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Experimental results
1- Galactic disk
2- Small masses (LMC/SMC) $10^{-7} - 10^{-2} \, M_\odot$
3- SMC
4- LMC
**Einstein radius:**

\[ R_E = \sqrt{\frac{4GM}{c^2}} D_{OS} x (1-x) \]

where \( x = \frac{D_{OD}}{D_{OS}} \)

**Angular separation of the images:**

\[ \sim \frac{2 R_E}{D_{OD}} \sim 10^{-3} \text{ arcsec} \]

a single image observed but amplified \((A \sim 1/u)\)

**Typical duration:**

\[ t_E = \frac{R_E}{v_t} = 90 \sqrt{\frac{M}{M_\odot}} \text{ days} \]

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**Diagram:**

- Observer \( O \)
- Déflecteur \( D \)
- Source star \( S \)
- Image 1
- Image 2
- Light rays trajectory in plane of deflector

(Paczyński, 1986)
compact objects

- Symmetric
- Achromatic
- Unique

surveys: EROS 2, MACHO, OGLE 2
follow-up: PLANET, GMAN
$A_0 = 2.5$

$t_E = 23$ days
BLENDDING

\[ 2.5 \log(\text{Flux}) \]

<table>
<thead>
<tr>
<th>time</th>
<th>6.2</th>
<th>6</th>
<th>5.8</th>
<th>5.6</th>
<th>5.4</th>
<th>5.2</th>
<th>5</th>
<th>4.8</th>
<th>4.6</th>
<th>4.4</th>
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**Total base flux** \((F_1 + F_2)\)

**Base flux of magnified star** \((F_1)\)

**reconstructed magnification**

**real magnification**

\[ F_{\text{tot}} = A(t) F_1 + F_2 \]
TRIPLE DEGENERACY

\[ A_0 = \frac{u_0^2 + 2}{u_0 \sqrt{u_0^2 + 2}} \]

\( t_E \):

\[ t_E = \frac{R_E}{v_t} = \frac{\sqrt{\frac{4 G m_{\text{mde}}}{c^2} D_{OS} x (1-x)}}{v_t} \]

\( u_0, t_0 \): randomly distributed (statistical tests of consistency on all events)

mass function (Dirac)

dark matter distribution model in halo (or Clouds)

velocity distribution model
- 1m primary mirror
- 2 x 8 CCD's covering 1 square degree
- dichroic cube => red and blue simultaneously
- automatic pointing and guiding system
DATA ANALYSIS

- Images → Star catalogue
- Selection criteria based on microlensing properties
- Find significant variation
- Select variations compatible with microlensing
- Rejection of variable stars

Efficiency through Monte Carlo simulation on light curve

Estimate blending effect through simulated images

Backgrounds unknown
EROS FIELDS TOWARDS THE GALACTIC SPIRAL ARMS

Sun

D = 7 kpc

Norma-Cygni

Persee

θ Mus

ECU-Croix

Sagittaire-Carene

γ Nor

γ Sct

β Sct

(in kpc)
Recent Results towards the Galactic Spiral Arms (EROS experiment)

- All fields: 7 events (~ as expected)
- Excess towards $\gamma$ Sct (5 observed vs. 1.6 expected)
  Mostly short durations $\Rightarrow$ bulge events

![Graph showing the distribution of events across different stellar locations and distances in the Galactic Spiral Arms. The x-axis represents Galactic longitude in degrees, and the y-axis represents $\tau \times 10^6$. The graph displays contributions from Total, Disk, Bulge, and Halo components, with peaks at specific longitudes and distances, indicating excess events towards $\gamma$ Sct.](image-url)
1993 : EROS 1, MACHO, OGLE
First microlensing events

1996 : EROS 1
2 candidates towards LMC \( t_E \sim 25 \text{ days} \)
→ exclusion contour

1997 : MACHO
6-8 candidates towards LMC \( t_E \sim 40 \text{ days} \)
→ positive detection, \( M = 0.5 \, M_\odot \)
20-100% of standard halo

1996 - 1998 : EROS 1 + MACHO
No short duration event \( (t_E < 15 \text{ days}) \)
→ No dark objects \( 10^{-7} \, M_\odot < M < 10^{-2} \, M_\odot \)
EXCLUSION CONTOUR

Halo mass fraction (%)

Deflector mass ($M_\odot$)

- Objects with mass in range $[10^{-7} - 0.02] M_\odot$
  - make up at most 20% of standard halo
  - $M_{TOT} < 1 \times 10^{11} M_\odot$ (~ model-independant)
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No short duration event \( (t_E < 15 \text{ days}) \)
\( \rightarrow \) No dark objects \( 10^{-7} M_{\odot} < M < 10^{-2} M_{\odot} \)

1998: EROS 2, MACHO
First SMC candidate \( t_E \sim 130 \text{ days} \)
\( \rightarrow \) First self-lensing hint

1999: EROS 2 (SMC Data)
One candidate on two years of date \( (11 \times 10^6 \text{ star.years}) \)
\( \rightarrow \) Exclusion contour (extended towards \( M \sim 0.1 M_{\odot} \))
ERSOS 2 SMC ANALYSIS

- 2 years have been analysed and published
- 8.6 deg$^2$ spread over 10 fields
- 5.3 million stars
- Sampling : 1 measurement/2-4 days

One event (SMC-97-1)

DETECTION OF PARALLAX EFFECT

- events with large $t_E$
- simultaneous observation with a satellite in orbit around the Sun

**FIRST SMC CANDIDATE**

- Flux $R$: $u_0 = 0.42$
- Time $t_E = 129$ days
- $\chi^2 = 261 / 279$
  (once modulation included)

- **Intrinsic variable star**
- Period $P = 5.1$ days
- 5% peak-to-peak
no detectable effect

⇒ at 95% CL: \( \frac{M}{M_0} \cdot \frac{x}{(1-x)} > 0.7 \)  where \( x = \frac{D_{OD}}{D_{OS}} \)

PARALLAX ANALYSIS
ON CANDIDATE LIGHT CURVE

2 possible interpretations:
- deflector in the halo: \( x < \frac{2}{3} \) and \( M > 0.6 \, M_0 \)
- deflector in the SMC: \( x \approx \frac{9}{10} \) and \( M \approx 0.1 \, M_0 \)
EXCLUSION CONTOUR

Mass of the deflectors ($M_o$) vs. Halo mass fraction (%)

- Excluded at 95% CL by EROS 1 (red dashed line)
- Excluded at 95% CL by EROS 2 SMC (blue line)
- Permitted by MACHO at 95% CL (green shaded area)
MICROLENSING : PRESENT STATUS

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First microlensing events

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1998 : EROS 2, MACHO
First SMC candidate $t_E \sim 130$ days
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1999 : EROS 2 (SMC Data)
One candidate on two years of date ($11.10^6$ star.years)
→ Exclusion contour (extended towards $M \sim 0.1 \, M_\odot$)

1999 : EROS 2, MACHO, OGLE, PLANET, MPS
Binary lens event towards SMC
→ New self-lensing hint

1999 : EROS 2 (LMC Data)
LMC data, on 25 square degrees and 2 years of data
→ 2 candidates, new combined exclusion plot
**BINARY LENSES**

\[ d\zeta = J\, dz \]

\[ \text{amp} = \frac{1}{|\text{det} J|} \]

thus \( \text{amp} = \infty \) if \( \text{det} J = 0 \)

\[ \text{caustic curve} \]

in source plane

\[ \text{light curve : } u_0, t_0, t_E \]

\[ q = \frac{m_1}{m_2}, a, \theta \]
EVENT 98-SMC-1
ERSOS 2 LMC ANALYSIS

• 2 years have been analysed
• 25 deg² spread over 43 fields
• 17.5 million stars
• Sampling : 1 measurement/4-6 days

Two events

Cut on accumulation in HR diagram (bright blue stars) + Amplification and chromatism

\[ A < 1.6 \]
\[ \frac{(A_R - 1)}{(A_B - 1)} > 1.2 \]
Consistent with binary lens (with parallax or xarallap)
Low main sequence star, achromatic

Previous variation in 1995 (MACHO)
$u_0 = 0.20(0.01)$
$t_E = 106(3) \text{ days}$
$\chi^2 / \text{dof} = 400/150$

Bad $\chi^2$ but passes all selection criteria
Accepted as candidate
$u_0 = 0.23(0.01)$

$t_F = 39(3) \text{ days}$

$\chi^2 / \text{dof} = 183/135$

Chromatic event, 72(7)% of base flux in amplified
EXCLUSION CONTOUR

- Permitted by MACHO at 95% CL
- Excluded by EROS 1 ( ) at 95% CL
- Excluded by EROS 2 LMC ( — ) at 95% CL

Mass of the deflectors ($M_o$) vs Halo mass fraction (%)
EROS 1 # 2 was a variable star, compatible with microlensing. New variation 8 years later. Confirmed on MACHO data.

EROS 1 # 2 is no longer a microlensing candidate

EROS 1 upper limited should be revised downward
EROS COMBINED LIMIT

Considered as

One single experiment with 3-4 events
Excluded at 95% CL by EROS1 1990-95 and EROS2 1996-98
with 3 candidates
with 4 candidates

Mass of the deflectors ($M_o$)

Halo mass fraction (%)

EROS COMBINED LIMIT

Excluded at 95% CL by EROS1 1990-95 and EROS2 1996-98

with 3 candidates
with 4 candidates

EROS 1 (plates) 1 cand
EROS 2 SMC 0-1 cand
EROS2 LMC 2 cand

Permitted by MACHO 6yr at 95% CL

Halo mass fraction (%)

Mass of the deflectors ($M_\odot$)
CONCLUSIONS

Galactic structure
- Galactic Spiral Arms: 7 events
  constraints on structure: extension of the bar

SMC results
- 1 event with very long $t_E$ (129 days)
  most probably in SMC
- 1 binary event with best time coverage ever
  most probably in SMC

LMC results
- no halo (<10%) compact objects in mass range
  $10^{-7} \, M_\odot - 0.02 \, M_\odot$
- only 1 event left for EROS1
- 2 events for EROS 2

EROS 1+2 SMC+LMC combined result
- less than
  100% of standard halo
  40% of standard halo
  20% of standard halo
  in mass range
  $10^{-7} \, M_\odot - 3 \, M_\odot$
  $10^{-7} \, M_\odot - 1 \, M_\odot$
  $10^{-7} \, M_\odot - 0.1 \, M_\odot$

compatible with LMC self-lensing if $\sigma_v$ (LMC) large