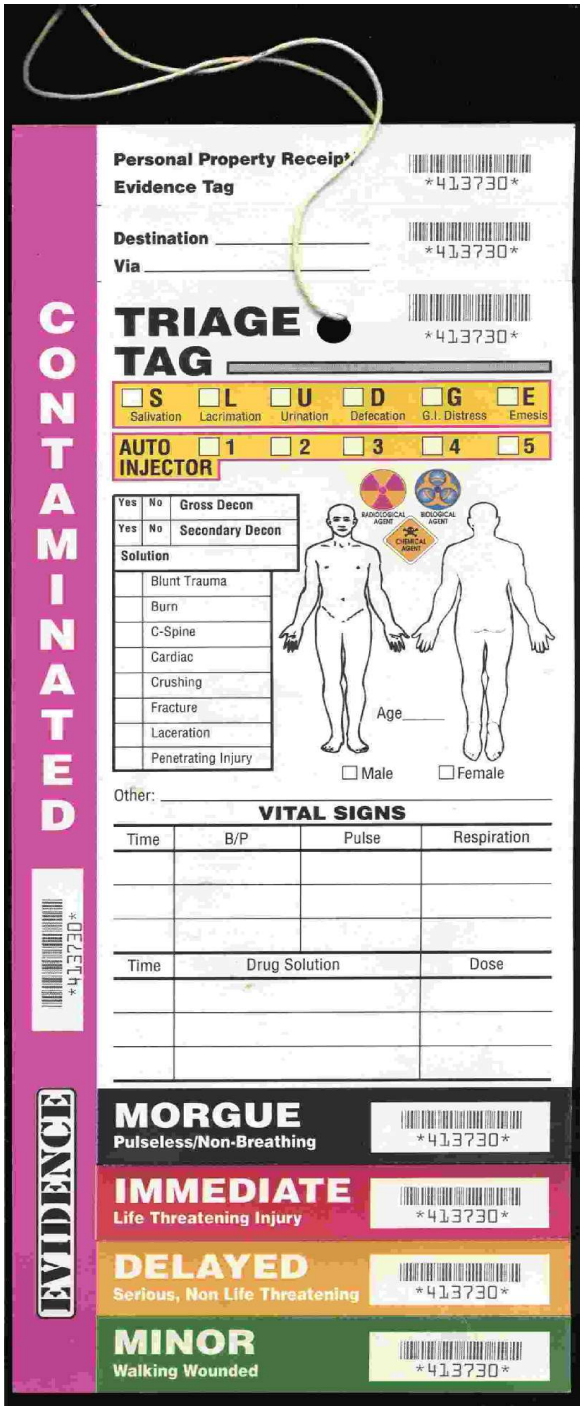
Large-Telescope Instrumentation For Time-Domain Astronomy

(Andy Gould – Ohio State)

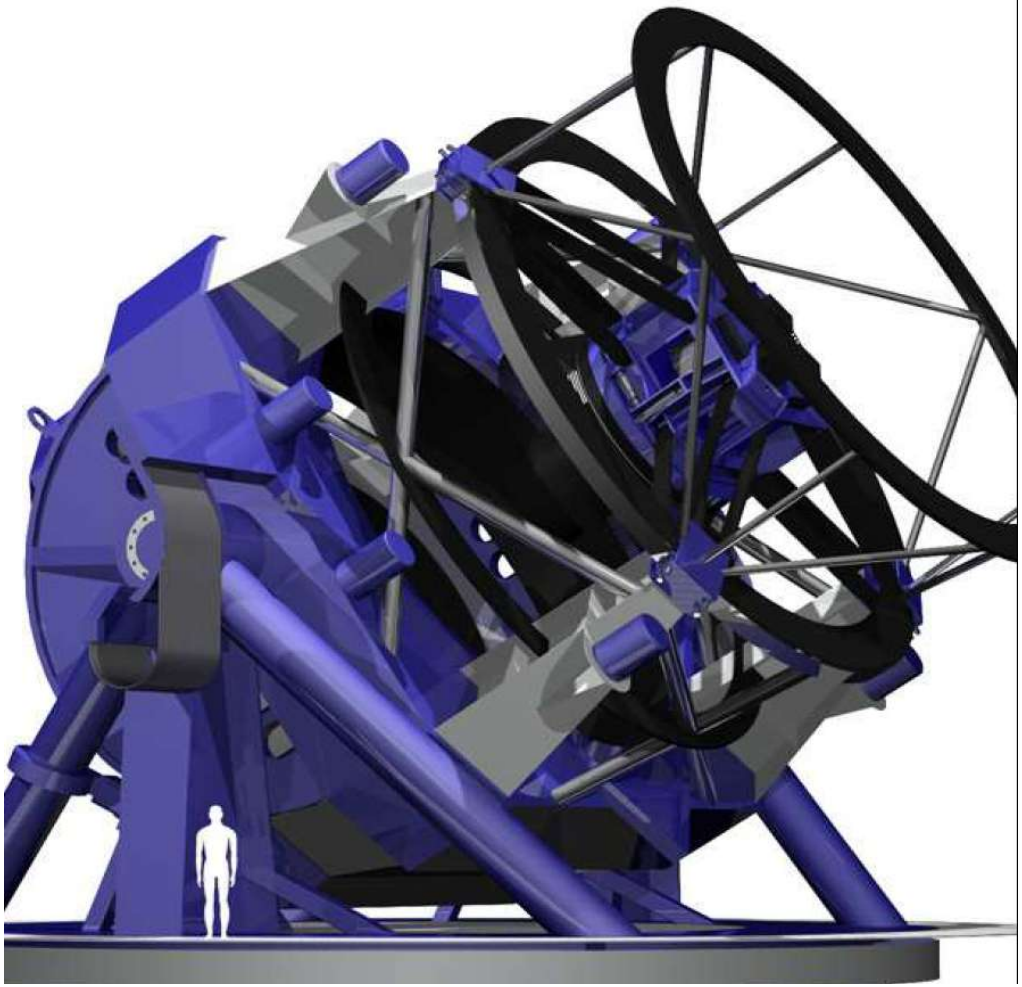
- Transients:
  GRBs
  Novae
  Supernovae
  Occultations
  Microlensing Events
  New Phenomena
- Astrometry:
  Parallaxes
  Proper Motions
- Planets:
  Doppler
  Transits
  Astrometry
  Microlensing
- Variables:
  CVs
- Solar System:
  KBOs, NEOs

TRIAGE

- Already Being Done
- Ripe for Large-Telescope Instruments
- Smaller = Better



- 6.5m (equiv), 10 deg^2
- 15 sec exposures
- Every 3 nights
- 16 < V < 24
- 10 mas astrometry (systematics)



LSST: What's Left?

- SURVEYS
- V<16
  (a lot!)
- Timescale < 3 days
  (GRBs, ulensing, occultations, unknowns)
- Spectroscopy
  (RV planet searches)
- Ultra-deep

- TARGETED
- Just About Everything

Coming Sooner (and Brighter):

Pan-STARRS
UNIVERSITY OF HAWAI'I

- 1.8m, 7 deg^2 (ultimately 4 mirrors)
- 30 sec exposures
- 3 obs/lunar cycle
- 14 < V < 23

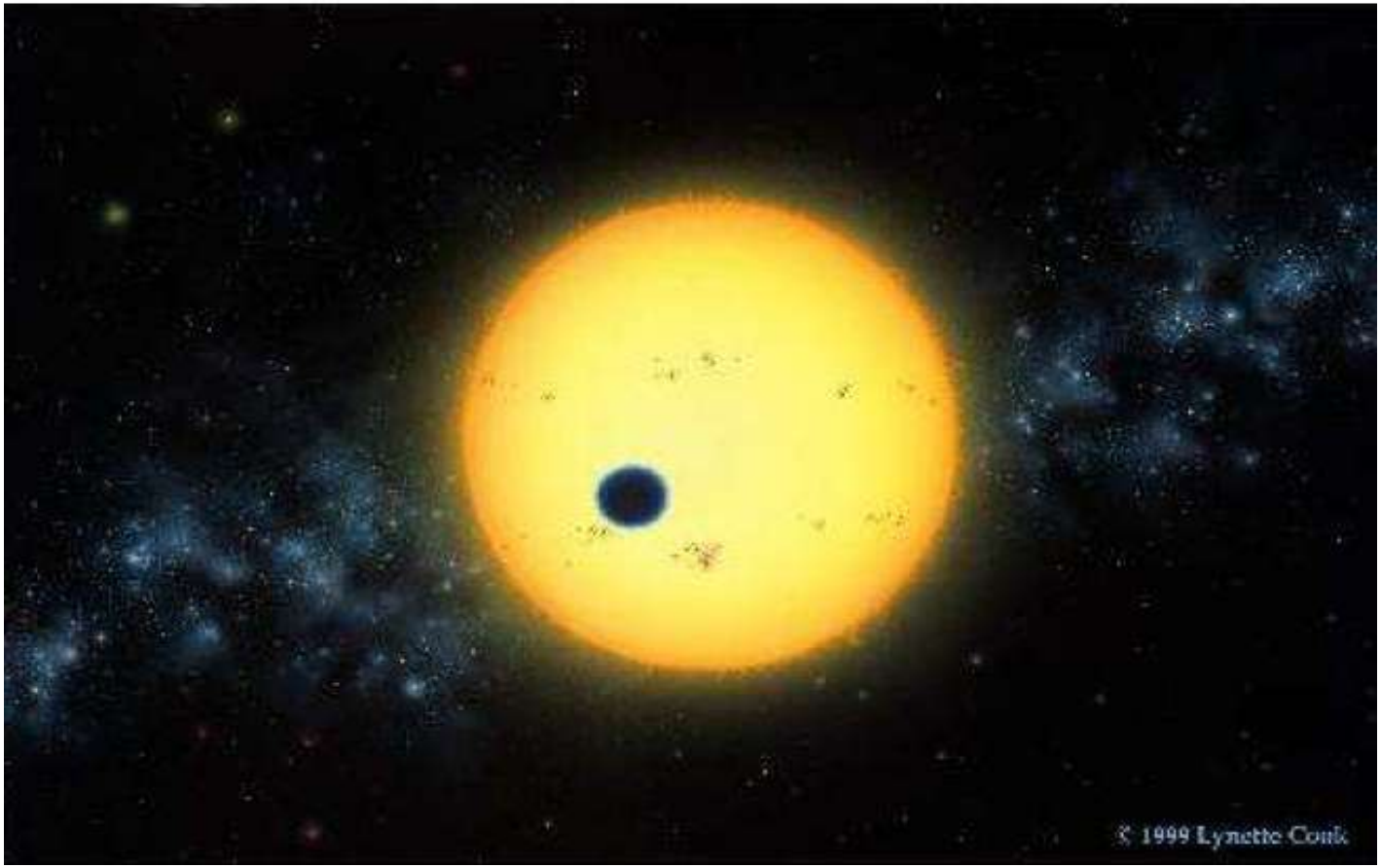
- **2 DELTA's**
- 14<V<16 removed
- Single-Telescope survey begins “soon”

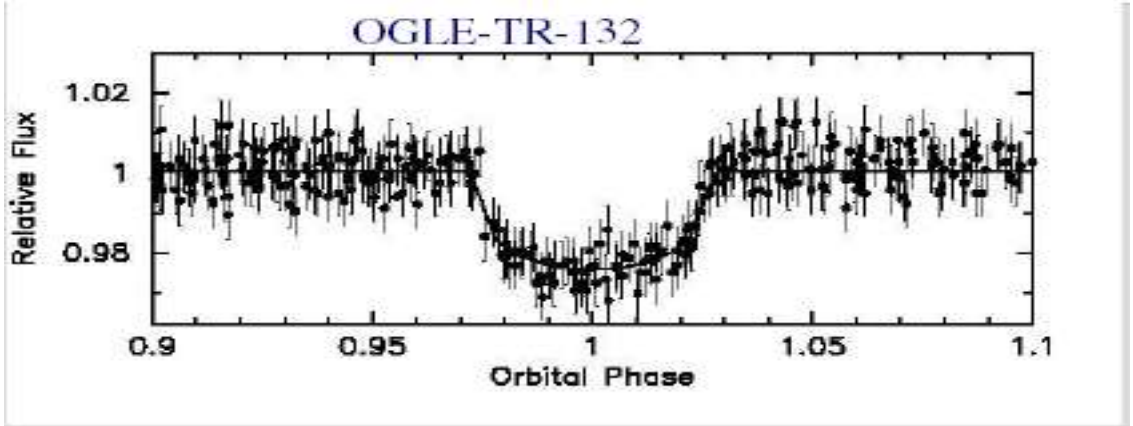
Genesis of KELT

(Kilodegree Extremely Little Telescope)

- 2 inch lens
- f/1.8
- 4Kx4K chip
- (23 deg)^2 FOV

Transiting Planets





A “Surface-Brightness” Problem

- KELT equation

$$\gamma = \frac{K\mathcal{E}\mathcal{L}^2 T}{4\pi\mathcal{F}^2}$$

- K: throughput const.
- E: time efficiency
- L: detector length
- T: experiment duration
- F: Focal ratio
- gamma: photons rec'd

Using All-Sky Surveys to Find Planetary Transits

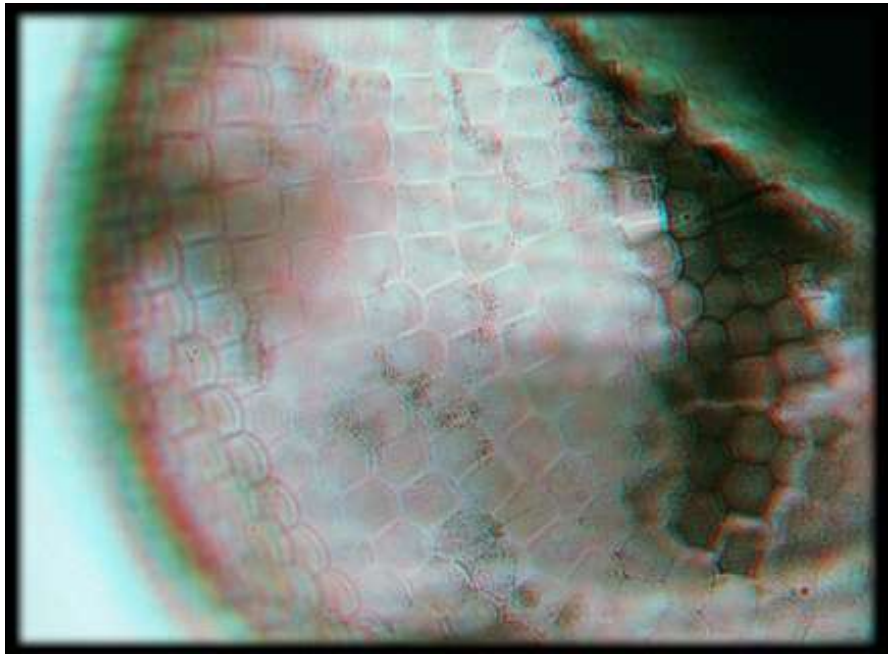
Joshua Pepper, Andrew Gould and D. L. DePoy

Why No Scaling With Primary Diameter, D?

- Fix focal ratio (F) and detector size (L)
- Double D --> 4x Area --> (1/4)x Exposure time
- But ... (1/4)x Field --> 4x More exposures
- Smaller D --> Smaller time fraction in readout
- --> Choose smaller and smaller D, until ...
- ... Sky dominates [V ~ 12 + 5*log(D/5cm)]
- [Assumes: pixel/F=5 um, V(sky)=21.3]

Fly's Eye Telescope

- 120 4-inch telescopes
- 5K commercial chips
- 9 um, 7" pixels
- 10,000 deg^2
- 30 sec exposures
- 3% at V=14
- Saturates at V~8.5
- Parts: $1.5M



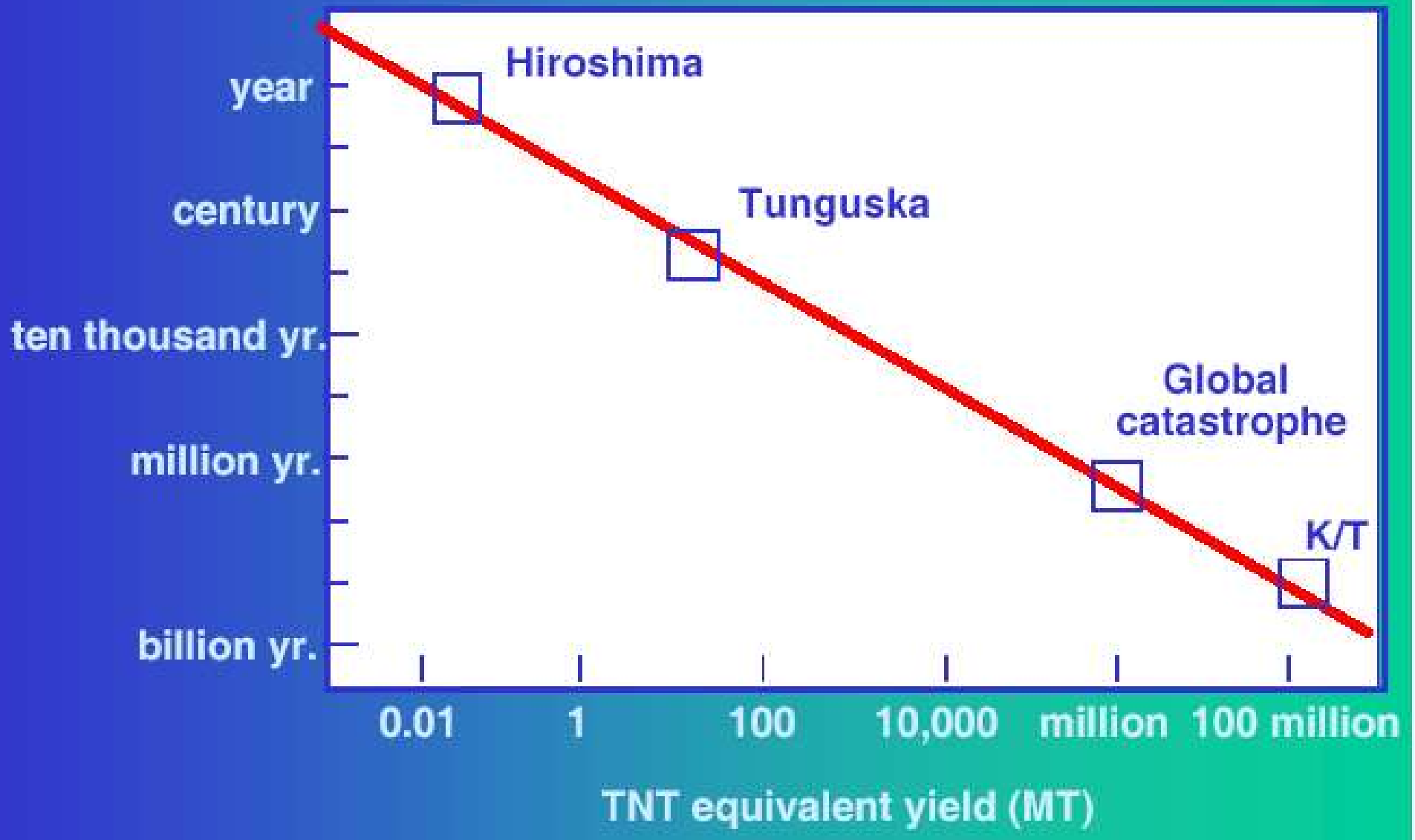
Lazy-Susan Mount

Fly's Eye Applications

- Transits
- Jupiters:
  V=13: P<1yr
- Neptunes:
  V=11: P < 4 days
- Earths:
  V=10 M-star
  Habitable Zone
- GRBs
  Optical Afterglows
  Alerts to SWIFT!!!
- Nova, SN, rises
- New Phenomena
- Killer Rocks


DON'T WORRY, WE HAVE A DISASTER PLAN.
©2005 Thaves / Dist. by NEA, Inc. E-mail:Bob.Thaves@ad.com
10-17
THAVES

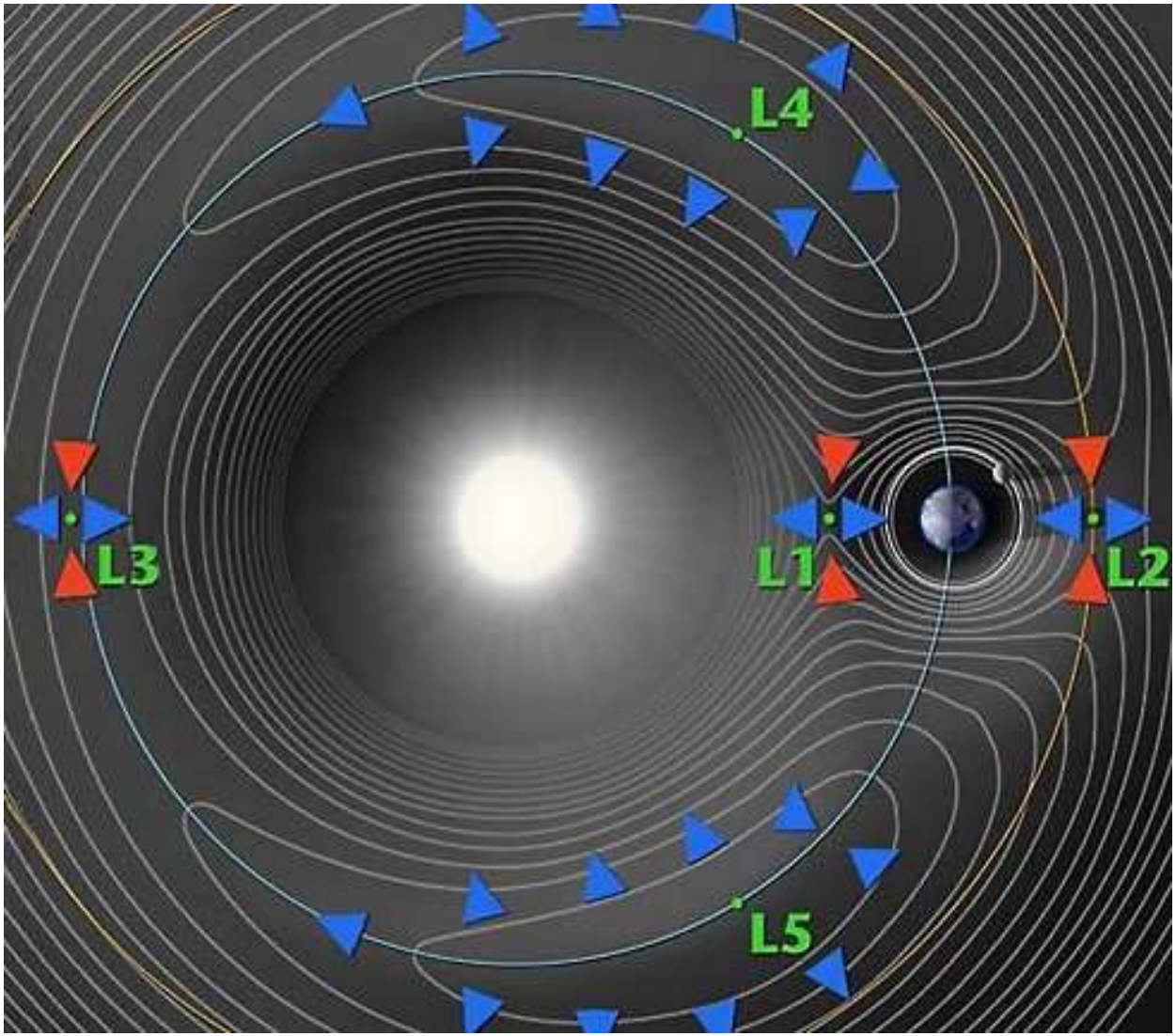
Terrestrial Impact Frequency



Morrison August 2006

Perhaps Complemented by a ...

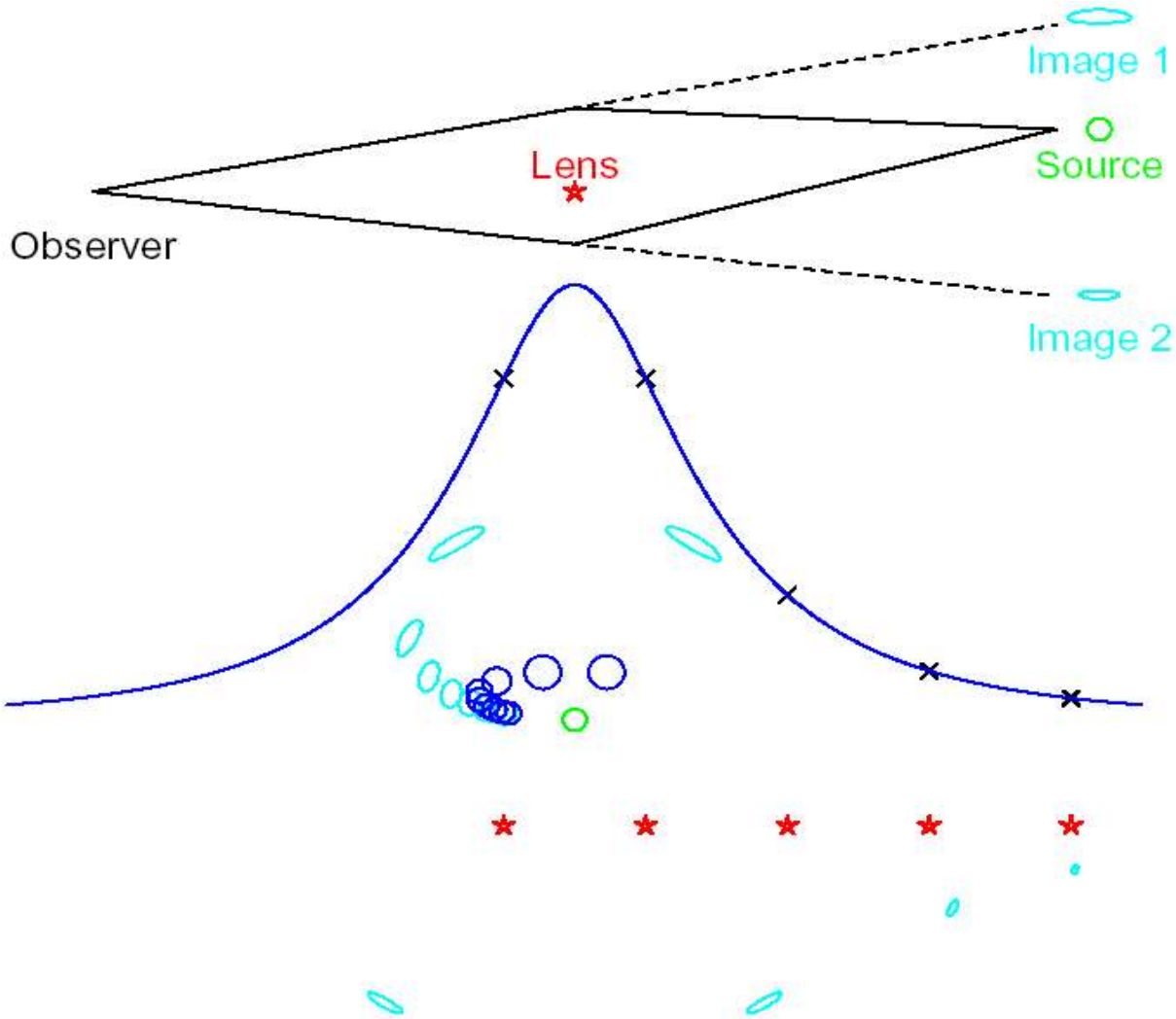
- Satellite at L1



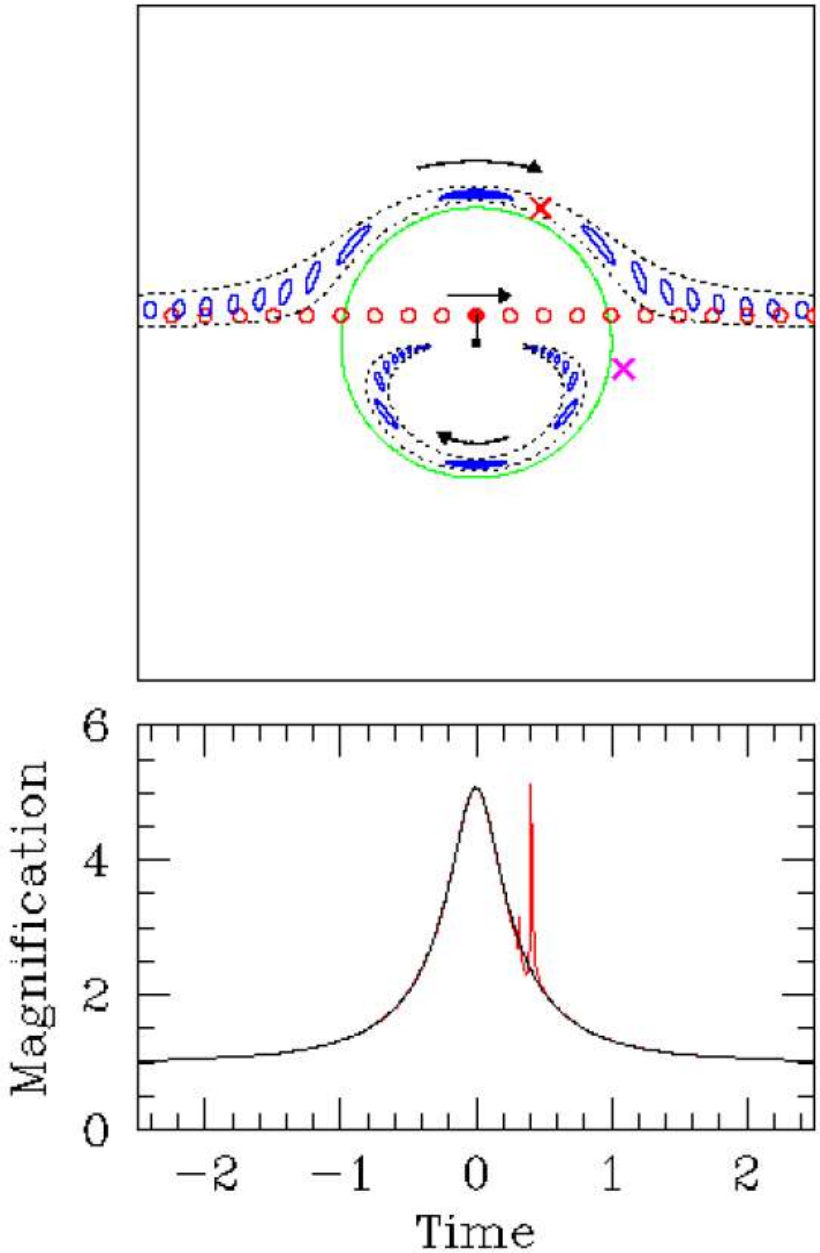
Time-Domain Parameter Space for Large-Telescope Instruments
I: Photometry Surveys

- Smaller Area/Deeper/Crowded/Higher Sampling
- LSST: (33m^2)x(10 deg^2)x(15s/30hrs)
  = 0.05 m^2 deg^2
- Examples
  1) Microlensing (Bulge)
  2) Microlensing (M31, other?)
  3) Supernovae (e.g. DES)
  4) Other?

How Microlensing Works



How Microlensing Finds Planets



Generation 0

- Eddington 1920, Space, Time, and Gravitation
- Chwolson 1924, Astron. Nachr. 221, 329
- Einstein 1936a, Science, 84, 506

  "Some time ago R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request .... there is no great chance of observing this phenomenon."

- Einstein 1936b (private letter to Science editor)

  "Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."

Generation -1: Einstein (1912)

[Renn, Sauer, Stachel 1997, Science 275, 184]

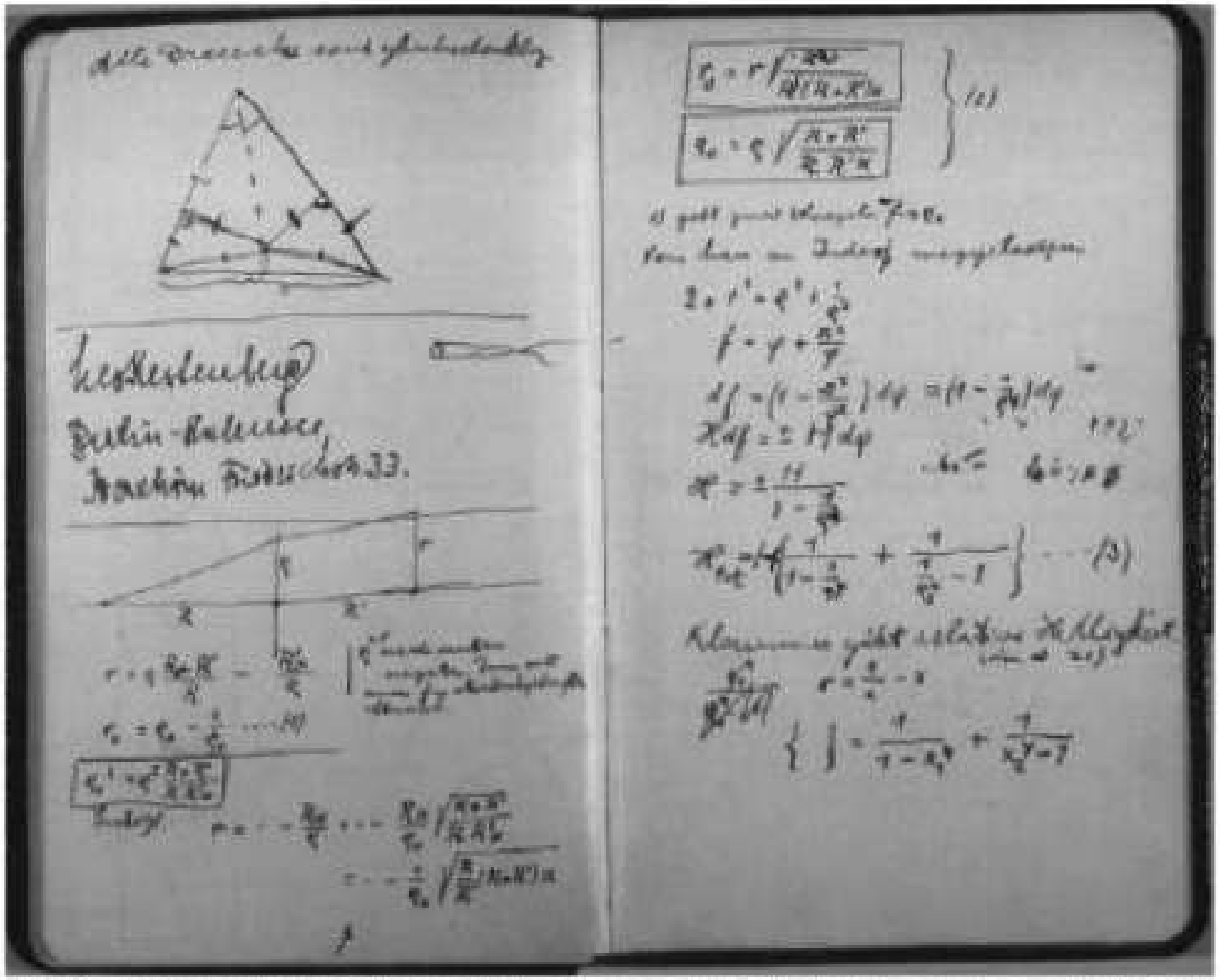


Fig. 1. Notes about gravitational lensing dated to 1912 on two pages of Einstein's scratch notebook [12]. [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem]

Massive Surveys Induce Optimism ...

GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

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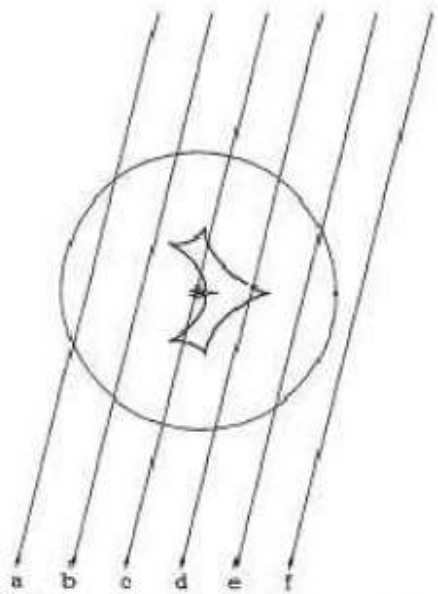
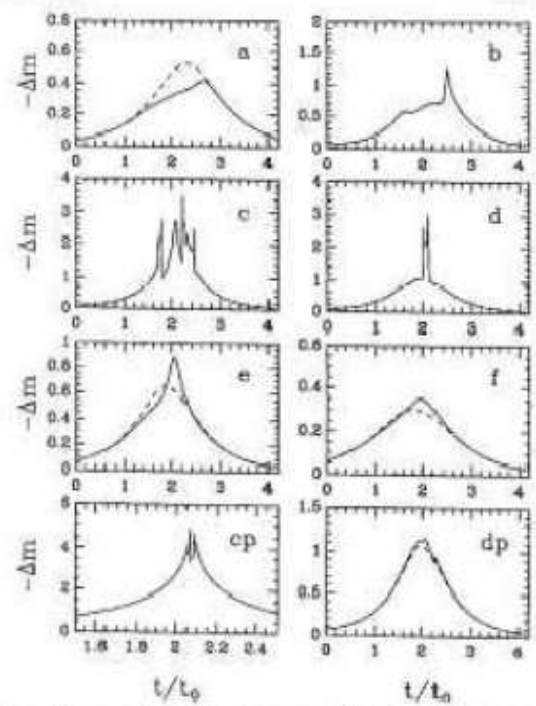
Received 1991 March 12; accepted 1991 April 2





1.—Geometry of microlensing by a binary, as seen in the sky. The y star of 1 $M_\odot$ is located at the center of the figure, and the secondary of $_5$ or 0.001 $M_\odot$ is located on the right, on the Einstein ring of the y. The radius of the ring is 1.0 mas for a source located at a distance of 8 d the lens at 4 kpc. The two complicated shapes around the primary are

the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.

... And Need for Followup!

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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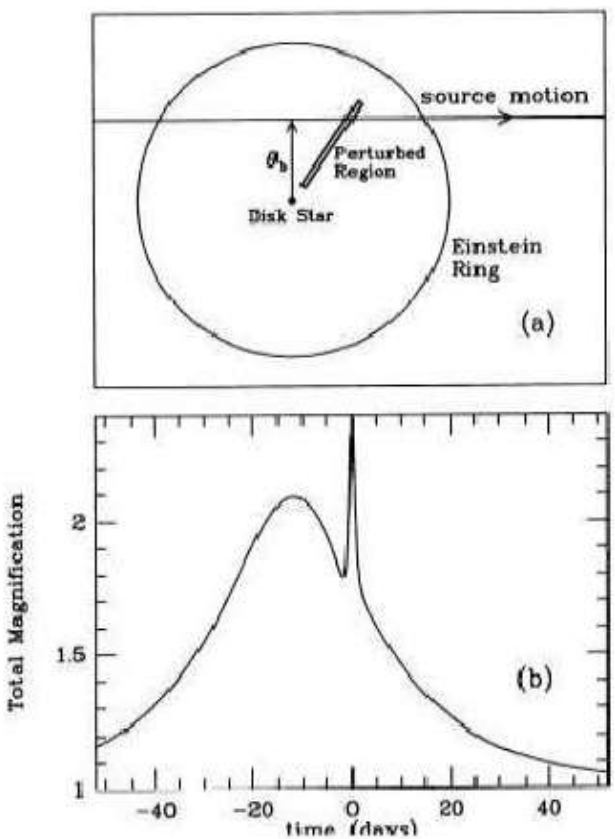
Received 1991 December 26; accepted 1992 March 9



5. OBSERVATIONAL REQUIREMENTS

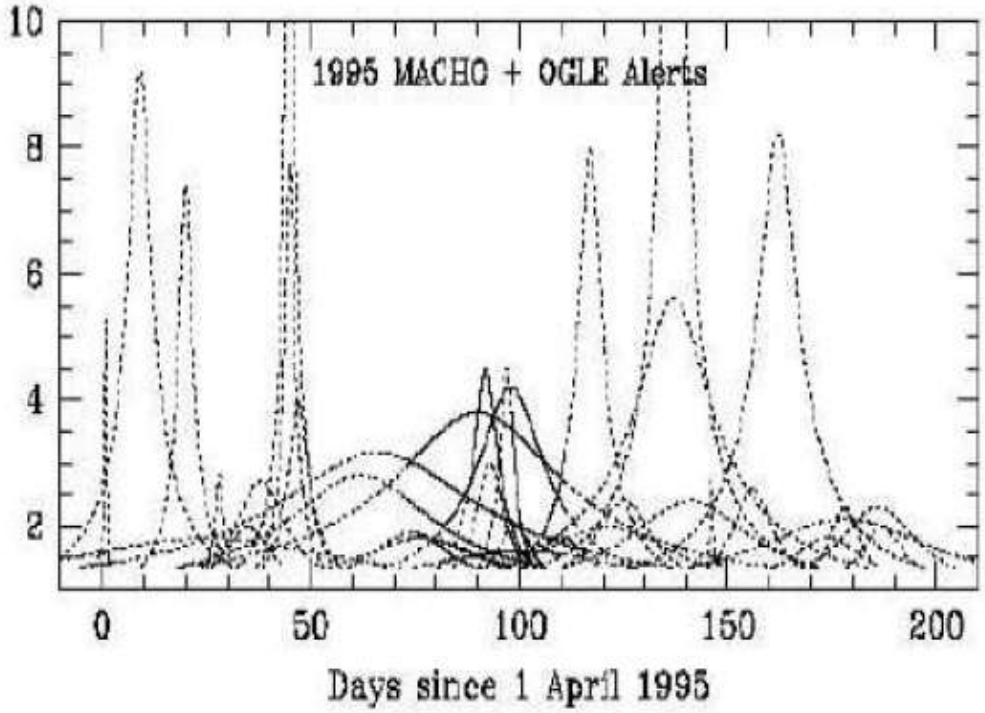
Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the observation of millions of bulge stars on the order of once per day. The second step involves the observation of a handful of stars many times per day. In the following we give a rough outline of what is required for each of these steps.

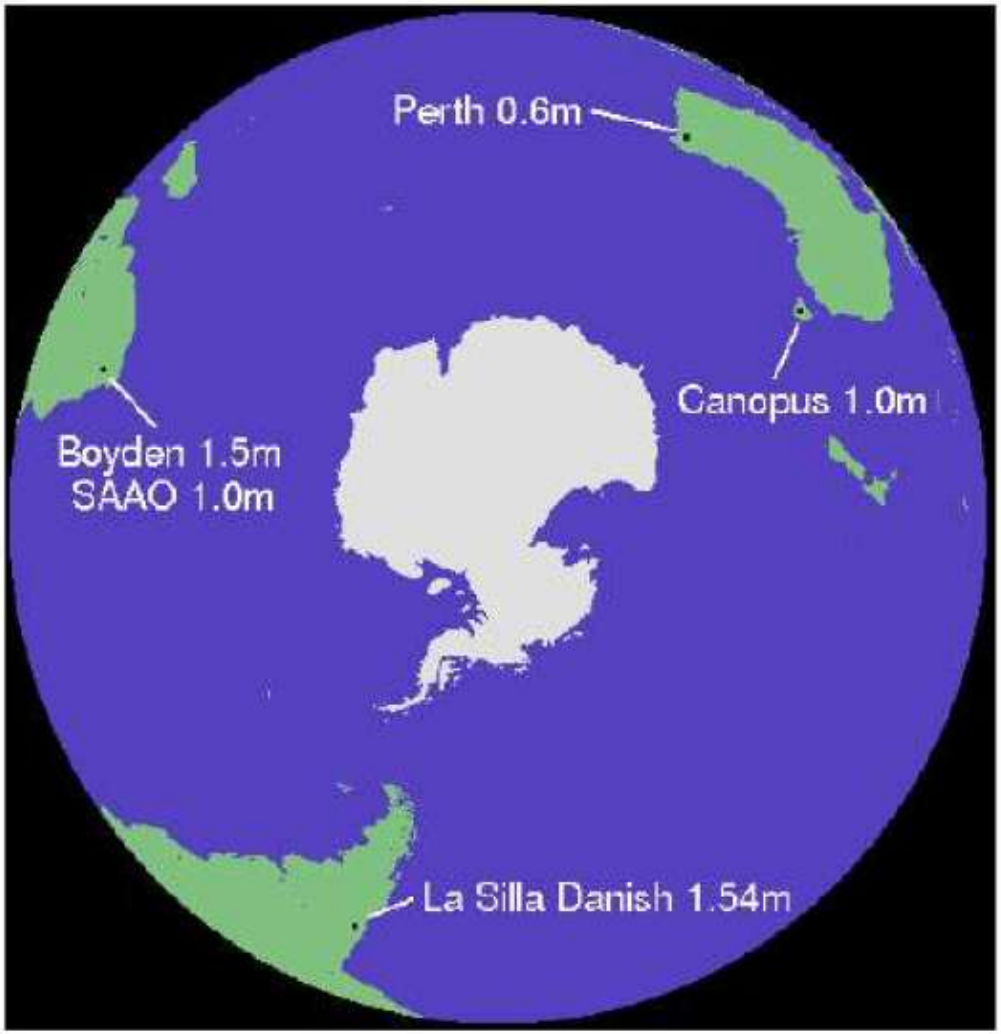
While observations from one site would be useful, there are advantages to be gained by observing from several sites. First,

two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out two observations per night. During the near-December season,

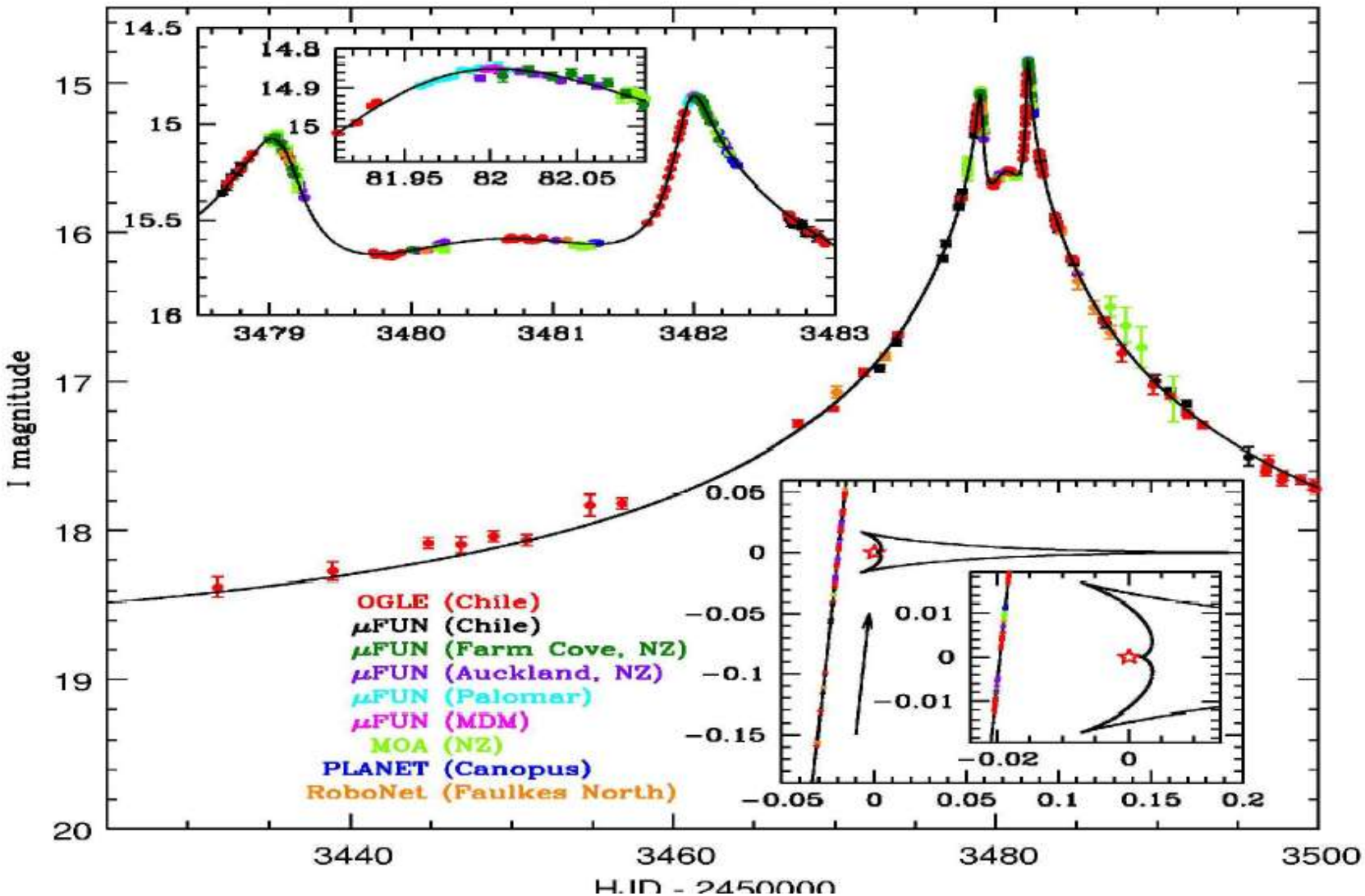
1995 PLANET Pilot Season

- Albrow et al. 1998 ApJ, 509, 687





Second Microlensing Planet



The New Zealand Connection

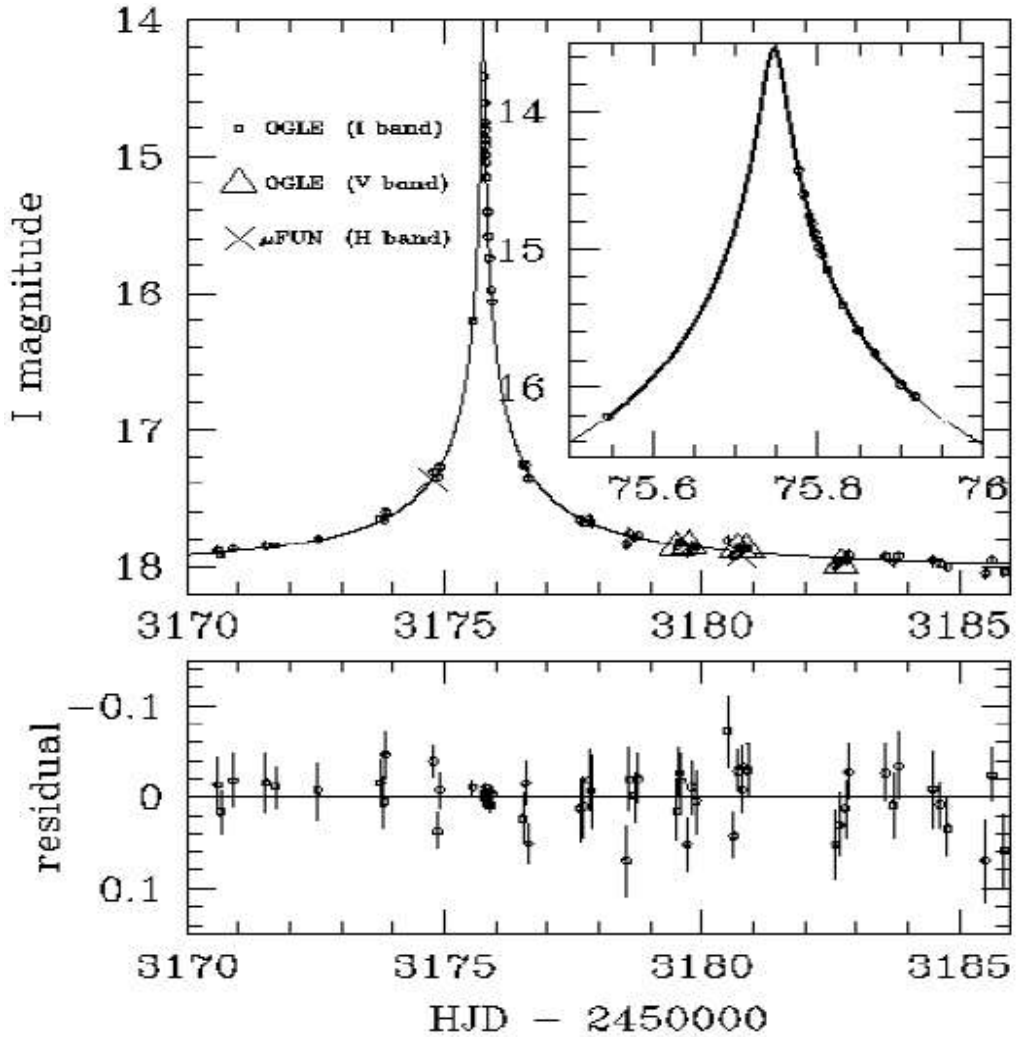
Grant, Ian, Jennie, Phil

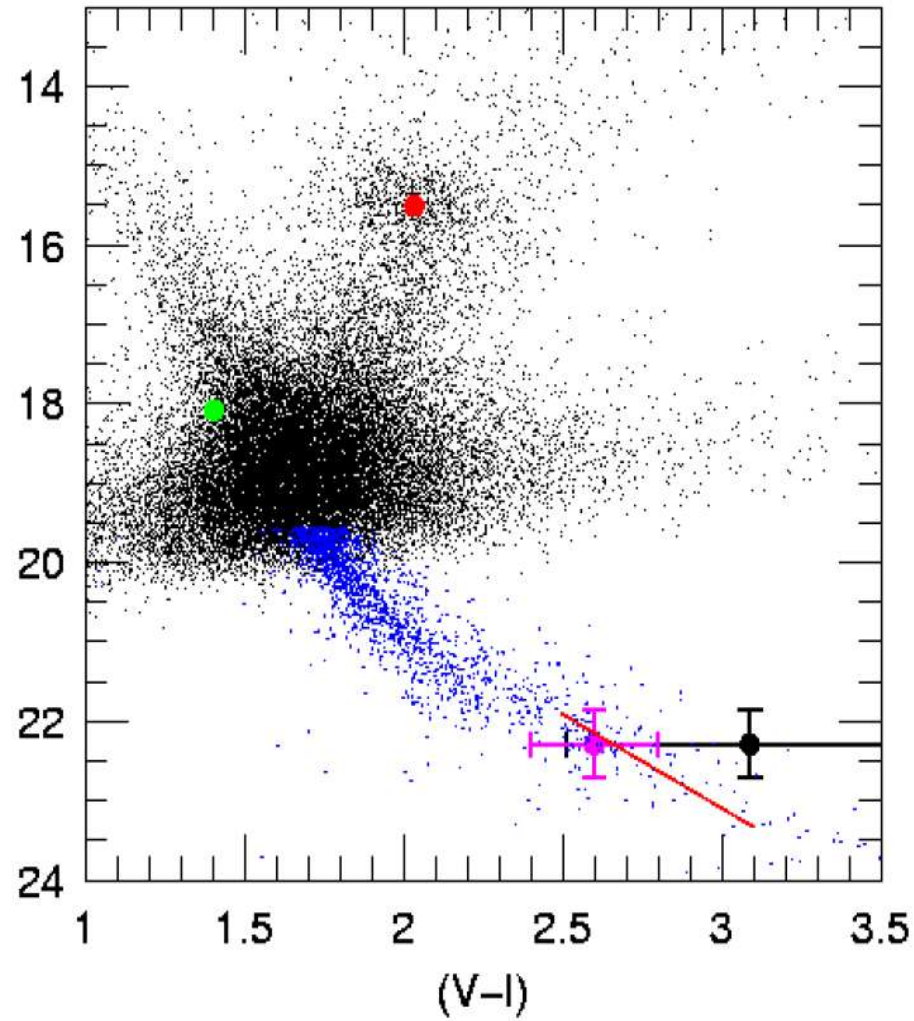
Amateurs + Professionals

"It just shows that you can be a mother you can work full-time, and you can still go out there and find planets."

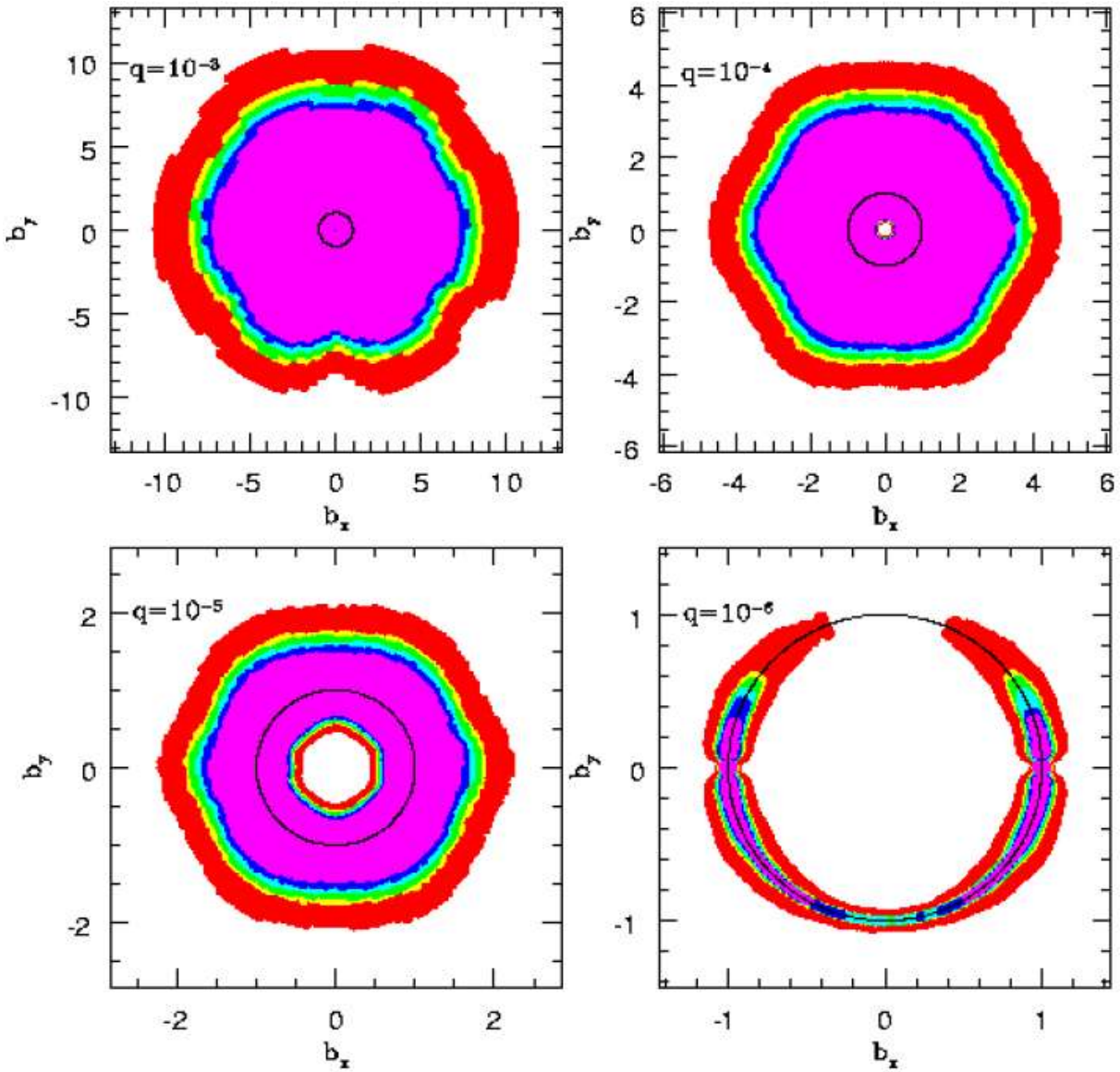
Jennie McCormick
(Amateur Astronomer, Auckland, New Zealand)

OGLE-2004-BLG-343
A Magnification A=3000 Event



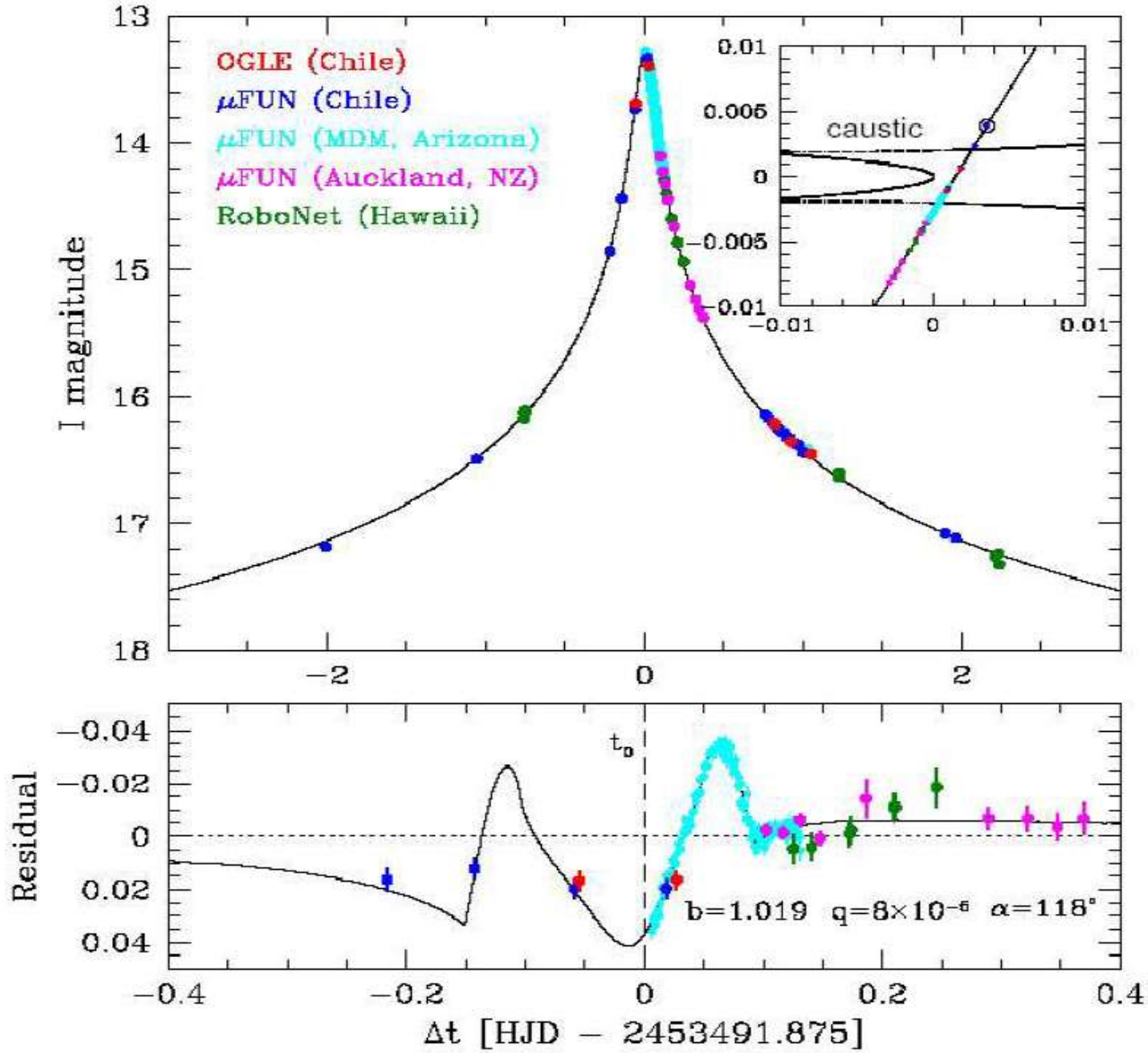


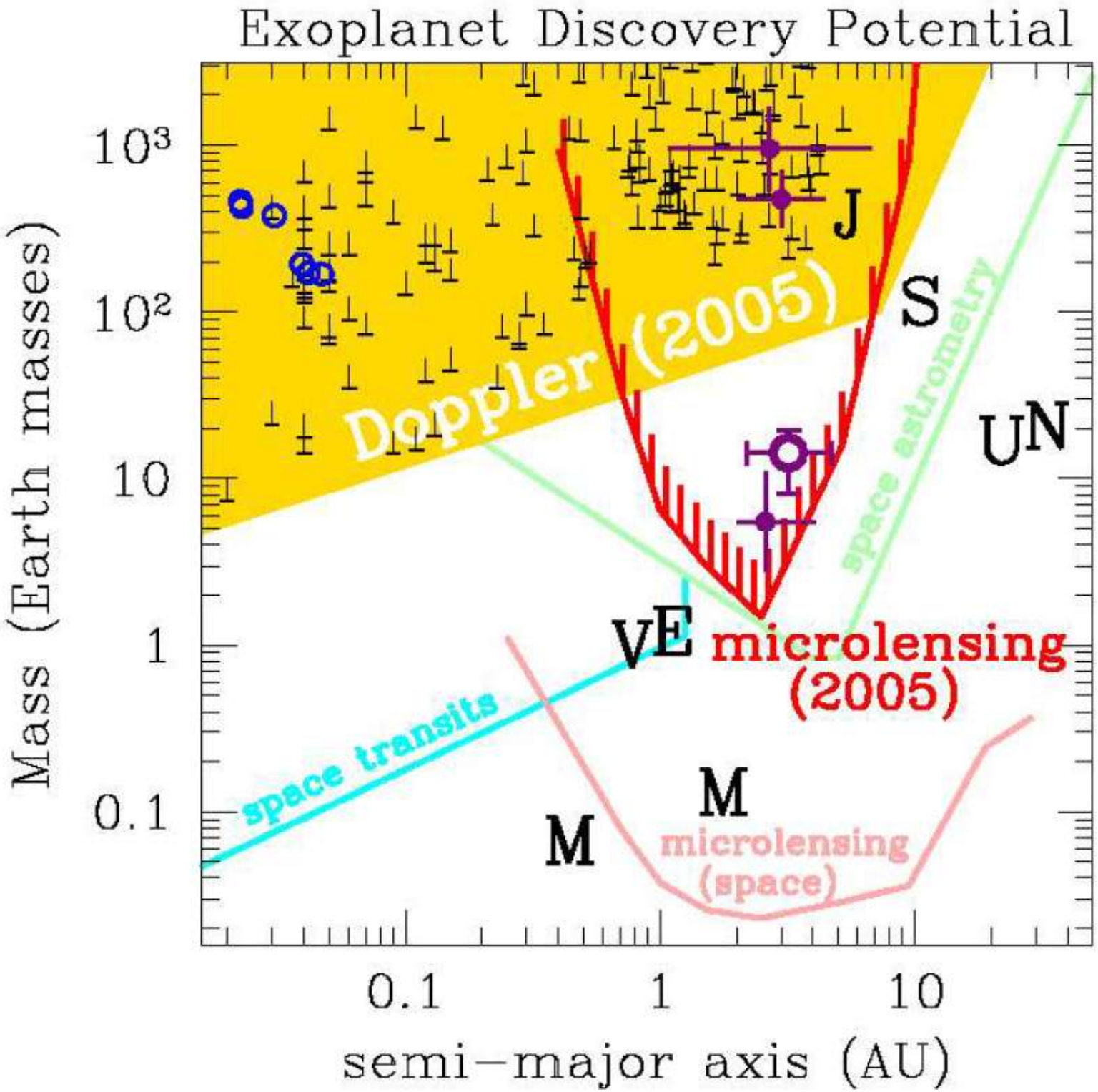
Sensitivity to Planets



OGLE-2005-BLG-169

Cold Neptune in Hi-Mag Event

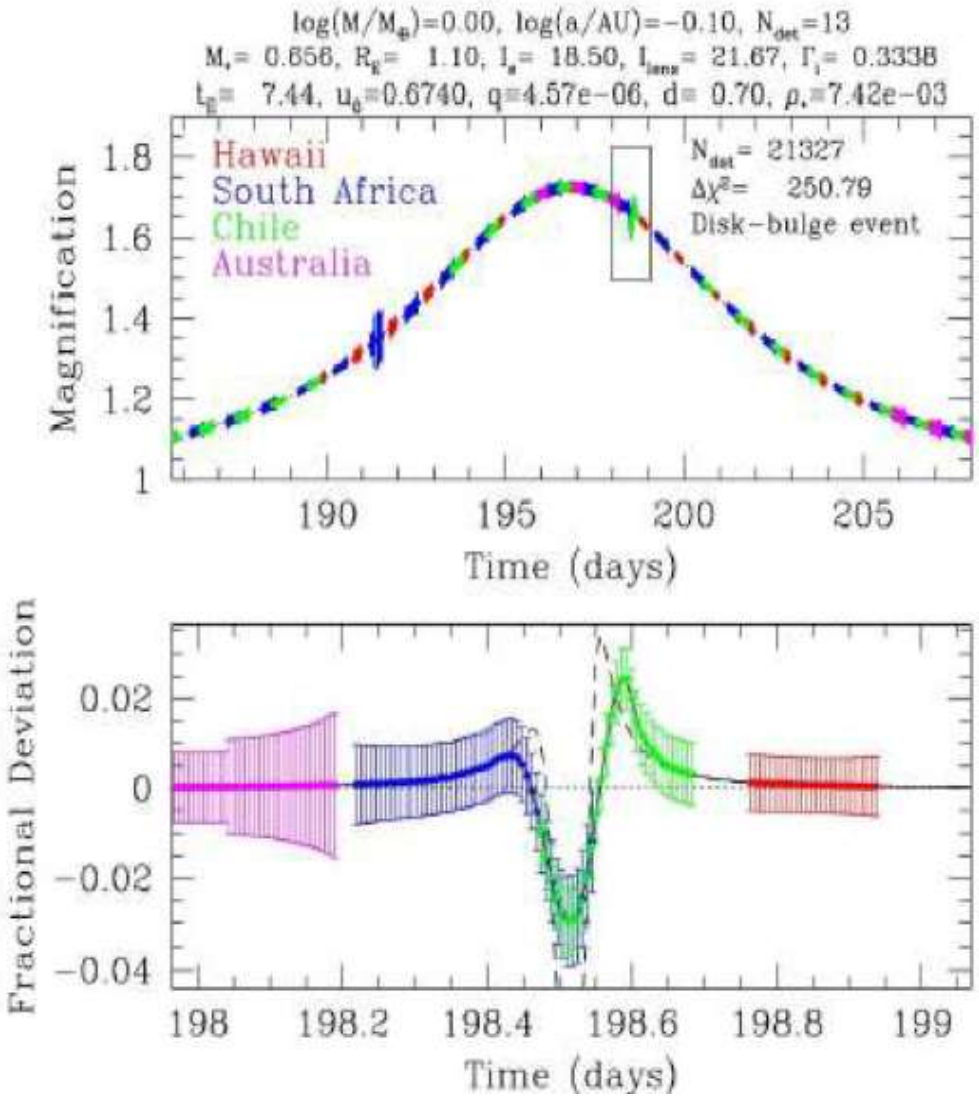


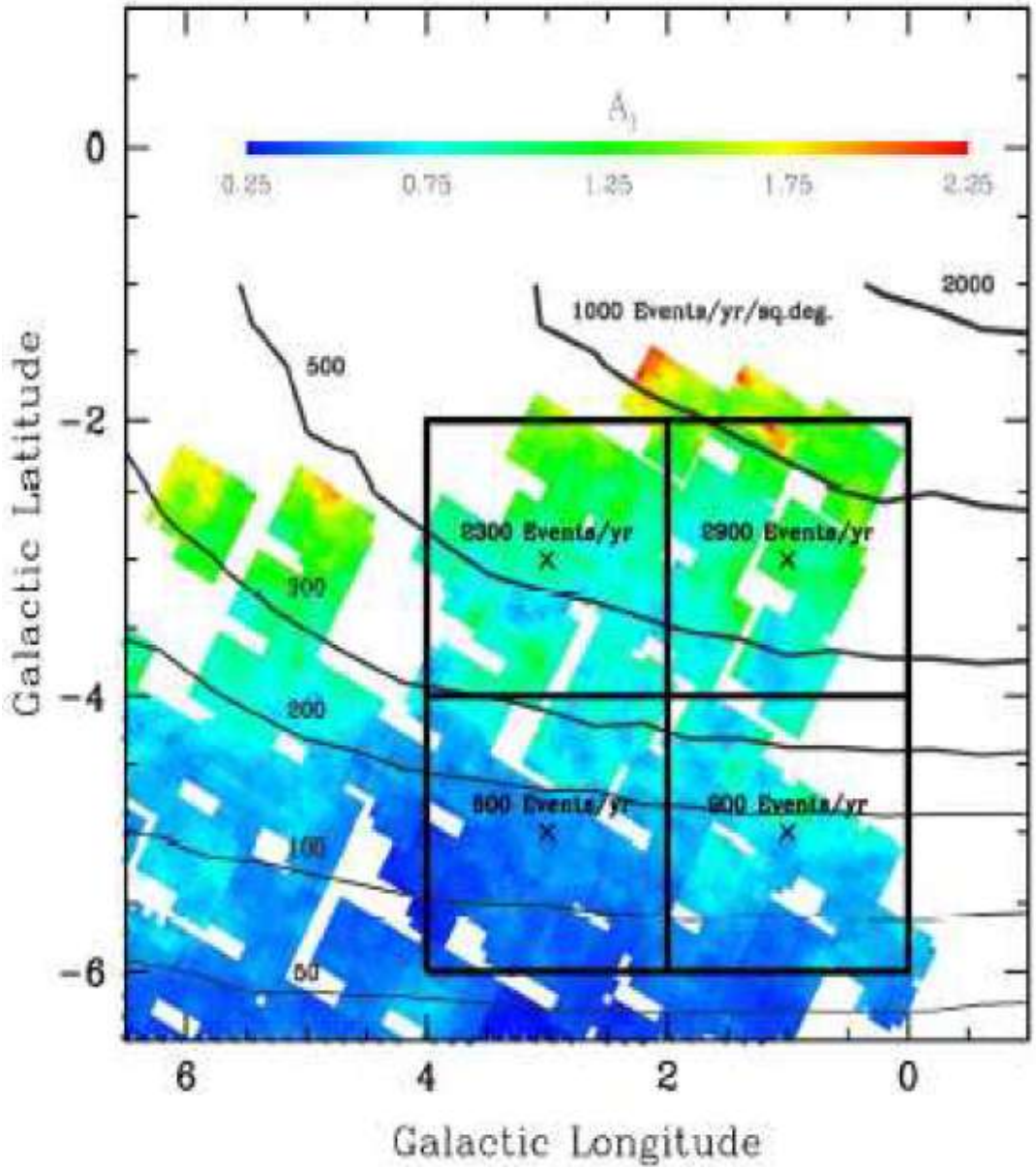

Exoplanet Discovery Potential
Mass (Earth masses)
semi−major axis (AU)
10³
10²
10
1
0.1
0.1
1
10
Doppler (2005)
J
S
UN
space astrometry
VE
microlensing
(2005)
space transits
M
M
microlensing
(space)

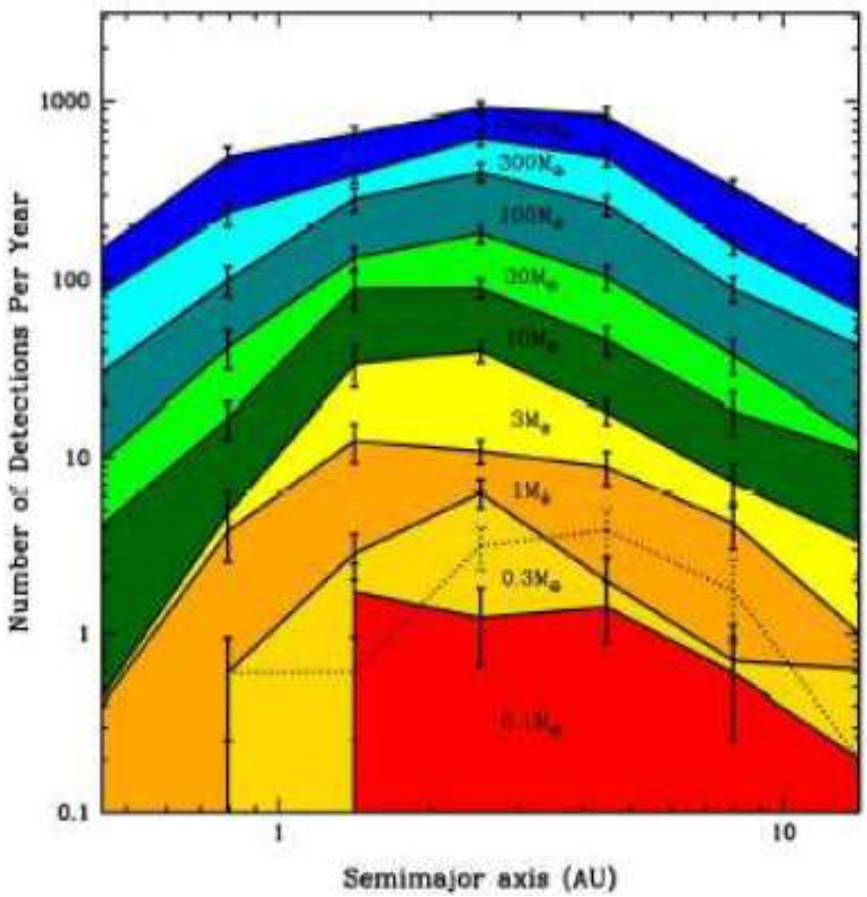
NextGen Microlensing Planet Search

Simulations by Scott Gaudi

- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit




A_I
0.25
0.75
1.25
1.75
2.25
1000 Events/yr/sq.deg.
2000
500
300
200
100
50
2300 Events/yr
2900 Events/yr
800 Events/yr
600 Events/yr
Galactic Latitude
Galactic Longitude
0
-2
-4
-6
6
4
2
0


Number of Detections Per Year
Semimajor axis (AU)
1000
100
10
1
0.1
1
10
300M⊕
100M⊕
30M⊕
10M⊕
3M⊕
1M⊕
0.3M⊕
0.1M⊕

Summary of Baseline Results

loga/AU)	-0.35	-0.10	0.15	0.40	0.65	0.90	1.15
Γ (yr^{-1})	0.4±0.4	3.8±1.2	12.5±3.1	10.9±1.7	8.8±1.9	4.3±1.2	1.0±0.7

Every MS star has one Earth-mass planet

loga/AU)	-0.35	-0.10	0.15	0.40	0.65	0.90	1.15
Γ (yr^{-1})	0	0.6±0.3	0.6±0.4	3.1±0.9	3.9±1.2	1.8±0.9	0.2±0.2

Every MS star has one Earth mass ratio planet

$\log(M/M_{\oplus})$	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Γ (yr^{-1})	1.5±0.3	3.7±0.5	12±1	30±3	78±8	150±10	350±20	590±30	1012±40

2 planets per star, uniformly distributed in log a in the range 0.4-20 AU

Time-Domain Parameter Space for Large-Telescope Instruments

II: Targeted Photometry

- Target of Opportunity

  High-mag microlensing events

  GRBs

  Unclassified Transients

- Periodic Variables

  Transits

- High-Speed and Ultra-High Speed

  Cataclysmic Variables

  Occultations

ULTRACAM (VLT)

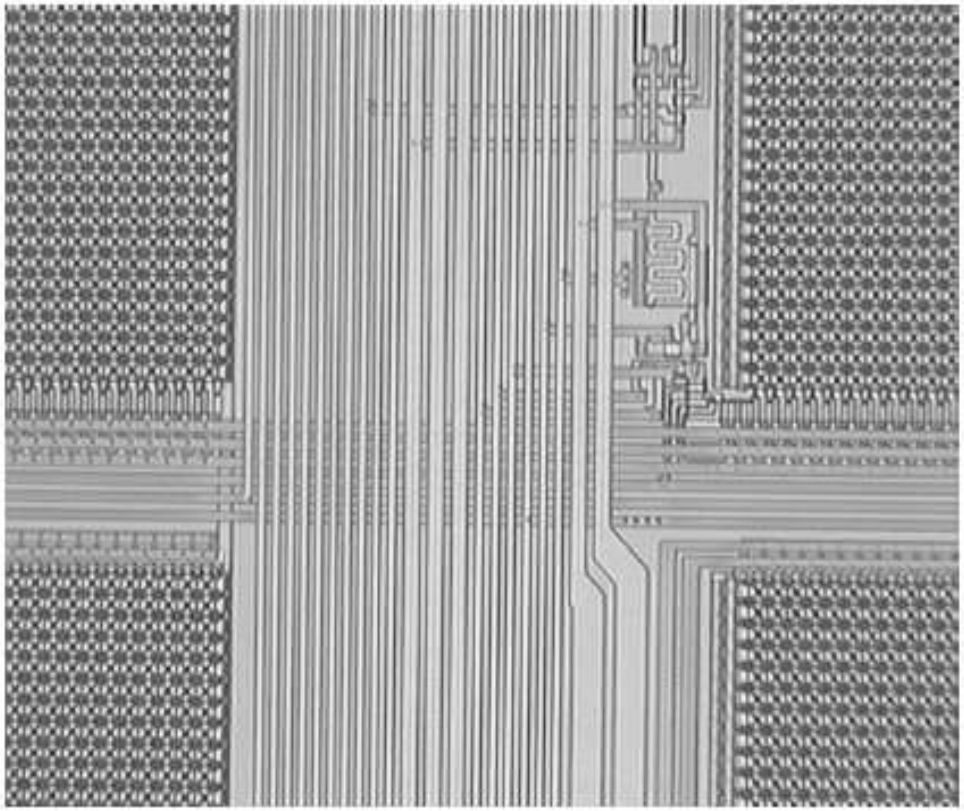
- 2.5' FOV
- 0.15" pixels
- up to 500 Hz
- Simultaneous 3-color

ULTRACAM Mounted on Visitor Focus of MELIPAL

ESO PR Photo 19a/05 (9 June 2005)

WIYN Orthogonal-Transfer Chips

- Separate (rapid)readout for bright stars
- Primary purpose: tip-tilt corrections
- Could be used for high-speed photometry



Time-Domain Parameter Space for Large-Telescope Instruments

III: Targeted Spectroscopy

- Target of Opportunity

  High-mag microlensing events

  GRBs

  SNe

  Unclassified Transients

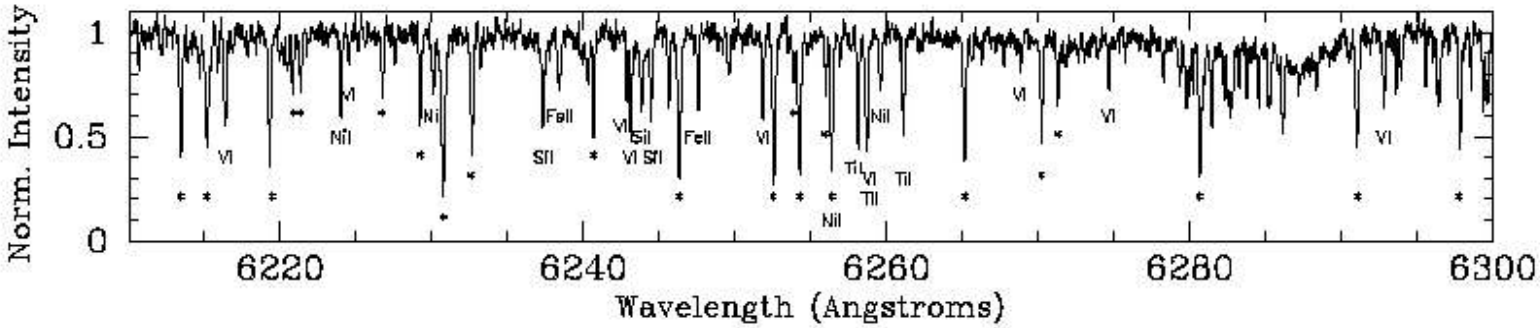
- Periodic Variables

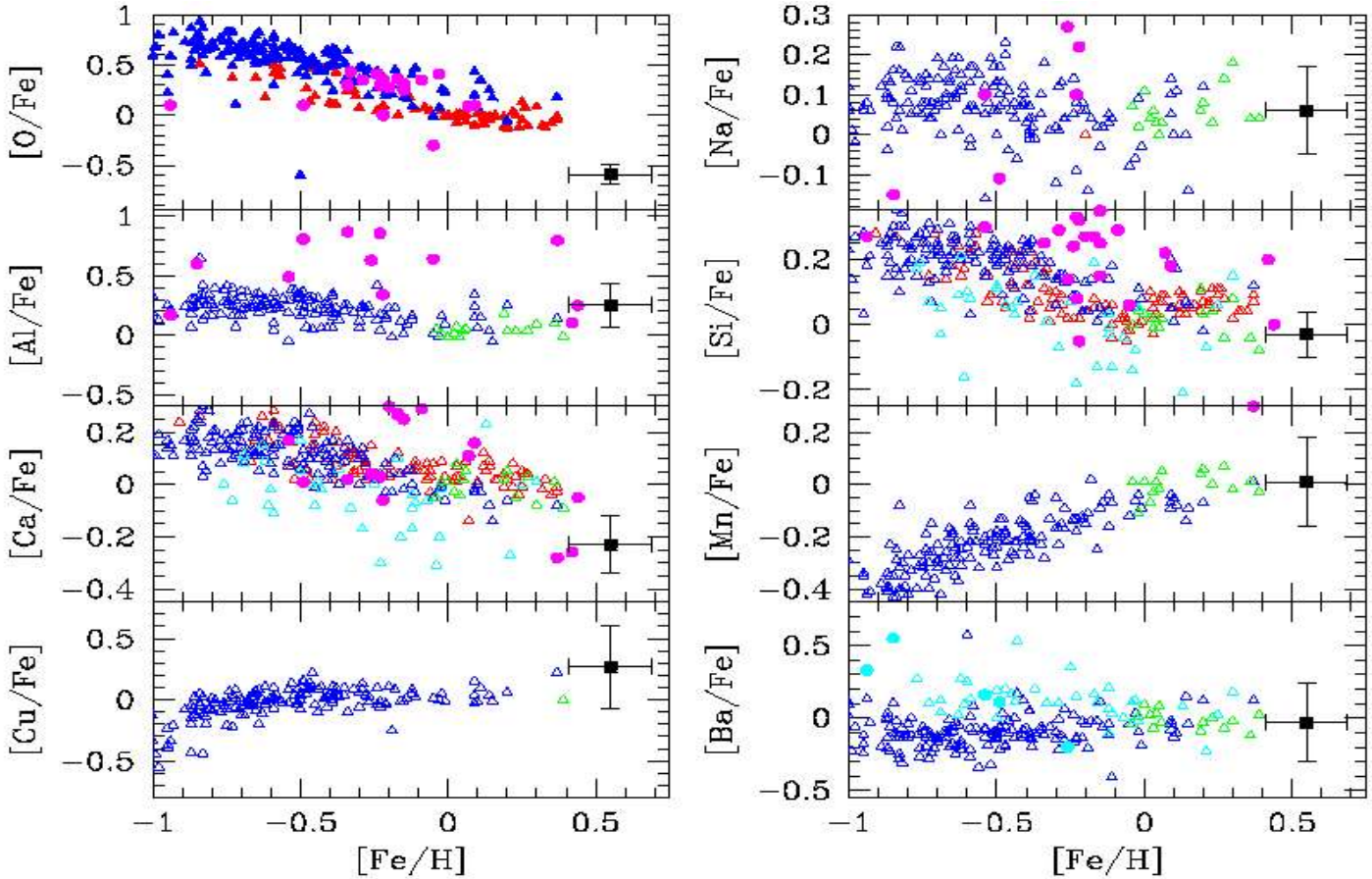
  Transits

  RV

OGLE-2006-BLG-265

15-min exposure on “V=20” star





Time-Domain Parameter Space for Large-Telescope Instruments

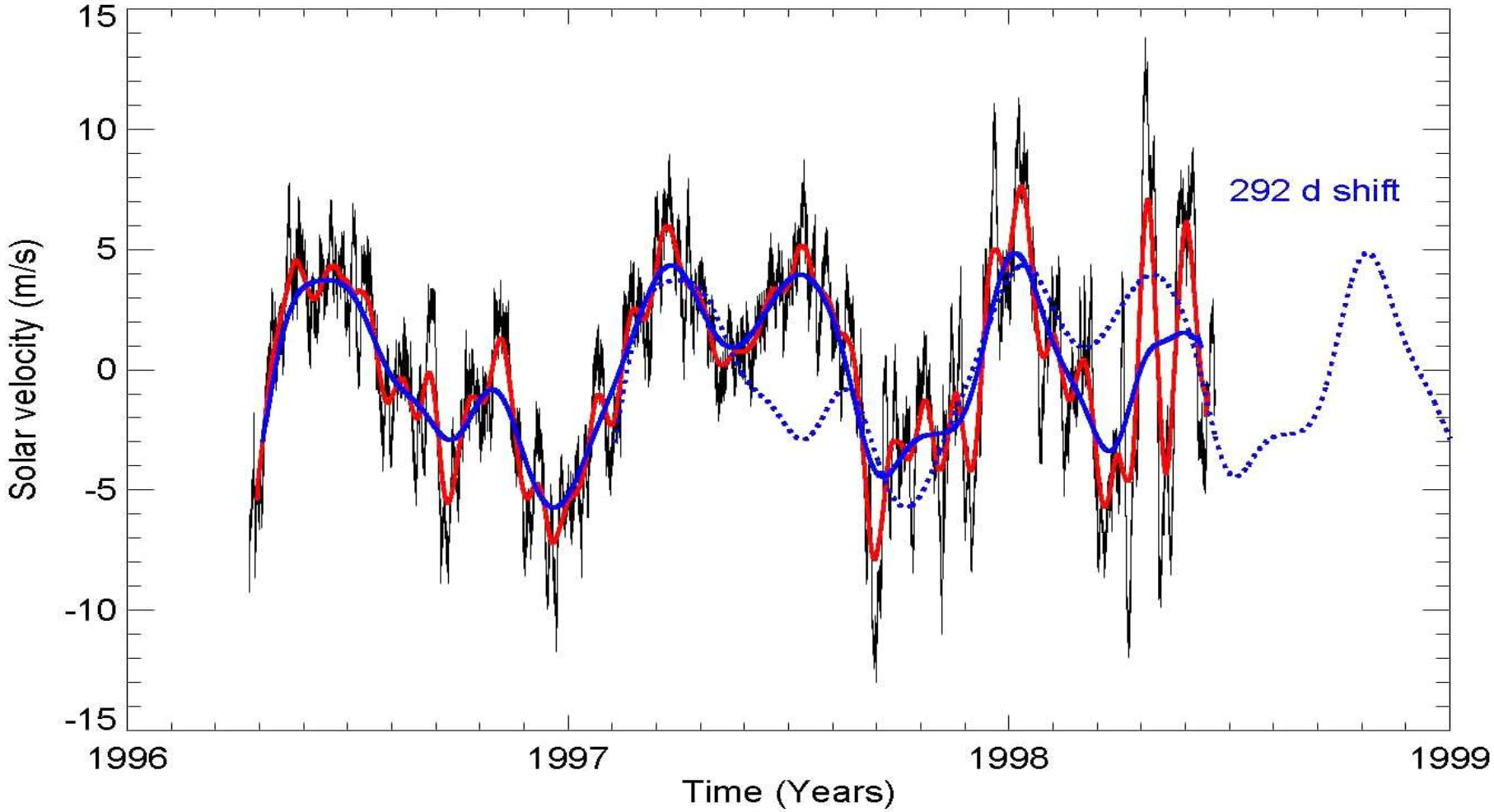
IV: Spectroscopy Survey

- RV Planet Searches
- Multi-Object
  (Surface Brightness Prob)
- Single-Object
  Earth-mass habitable-zone planets

Standard Lore on RV Precision

- 1 m/s per observation achievable
- Can continue to beat down noise by root-N
- Fundamental limit: stellar-atmosphere noise
- Dramatically confirmed in Sun

SOHO RV Data


15
10
5
0
-5
-10
-15
Solar velocity (m/s)
1996
1997
1998
1999
Time (Years)
292 d shift

Earth-Mass Habitable-Zone RV Search

- Slightly earlier (Mv=6) stars more stable
- sigma = 1m/s: D=6m, 5 min exp, at 10pc (V=6)
- Reflex speed = 17 cm/s
- Each measurement: ~Reflex/sqrt{3} = 10 cm/s
- 2500 measurements for 5 sigma detection
- (80 meas/night)x(250 night/yr)x5yrs = 10^5 meas
- Could probe 40 stars

Summary

- Targeted Photometry:
  Rapid, reliable access to “standard instruments”
  +High-speed photometers (“specialized”)
- Targeted Spectroscopy:
  Rapid reliable access to “standard instruments”
- Photometric Surveys :
  Microlensing, SN [need semi-dedicated access]
- Spectroscopic Surveys:
  Dedicated RV search for Habitable Earths