Griest - 0

Baryonic Dark Matter and MACHOs.

Kim Griest
Y2000

Inventory of Baryons

Today (redshift ≈ 0)

$\Omega_{\text{STARS}} \approx .0035$	Local M/L + universe LF
$\Omega_{\text{gas in gal.}} \approx .0006$	HI 21 cm, CO, Lyα, OVI
$\Omega_{\text{gas in clusters}} \approx .0025$	X-ray

otal $\Omega_{\text{identified}} \approx .007$

Redshift 2-4

$\Omega_{\text{baryon}} \gtrsim .034 \pm ?$ Lyα forest (QSO spectra)

Redshift $z \approx 1100$

$\Omega_{\text{baryon}} \approx ?$ CMB: small 2nd acoustic peak ⇒ large Ω_B ?

Very high redshift

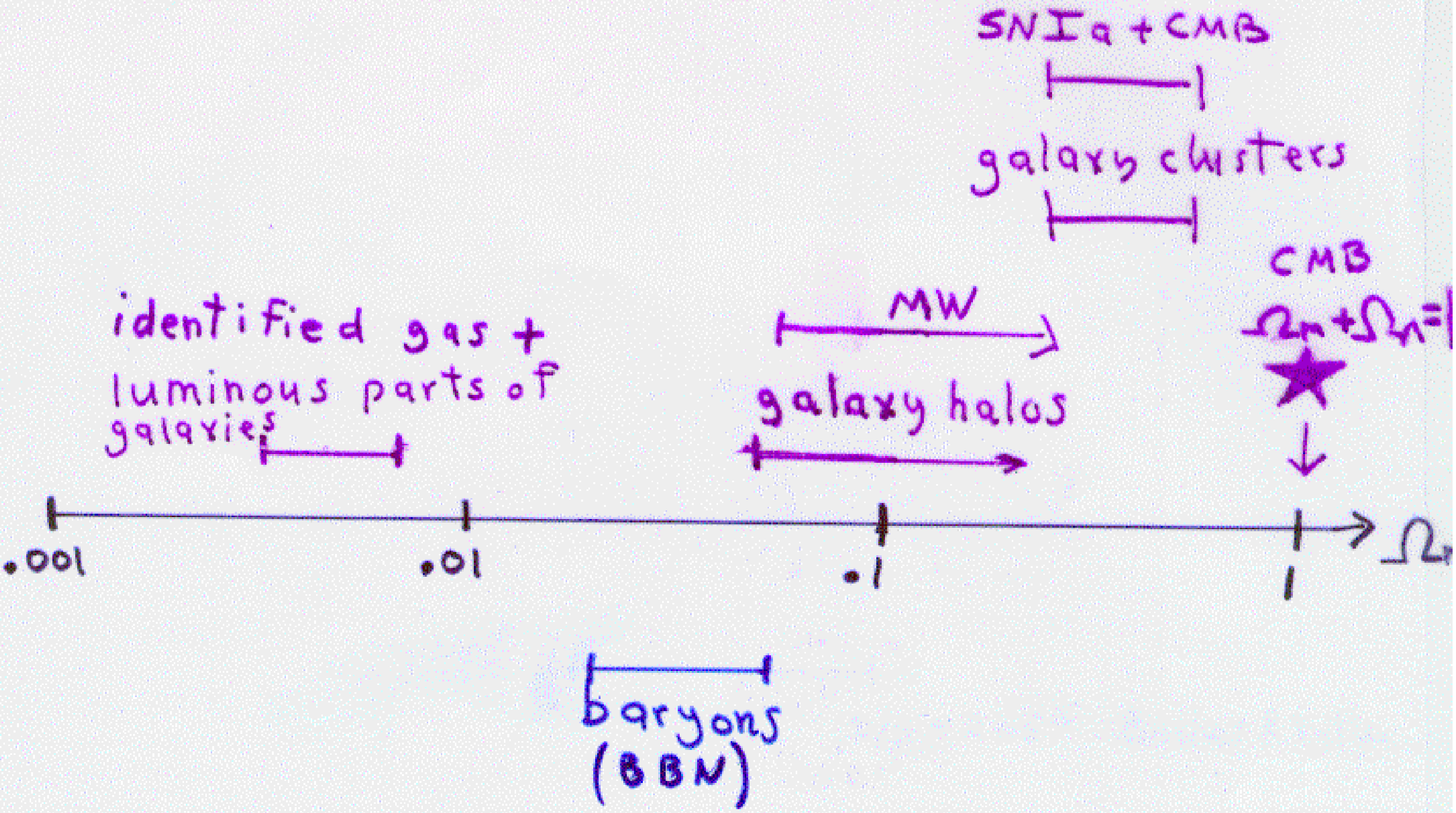
$\Omega_{\text{baryon}} \approx .04$ standard Big Bang nucleosynthesis

$h = .7$

$\Omega \equiv \rho/\rho_{crit}$

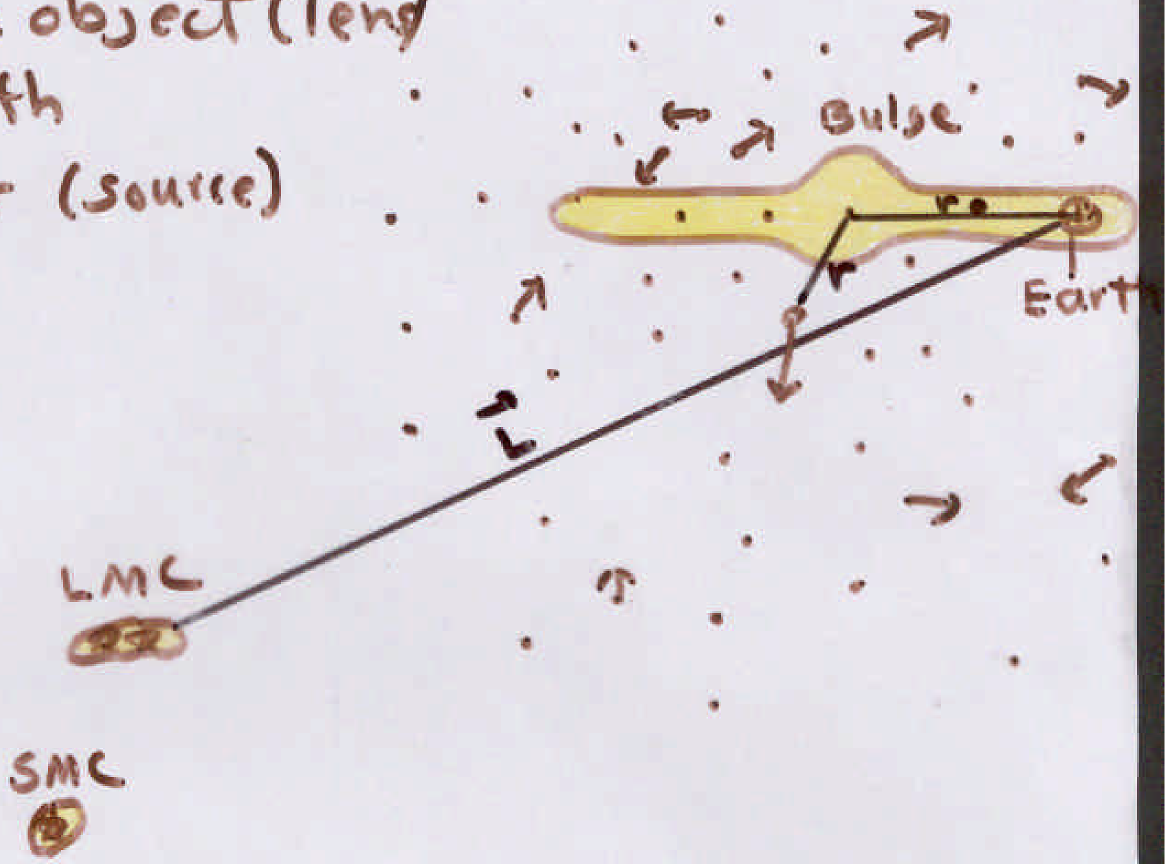
Mass Density of Universe Inventory

$$\Omega_m = \frac{\rho_m}{\rho_{crit}}$$



Galaxy, halo, LMC

- • dark object (lens)
- ⊕ Earth
- ☆ star (source)



$$\rho(x) = \rho_0 \frac{(a^2+r_0^2)}{a^2+r^2}$$

$$f(v)\,d^3v = \frac{e^{-v^2/v_c^2}}{\pi^{3/2} v_c^3}\,d^3v$$

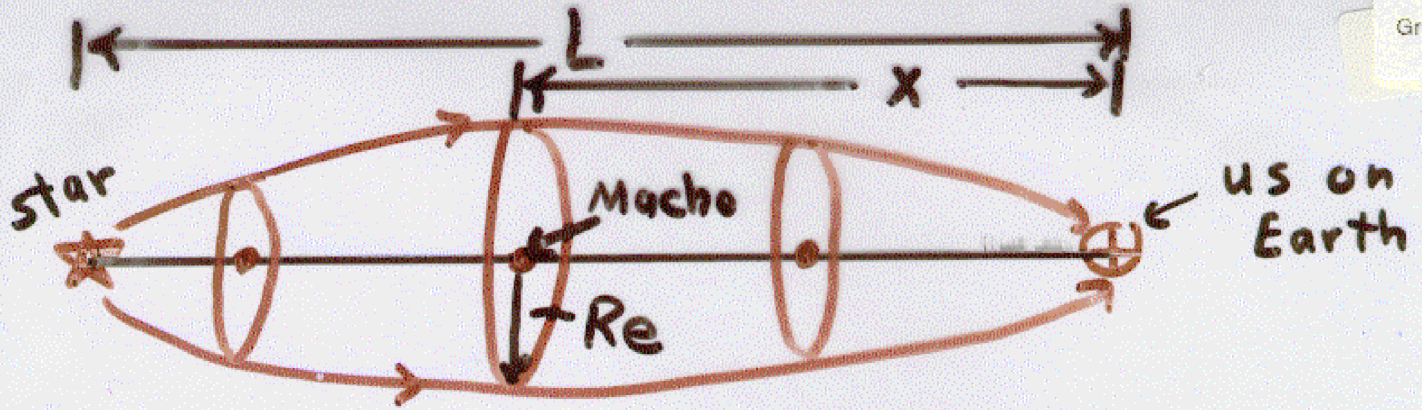
$r_0 = 8$ kpc

$a \approx 5$ kpc

$v_c \approx 200$ km/s

$\rho_0 \approx .3$ GeV/cm^3

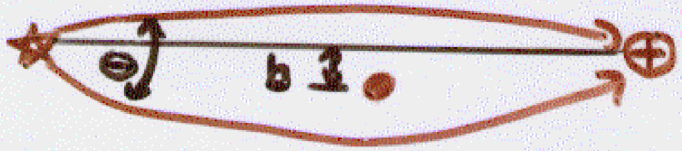
$L \approx 50$ kpc



If source, lens, observer perfectly aligned get "Einstein ring" (from $\Theta = \frac{4mG}{r}$)

$$R_e = 2\sqrt{\frac{Gm}{L}x(L-x)} = 2.85\,\text{A.U.}\left[\frac{m}{M_\odot}\,\frac{L}{\text{kpc}}\,\frac{x}{L}\left(1-\frac{x}{L}\right)\right]^{1/}$$

If not aligned, get 2 images



$u = \frac{b}{R_e}$ change with time

$\Theta \approx 10^{-3}$ arcsec (for LMC and $1 M_\odot$)

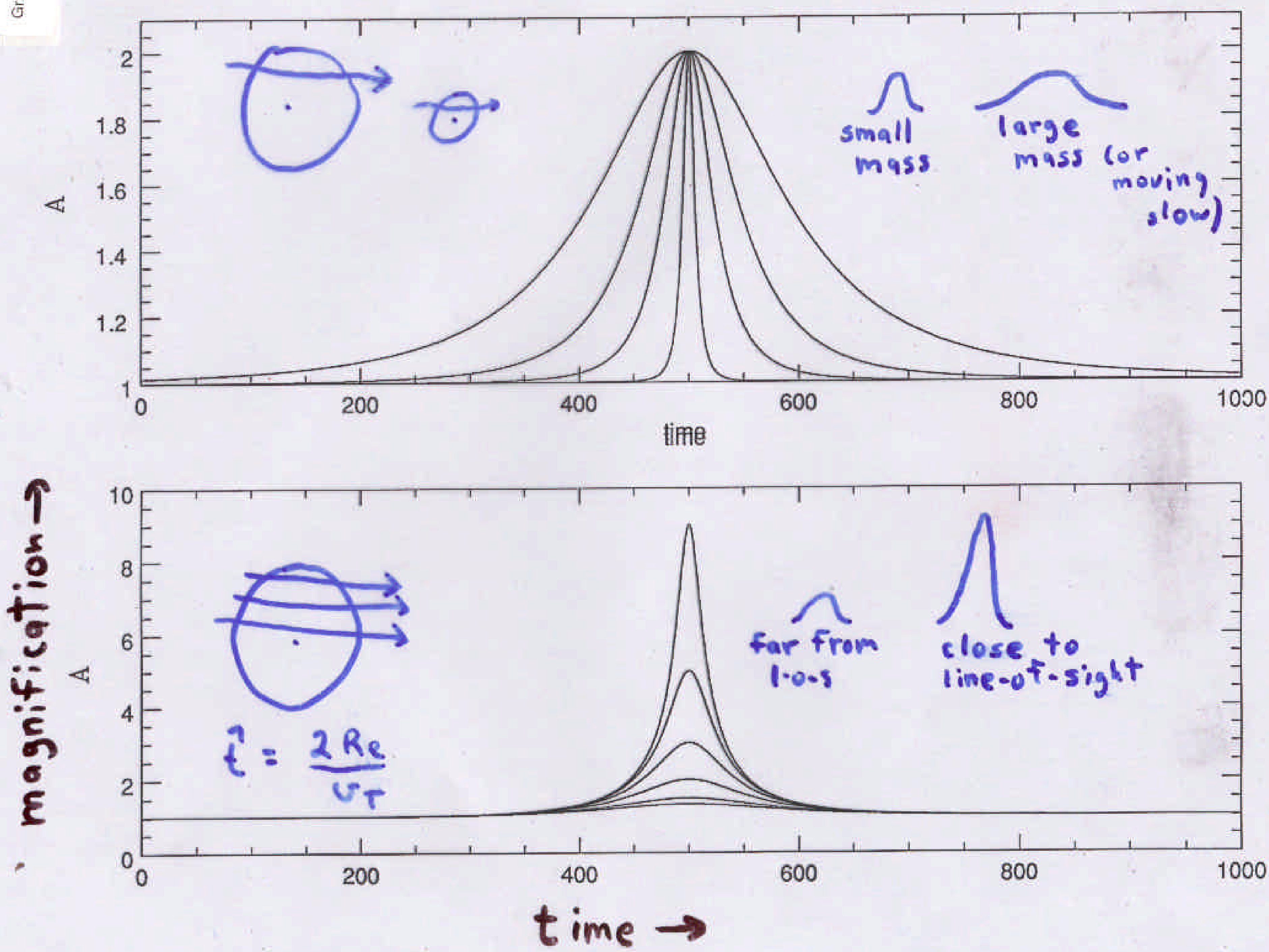
$\Rightarrow$ images not resolved

but light from 2 images add

$\Rightarrow$ source is Magnified

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}} \sim \frac{1}{u}\quad,\quad u(t) = \left(u_{min}^2 + \left(\frac{2(t-t_0)}{\hat{t}}\right)^2\right)^{1/2}$$

Physical info in $\hat{t} = \frac{2R_e}{v_\perp} \propto \sqrt{m}$


A
2
1.8
1.6
1.4
1.2
1
0
200
400
600
800
1000
time
small mass
large mass (or moving slow)
magnification →
A
10
8
6
4
2
0
0
200
400
600
800
1000
$\hat{t} = \frac{2R_e}{v_T}$
far from l-o-s
close to line-of-sight
time →

☆ For stars in LMC, typical event duration

$$\hat{t} \approx 130\,\text{day}\sqrt{m/M_\odot}$$

$\Rightarrow$ sensitivity from $10^{-7}\,M_\odot$ to $10\,M_\odot$ for sampling from hours to several years

☆ Need to monitor millions of stars since probability of given star being lensed (called τ, optical depth) is $\tau \approx 5\times10^{-7}$

MACHO COLLABORATION

C. Alcock	LLNL
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T. Axelrod	MSSSO
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D. Bennett	Notre Dame
K. Cook	LLNL
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K. Griest	UC San Diego
M. Lehner	Sheffield
S. Marshall	LLNL
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B. Petersen	MSSSO
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P. Quinn	ESO
C. Stubbs	U Washington
W. Sutherland	Oxford
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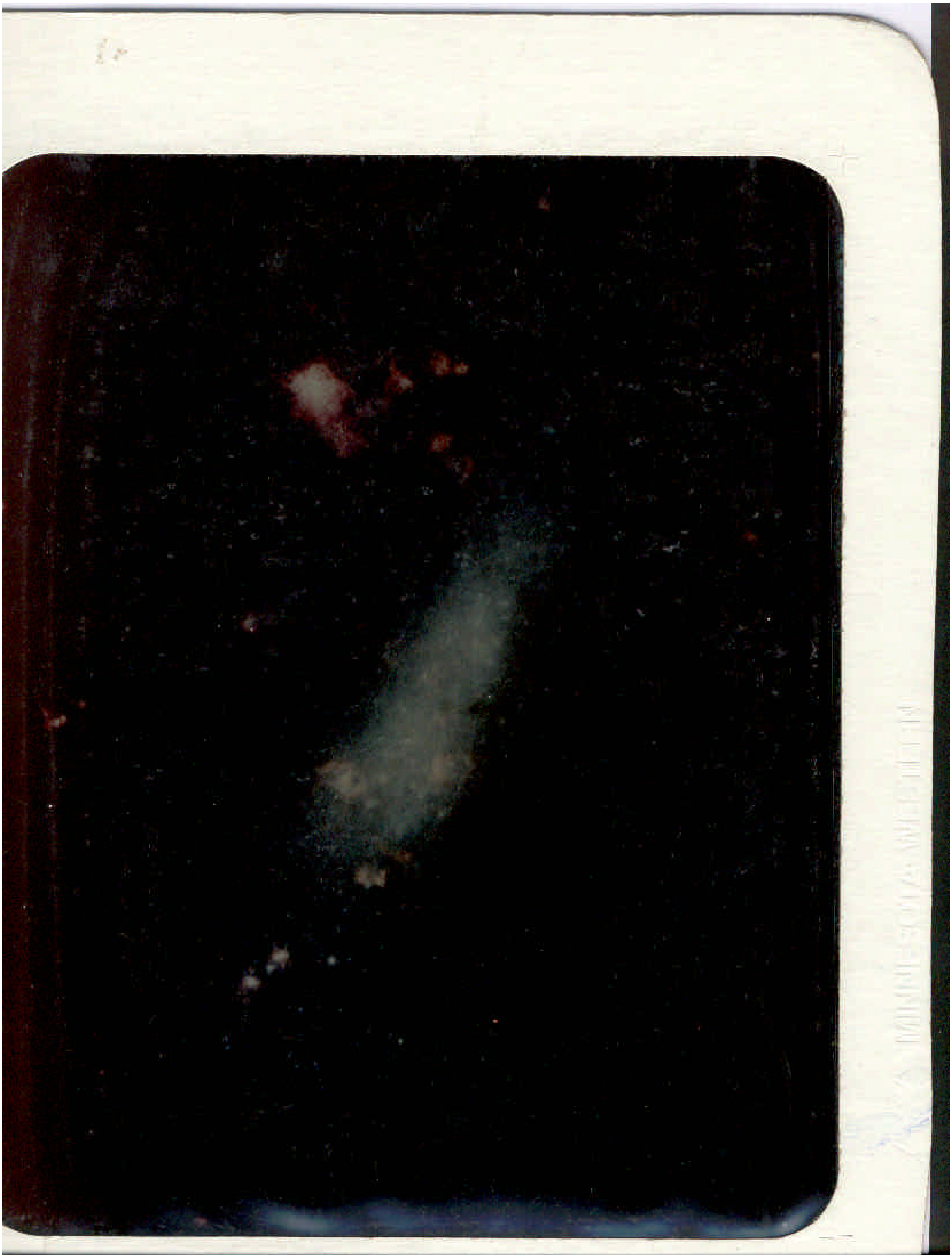
D. Welch	McMaster
A. Drake	MSSSO
M. Geha	LLNL
C. Nelson	LLNL
P. Popowski	LLNL
A. Tomaney	UW

(Also EROS, OGLE
microlens surveys)

MACHO PROJECT

- 25 scientists, ~10 institutions
- search for microlensing: dark matter
  variable stars
- Monitor 65 million stars in LMC, SMC, bulge
  - 80Mb image every 3-10 min all night for 7.5y
  - Raw data rate: 250 kb/sec, but day, weather, computer backlog
    ⇒ 1 Tb/year
  - Real time Flat field → Disk → tape
    → tape
    → Mass storage
  - Semi-Real time photometry → Disk → Alert system
  - Assemble into lightcurves
    - ⓐ Real time for individual star
    - ⓑ Batch for main analysis
  - Run analysis over all lightcurves
  - Run simulated data through system for efficiency
  - Use much smaller output lc + stats for dark matter, variable science analysis



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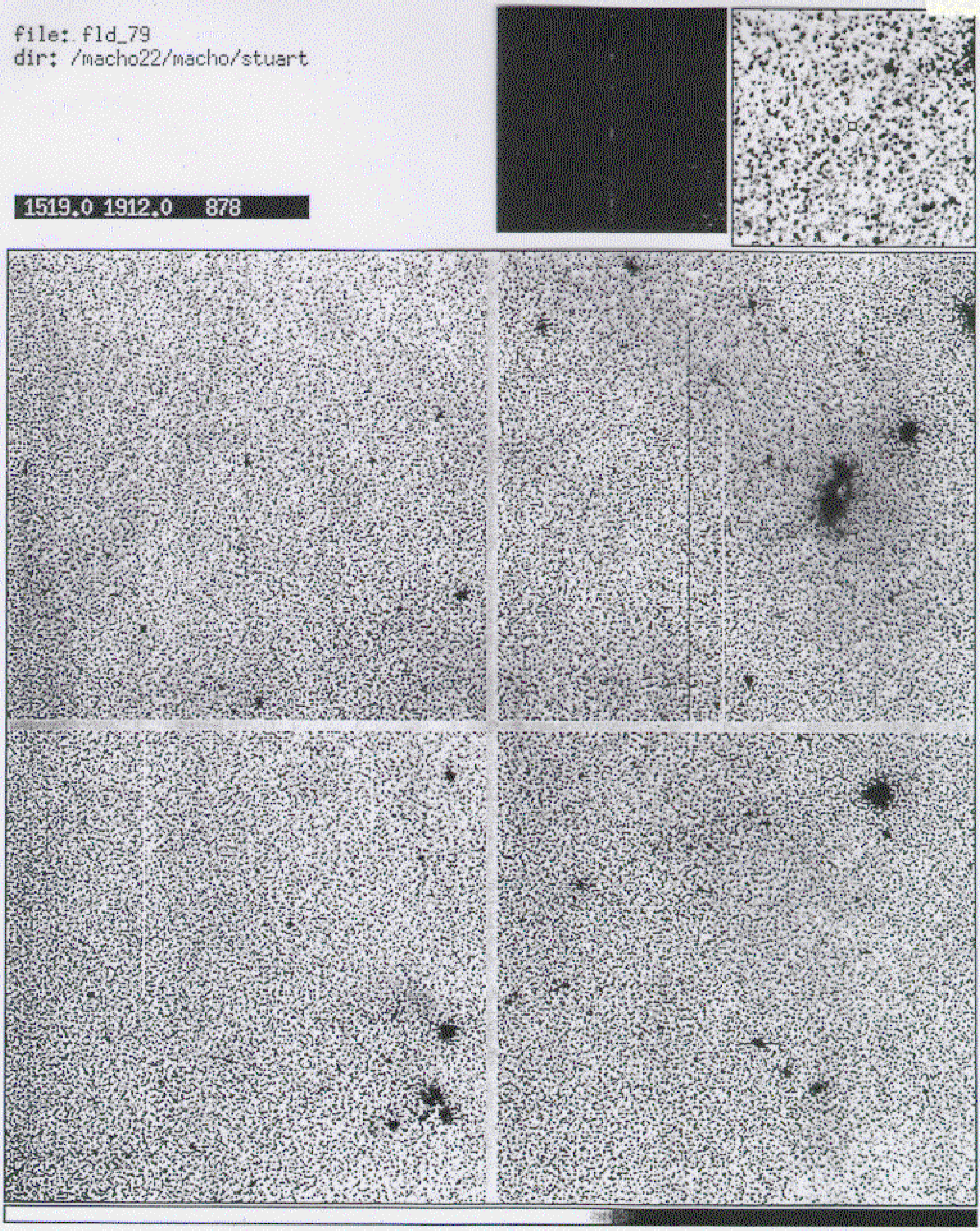


```
file: fld_79
dir: /macho22/macho/stuart
```

```
1519.0 1912.0   878
```

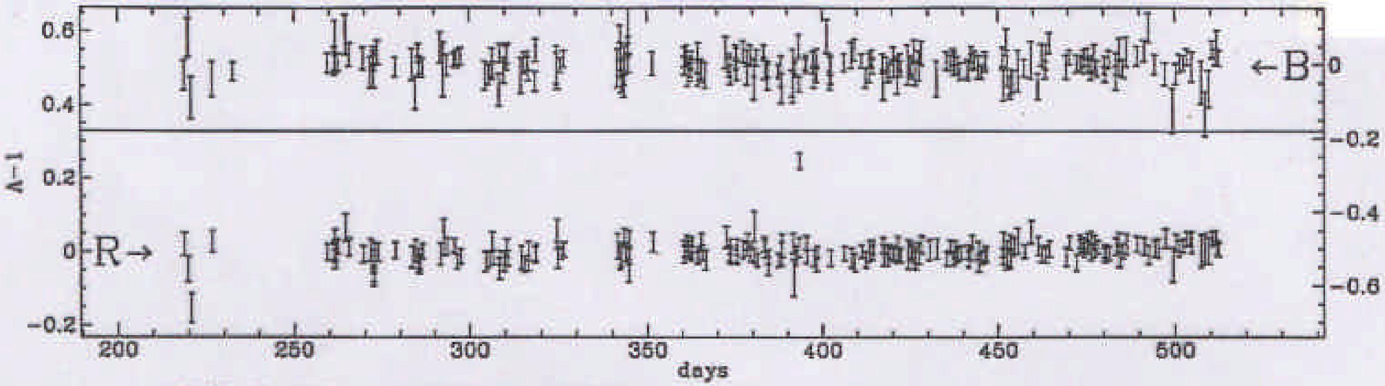
/macho22/macho/stuart/fld_79

SAOimage stuart@convict Sun Sep 26 09:58:31 1993

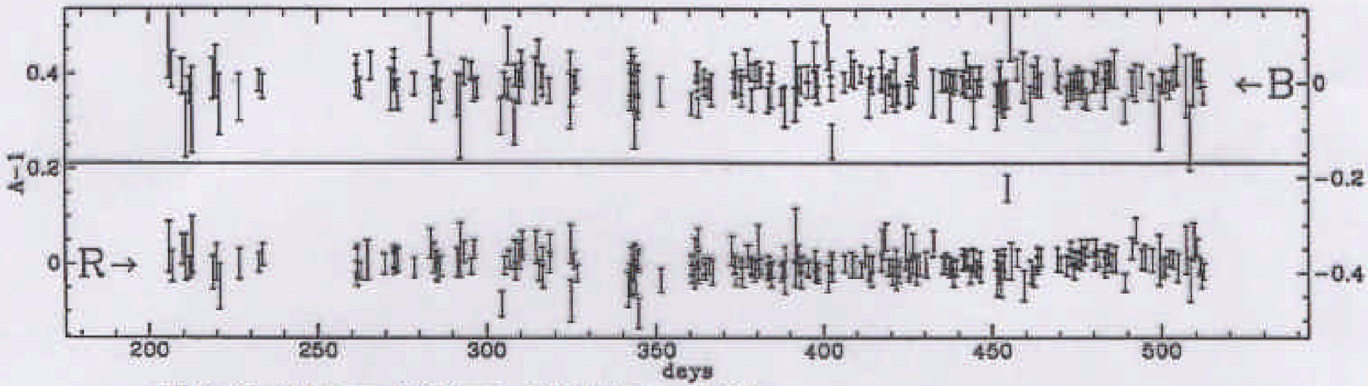
Random from 77014

moorei sadaie4, Jul 21 16:02:49 1993

128/0, tile=77014 seq=8279 Rmag=17.3394 Vmag=17.98



154/0, tile=77014 seq=9995 Rmag=17.49 Vmag=18.0562



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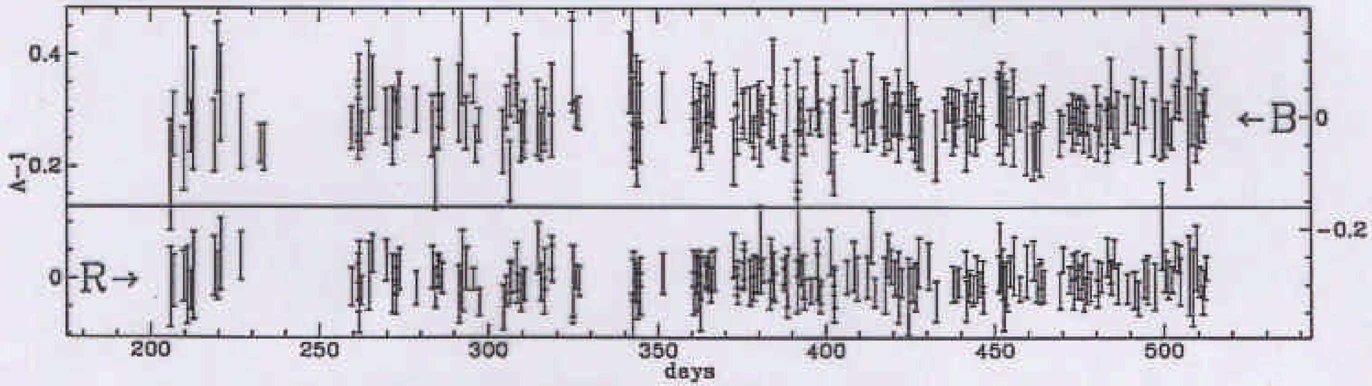
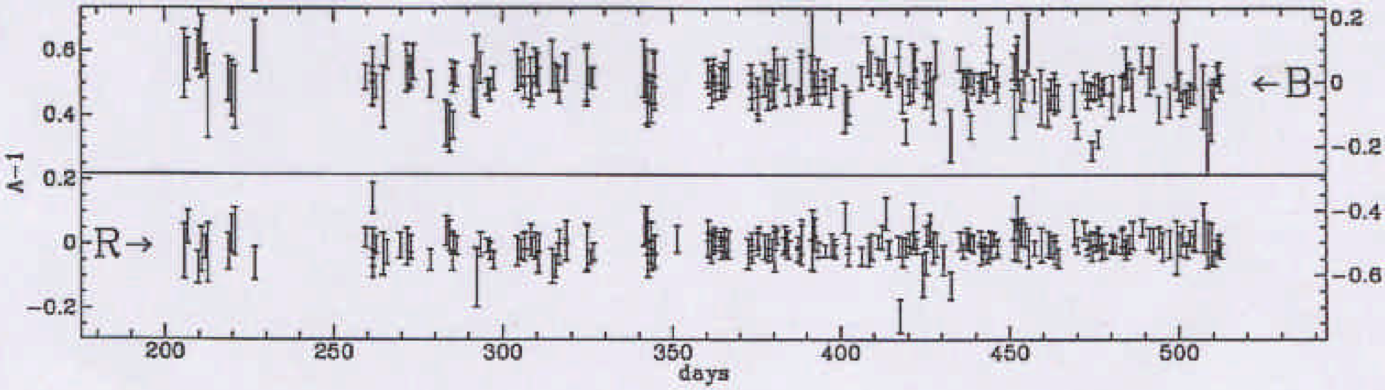


239/0, tile=77014 seq=15532 Rmag=17.8976 Vmag=18.5198

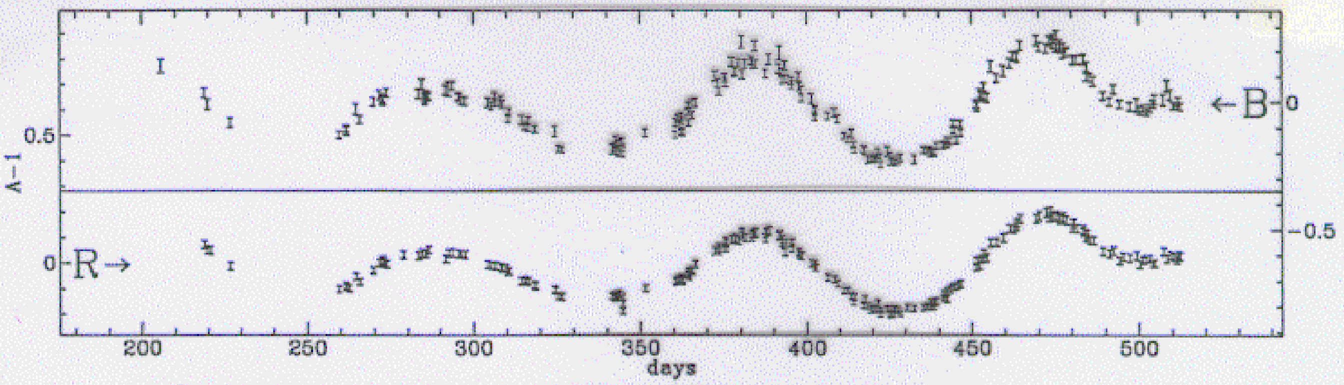


77014

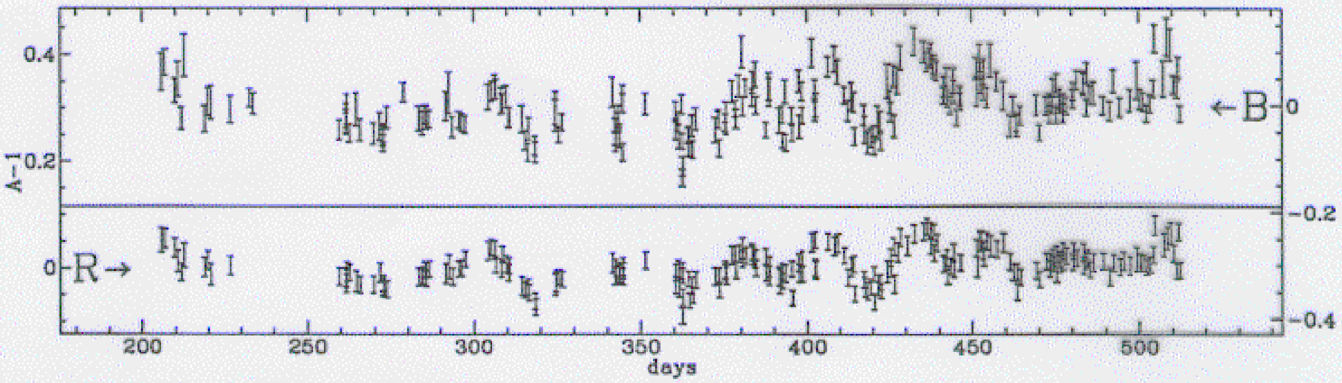
macro: sodolc4, Jul 21 16:05:01 199

Griest - 1

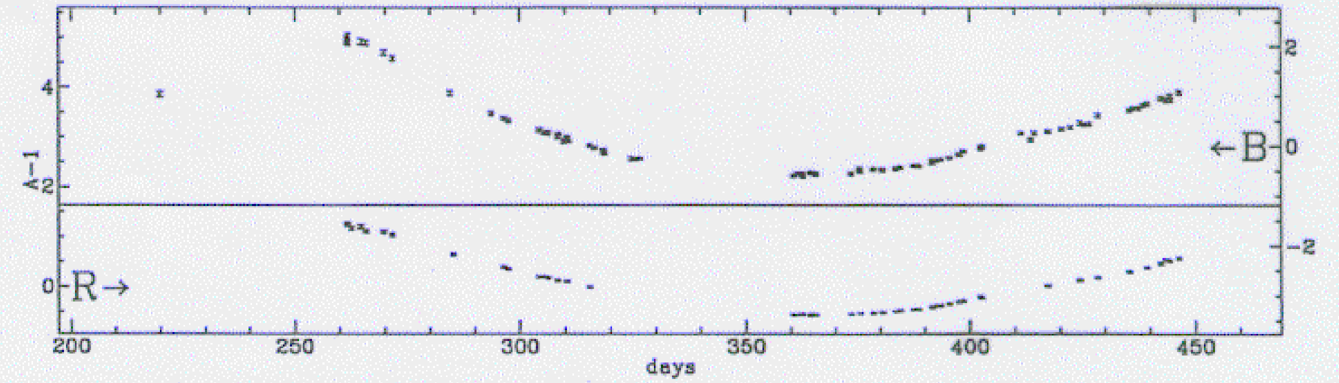
1/0, tile=77014 seq=187 Rmag=15.231 Vmag=16.5567



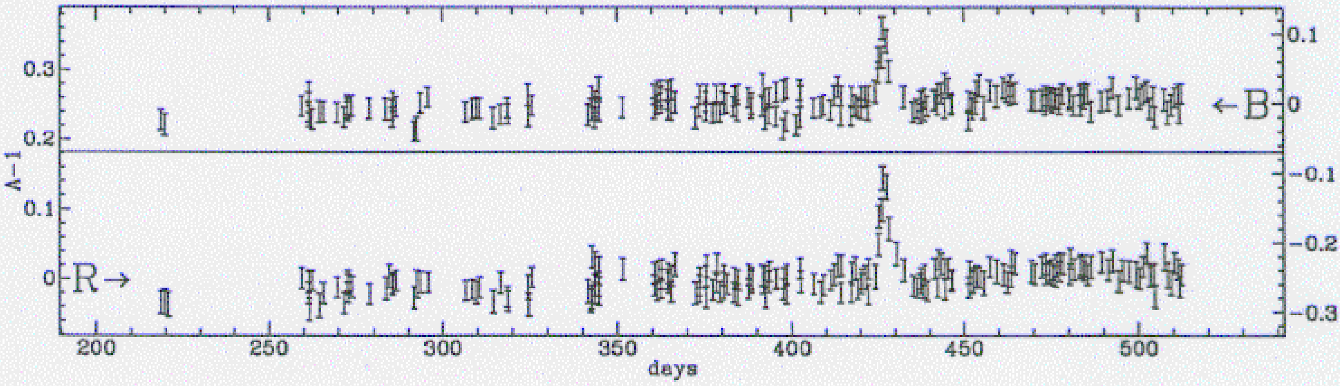
16/0, tile=77014 seq=1177 Rmag=15.9289 Vmag=16.8745



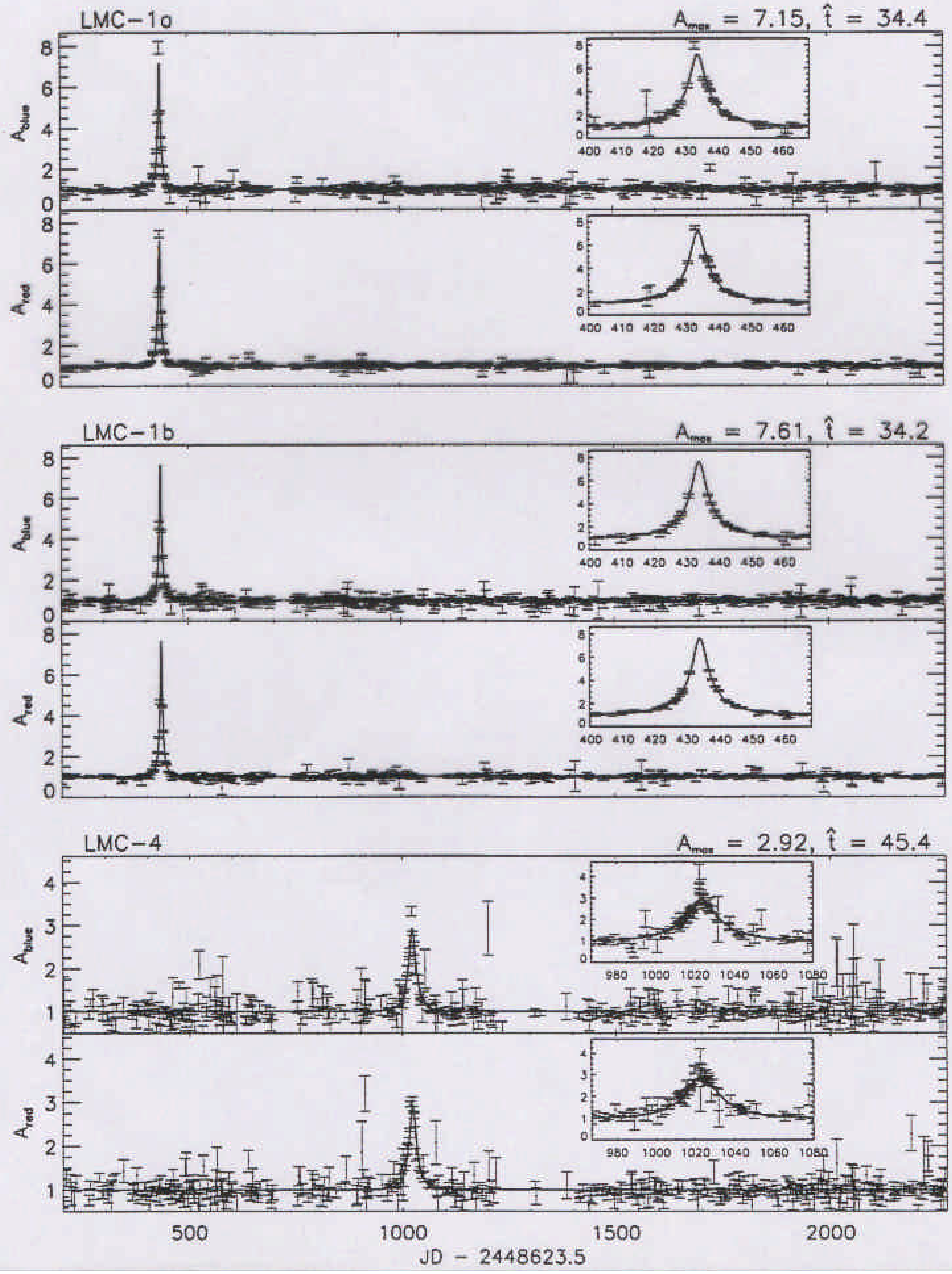
44/0, tile=77014 seq=3275 Rmag=16.2019 Vmag=17.566

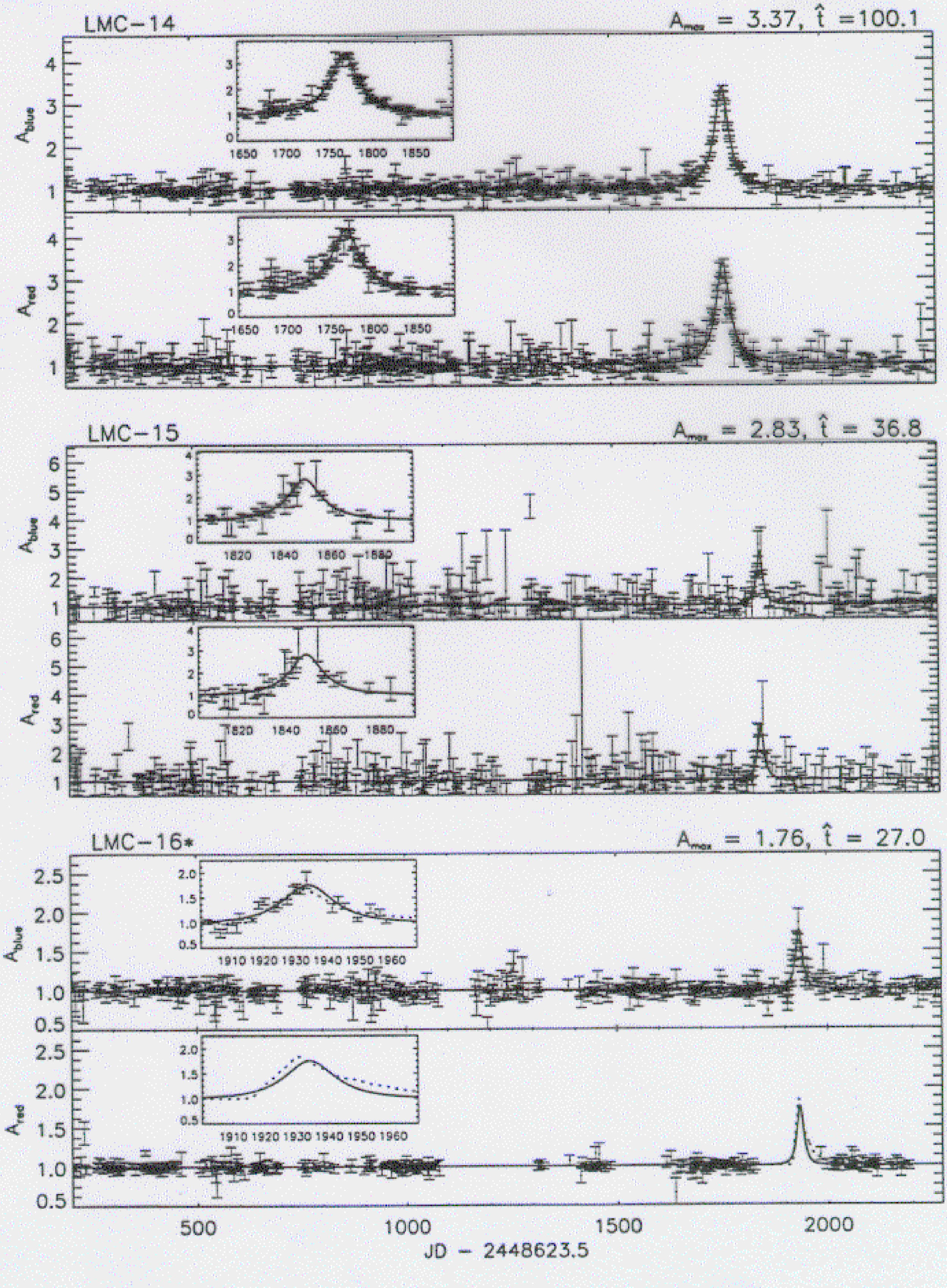


32/0, tile=77014 seq=2472 Rmag=15.9389 Vmag=15.9545



Griest - 14


LMC-1a
A_max = 7.15, t̂ = 34.4
A_blue
A_red
LMC-1b
A_max = 7.61, t̂ = 34.2
A_blue
A_red
LMC-4
A_max = 2.92, t̂ = 45.4
A_blue
A_red
0
2
4
6
8
400 410 420 430 440 450 460
1
2
3
4
980 1000 1020 1040 1060 1080
500
1000
1500
2000
JD - 2448623.5


LMC-14
A_{max} = 3.37, $\hat{t}$ =100.1
A_{blue}
A_{red}
1650 1700 1750 1800 1850
LMC-15
A_{max} = 2.83, $\hat{t}$ = 36.8
A_{blue}
A_{red}
1820 1840 1860 1880
LMC-16*
A_{max} = 1.76, $\hat{t}$ = 27.0
A_{blue}
A_{red}
1910 1920 1930 1940 1950 1960
500 1000 1500 2000
JD − 2448623.5

SELECTION CRITERIA

Description	Year 2 (A97)	Criteria A	Criteria B
Min. coverage	$bmrN \geq 7$ > 40 baseline points $\widehat{t} < 300$	$rN > 0$ & $bN > 0$ > 45 baseline points $\widehat{t} < 600$ $t_{\max} > 310$	> 65 simul. baseline points $\widehat{t} < 600$ $t_{\max} > 310$
SN87A echo	$10' \times 10'$ square excl.	$10' \times 10'$ square excl.	$10' \times 10'$ square excl.
Crowd & PSF	$f_{CRD} < \left(\Delta\chi^2/(\chi^2/N_{\rm dof})\right)^{10/9}/520$ & $crdrej < 0.05$	None	$pkcrdrej +$ $pkpsfrej < 0.2$
Bumper cut	$V > 17.5$ & $V - R < 0.9$	$V > 17.5$ & $V - R < 0.9$	$V > 17$ & ($A_{\max} > 1.75$ or $V > 19$ or $V - R > 0.4$)
Variable cut	None	$bauto/rauto > 0.75$	$pfwsr > 0.6$ & $rbcrossout < 0.75$
High points	6 pts. $> 2\sigma$ & ≥ 1 pt. on rise & fall	7 pts. $> 2\sigma$	10 pts. $> 2\sigma$ & $N_{\rm hi}/N_{\rm pk} > 0.9$
Baseline fit	$\chi^2_{\rm ml-out}/N_{\rm dof} < 4$	$\chi^2_{\rm ml-out}/N_{\rm dof} < 1.8$	$\chi^2_{\rm ml-out}/N_{\rm dof} < 4$ & $\chi^2_{\rm robust-out}/N_{\rm dof} < 1.5$
2nd S/N	$\Delta\chi^2/(\chi^2_{\rm peak}/N_{\rm dof}) > 200$	$\Delta\chi^2/(\chi^2_{\rm peak}/N_{\rm dof}) > 350$	None
Main S/N	$\Delta\chi^2/(\chi^2_{\rm ml}/N_{\rm dof}) > 500$	$\Delta\chi^2/(\chi^2_{\rm ml}/N_{\rm dof}) > 400$	$\Delta\chi^2/(\chi^2_{\rm ml}/N_{\rm dof}) > 300$
Magnification	$A_{\max} > \max(1.75, 1 + 2\overline{\sigma})$	$A_{\max} > \max(1.49, 1 + 3.5\overline{\sigma})$	$A_{\max} > \max(1.34, 1 + 4\overline{\sigma})$
2nd peak	None	None	$pfrdev2 < 90$
Supernova cut	By eye	$\Delta\chi^2_{\rm SN-ML} > 0$ & not event 22	$\Delta\chi^2_{\rm SN-ML} > 0$

TABLE 1

Efficiency Corrected Event Durations

Event	$\hat{t}$	$\hat{t}_{st}$
1......	34.2	44.5
4......	45.4	59.0
5......	75.6	98.1
6......	91.6	118.9
7......	102.9	133.6
8......	66.4	86.2
*9......	183.1	143.4
13......	100.1	130.0
14......	100.1	130.0
15......	36.8	47.7
18......	74.2	96.4
*20......	72.7	94.3
21......	93.2	121.0
*22......	229.4	297.4
23......	85.2	110.7
25......	85.2	110.7
*27......	50.5	65.6

2-year
↑ analysis

↓
5 year
analysis

What do LMC events mean?

Goal: Measure and/or limit amount of baryonic material in the Halo.
sensitivity to $10^{-7} M_\odot - 1 M_\odot$ range

① No events seen with $\hat{t} < 20$ days
⇒ strong limits on Machos in $10^{-7} - 0.1 M_\odot$ range

② 13-17 events with $34 < \hat{t} < 230$ days
⇒ estimate mass of Machos, Halo mass in machos, and fraction of Halo in Macho's

Need to compare observations with expected results from a Halo model
⇒ model dependence of results
(Milky Way Halo not well characterized)

② Also requires assumptions that all events are
a) due to microlensing
b) lenses are in Halo

① Limits are more robust since these assumptions are not needed

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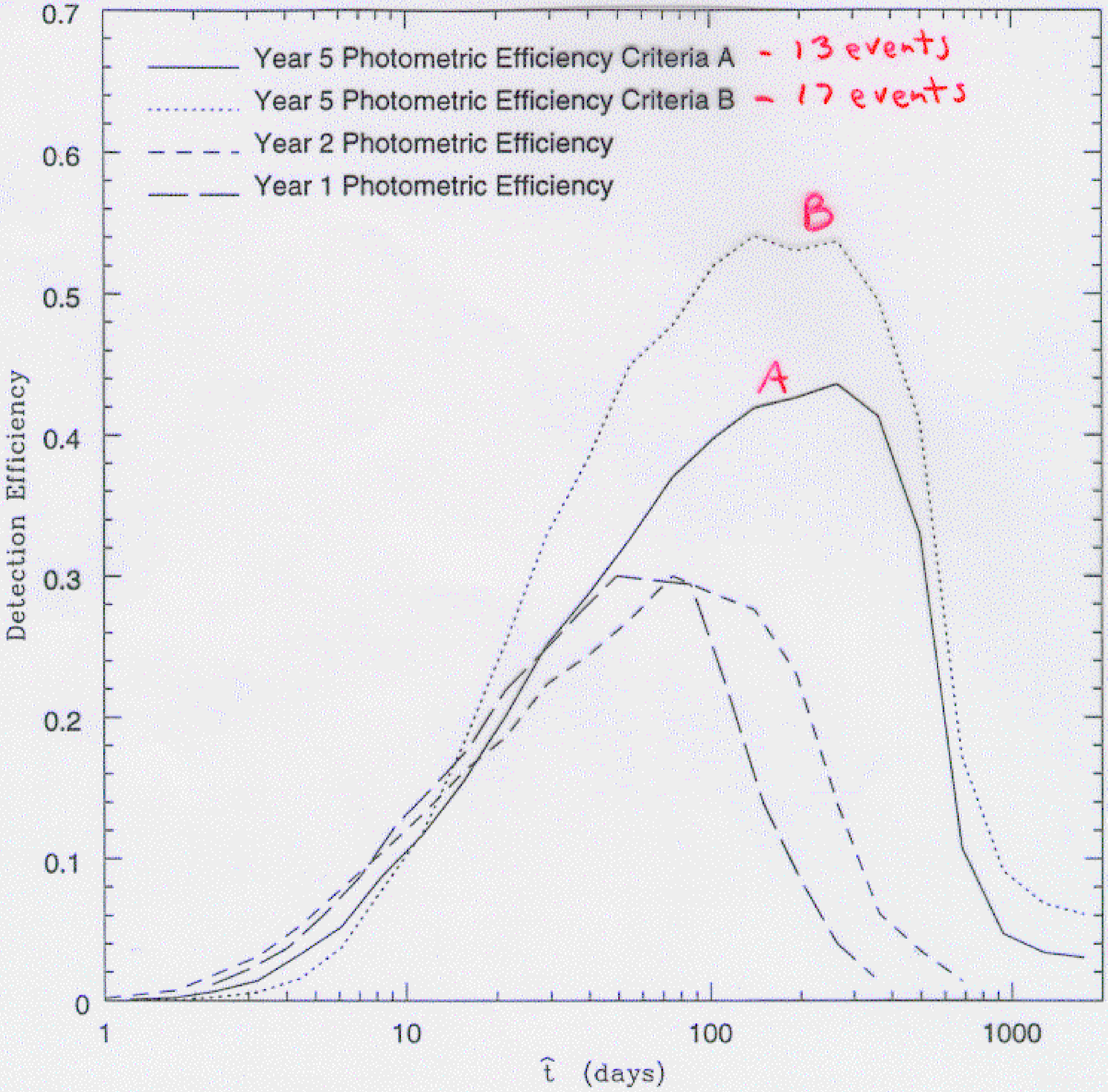
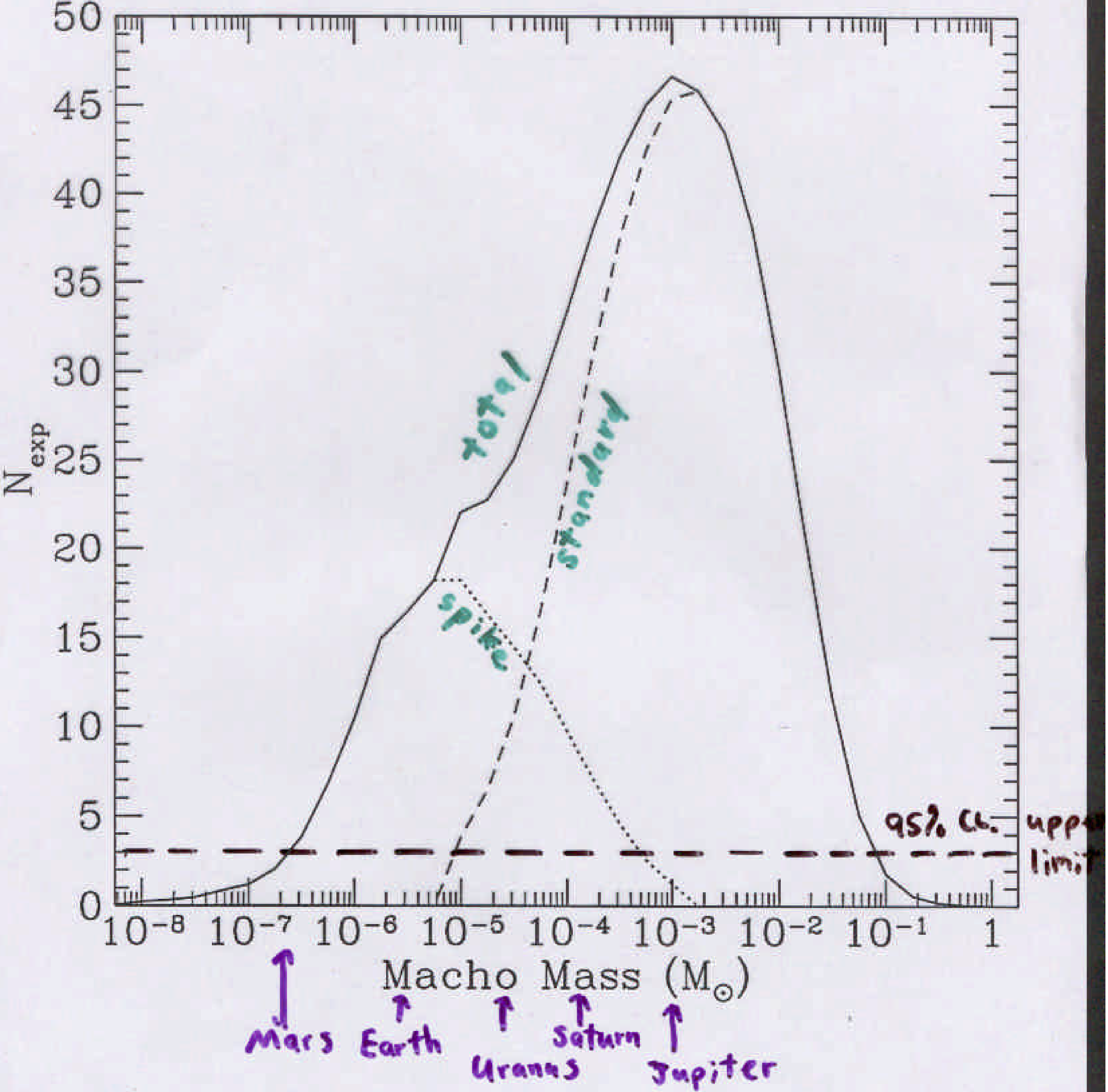
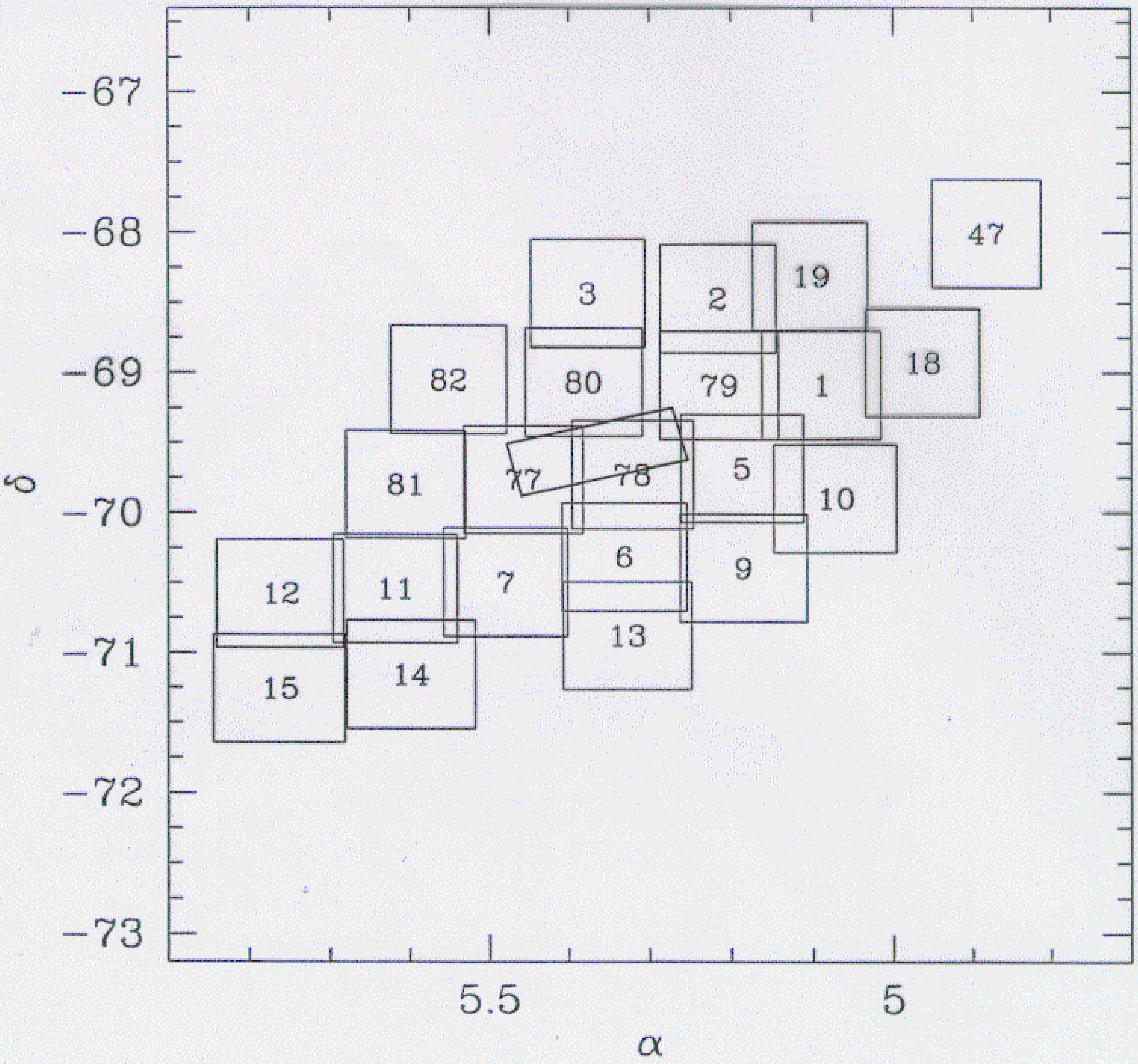

Year 5 Photometric Efficiency Criteria A
- 13 events
Year 5 Photometric Efficiency Criteria B
- 17 events
Year 2 Photometric Efficiency
Year 1 Photometric Efficiency
B
A
Detection Efficiency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1
10
100
1000
$\hat{t}$ (days)

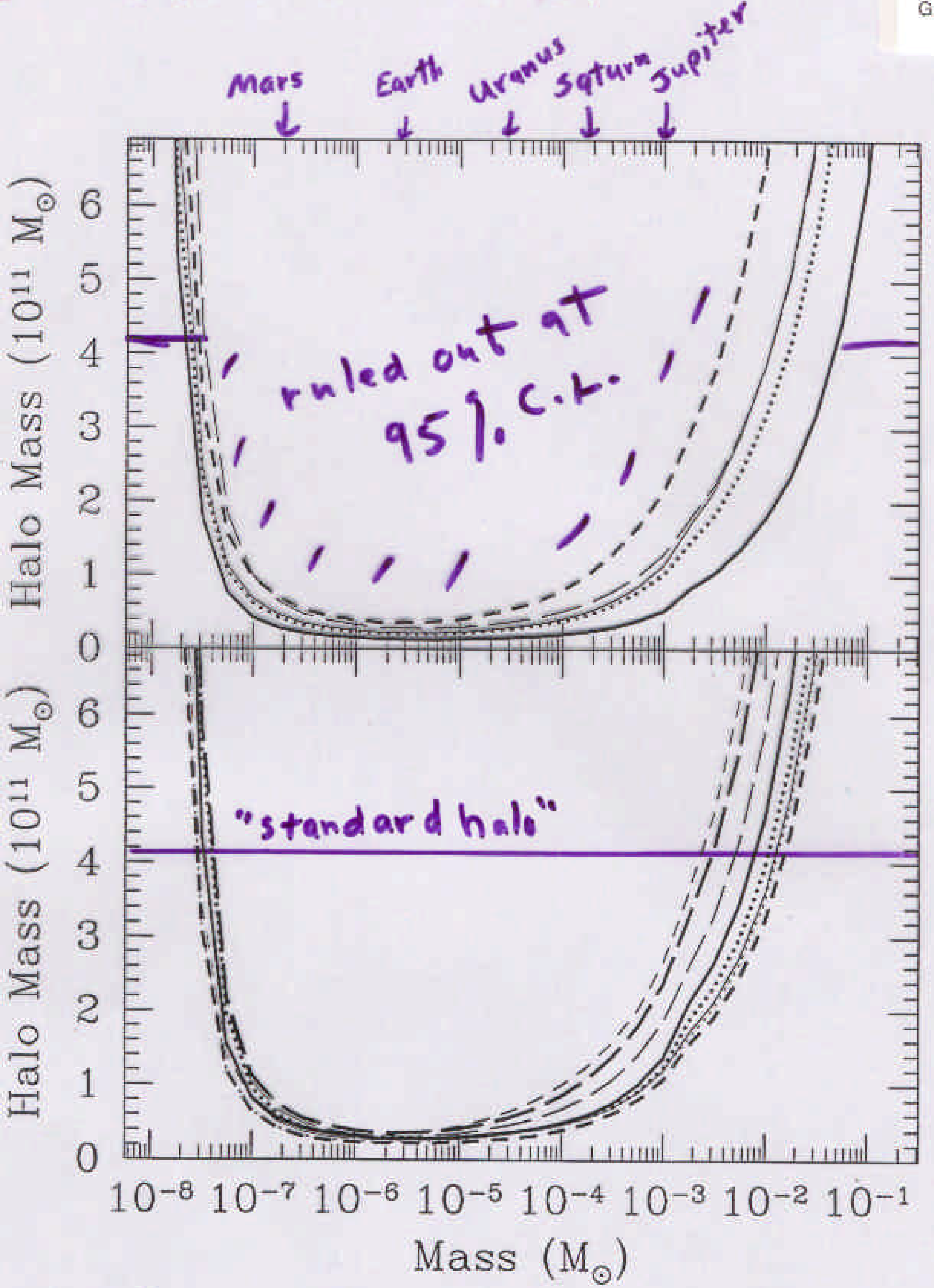

0
5
10
15
20
25
30
35
40
45
50
N_exp
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
Macho Mass (M_⊙)
total
standard
spike
95% c.l. upp
limit
Mars
Earth
Uranus
Saturn
Jupiter

Combined EROS + MACHO limit on low mass Machos.



ApJL, 499, L9 (1998) Matt Lehner & Cecile Renault

Combined EROS + MACHO limits:



Objects with $10^{-7} < m < 10^{-3}$ $M_\odot$ make up less than 25% of DM.

$3.5 \times 10^{-7} < m < 4.5 \times 10^{-5}$ $M_\odot$, less than 10% of DM.

TABLE 12
MICROLENSING BY STARS

Population	$\tau \times 10^{-8}$	$\langle \hat{t} \rangle$ (days)	$\langle l \rangle$ (kpc)	$\Gamma \times 10^{-8}(\mathrm{yr}^{-1})$	N_{exp} (A)	N_{exp} (B)
Thin disk	0.36	101	1.3	1.7	0.38	0.49
Big thin disk (F)	0.59	101	1.3	2.7	0.60	0.79
Thick disk	0.20	104	3.6	0.90	0.20	0.26
Spheroid	0.20	129	8.8	0.90	0.19	0.25
LMC disk(w/ halo)	1.6	120	50	5.8	1.3	1.7
LMC disk(w/o halo)....	2.6	120	50	9.8	2.2	2.9
				total	2.1-3.2	2.7-4.2

This table shows microlensing quantities for various lens populations, with the density and velocity distributions and PDMF described in the text. τ is the optical depth, $\langle l \rangle$ is the mean lens distance, and Γ is the total theoretical microlensing rate, but in all cases excluding bright lenses (see text). The expected number of events N_{exp} includes our detection efficiency averaged over the $\hat{t}$ distribution. The LMC values are averaged over the locations of our 30 fields. N_{exp} is the number of expected events using either selection criteria set A (13 events), or criteria set B (17 events). Two models of the LMC are considered, one with a dark halo and one without. Lensing from the LMC stellar disk only is shown in this table, lensing from the dark LMC halo is discussed elsewhere.

Beyond Limits

Have seen 13-17 events, but expect ~2-4 from non-halo microlensing.
(i.e. disk lenses, LMC disk, LMC halo, spheroid)

Probability of finding these events, given model is likelihood function

$$\mathcal{L}(m,f) = e^{-N_{exp}(m,f)} \prod_{i=1}^{N_{obs}} \mu_i$$

$$\mu_i = f E \epsilon(\hat{t}_i) \frac{d\Gamma}{dt}(\hat{t}_i)$$

Maximise to find most likely Macho mass m, and halo fraction f. (use prior $\frac{dm}{m}$ & df)

Estimate total mass in Machos by

$$M_{ML} = f_{ML} M_{50}(\text{halo})$$, M_{50} = mass with
50kpc in mod

Can also estimate optical depth

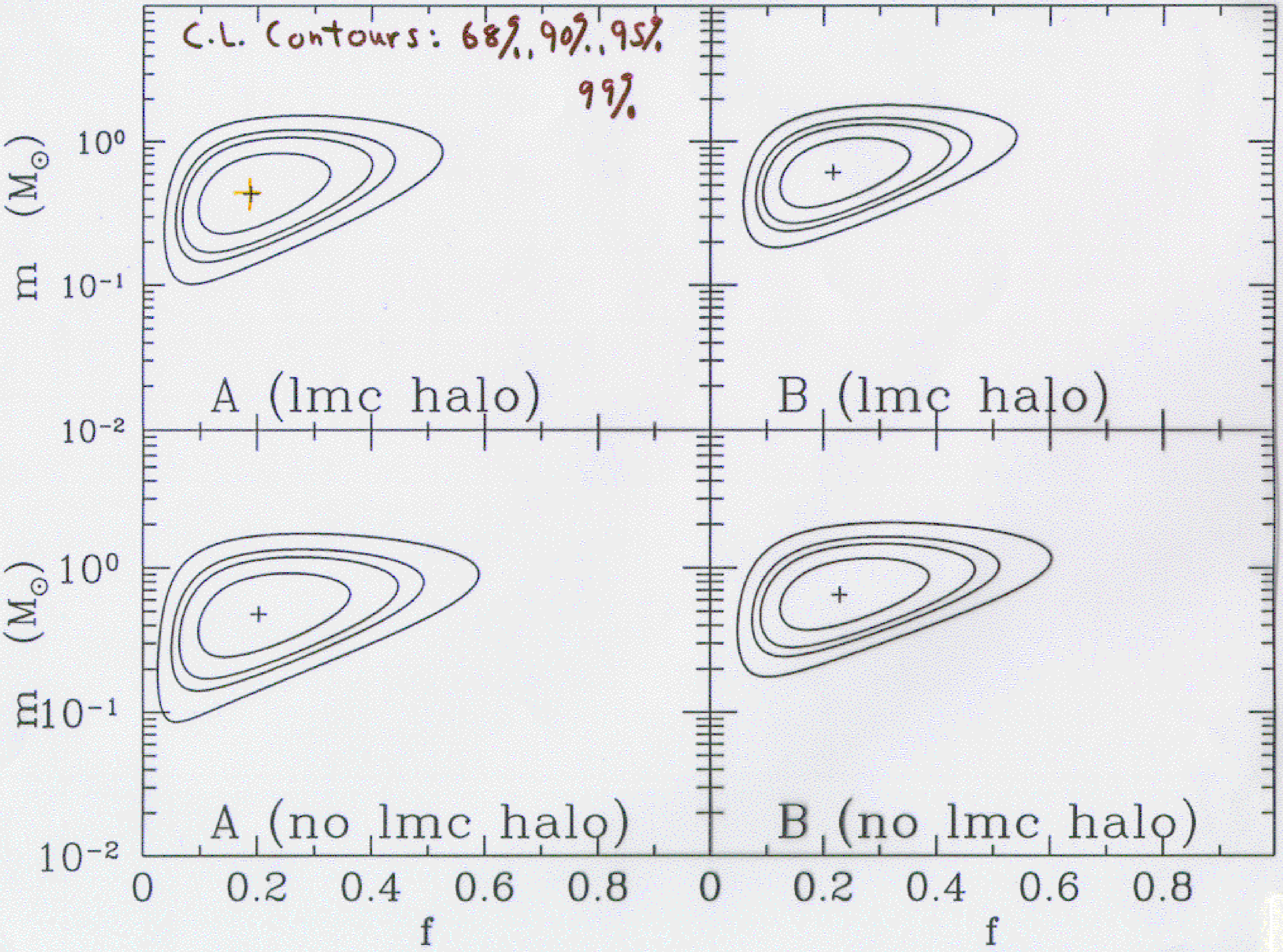
$$\tau_{ML} = (\tau_{model}) f_{ML}$$

or model independent

$$\tau_{obs} = \frac{\pi}{4} \frac{N_{obs}}{E} \frac{1}{N_{obs}} \sum_{i=1}^{N_{obs}} \frac{\hat{t}_i}{\mathcal{E}_i(\hat{t}_i)} \approx 1.2 \times 10^{-7}$$

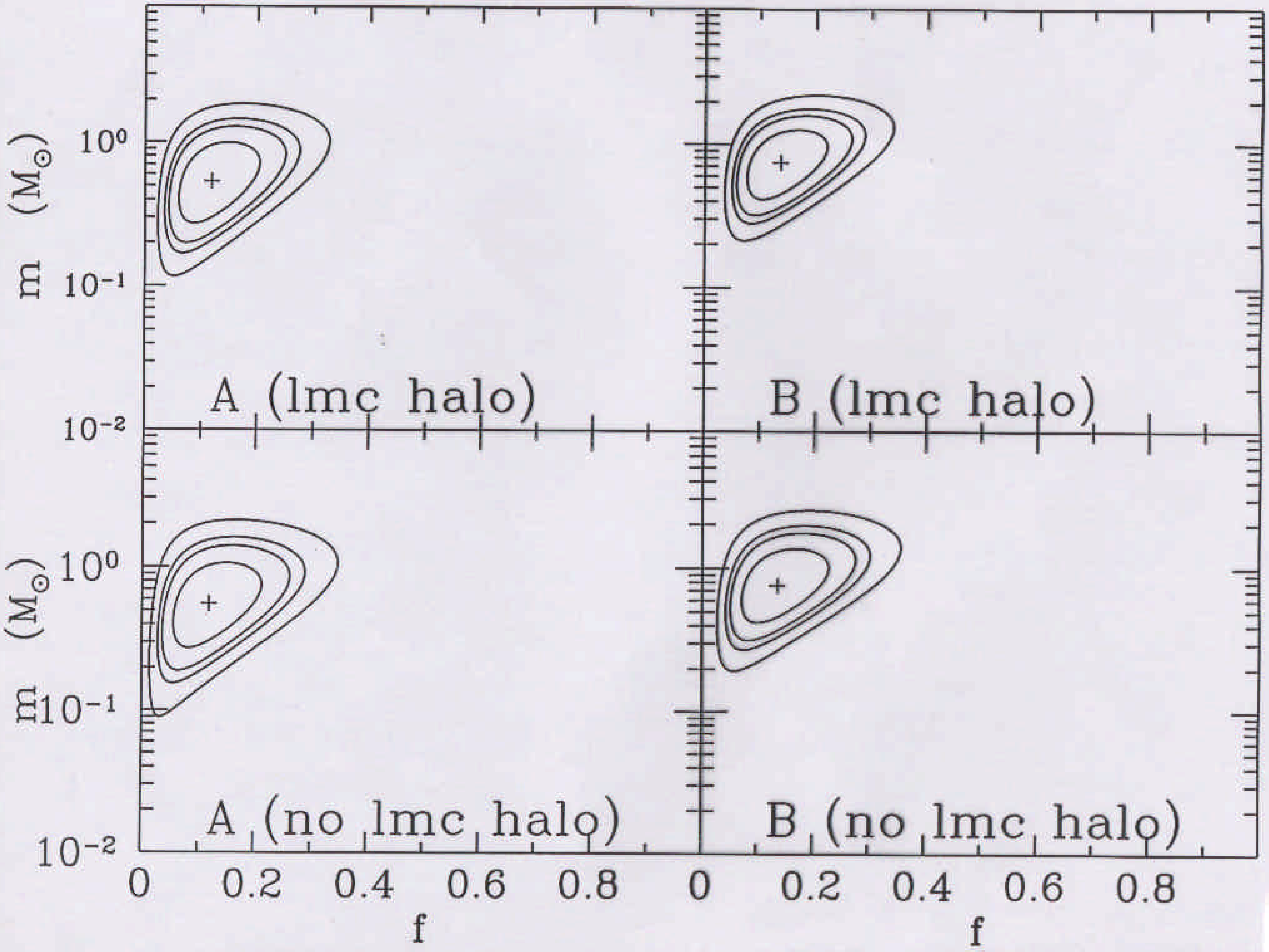
Full macho halo $\Rightarrow \tau = 4.7 \times 10^{-7}$

MODEL S: STANDARD DARK HALO



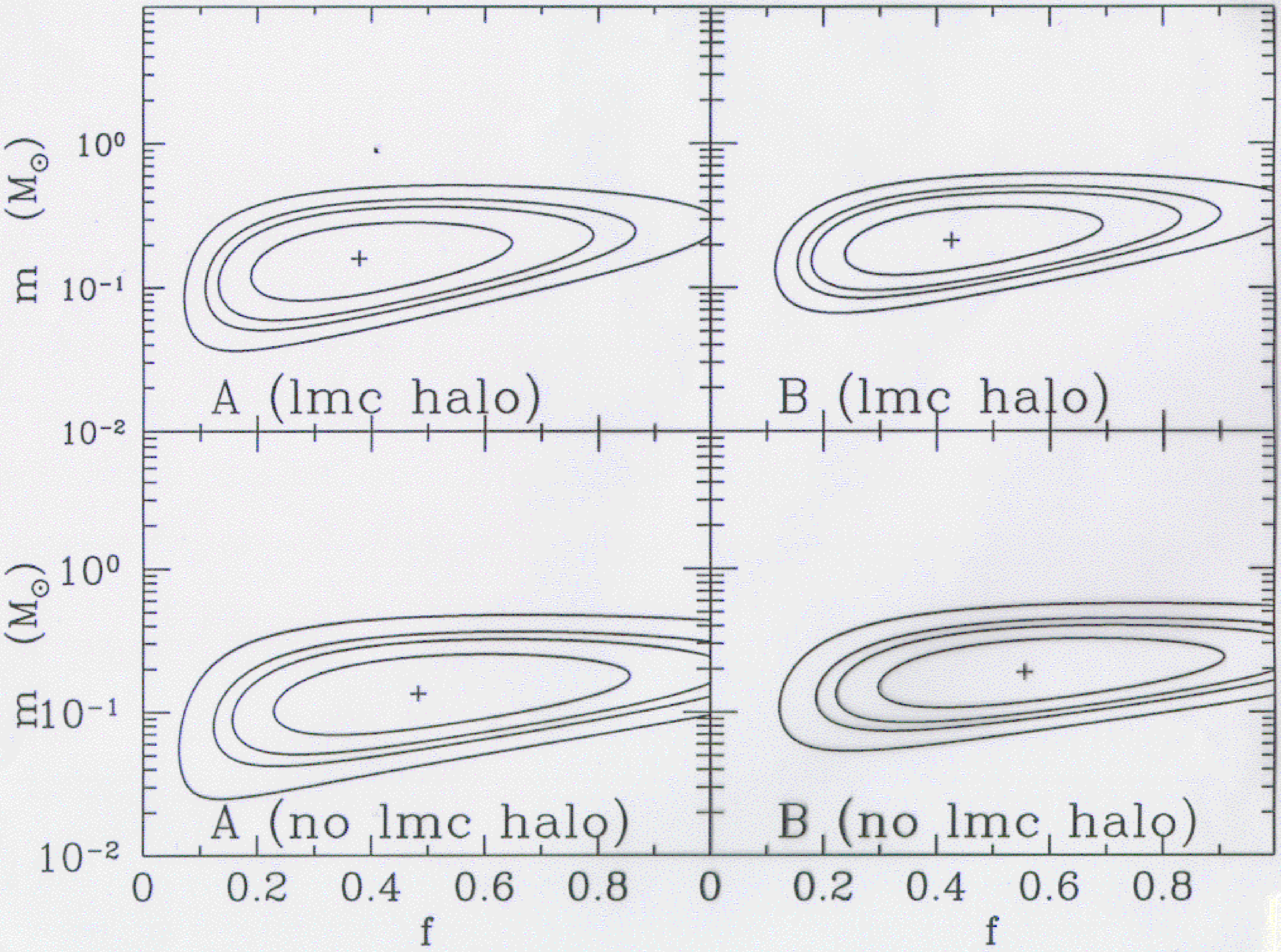
C.L. Contours: 68%, 90%, 95%, 99%

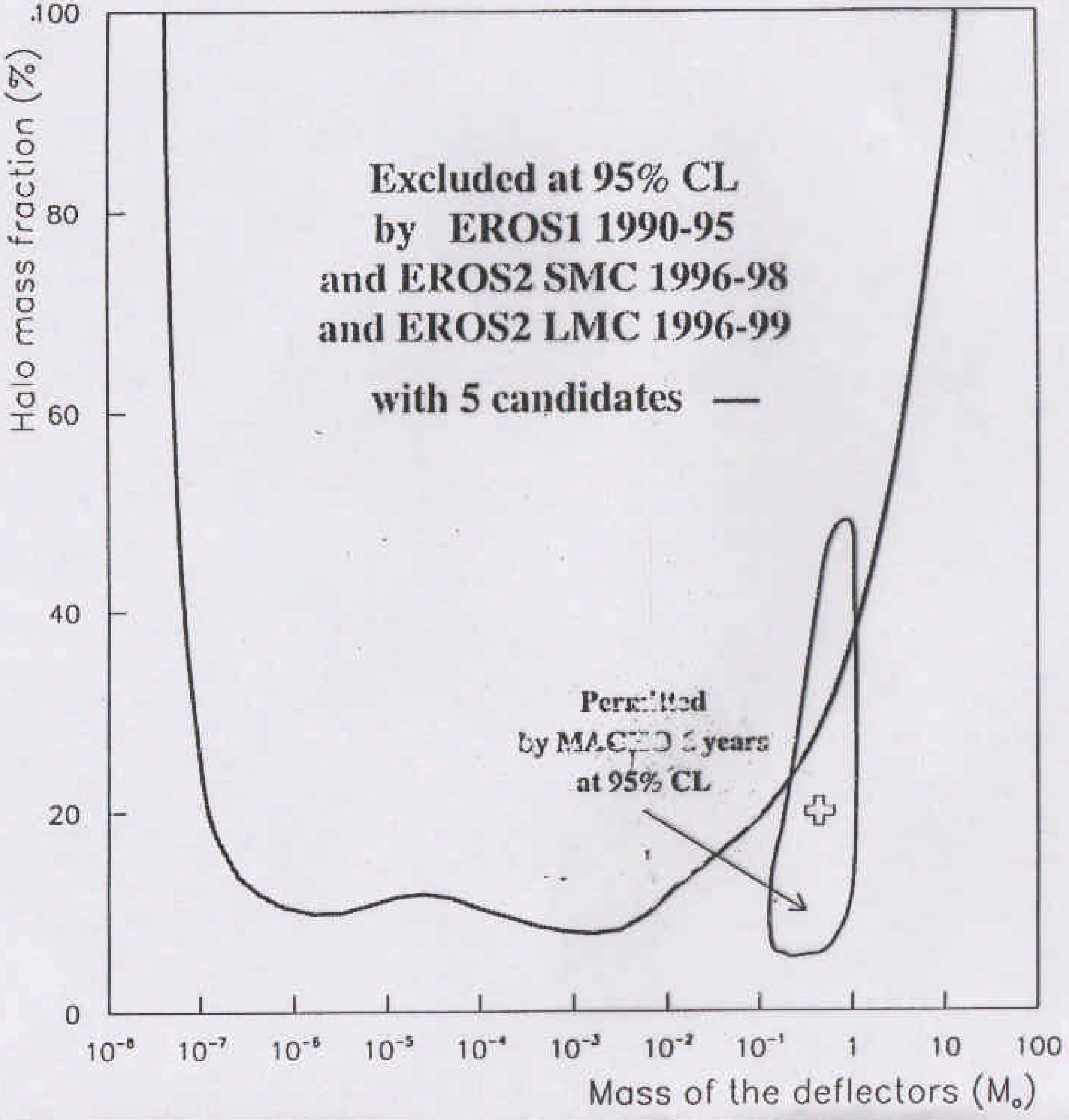
MODEL B: VERY LARGE HALO



Griest - 2

MODEL F : VERY SMALL HALO




Excluded at 95% CL
by EROS1 1990-95
and EROS2 SMC 1996-98
and EROS2 LMC 1996-99
with 5 candidates —
Permitted
by MACHO [illegible] years
at 95% CL
Halo mass fraction (%)
100
80
60
40
20
0
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
100
Mass of the deflectors ($M_{\odot}$)

total Mass in Machos

optical depth

TABLE 13
MAXIMUM LIKELIHOOD FITS

Model/ Events	Comment	$m_{\rm ML}$ ($M_\odot$)	$f_{\rm ML}$	$f_{\rm ML} M_{\rm H}$ ($10^{10}\,M_\odot$)	$\tau_{\rm ML}$ (10^{-8})	$N_{\rm exp}$ MW	$N_{\rm exp}$ LMC halo	$N_{\rm exp}$ stars
S/13	standard	$0.60^{+0.28}_{-0.20}$	$0.21^{+0.10}_{-0.07}$	8.5^{+4}_{-3}	10^{+5}_{-3}	9.6	0	3.0
S/13	standard	$0.54^{+0.26}_{-0.18}$	$0.20^{+0.08}_{-0.06}$	$7.9^{+3.4}_{-2.6}$	11^{+5}_{-4}	9.4	1.1	2.1
S/17	standard	$0.79^{+0.32}_{-0.24}$	$0.24^{+0.09}_{-0.08}$	10^{+4}_{-3}	11^{+4}_{-4}	12.7	0	3.9
S/17	standard	$0.72^{+0.30}_{-0.20}$	$0.22^{+0.08}_{-0.07}$	9.1^{+3}_{-3}	12^{+5}_{-4}	12.4	1.4	2.7
B/13	big halo	$0.68^{+0.35}_{-0.22}$	$0.12^{+0.06}_{-0.04}$	8.8^{+4}_{-3}	10^{+5}_{-4}	9.7	0	3.0
B/13	big halo	$0.66^{+0.30}_{-0.22}$	$0.12^{+0.05}_{-0.04}$	8.8^{+4}_{-3}	11^{+5}_{-4}	9.8	0.62	2.1
B/17	big halo	$0.92^{+0.40}_{-0.28}$	$0.14^{+0.06}_{-0.04}$	10^{+4}_{-3}	11^{+5}_{-4}	12.5	0	3.9
B/17	big halo	$0.87^{+0.35}_{-0.26}$	$0.14^{+0.05}_{-0.04}$	10^{+4}_{-3}	12^{+5}_{-4}	12.9	0.78	2.7
F/13	small halo	$0.16^{+0.08}_{-0.05}$	$0.50^{+0.22}_{-0.18}$	10^{+4}_{-4}	10^{+4}_{-3}	9.5	0	3.2
F/13	small halo	$0.19^{+0.09}_{-0.06}$	$0.39^{+0.17}_{-0.13}$	8.0^{+3}_{-3}	11^{+4}_{-3}	7.0	3.3	2.3
F/17	small halo	$0.22^{+0.09}_{-0.06}$	$0.57^{+0.21}_{-0.17}$	11^{+4}_{-4}	11^{+4}_{-3}	12.5	0	4.2
F/17	small halo	$0.25^{+0.10}_{-0.07}$	$0.44^{+0.16}_{-0.13}$	9.0^{+3}_{-3}	11^{+4}_{-4}	9.2	4.3	3.0

The first column shows the model as defined in A96 and A97, and the number of microlensing candidates used; either 13 from selection criteria set A, or 17 from criteria set B. Model S is given by eq. 4 and has a typical size halo, Model B has a halo as large as possible, and Model F has a halo as small as possible with a large thin disk. Columns 3 & 4 show the maximum likelihood MACHO mass and halo fraction from Section 6.2.3. Columns 5 & 6 show the implied total mass of MACHOs within 50 kpc of the Galactic center, and the resulting halo optical depth. For models with dark LMC halos, the sum of LMC and Milky Way MACHO optical depth is shown. Column 7 shows the number of expected events from the Milky Way halo, column 8 shows the number of expected events from the LMC halo, and column 9 shows the expected number of events from stars (from Table 12). Every Milky Way model is shown twice, once with a dark LMC halo, and once with the dark LMC halo set to zero. See the text for more explanation.

→ All MACHO halo ruled out

→ Masses 0.1 – 1.0 $M_\odot$ preferred

→ Halo Fraction 8% – 40% preferred

→ Total mass in MACHOs ~ 8-10 $\times 10^{10} M_\odot$

standard MW disk has ~ 6 $\times 10^{10} M_\odot$

MW halo has ~ 4-6 $\times 10^{11} M_\odot$

⇒ Machos a significant component of Galaxy

But mass range is problematic

IF $m < .08 M_\odot$ could accept, but HST rules out > 2% of DM in main sequence stars.

What could they be?

White dwarf stars?

- $m \simeq 0.6\ M_\odot$ ✓
- Visible in HST Hubble deep field? (debated: maybe not) or yes!! (Mendez & Minniti HDF(S))
- Visible in proper motion surveys? (~~no~~ or yes? several new surveys started to check) or Yes!! Ibata et al. in HST or no!! Flynn et al or Yes!! 2 more seen! 10% of halo
- How form? unknown ↑ Galactic pollution? ↖ Yes! (problematic)

Primordial Black holes?

- QCD phase transition - only need factor of 10 contraction! (fine tuned)
- Inflation (e.g. Linde) (fine tuned)

Q-balls, etc? (Kusenko, Shaposhnikov, etc.) (Griest & Kolb 1989)

↖

Neutron stars? ← formation theory w/o bad consequences?

Regular Black holes? ←

No convincing Candidate. but maybe there anyway!

Alternative Explanations

- LMC/LMC lensing (Sahu, Nature 1994)

  ↙ Alcock et al., Gould, etc. differ, Weinberg, Gyuk, et al., Aubourg et al.

- Intervening dwarf galaxy (Zhao ; Zaritsky and Lin)

  ↙ RR Lyrae Minniti - Alcock et al.

  ↳ estimated $\tau \approx 40\%$ observ

  ↙ Gould, Bennett : $\tau = 5-10\%$ *if* real

  ↳ Beaulieu & Sackett, Alves, etc. MACH Johnsto

  not intervening, effect of stellar evolution.

  → Zaritsky et al *yes!* → Gould *no*!

- Warps or Flares in disk (Turner, Gyuk, Evans)

- Something special about LMC line-of-sight? (Check others : SMC ?)

- etc.

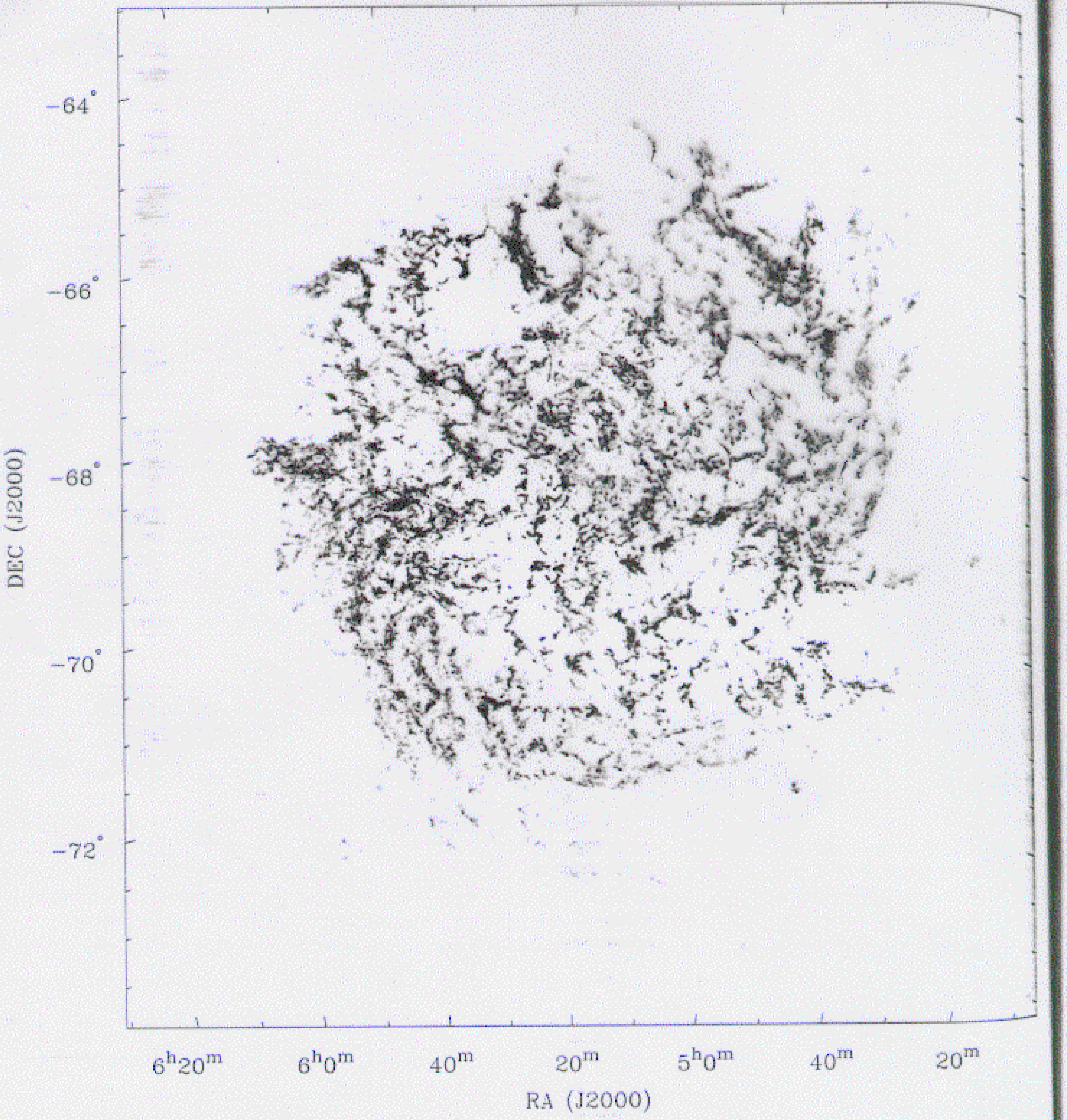


FIG. 1.—Peak H I surface brightness map for the LMC. This map is sensitive to the H I cloud with the highest surface density lying along the line of sight and it emphasizes the filamentary, bubbly, and flocculent structure of the ISM in the LMC.

The median pitch angle of the spiral features in the outer parts (at radii ~ 3 kpc) is ~25°. With a flat rotation curve ($v = 70$ km s^{-1}), this implies an average lifetime of ~90 Myr, or about a third of a galactic rotation period. The spiral arms are trailing only if the LMC is rotating clockwise on the sky. *Hipparcos* proper-motion studies (Kroupa & Bastian 1997) indicate a similar, though more tentative, result. Since the northern part of the disk is rotating away from us, this geometry implies that the closest part of the LMC is in the east. In this region we expect the outskirts of the disk (at radius ~ 3.6 kpc) to be some 2.7 ± 1.0 kpc closer on the eastern edge than on the western edge. This result is in good agreement with direct determinations through Cepheid distances, which give position angles for

Gyuk, Dalal, K.G.
Self-Lensing Models of the LMC

Examined range of models
consistent with observations

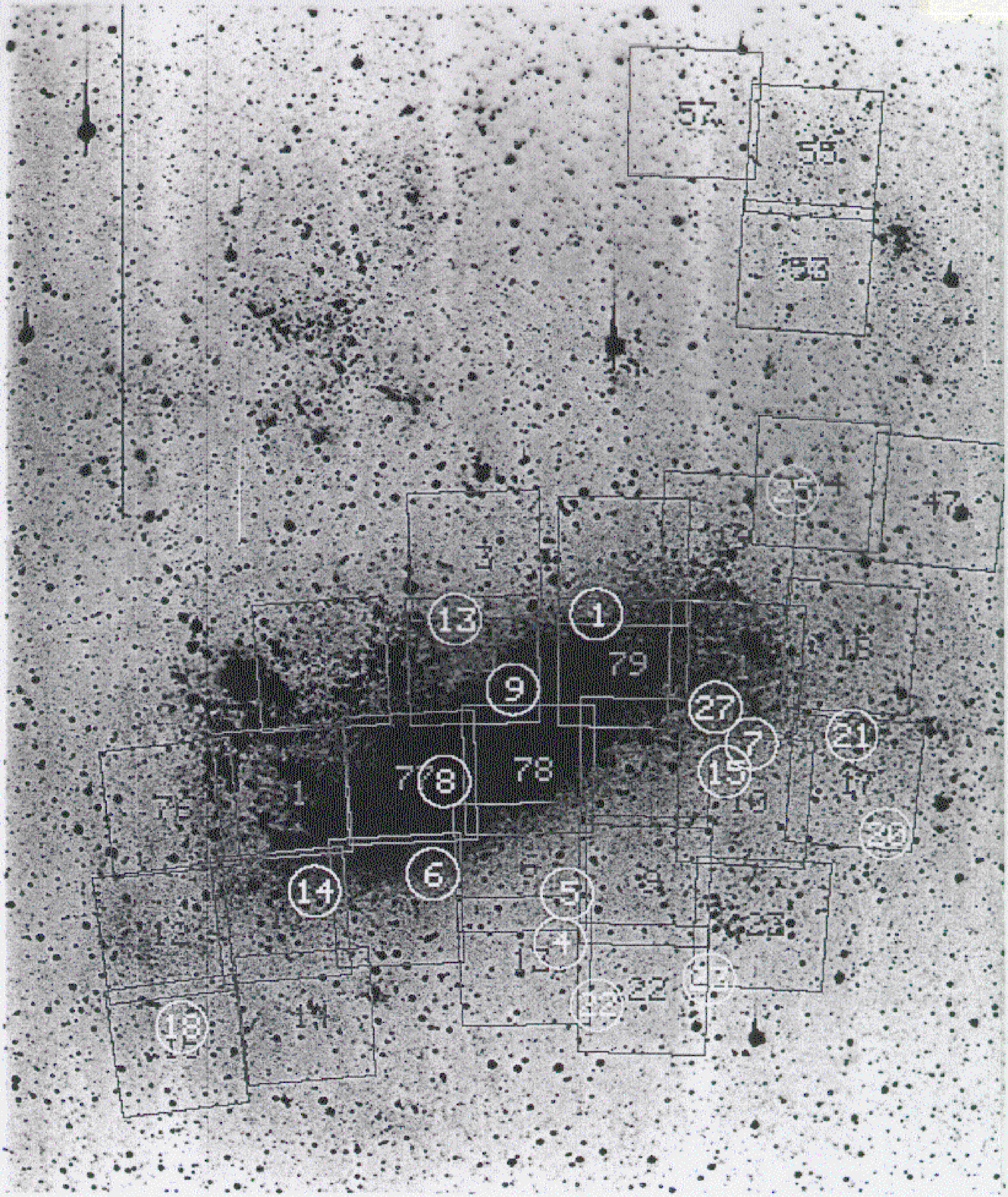
Source/Lens geometry	Relative Weight			Preferred Values			Allowed Range
	22	30	82	22	30	82	(22 fields)
disk/disk	0.61	0.67	0.79	1.46	1.34	1.04	0.23-5.81
disk/bar	0.61	0.67	0.79	0.87	0.72	0.39	0.11-4.07
bar/disk	0.39	0.33	0.21	1.25	1.24	1.23	0.40-4.13
bar/bar	0.39	0.33	0.21	1.37	1.36	1.33	0.32-4.00
total bar+disk	1	1	1	2.44	2.24	1.67	0.47-7.84
(disk+bar)/dark halo	f_M	f_M	f_M	7.75	7.73	7.18	0 - 22.6

Table 1: Optical depths for LMC self lensing in units of 10^{-8}, averaged over the 22 fields of Alcock et al. (1997a). The dark halo result is for a MACHO fraction $f_M = 1$. Note that the relative weights apply only to the the preferred set of parameters.

preferred value $\tau = 2.4 \times 10^{-8}$

$\tau_{Macho}(5 \text{ year}) \approx 1.2 \times 10^{-7}$

Griest - 35


57
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22
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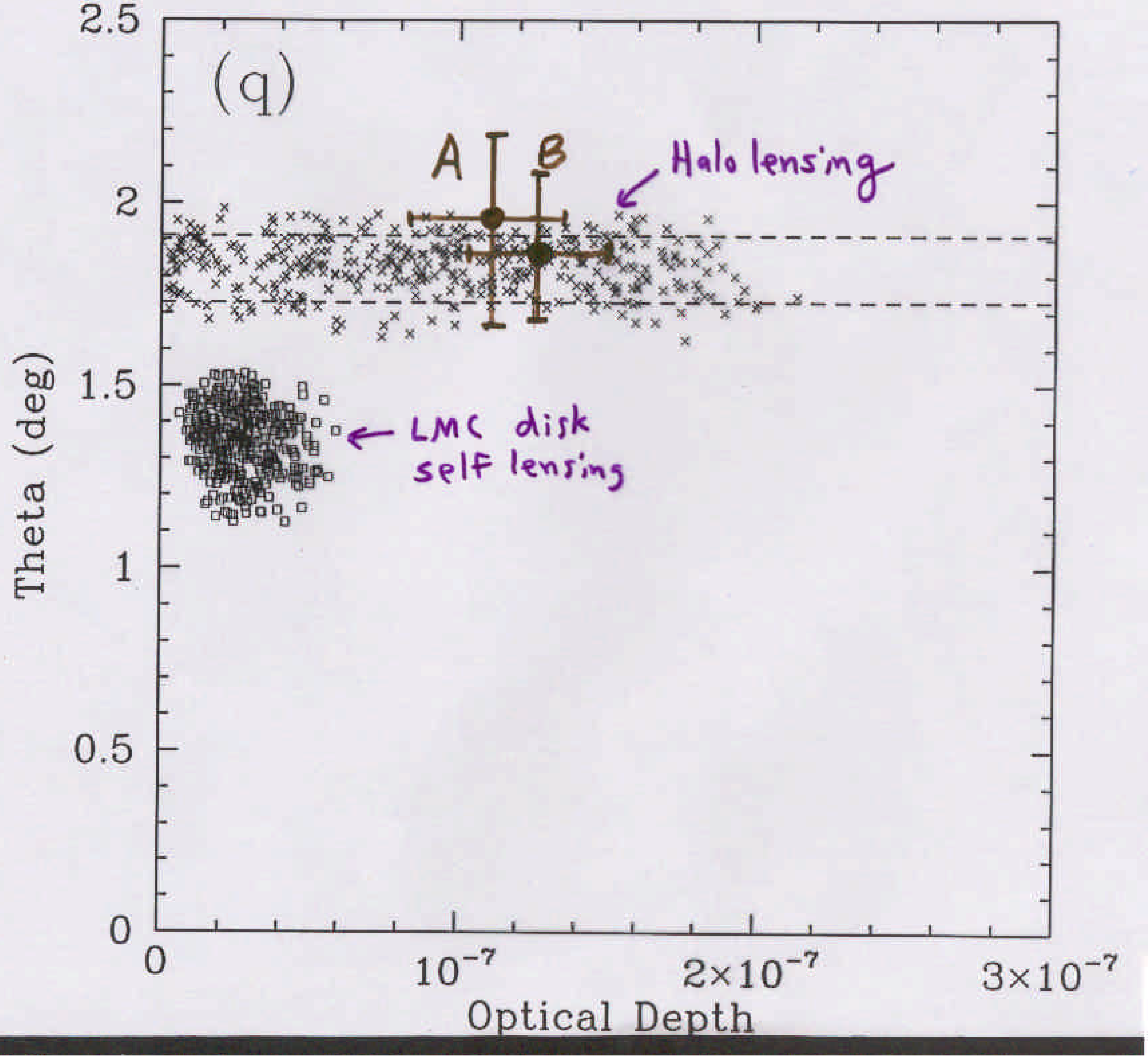
18
14

30 fields

Gyuk, Dalal, K.G.



Conclusions

→ All MACHO halo ruled out
  ⇒ Ball in court of WIMP, axion, etc. searches

→ ~15 good microlensing events unexplained.

Could be ~20% of DM
  ⇒ Dominant identified component of galaxies
  ⇒ Major change to galaxy/star formation ideas

Could be LMC halo lensing – but why aren't lenses seen?

→ Need to identify distances to lenses.
  ⇒ New surveys & techniques.

→ Are white dwarfs really there?