Search for black holes in the Galactic Halo by Gravitational Microlensing

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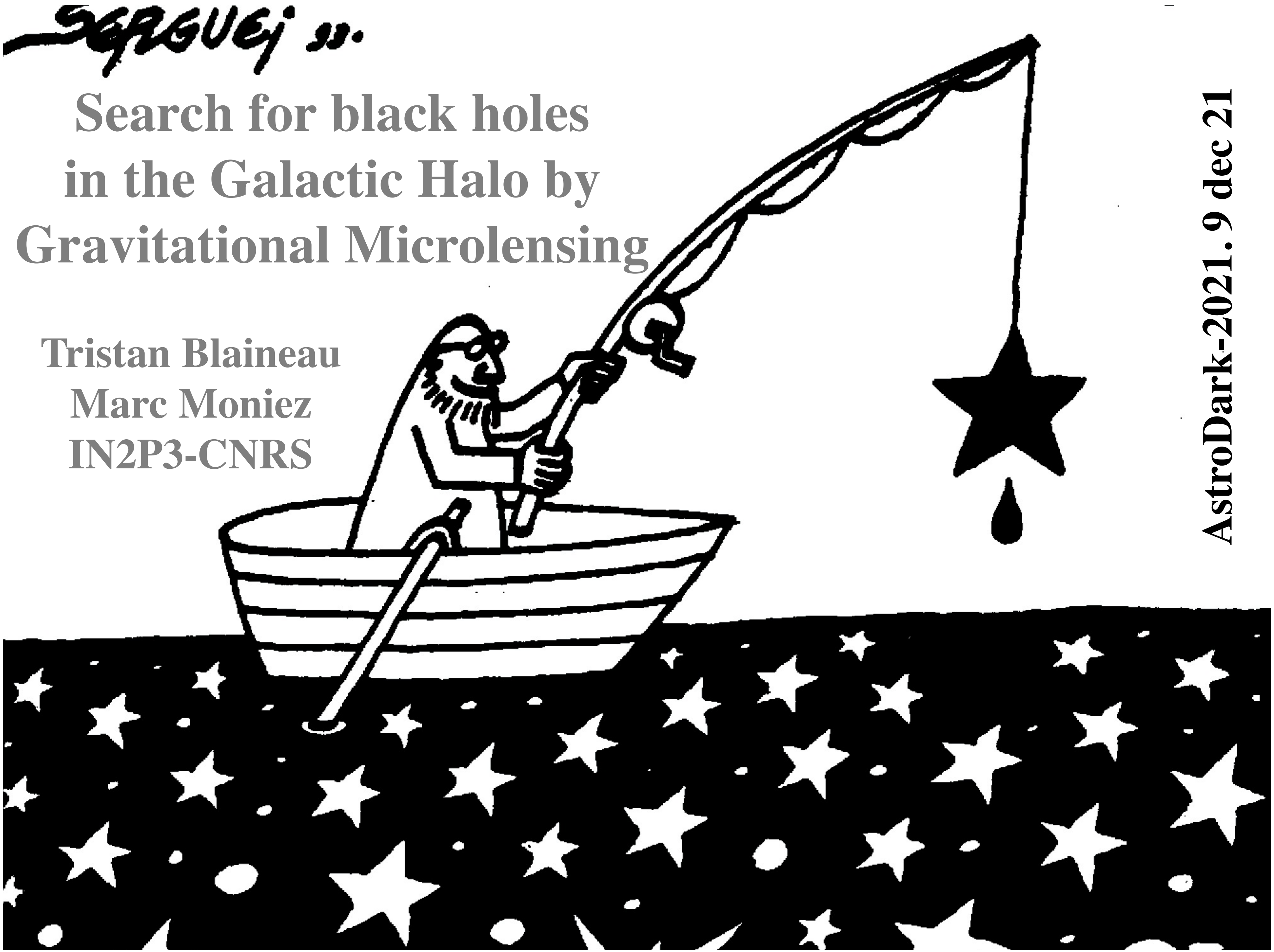
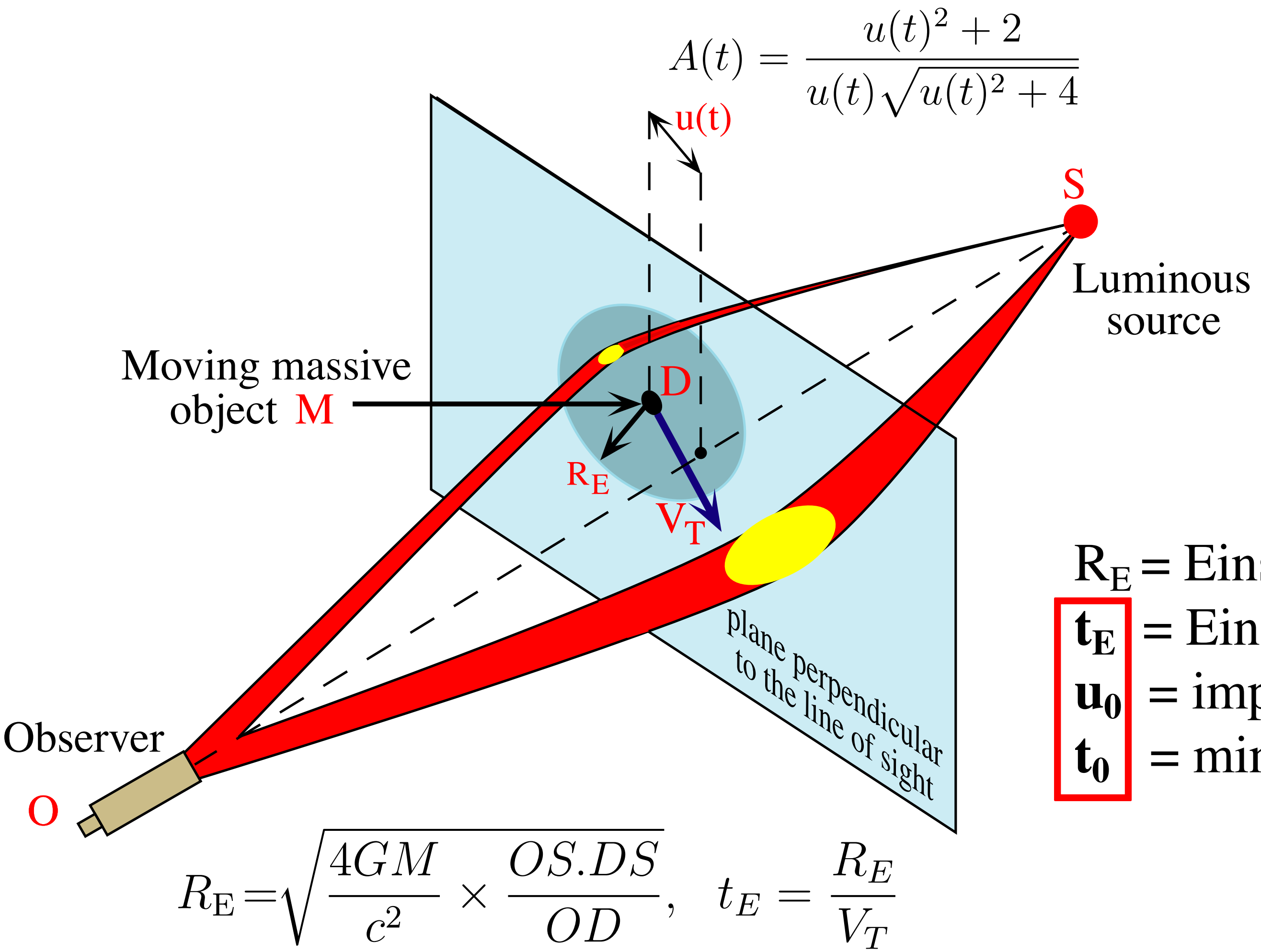


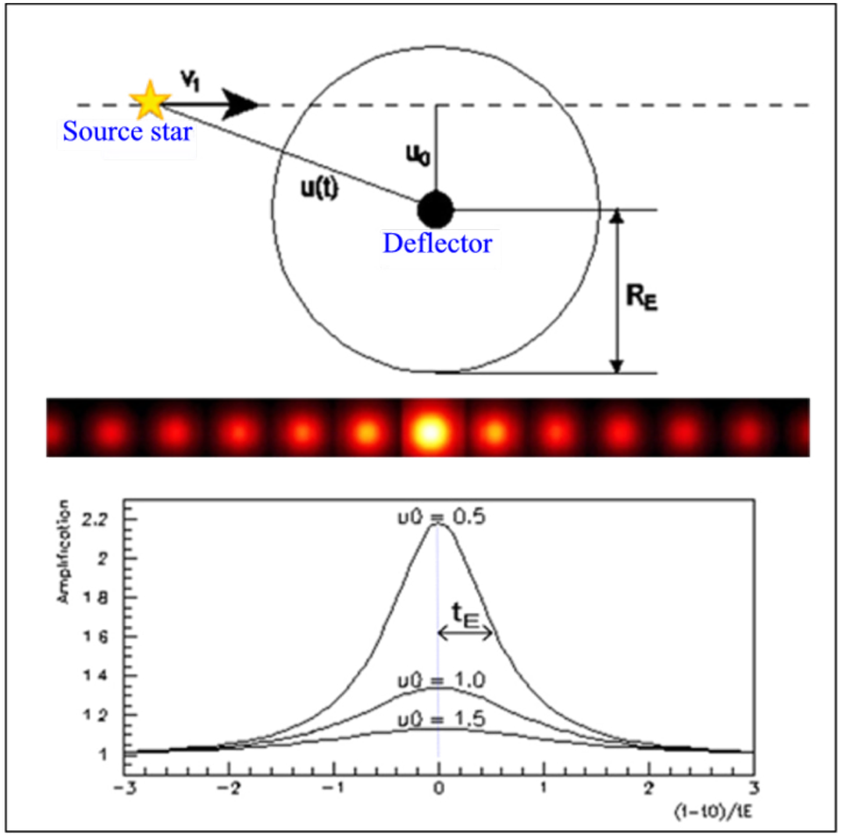
AstroDark-2021. 9 dec 21

Gravitational microlensing effect



R_E = Einstein radius
$\mathbf{t_E}$ = Einstein duration
$\mathbf{u_0}$ = impact parameter
$\mathbf{t_0}$ = minimum approach time

Description of a microlensing event



Light curve characteristic:

- Symmetric
- Achromatic
- Unique (~1 evt / 10^6★)

Point-lens, point source, rectilinear relative motion

The optical depth τ

- probability for a star to be behind an Einstein disk

- disk surface α R_E^2 α M_{lens}

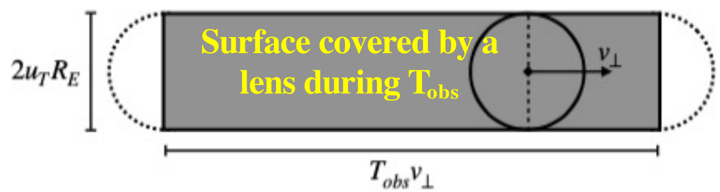
$\Rightarrow \tau \, \alpha \, \Sigma M_{lens}$

α **total mass** of the probed structure

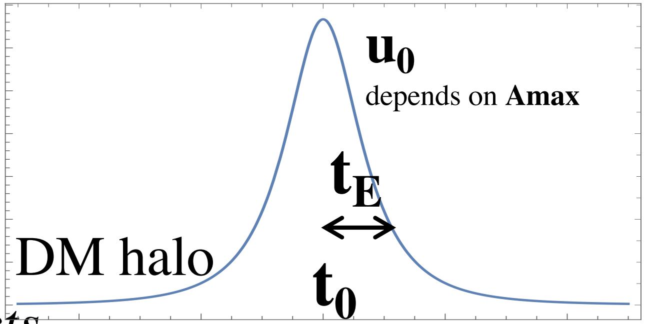
The number of events with u_0<1 in T_{obs}

α surface swept by Einstein disks

$\alpha \; \Sigma R_E \, . \, Vt \, . \, N_{star} \, . \, T_{obs}$



The LMC is monitored for microlensing since the 90s'



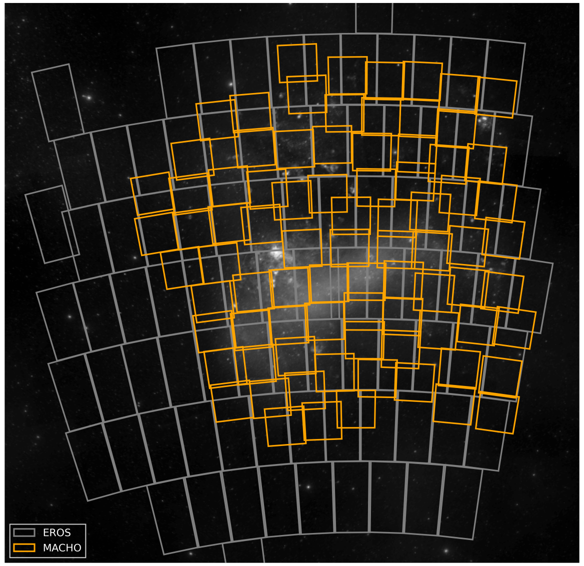
-> search for massive compact objects within the galactic DM halo
At this epoch: *sub-stellar and stellar mass objects*

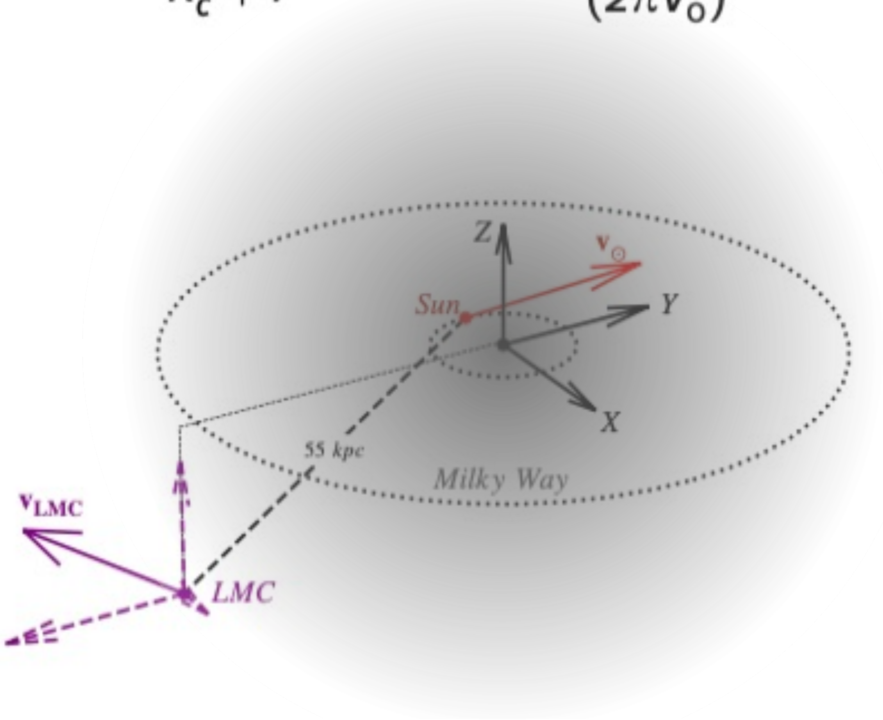
- Pseudo-isothermal spherical halo model $\Longrightarrow$ conventionally used to determine the constraints on the quantity of MACHOs in the halo.

$$\rho(r) = \rho_0 \frac{R_c^2 + R_\odot^2}{R_c^2 + r^2} \qquad p(v) = \frac{4\pi v^2}{(2\pi v_\odot^2)^{3/2}} e^{-\frac{v^2}{2v_\odot^2}}$$

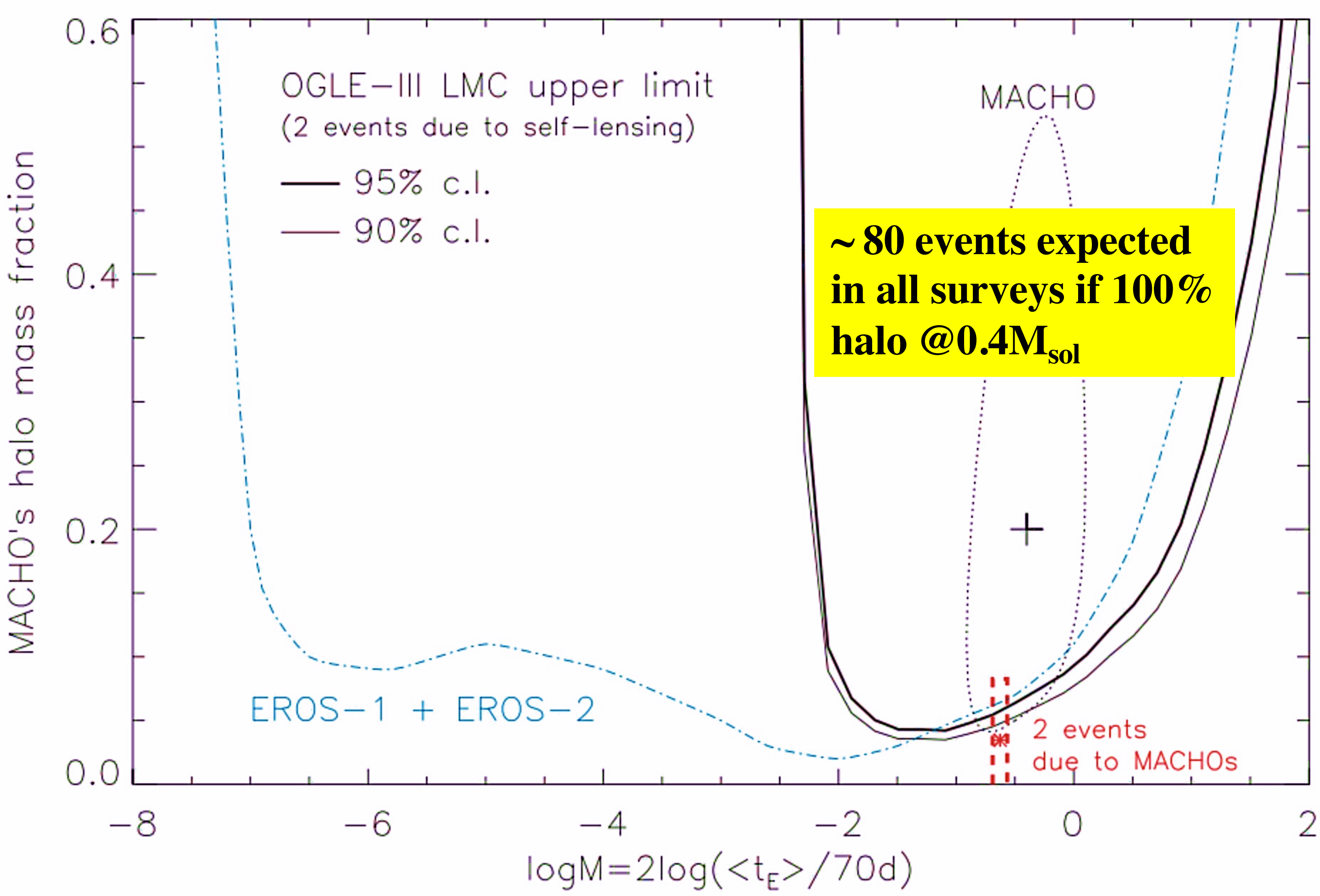
$\rho_0 = 0.008\ M_{sol}/pc^2$
$R_C = 5kpc$
$R_{sol} = 8.5kpc$
$v_0 = 155\ km/s$
$v_{sol}\ /\ v_{LMC}$ …

$\tau \sim 4.5 \times 10^{-7}$

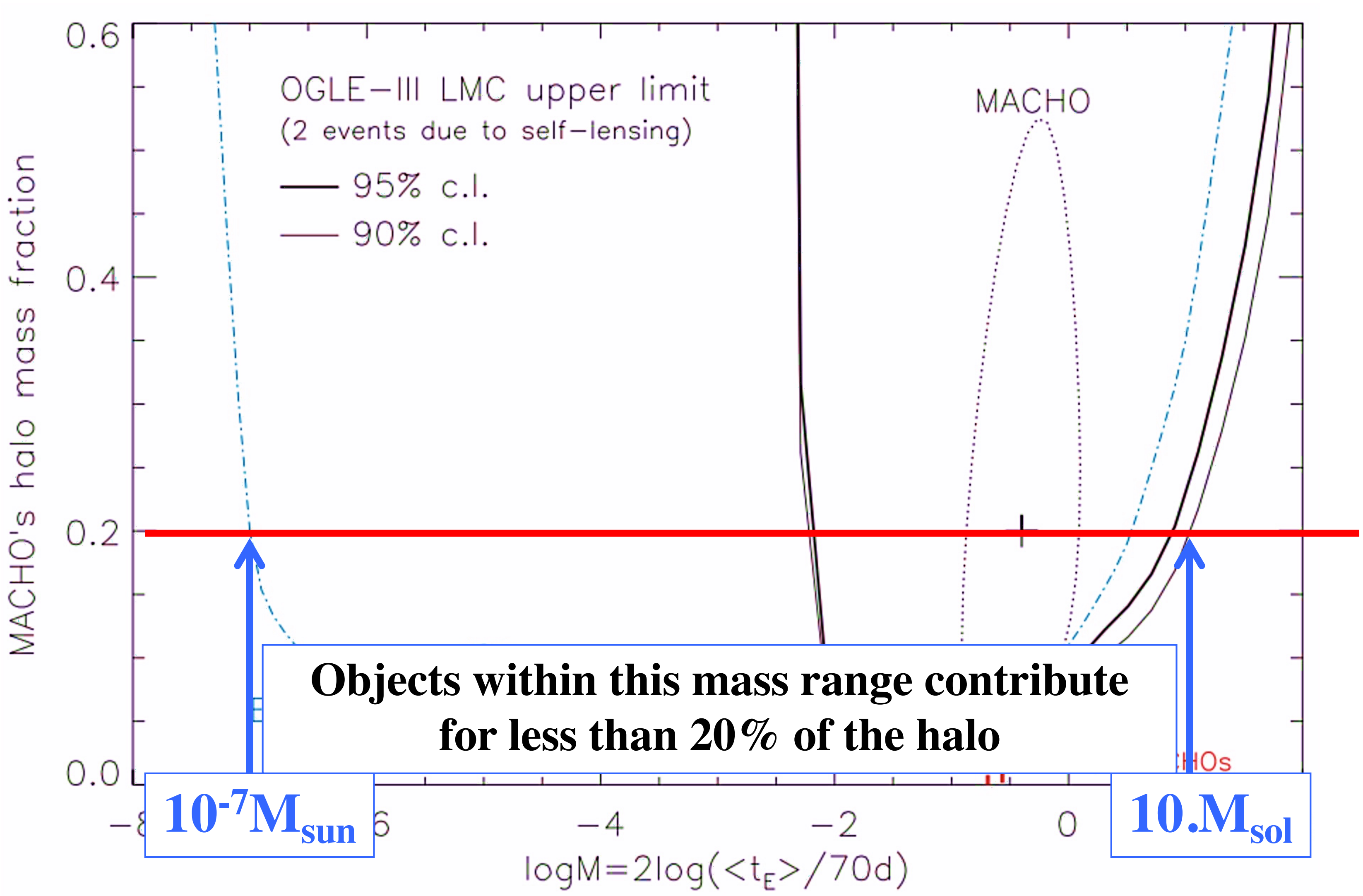




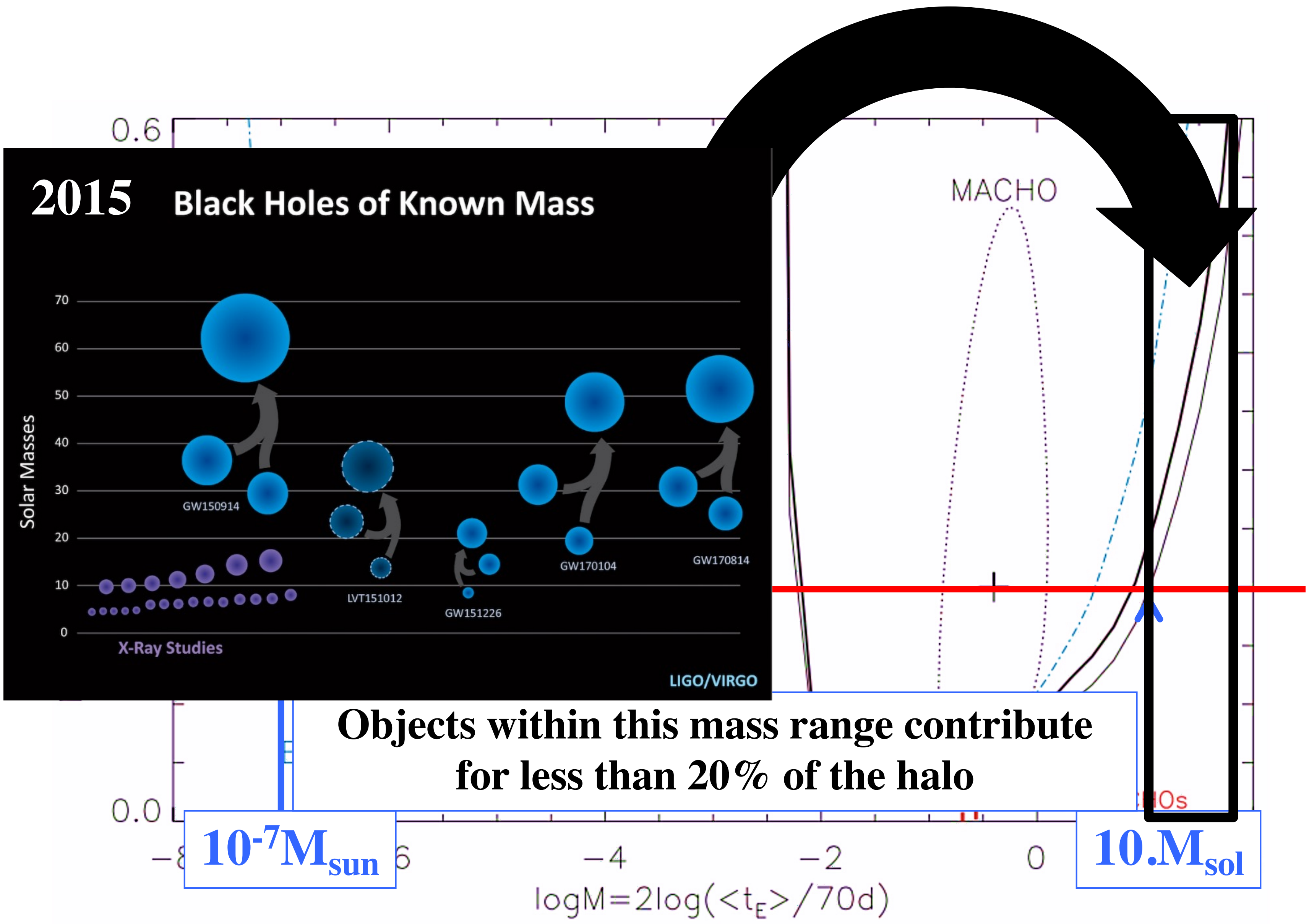
The Milky way halo: LMC surveys



The Milky way halo: LMC surveys



Detected black holes are just heavier



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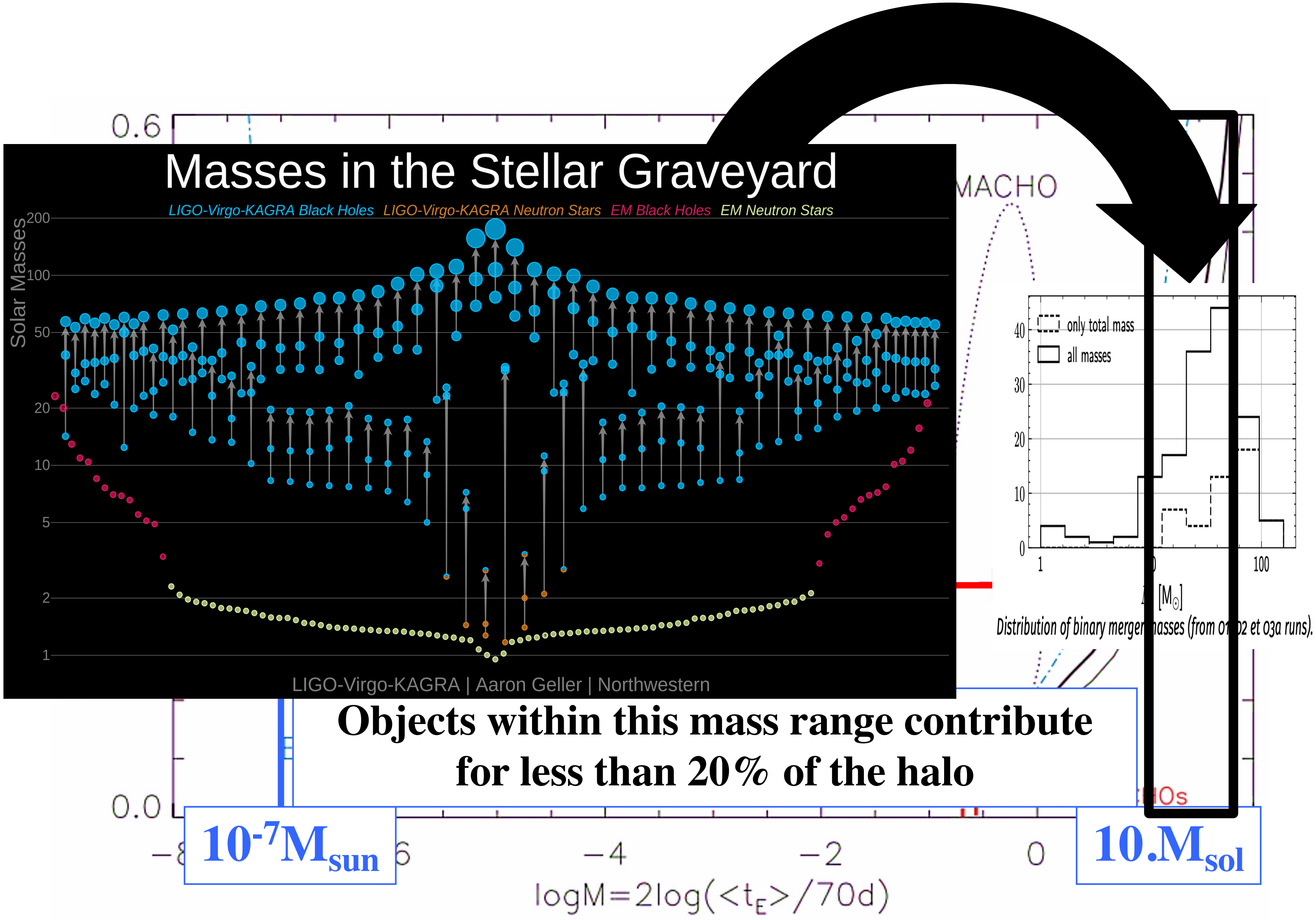


Search for very long events with joined data analysis: MEMO project

Heavy lenses produce long duration events

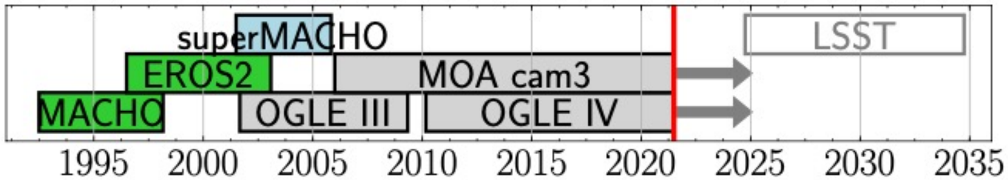
$<t_E> \sim$ 70 days x sqrt(M_{lens}/M_{sol}) (2yrs for 100M_{sol} lens)

Detection efficiency of the past surveys **vanishes** for such durations, because:

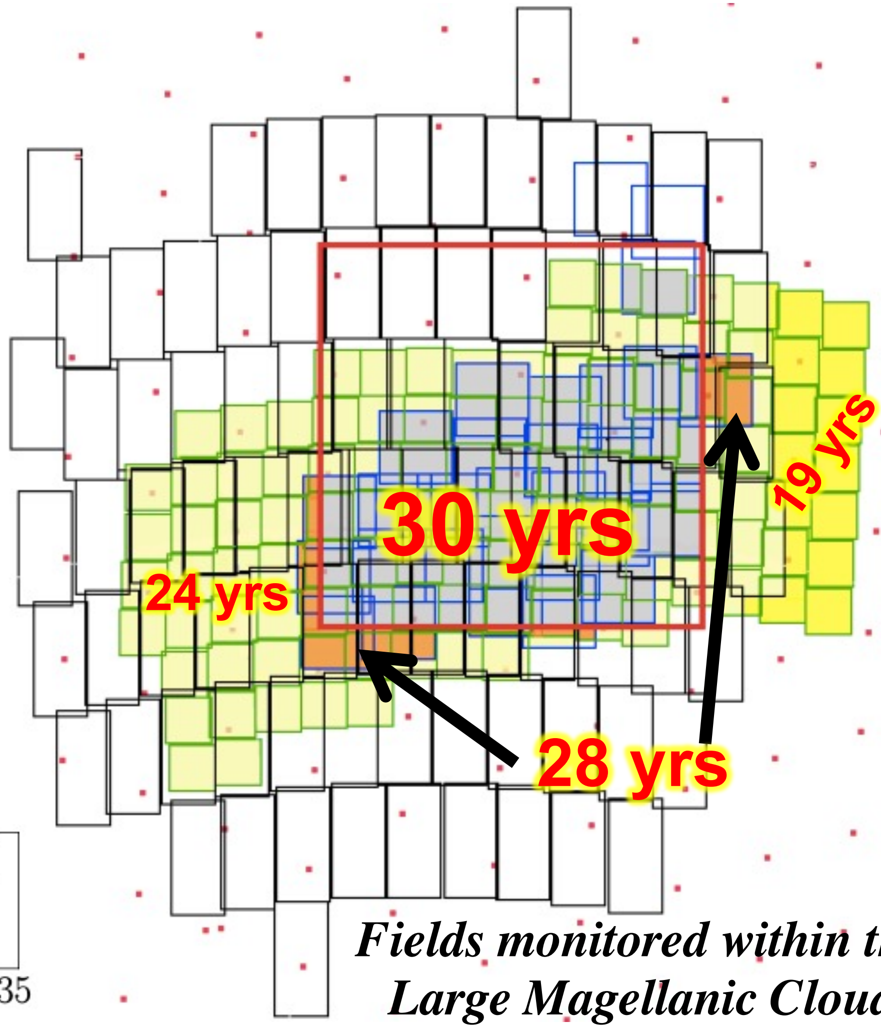
- Limited duration Δt of each survey (3-8 yrs)
- Multi-year search suffer from telescope/filter ageeing/transmission variations
- Observation/Analysis optimized for light lenses

MoaErosMachOgle combined light-curves provides much more extended light-curves.

Here only the combination of EROS2 and MACHO has been performed

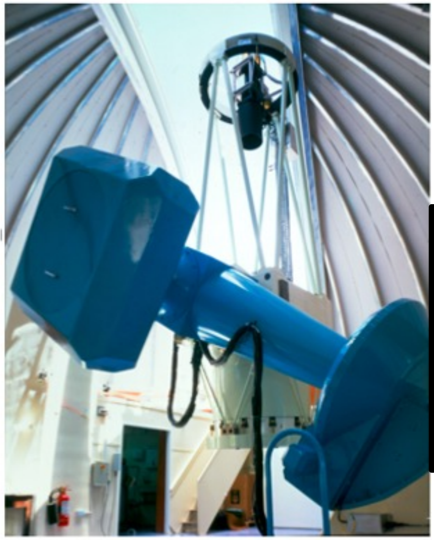


Observation time span of the surveys toward the LMC.



Fields monitored within the Large Magellanic Cloud produced by A. Mirhosseini

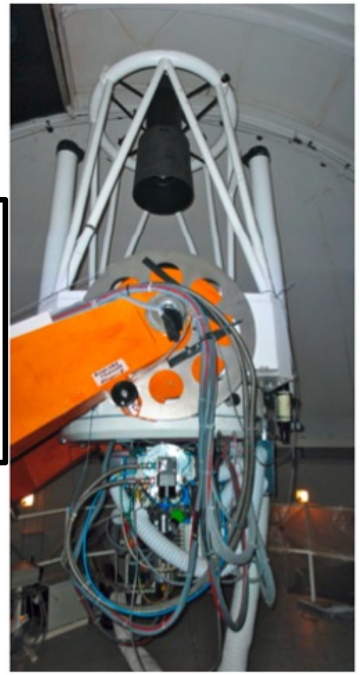
EROS2 and MACHO



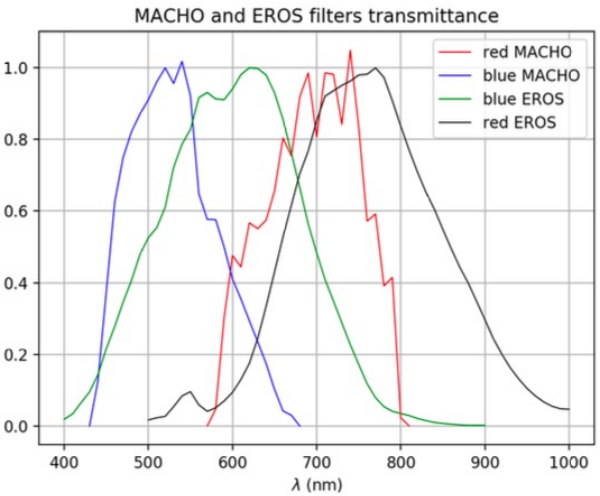
Great Melbourne Telescope (MACHO).

Systematic surveys towards the LMC

MACHO	EROS2
• **1.27m** telescope in Australia • 2 cameras with dichroic • **4 CCD** 2Kx2K pixels each • Field of view: **0.5 deg²**	• **1m** telescope in Chile • 2 cameras with dichroic • **8 CCD** 2Kx2K pixels each • Field of view: **1 deg²**

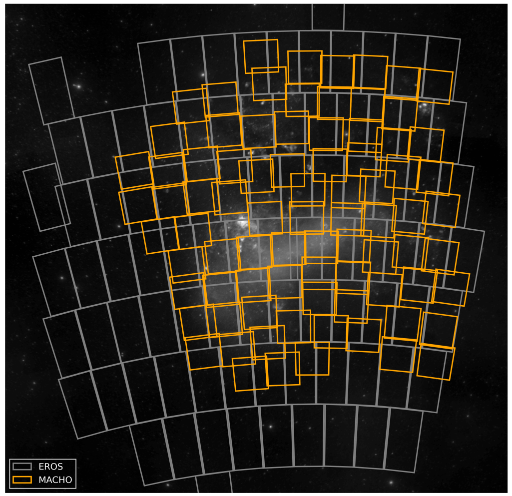


Telescope MarLy (EROS).



- 2+2 wide bandwidth filters
- ≈ **1** To light curves databases (∼25 To of images)
- between 500 and 4000 total individual measurements overall per source
- directly available databases
- light curves already partly processed

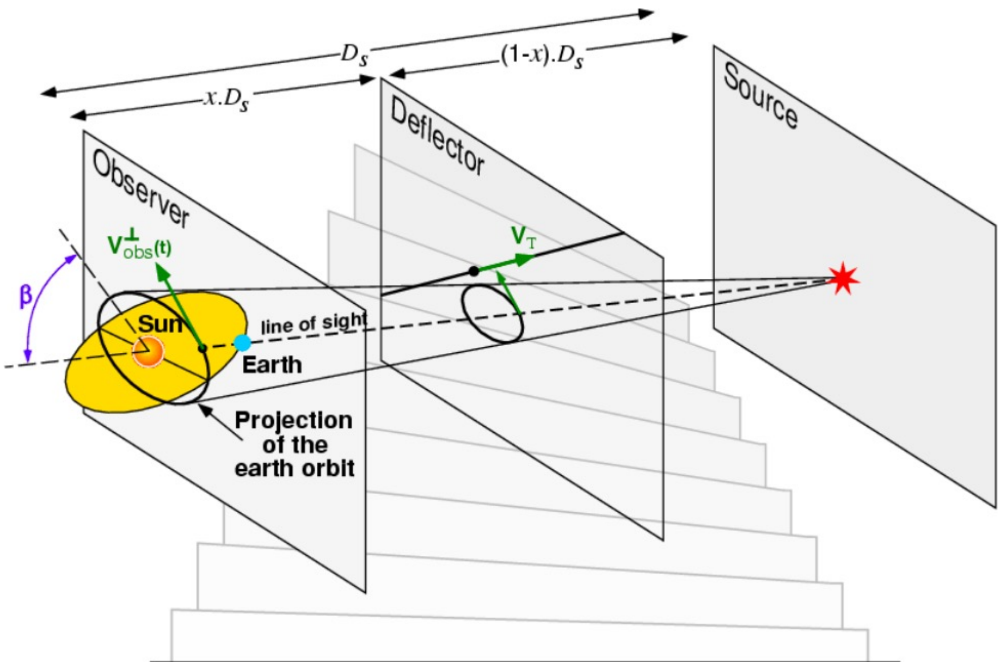
LMC fields



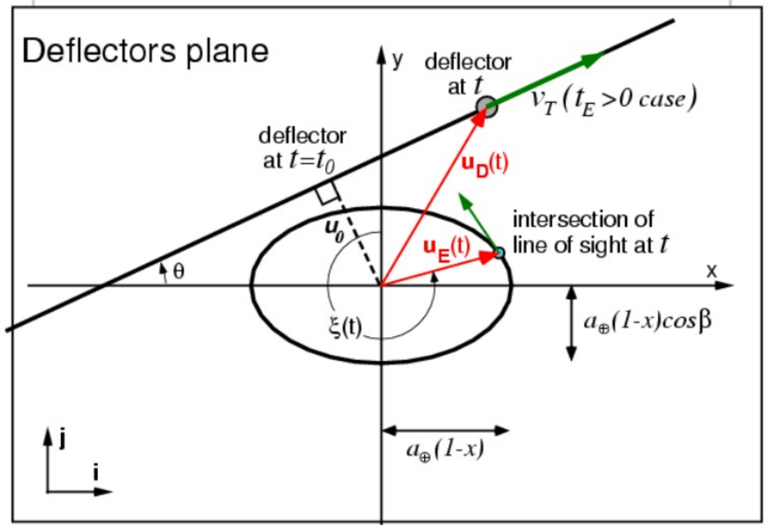
	EROS only	MACHO only	common
Dates (m/yr)	7/92-1/00	7/96-2/03	7/92-2/03
Duration (year)	6.7	7.7	10.6
Sources $\times 10^6$	15.8	$6.9^{(a)}$	14.1

$\Longrightarrow$ 14.1×10^6 stars in common over 10.6 years.

Does parallax complicate the analysis?



- Due to Earth orbiting, apparent trajectory of the lens w/r line-of-sight is an **hypocycloid**
- u(t) (and magnification) shows modulations with 1 year caracteristic time

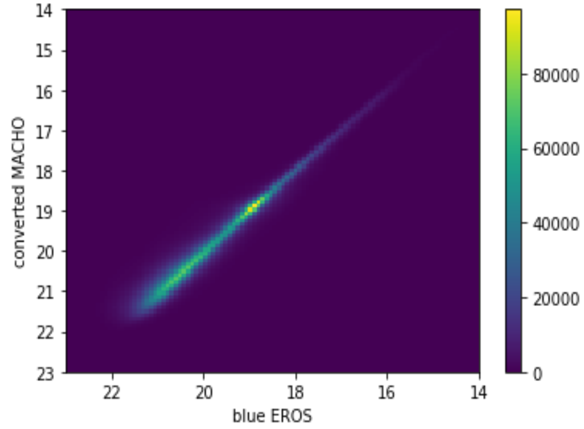


In the worst scenario, less than **7%** of events could be missed by a simple search algorithm.
(Blaineau & Moniez (2020))

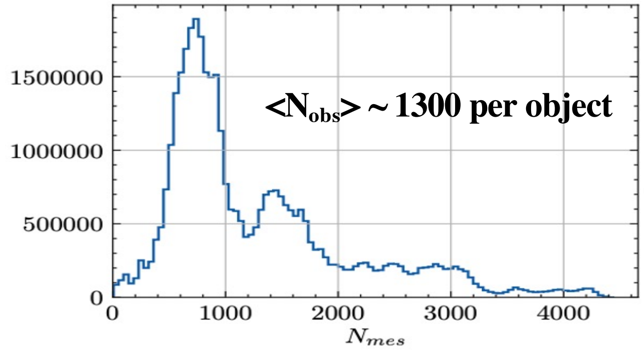
-> We neglect this effect in the search, but simulate it in the efficiency calculation

Association, cleaning…

- **Cross-identification EROS-MACHO catalogs** (using GAIA)
  - To better than 0.1 arcsec in (α,δ)
  - To the photometric precision in flux



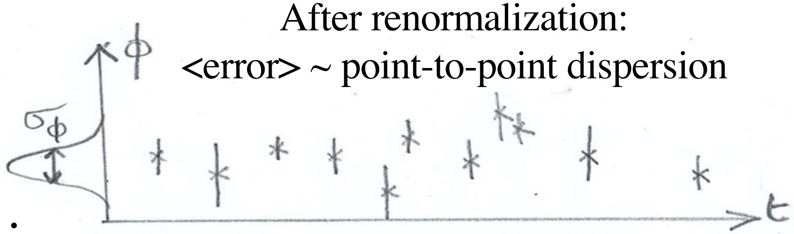
- **Improved cleaning**
  - 3% of MACHO and 1% of EROS problematic measurements removed
  - Keep light-curves with > 200 points



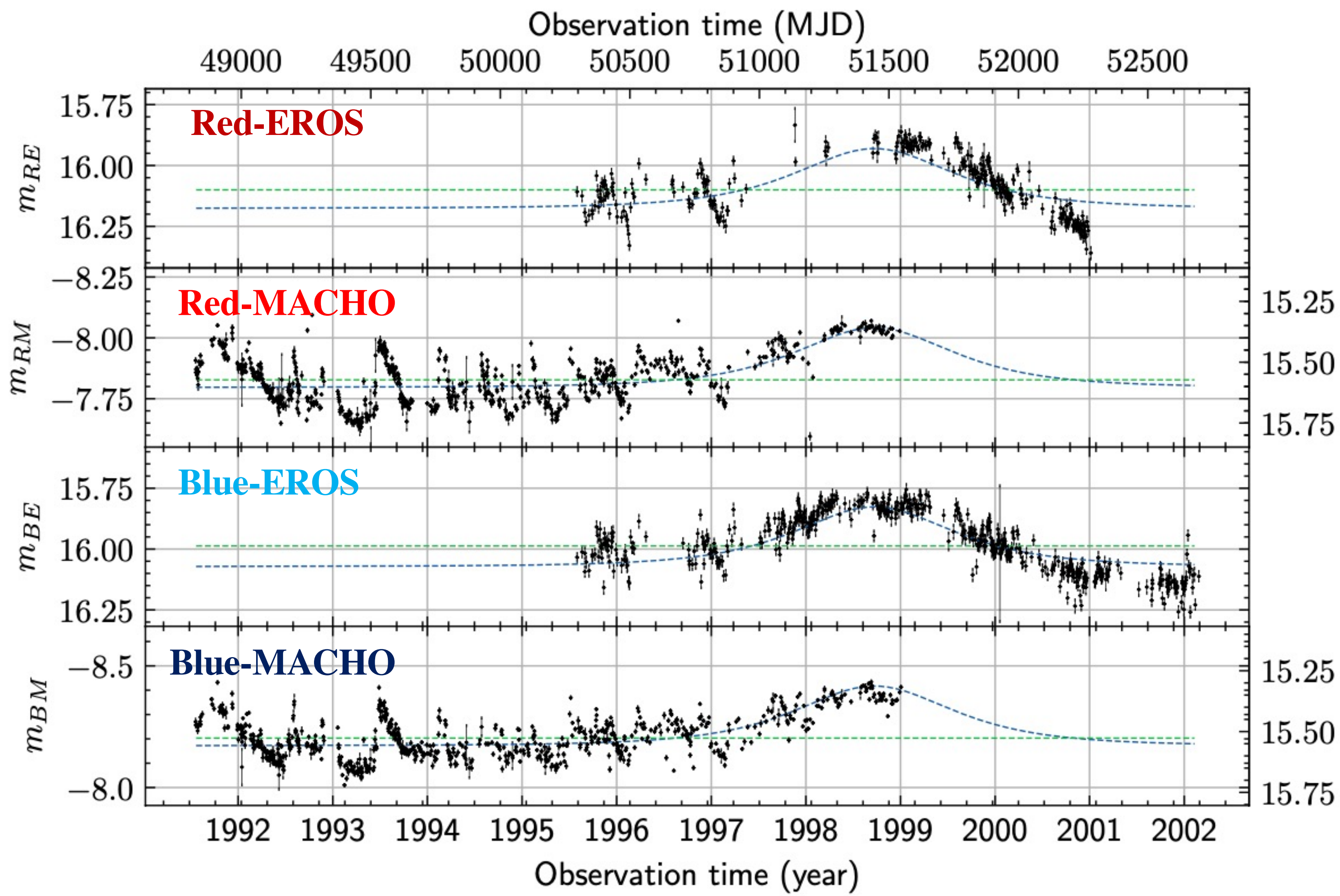
Total number of observations for each source.

- **Homogenize photometric uncertainties**
  - Underestimated by MACHO
  - Overestimated by EROS for faint stars
  - Global normalization to have errors compatible with the point-to-point dispersion

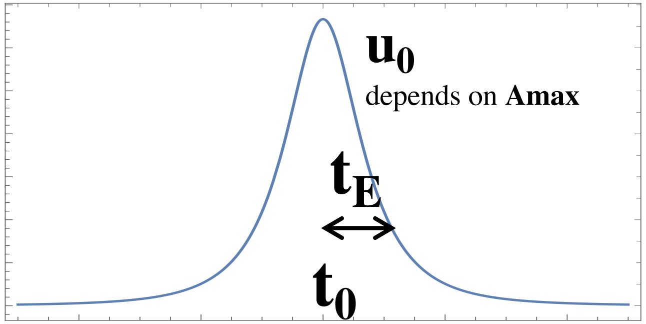
After renormalization:
<error> ~ point-to-point dispersion



Combined light-curve



Discriminant analysis



Based on the comparison of the χ^2 of a constant fit and a microlensing fit, **simultaneous to the 4 light curves**.

- Constant fit (flat) : 4 parameters, **1 mean flux/colour**.

- Microlensing fit (μ) : 7 parameters, common $\mathbf{u_0}$, $\mathbf{t_0}$, $\mathbf{t_E}$, **1 base flux/colour** (could be more than 4 when adding OGLE/MOA)

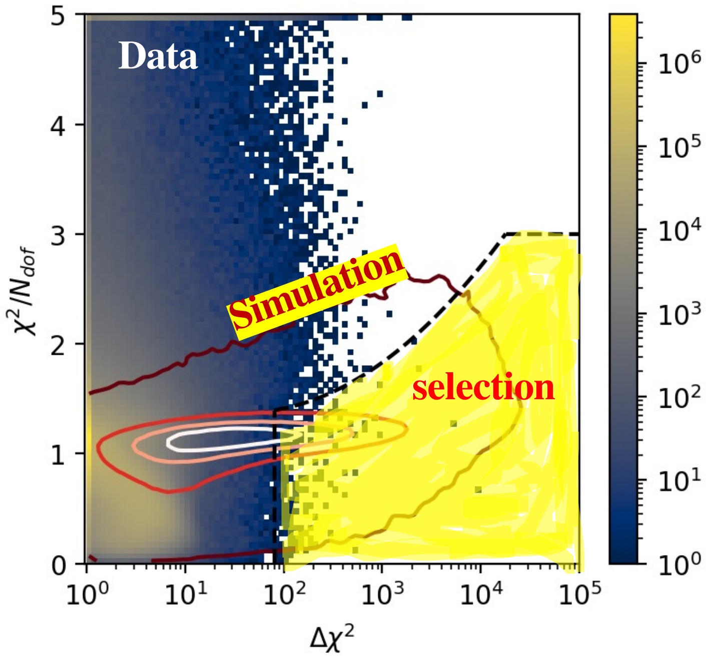
Goodness of microlensing → χ^2_μ / N_{dof},

difference (flat – microlensing) → $\Delta\chi^2 = \frac{\chi^2_{flat} - \chi^2_\mu}{\sqrt{2N_{dof}}} \frac{1}{\chi^2_\mu / N_{dof}}$

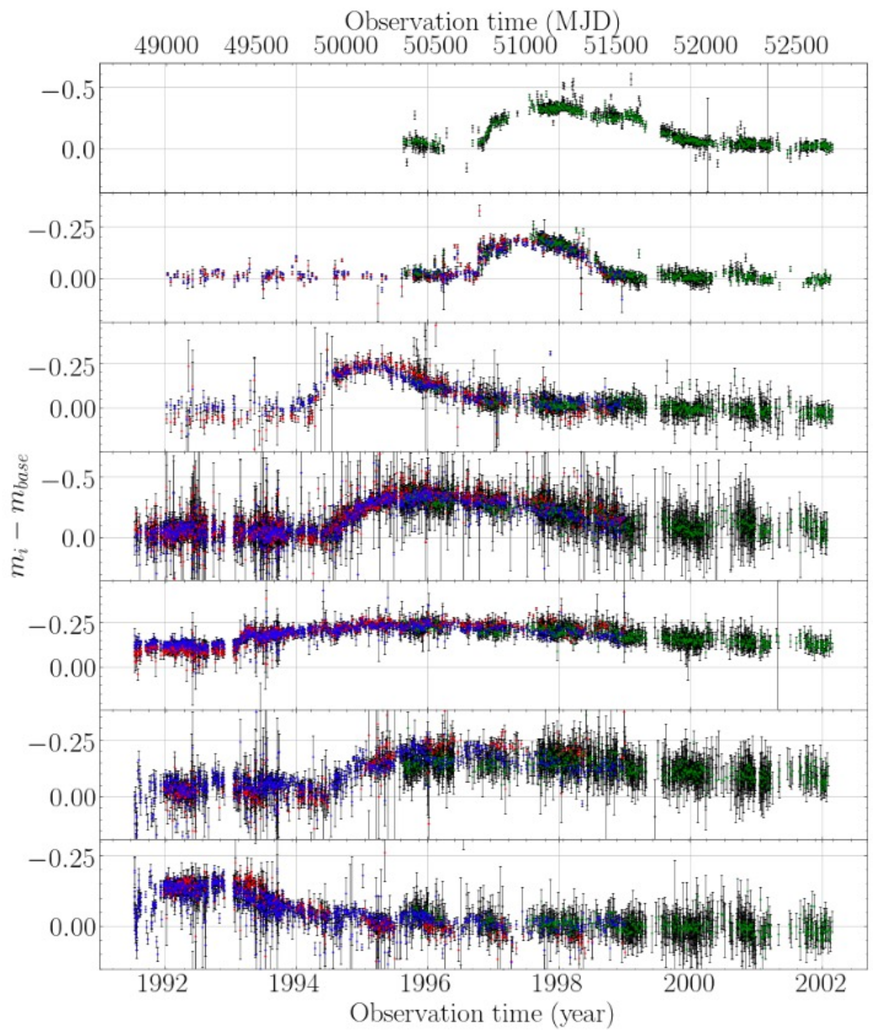
Require long events but well contained

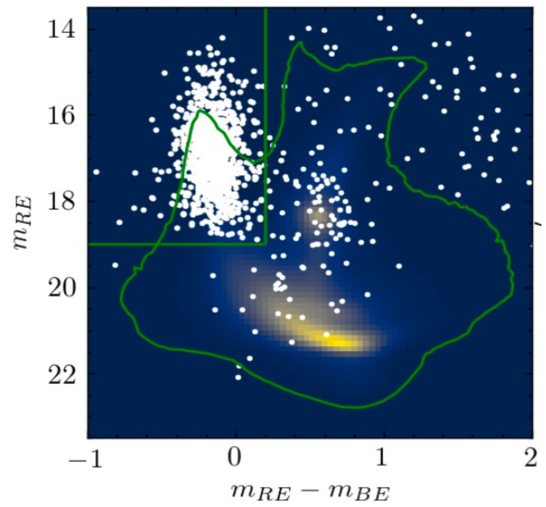
$100 \text{ days} < t_E^{fitted} < T_{obs}/2 \sim 2000 \text{ days}$

$T_{start} + 200 \text{ days} < t_0 < T_{end}$



Main remaining artefacts





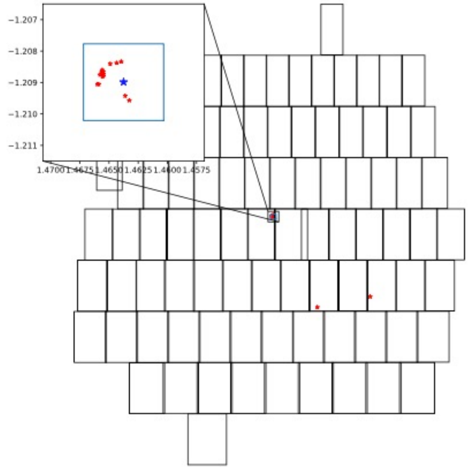
← examples of *blue bumpers*
red EROS : black
red MACHO : red
blue EROS : green
blue MACHO : blue

Blue bumpers

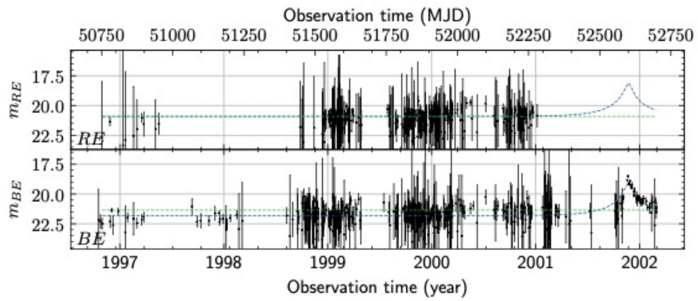
- Short variables were known in past surveys
- Increase faster than it decrease
- Can last several years
- Be stars ?

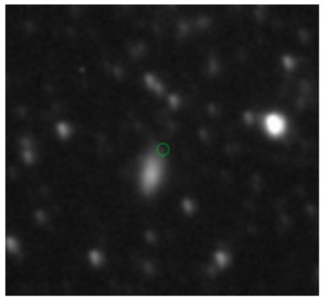
Other remaining artefacts

- **SN1987A echoes**
  - Diffusion of the light emitted by the SN, superimposed on a monitored star
  - Remove a small patch of sky
- One **QSO** (catalogued)
- One **YSO** (Young Stellar Object – variable, catalogued)
- One clear **SN** (not catalogued)

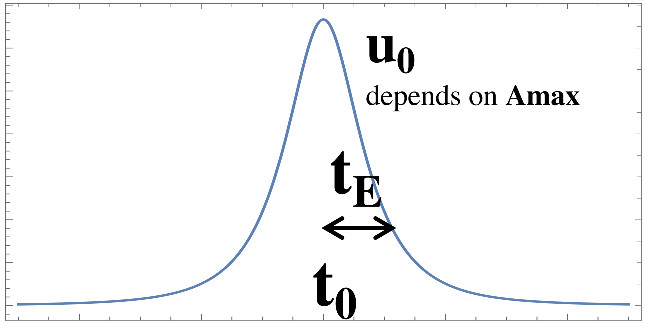


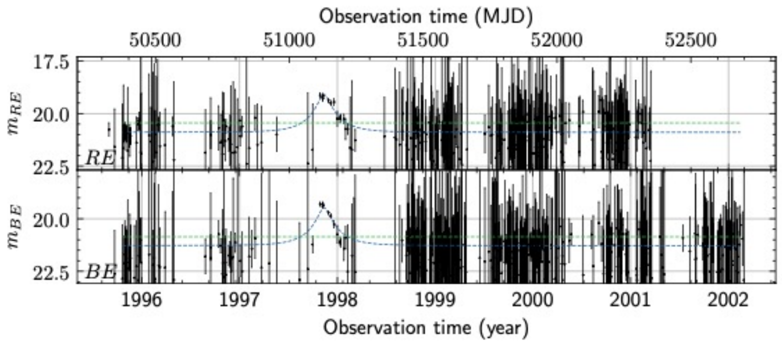
Positions of the remaining candidates relative to EROS fields. Removed area ≈ 0.14° × 0.14°



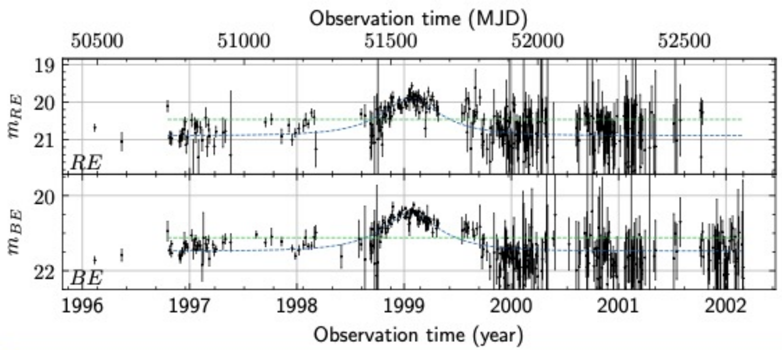


Candidates: only 2





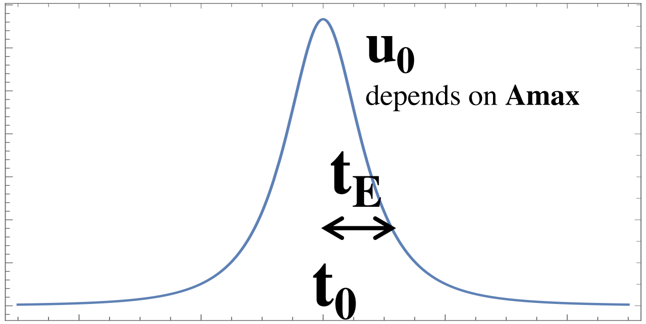
$u_0 = 0.19$, $t_E = 106$ d.
Very asymmetric, strong (apparent) amplification, low probability of being microlensing



$u_0 = 0.41$, $t_E = 183$ d.
Suspicious brightness variations

We cannot formally reject these « low quality » candidates without using more criteria.

Expected signal from the standard halo (S model)

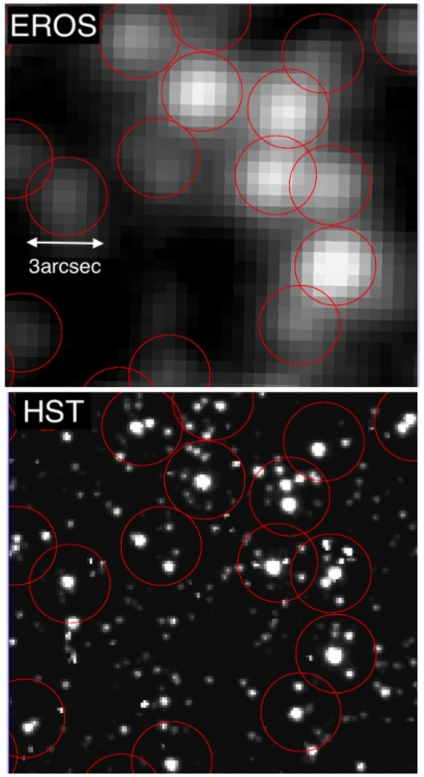


Simulation based on the observed (stable) light-curves modified by simulated microlensing according to the standard DM halo :

- *Preserving the initial deviations from the base flux*
- *Taking into account the variation of photometric precision with the flux*

Since MACHO or EROS objects are blends of several stars

- *Use* ***HST*** *images to infer the content of MACHO and EROS objects*
- *Microlensing is simulated on each component and the resulting light curve is the sum of a magnified and stable components*



New: Blend in binary systems (not resolved by HST in LMC) ?

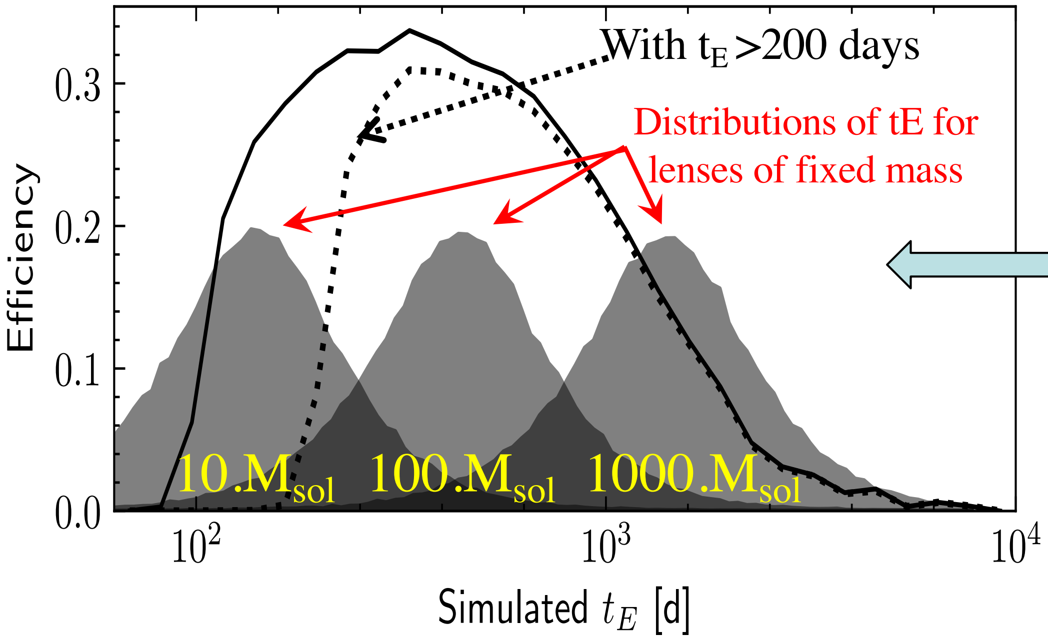
For microlensing by **heavy lenses** (long time scale, large R_E):

- *Using the GAIA database, we estimate < 7% of the sources are binaries separated by more than 50AU, inducing blend effect for long duration events (to be published) - binaries closer than 50AU are ~ identically magnified by a large Eintein disk.*

-> Impact of binarity neglected (conservative)

Expected signal from the standard halo (S model)

$$\varepsilon = \frac{\textit{All selected events from simulation}}{\textit{simulated events with } u_0 < 1 \textit{ and } t_0 \textit{ in observation epoch}}$$



Depends on

Halo model for compact objects

- Spatial distribution
  -> derive optical depth to LMC
  $\tau \sim 4.5\text{x}10^{-7}$
- **V_T** distribution
- **Mass** distribution (here **δ(M)**)
  -> derive **t_E distribution**

Mean detection efficiency

- Estimated as a **function of t_E**

Proportional to

- **T_{obs}**
- **N**$_{\textbf{star in LMC}}$ = 0.95 x $N_{\text{star catalog}}$
  (< 5% Milky Way stars –from GAIA data)

Final correction: max 10% of events can escape detection because they are exotic (double lens…)

Exclusion limit

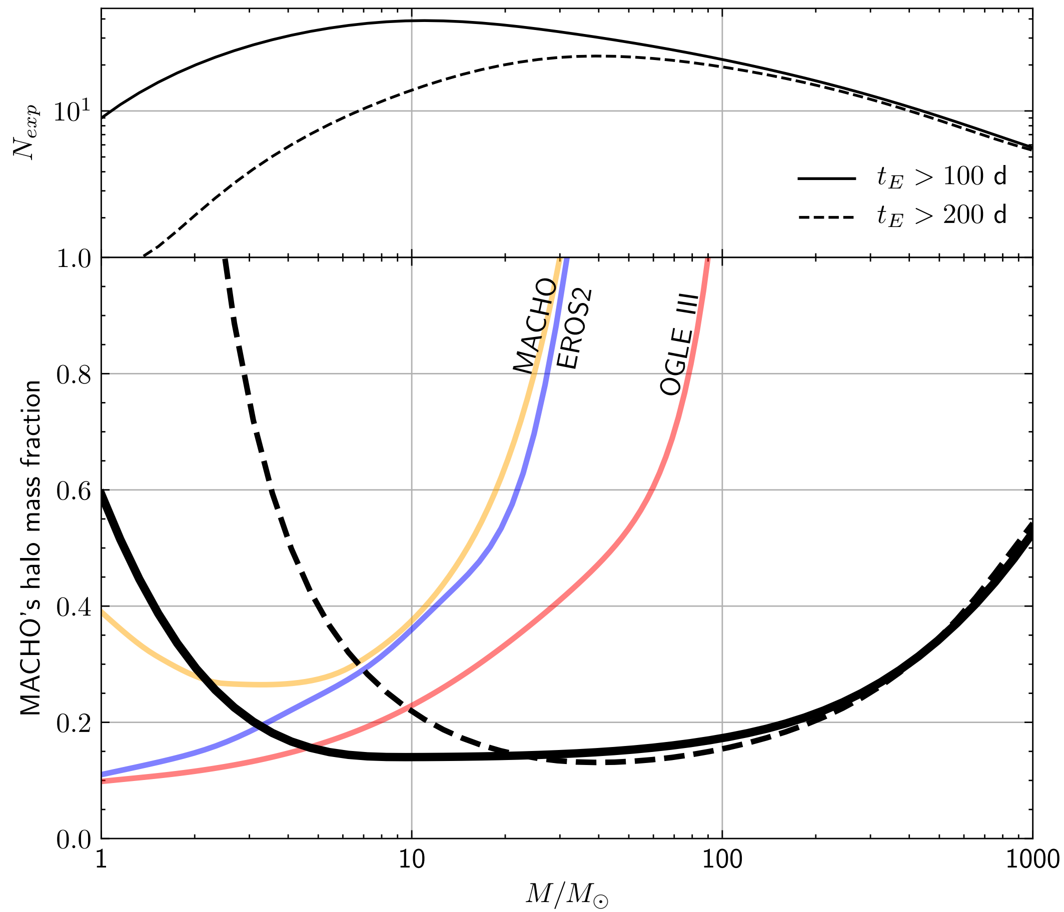
This analysis

- ~ **0.64** events expected from self-lensing+disk (with 100 < t_E < 200 days)
- **2** events observed
- Likelihood analysis to find 95% CL exclusion limit

If we further require t_E > 200 days

- **0** events expected from self-lensing+disk
- **0** event observed
- Poissonian analysis: 3 events excluded at 95%CL

Agree for high mass exclusion



Several sources of gain

- **Previous analysis explicitely rejected long events**
  - To have a long enough baseline / reject LPV
  - Here we use published catalogs
- **Cumulate EROS + MACHO statistics**
- **14.1 million light-curves monitored for 10.6 years**
  - Detection efficiency for these curves is x by 1.6
  - Contribute for ½ of the expected detections for a halo made of 1000.M_{sol} lenses

Conclusions, perspectives

Microlensing observations and the Galactic halo

- ✓ We have combined EROS2 + MACHO data towards LMC
  - ✓ SMC not analyzed (only 5.2 million sources)
- ✓ **Objects with $M < 1000.M_{sol}$ do not dominate the Galactic DM halo (@95%CL)**

What about the black holes responsible for the GW?

- ✓ Either they are scarce and do not explain the DM
- ✓ And/or they are in the visible structures of the Milky Way? -> microlensing towards the Galatic Bulge and spiral arms

Perspectives

- ✓ Short term: do combined analysis from **all** databases (incl. MOA and OGLE)
- ✓ Make database ready for looking back in the case of emerging events
- ✓ Long term LSST
  - 10 year wide field monitoring from 2024
  - Includes repeated observations towards Galactic plane + LMC/SMC
  - Median repetition rate: 3 days between observations
  - 6 different filters
  - Combine LSST with the historical surveys -> > 30years