The next generation of microlensing planet searches

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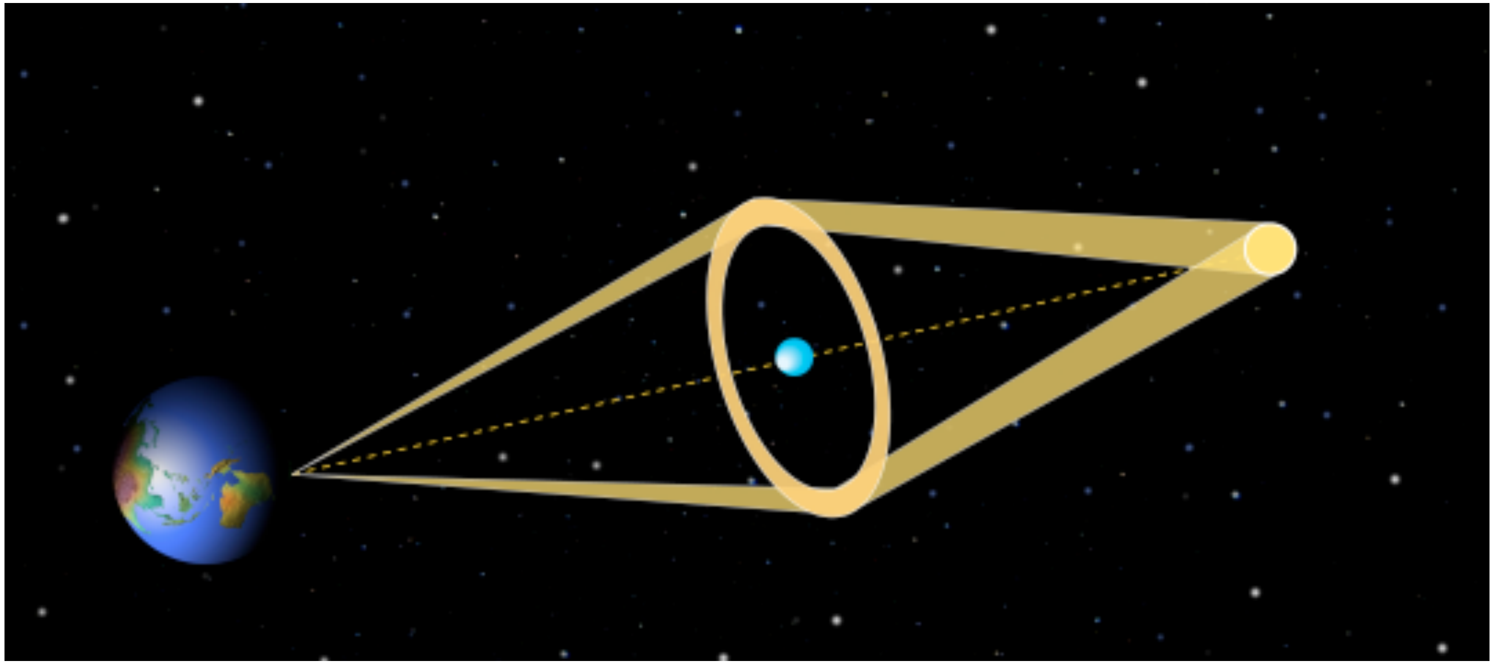
Microlensing: Relativity in action!

- Einstein 1915: a massive object in the line of sight will produce multiple images of a 'source'
- Individual images are separated by ~mas, can't be resolved but net magnification effect (Einstein 1936)
- Alignment needs to be so precise that Einstein thought this effect would never observed because of only $\sim 10^{-6}$ chance

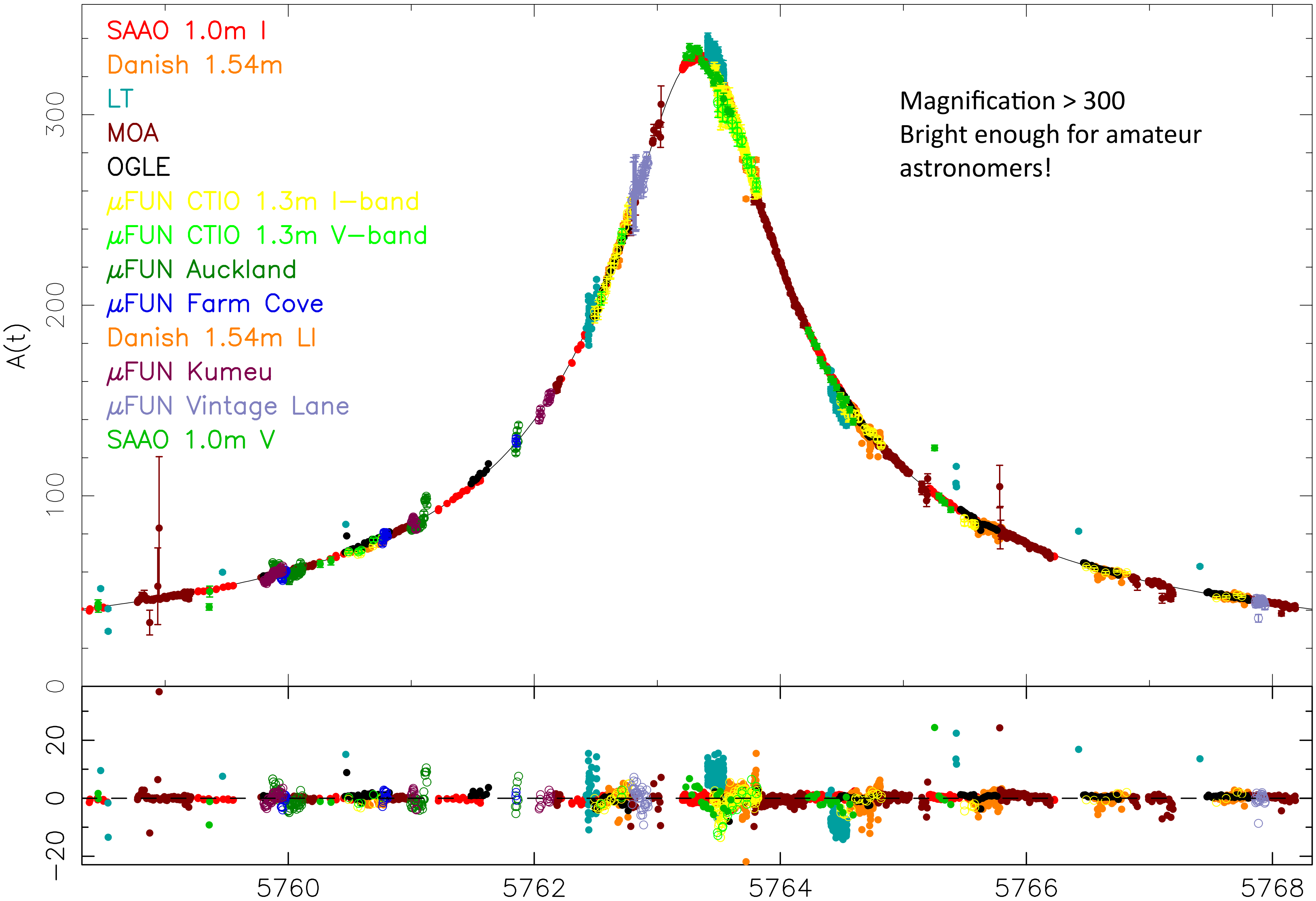
Theory to observations

- 1986: Paczynski suggests using microlensing to search for MACHOs (dark matter) → EROS and MACHO teams
- 1989: first detection of the microlensing effect by Irwin et al.
- 1991: Paczynski suggests using it to search for planets, founds OGLE in 1992; start of Bulge monitoring

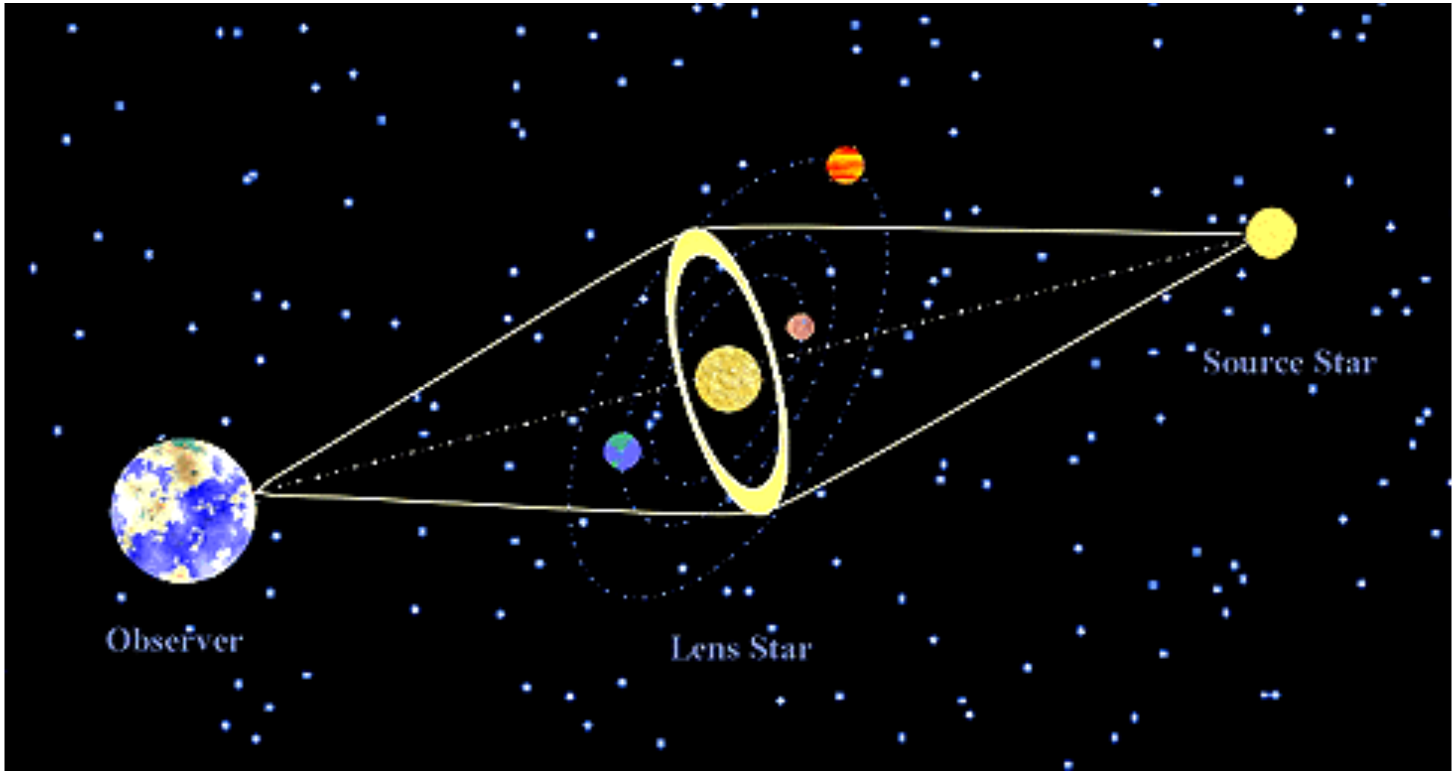
Single-lens microlensing



Credit: University of Victoria, NZ


SAAO 1.0m I
Danish 1.54m
LT
MOA
OGLE
μFUN CTIO 1.3m I−band
μFUN CTIO 1.3m V−band
μFUN Auckland
μFUN Farm Cove
Danish 1.54m LI
μFUN Kumeu
μFUN Vintage Lane
SAAO 1.0m V
Magnification > 300
Bright enough for amateur astronomers!
A(t)
0
100
200
300
−20
0
20
5760
5762
5764
5766
5768

Finding planets with microlensing

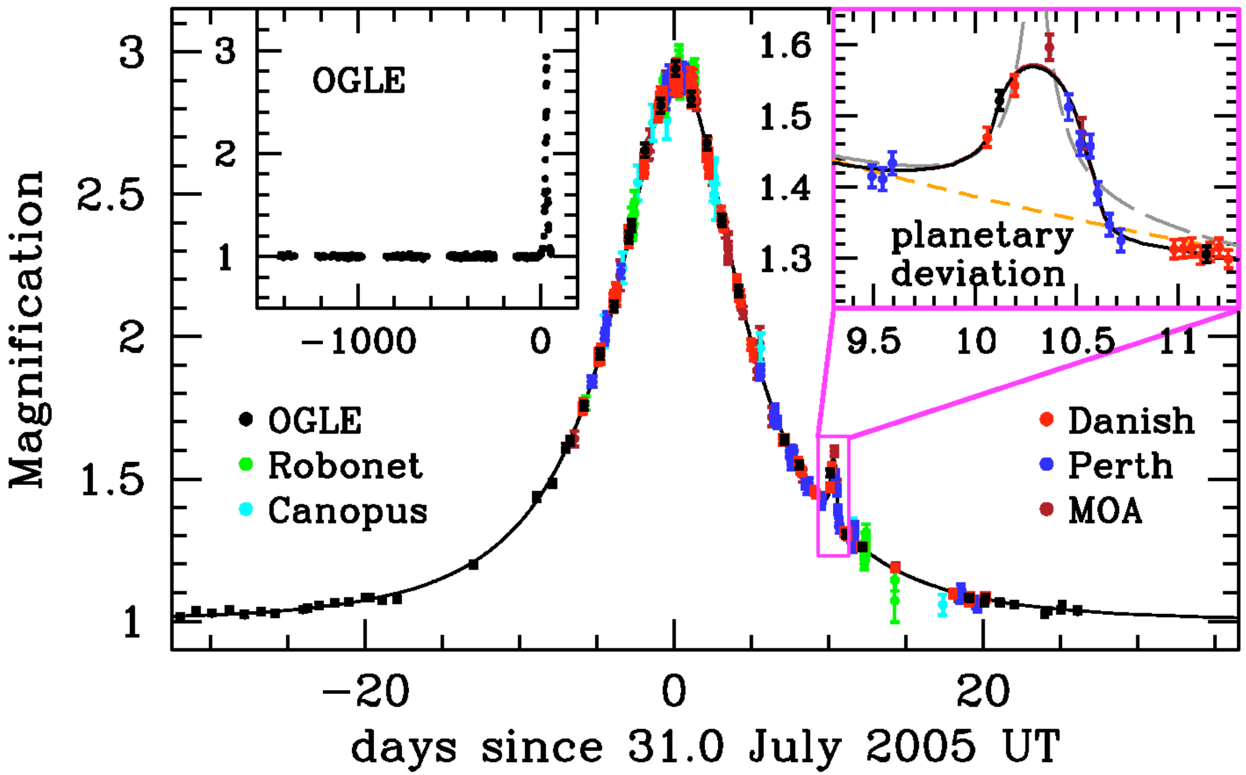


Credit: Rick Hessman (Göttingen)

Planetary systems as lenses

- Multiple bodies in lens (e.g. planets) add a whole layer (/ a number of layers) of complexity
- Give rise to caustics, regions of space where magnification gradient is large
- Source approaching/ hitting caustics gives rise to lightcurve "anomalies"
- Strength of signal is *not* strongly mass-dependent, but duration is
- Main limiting factor: source star size (large sources wash out short signals)

Lightcurve “anomalies”

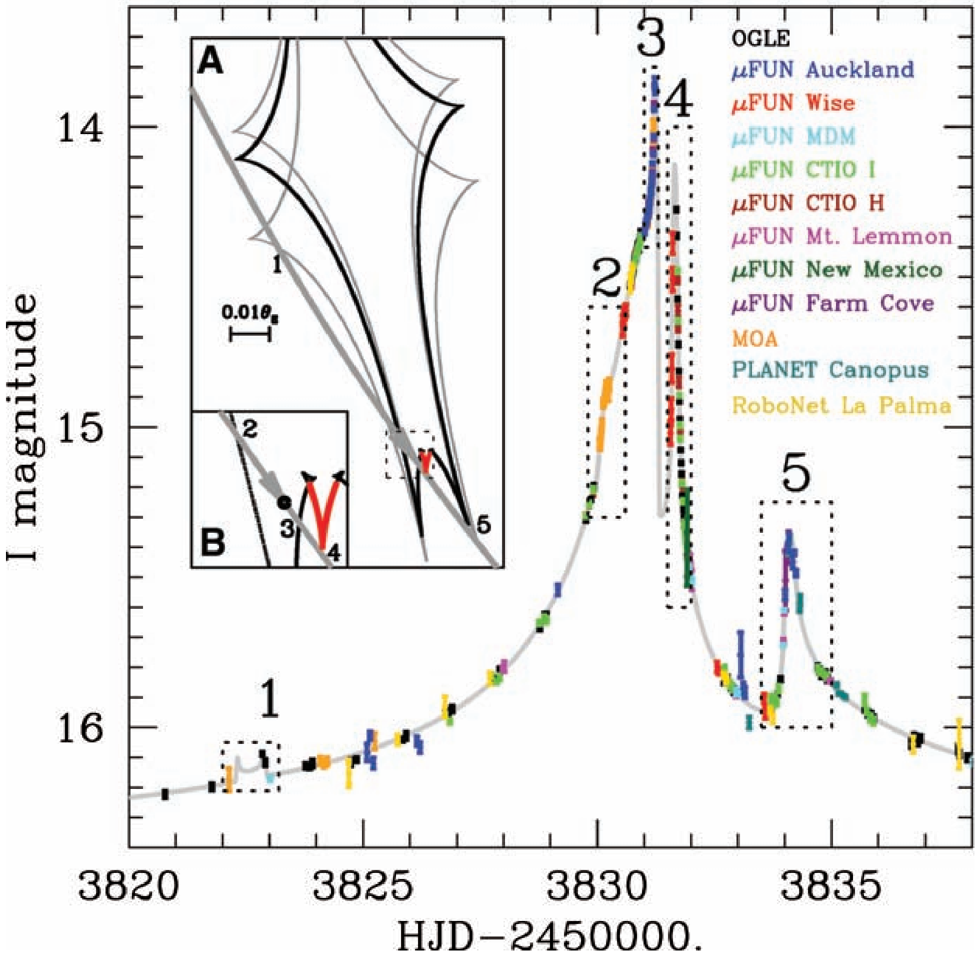


Beaulieu et al. 2006

OGLE-2005-BLG-390Lb

First low-mass (5.5 M_E), cool, rocky exoplanet

‘Textbook’ microlensing anomaly, lasted ~1 day

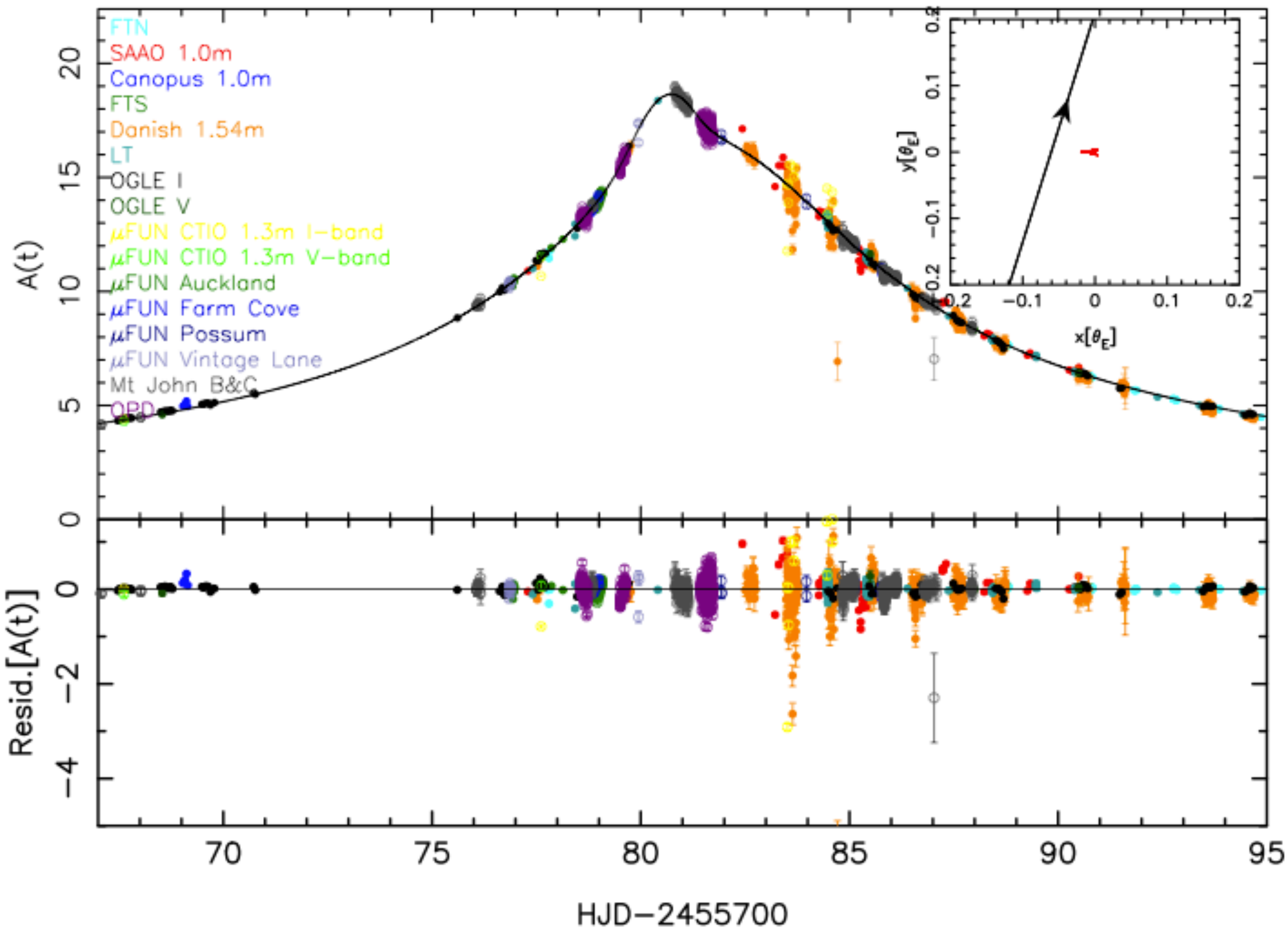


OGLE-2006-BLG-109Lb, c

A 'scaled down' Jupiter+Saturn analogue

Lots of subtle deviations in data, required modelling orbital motion of the planet around the lens

Gaudi et al. 2008

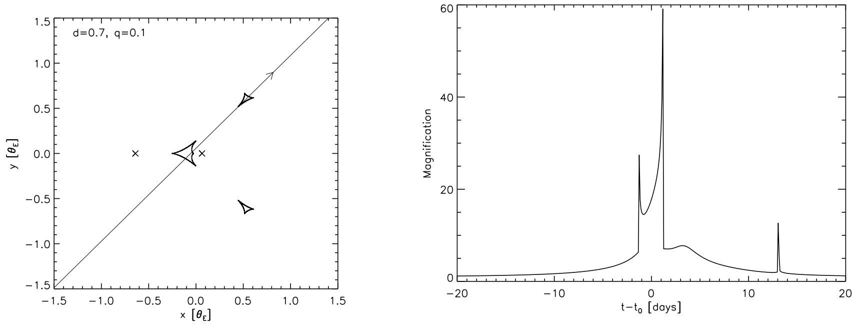


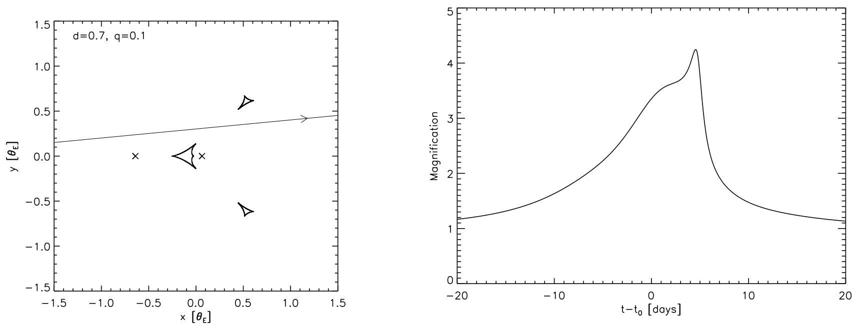
Kains et al. 2012 in prep.

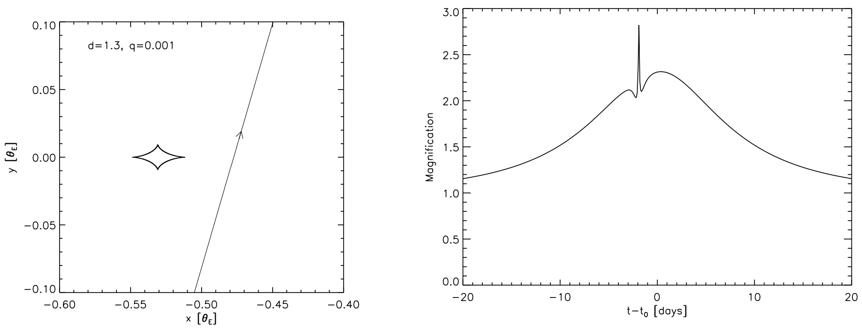
Anomalies

- No simple selection criterion
- Microlensing “anomalies” (e.g. planetary signals) come in a huge variety of shapes and timescales (few hours - few days)
- Non-planetary signals can mimic planetary ones

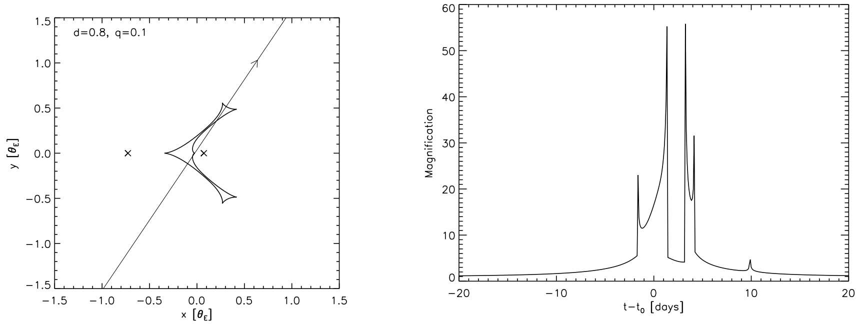
Microlensing anomalies zoo

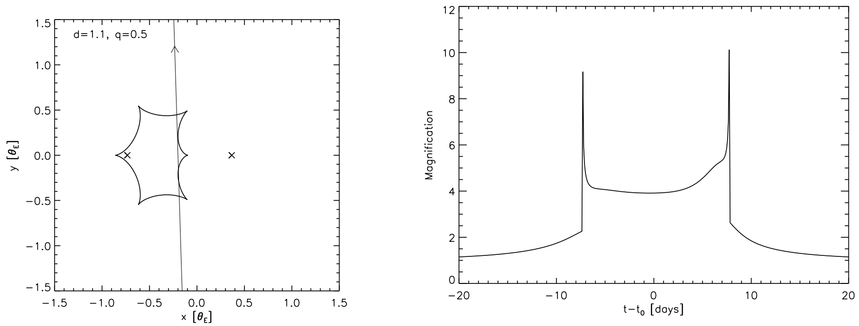


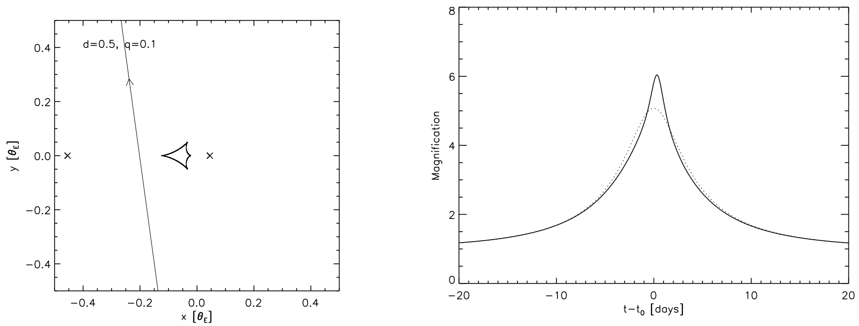




Microlensing anomalies zoo





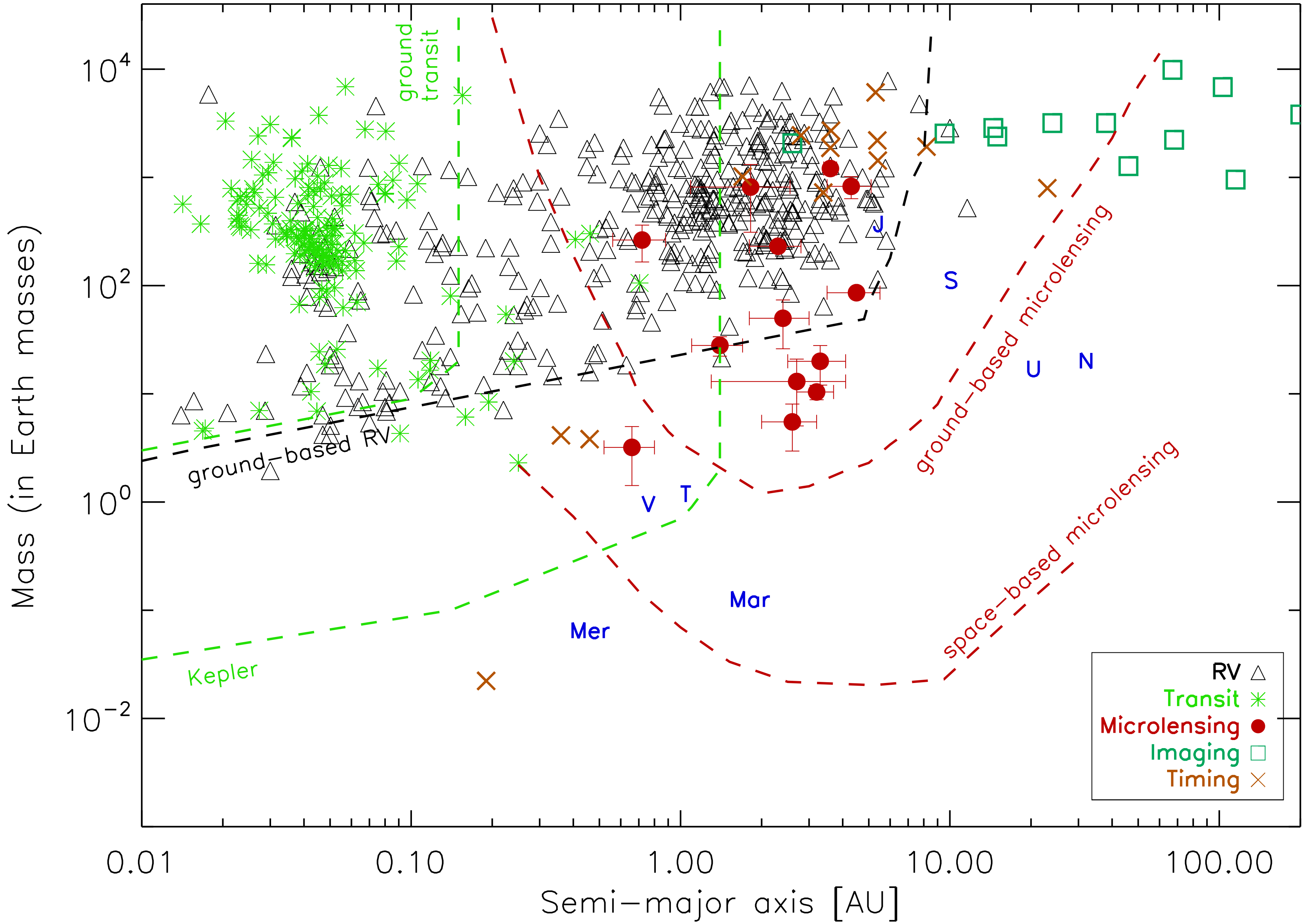


NK PhD thesis

Why microlensing?

- Niche in parameter space of planet detection methods: cool (1-10 AU) low-mass planets
- Can probe distant (1-8 kpc) planets
- Only way to probe free-floating planet populations (Sumi et al. 2011)

→ A great complement to other methods to test models of planet formation



Mass (in Earth masses)
Semi−major axis [AU]
0.01
0.10
1.00
10.00
100.00
10^4
10^2
10^0
10^{-2}
ground transit
ground−based RV
Kepler
ground−based microlensing
space−based microlensing
Mer
V
T
Mar
J
S
U
N
RV
Transit
Microlensing
Imaging
Timing

How things work

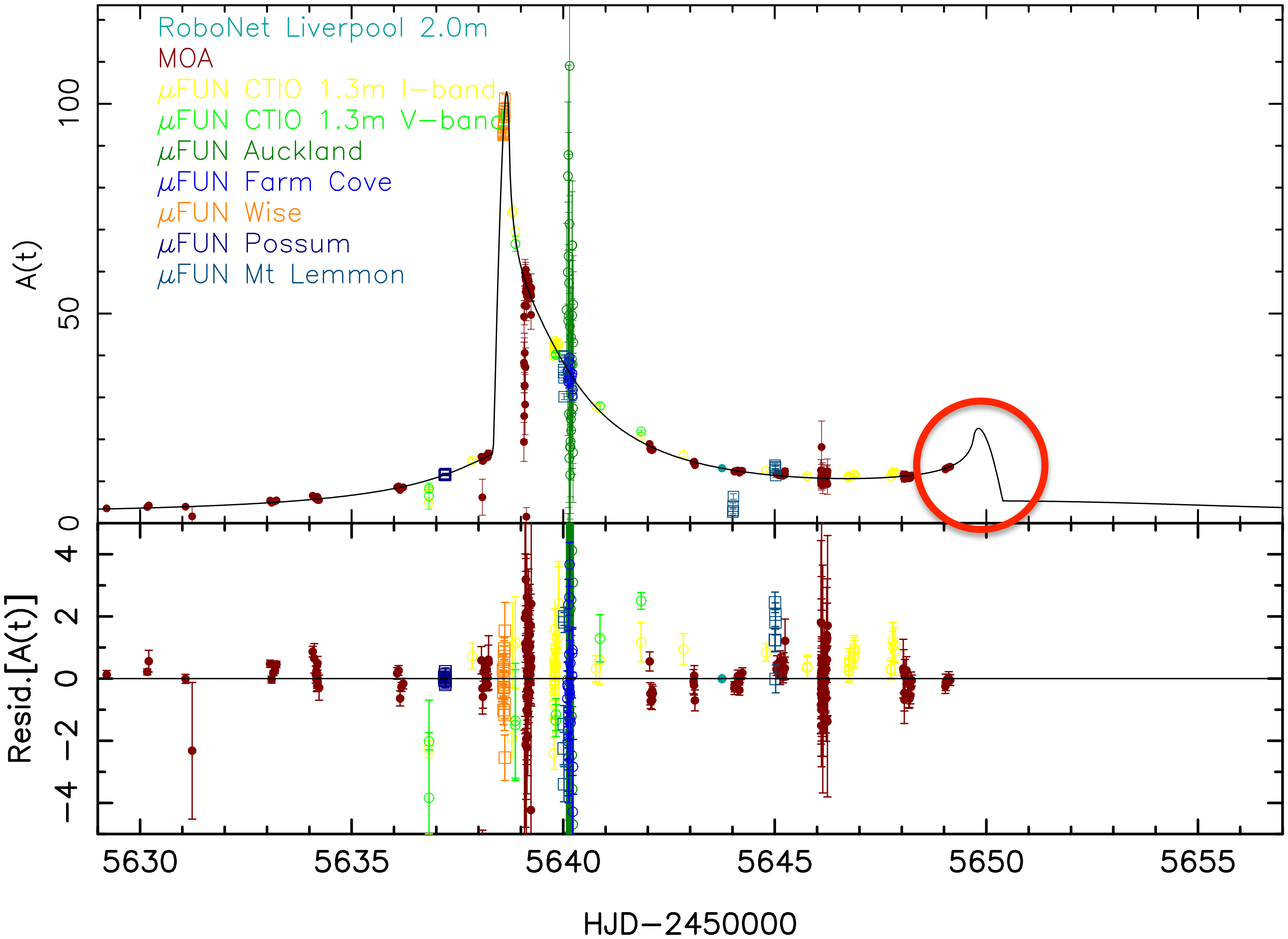
- Survey teams (OGLE, MOA) monitor the Bulge and send out microlensing alerts
- Follow-up teams (MiNDSTEp, PLANET, μFUN, …) select promising candidates and try to catch short planetary anomalies
- Up to 2011: anomaly alerts, modelling done “by hand” with humans looking at lightcurves

New generation microlensing observations

- Since 2011: OGLE-IV upgrade → 1500+ microlensing events/ season
- Can't follow up all of them, and difficult to select which ones to observe
- "By hand" only approach not possible anymore
- Massive effort into automatising:
  - Anomaly detection (e.g. Dominik et al. 2007)
  - Modelling (e.g. Kains et al. 2009, 2012, Cassan et al. 2008, 2010, Bozza…)
  - Follow-up observations (robotic telescopes)

Real-time modelling

- A microlensing event only happens once! So need to nail down any lightcurve features to constrain lens (/planet) properties
- Real-time modelling allows us to predict possible upcoming features and make sure they are observed
- Microlensing modelling is computationally intensive (a single modelling run can take days), and the parameter space is very complex


RoboNet Liverpool 2.0m
MOA
μFUN CTIO 1.3m I−band
μFUN CTIO 1.3m V−band
μFUN Auckland
μFUN Farm Cove
μFUN Wise
μFUN Possum
μFUN Mt Lemmon
A(t)
Resid.[A(t)]
HJD−2450000
5630
5635
5640
5645
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50
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−2
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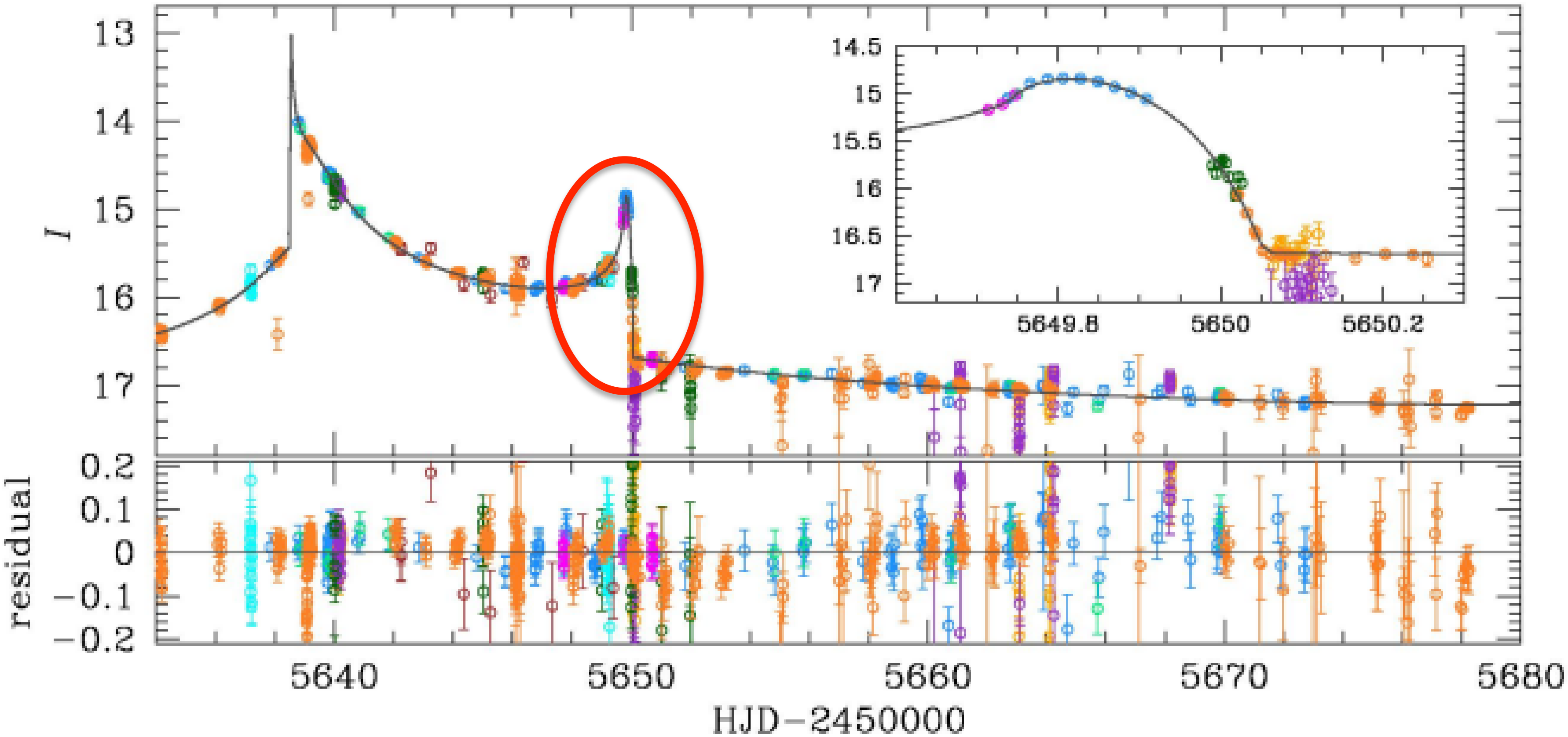
2
4

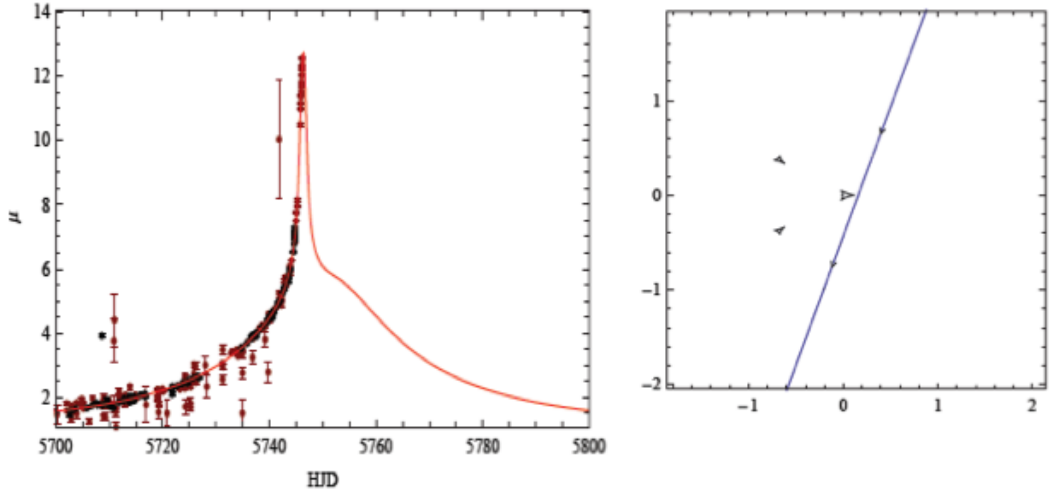
Model by NK

And a few days later…

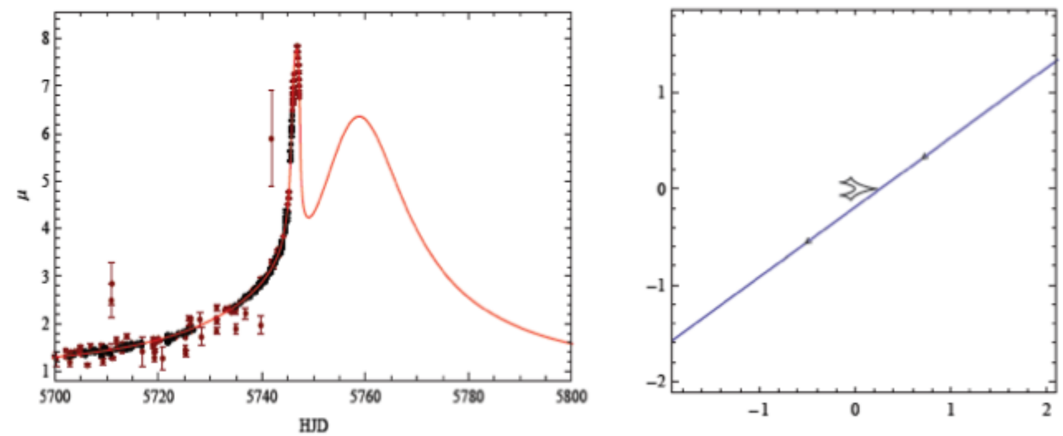


Model by C. Han+

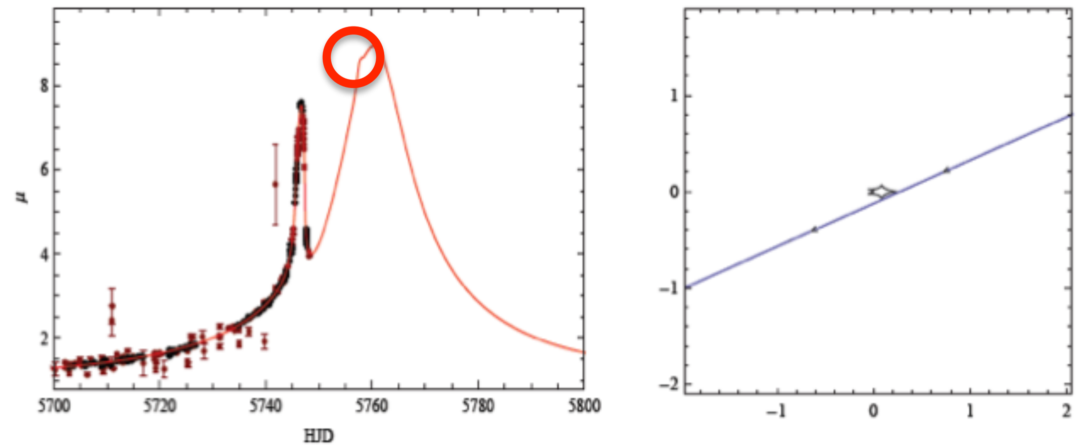
Real-time modelling by V. Bozza



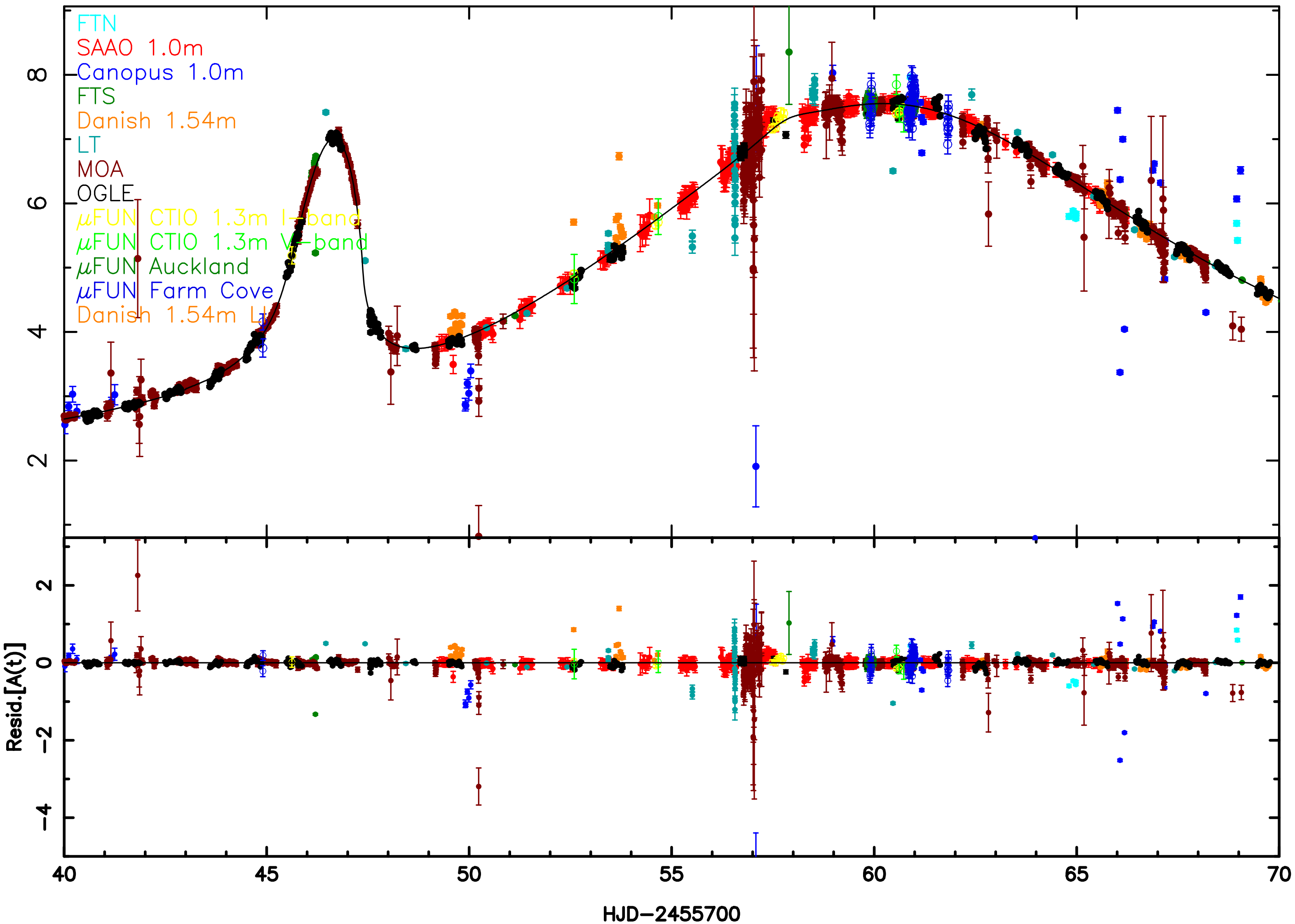
12 hours later



36 hours later: ~final model, predicts another feature

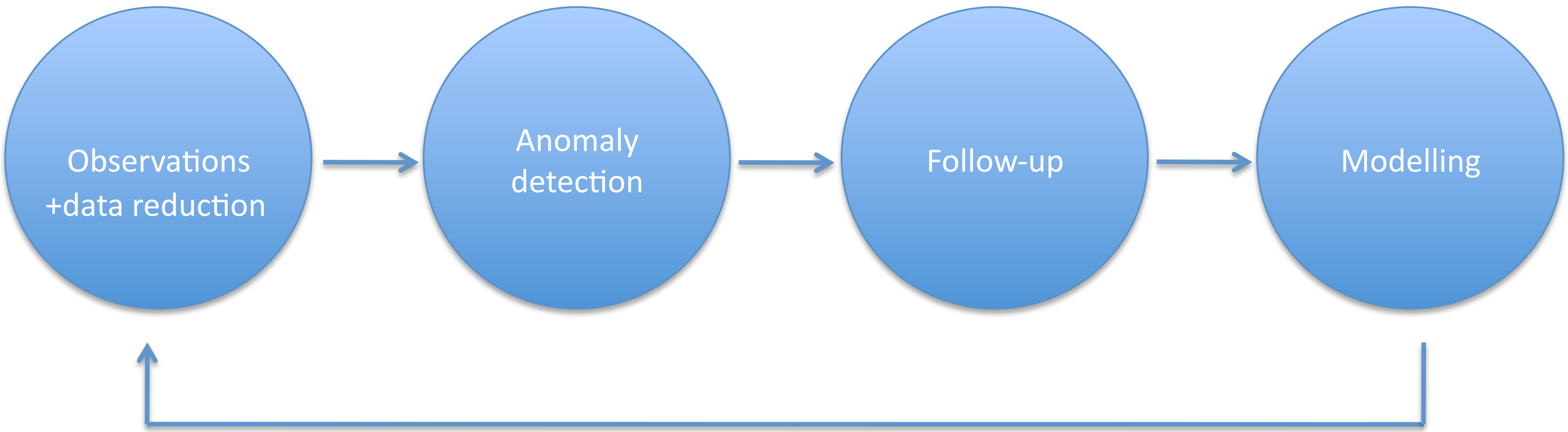


Final model


FTN
SAAO 1.0m
Canopus 1.0m
FTS
Danish 1.54m
LT
MOA
OGLE
μFUN CTIO 1.3m I-band
μFUN CTIO 1.3m V-band
μFUN Auckland
μFUN Farm Cove
Danish 1.54m Lu
Resid.[A(t)]
HJD−2455700

Immediate future: robotic telescopes

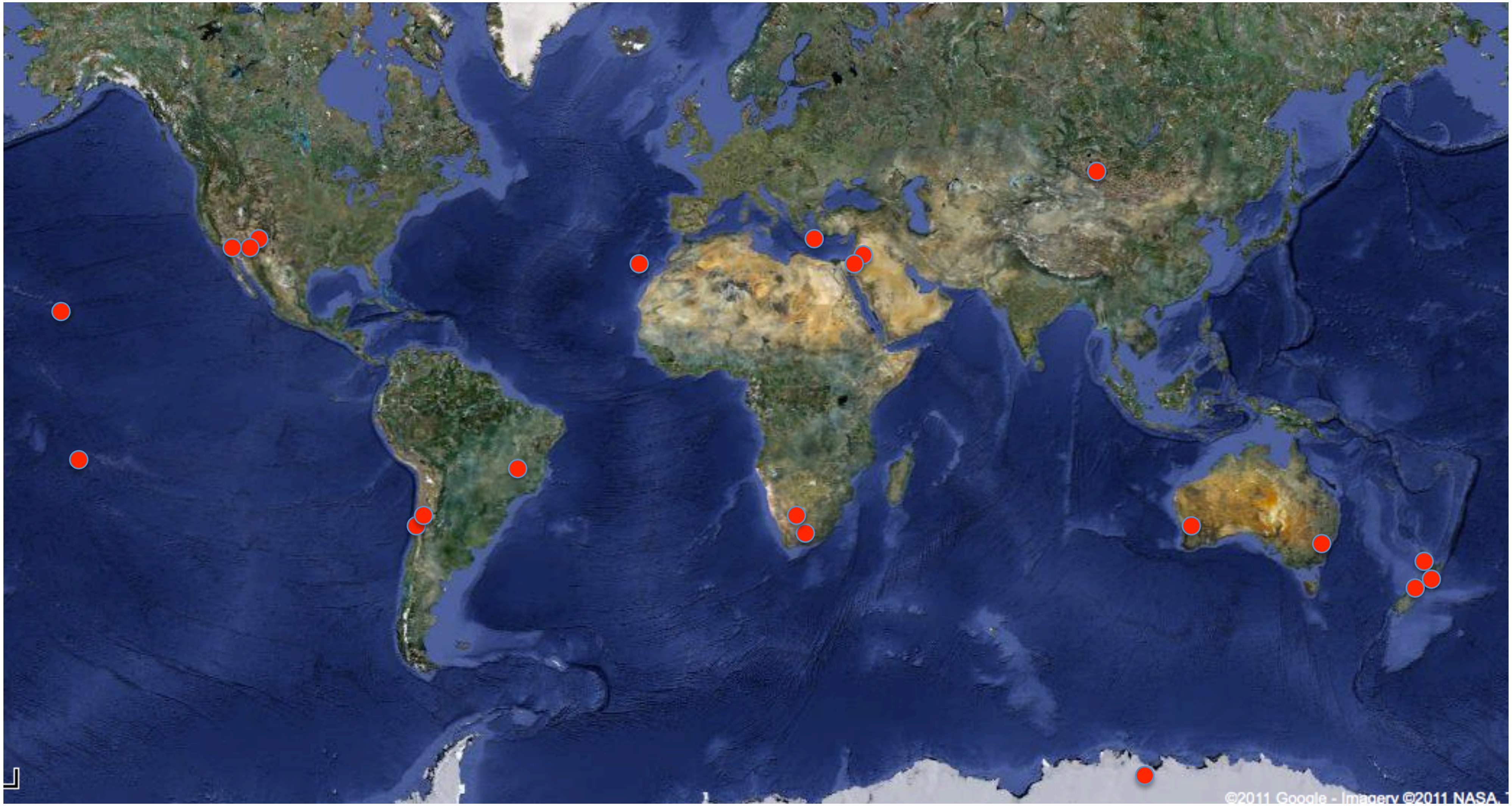
- Aim: remove as much of the human element as possible so that we can extract unbiased statistics from microlensing observations
- Ideally, self-sufficient (!) robotic telescope network system:



Robotic telescope networks

- LCOGT: 2 x 2m already in use, 4 x 1m being set up, long-term up to 40 telescopes; significant time set aside for educational use
- KMTNet: Korean network, 3 x 1.6m with 24h coverage
- SONG: Danish network (U. of Aarhus) of 1-m class telescopes. Primary science: asteroseismology and microlensing

LCOGT, KMTNet, SONG will all have microlensing as a major focus; full longitudinal coverage + robotic



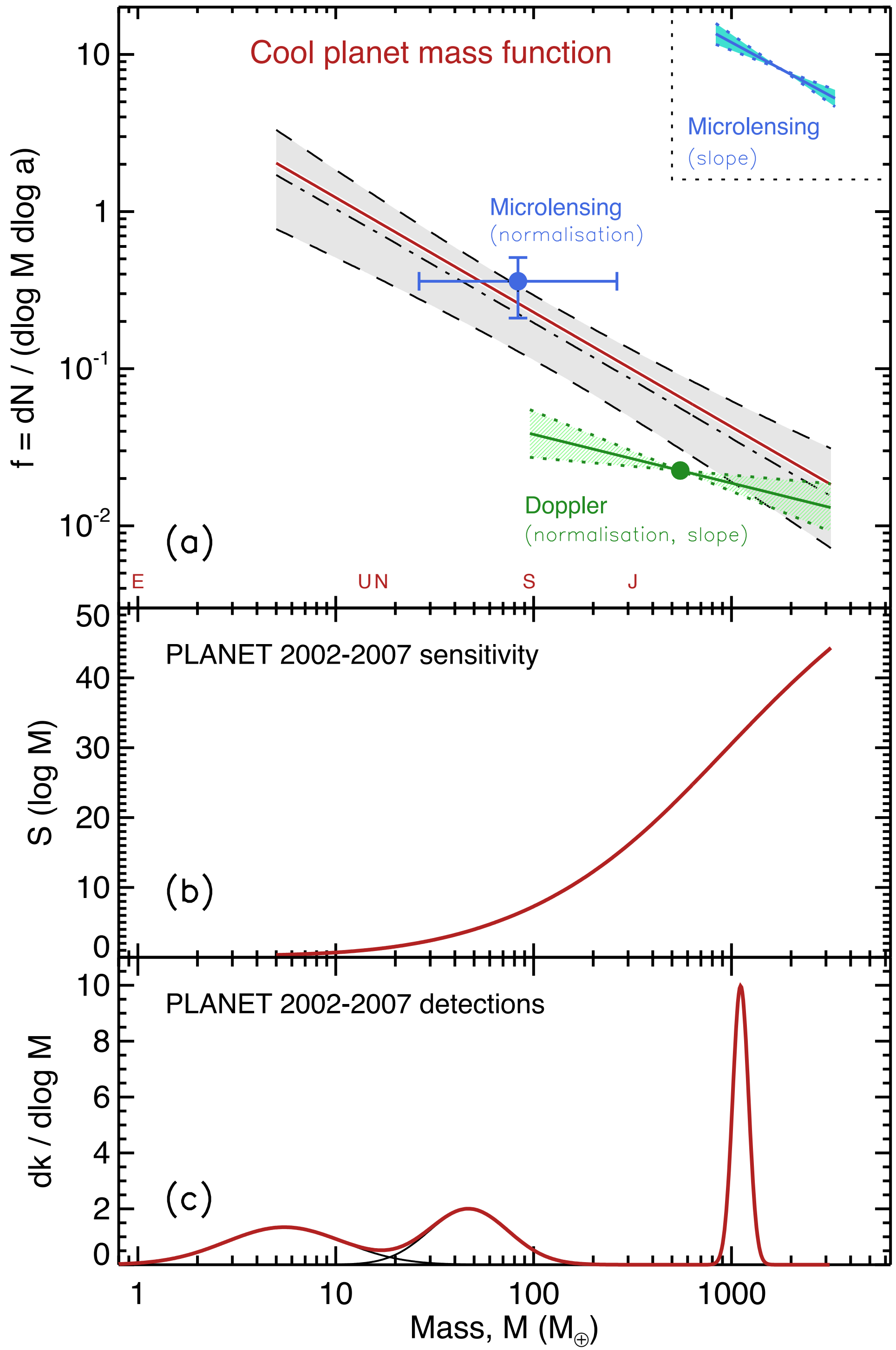
Longer-term: microlensing from space?

- Photometric accuracy → low-mass source stars, more events, more sensitivity to smaller planets
- Continuous coverage
- Space microlensing would be sensitive to ~Mars-mass planets at 1-10 AU which are predicted by planet formation models (e.g. Ida & Lin, Alibert et al. 2011 etc.) to be abundant
- Euclid Legacy Science (e.g. Beaulieu et al. 2009)
- WFIRST?

Conclusions

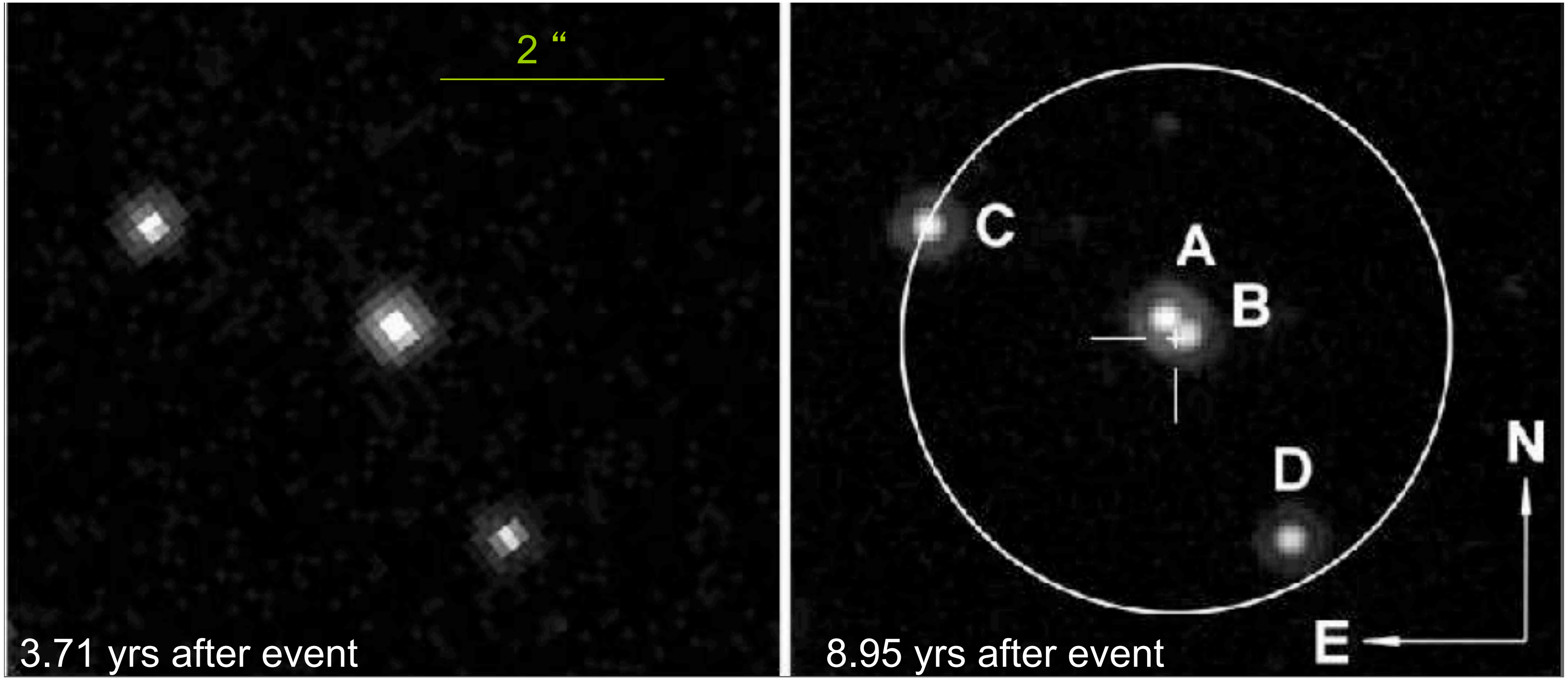
- Microlensing is slowly realising its potential: only 13 planets detected, but plenty of information from non-detections (e.g. cool planet mass function, Cassan et al. 2012: on average > 1 planet per star)
- A vital complement to other methods
- The next few years will see a dramatic improvement in efficiency and returns of microlensing observations thanks to robotic telescopes and automation → build up statistics
- Pave the way for space-based microlensing?

Cassan et al. (2012)
mass function



Detecting the lens

MACHO-95-BLG-37 with HST



Alcock et al. 2001

Kozlowski et al. 2007