# MACHOS

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MACHOs have been long standing candidates for Galactic dark matter. In 1986, it was suggested that the microlensing of sources in dense stellar fields could constrain the mass fraction of MACHOs in the dark dalo. After 10 years of experimental search, MACHOs have been ruled out as major contributors to Galactic dark matter over a wide mass range. However, the explanation of observational results towards the Large Magellanic Cloud is still controversial.

## 1 Introduction

From primordial nucleosynthesis bounds, it is believed that dark matter cannot be fully composed of baryons. However, a large fraction of the Galactic dark matter might be composed of baryons [1]. They have to be hidden either in very cold molecular clouds, or in dark compact objects, the so-called MACHOs ( Massive Astrophysical Compact Halo Object). Examples of MACHOs are snowballs, planets, brown dwarfs, red dwarfs, dead stars such as white dwarfs and neutron stars, and black holes. MACHOs are difficult to observe directly, although their direct detection is sometimes possible, e.g section 4.3. In 1986, B.Paczyński [2] showed that MACHOs in the mass range from $[10^{-7} - 10^{2}]M_\odot$ could be discovered or strongly constrained by studying the microlensing of resolved stars in the Large Magellanic Cloud (LMC).

## 2 Microlensing expectations

Gravitational lensing is a consequence of the deflection of light by massive bodies ("lenses"). Compact lenses like MACHOs distort the light beam from background sources and create two images. For sources located in the Magellanic Clouds and lenses in the Galactic halo with masses less than 100 $M_\odot$, the typical separation of the images is less than 1 *mas*, too small to be resolved with present ground or space based telescopes. The source is said to be "microlensed". The total flux coming from the source is magnified independently of wavelength (achromaticity). It can be detected if the lens moves in front of the source. If the lens is a single compact object ("point lens") and the effects of the finite size of the source can be neglected ("point source"), the magnification, $A$, versus time, $t$, curve is given by

$$A = \frac{u^2+2}{u\sqrt{u^2+4}} \quad (1)$$

$$u^2 = u_o^2 + \left(\frac{t-t_o}{t_E}\right)^2 \quad (2)$$

where $u_o, t_o$ and $t_E$ are parameters. $t_E$ (the "timescale" of the event) is a function of the transverse velocity, of the lens distance and mass $m_{MACHO}$.

The motion of the Earth ("parallax") has to be taken into account for events with timescale over a few months. The effect of parallax is large when the lens is near the observer or when its mass is small. (Non)-observation of parallax on microlensing candidates constrains lens distances and masses.

More information is provided by binary microlensing events. Binary lenses produce caustics which are sometimes observed. If the radius of the source is known, the time taken by the source to cross the caustic line gives a measurement of the velocity of the projection of the source onto the lens plane (sec. 4.2).

The optical depth $\tau$ is the probability of observing a magnification of more than 34% towards a given direction at a given time; it is independent of $m_{MACHO}$. The contribution of halo lenses to the optical depth towards the LMC is expected to be $\tau^{LMC} \sim 5\ 10^{-7}$ for a standard dark halo fully comprised of MACHOs. The optical depth towards the SMC is in the range $\tau^{SMC} \sim 5 - 7\ 10^{-7}$, depending on the Galactic model. The timescale of events scales as $m^{1/2}_{MACHO}$. For a microlensing event observed towards the LMC, one has:

$$t_E \sim 70 \sqrt{\frac{m_{MACHO}}{M_\odot}} \text{ days} \tag{3}$$

The measurement of $t_E$ allows to estimate $m_{MACHO}$. The event rate towards the LMC is $\Gamma_{LMC} \sim 1.6\ 10^{-6}\sqrt{\frac{M_\odot}{m_{MACHO}}}$/star/year, assuming 100% experimental efficiency. Tens of million stars have to be monitored during years to obtain a signal. One has to use crowded fields such as the LMC or the SMC (Small Magellanic Cloud). Resolved stars from these fields are actually bright stars blended with a few fainter stars. Since any star in the blend can be lensed, observed microlensing events are in general chromatic.

## 3 Observational results

### *3.1 Early history (before 1999)*

By 1992, two experimental groups, the french `EROS` (`''EROS1''`) and the australo-american `MACHO` had started searching for Galactic dark matter with microlensing. `EROS` had a major hardware upgrade (`''EROS2''`) in 1996. Both experiments are monitoring the LMC and the SMC. The first microlensing candidates towards the LMC were reported in 1993 [3] [4]. The analysis of the first 2 years of `MACHO` data was published in 1997. A total of 8 candidate events were observed with a typical timescale $t_E = 50$ days (which translates into a typical mass $m_{MACHO} = 0.5 M_\odot$). The measured optical depth was

$$\tau^{LMC}_{MACHO 2yr} = 2.9^{+1.4}_{-0.9}\ 10^{-7}. \tag{4}$$

According to this result, roughly half (and possibly all) of the dark halo mass should be in compact objects. The analysis of `EROS1` gave two microlensing candidates towards the LMC. No microlensing candidate with $t_E < 17$ days was found by either experiment. Since this timescale corresponds to $m_{MACHO} \sim 0.05\ M_\odot$, a strong limit on the contribution of planet-sized objects to Galactic dark matter was set [5].

### *3.2 Recent results*

The analysis of the `EROS` 1996-1998 data taken towards the SMC came in 1999 [6]. Only 1 microlensing candidate was found, while a dark halo made of 0.5 $M_\odot$ objects would contribute 4-6. This translates into an upper limit on the halo mass fraction in 0.5 $M_\odot$ MACHOs $f_{MACHO} < 0.5$(95% CL). This limit is conservative, since it has been realized [10] that the "self-lensing" contribution to the signal towards the SMC may be substantial (see section 4.2). The event found is peculiar: its $t_E$ ($\sim$ 125 days) is longer than the $t_E$ of any event found towards the LMC. The parallax analysis suggests that the lens must be either very close to the SMC or heavy ($m_{lens} > 0.6 M_\odot (95\%\ CL)$). The interpretation as a "self-lensing" event is more natural.

The `MACHO` 1992-1998 LMC data analysis [9] has been presented in 2000. 13 (17) microlensing candidates have been found (depending on the cuts), while the estimated background is 2-4 events (see section 4.2). 55 (70) events were expected for a standard halo full of $\sim 0.5\ M_\odot$ MACHOs. Hence, the `MACHO` collaboration still claims the detection of a $0.15 - 0.9 M_\odot$ MACHO signal, but with a smaller halo mass fraction $f_{MACHO} \sim 0.2$. In terms of optical depth

$$\tau^{LMC}_{MACHO 5.7yr} = 1.2^{+0.4}_{-0.3}\ 10^{-7} \tag{5}$$

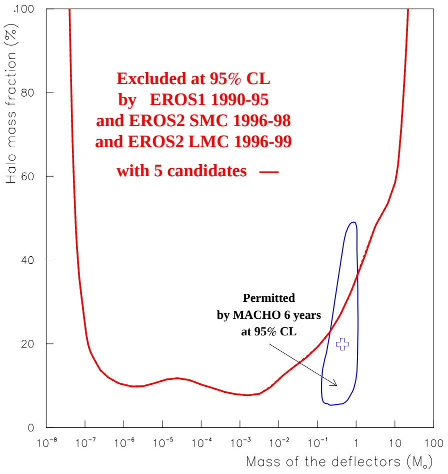

Figure 1. Exclusion/acceptance plot for MACHOs. The red solid curve is the 95% CL exclusion region of the EROS experiment. The blue line is the MACHO 95% CL acceptance contour obtained with their 5.7 year analysis (13 event sample).

Meanwhile, EROS [7] has extracted a limit from the EROS1 LMC (1990-1995), EROS2 LMC and SMC (1996-1998) combined data. A more stringent limit, taking into account the EROS2 1998-1999 data is available from reference [8]. One of the two EROS1 candidates (LMC-2), which was "magnified" in 1990 was seen to vary again in 1999. Four more microlensing candidates were found in the EROS2 LMC analysis. So EROS has a total of 5 (not especially nice) microlensing candidates (the SMC candidate is considered as self-lensing and not taken into account), while $\sim 30\ 0.5M_\odot$ MACHOs were expected towards the LMC. EROS has decided to set an upper limit instead of claiming a Galactic halo signal.

The EROS 95% exclusion region is compared with the MACHO signal region on figure 1. The results are clearly compatible, but the interpretation is different.

## 4 Discussion

The excess events seen by the MACHO collaboration towards the LMC can be either a signal (sec. 4.3) or a background. In the latter case, it can be no microlensing at all (sec. 4.1) or microlensing by "known" populations (sec. 4.2).

### *4.1 Variable star backgrounds*

Several variable star backgrounds to the microlensing search have been identified. The "blue bumpers" are young, bright, blue stars. Their flux variations are sometimes compatible with microlensing light curves, except for chromaticity. Fortunately, the interpretation of the observed event as the amplification of a faint star blended with the source turns out to be unphysical [8].

Cataclysmic variable bursts (e.g. dwarf novæ) can also be misinterpreted as microlensing events. The MACHO group shows evidence that some of its microlensing candidates could be supernovæ exploding in galaxies behind the LMC. These candidates are rejected when their light curves make a better fit to type Ia supernova templates than to microlensing light curves. EROS rejects this background by cutting on the asymmetry of the light curve.

Other sources of variable stars backgrounds are likely to exist (e.g EROS1 LMC-2). However a few "gold plated" microlensing events have been found by EROS and MACHO towards the SMC and the LMC (e.g MACHO alert LMC-99-2, event SMC-98-1). Thus variable stars can explain at most a fraction of the signal.

Known populations of stars contribute to the optical depth towards the LMC and the SMC. For instance, solar mass stars located in the LMC are too faint to be resolved by EROS or MACHO: they are "dark objects" for the microlensing surveys.

### *4.2 Self-lensing*

The major stellar populations to be considered are the Galactic disk and the various components of the Magellanic Clouds.

The contribution of stars in the Galactic disk to the optical depth is expected to be $\tau^{GD} \sim 10^{-8}$, an order of magnitude less than what is observed by `MACHO`.

The SMC is known to be elongated along the line of sight. Hence the lensing of a source in the SMC by a lens in the SMC ("self-lensing") is expected to be non negligible. The self-lensing optical depth towards the SMC has been estimated by various authors [10] [12] to be $\tau^{SMC} \sim (0.5-2)\ 10^{-7}$. The observation of 1 event corresponds to an optical depth of $\tau^{SMC}_{EROS} \sim 1\ 10^{-7}$ and is clearly compatible with the expectation from self-lensing. Towards the SMC, the self-lensing contribution to the signal is as large as (or larger than) the Galactic halo contribution.

This conclusion is supported by the analysis of binary event SMC-98-1. This event was detected online by the `MACHO` alert system. The source star is too faint to be on the `EROS` catalog. A joint effort of the microlensing community led to an intensive photometric follow-up of this event [13]. The measured proper motion (angular velocity) of the source: $\mu \sim 1.4$ km/s/kpc is incompatible with a lens located in the Galactic halo ($\mu \sim 15$ km/s/kpc) and compatible with a lens in the SMC ($\mu \sim 0.5$ km/s/kpc).

The idea that the microlensing signal from the LMC can be explained by self-lensing traces back to Wu [15] and Sahu [16]. The LMC is believed to be a thin disk seen with a tilt angle of $\sim 30$ deg . The LMC self-lensing models have been analyzed by Gyuk et al. [14]. These authors find a self-lensing optical depth in the range $(0.5-8)\ 10^{-8}$, depending on the parameters of the LMC model with a prefered value of $\tau^{LMC}_{self} \simeq 2.5\ 10^{-8}$. The central value is a factor of 5 smaller than the optical depth measured by the `MACHO` collaboration. The self-lensing background was estimated by `MACHO` with the preferred model of Gyuk et al. to be 2-4 events for their 5.7 years analysis [9], giving a Galactic Halo signal of 11-13 events. However several non-standard models of the LMC predict microlensing optical depths compatible with the observations [17] [18].

The self-lensing hypothesis can be tested observationally. The spatial distribution of observed candidates should scale like the distribution of sources (roughly flat) if the LMC sources are lensed by Galactic halo lenses. In the self-lensing hypothesis, the spatial distribution of events scales like the distribution of sources times the mass density in the LMC and should be concentrated towards the center of the LMC. The `MACHO` group [9] has compared the spatial distribution of their events to the predictions of the standard halo model and of the best self-lensing model of Gyuk et al [14]. The data are slightly (at the 2 $\sigma$ level) in favor of the standard halo hypothesis. However, as seen previously, the self-lensing optical depth predicted by Gyuk is smaller than the `MACHO` measurement by a factor of 5, so data should be compared to the predictions of other self-lensing models.

### *4.3 White dwarfs*

Assuming a Galactic Halo signal, the mass of the objects detected towards the LMC is $m_{MACHO} \simeq 0.5\ M_\odot$, which suggests white dwarfs (WD). These WD are old [11] ($\geq 14$ Gyr), faint, high proper motion stars. According to cooling models, old hydrogen WD with are still bright enough to be searched for by direct searches. Two white dwarf candidates (when 3.6 were expected for a halo full of WD) were found with two Hubble Deep Fields taken two years apart by Ibata et al. [19]. However Flynn et al [21] combined the results of reference [19] with the results of older photographic surveys and found a much smaller halo mass fraction in WD. A small positive signal (2 candidates found with 20 expected for $f_{WD} = 1$) compatible with `MACHO`'s results was claimed in reference [20]. A signal was also searched for by the `EROS` group [22]. The `EROS` data were taken over a

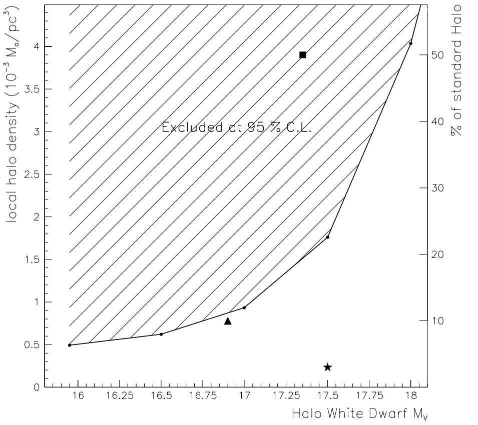

Figure 2. EROS2 exclusion plot for old Galactic white dwarfs. The square, the triangle and the star show respectively the results from Ibata et al. (1999), ibid. (2000) and Flynn et al.(1999)

large area of 440 square degrees, 250 of which have been analyzed. The analysis requires at least one astrometric measurement per year for 3 years. No candidate was found, while 20 were expected, assuming 14 Gyr old WD. As shown on figure 2, this rules out the Ibata et al 1999 result [19] and sets a 95% CL limit on the halo mass fraction in old WD.

## 5 Conclusion

After ten years of monitoring the Magellanic Clouds, it is now clear that MACHOs of less than a few $M_{\odot}$ cannot be a major contributor the Galactic mass budget. Strong limits have been set on the contribution to the dark Galactic Halo of low mass ($[10^{-6} - 10^{-2}]$ $M_{\odot}$) MACHOs ($f_{MACHO} < 0.1$), brown dwarfs ($f_{MACHO} < 0.2$) and 0.5 $M_{\odot}$ objects ($f_{MACHO} < 0.3$) .

The microlensing candidates seen towards the LMC are still not fully understood. Some of them (though not all of them) may be variable stars. The background from self-lensing should be small unless our understanding of LMC structure is incorrect. The existence of an old protogalactic WD population in the dark halo is still an open question. Direct searches show however that the halo mass fraction in old WD with an hydrogen atmosphere is less than 15 %.

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