

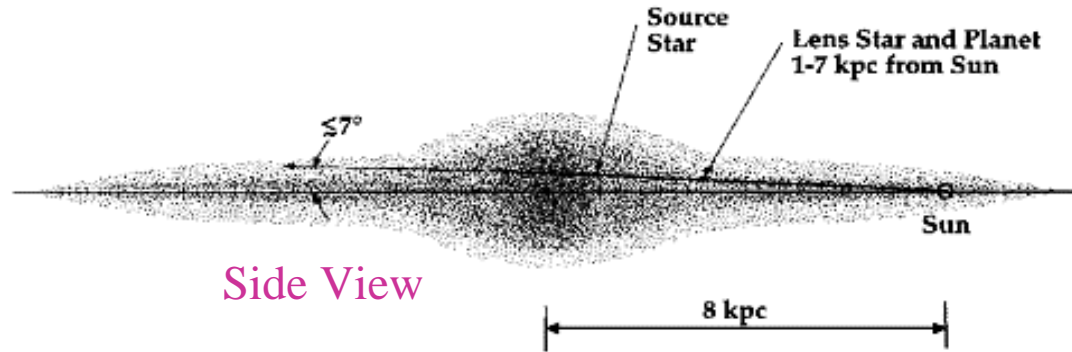
Ground Based Gravitational Microlensing Searches for Extra-Solar Terrestrial Planets

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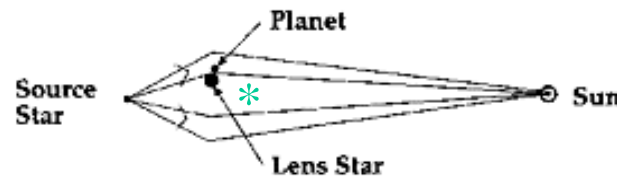
Abstract: A gravitational microlensing terrestrial planet search can be pursued best with a space telescope such as the GEST because of a few small numbers: the small microlensing probability, the low mass of the planets, and non-repeatability of microlensing planetary signals. Ground-based schemes are fundamentally constrained by the limited angular resolution and incomplete coverage of the microlensing light curves. In order to quantify the limitations of the ground-based programs, we study a realistically optimal case: dedicated VISTA with the wide field imager.

The gravitational microlensing signals of terrestrial planets are visible only in the light curves of main sequence stars. These stars are very crowded in the dense central Galactic bulge fields that are the prime target fields because of the enhanced microlensing rate and the line of sight through the Galactic disk. Nevertheless, it is possible to detect the gravitational microlensing signals of some terrestrial planets in light curves measured from excellent observing sites such as Paranal. However, the full duration of the planetary microlensing signals of Earth mass planets is about 1-day, and the lightcurves measured from a Paranal survey do not allow an unmistakable identification of the planetary nature of the signals nor a measurement of the planetary parameters. For a small subset of very short or high magnification events, it is possible to fully characterize the planetary deviations, but the overall sensitivity of these ground based surveys is only about 1% of that of a space based survey. The ground based surveys also have no sensitivity to the planetary abundance as a function of separation.

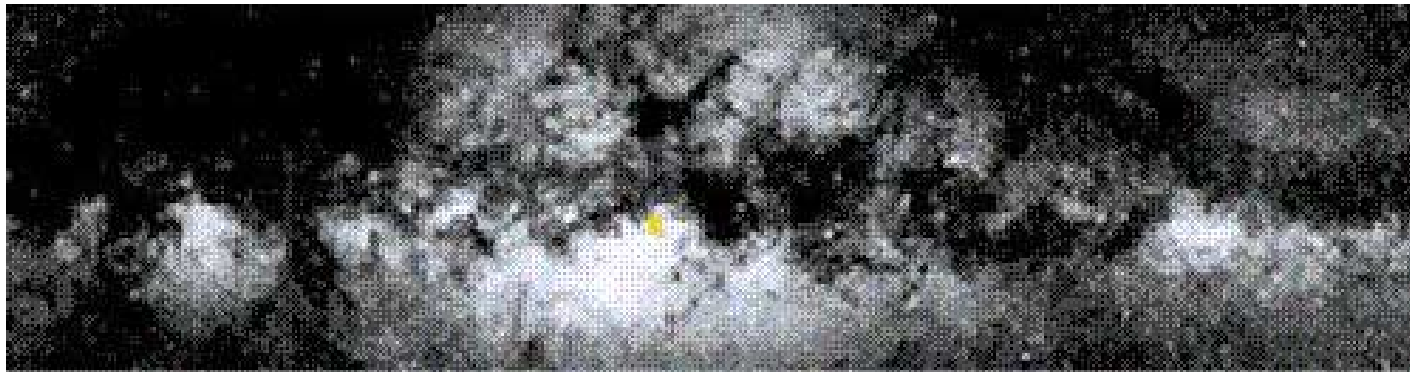
The Galactic Bulge is the Microlensing Planet Search Target Field



Side View

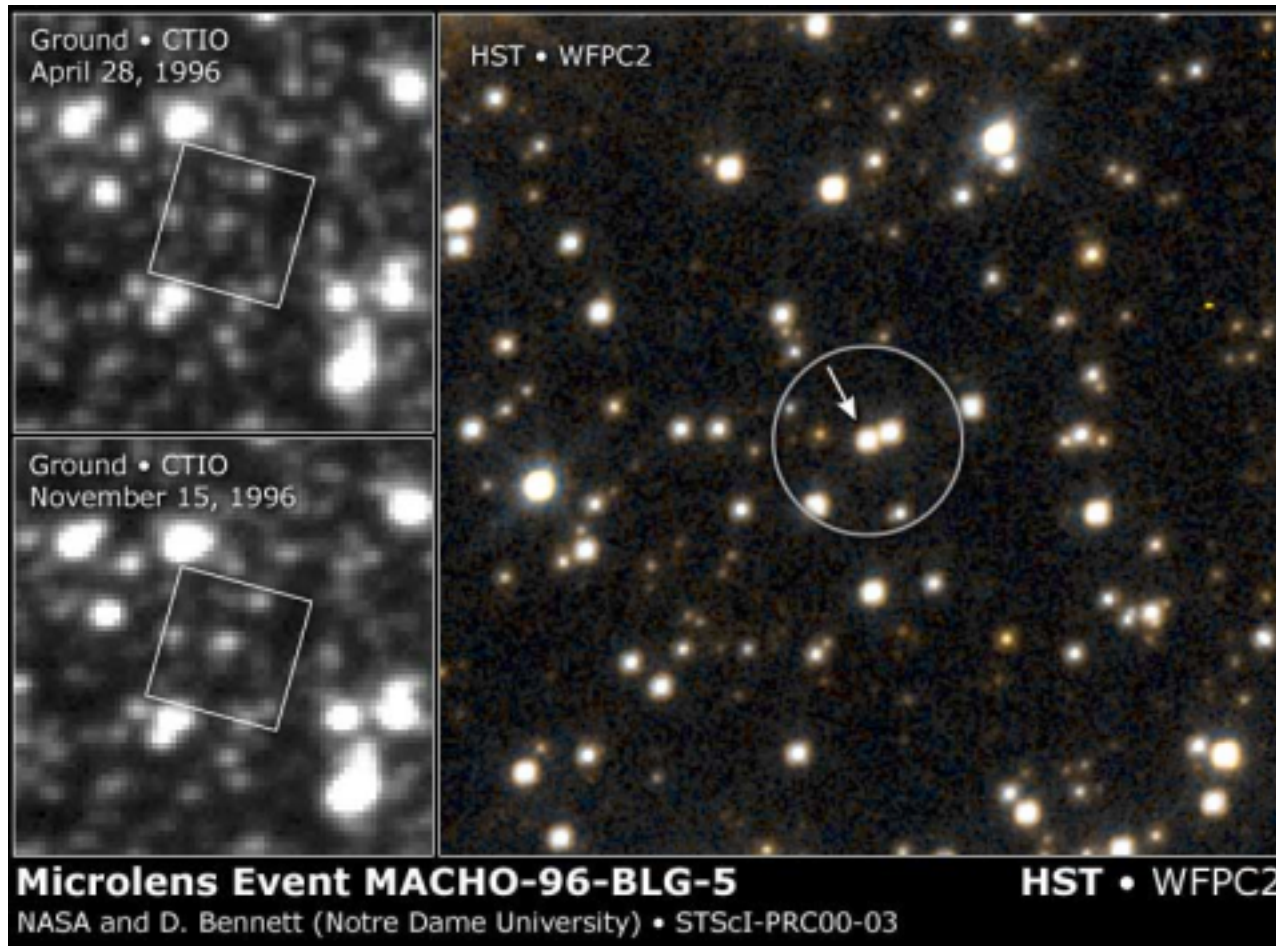


*binary lenses produce 3 or 5 images - not 4



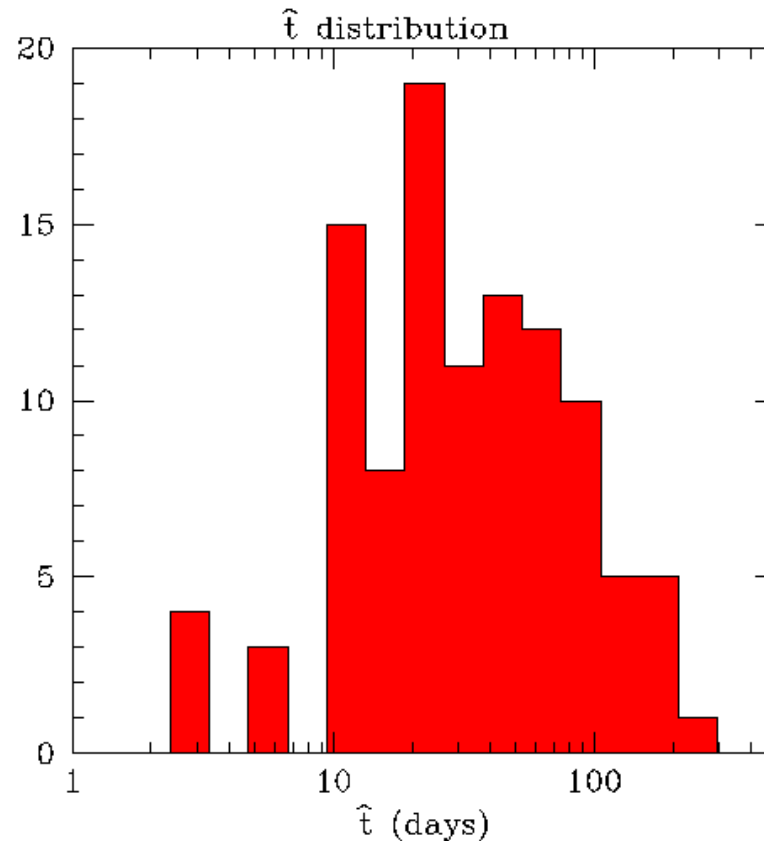
Optical view of the Galactic bulge. The central Galactic bulge has the largest microlensing probability and the highest density of source stars of any Galactic star field.

High Angular Resolution



A typical Galactic bulge microlensing field seen from the ground and space: On the left are CTIO 36" images in 1" seeing and on the right is an HST image of the squared area. The circle in the HST image indicates the 1" seeing circle. Since the microlensing beam size is small (~ 1 mas), only one (indicated) of the stars is lensed, and the blended light from the neighboring stars reduces the apparent lensing amplification and adds photon noise. Blending is a ubiquitous feature of the crowded central Galactic bulge fields, but it was not fully appreciated in some early estimates of the sensitivity of gravitational microlensing planet search programs. Blended main sequence stars had been misidentified as ~ 2 mag brighter "turn-off" stars.

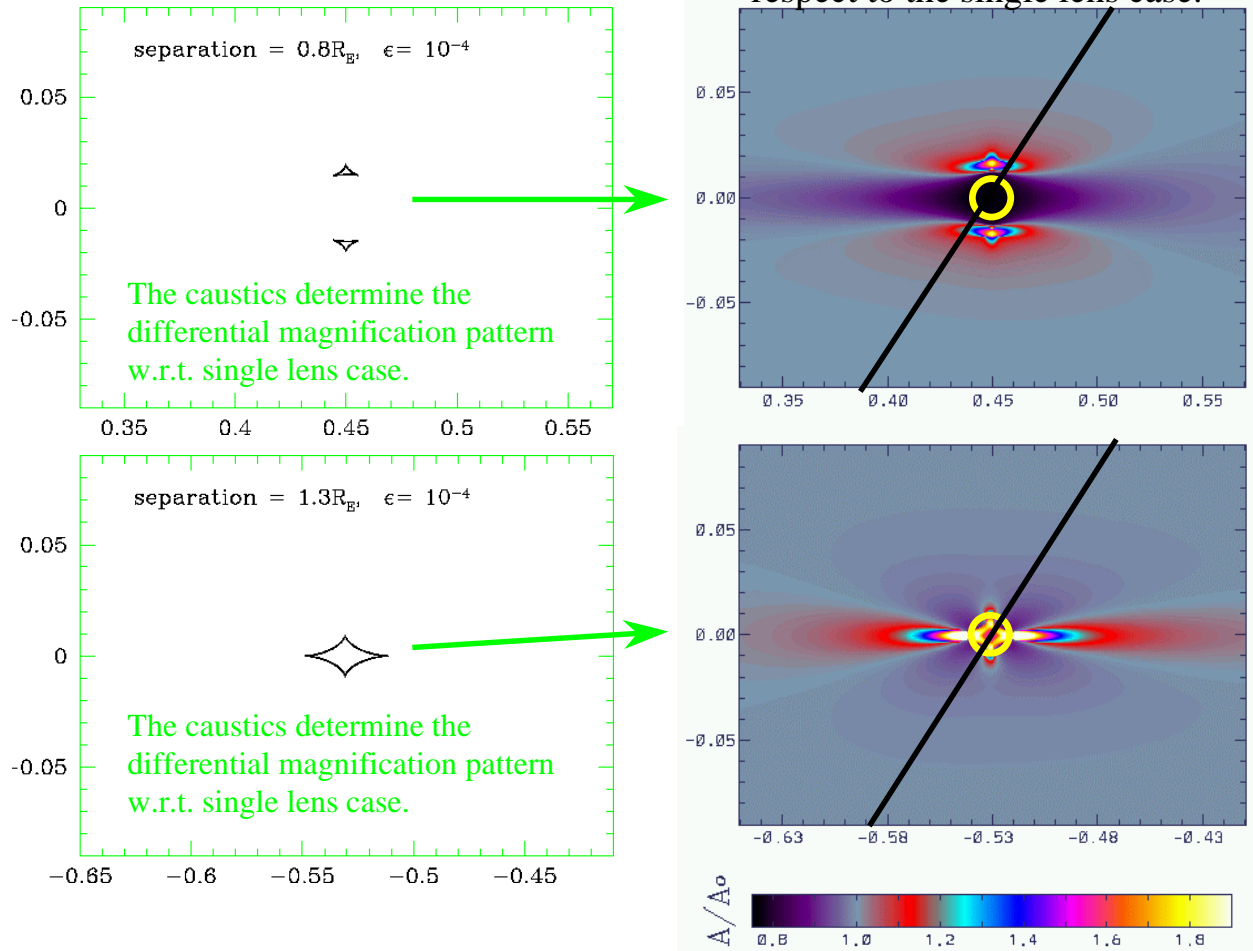
Timescales of Microlensing Events



The histogram above shows the event timescale distribution for stellar microlensing events observed by the MACHO Collaboration. The median Einstein Ring diameter crossing time is about 40 days and this scales as $M^{1/2}$, so for an Earth mass planet, 10^{-5} of a typical stellar mass, the Einstein Ring diameter crossing time is 300 times smaller: 3.2 hours.

Timescales of Planetary Deviations

Differential magnification patterns with respect to the single lens case:

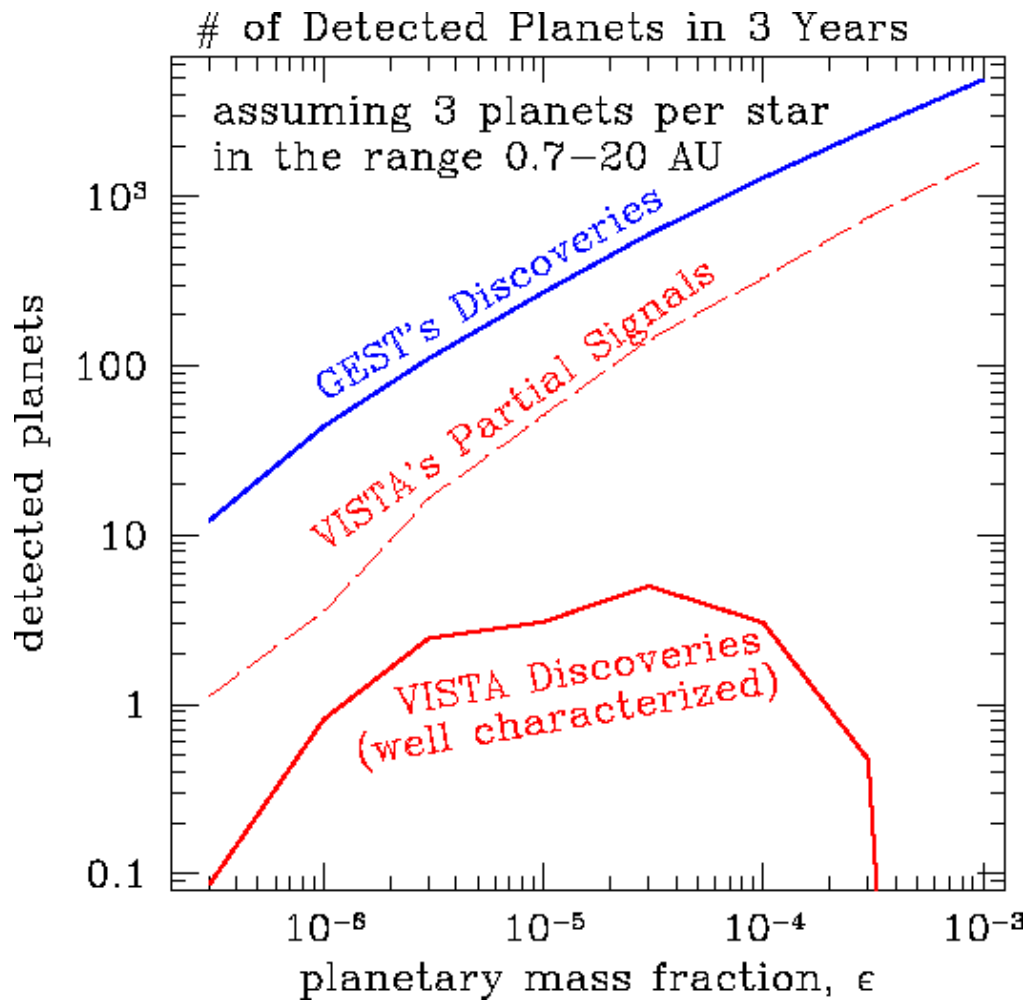


The light curve of a planetary deviation is determined by the gravitational lens caustic structure which is shown above for planets inside and outside the Einstein Radius. A planetary microlensing light curve deviation can be seen when a source star crosses the differential magnification pattern associated with the planetary caustic as shown by the black lines in the right hand panels. The yellow circles superimposed on the differential magnification patterns at right are the planetary Einstein Rings. It is apparent that the full duration of a planetary deviation is 5-10 times the planetary Einstein Diameter crossing time, or 16-32 hours, depending on the direction of the source trajectory.

Simulations of a Microlensing Survey with (1)

The VISTA telescope has recently been funded by the UK for construction in Paranal, the site of the VLT. It is a 4m wide FOV telescope which can image 2.25 square degrees. Based upon estimates of planet detection sensitivity in a 1997 ESO report by Sackett, a single-site microlensing planet search program has been proposed for VISTA. The VISTA microlensing planet search program was highly rated and is part of VISTA's Design Reference Mission which is used to study telescope design issues. It is anticipated that a VISTA planet search program might be allocated as much as 3 full Galactic bulge seasons during VISTA's 1st 10 years of operation (Sutherland, private communication). We have performed a realistic simulation of a VISTA microlensing planet search program, and the results are summarized in the Figure at right. We find that the vast majority of the planetary signals seen by the VISTA survey are partial signals in which a deviation from the stellar microlensing light curve can be detected, but the detected deviations cannot be characterized well enough to ensure that it is really caused by a planet and to determine the planetary mass and separation.

Simulations of a Microlensing Survey with (2)



For terrestrial planets (mass fraction, $\epsilon = 3 \times 10^{-6}$ or 10^{-5} , VISTA can see partial signals for 10–20% of the planets discovered by a space-based planet search mission such as GEST. However, when we demand that the VISTA detections be well sampled, then the number of VISTA terrestrial planet discoveries drops to about 1.4% of the number of Discoveries by GEST. We expect, at most, a handful of terrestrial planet discoveries from a 3-year VISTA at a cost per planet of more than 10 times that of a space mission like GEST. In addition, the VISTA events are much more strongly peaked at a separation of the Einstein Ring radius, R_E , and have brighter source stars than the discoveries from GEST. So, a VISTA survey will not be able to measure the abundance of planets as a function of semi-major axis or stellar type.

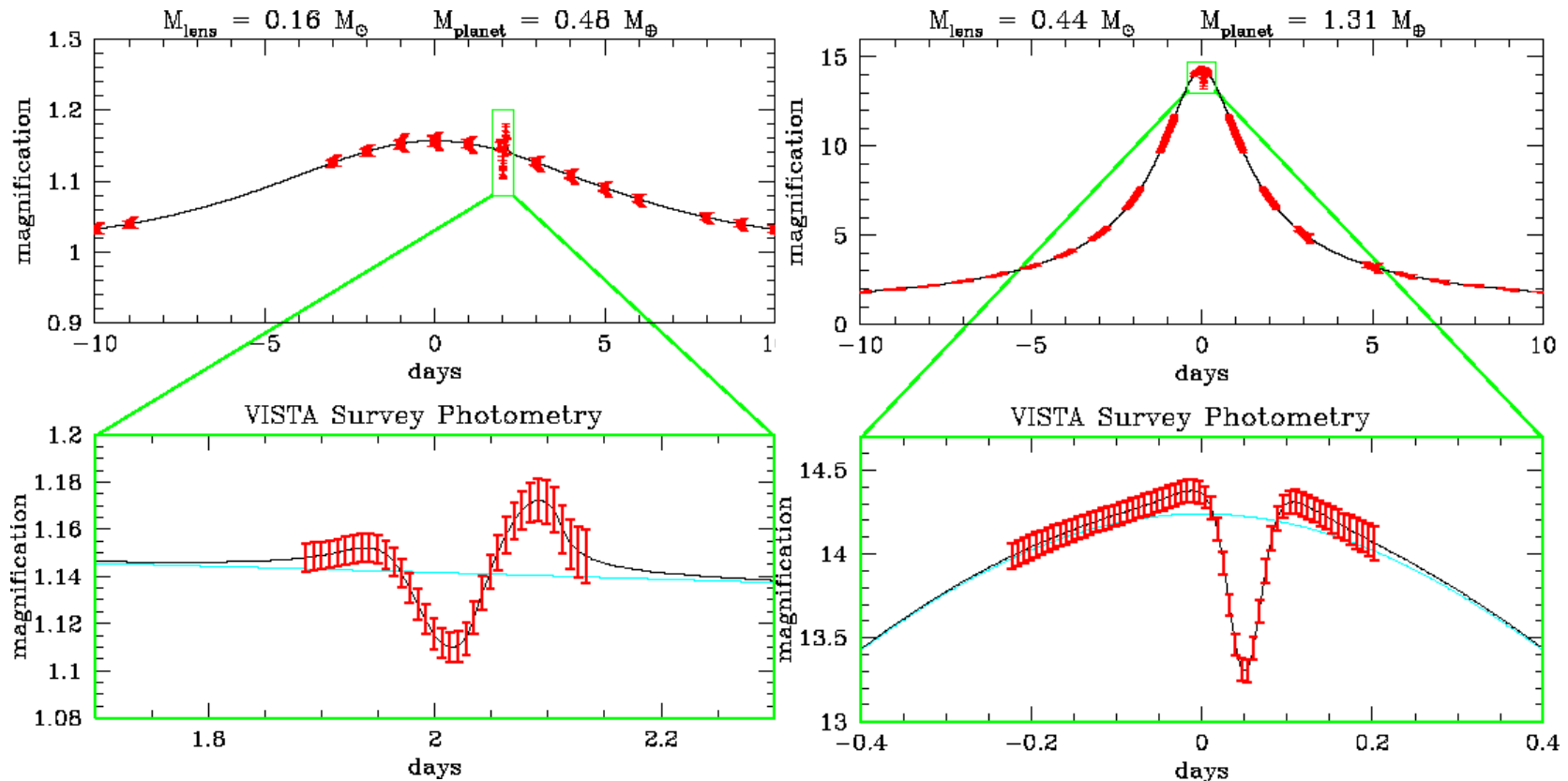


VIATA Simulation Details

- Paranal weather and seeing records obtained from the VLT web site for 1999 & 2000.
 - reduce seeing by 15% because 1999 & 2000 are “worse than average” years
- Simulate brightness of moonlit sky following Krisciunas & Schaefer, 1991
- seeing assumed to vary with seeing and airmass following Walker (1987)
- Assume that the bulge is observed whenever it is at less than ≤ 2.5 airmasses
- Continuous observations of 2.25 sq. deg. central Galactic bulge field
- HST luminosity function from Holtzman et al (1998)
- mass function from Kroupa (2000), Zoccali et al (2000)
- ~10,000 microlensing events in 3 seasons
- assume microlensing probability, $\tau = 3.4 \times 10^{-6}$
 - at Galactic coordinates: $l = 1.3^\circ$, $b = -2.4^\circ$
 - $\sim 1.6\sigma$ lower limit on measured value



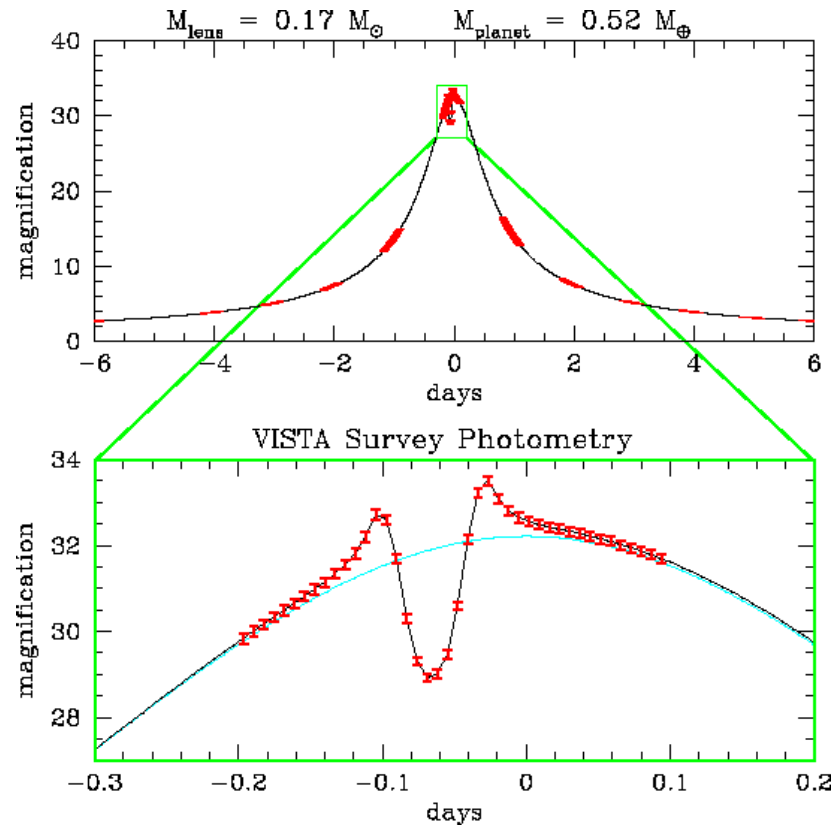
VISTA's Terrestrial Planetary Discoveries (1)



The light curves above are examples of the handful of terrestrial planet discoveries expected in the VISTA survey. They are distinguished from the more typical, partially sampled terrestrial planetary lightcurves (shown on following pages) by having higher relative lens-source velocities (left), or having planetary deviations at high magnification with the star-planet separation very close to the Einstein Ring radius. Our sampling requirement is that 80% of the full planetary light curve deviation must be sampled as well as 50% of each positive and negative feature. We define the planetary deviation to be the part of the light curve that varies from the stellar lensing light curve by more than 0.3%, so that both the “beginning” and the “end” of the deviation are included. These time sampling constraints are necessary to ensure that the planetary light curve deviations can be used to determine the planetary parameters and to ensure that the event cannot be due to other non-standard microlensing effects such as lensing of a binary source star with a large brightness ratio.



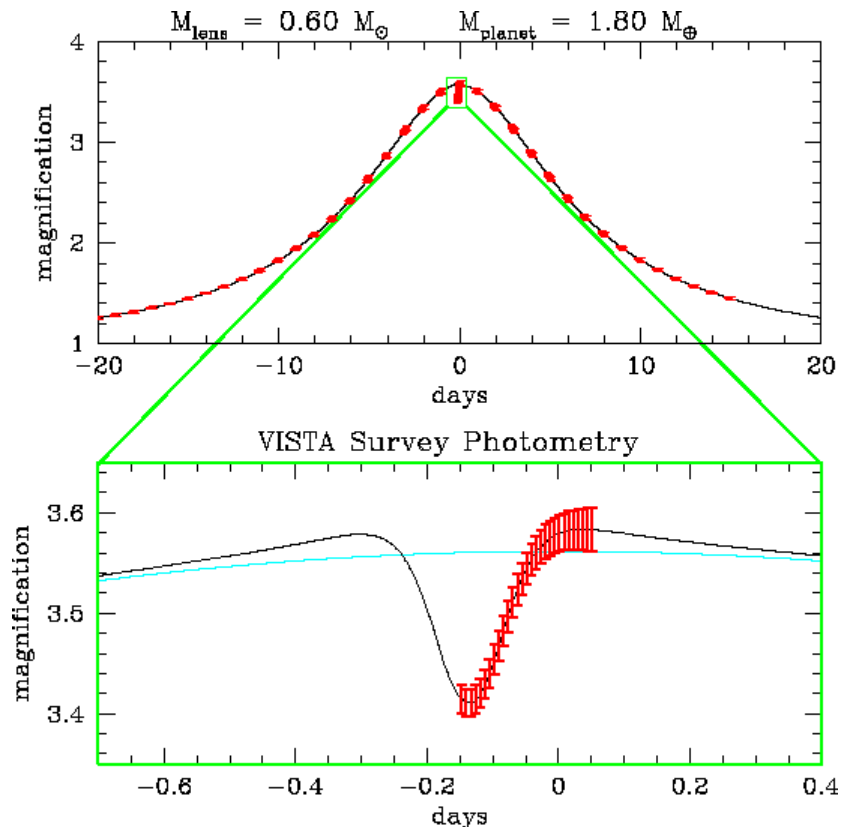
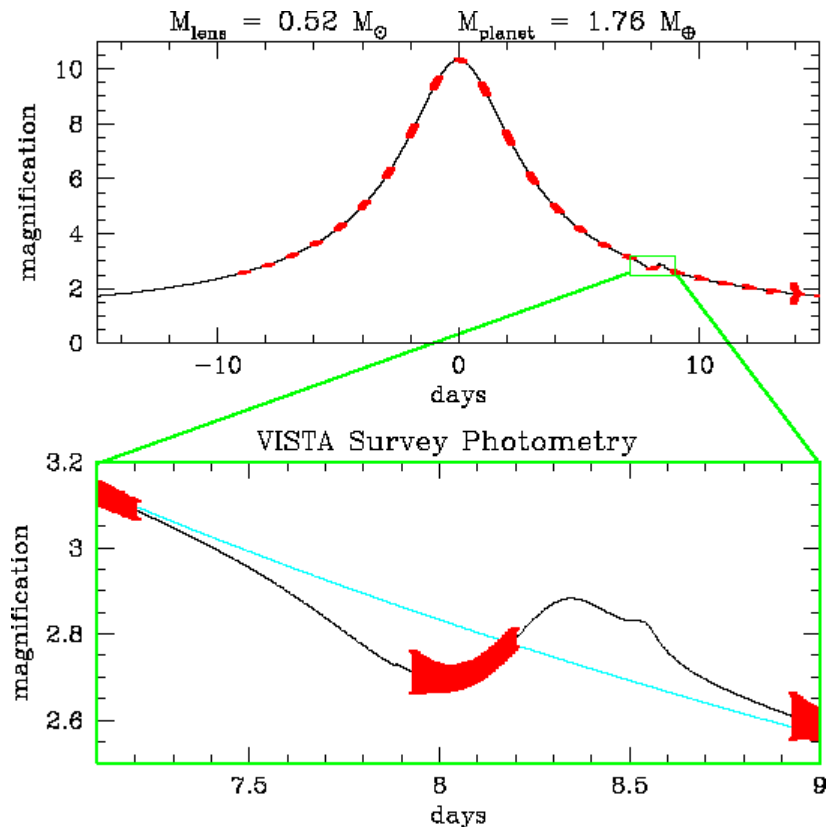
VISTA's Terrestrial Planetary Discoveries (2)



Another example of the handful of terrestrial planet discoveries expected in the VISTA survey.



VISTA's Terrestrial Planetary Discoveries (3)

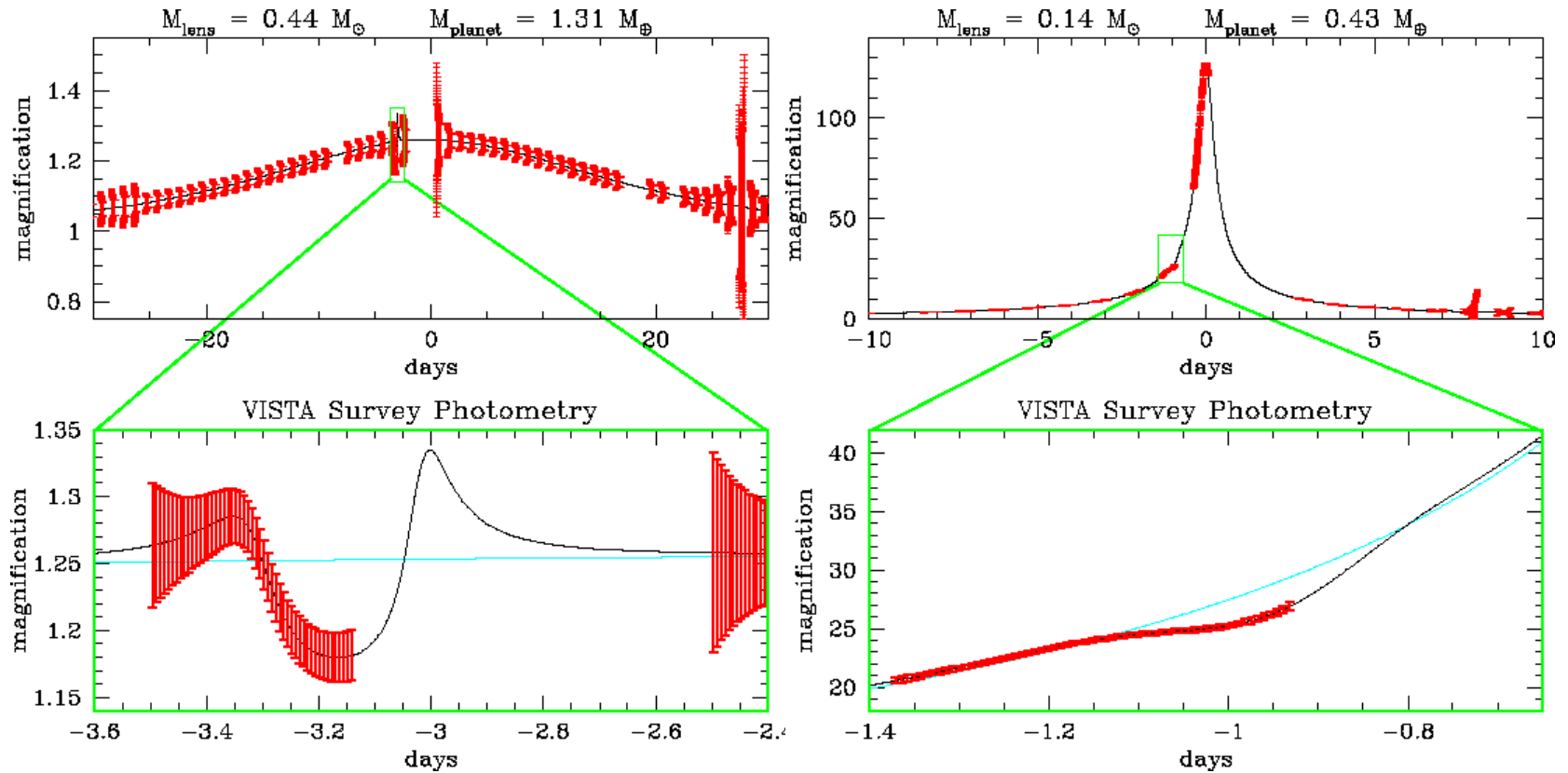


Examples of partially sampled terrestrial planetary lightcurves from the simulated VISTA survey. These have failed one or more of the following sampling criteria:

- 80% of the full planetary light curve deviation must be sampled
- 50% of each positive and negative region of the planetary light curve deviation must also be sampled.



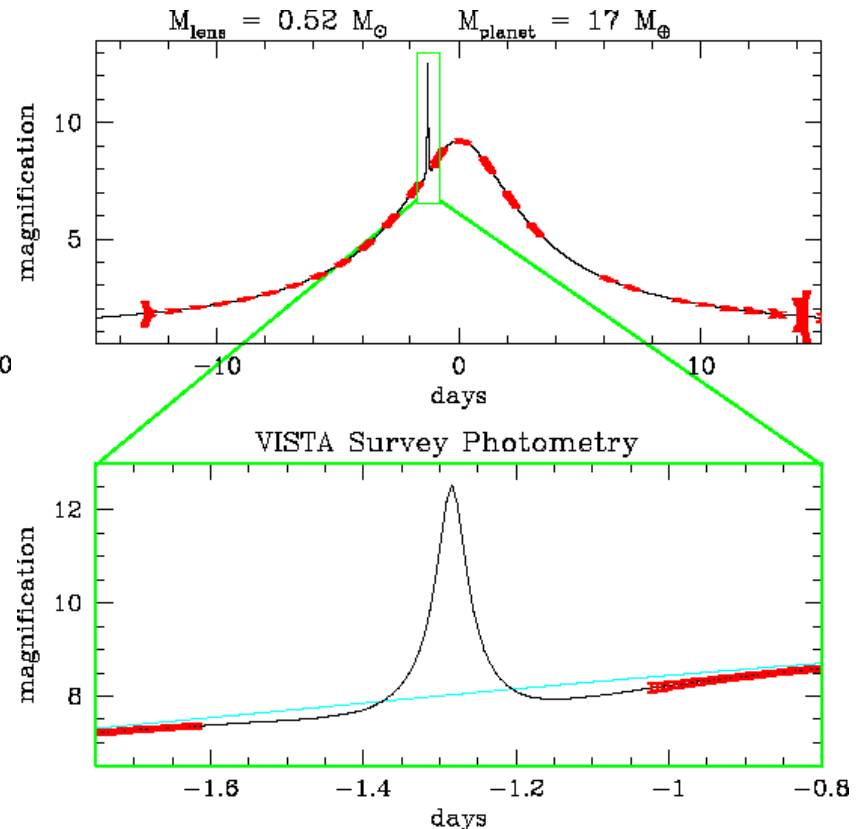
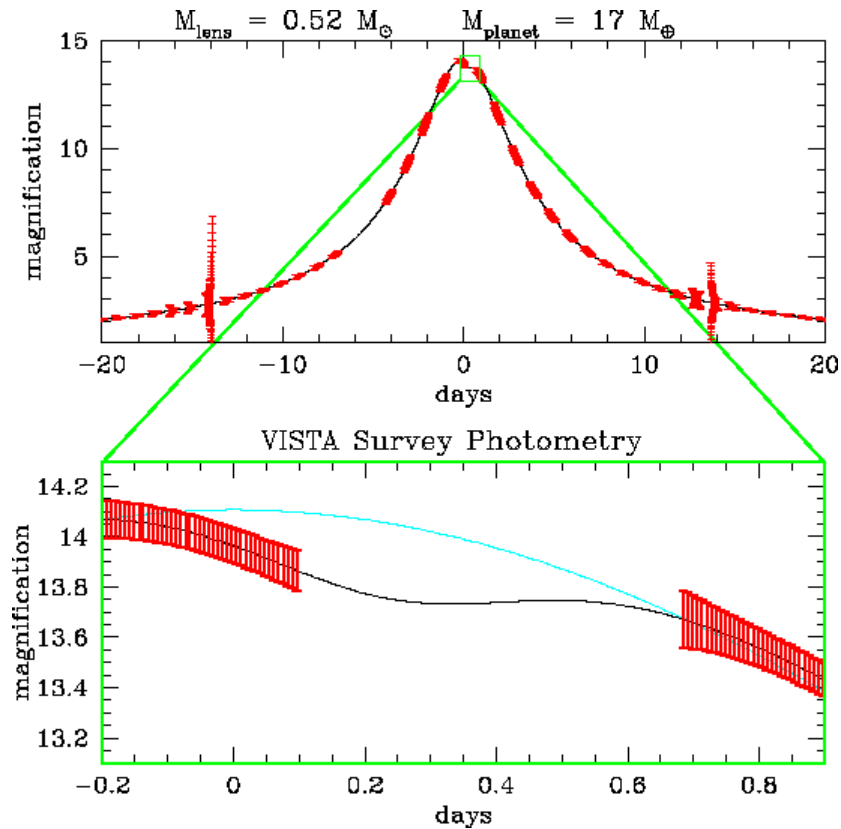
VISTA's Terrestrial Planetary Discoveries (4)



More examples of partially sampled terrestrial planetary lightcurves from the simulated VISTA survey.



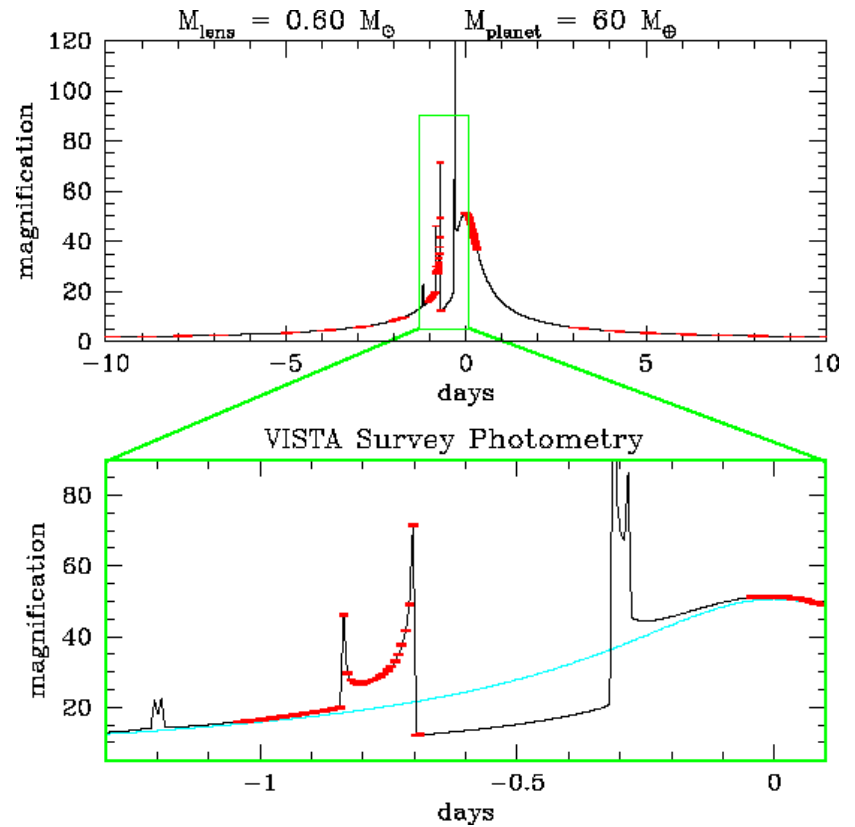
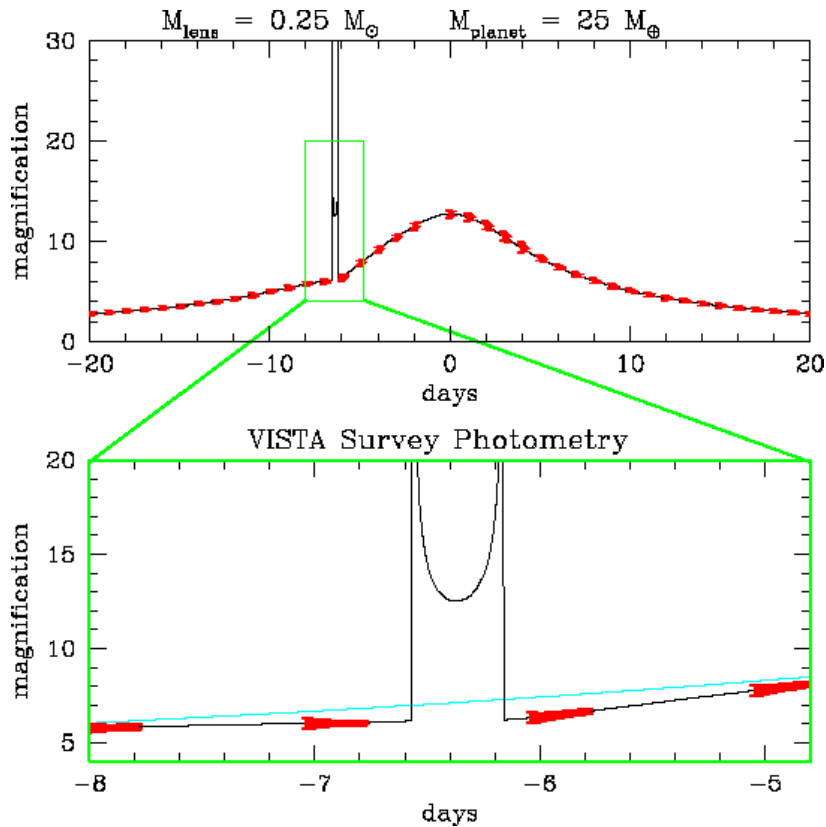
's Massive Planetary Light Curves (1)



These figures show light curves of massive planet events from our VISTA simulations. As the lens mass increases, the probability that the event will pass our time sampling criteria decreases quite sharply as indicated in our “# of detected planets” plot (on page 7). For planets in the 10-100 M_{\oplus} range, there are very few planetary lensing events which have a light curve deviation short enough to be covered from a single site, but most of these events have important features that require observations at intervals of every few hours. Thus, a VISTA survey will be able to discover very few planets in this mass range. This is the reason that our simulated planetary discovery sensitivity falls so sharply at higher masses.



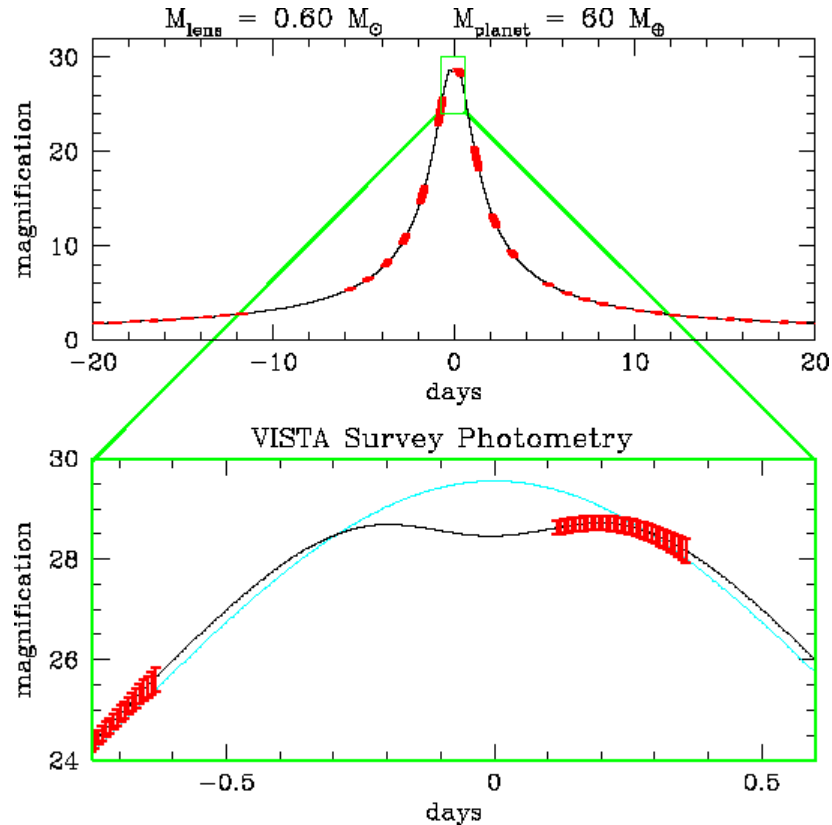
's Massive Planetary Light Curves (2)



More examples of planetary signals in the 10-100 M_{\oplus} range, where there are very few planetary lensing events which have a light curve deviation short enough to be covered from a single site. Thus, a VISTA survey will be able to discover very few planets in this mass range.



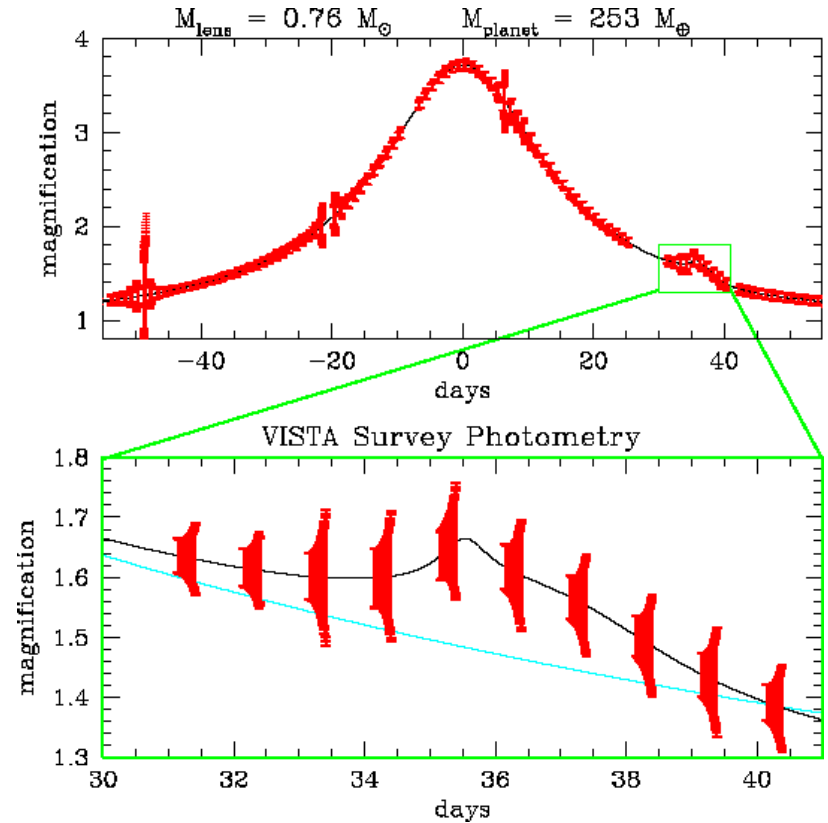
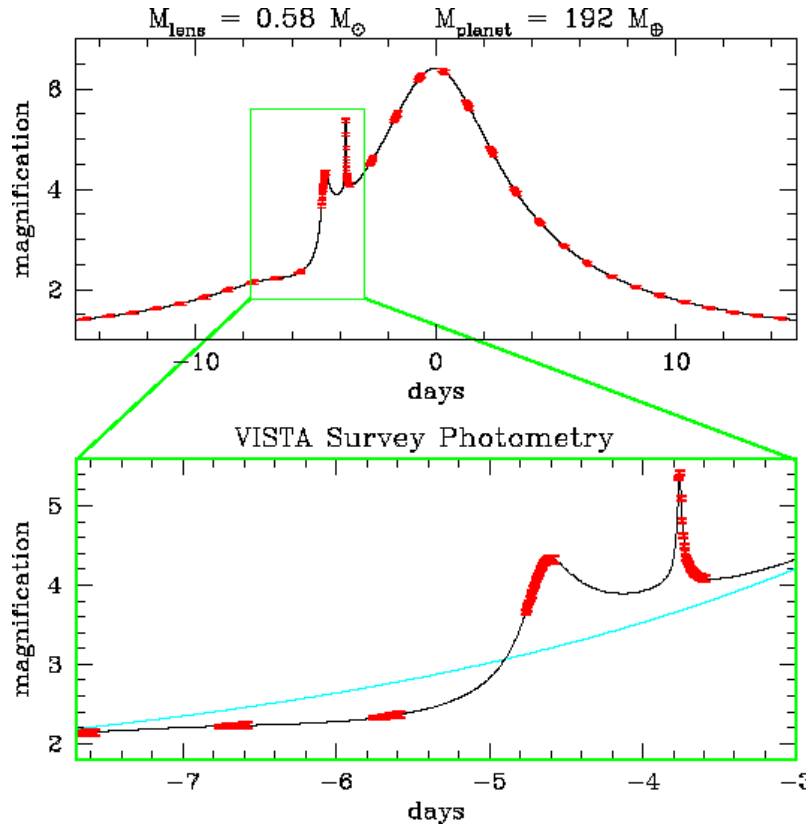
's Massive Planetary Light Curves (3)



A final example of a planetary signal in the 10-100 M_{\oplus} range, where there are very few planetary lensing events which have a light curve deviation short enough to be covered from a single site. A VISTA survey will be able to discover very few planets in this mass range.

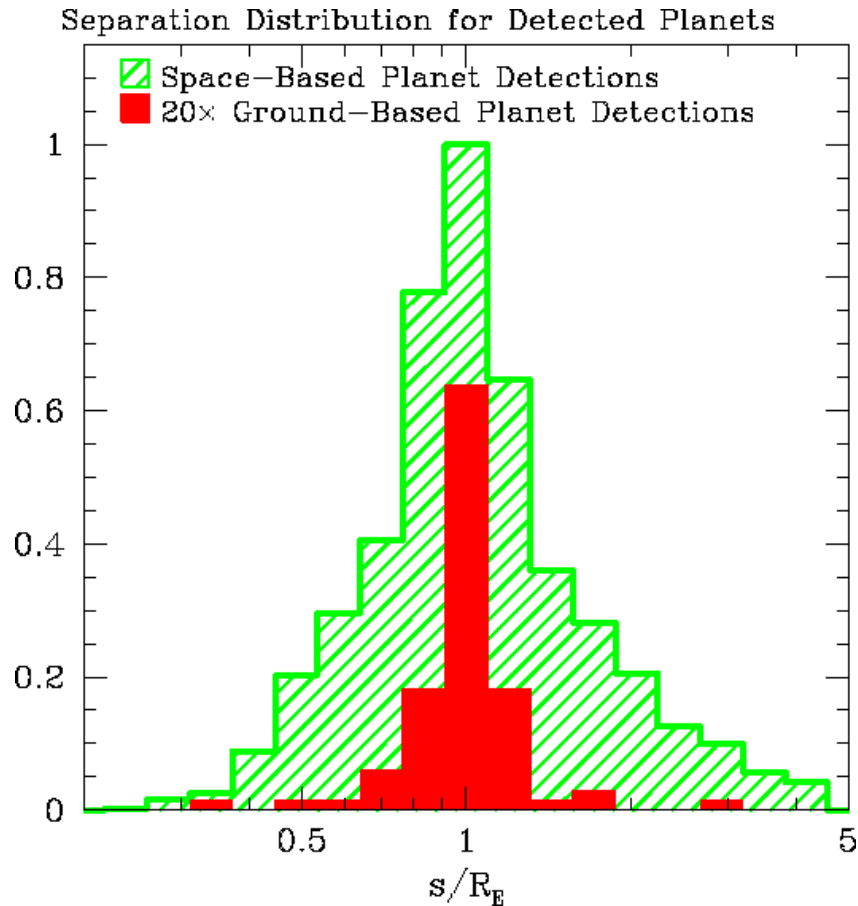


's Massive Planetary Light Curves (4)



These figures show light curves of massive planet events with $M \geq 100 M_{\oplus}$ from our VISTA simulations. In this mass range, the planetary events (such as the one on the right) can be long enough so that a single site can get enough data to characterize the planetary light curve deviation. Our detection criteria does not take this possibility into account. However, there are still some Jupiter-mass planet events (such as the one on the left) where additional sampling is desired.

Sensitivity vs. Separation



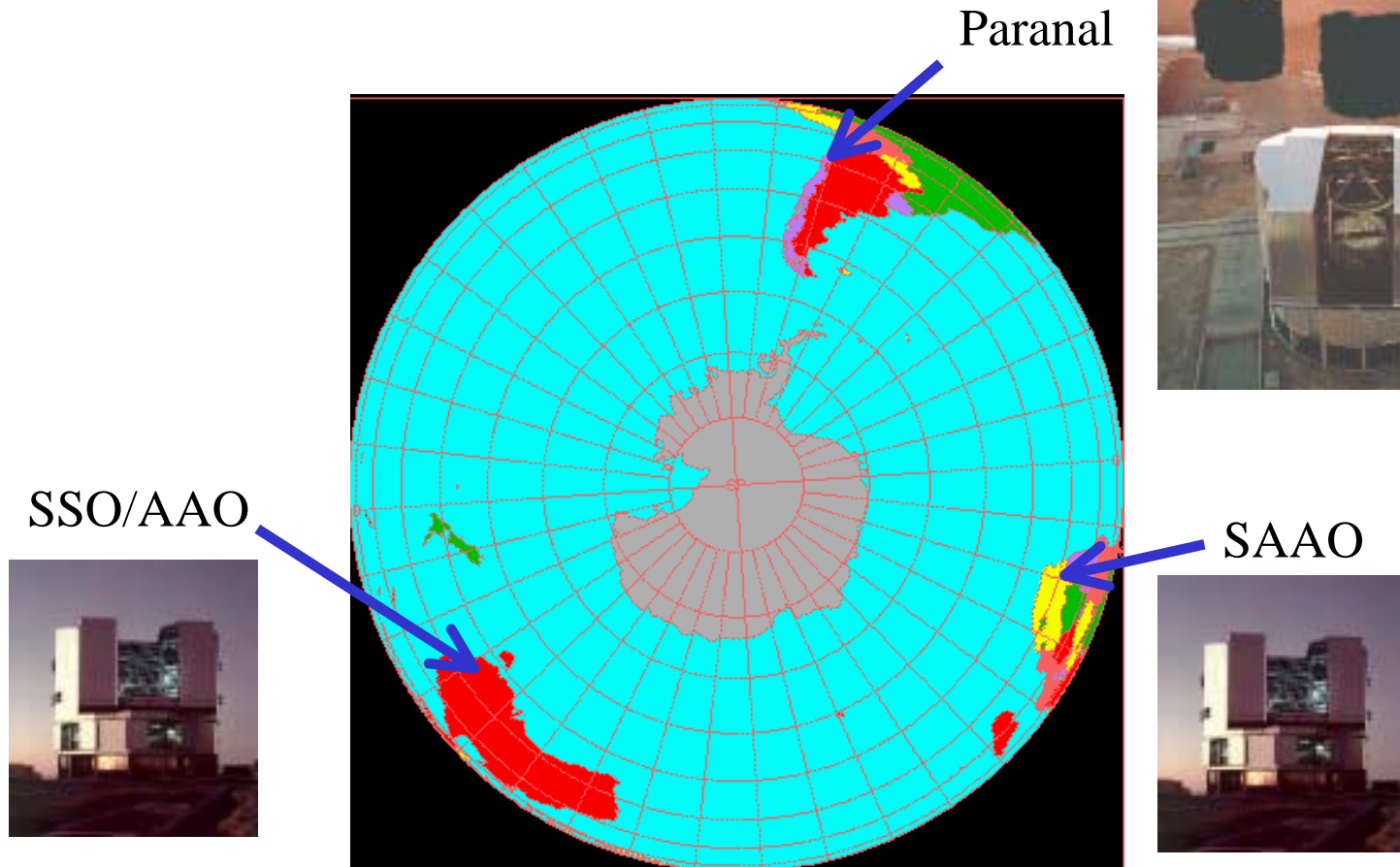
The distribution of separations for well sampled planetary events is compared for a space-based microlensing planet search program like GEST, and a ground-based program which might be run on VISTA. The narrow range of planetary sensitivity from the ground, and small number of planetary detections indicate that the VISTA survey cannot measure the abundance of planets as a function of separation.

If VISTA Won't Do the Job, What About Other Ground based Options?



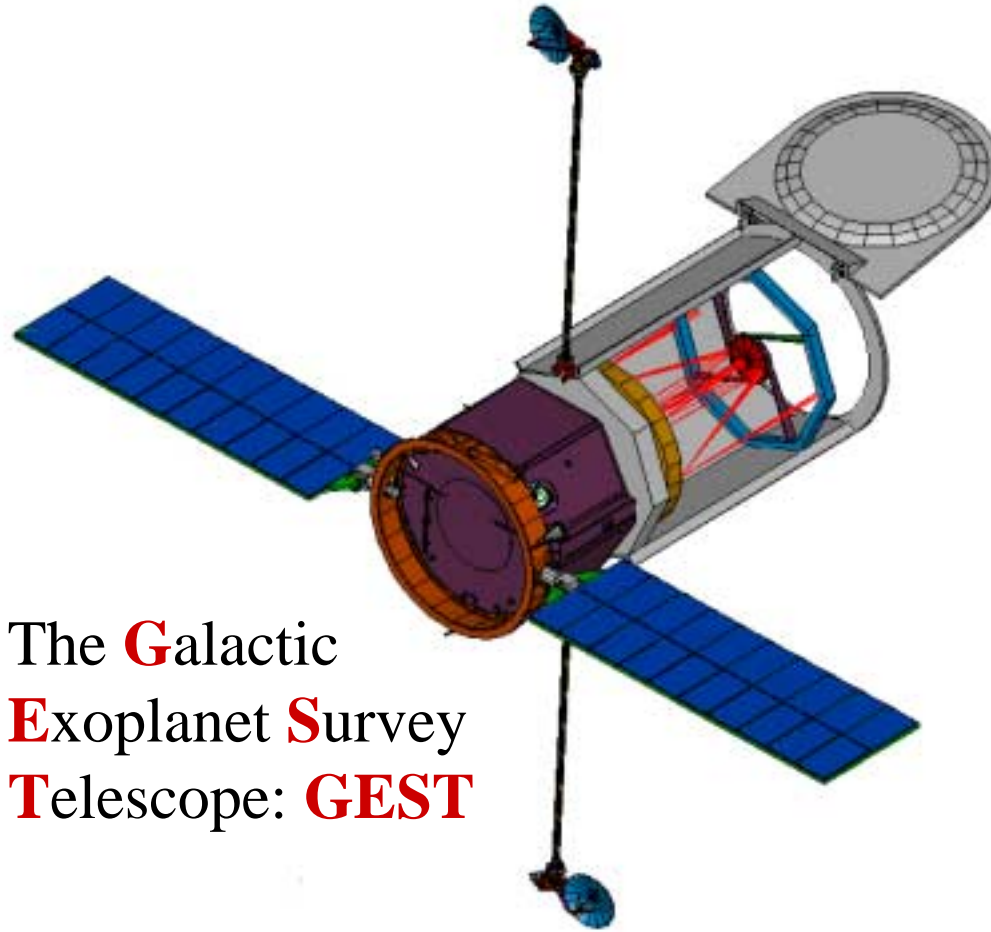
- What about the LSST? It's a 6.5-8m telescope with a larger FOV than VISTA?
 - The main problem of the VISTA survey, poor sampling, is not addressed, and the associated difficulty in measuring the planetary abundance as a function of separation will remain.
 - The effect of the larger aperture is partially offset by systematic photometry errors due to stellar blending.
 - The effect of a larger field-of-view is partially offset by the fact that the additional field looks at an area with a smaller microlensing event rate.
 - In all, LSST may improve the planetary detection by a factor of ~ 3 or so, at a cost of $5\times$ VISTA.
- To address the main difficulty of poor sampling, we must observe from other sites besides Paranal
 - We must use wide FOV telescopes, so that we can observe ~ 100 microlensing events in a single image. Otherwise, we cannot get accurate photometry on
 - There are no comparable sites to Paranal in South Africa, and Australia has no observing sites with decent seeing.
 - We might try to compensate for the poor signal to noise by getting larger telescopes
 - but, no review committee will approve a proposal to put a very large and expensive telescope in a poor observing site
 - Wide FOV 8m telescopes cost as much as a MIDEX mission (before operating expenses).

What About Other Ground based Options?



Even if we put 2 of the 4 VLT telescopes in South Africa and Australia, we still wouldn't have an effective planet search system. So, don't hijack the VLT!

The Solution is to Use a Space Based Wide FOV Telescope:



The **G**alactic
Exoplanet **S**urvey
Telescope: **GEST**