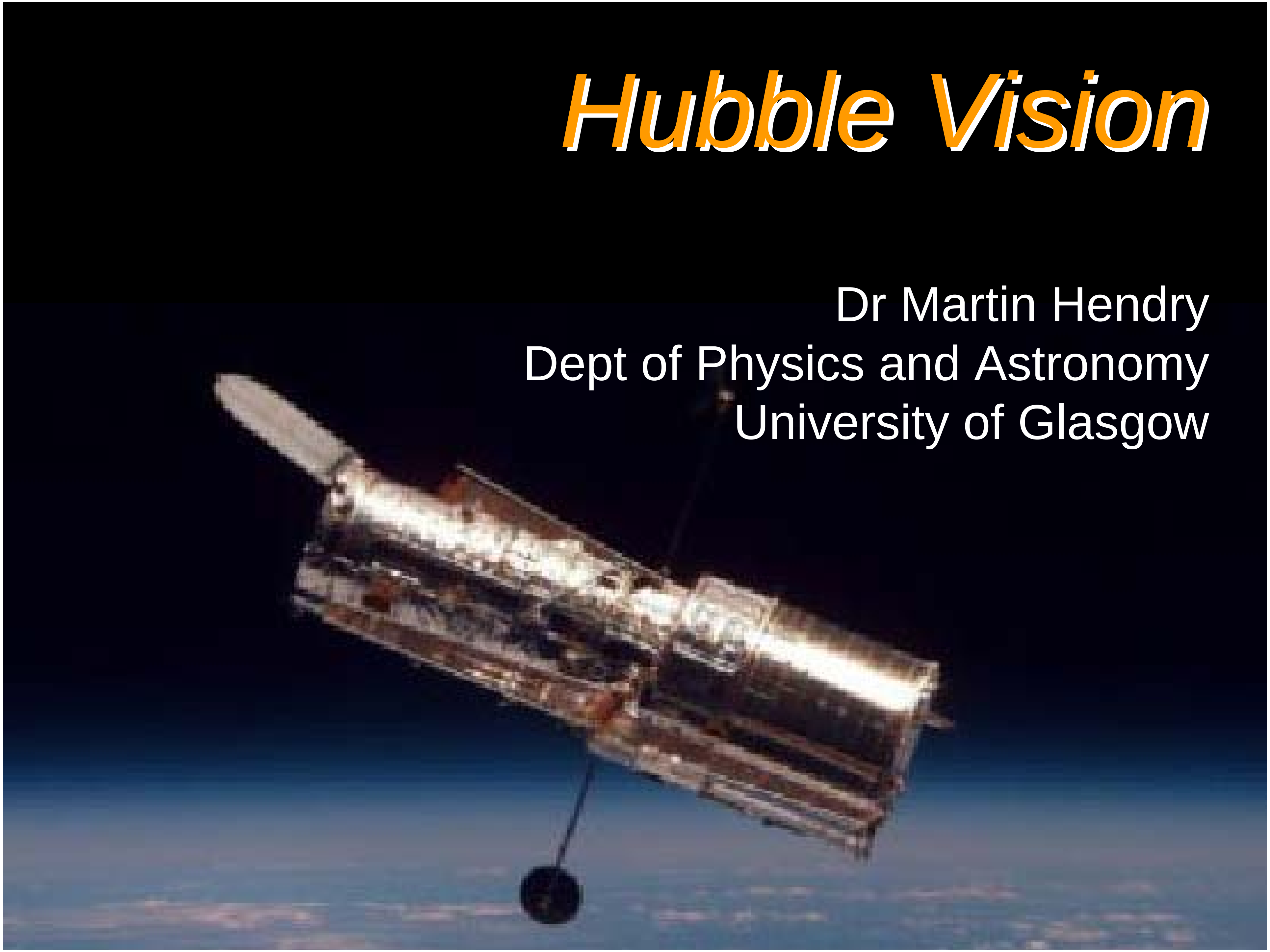
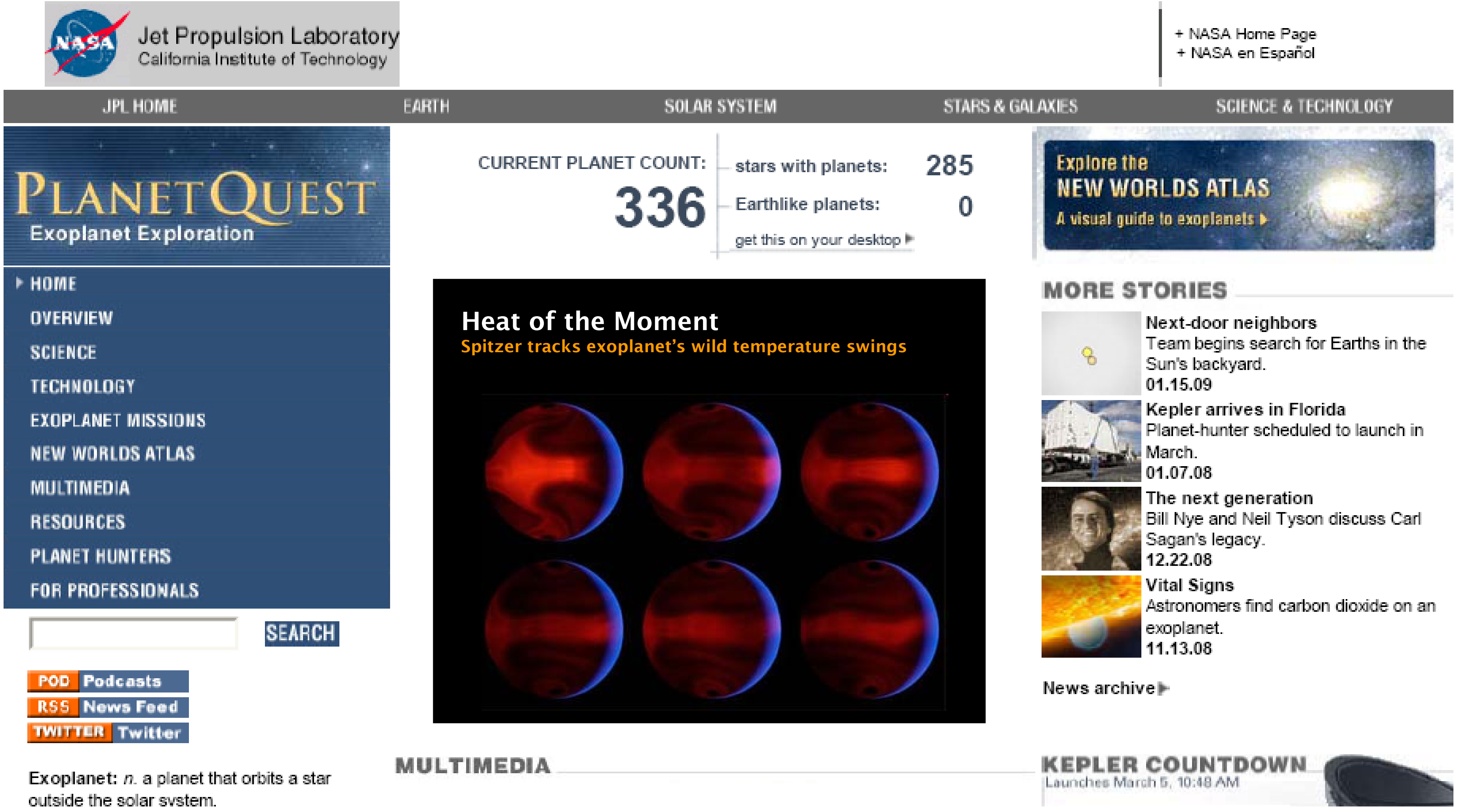
Hubble Vision

Dr Martin Hendry
Dept of Physics and Astronomy
University of Glasgow

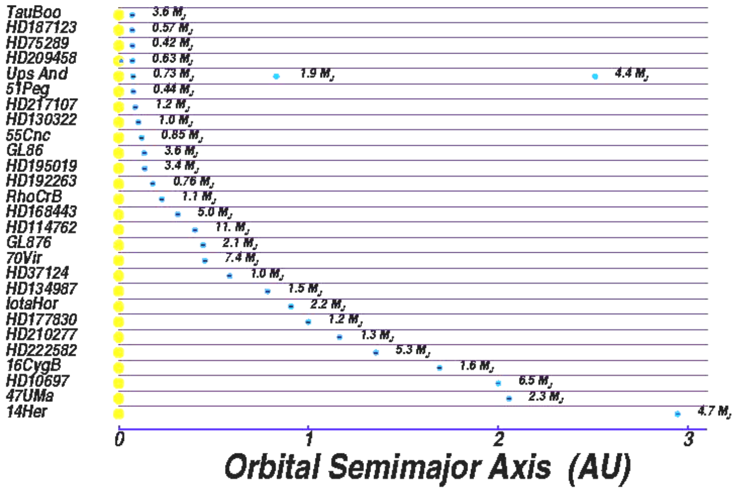


In the past 14 years we have found many planets orbiting other stars in our galaxy…



What have we learned about exoplanets?

Highly active, and rapidly changing, field



2000: 29 exoplanets

What have we learned about exoplanets?

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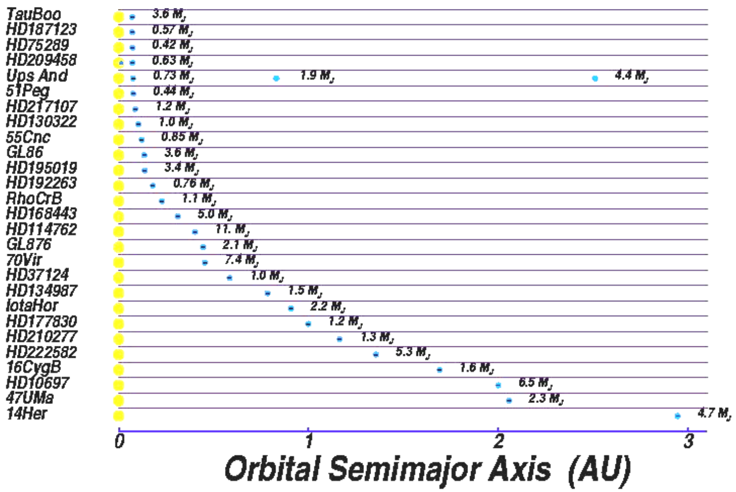
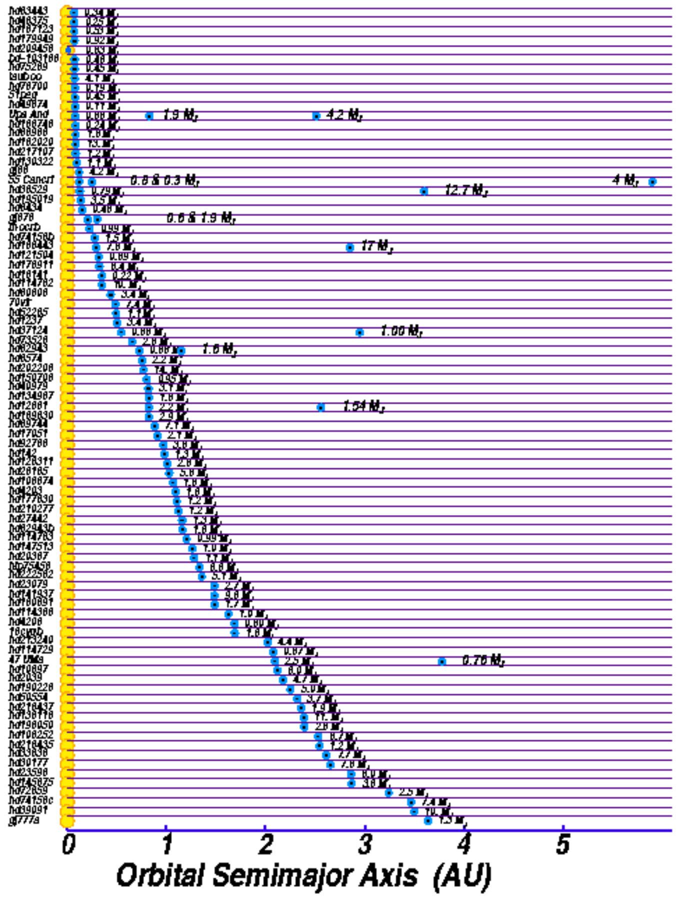


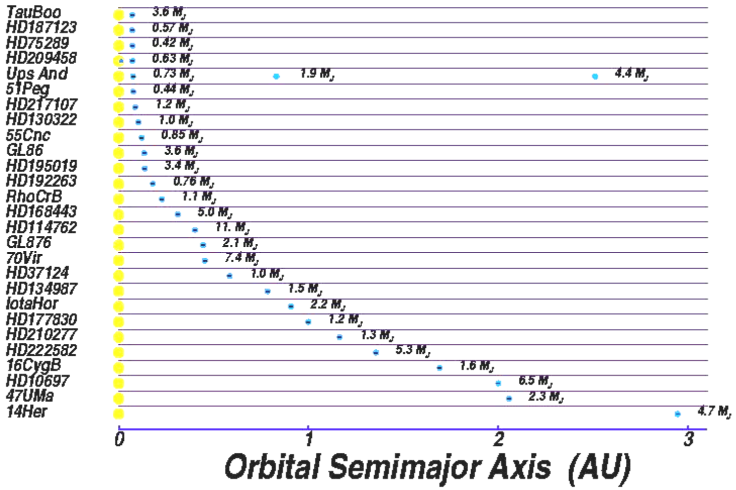
2000: 29 exoplanets



2005: 136 exoplanets

What have we learned about exoplanets?

Highly active, and rapidly changing, field

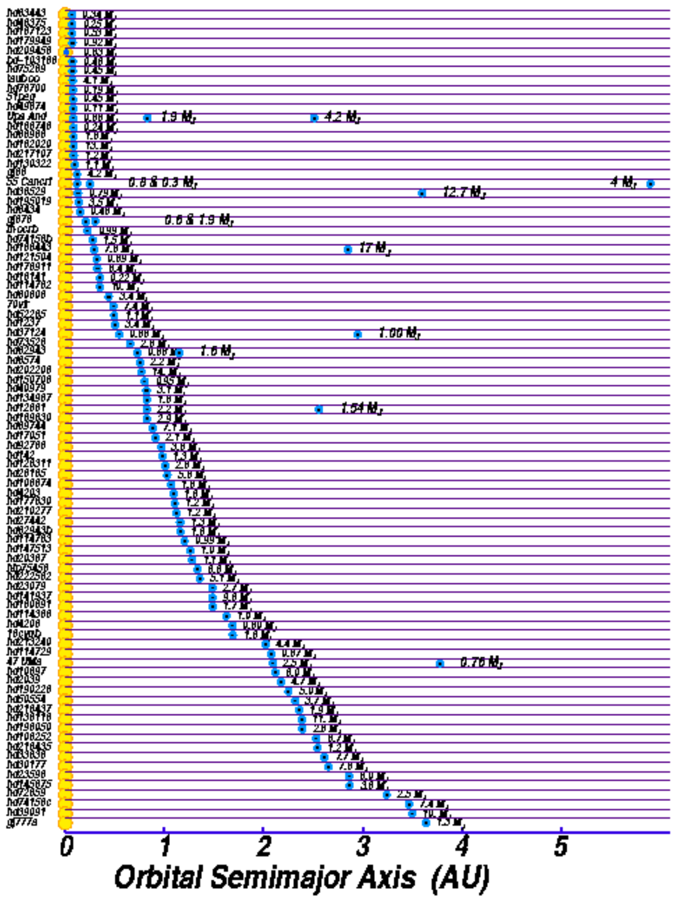


2000: 29 exoplanets

Up-to-date summary at

http://www.exoplanets.org

Now finding less massive planets further from their parent star



2005: 136 exoplanets

Exoplanets are ‘drowned out’ by their parent star. Impossible to image directly with current telescopes (~10m mirrors)…

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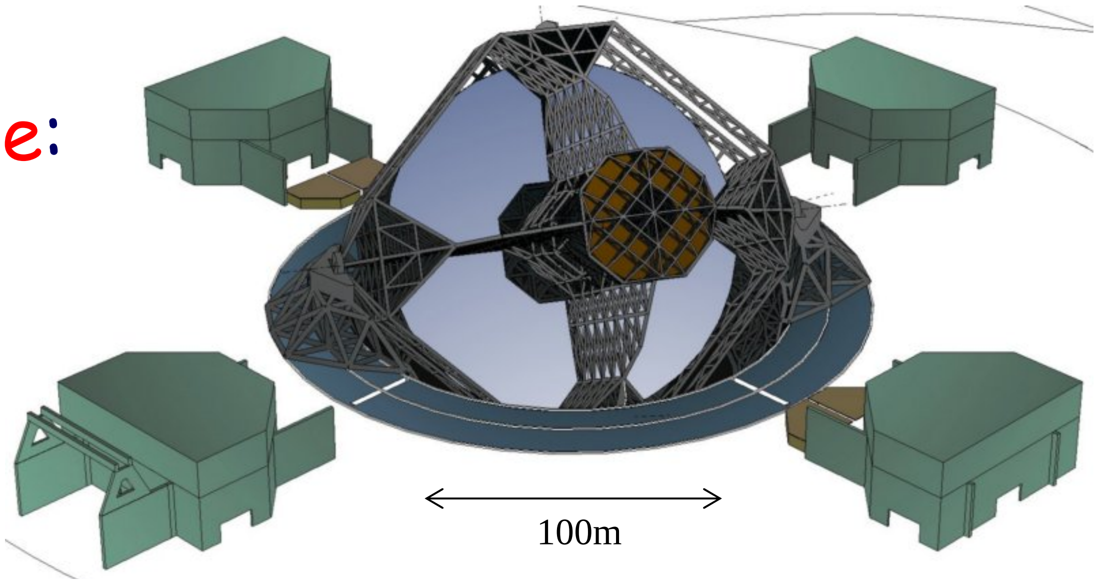
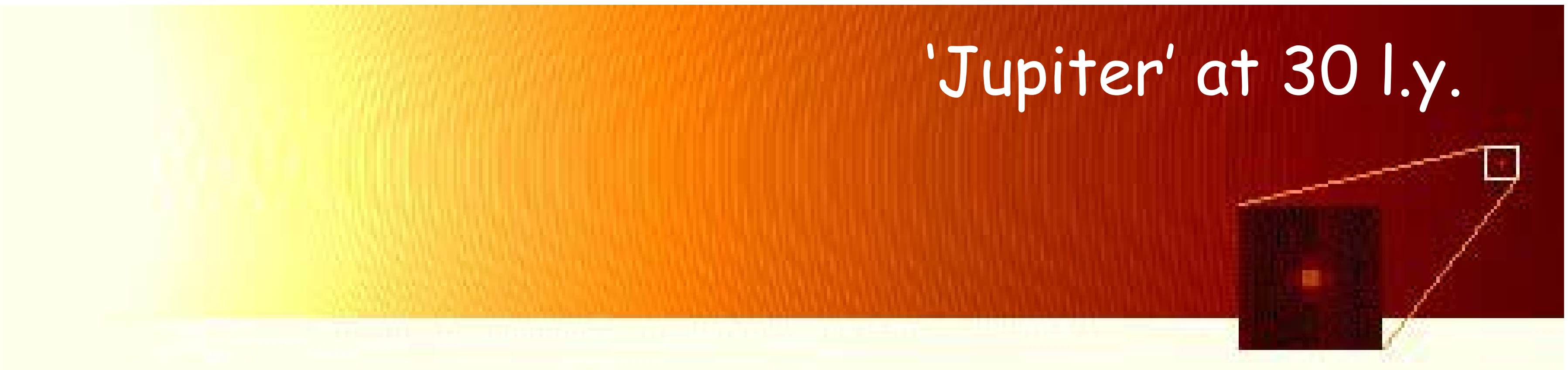
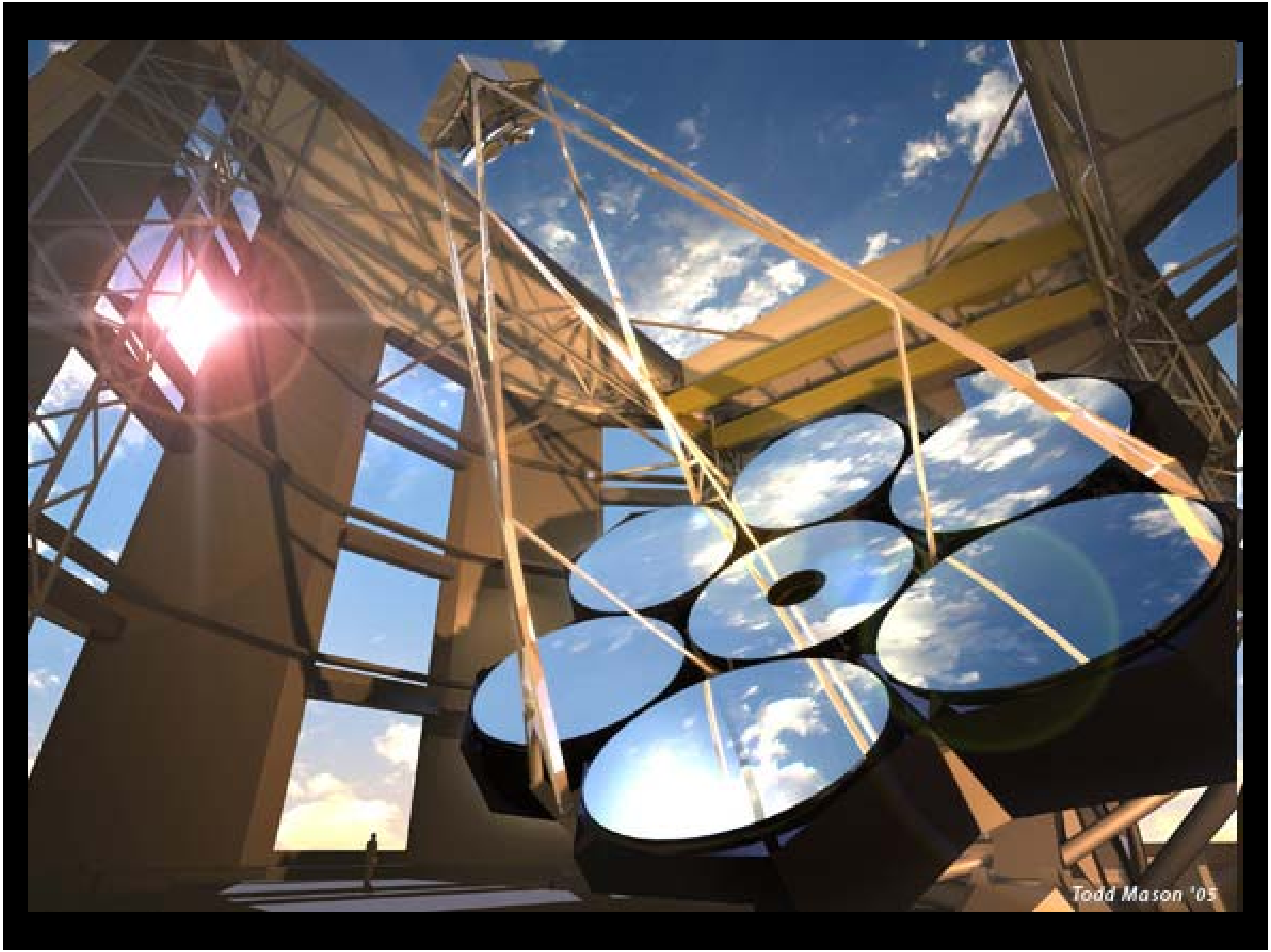
Need OWL telescope:

100m mirror

Completed ????






Todd Mason '05

1. How can we detect extra-solar planets?

- They cause their parent star to 'wobble', as they orbit their common centre of gravity

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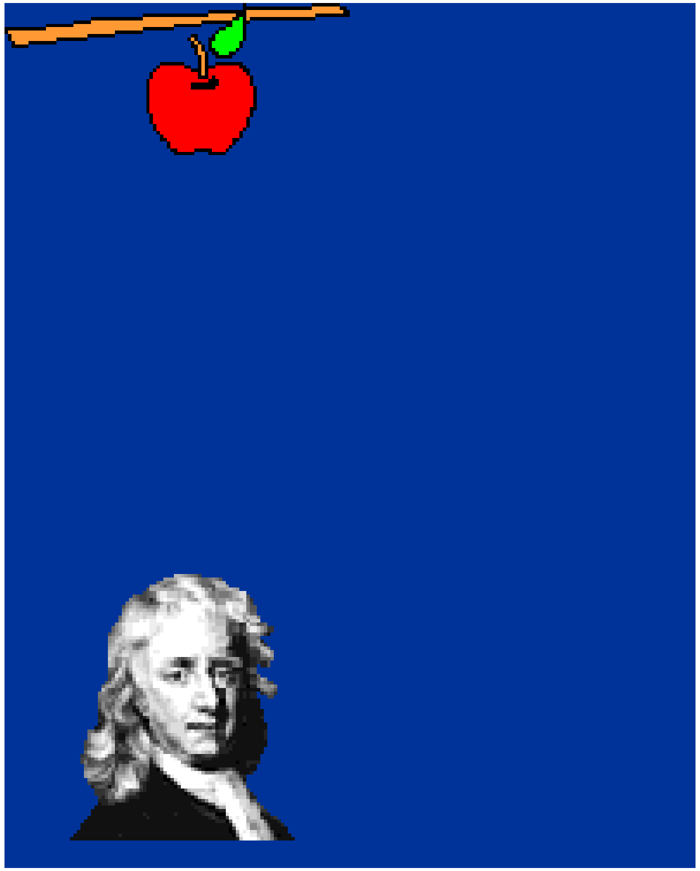
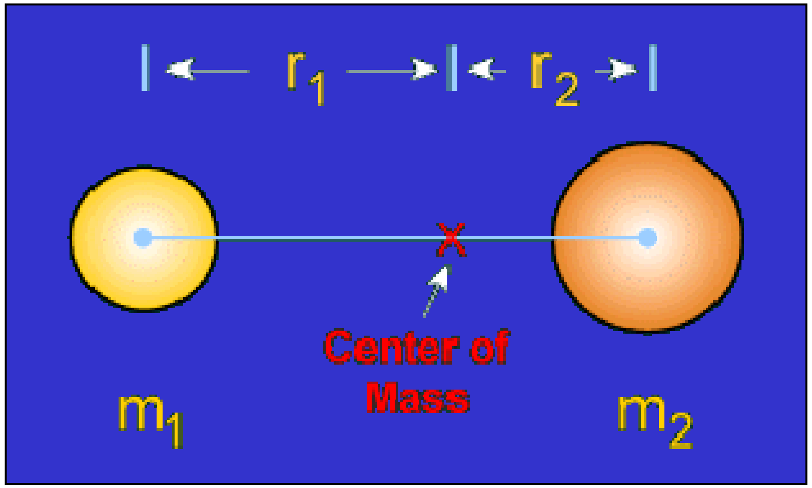
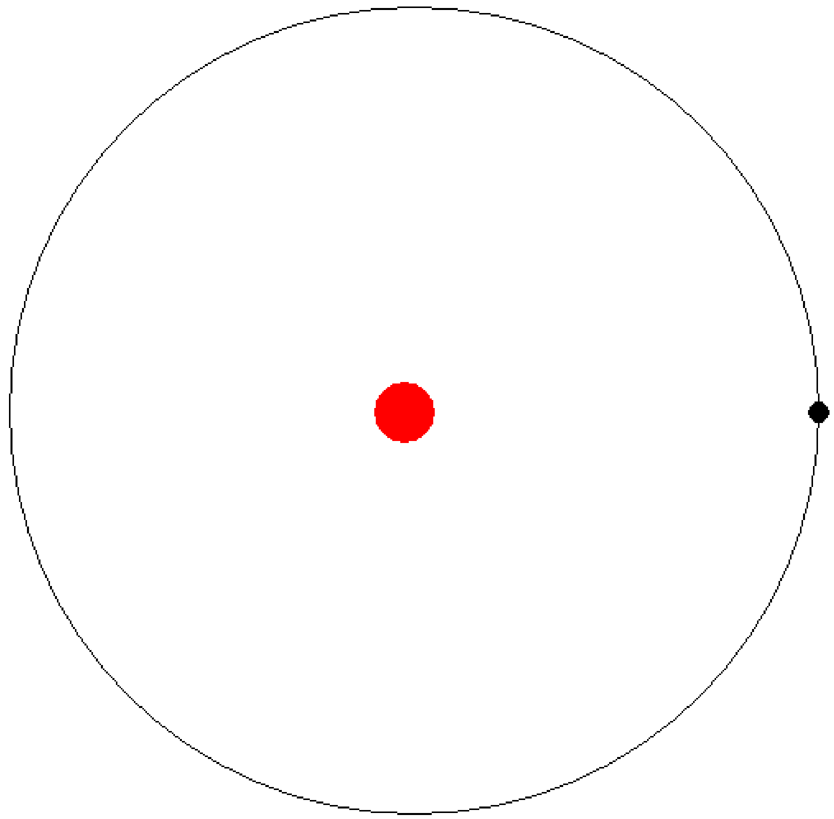




Star + planet in circular orbit about centre of mass



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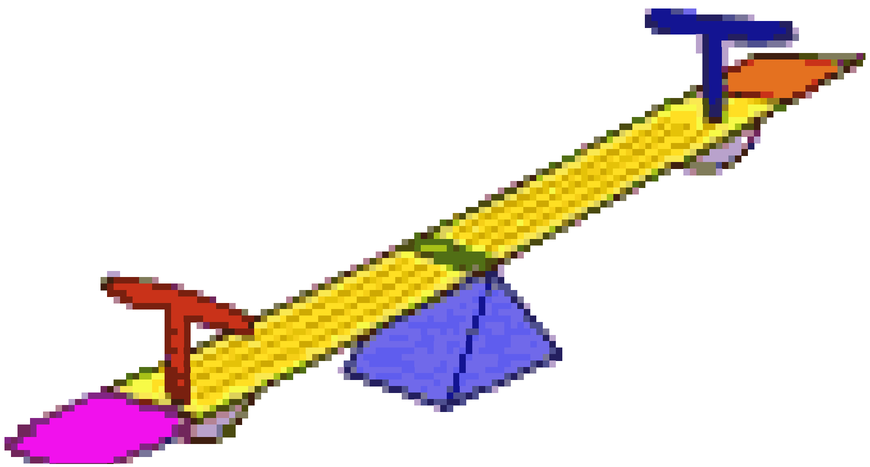
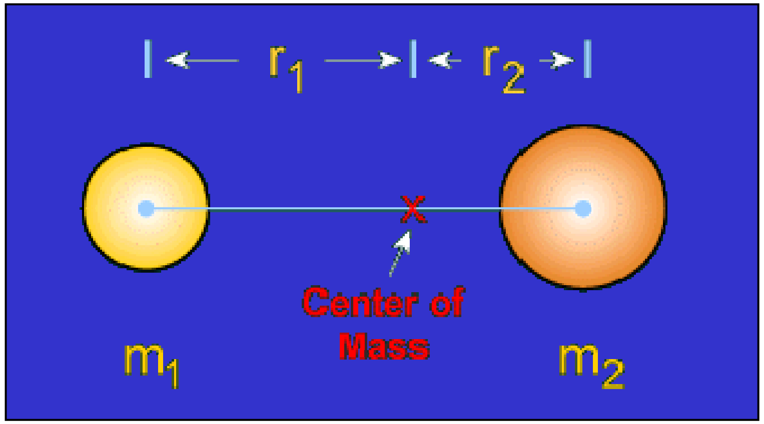


Star + planet in circular orbit about centre of mass

Can see star 'wobble', even when planet is unseen.

But how large is the wobble?...

Star + planet in circular orbit about centre of mass

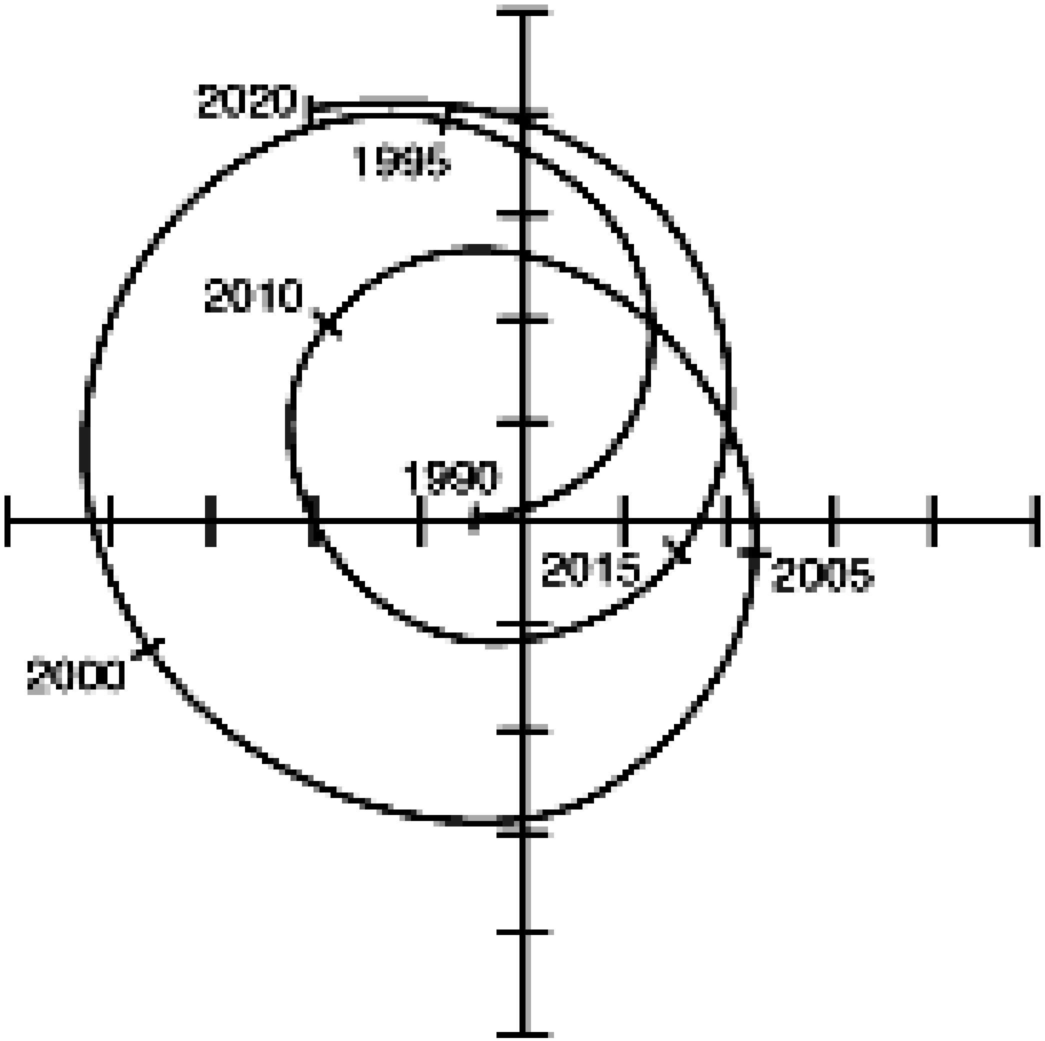


Can see star 'wobble', even when planet is unseen.

e.g. 'Jupiter' at 30 l.y.

But how large is the wobble?...

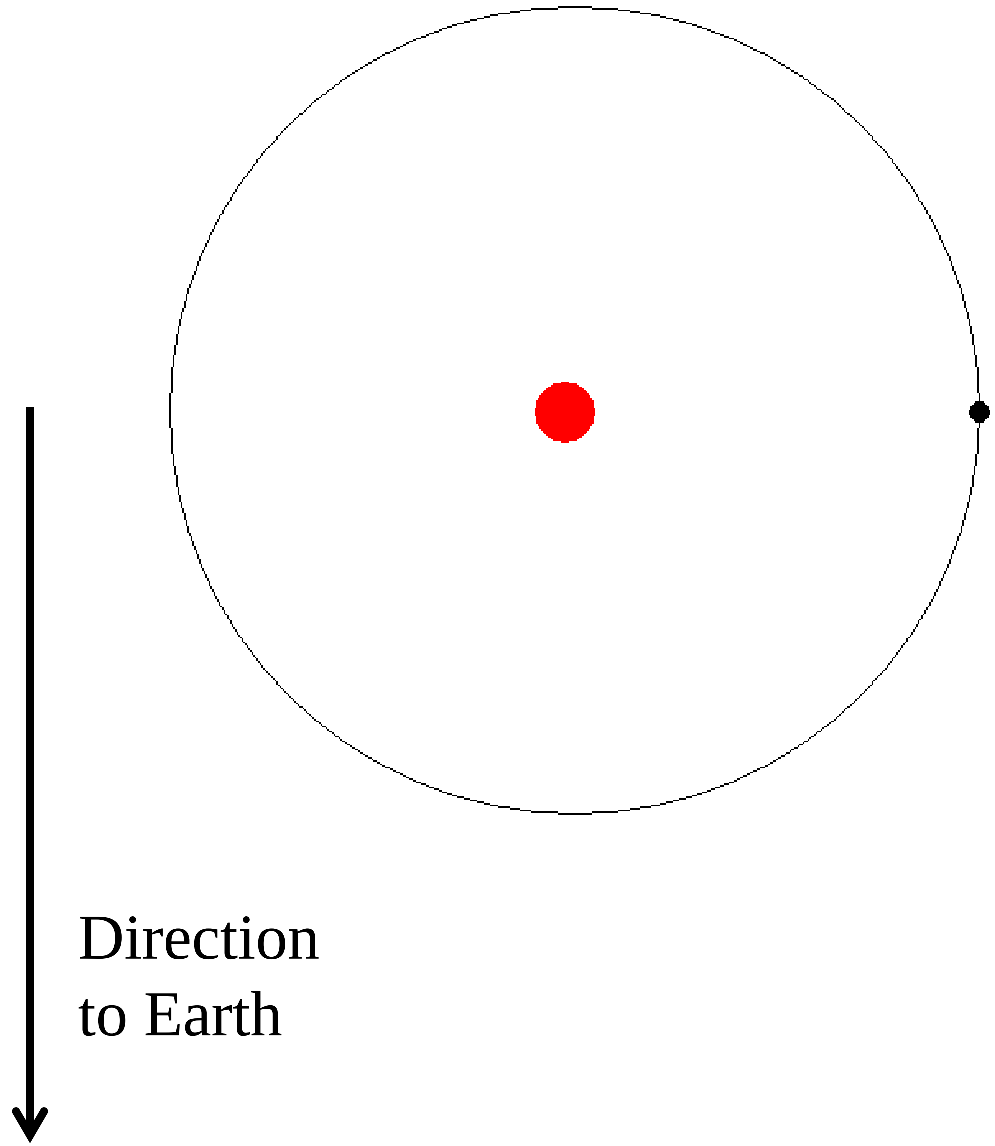
= one three *millionth* of the width of the Full Moon !!!



Detectable routinely with SIM (launch date ????) but ***not*** currently

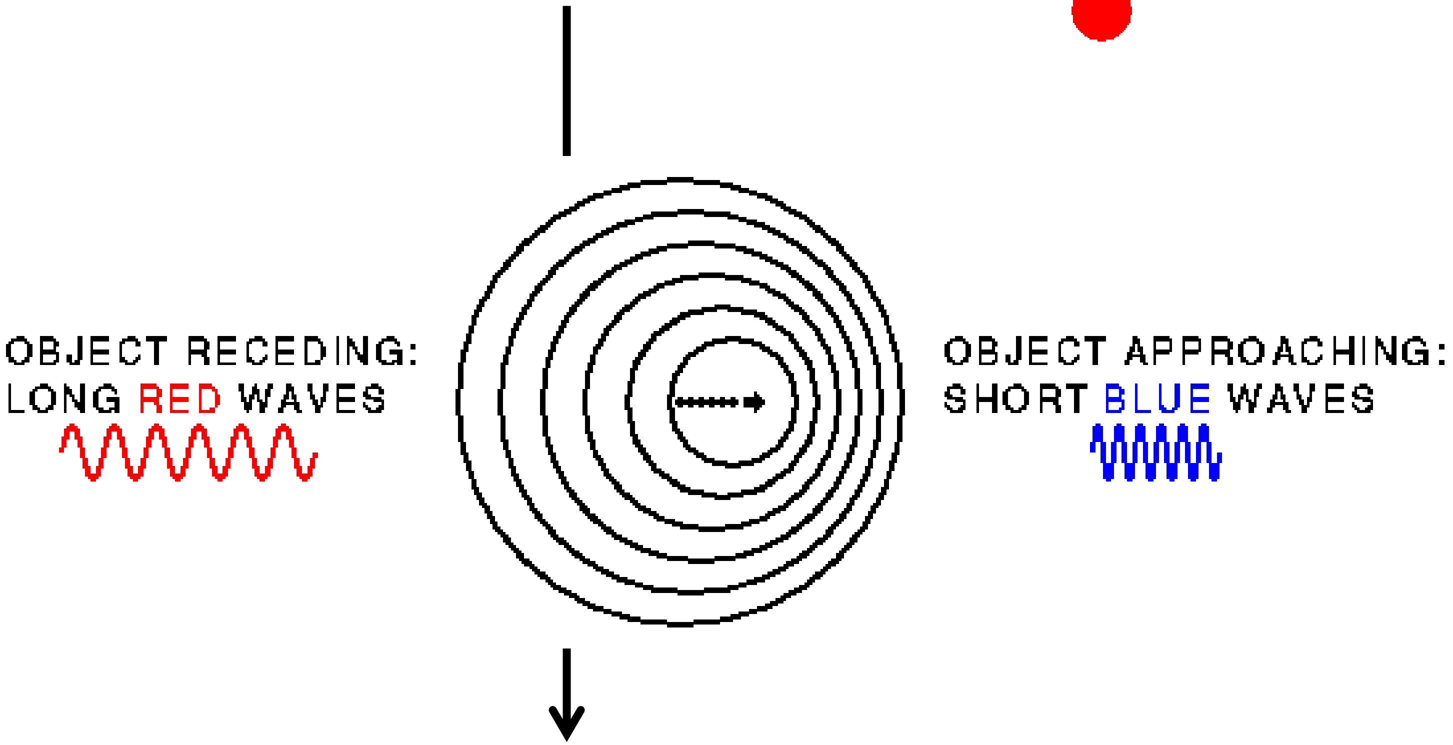
The Sun's "wobble", mainly due to Jupiter, seen from 30 light years away = width of a 5p piece in Baghdad!

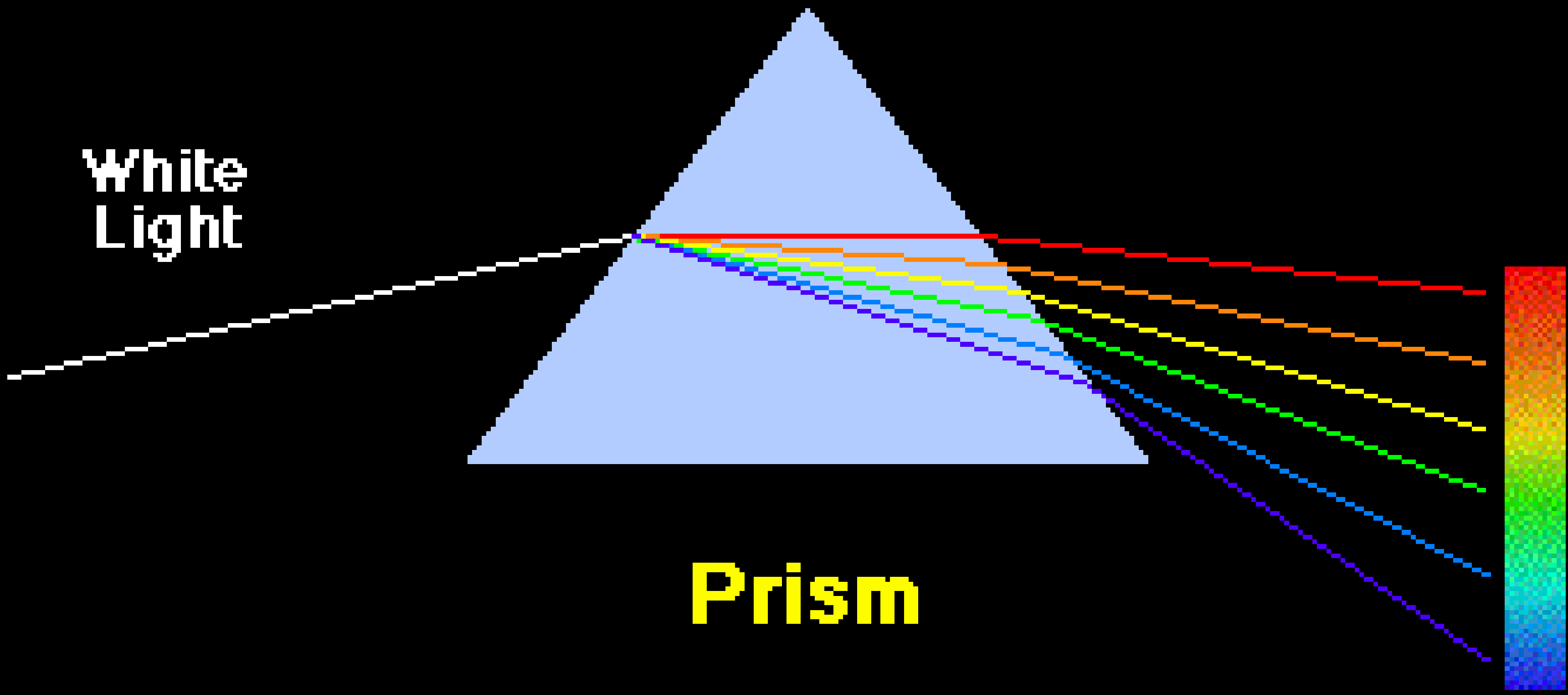
Suppose line of sight is in
orbital plane



Suppose line of sight is in
orbital plane

Star has a periodic motion
towards and away from
Earth

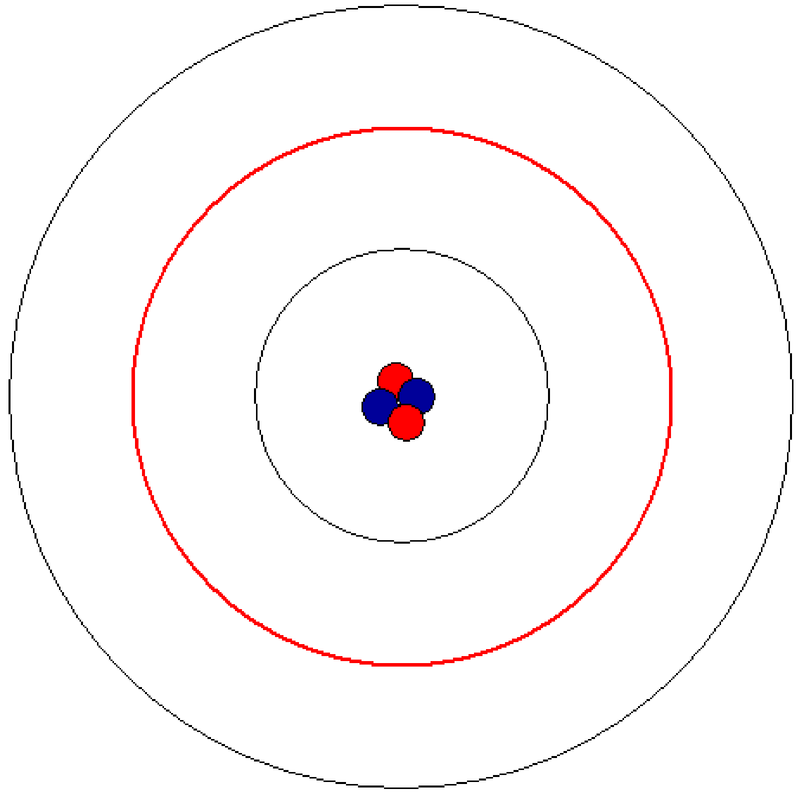




Spectroscopy

Absorption Spectrum

Electron orbiting nucleus of atom absorbs light of the precise energy needed to make it jump to higher energy level.



Absorption Spectrum

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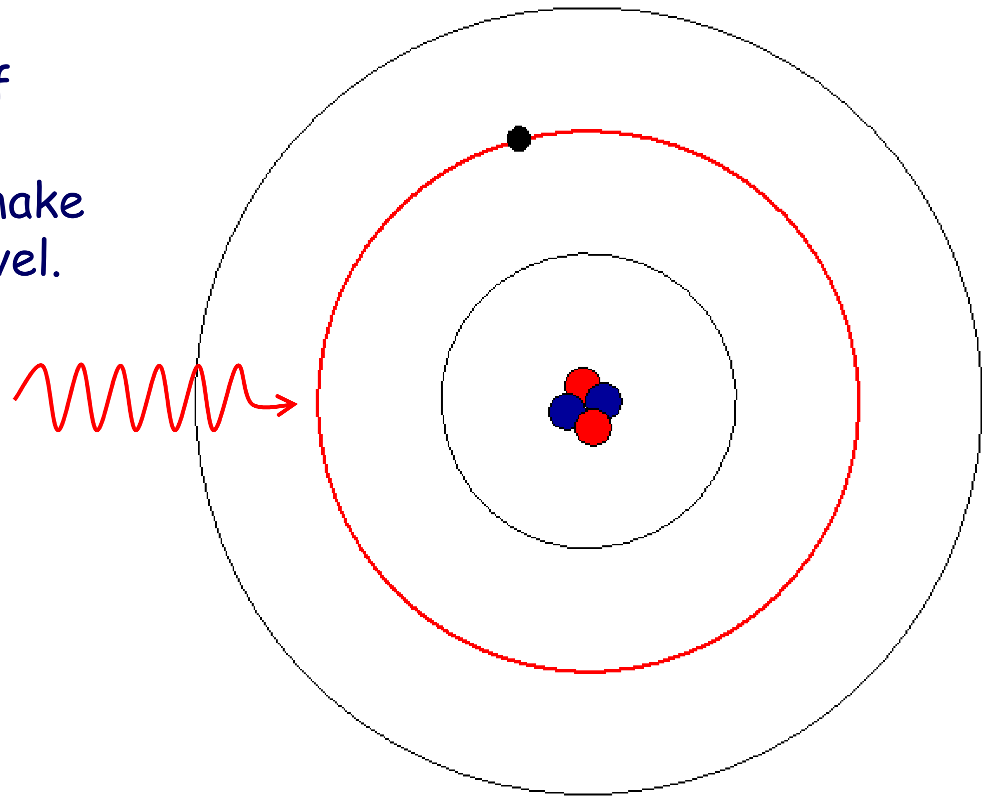
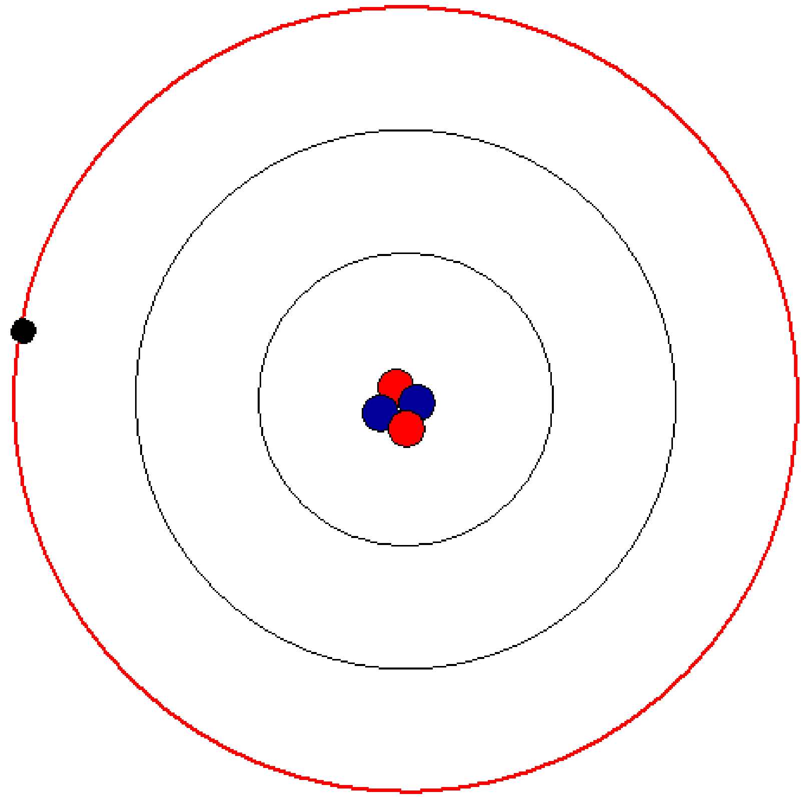
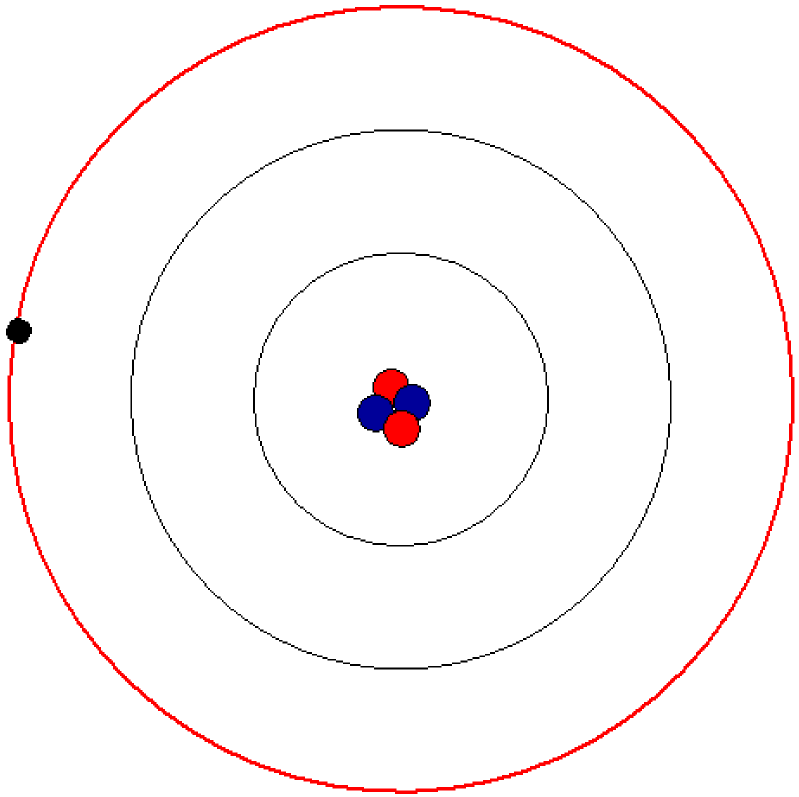


Absorption Spectrum

Electron orbiting nucleus of atom absorbs light of the precise energy needed to make it jump to higher energy level.



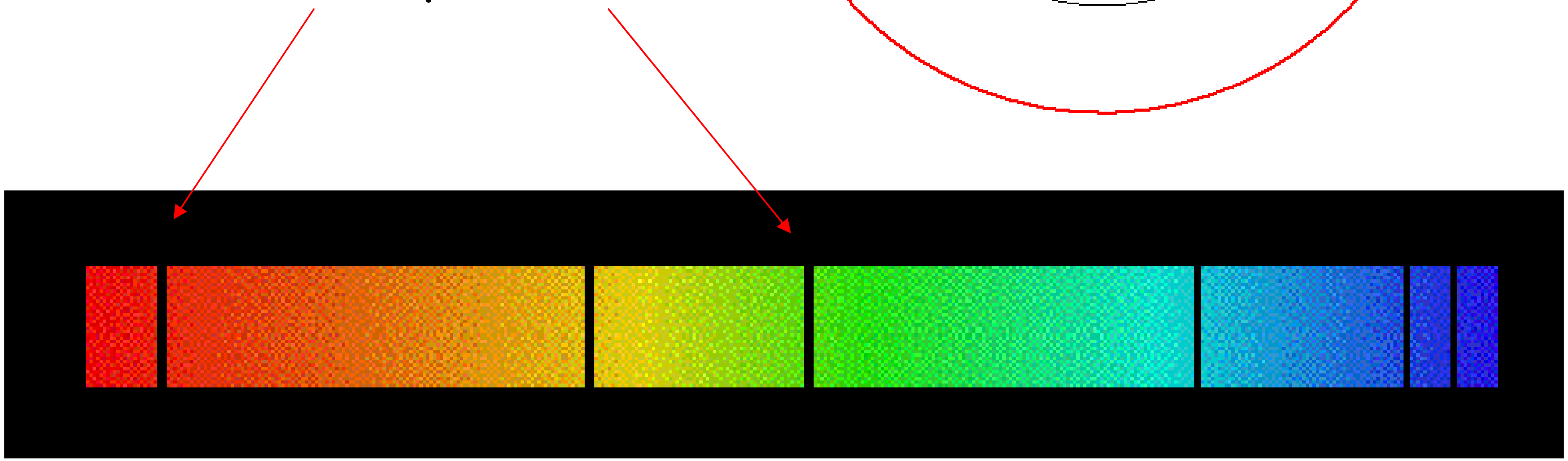
Absorption Spectrum

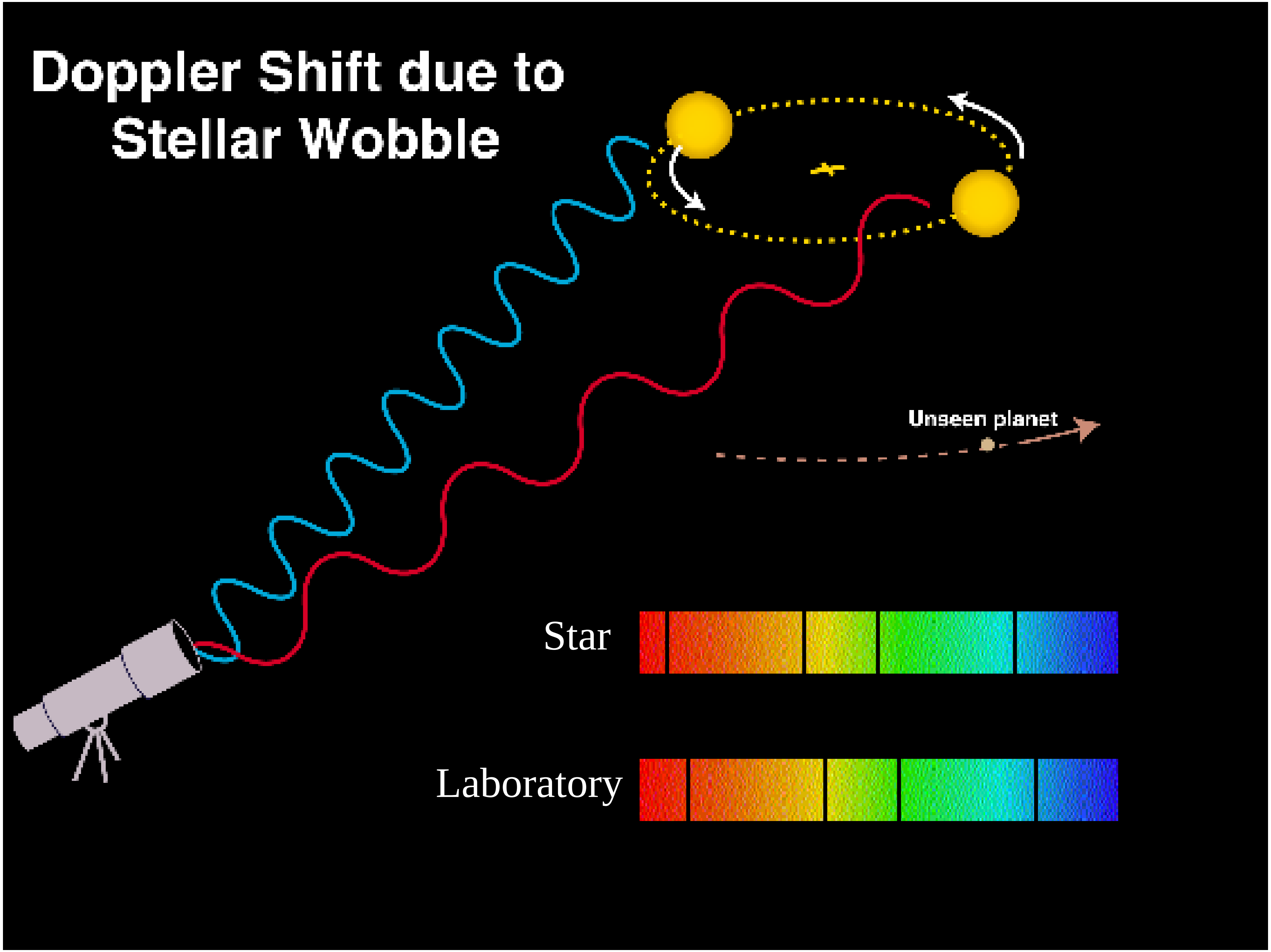


Electron orbiting nucleus of atom absorbs light of the precise energy needed to make it jump to higher energy level.

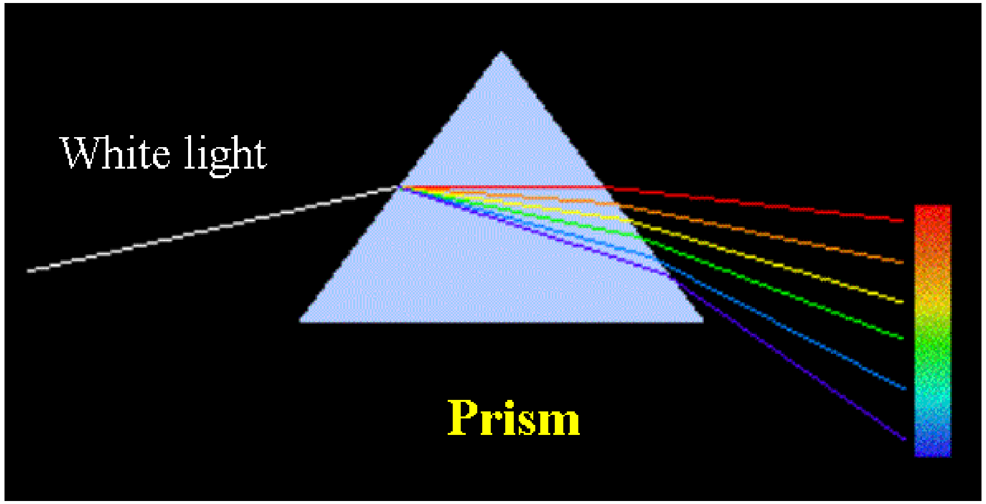
This energy is now missing from the spectrum of light:

Dark Absorption Line




Doppler Shift due to
Stellar Wobble
Unseen planet
Star
Laboratory

Stellar spectra are observed using prisms or diffraction gratings, which disperse starlight into its constituent colours



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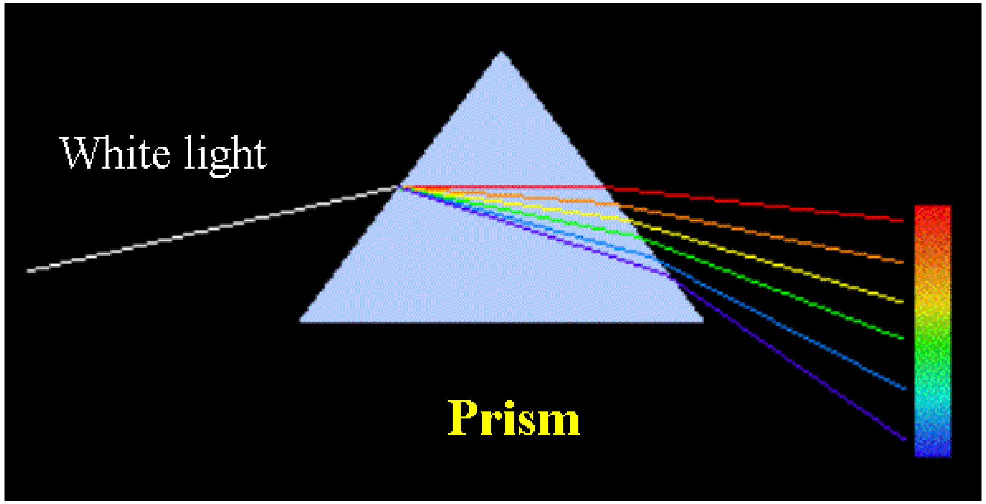


Doppler formula

Change in wavelength

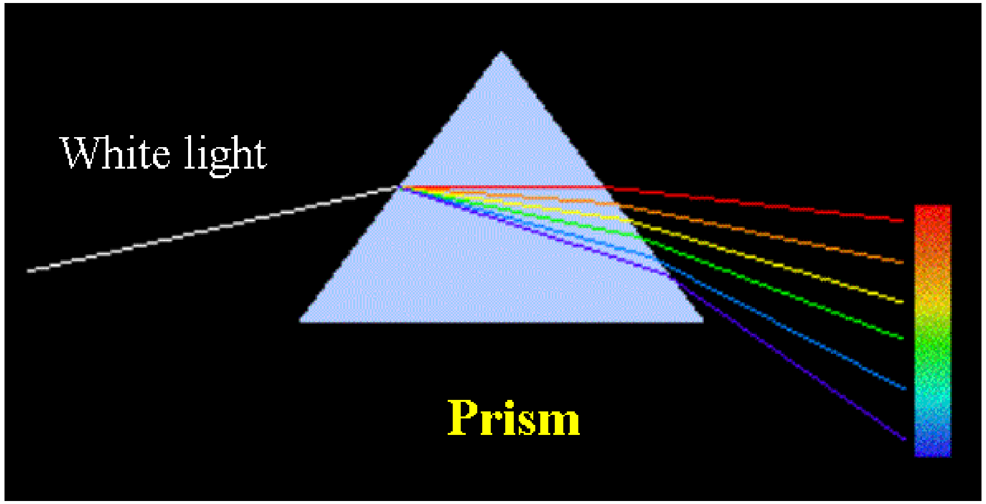
Radial velocity

$$\boxed{\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

Wavelength of light as measured in the laboratory

Speed of light

Stellar spectra are observed using prisms or diffraction gratings, which disperse starlight into its constituent colours



Doppler formula

Change in wavelength

Radial velocity

$$\boxed{\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

Wavelength of light as measured in the laboratory

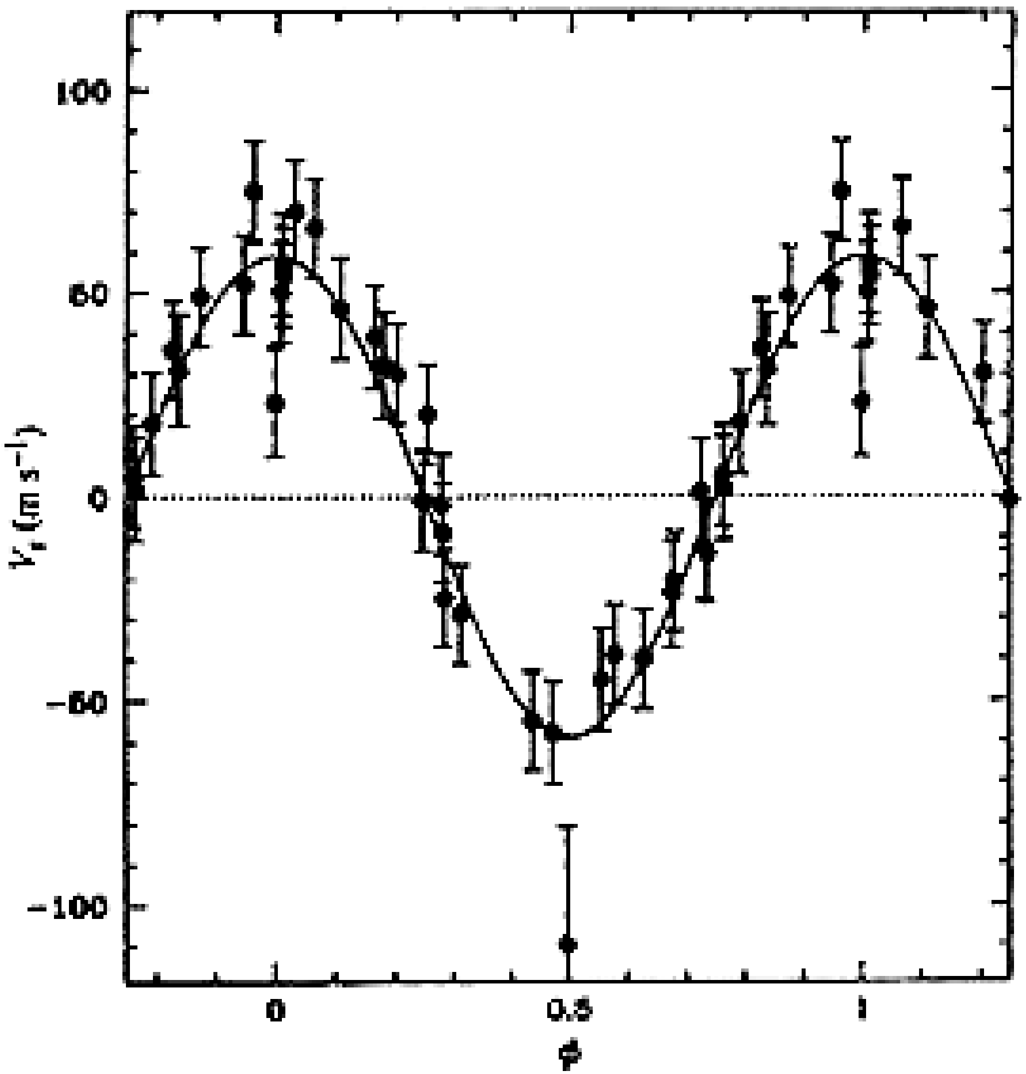
Speed of light

Limits of current technology:

$$\frac{\Delta\lambda}{\lambda_0} \approx 300 \text{ millionth}$$

$$\Rightarrow \boxed{v \approx 1\,\mathrm{ms^{-1}}}$$

51 Peg – the first new planet



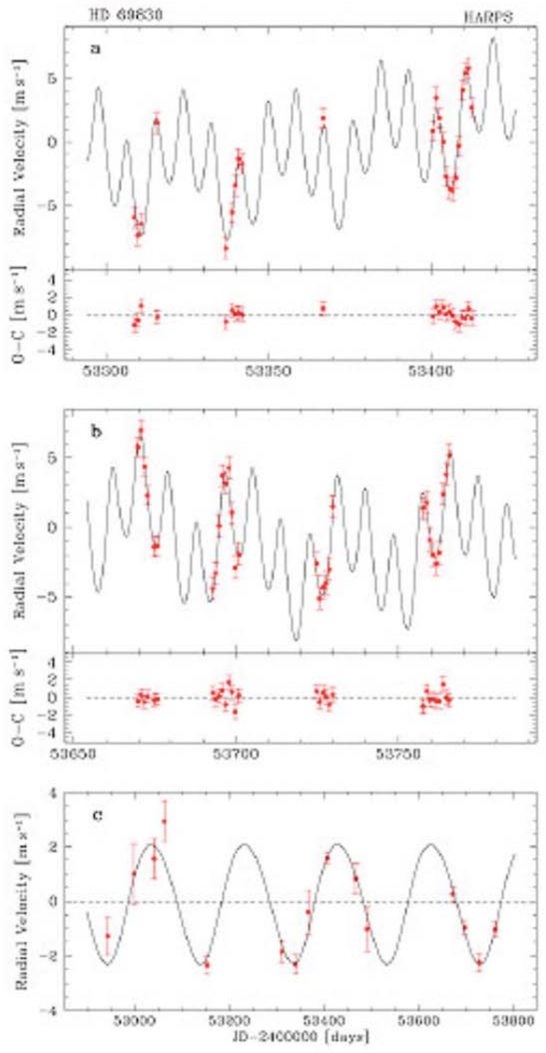
Discovered in 1995

Doppler wobble

$$v = 55\,\mathrm{ms}^{-1}$$

Multiple Doppler planets

- Wobbles on top of wobbles can also reveal multiple planet systems



Radial Velocity Measurements of HD 69830
(HARPS/3.6m)

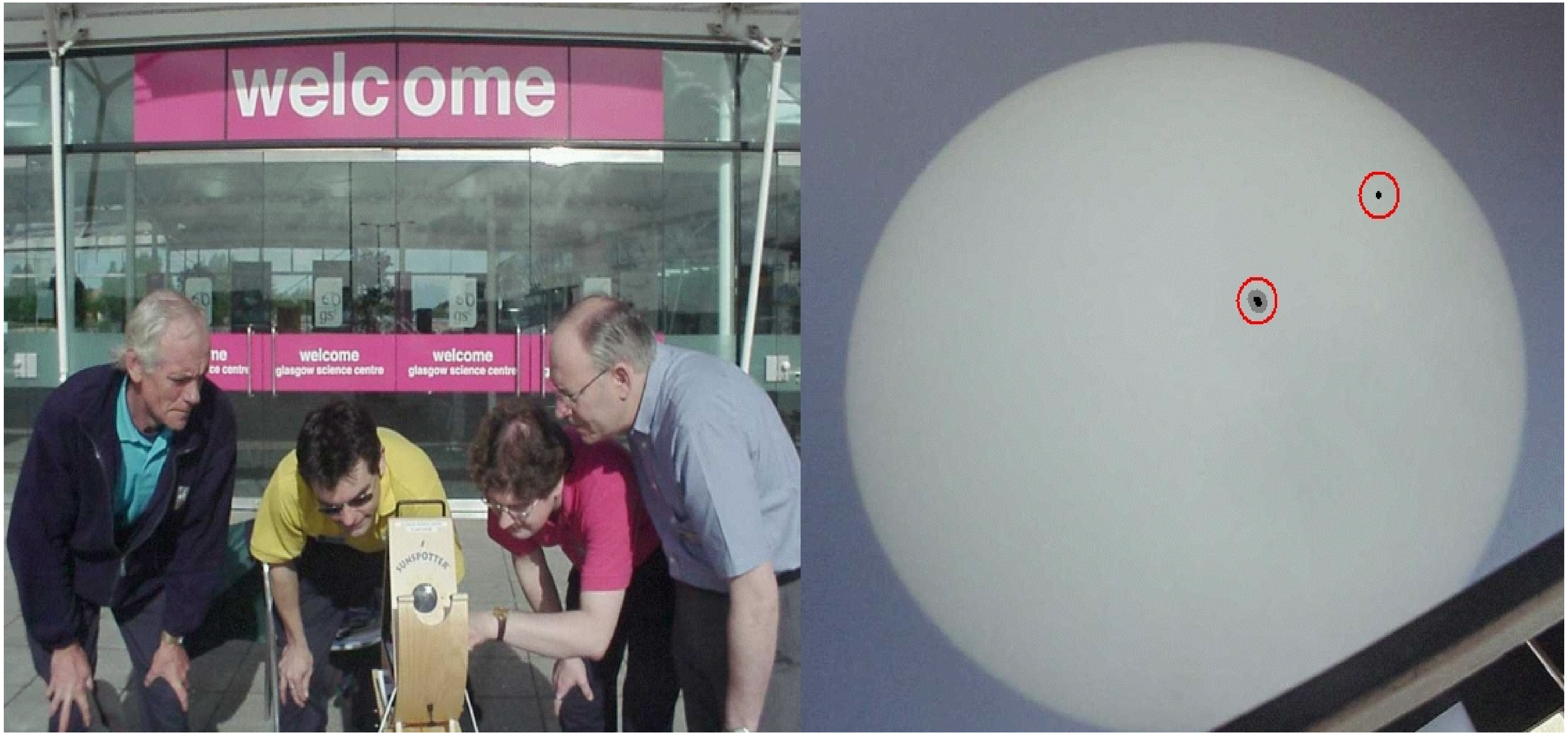
ESO Press Photo 18c/06 (18 May 2006) © ESO

Artist View of Planetary System Around HD 69830

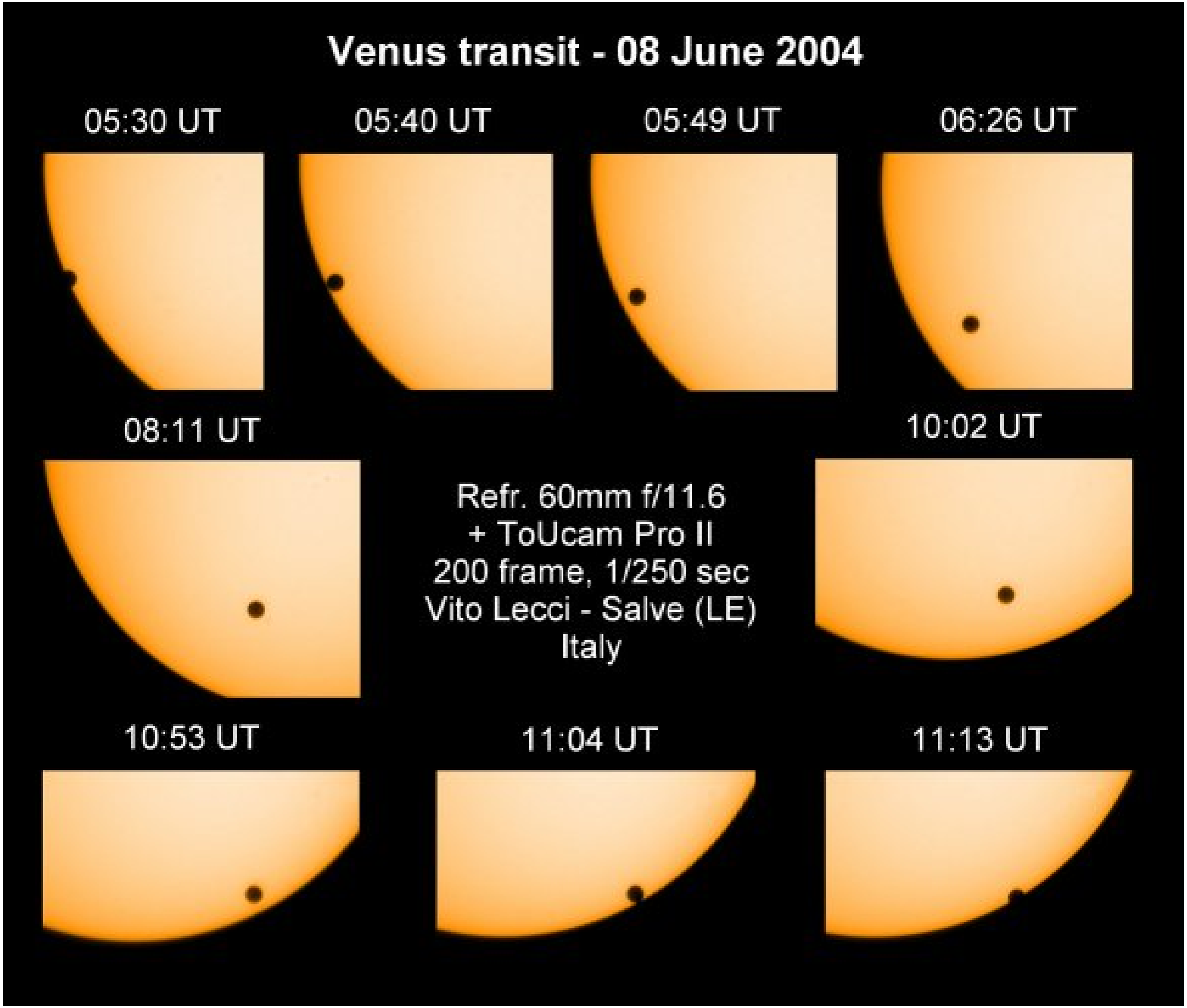
ESO Press Photo 18b/06 (18 May 2006) © ESO

HD 69830: A planetary system containing 3 Neptune-like planets

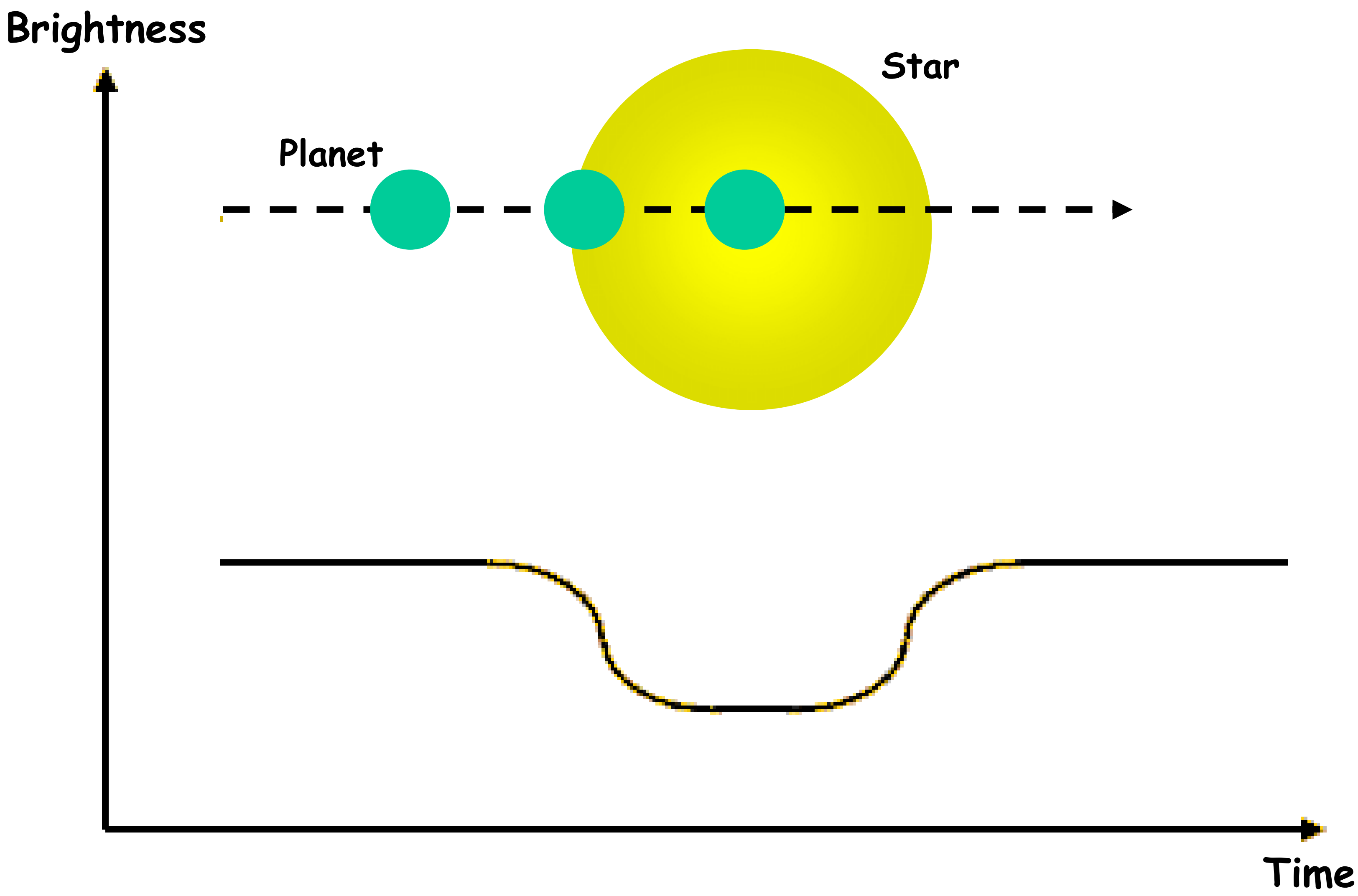
In recent years a growing number of exoplanets have been detected via **transits** = temporary drop in brightness of parent star as the planet crosses the star's disk along our line of sight.

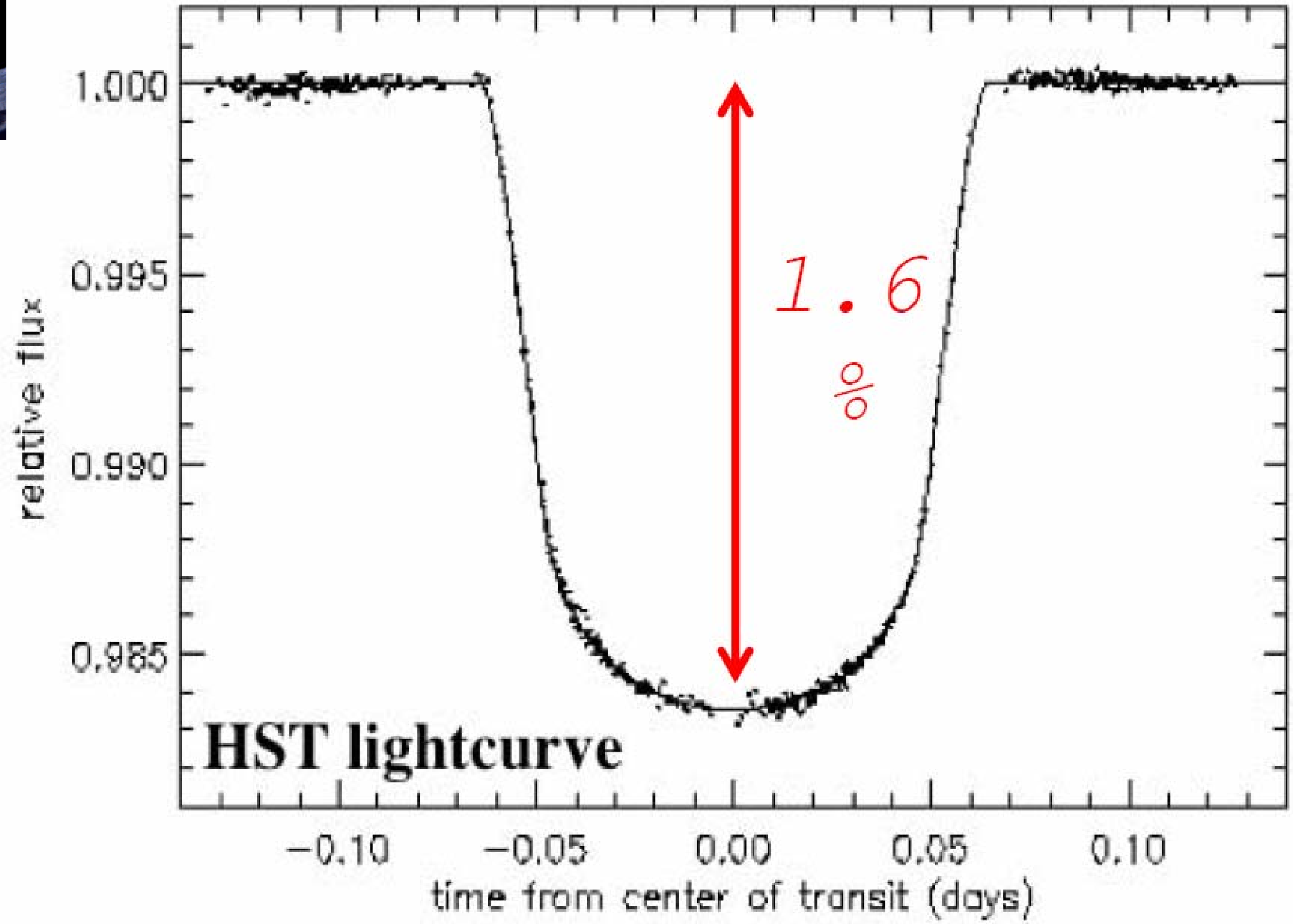


Transit of Mercury: May 7th 2003

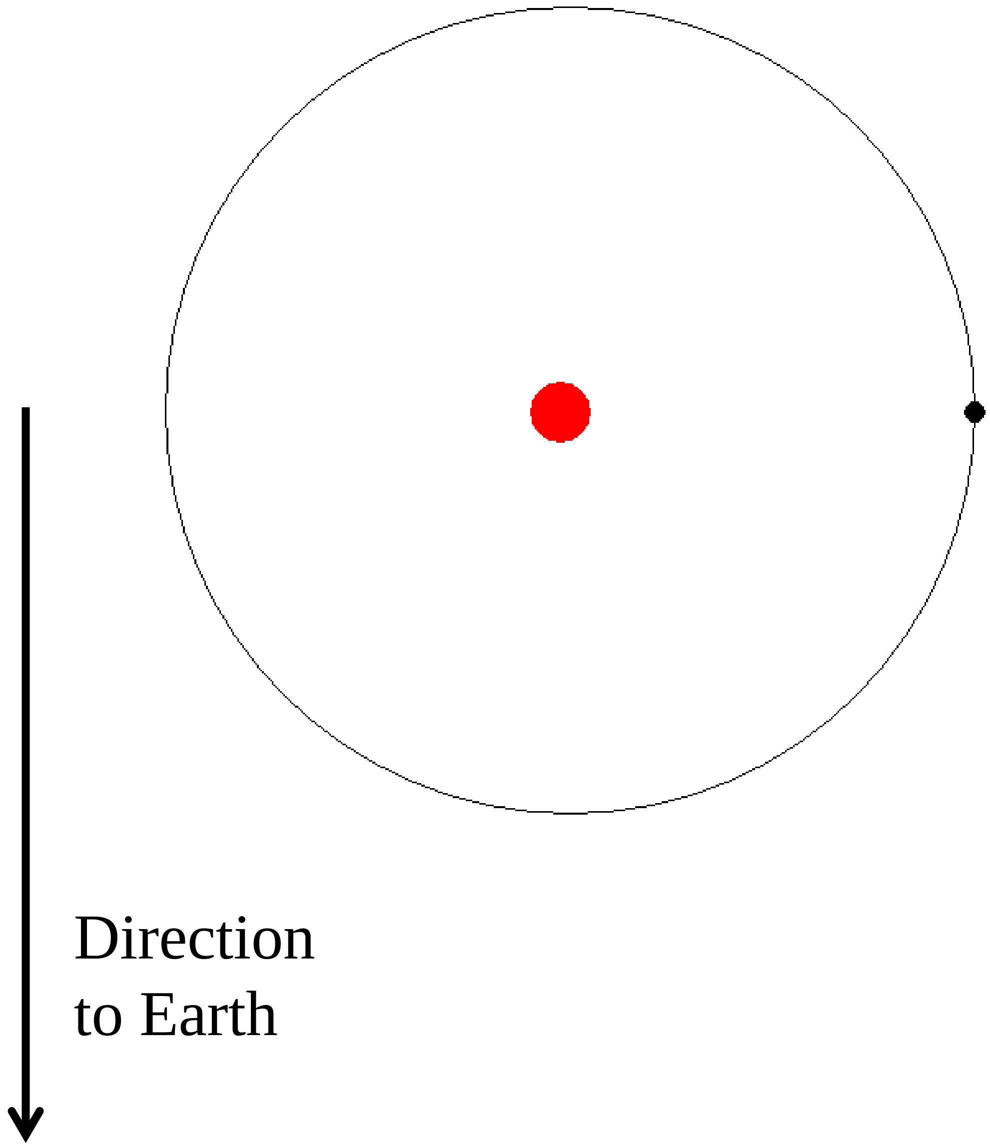

Venus transit - 08 June 2004
05:30 UT
05:40 UT
05:49 UT
06:26 UT
08:11 UT
Refr. 60mm f/11.6
+ ToUcam Pro II
200 frame, 1/250 sec
Vito Lecci - Salve (LE)
Italy
10:02 UT
10:53 UT
11:04 UT
11:13 UT

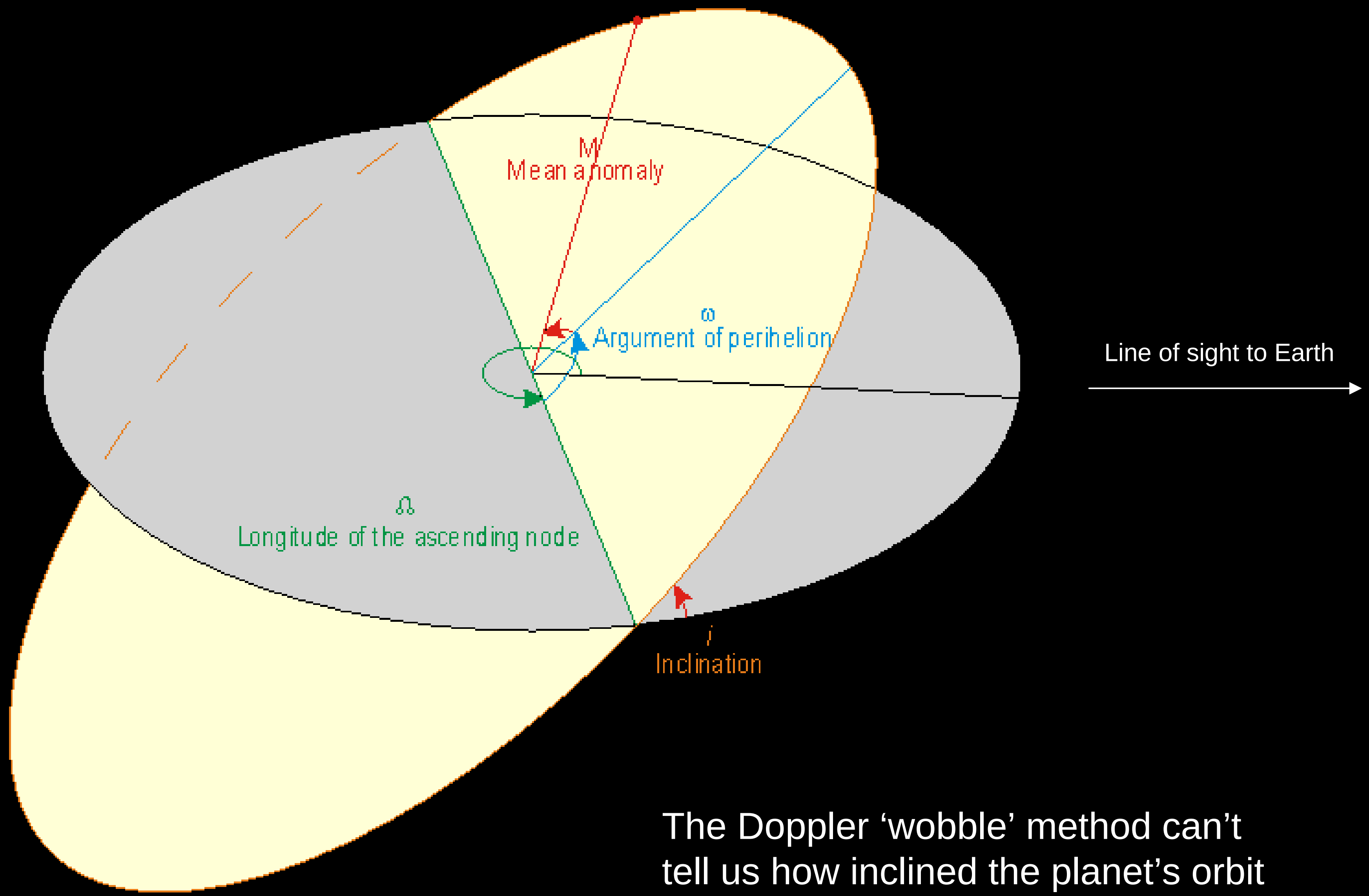
Detecting exoplanets from transits




1.000
0.995
0.990
0.985
relative flux
1.6 %
HST lightcurve
−0.10
−0.05
0.00
0.05
0.10
time from center of transit (days)

Suppose line of sight is in
orbital plane





The Doppler ‘wobble’ method can’t tell us how inclined the planet’s orbit is. That limits what we can say about its mass.

By combining (ground-based) Doppler ‘wobble’ measurements with precision HST astrometric measurements of the position of the star on the sky, we can tell the difference between a highly inclined orbit and one which is lies along our line of sight to the star.

This lets us improve our mass determination for the planet….

accepted to AJ May 13, 2007

The Mass of the Candidate Exoplanet Companion to HD 33636 from *HST* Astrometry and High-Precision Radial Velocities[1]

Jacob L. Bean,[2] Barbara E. McArthur,[3] G. Fritz Benedict,[3] Thomas E. Harrison,[4] Dmitry Bizyaev,[5] Edmund Nelan,[6] & Verne V. Smith[7]

ABSTRACT

We have determined a dynamical mass for the companion to HD 33636 which indicates it is a low-mass star instead of an exoplanet. Our result is based on an analysis of *Hubble Space Telescope* (*HST*) astrometry and ground-based radial velocity data. We have obtained high-cadence radial velocity measurements spanning 1.3 years of HD 33636 with the Hobby-Eberly Telescope at McDonald Observatory. We combined these data with previously published velocities to create a data set that spans nine years. We used this data set to search for, and place mass limits on, the existence of additional companions in the HD 33636 system. Our high-precision astrometric observations of the system with the *HST* Fine Guidance Sensor 1r span 1.2 years. We simultaneously modeled the radial velocity and astrometry data to determine the parallax, proper motion, and perturbation orbit parameters of HD 33636. Our derived parallax, $\pi_{abs} = 35.6 \pm 0.2$ mas, agrees within the uncertainties with the *Hipparcos* value. We find a perturbation period $P = 2117.3 \pm 0.8$ days, semimajor axis $a_A = 14.2 \pm 0.2$ mas, and system inclination $i = 4\overset{\circ}{.}1 \pm 0\overset{\circ}{.}1$. Assuming the mass of the primary star $M_A = 1.02 \pm 0.03\ M_\odot$, we obtain a companion mass $M_B = 142 \pm 11\ M_{Jup} = 0.14 \pm 0.01\ M_\odot$. The much larger true mass of the companion relative to its minimum mass estimated from the spectroscopic orbit parameters ($M \sin i = 9.3\ M_{Jup}$) is due to the near face-on orbit orientation. This result demonstrates the value of follow-up astrometric observations to determine the true masses of exoplanet candidates detected with the radial velocity method.

Subject headings: astrometry – planetary systems – stars: individual (HD 33636) and distances – techniques: radial velocities and interferometric

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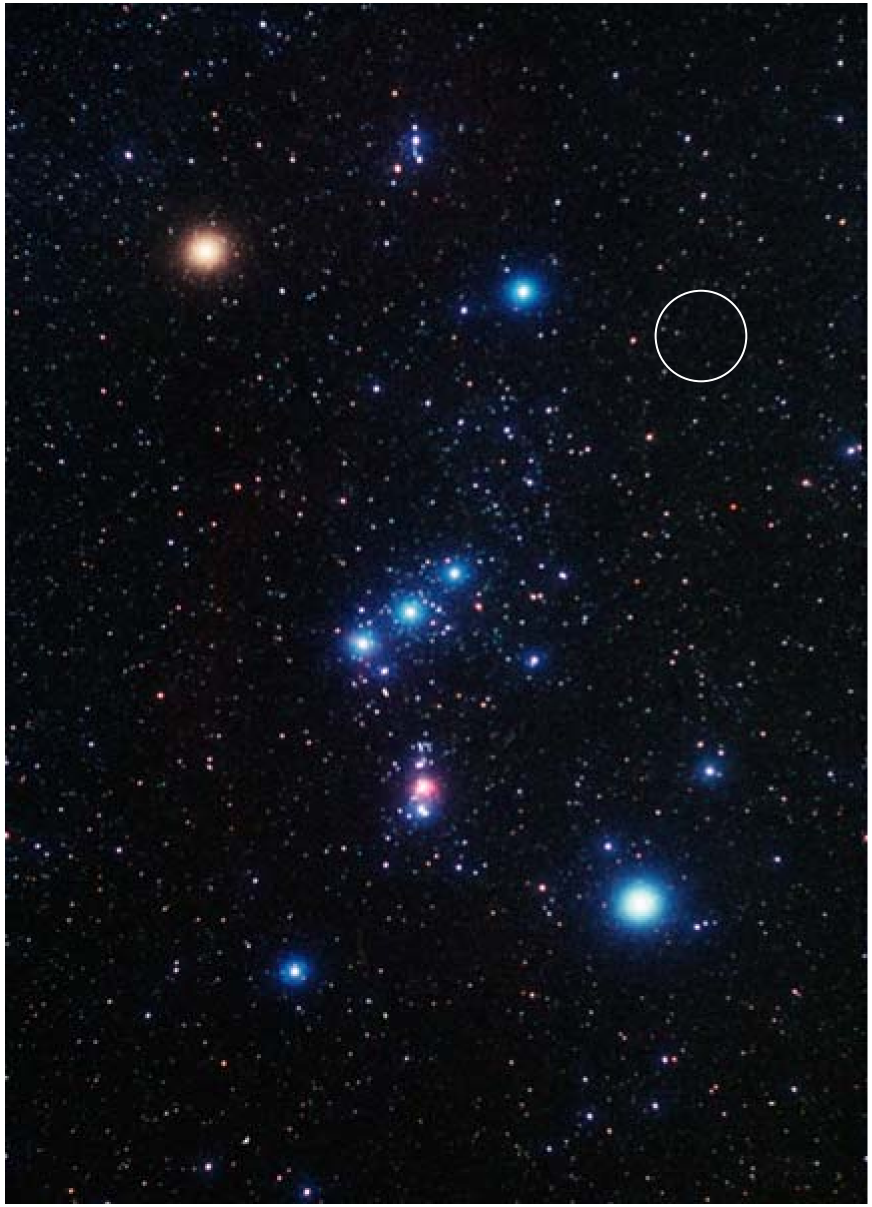

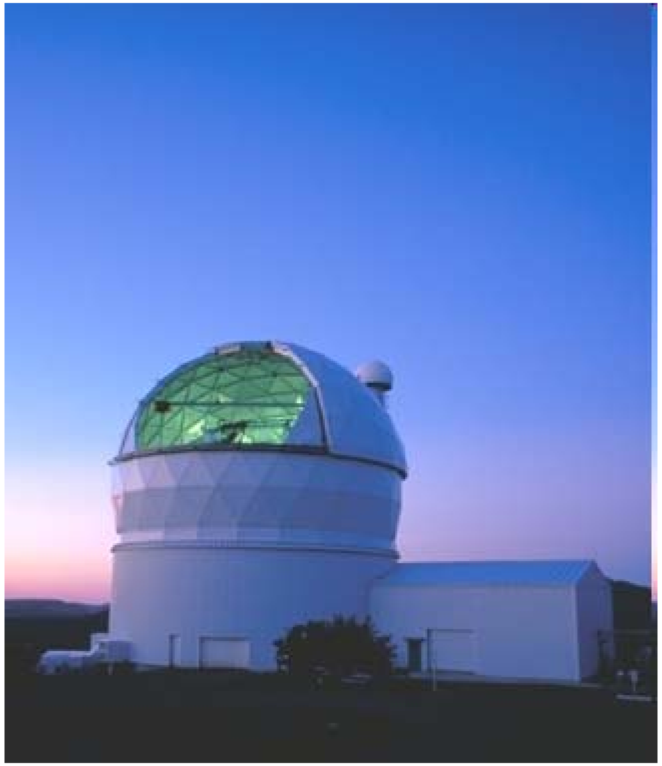

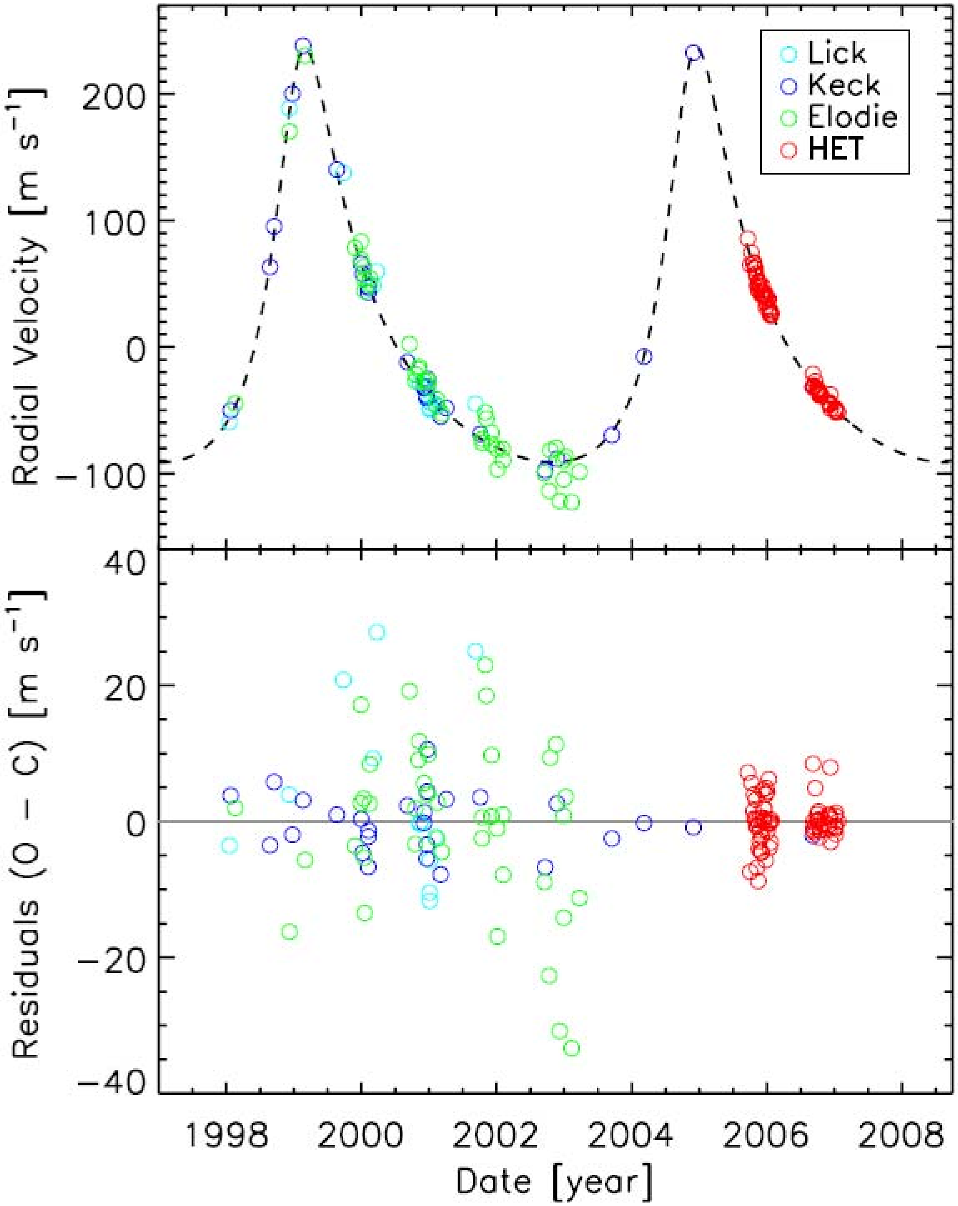

Lick
Keck
Elodie
HET
Radial Velocity [m s^{-1}]
200
100
0
−100
Residuals (O − C) [m s^{-1}]
40
20
0
−20
−40
1998
2000
2002
2004
2006
2008
Date [year]

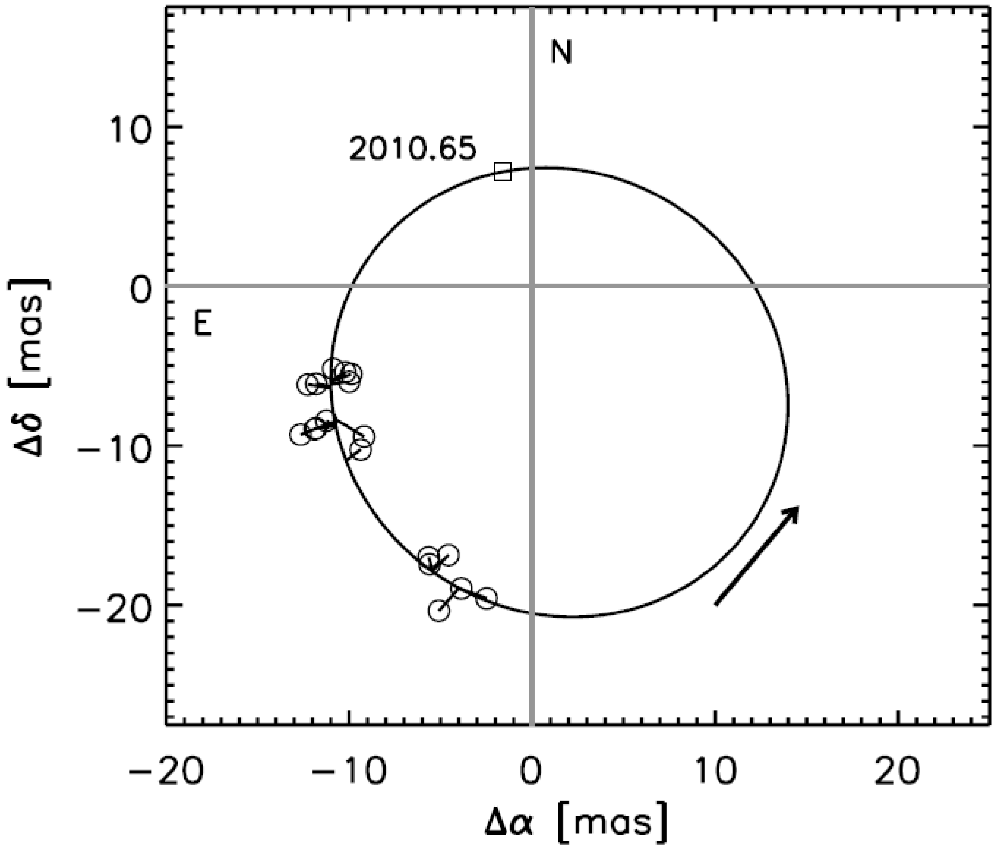

Fig. 3.— Perturbation orbit of HD 33636 on the sky (line). The open circles are the *HST* epoch normal points and are connected to the derived orbit by residual vectors. The *HST* data cover 20% of the orbit period. The orbital motion direction is indicated by the arrow. The square marks the location of periastron passage and the next time of occurrence is labeled.

By combining (ground-based) Doppler ‘wobble’ measurements with precision HST astrometric measurements of the position of the star on the sky, we can tell the difference between a highly inclined orbit and one which is lies along our line of sight to the star.

This lets us improve our mass determination for the planet….

…And sometimes lets us work out that it isn’t a planet at all!

accepted to AJ May 13, 2007

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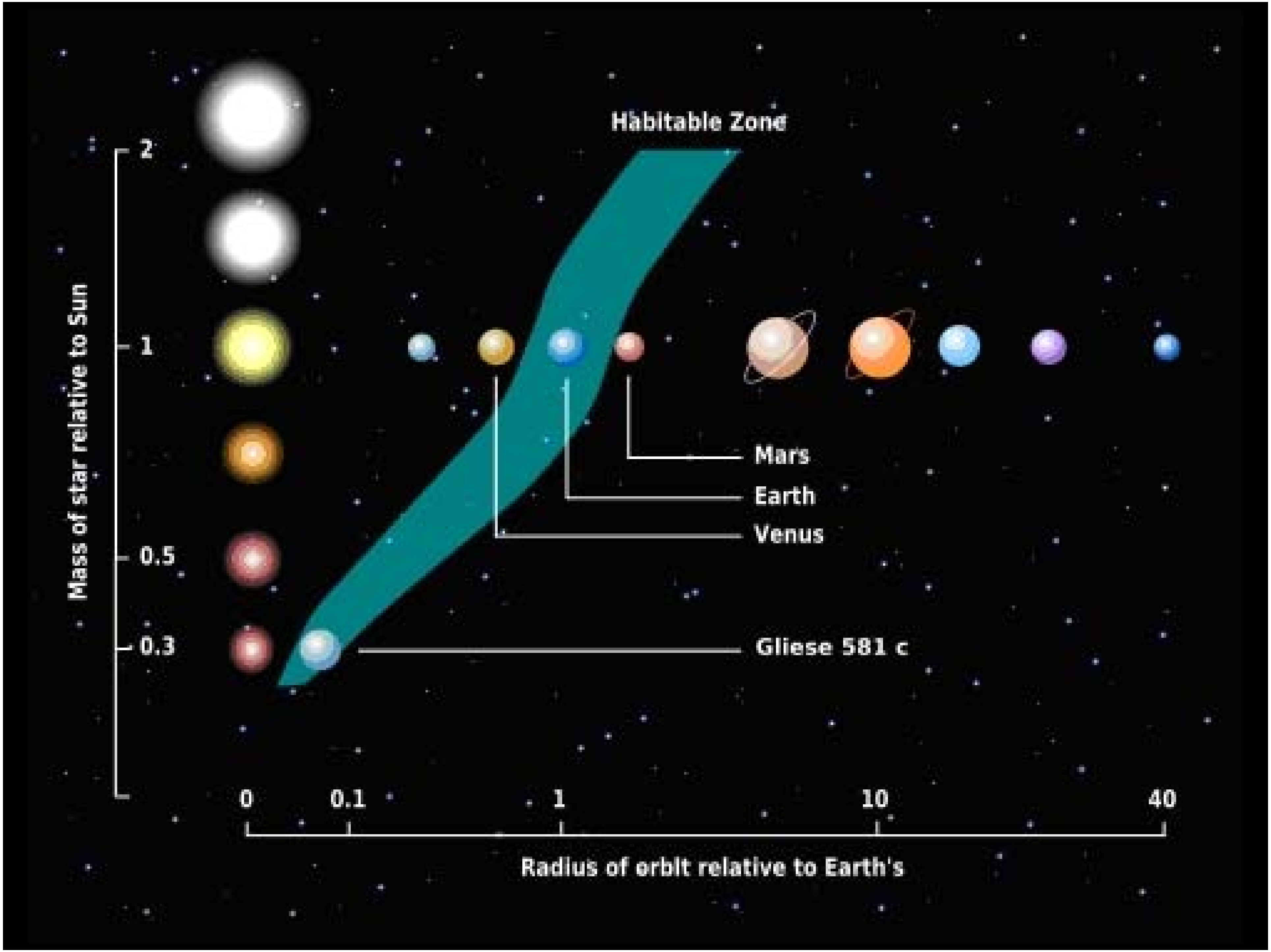
"It's life, Jim, but not as we know it…"

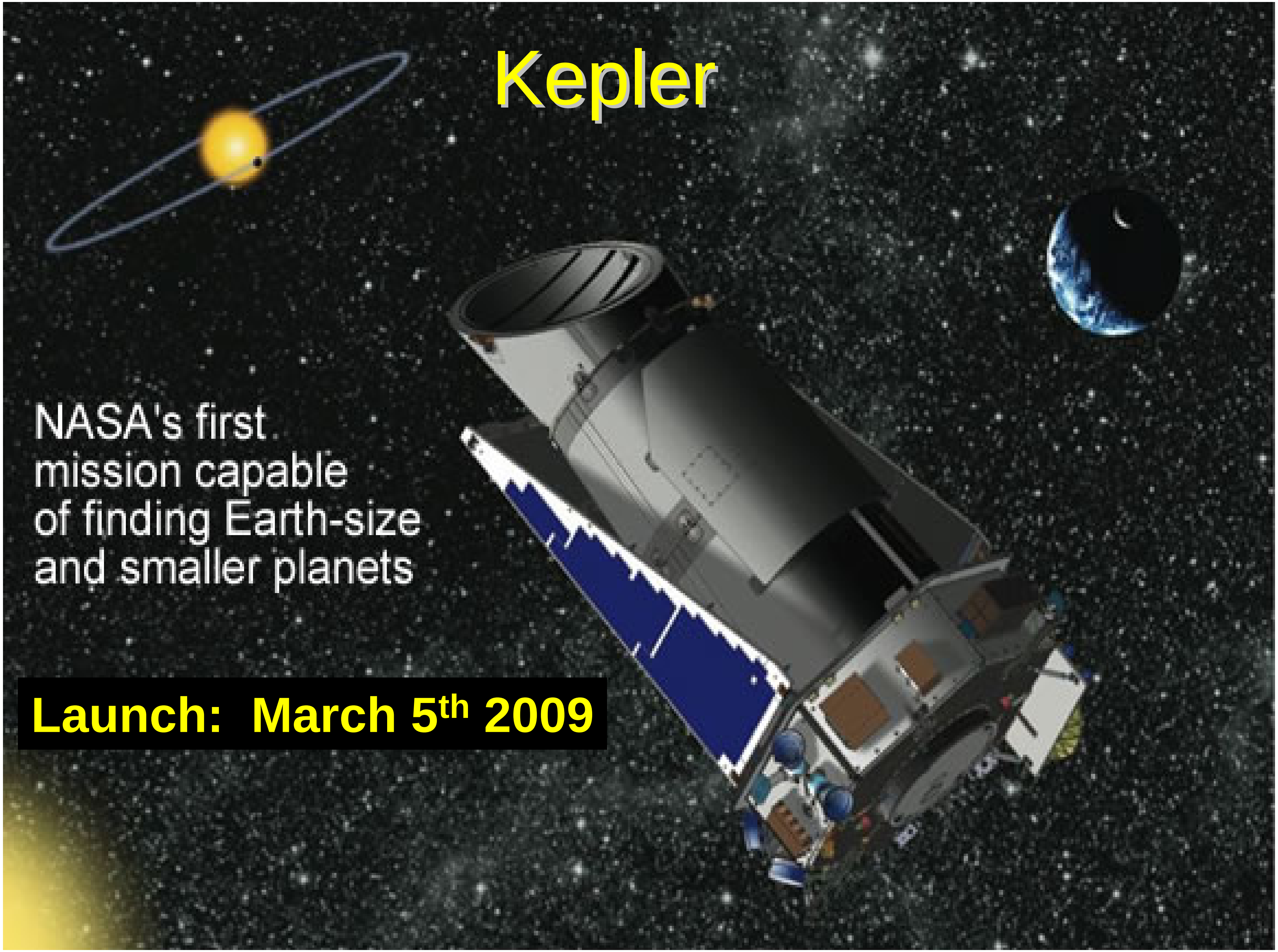
"It's life, Jim, and just as we know it…"

- Water
- Oxygen
- Carbon Dioxide



Habitable Zone
Mass of star relative to Sun
2
1
0.5
0.3
Mars
Earth
Venus
Gliese 581 c
0
0.1
1
10
40
Radius of orbit relative to Earth's

Kepler



Launch: March 5^{th} 2009

DETECTION OF OXYGEN AND CARBON IN THE HYDRODYNAMICALLY ESCAPING ATMOSPHERE OF THE EXTRASOLAR PLANET HD 209458B

A. Vidal-Madjar,[1] J.-M. Désert,[1] A. Lecavelier des Etangs,[1] G. Hébrard,[1] G. E. Ballester,[2] D. Ehrenreich,[1] R. Ferlet,[1] J. C. McConnell,[3] M. Mayor,[4] and C. D. Parkinson[5]

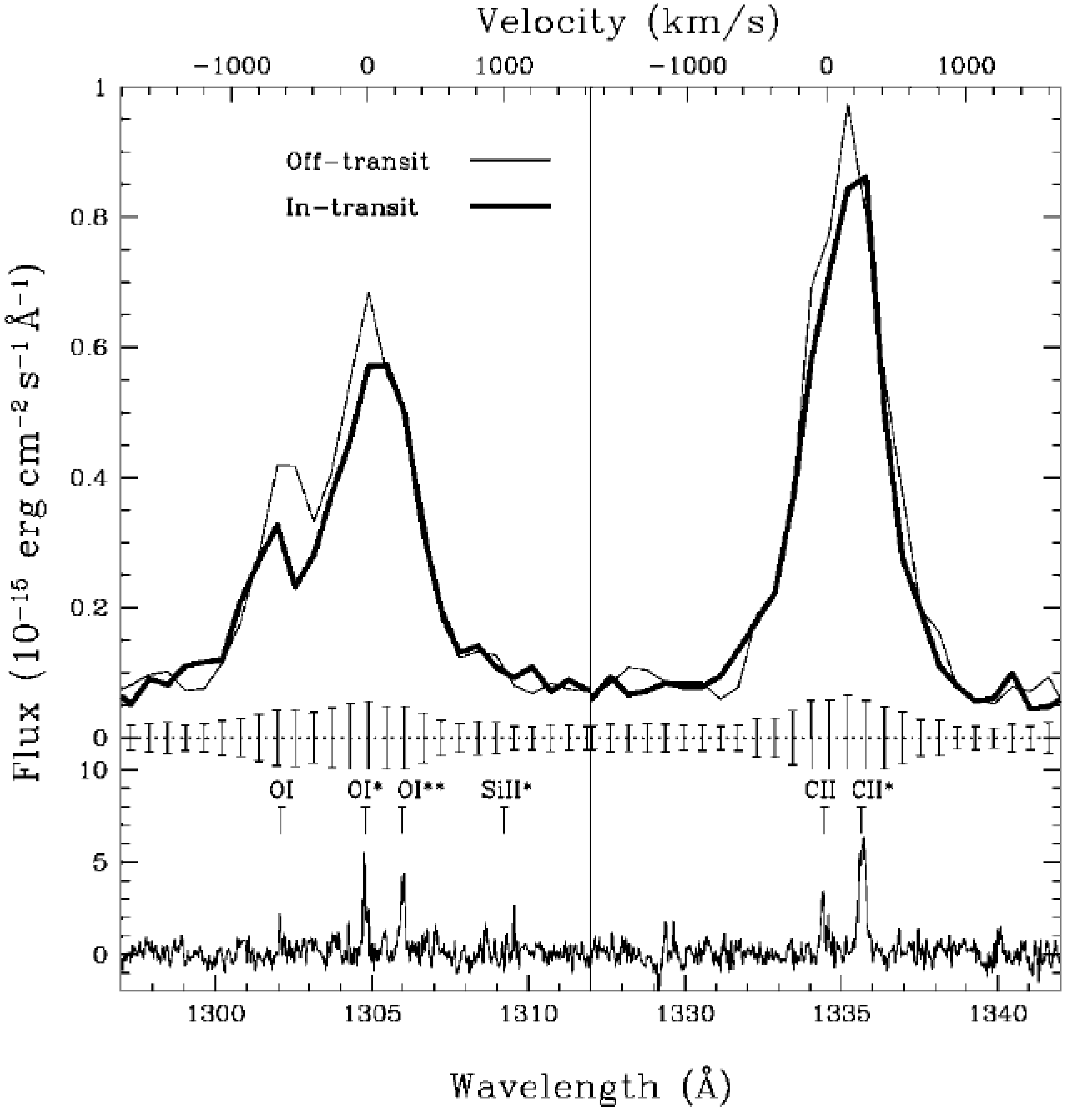
Received 2003 December 23; accepted 2004 February 4; published 2004 March 1

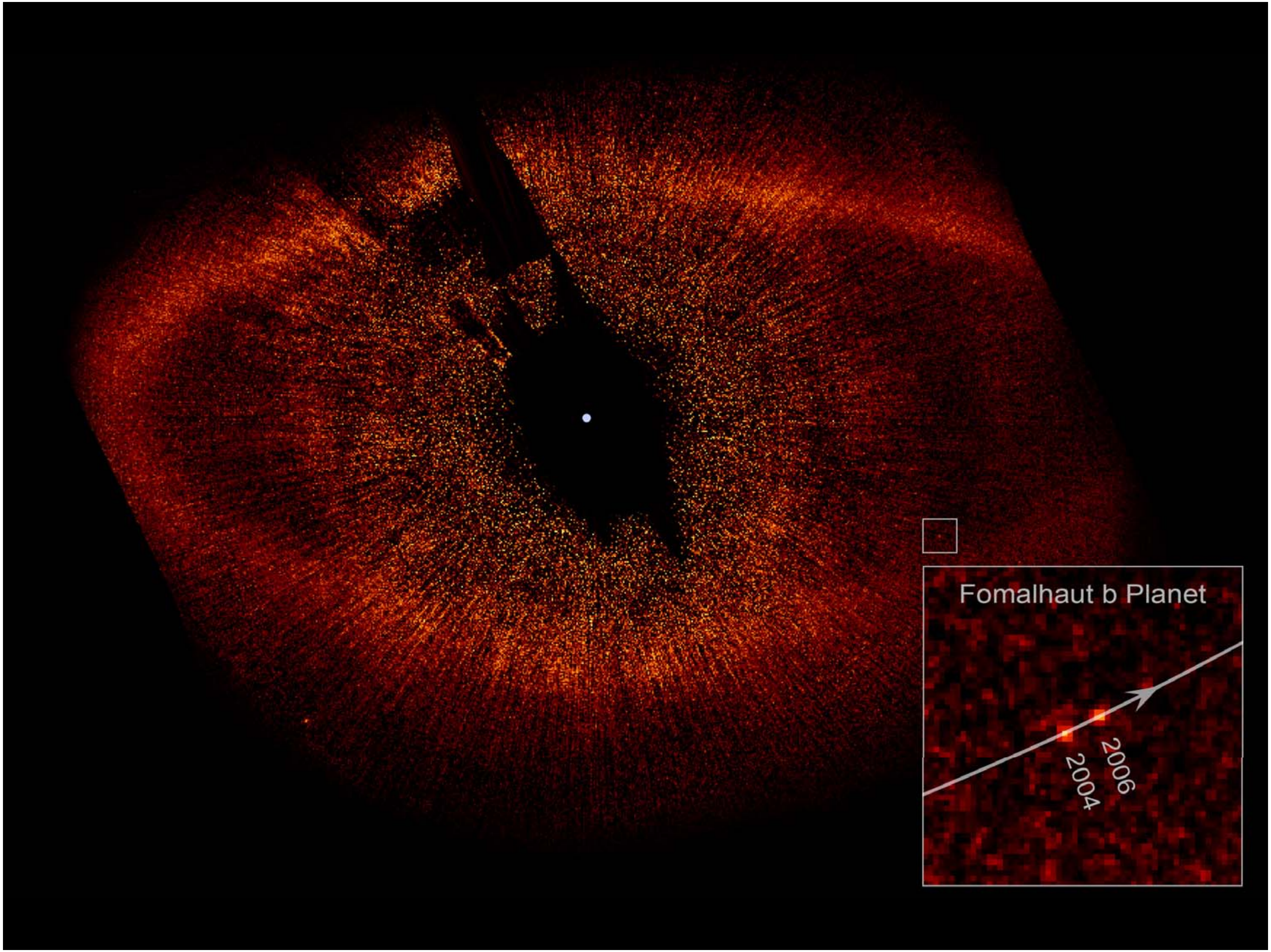
ABSTRACT

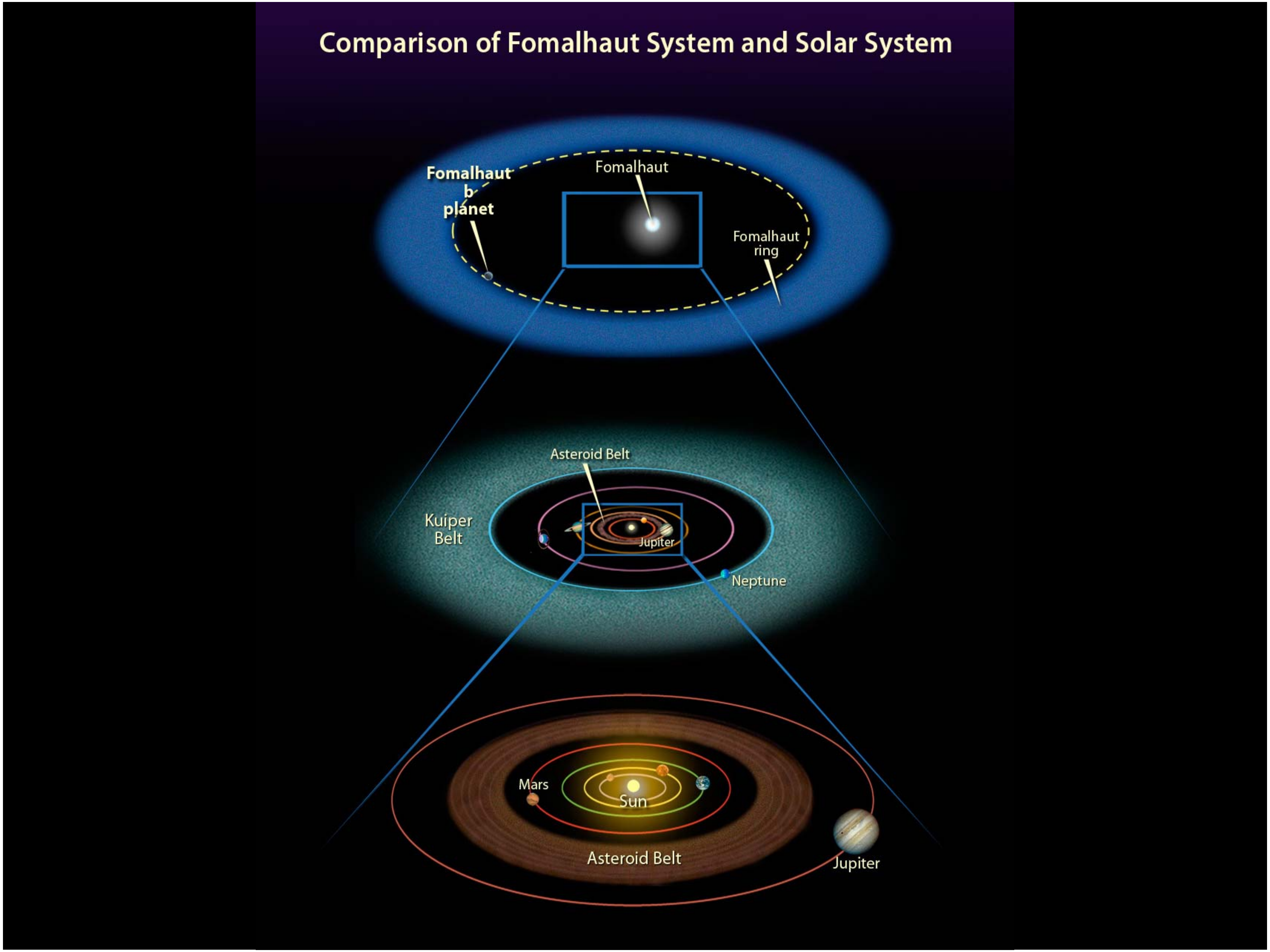
Four transits of the planet orbiting the star HD 209458 were observed with the Space Telescope Imaging Spectrograph on board the *Hubble Space Telescope*. The wavelength domain (1180–1710 Å) includes H I as well as C I, C II, C IV, N V, O I, S I, Si II, Si III, and Si IV lines. During the transits, absorptions are detected in H I, O I, and C II (5% ± 2%, 13% ± 4.5%, and 7.5% ± 3.5%, respectively). No absorptions are detected for other lines. The 5% mean absorption over the whole H I Lyα line is consistent with the previous detection completed in 2003 at higher resolution (Vidal-Madjar et al.). The absorption depths in O I and C II show that oxygen and carbon are present in the extended upper atmosphere of HD 209458b (nicknamed "Osiris"). These species must be carried out up to the Roche lobe and beyond, most likely in a state of hydrodynamic escape.

Subject headings: planetary systems — stars: individual (HD 209458)

On-line material: color figures

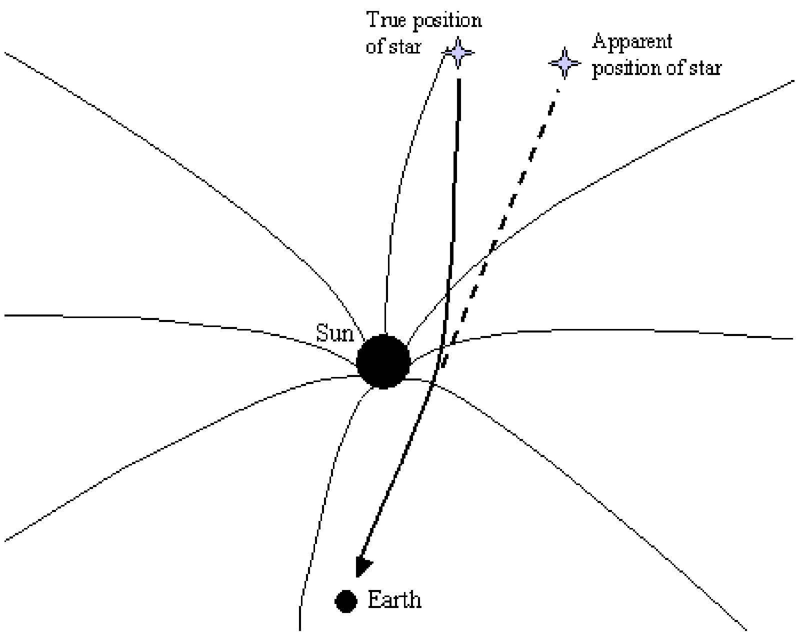



Fomalhaut b Planet
2004
2006

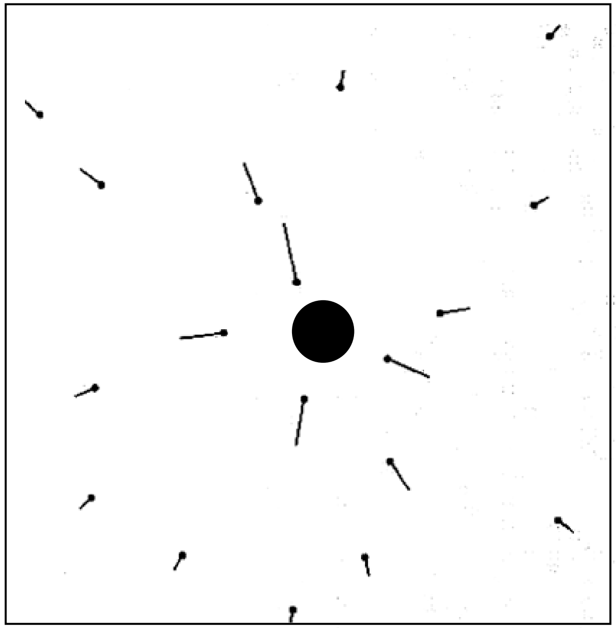

Comparison of Fomalhaut System and Solar System
Fomalhaut b planet
Fomalhaut
Fomalhaut ring
Asteroid Belt
Kuiper Belt
Jupiter
Neptune
Mars
Sun
Asteroid Belt
Jupiter

Another method for finding planets is gravitational lensing

The physics behind this method is based on Einstein's General Theory of Relativity, which predicts that gravity *bends* light, because gravity causes spacetime to be curved.



This was one of the first experiments to test GR: Arthur Eddington's 1919 observations of a total solar eclipse.



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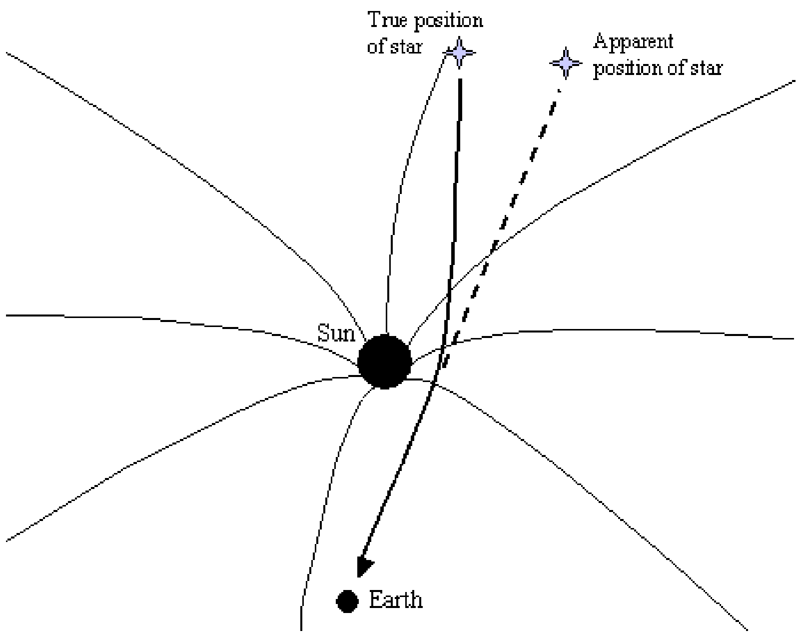

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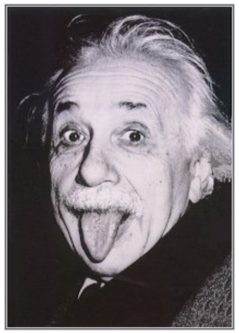
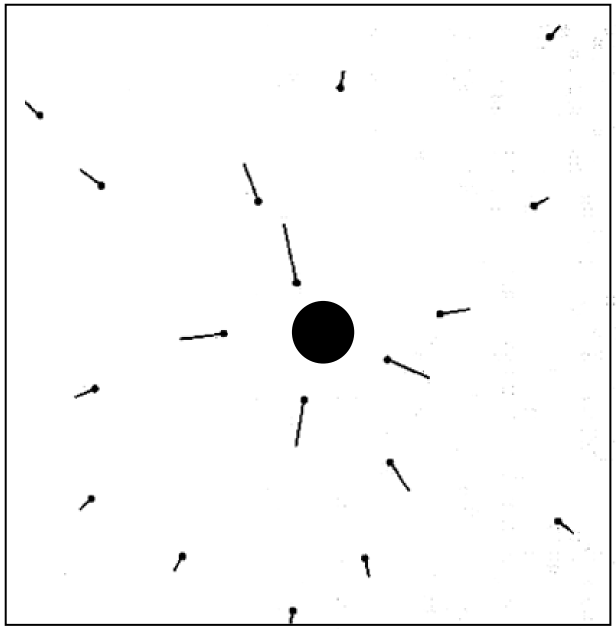
GR passed the test!



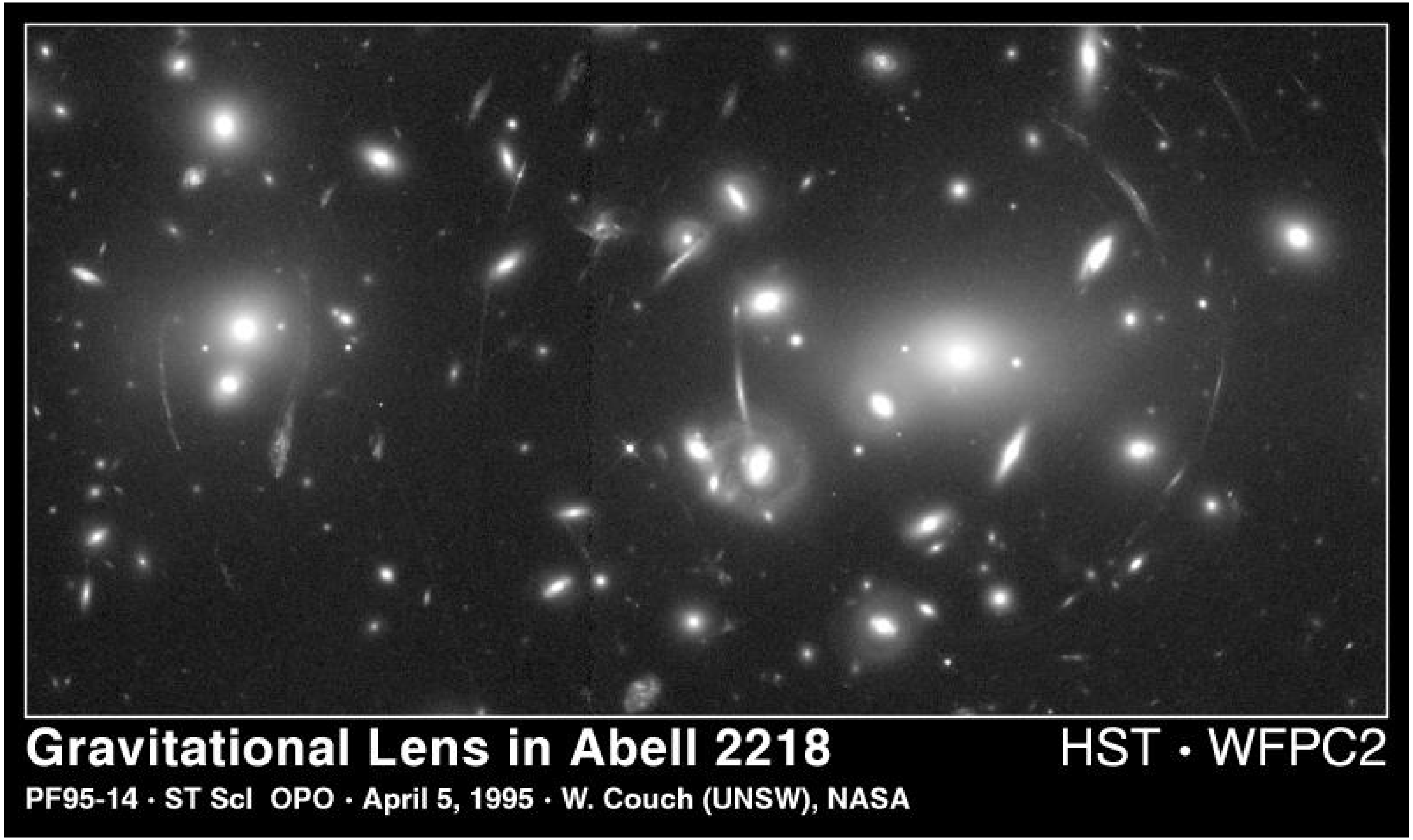


"He was one of the finest people I have ever known…but he didn't really understand physics because, during the eclipse of 1919 he stayed up all night to see if it would confirm the bending of light by the gravitational field. If he had really understood general relativity he would have gone to bed the way I did"

Einstein, on Max Planck

Another method for finding planets is gravitational lensing

If some massive object passes between us and a background light source, it can bend and focus the light from the source, producing multiple, distorted images.



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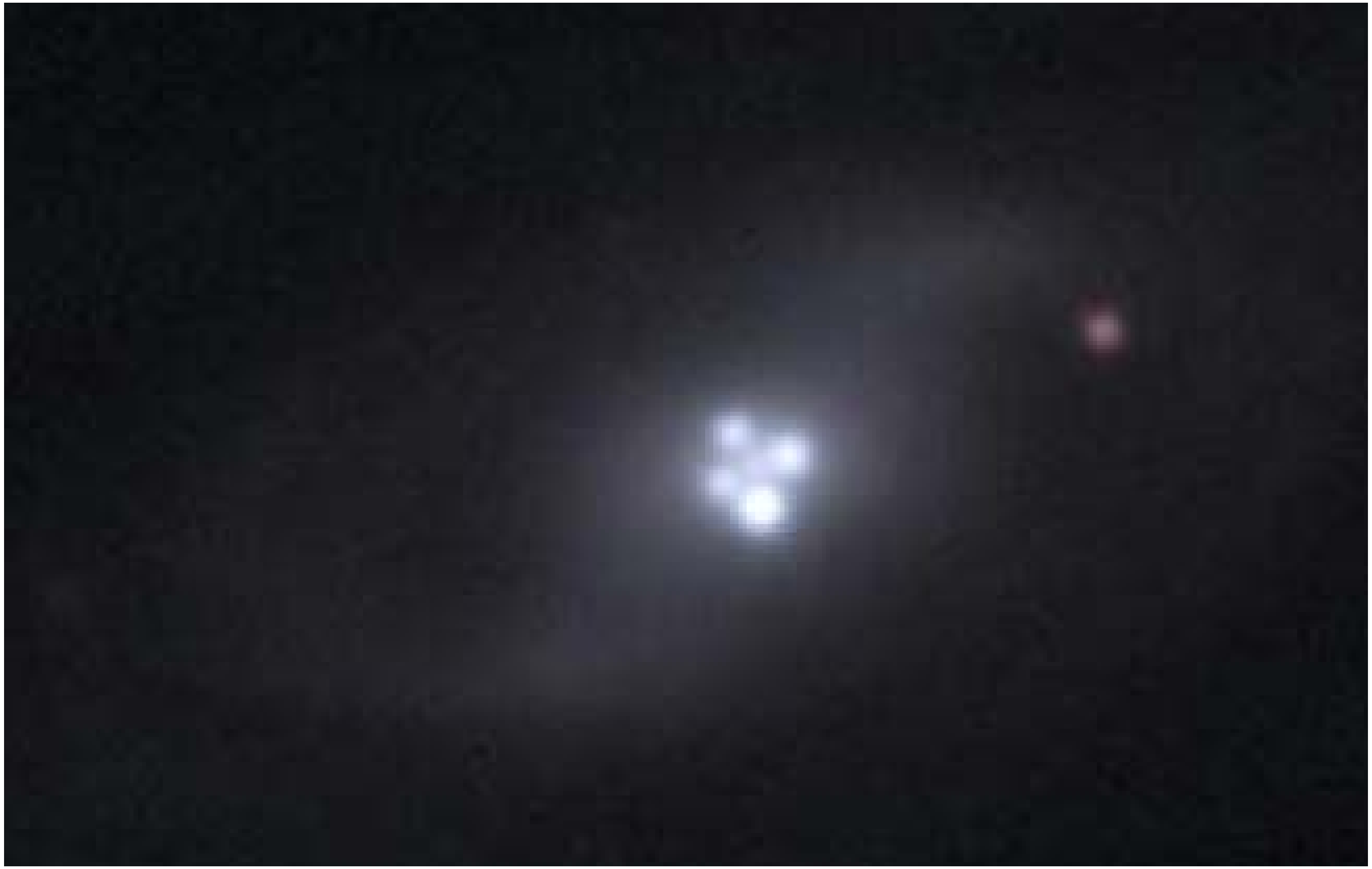

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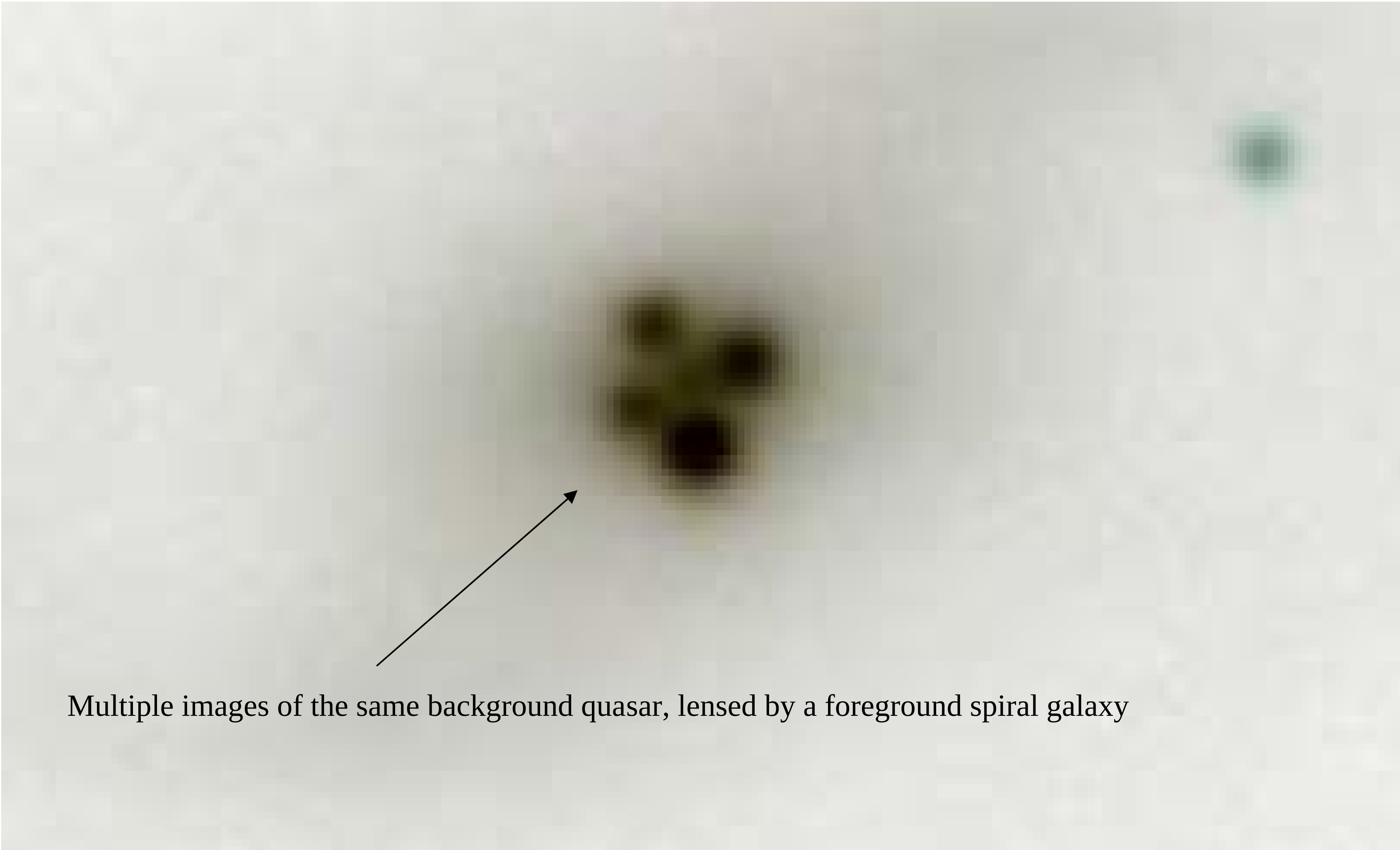
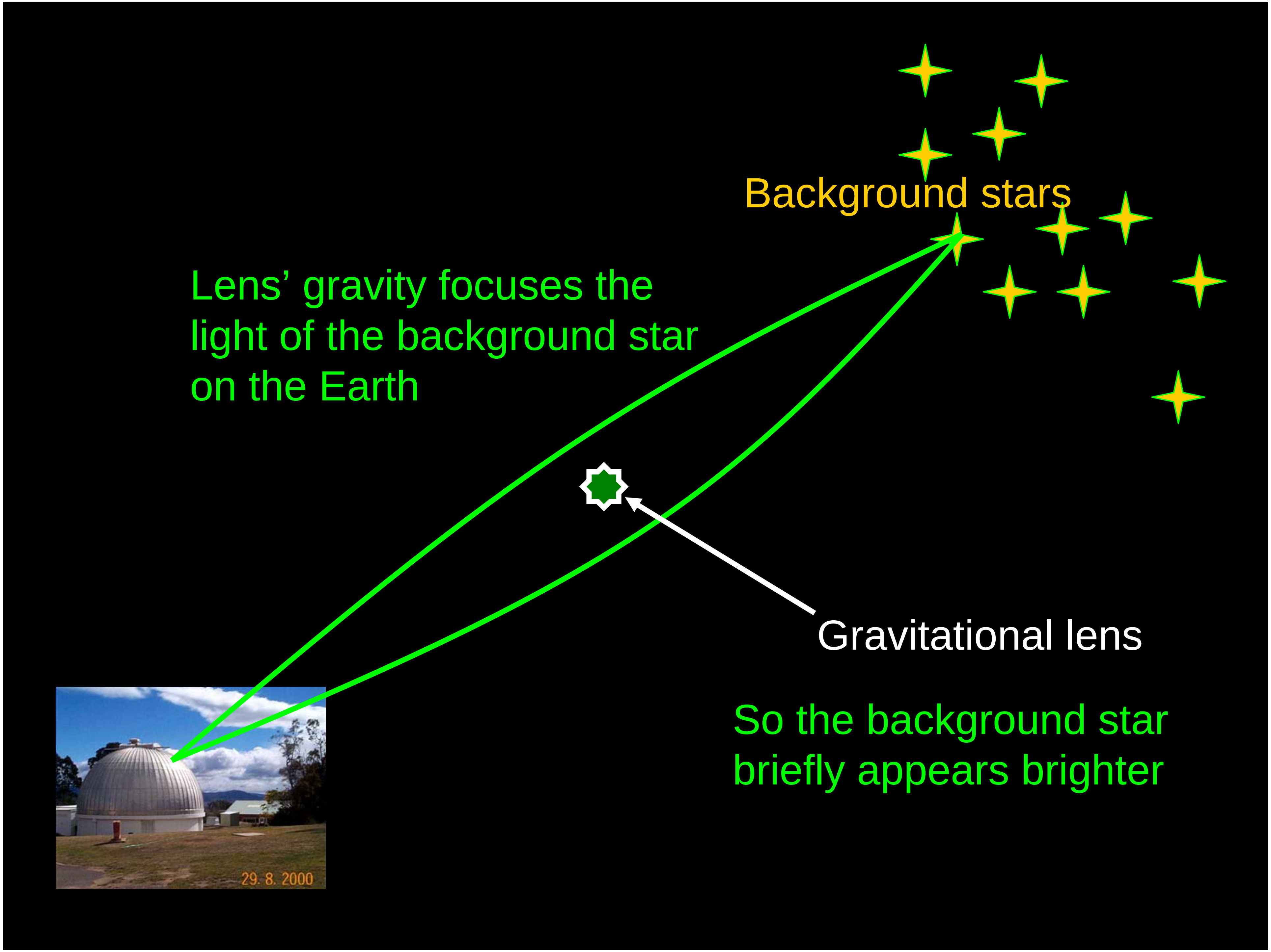


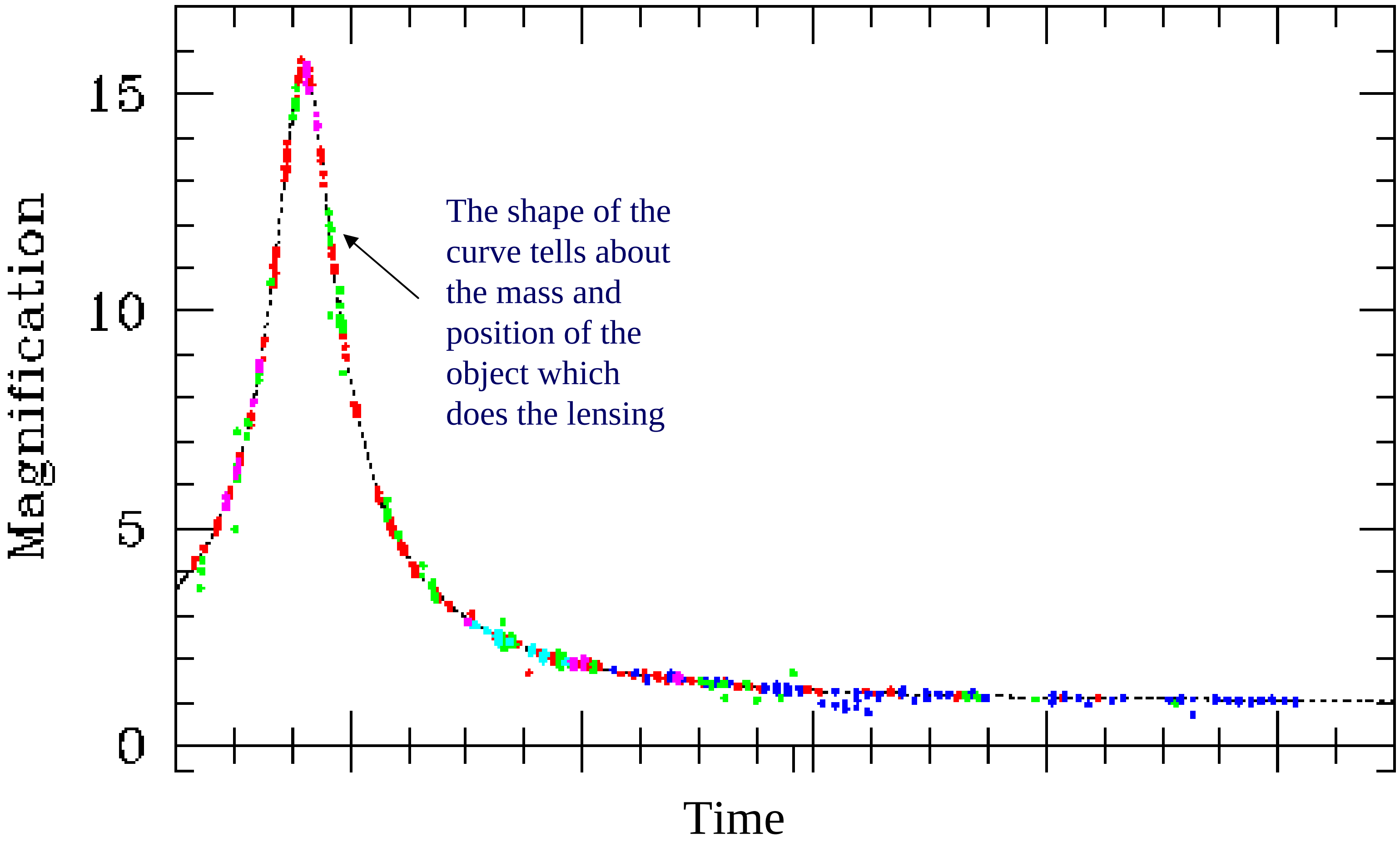
Multiple images of the same background quasar, lensed by a foreground spiral galaxy

Even if the multiple images are too close together to be resolved separately, they will still make the background source appear (temporarily) brighter.


Background stars
Lens' gravity focuses the
light of the background star
on the Earth
Gravitational lens
So the background star
briefly appears brighter
29. 8. 2000

Even if the multiple images are too close together to be resolved separately, they will still make the background source appear (temporarily) brighter.

We call this case **gravitational microlensing**. We can plot a light curve showing how the brightness of the background source changes with time.



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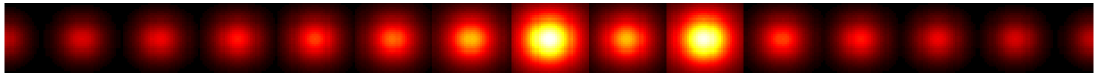
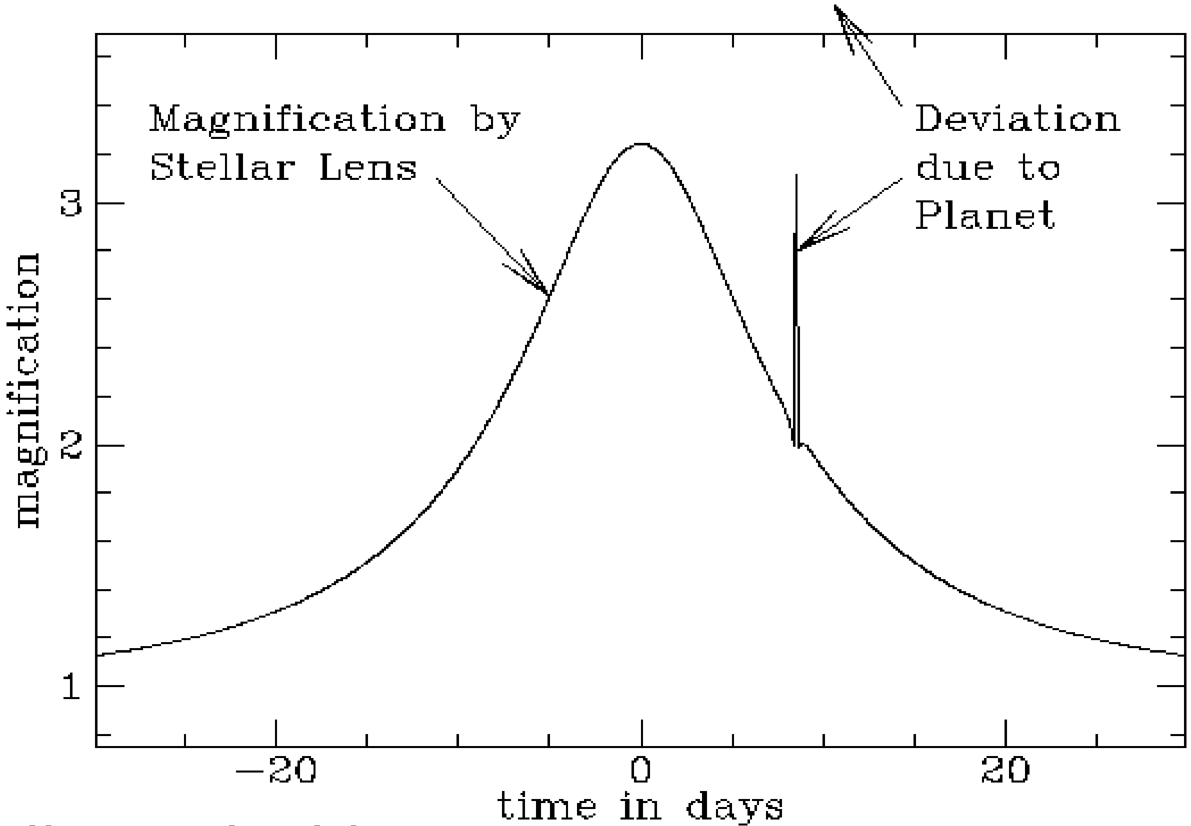


If the lensing star has a planet which *also* passes exactly between us and the background source, then the light curve will show a second peak.



Even low mass planets can produce a high peak (but for a short time, and we only observe it once...)

Could in principle detect Earth mass planets!

Looking to the Future

Gravitational microlensing satellite?   Launch date ????

Could detect mars-mass planets

The Microlensing Planet Finder:

Completing the Census of Extrasolar Planets in the Milky Way

D. P. Bennett[a], I. Bond[b], E. Cheng[c], S. Friedman[d], P. Garnavich[a], B. Gaudi[e], R. Gilliland[d], A. Gould[f], M. Greenhouse[g], K. Griest[h], R. Kimble[g], J. Lunine[i], J. Mather[g], D. Minniti[j], M. Niedner[g], B. Paczynski[k], S. Peale[l], B. Rauscher[g], M. Rich[m], K. Sahu[d], D. Tenerelli[n], A. Udalski[o], N. Woolf[i], and P. Yock[p]

[a] University of Notre Dame, Notre Dame, IN, USA
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[c] Conceptual Analytics, LLC, Glen Dale, MD, USA
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[h] University of California, San Diego, CA, USA
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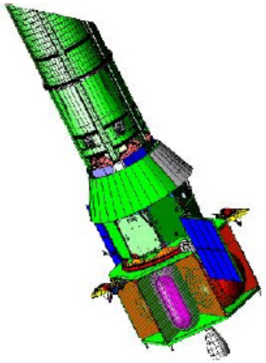
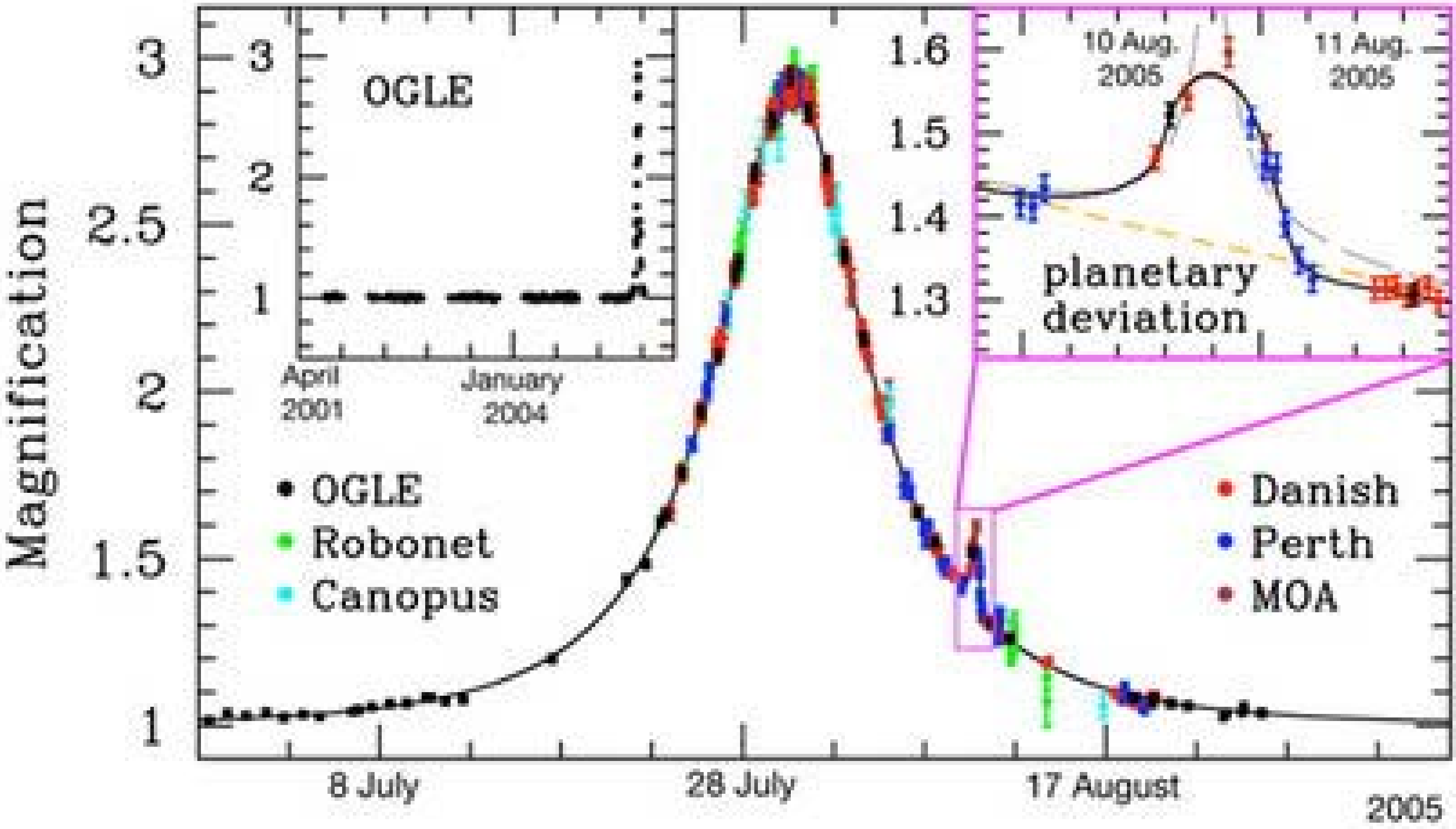
[k] Princeton University, Princeton, NJ, USA
[l] University of California, Santa Barbara, CA, USA
[m] University of California, Los Angeles, CA, USA
[n] Lockheed Martin Space Systems Company, Sunnyvale, CA, USA
[o] Warsaw University, Warsaw, Poland
[p] University of Auckland, Auckland, New Zealand



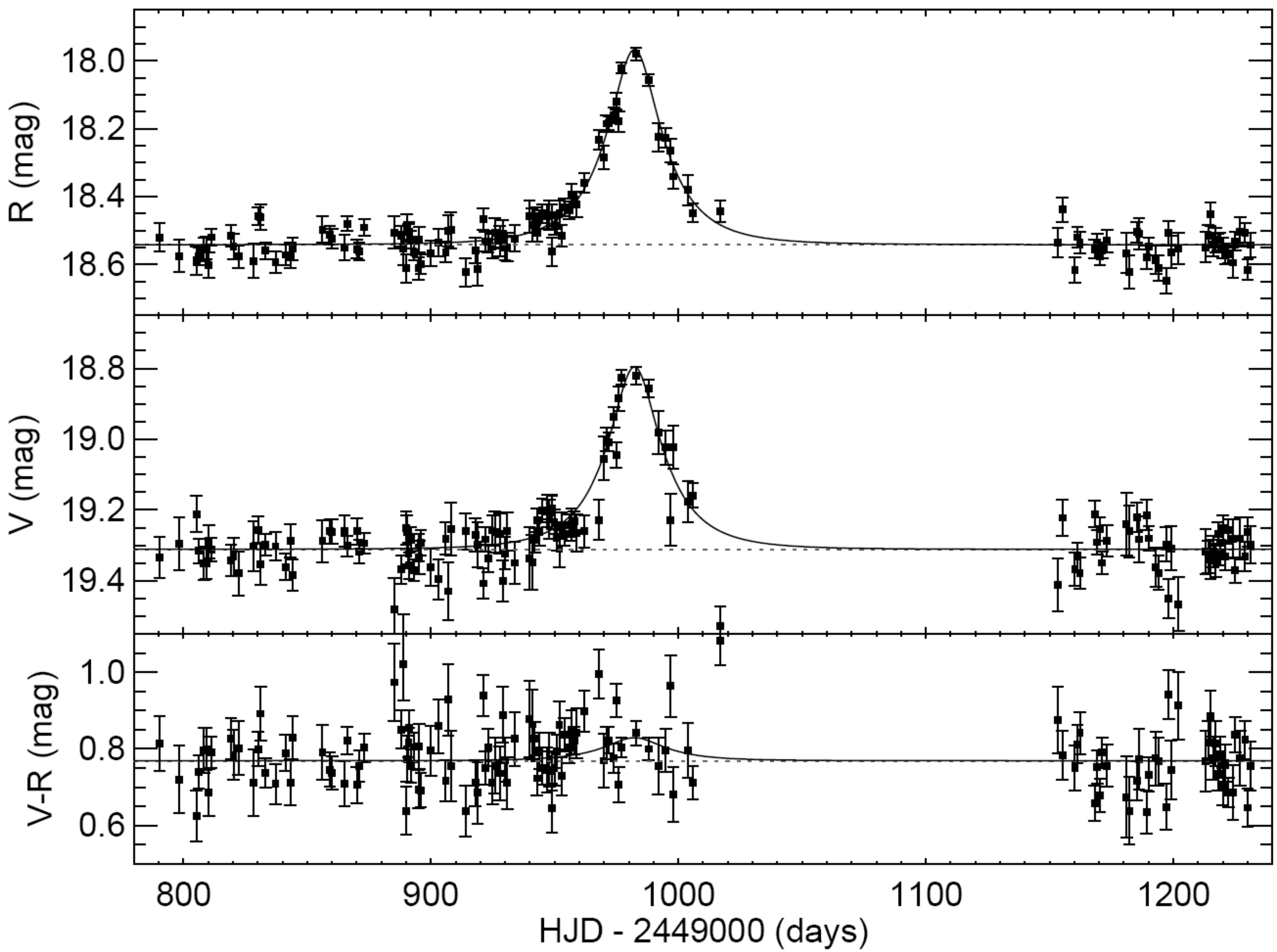
Jan 2006: ground-based detection of a 5 Earth-mass planet via microlensing



Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

MACHO-95-BLG-37



THE FIRST DIRECT DETECTION OF A GRAVITATIONAL μ-LENS TOWARD THE GALACTIC BULGE[1]

S. Kozłowski[2], P.R. Woźniak[3], S. Mao[2] & A. Wood[2]

Draft version August 31, 2007

ABSTRACT

We present a direct detection of the gravitational lens that caused the microlensing event MACHO-95-BLG-37. This is the first fully resolved microlensing system involving a source in the Galactic bulge, and the second such system in general. The lens and source are clearly resolved in images taken with the High Resolution Channel of the Advanced Camera for Surveys on board the *Hubble Space Telescope (HST)* ~ 9 years after the microlensing event. The presently available data are not sufficient for the final, unambiguous identification of the gravitational lens and the microlensed source. While the light curve models combined with the high resolution photometry for individual objects indicate that the source is red and the lens is blue, the color-magnitude diagram for the line of sight and the observed proper motions strongly support the opposite case. The first scenario points to a metal-poor lens with mass $M \approx 0.6 M_{\odot}$ at the distance $D_{l} \approx 4$ kpc. In the second scenario the lens could be a main-sequence star with $M = 0.8$–$0.9 M_{\odot}$ about half-way to the Galactic bulge or in the foreground disk, depending on the extinction.