The 15th International Conference on Gravitational Microlensing
University of Salerno
January 20-22, 2011

Analysis of (OGLE-III) microlensing events towards the LMC

Luigi Mancini
University of Sannio

Sebastiano Calchi Novati
University of Salerno

Dark Matter in the Galactic Halo?

- The microlensing surveys towards the Magellanic Clouds and M31 have demonstrated the existence of compact objects that act as gravitational lenses somewhere between us and the galaxy target.

Alcock et al., ApJ 542, 281 (2000)	LMC	MACHO
de Jong et al., A&A 417, 461 (2004)	M31	MEGA
Calchi Novati et al., A&A 443, 911 (2005)	M31	POINT-AGAPE
Tisserand et al., A&A, 469, 387 (2007)	LMC & SMC	EROS-II
Wyrzykowski et al., MNRAS 397, 1228 (2009)	LMC	OGLE-II
Calchi Novati et al., ApJ 695, 442 (2009)	M31	PLAN
Wyrzykowski et al., MNRAS 407, 189 (2010)	SMC	OGLE-II
Wyrzykowski et al., MNRAS, in press (2010)	LMC	OGLE-III
Riffeser's talk; Lee's poster	M31	WeCAPP/PAndromeda

- The nature of the observed events is still an open issue:

  dark matter or luminous matter?

- The experimental results reported so far <u>towards the LMC</u> are in agreement to exclude that the Galactic halo is formed by MACHOs with masses in the range $(10^{-2} – 10^{-1})\ M_{\odot}$.
- Yet, a relevant discrepancy still exists for the existence of compact halo objects in the mass range $(0.1 – 1)\ M_{\odot}$.

- The experimental results reported so far towards the LMC are in agreement to exclude that the Galactic halo is formed by MACHOs with masses in the range $(10^{-2} – 10^{-1})\ M_{\odot}$.
- Yet, a relevant discrepancy still exists for the existence of compact halo objects in the mass range $(0.1 – 1)\ M_{\odot}$.

- The **MACHO** collaboration claimed that the fraction of Halo in form of MACHOs is roughly $f \approx 20\%$.

  Alcock et al., ApJ 542, 281 (2000)

  Bennett, ApJ 633, 906 (2005)

- The experimental results reported so far towards the LMC are in agreement to exclude that the Galactic halo is formed by MACHOs with masses in the range ($10^{-2} - 10^{-1}$) $M_{\odot}$.
- Yet, a relevant discrepancy still exists for the existence of compact halo objects in the mass range (0.1 – 1) $M_{\odot}$.

- The **MACHO** collaboration claimed that the fraction of Halo in form of MACHOs is roughly $f \approx 20\%$.

  Alcock et al., ApJ 542, 281 (2000)

  Bennett, ApJ 633, 906 (2005)

- On the other hand, the **EROS** and the **OGLE** collaborations concluded that the expected self-lensing rate is sufficient to explain the observed events.

  Tisserand et al., A&A, 469, 387 (2007)

  Wyrzykowski et al., MNRAS 397, 1228 (2009)

  Wyrzykowski et al., MNRAS, in press (2010)

- The experimental results reported so far <u>towards the LMC</u> are in agreement to exclude that the Galactic halo is formed by MACHOs with masses in the range ($10^{-2} - 10^{-1}$) $M_{\odot}$.
- Yet, a relevant discrepancy still exists for the existence of compact halo objects in the mass range (0.1 – 1) $M_{\odot}$.

- The **MACHO** collaboration claimed that the fraction of Halo in form of MACHOs is roughly $f \approx 20\%$.

  Alcock et al., ApJ 542, 281 (2000)

  Bennett, ApJ 633, 906 (2005)

- On the other hand, the **EROS** and the **OGLE** collaborations concluded that the expected self-lensing rate is sufficient to explain the observed events.

  Tisserand et al., A&A, 469, 387 (2007)

  Wyrzykowski et al., MNRAS 397, 1228 (2009)

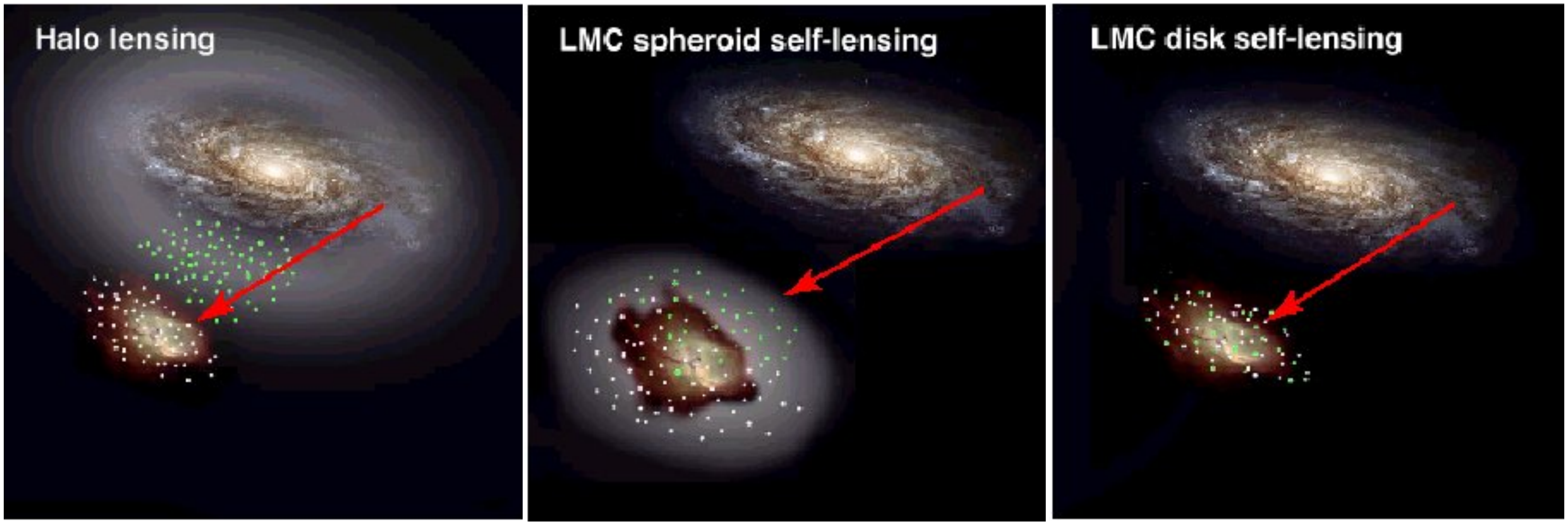
  Wyrzykowski et al., MNRAS, in press (2010)

Microlensing events of the LMC are better explained by stars within the LMC than by MACHOs

Sahu, PASP 106, 942 (1994)

- It is therefore important to address the issue of the nature of the observed events, either to be attributed to MACHO lensing, self lensing, or lensing due to other luminous populations.
- Due to the limited number of events observed to date it is not yet clear which scenario or combination of scenarios explains the observed lensing.

Jetzer et al., A&A 393, 129 (2002)

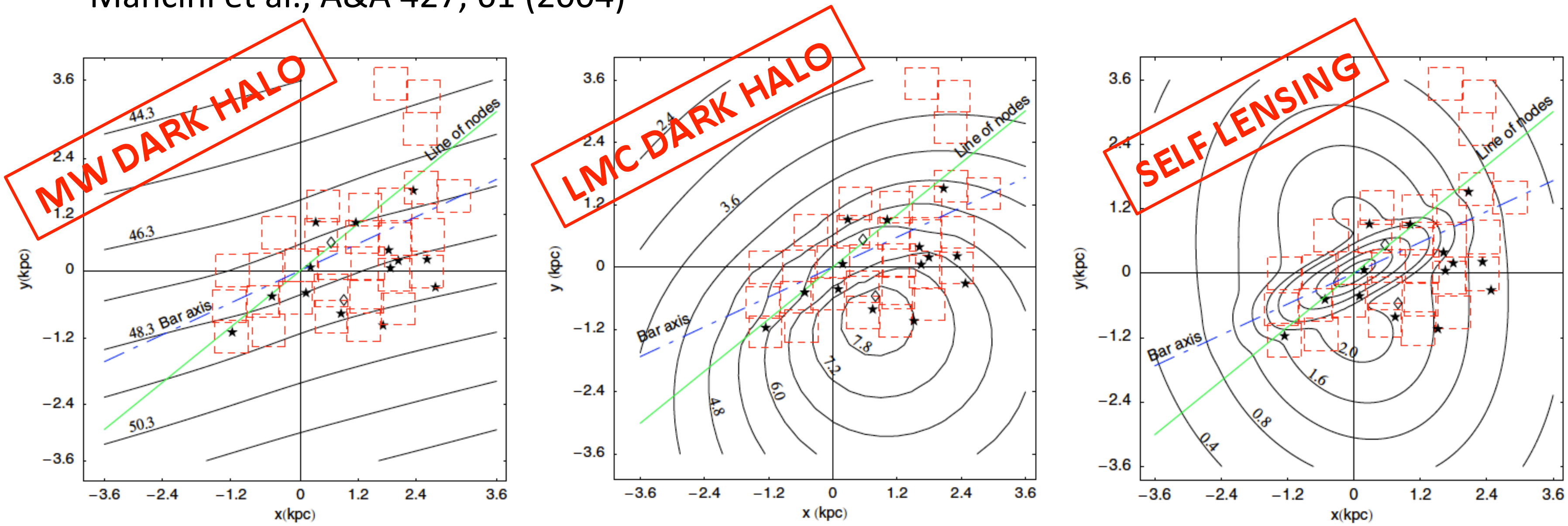


- It is therefore important to address the issue of the nature of the observed events, either to be attributed to MACHO lensing, self lensing or lensing due to other luminous population.
- Due to the limited number of events observed to date it is not yet clear which scenario or <u>combination</u> of scenarios explains the observed lensing.

Jetzer et al., A&A 393, 129 (2002)

- Each of these lens populations produces a signature in the **optical depth** as a function of position across the face of the LMC.

Mancini et al., A&A 427, 61 (2004)



- Considering the set of events reported by the MACHO collaboration we shown that, on the basis of both their number and characteristics (event duration and spatial distribution), they **cannot** all be attributed to self lensing.

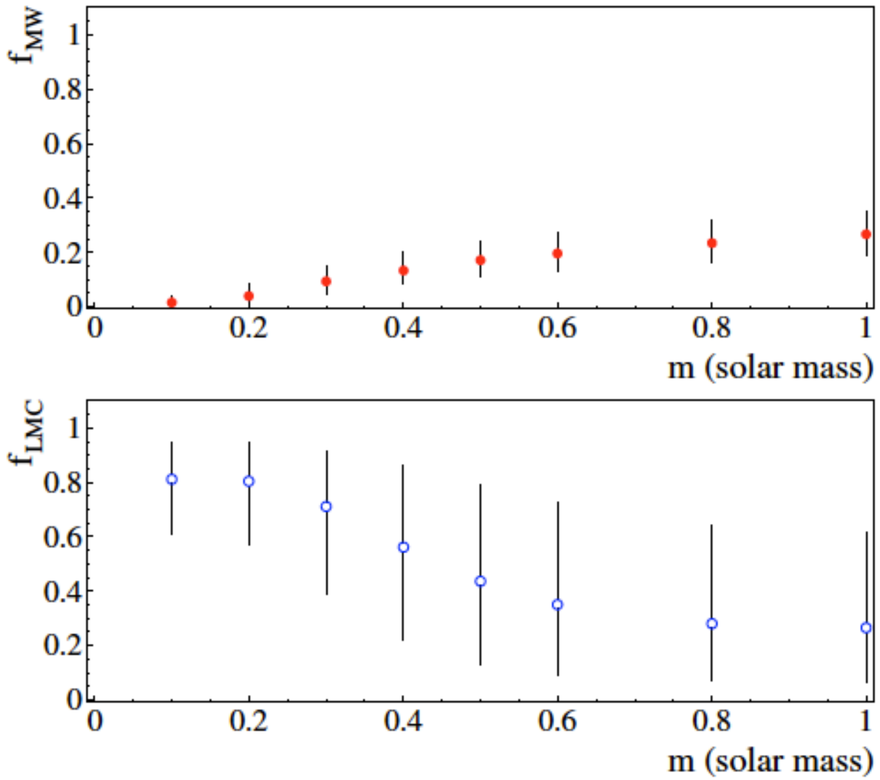
  Mancini et al., A&A 427, 61 (2004)

- Considering the set of events reported by the MACHO collaboration we shown that, on the basis of both their number and characteristics (event duration and spatial distribution), they cannot all be attributed to self lensing.

  Mancini et al., A&A 427, 61 (2004)

- We also considered the possible role played by the *LMC dark halo*, suggesting that the halo fraction in form of MACHOs for the Milky Way and the LMC might not be equal.

  Calchi Novati et al., A&A 459, 407 (2006)



Result of the likelihood analysis. Median value with 68%CL errors, as a function of the MACHO mass.

- We have also discussed the results of the **OGLE-II** towards LMC.

  The OGLE-II campaign sampled the <u>bar region</u> of the LMC only.

- We found an upper limit for the halo mass fraction in the form of MACHOs, at 95% CL, of about
  - 15% in the mass range $(10^{-2} - 10^{-1})\ M_{\odot}$ 26% for 0.5 $M_{\odot}$.

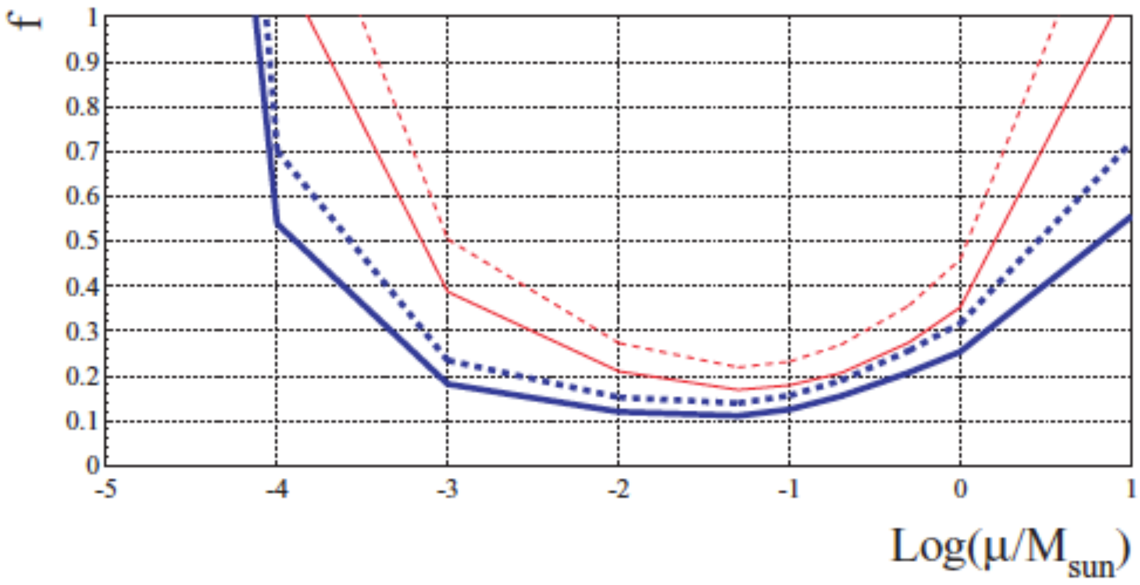
  The number of expected events from the luminous population is 1.5 (0.65)

  Calchi Novati et al., MNRAS 400, 1625 (2009)

<u>Likelihood analysis</u>

90% and 95% CL (solid and dashed lines) upper limits for the halo mass fraction in the form MACHOs.

The blue and red lines indicate the results for the *All and Bright sample of sources.*



- Here we want to discuss the results of the **OGLE-III** towards LMC.

- **OGLE-III**
  - 116 fields (40 square degrees)
  - ≈ 8 years (2001-2009)
  - 5.5 milions of stars *All sample* *Bright sample*
  - events 2 0

Wyrzykowski et al., MNRAS, in press (2010)

- **OGLE-II**
  - 21 fields (4.72 square degrees)
  - ≈ 4 years (1996-2000)
  - 35 milions of stars *All sample* *Bright sample*
  - events 2 0

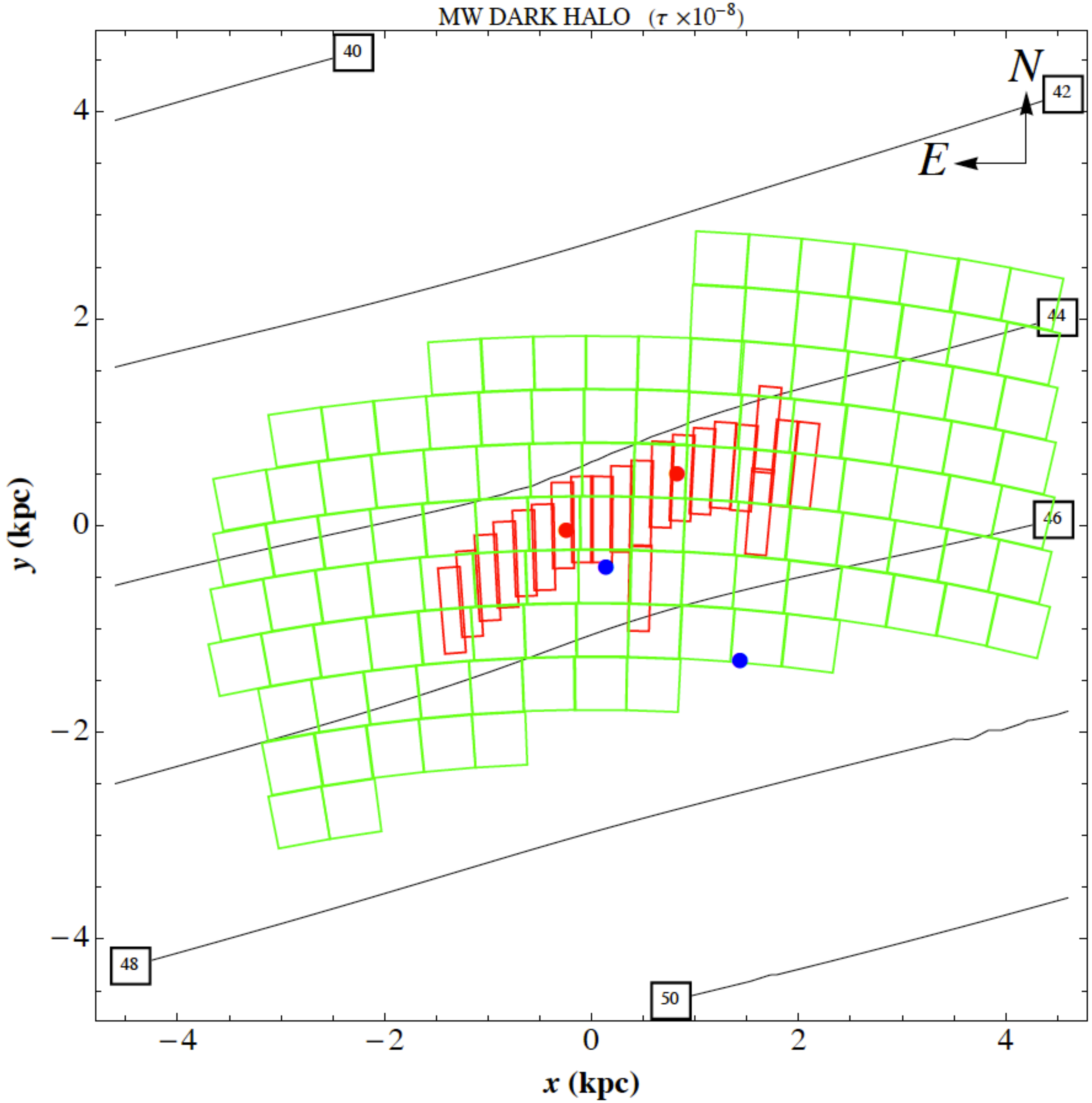
Wyrzykowski et al., MNRAS 397, 1228 (2009)

Models

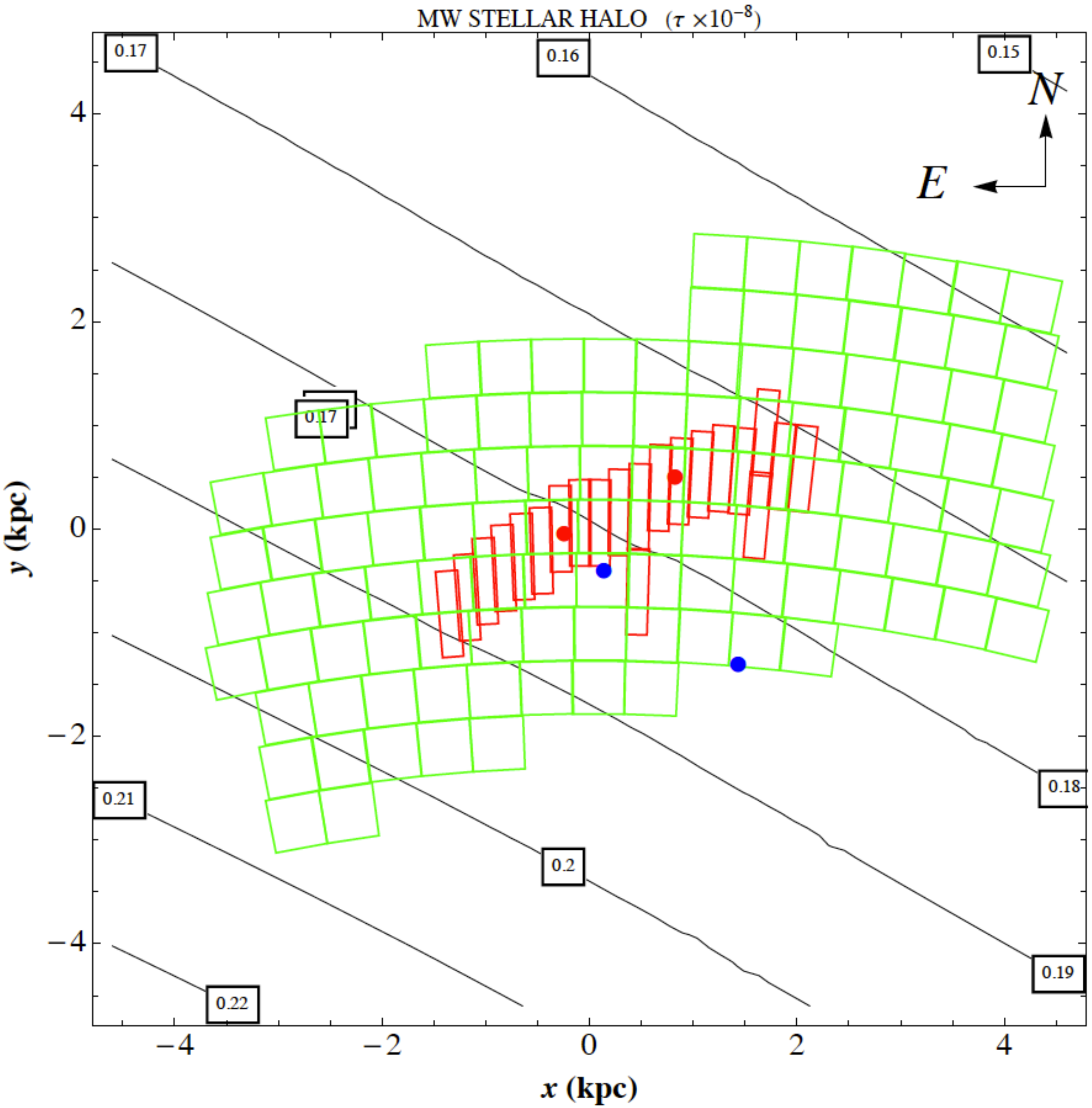
- We adopt the same models used in our previous analyses
  Mancini et al., A&A 427, 61 (2004)
  Calchi Novati et al., MNRAS 400, 1625 (2009)

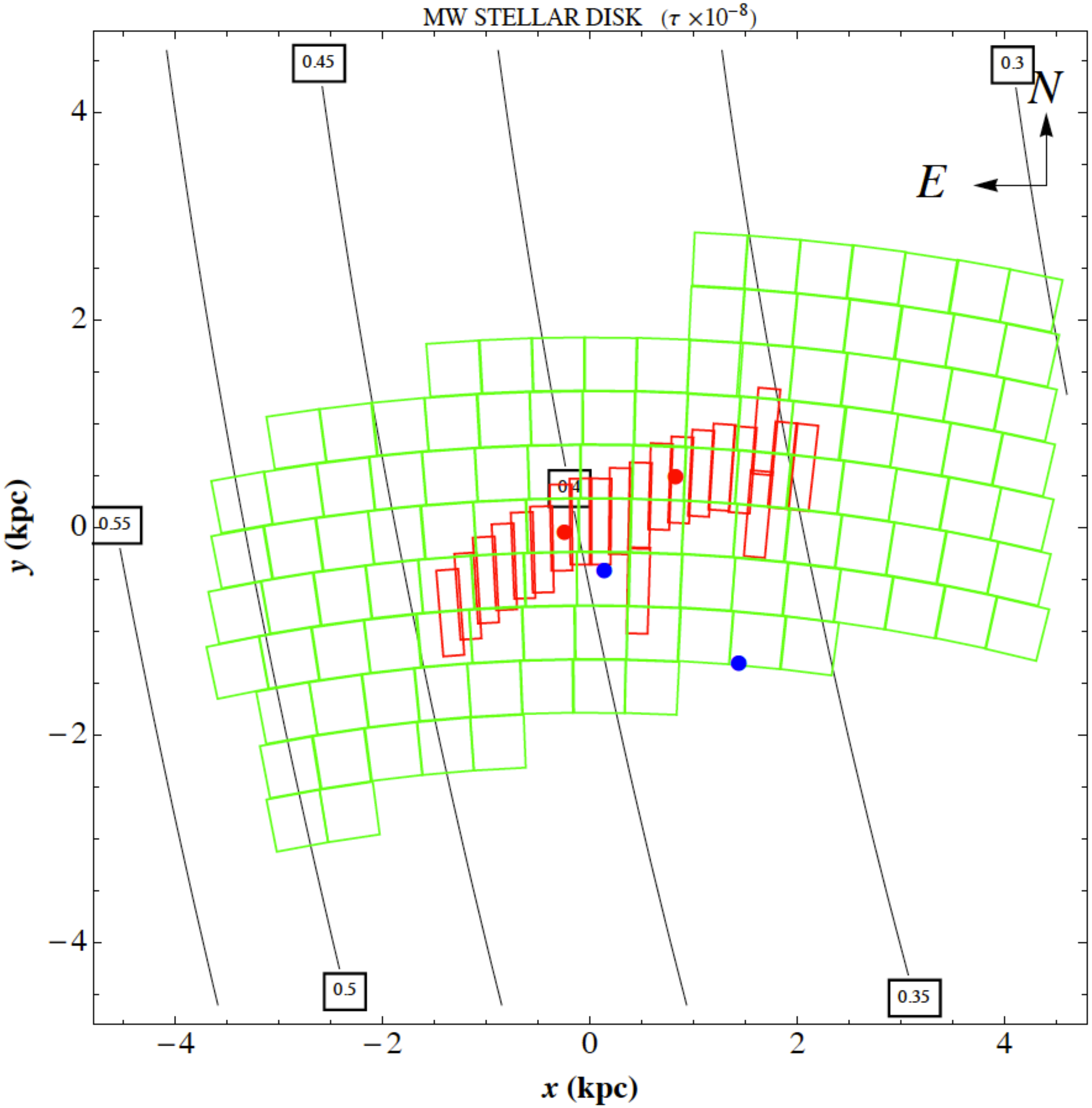
- For the LMC components (disk, bar, halo, dark halo), we based on the papers of van der Marel et al.
  van der Marel, AJ 122, 1827 (2001)
  van der Marel & Cioni, AJ 122, 1807 (2001)
  van der Marel et al., AJ 124,2639 (2002)

- For the MW componets (disk, bulge, halo, dark halo), we used "standard models".
  Alcock et al., ApJ 542, 281 (2000)
  Han & Gould A., ApJ, 592, 172 (2003)
  Calchi Novati et al., A&A 480, 723 (2008)

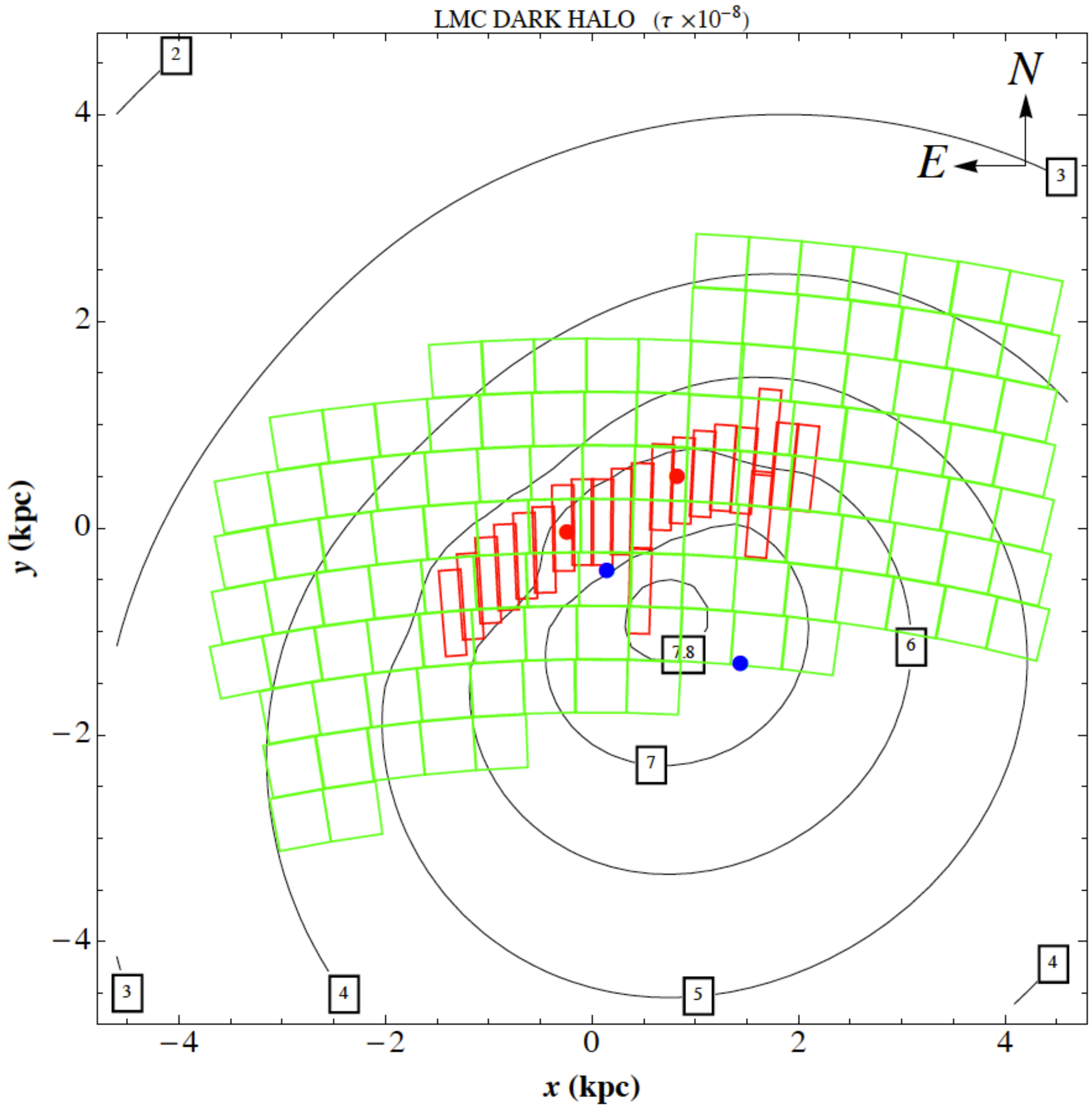


MW DARK HALO (τ ×10−8)
40
42
44
46
48
50
N
E
y (kpc)
x (kpc)
4
2
0
−2
−4
−4
−2
0
2
4

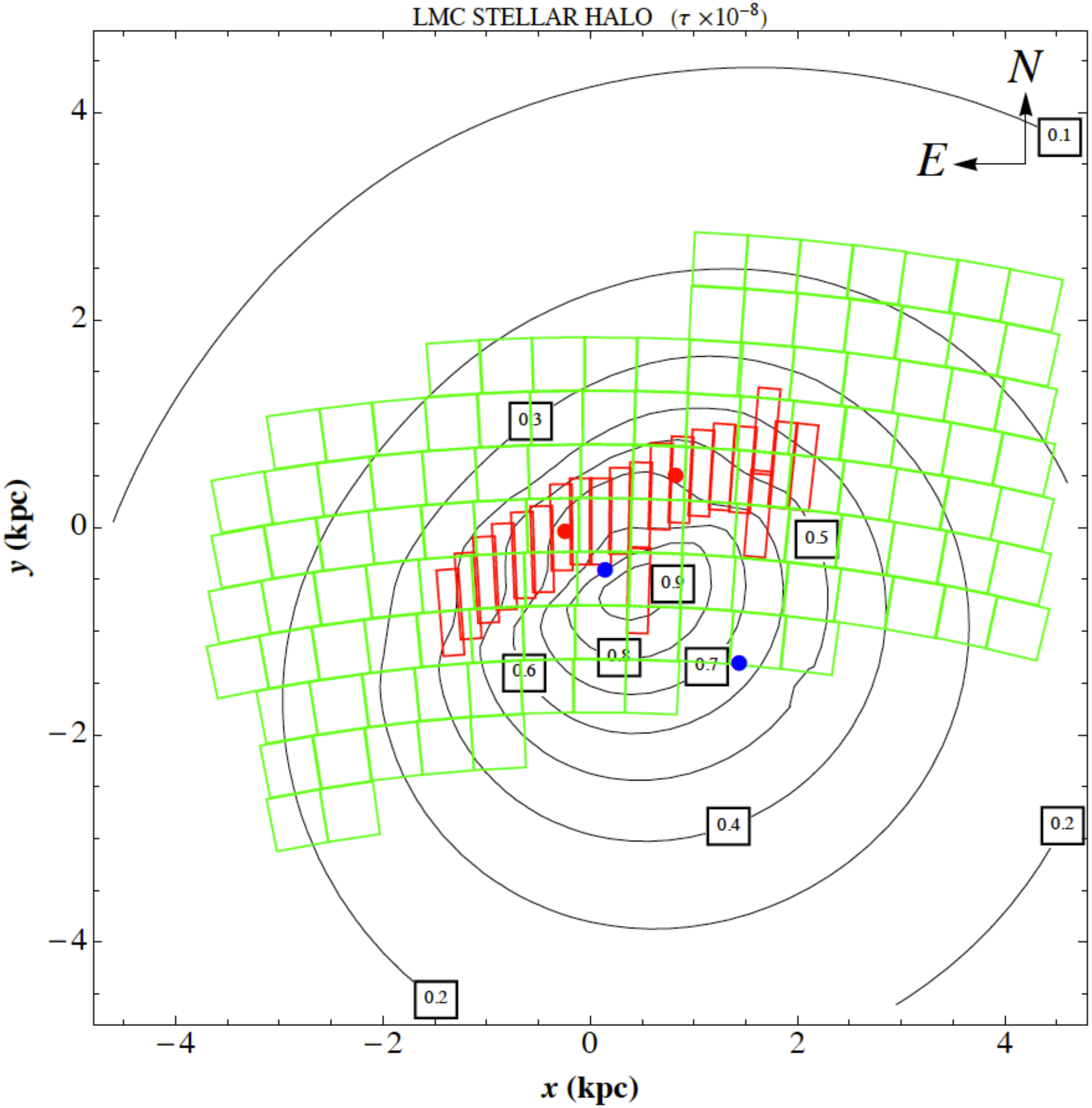

MW STELLAR HALO ($\tau \times 10^{-8}$)
0.17
0.16
0.15
N
E
0.17
0.18
0.21
0.2
0.19
0.22
4
2
0
−2
−4
y (kpc)
x (kpc)



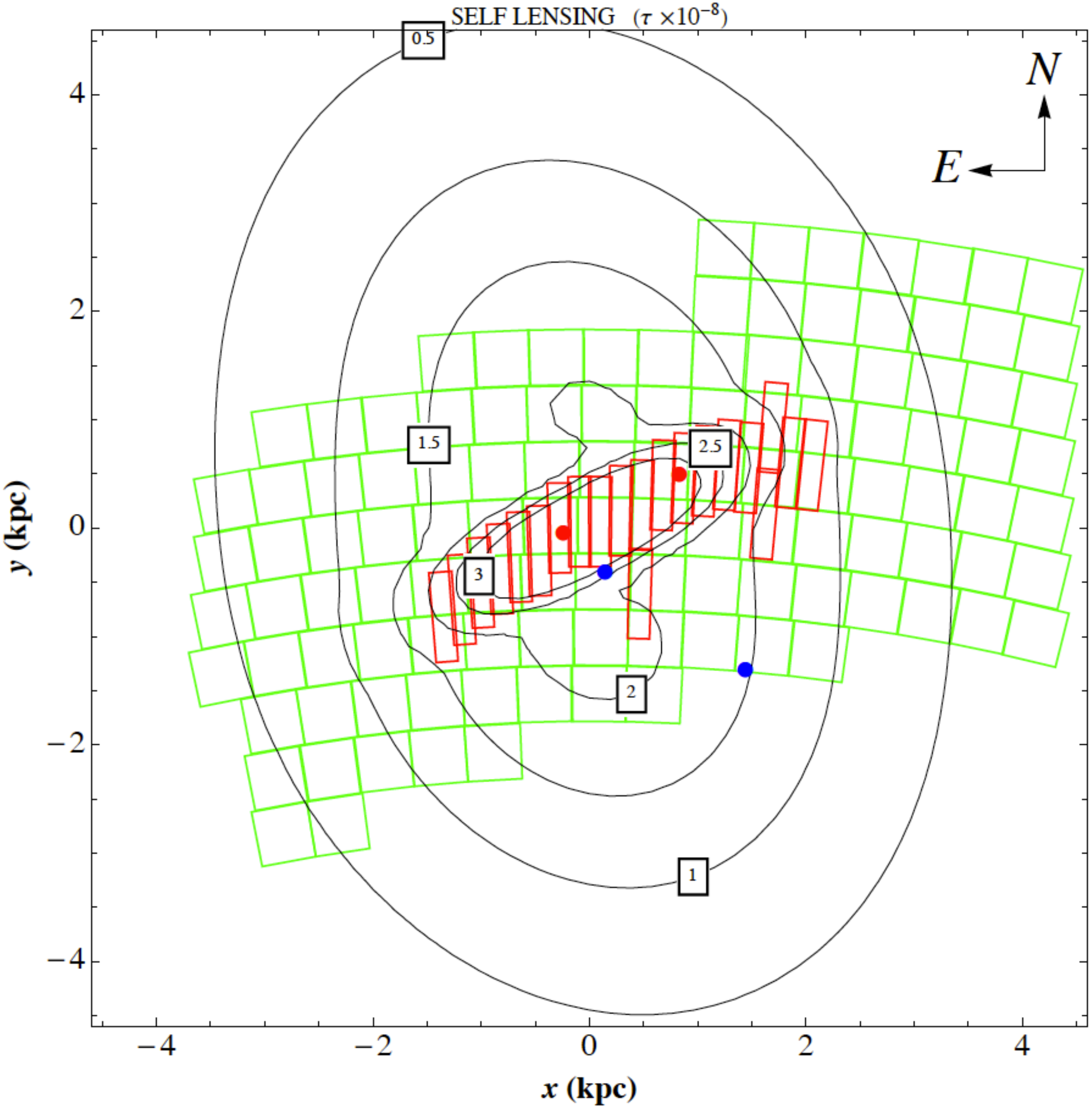
MW STELLAR DISK ($\tau \times 10^{-8}$)
0.45
0.3
N
E
0.4
0.55
0.5
0.35
y (kpc)
x (kpc)
4
2
0
−2
−4



LMC DARK HALO ($\tau \times 10^{-8}$)
N
E
2
3
3
4
4
5
6
7
7.8
4
2
0
−2
−4
−4
−2
0
2
4
x (kpc)
y (kpc)



LMC STELLAR HALO ($\tau \times 10^{-8}$)
N
E
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.2
y (kpc)
x (kpc)
4
2
0
−2
−4



SELF LENSING (τ ×10^−8)
0.5
1
1.5
2
2.5
3
N
E
y (kpc)
x (kpc)
4
2
0
−2
−4
−4
−2
0
2
4

OGLE-III expected number of events for the luminous populations

	n_{exp} (All sample)	n_{exp} (Bright sample)
LMC SELF LENSING	1.54	0.59
LMC STELLAR HALO	0.50	0.19
MW DISK	0.43	0.09
MW STELLAR HALO	0.24	0.17
TOTAL	**2.71**	**1.04**

OGLE-III expected number of events for the dark populations (0.5 $M_{\odot}$)

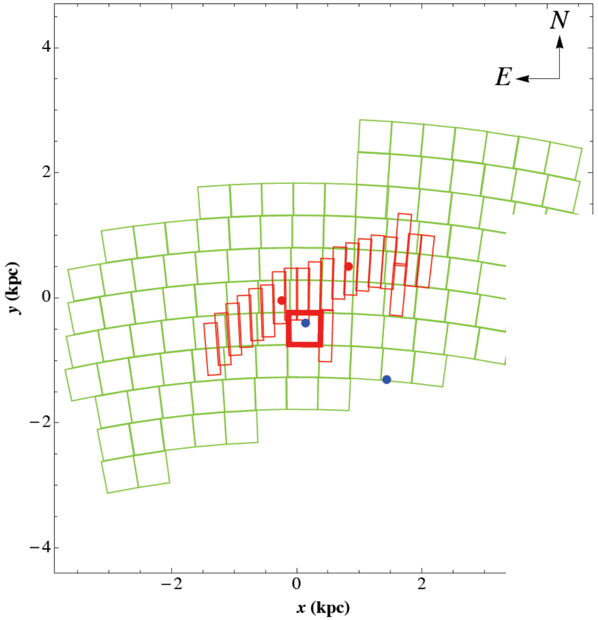
	n_{exp} (All sample)	n_{exp} (Bright sample)
MW DARK HALO	62.0	24.1
LMC DARK HALO	5.3	2.0

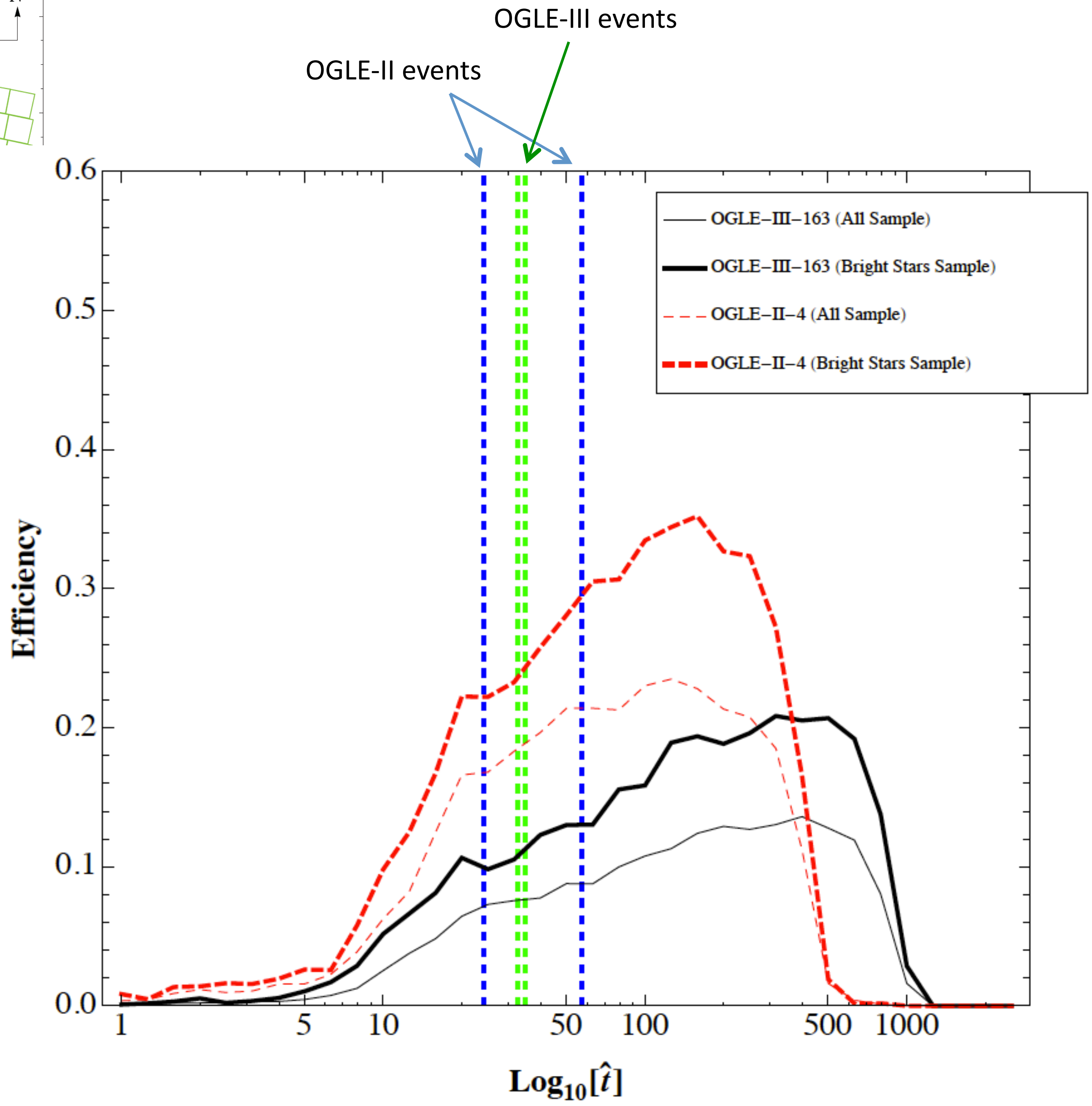
OGLE-III Vs. OGLE-II
expected number of events for the <u>luminous</u> populations

	OGLE-III n_{exp} (All sample)	OGLE-II n_{exp} (All sample)	OGLE-III n_{exp} (Bright sample)	OGLE-II n_{exp} (Bright sample)
LMC SELF LENSING	1.54	1.10	0.59	0.46
LMC STELLAR HALO	0.50	0.20	0.19	0.09
MW DISK	0.43	0.12	0.09	0.06
MW STELLAR HALO	0.24	0.07	0.17	0.03
TOTAL	**2.71**	**1.47**	**1.04**	**0.64**

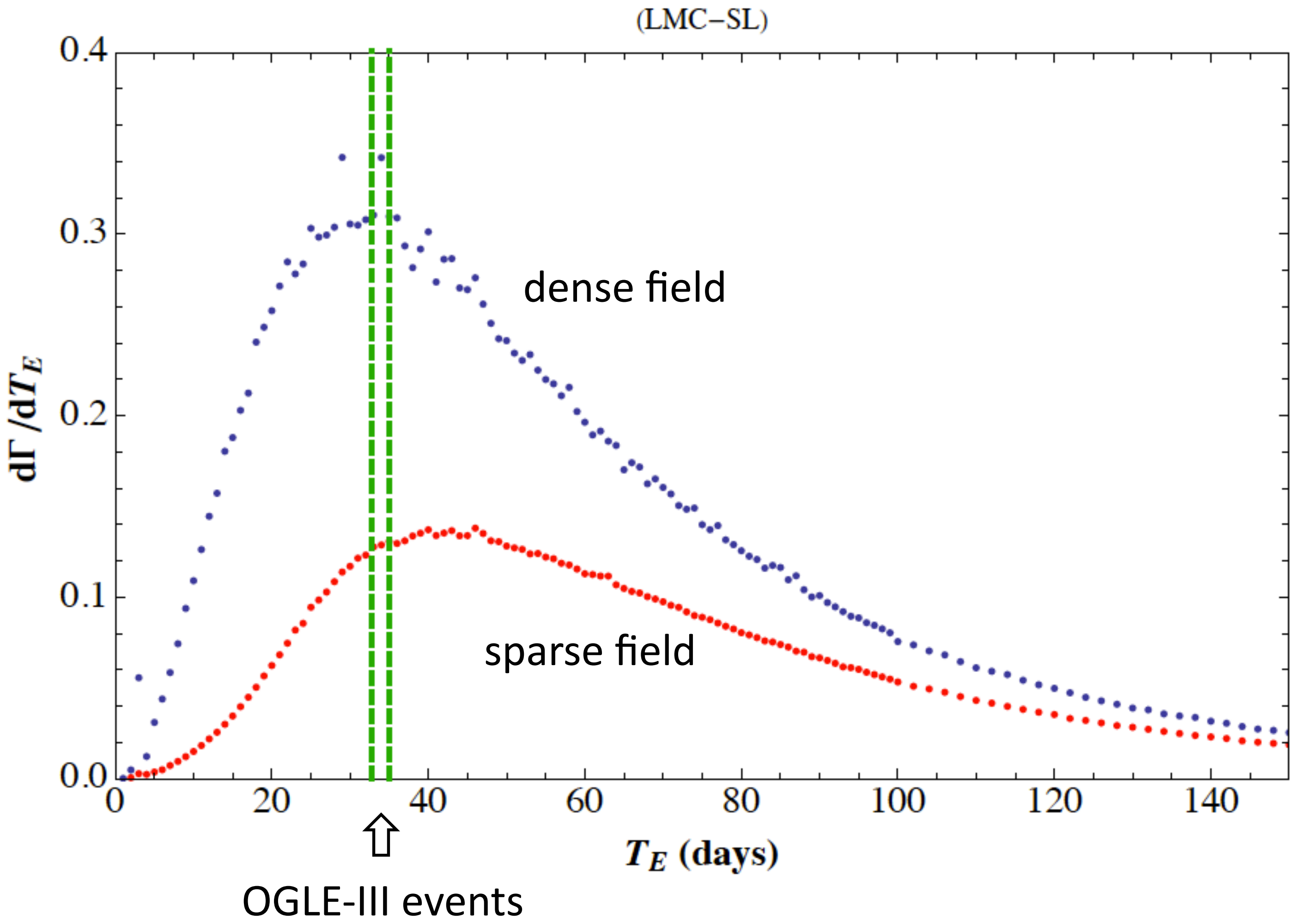
OGLE-III Vs. OGLE-II
expected number of events for the <u>dark</u> populations (0.5 $M_{\odot}$)

	OGLE-III n_{exp} (All sample)	OGLE-III n_{exp} (Bright sample)	OGLE-II n_{exp} (All sample)	OGLE-II n_{exp} (Bright sample)
MW DARK HALO	62.0	18	24.1	7.7
LMC DARK HALO	5.3	1.5	2.0	0.7


N
E
4
2
0
−2
−4
y (kpc)
−2
0
2
x (kpc)

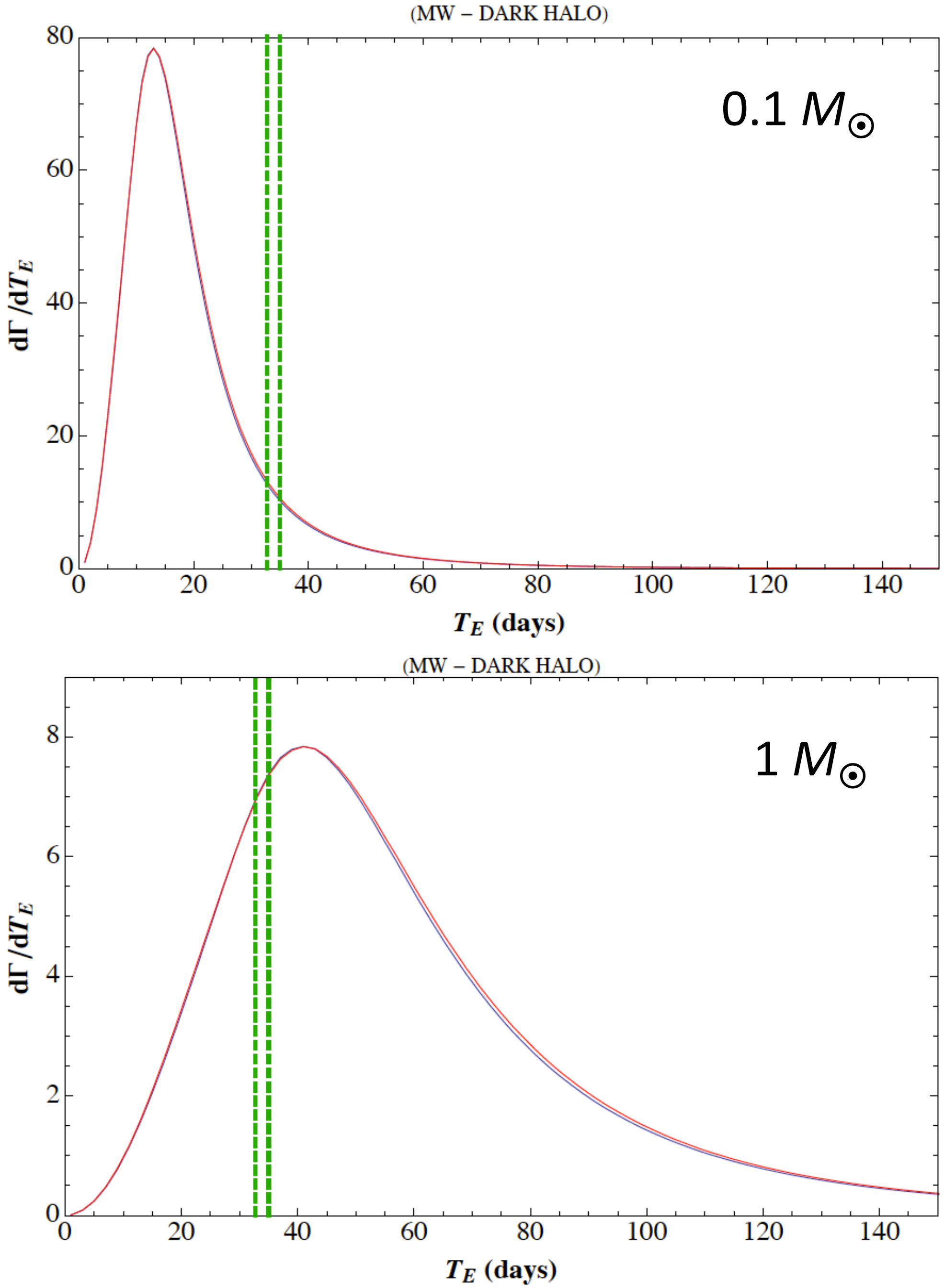

OGLE-III events
OGLE-II events
OGLE−III−163 (All Sample)
OGLE−III−163 (Bright Stars Sample)
OGLE−II−4 (All Sample)
OGLE−II−4 (Bright Stars Sample)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Efficiency
1
5
10
50
100
500
1000
$Log_{10}[\hat{t}]$

- Microlensing differential rate towards the LMC, corrected for the OGLE-III efficiency: LMC self lensing

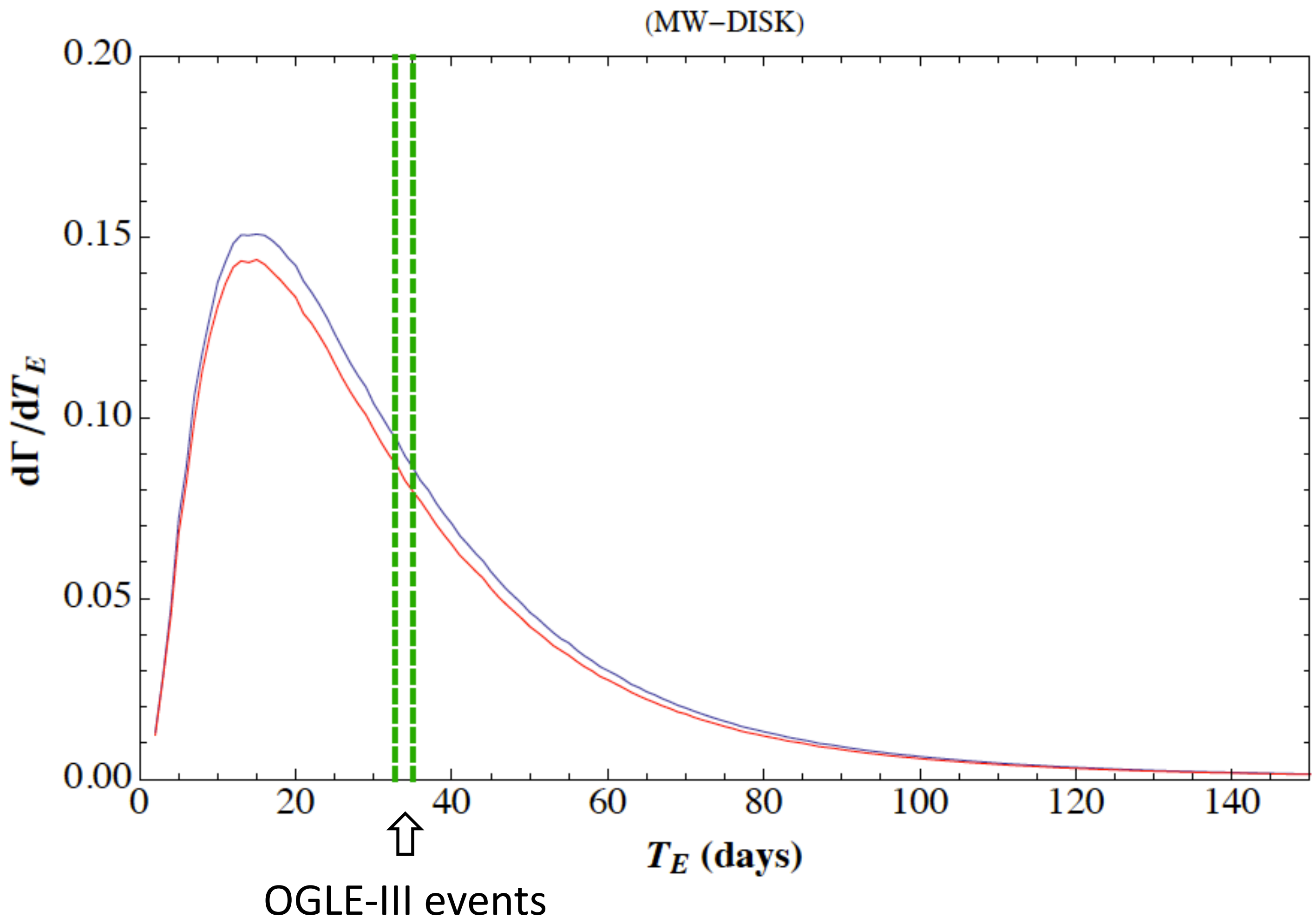


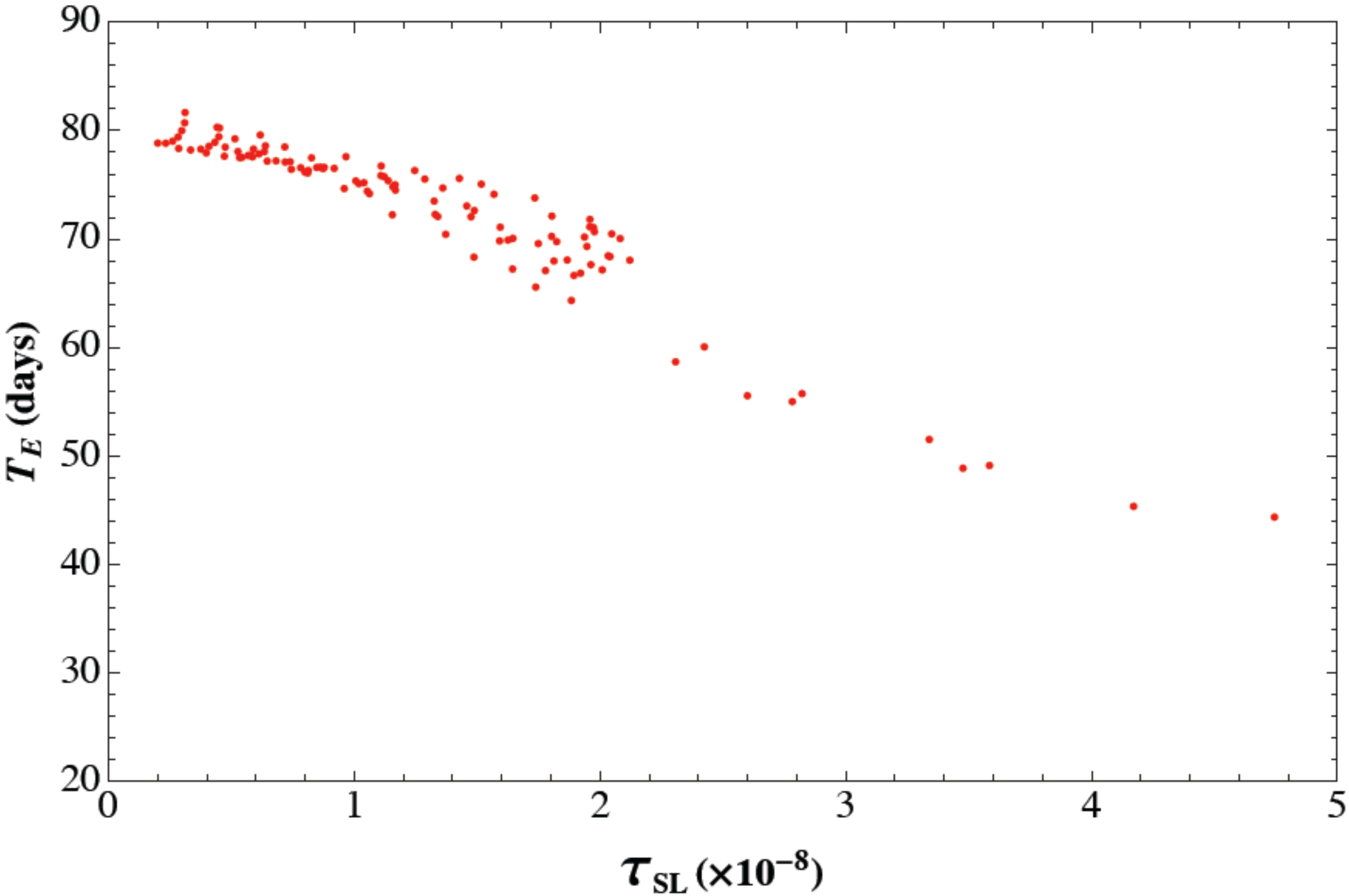
- Microlensing differential rate towards the LMC, corrected for the OGLE-III efficiency:

  Galactic dark matter halo

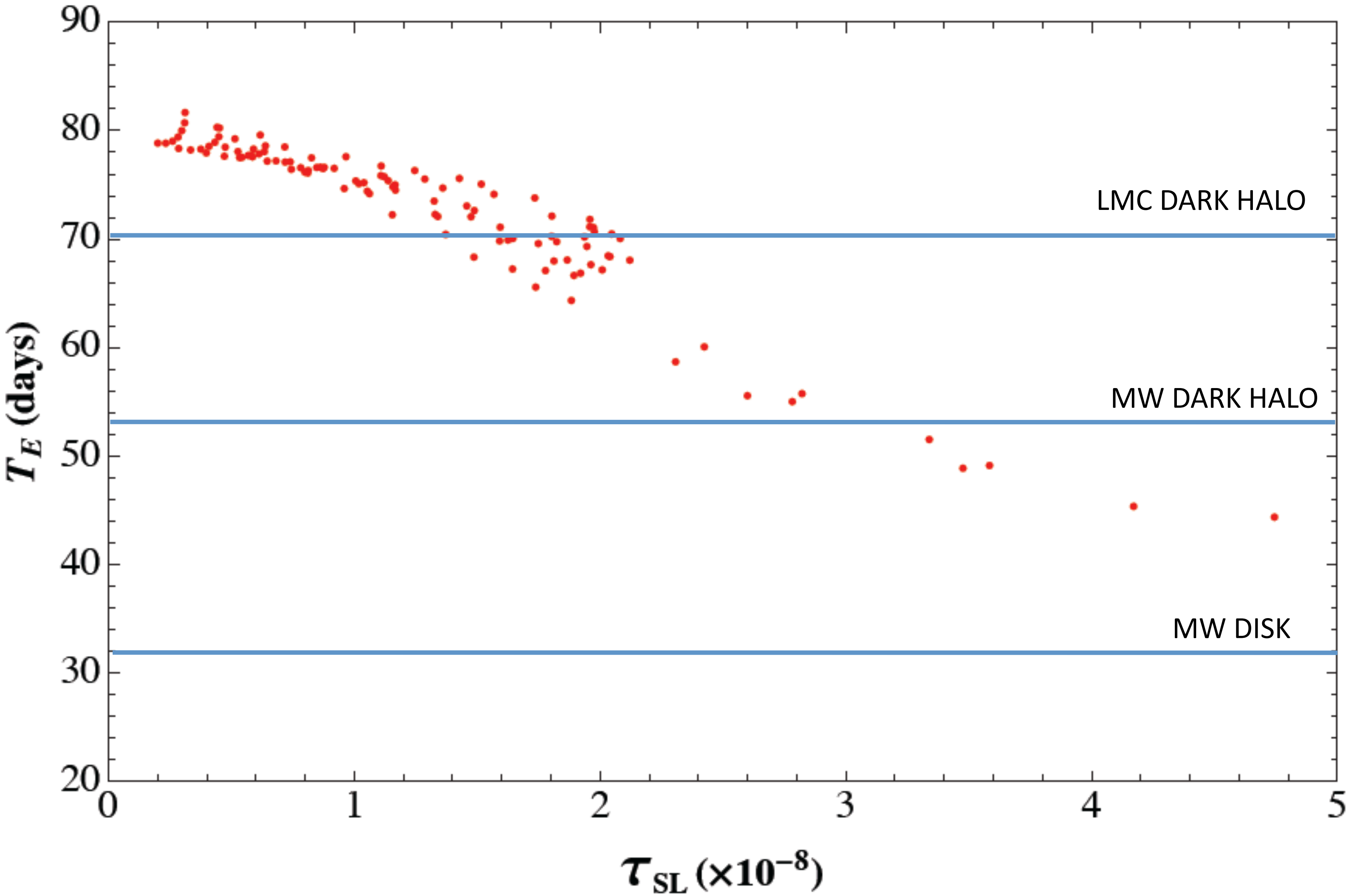


- Microlensing differential rate towards the LMC, corrected for the OGLE-III efficiency: MW disk

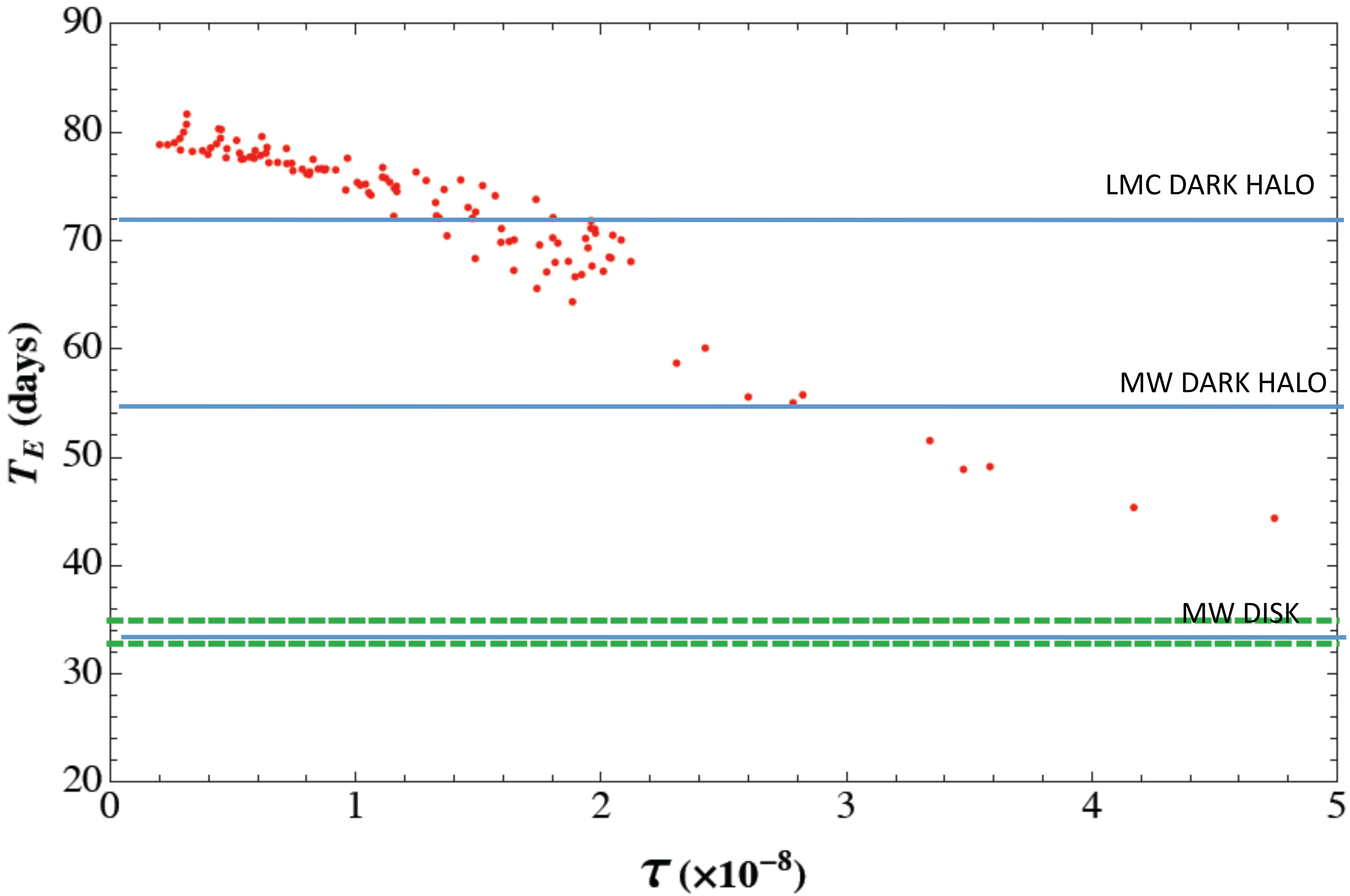




90
80
70
60
50
40
30
20
T_E (days)
0
1
2
3
4
5
τ_{SL} ($\times 10^{-8}$)



90
80
70
60
50
40
30
20
0
1
2
3
4
5
LMC DARK HALO
MW DARK HALO
MW DISK
T_E (days)
τ_{SL} ($\times 10^{-8}$)



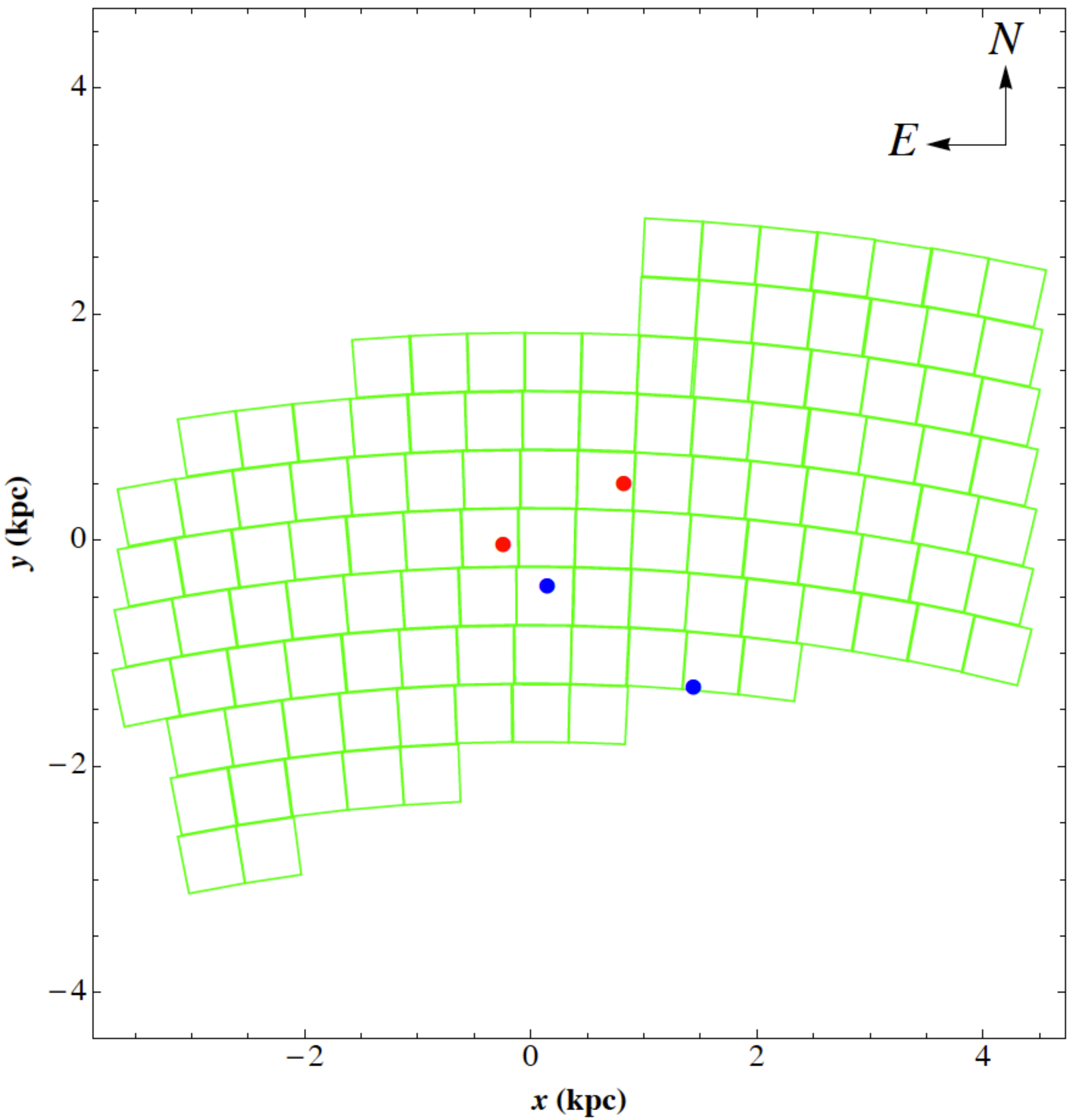
90
80
70
60
50
40
30
20
0
1
2
3
4
5
T_E (days)
τ ($\times 10^{-8}$)
LMC DARK HALO
MW DARK HALO
MW DISK

OGLE-III

- 116 fields

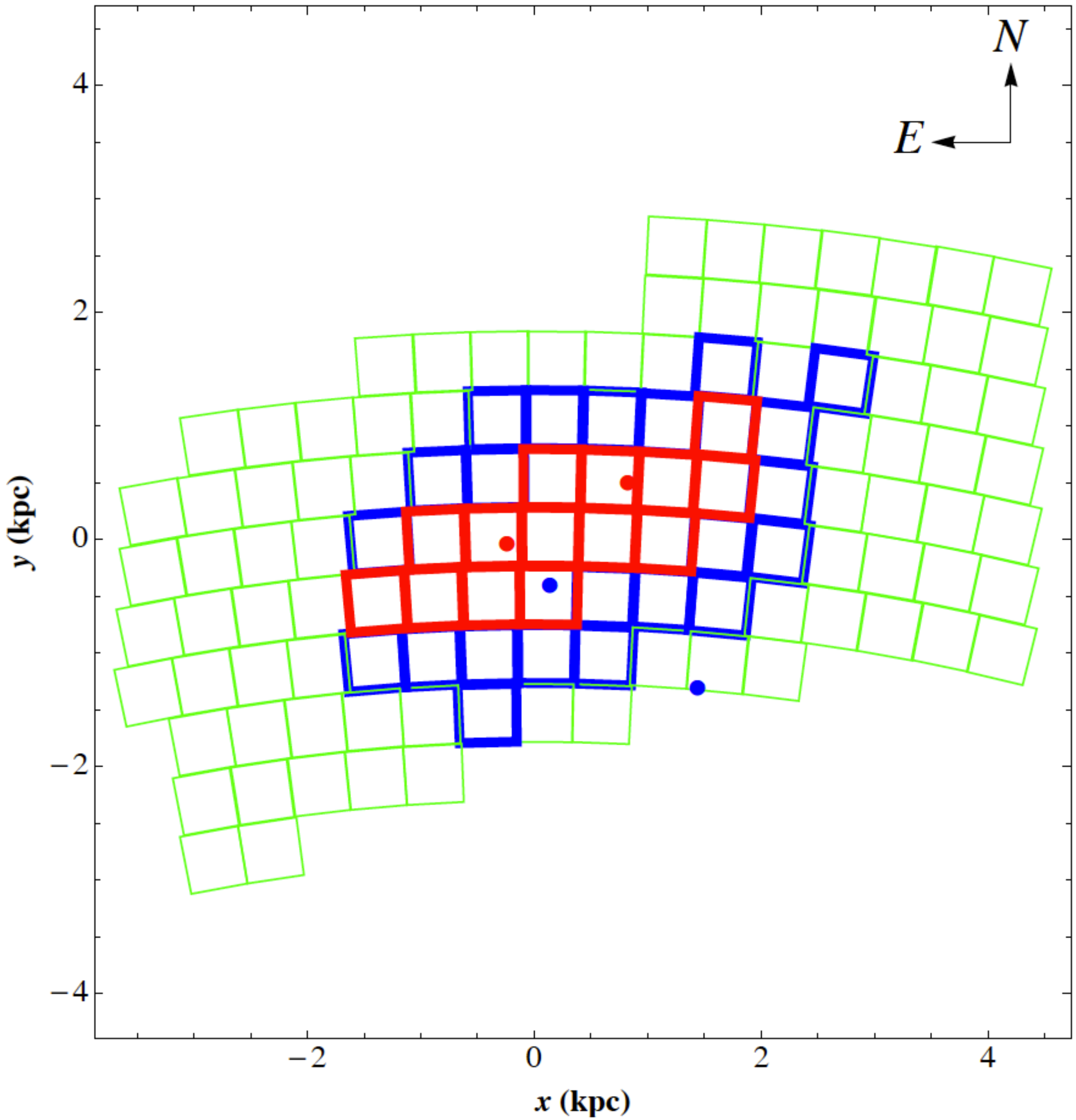
field-122 sparse

field-163 dense



OGLE-III

- 14 fields > 400×10^3 stars
- 22 fields < 400×10^3 stars
- <u>80 fields</u> < 200×10^3 stars



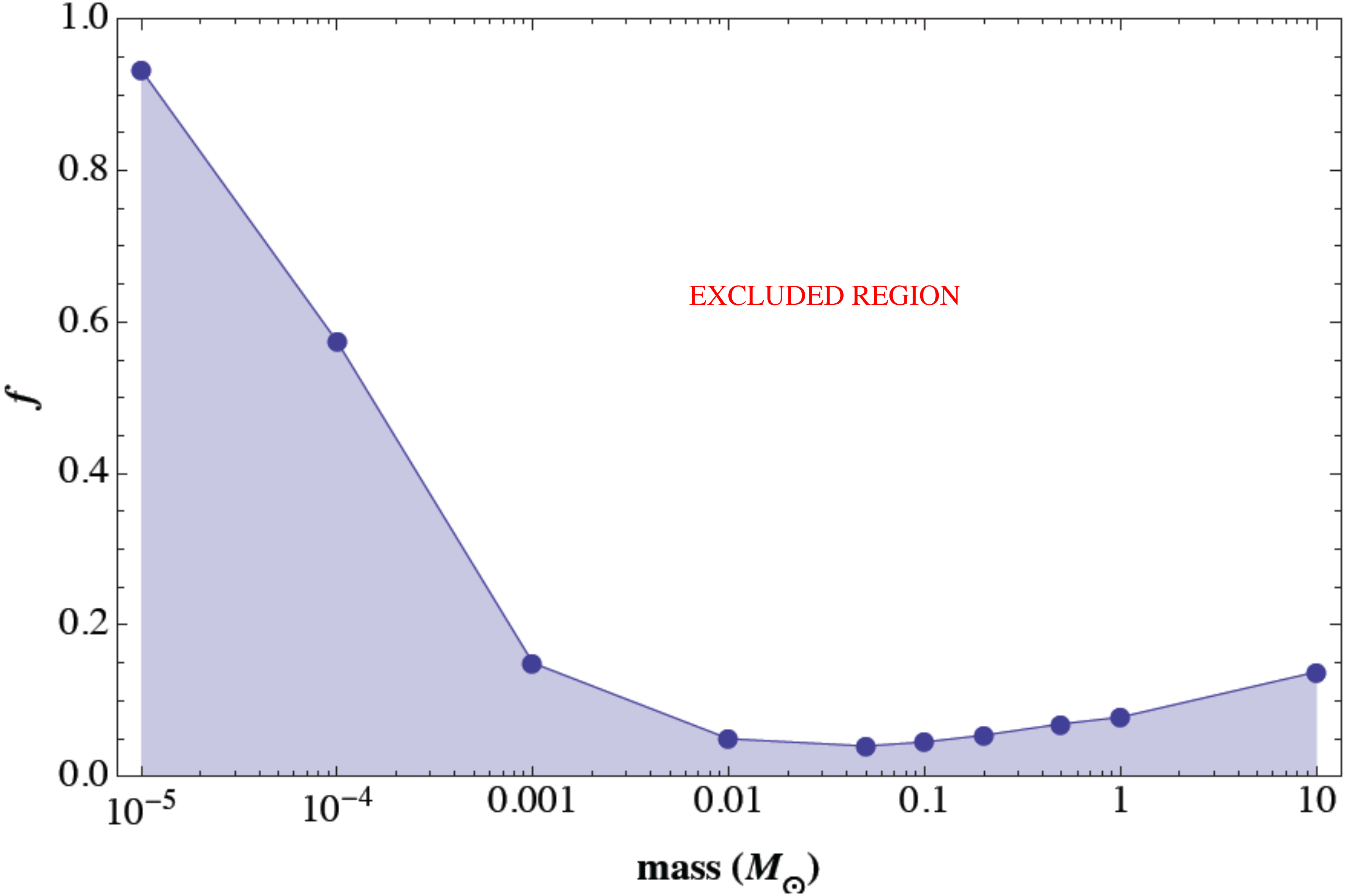
OGLE-III expected number of events for the luminous populations

	n_{exp} (14 fields)	n_{exp} (22 fields)	n_{exp} (80 fields)
LMC SELF LENSING	0.6	0.4	0.4
Other components	0.3	0.3	0.3

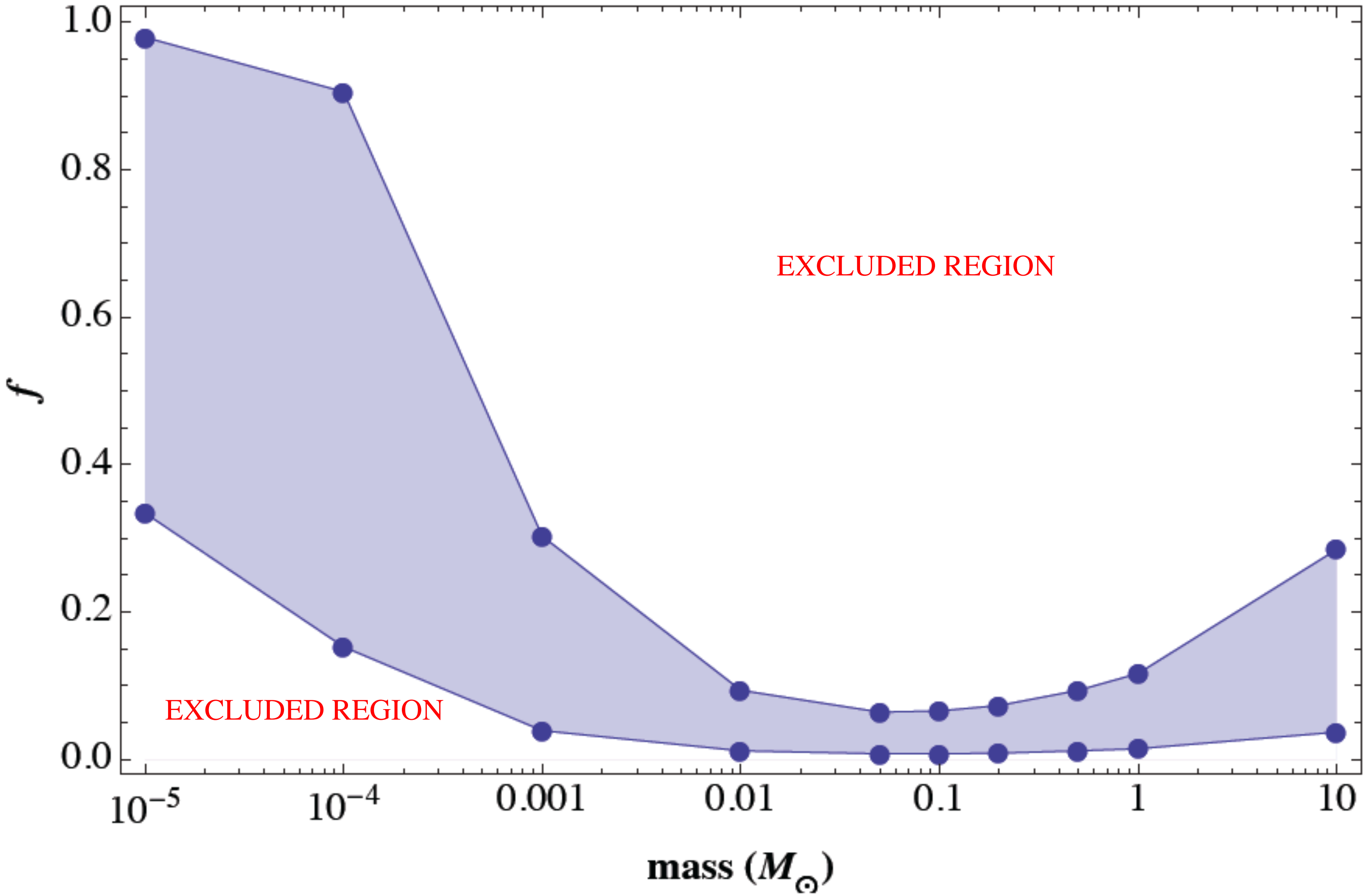
OGLE-III expected number of events for the dark populations (0.5 $M_{\odot}$)

	n_{exp} (14 fields)	n_{exp} (22 fields)	n_{exp} (80 fields)
MW DARK HALO	15	20	28
LMC DARK HALO	1.4	1.8	2.1

The line denotes 95% C.L. upper limits for the halo mass fraction in the form of compact halo objects **IF** the OGLE-III events are due to dark and luminous matter.



The lines denotes 95% C.L. limits for the halo mass fraction in the form of compact halo objects **IF** the OGLE-III events are due **only to dark matter**.



Conclusions

- The halo mass fraction in the form of MACHOs is very low (compatible with 0) for OGLE-III.
- The OGLE-III observed signal (2 events) is compatible with the expected signal from the luminous lens components, n_{exp} = 2.7

Conclusions

- The halo mass fraction in the form of MACHOs is very low (compatible with 0) for OGLE-III.
- The OGLE-III observed signal (2 events) is compatible with the expected signal from the luminous lens components, with n_{exp} = 2.7

⬇

SELF LENSING

Conclusions

- The halo mass fraction in the form of MACHOs is very low (compatible with 0) for OGLE-III.
- The OGLE-III observed signal (2 events) is compatible with the expected signal from the luminous lens components, with $n_{exp} = 2.7$

↓

SELF LENSING

- However, the typical duration for LMC self-lensing is of 50 days, whereas
  - OGLE-LMC-03 $T_E = 34.97$ days
  - OGLE-LMC-04 $T_E = 32.76$ days

- The duration and the position of OGLE-LMC-03 are compatible with a lens in the disk of the Milky Way.

Models: the LMC

- The disc and the bar are considered to be centred in the same position at a distance of D = 50.1 kpc.
- We assume a bar mass of M_{bar} = 1/5 M_{disc}, with a total visible mass in disc and bar of $M_{bar} + M_{disc} = 2.7\times10^9\ M_\odot$

  Sahu, PASP 106, 942 (1994)

  Gyuk et al., ApJ 535, 90 (2000)

  van der Marel et al., AJ 124,2639 (2002)
- The shape of the LMC disc is elliptical, with an inclination angle of 34°.
- The disc vertical distribution is described by a sech^2 function, with a flaring height scale of about 0.3 kpc.
- We use a scale length for the disc exponential planar distribution of 1.54 kpc, and a boxy-shaped bar (Zhao & Evans 2000) with length and height scale of 1.2 and 0.44 kpc, respectively.

  Zhao & Evans, ApJ 545, L35 (2000)

Models: the LMC

- For the velocity distribution, we assume a Gaussian isotropic profile with line-of-sight velocity dispersion of 20.2 km/s for disc stars (acting both as sources and lenses) and 24.7 km/s (Cole et al. 2005) for bar stars (sources and lenses)

  van der Marel et al., AJ 124,2639 (2002)

  Cole et al., AJ 129, 1465 (2005)

  Mancini, A&A 496, 465 (2009)

- For the lens mass function we use a broken power law

$$\xi(\mu_1) \propto \mu_1^{-\alpha}$$

- with α equal to
  - 1.3 in the mass range (0.08,0.5) $M_\odot$
  - 2.3 in the mass range (0.5,1) $M_\odot$
  - 4.5 for $\mu_l > 1$ $M_\odot$

  Kroupa, Science, 295, 82 (2002)

  Kroupa, Lecture Notes in Physics. Vol. 760 (2008)

Models: the LMC

- The total dynamical mass of the LMC, $8.7\times10^{9}\ M_{\odot}$, as compared to the luminous components, requires that more than half of it be comprised in a dark matter halo component

  van der Marel et al., AJ 124,2639 (2002)

- To study the possible contribution of LMC MACHO objects to the lensing signal, we assume an isothermal spherical density profile with core radius of 2 kpc and a velocity dispersion of 46 km/s

  Alcock et al., ApJ 542, 281 (2000)

  van der Marel et al., AJ 124,2639 (2002)

Models: the Milky Way

- Along the line of sight towards the LMC, the Milky Way provides two further luminous lens populations: the disc and the stellar halo.

- For the disc density distribution, we use a length-scale for the exponential profile of 2.75 kpc and a height scale ($sech^2$ model) of 0.25 kpc.

  Han & Gould A., ApJ, 592, 172 (2003)

  Calchi Novati et al., A&A 480, 723 (2008)

- For the mass function we use as a power law, including the brown dwarf mass range

  Kroupa, Science, 295, 82 (2002)

- We use a Gaussian isotropic velocity distribution with line-of-sight velocity dispersion of 30 km/s.

Models: the Milky Way

- For the MW stellar halo we consider stars up to a mass of 0.9 $M_\odot$, and we use a mass distribution with a

$$\rho \propto r^{-3}$$

radial profile (flattening 0.6) and line-of-sight velocity dispersion of 120 km/s

Chabrier, PASP 115, 763 (2003)

Helmi, A&AR 15, 145 (2008)

- For the dark matter Halo, we use the "standard" isothermal spherical density profile with core radius of 5 kpc, local density of 7.9×10^6 $M_\odot/\mathrm{kpc}^3$, and a line-of-sight velocity dispersion of 155 km/s.
- For the mass of MACHOs, we consider a set of delta function in the mass range (10^{-5}–10) $M_\odot$.

Alcock et al., ApJ 542, 281 (2000)