MACHOs

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Dark matter candidates

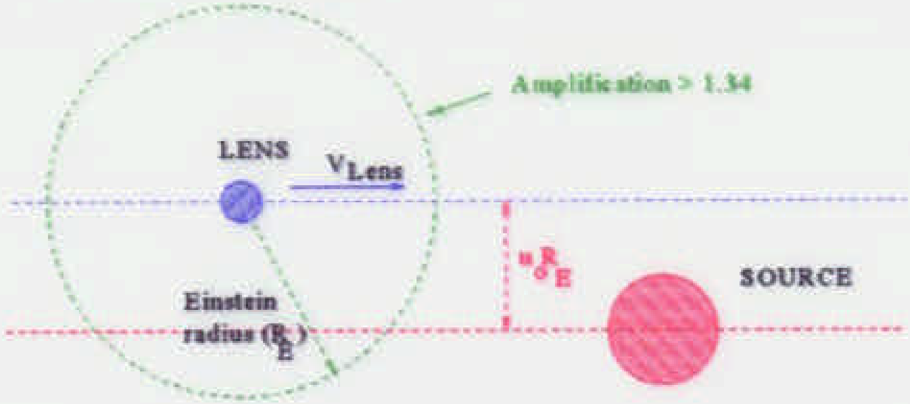
Massive Astronomical Compact Halo Objects

	(Some) constraints
Baryonic	
· Gas	
· Neutron stars	Heavy elements production
· White dwarfs	Heavy elements production unless pregalactic
· Red dwarfs	ISO/HST
· Brown dwarfs	EROS/MACHO
· Planets	unobserved (PLANET)
· Snowballs	EROS/MACHO
Non baryonic	
· Black holes	Heavy element production unless primordial
· WIMPS	
· Axions	
· ..	

microlensing basics

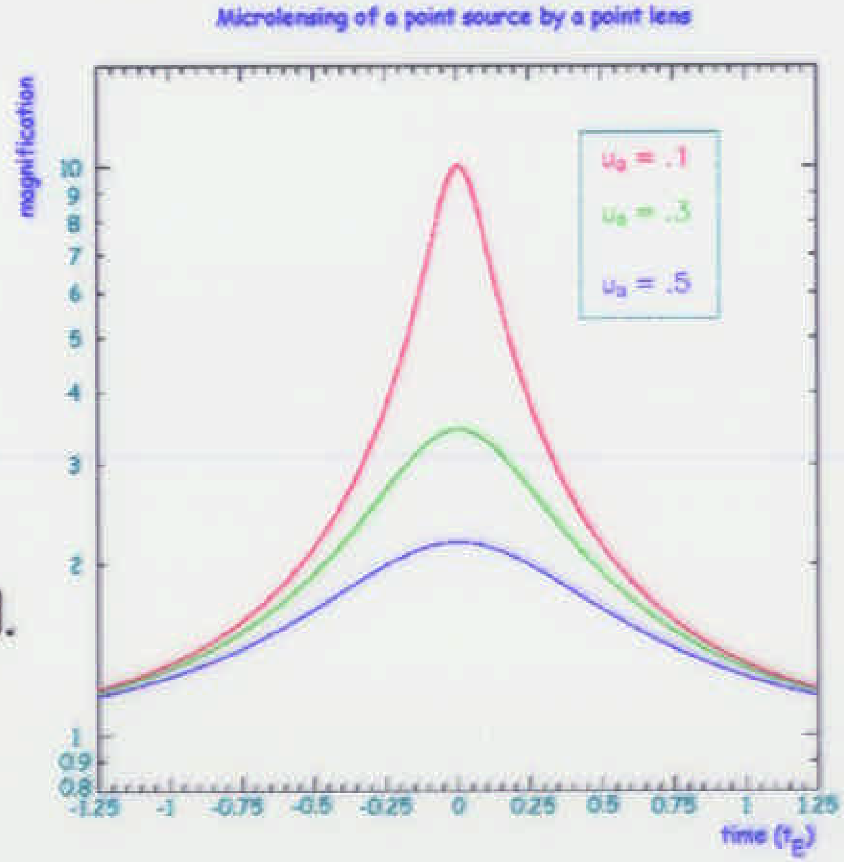
flux from source star **magnified** by A>1.34 (source inside the Einstein radius):

$$R_E = \sqrt{\frac{4GM_{Lens}}{c^2}\frac{D_{Lens}D_{Lens-Source}}{D_{Source}}}$$



- The magnification is achromatic.
- For the simplest case (point lens/point source), only the Einstein radius crossing time:

$$t_E = \frac{R_E}{v^T_{Lens}} = f(M, D_{Lens}, v^T_{Lens})$$ can be measured.



Optical depth, event rates

optical depth τ : probability(microlensing with A>1.34) in a given direction at any time.

- $\tau \propto D_s^2$, independant of MACHO mass M
- typical values (dark Halo 100% in MACHOs):

  $\tau_{LMC} \approx 5\ 10^{-7}$

  $\tau_{SMC} \approx (5\text{-}7)\ 10^{-7}$

Einstein radius crossing time $t_E \approx 75 \left(\frac{M}{M_o}\right)^{1/2}$ days $\Rightarrow$ M

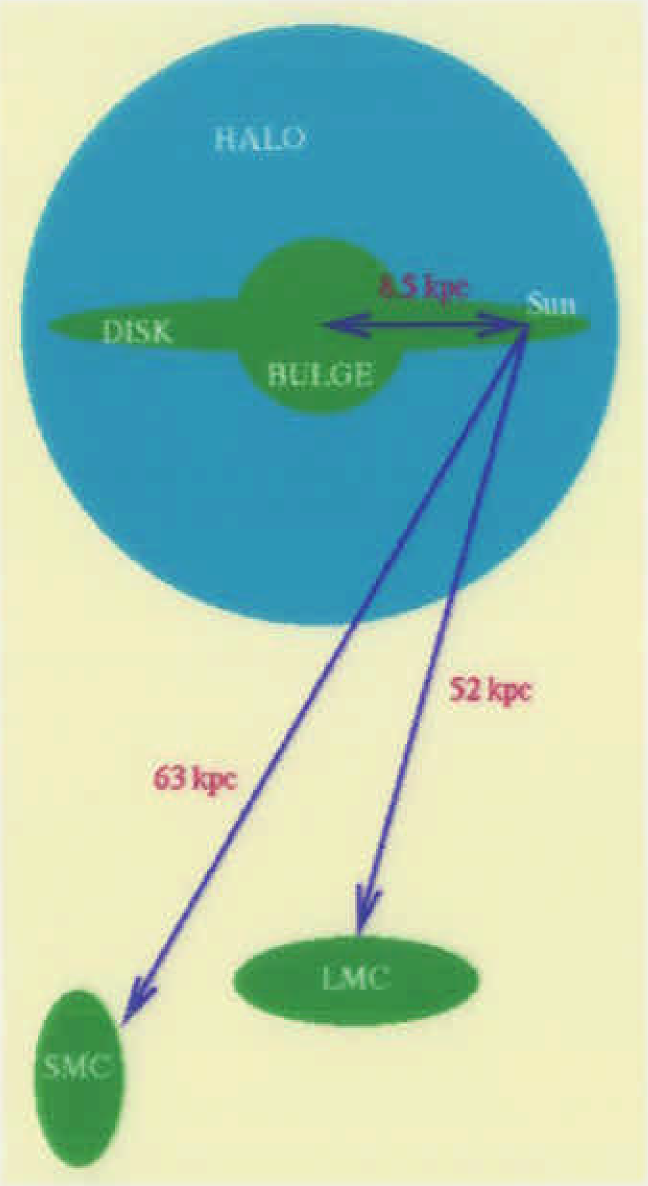
Event rate: $\Gamma = \frac{N_{events}}{T_{observ} N_{stars}} = \frac{2}{\pi} \frac{\tau}{t_E} \varepsilon(t_E) \approx 10^{-6} \sqrt{\frac{M_o}{M}}$ /star/yr (std halo)

has to monitor ~ 10^7 stars during years!

Optical depth obtained from event rate by:

$$\tau = \frac{1}{N_{stars} T_{observ}} \frac{\pi}{2} \sum_{events} \frac{t_E}{\varepsilon(t_E)}$$

EROS2 targets



Spiral Arms: disk lenses

$\tau_{expect} \sim 5\ 10^{-7}$

LMC, SMC: halo lenses

$\tau_{expect} \sim (1\text{-}5)\ 10^{-7}$

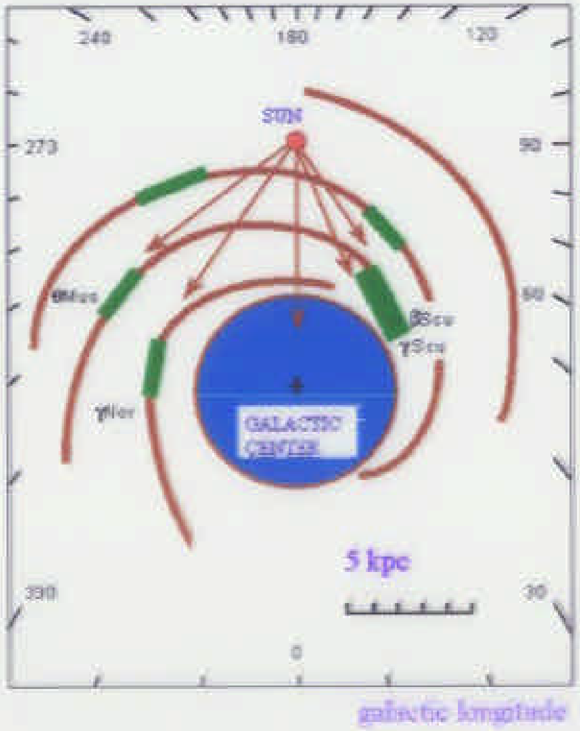
$\tau_{meas} \sim 2\ 10^{-7}$

Galactic Center: bulge + disk lenses

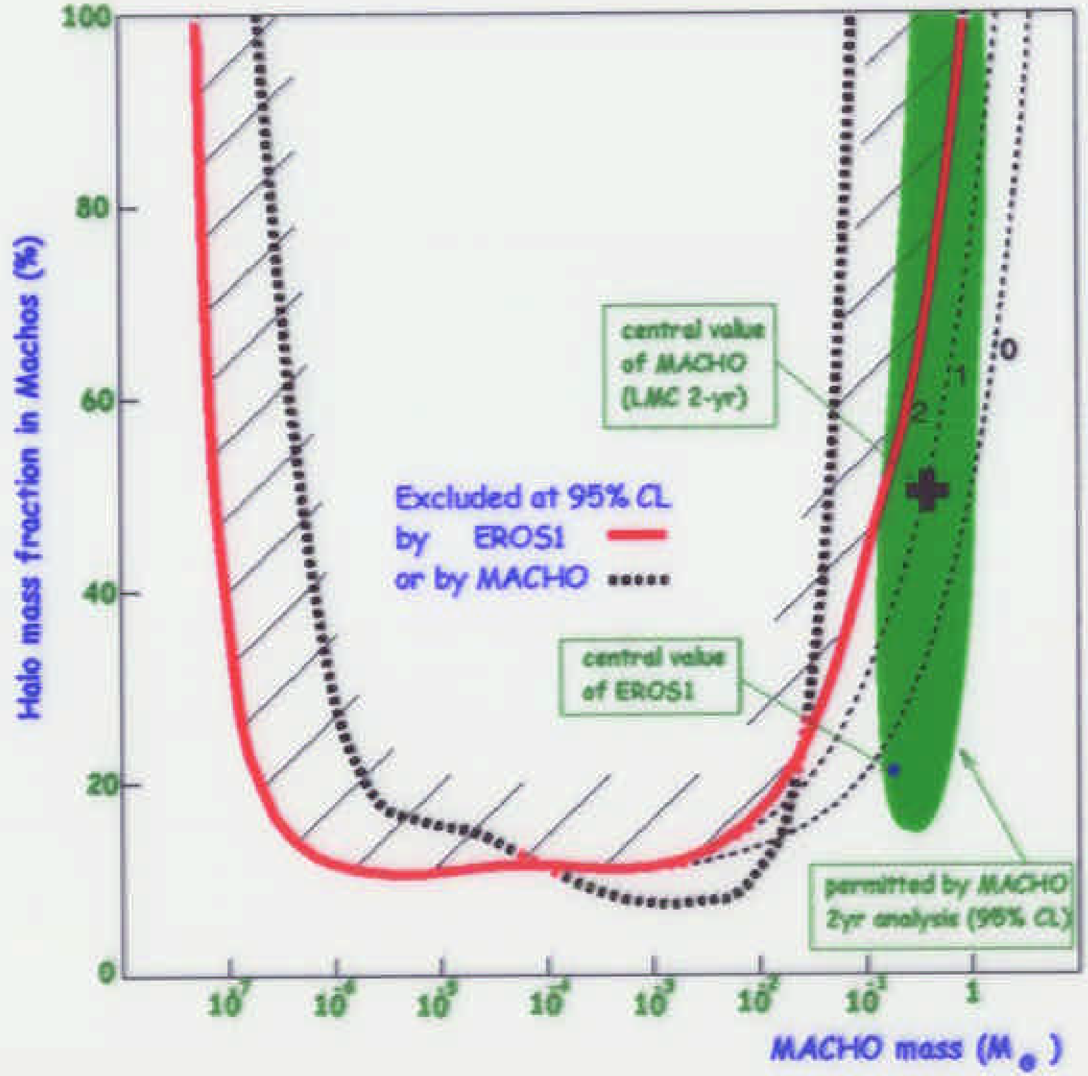
microlensing exotica

$\tau_{expect} \sim 5\ 10^{-7}$

$\tau_{meas} \sim (1\text{-}3)\ 10^{-6}$



Status of MACHO searches in 1997



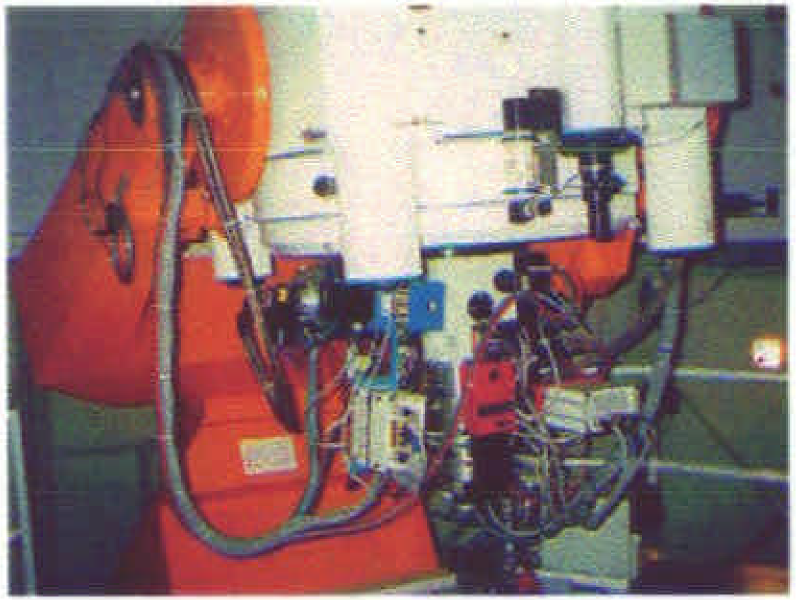
- no event with duration $t_E < 17$ days (EROS1/MACHO)

  $\Rightarrow f_{MACHO} < 0.1$ (95% CL)
  (M_{MACHO} in $[10^{-7}\ 10^{-2}]\ M_\odot$)

- MACHO: 8 candidates
  positive detection
  $M_{MACHO} \sim 0.5\ M_\odot$
  $f_{MACHO} \sim 50\ \%$

- EROS1 : Upper limit from 2 candidates
  $f_{MACHO} < 0.6$ @ $0.5\ M_\odot$
  (C.Renault et al (EROS), A & A, 329,532 (1998))

The EROS2 setup



- dedicated 1 m telescope
- installed at ESO LaSilla observatory (Chile)
- Simultaneous imaging in 2 optical passbands:
  - « V » band : $\lambda_o = 550$ nm, $\delta\lambda = 150$ nm
  - « R » band : $\lambda_o = 750$ nm, $\delta\lambda = 150$ nm
- 2 wide field CCD cameras
  8 x 4 M pixels each
  1 square degree in sky imaged.
- ~ 80 images = 20 Gbytes/night
  15 Tbytes expected by 2002
- alert system (« trigger »)
  ⇒ better time sampling on interesting events

Not enough stellar mass MACHOs in the Galactic Halo

- EROS2 SMC 2 year analysis :

1999 $f_{MACHO} < 50\%$ (95% CL) @ $M_{MACHO} = 0.5\ M_{\odot}$

C.Afonso et al., A & A 344, L63 (1999)

- EROS2 LMC 2 year analysis

2000 $f_{MACHO} < 30\%$ (95% CL) @$M_{MACHO} = 0.5\ M_{\odot}$ (combines EROS1/2)

T.Lasserre et al., A & A 355, L39 (2000)

- MACHO LMC 5.7 year analysis

2000 $f_{MACHO} = 8\%-50\%$ (2σ) with $M_{MACHO} \sim 0.4\ M_{\odot}$
$\tau_{LMC} = 1.4^{+0.4}_{-0.3} \times 10^{-7}$

C.Alcock et al., astro-ph/0001272 (2000)

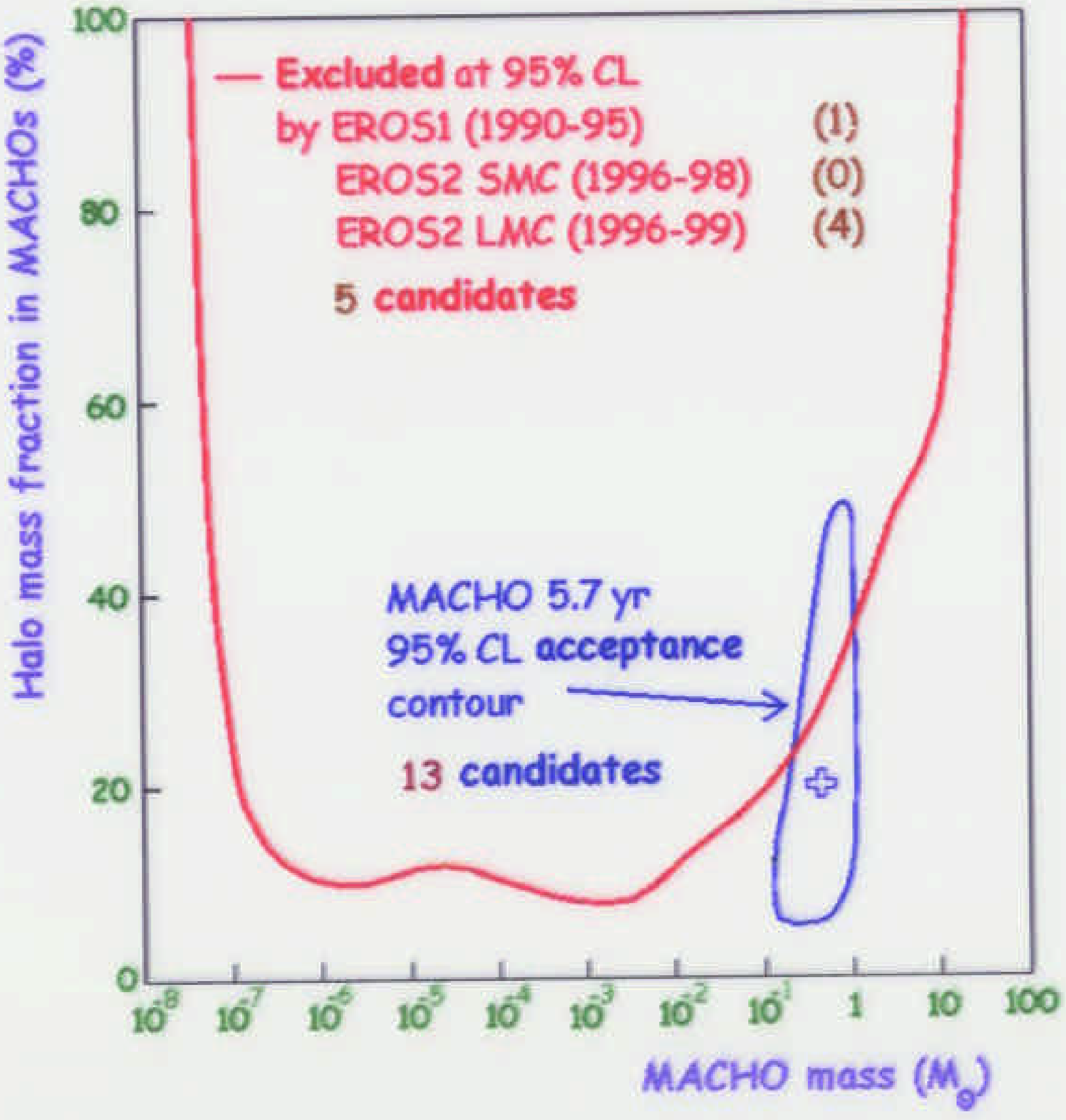
EROS2 LMC 3 year analysis available

EROS versus MACHO

	EROS2 LMC	EROS2 SMC	EROS1 LMC	MACHO LMC
# stars (million)	25.5	5.3	4.1	10.7
area (sq. degrees)	39 (64)	9.	27.	15.
analyzed exposure time (yr)	3.	2.	3.	5.7
efficiency (@50 days)	15%	18%	12%	40% (50%)
candidates	4	1(0)	2(1)	13(17)
expected (full halo 0.5 Mo)	26.	6(4)	2.4	55.
expected (20% halo 0.5 Mo)	5.2	1.2(0.8)	0.5	11.
expected (all data, 20% halo)	10.4	3.6	0.5	15.

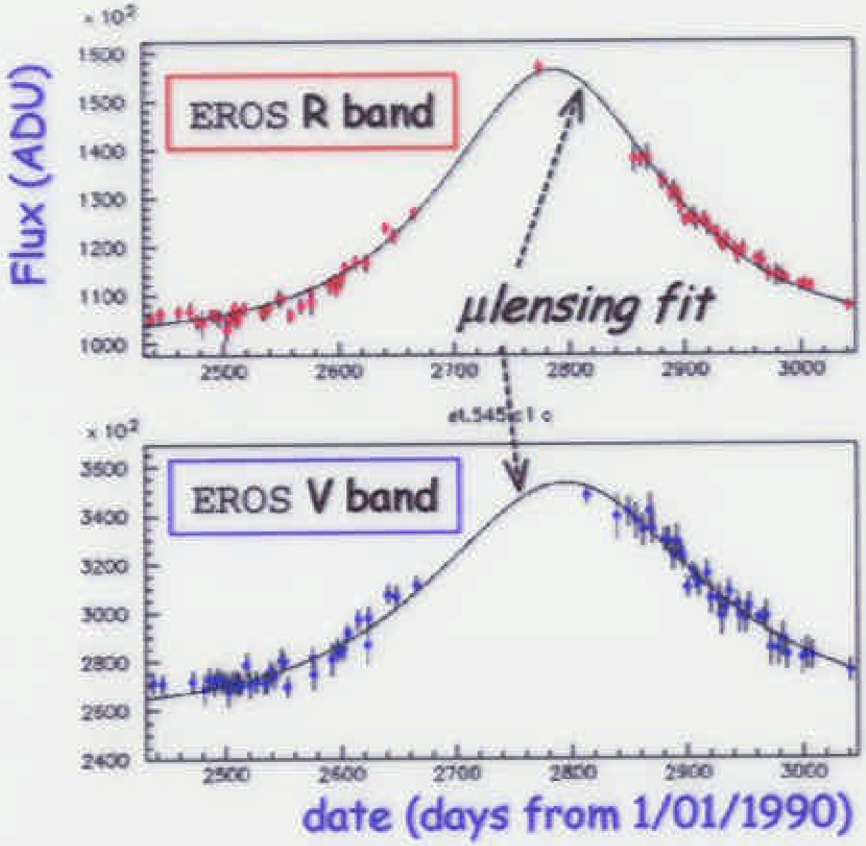
- MACHO: larger exposure time
- EROS: data taken over a larger area (test of self-lensing)
  less blending (crowding smaller)
  data towards 2 targets (LMC/SMC)

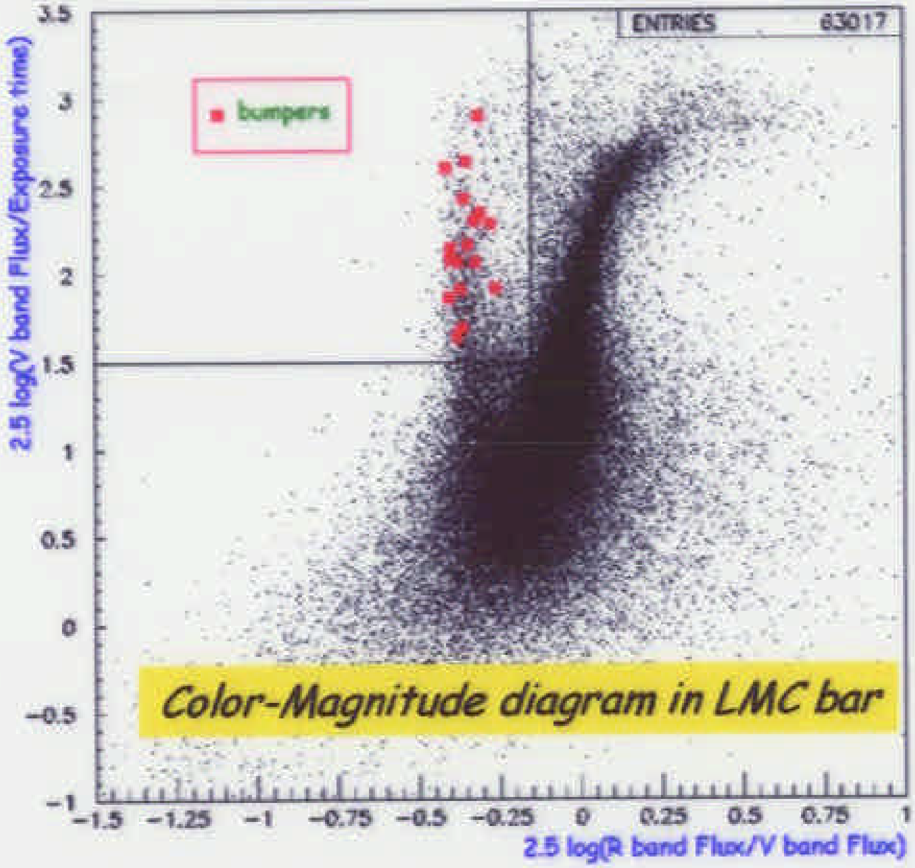
EROS 1/2 constraints on MACHOs



- $f_{MACHO} < 30\%$ (95% CL) @ $M_{MACHO} = 0.5\ M_\odot$
- Standard Halo with $f_{MACHO} = 100\%$ ruled out ($M_{MACHO} < 10\ M_\odot$)
- $< 20\%$ Brown Dwarfs (M_{MACHO} in $[10^{-2}\ 0.08]\ M_\odot$)
- EROS:
  central value of $f_{MACHO} \sim 10\%$
  BUT no signal claimed

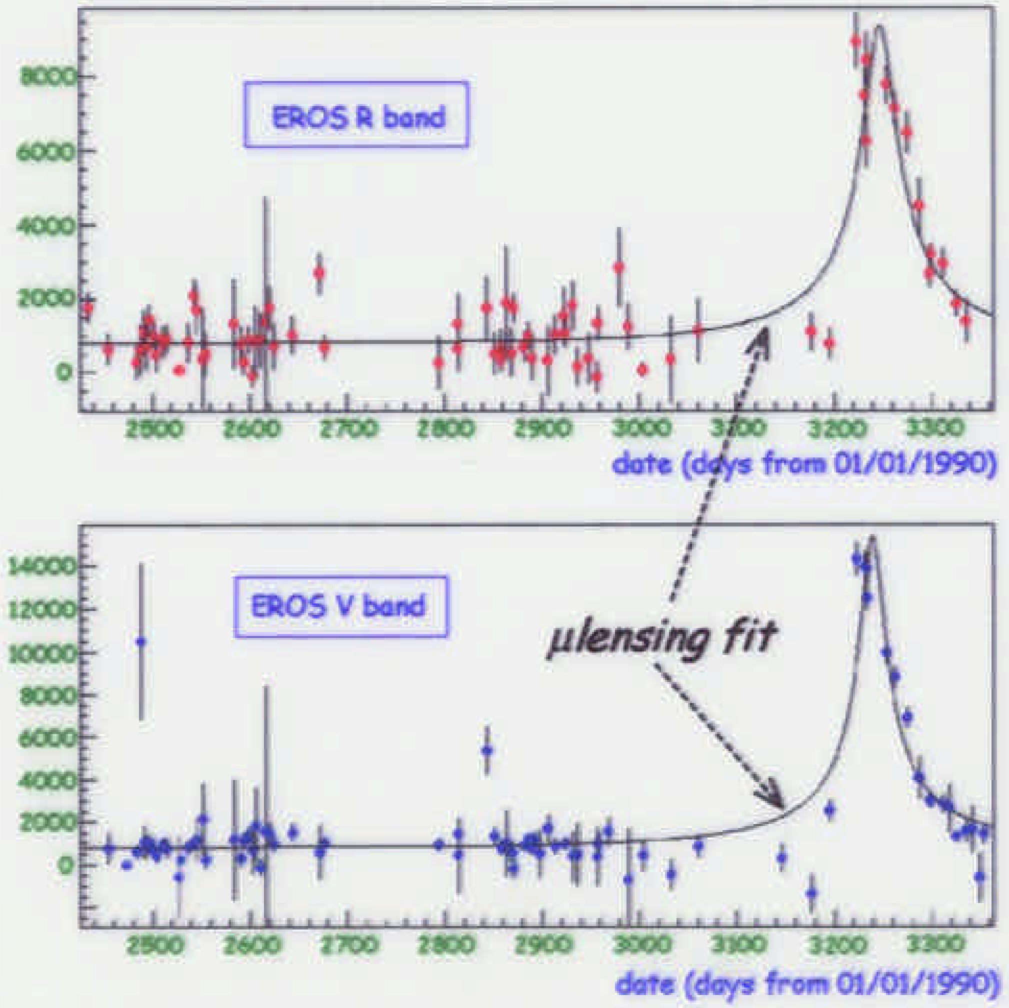
Variable star background: "blue bumpers"





- ~ 300 bumpers consistent with µlensing shape in each color in LMC data
- chromatic magnification (R band > 20% more magnified than V band)
- low magnification (<1.6)

Variable star background: novae & "supernovae"



> asymmetric light curves.

> might simulate a µlensing with a small crossing time t_E with poor time sampling

> EROS:

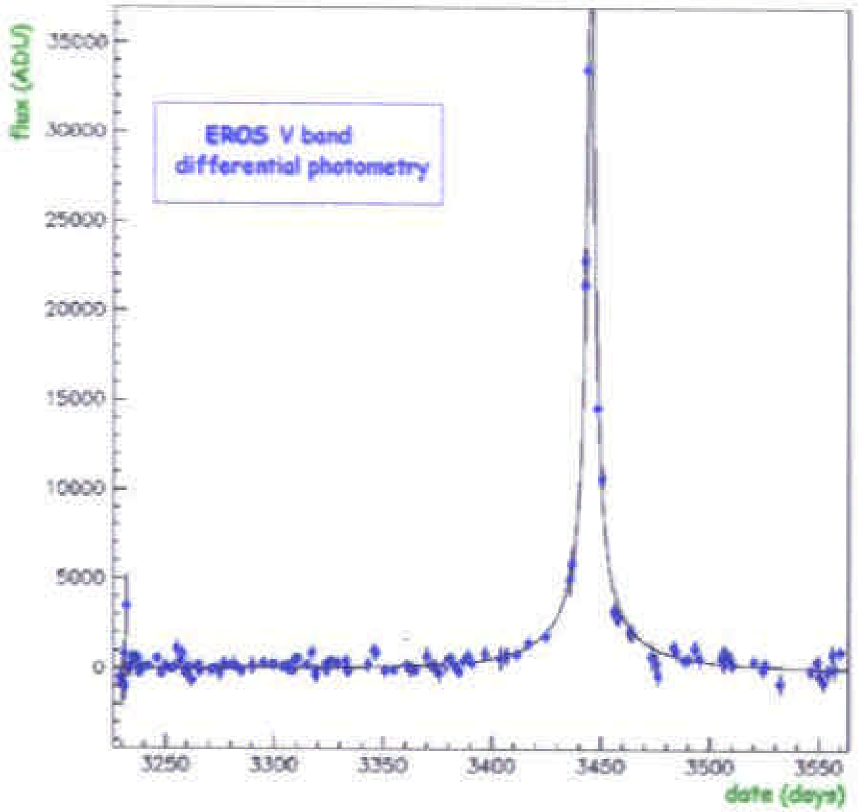
- < 5 events expected (3 yrs)
- rejected by comparing rise/fall times

> MACHO:

- < 2-6 events expected (5.7 yrs)
- rejected by comparing a SN fit to a µlensing fit

Have we observed *any* real μlensing towards the Magellanic Clouds?

LMC

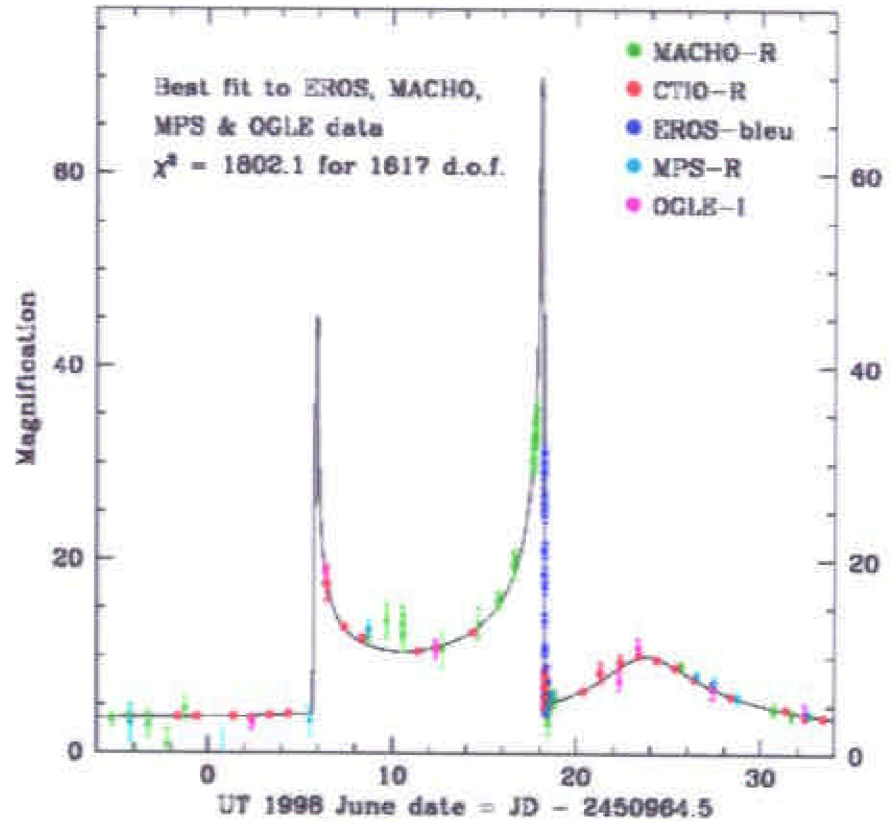


MACHO alert 99-LMC-2

t_E = 65.8 ±4.8 days

Magnification ~ 50

SMC



MACHO alert 98-SMC-1

binary lensing

C.Afonso et al. (EROS,MACHO,MPS, OGLE,PLANET),ApJ 532, 340 (2000)

Microlensing by known stellar populations

> "Ordinary" stars contribute to the μlensing signal:

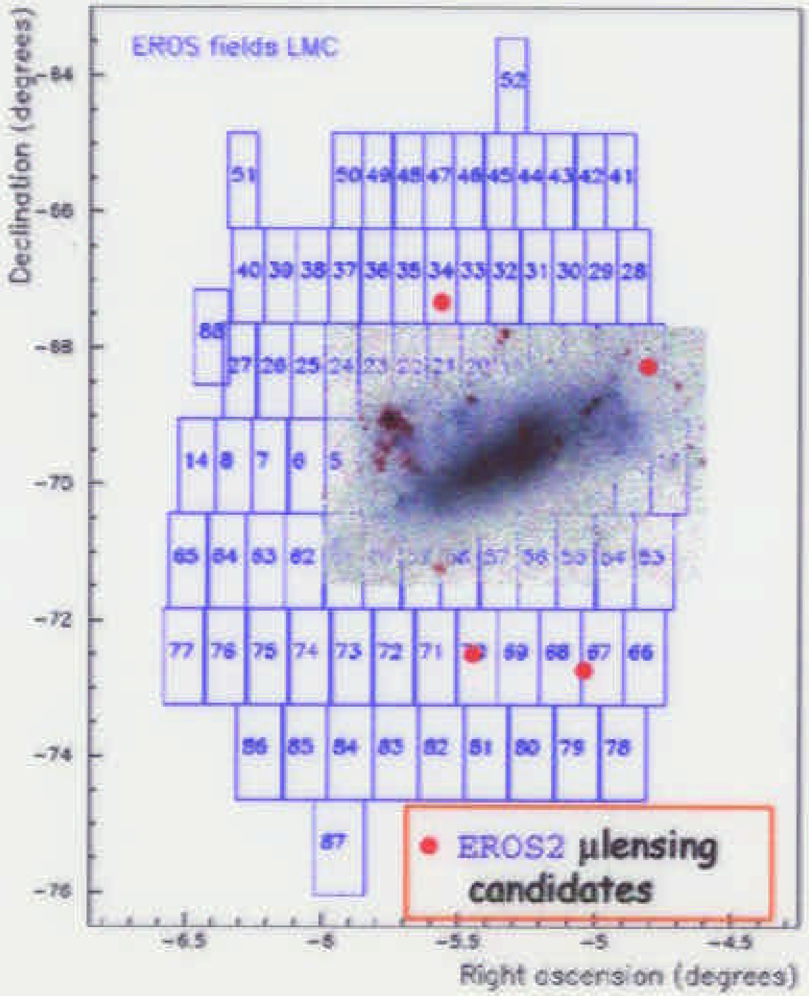
> Lenses in the Galactic Disk:
MACHO: < 1 event

> Lenses in the Magellanic Clouds ("*self lensing*"):

> LMC: ~ 5% of full Halo signal
- ~ 2-3 events (MACHO)
- ~ 0.5 events (EROS)

But can be more in "non-standard" LMC models.

> SMC: ~ 20% of full Halo signal
- ~ 1 event (EROS)



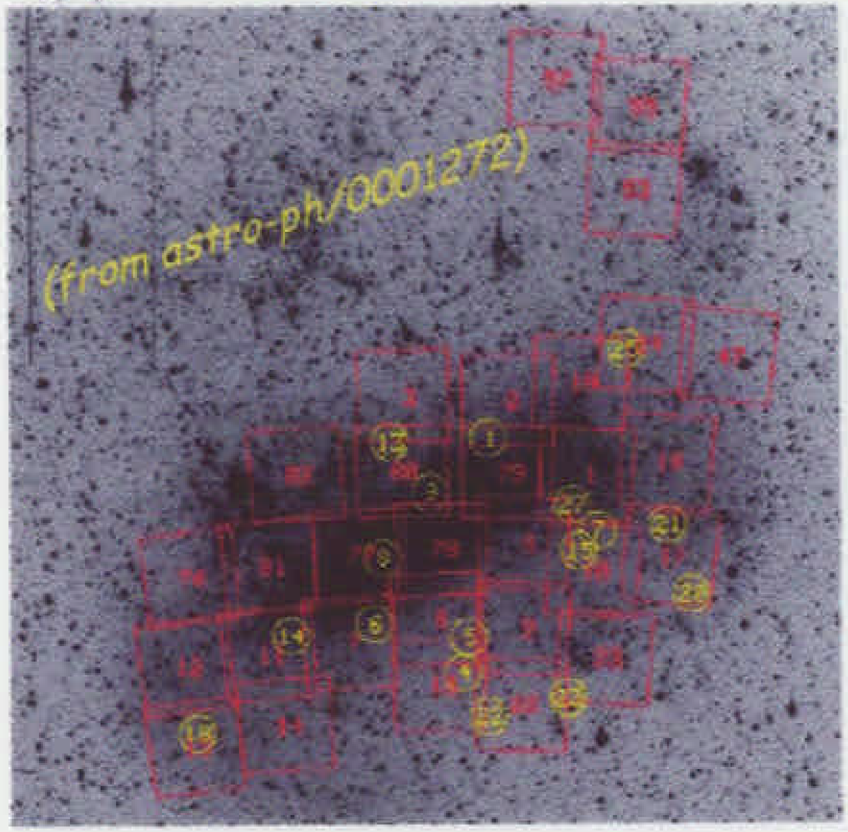
Halo: flat spatial distribution
Self-lensing: $\propto \rho_{LMC}^2$

Tests of the "self-lensing" hypothesis

› *Spatial distribution of events:*

MACHO:

- mean spatial separation compatible with flat
- favors Galactic Halo models over the self-lensing model of Gyuk et al. (2σ effect).
- More statistics needed.



› *Light curve analysis:*

▸ SMC:

2 events detected by MACHO/EROS both probable self-lensings:

SMC-97-1: no distorsion due to Earth motion ("parallax")

SMC-98-1: projected velocity of lens measured too small for Galactic Halo

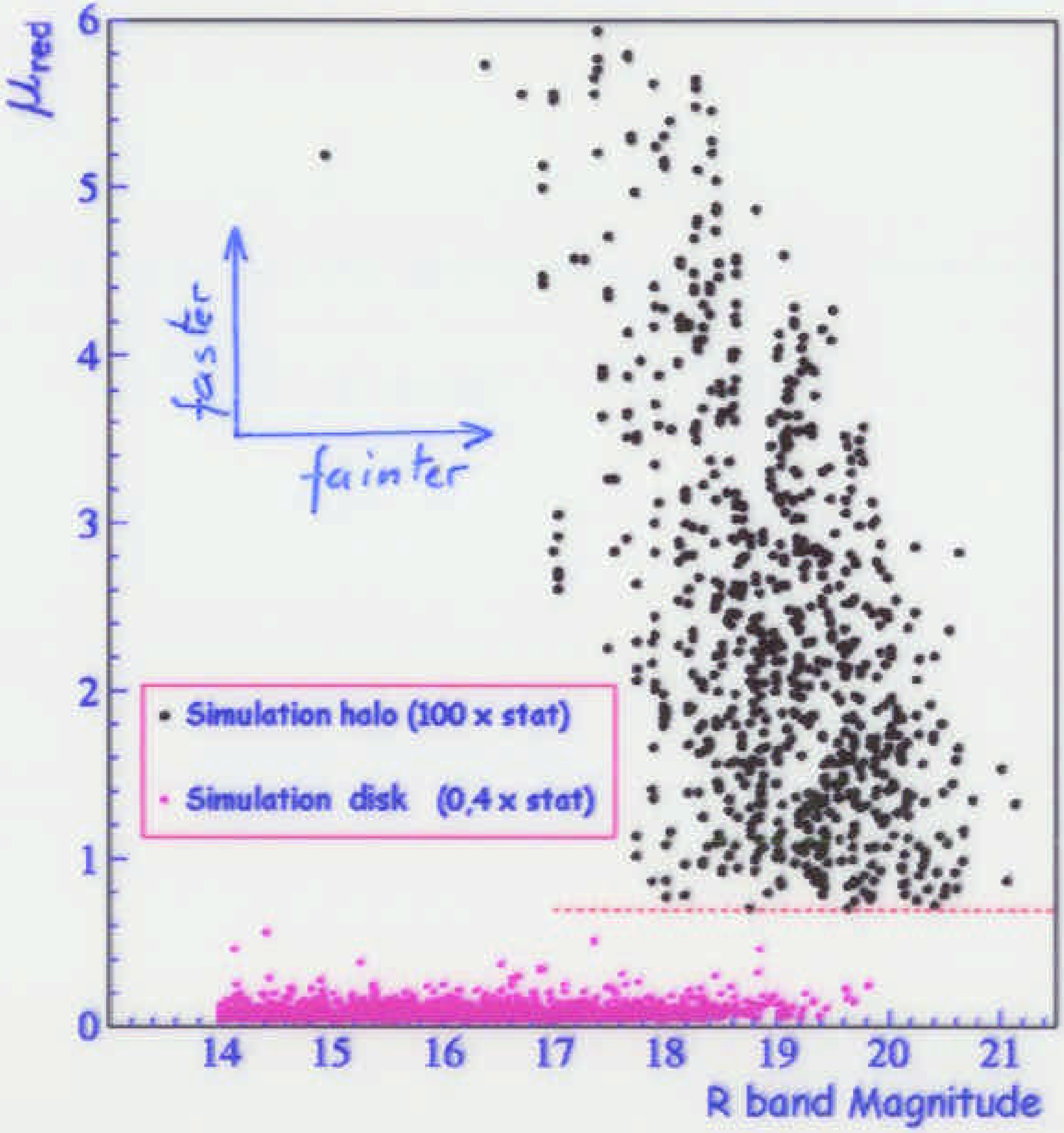
▸ LMC:

detection of "parallax" possible (needs alert system +extensive follow-up)

EROS2 direct search for halo white dwarfs

typical velocities:

- halo star
  - ~ 250 km/s
  - = 1/4000 pc/an
  - = 1"/an @ 50 pc
- disk star
  - ~ 30 km/s
  - = 0.1"/an @ 50 pc



MACHO candidates

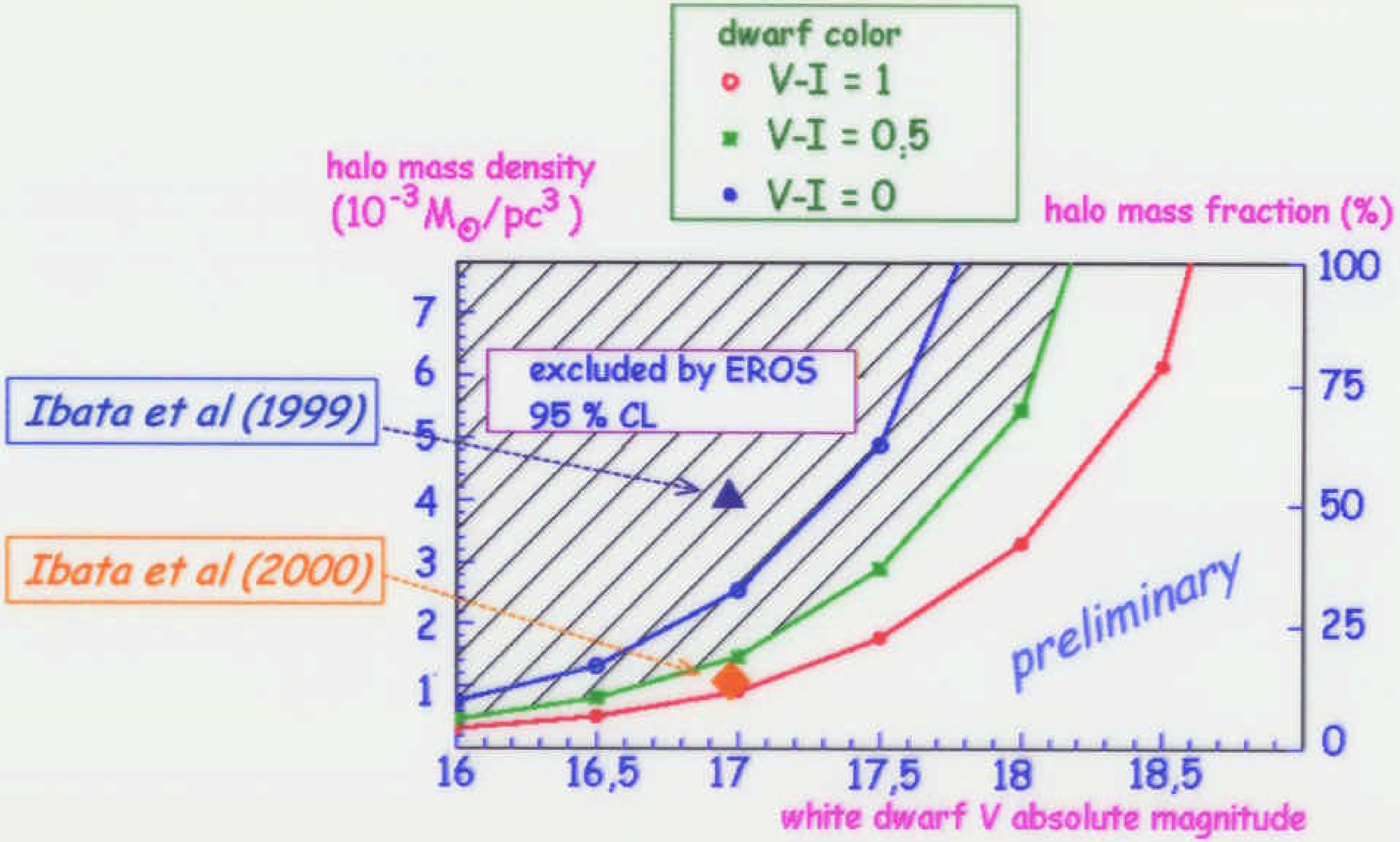
- Most popular candidate for 0.5 $M_{\odot}$ objects: white dwarfs

- Direct detection claimed:
  ~ 50% of dark halo: R.Ibata et al., ApJ 524, L95 (1999)
  ~ 20% of dark halo: R.Ibata et al., ApJ 532, L41 (2000)

- Direct detection possible with EROS ⇒ high transverse motion survey

	EROS2	Ibata et al 1999	Ibata et al 2000
surveyed volume (pc3)	2100. (3700.)	560.	1800.
number of epochs	3	2	2(3)
candidates	0	2	2
expected (100% halo WD)	20	3.6	20

Halo white dwarfs : exclusion diagram



Conclusion: no answer (yet)

Galactic Dark Matter is made of:

- < 10% MACHOs with mass in $[10^{-6}-10^{-2}]\ M_{\odot}$
- < 20% brown dwarfs
- < 30% 0.5 $M_{\odot}$ MACHOs
- < 15% old white dwarfs (1,4 10^{10} yrs)

The μlensing events observed towards the LMC are not fully understood.

- variable stars?
- μlensing by "known" stellar populations (self-lensing)?
- white dwarfs in the Galactic Halo?
- black holes? ...