16th International Conference on Gravitational Microlensing, 2012

Terrestrial Parallax in the Low-mass Event MOA-2011-BLG-274 and A Preliminary Search for Low-mass Objects in the Database of the WISE Space Mission

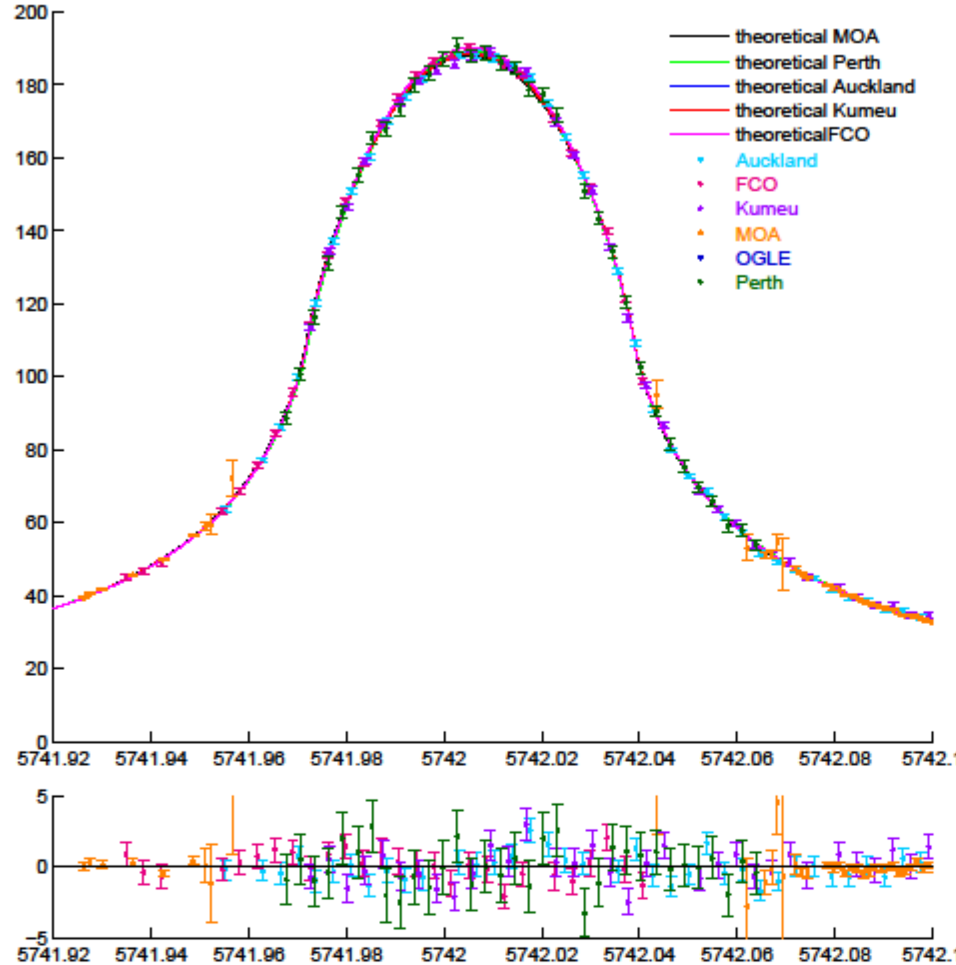
Matthew Freeman

MOA-2011-BLG-274

- tE = 3.06 days
- Either fast moving or small mass lens

- ρ = 0.0112, in typical events ρ = 0.001
- $\rho = \theta_S/\theta_E$
- Either source star is 10x as large or mass (Einstein radius) is 10x as small

- Source star has usual luminosity. Thus, very low mass lens



Differences in analysis

- This event has also been analysed in the paper:

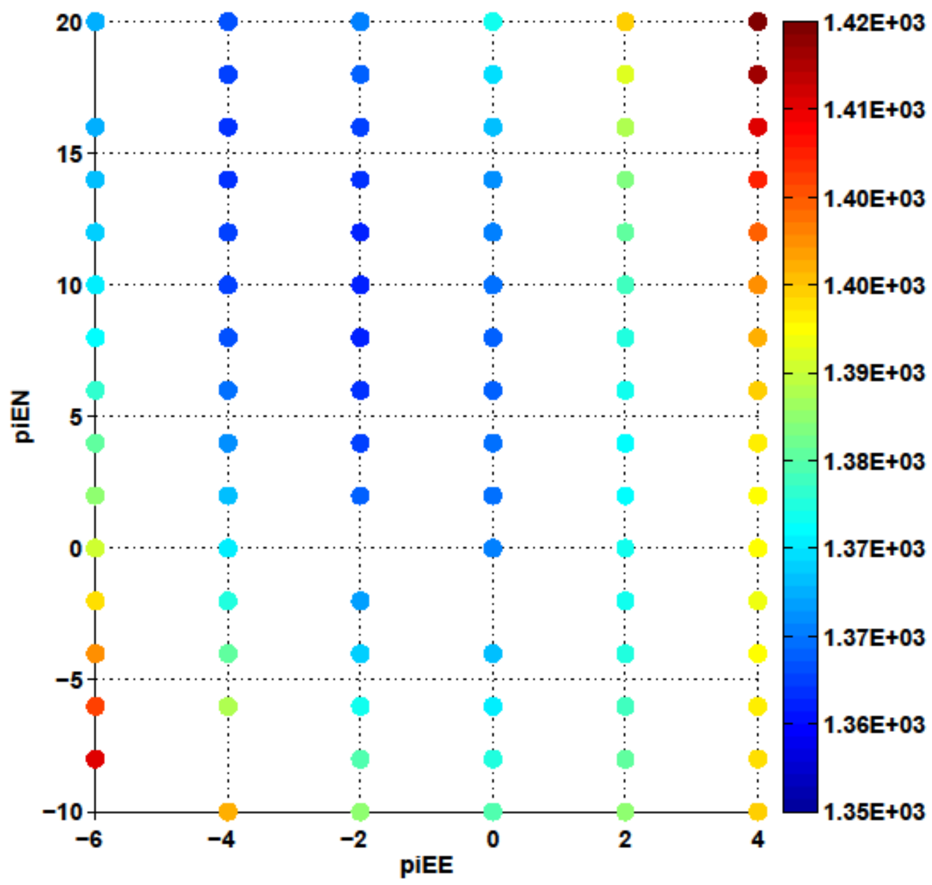
  'Characterizing lenses and lensed stars of high magnification gravitational microlensing events with lenses passing over source stars', JY Choi et al, arXiv:1111.4032

Differences:

- Perth data rereduced because it appeared relatively noisy compared to Auckland data with similar sized telescopes, and Perth weather was excellent.
- Renormalised error bars for all datasets
- In particular, MOA data renormalised at baseline and at peak magnification
- Included OGLE data

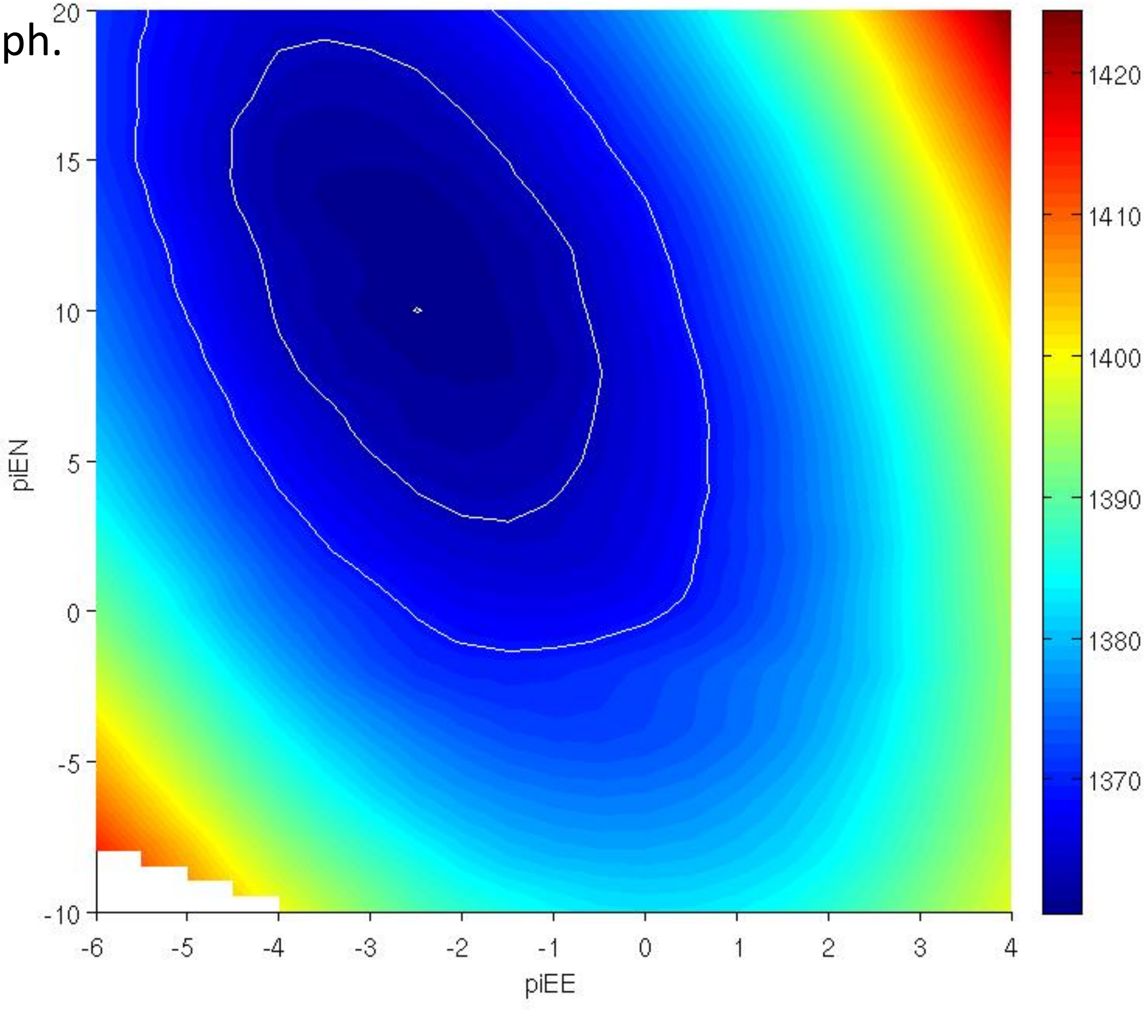
Parallax measurements

- Calculation of χ^2 for each pair of parallax values
- Shows a best fit at
- piEE =-2
- piEN = 10
- Large area of uncertainty



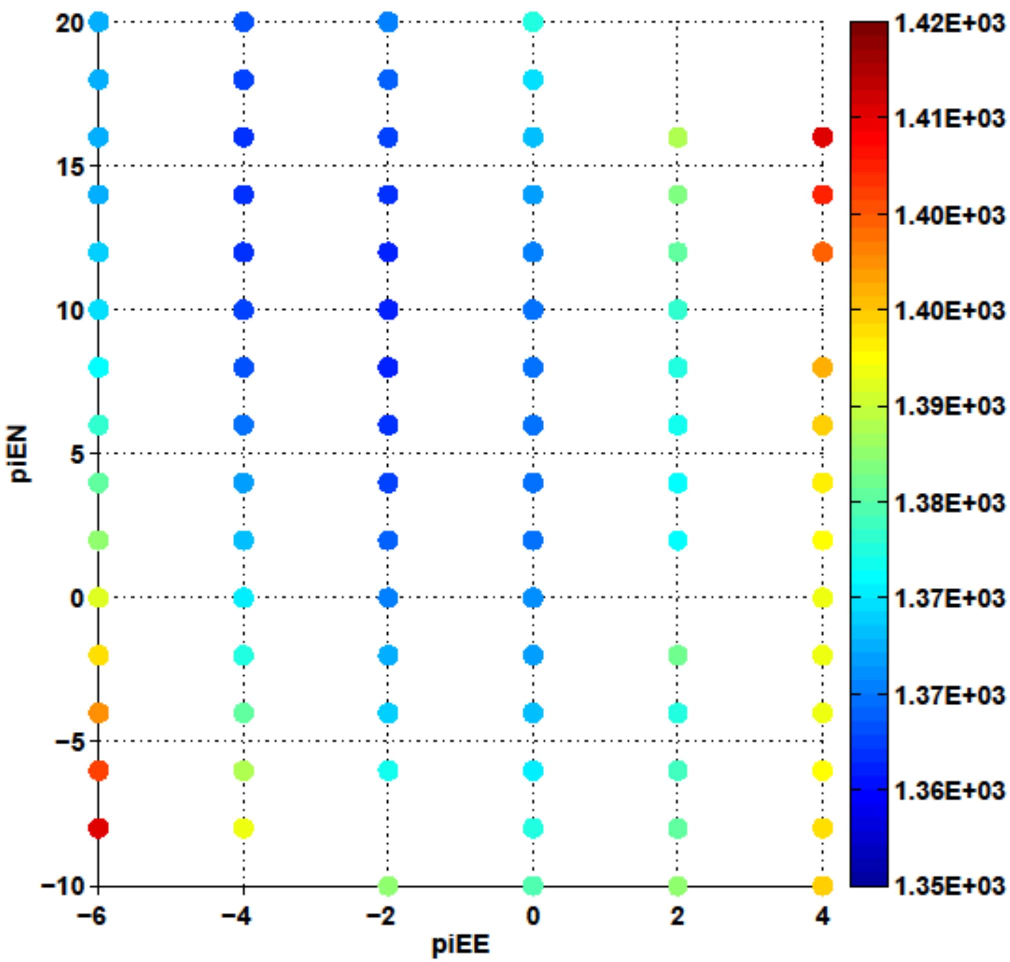
Parallax interpolated

- Interpolation of previous graph.
- Lines at 2 sigma and 3 sigma



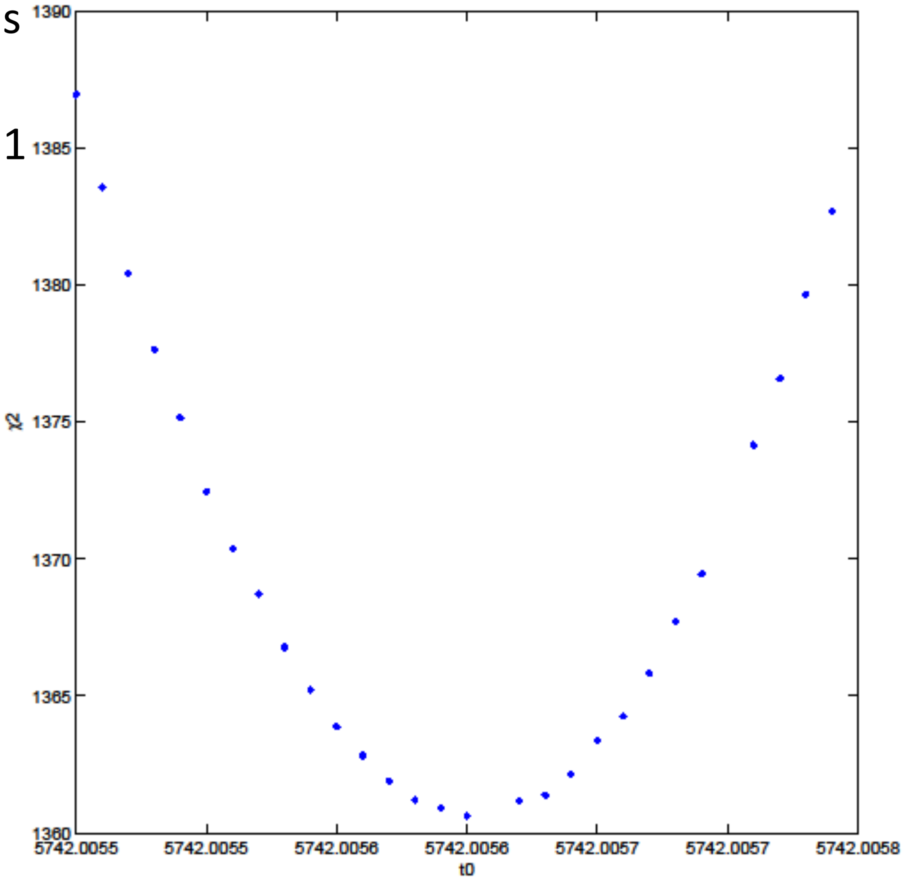
Testing change of θ

- Just done to test our program
- With no planets, changing the source star track angle should have no effect
- Rectangular pixels are used for the magnification map, could cause small deviations
- The parallax plot with a changed value of theta = 0.3 shows only a very small difference, <1 χ^2



Marginalisation of t0

- For each fixed value of t0 a minimum is found
- Gives error estimates – an increase of 1 $\chi2$ is one sigma.
- 0.00001 interval between points (~1 sec)
- 1 sigma = ~2.5 divisions =
- = 0.000025 days
- = ~2 seconds
- So we can measure time differences with fairly good accuracy.



Source star parameters

- $(V-I)_0 = 0.76$ and $I_0 = 17.96$ (private communication from A. Gould using CTIO field stars)

- Assuming the source distance is in the bulge at 8 kpc , the above implies $M_I = 3.445$ and $M_V = 4.205$

- The nearest star on isochrones of L. Girardi et al (A&A **391**, 195, 2002) with age = 10 billion years and solar abundance Z = 0.019 has temp = 5688K, surface gravity log g = 4.083 and radius r_s/r_{solar}= 1.492. Hence angular source star radius θs = 0.87 μas (0.85 μas obtained by A. Gould).
- Linear limb darkening coefficients from Antonio Claret (A&A **363**, 1081, 2000):-

	V	R	I
u	0.619	0.564	0.469

Limb darkening coefficients

	Filter Colour	Passband	u	u (A.Gould)	u compromise
OGLE	I	I	0.47	0.45	0.47
MOA	Red	(R+I)/2	0.51	0.49	0.51
Kumeu, Auckland	Red	(2R+I)/3	0.52	0.52	0.52
Perth, Farm Cove	White (no filter)	(V+R)/2	0.58	0.51	0.53

u = linear limb darkeing coefficient
(V+R)/2 = unfiltered + reddening from dust

Calculation of lens mass/distance

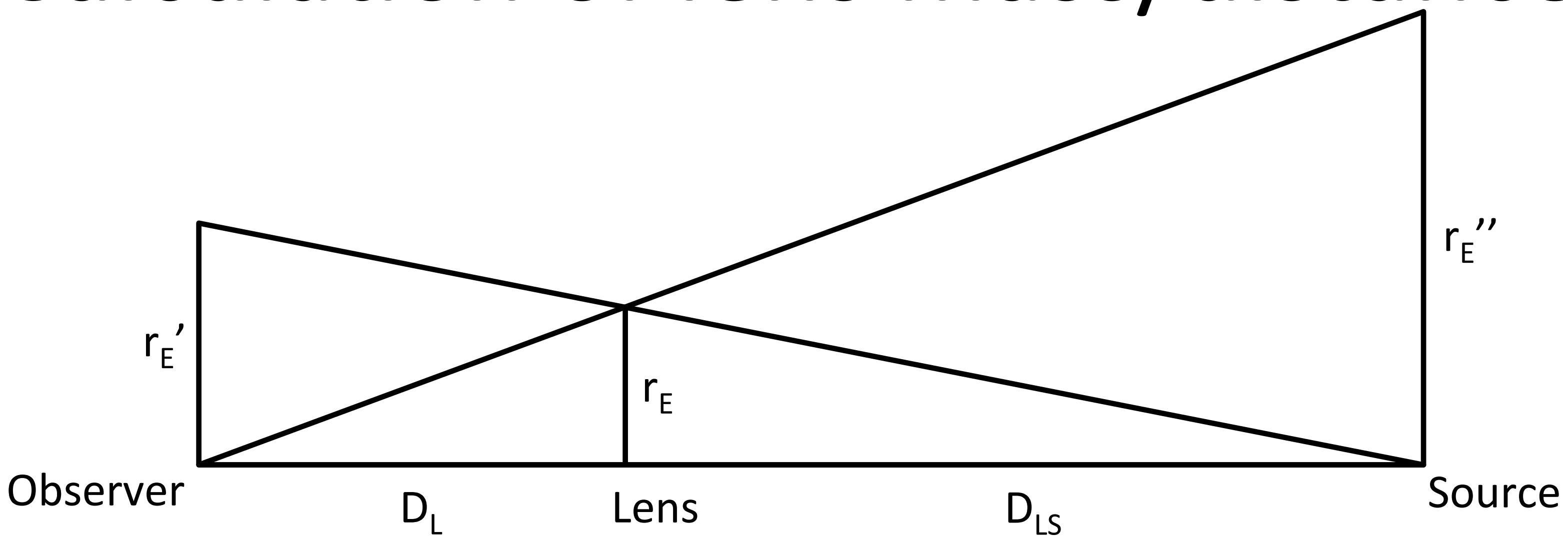


Diagram created by Andy Gould

- π_E = 10.20
- $r_s = 1.492 \times r_{solar} = 1.492 \times 6.96 \times 10^8$ m $= 1.04 \times 10^9$ m
- ρ = 0.0112

- $r_E' = AU/\pi_E = 1.5 \times 10^{11}\text{m}/10.20 = 1.47 \times 10^{10}\text{m}$
- $r_E'' = r_s/\rho = 1.04 \times 10^9\text{m} /0.0112 = 9.27 \times 10^{10}\text{m}$
- $D_s = 8$ kpc $= 2.42 \times 10^{20}\text{m}$

Calculation of lens mass/distance

- **$1/r_E = 1/r_E' + 1/r_E''$** (from the geometry of the previous diagram)
- $r_E = 1.27 \times 10^{10}$ m = 0.085 AU
- $D_L = D_S r_E / r_E''$ = **1.09 kpc**
- $r_E = \sqrt{(4GM_L/c^2)} \times \sqrt{(D_L D_{LS}/D_S)}$
- $M_L = r_E 2c2D_S/4GD_L D_{LS} = 1.86 \times 10^{27}$ kg = **0.97 MJ**

Result – Jupiter mass object

- The 2 sigma error contour gives range of 0.5 to 2 Jupiter masses
- This is a fairly large range, but not too bad for microlensing. Uncertainties in mass are usual.

Peak magnification times

Telescope	Tmax (HJD)	Tmax – Tmax,moa (seconds)
Perth	5742.005536	19
Farm Cove	5742.005472	12
Kumeu	5742.005470	12
MOA	5742.005316	-

These time differences show that parallax is detectable in this event.

Calculation of trajectory

- Best fit u_{min} = 0.00255
- Hence $u_{min,observer\ plane}$ = 0.00255 x r_E

  = 0.00255 x 1.47 x 10^{10} m

  = 37,485 km = 5.88 r_{Earth}
- Direction = $\tan^{-1}(-2/10)$ = 11.3° west of North
- Speed = r_E'/t_E
- ≈ 1.47 x 10^{10} m / 3 days ≈ 60 km/sec
- Hence $t_{0,Auckland} - t_{0,Mt\ John}$ ≈ 650 km/ 60 km s^{-1} ≈ **11 seconds** (observed ≈ 12 secs)
- Note that the peak magnification at FCO was higher than that at Perth which had the same limb darkening. Hence trajectory is east of Australasia as shown below, not west.

Track in observer plane

5.9 earth radii away.

Detectability of exomoons

- This object has a mass similar to that of Jupiter.
- Could have orbiting moons (although no sign yet in light curve)

Jupiter's Moons

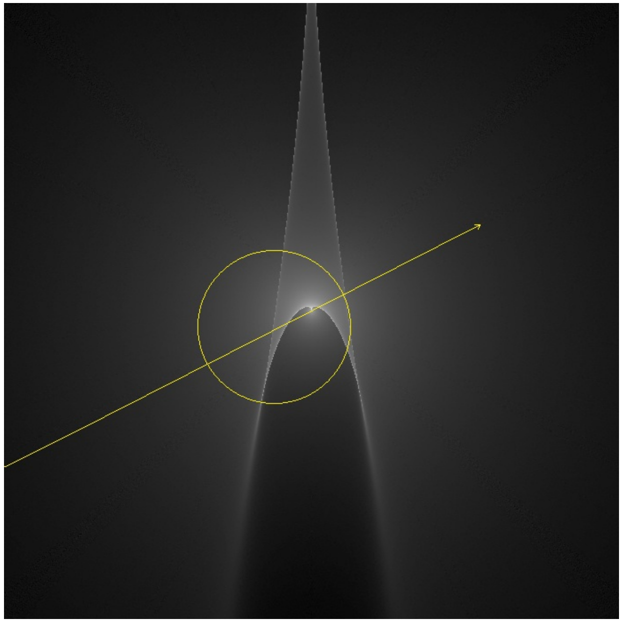
	Mass (kg)	Mass ratio $q=M/M_J$	Orbital radius (m)	Orbital radius r_E
Io	8.93×10^{22}	4.7×10^{-5}	4.22×10^{8}	0.033
Europa	4.80×10^{22}	2.5×10^{-5}	6.71×10^{8}	0.052
Ganymede	1.48×10^{23}	7.8×10^{-5}	1.07×10^{9}	0.083
Callisto	1.08x10^23	5.7×10^{-5}	1.88×10^{9}	0.146

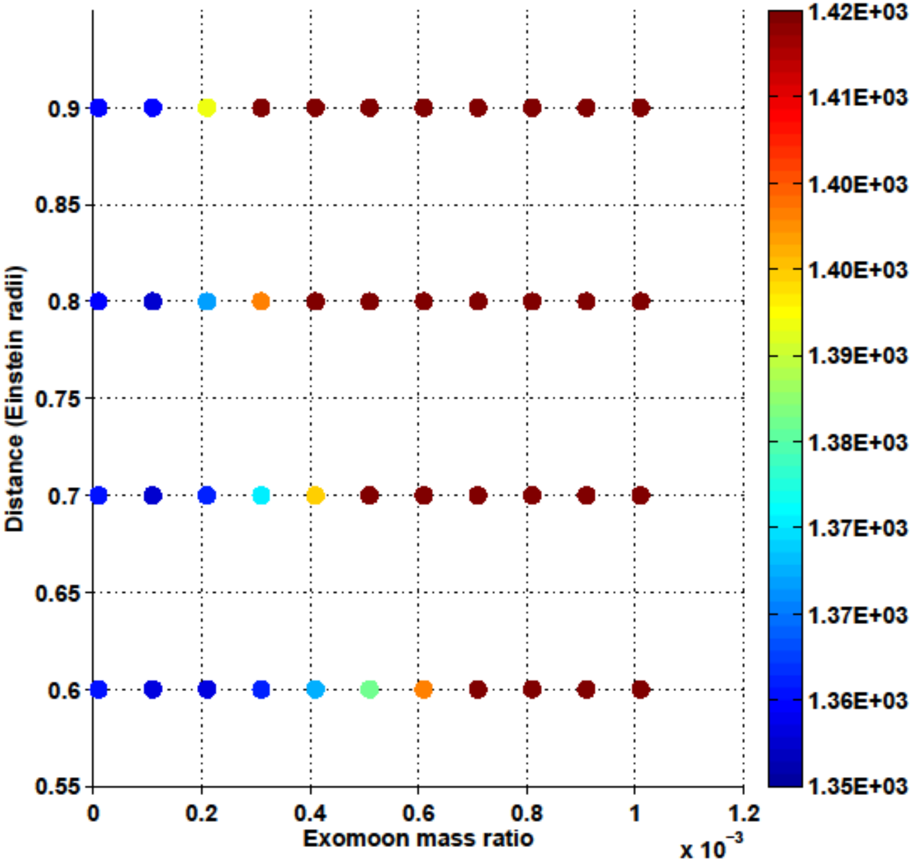
- Mass ratios and orbital radii are both an order of magnitude too small to be detected by gravitational lensing.
- Cold look for larger moons further out

Possibility of adding a moon

χ^2 for each pair of parameters,: distance and mass

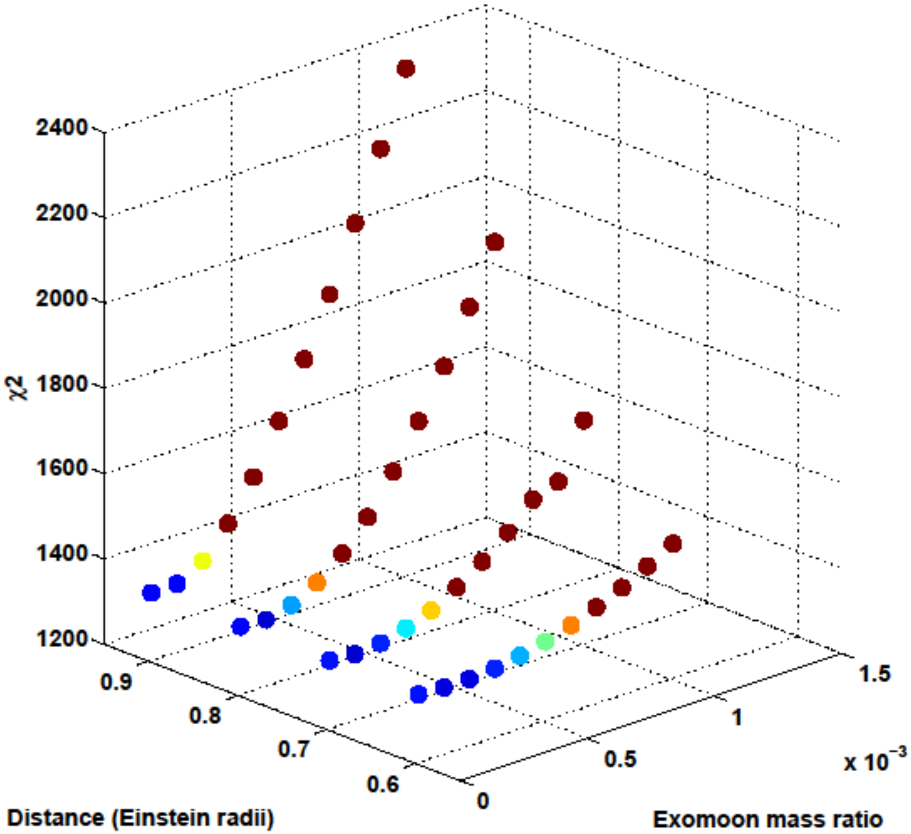
Star diameter = 1000 pixels
Our code is good for free floating planets – a larger star reduces the effect of the rectangular pixels





Possibility of adding a moon

- Same plot again in 3D
- Could be small moons in close orbit.
- Larger moons close to the Einstein radius are excluded



Light curve with moon

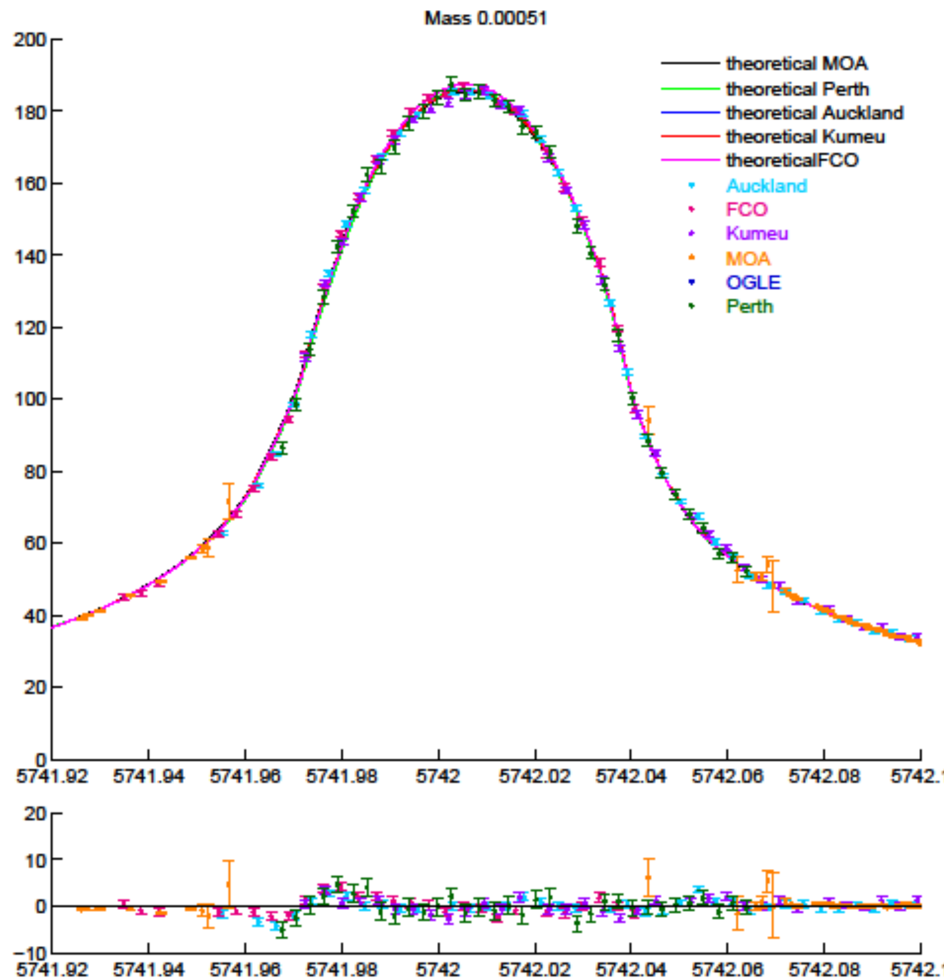
Model with a moon orbiting

Mass ratio 0.0005

Distance 0.9 r_E

– increases χ2 by 300

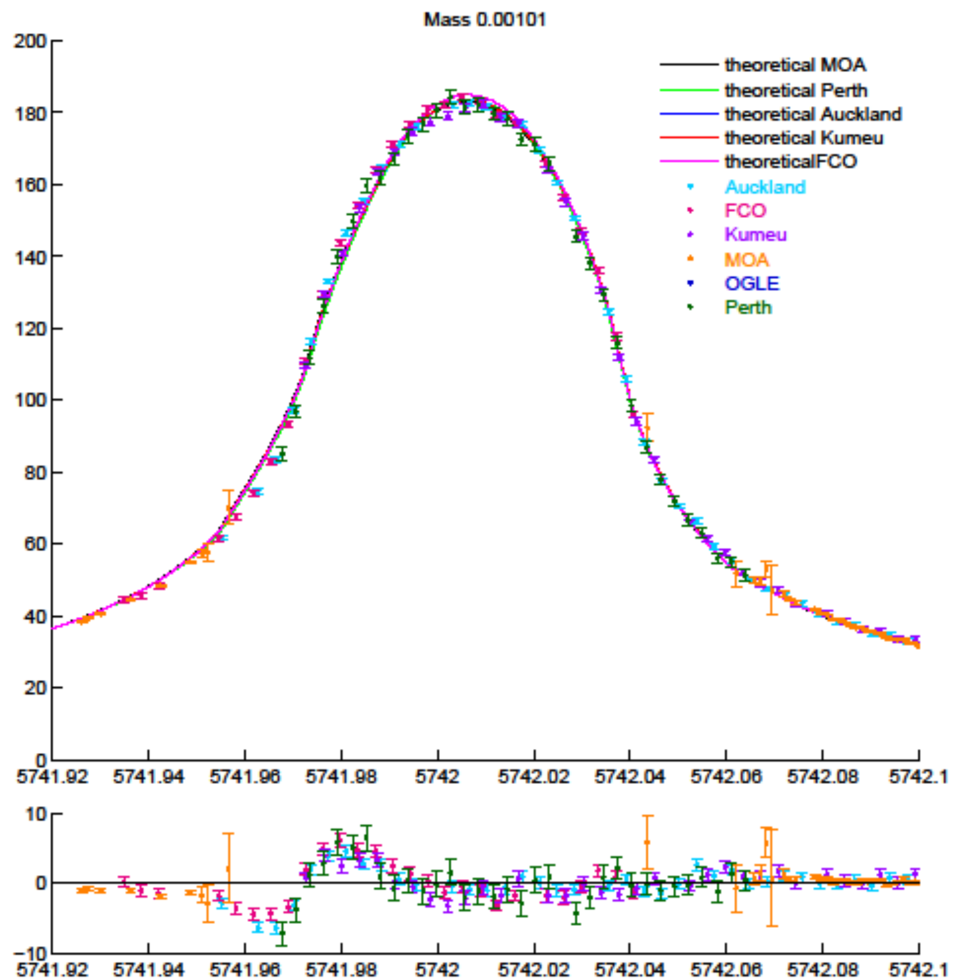
Can see a deviation in the residuals



Larger moon

With a moon twice as large, there is a very noticeable deviation.
Mass ratio 0.001
Distance 0.9 r_E

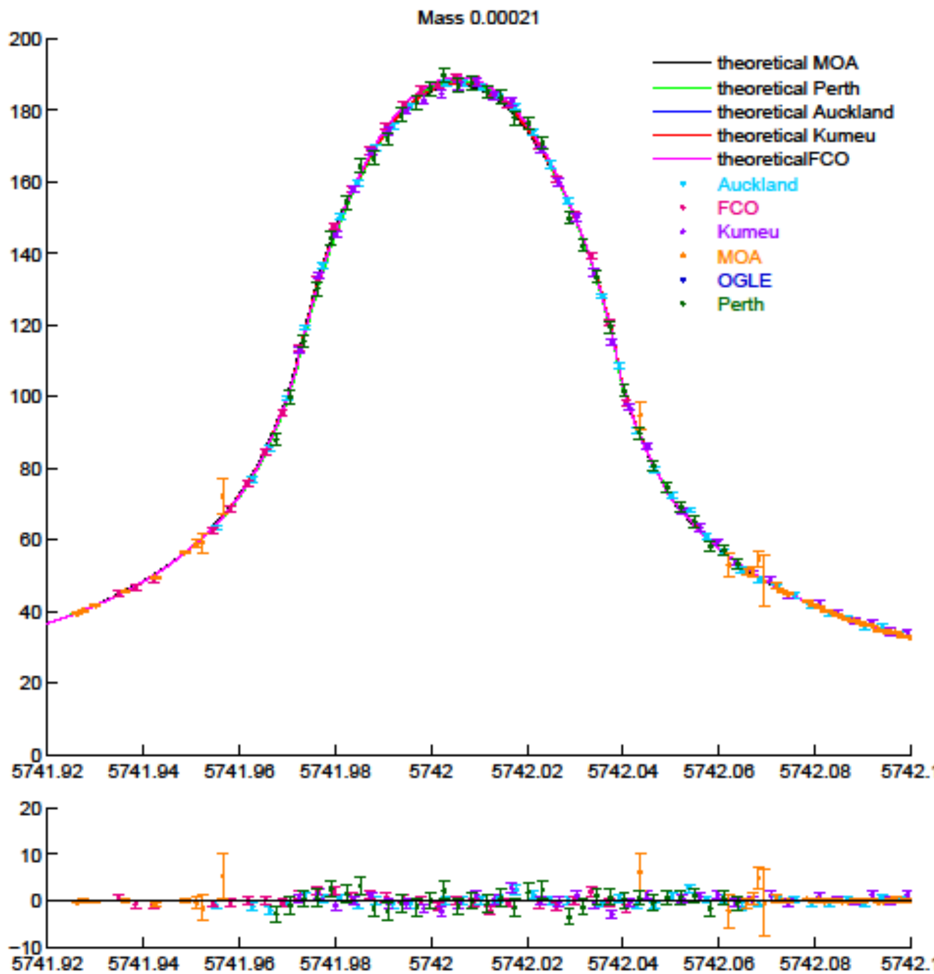
A moon this size can be excluded



Smaller moon

A smaller moon produces a smaller deviation (but still a noticeable increase in χ^2).
Mass ratio 0.0002
Distance 0.9 r_E

More searching may find such a moon



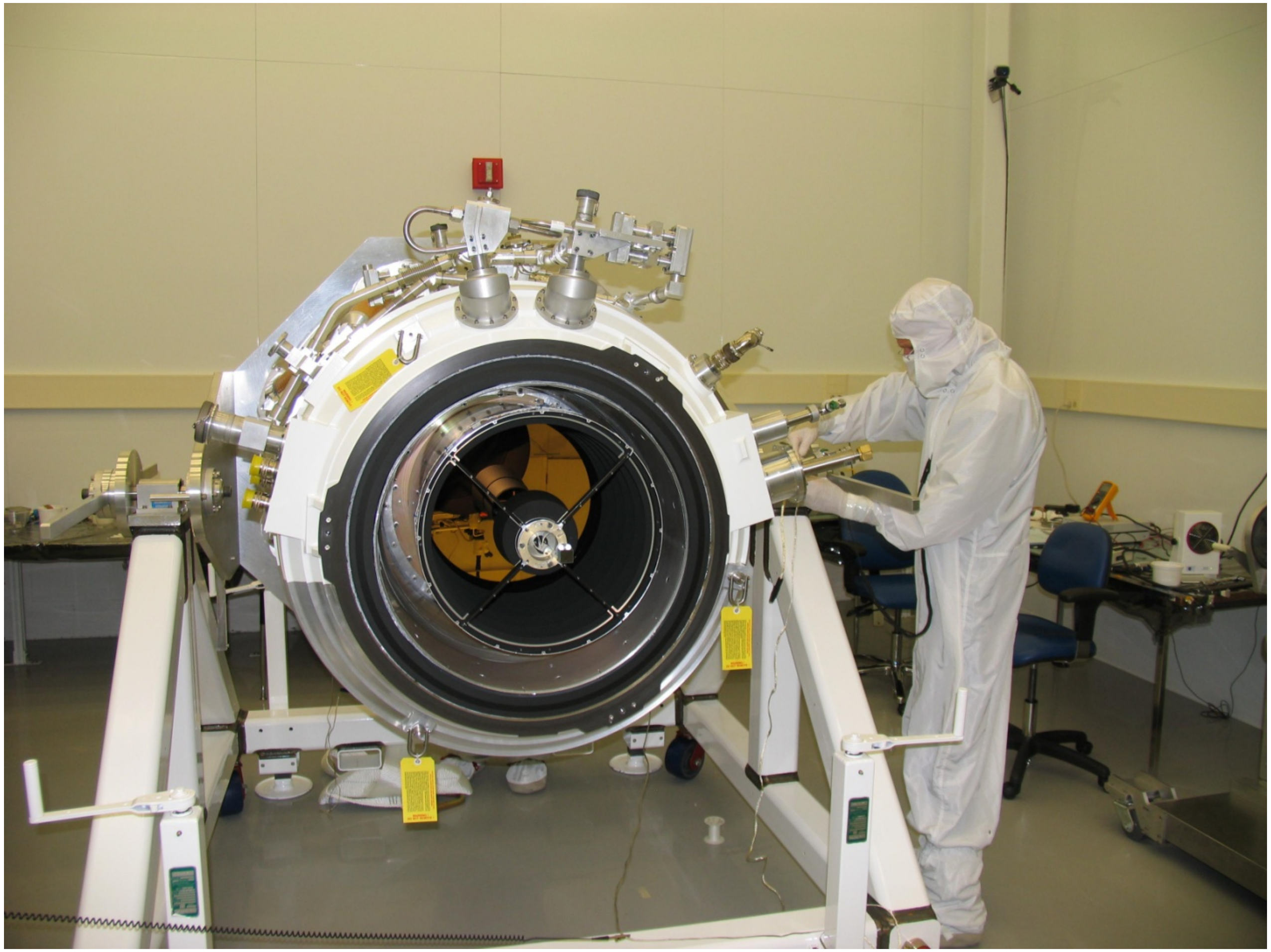
Still to do

- Search for a stellar companion to this planet.
- Because the light curve is so good we should be able to exclude a star out to a large distance.

WISE data analysis, by John Bray

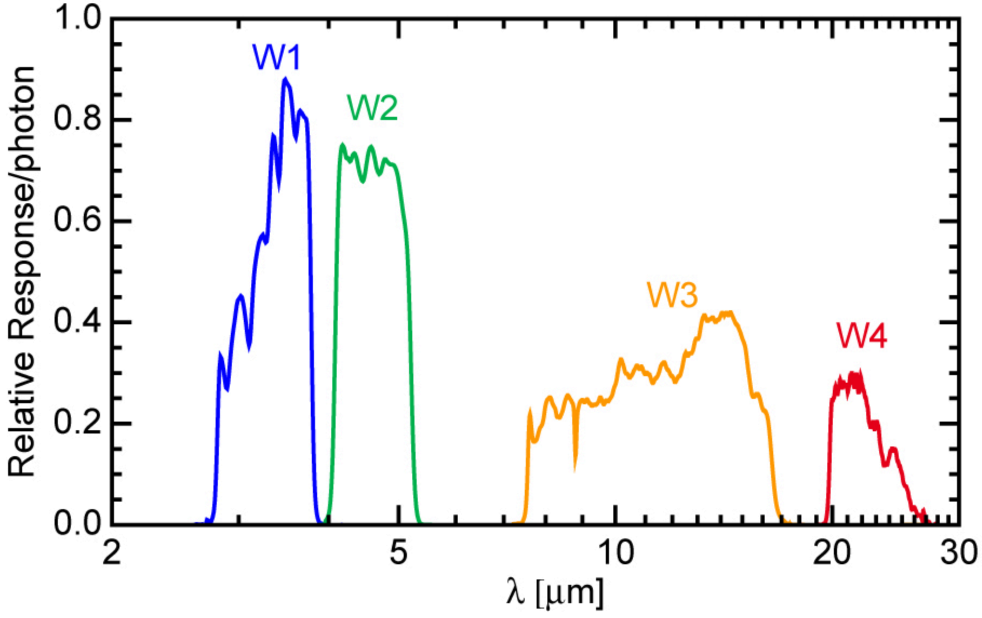
- Puzzle – surprisingly high number of free-floating Jupiters!
- Sumi et al found 1.8 free-floating Jupiters per star (Nature 473, 349, 2011)
- Cassan et al report 17% of stars host an orbiting Jupiter (Nature 481, 167, 2012)
- The measurements suggest either most Jupiters are ejected, or most free-floating Jupiters are born free (i.e. they are very cool sub-brown-dwarfs).
- May be able to test the second possibility by searching for very cool sub-brown-dwarfs (late Y dwarfs) in the WISE database.
- We merely wish to bring the WISE mission to the attention of the microlensing community, we are not attempting to compete with the WISE group

WISE telescope



40cm widefield telescope cooled by solid hydrogen cryostat to <12K, detectors to <7.5K

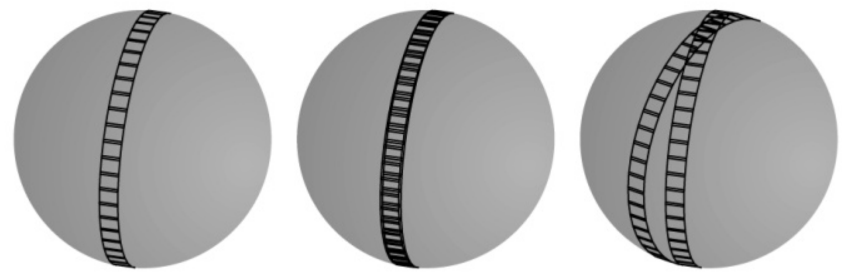
WISEPassbands



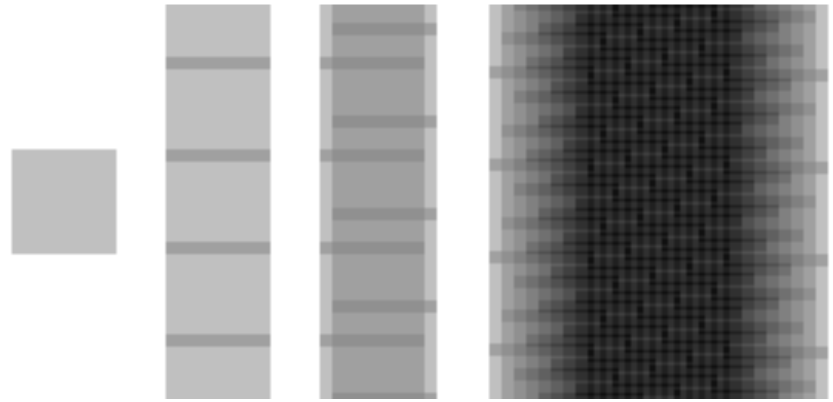
(E. Wright et al arXiv:1008.0031)

WISE Orbit

(E. Wright et al arXiv:1008.0031)

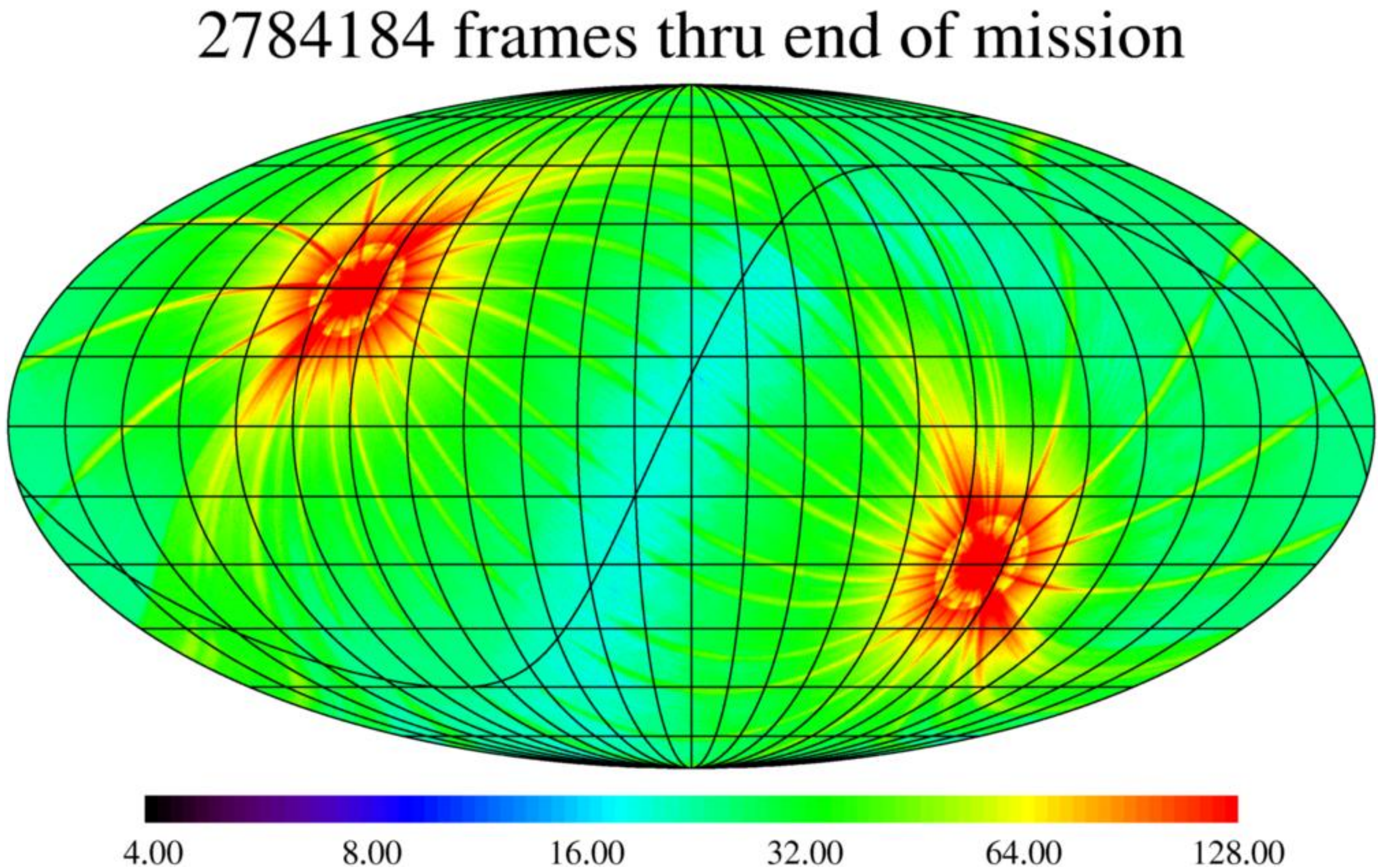


WISE coverage is very redundant at the poles



1 frame 1 orbit 2 orbits Many orbits

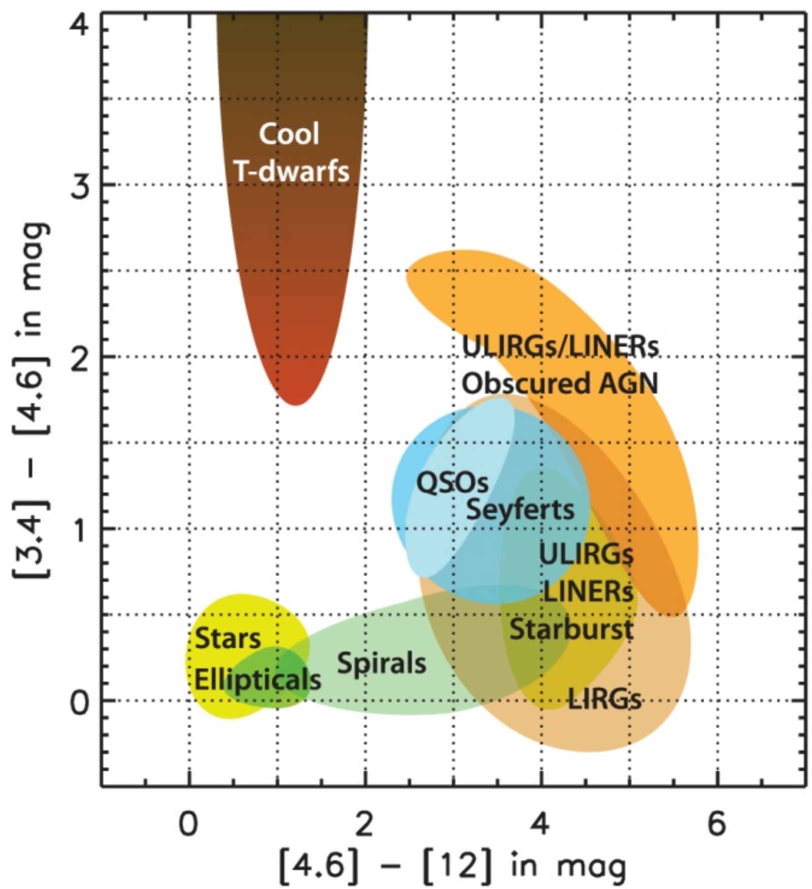
WISE Coverage



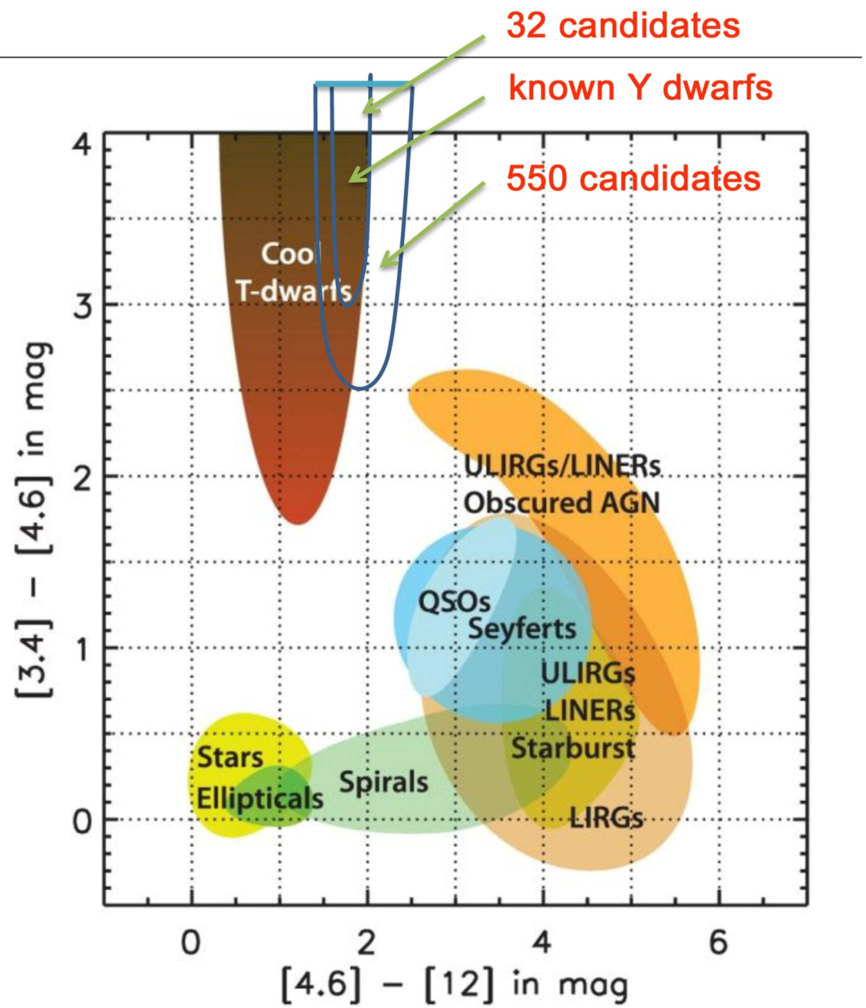
WISE has surveyed the whole sky twice.

WISE colour-colour populations

- Emission by cool brown dwarfs at 4.6um due to lack of methane absorption

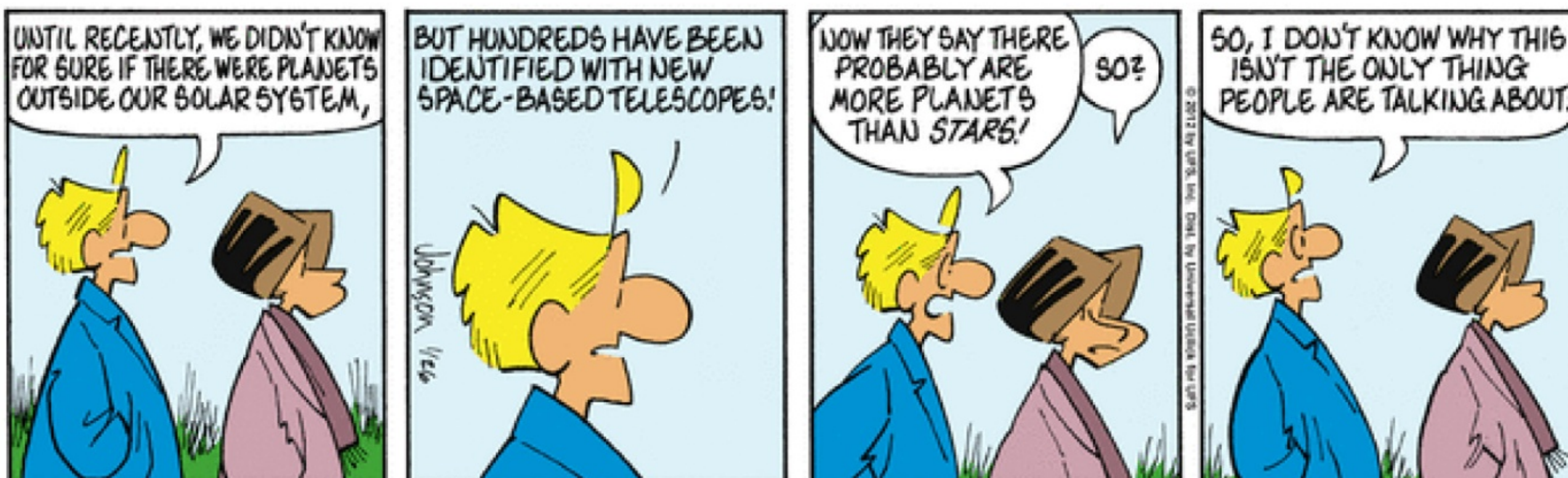


Search region (preliminary data only)



Thanks to

- Michael Albrow
- Christine Botzler
- John Bray
- Sean Davidson
- Dimitri Douchin
- Andy Gould
- Yvette Perrott
- Lydia Philpott



Best fit

- From first parallax run
- Umin 0.00255
- θ 0.5
- Ssr 0.0112
- t0 5742.00565
- tE 3.06
- piEE -2
- piEN 10
- χ^2 1350.83349

Parameters for two moons

- Mass 0.00051
- 0.00359 0.5 0.0112 5742.00526 3.07 -2 10
- $\chi^2 = 1661.9592$

- Mass 0.00101
- 0.00423 0.5 0.0112 5472.00508 3.04 -2 10
- $\chi^2 = 2389.0983$

- Umin changed a lot due to the exomoon