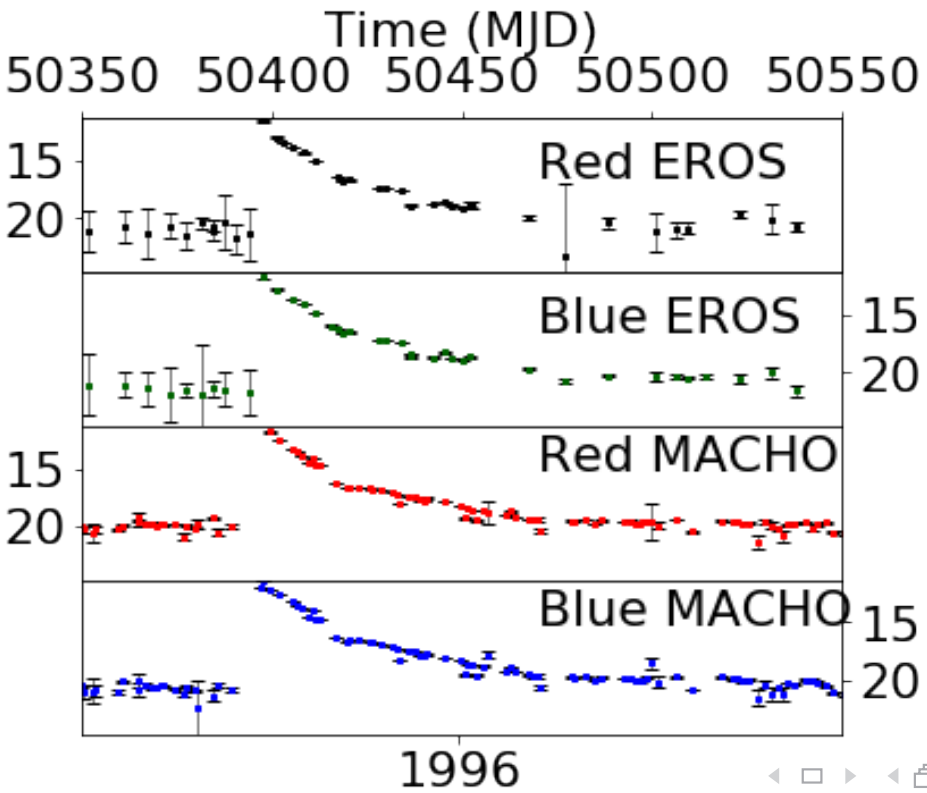
Preliminary analysis : Known genuine transients

Similar variabilities already identified:

- Supernovae : Short and systematically asymmetric variations (no specific cut yet).



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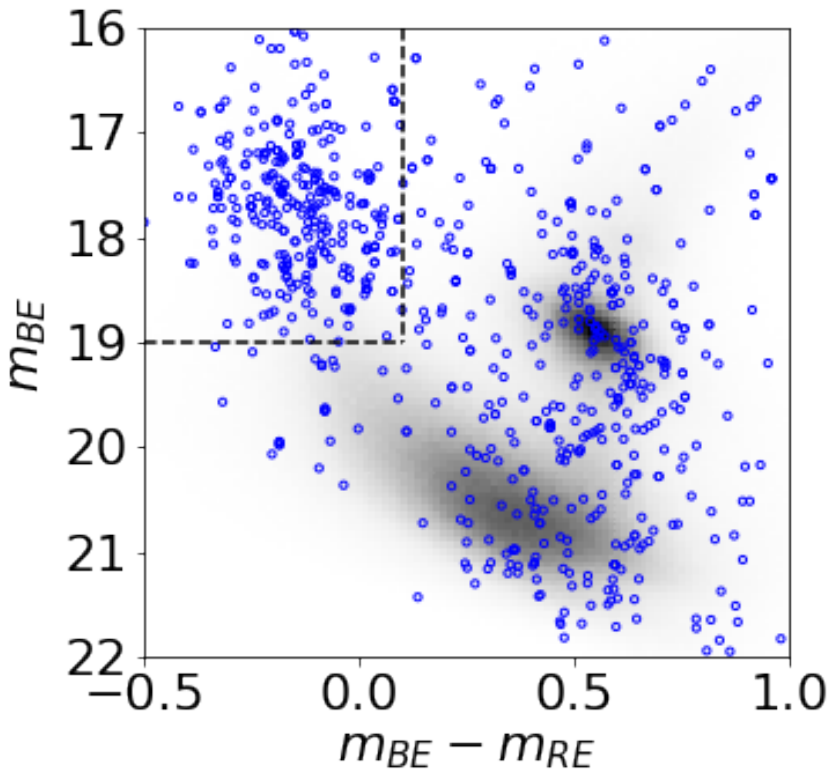

Color-magnitude diagram (grey scale).
Dots are light curves that pass all cuts (except SN1987A echoes).
Microlensing is independent of the source => the candidate col-mag distribution should follow the source distribution.
Overdensity of candidates in the blue end of the main sequence.

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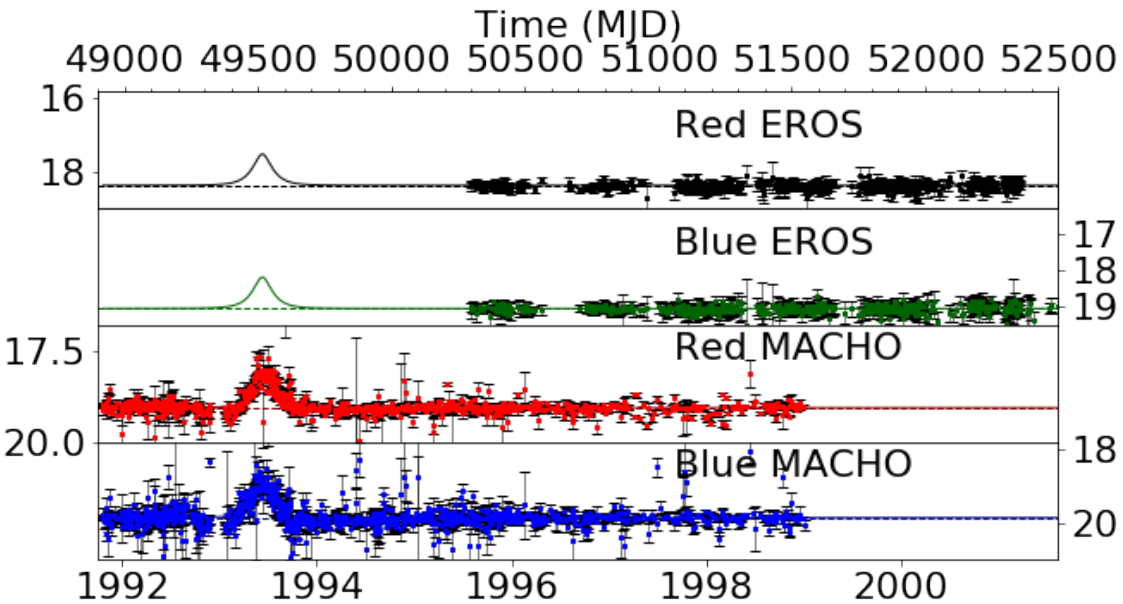
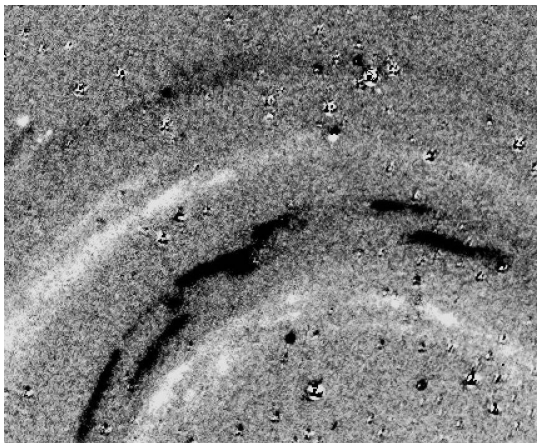
- Blue bumpers : light curves from stars in particular zone of the color-magnitude diagram looking like short duration microlensing events. Discovered in the first microlensing searches.
- SN1987A echoes : light from SN1987A diffused by dust clouds mimicking microlensing light curves. Removed by spatial exclusion around SN1987A ($0.15^\circ \times 0.15^\circ$).





Difference of 2 EROS images taken 5 years apart.

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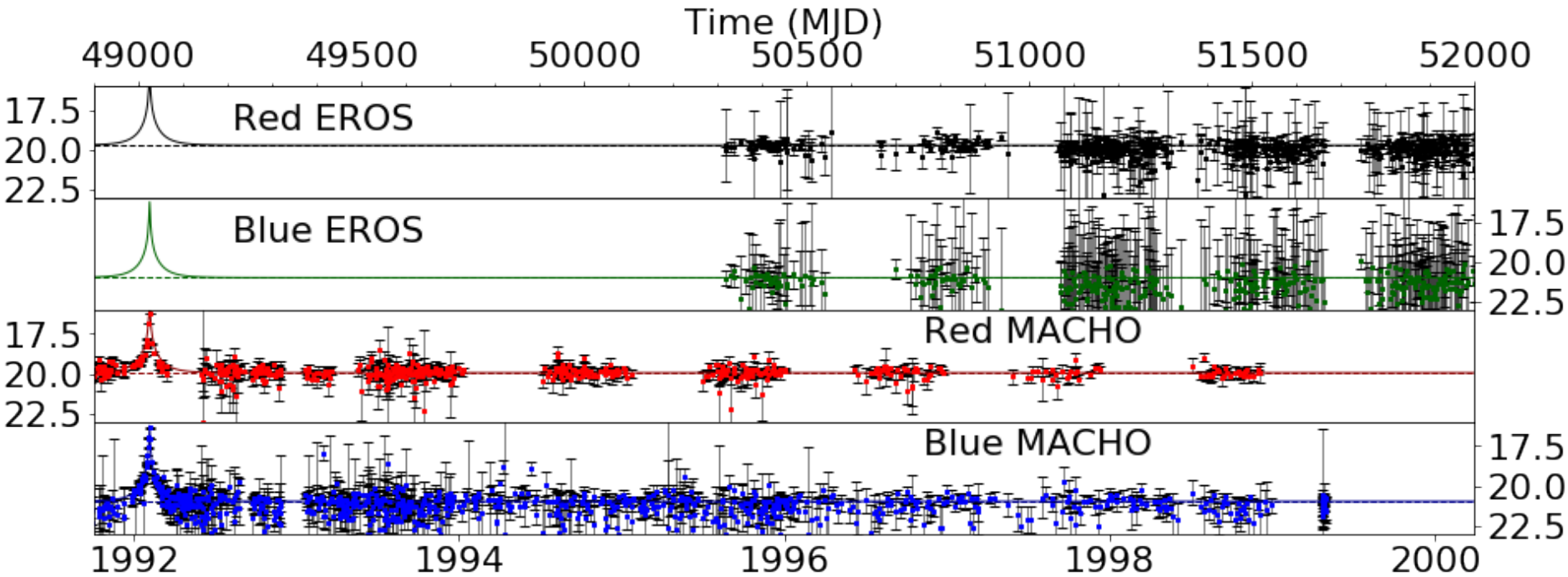
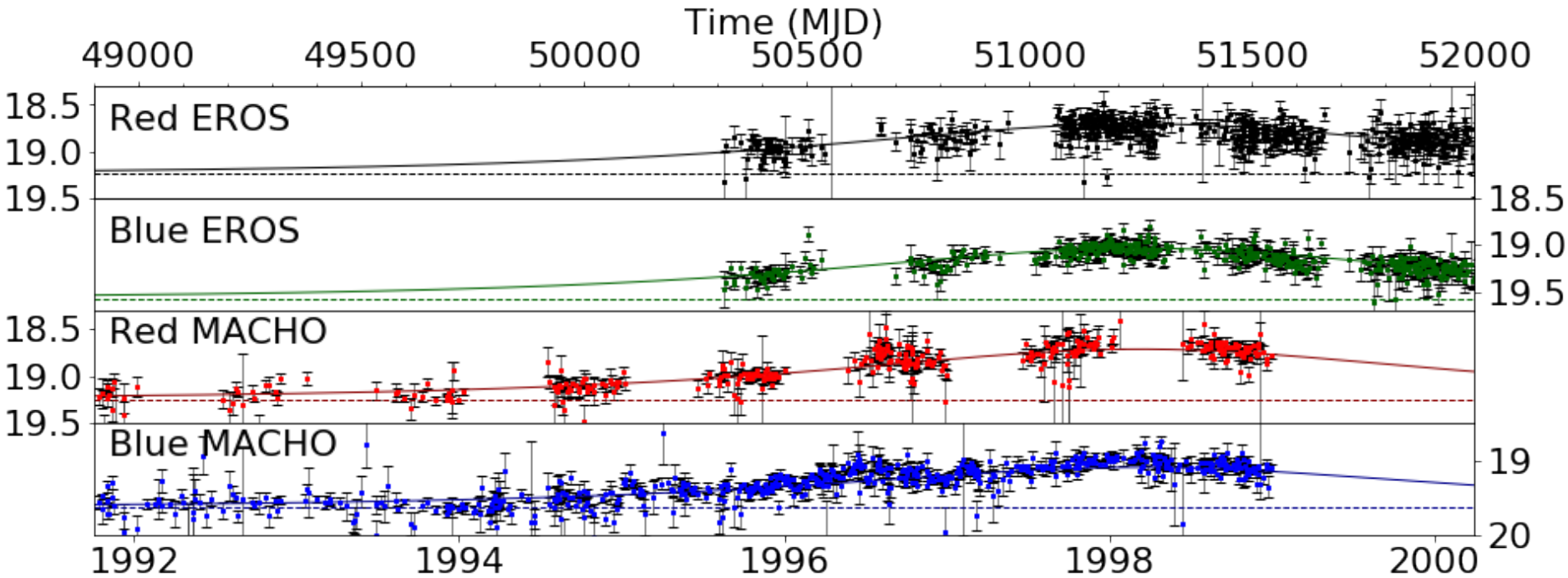
472 light curves remain.

We find again all the past candidates that have been published with light curves in both EROS2 and MACHO catalogues (8 events).



Focus on long time scale search : $t_E > 50$ days.

- AGNs identified by cross-match with CDS. Show structured variations. (concerns around 25 light curves)



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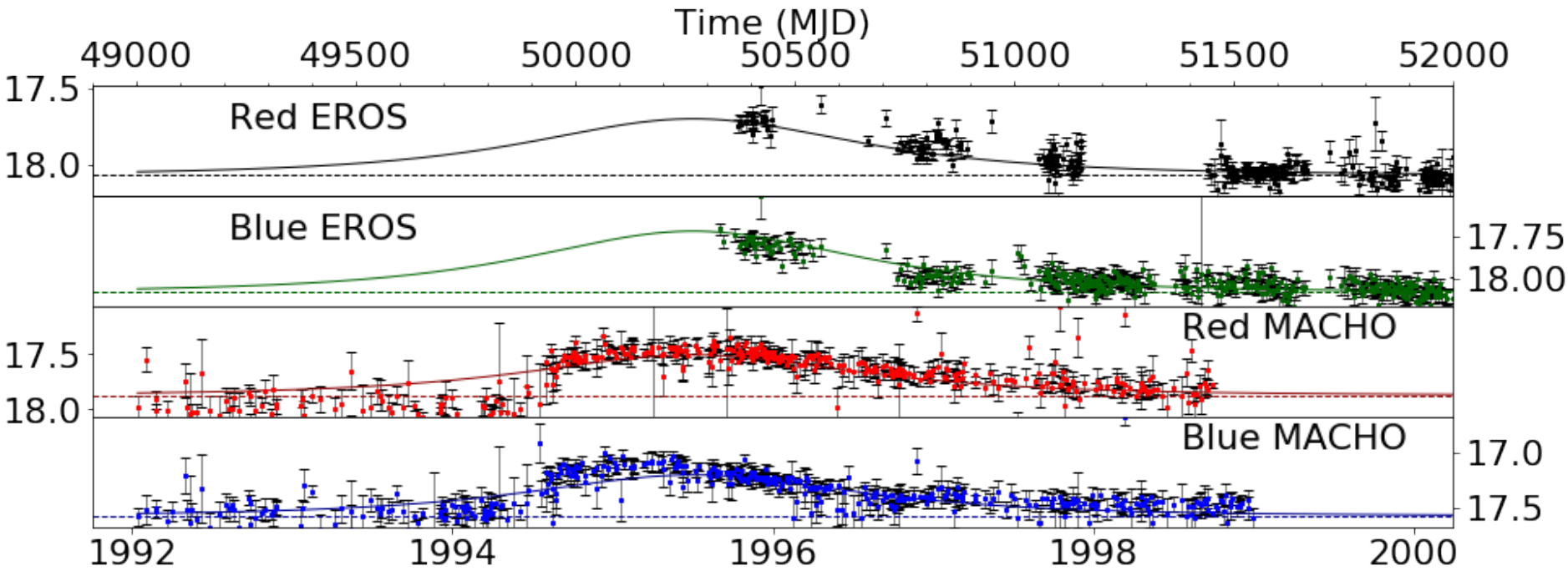
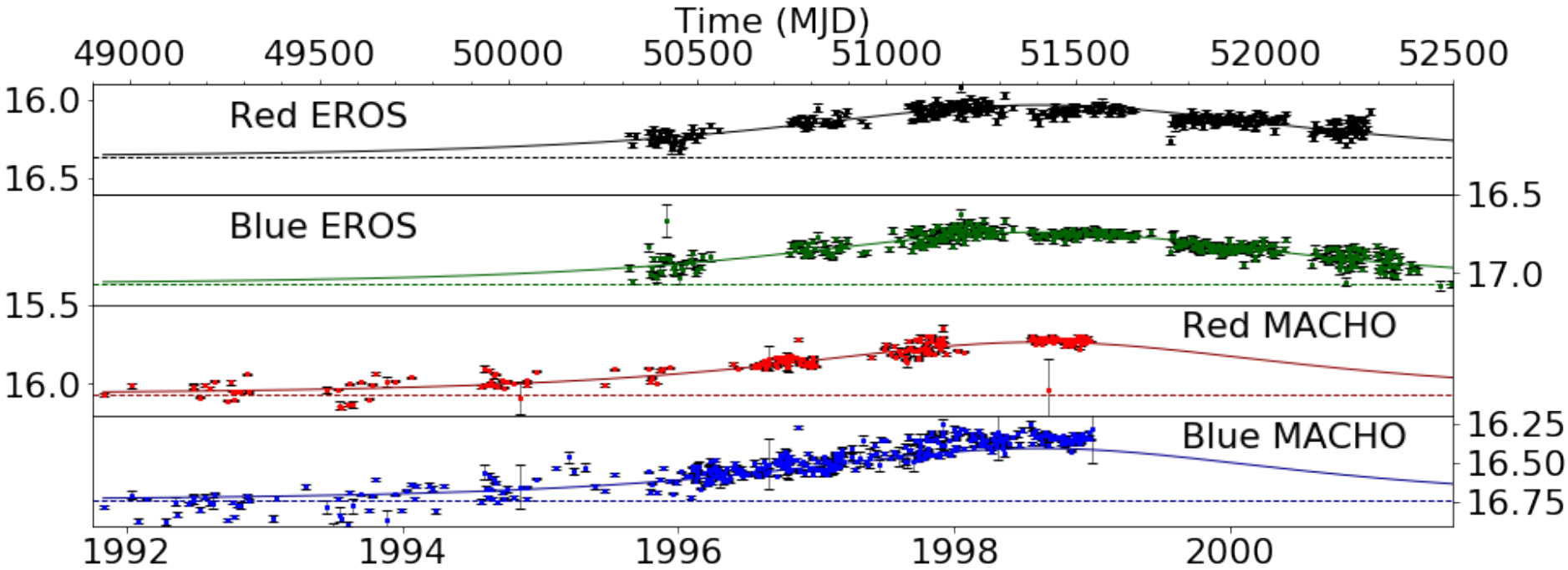
- Group of curves exhibiting the same behaviour : quickly increasing-slowly decreasing light curves, on several years (more than a dozen events).



No obvious microlens event

No obvious microlens event so I show you what approaches the most



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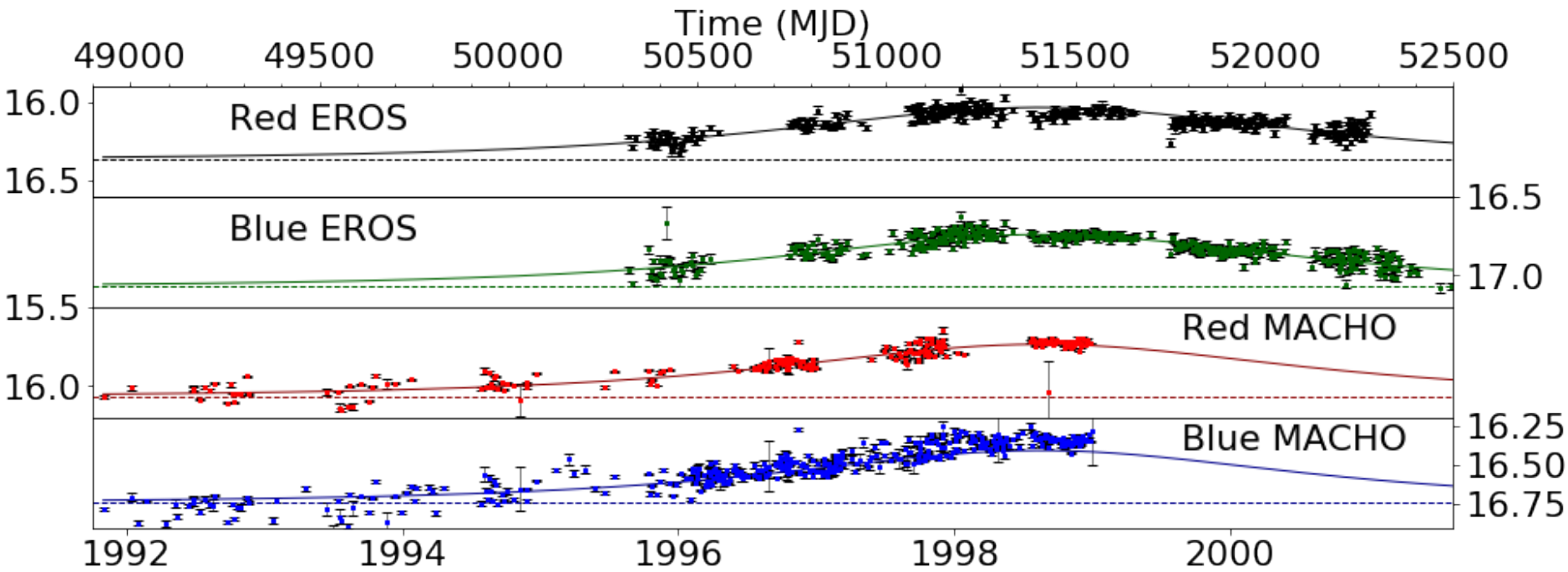

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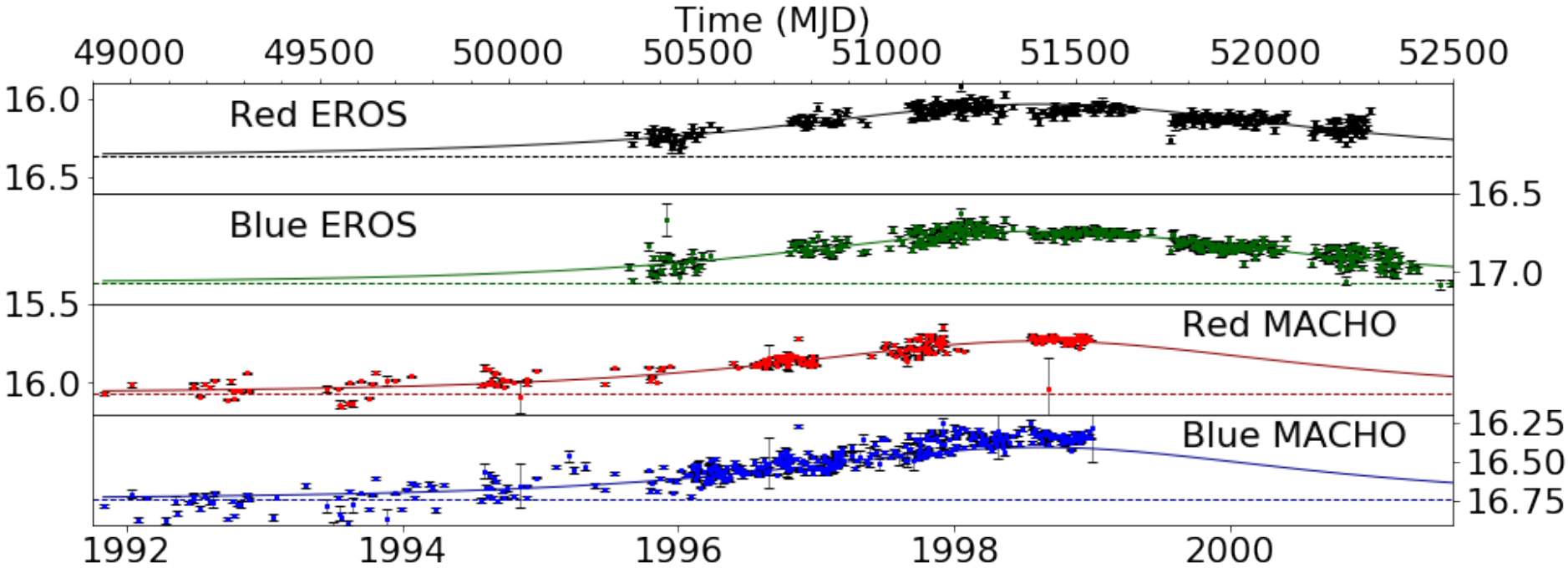

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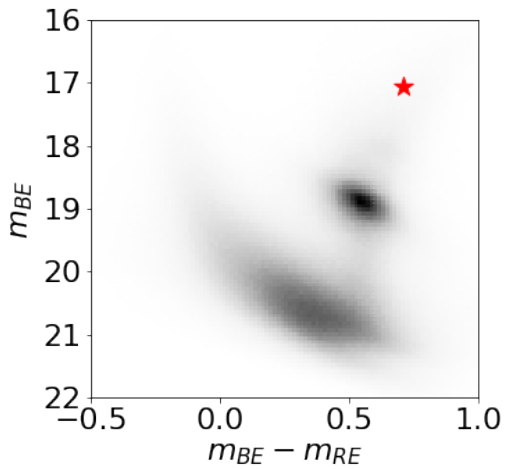
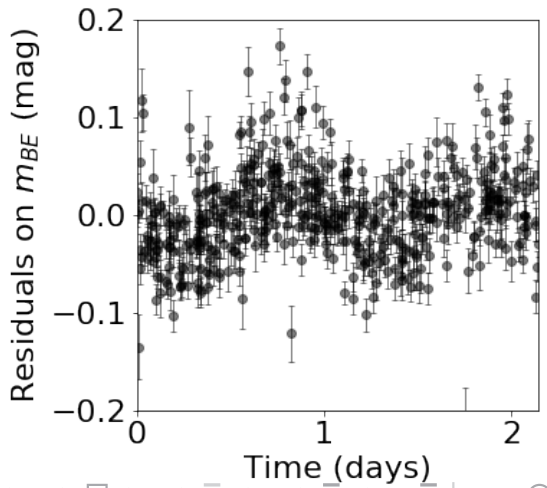
Doubtful : short periodicity of 1.07 days.

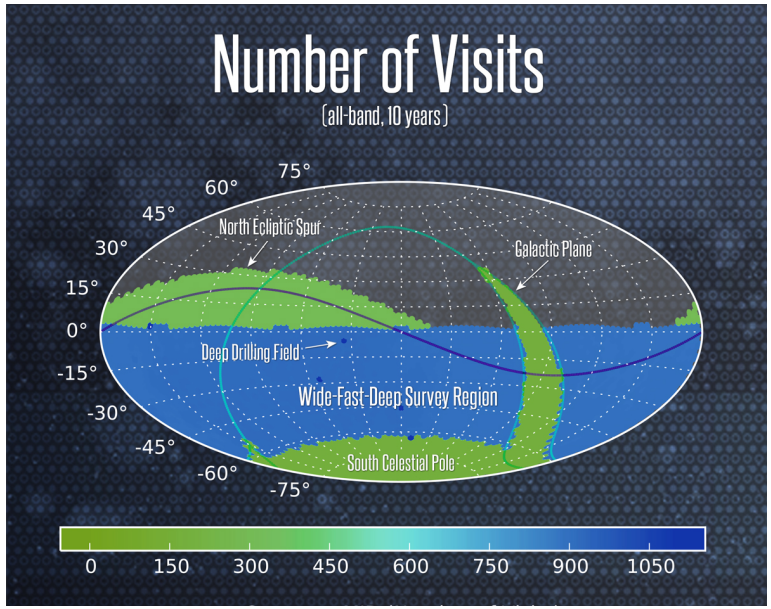




- 10 years duration, several filters, excellent photometric precision (10 times better than EROS2 or MACHO), $O(10^8)$ stars toward Milky Way and Magellanic Clouds. Simulations needed to assess its potential for long timescale microlensing $\rightarrow$ thesis chapter.

Lens type	**Past** per decade per deg^2	**Present** per decade per deg^2	**LSST** per decade per deg^2	**LSST** per decade **over 150** deg^2
M dwarfs	2.2	46	920	1.4×10^5
L dwarfs	0.051	1.1	22	3200
T dwarfs	0.36	7.6	150	2.3×10^4
WDs	0.4	8.6	170	2.6×10^4
NSs	0.3	6.1	122	1.8×10^4
BHs	0.018	0.38	7.7	1200

(a) Estimated microlens event rate toward Galactic Bulge (from LSST white paper).



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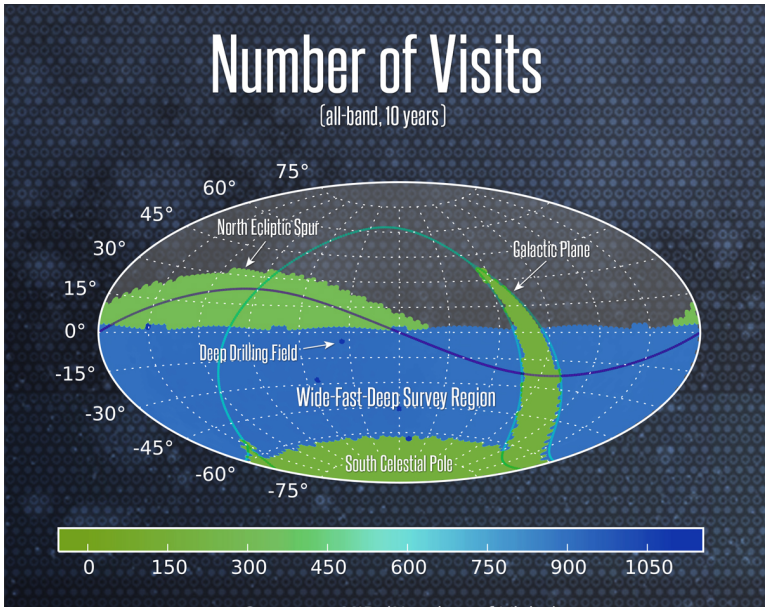

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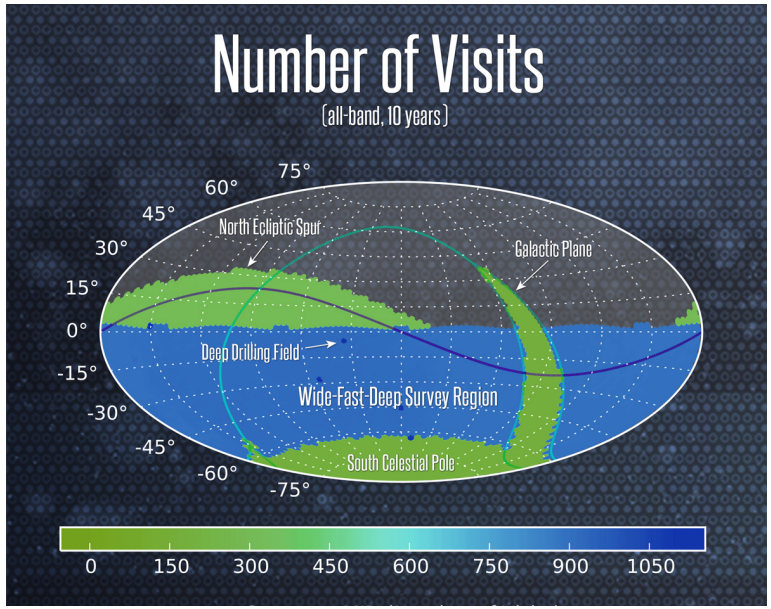

- More complex effects to take into account : parallax[1], blending...
- Shorter events and exoplanet search → broker Fink.

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Conclusion and perspectives

What has been done:

- Merging of EROS2 and MACHO surveys
- A preliminary analysis has been conducted : no obvious candidate found

What comes next :

- Exclusion analysis : efficiency estimate, dark matter distribution modeling...
- *Opportunity of reprocessing the images with modern methods (differential photometry).*
- *Aggregate more data (superMACHO, OGLE, MOA... -> LSST)*
- Simulation of LSST efficiency for this type of search.
- Microlensing alerts for the Fink broker.

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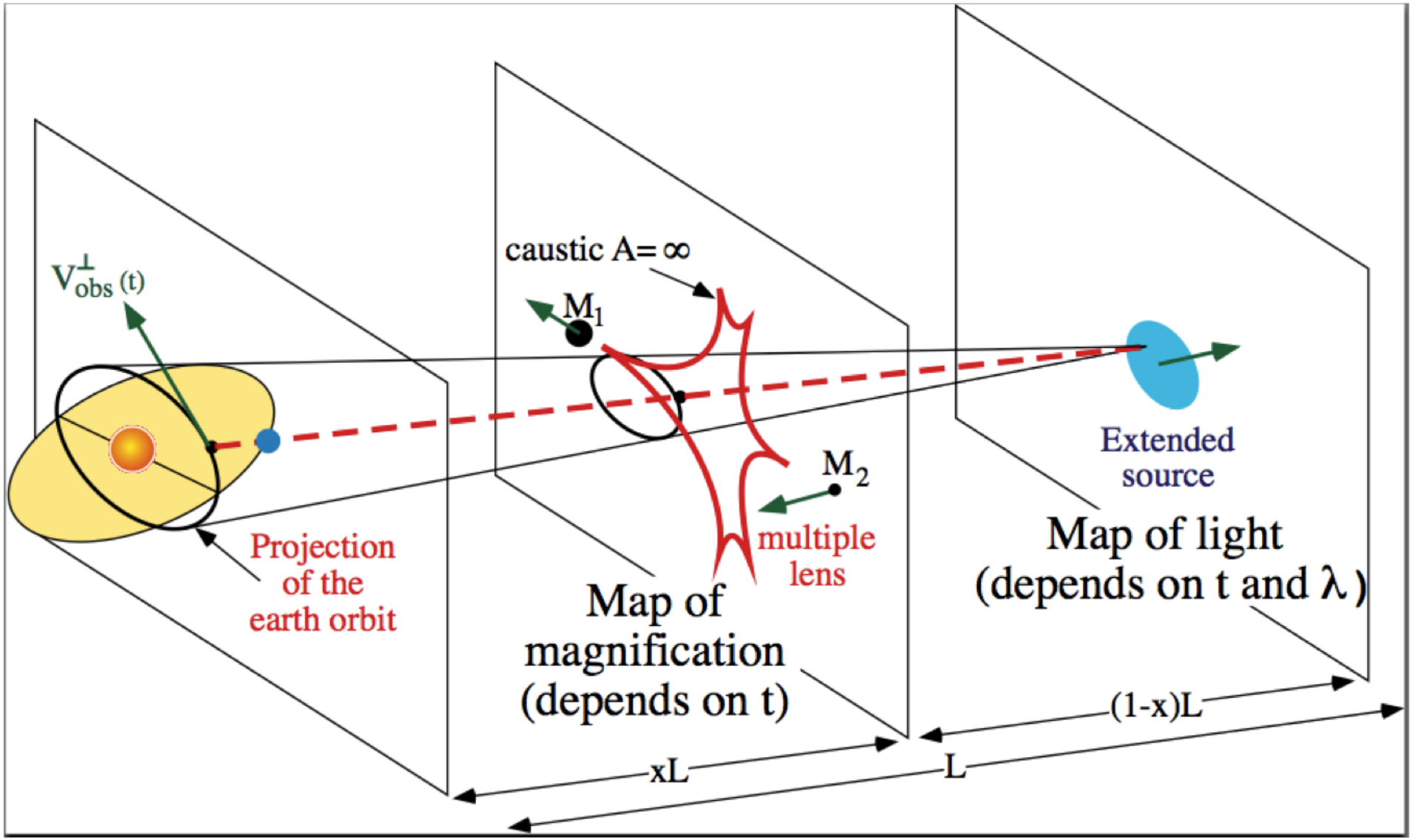
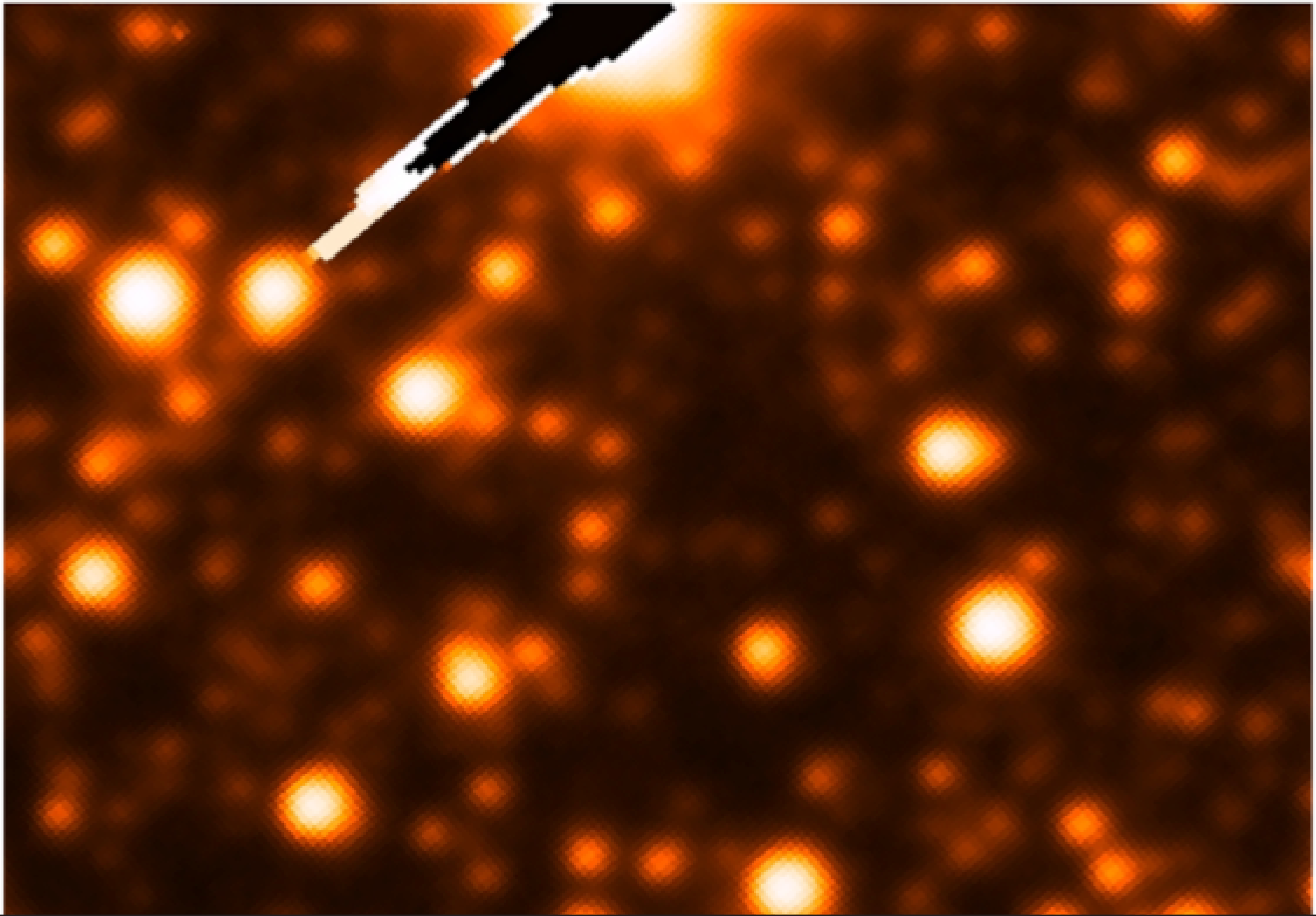
Thanks for your attention !

Backup

Other effects



Blending



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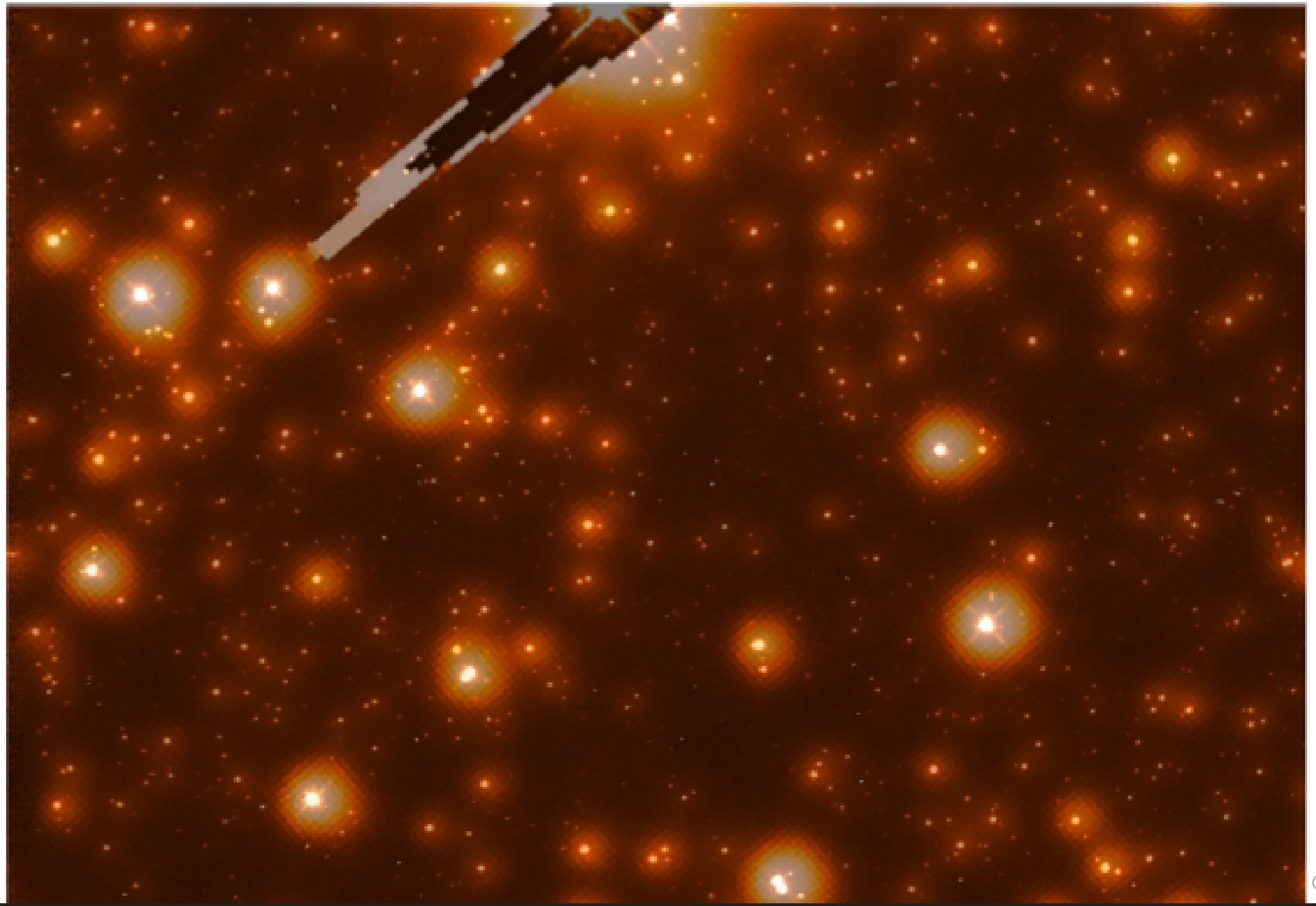
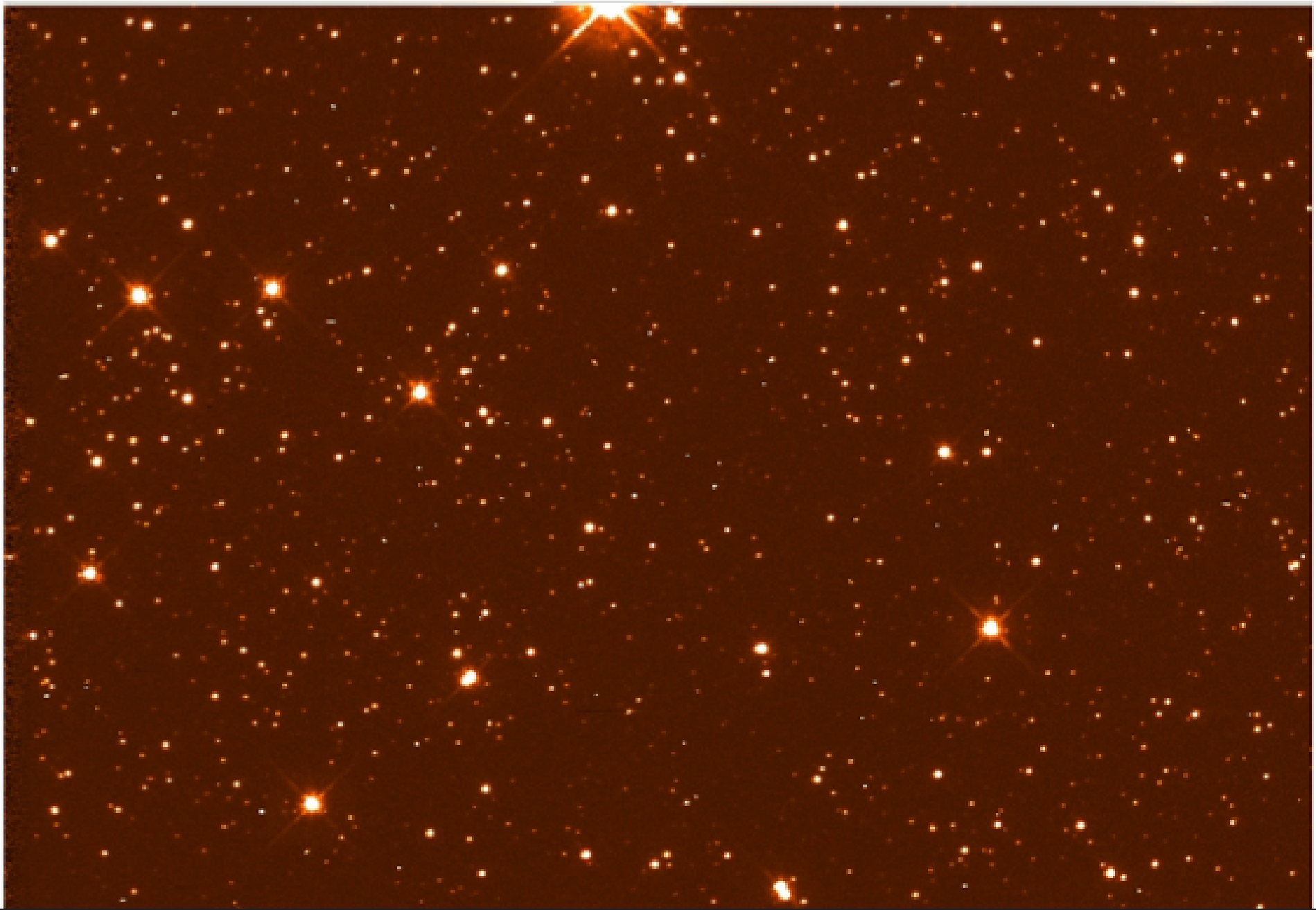
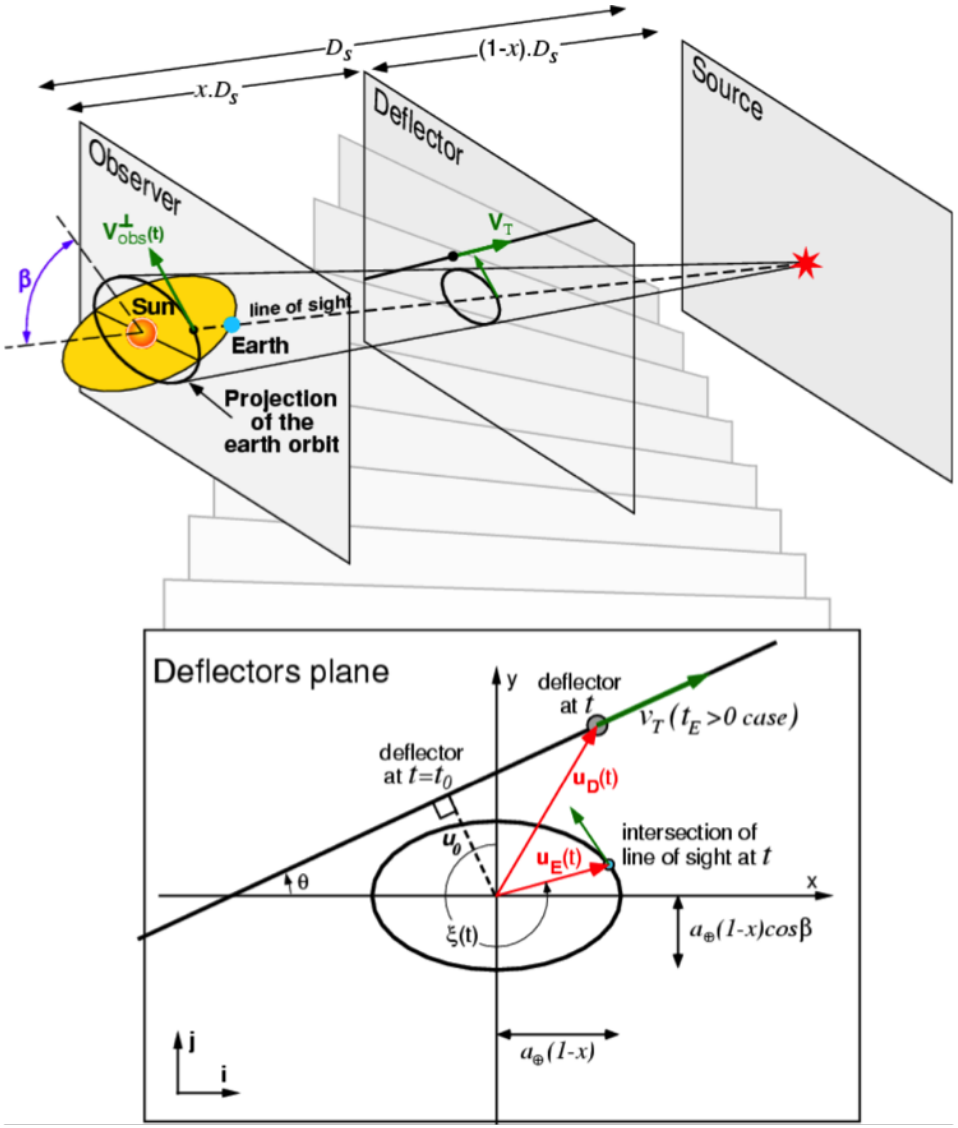
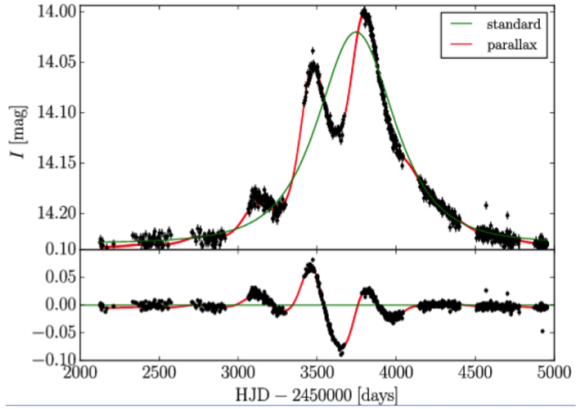


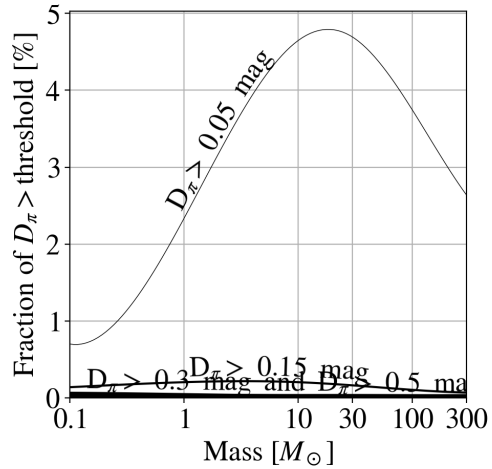
Blending

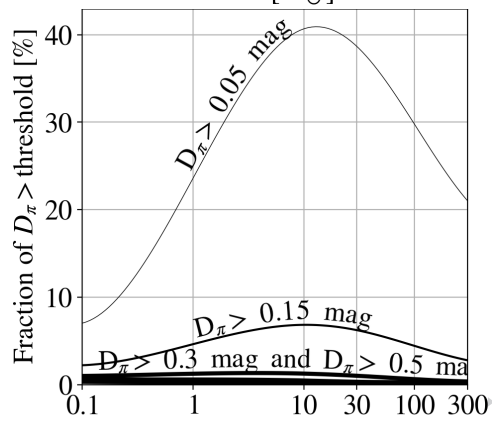


Parallax

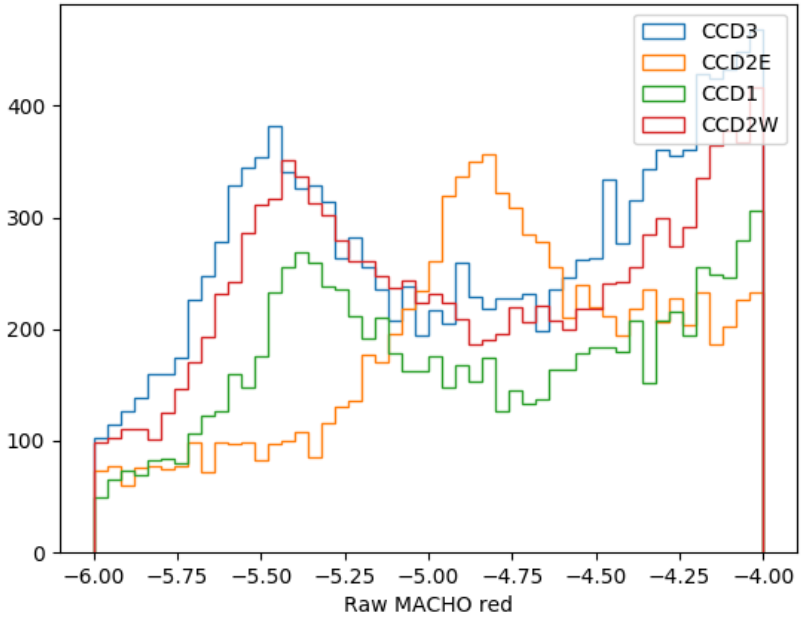

D_S
$x.D_S$
$(1-x).D_S$
Observer
Deflector
Source
$V^{\perp}_{obs}(t)$
V_T
β
Sun
line of sight
Earth
Projection of the earth orbit
Deflectors plane
y
deflector at t
$v_T\,(t_E>0\ case)$
deflector at $t=t_0$
$u_D(t)$
u_0
$u_E(t)$
intersection of line of sight at t
θ
x
$\xi(t)$
$a_\oplus(1-x)cos\beta$
$a_\oplus(1-x)$
j
i

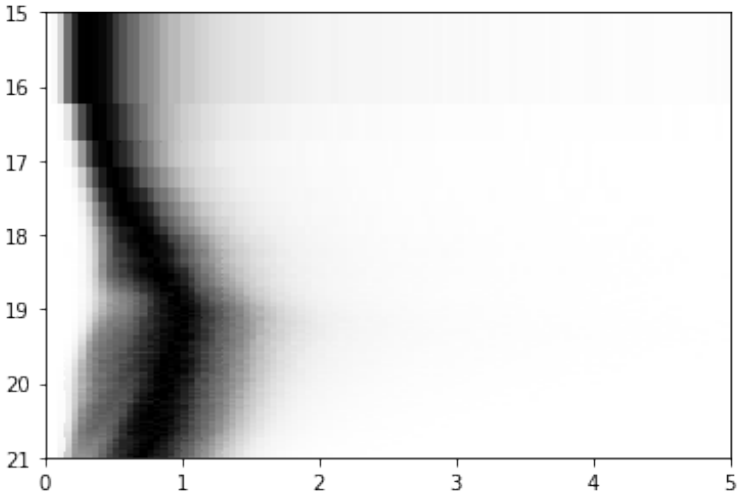

standard
parallax
I [mag]
HJD − 2450000 [days]

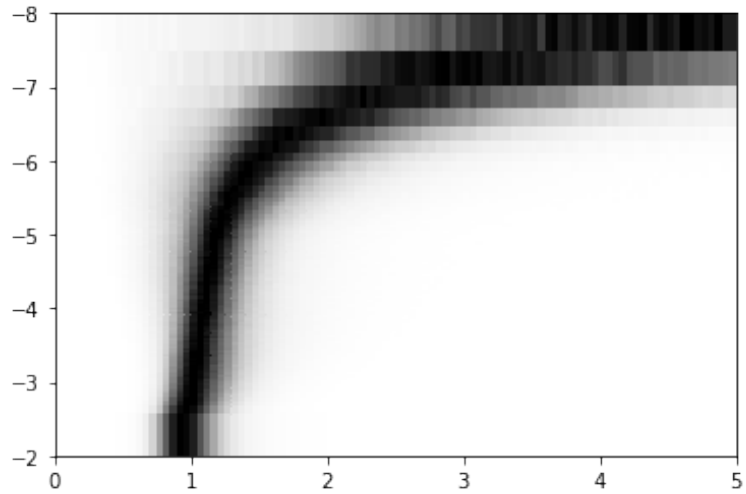

Fraction of $D_\pi >$ threshold [%]
$D_\pi >$ 0.05 mag
$D_\pi >$ 0.15 mag
$D_\pi >$ 0.3 mag and $D_\pi >$ 0.5 ma
Mass [$M_\odot$]


Fraction of $D_\pi >$ threshold [%]
$D_\pi >$ 0.05 mag
$D_\pi >$ 0.15 mag
$D_\pi >$ 0.3 mag and $D_\pi >$ 0.5 ma

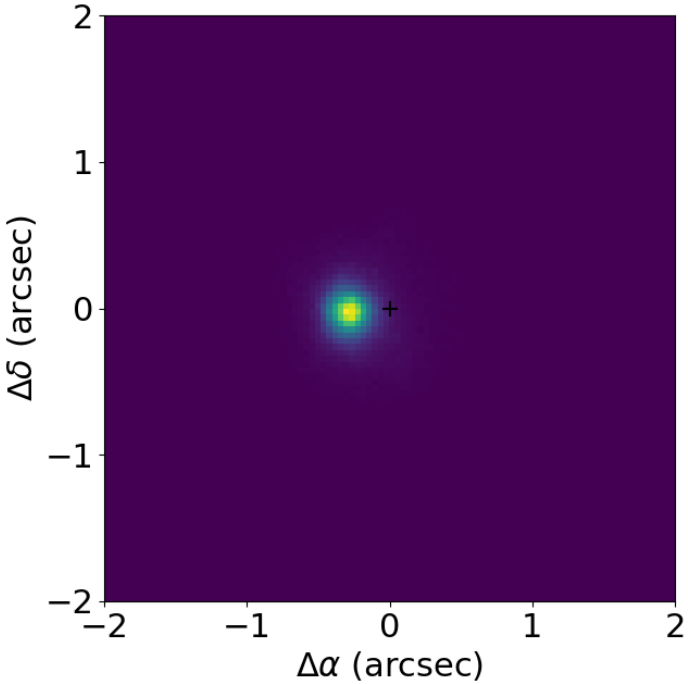
Photometry


CCD3
CCD2E
CCD1
CCD2W
400
300
200
100
0
−6.00
−5.75
−5.50
−5.25
−5.00
−4.75
−4.50
−4.25
−4.00
Raw MACHO red

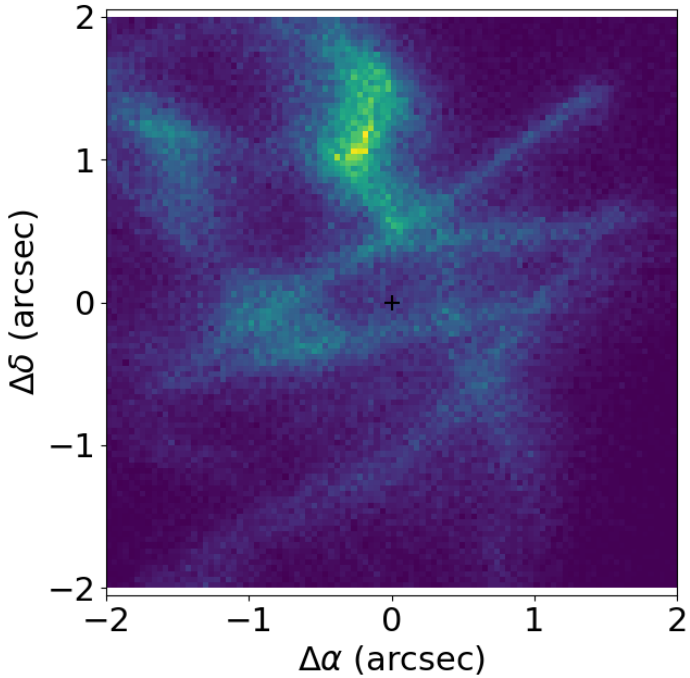

15
16
17
18
19
20
21
0
1
2
3
4
5


−8
−7
−6
−5
−4
−3
−2
0
1
2
3
4
5

Problematic astrometry from MACHO :
Distributions of the differences of positions between EROS stars and their counterparts from ...



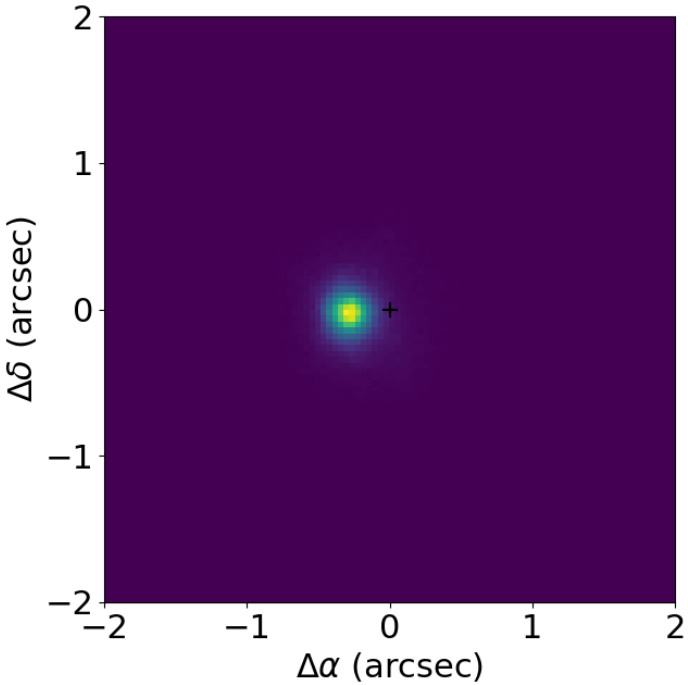
(a) OGLE-III



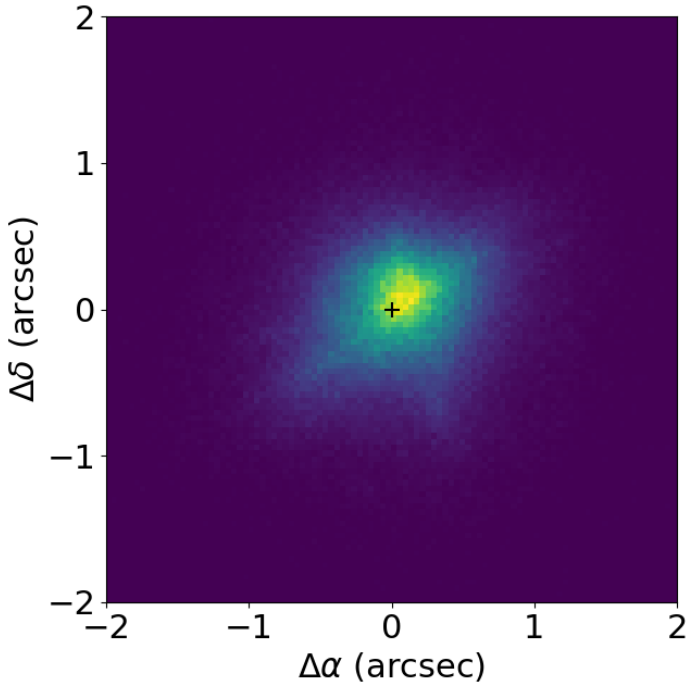
(b) MACHO

Other minor problems with photometry, both in EROS and MACHO.

Problematic astrometry from MACHO :
Distributions of the differences of positions between EROS stars and their counterparts from ...



(a) OGLE-III



(b) corrected MACHO

Other minor problems with photometry, both in EROS and MACHO.