Gravitational Microlensing Observations

Optical Astronomy from an Urban Observatory

Grant Christie

Stardome Observatory, Auckland

New Zealand and the Beginnings of Radio Astronomy

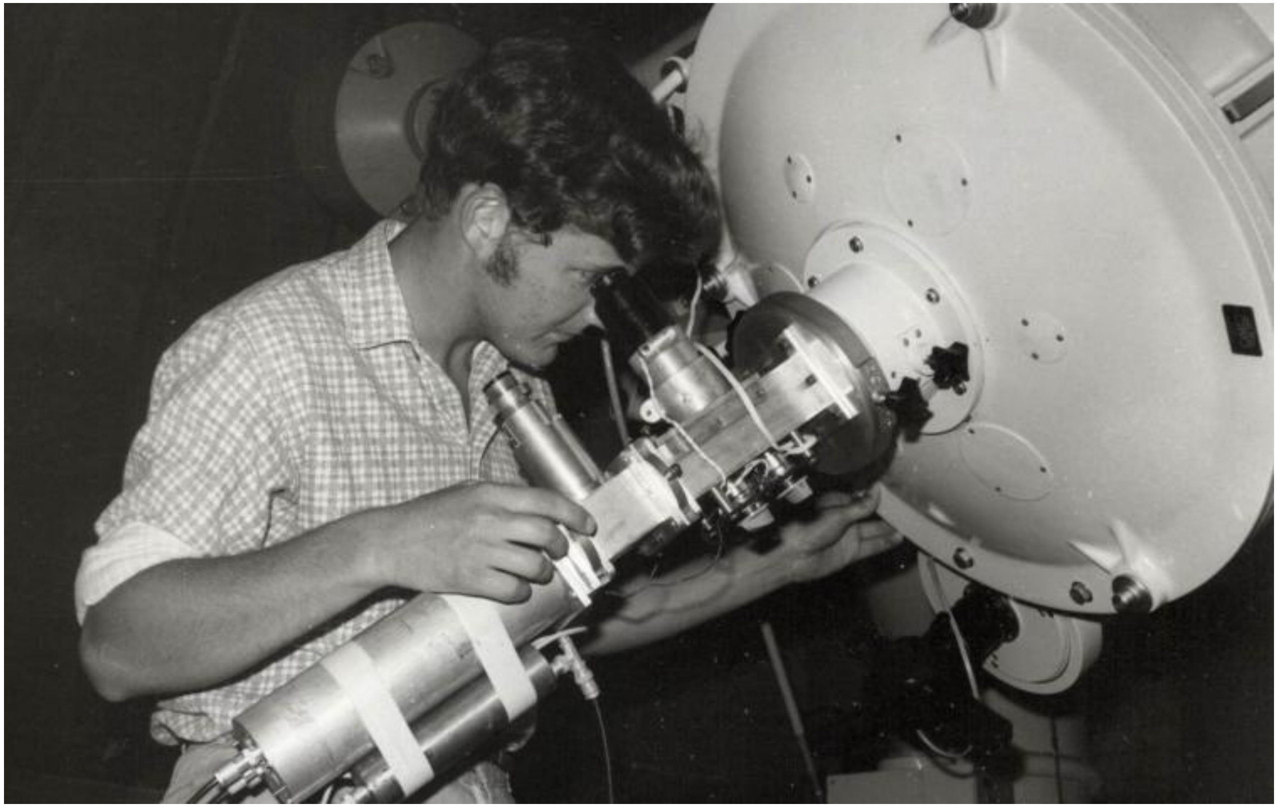
Orewa, Jan 30-31, 2013

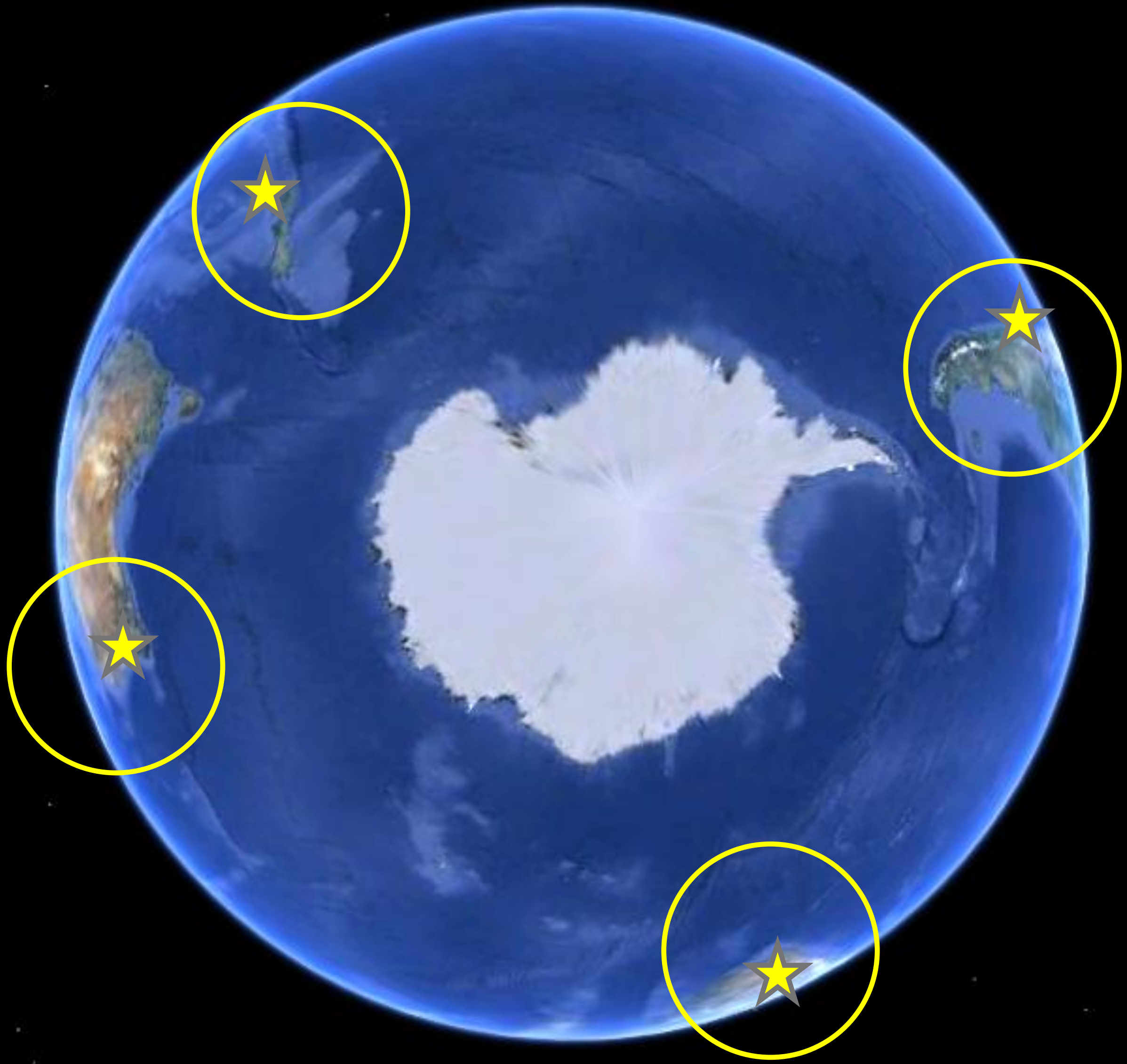
Auckland Observatory opened on March 21, 1967
The 0.5m Zeiss Cassegrain was the largest telescope in New Zealand

UBV Photoelectric Photometer (1969-1999)

Research Programmes

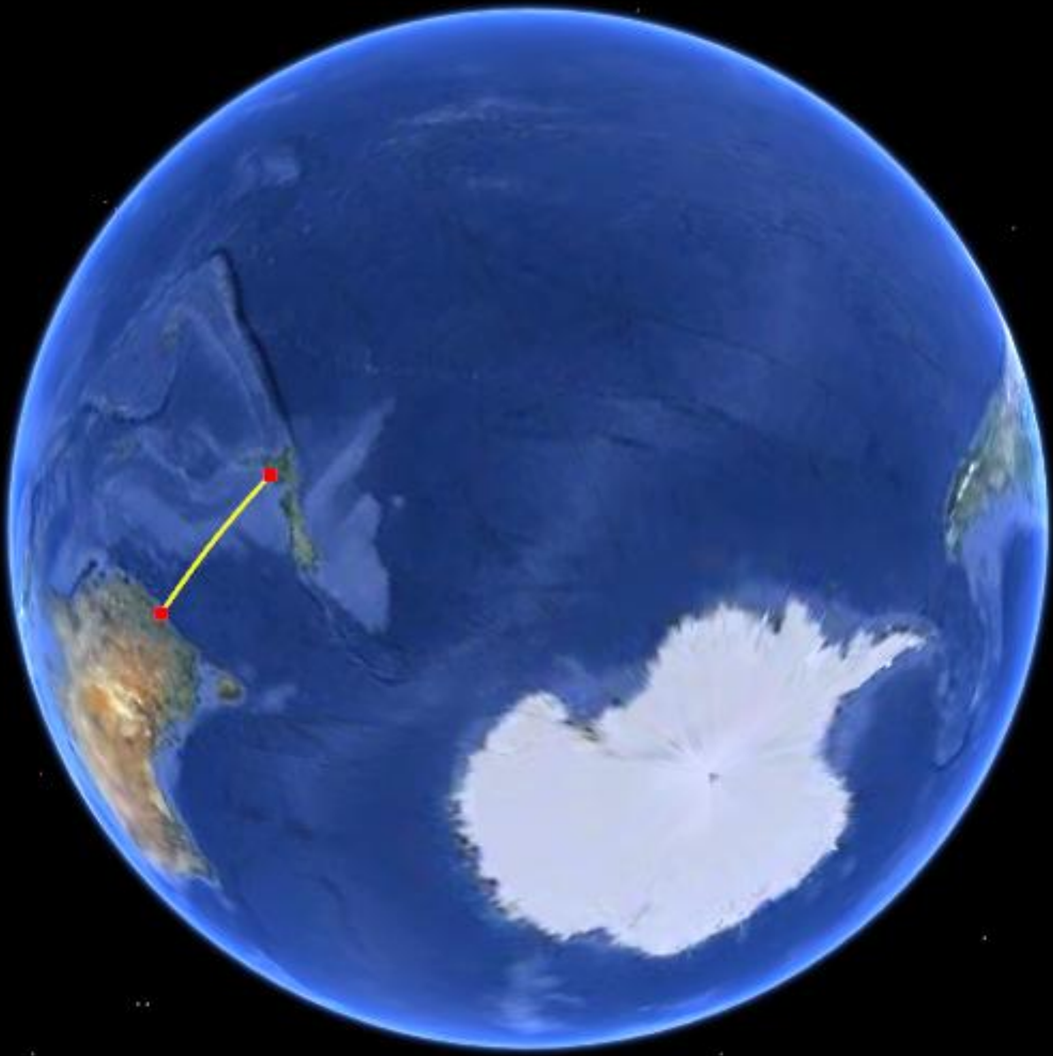
- Sequence determination for the VSS
- Cataclysmic binaries (discovered superhumping)
- Long period variables
- Cepheids
- Delta Scuti variables (large amplitude)
- Eclipsing binaries (EW)





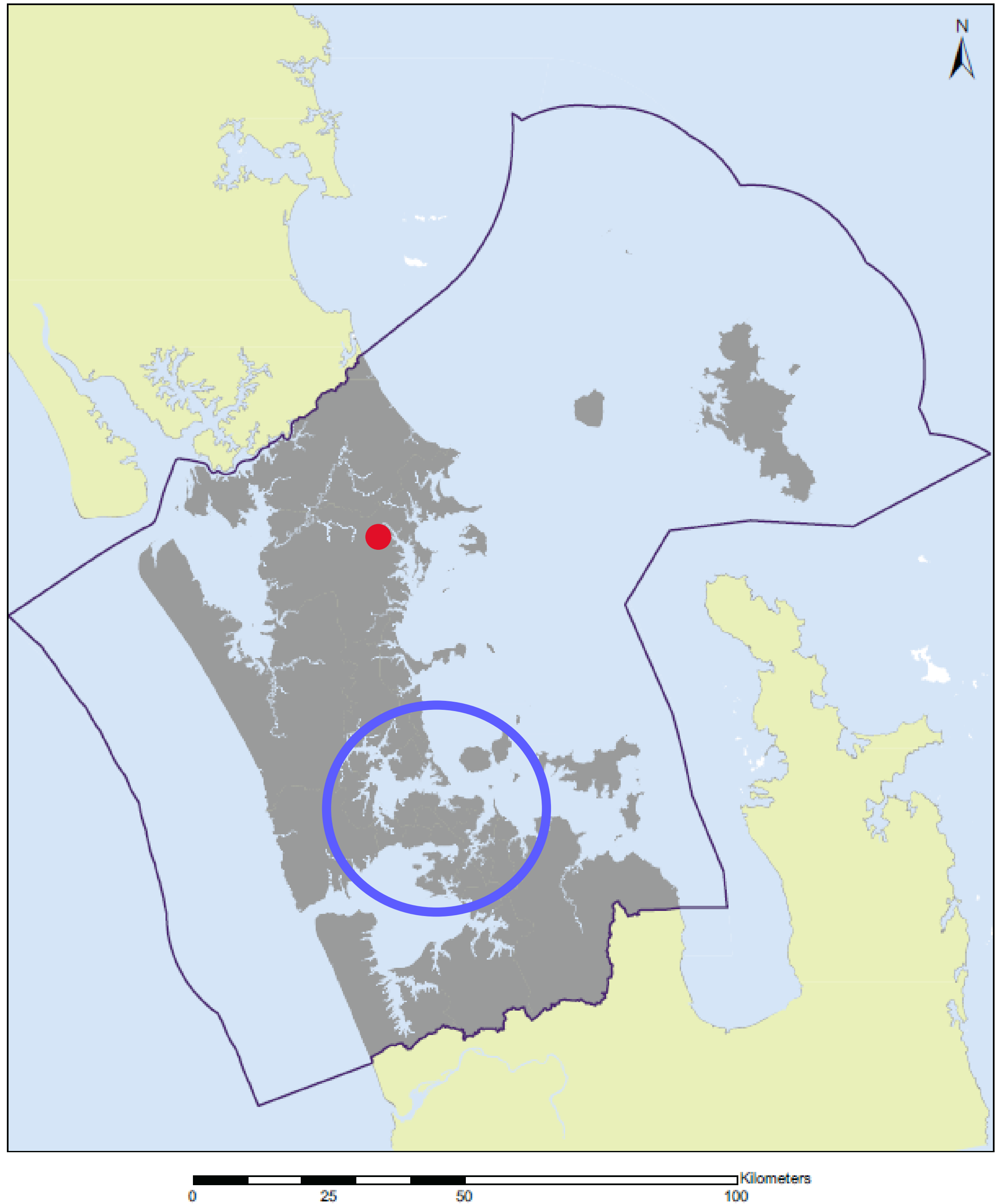
Auckland to Chile – 9,800km

Auckland to Australia – 2,100km



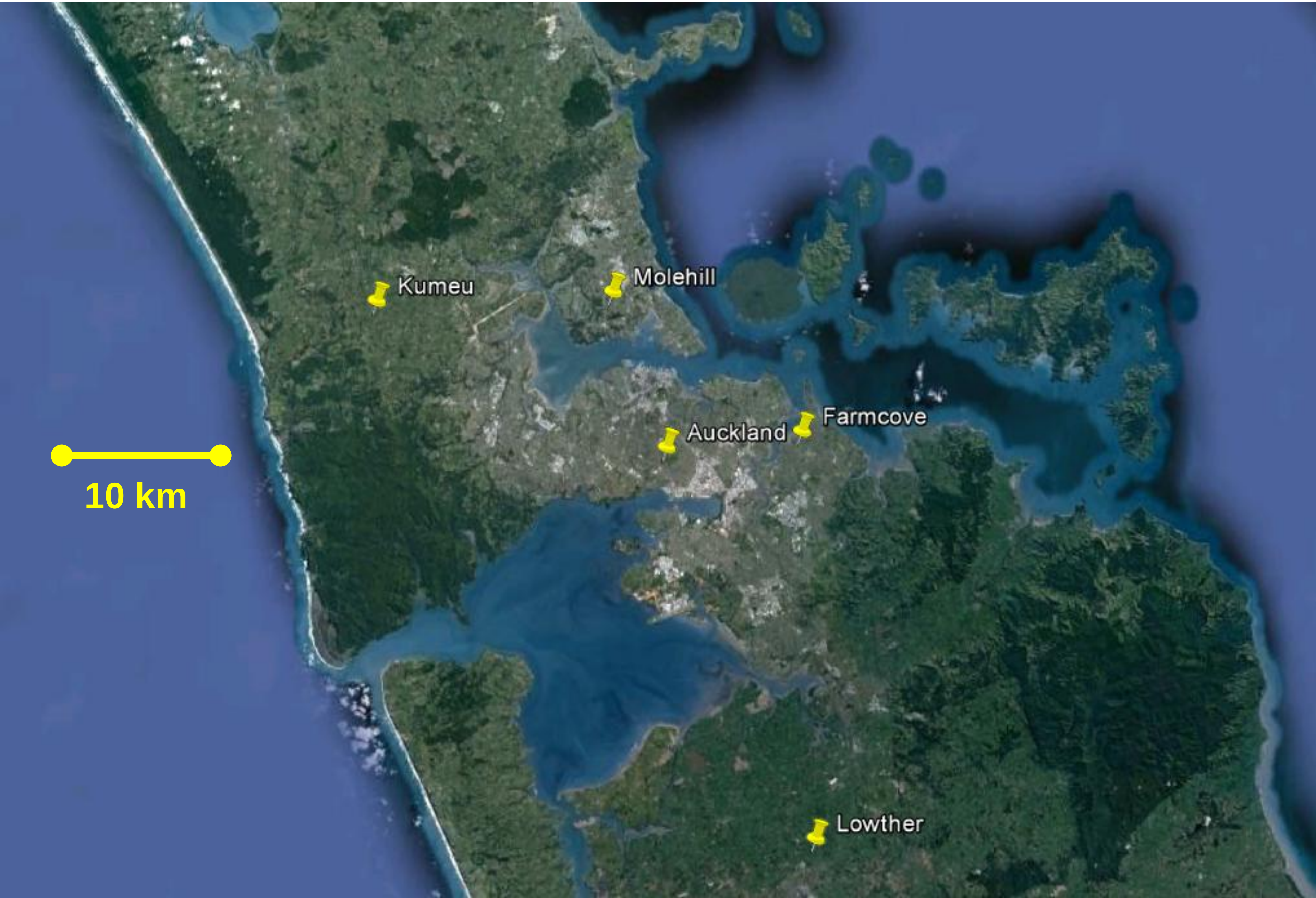
New boundaries of Auckland City 2010

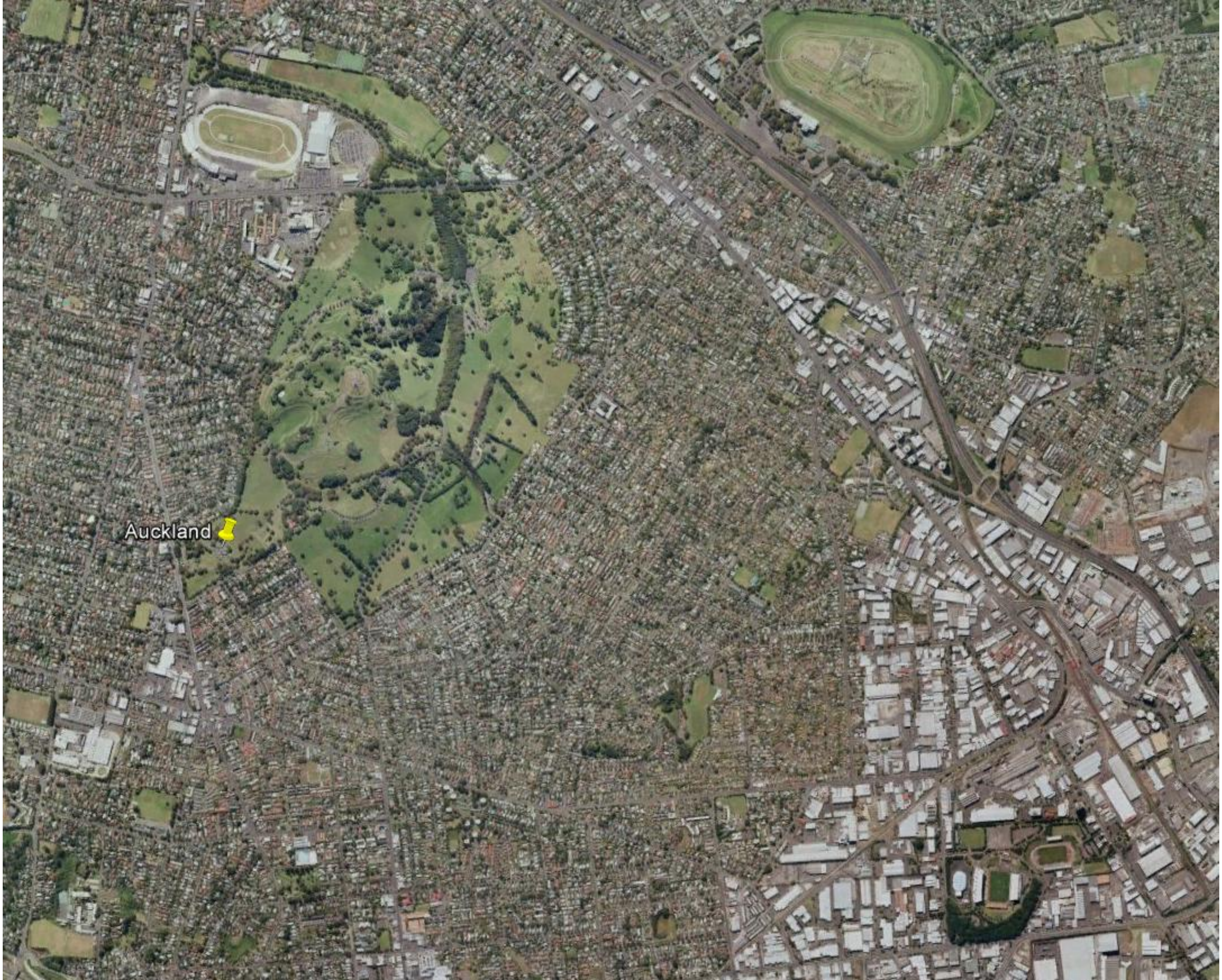
- ~1.4 million people
- ~50,000 street lights
- ~4,500 km^2



Latitude 36^{o} 54’ S

Photometric Observatories in Auckland




Auckland

0.5m Zeiss Cassegrain (F13.3)

Installed 1967

UBV photoelectric photometry 1969-1999

Funding available for a technological upgrade

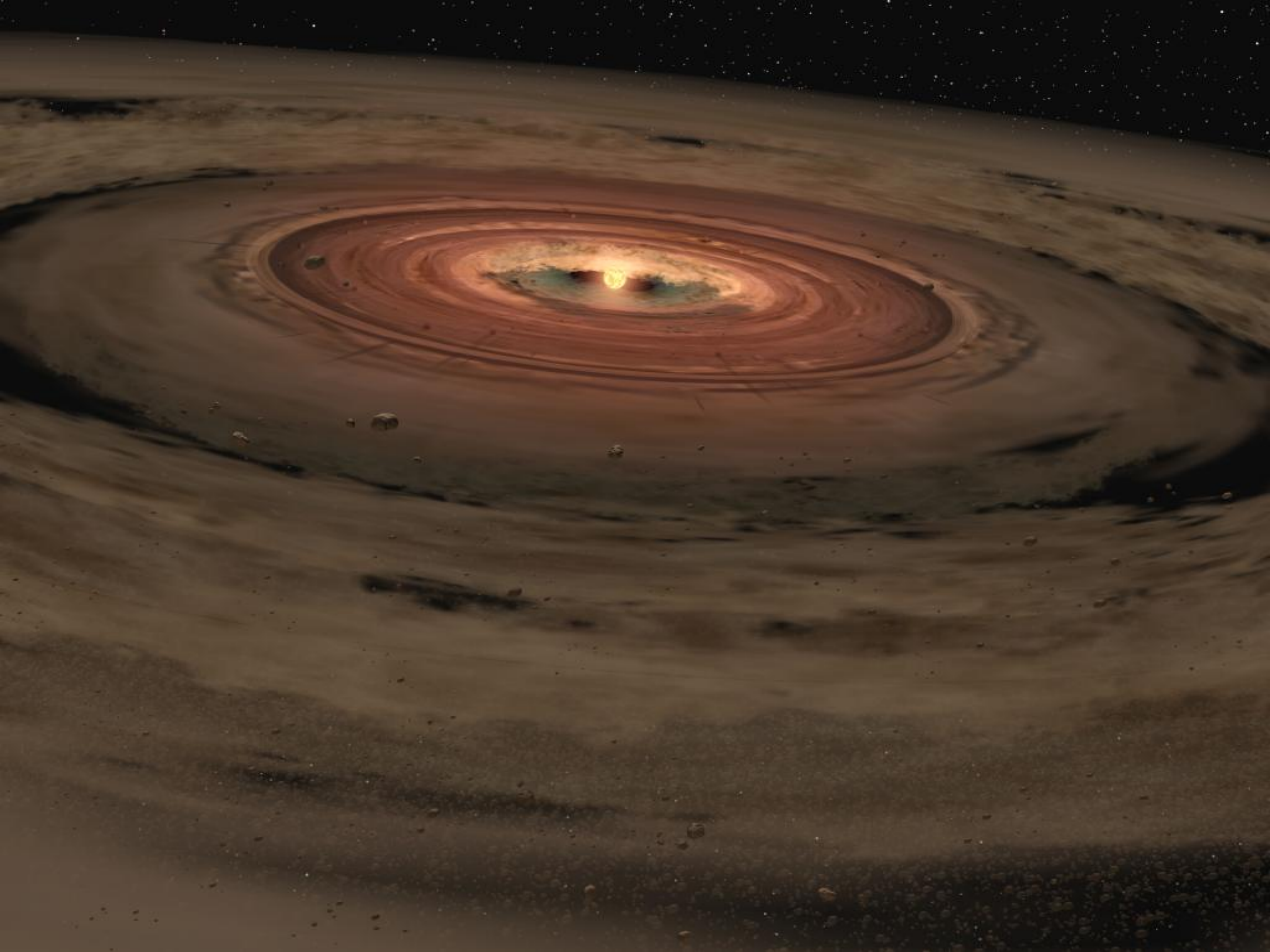
0.4m Meade LX200
ACF F/10

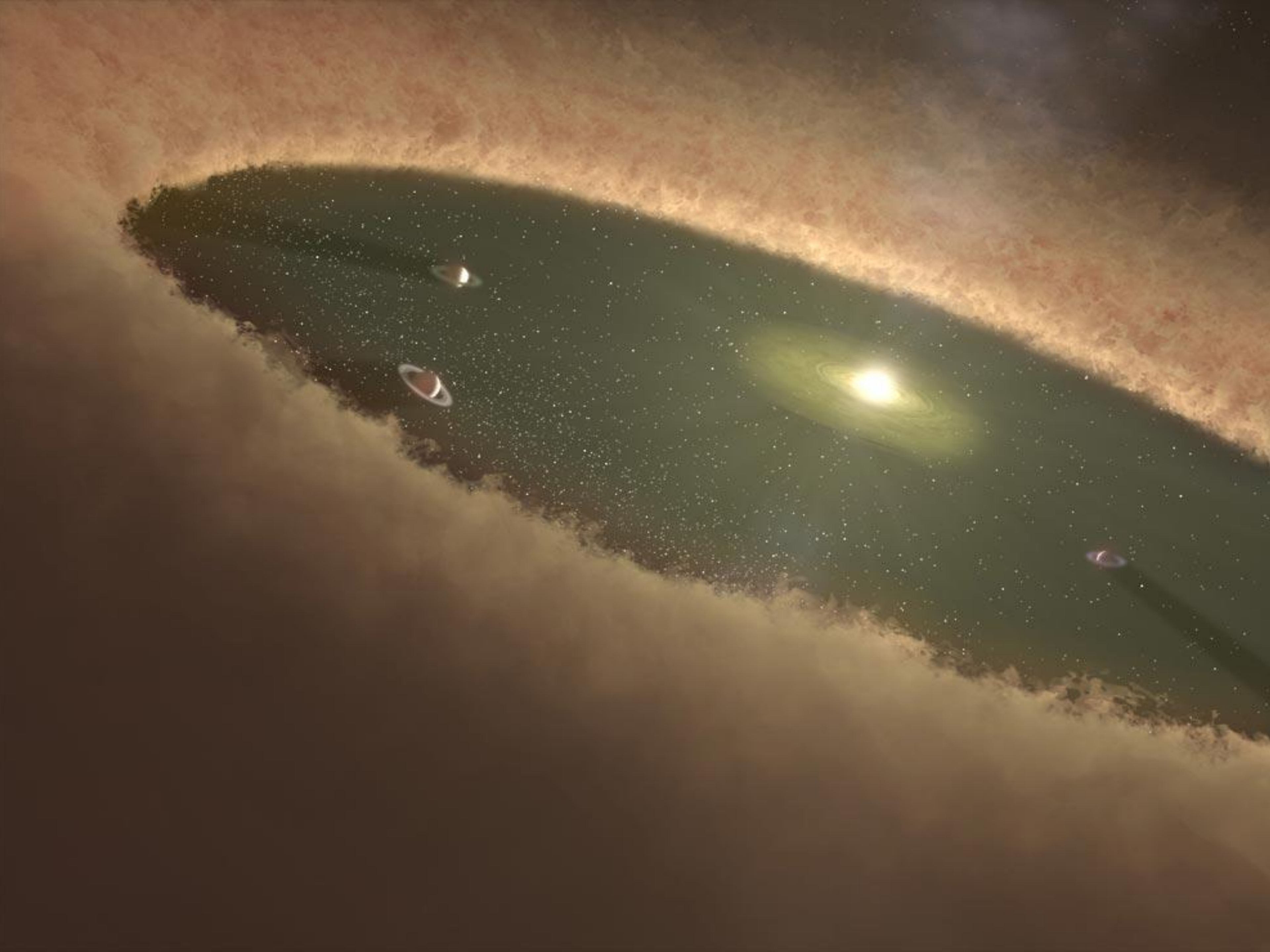
Paramount GT1100s

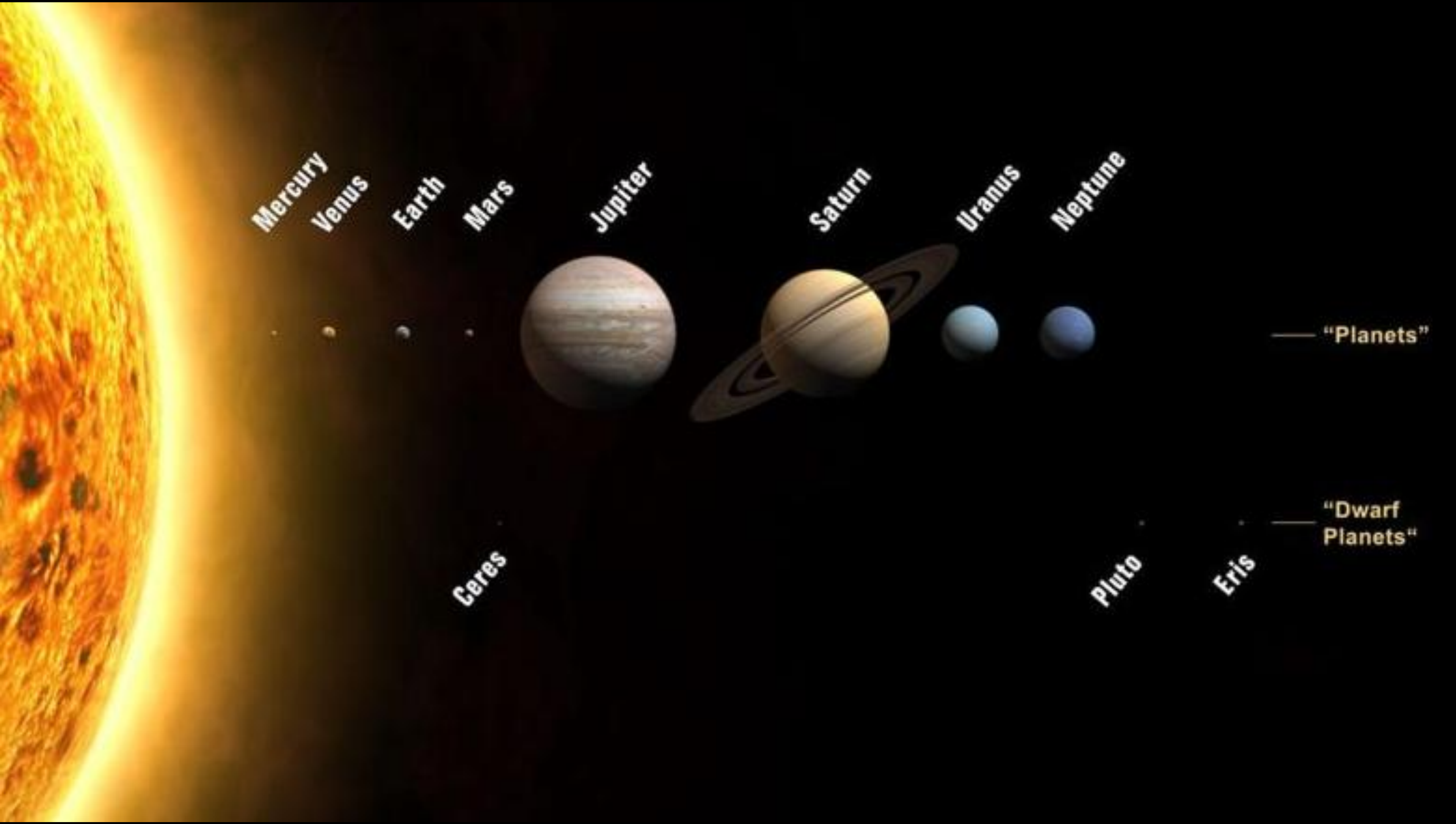
STL-6303E CCD (BVRI)

Extra-solar Planets

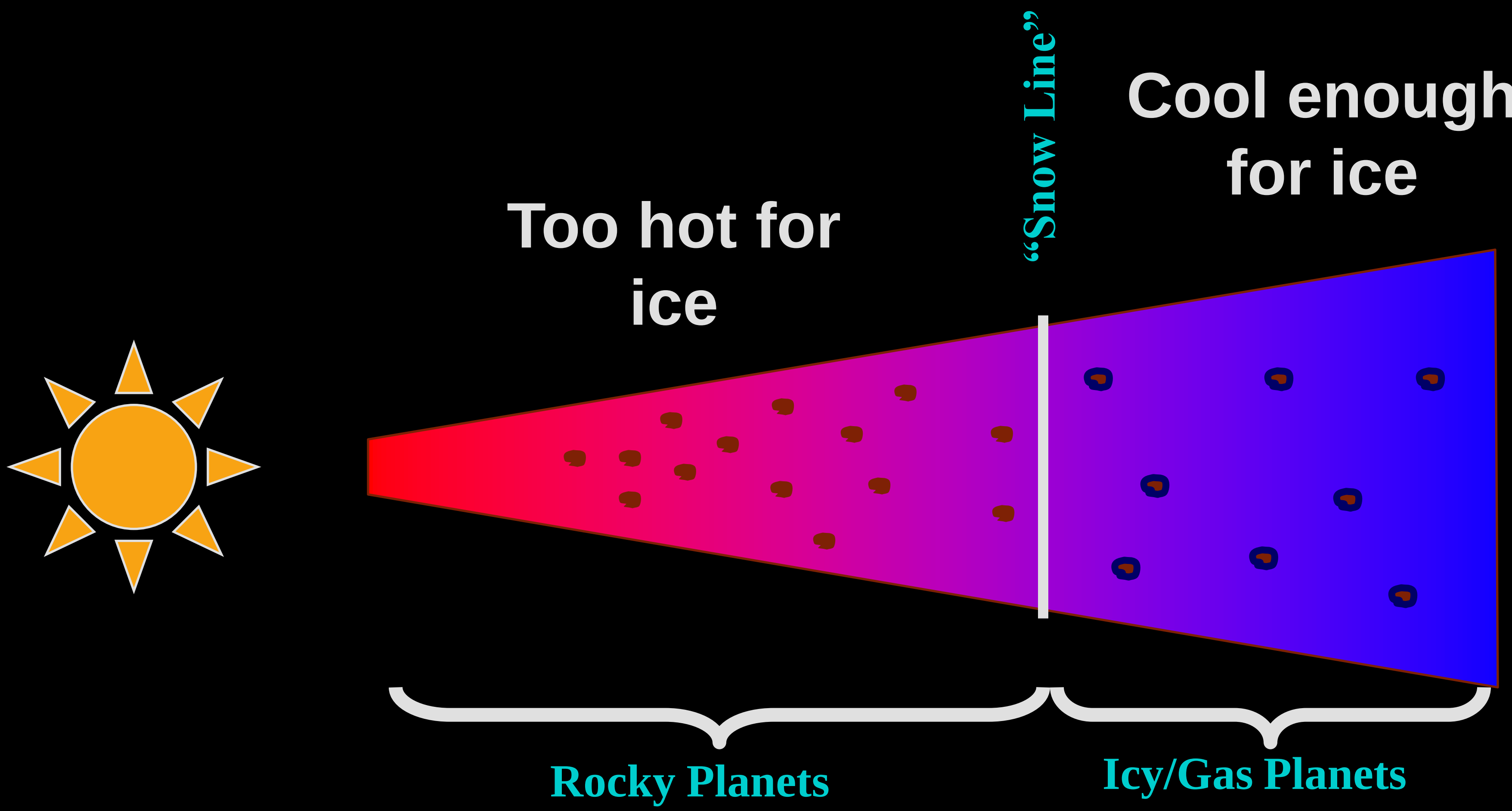
- How many stars have planets?
- How do planets form?
- Is our solar system typical?
- Are there other Earths?
- How many can support life?

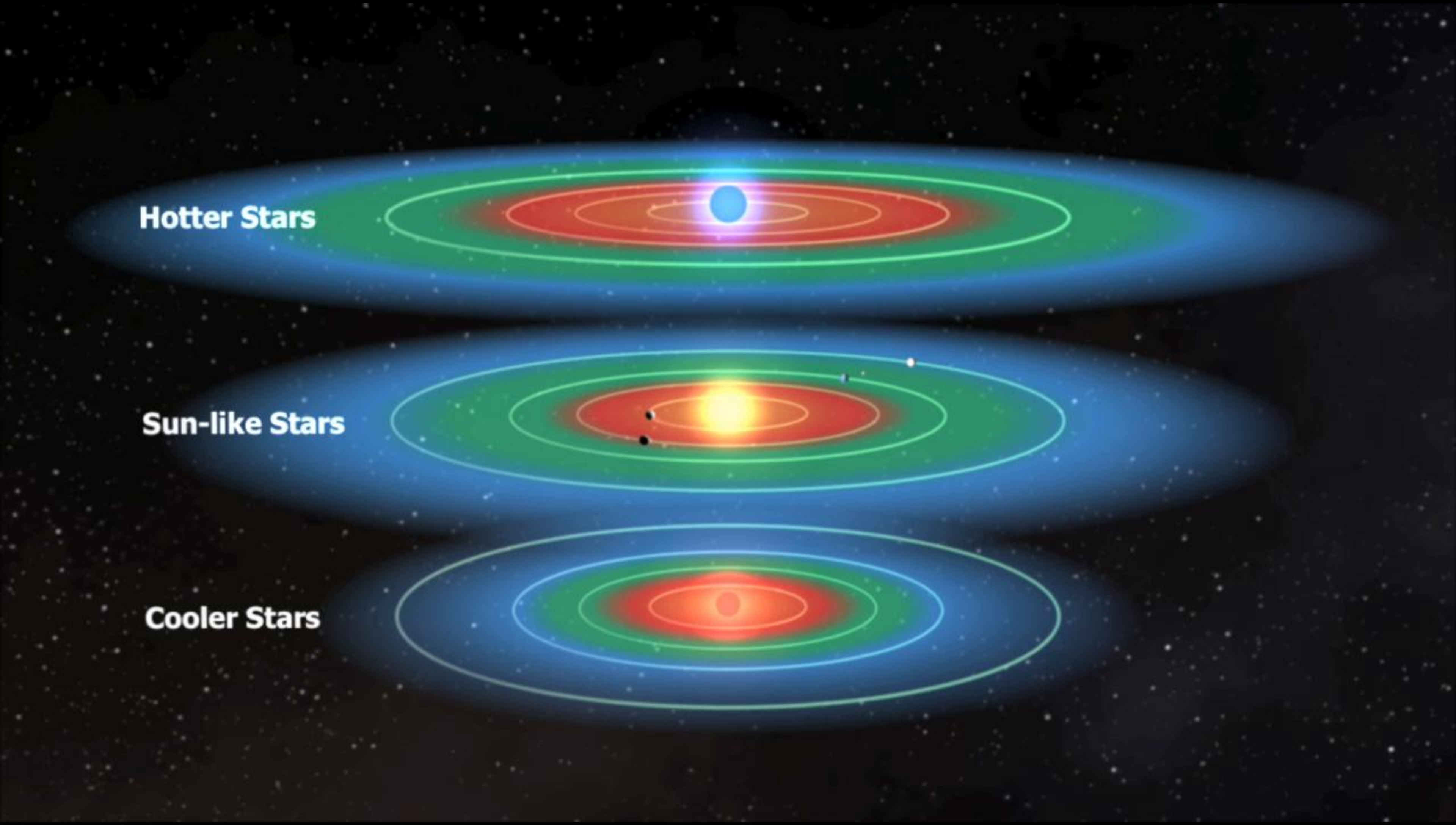


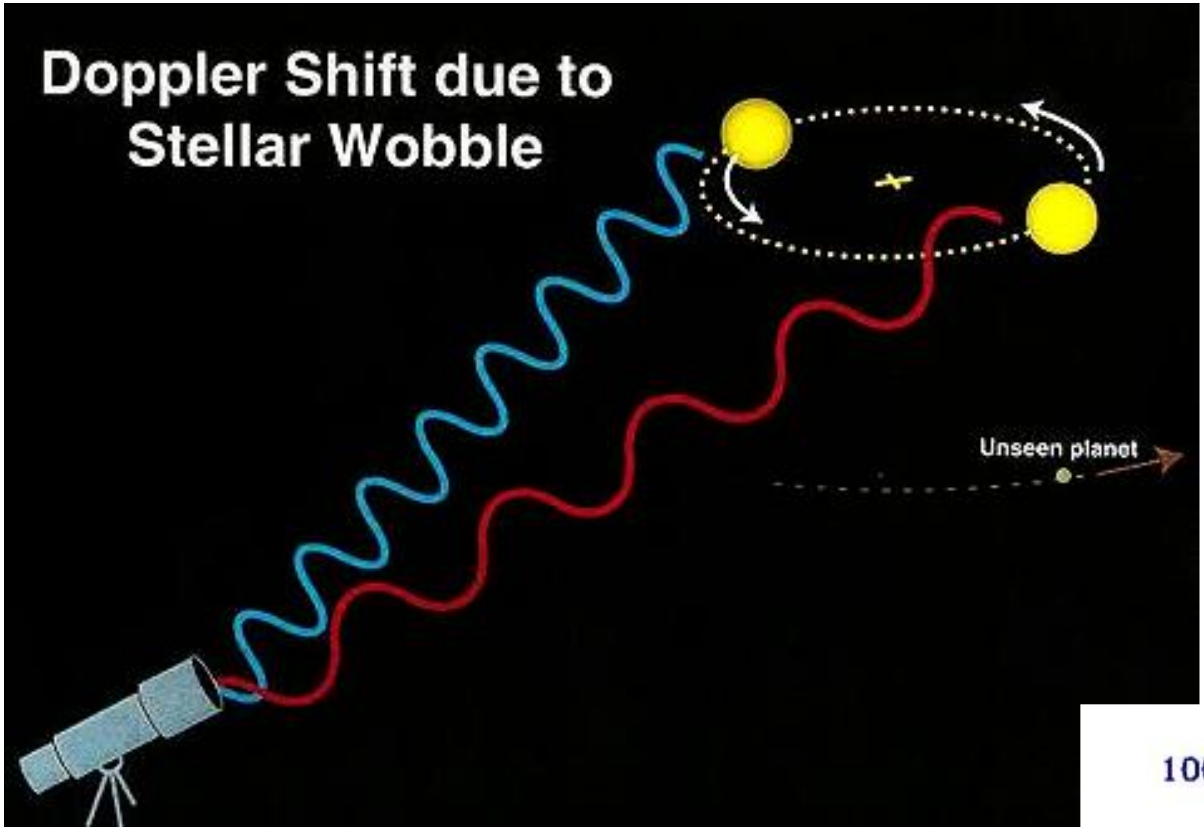


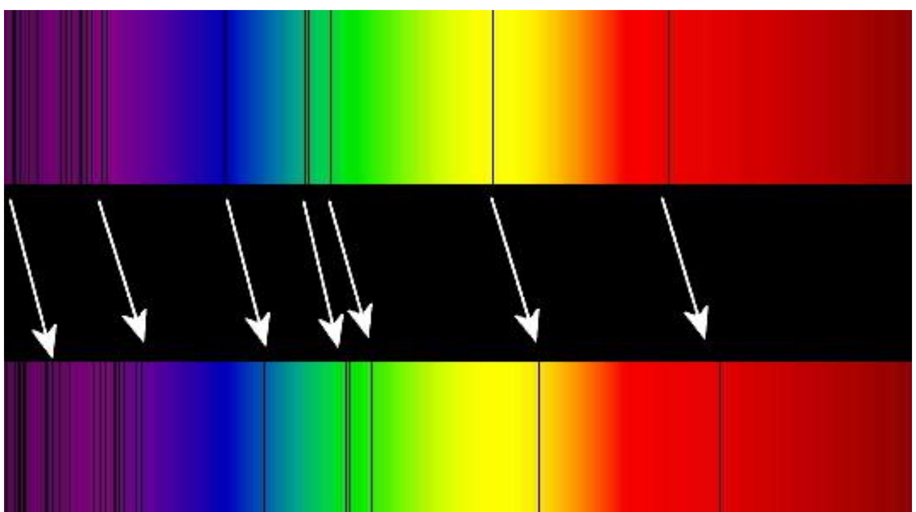

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Ceres
Pluto
Eris
"Dwarf Planets"

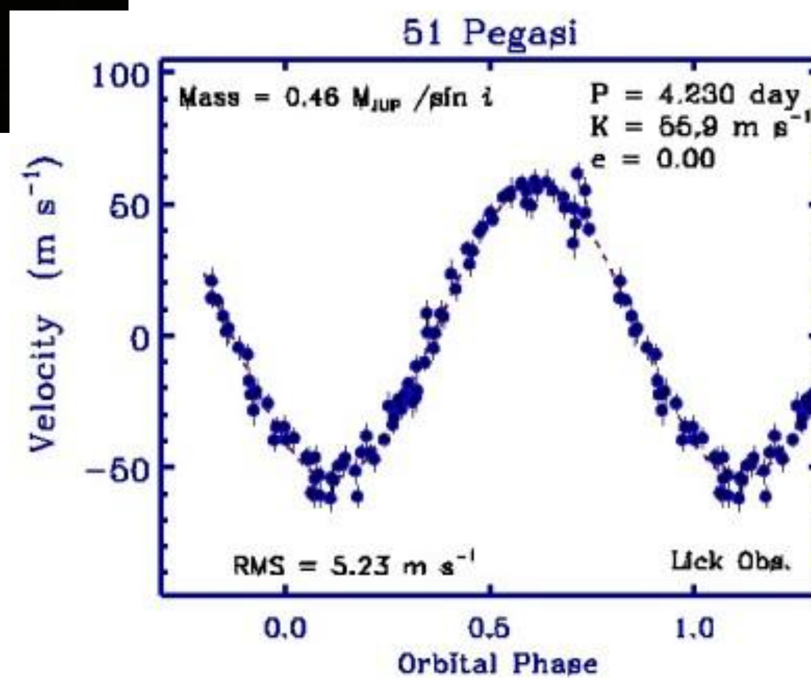
The “Snow Line”



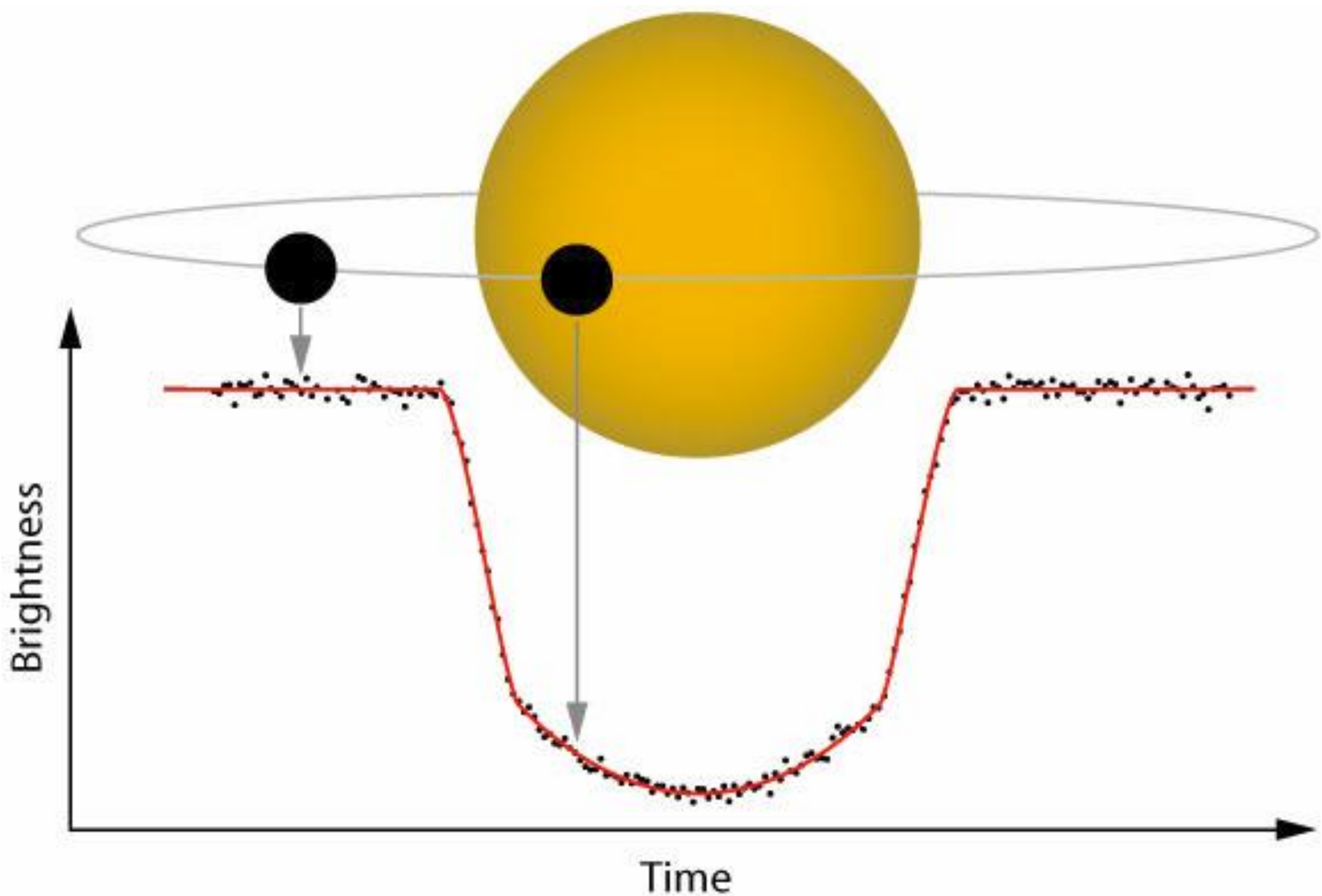

Hotter Stars
Sun-like Stars
Cooler Stars


Doppler Shift due to
Stellar Wobble
Unseen planet




51 Pegasi
Mass = 0.46 M_JUP /sin i
P = 4.230 day
K = 55.9 m s^-1
e = 0.00
RMS = 5.23 m s^-1
Lick Obs.
Velocity (m s^-1)
Orbital Phase
100
50
0
-50
0.0
0.5
1.0

Kepler Space Telescope

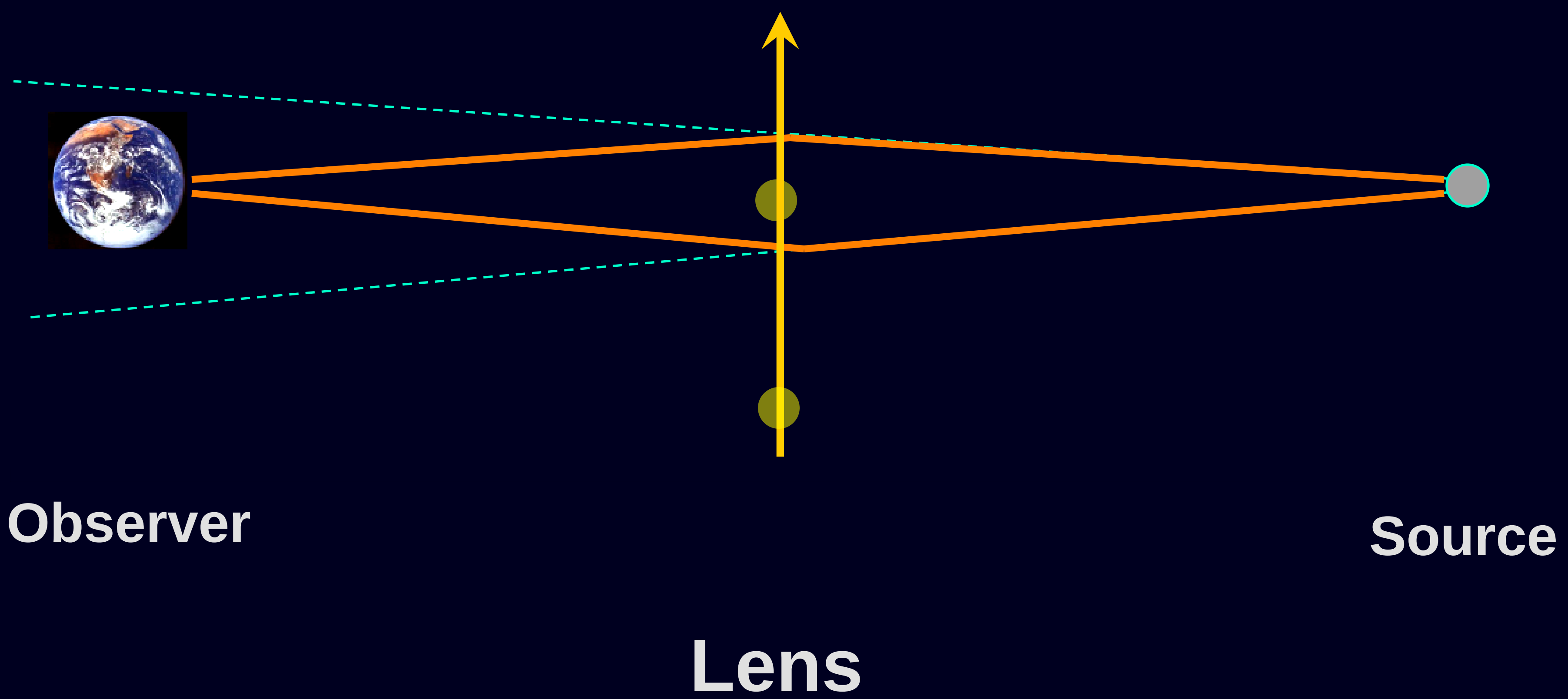


MicroFUN
Ohio State University

- Planet discovery by microlensing
- Pro-Am collaboration
- Cutting-edge science that engages the public

Google: "microfun"

Gravitational *micro*lensing



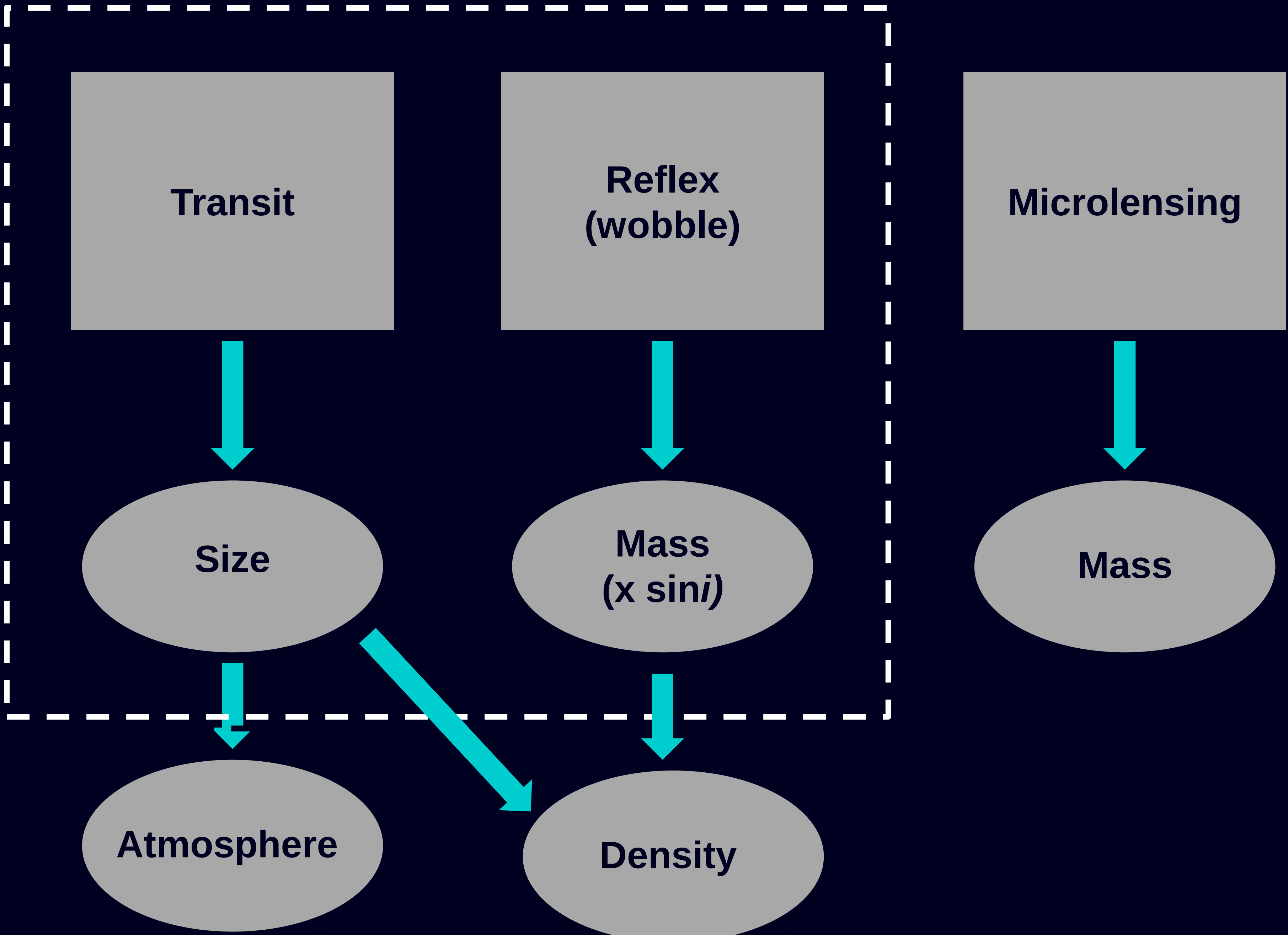
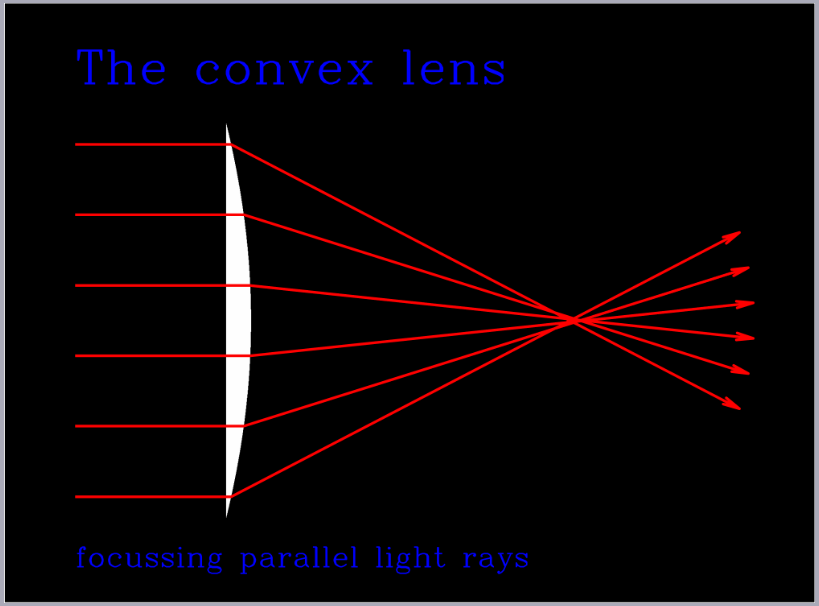
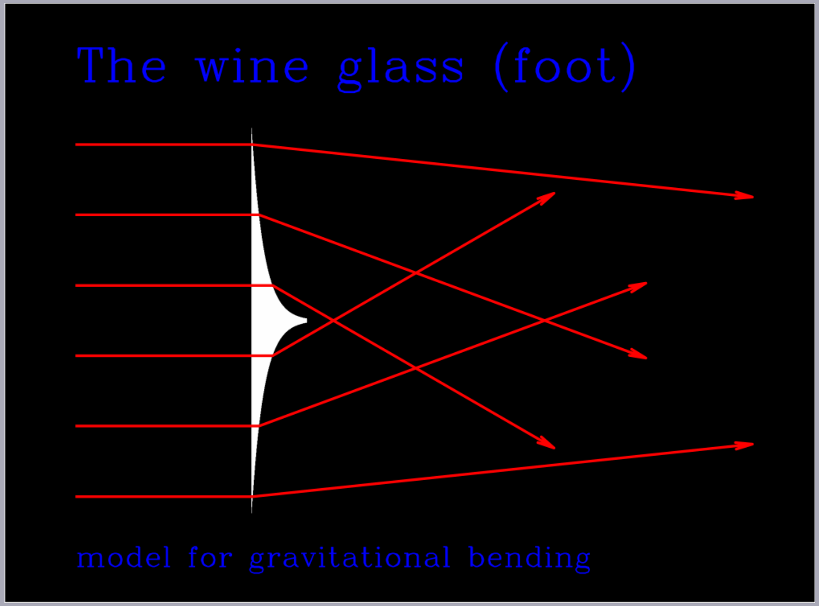
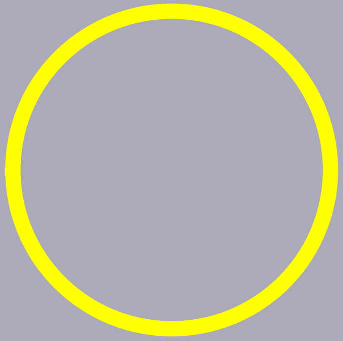

Transit
Reflex
(wobble)
Microlensing
Size
Mass
(x sin*i*)
Mass
Atmosphere
Density

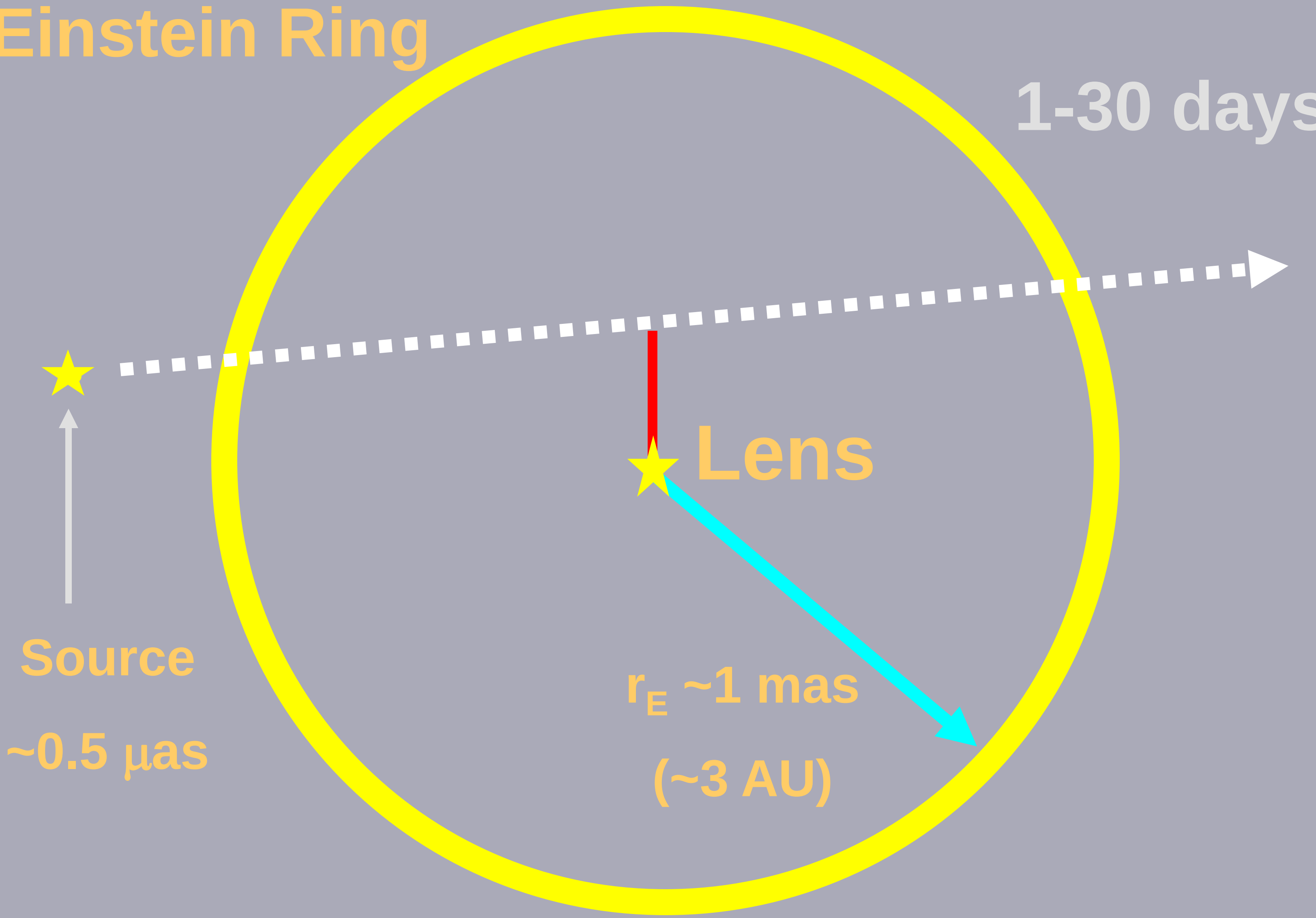
Image formed of a point source at infinity





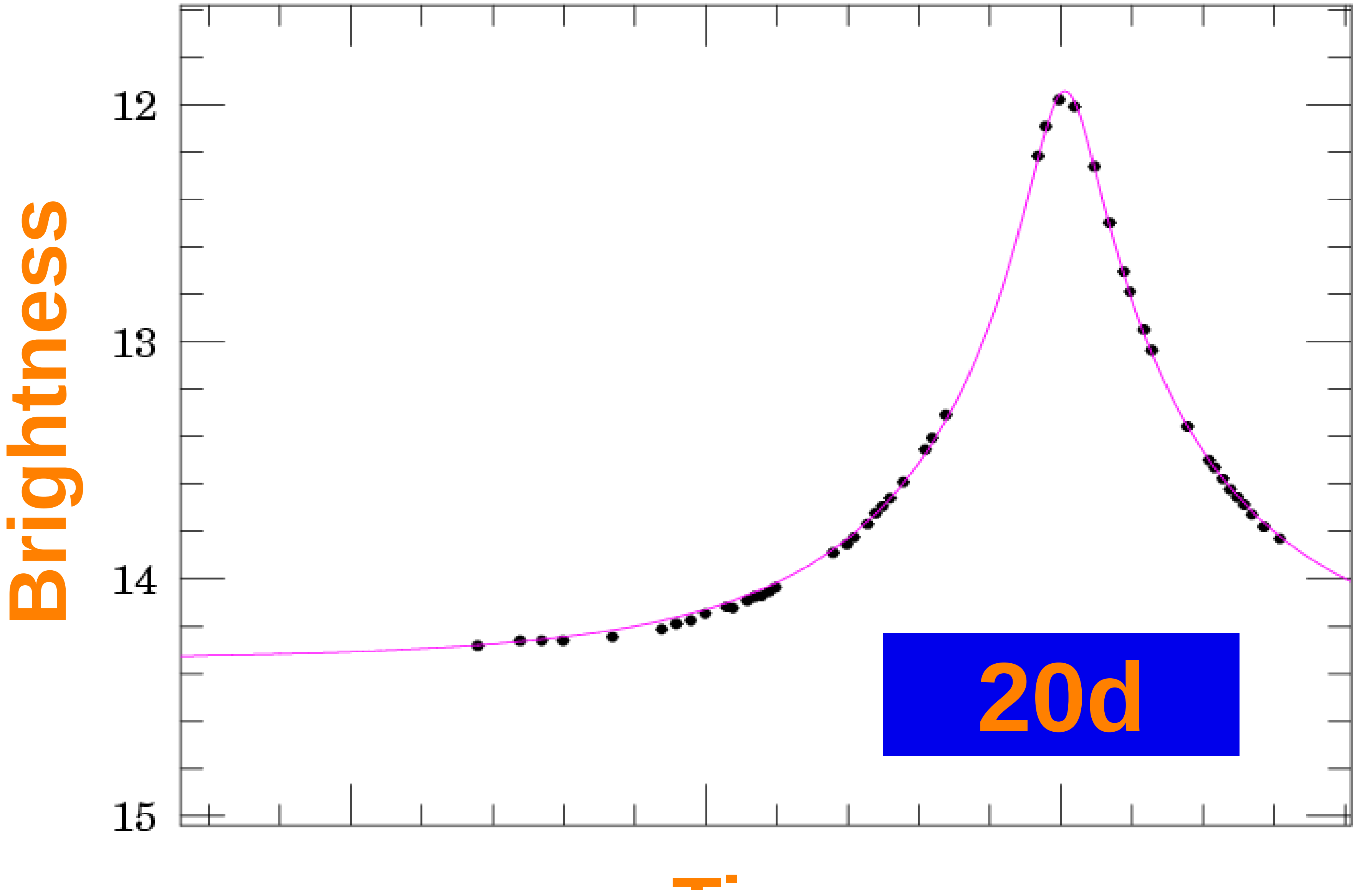


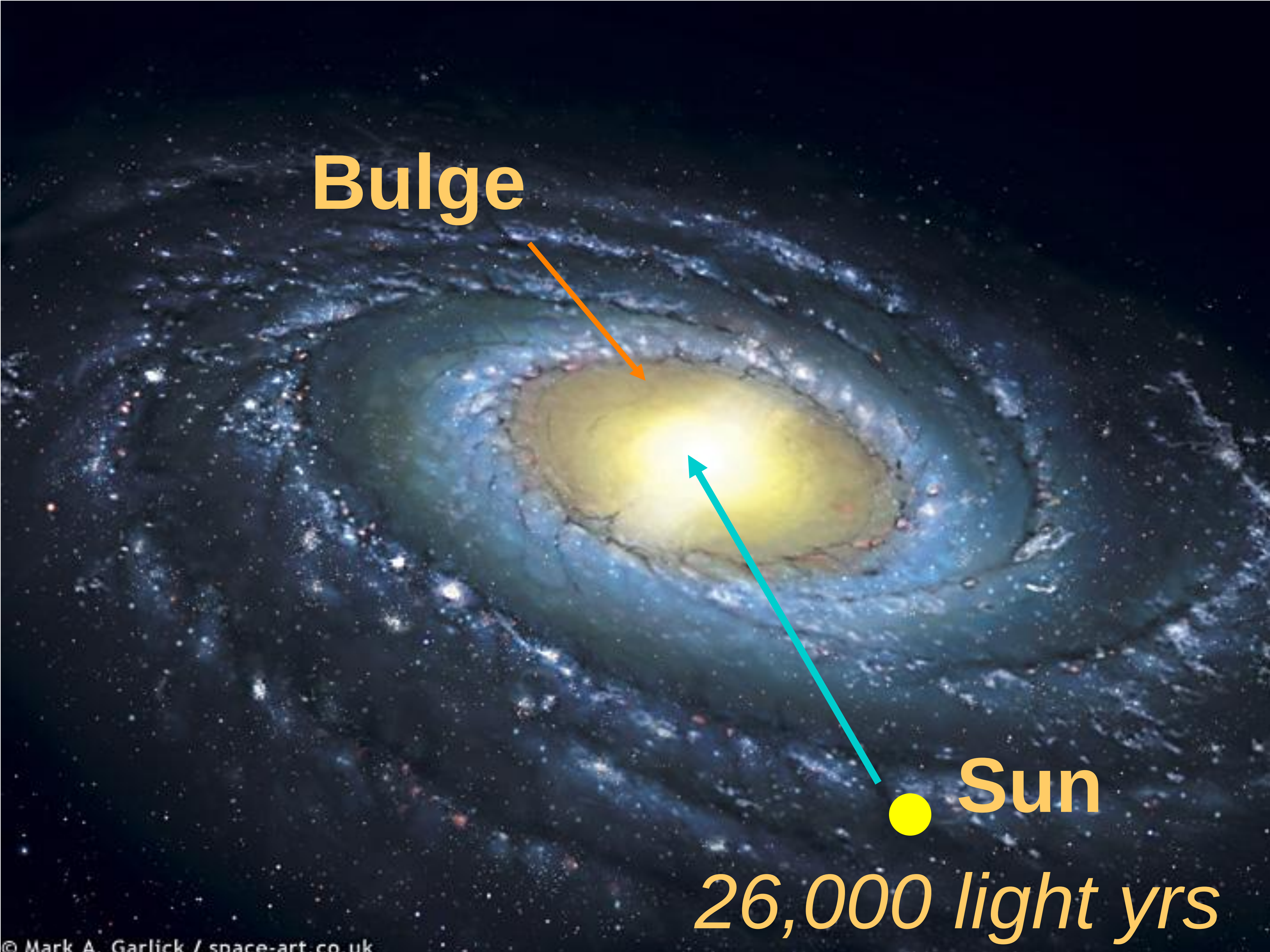
Einstein Ring

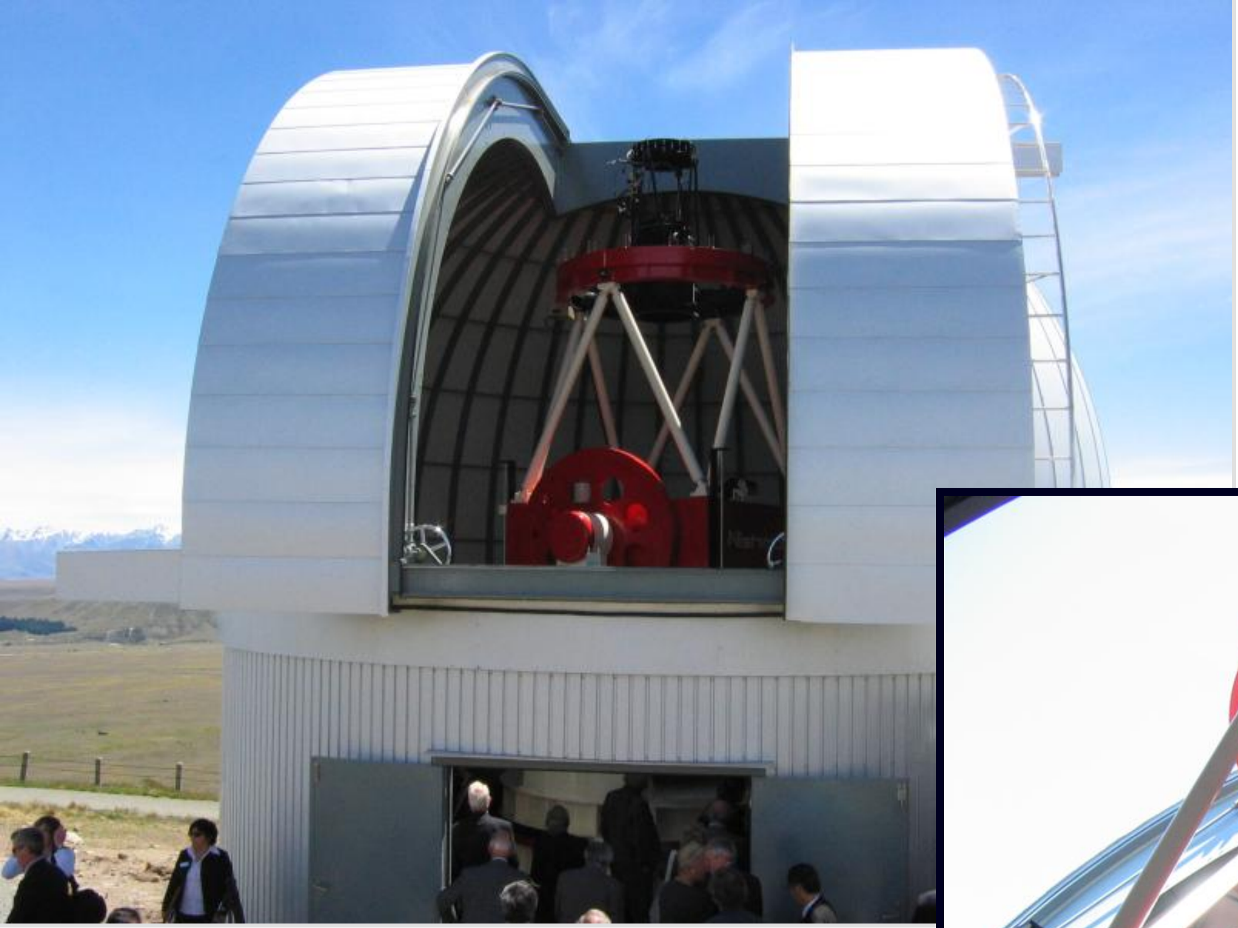


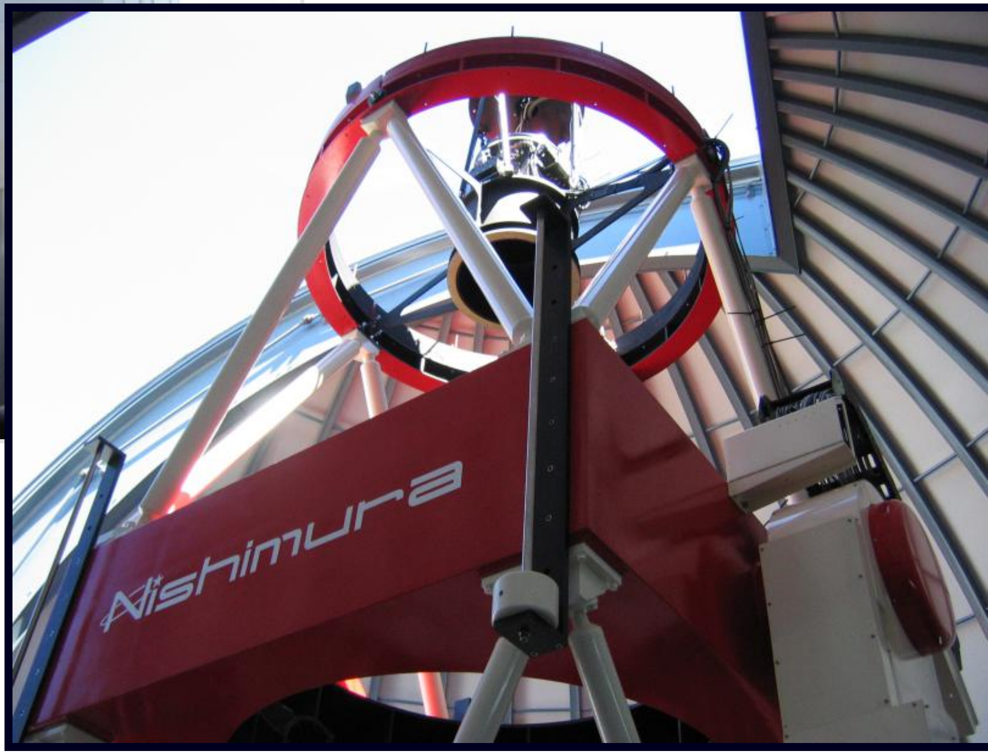
The chance of seeing this is less than 1 in 500,000

Simple Event – no planets




Bulge
Sun
26,000 light yrs
© Mark A. Garlick / space-art.co.uk





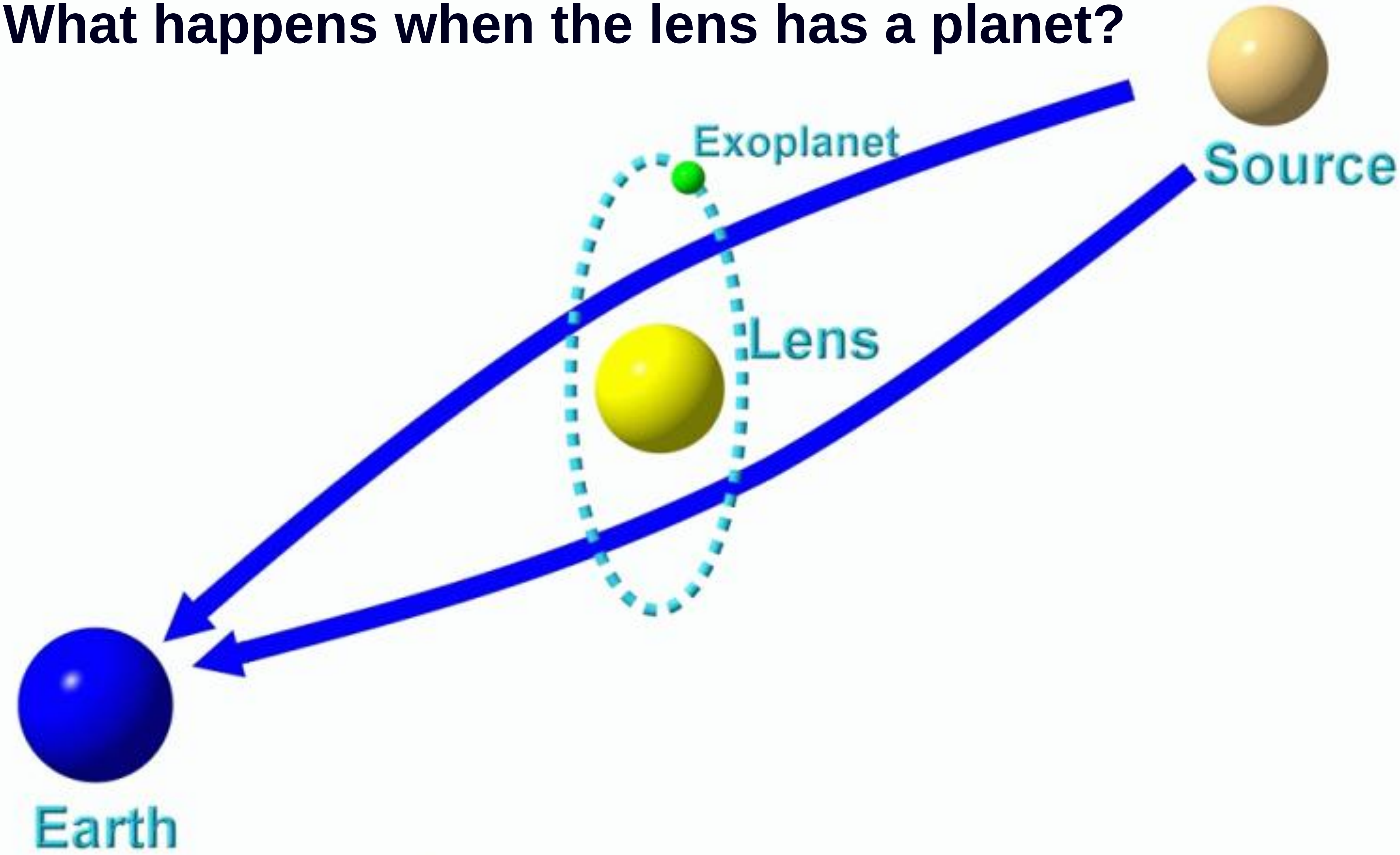
1.8m MOATEL

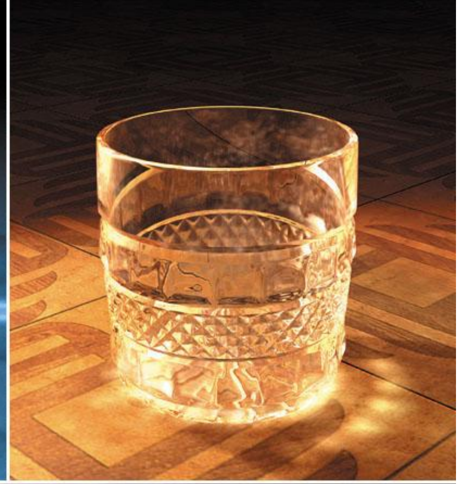
MOA – Mt John Observatory, NZ

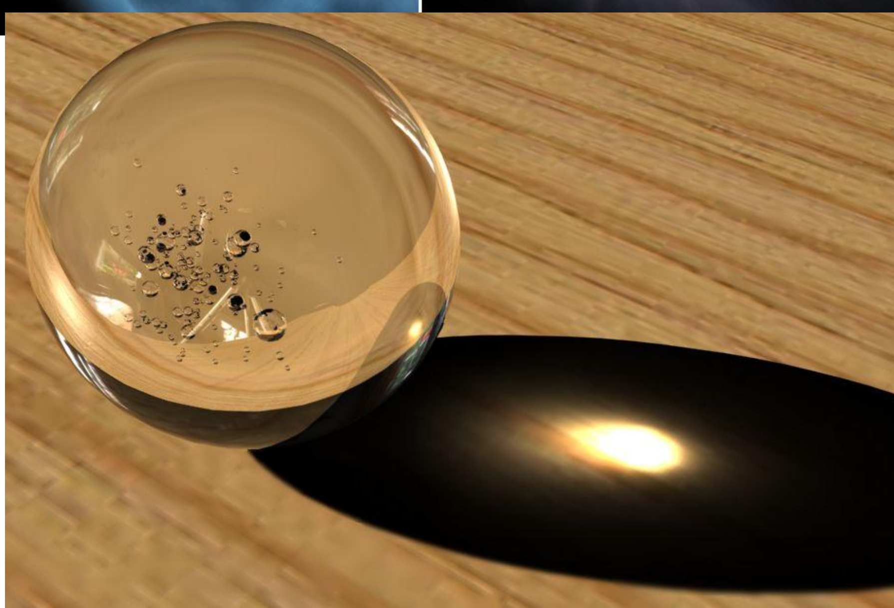
OGLE - Las Campanas, Chile

1.3m Warsaw University Telescope

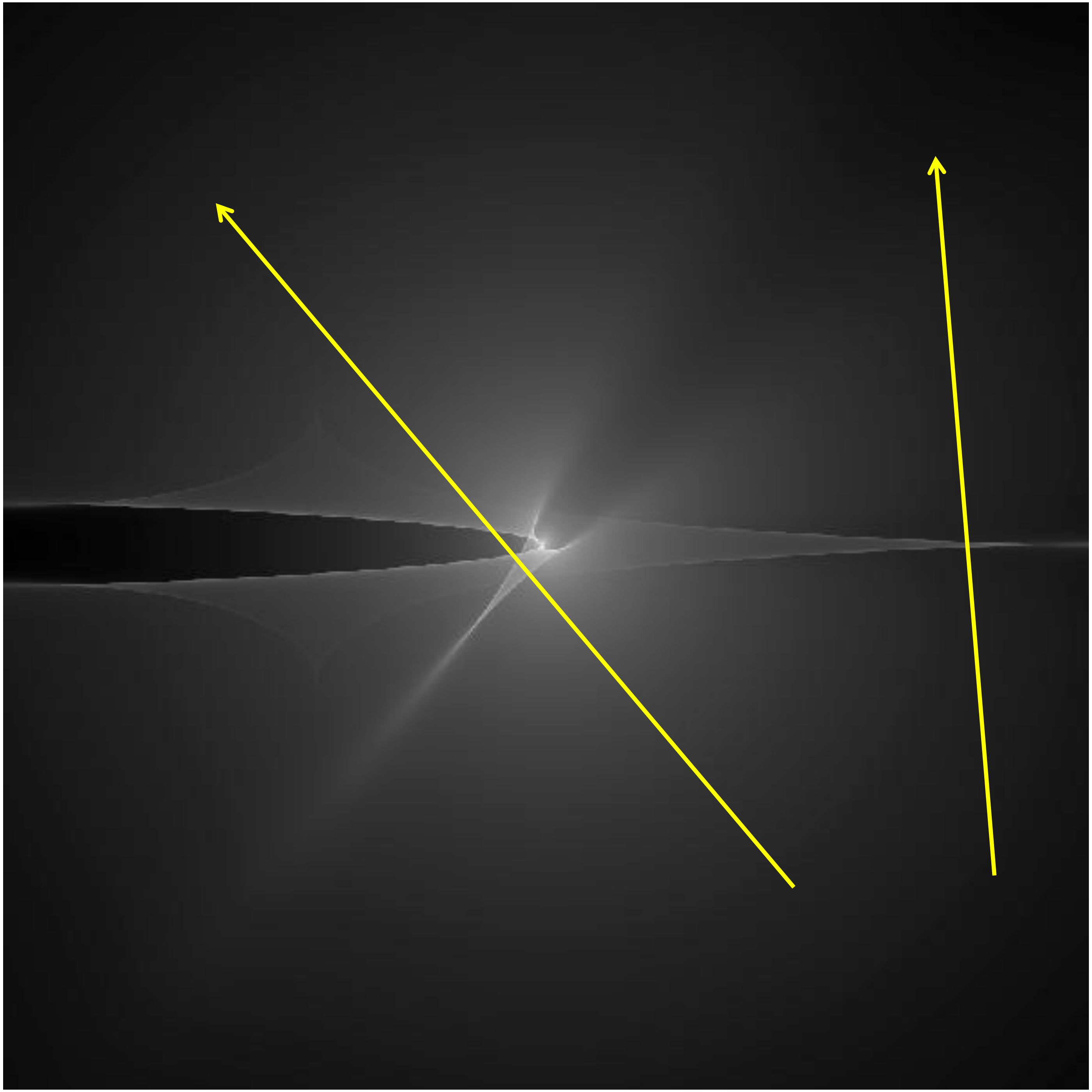
What happens when the lens has a planet?

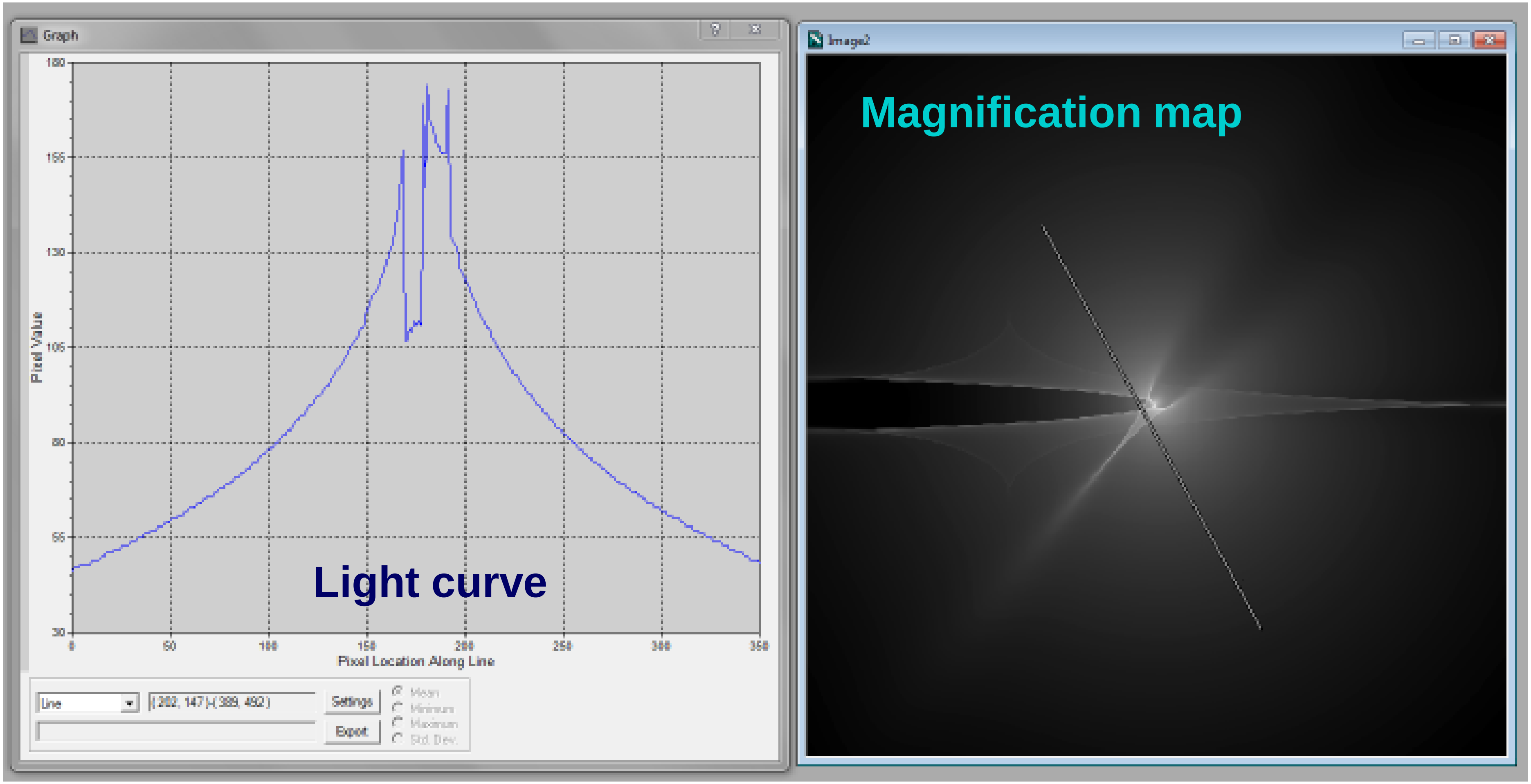


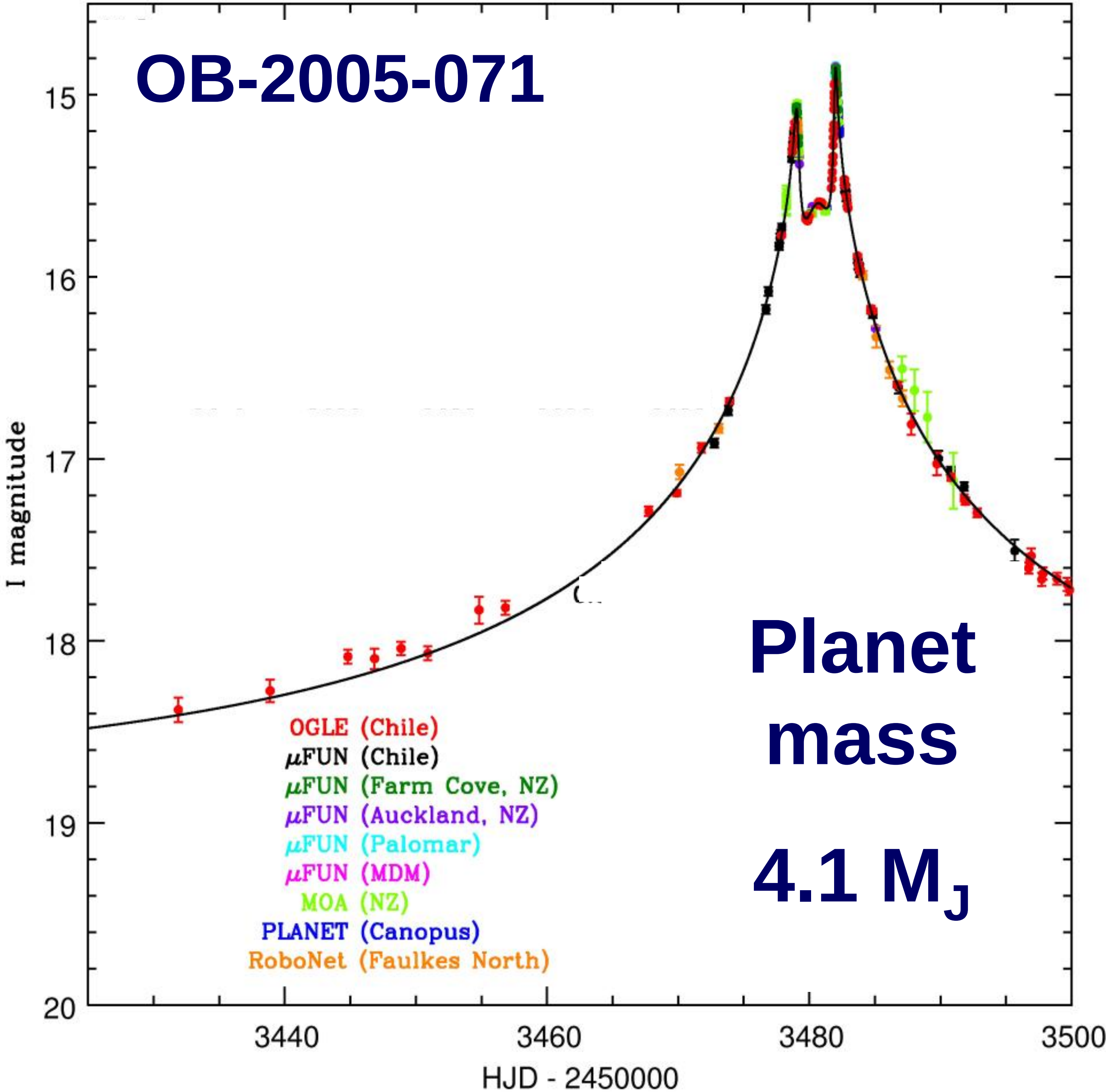

Magnification map for a star with two planets





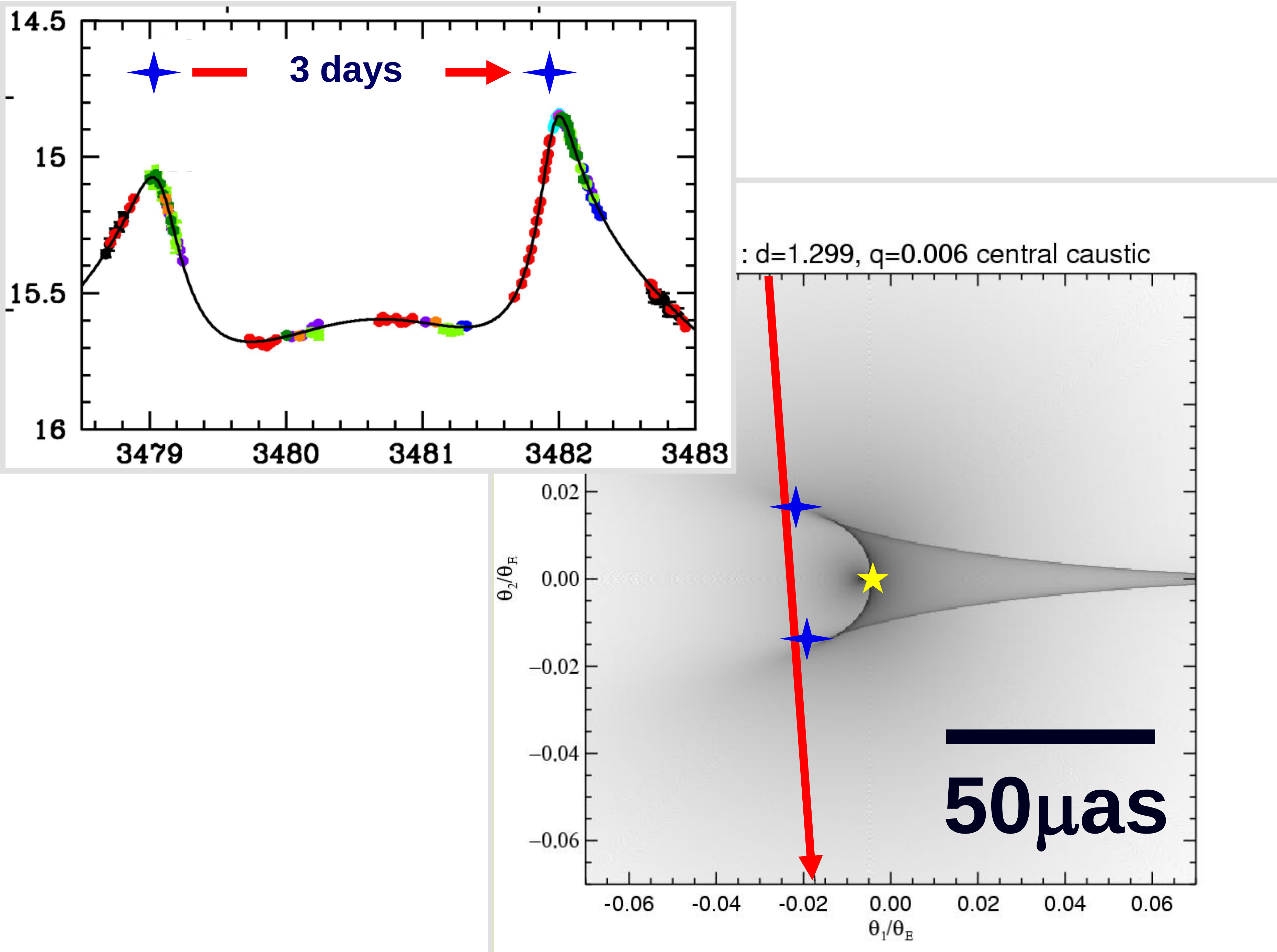
An amazing range of "light curves" can be generated depending on the path taken through the lens by the background star

OB-2005-071



Planet mass

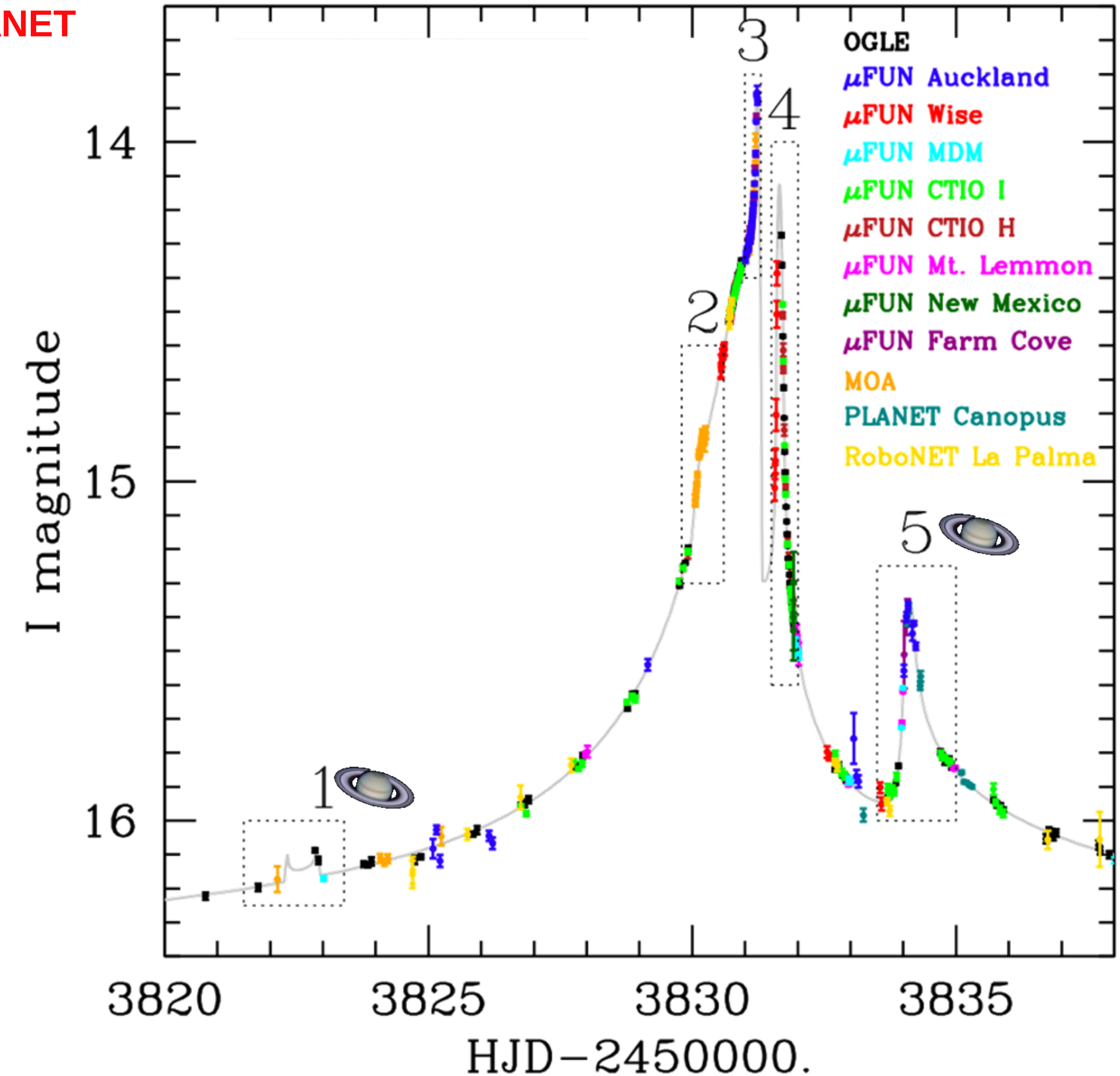
4.1 M_J


3 days
14.5
15
15.5
16
3479
3480
3481
3482
3483
: d=1.299, q=0.006 central caustic
0.02
0.00
−0.02
−0.04
−0.06
θ_2/θ_E
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
θ_1/θ_E
50µas

OGLE-2006-BLG-109

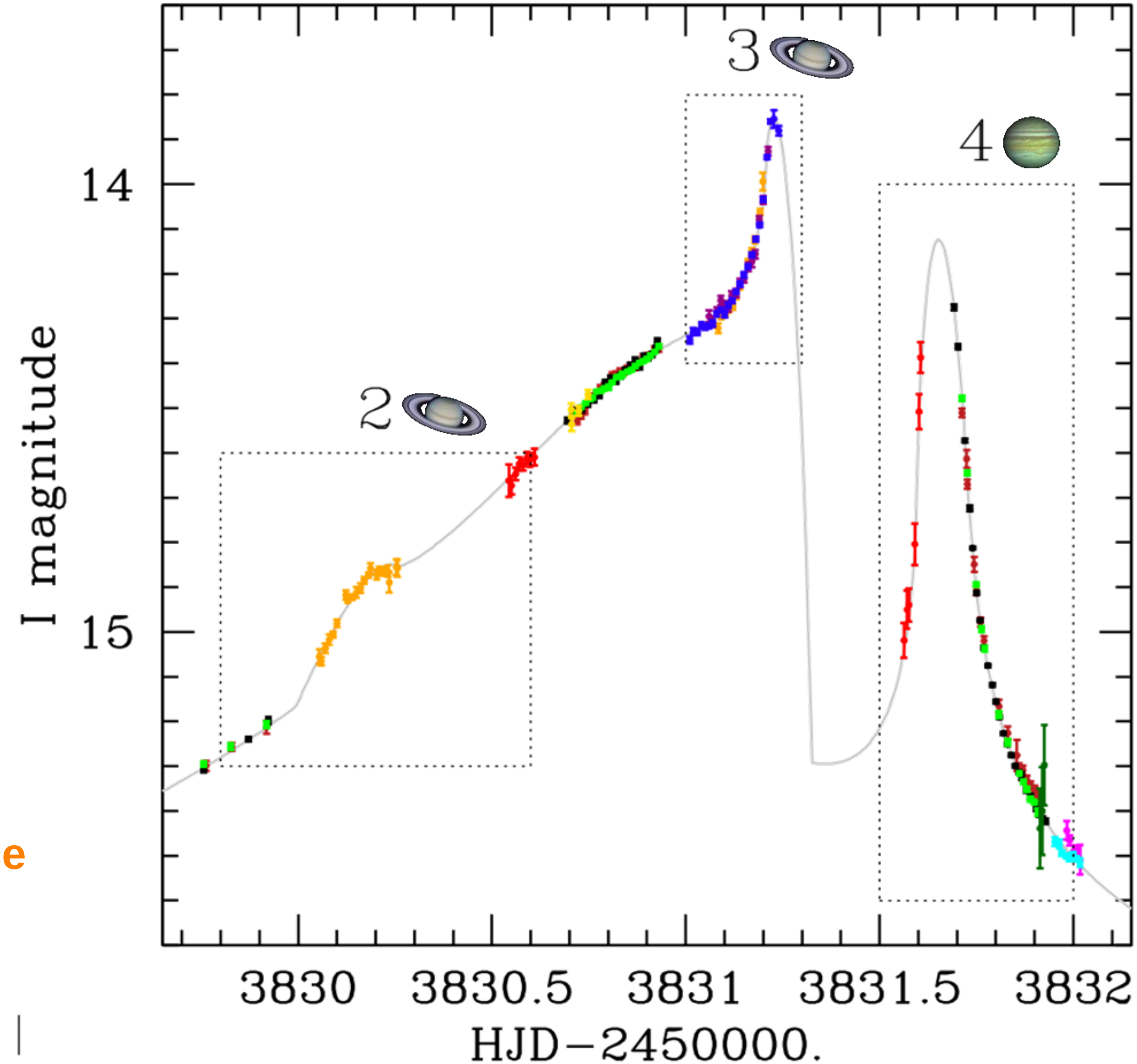
μFUN, OGLE, MOA & PLANET

- **5 distinct planetary light curve features**
- **Feature #4 requires an additional planet**
- **Planetary signals visible for 11 days**
- **need orbital motion of the Saturn-mass planet and the Earth**

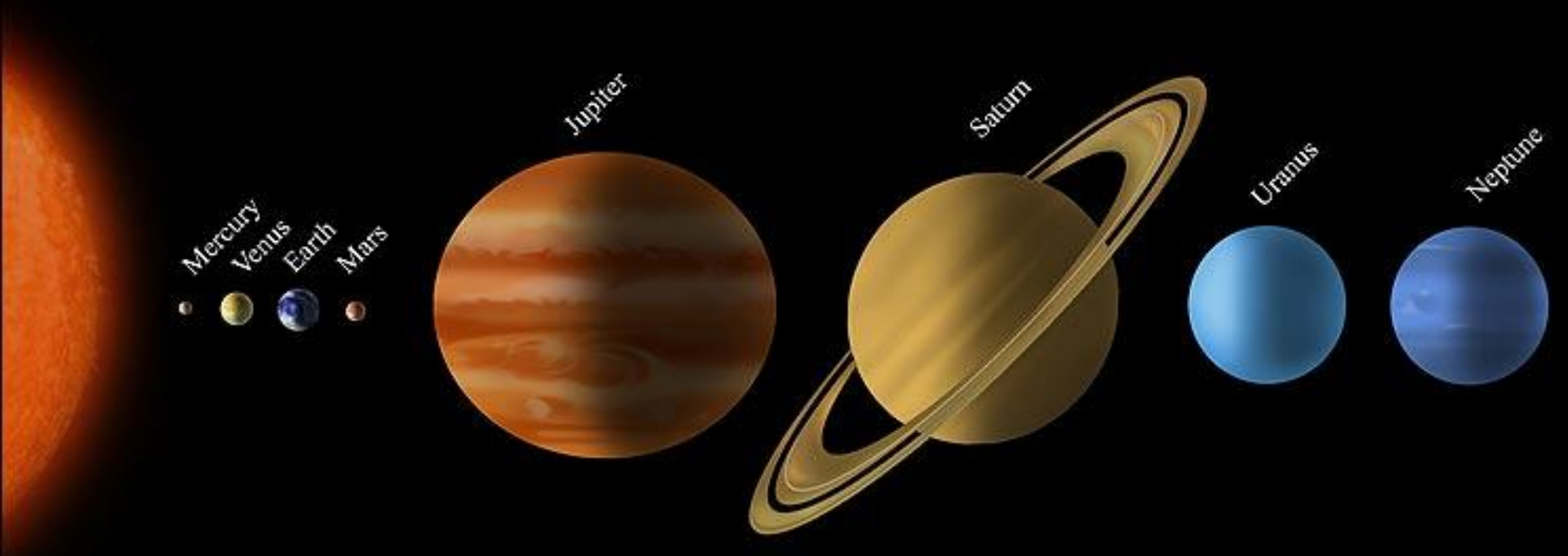


OGLE-2006-BLG-109

- μFUN (Gaudi) obtained a model approximately predicting features #3 & #5 prior to the peak
- But feature #4 was not predicted - because it is due to the Jupiter - not the Saturn



Gaudi *et al* (2008) published in Science



Our Solar System

OGLE-2006-BLG-109

OGLE-2012-BLG-0026Lb, c

A new two-planet system

March 2012

ApJ ***762****, L28, 6 pp. (2013)*

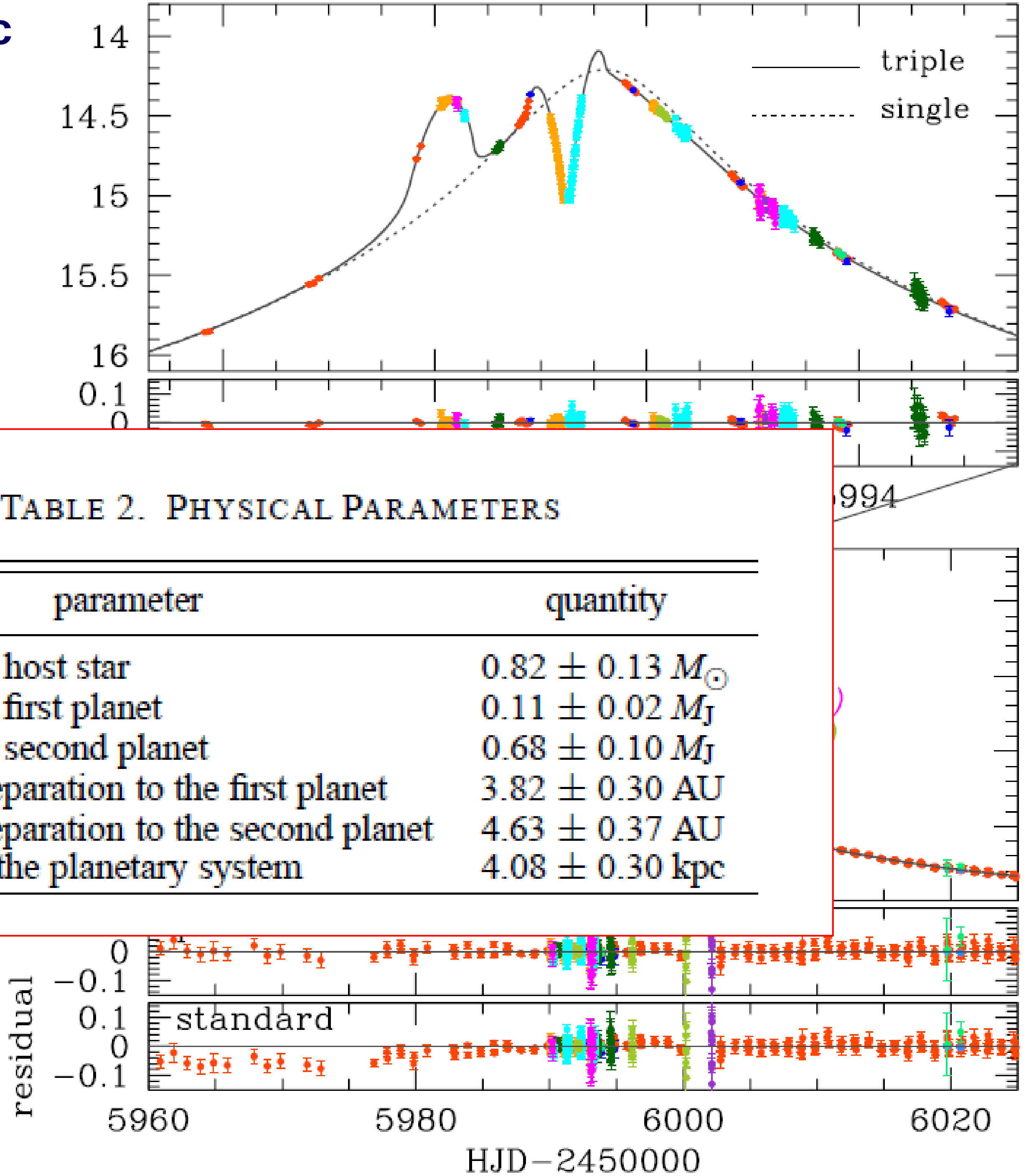
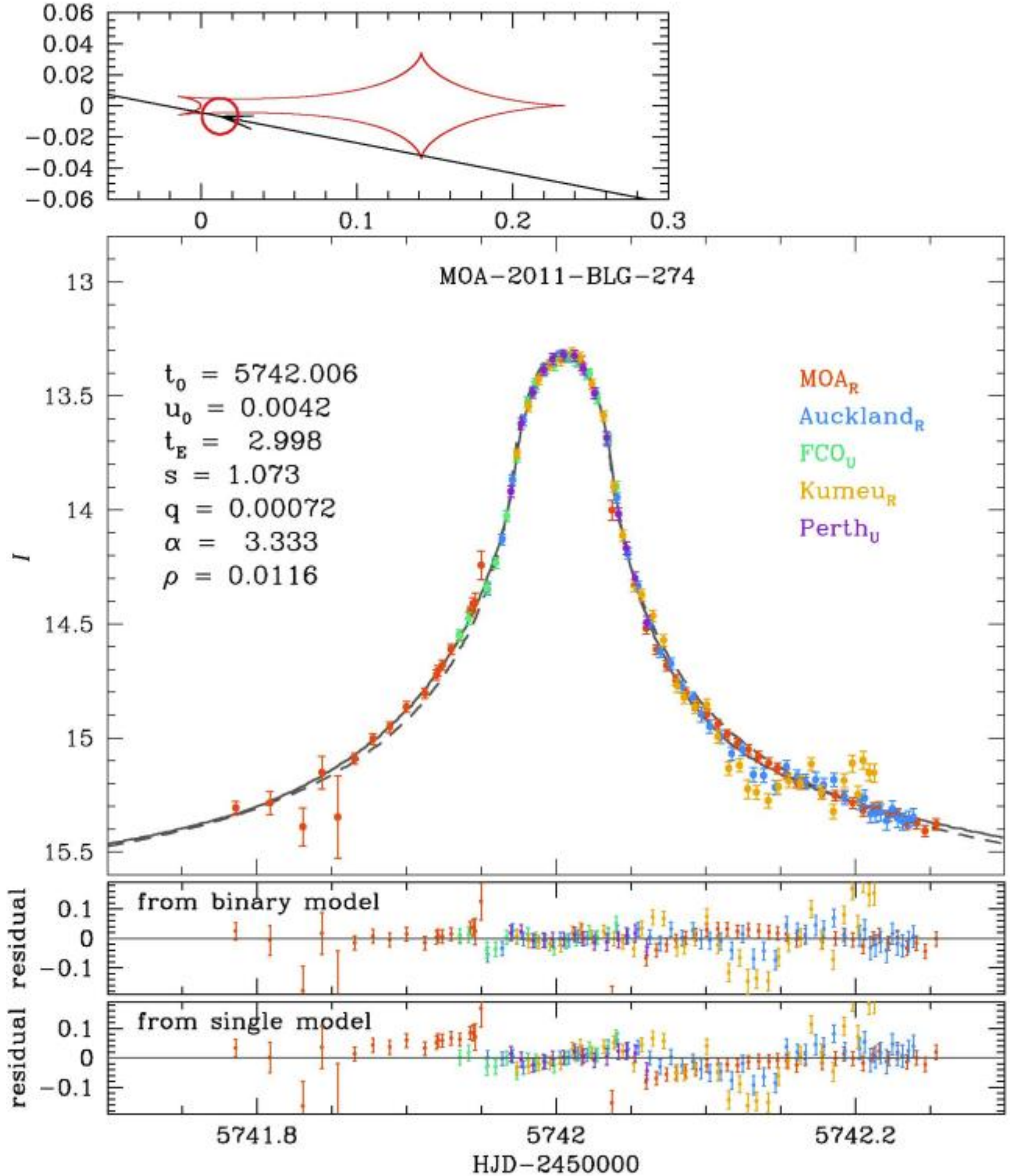


TABLE 2. PHYSICAL PARAMETERS

parameter	quantity
mass of the host star	$0.82 \pm 0.13\ M_{\odot}$
mass of the first planet	$0.11 \pm 0.02\ M_{\mathrm{J}}$
mass of the second planet	$0.68 \pm 0.10\ M_{\mathrm{J}}$
projected separation to the first planet	3.82 ± 0.30 AU
projected separation to the second planet	4.63 ± 0.37 AU
distance to the planetary system	4.08 ± 0.30 kpc

Very small planet orbiting a brown dwarf



Results to Date

- 20+ planets (2004-2012) .... 7 in the last season
- Planetary system with Saturn/Jupiter analog (2006)
- Second 2-planet system (2012)
- Planets orbiting brown dwarfs
- 13 publications in 2012 (11 ApJ, 1 MNRAS, 1 A&A)
- Networks of small telescopes are effective at detecting exoplanets

Acknowledgements

MicroFUN

MICROLENSING FOLLOW- UP NETWORK

THE OHIO STATE UNIVERSITY DEPARTMENT OF ASTRONOMY

Tim Natusch
Haydn Ngan
Tony Burns

Jennie McCormick

David Moorhouse
Guy Thornley

Marc Bos

What have we learned?

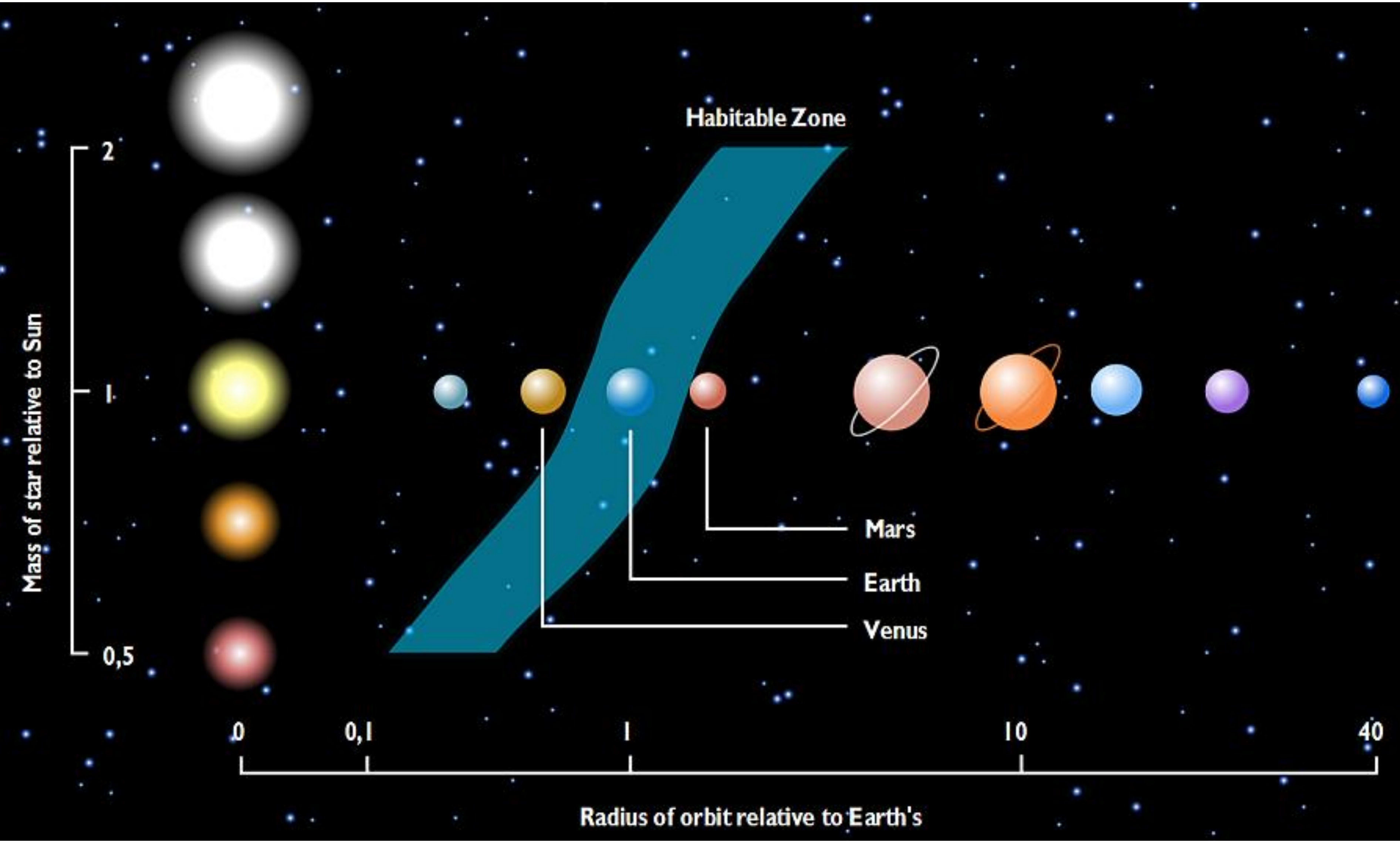
- Planets are common
- Our solar system seems to be typical. We estimate that ~12% of all stars have a solar system like ours
- There may be 2 nomad planets for every star in the galaxy
- Small telescopes can find planet

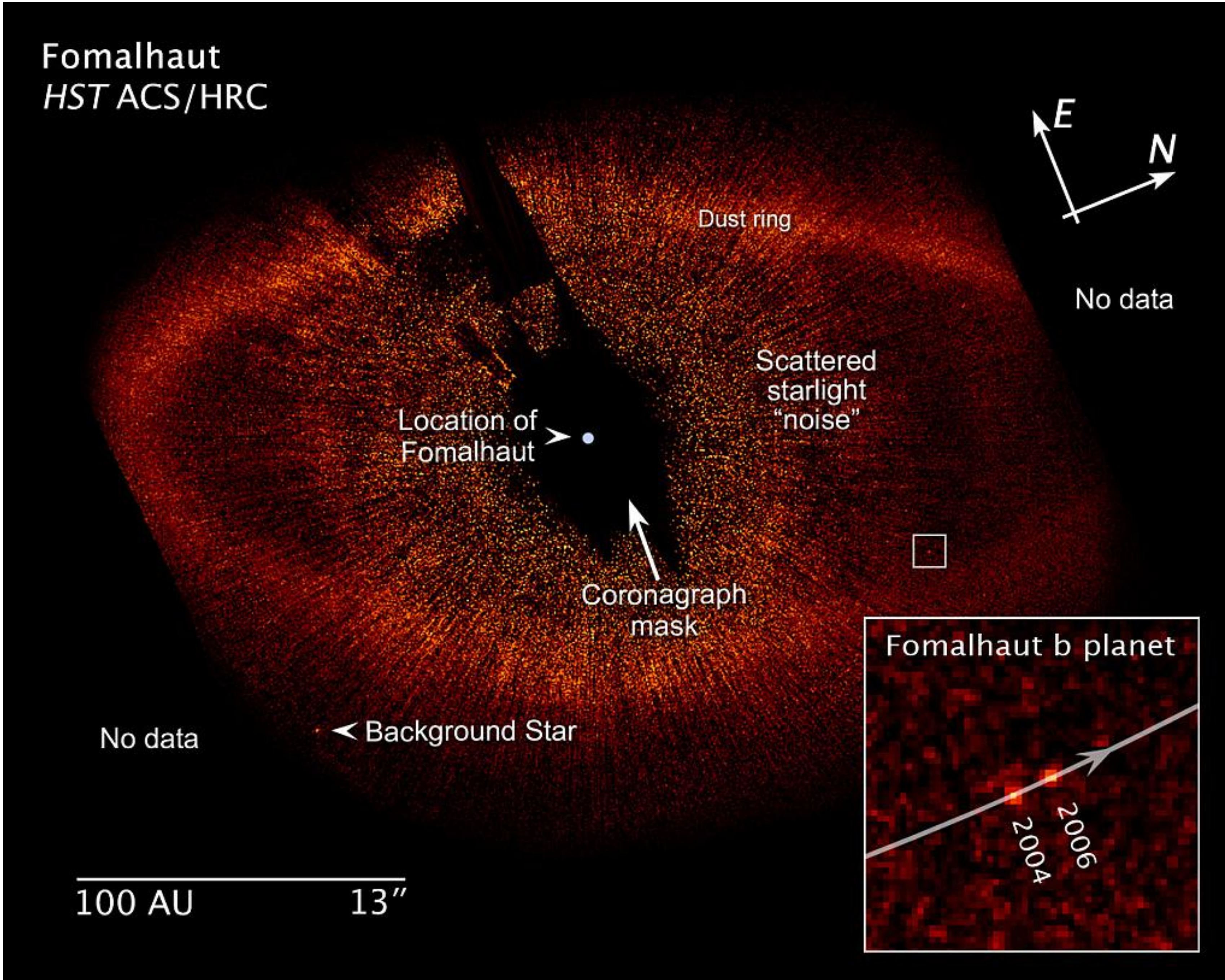
Farm Cove Observatory

Jennie McCormick

0.35m F/10 Meade LX200R

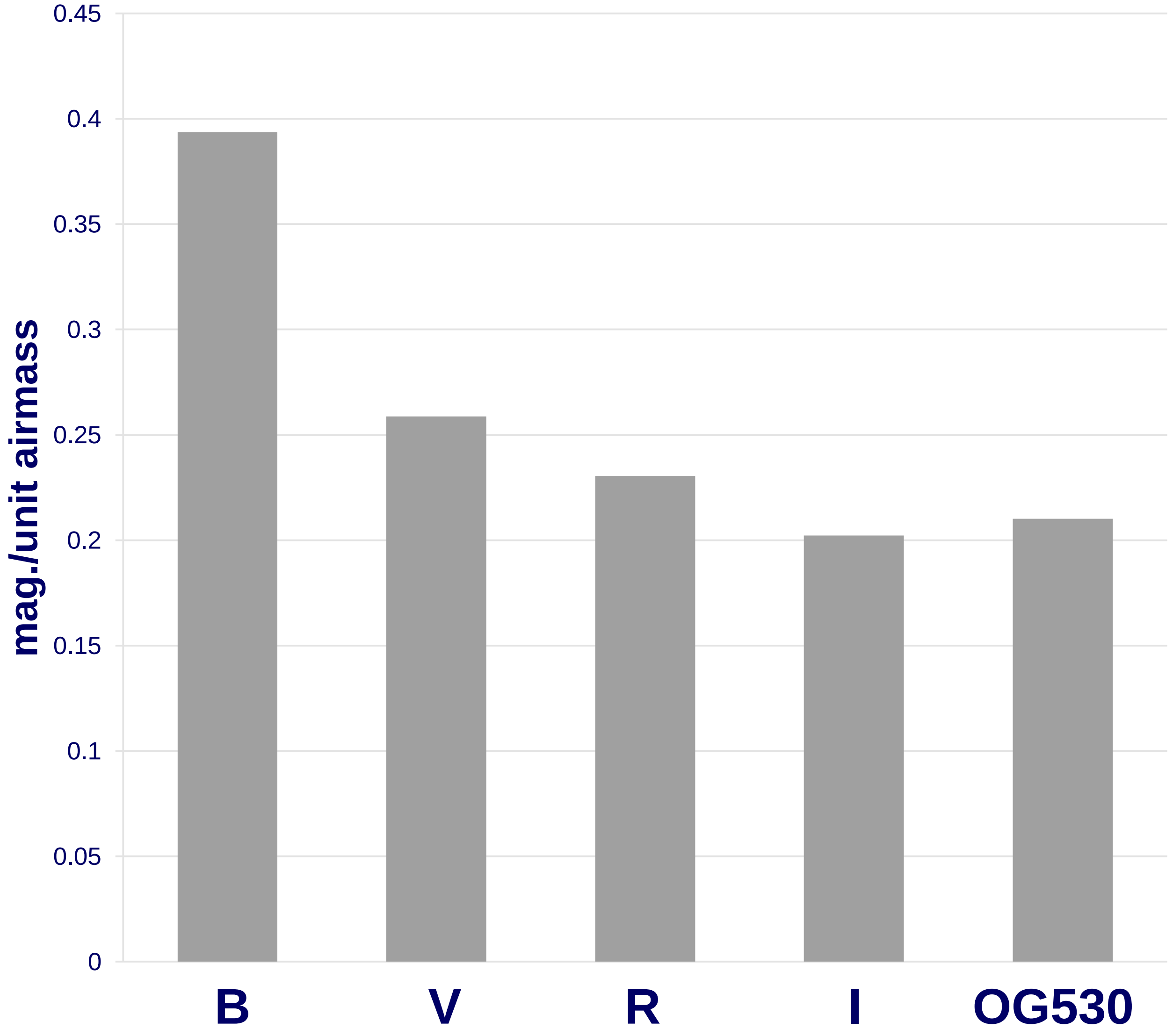
ST8XME CCD


Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

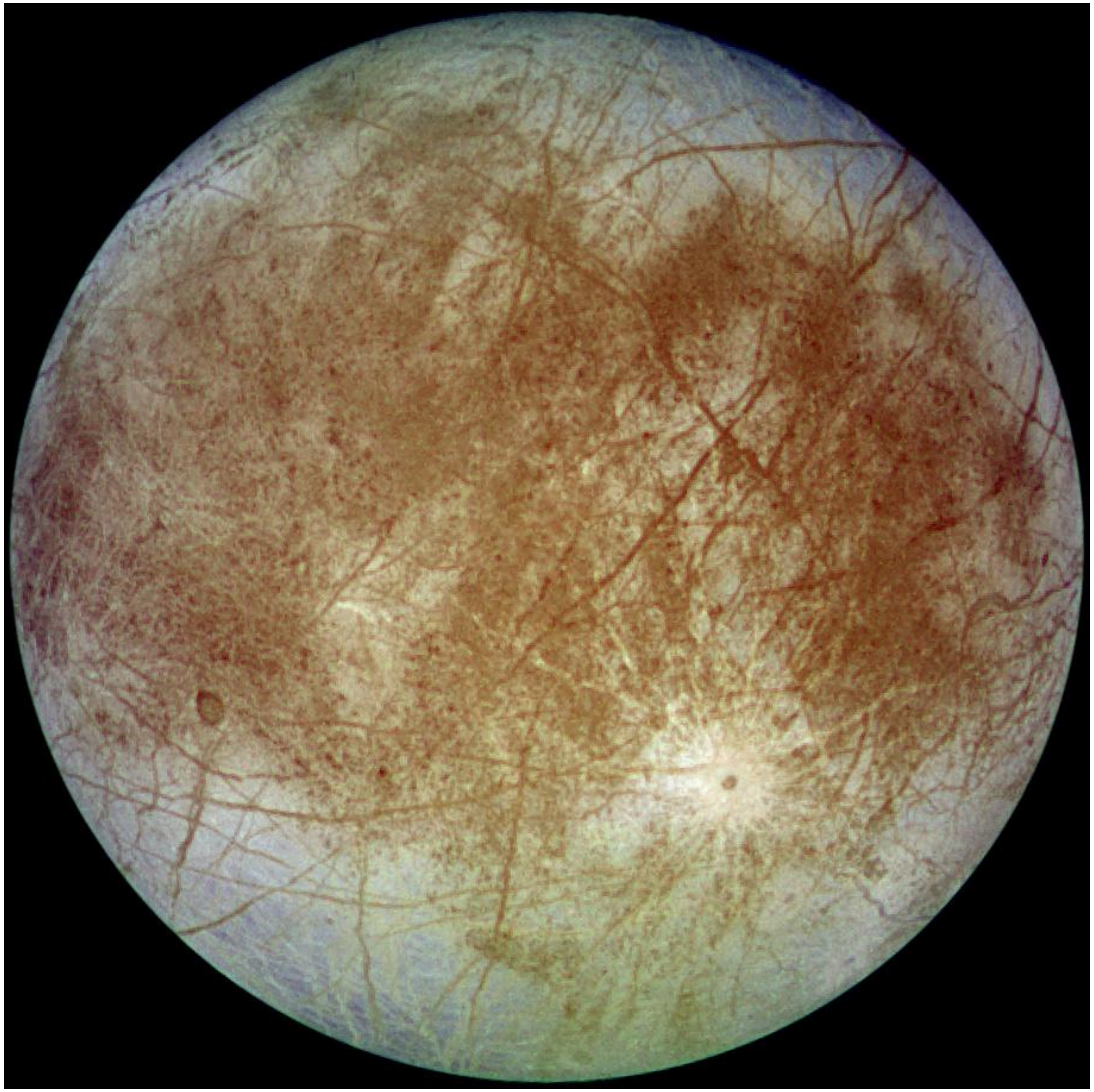


Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered
starlight
"noise"
Location of
Fomalhaut
Coronagraph
mask
Fomalhaut b planet
2006
2004
No data
Background Star
100 AU
13"

Auckland Observatory: Atmospheric Extinction



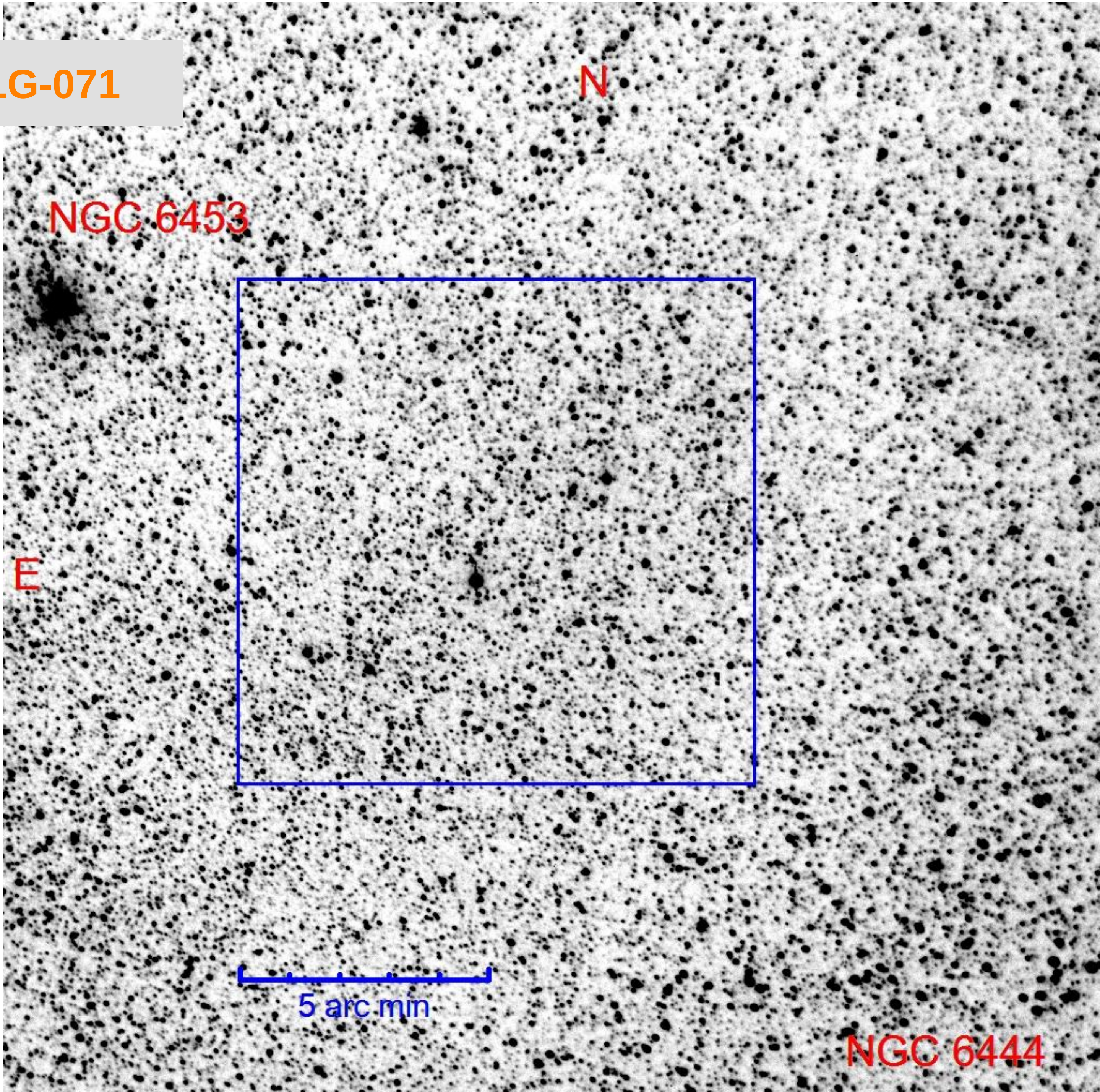
“Nomad” planets: Life may not need a sun



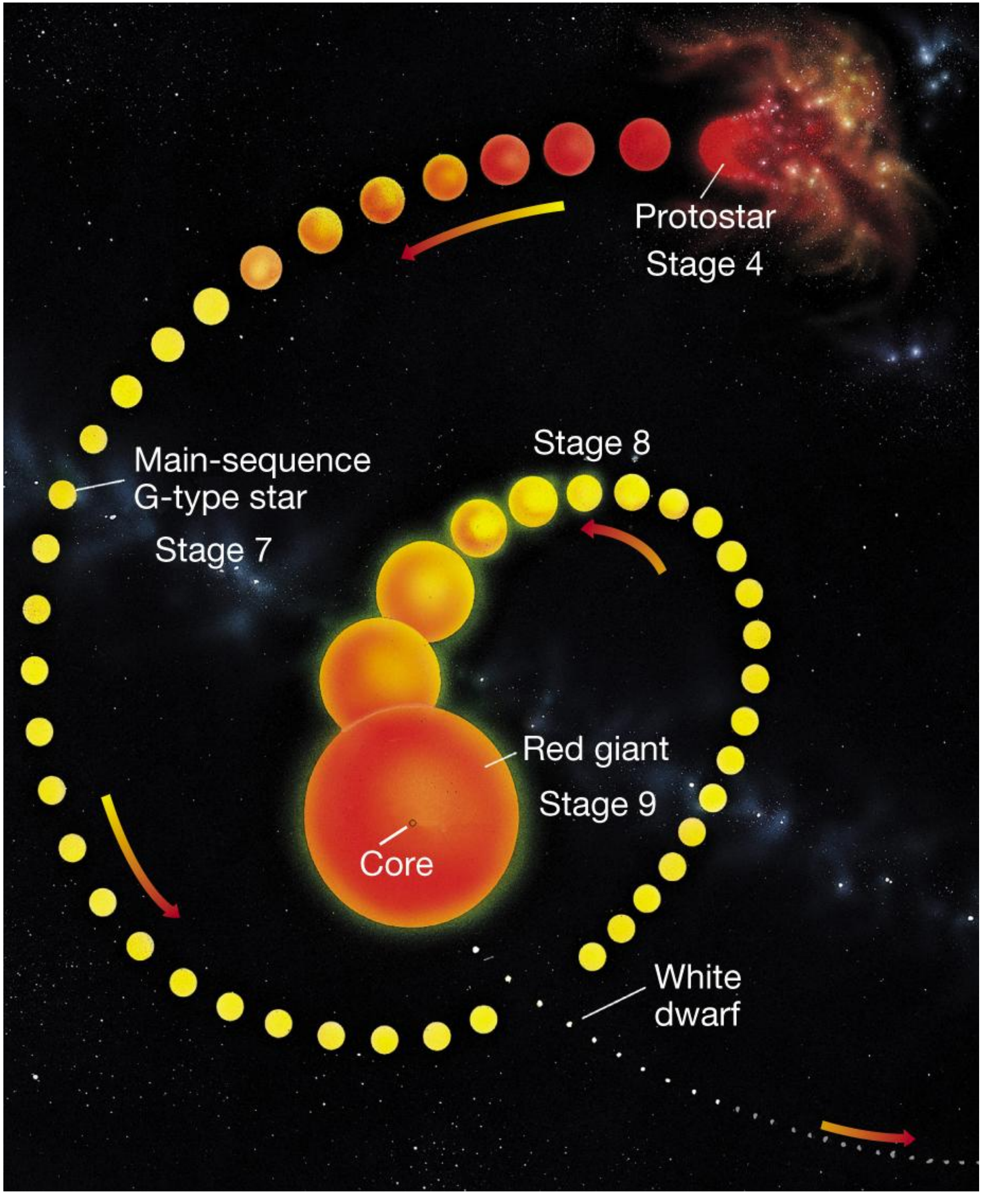
Europa may have life in an ocean 20 km beneath its icy surface


Thank you

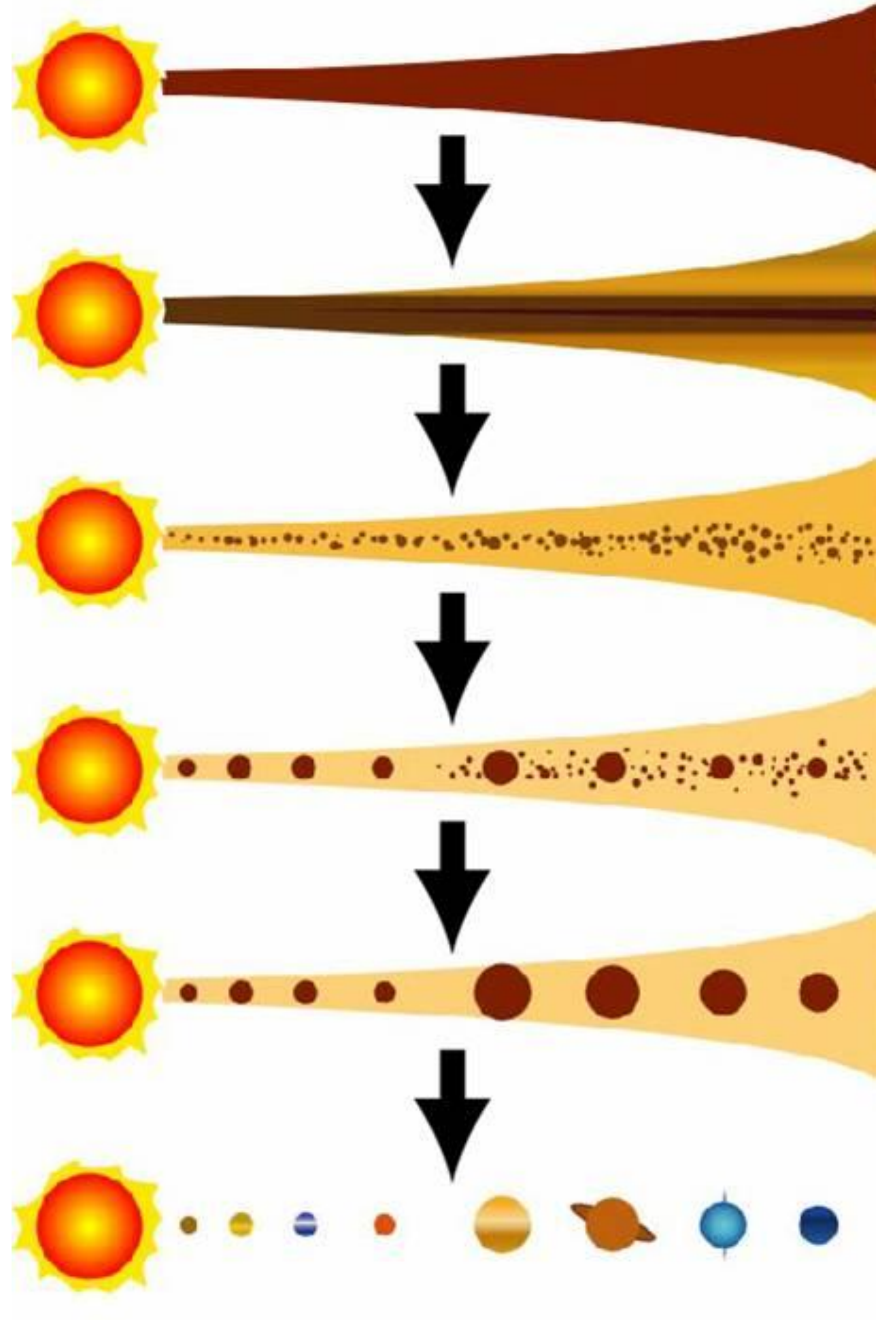
OGLE-2005-BLG-071



The Life Cycle of the Sun



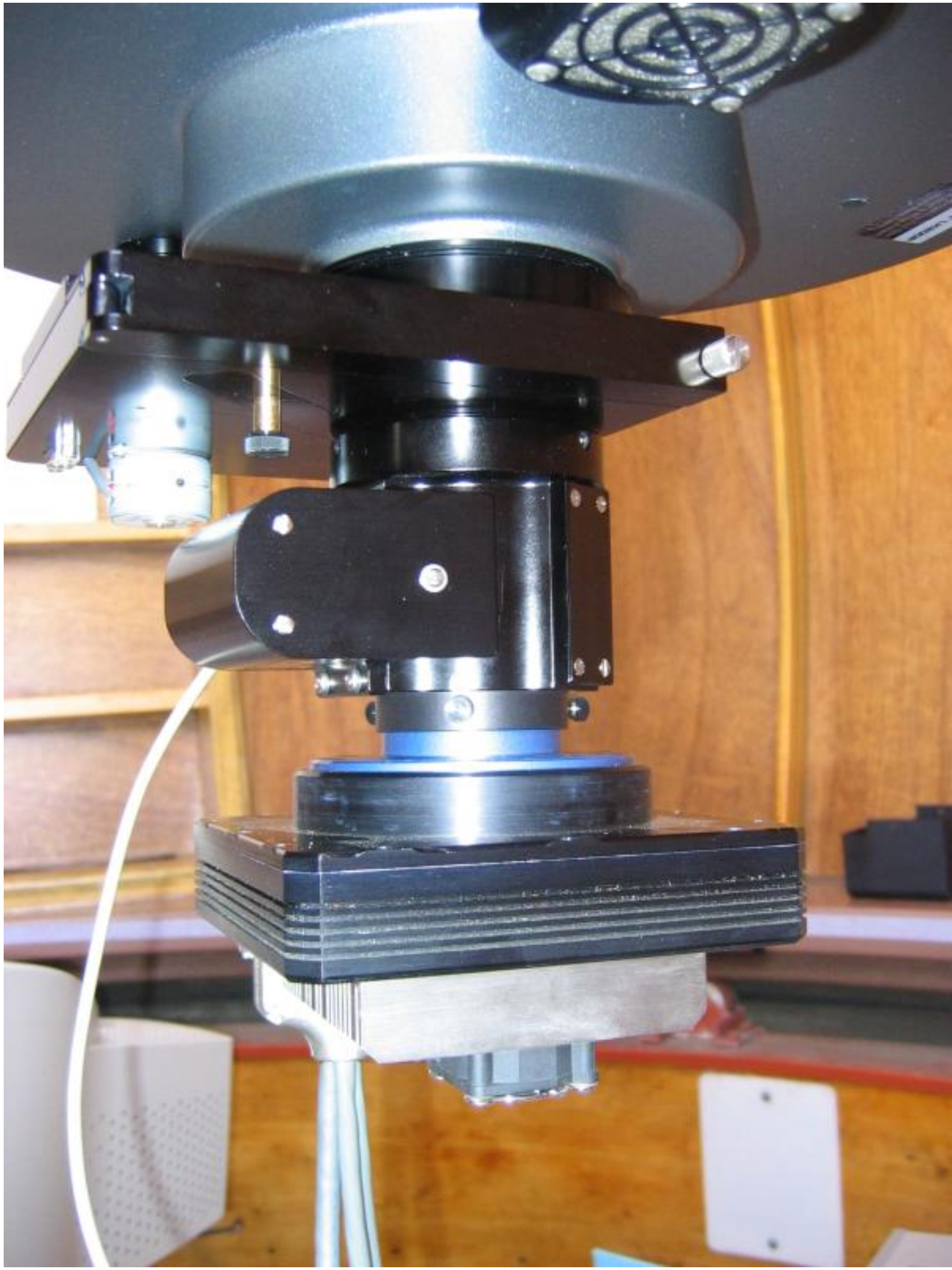
Stages in the formation of a new planetary system



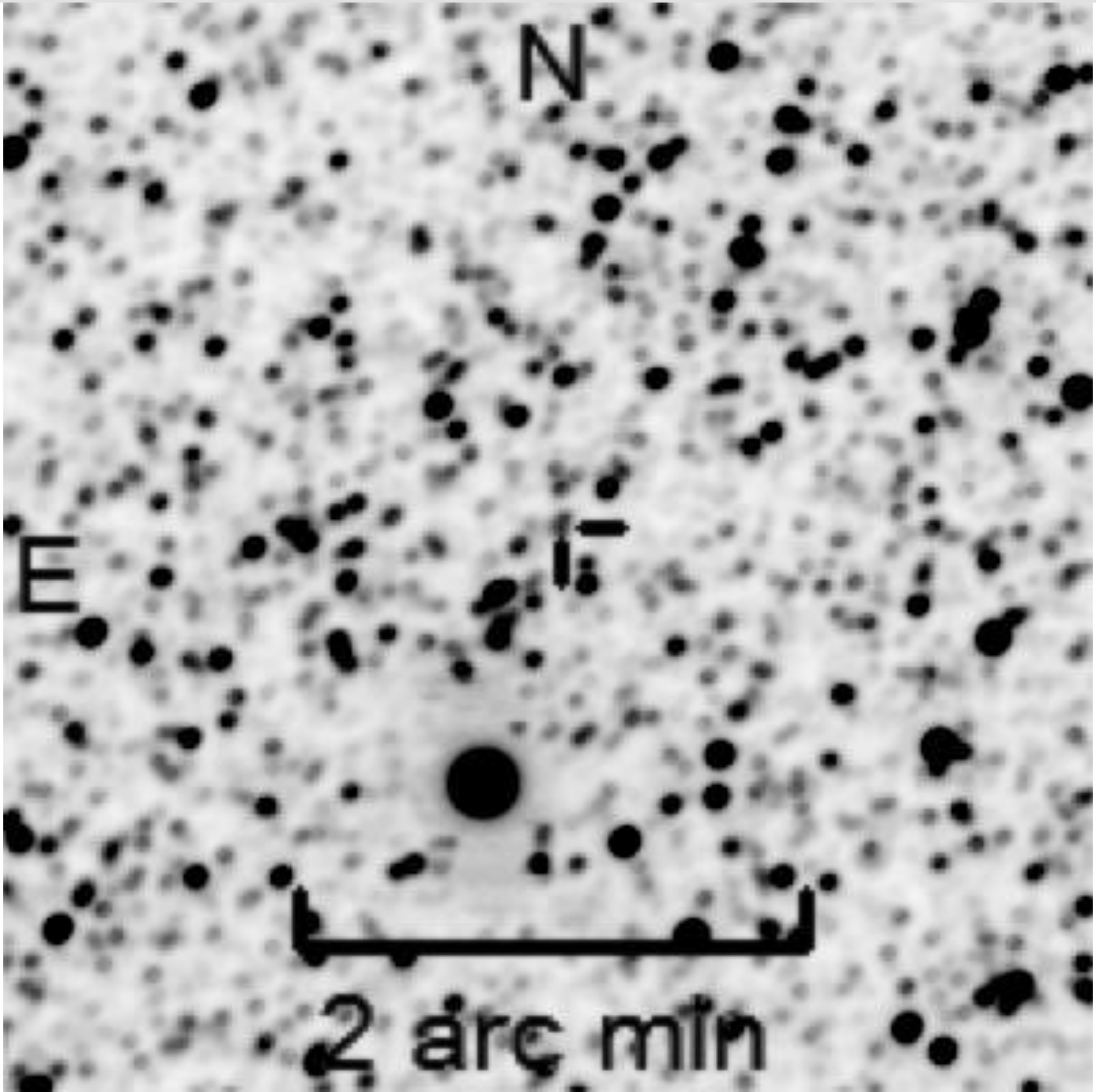
Optec filter wheel

Optec TCF focuser

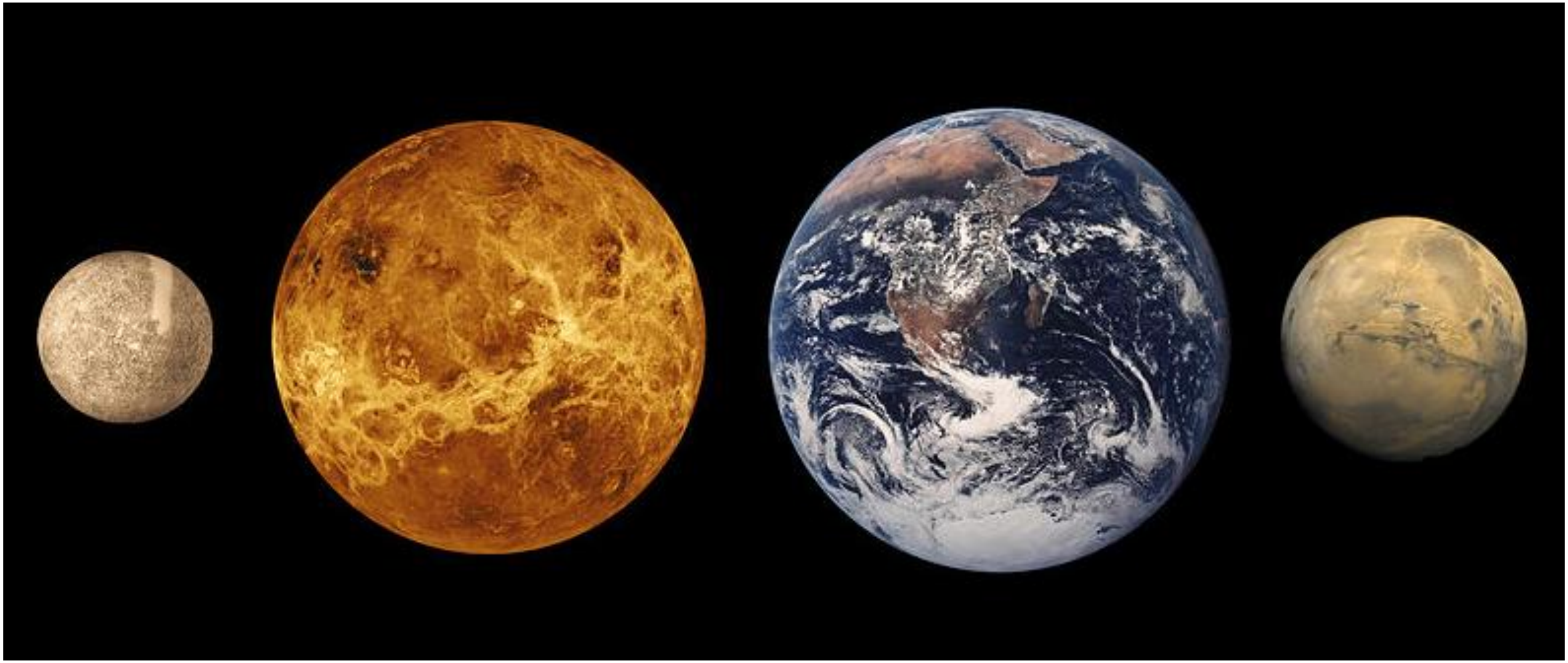
Apogee AP8p CCD



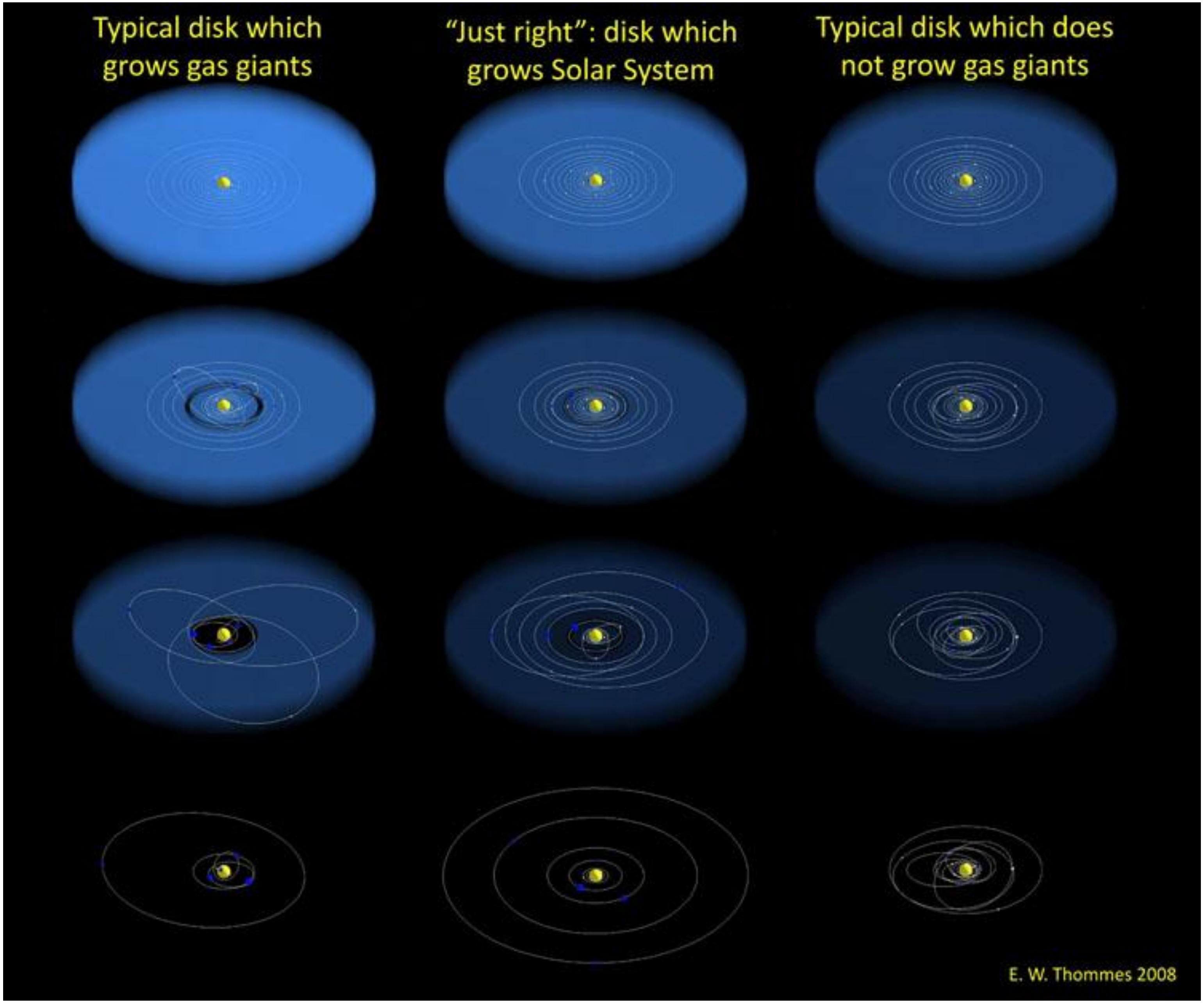
OGLE-2005-BLG-071

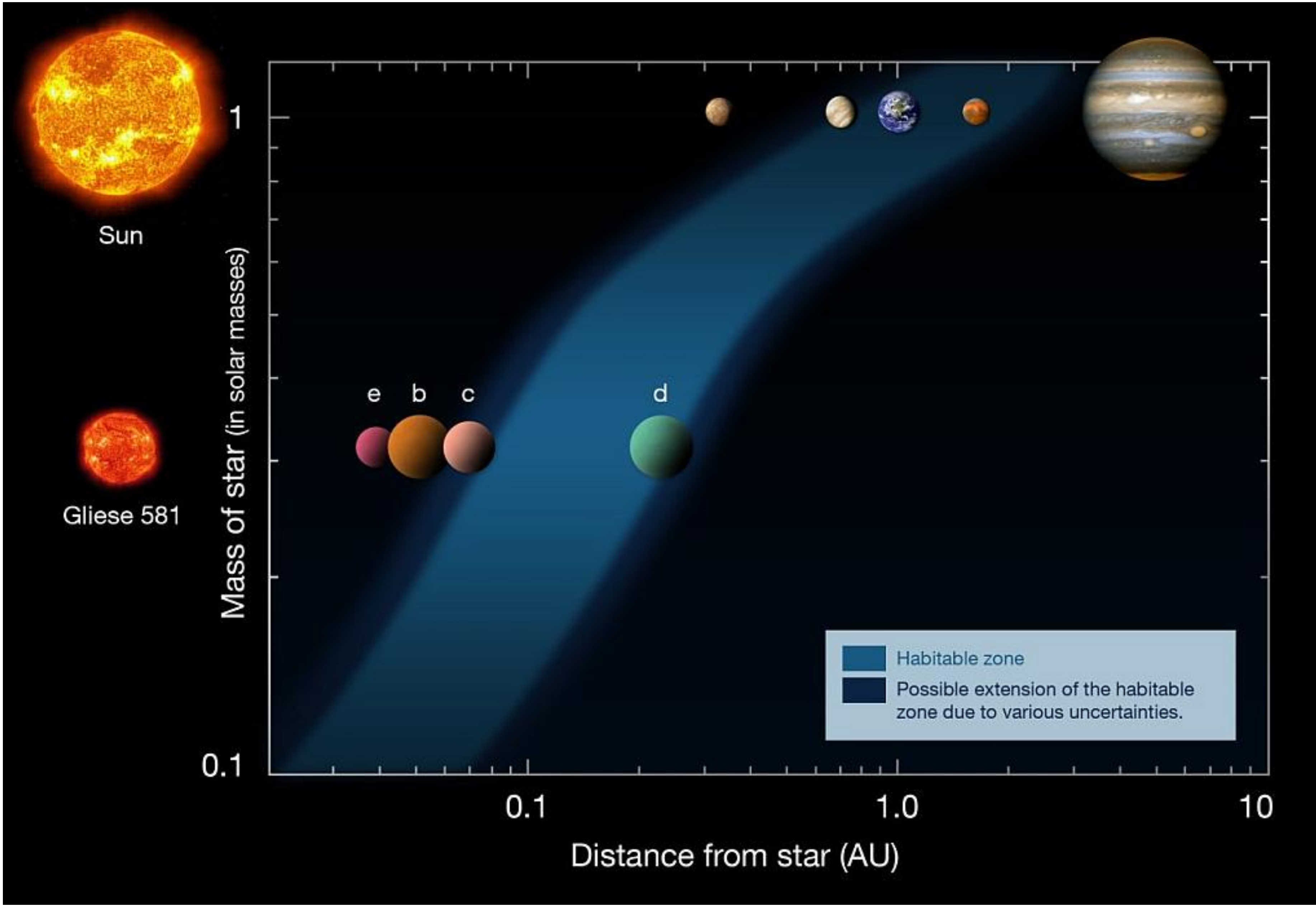


The inner terrestrial planets

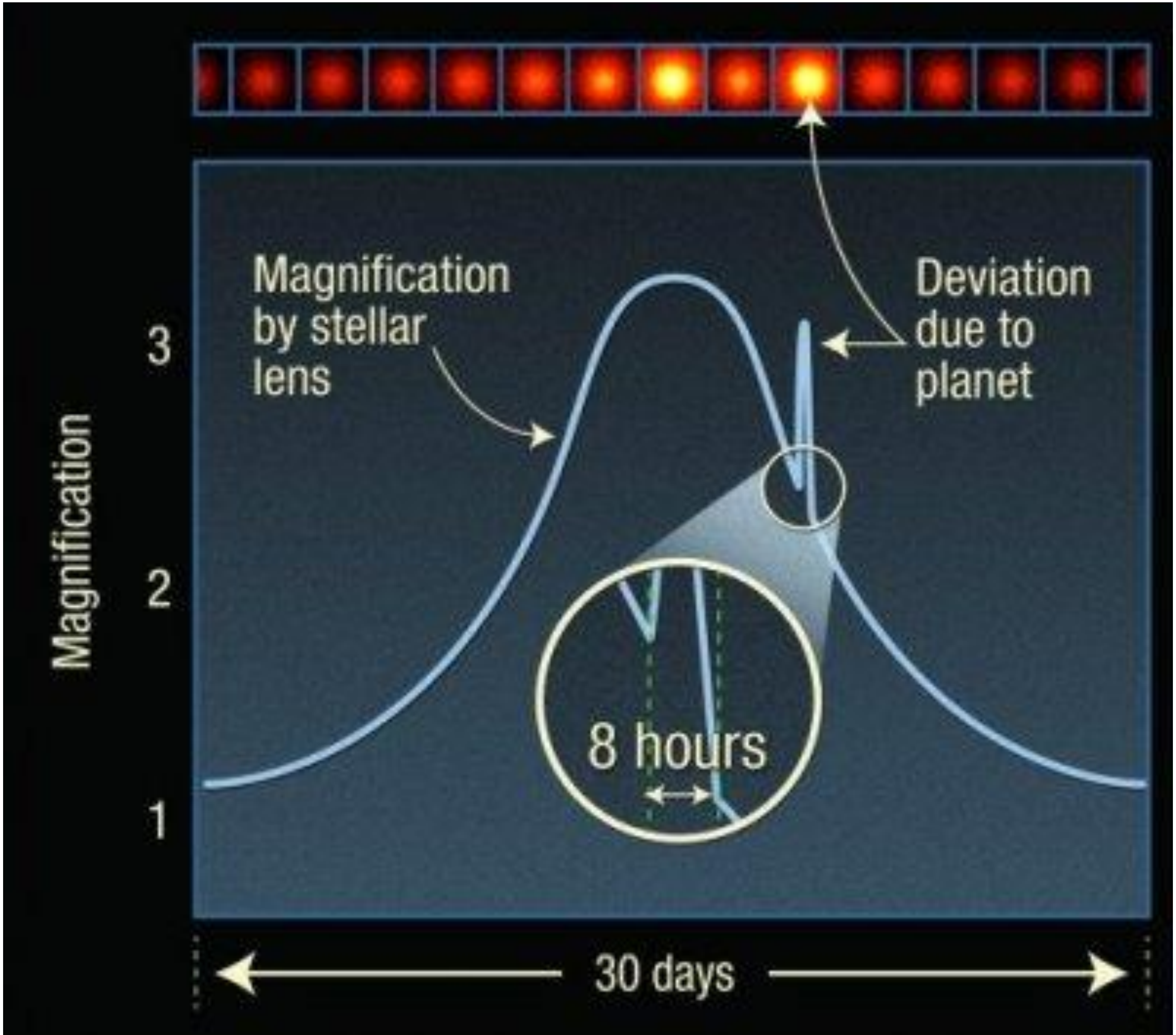


Mercury Venus Earth Mars

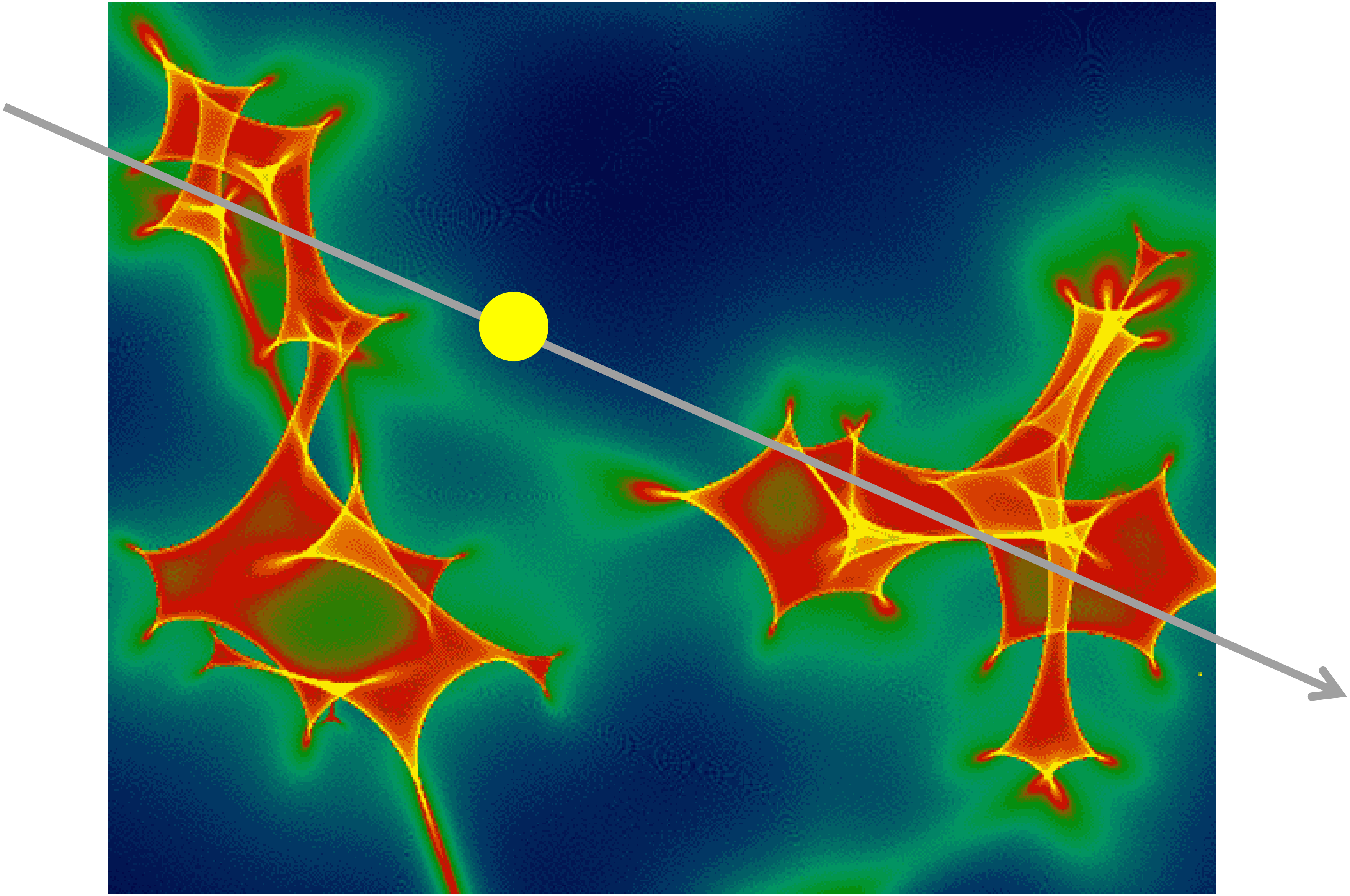

Typical disk which grows gas giants
"Just right": disk which grows Solar System
Typical disk which does not grow gas giants
E. W. Thommes 2008



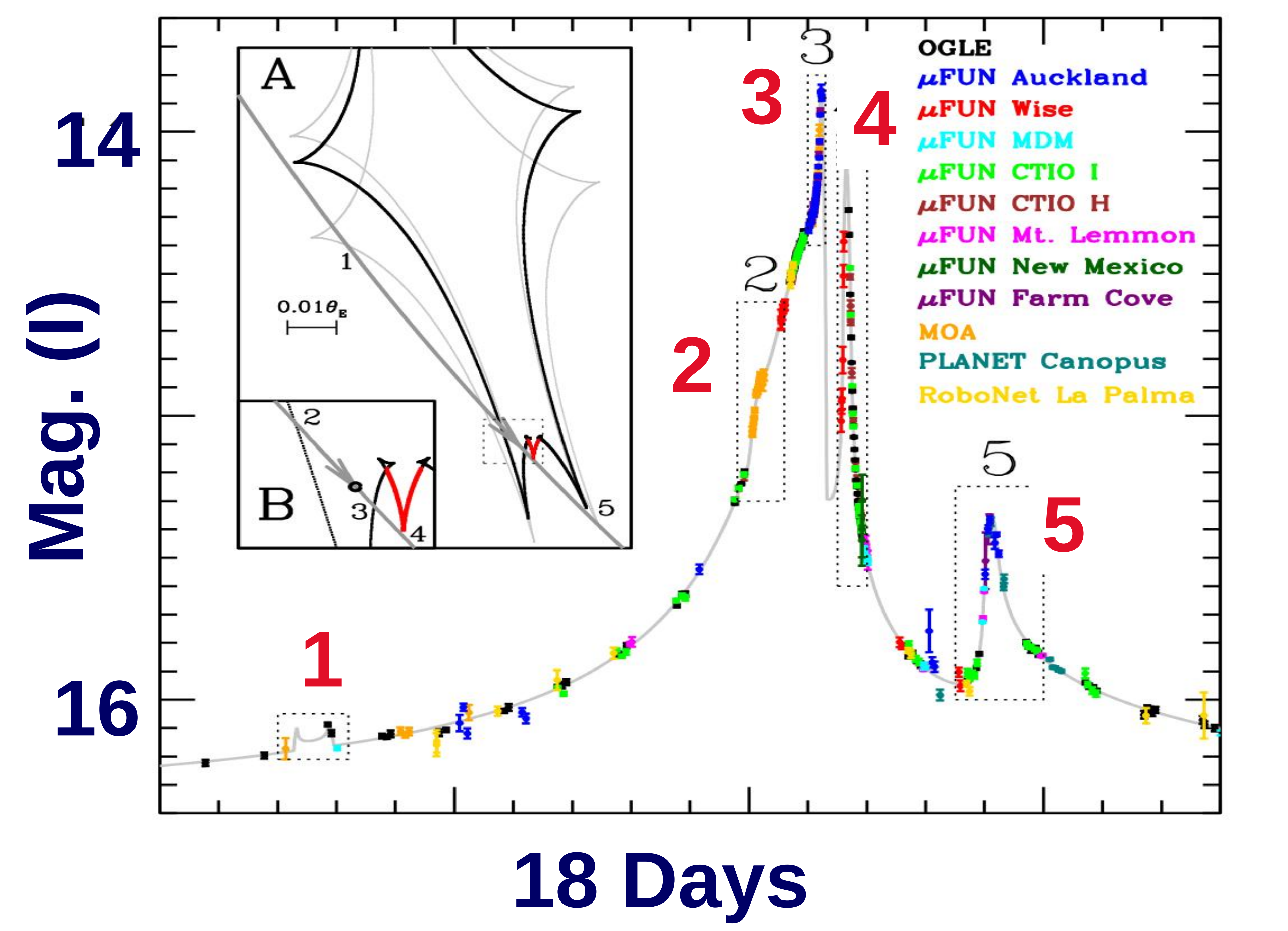
Sun
Gliese 581
Mass of star (in solar masses)
1
0.1
e
b
c
d
Habitable zone
Possible extension of the habitable zone due to various uncertainties.
0.1
1.0
10
Distance from star (AU)



Magnification by stellar lens
Deviation due to planet
Magnification
3
2
1
8 hours
30 days



Multiple masses create a complicated caustic pattern

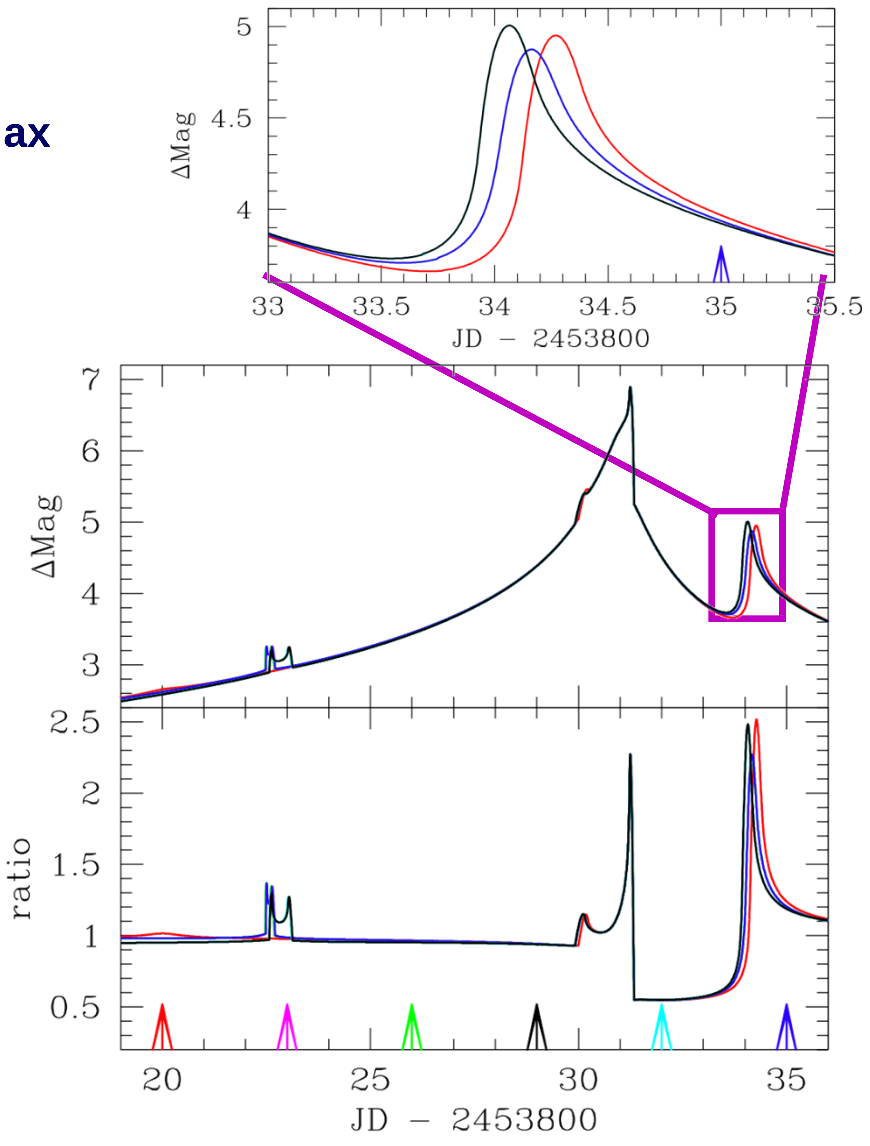


14
16
Mag. (I)
18 Days
1
2
3
4
5
A
B
0.01θE
OGLE
μFUN Auckland
μFUN Wise
μFUN MDM
μFUN CTIO I
μFUN CTIO H
μFUN Mt. Lemmon
μFUN New Mexico
μFUN Farm Cove
MOA
PLANET Canopus
RoboNet La Palma

Effect of Parallax & Orbital Motion

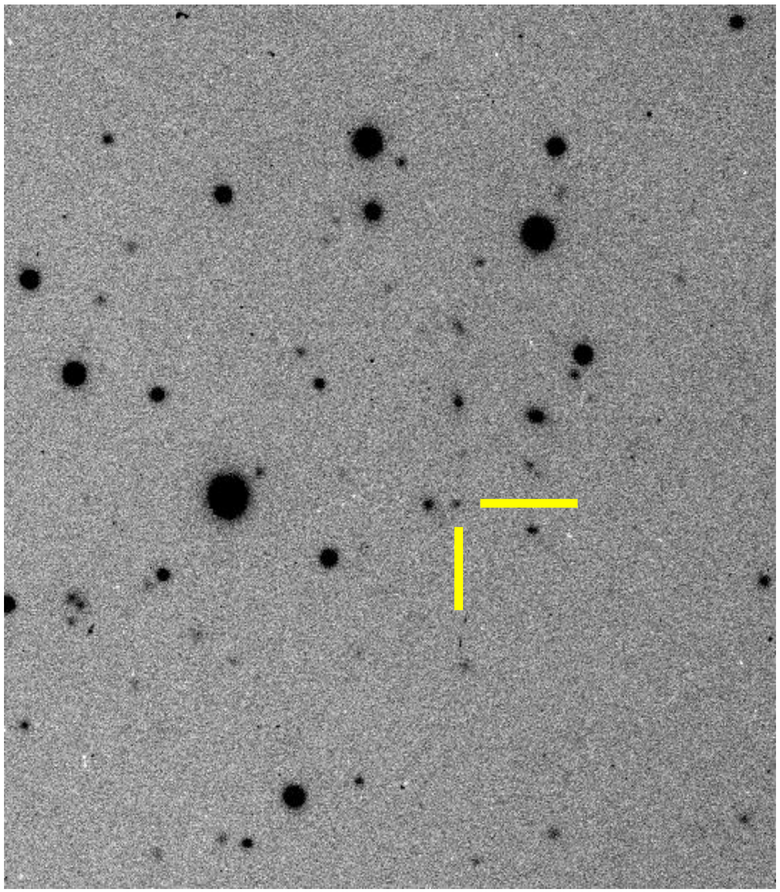
- red curve: neither orbital motion nor parallax
- blue curve: orbital motion, but no parallax
- black curve is the full model

Star's gravity removed – planets only



GRB091029 z = 2.75

Stardome 0.4m + CCD



GROND on 2.2m

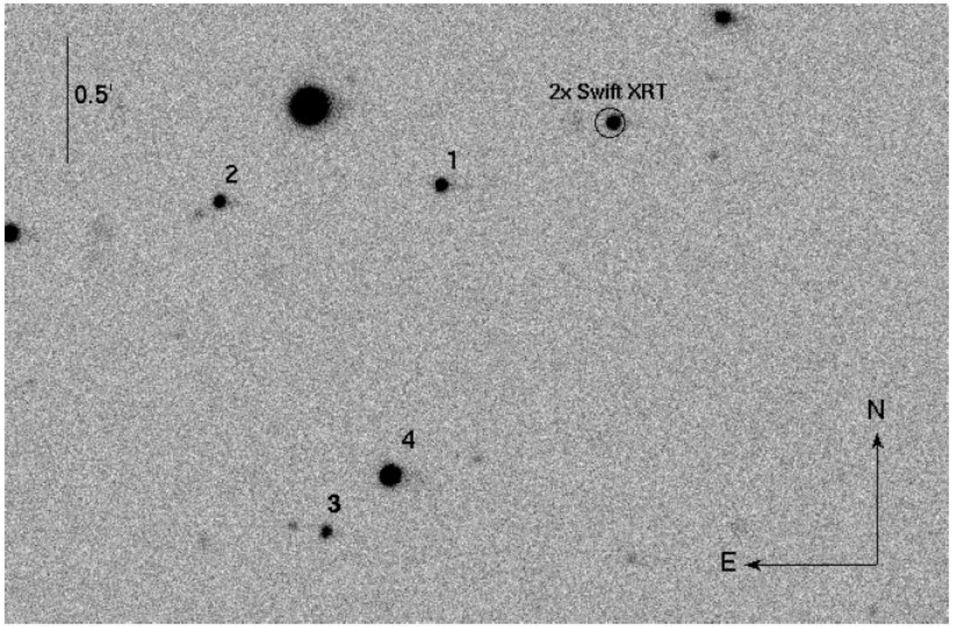


Fig. 1. GROND g'-band image of the field of GRB 091029 obtained 463 s after T_0. The optical afterglow is shown inside the *Swift* XRT error circle with double diameter for better clarity. The secondary standard stars are numbered from 1 to 4 and their magnitudes reported in Table 1.

Exposure: 35min

SUBJECT: GRB 091029: Observations from Stardome Observatory

G. W. Christie (Stardome Obs., New Zealand), S. Dong (IAS, Princeton), A. de Ugarte Postigo (ESO, Chile) and T. Natusch (Stardome Obs., New Zealand) report:

The fading afterglow (Filgas et al., GCN 10098; LaCluyze et al., GCN 10099; de Ugarte et al., GCN 10104; Marshall et al. GCN 10108) was clearly detected in all images over the observing period, yielding the following psf photometry(DOPHOT) :

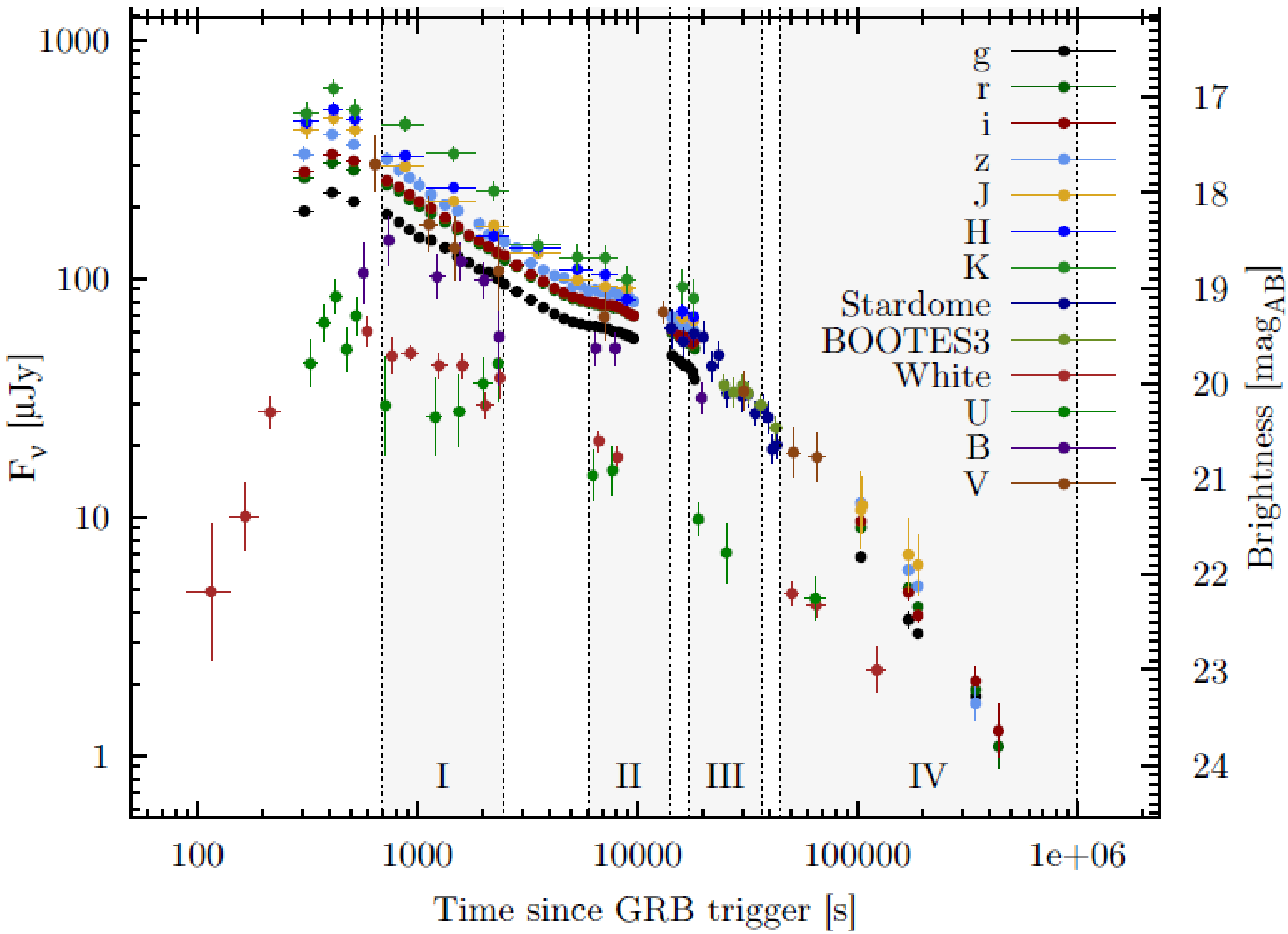
UT (mid)	delT	R1	Err (statistical)
29.32713	3.901	19.34	0.09
29.34906	4.428	19.32	0.08
29.37120	4.959	19.43	0.08
29.39311	5.485	19.46	0.08
29.41503	6.011	19.67	0.08
29.43360	6.456	19.57	0.08
29.45862	7.057	19.73	0.08
29.50946	8.277	19.93	0.12
29.53164	8.809	19.94	0.09
29.56044	9.501	20.16	0.09
29.59390	10.304	20.21	0.11
29.61620	10.839	20.21	0.13
29.63853	11.375	20.36	0.16
29.66081	11.910	20.41	0.17

where delT is the mid-exposure time in hours since trigger. Photometric calibration was done against USNOB1 0340-0030262

RA (J2000.0): 04h 00m 38.61s, DEC(J2000.0): -55d 55' 37.3"
assuming R1=16.40.

GRB 091029: At the limit of the fireball scenario

R. Filgas[1,2], J. Greiner[1], P. Schady[1], A. de Ugarte Postigo[3,4], S. R. Oates[5], M. Nardini[6,1], T. Krühler[4,1,7], A. Panaitescu[8], D. A. Kann[9], S. Klose[9], P. M. J. Afonso[1★], W. H. Allen[10], A. J. Castro-Tirado[3], G. W. Christie[11], S. Dong[12], J. Elliott[1], T. Natusch[13], A. Nicuesa Guelbenzu[9], F. Olivares E.[1], A. Rau[1], A. Rossi[9], V. Sudilovsky[1], and P.C.M. Yock[14]




Auckland
500m


200m

Photometric Observatories in Auckland

Auckland Observatory (Stardome)
0.4m Meade ACF, Paramount GT1100s, STL6303E CCD
Filters: BVRI, OG530
Gravitational microlensing, variable stars, astrometry

Farmcove Observatory
0.35m Meade ACF, SBIG ST8ME CCD
Gravitational microlensing, variable stars, astrometry

Kumeu Observatory
0.35m Celestron SCT, SBIG 2000
Filters: OG530
Gravitational microlensing, variable stars

Molehill Observatory
0.30m Meade SCT, custom mount, SBIG ST8ME CCD
Gravitational microlensing, variable stars

Lowther Observatory
0.25m Meade SCT, SBIG ST7ME CCD
Variable stars

Collaborations

MicroFUN
Ohio State University

Center for Backyard Astrophysics
Columbia University

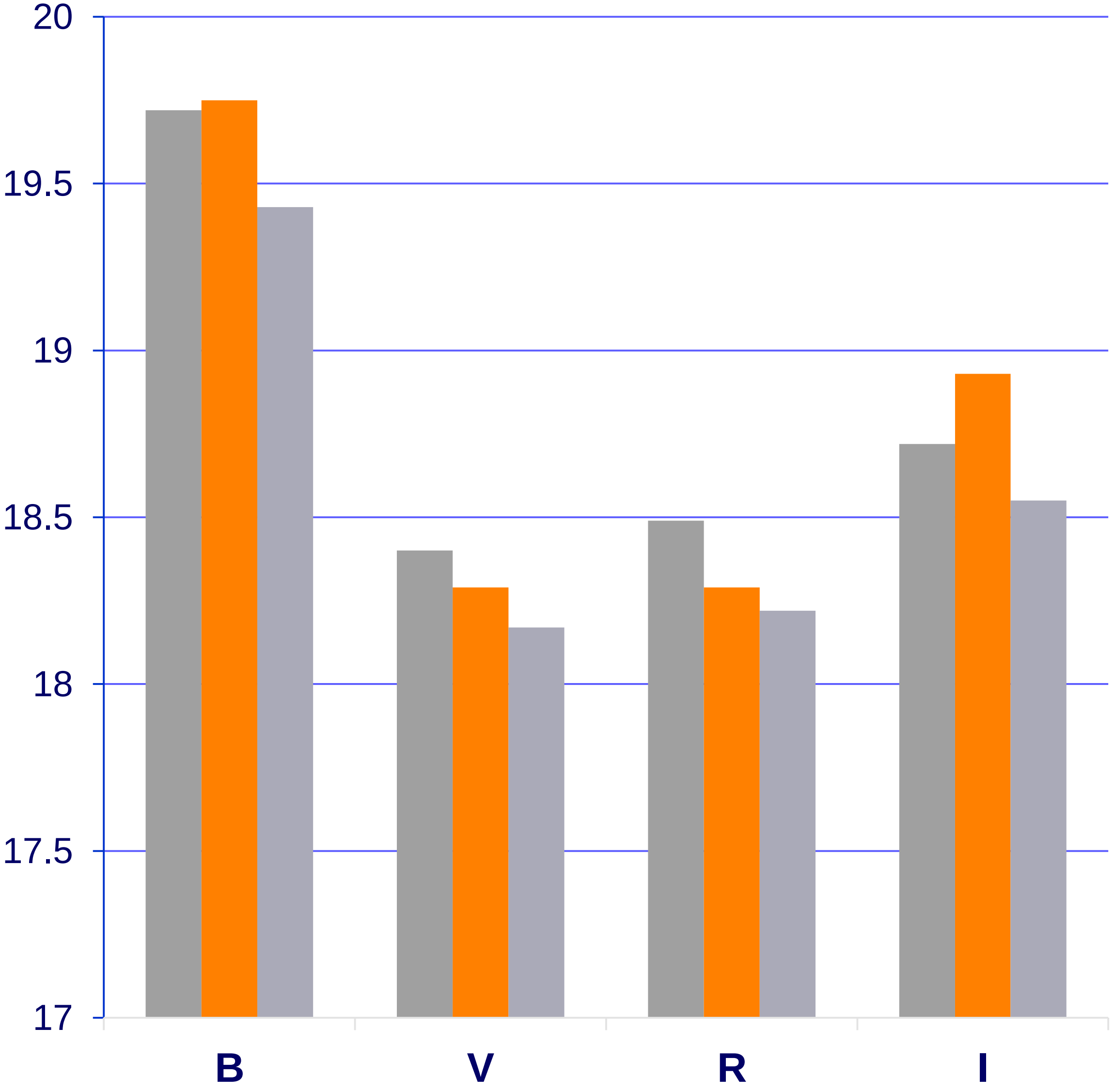
Minor Planets Center (MPC)
Boston MA

View west from the summit of Maungakiekie (One Tree Hill)

Auckland Observatory: Sky Background

Magnitudes (arc-sec)$^{-2}$

	z=30	z=50	FM 12
B	19.72	19.75	19.43
V	18.40	18.29	18.17
R	18.49	18.29	18.22
I	18.72	18.93	18.55



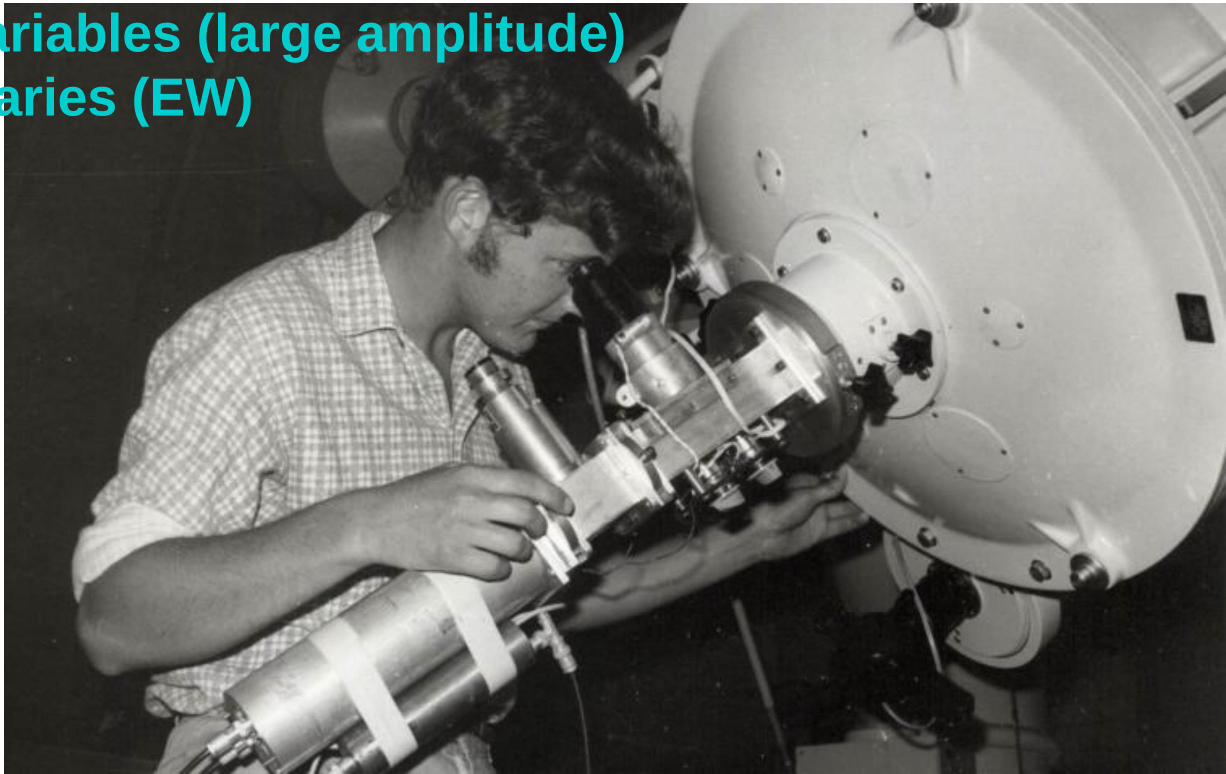
View from the summit of Maungakiekie (One Tree Hill)
Looking north

View from the summit of Maungakiekie (One Tree Hill)
Looking south

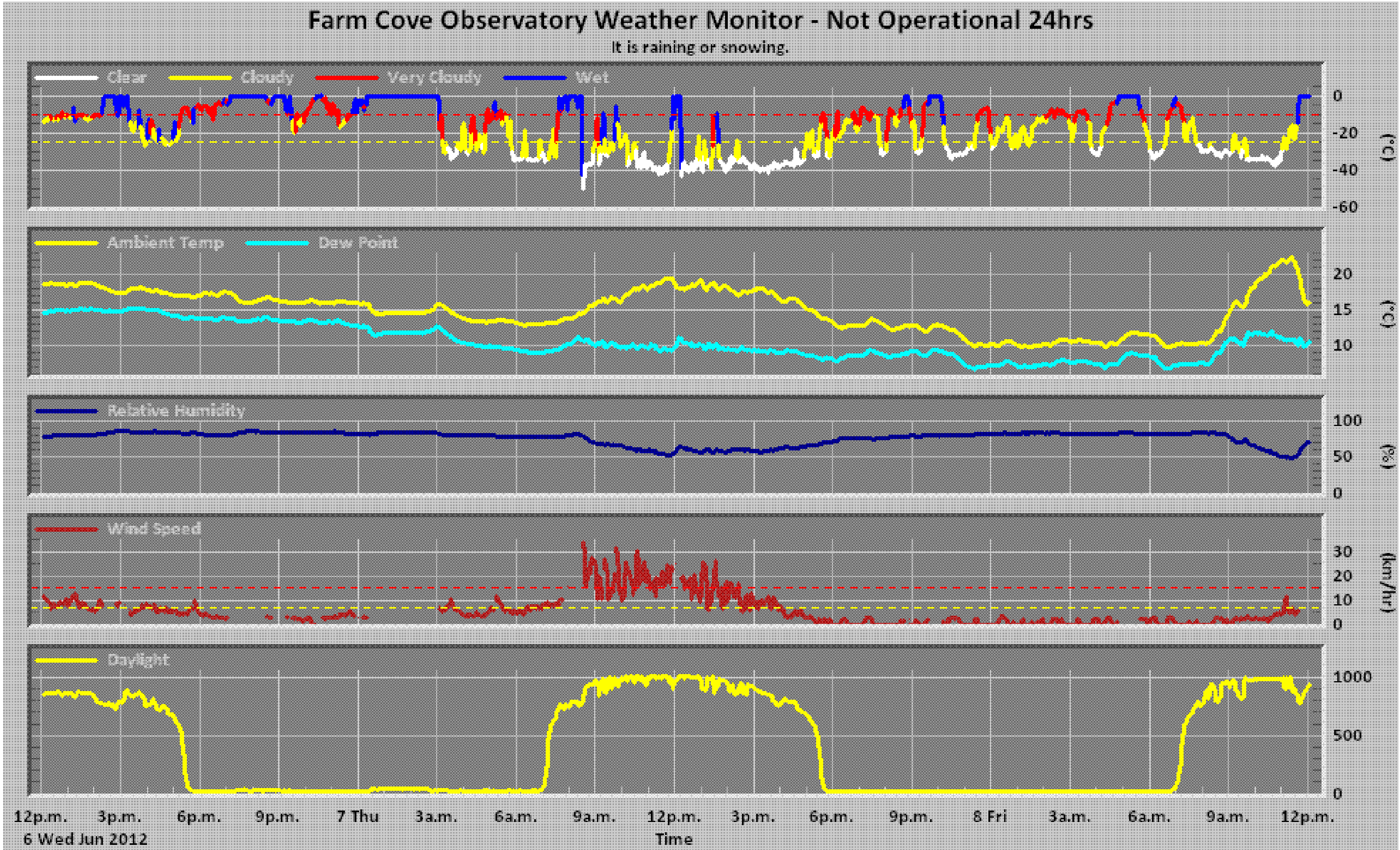
UBV Photoelectric Photometer (1969-1999)

Research Programmes

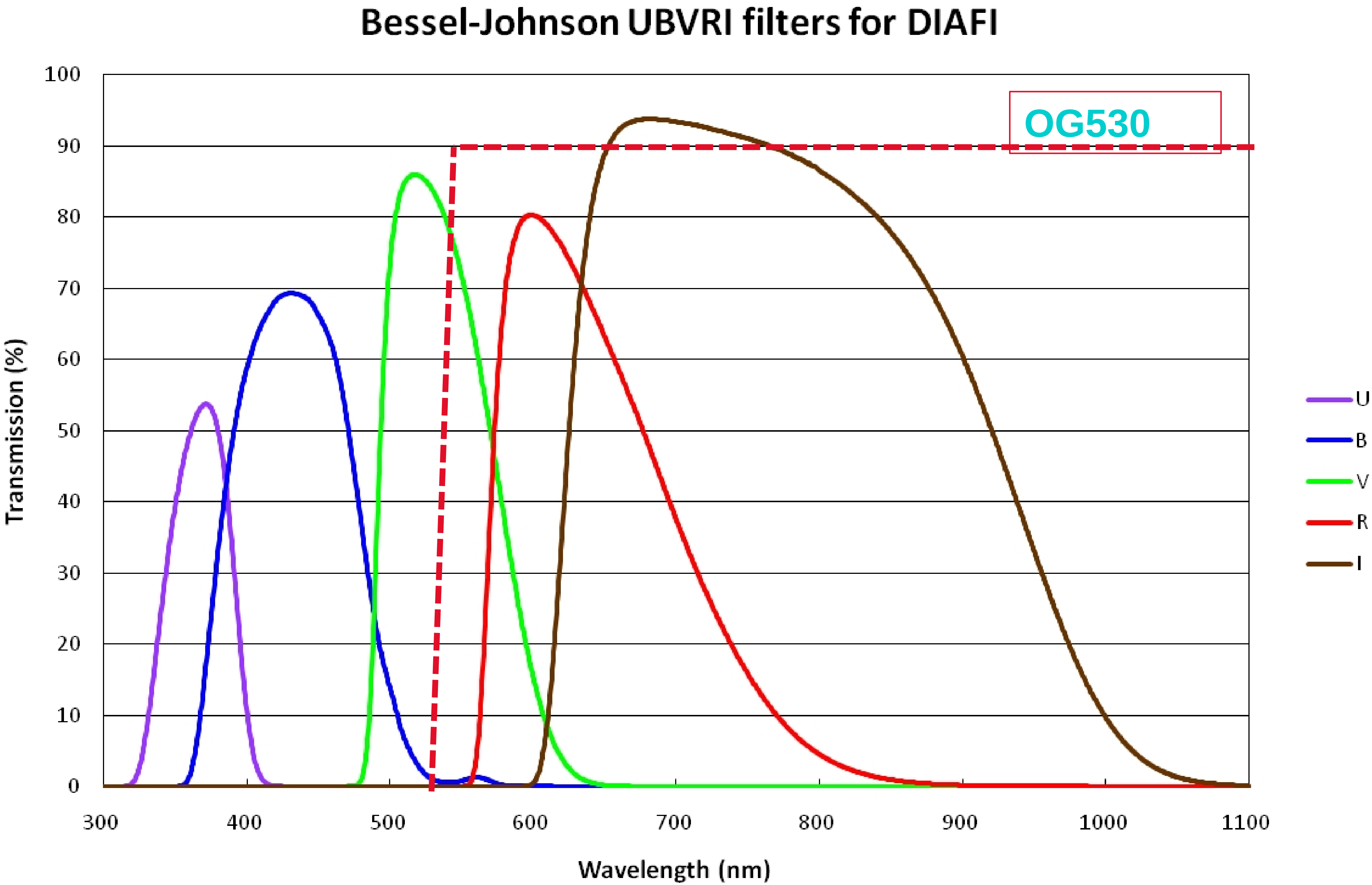
- Sequence determination for the VSS
- Cataclysmic binaries (discovered superhumping)
- Long period variables
- Cepheids
- Delta Scuti variables (large amplitude)
- Eclipsing binaries (EW)



30 years of atmospheric extinction data and measurements of sky background brightness in the U, B and V bands using the same instrument.



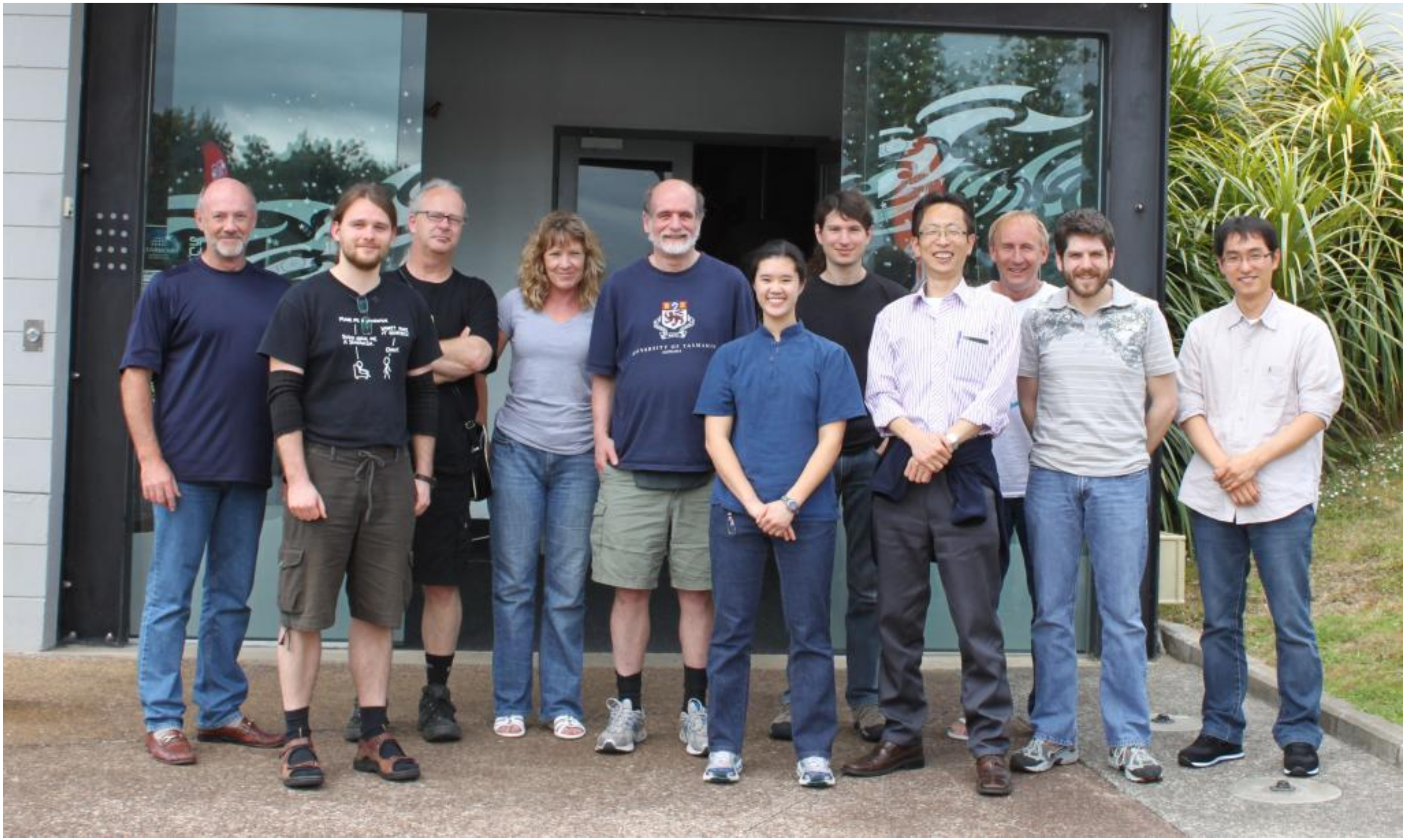
Farm Cove Observatory Weather Monitor - Not Operational 24hrs
It is raining or snowing.
Clear
Cloudy
Very Cloudy
Wet
0
-20
-40
-60
(°C)
Ambient Temp
Dew Point
20
15
10
(°C)
Relative Humidity
100
50
0
(%)
Wind Speed
30
20
10
0
(km/hr)
Daylight
1000
500
0
12p.m.
3p.m.
6p.m.
9p.m.
7 Thu
3a.m.
6a.m.
9a.m.
12p.m.
3p.m.
6p.m.
9p.m.
8 Fri
3a.m.
6a.m.
9a.m.
12p.m.
6 Wed Jun 2012
Time

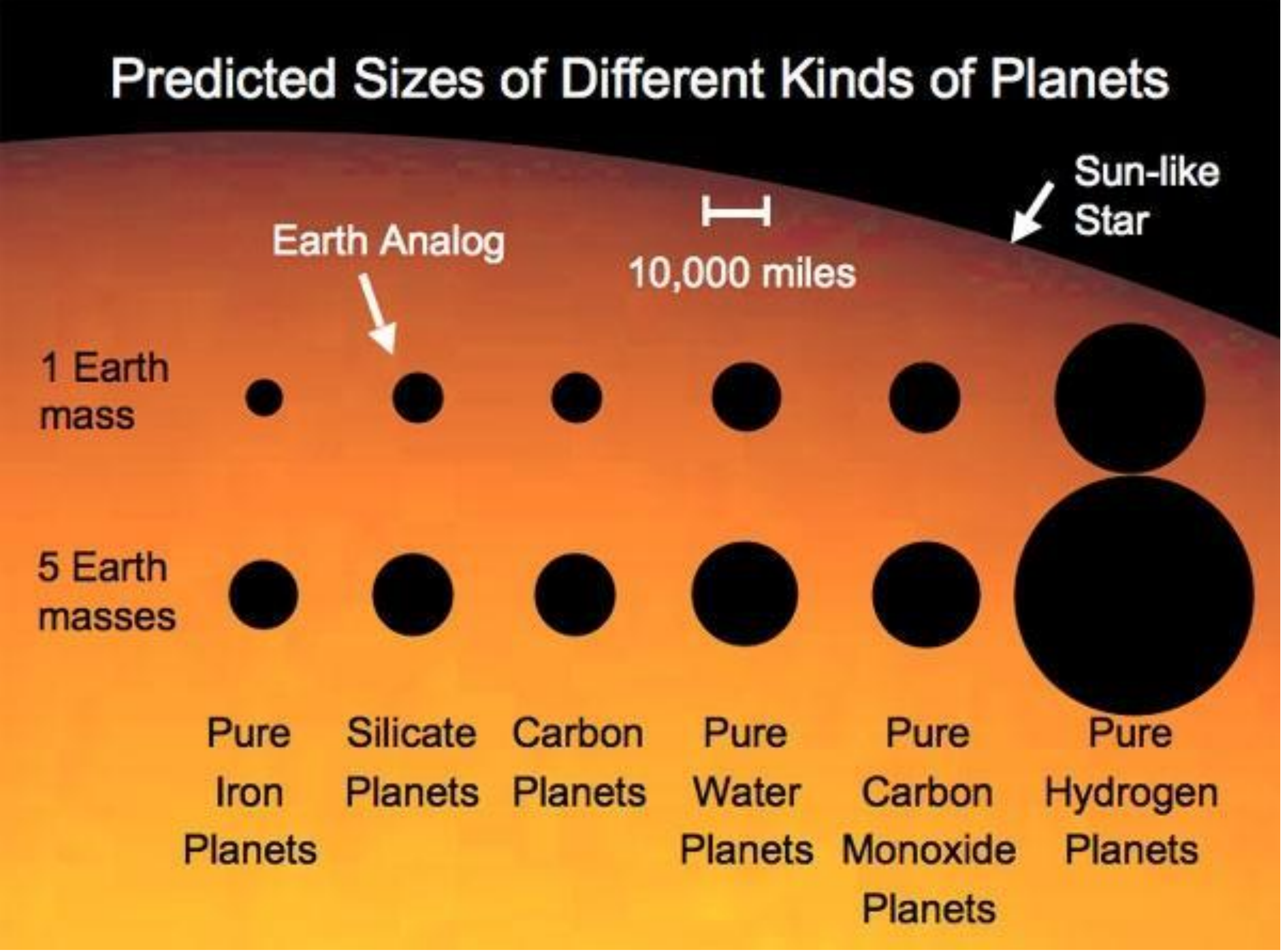

Bessel-Johnson UBVRI filters for DIAFI
OG530
Transmission (%)
Wavelength (nm)
100
90
80
70
60
50
40
30
20
10
0
300
400
500
600
700
800
900
1000
1100
U
B
V
R
I

THE OHIO STATE UNIVERSITY DEPARTMENT OF ASTRONOMY

MicroFUN

MICROLENSING FOLLOW- UP NETWORK

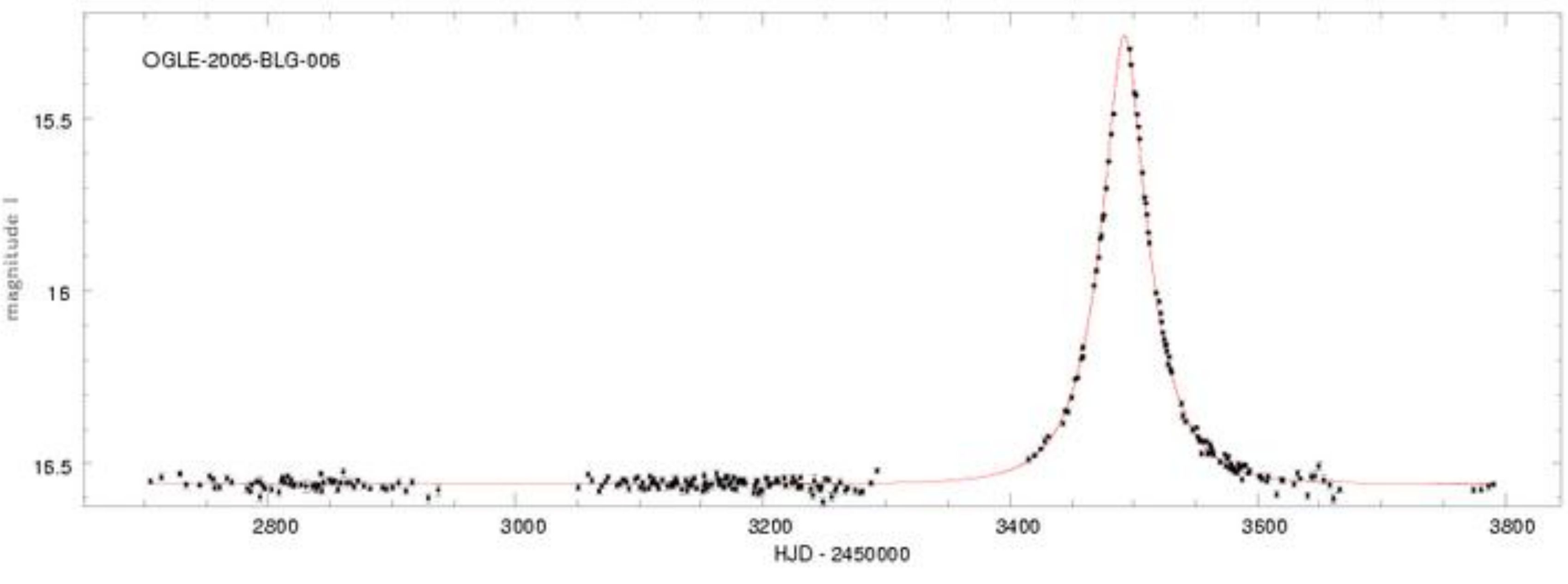




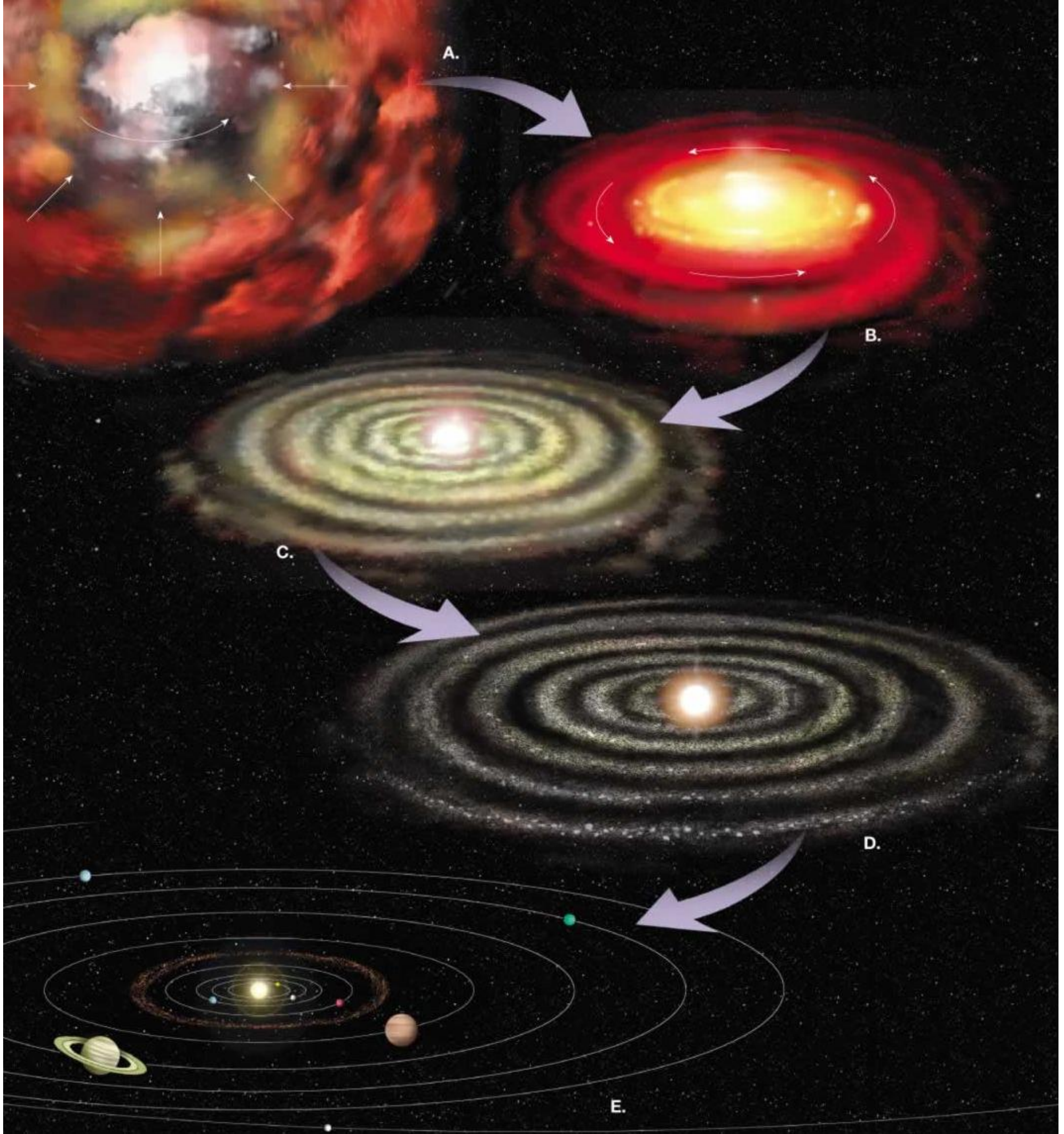
Predicted Sizes of Different Kinds of Planets
Sun-like Star
Earth Analog
10,000 miles
1 Earth mass
5 Earth masses
Pure Iron Planets
Silicate Planets
Carbon Planets
Pure Water Planets
Pure Carbon Monoxide Planets
Pure Hydrogen Planets

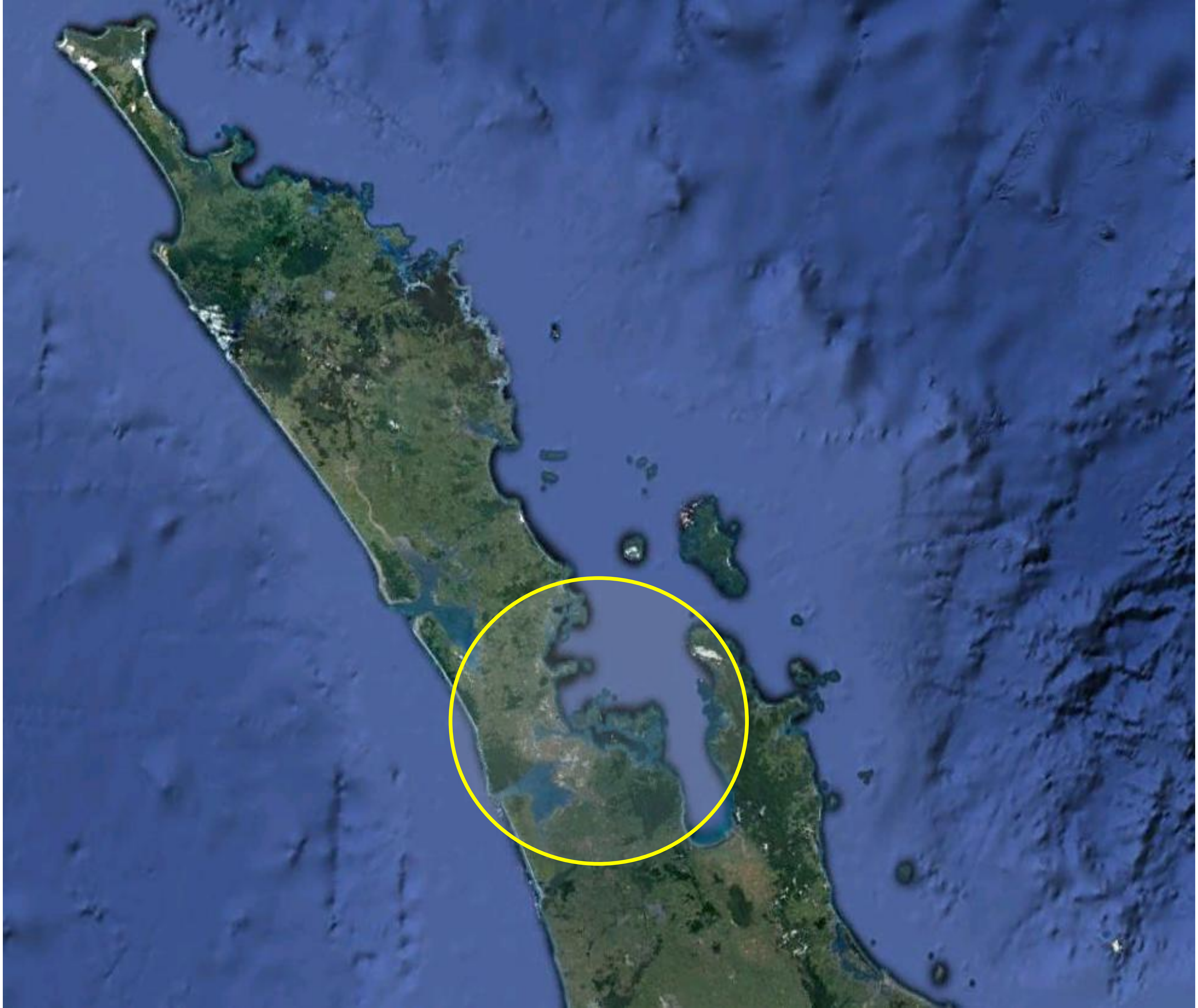
Microlensing Surveys

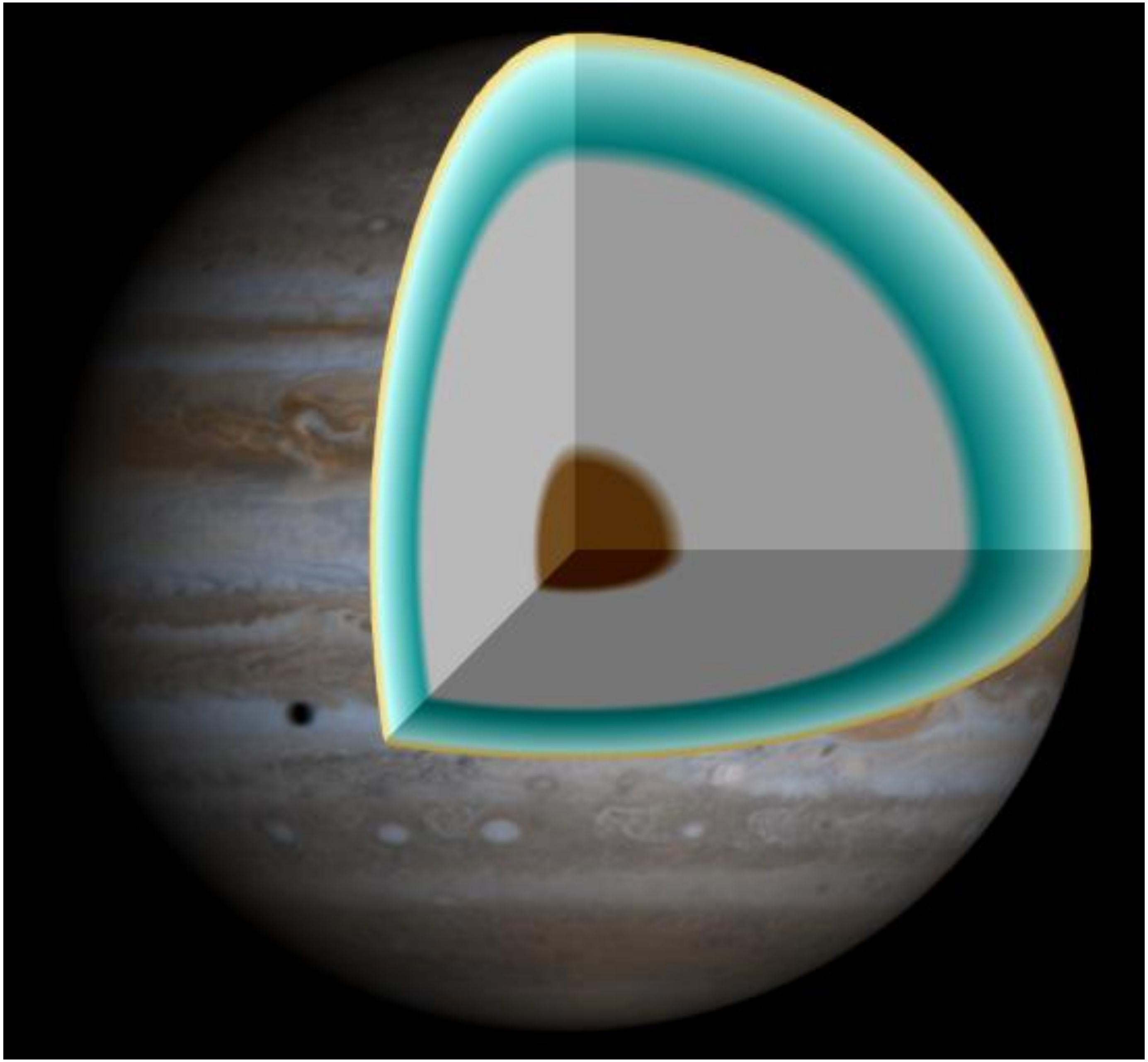
- Measure the brightness of ~10^8 stars per night
- Detect ~10^3 events per year
- Issue alerts for events by email - and Twitter



Stages in the formation of the Solar System







Microlensing – pros

- Detects mass, not luminosity
- Samples the entire mass range G to M *plus* brown dwarfs, white dwarfs, neutron stars and black holes
- Planets in both the galactic disk and the bulge
- “Instantaneous” planetary detection
- Planets beyond the “snowline”
- Planets as small as Mars
- Multiple planets (in high-mag events)
- Free-floating (nomad) planets
- Powerful test of planet formation theories
- Can show the *absence* of planets

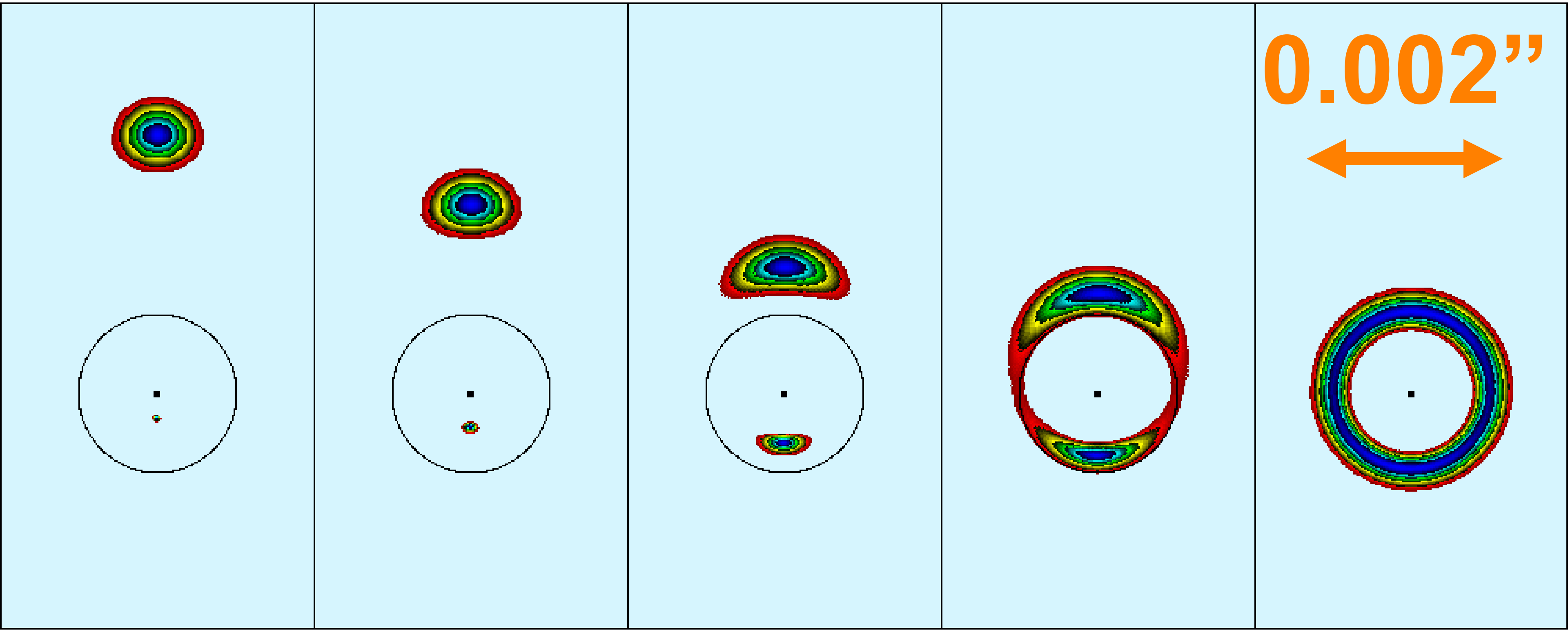
Microlensing –cons

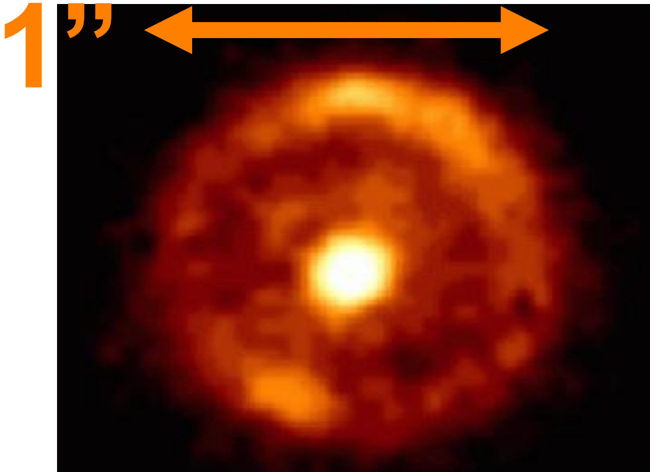
- Precise alignments are rare
- Alignments don’t repeat
- Discoveries are very distant – we’ll never go there!
- Some solutions are degenerate

Planets orbiting the lensing star produce “caustics” - disturbances in the gravitational lens

They make the lens wrinkly

Looking through a gravitational lens





Lensing galaxies make much bigger rings