Search for intermediate mass black holes by combining MACHO and EROS data

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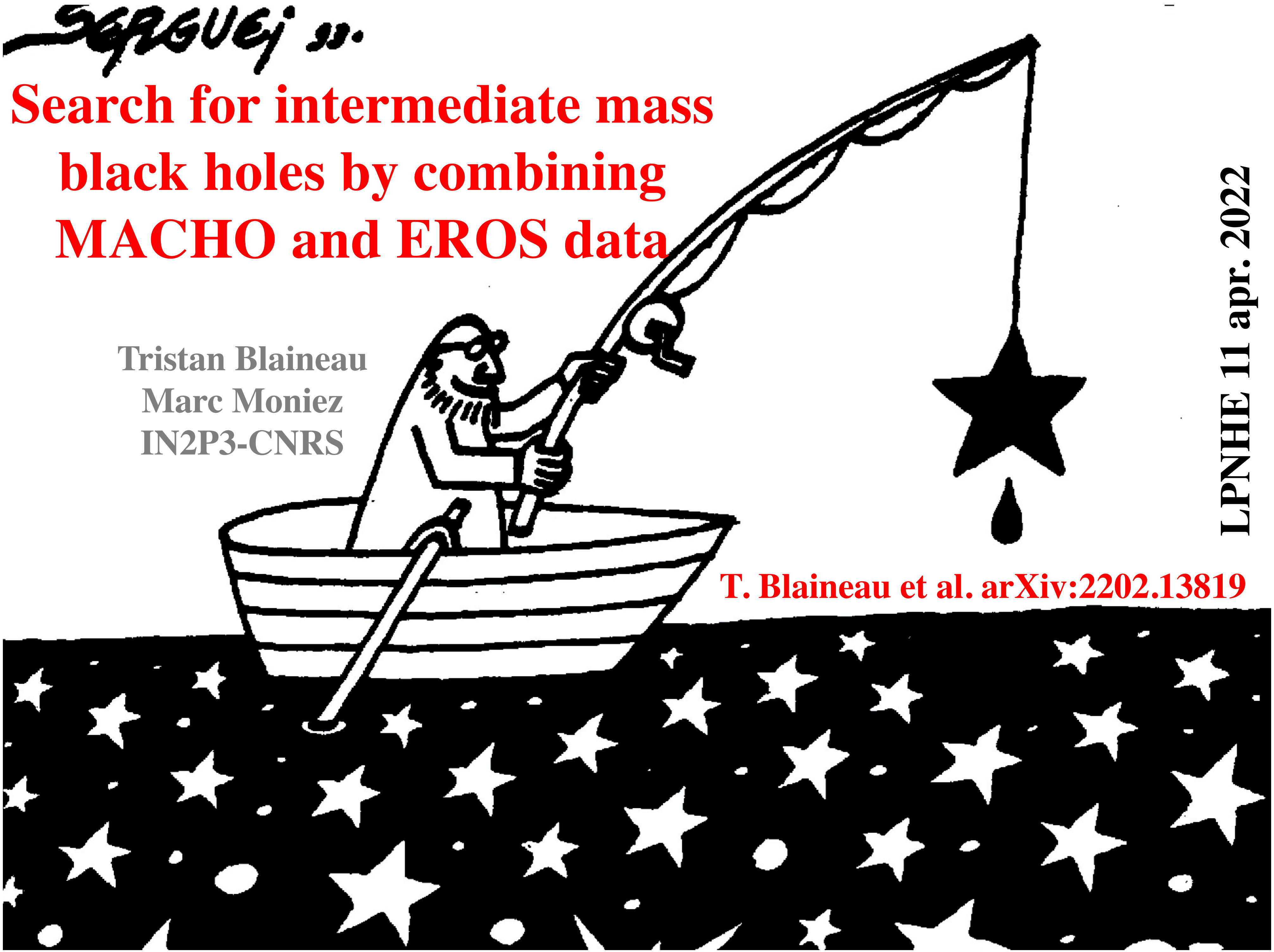


LPNHE 11 apr. 2022

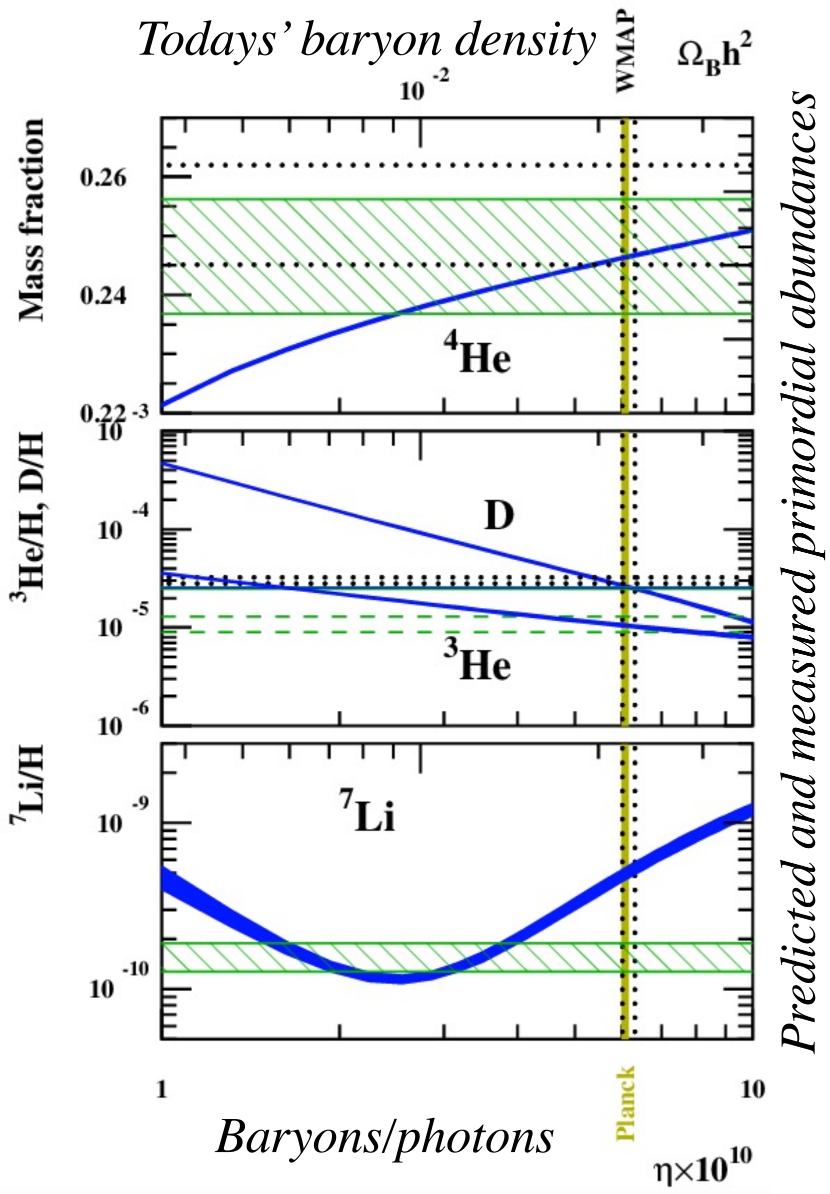
T. Blaineau et al. arXiv:2202.13819

Summary

- Where are the baryons in our galaxy?
  - **Old question**: sub-stellar mass objects as hidden matter?

  -> *Past searches for massive compact objects with microlensing*
- The opening of a new era after the GW discoveries
  - **New question**: where are the intermediate mass black holes?
- Data mining in historical archives EROS + MACHO
  - Combine / homogenize observations
- Specificities of the search for heavy objects
  - Search for multi-year microlensing events
- New exclusions from old data

Todays' cosmic abundance of Baryons



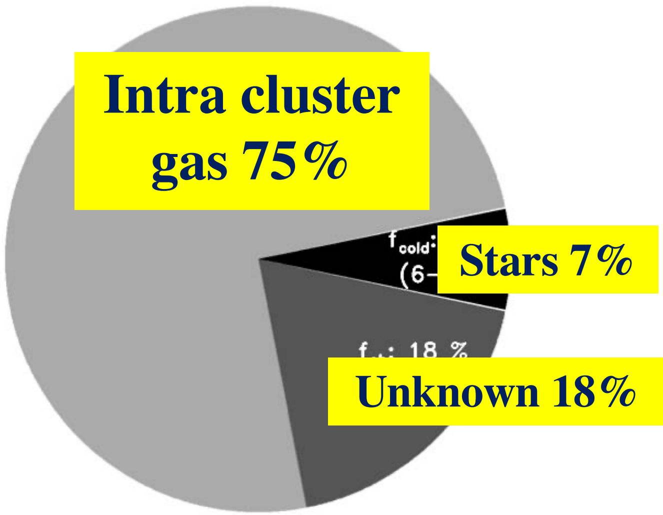
Primordial nucleo-synthesis + CMB
=> $\Omega_b = 0.05$

The fraction of baryons in matter is $f_b = 17\%$

- Mainly made of H + 25% He in mass

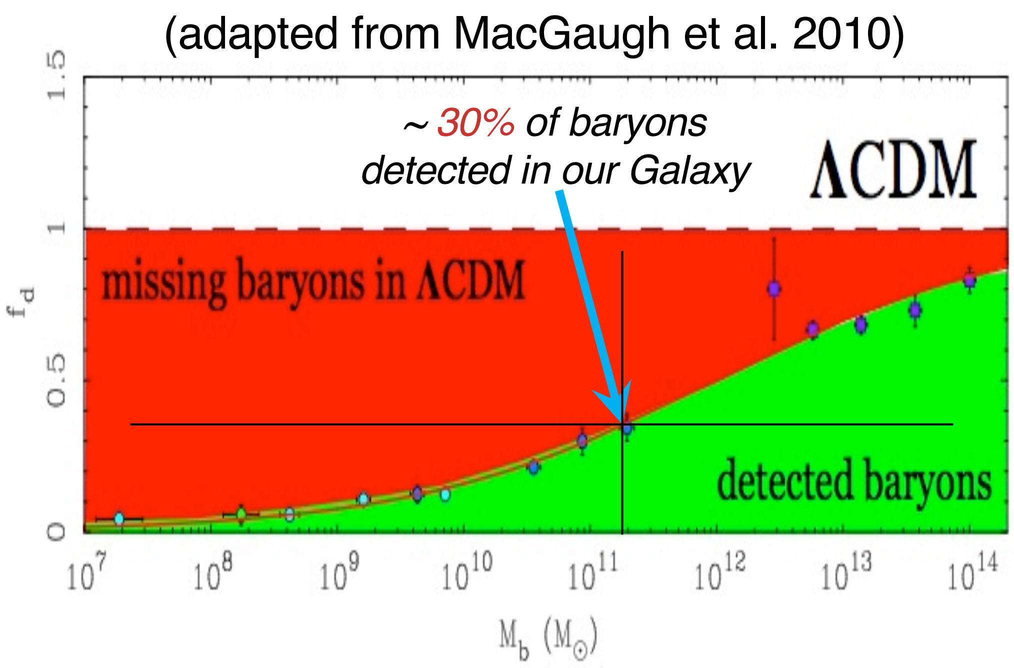
Cluster baryonic pie

Most of the baryonic mass in clusters is in hot, X-ray-emitting gas



More unknown baryons at smaller scales

Cosmic Baryonic Fraction: $f_b = \dfrac{M_b}{M_b + M_{CDM}} \approx 0.17$



Situation of the Milky-Way

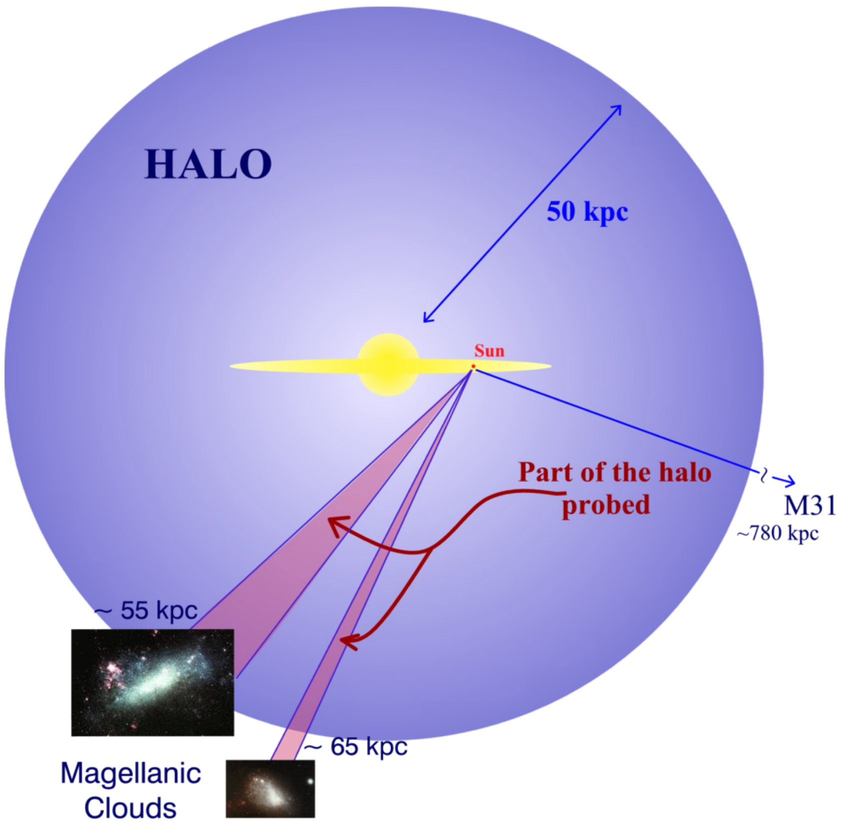
- **Visible mass** is **6.1x10^{10}** M$_{sol}$ +/- 0.5 (~5 stars, ~1 gas)
- **Dynamical mass** range from **5x10^{11}** M$_{sol}$ (until LMC) to 2x10^{12} M$_{sol}$ (until Leo I)
  -> Visible mass fraction < 10%
  -> We see (probably much) less than half of the expected baryons

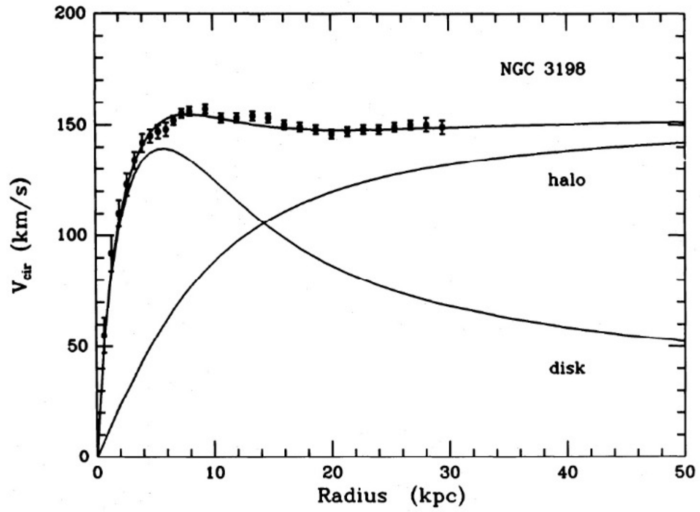
2 options

- **baryon/DM** ratio varies with the scale -> find segregation mechanism
- Baryons are **undetectable** in smaller structures -> where are they hidden?

Very unsatisfactory isn't it?

Initial motivation for microlensing searches (90's): contribution of **compact objects** to the galactic halo



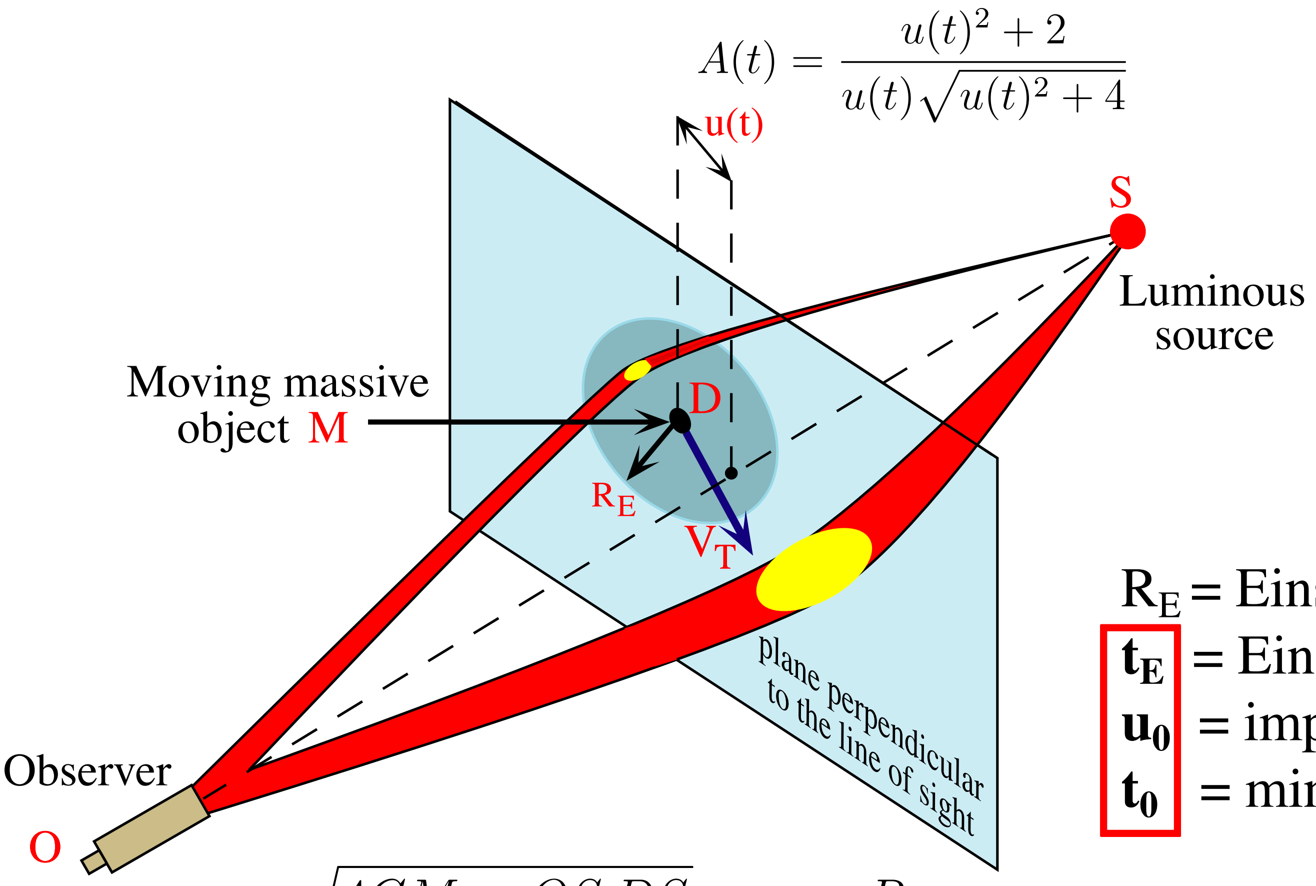


Rotation curve of NG 3196, from van Albada et al. 1985.

- Sub-stellar mass or invisible stellar mass **baryonic** objects
- Others (accreted particles)
  - If extended, should be transparent or with opaque radius < R_E ~ 1AU to be a lens

Includes black holes and non baryonic massive objects

Gravitational microlensing effect



$$R_E = \sqrt{\frac{4GM}{c^2} \times \frac{OS.DS}{OD}}, \quad t_E = \frac{R_E}{V_T}$$

R_E = Einstein radius

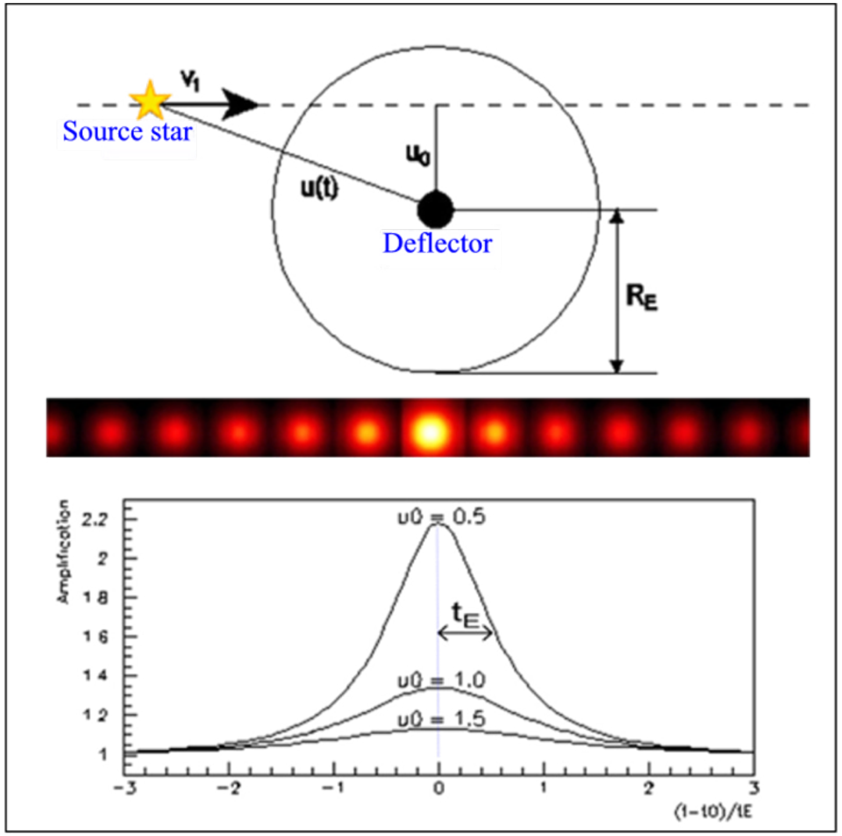
t_E = Einstein duration

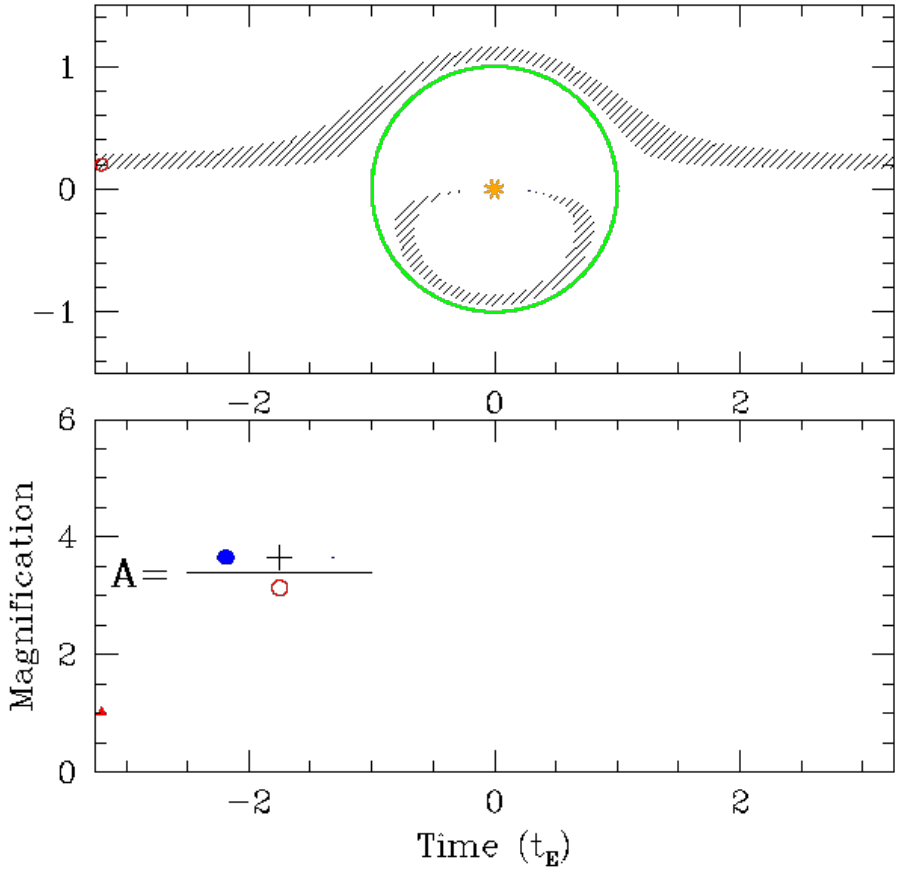
u_0 = impact parameter

t_0 = minimum approach time

Description of a microlensing event

Point-lens, point-source, rectilinear relative motion





<u>**Light curve characteristic**</u>:

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

Probability/rate of microlensing events

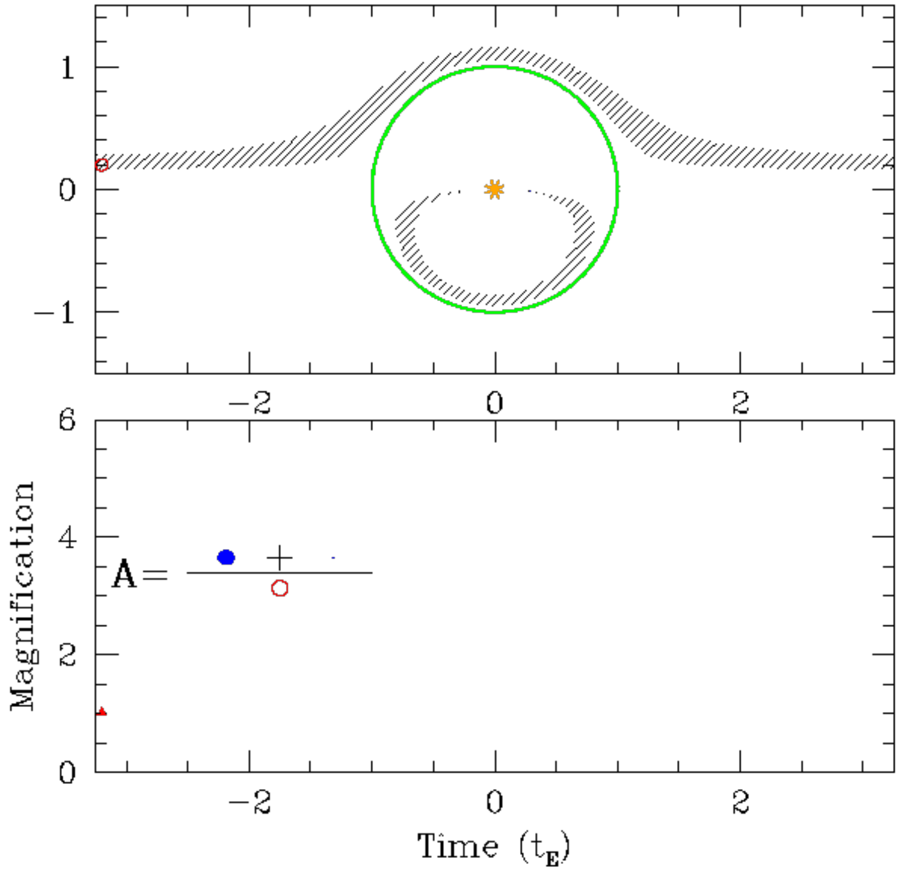
The optical depth τ

- probability for a star to be behind an Einstein disk at a given time (Amplification > 1.34)

- disk surface $\alpha\ R_E^2\ \alpha\ M_{lens}$

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

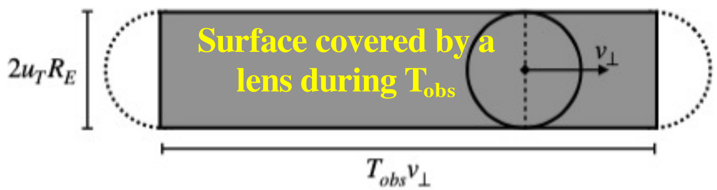
α **total mass** of the probed structure



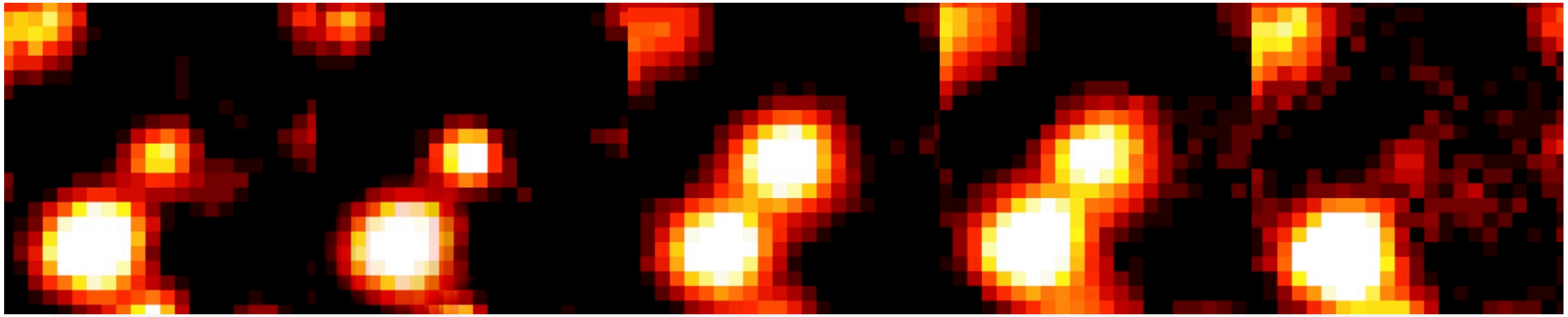
The number of events with $u_0<R_E$ in T_{obs}

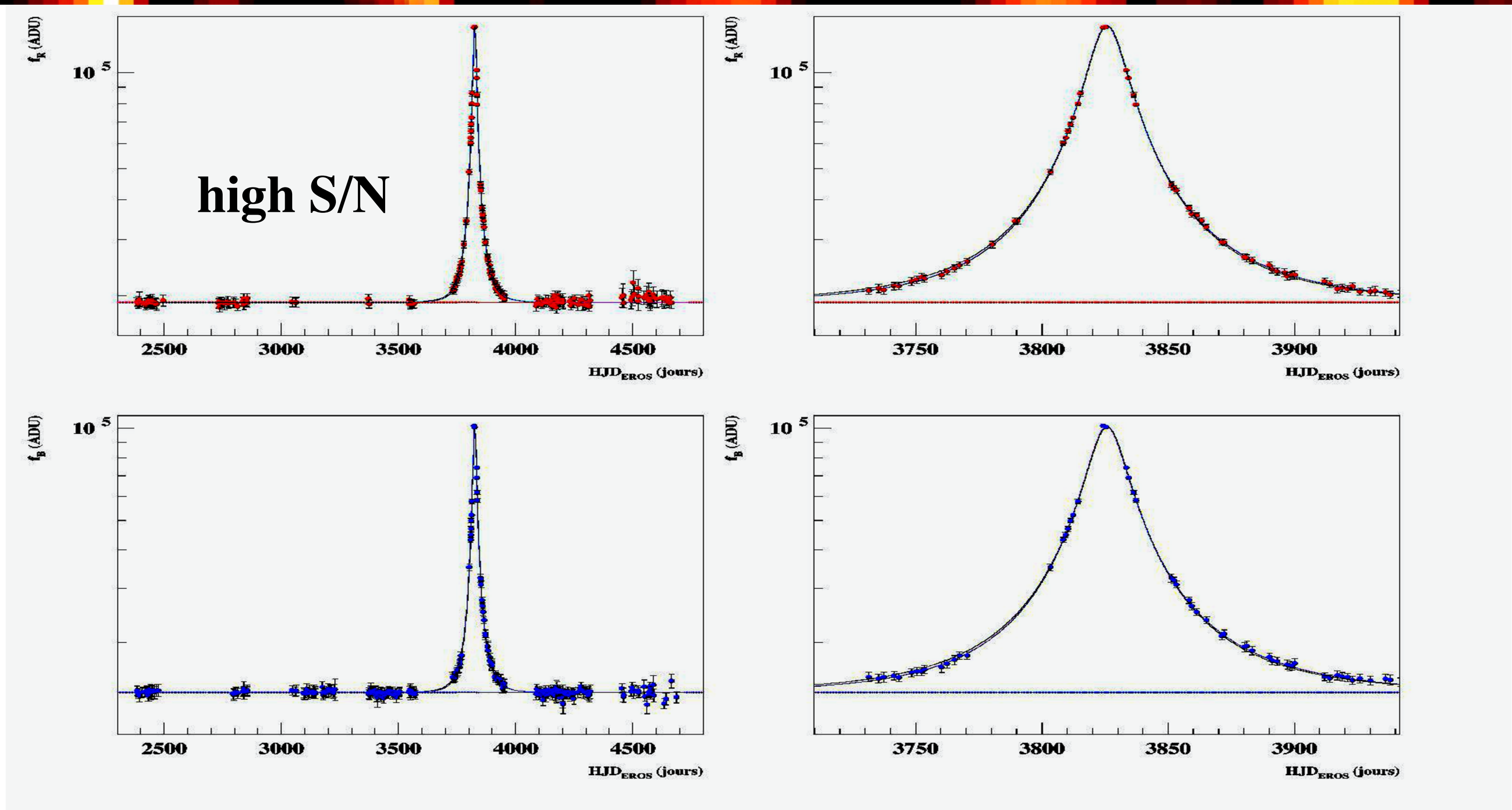
α surface swept by Einstein disks

=> $\mathbf{N_{events}}\ \boldsymbol{\alpha}\ \ \Sigma_{lens} R_E\ .\ V_T\ .\ N_{star}\ .\ T_{obs}$

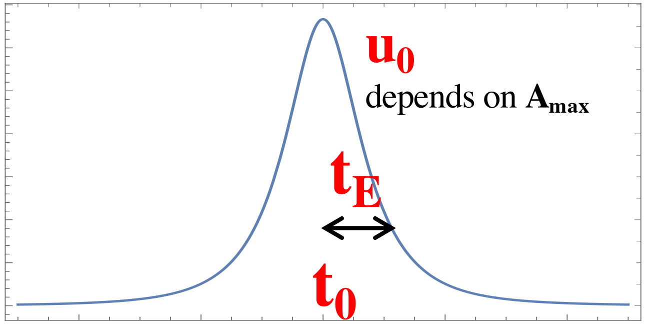


Example of a real candidate

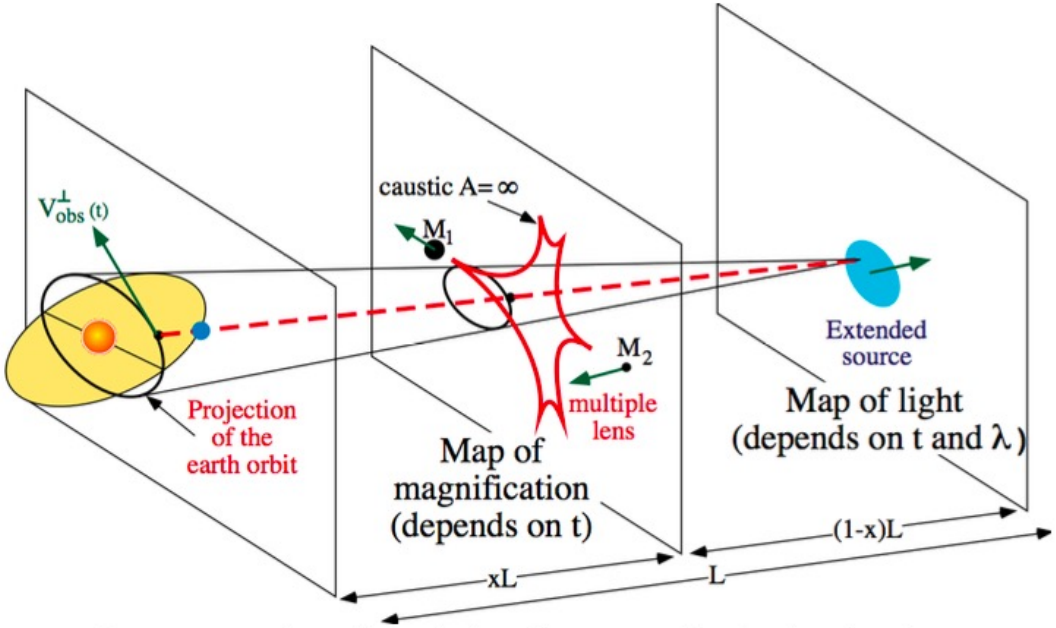




Beyond point source point lens rectilinear microlensing (PSPL)

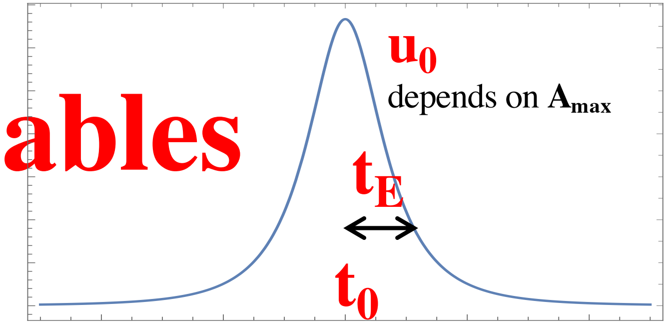


- finite size source
- binary lens
- parallax
- blending
- binary source, "xallarap"



Representation of deviation from standard microlensing.

The microlensing observables



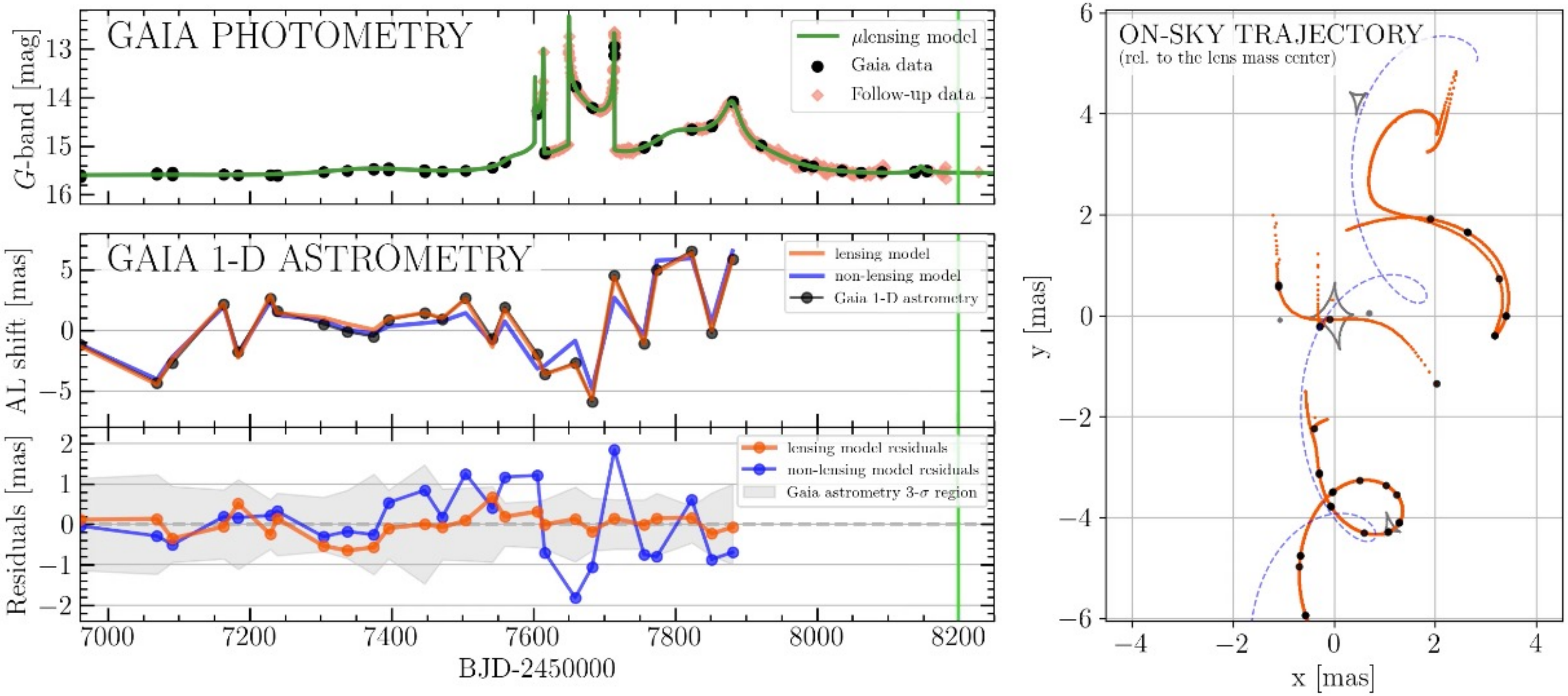
- **Simple events** (point-source, point-lens, constant v_T)
  - Event by event Einstein radius crossing time t_E
  - ***Statistical information from a series of events:***
    - optical depth $\boldsymbol{\tau}$ and t_E distribution
    -> Constraints on total (*visible* + *hidden*) mass
    -> Constraints on lens mass function
    -> Constraints on relative obs/lens/source kinematics

- **Non-standard events**
  - Parallax, Xallarap, extended source, multiple lens/sources… -> extra-information on distance, mass, velocity
  - Not considered here for statistical studies

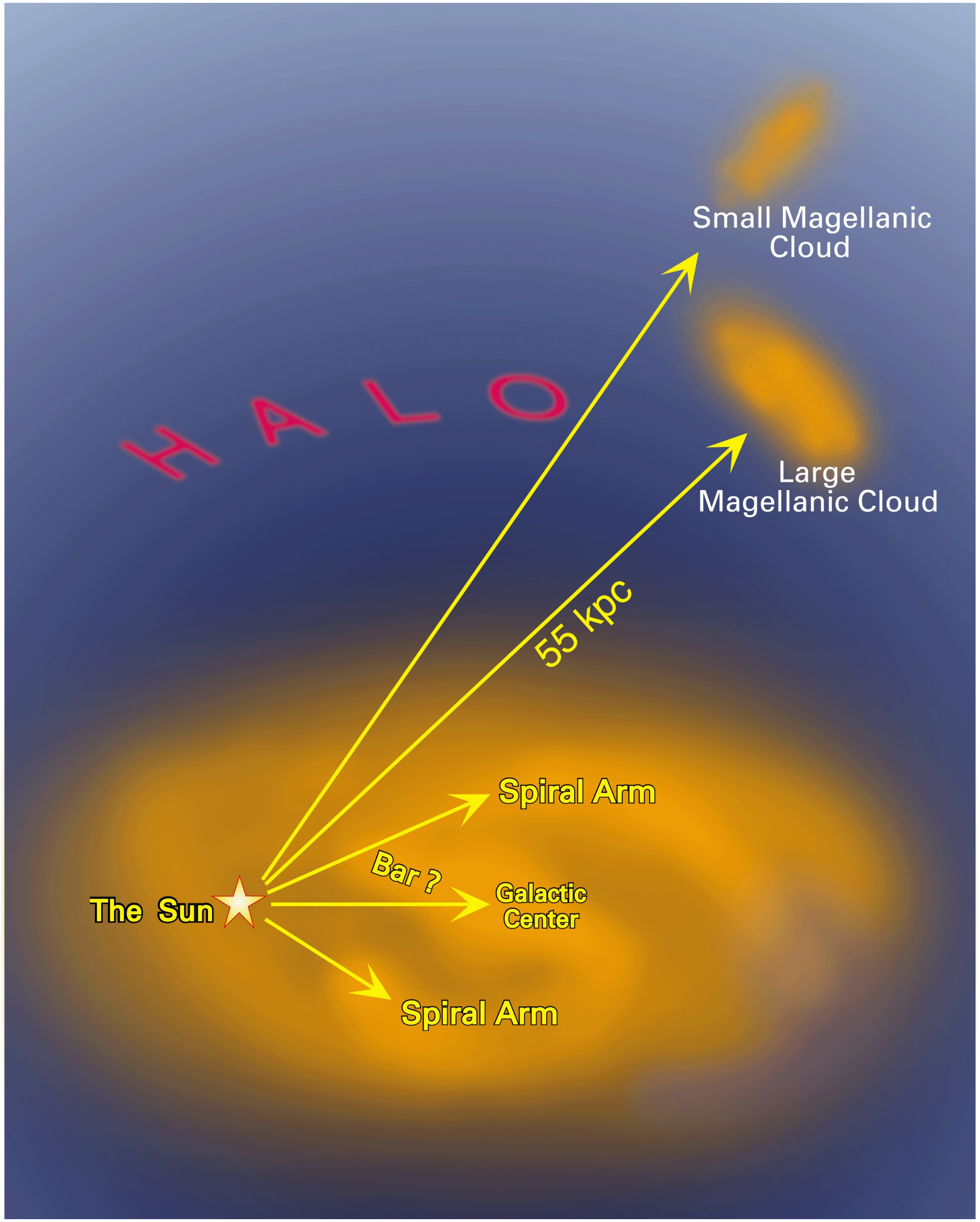
History

- 1986: B. Paczynski paper
- 1989: EROS1 starts
- 1993: First detections by EROS, MACHO, OGLE
- 1998: First multi-telescope follow-up of a caustic crossing event
- 2000-2010: limits on dark matter published
- 2017: **come-back**…

A complicated recent event (GAIA + follow up)



http://www.astrouw.edu.pl/~krybicki/Gaia16aye_animations.html



Main targets

monitored since 1990's

- **Magellanic Clouds** => probe hidden matter in **halo** ($\tau_{LMC} \sim$ **4.7x10**$^{-7}$)
- **Galactic center** => probe ordinary stars as lenses in **disk/bulge** ($\tau_{GC} \sim$ **2.10**$^{-6}$)
- **Spiral arms** => probe ordinary stars in **disk, bar** + hidden matter in **thick disc** ($\tau_{GSA} \sim$ **5.10**$^{-7}$)
- **M31**

Census of the measured/measurable directions to probe milky-way structure 1990 - 2017

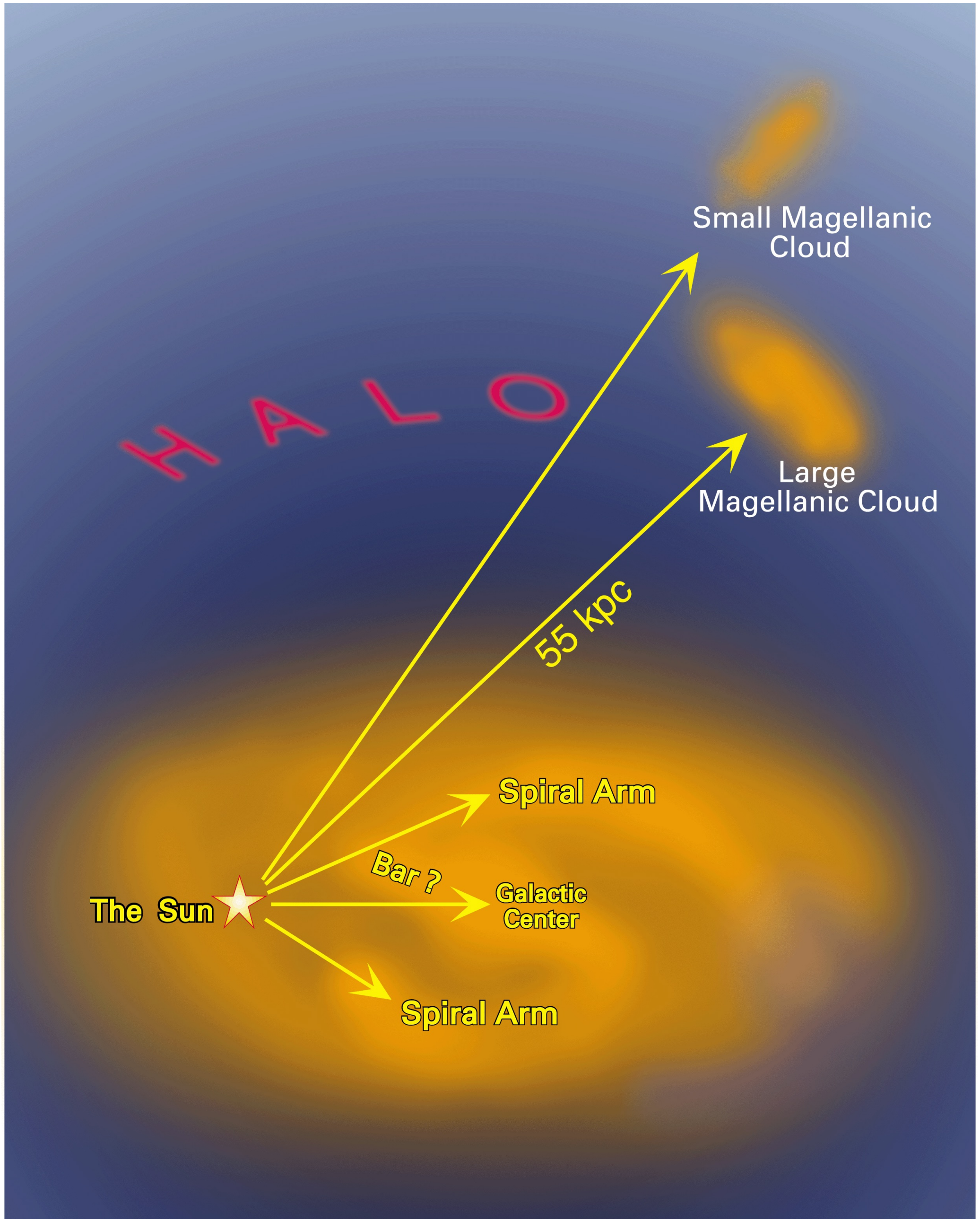
- **Galactic center**: all surveys found **thousands of events** mainly due to known objects -> **bright past & future** (search for extrasolar planets…)
- **Galactic arms:** 4 (low extinction) directions in (V, I): EROS
  - For visible passbands -> LSST
  - **Enormous** potential in infra-red (free from extinction): VISTA
  - Long-term future -> WFIRST
- **Galactic halo:** LMC/SMC search for non luminous compact objects

  -> 30 years of monitoring with Moa+**E**ros+**M**acho+**O**gle **!**

  Very few events found, compatible with expectations from normal Milky Way disk & LMC objects (self-lensing)

  – **M31**: AGAPE/MEGA. Difficulty of the pixel-lensing technique; combine Milky-way + M31 lenses

  – Globular clusters (M22)



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- **Magellanic Clouds** => probe hidden matter in **halo** ($\tau \sim$ **4.7x10^{-7}**)

Halo model

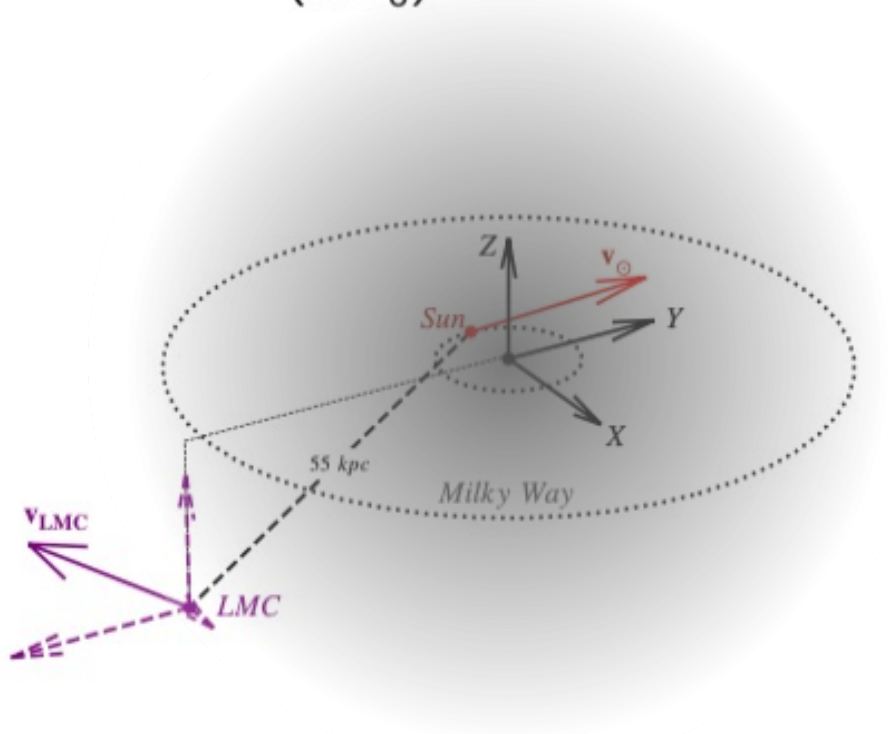
- Pseudo-isothermal spherical halo model $\Longrightarrow$ conventionally used to determine the constraints on the quantity of MACHOs in the halo.

$$\rho(r) = \rho_0 \frac{R_c^2 + R_\odot^2}{R_c^2 + r^2} \qquad p(v) = \frac{4\pi v^2}{(2\pi v_0^2)^{3/2}} e^{-\frac{v^2}{2v_0^2}}$$

$\rho_0 = 0.0079\ M_{sun}/pc^2$
$R_C = 5$ kpc
$R_{sun} = 8.5$ kpc
$D_{LMC} = 49.5$ kpc
$v_0 = 155$ km/s
v_{sun} , v_{LMC} …

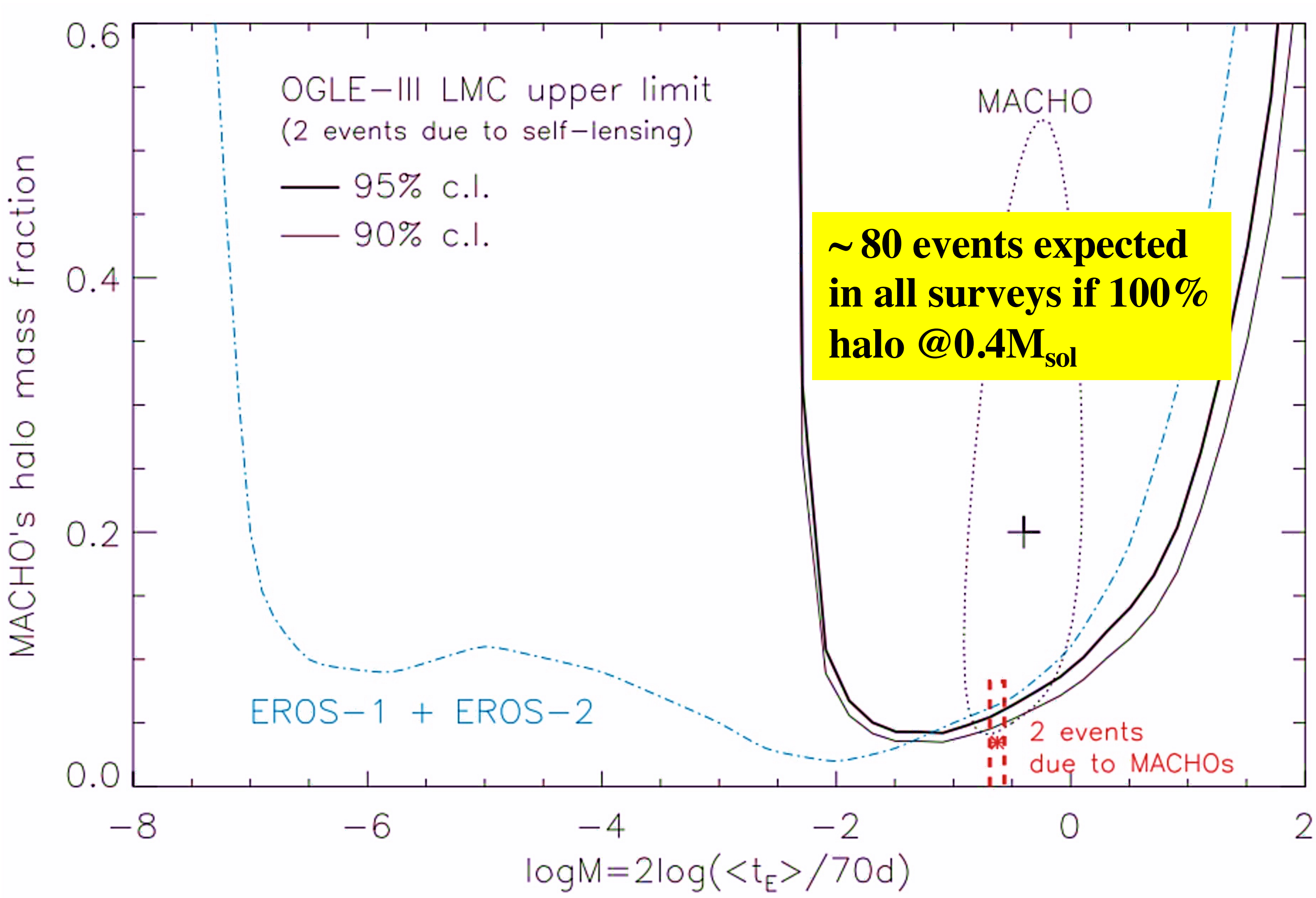
$\downarrow$

$\tau \sim 4.7 \times 10^{-7}$
$\langle t_E \rangle \sim$ **63**days $(M_{lens}/M_{sol})^{1/2}$



Before GW-Era (2017)

Milky way halo: constraints from LMC microlensing



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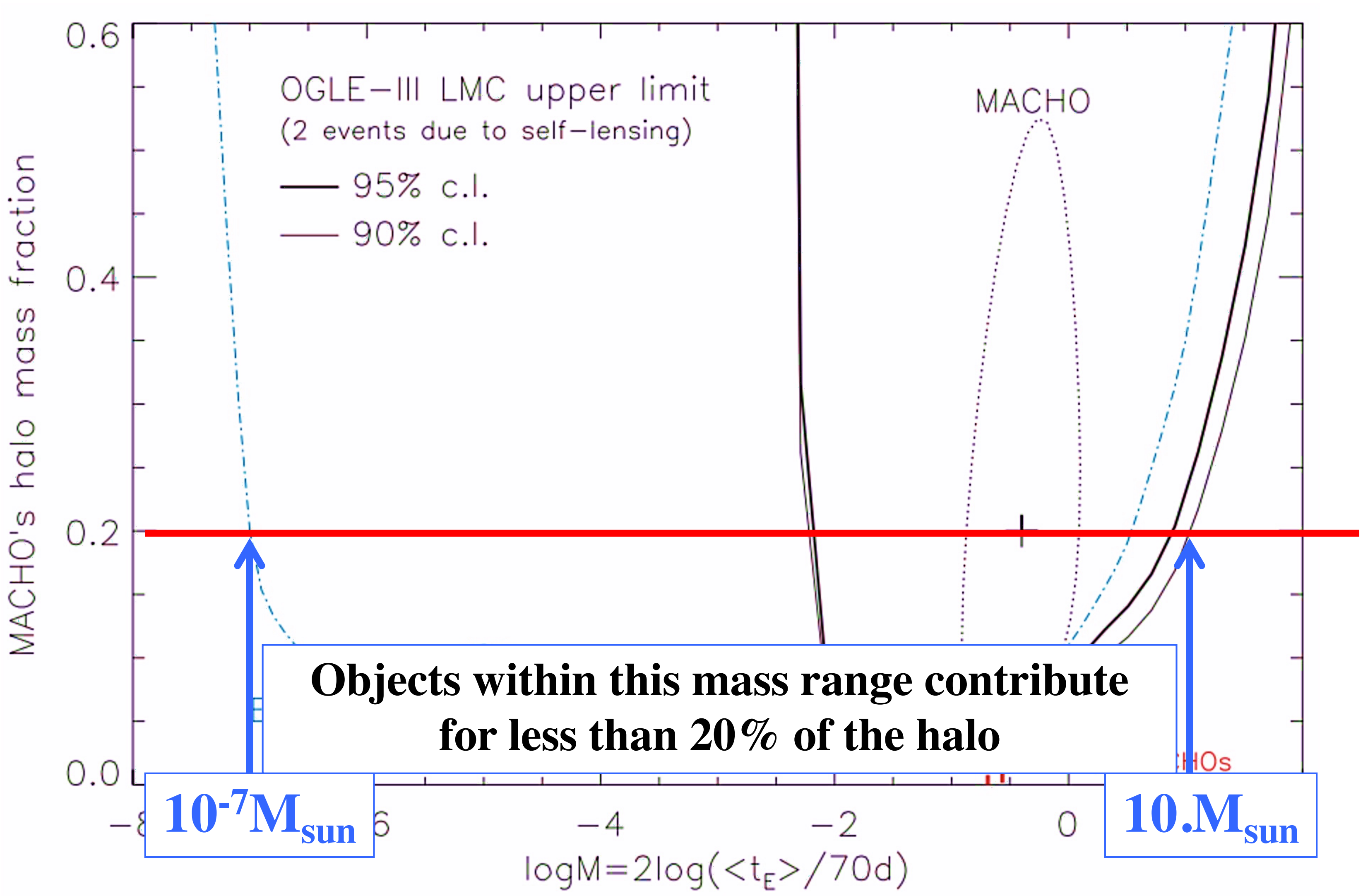
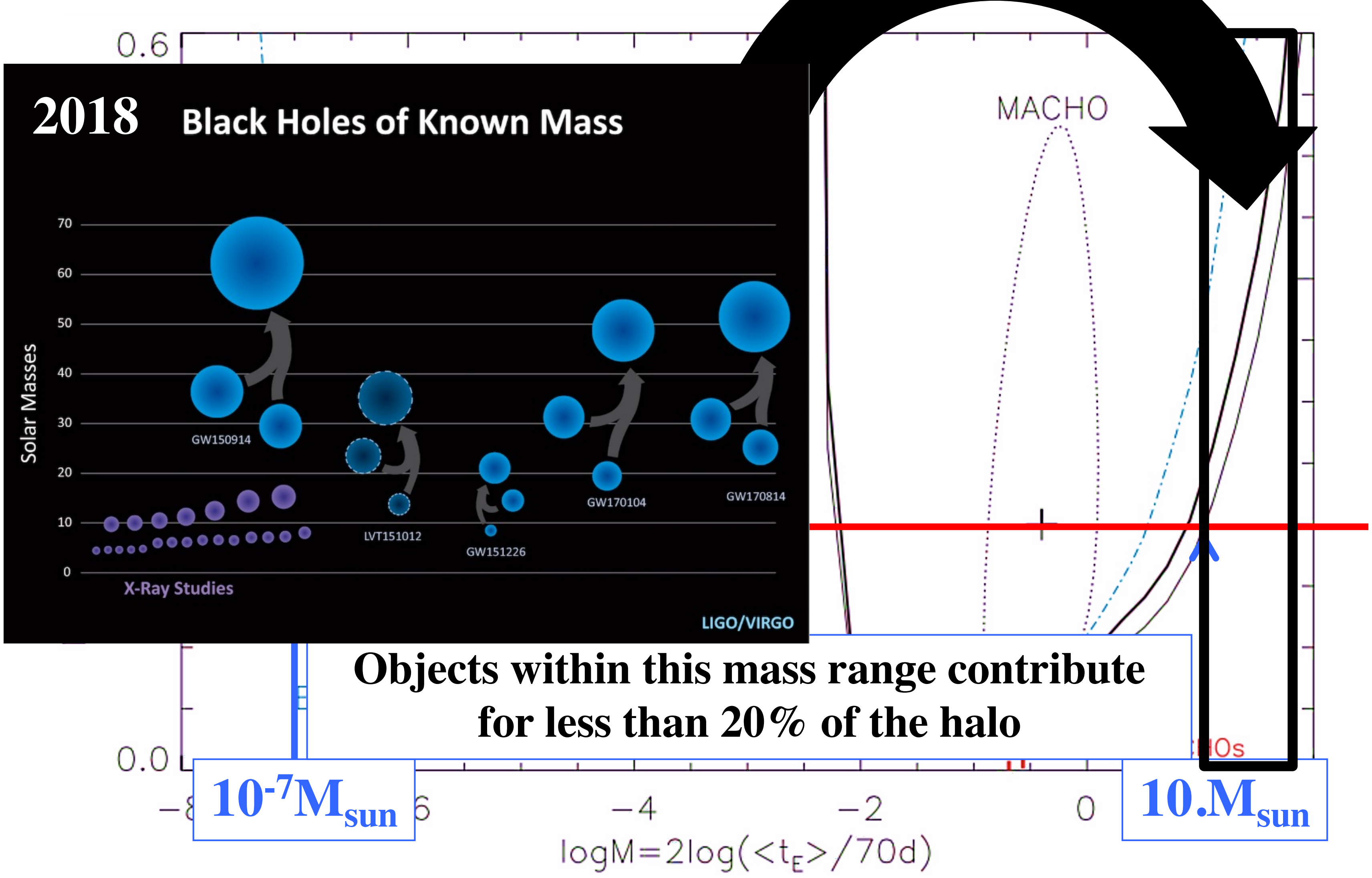


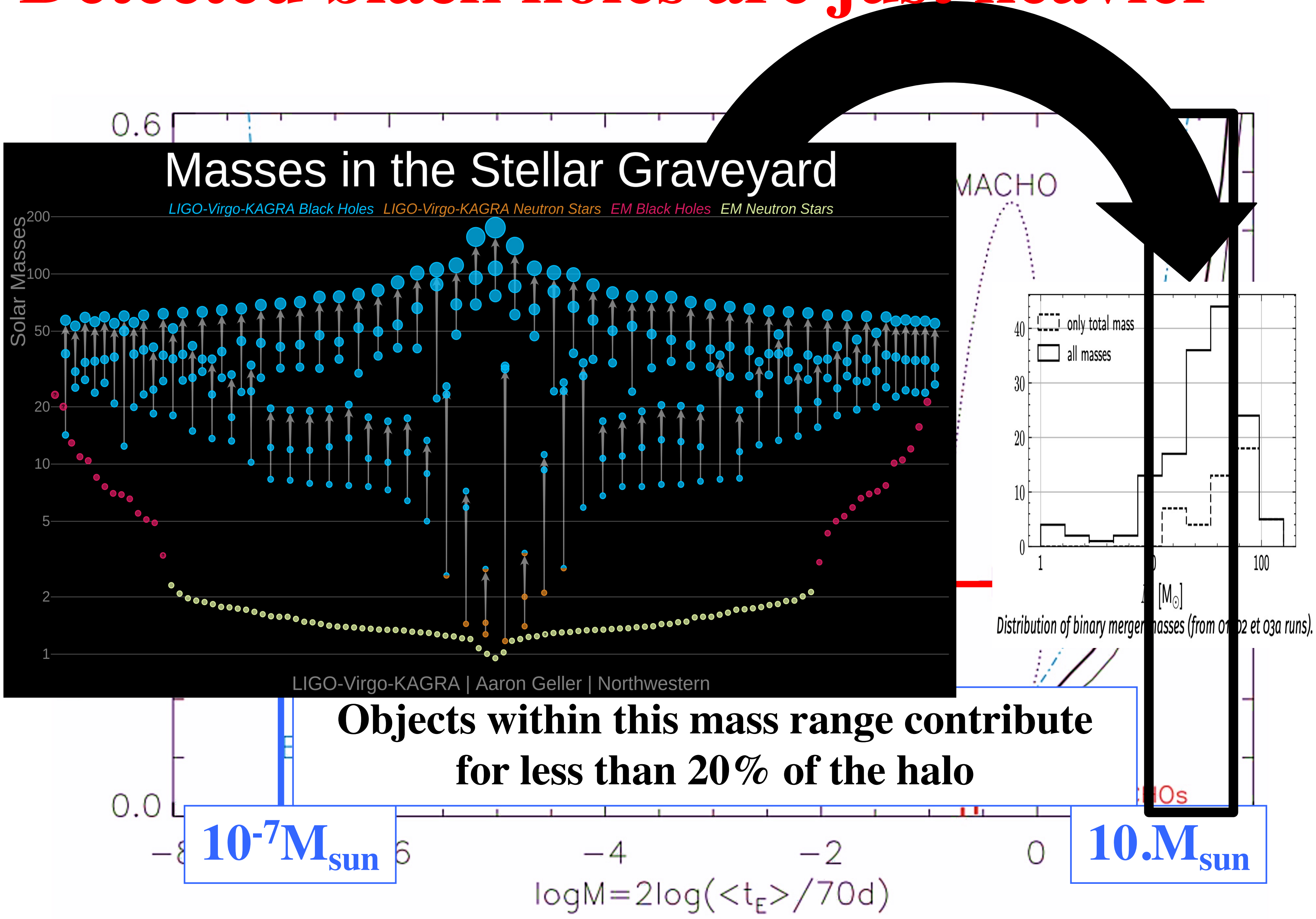
GW-Era (post-2017)

Detected black holes are just heavier



Year 5 GW-Era

Detected black holes are just heavier



Primordial black holes

- Primordial black holes (PBH) results from primordial over-densities collapsing
- Typical mass related to the mass $\boldsymbol{M_H}$ inside Hubble radius at time $\boldsymbol{t}$:

$$M = \gamma M_H = \gamma \frac{c^3 t}{G} \sim 2.05 \times 10^5 \gamma \left[\frac{t}{1\ \mathrm{s}} \right] M_\odot$$

- Precise relation depends on collapse details through γ
- Wide mass range authorized for resulting PBHs (e.g. at Planck time $10^{-43}\mathrm{s} \implies M \sim 10^{-5}$ g; at $t = 1\mathrm{s} \implies M \sim 10^5\ \mathrm{M}_\odot$)

No constraint from BigBang nucleosynthesis

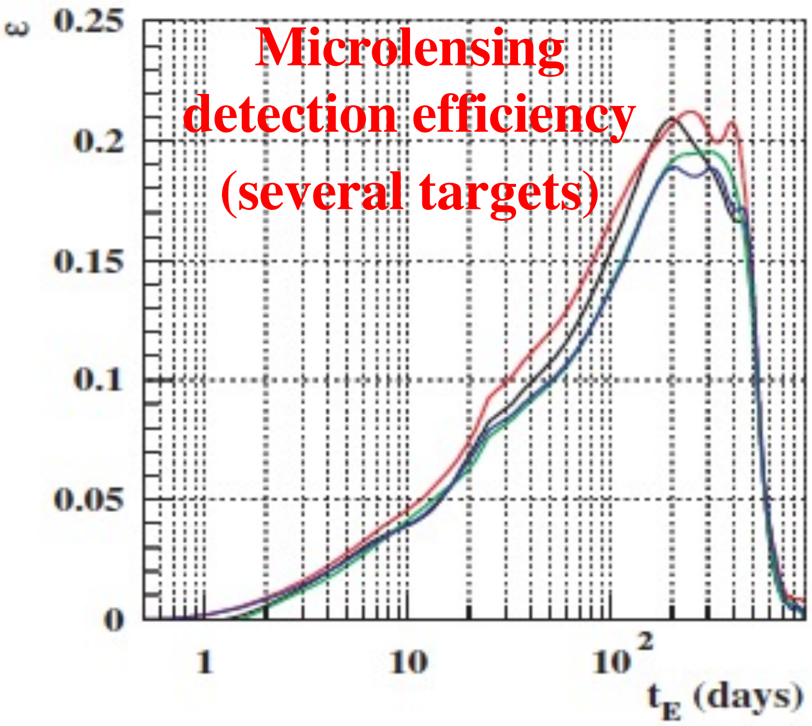
Microlensing from >10.M_{sun} black holes: Why historical surveys where insensitive?

Heavy lenses produce long duration events

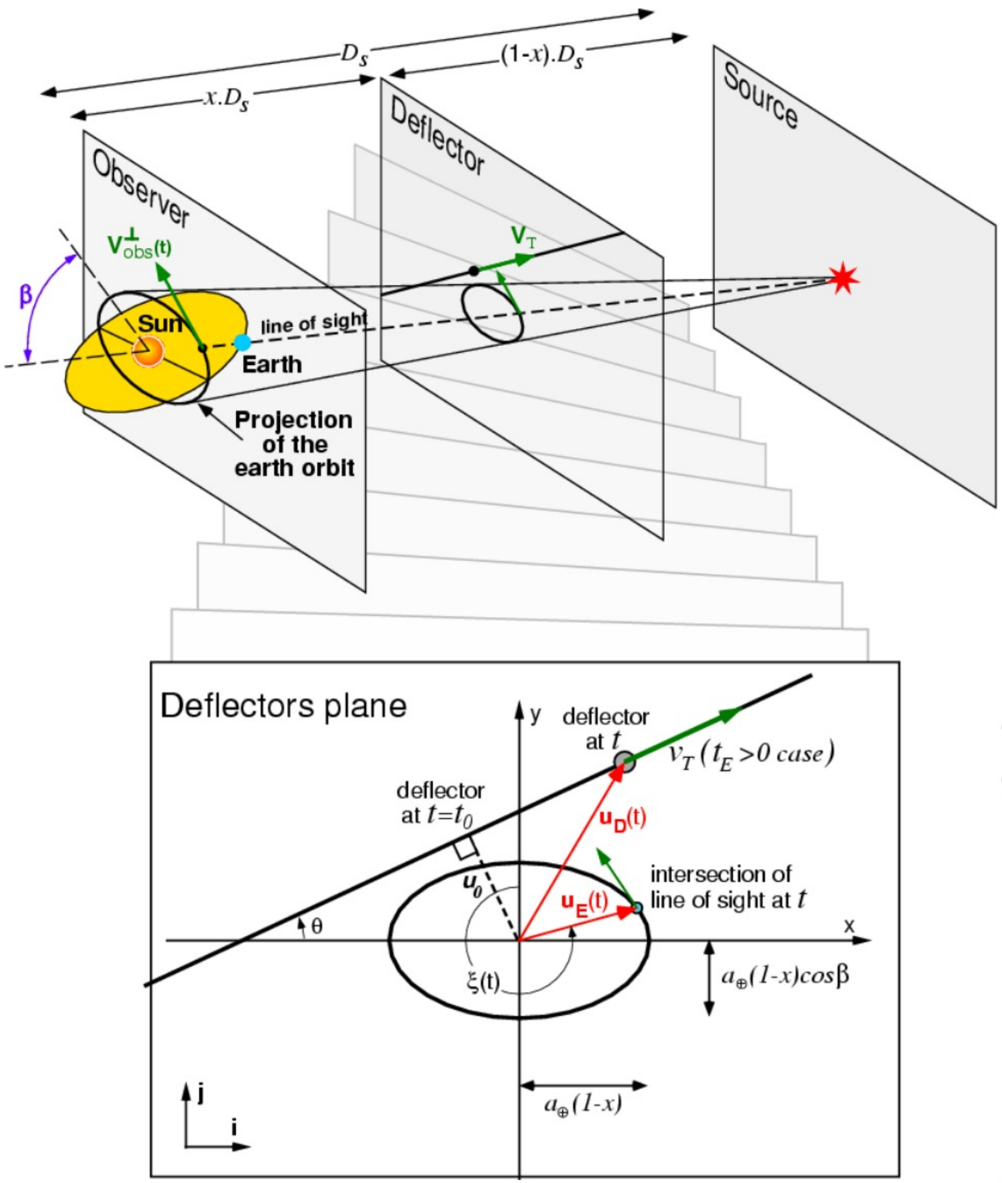
$$< t_E > \sim 63\ days \times \sqrt{\frac{M_{lens}}{M_{sun}}}$$ (~ 2yrs for 100M_{sun} lens)

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

- **Limited duration T_{obs}** of each survey (3-8yrs)
- **Observations/Analysis strategies**:
  - Optimized for light objects
  - Required events fully contained within Δt
  - Multi-year search suffer from telescope/filter ageeing/transmission variations…



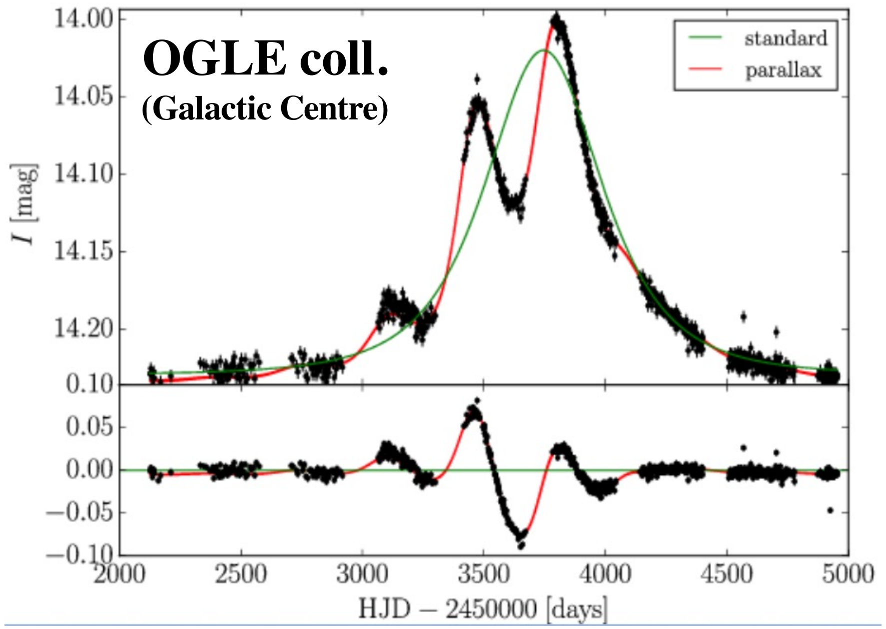
Does parallax complicate the analysis?



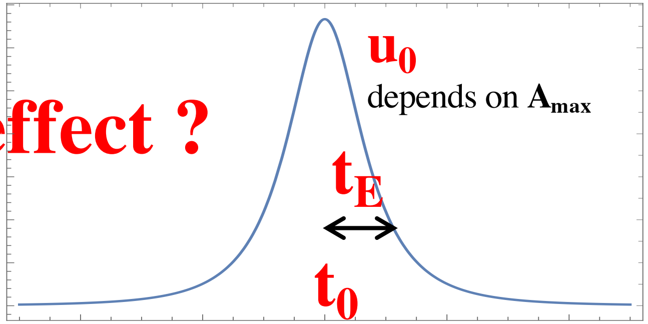
multi-year duration events have more chances to be affected by annual parallax

-> Apparent trajectory of the lens w/r line-of-sight: **hypocycloid**

- u(t) (and magnification) shows modulations with 1 year characteristic time



What is the risk to miss microlensing effect ?

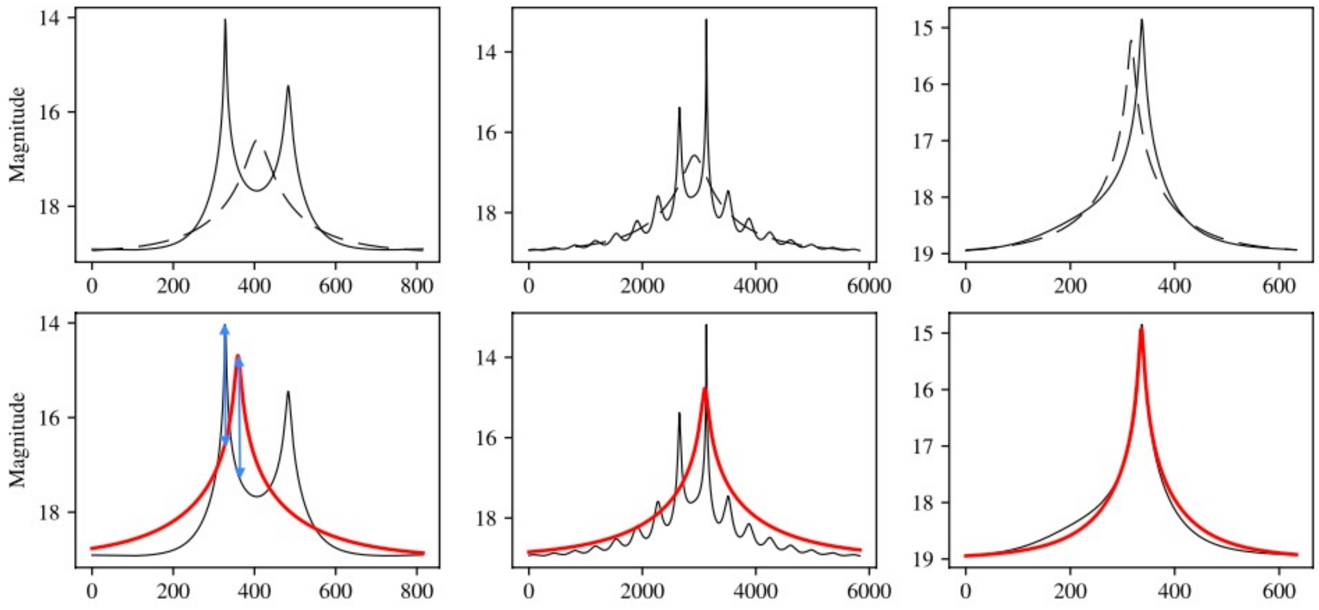


- to be as general as possible we simulate "analytical" light curves
- we quantify the distance between the event seen from the earth and the fitted one seen from the Sun

$$D_\pi = \min_{t_E,t_o,u_o} \{\max_t |m_\oplus(t) - m_\odot(t, t_E, t_o, u_o)|\}$$

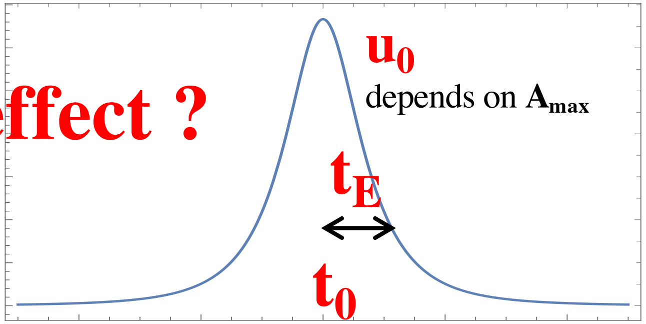
Simulated parallax microlensing

Fitted PSPL microlensing

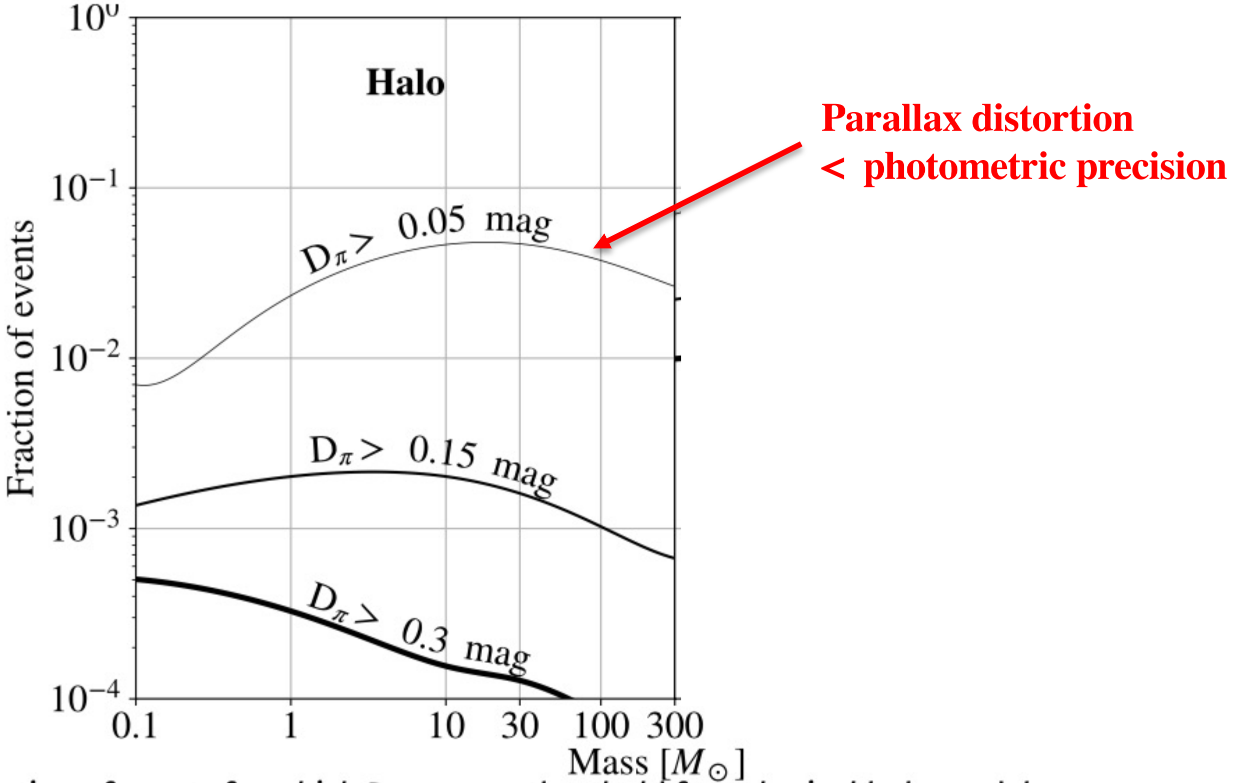


What is the risk to miss microlensing effect ?

(A&A, 636, L9, 2020)



- to be as general as possible we simulate "analytical" light curves
- we quantify the distance between the event seen from the earth and the fitted one seen from the Sun
- In the worst case scenario we miss **at most 6% of events**.

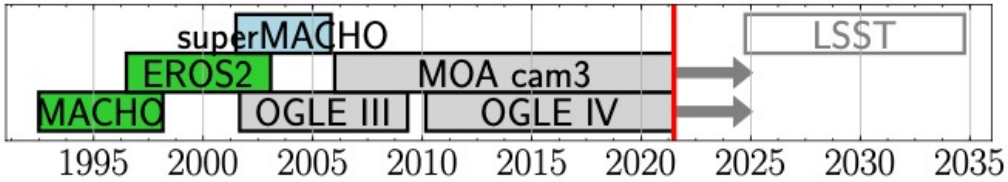


Fraction of events for which D_π cross a threshold for spherical halo model

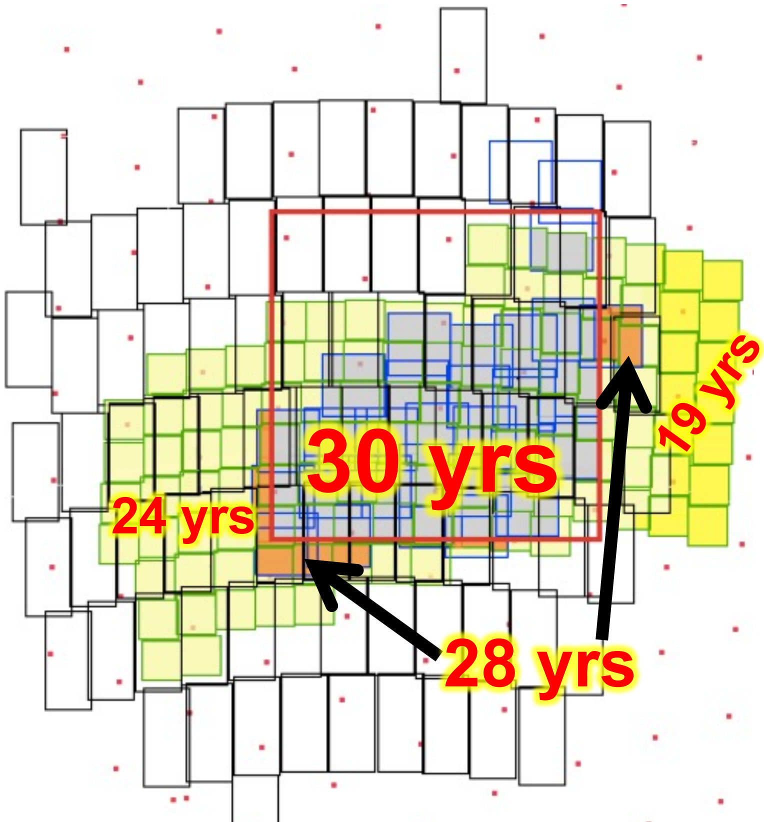
Search for very long events with joint data analysis: MEMO project *(A&A, 618, L4, 2018)*

Moa**E**ros**M**ach**O**gle 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.



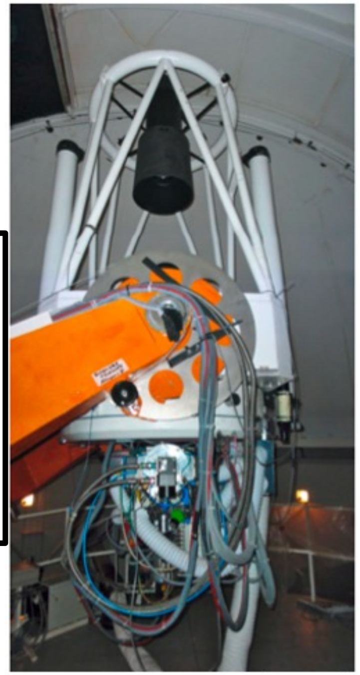
Fields monitored within the Large Magellanic Cloud

EROS2 and MACHO

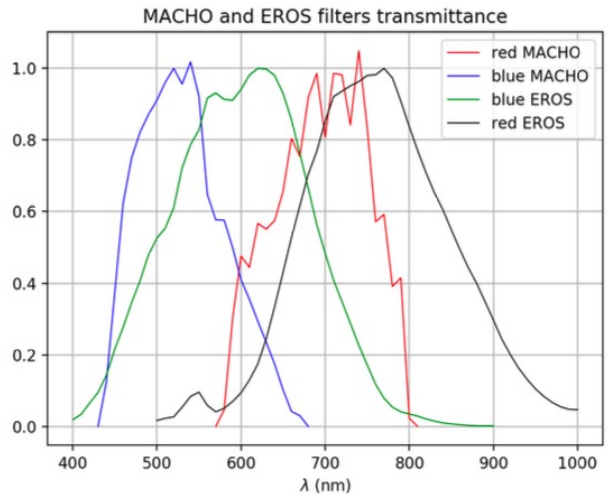
Microlensing surveys towards the LMC

Great Melbourne Telescope (MACHO).

MACHO	EROS2
• **1.27m** telescope in Australia	• **1m** telescope in Chile
• 2 cameras with dichroic	• 2 cameras with dichroic
• **4 CCD** 2Kx2K pixels each	• **8 CCD** 2Kx2K pixels each
• Field of view: **0.5 deg²**	• Field of view: **1 deg²**
• Monitored 82 fields (**39 deg²**)	• Monitored 88 fields (**88 deg²**)

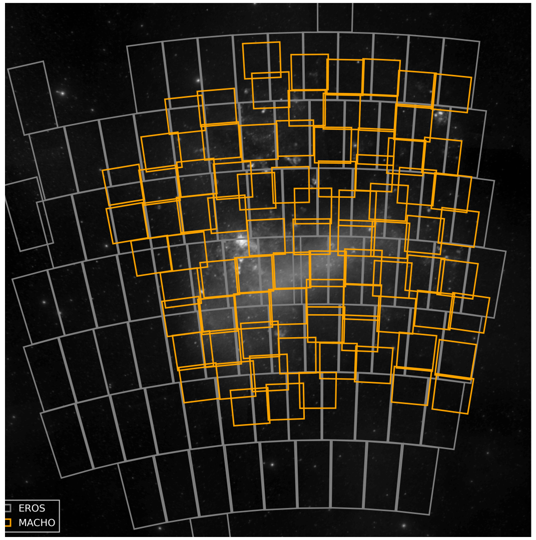


Telescope MarLy (EROS).



- 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



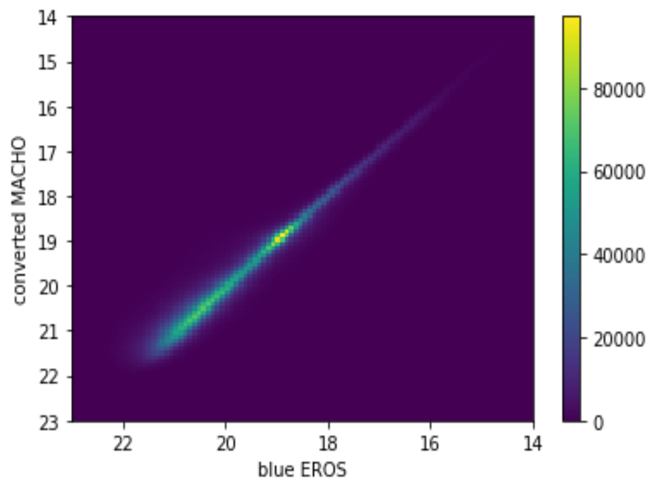
	EROS only	MACHO only	common
Dates (m/yr)	7/96-2/03	7/92-1/00	7/92-2/03
Duration (year)	6.7	7.7	10.6
Sources $\times 10^6$	15.8	$6.9^{(a)}$	14.1

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

Association, cleaning

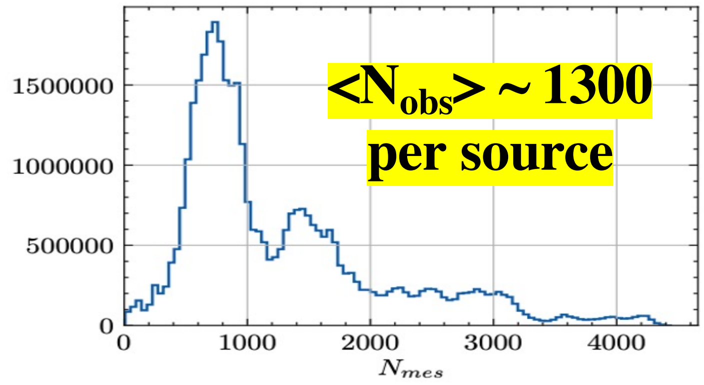
Cross-identification of the EROS-MACHO catalogs (using GAIA)

- To better than 0.1 arcsec in (α,δ)
- To the photometric precision in flux



Improved cleaning

- problematic measurements removed
- Keep light-curves with > 200 points

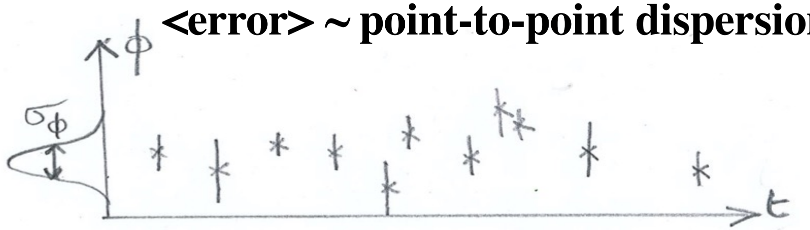


Total number of observations for each source.

Homogenize photometric uncertainties

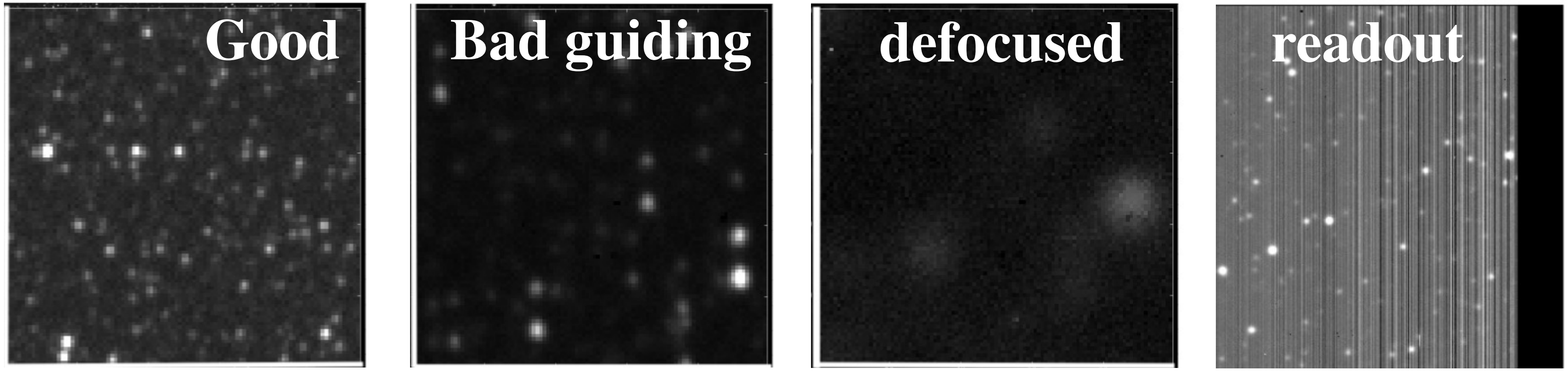
- Sometimes underestimated by MACHO
- Overestimated by EROS for faint stars
- Global normalization of errors

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



Cleaning low quality images/measurements

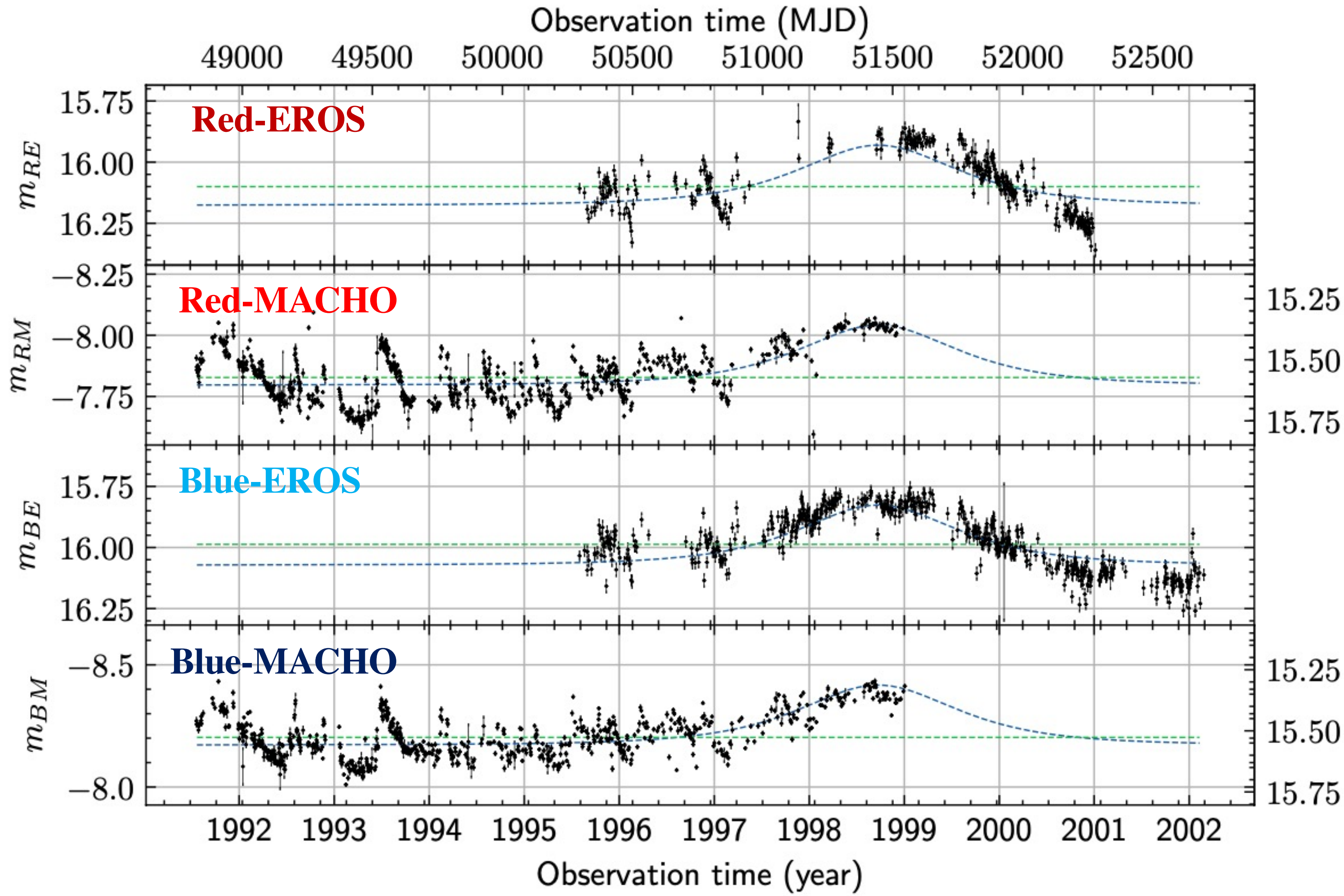
Images from MACHO



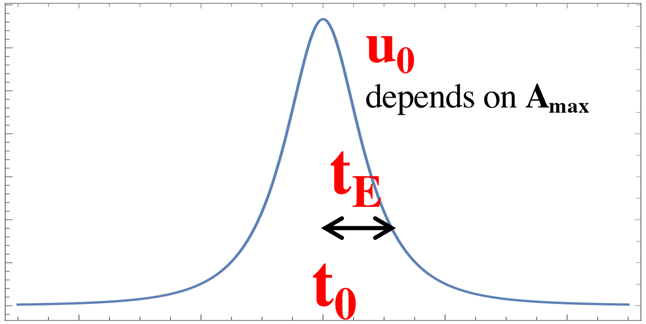
Images from EROS.

Cleaning: 3% of Macho and 1% of EROS measurements removed

Combined light-curves



Microlensing search: 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 **u_0, t_0, t_E, 1 base flux/colour** (could be more than 4 when adding OGLE/MOA)

Goodness of μlensing ↓ χ^2_μ/N_{dof},

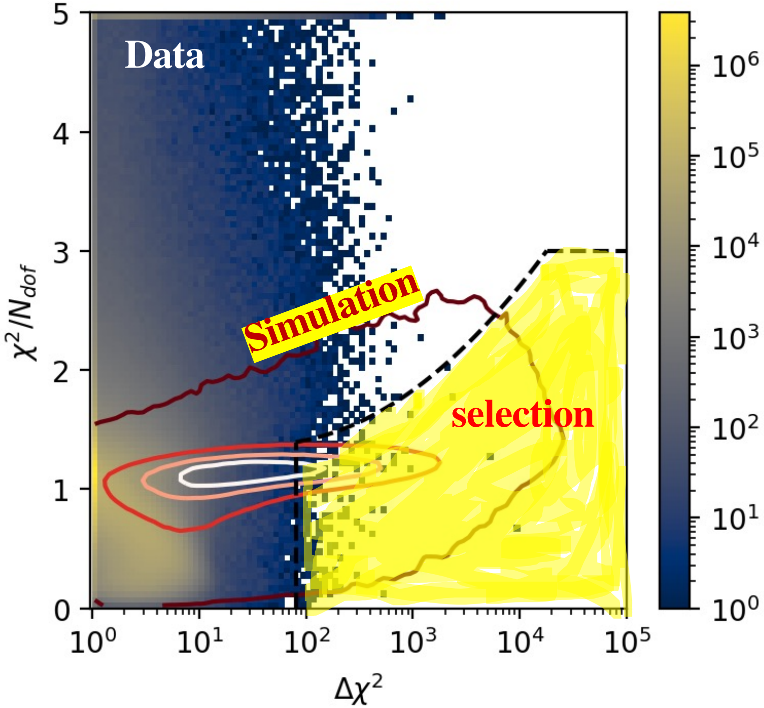
difference (flat – μlensing) ↓

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

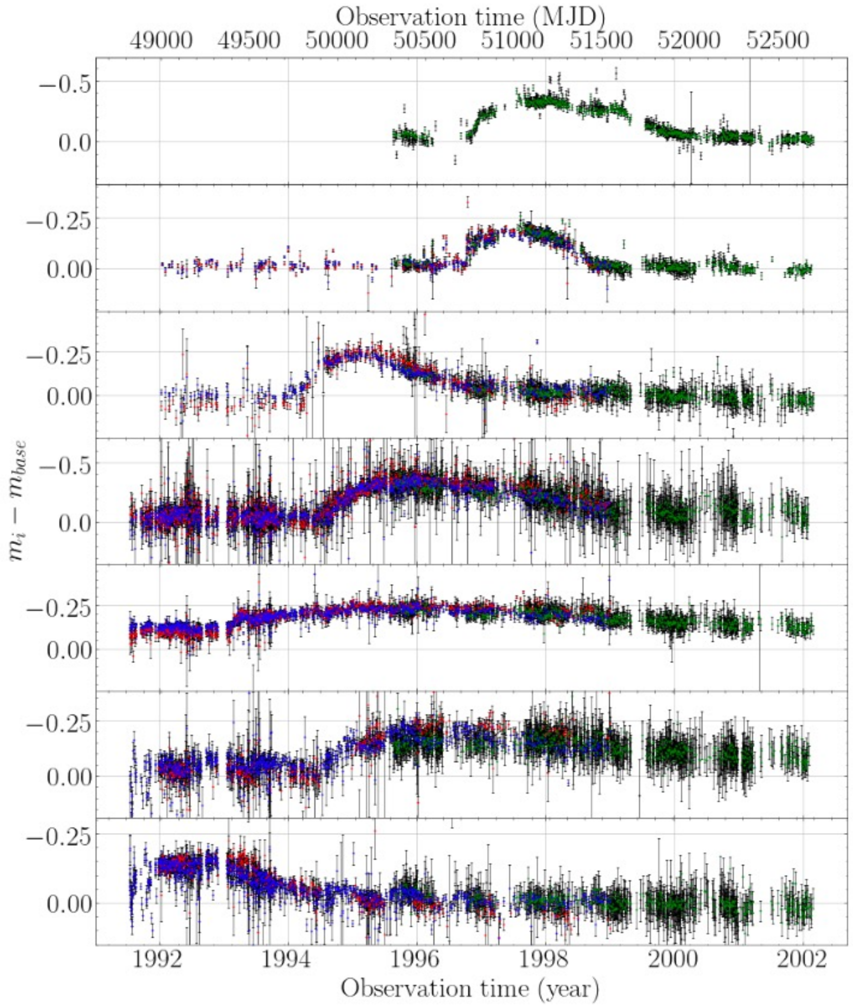
Require long events and well contained

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

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



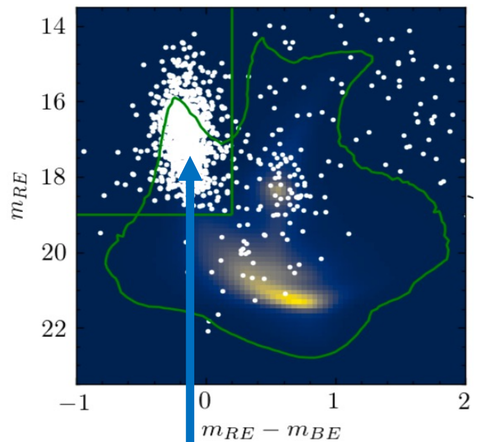
Main remaining artefacts (known)



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

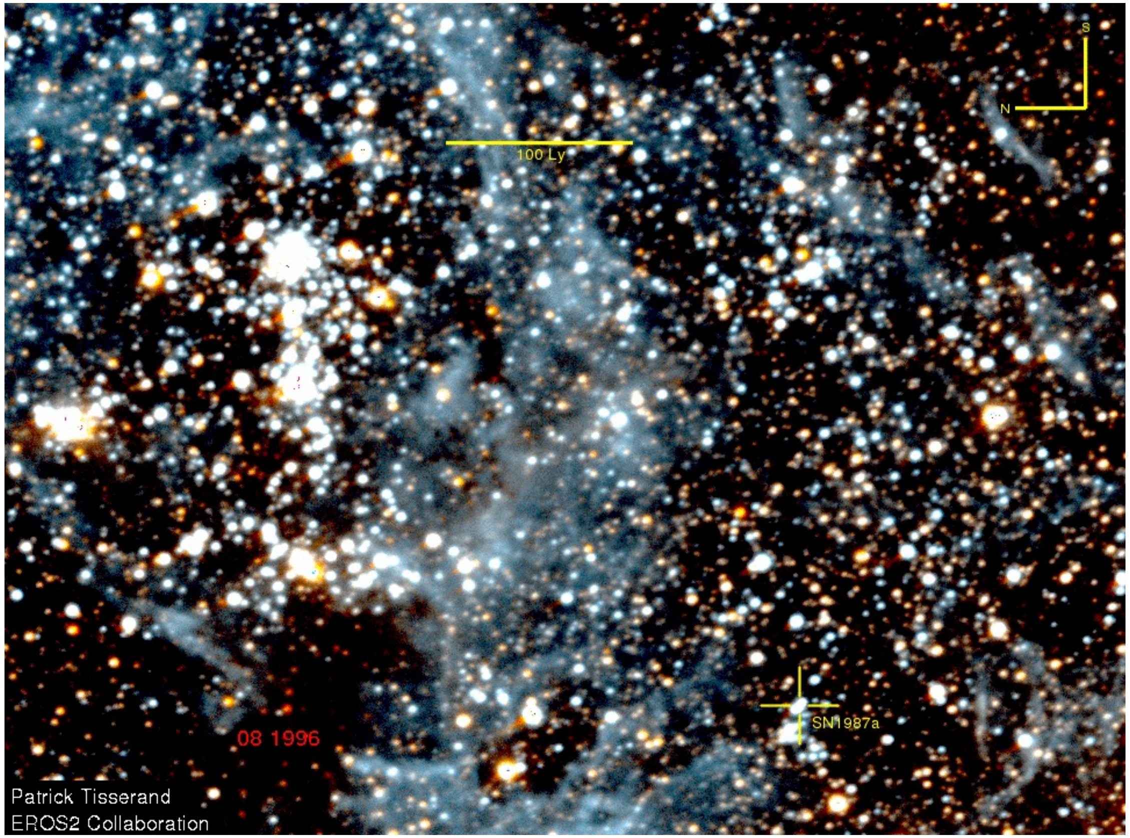
Blue bumpers (Be stars)

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

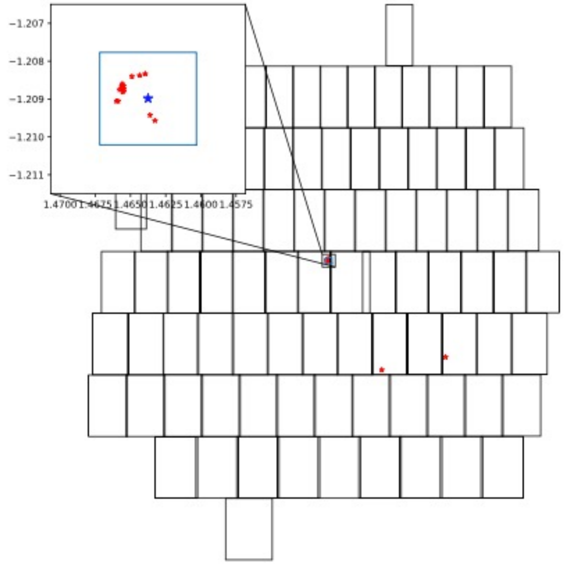


Require larger fitted magnification for candidates in the **blue bumper CMD zone**:
$u_0^{fitted} < 0.9$ (corresponds to Amp. > 1.38)

Remaining artefacts (2)

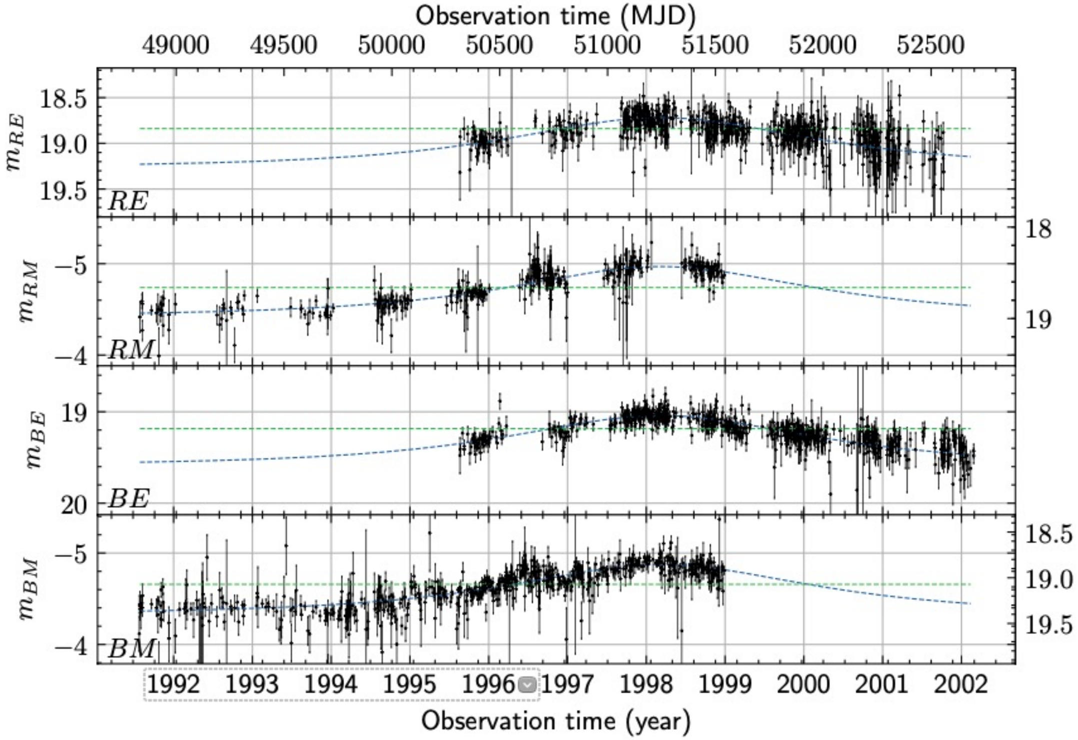


- **SN1987A echoes**
- Diffusion of the light emitted by the SN superimposed on a monitored star
- Vary with time (expansion) -> brightness seems to vary
- Remove a small patch of sky

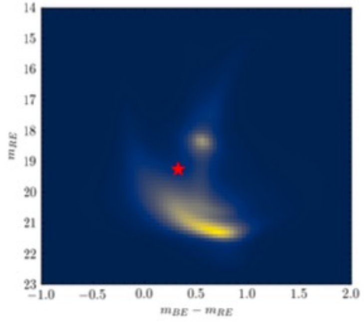


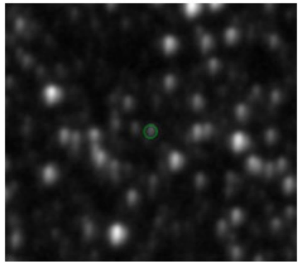
Positions of the remaining candidates relative to EROS fields. Removed area ≈ 0.14° × 0.14°

Remaining artefacts (3)



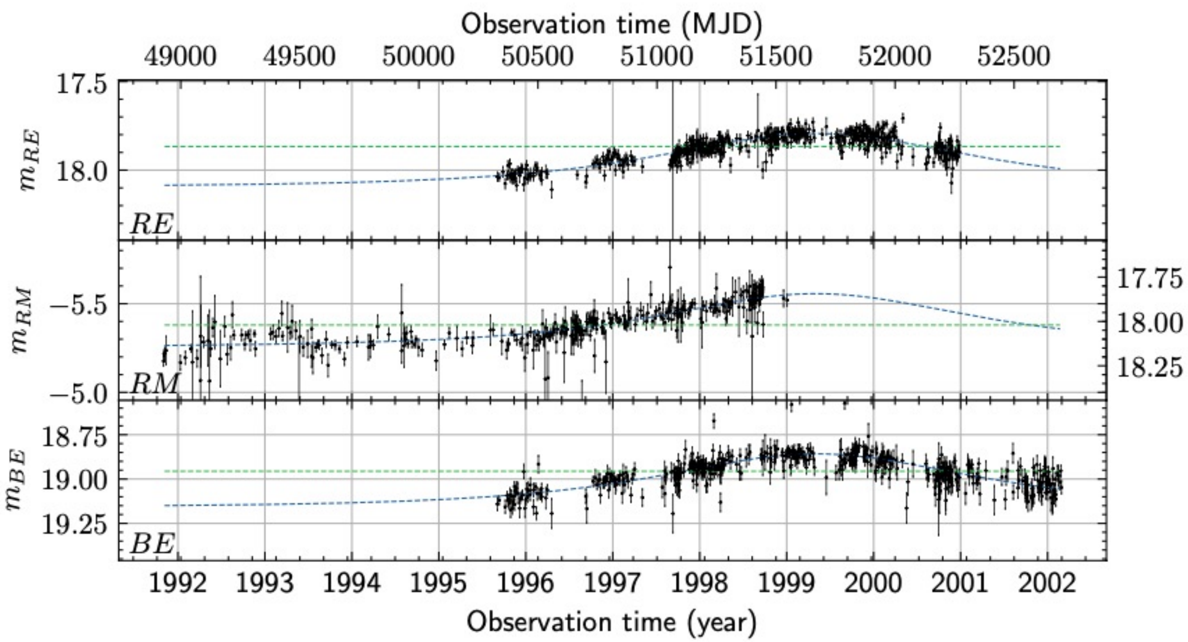
Position in CMD diagram



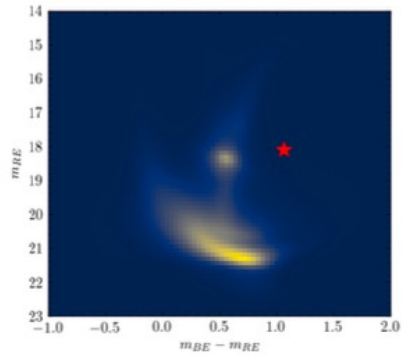


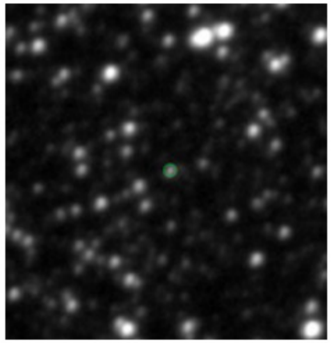
Fitted parameters : $u_0 = 0.72$, $t_E = 1004$ days, $t_0 = 51245$.
Identified as a QSO (*Quasi-Stellar Object*).
Appears in two independent catalogs of QSOs toward the LMC using IR, X and confirmed by spectroscopy.

Remaining artefacts (4)



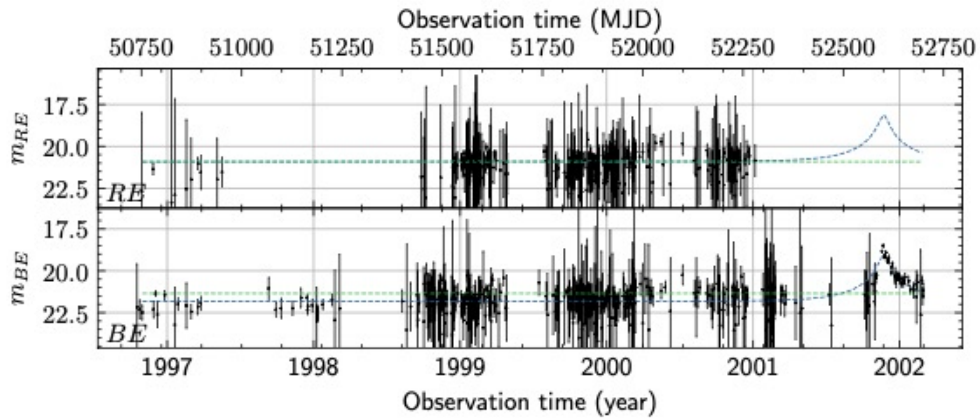
Position in CMD diagram

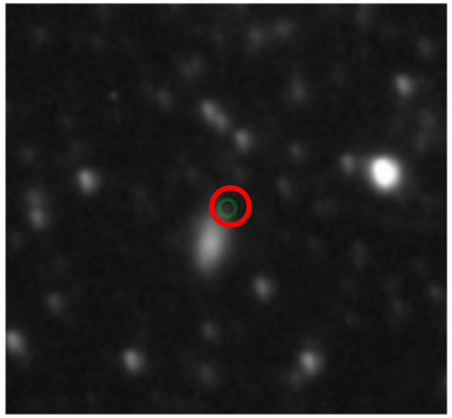




Fitted parameters : $u_0 = 1.03$, $t_E = 772$ days, $t_0 = 51667$.
Identified as a likely YSO (*Young Stellar Object*) in an existing catalog.
Know variable objects.

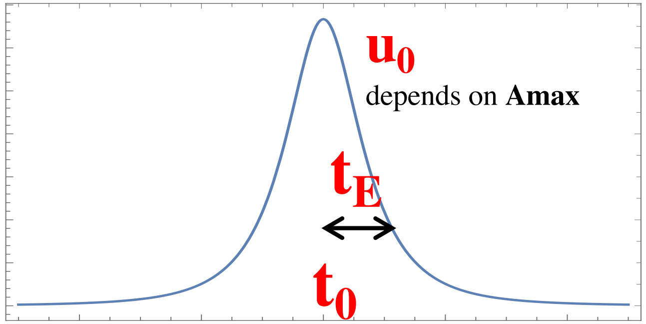
Remaining artefacts (5)

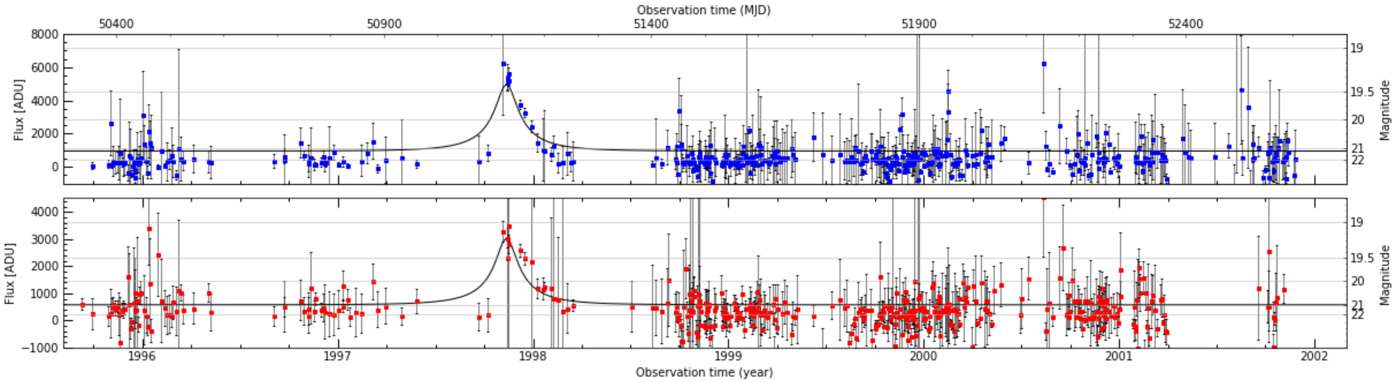




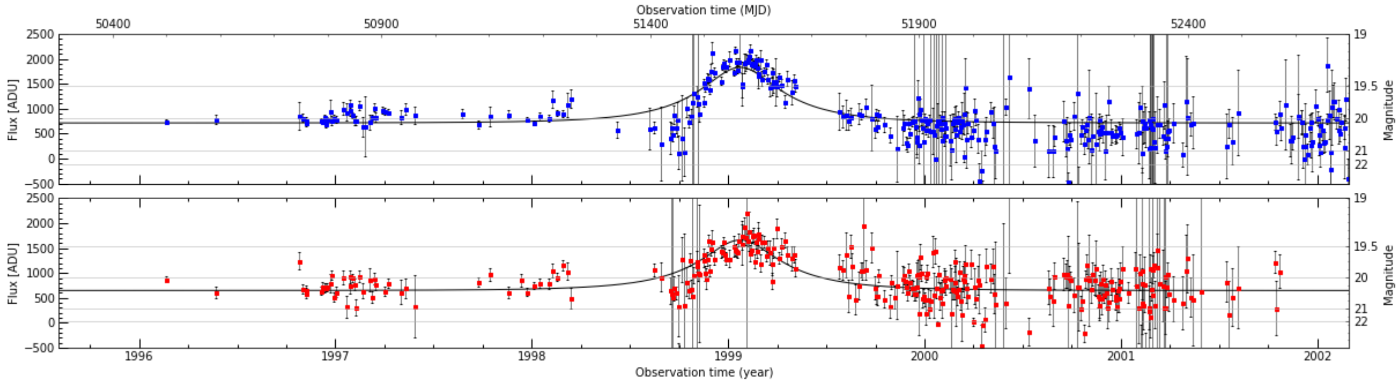
Unambiguous supernova (shape, amplitude, duration, in a galaxy)

Candidates: only 2





u_0=0.19, t_E=106 days.
Asymmetric, high magnification, 0.6'' shift from min to max.
-> probably SNII-L or P



u_0=0.41, t_E=183 days.
Suspicious variations outside main peak.

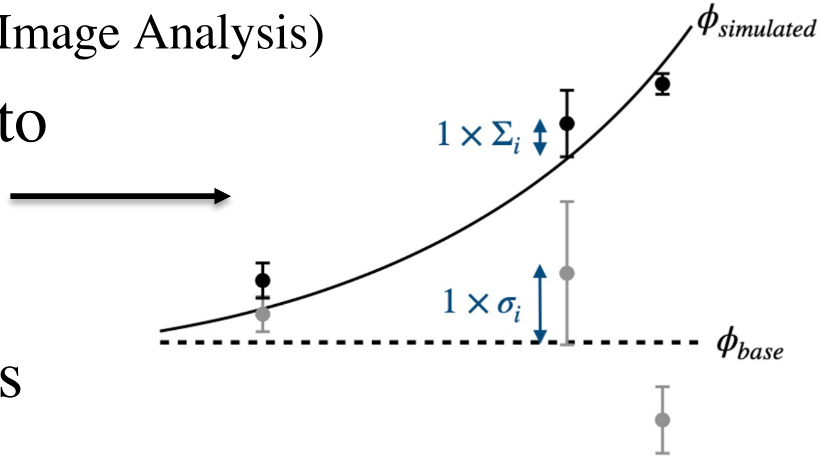
We cannot formally reject these « low quality » candidates without using more criteria (and losing efficiency)

-> *We chose to keep them for exclusion limit computation*

-> *with negligible impact*

Efficiency estimates

- Mathematically, microlensing detection efficiency is **zero** (infinite range of gravitation)
- It's a matter of definition -> define efficiency as the ratio of detected events to generated events
  - With uniform impact parameter $u_0 < 1$ (typically)
  - With uniform max. mag. time t_0 during the observed period
  - For a given source population (bright, red giants...)
    - Resolved sources or not (Differential Image Analysis)
- Simulated microlensing according to the halo parameters are applied to *real light-curves (grey->black points)*



-> Then subjected to the same analysis

Efficiency: complications

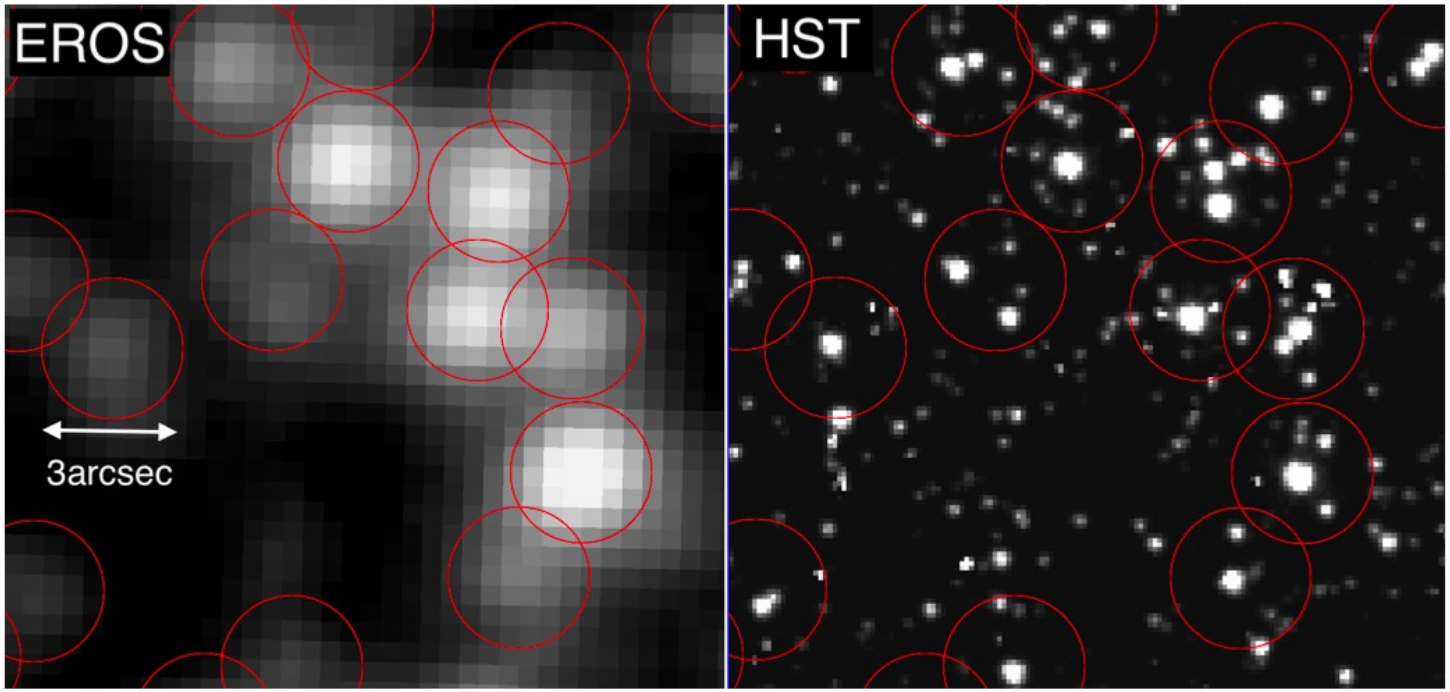
- **Blending:** an object may contain light from several stars
  -> But only one is lensed
  - Impacts Paczynski curve shape and reconstructed t_E
    - $\varepsilon(t_{E\ rec.})$ differs from $\varepsilon(t_{E\ generated})$
  - Changes the effective # of stars
    - A minor (not catalogued) contributor to an object can emerge with microlensing, apparently increasing ε
    - Images from space telescopes provides true underlying luminosity function and includes spatial correlation between the blend components
- **Contribution from non-standard events** (binary lenses…)
  - Generally not generated when estimating efficiency
  - Can be statistically estimated (<10%)
- **High statistics needed** for reliable use of efficiency (for τ estimates)
  - ε is an *average* with large variations from event to event

$$\tau = \frac{1}{N_{obs}\Delta T_{obs}} \frac{\pi}{2} \sum_{events} \frac{t_E}{\epsilon(t_E)}$$

Blending

One needs to know what is behind an observed light-curve.

- a MACHO or EROS object in a crowded field is often a blend of several stars
- Microlensing has to be simulated on each component and the resulting light curve is the sum of a magnified and stable components



Comparison of the same region of the sky seen by EROS2 and HST. Red circles are sources detected in EROS.

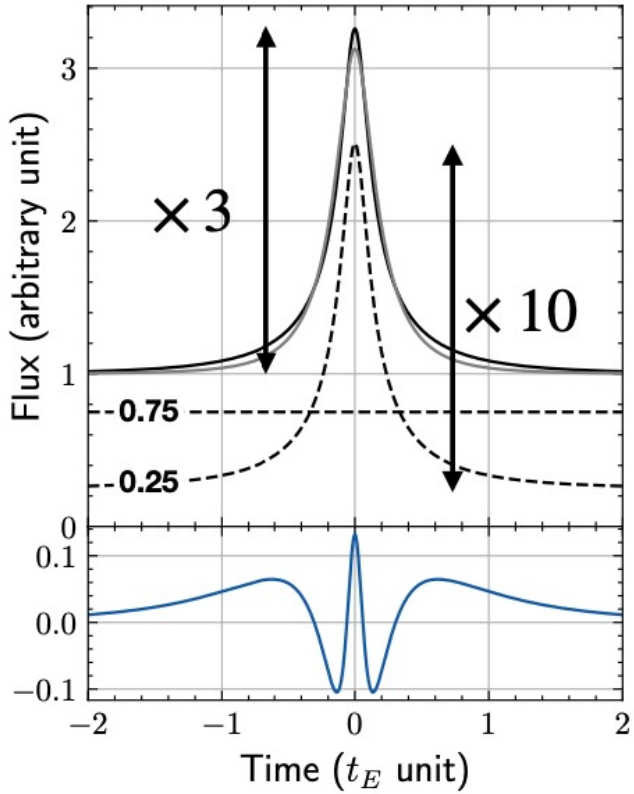
Blending (based on HST data)

Effect of blending on microlensing search :

- greater real number of stars than in catalogues $\Longrightarrow$ greater $\boldsymbol{N_{exp}}$
- lower apparent amplification $\Longrightarrow$ lower efficiency
- apparent $\boldsymbol{t_E}$ < real $\boldsymbol{t_E}$
- reduced efficiency due to curve shape
- loss of achromaticity

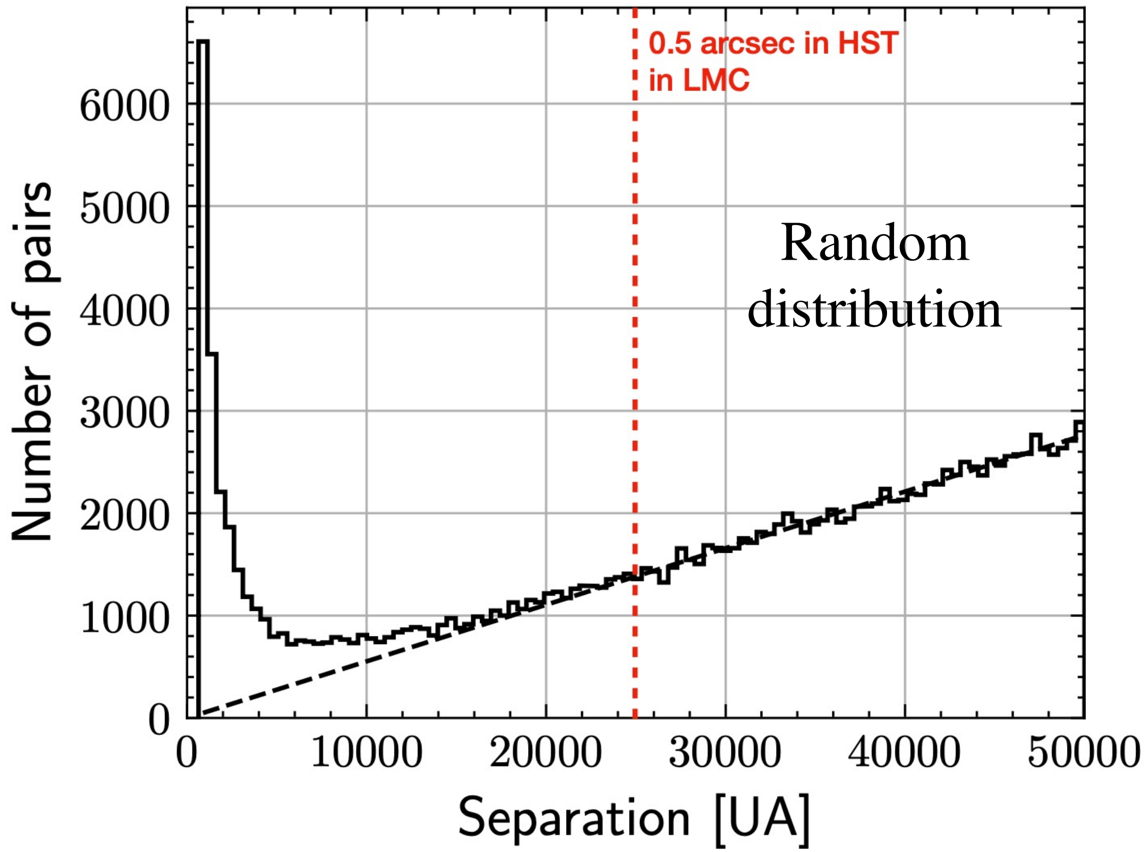
Using HST images :

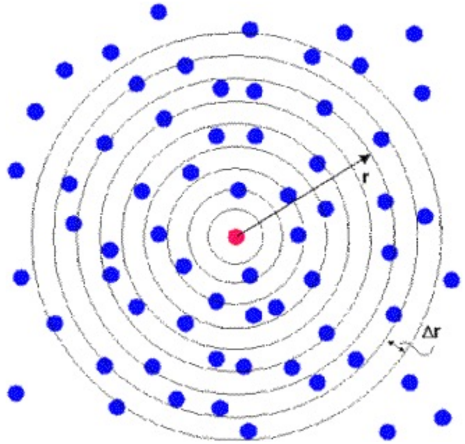
- we estimated number of stars in EROS/MACHO sources
- we computed individual contribution of each star by source
- it was done in two fields of different densities
- the dimmest sources are the most blended



Effect of blending on amplification curve. Dotted lines: 2 individual stars light curves. Black line : resulting source light curve. Grey line: best fit of PSPL light curve. Bottom: residual between PSPL best fit and blended light curve.

Do we expect blending by very close neighbours not detected in HST ?





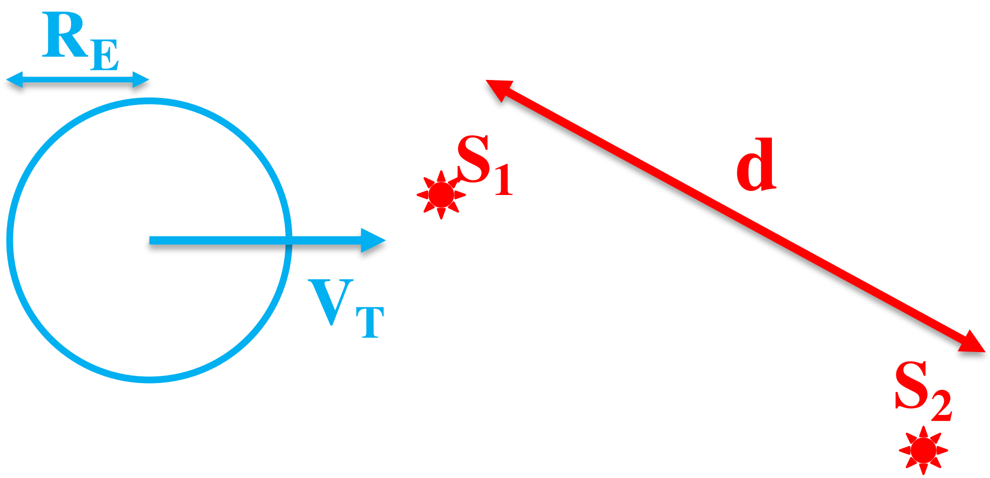
Number of neighbours at [r,r+Δr]

- Should increase linearly with r for a random distribution
- GAIA catalog of nearby stars shows clear excess w/r random for separation < 10000AU
- Corresponds to < 0.1 arcsec angular separation in LMC

Binary sources

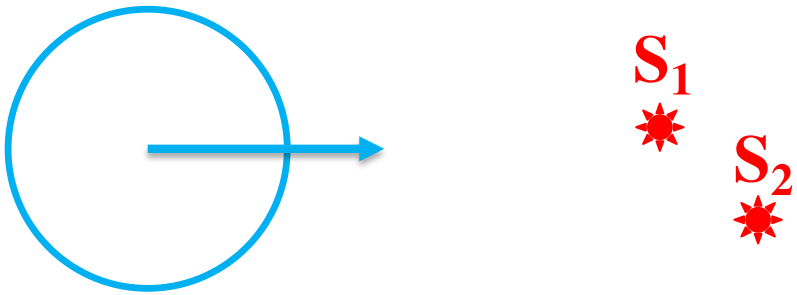
- **$d \gg R_E$**

-> Only 1 source magnified
= blend



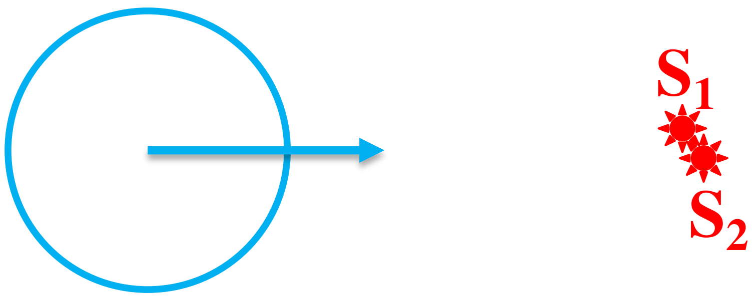
- **$d \sim R_E$**

-> 2 differently magnified sources
= blend (2nd type)

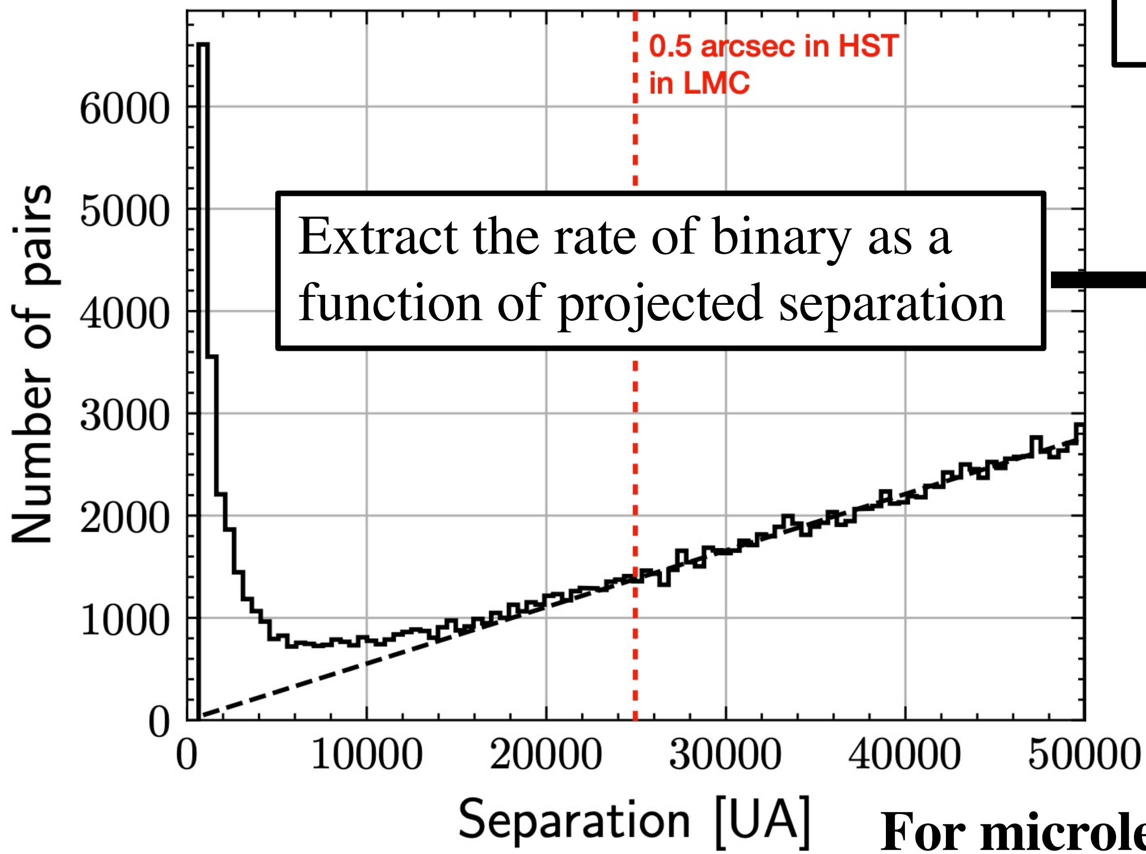


- **$d \ll R_E$**

-> 2 ~ equally magnified sources
= no-blend

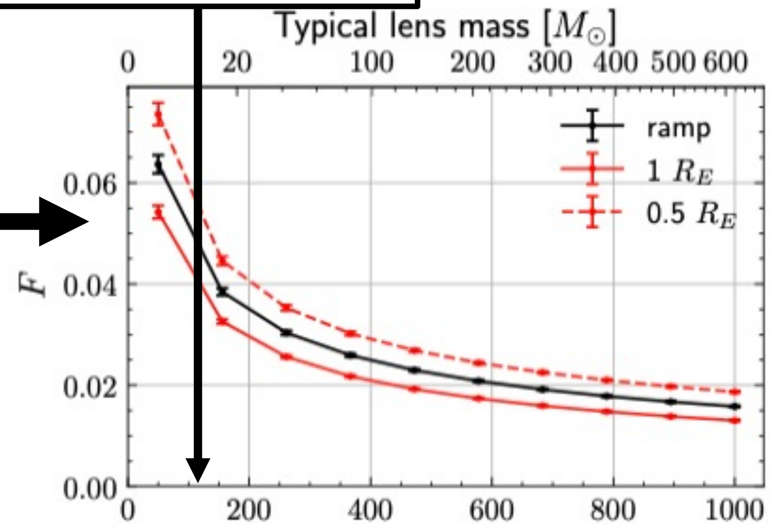


Do we expect blending by very close neighbours not detected in HST ?



Extract the rate of binary as a function of projected separation

for t_E > 1yr event
R_E >> 50 AU

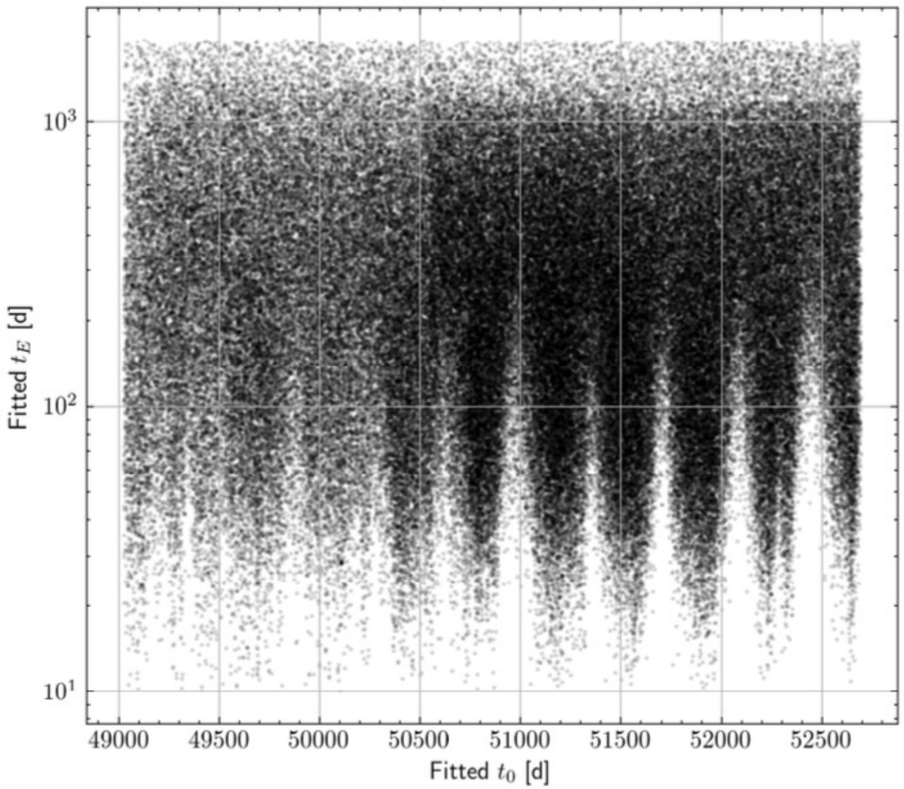


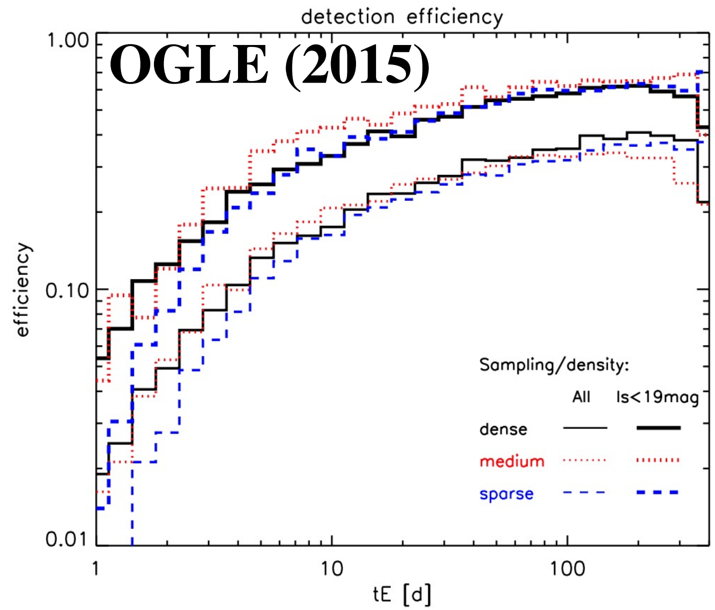
Integrated binary rate as a function of the separation from abscissa [AU] to infinity

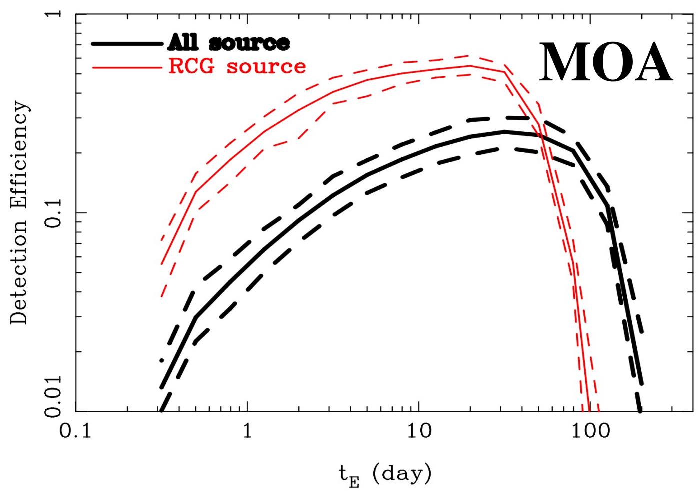
For microlensing by heavy lenses

- < 7% of the sources are binaries with blend effect
- closer binaries are identically magnified
- -> Negligible impact (conservative)

Efficiency

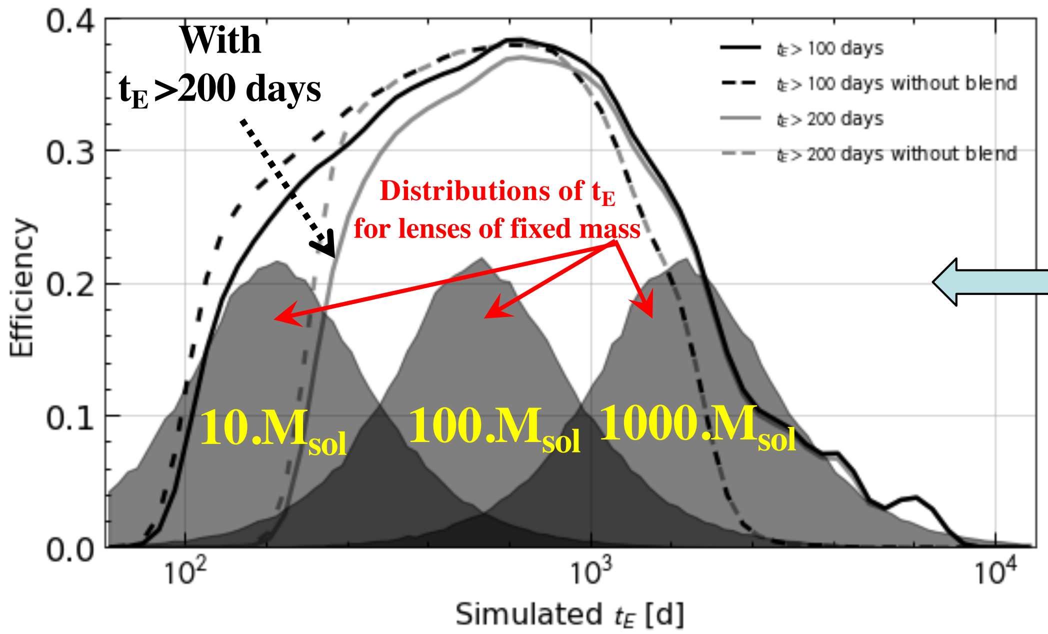






- Averaged on a given source population (RG, all)
- Depends on sampling and environment
- Averaged on u_0, t_0 -> to obtain a Function of t_E only

Expected signal
from the standard dark matter halo (S model)



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

 # events depends on

Halo model for compact objects

- **Spatial** distribution
  -> derive optical depth to LMC
  $\tau \sim 4.6 \times 10^{-7}$
- **Velocity** distribution
- **Mass** distribution (here **δ(M)**)
  -> derive **t_E distribution**

Mean detection efficiency

- Estimated as a **function of t_E**

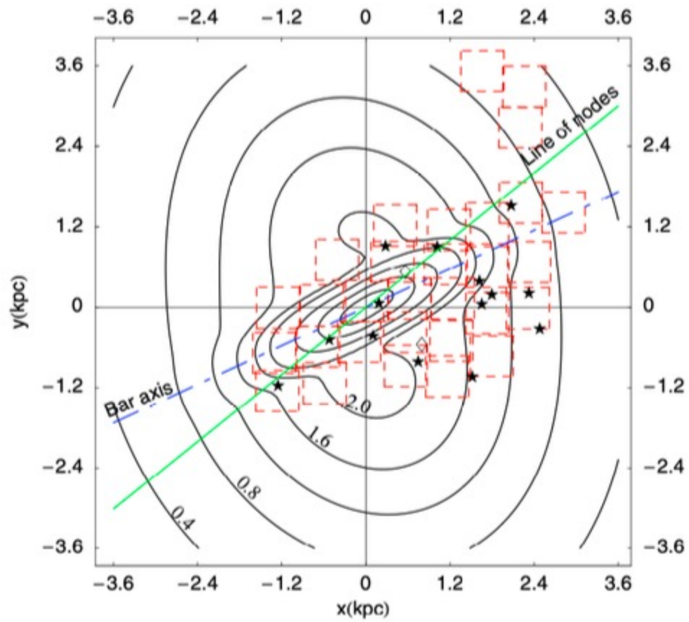
 # events proportional to

- T_{obs}
- $N_{star\ in\ LMC} = 0.95 \times N_{star\ catalog}$
  (< 5% Milky Way stars –from GAIA data)

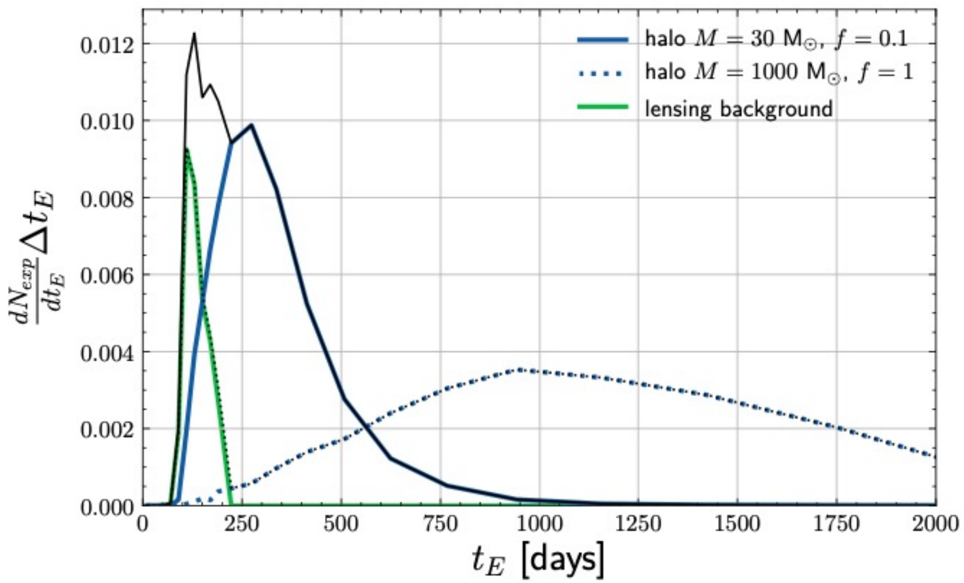
Final correction: max 10% of events can escape detection because they are exotic (double lens…)

Microlensing background

- **Stars in the Milky Way disk**: uniform over all fields
- **Stars in LMC** (self-lensing): concentrated around the LMC bar
- Estimated and adapted to our efficiency from *Calchi-Novati & Mancini 2011*



Optical depth contour for self-lensing. In red: a fraction of the MACHO fields. From Mancini 2004.



Distribution of number of expected events in t_E intervals.

Exclusion limit (T. Blaineau et al. arXiv:2202.13819)

This analysis

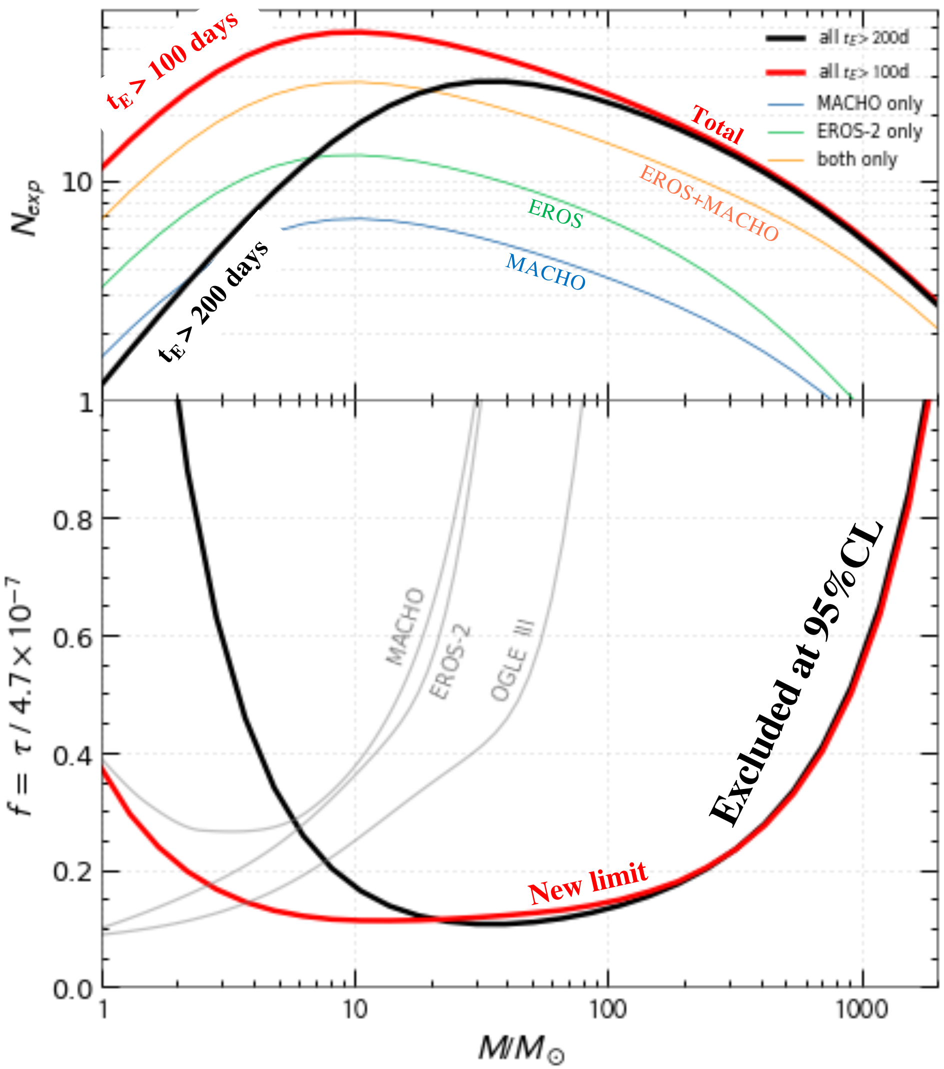
- ~ **0.64** events expected from LMC self-lensing+disk (with $100 < t_E < 200$ days)
- **2** candidates selected
- Likelihood analysis to find 95% CL exclusion limit

If we further require $t_E > 200$ **days**

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

High mass exclusion unchanged

Expected events from the standard halo



Several sources of gain

- Previous analysis explicitely rejected long events
  - To have a long enough baseline / reject LPV
  - Here we use published catalogs of LPVs
- Cumulate EROS + MACHO statistics
- 14.1 million light-curves monitored for 10.6 years.
  - Contribute for 72% of the expected detections for a halo made of 1000 M_{sol} lenses

  -> Detection efficiency for these curves is x4

Conclusions, perspectives

Microlensing observations and the Galactic halo

- ✓ We have combined EROS2 + MACHO data towards LMC
- ✓ If black holes make the hidden halo mass, expect > 6 events for < $1000M_{sol}$ objects
- ✓ **Objects with M < $1000.M_{sol}$ do not dominate the Galactic DM halo (@95%CL)**

What about the black holes responsible for the GW?

- ✓ Do not constitute the Galactic DM
- ✓ In the visible structures of the Milky Way (end-point of IMF)? -> 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 -> **> 40 years**