

GRAVITATIONAL MICROLENSING

*New synergy between ground-based observations,
space observations and theory*

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Structure evolution and cosmology

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CONTENTS

- I. A quick summary of basic concepts in microlensing
- II. Galactic structure : halo & bar properties
- III. Nature of lenses : problems
- IV. Gravitational imaging of stars : unveiling photospheres
- V. Prospects

GRAVITATIONAL MICROLENSING : THE CONCEPT

Simple test cases with a Schwarzschild lens

- Simulated event with impact parameter 0.20
- Simulated event with impact parameter 0.05
- Event at 0 impact parameter (the Chwolson/Link/Einstein ring)

BASIC CONCEPTS IN MICROLENSING

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Magnification of a point source by a Schwarzschild lens

$$A_p(t) = (y^2 + 2)/y\sqrt{y^2 + 4}$$

$$y = \sqrt{\alpha_p^2 + (t - t_o)^2/t_E^2}$$

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$\alpha_p = \theta_p/\theta_E$ minimum impact parameter (at $t = t_o$)

$t_E = D_{OL} \times \theta_E/v_{\perp}$ time scale

$\theta_E = \sqrt{(4GM_L/c^2) \cdot (D_{LS}/D_{OL}D_{OS})}$ Angular Einstein radius

Expected ML event properties :

- | | |
|----------------------|--|
| 1 – symmetric in t | 4 – $\forall$ position $\in$ HRD |
| 2 – achromatic | 5 – uniform distribution of α_p |
| 3 – unique | 6 – τ uncorrelated to $A_p(t_o)$ |

Expected number of events : optical depth

$$\bar{\tau} = \int_o^{D_{OS}} d\ell \pi \theta_E(\ell)^2 \ell^2 \frac{\rho(\ell)}{M_L}$$

- i.* does not depend on M_L , just on the spatial density along l.o.s.
- ii.* number of events : $N_{events} = \left(\frac{T}{t_E} \right) \epsilon(t_E) \tau N_*$

Is it a new type of variable star ?

ML characteristic features :

- 1 τ of days/months
- 2 non periodic
- 3 amplitude of some $0.1 \cdot 10^{\pm 1}$ mag
- 4 achromatic
- 5 symmetric

variability type	violates criteria #
pulsating stars	2 4 5
binaries	2
flares	1 4 5
spots	2 4
outbursts	3 4 5
envelope ejections	4? 5

Microlensing surveys : a quick summary

Program		$N_* / 10^6$	Δt	events
EROS1 (LMC)	Schmidt	2	11 months	2
	CCD	0.02	11 months	0
EROS2	LMC	25.5	3 years	5
	SMC	5.3	3 years	1
	arms	9.1	3 years	7
MACHO	LMC	11.9	5.7 years	13–17
	SMC	8.2	4 years	2
	Bulge	17	3 years	99
OGLE II	Bulge	20.5	3 years	314
DUO (plates)	Bulge	12	6 months	12
POINT-AGAPE	M31	pixel lensing	3 seasons	3+139 ?
MEGA+VATT	M31	pixel lensing	5 seasons	6 ?

Partial list of results on $\bar{\tau}$

Observations towards the Large Magellanic Cloud :

$$\bar{\tau}_{\text{LMC}} \sim (1.2_{-0.3}^{+0.4}) \times 10^{-7} \text{ } (\pm 25\% \text{ syst}) \quad \text{MACHO 13-17 events}$$

More than expected from known stellar populations
but about 20% of a full halo..

Observations towards the Galactic Bulge :

$$\begin{array}{ll} \bar{\tau}_{\text{bulge}} \sim (3.3 \pm 1.2) \times 10^{-6} & \text{OGLE 9 events} \\ \bar{\tau}_{\text{bulge}} \sim (3.23 \pm 0.5) \times 10^{-6} & \text{MACHO 99 events} \end{array}$$

a factor 3 larger than expected from a spherical bulge

WHAT ARE THE LENSES ?

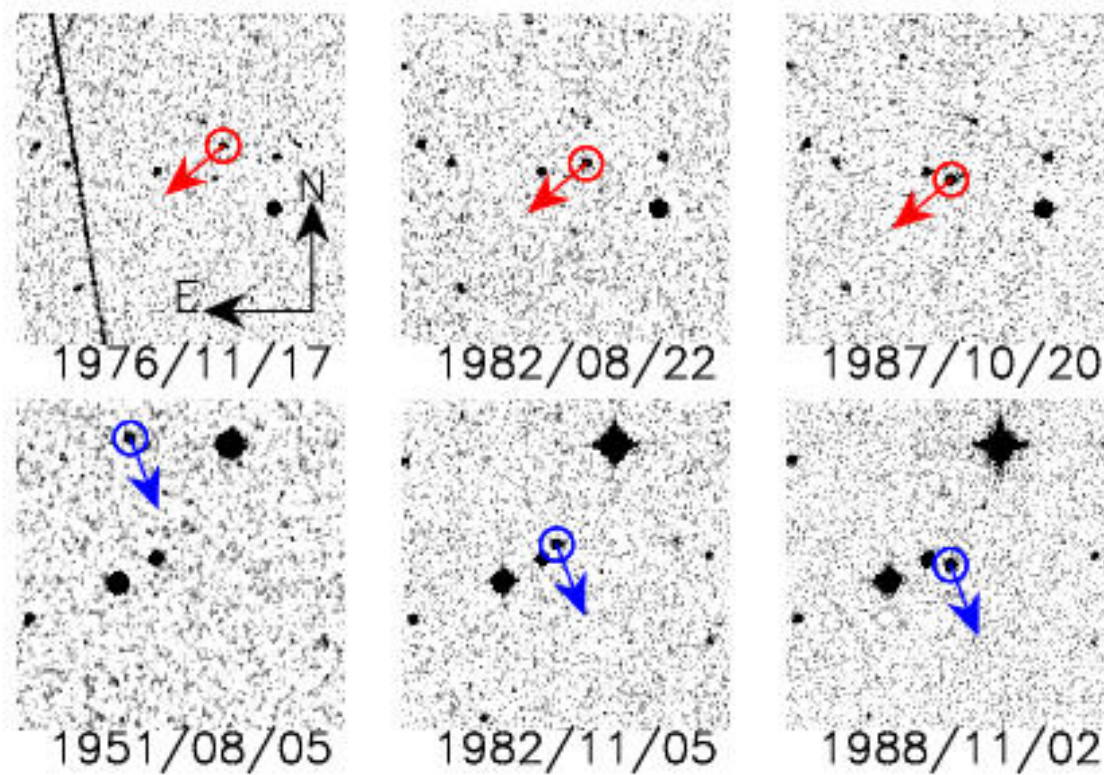
Inferred typical mass of $0.2 M_{\odot}$ (but large dispersion: 0.01 to $0.9 M_{\odot}$)

M dwarfs Far too few, even in thick disc

Black holes Unless top heavy IMF, not enough of them

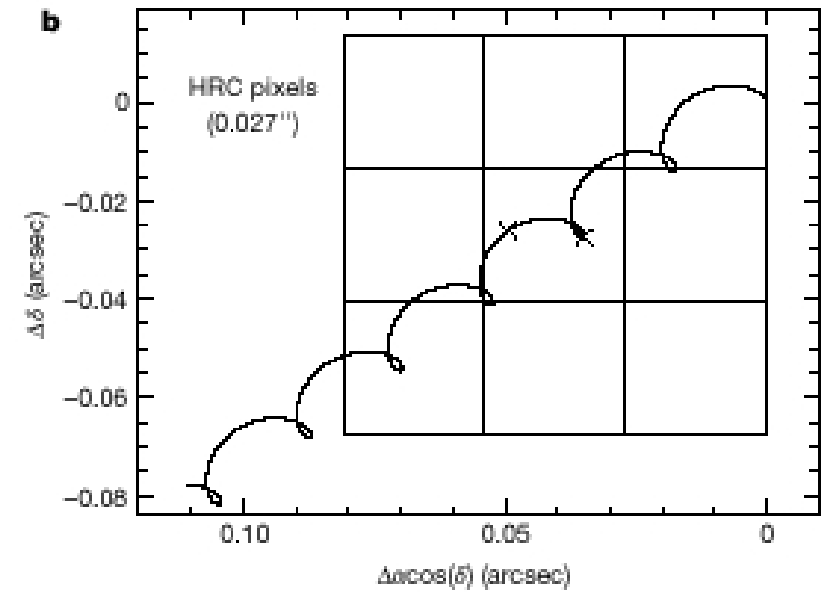
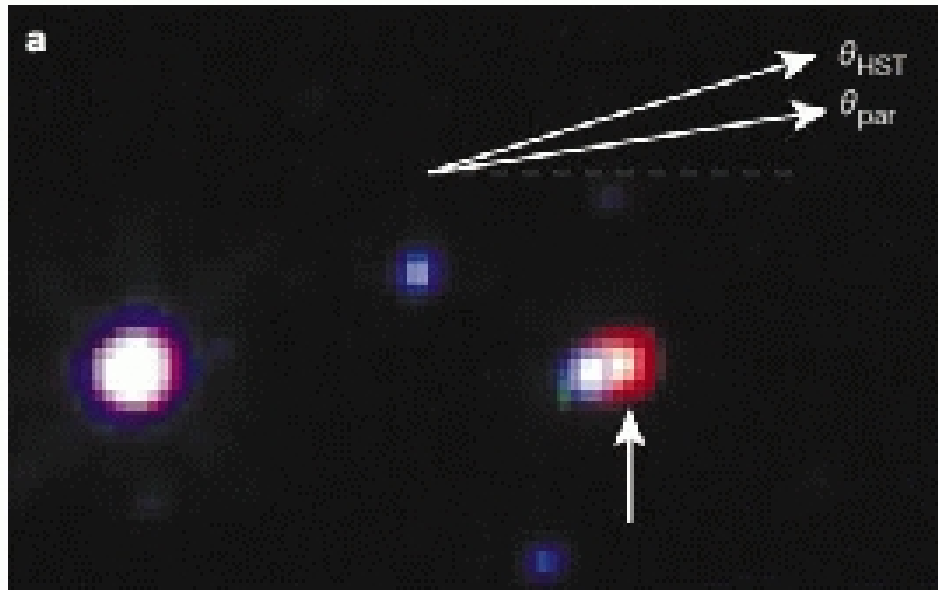
White dwarfs But galaxies would be too bright at high z

Yet evidence for a white dwarf population in the halo ?



Ibata et al. (2000), Méndez & Minniti (2001)

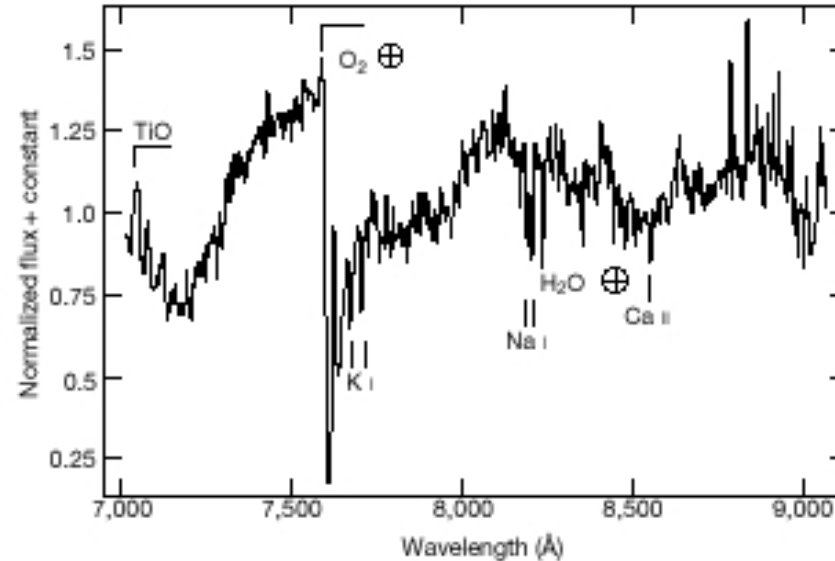
TOWARDS DIRECT DETECTIONS



combining HST (imaging) + VLT (spectra)

FORS2 spectra at VLT

- Call blend of LMC star (F type) plus lens
- Presence of KI, NaI but absence of TiO (7100Å), VO $\Rightarrow$ M4-5 V



Alcock et al. (2001) Nature **414**, 617

GRAVITATIONAL IMAGING OF STARS

Compare the stellar angular radius to the Einstein radius :

$$\theta_* = 0.0465 \left(\frac{R_*}{10R_\odot} \right) \left(\frac{D_{OS}}{\text{kpc}} \right)^{-1} \text{milliarcsec}$$

$$\theta_E = 0.902 \left(\frac{M_L}{0.1M_\odot} \right)^{1/2} \left(\frac{D_{OS}}{\text{kpc}} \right)^{-1/2} \cdot \left(\frac{D_{LS}}{D_{OS}} \right)^{1/2} \left(1 - \frac{D_{LS}}{D_{OS}} \right)^{-1/2} \text{m.a.s}$$

○ **Expected number of transit events :** $\mathcal{F} = \langle \theta_* \rangle \times \langle \frac{1}{\theta_E} \rangle$

When $D_{LS} \ll D_{OS}$ the sources are not point-like, and some subtle effects may appear

○ Magnification of extended sources

$$A_{ext}(\theta) = \int_{\underline{\Omega}} d\varpi B(\varpi) A_p(\theta) / \int_{\underline{\Omega}} d\varpi B(\varpi)$$

$$\alpha_* = \theta_*/\theta_E$$

$$\gamma = \theta/\theta_*$$

$$x = r/R_* = \theta_r/\theta_*$$

$$A_{ext}(\gamma) = \left[\int_0^{2\pi} d\phi \int_0^1 dx \cdot x \cdot B(x) \cdot A_p(p\alpha_*) \right] \left[2\pi \int_0^1 dx \cdot x \cdot B(x) \right]^{-1}$$

with $p^2 = \gamma^2 + x^2 + 2 \cdot \gamma \cdot x \cos \phi$

① **Uniform brightness profile** If $B(x) = \text{constant}$, then for $\gamma = 0$:

$$A_u^{\text{max}} = \left(1 + 4/\alpha_*^2\right)^{1/2}$$

② **Point source limit** $\gamma \gg 1 \implies p^2 \approx \gamma^2 \implies$

$$A_p(\gamma) = (y^2 + 2)/y(y^2 + 4)^{1/2} \quad \text{with } \gamma\alpha_* = \theta/\theta_E = y$$

③ **Actual stars : limb darkening profiles**

$\implies$ chromatic effects due to differential amplification across the disc

SPECTROSCOPIC EFFECT

- Milne–Eddington approximation (Chandrasekhar, 1947) :

$$\rho = \sigma / [\sigma + \kappa_c]$$

$$\beta_\lambda = \kappa_\lambda \phi_\lambda / [\sigma + \kappa_c]$$

$$\wp = [1 - \rho + \epsilon \beta_\lambda] / [1 + \beta_\lambda]$$

If $B_c = a + b\tau$ and $B_\lambda = a + p_\lambda \tau_\lambda$ and $\wp, \epsilon$ and ρ are constants, then :

$$I_\lambda^o(\mu) = (a + p_\lambda \mu) + \frac{(p_\lambda - \sqrt{3}a)(1 - \wp)}{\sqrt{3}(1 + \sqrt{\wp})(1 + \sqrt{3\wp}\mu)} \quad \text{and} \quad I_c^o(\mu) = a + b\mu$$

Two extreme cases :

○ Resonance line : $\epsilon = 1$ and $\wp = 1$

$$r_\lambda = \frac{I_\lambda^o(\mu)}{I_c^o(\mu)} = \frac{1 + (b/a)(\mu/[1 + \beta])}{1 + (b/a)\mu}$$

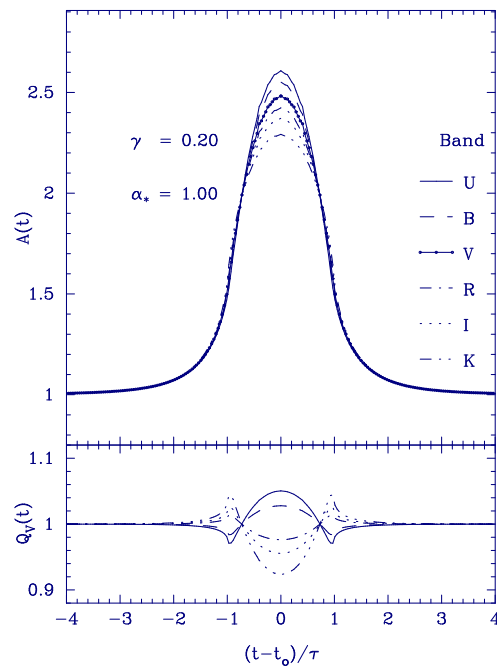
when $\mu \rightarrow 0$, then $r_\lambda \rightarrow 0$ and the line vanishes at the limb...

○ Strong scattering line : $\epsilon = 0$ and $\beta_\lambda \rightarrow \infty$ then $\wp \rightarrow 0$

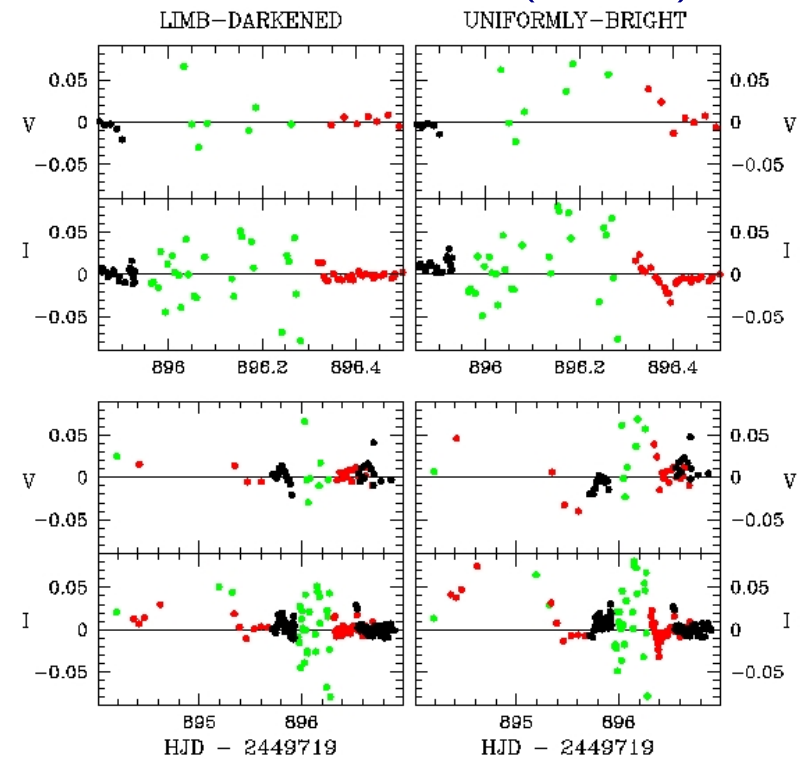
thus $\forall \mu$: $I_\lambda^o(\mu) \rightarrow 0$ and the centre of the line remains dark at all positions across the stellar disc

CHROMATIC EFFECTS IN MICROLENSING EVENTS

Predictions Valls-Gabaud (1994)

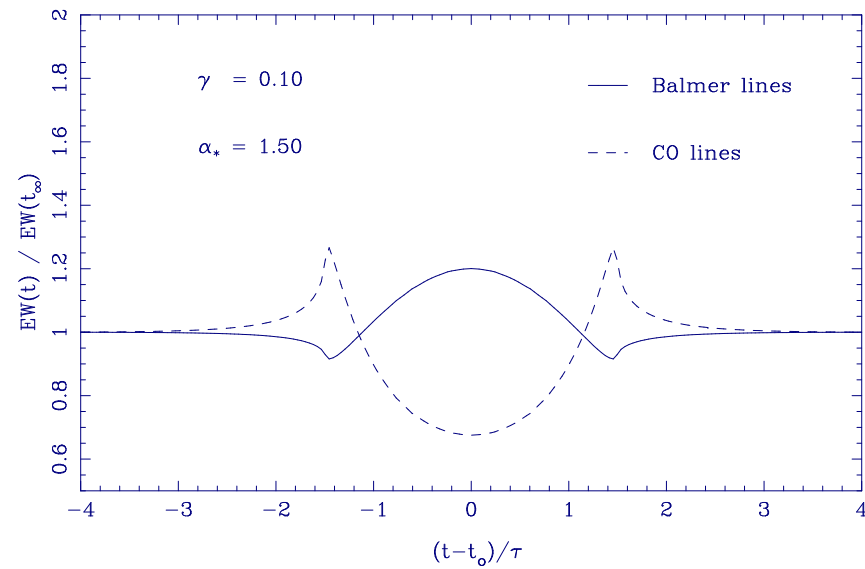


Observations Albrow et al. (2001a)



SPECTROSCOPIC EFFECTS IN MICROLENSING EVENTS

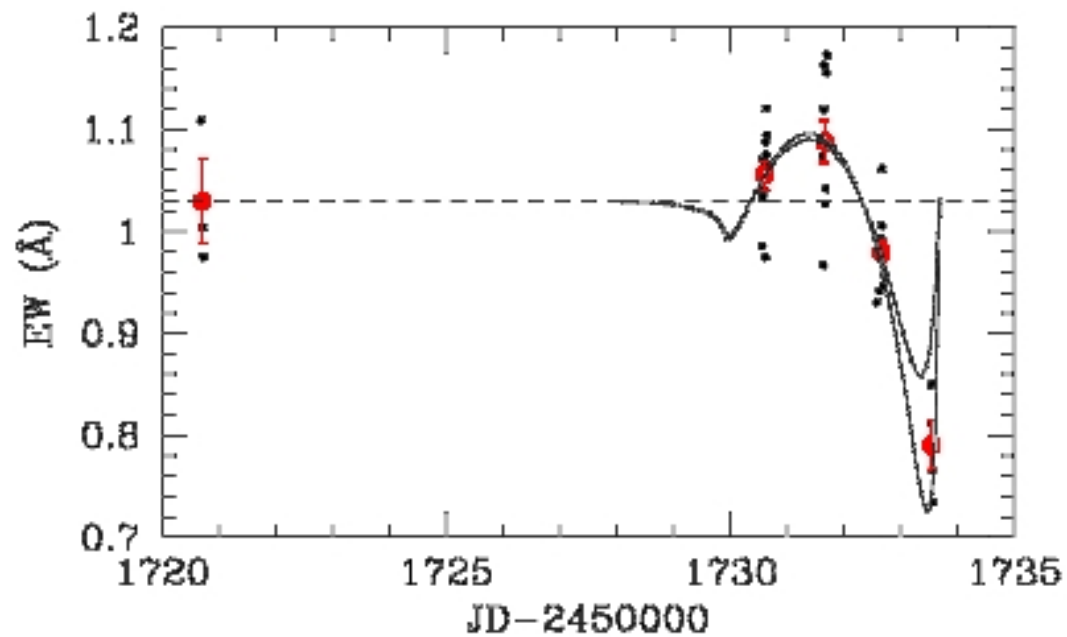
Predictions
Valls-Gabaud (1994)



SPECTROSCOPIC EFFECTS IN MICROLENSING EVENTS

Observations

Albrow et al. (2001b)



M31 as a unique microlensing target

Basic idea (Crofts 1992, Baillon et al. 1993)

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 $\Rightarrow$ many more events expected for given MACHO abundance

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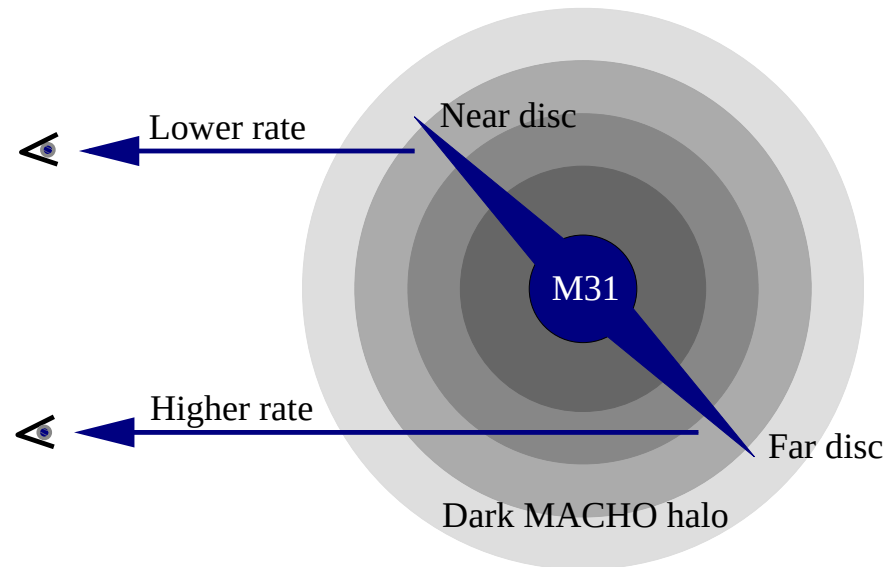
1. External galaxy, with $\mathcal{O}(10^{10})$ sources and proper halo :
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2. Additional line of sight through the Galactic halo :
 $\Rightarrow$ disentangle self-lensing interpretations for LMC/SMC

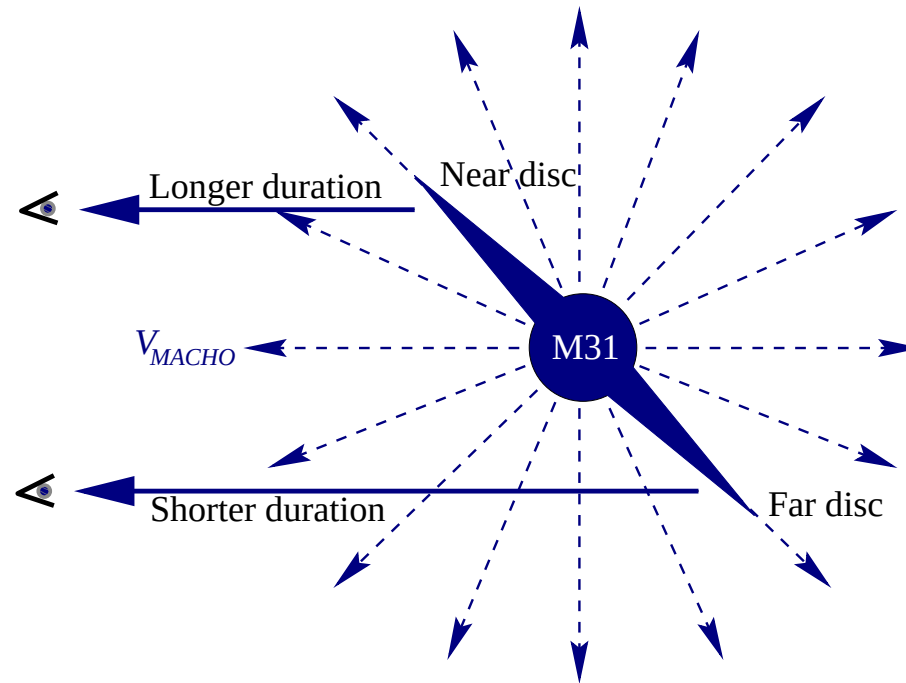
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1. External galaxy, with $\mathcal{O}(10^{10})$ sources and proper halo :
⇒ many more events expected for given MACHO abundance
2. Additional line of sight through the Galactic halo :
⇒ disentangle self-lensing interpretations for LMC/SMC
3. External viewpoint :
⇒ mapping the MACHO spatial distribution across M31

4. Inclination ($i = 77^\circ$) $\Rightarrow$ gradient in ML rate
 $\Rightarrow$ unique spatial asymmetry (if roundish halo)



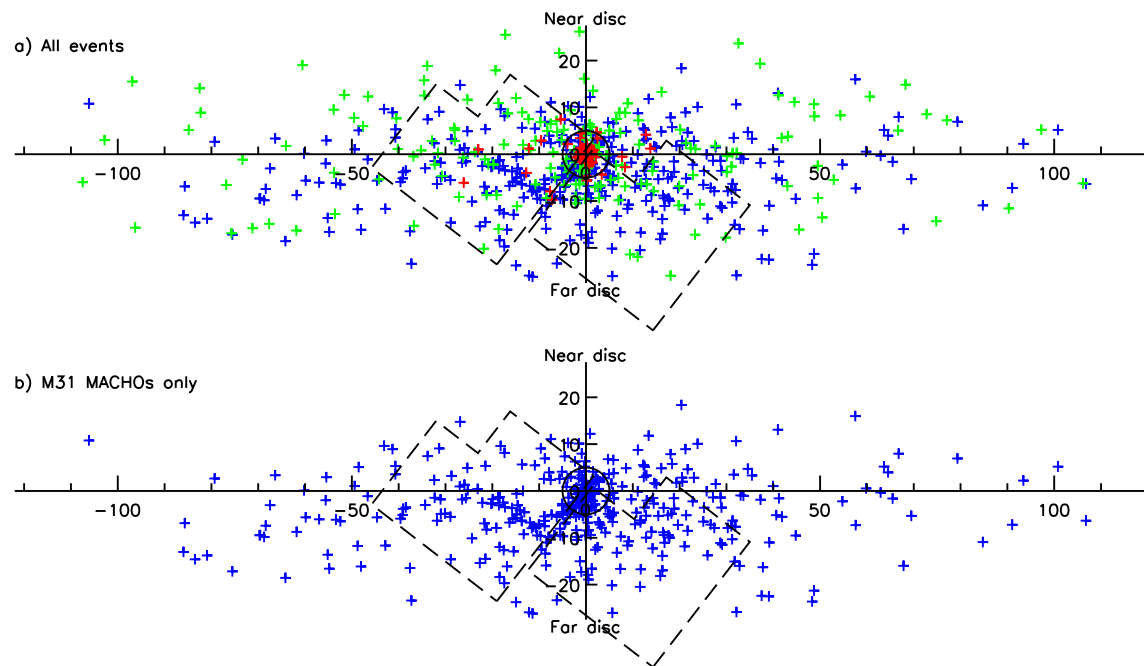


5. Constraints on velocity distribution function of MACHOS :
⇒ near/far timescale asymmetry if strong radial anisotropy

MACHOS IN M31 BY PIXEL LENSING : THE *POINT-AGAPE* SURVEY

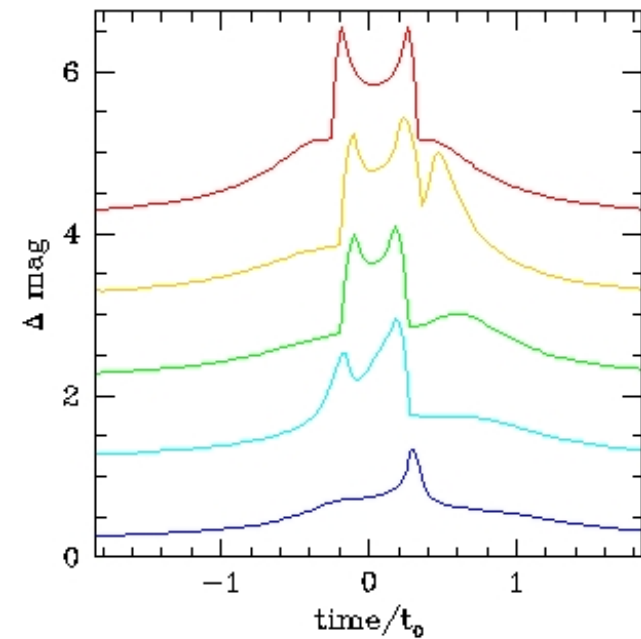
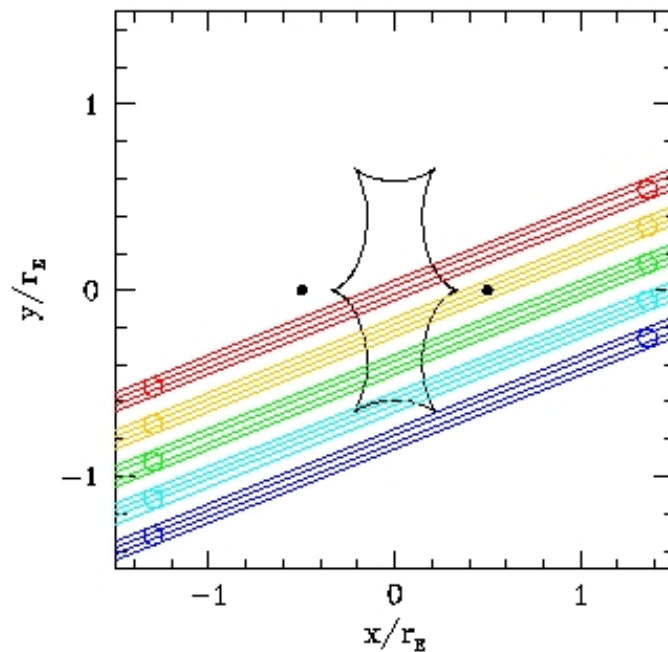
WFC at INT : large field, same instrument (same systematics), 3 seasons

Expected events : Monte Carlo simulations, Kerins et al. (2001) MNRAS **323** 13

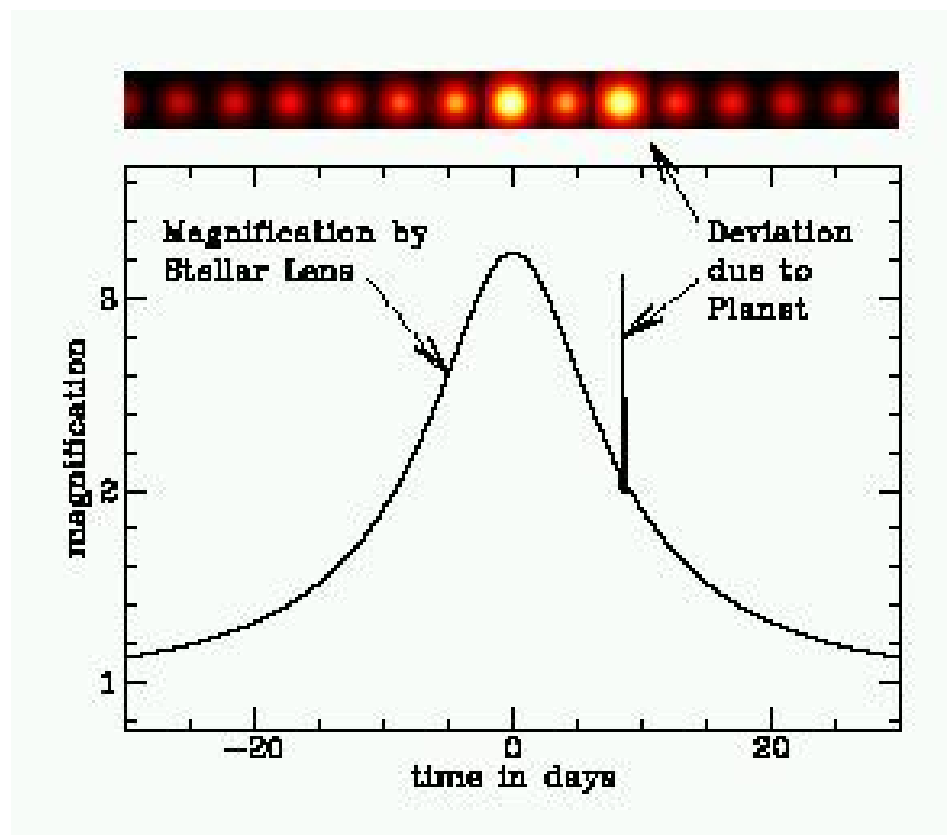
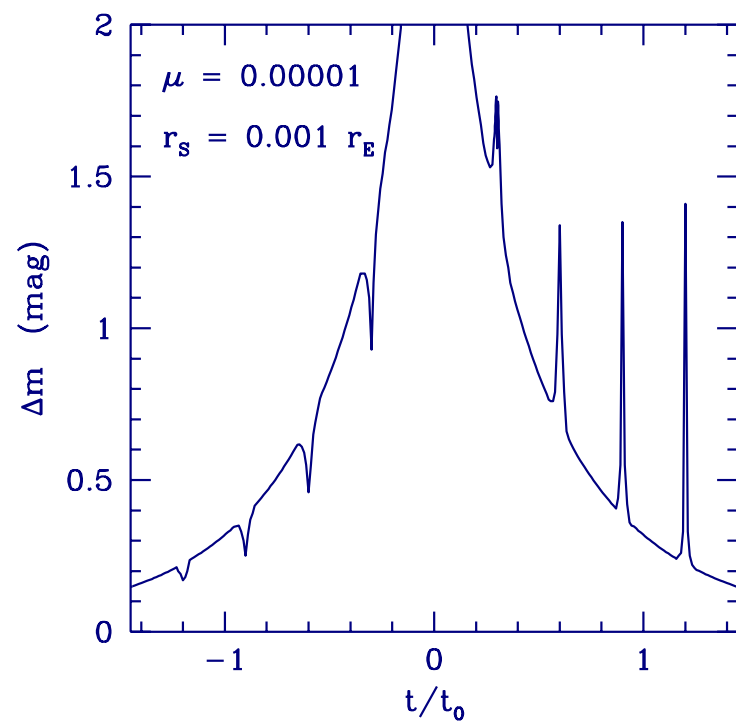


FROM SIMPLE TO WORSE, YET INTERESTING

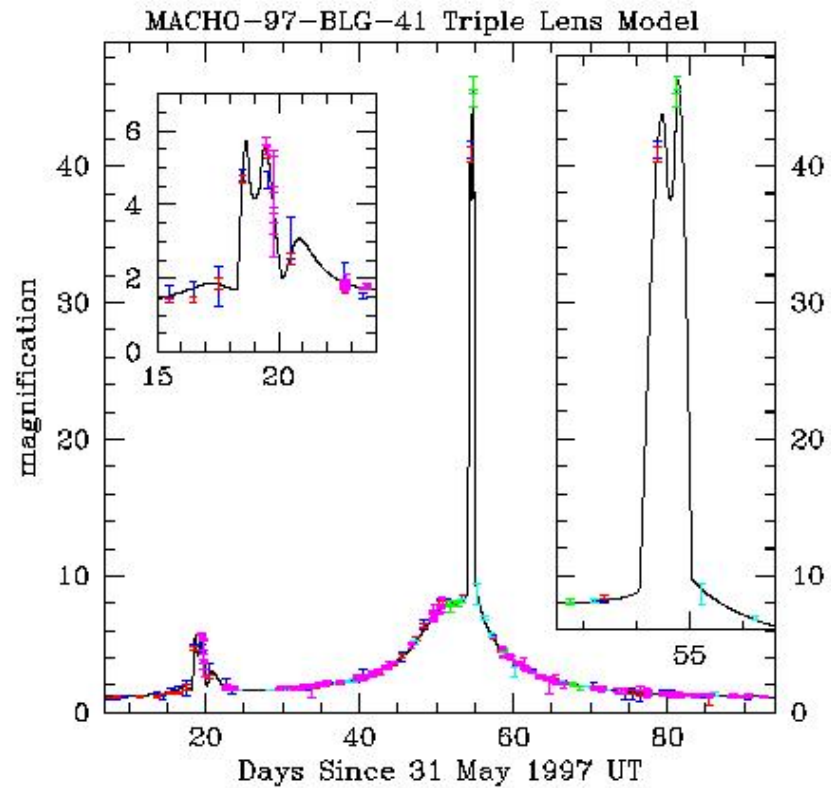
The zoo of binary lenses



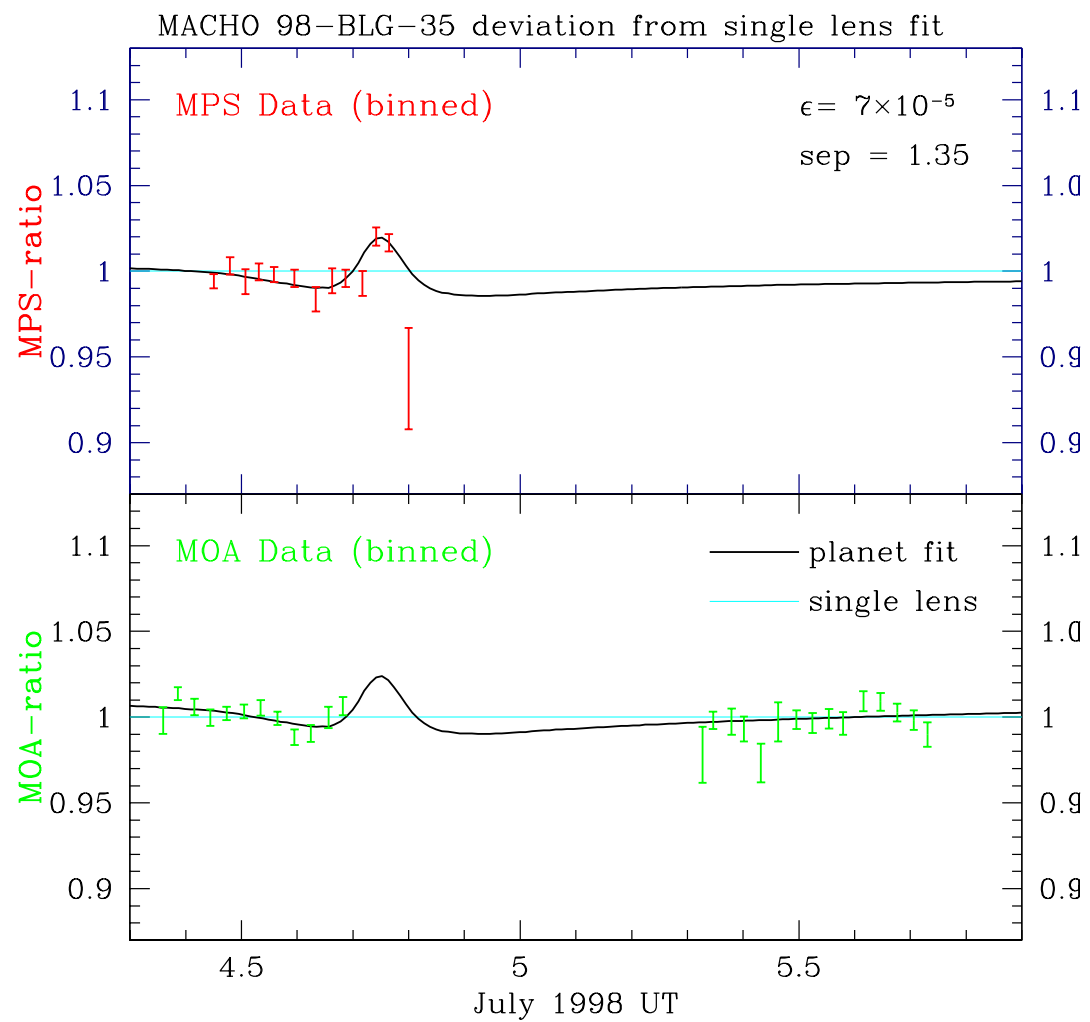
Binary events lift partially the degeneracy between mass and distance



A possible $3.5 M_J$ planet at 7 AU in a binary system

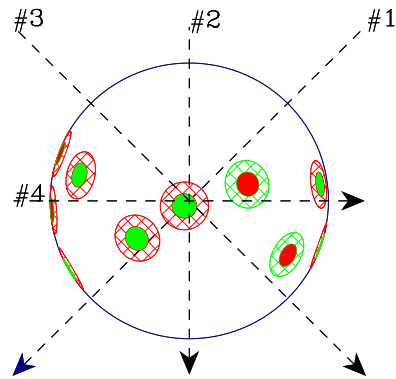


Bennett et al. (1999) Nature **402** 57



CONTAMINATION BY STELLAR SPOTS ??

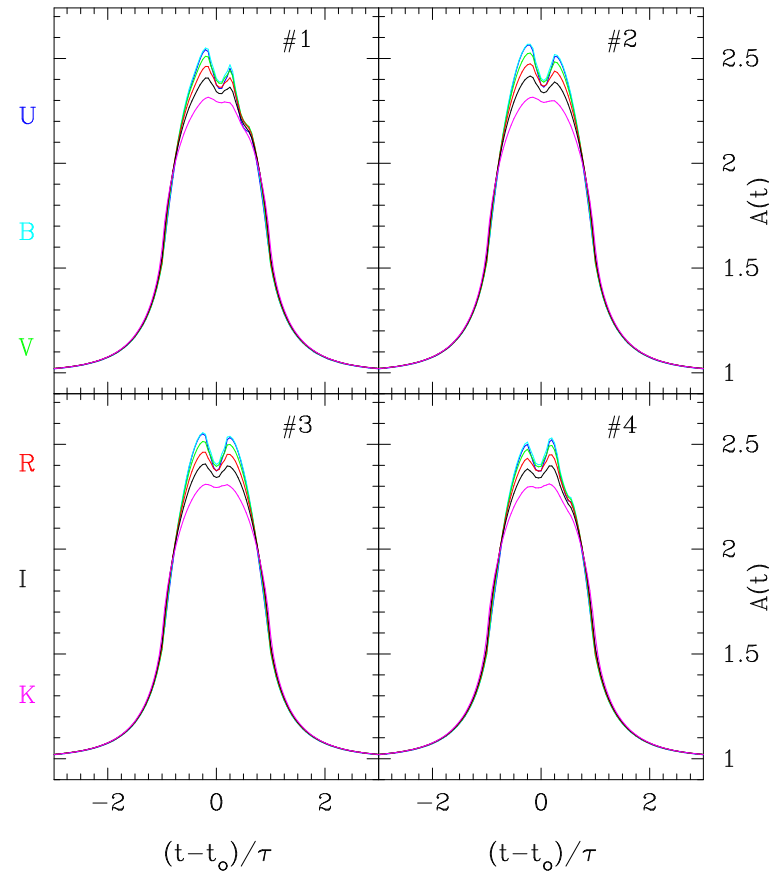
$$\alpha_* = 1.0 \quad i = 90.0$$



$$T_{\text{eff}} = 4000 \text{ K} \quad \log g = 2.0$$

$$P_* = 0. \text{ LD : LIN} \quad N_{\text{spot}} = 10$$

#	γ_o	θ_o
1	0.0	135
2	0.0	180
3	0.0	225
4	0.0	270



Bryce, Hendry & DVG (2002)

SUMMARY

Results

0. Unambiguous detection of ML events within the Local Group
1. MACHOs may account for about 20% of the mass of the halo
2. The Galactic bulge is barred
3. First imaging of stellar photospheres

Prospects

0. Upgraded ML setups (SUPERMACHO) /
/ dedicated telescopes (OGLE-III)
1. Increase LMC statistics to get proper constraints on f_{halo} and m_L :
microlensing optical depth τ maps and mass function of lenses
2. Nature of lenses? Very long timescale events?
3. Control experiments :
M31 (AGAPE) : essential to understand nature of DM haloes
GAIA : ML vs dynamical estimates of DM

Implications

Nature of the lenses : compact baryonic dark matter
vs diffuse lukewarm baryons in clusters ?

Finite size effects : gravitational imaging : stellar atmospheres

Massive databases of stellar variability : stellar structure and evolution

Distant (?) future : dedicated telescope in orbit : no degeneracy

No light, but rather darkness revealed

Milton