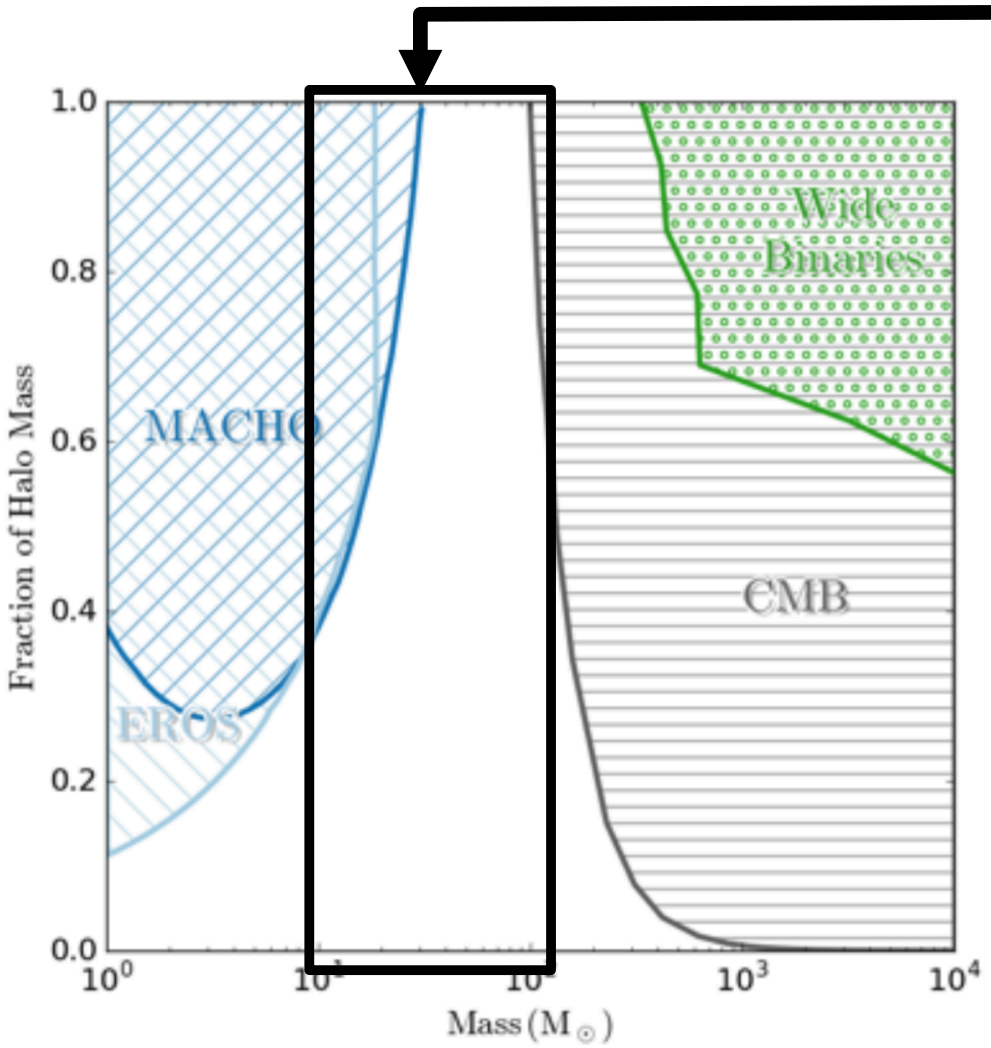
Search for intermediate mass black holes as dark matter using gravitational microlensing

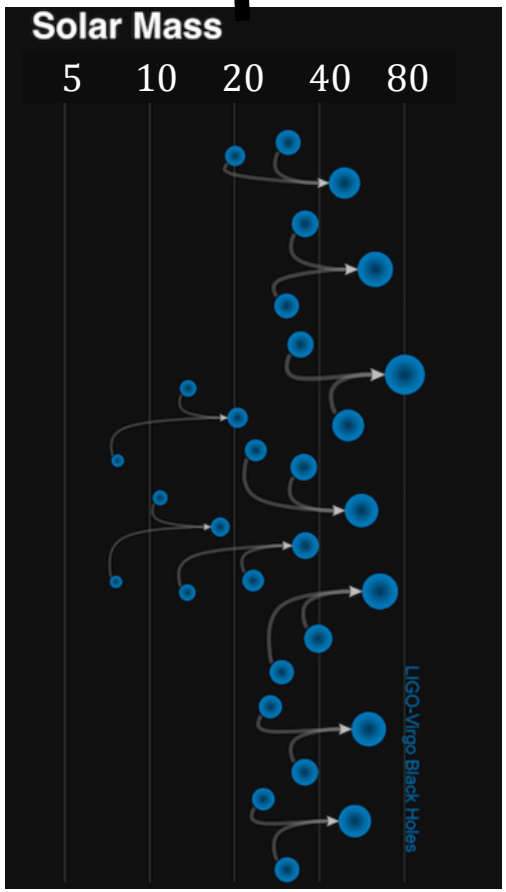
Tristan Blaineau

LAL, IN2P3, CNRS

Action Dark Energy, November 21, 2019

Motivation : Observation of IMBHs





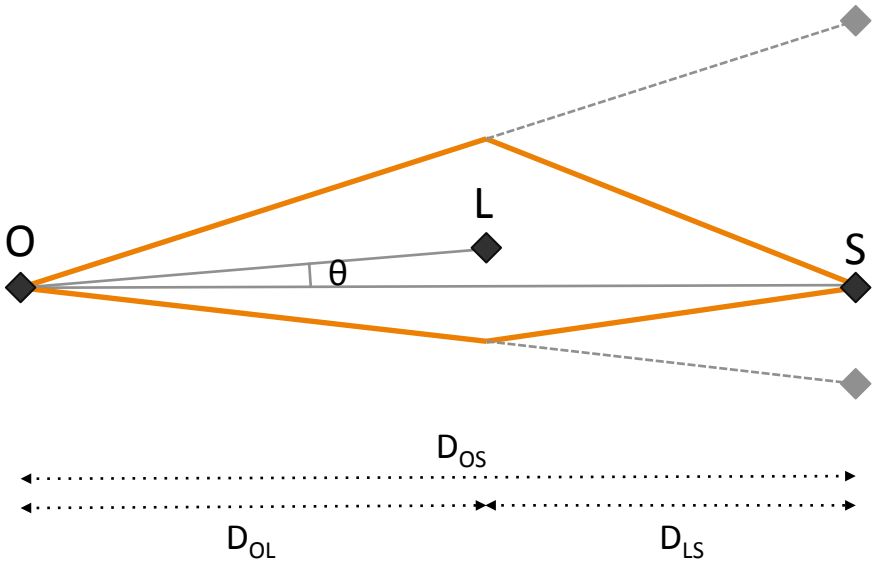
LIGO/Virgo Black holes

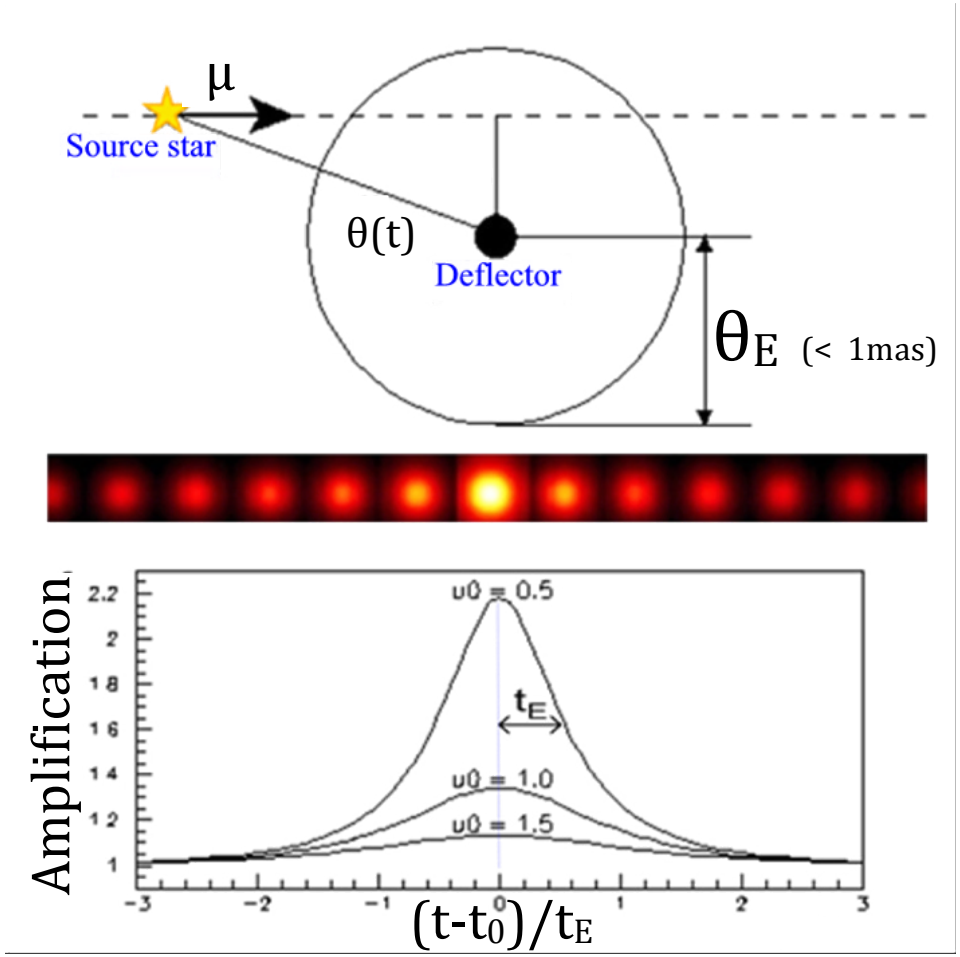
Constraint gap between ~ 10 and $\sim 100 M_\odot$.
Coincidentally LIGO/Virgo discovered black holes in this mass range.

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).

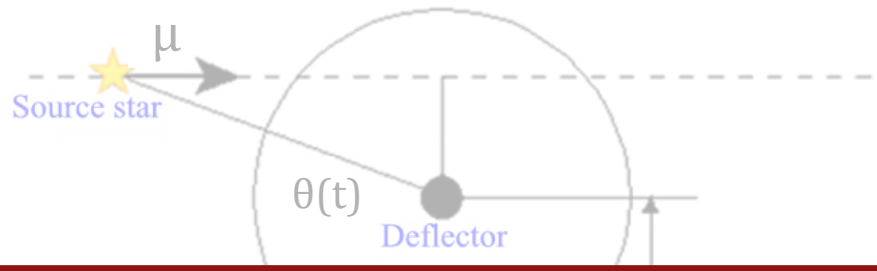




Microlensing : gravitational lensing but only the **magnification** is significant.

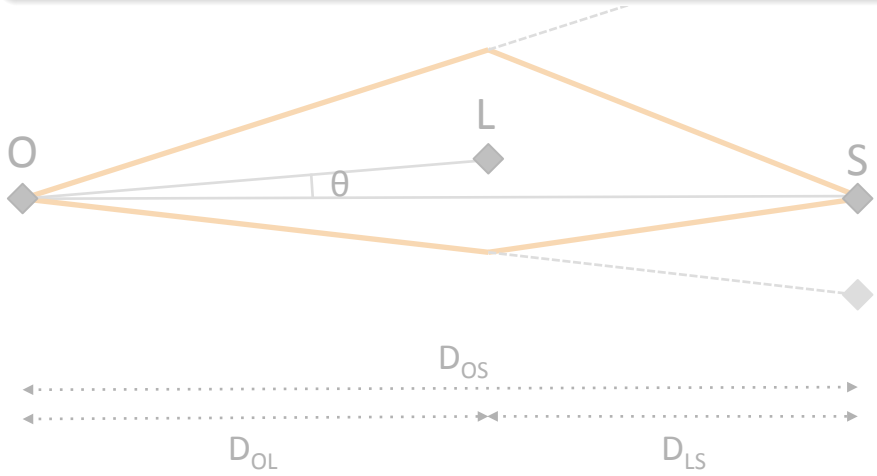
The magnification depends on the normalized distance $u(t) = \frac{\theta(t)}{\theta_E}$ between the source and the lens and is **time-dependent**.

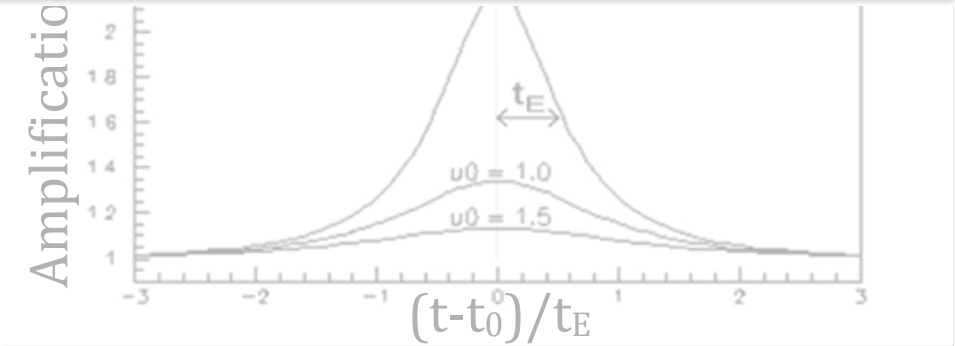
The Einstein time is the characteristic time :



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.





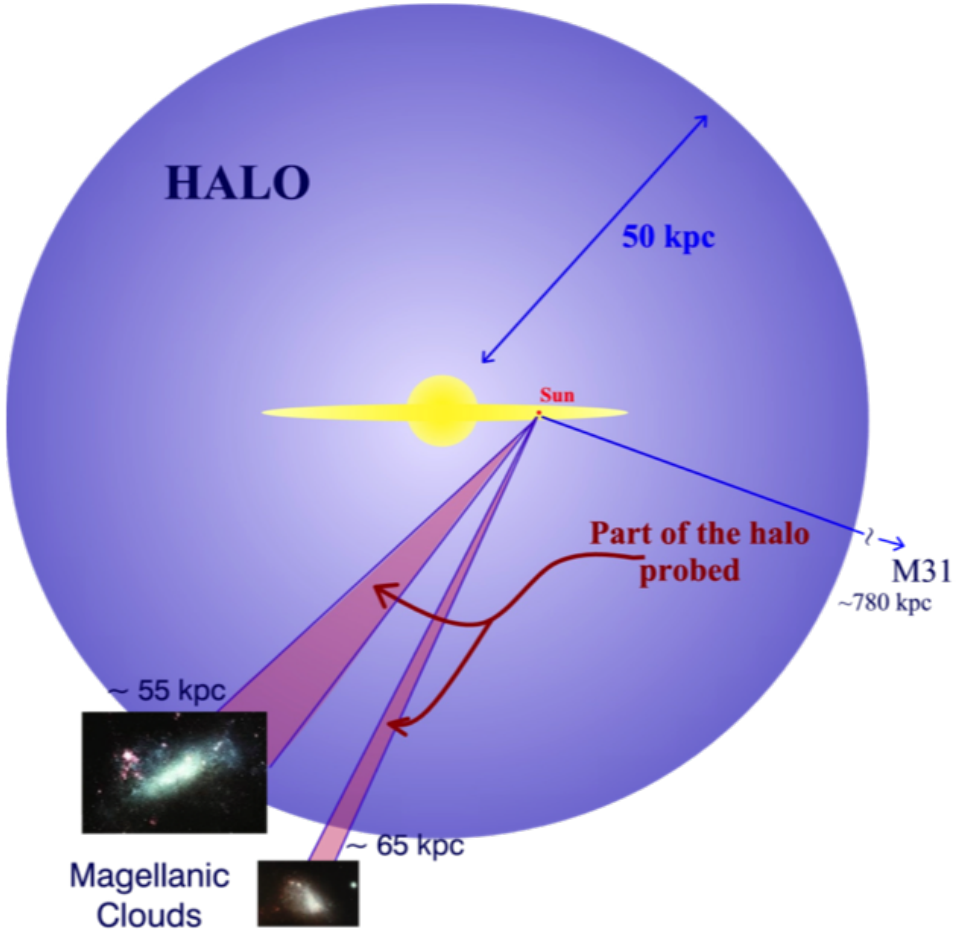
Dark matter search : How to use microlensing ?

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

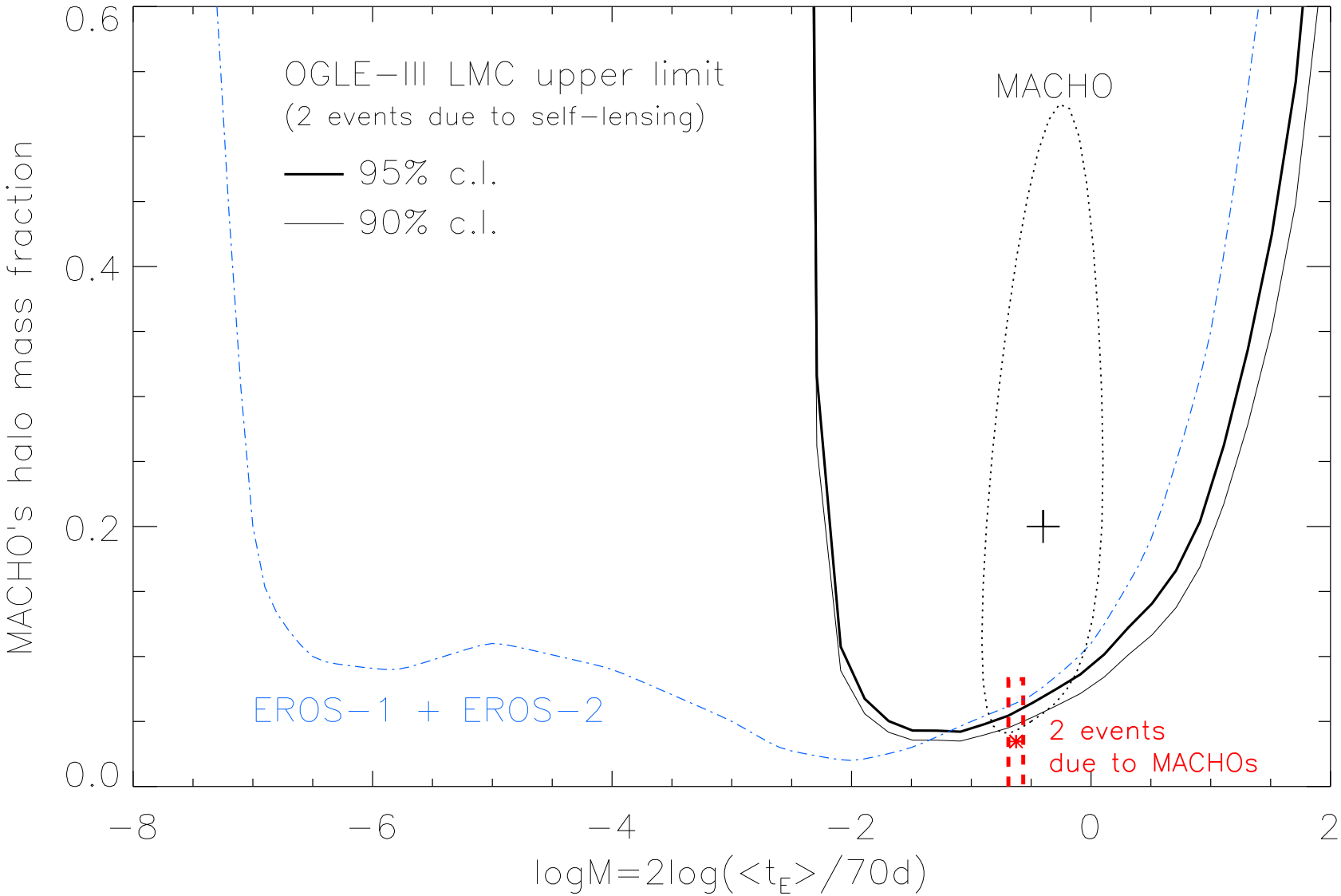
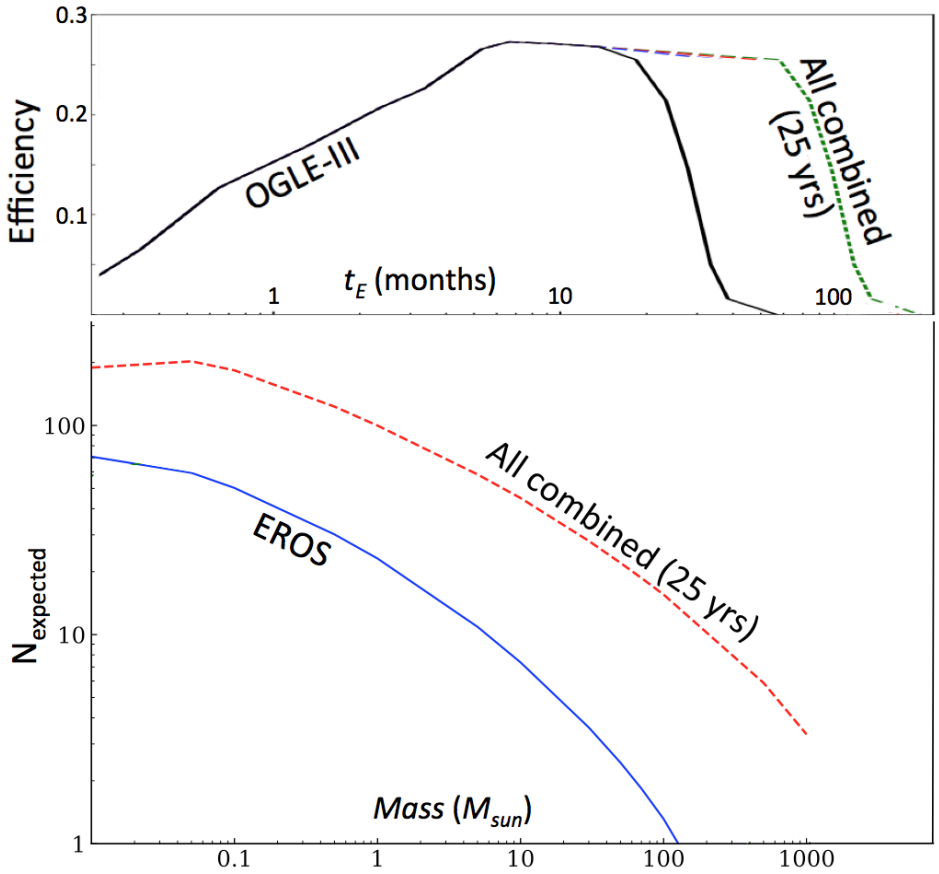


Figure from Wyrzykowski+2010

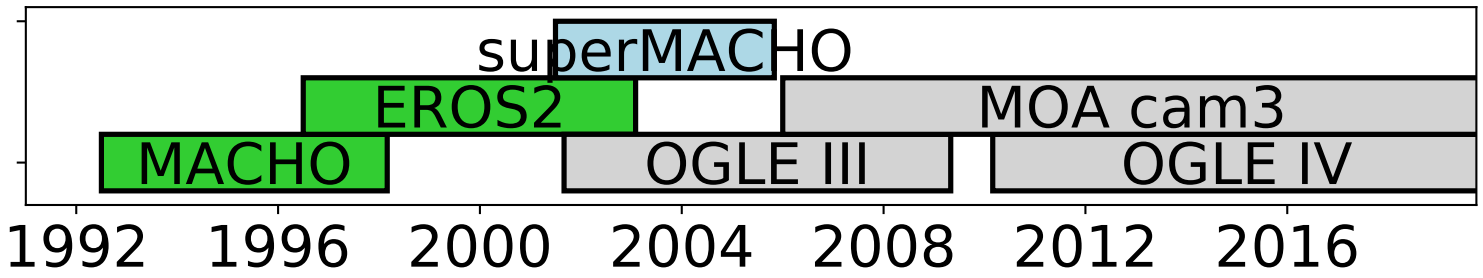
Dark matter search : Extending constraints range



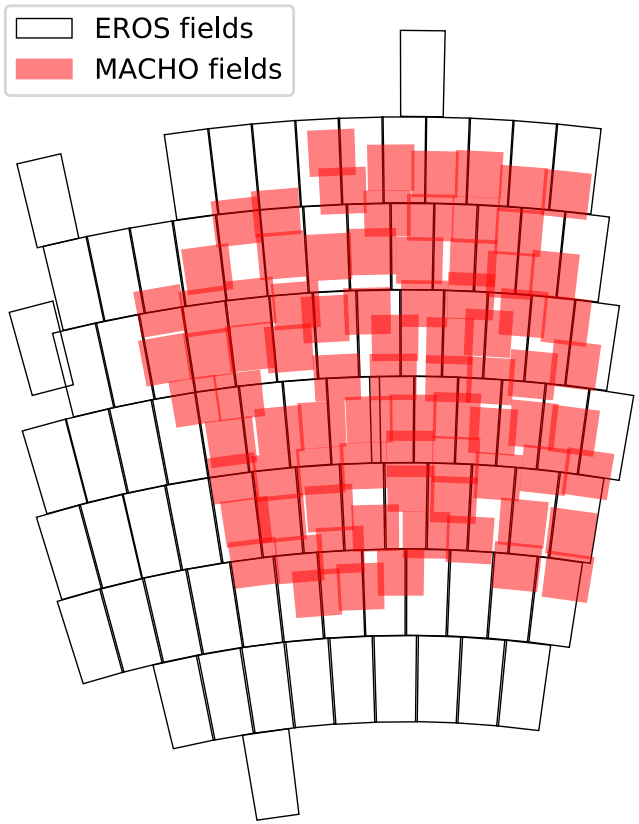
Adapted from Mirhosseini & Moniez 2018

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

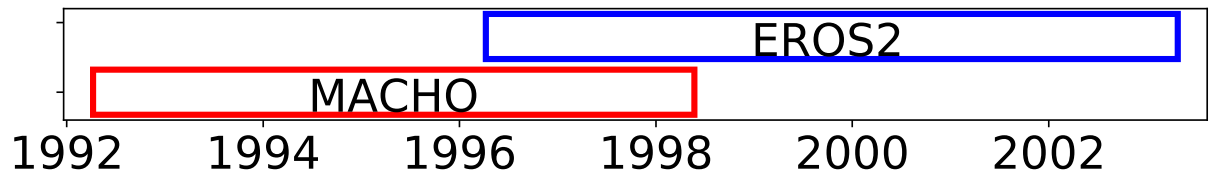
Past surveys had their efficiency limited by their duration.
We can merge them to extend the total time span.
Efficiency of merging existing catalogues has been estimated (MACHO, EROS2, OGLE-III and OGLE-IV).
Sensitivity up to $\sim$ 1000 $M_\odot$.



Catalogue merging : EROS2 and MACHO



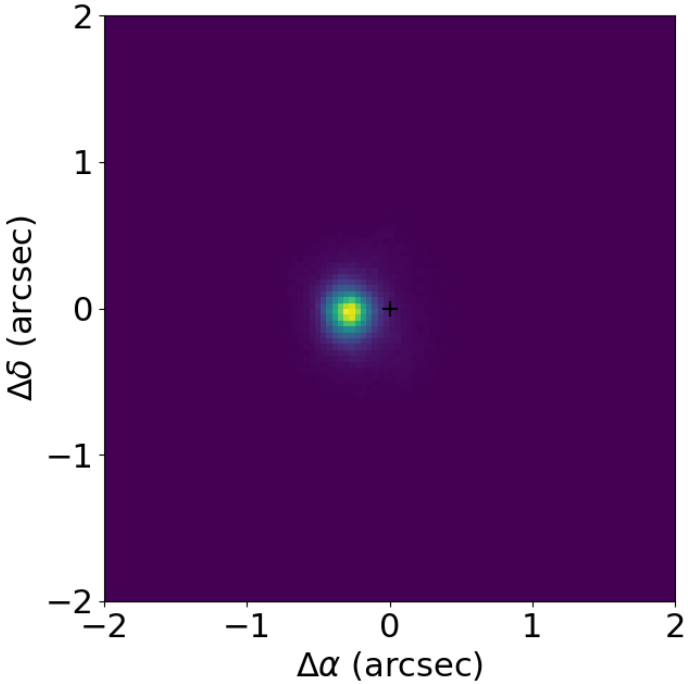
We currently have only access to the MACHO and EROS2 databases.
Search for microlensing over **10.6 years** in a combined catalogue of **14.10^6 light curves.**
Each survey uses 2 non standard filters.
($\sim$ 1700 measures for each star, $\sim$ 700Go photometric database).



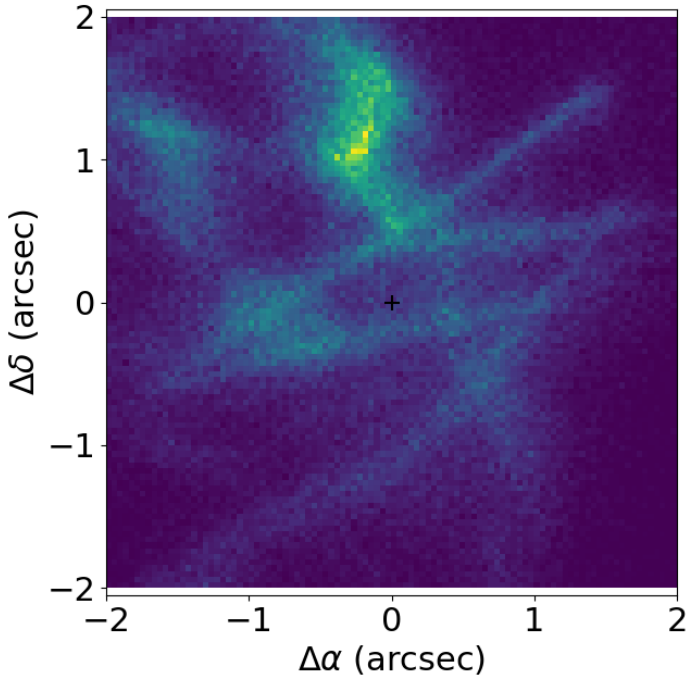
Survey	Dates	Duration (year)	Sky coverage (deg^2)	Number of stars ($x10^6$)
MACHO	07/92 - 01/00	5.7	40	22.3
EROS2	07/96 - 02/03	6.7	84	28.8
EROS2+MACHO	**07/92 - 02/03**	**10.6**	**$\sim$40**	**$\sim$14**

Catalogue merging : Few problems encountered

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



(a) OGLE-III

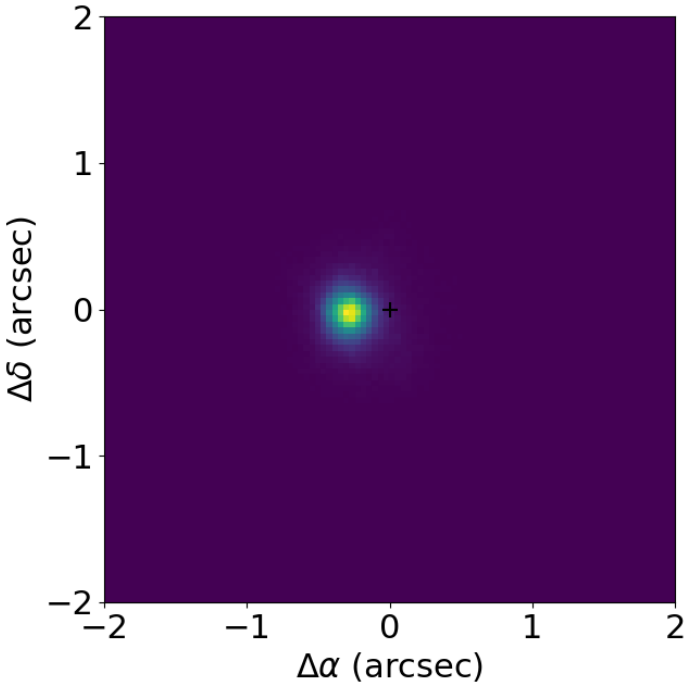


(b) MACHO

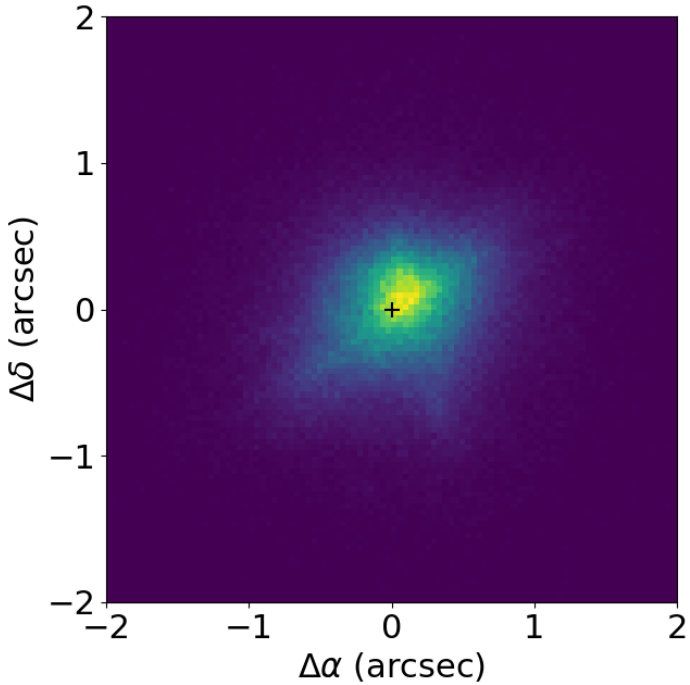
Other minor problems with photometry, both in EROS and MACHO.

Catalogue merging : Few problems encountered

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.

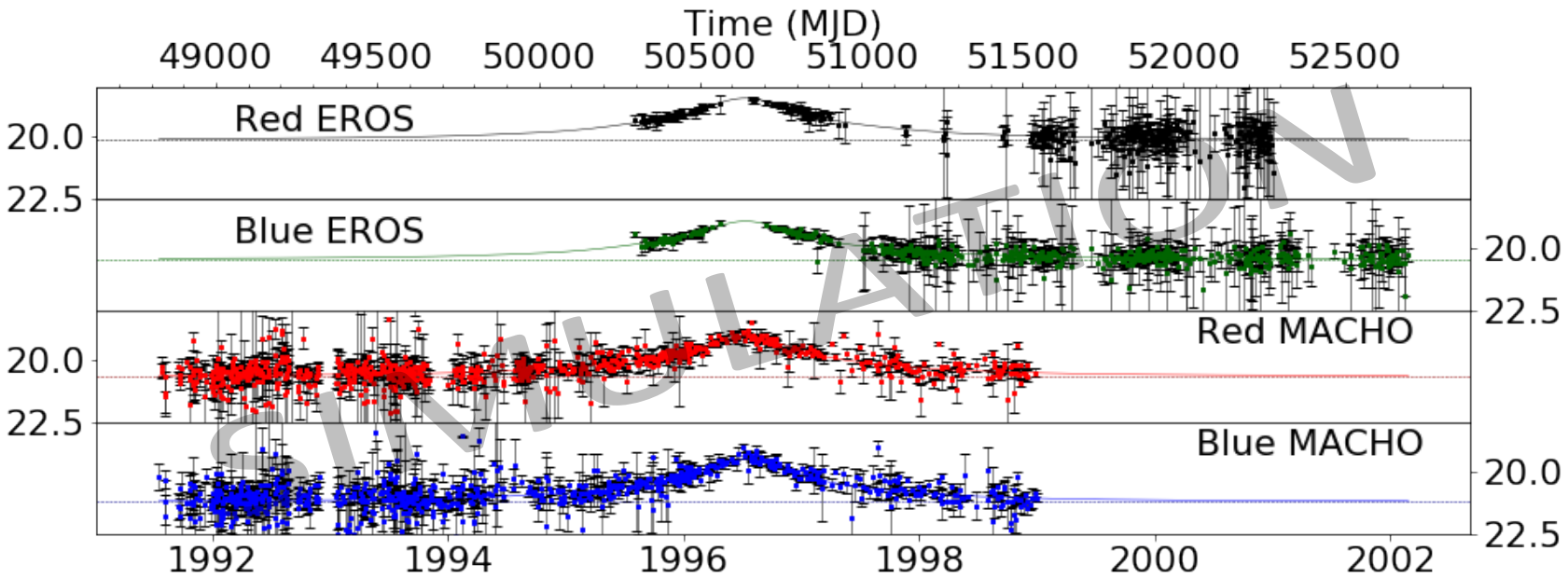
Preliminary analysis : Search of microlensing events

Brute-force : systematic fit of a simple microlensing event to each color compared with the fit of a constant light curve.

Preliminary analysis : Search of microlensing events

Brute-force : systematic fit of a simple microlensing event to each color compared with the fit of a constant light curve.
7 parameters to fit :

- 3 parameters coming from the deflector mass and geometrical configuration, common to all filter colors.
- 4 flux parameters for the source, one for each filter color.



Brute-force : systematic fit of a simple microlensing event to each color compared with the fit of a constant light curve.
7 parameters to fit :

- 3 parameters coming from the deflector mass and geometrical configuration, common to all filter colors.
- 4 flux parameters for the source, one for each filter color.

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

Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

Preliminary analysis : Event selection

Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to remove instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)

Preliminary analysis : Event selection

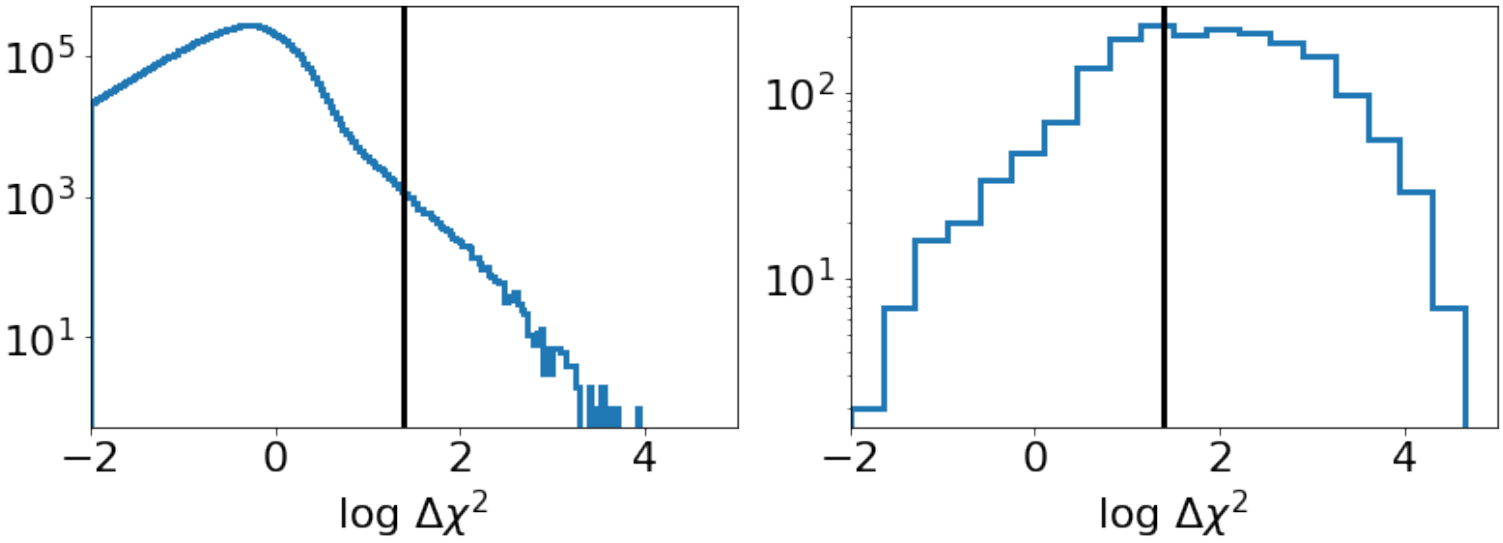
Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to remove instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)
- Measurement per color $N > 7$.

Preliminary analysis : Event selection

Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to remove instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)
- Measurement per color $N > 7$.
- Improvement between microlens fit and flat fit $\Delta\chi^2 > 25$ (black line)



(a) Real data

(b) Simulated microlensing light curves

Preliminary analysis : Event selection

Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to remove instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)
- Measurement per color $N > 7$.
- Improvement between microlens fit and flat fit $\Delta\chi^2 > 25$
- Improvement on both colors: $\Delta\chi^2_{\text{red}} > 8$ & $\Delta\chi^2_{\text{blue}} > 8$

Preliminary analysis : Event selection

Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to remove instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)
- Measurement per color $N > 7$.
- Improvement between microlens fit and flat fit $\Delta\chi^2 > 25$
- Improvement on both colors: $\Delta\chi^2_{\text{red}} > 8$ & $\Delta\chi^2_{\text{blue}} > 8$
- Goodness of microlens fit $\chi^2_\mu / N_{\text{dof}} < 2$

Preliminary analysis : Event selection

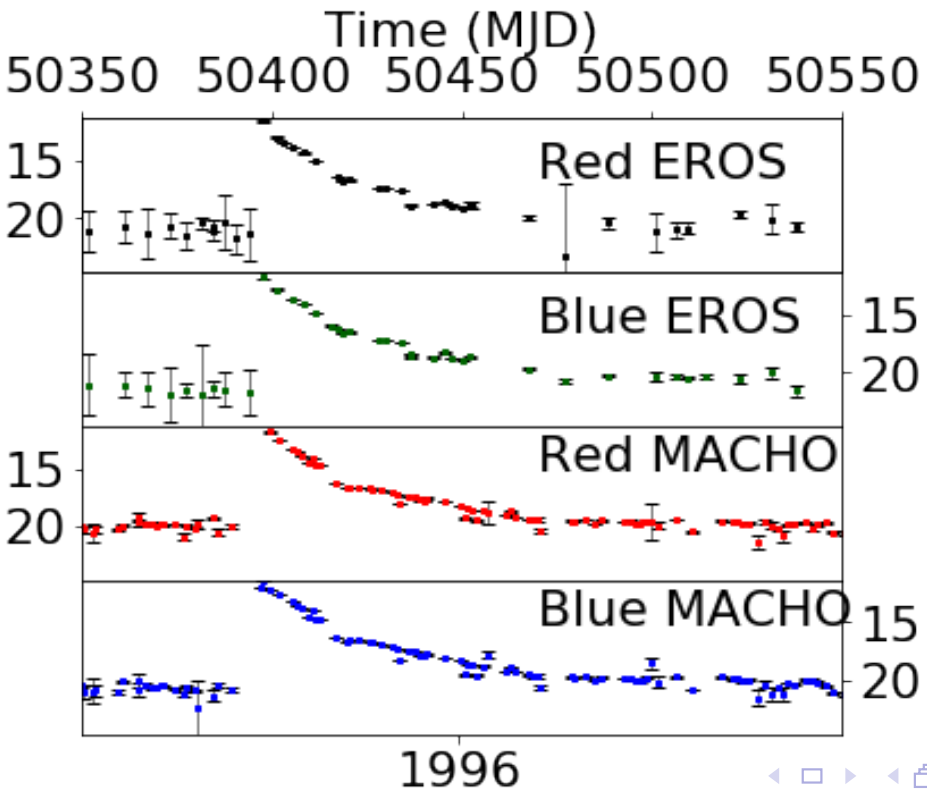
Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to remove instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)
- Measurement per color $N > 7$.
- Improvement between microlens fit and flat fit $\Delta\chi^2 > 25$
- Improvement on both colors: $\Delta\chi^2_{\text{red}} > 8$ & $\Delta\chi^2_{\text{blue}} > 8$
- Goodness of microlens fit $\chi^2_\mu / N_{\text{dof}} < 2$
- Identify and reject known variable phenomena

Preliminary analysis : Known genuine variabilities

Physical noise already identified:

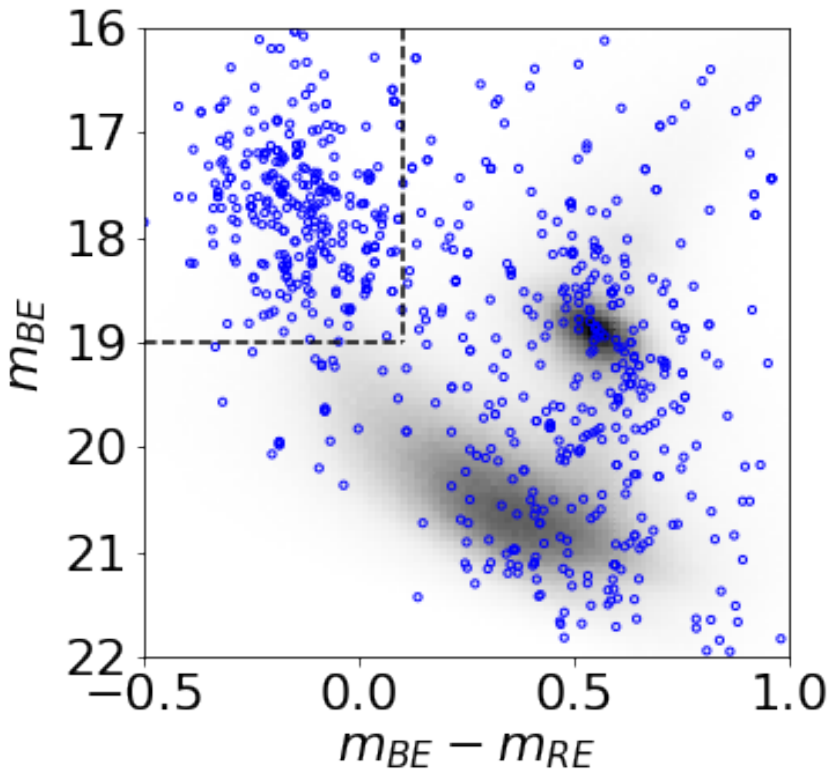
- Supernovae : Short and systematically asymmetric variations (no specific cut yet).



Preliminary analysis : Known genuine variabilities

Physical noise already identified:

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

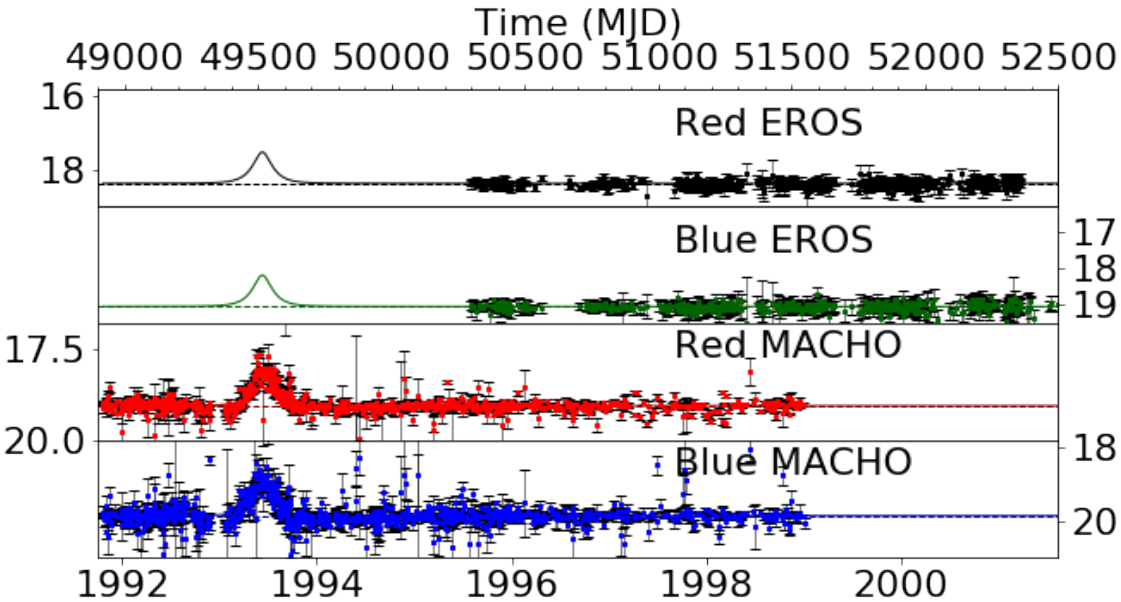


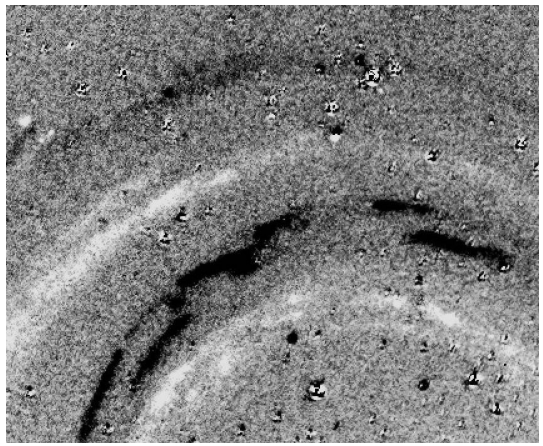
Color-magnitude diagram (grey scale).
Dots are light curves that pass all cuts (except SN1987A echoes).
Microlensing is independent of the source => the candidate col-mag distribution should follow the source distribution.
Overdensity of candidates in the blue end of the main sequence.

Preliminary analysis : Known genuine variabilities

Physical noise already identified:

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

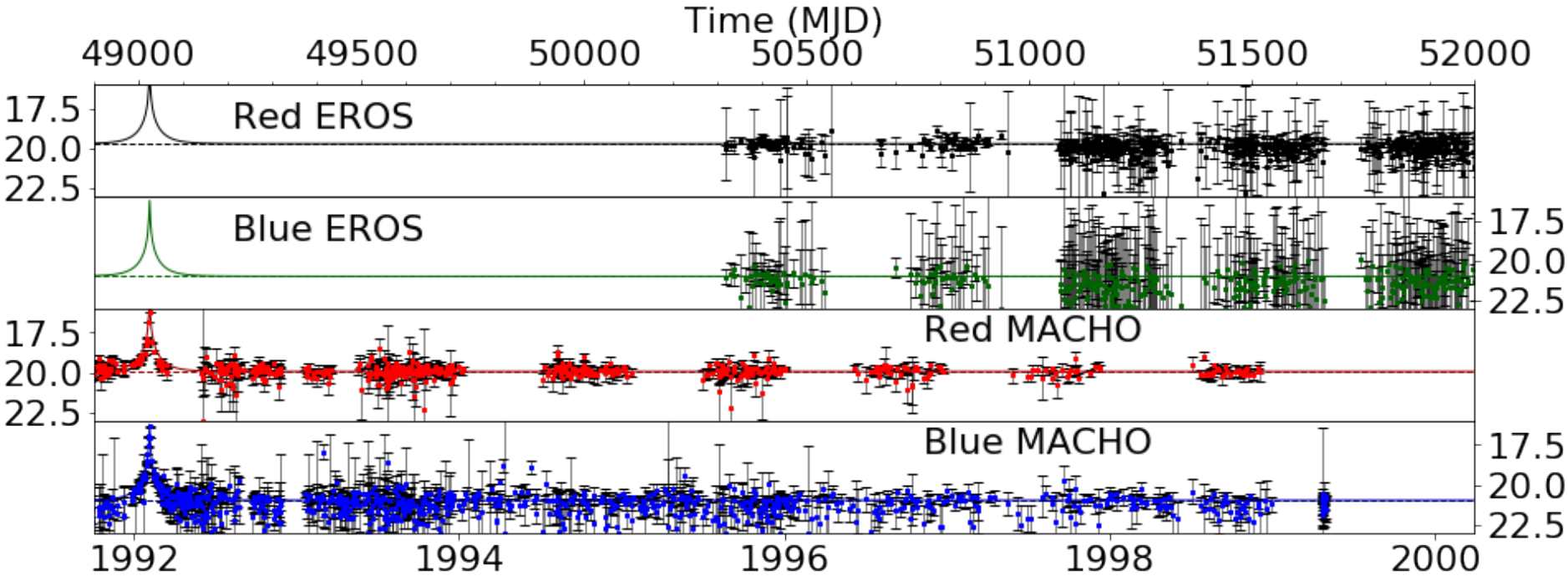
Disclaimer : Not definitive, quite tolerant on purpose and we explored even less restrictive cuts.

- We try to identify instrumental noise (bad images, bad pixels, ... causing measure points very far away from the baseline)
- Measurement per color $N > 7$.
- Improvement between microlens fit and flat fit $\Delta\chi^2 > 25$
- Improvement on both colors of a same survey : $\Delta\chi^2_{\text{red}} > 8$ & $\Delta\chi^2_{\text{blue}} > 8$
- Goodness of microlens fit $\chi^2_\mu / N_{\text{dof}} < 2$
- Identify and reject known variable phenomena

472 light curves remain.

Preliminary analysis : Known microlenses

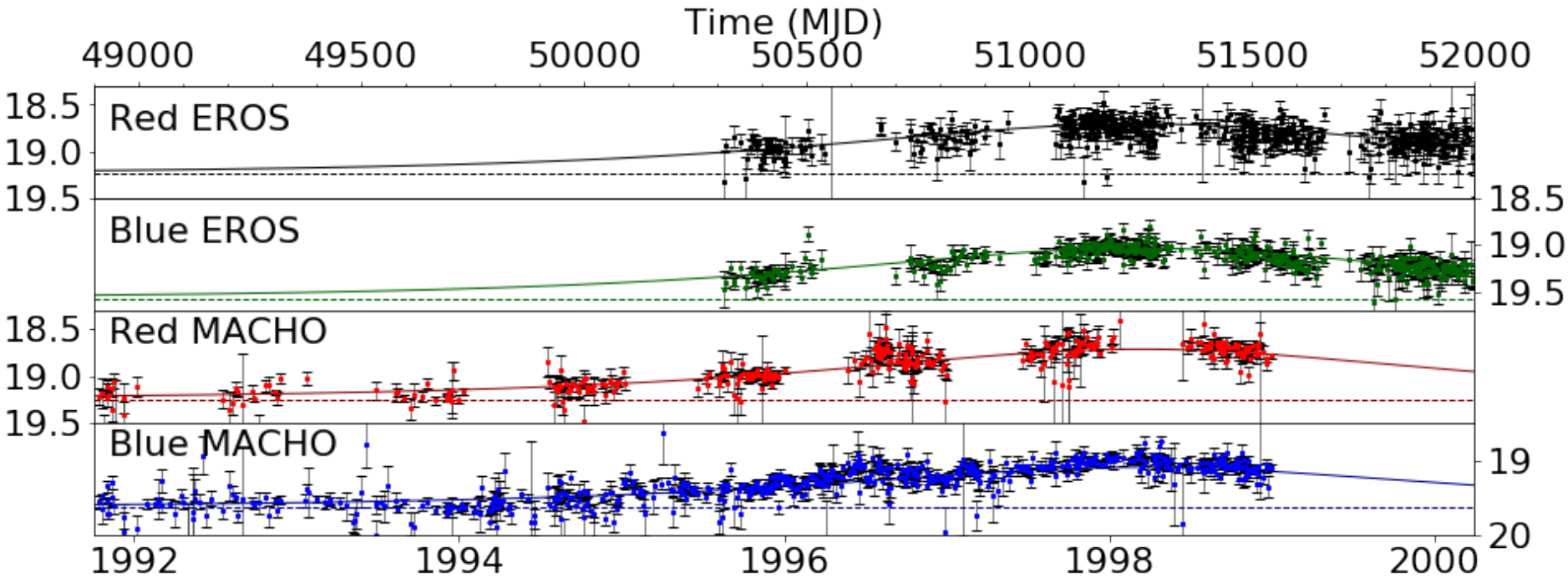
We find again all the past candidates that have been published with light curves in both EROS2 and MACHO catalogues (8 events).



Preliminary analysis : Contaminating slowly varying light curves

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

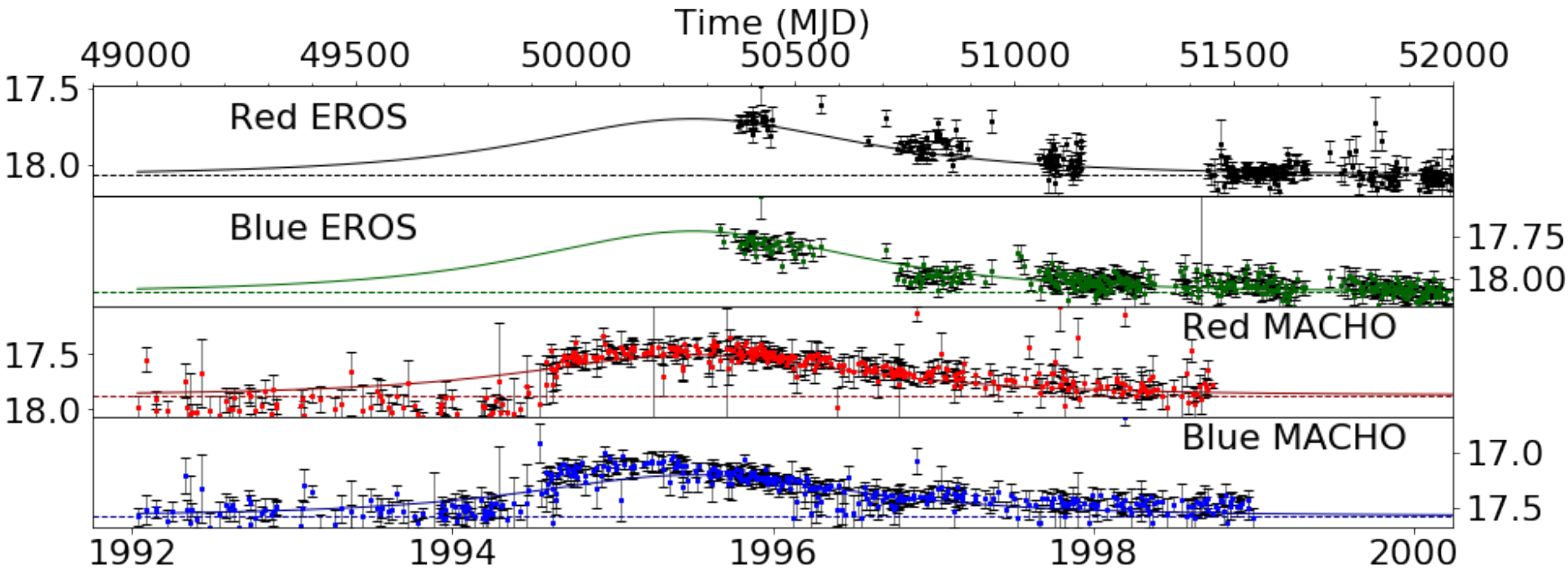
- AGNs identified by cross-match with CDS. Show structured variations. (concerns around 25 light curves)



Preliminary analysis : Contaminating slowly varying light curves

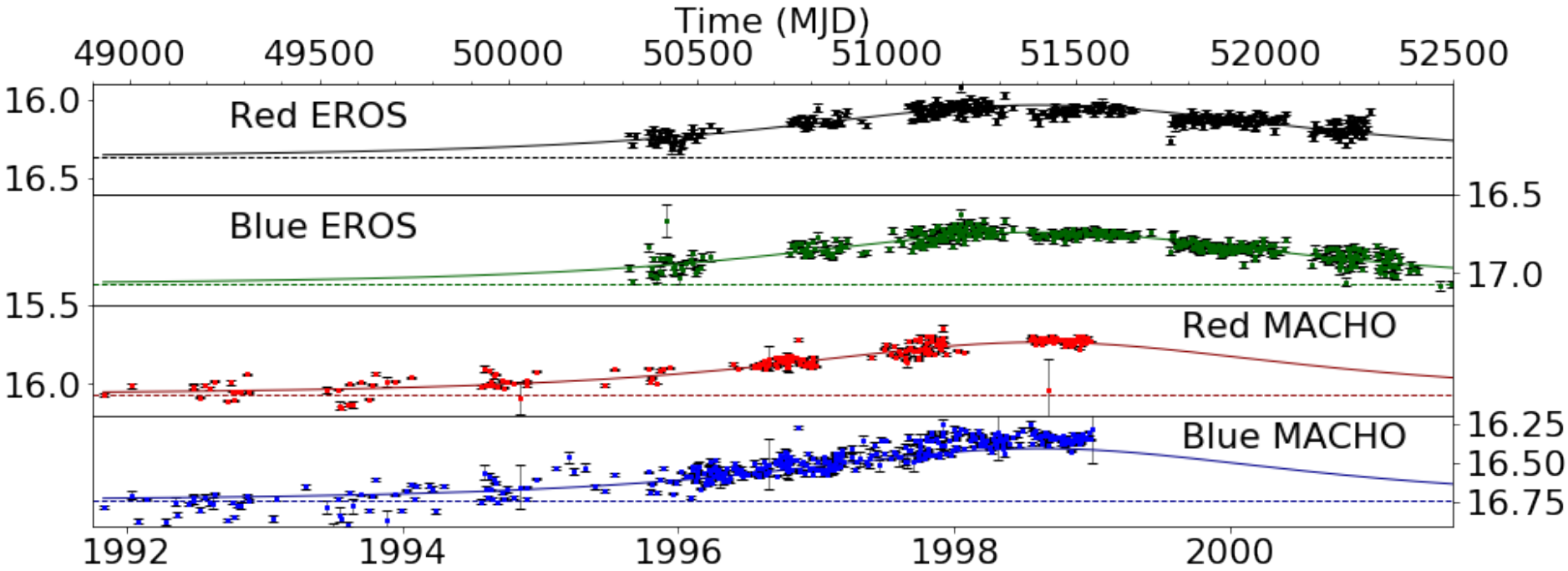
Focus on long time scale search : $t_E > 50$ days.

- AGNs identified by cross-match with CDS. Show structured variations. (concerns around 25 light curves)
- Group of curves exhibiting the same behaviour : quickly increasing-slowly decreasing light curves, on several years (more than a dozen events).



Preliminary analysis : Interesting light curve

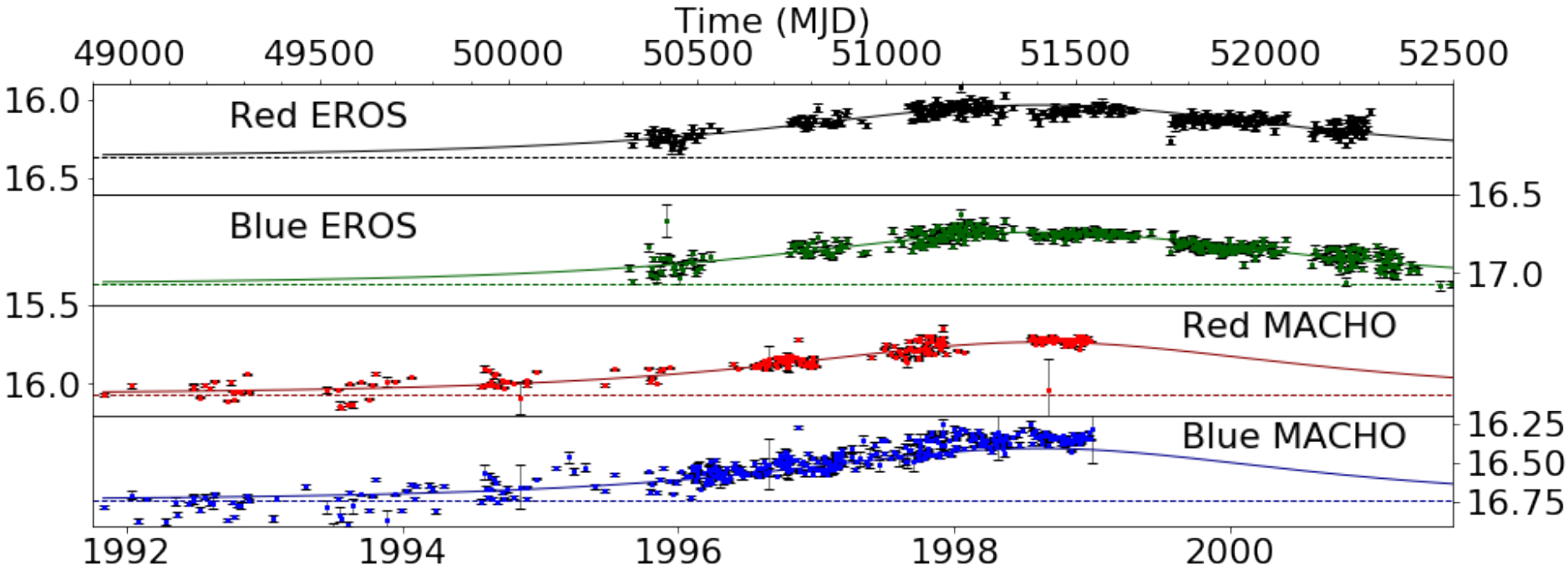
No obvious microlens event so I show you what approaches the most



Looks like a microlensing event
with $t_E \approx 800$ days ($\sim 130\ M_\odot$)

Preliminary analysis : Interesting light curve

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

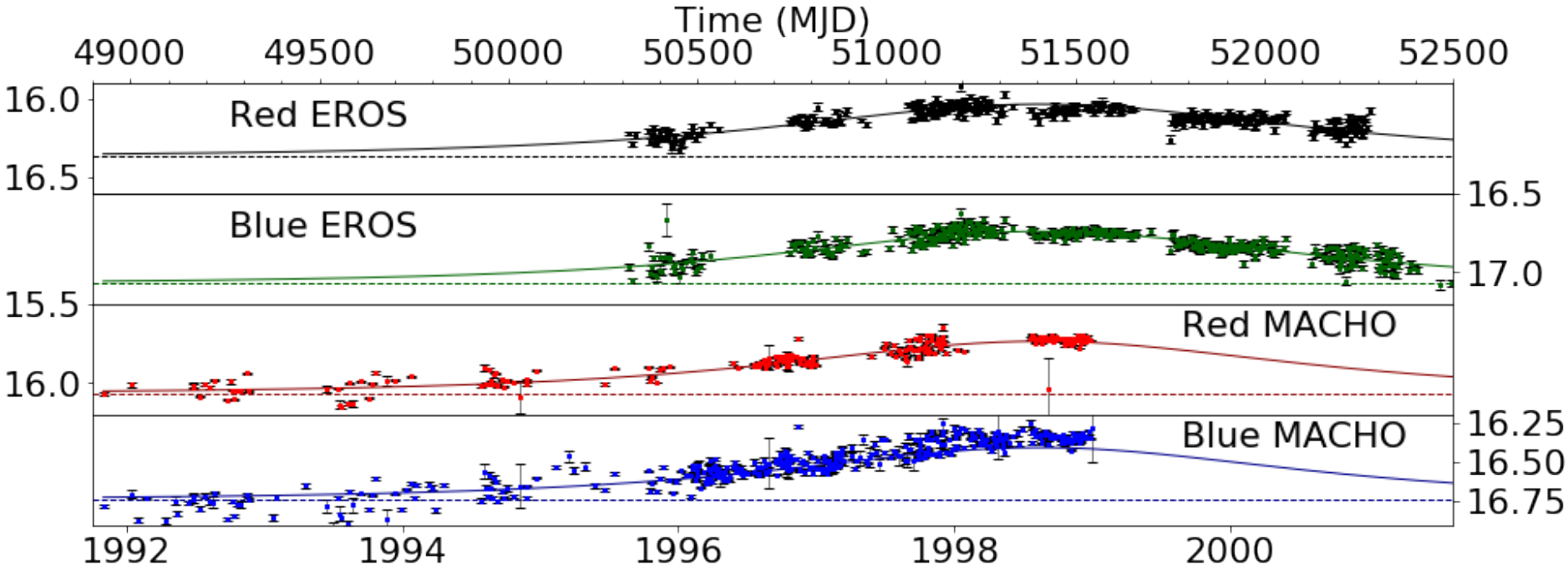


Looks like a microlensing event with $t_E \approx 800$ days ($\sim 130\ M_\odot$)

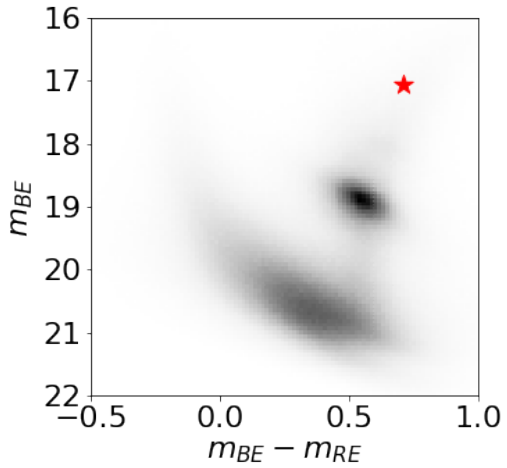
Show interest of merging catalogues.

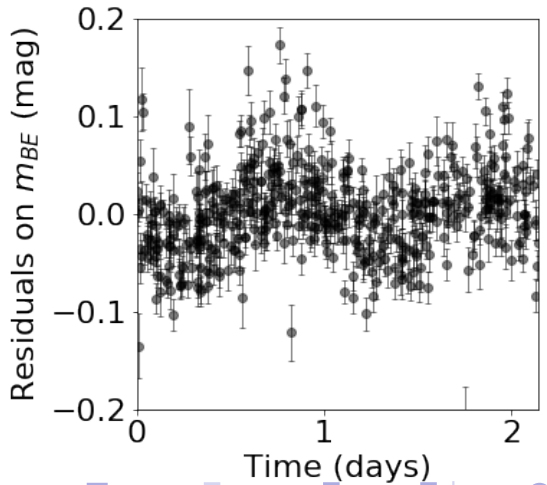
Preliminary analysis : Interesting light curve

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



Looks like a microlensing event with $t_E \approx 800$ days ($\sim 130\ M_\odot$)
Show interest of merging catalogues.
Doubtful : short periodicity of 1.07 days.





Conclusion and perspectives

What I didn't mention:

- Non standard microlensing effects (parallax and blending) have been studied in detail for interesting events.

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[1], dark matter distribution modeling...
- Opportunity of reprocessing the images with modern methods (differential photometry).
- Aggregate more data (superMACHO, OGLE, MOA...)

+ LSST forecast

[1] paper on impact of parallax under finalisation

Conclusion and perspectives

What I didn't mention:

- Non standard microlensing effects (parallax and blending) have been studied in detail for interesting events.

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[1], dark matter distribution modeling...
- Opportunity of reprocessing the images with modern methods (differential photometry).
- Aggregate more data (superMACHO, OGLE, MOA...)

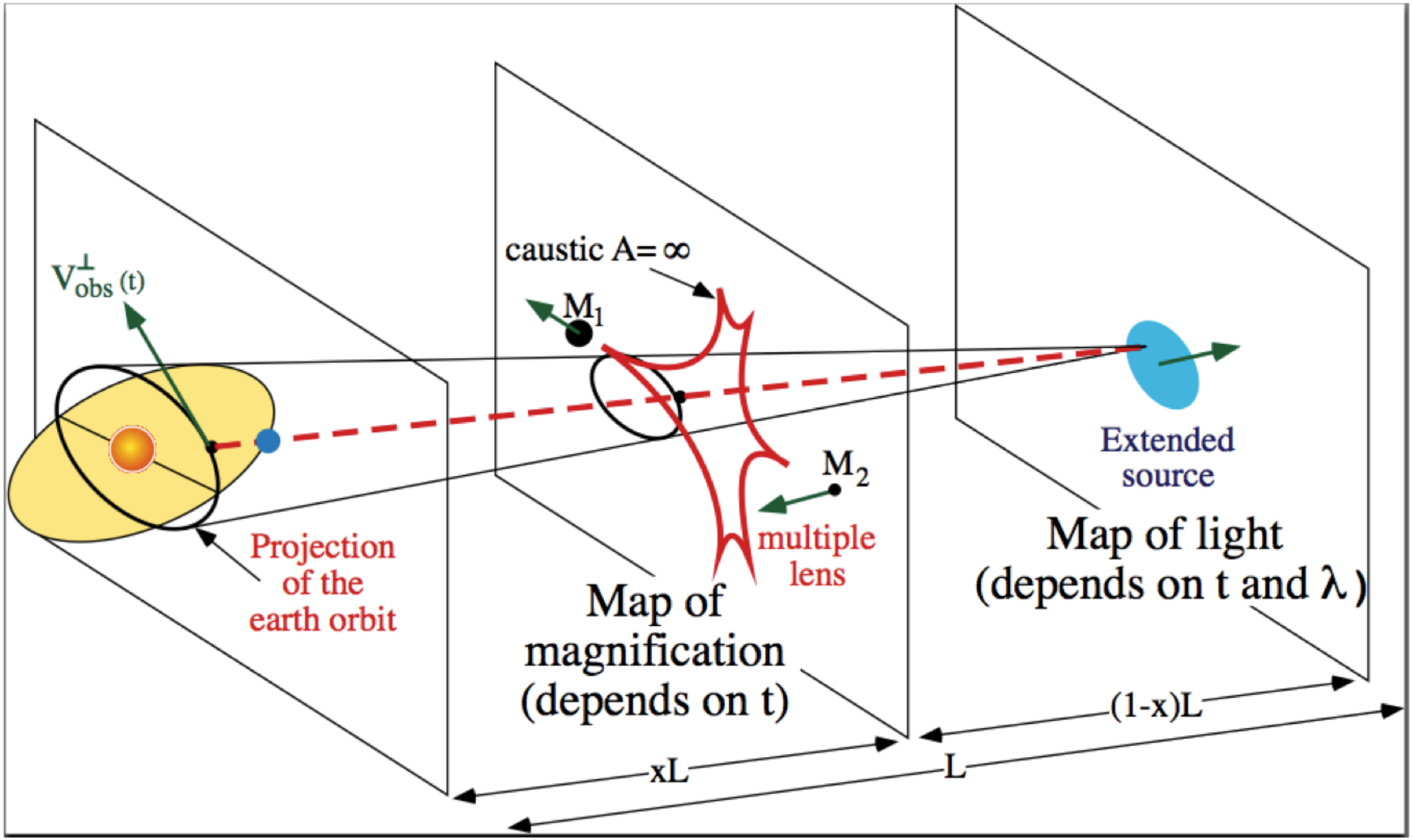
+ LSST forecast

Thanks for your attention !

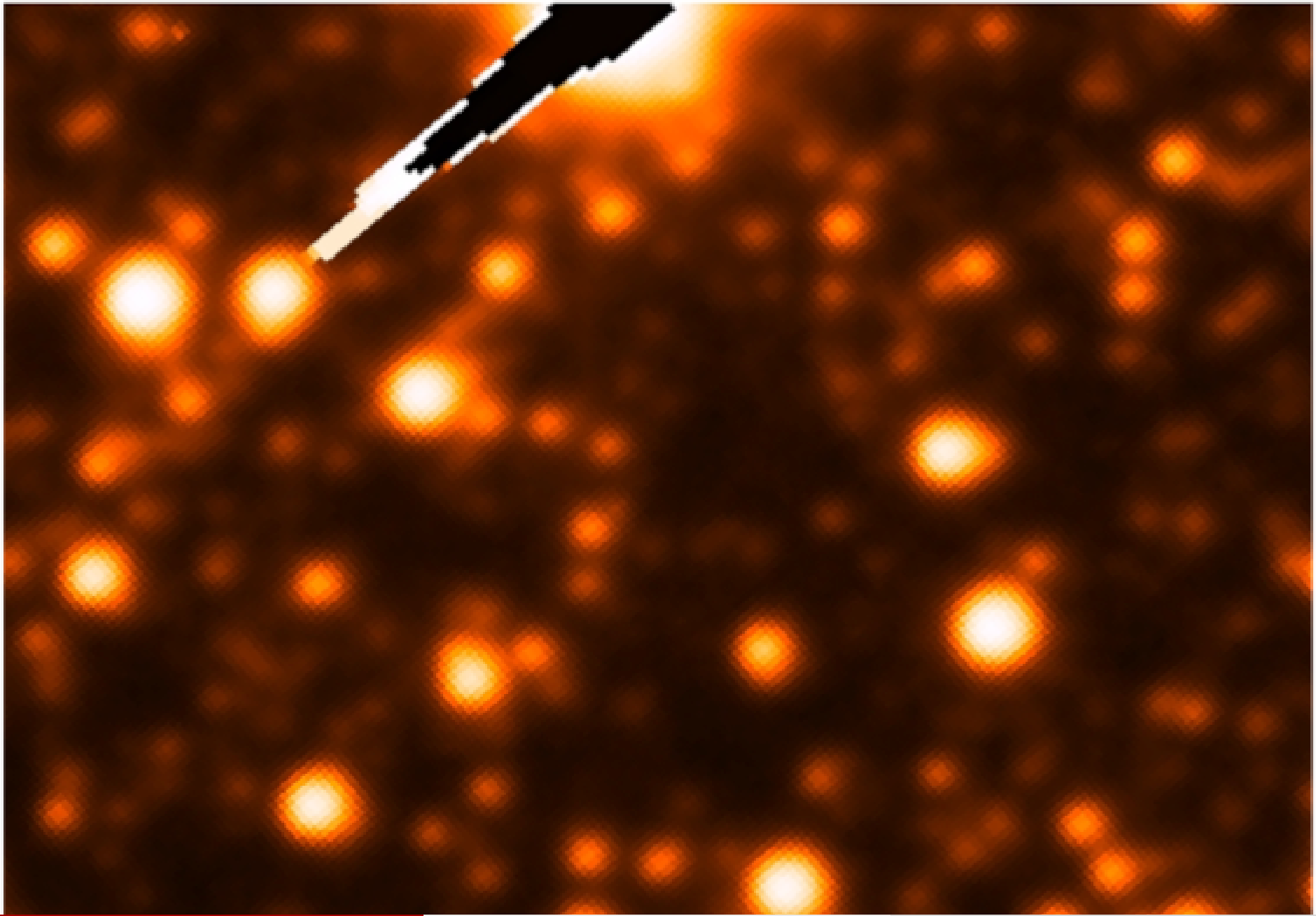
[1] paper on impact of parallax under finalisation

Backup

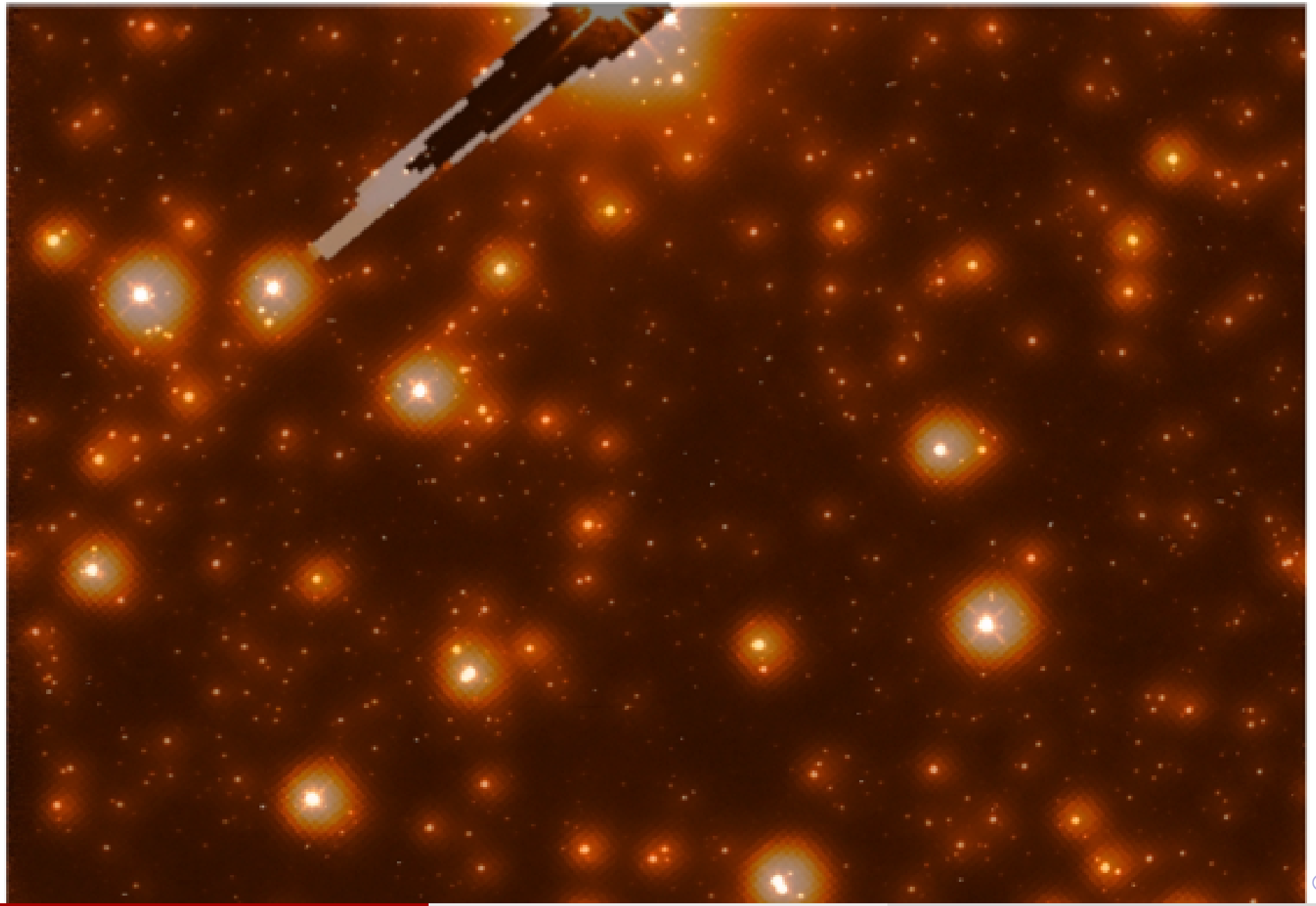
Other effects



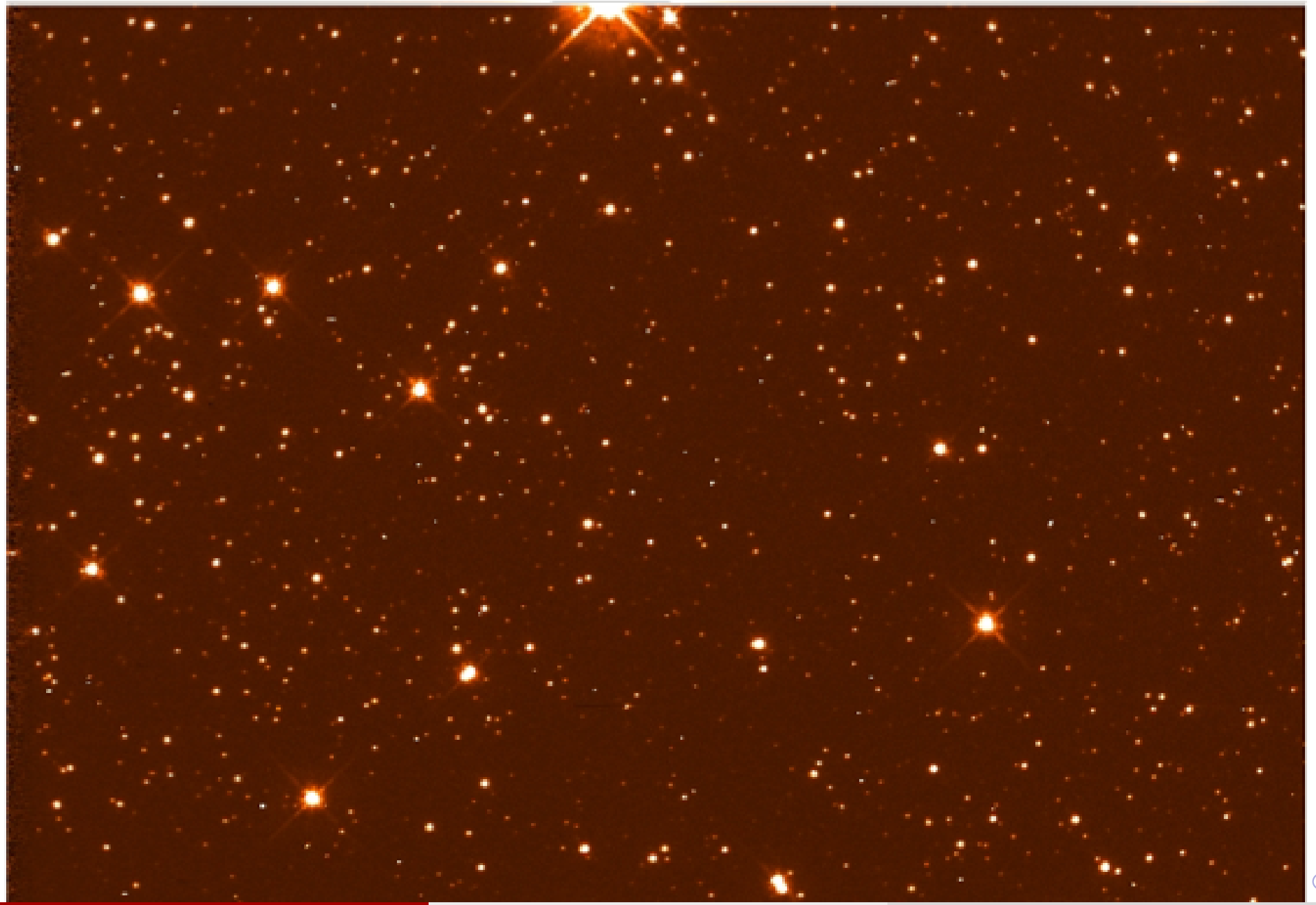
Blending



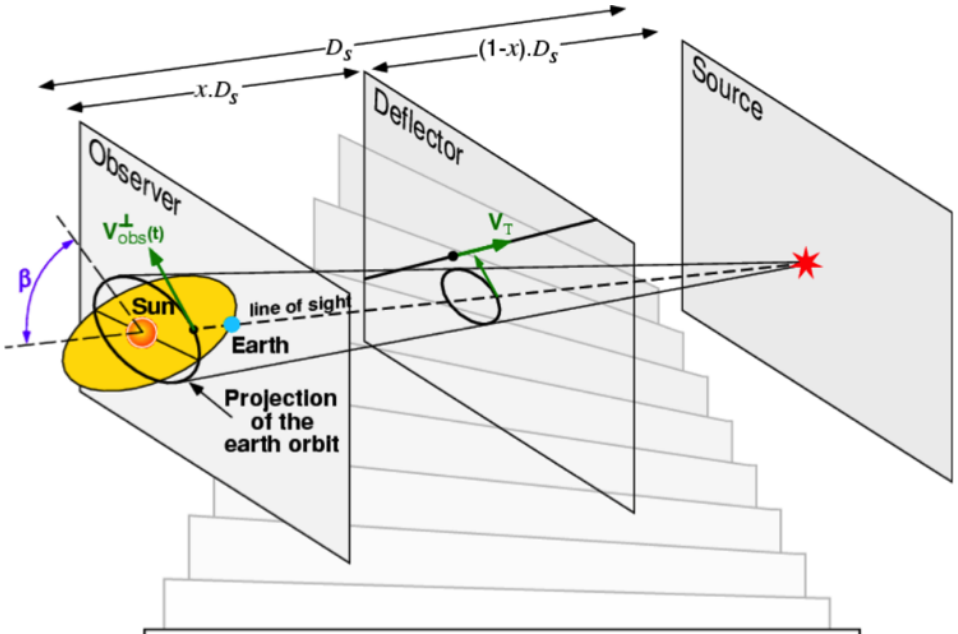
Blending

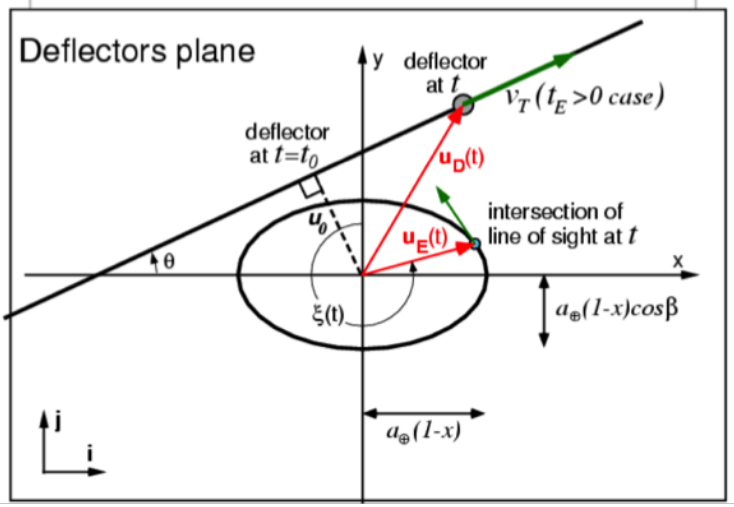


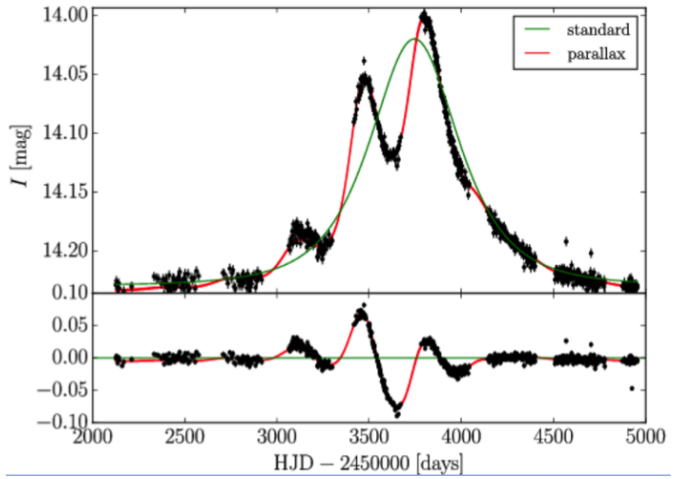
Blending

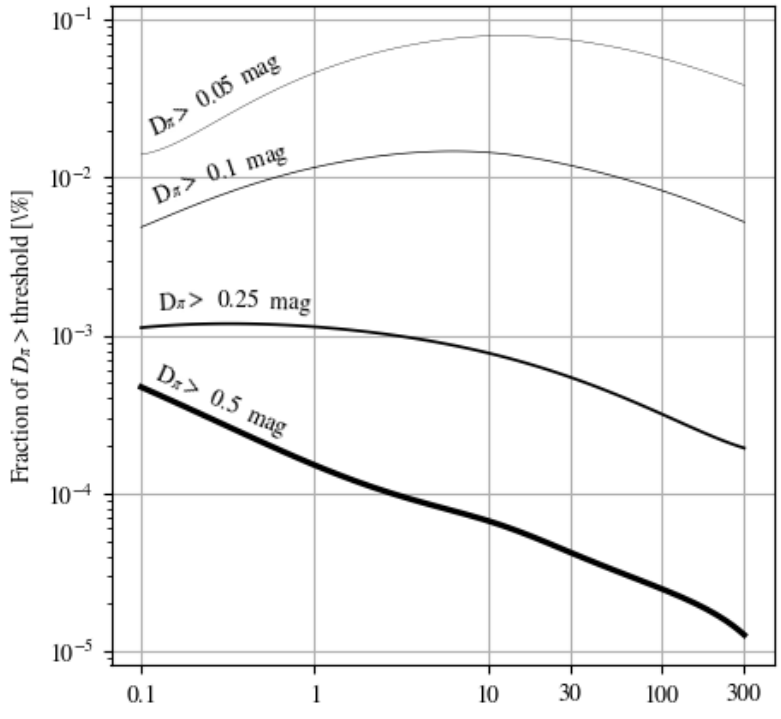


Parallax

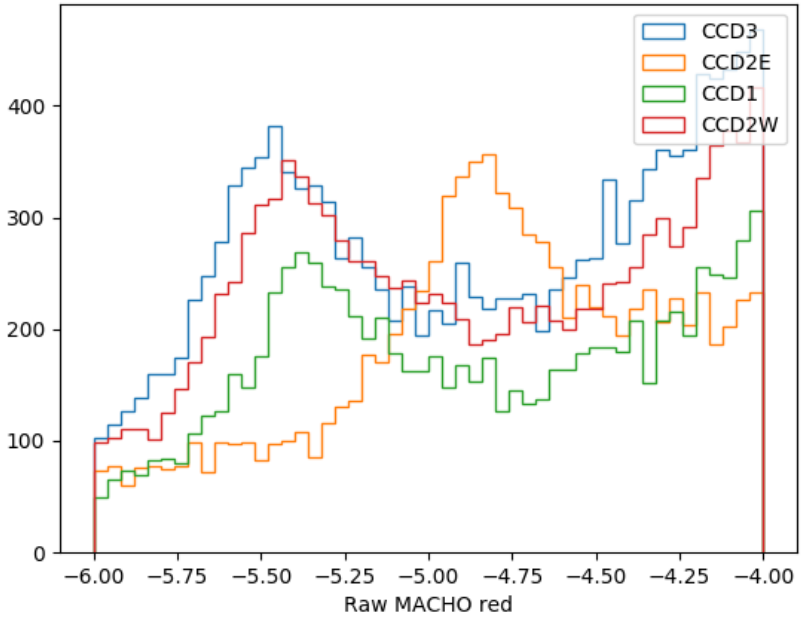

D_S
$x.D_S$
$(1-x).D_S$
Observer
Deflector
Source
$V^{\perp}_{obs}(t)$
V_T
β
Sun
line of sight
Earth
Projection of the earth orbit

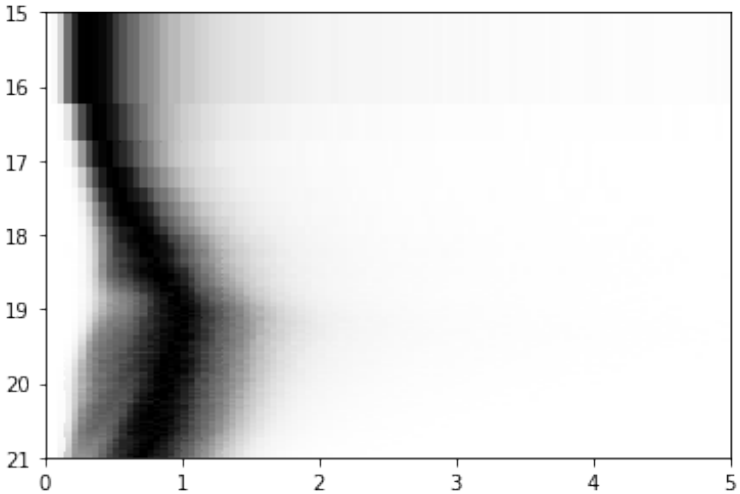

Deflectors plane
y
deflector at t
v_T (t_E >0 case)
deflector at $t=t_0$
$u_D(t)$
intersection of line of sight at t
u_0
$u_E(t)$
θ
x
ξ(t)
$a_\oplus(1-x)cos\beta$
$a_\oplus(1-x)$
j
i

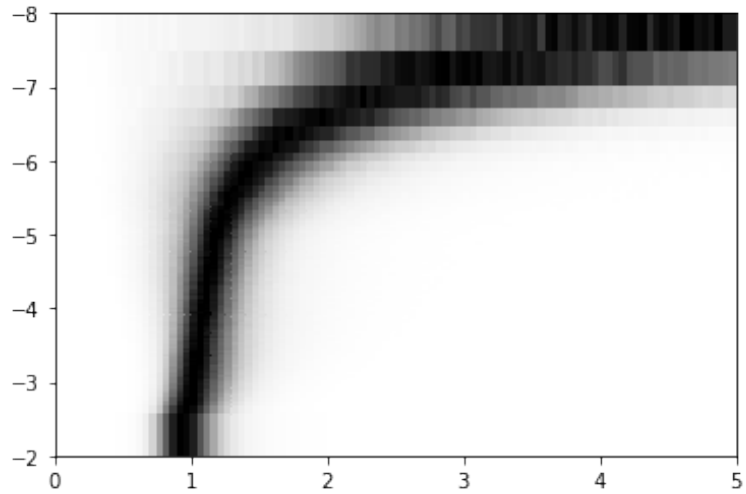

standard
parallax
I [mag]
HJD − 2450000 [days]


D_π> 0.05 mag
D_π> 0.1 mag
D_π> 0.25 mag
D_π> 0.5 mag
Fraction of D_π > threshold [%]

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