Other planetary systems

Exoplanets are faint!

Planets are seen only by reflected light at optical wavelengths

At the distance of another star the faint light of a planet is lost in the glare of the star

Even in the infrared, where a Sun-like star puts out less light and a planet glows by its own thermal (blackbody) emission, it's not possible to get an image of an Earth or even a Jupiter

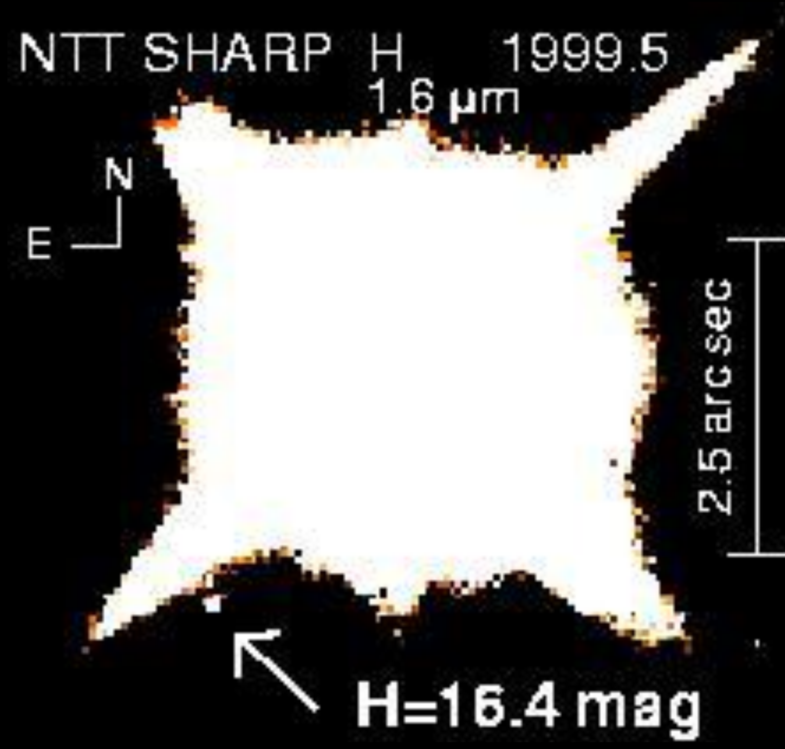

image of a binary star with a faint companion barely visible even in IR

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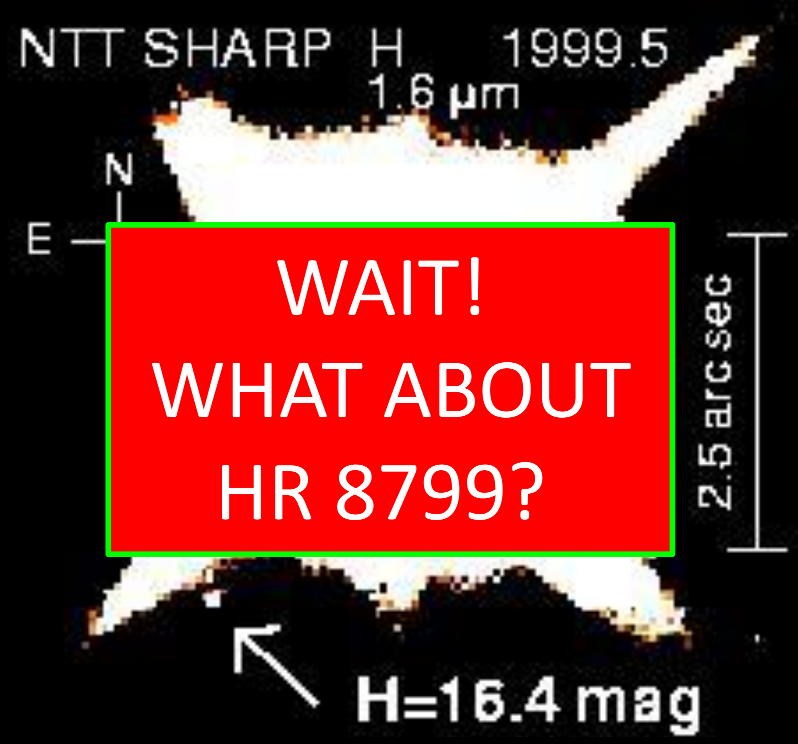

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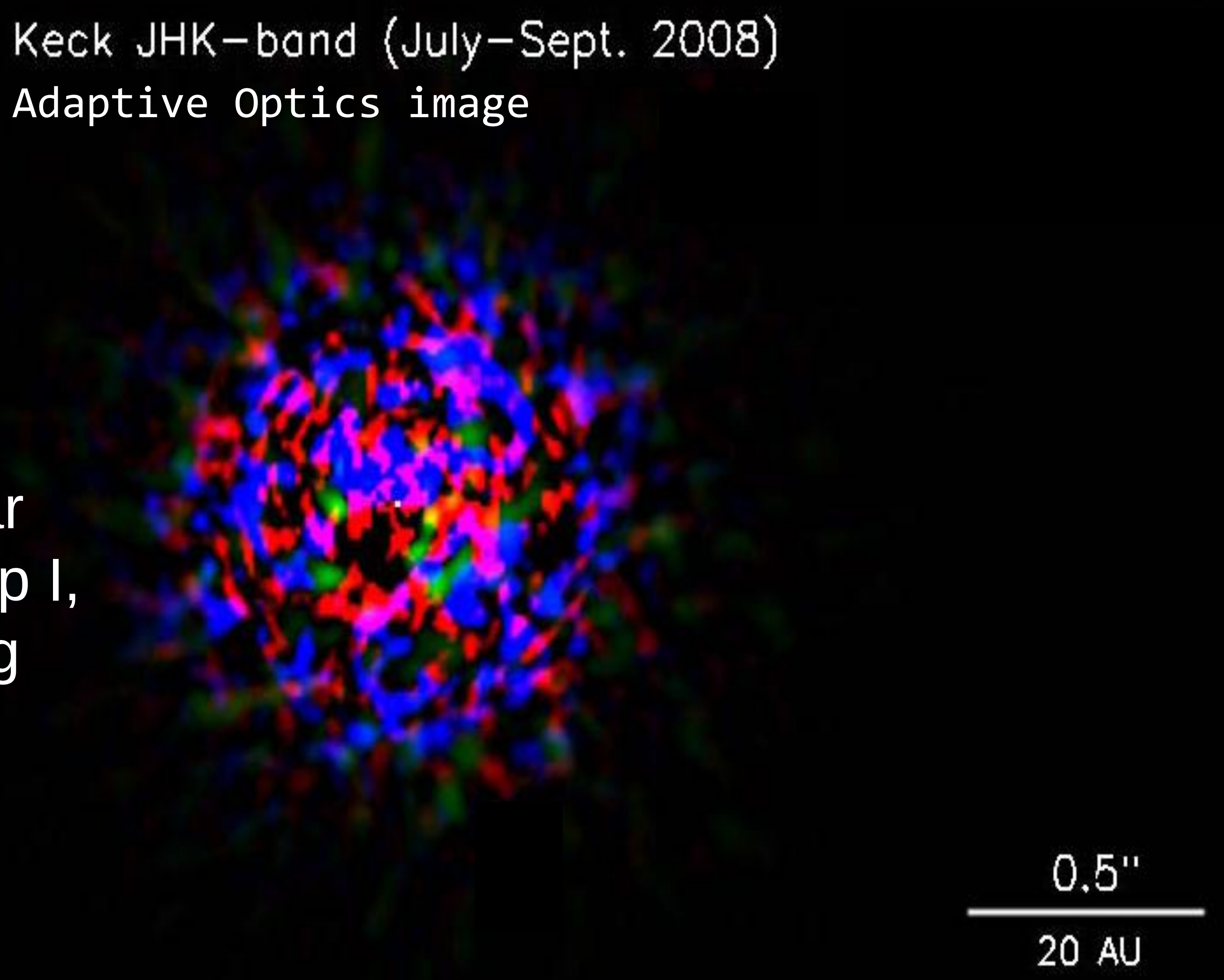
HR 8799



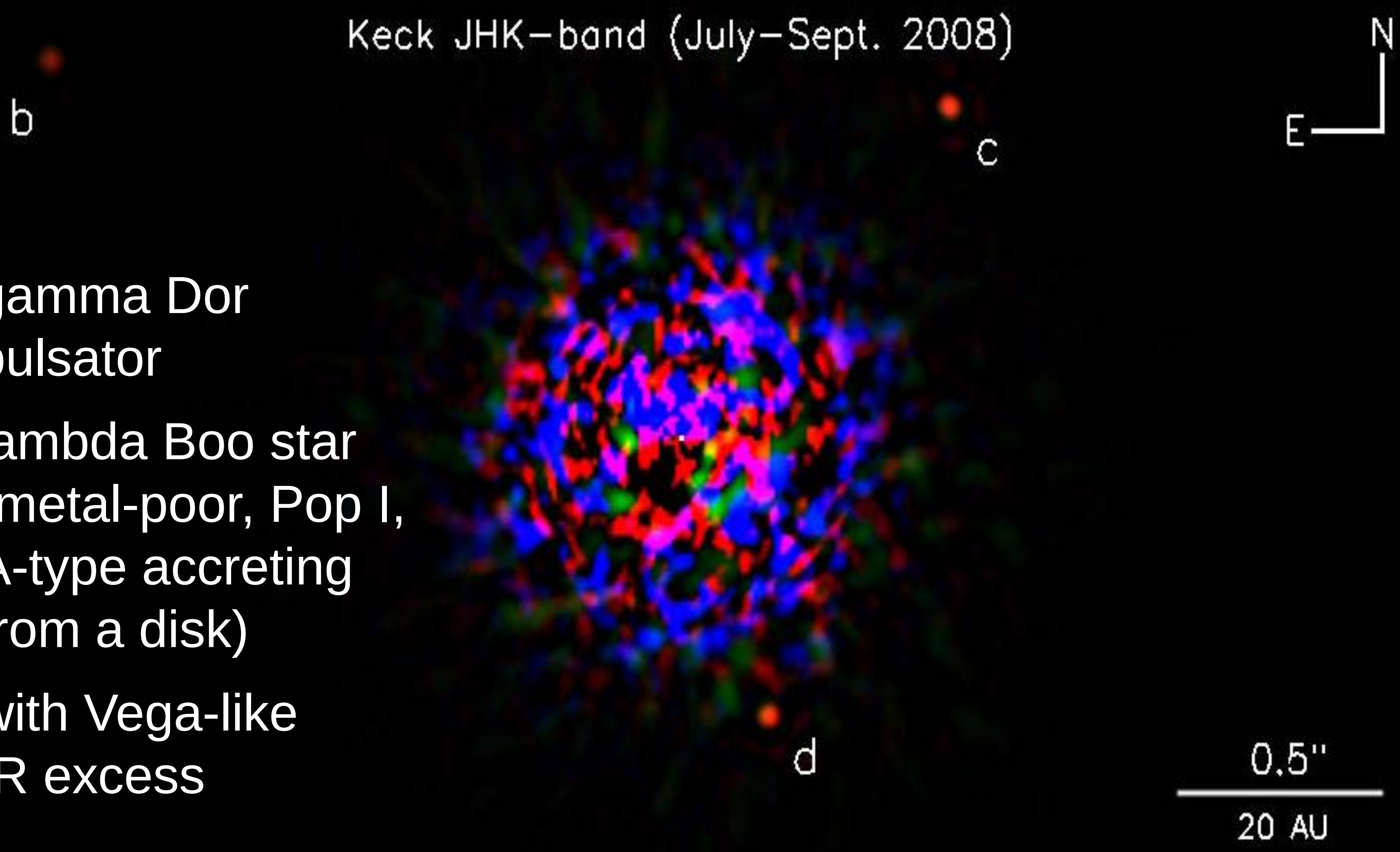
gamma Dor
pulsator

lambda Boo star
(metal-poor, Pop I,
A-type accreting
from a disk)

with Vega-like
IR excess

Marois et al. 2008 *Science* 322, 1348

HR 8799



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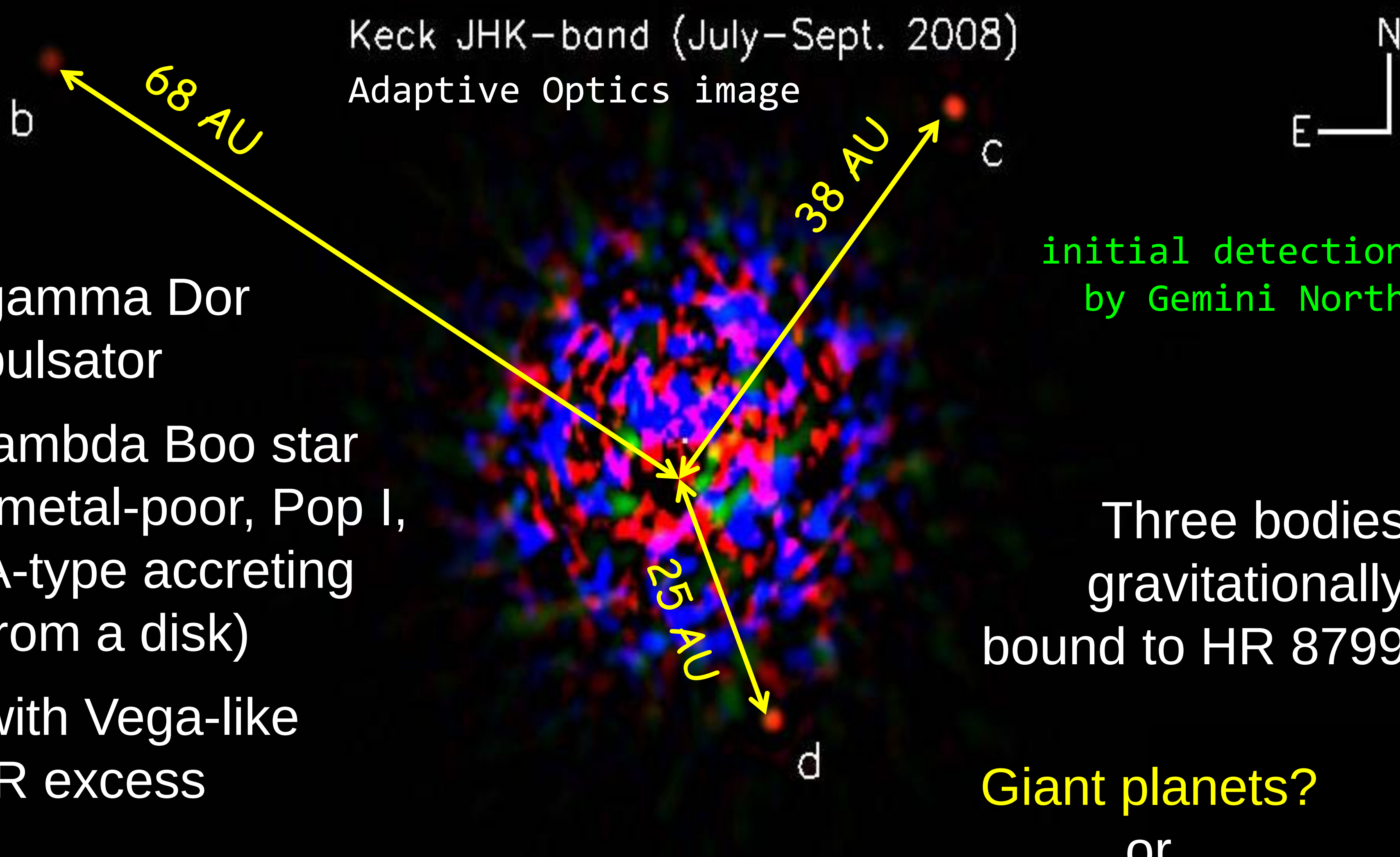


initial detection
by Gemini North

gamma Dor
pulsator

lambda Boo star
(metal-poor, Pop I,
A-type accreting
from a disk)

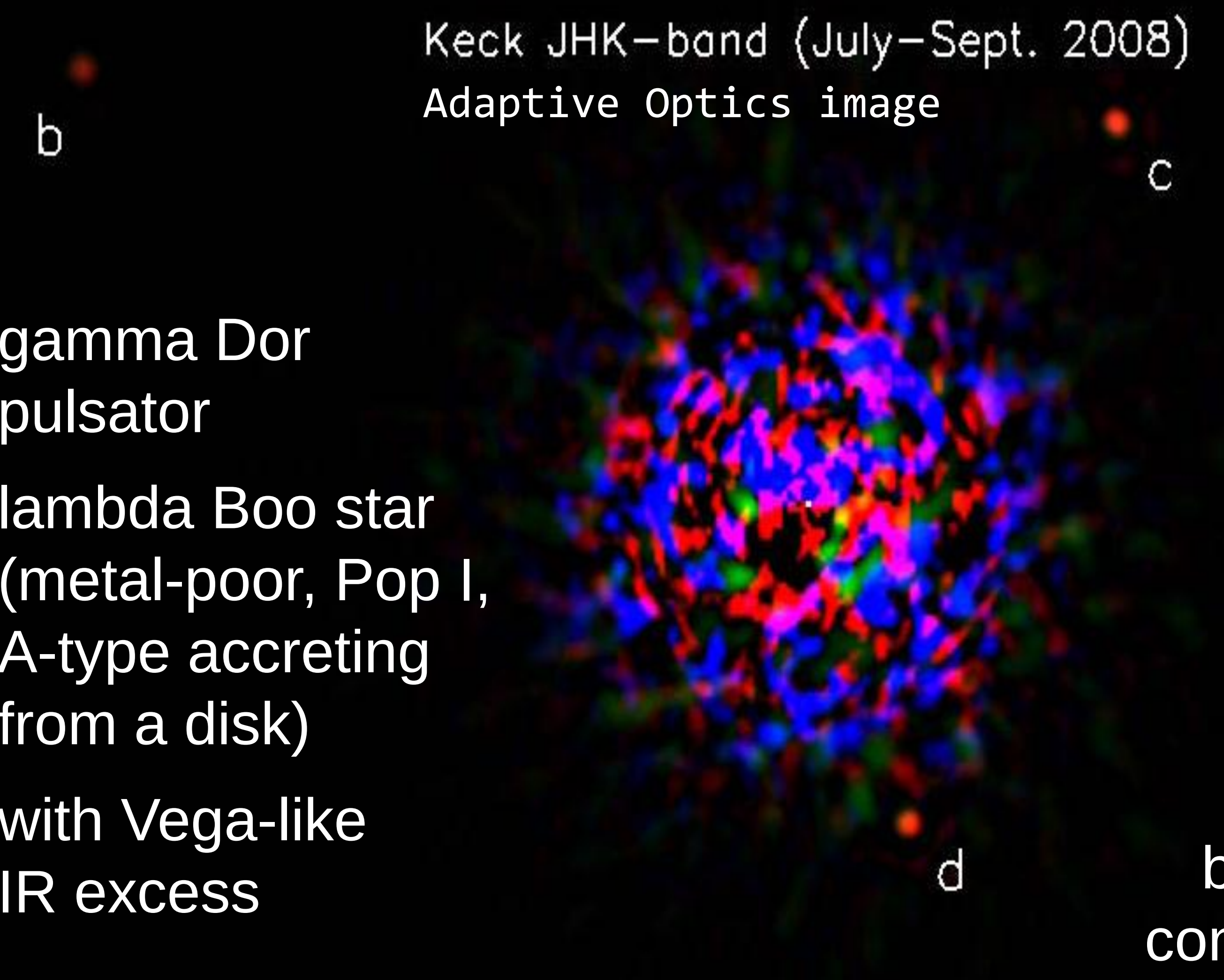
with Vega-like
IR excess

Three bodies
gravitationally
bound to HR 8799

Giant planets?
or
Brown dwarfs?

Marois et al. 2008 *Science* 322, 1348

HR 8799



gamma Dor pulsator

lambda Boo star (metal-poor, Pop I, A-type accreting from a disk)

with Vega-like IR excess

If the star is older than about 300 Myr companions would be brown dwarfs *not* planets

based on IR flux contrast fits to star

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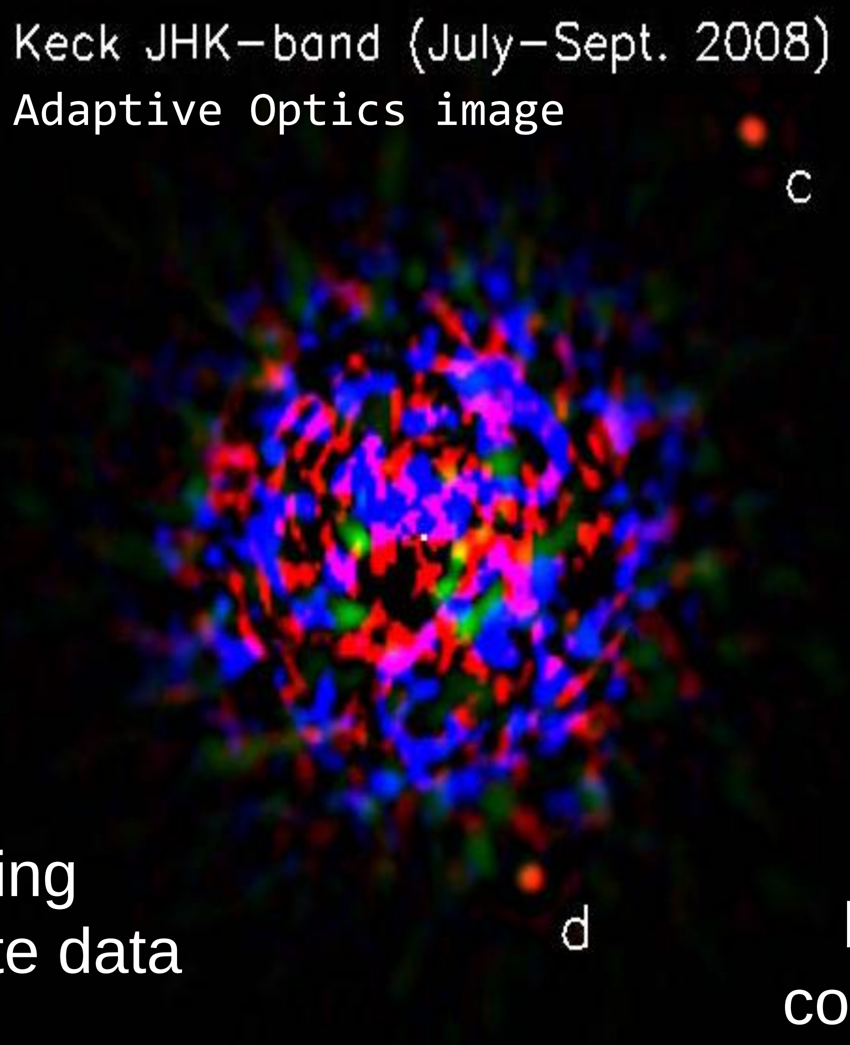

gamma Dor pulsator

4 frequencies (2 to 0.24 c/d) consistent with g-modes

but strong aliasing even in multi-site data

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Zerbi et al. 1999 *MNRAS* 303, 275

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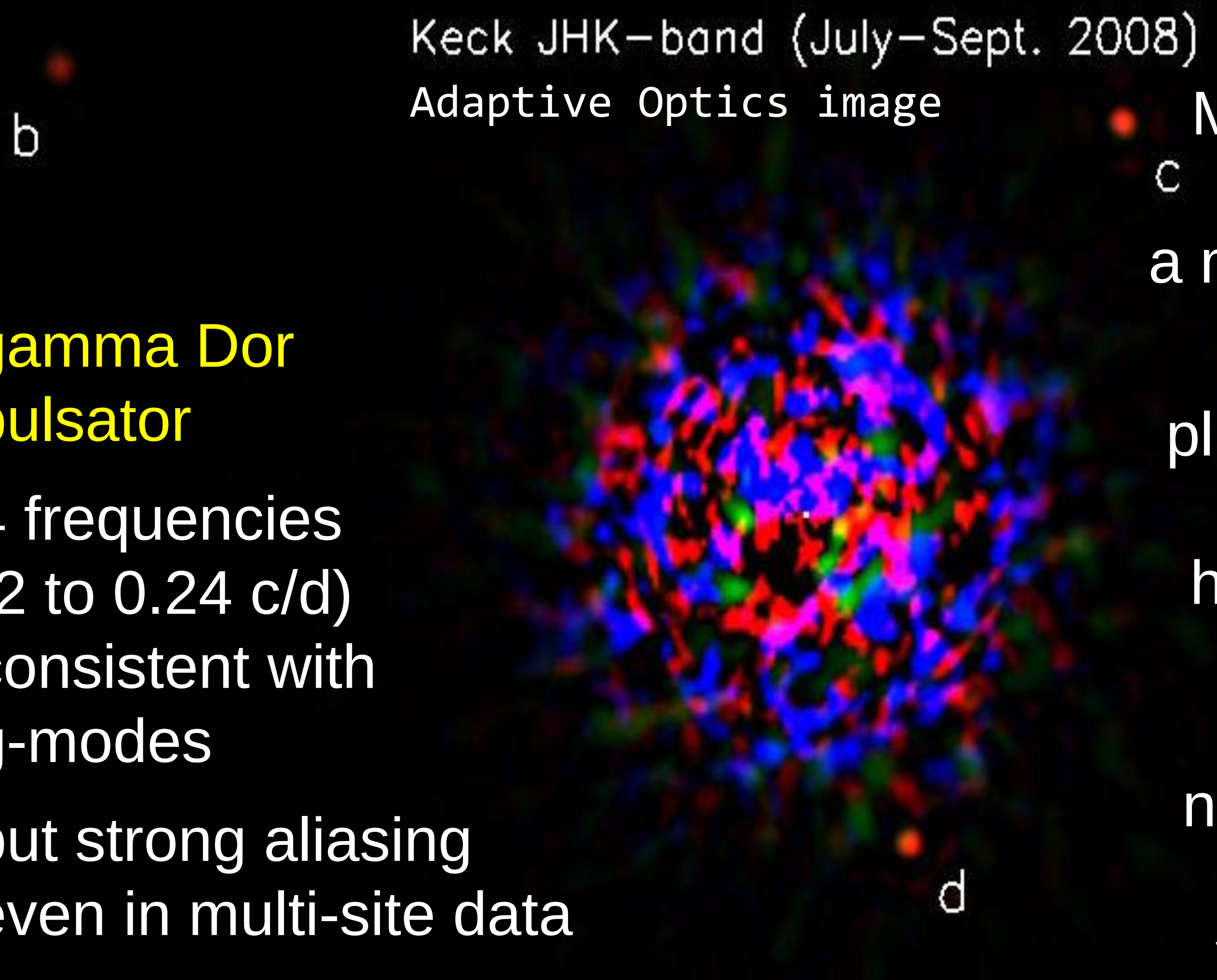

gamma Dor pulsator

4 frequencies (2 to 0.24 c/d) consistent with g-modes

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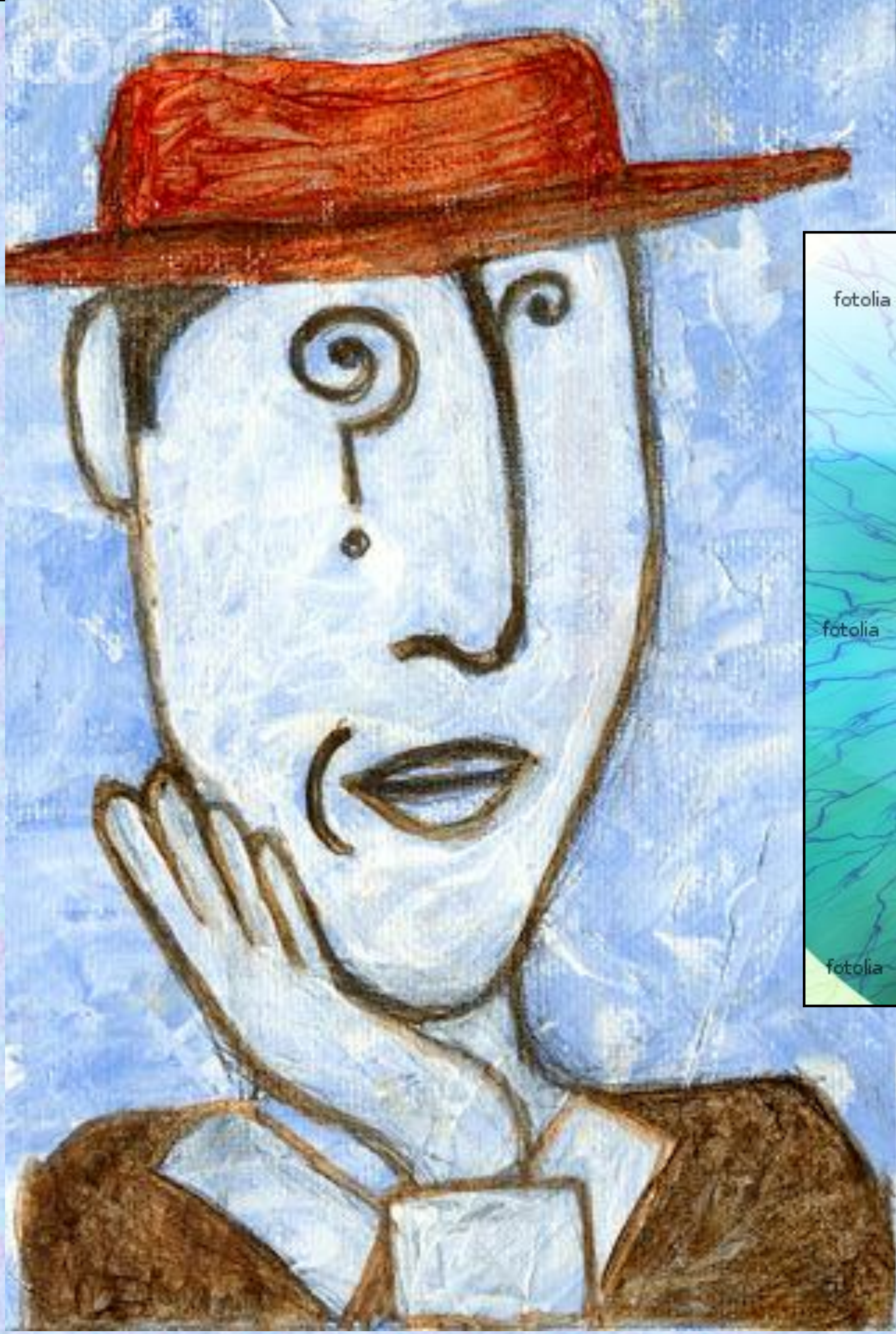
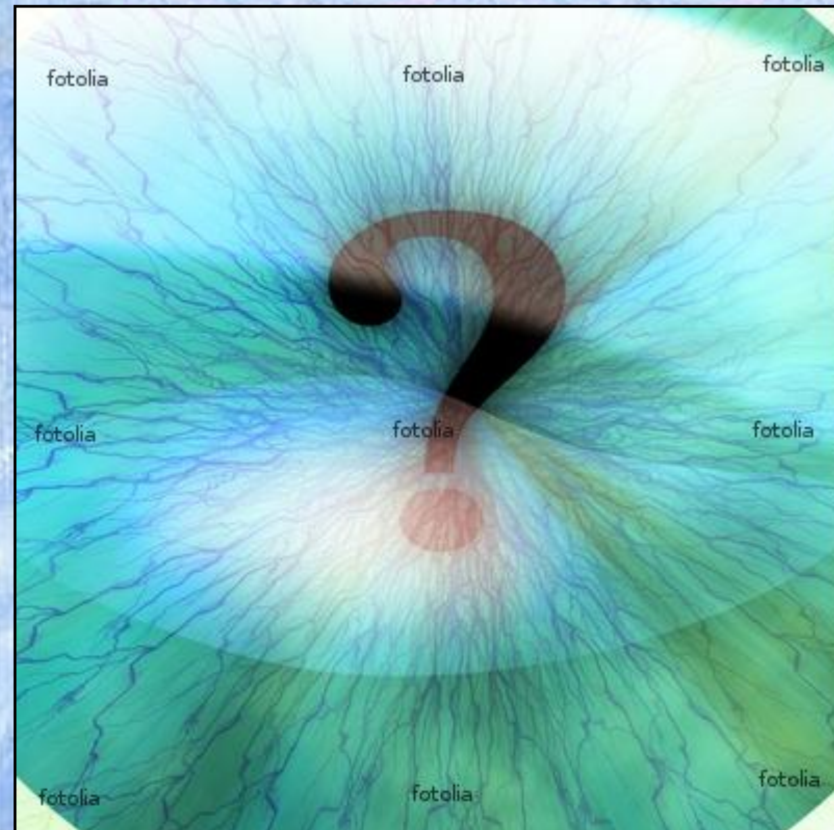
Marois, Walker, Matthews et al.

MOST monitored HR 8799 for a month and a half last summer

plus simultaneous high-resolution high-S/N HARPS spectroscopy to help identify non-radial modes

seismic analysis to place constraints on age of system




fotolia

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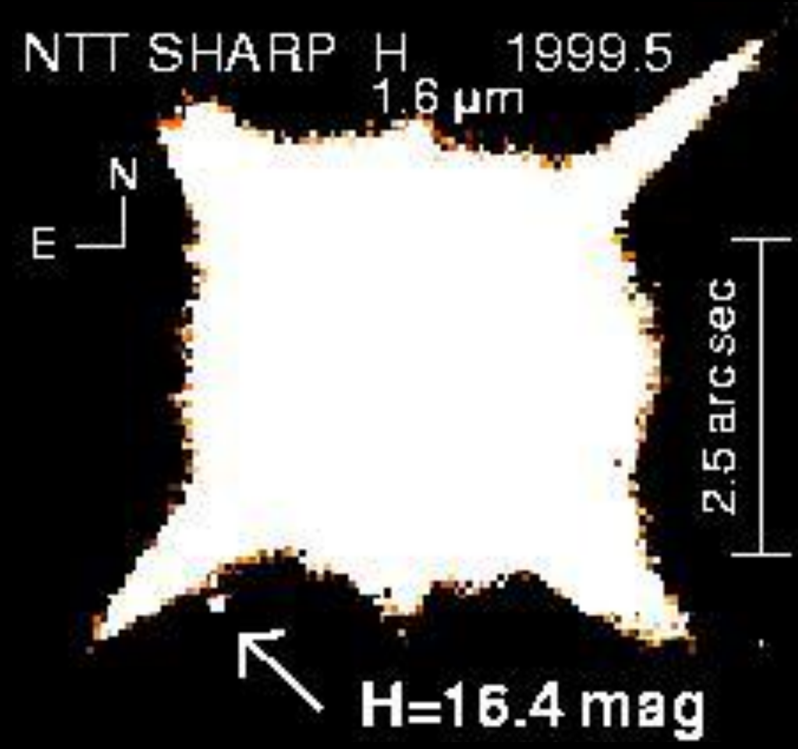


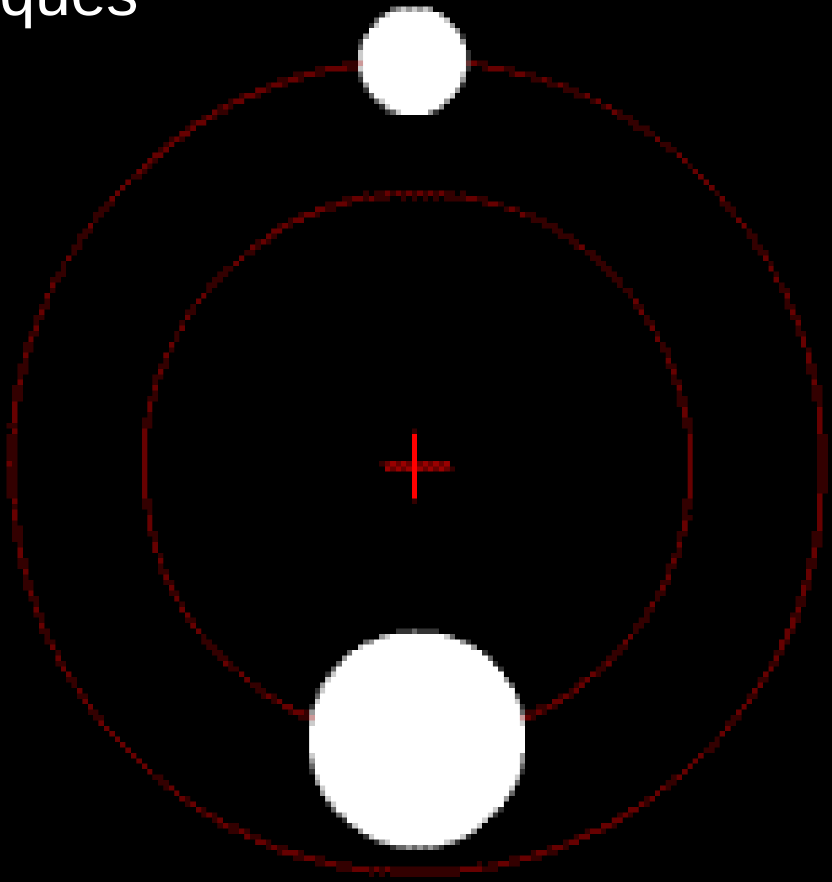
image of a binary star with a faint companion barely visible even in IR

Other planetary systems

Searching for exoplanets

We must rely on indirect techniques

A star and planet orbit around a common *centre of mass* which is much closer to the centre of the star because it is much more massive



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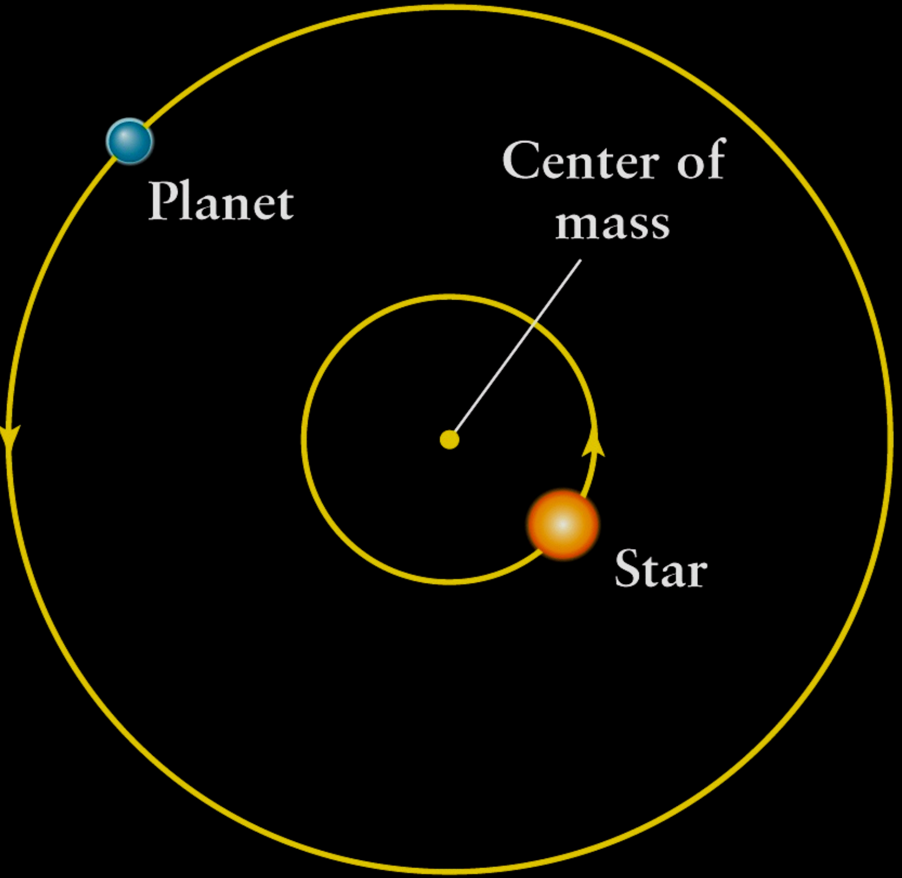

Other planetary systems

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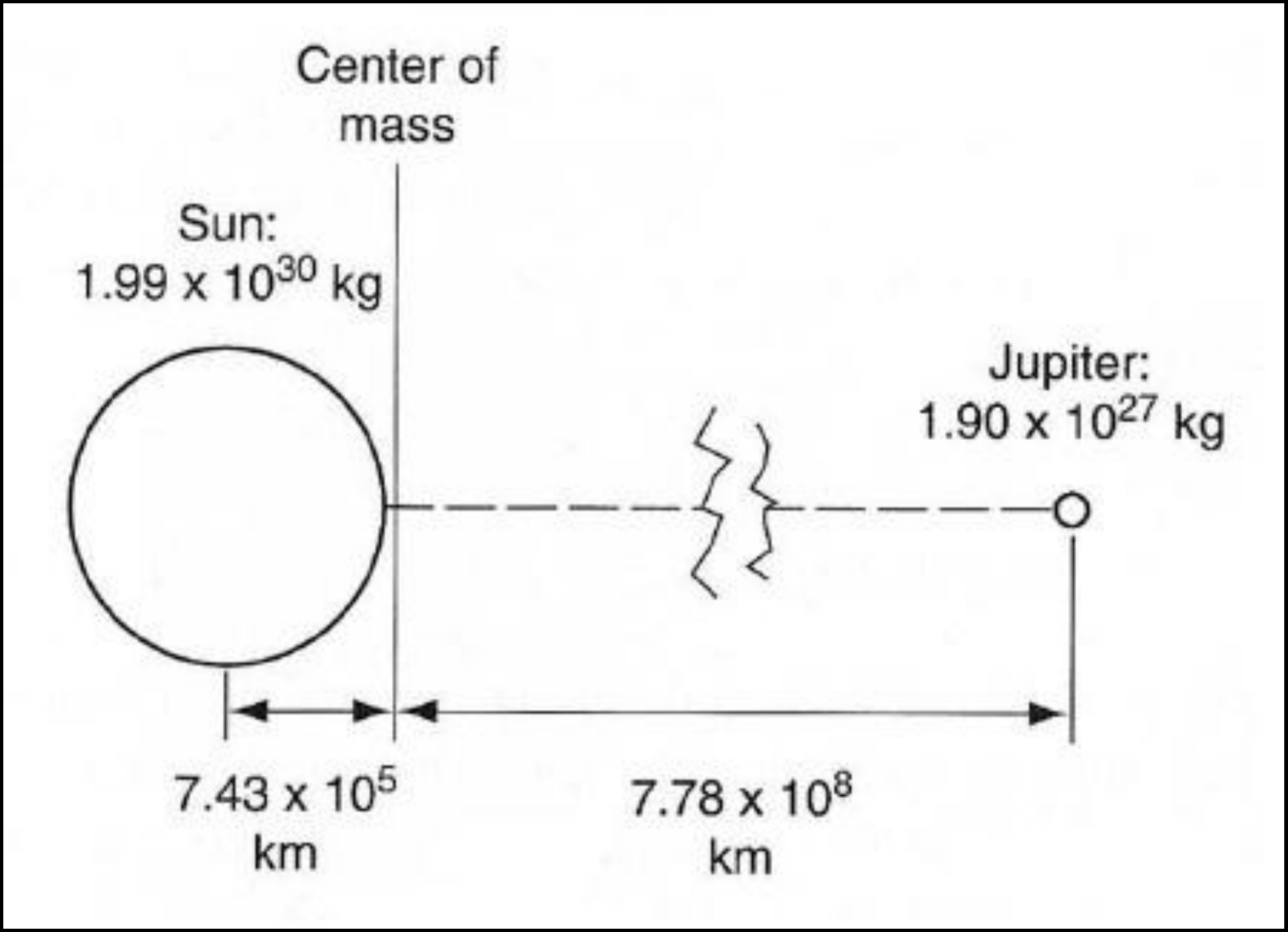

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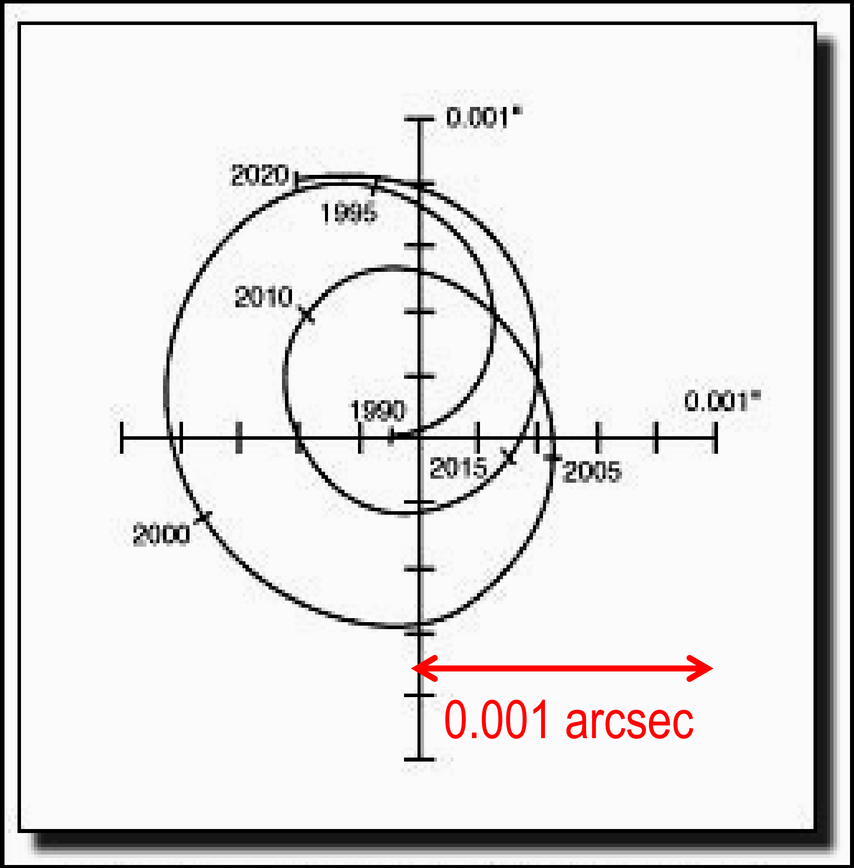

The Sun's position as seen from above the plane of the ecliptic changes mainly due to its wobble caused by Jupiter's 12-year orbit

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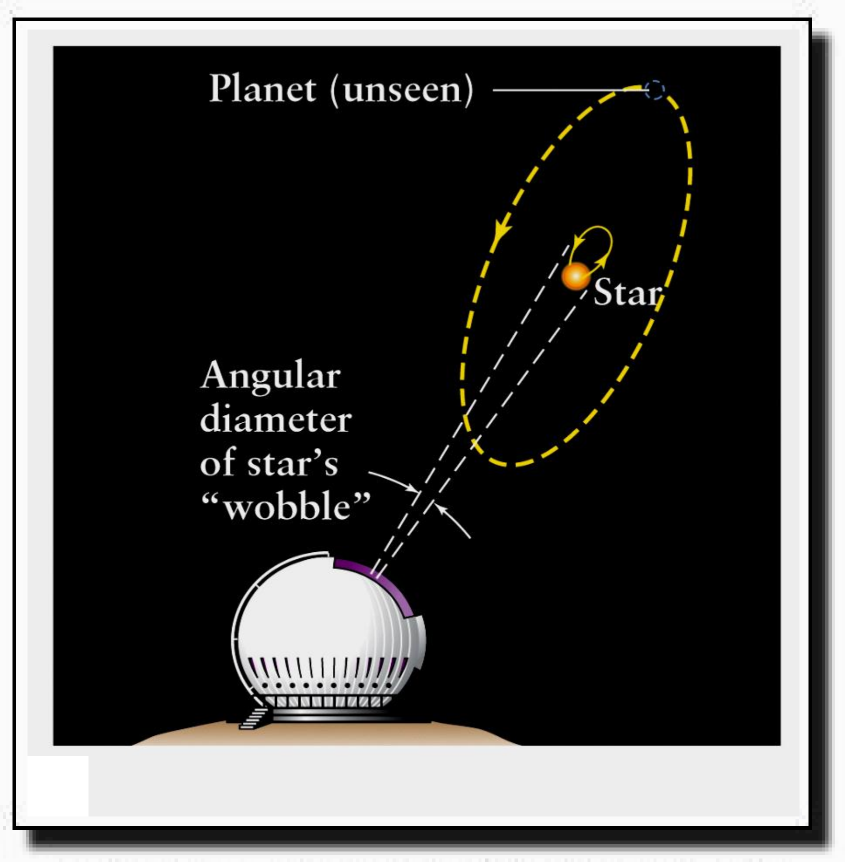
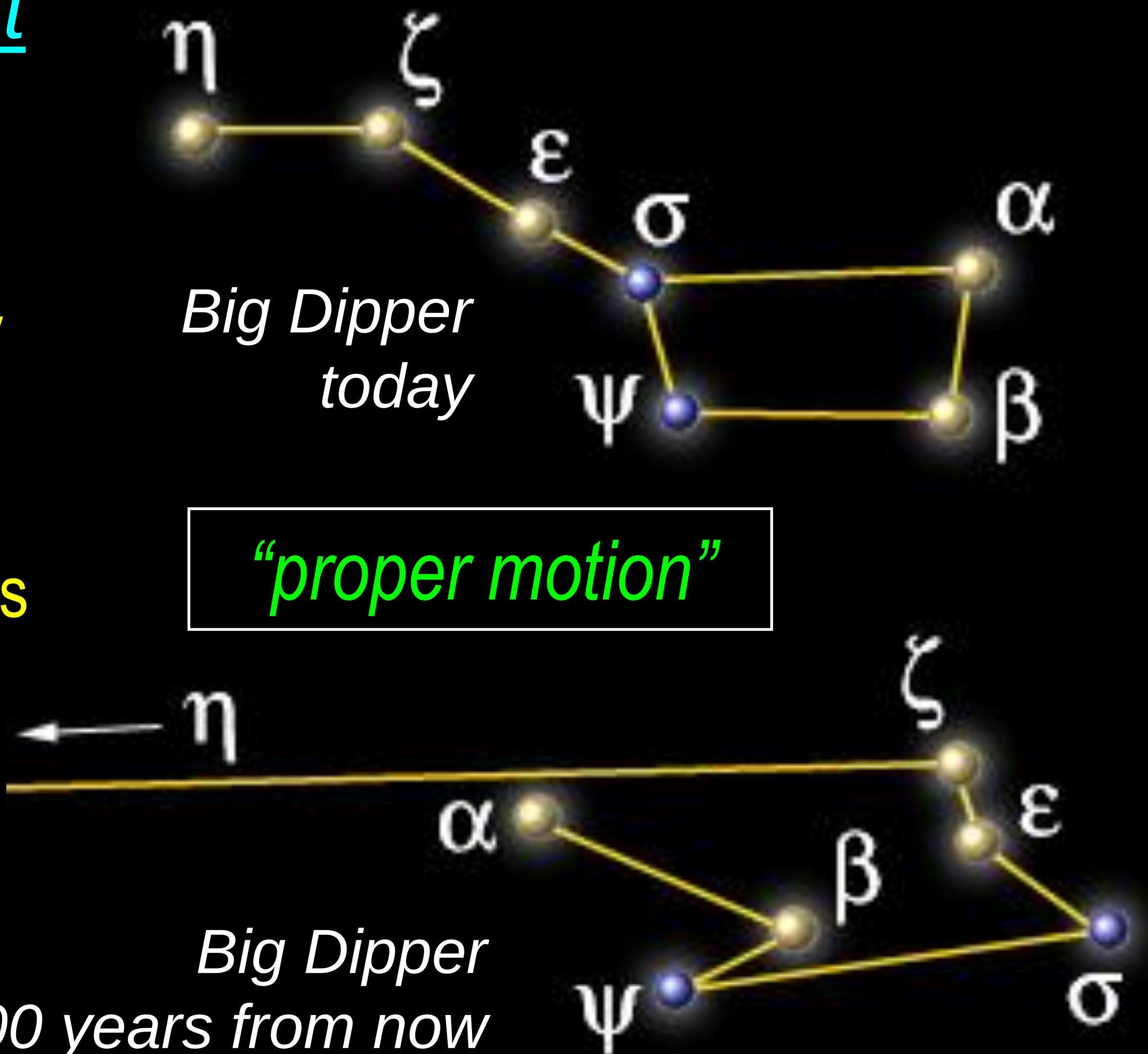


The angular extent of a star's wobble due to an unseen planet is too small to be measured reliably by current instruments and techniques

Constant as the Northern Star

Not so constant

Stars are moving around the centre of the Milky Way Galaxy at high speeds but they are so distant it takes many thousands of years to see by eye their changes in relative position in the sky



Big Dipper today

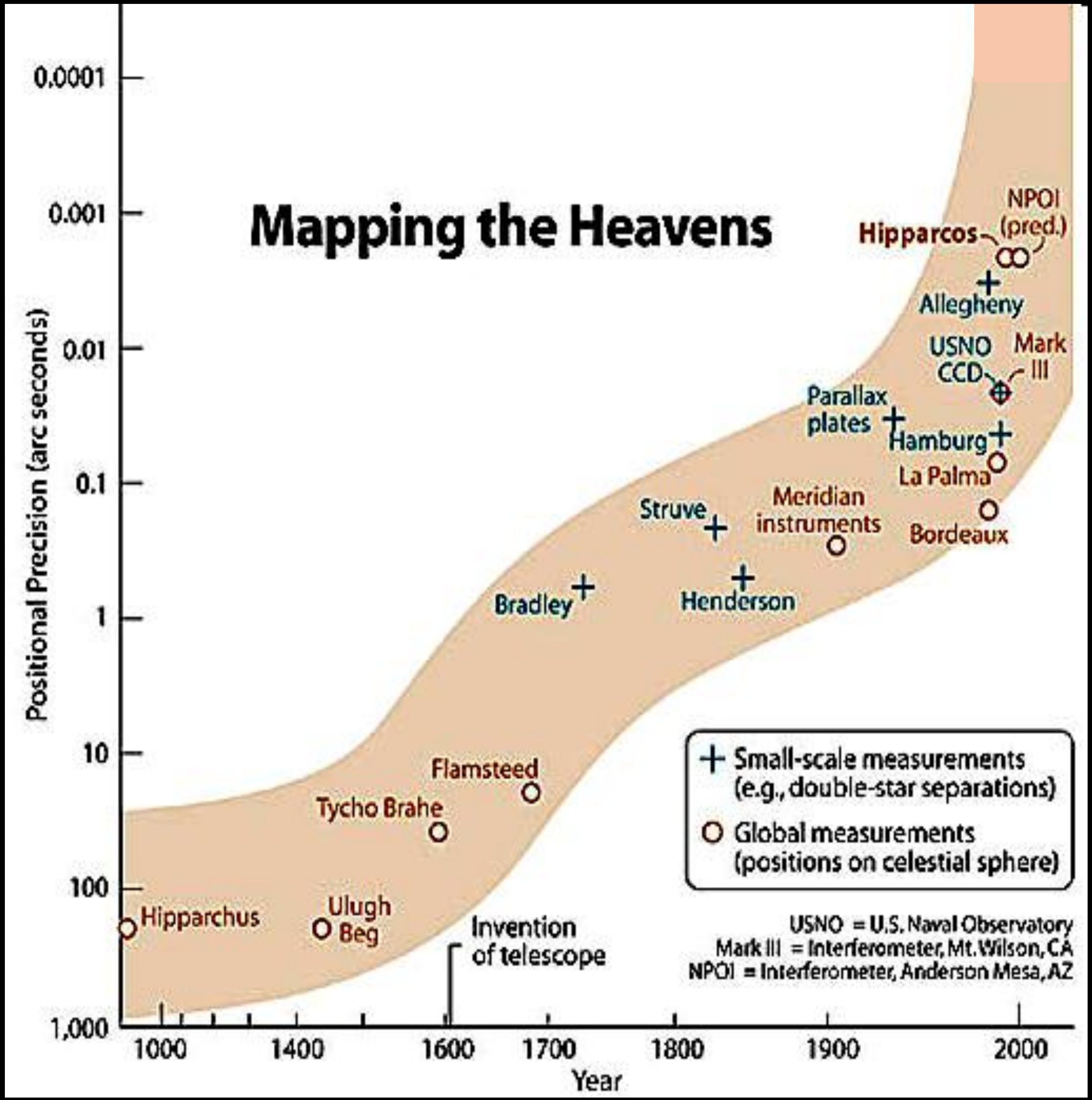
"proper motion"

Big Dipper 10,000,000 years from now

Proper motions

Astrometry

Astronomers
have over time
improved
the accuracy
with which
we can measure
positions of stars
in the sky

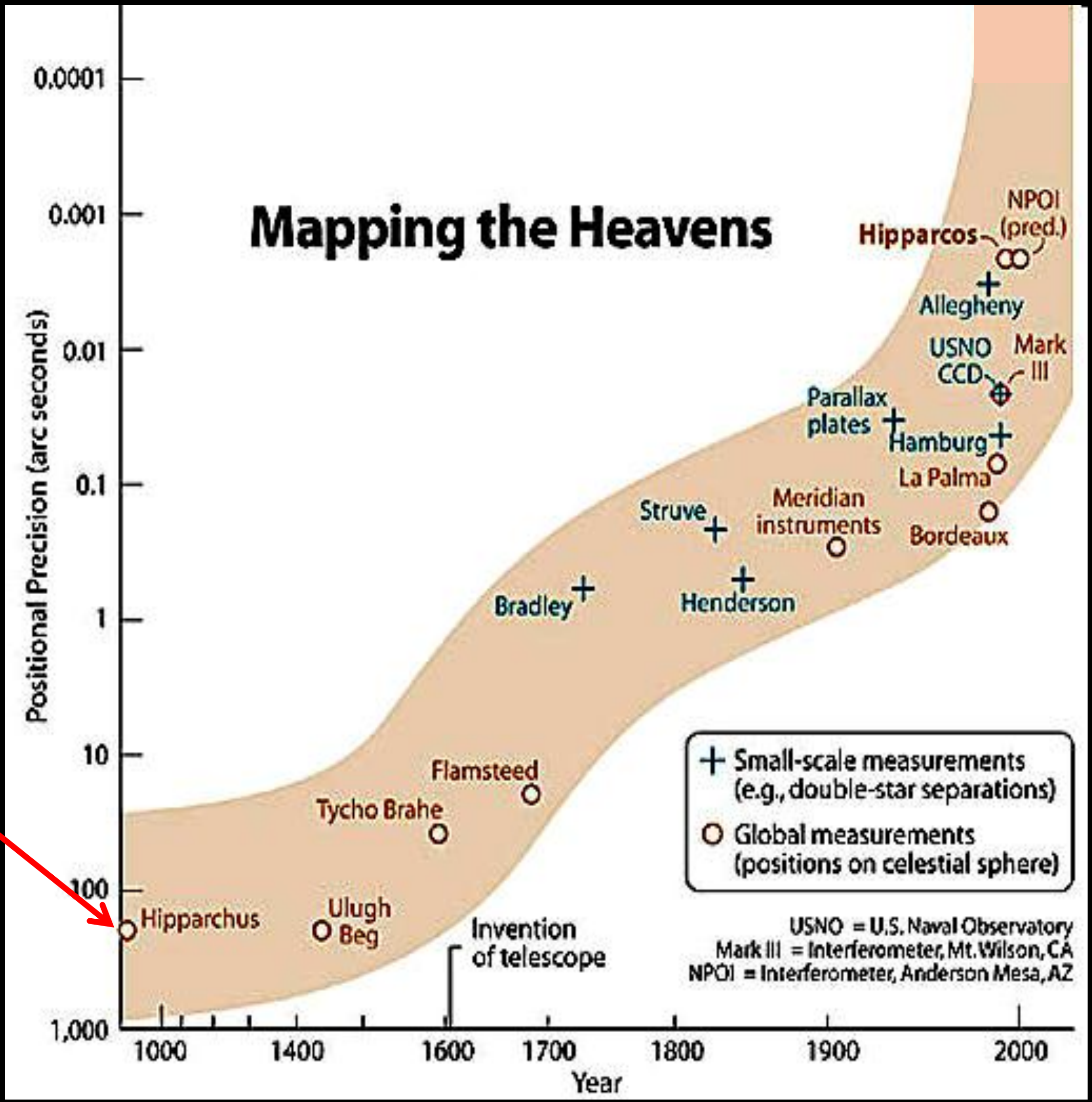


Proper motions

Astrometry

Astronomers have over time improved the accuracy with which we can measure positions of stars in the sky

From *~180 arcsec* in Hipparchus' time

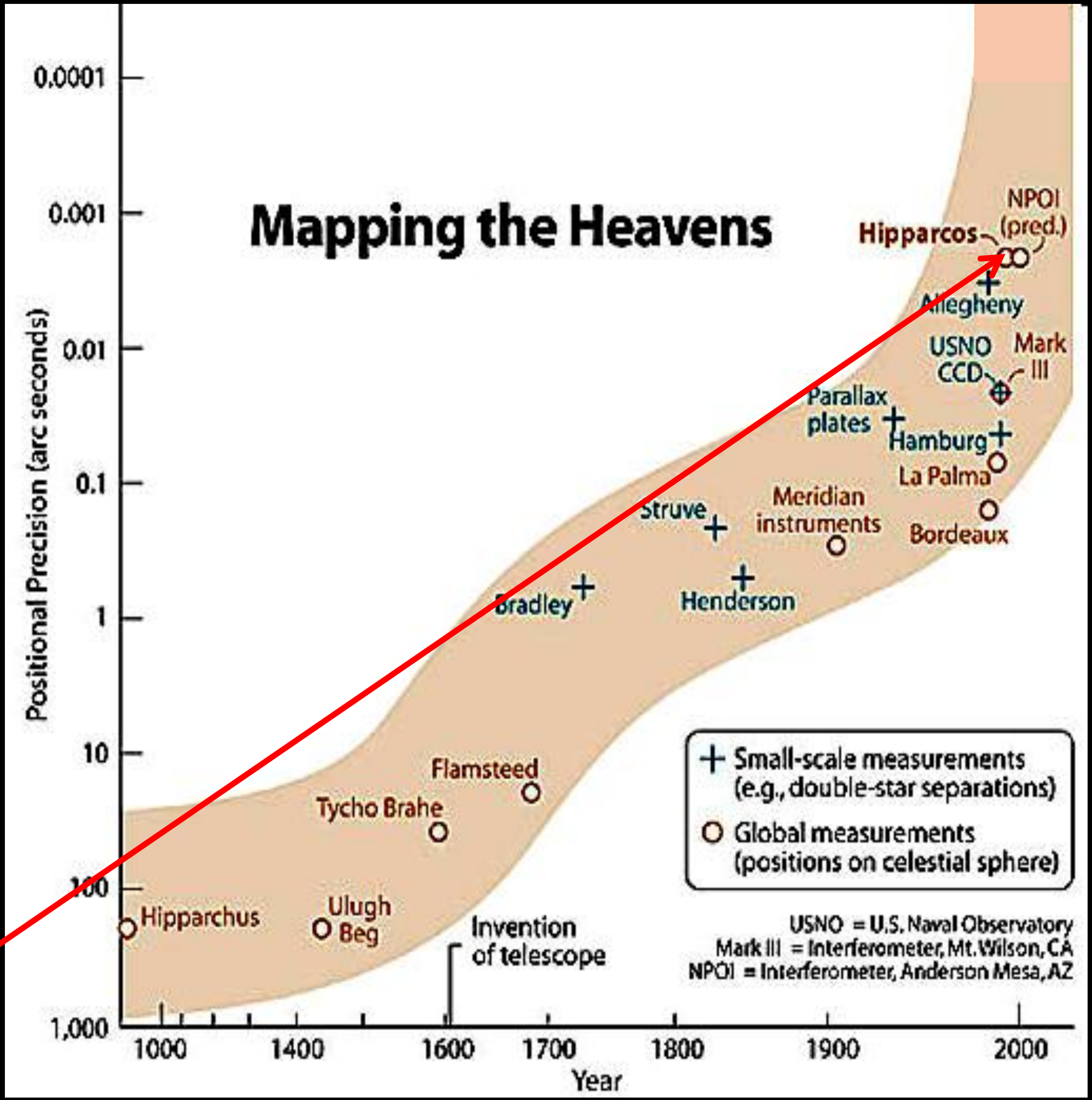


Proper motions

Astrometry

Astronomers have over time improved the accuracy with which we can measure positions of stars in the sky

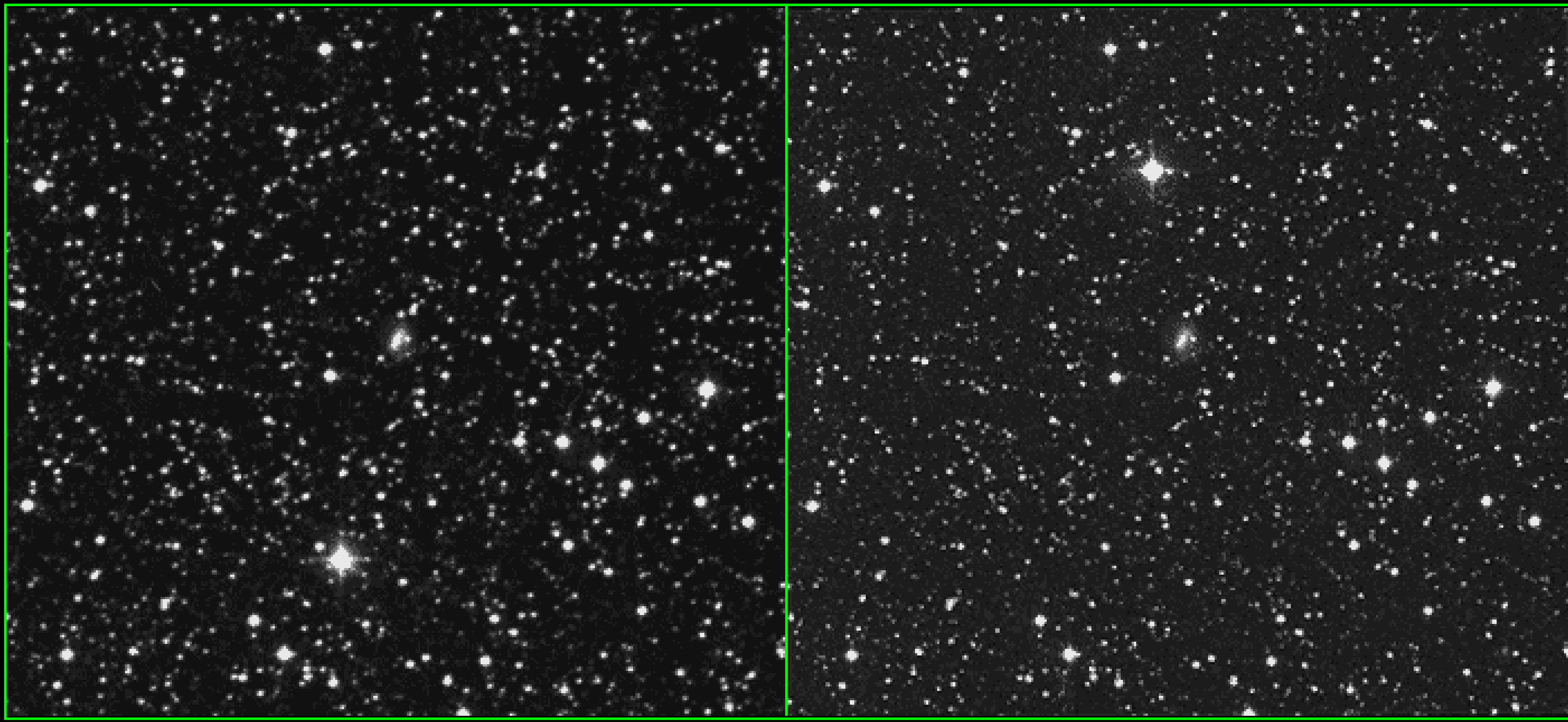
From *~180 arcsec* in Hipparchus' time to *1 milliarcsec (1 mas)* today



Proper motions

Motion of stars

Spot the moving star



These two photos, of a small patch of the sky only
a fraction of a degree across, were taken several years apart

Proper motions

Motion of stars

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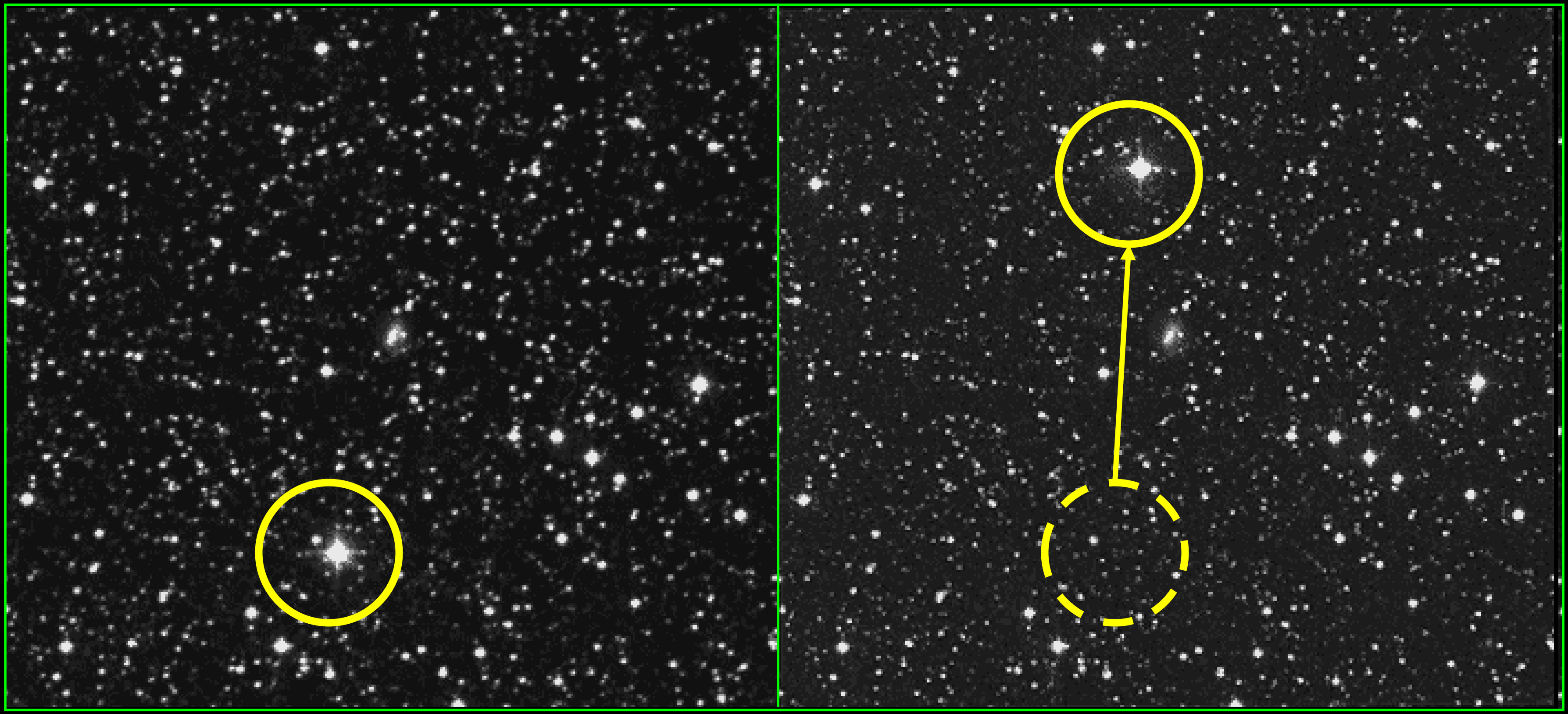

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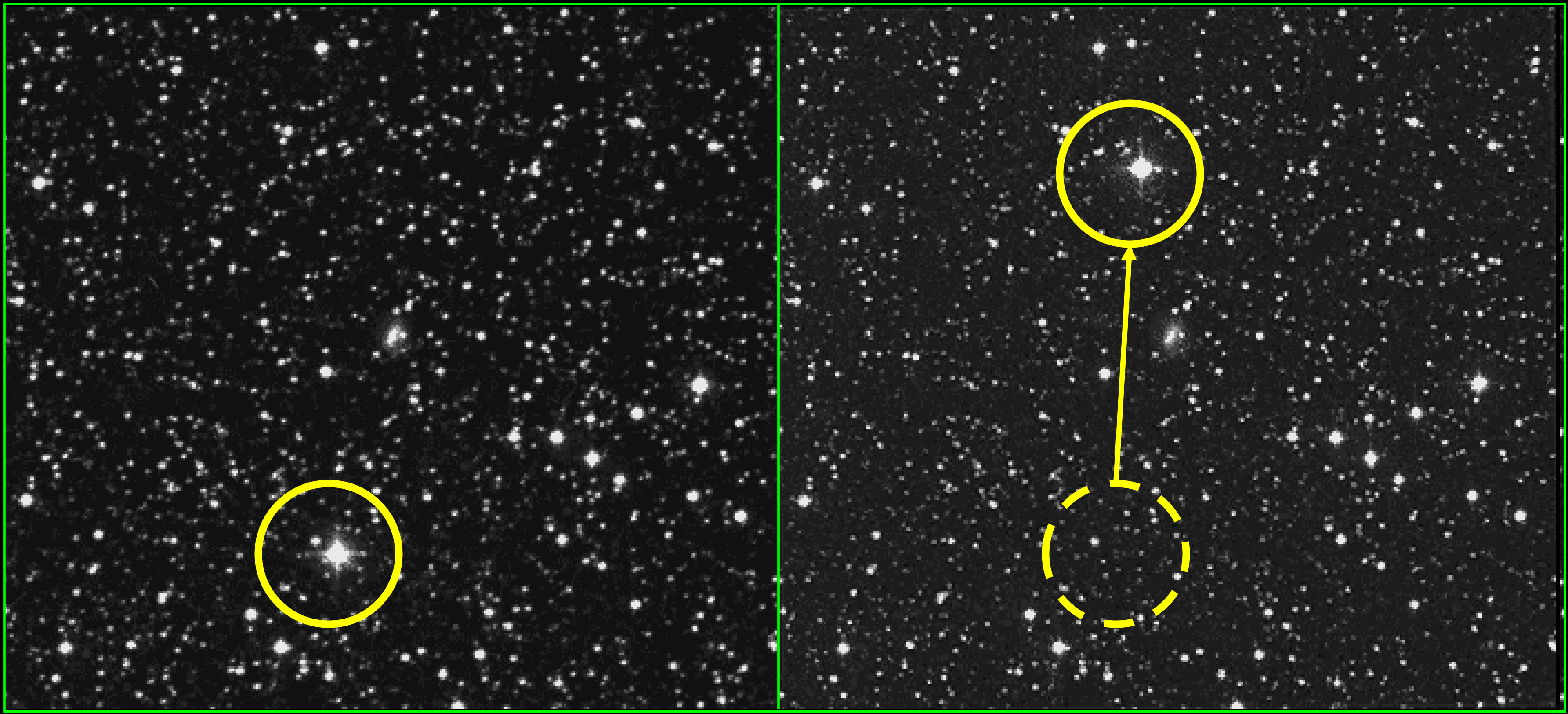


All stars are physically moving relative to the Sun but most are so far away that even accurate astrometry can't show it clearly

Proper motions

Motion of stars

Spot the moving star

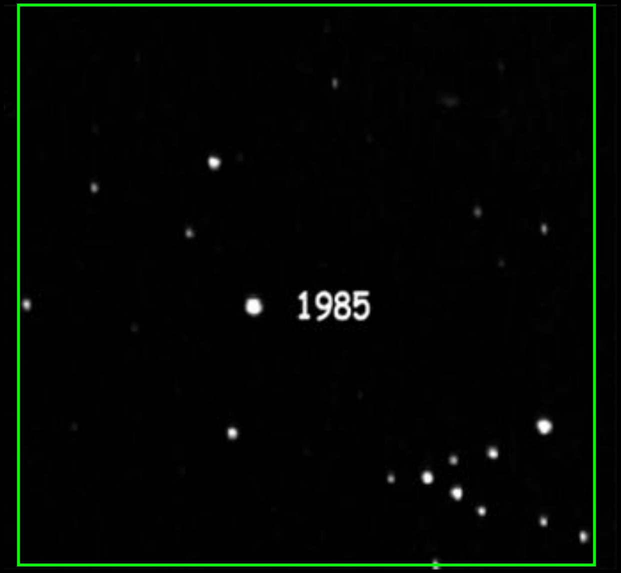
All stars are physically moving relative to the Sun but most are so far away that even accurate astrometry can't show it clearly

Proper motions

Proper motion

Astronomers call the apparent angular motion of stars across the sky "*proper motion*"

This is an actual motion relative to other stars *not* just the diurnal (daily) circular motion of *all* stars in the sky due to the rotation of the Earth



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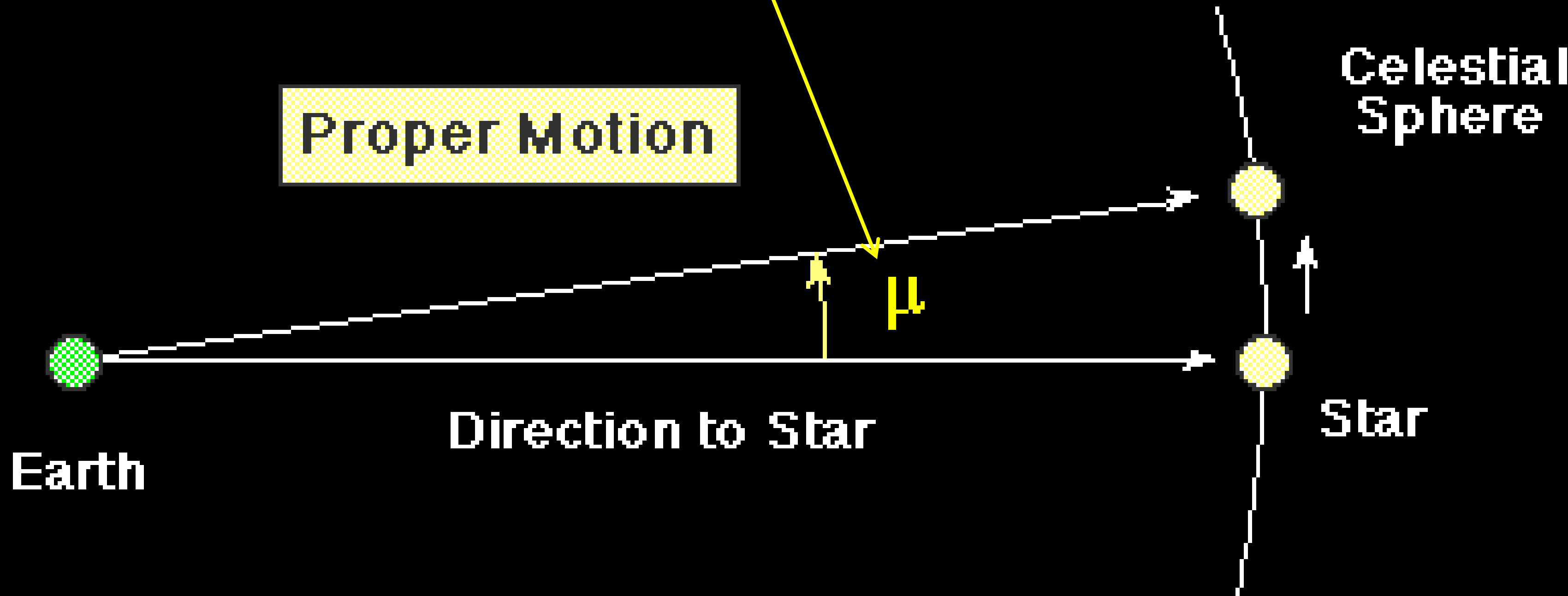

Proper motions

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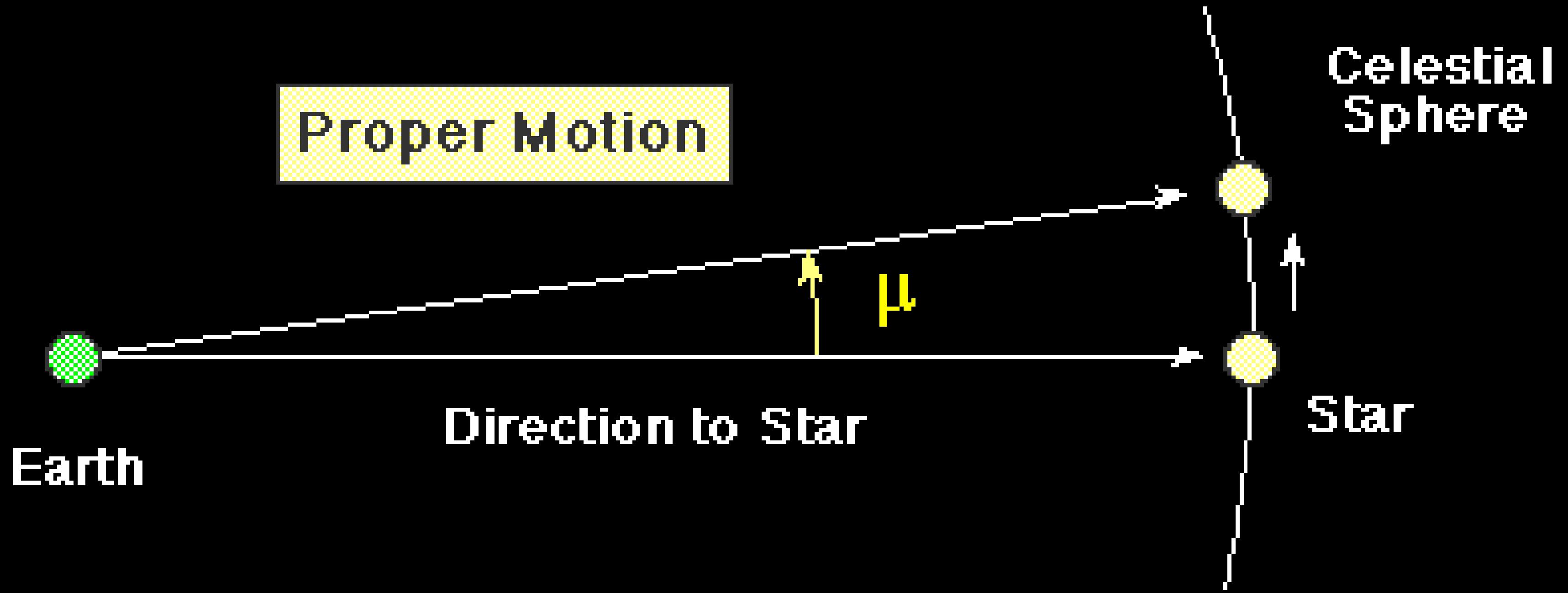
Astronomers call the apparent angular motion of stars across the sky "*proper motion*"

Proper motion is an angular speed and since the apparent motions of stars are so small we use units of arcseconds per year (arcsec/yr = "/yr)

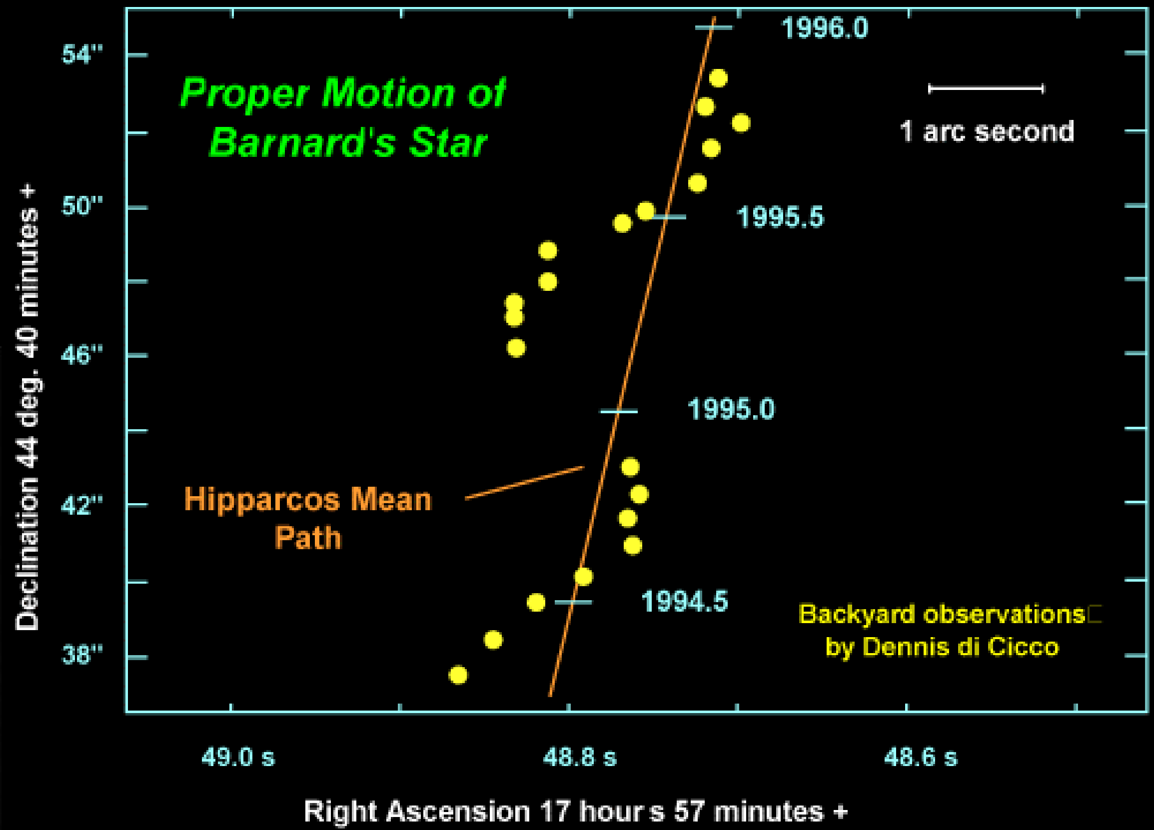


Proper motions

Proper motion

The star with the largest observed proper motion is Barnard's Star

μ ~ 10 arcsec/yr

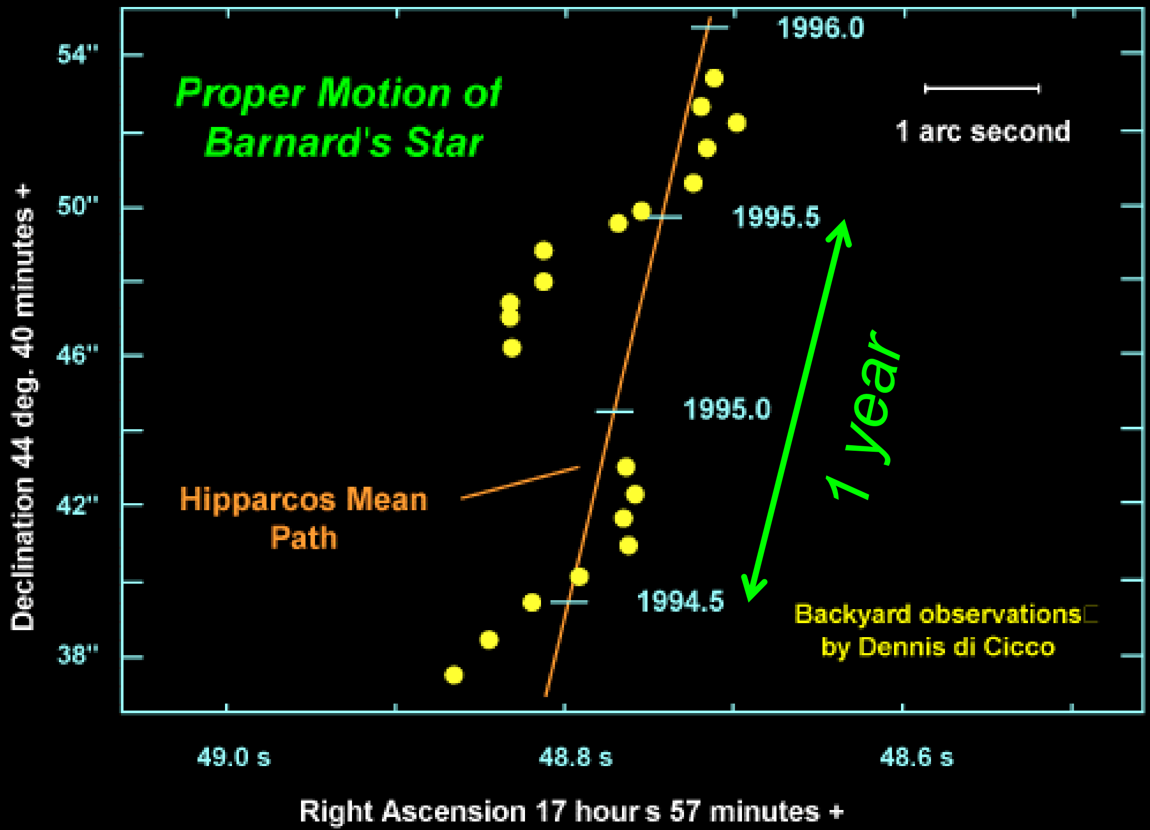


Proper motions

Proper motion

The star with the largest observed proper motion is Barnard's Star

The wave pattern you see in this chart of its motions is due to the *parallax* effect of the orbital motion of the Earth around the Sun



Proper motions

The first exoplanet?

Peter van de Kamp – with data from the Sproul Observatory – found a planet

1.6 Jupiter masses
P ~ 24 – 25 yr

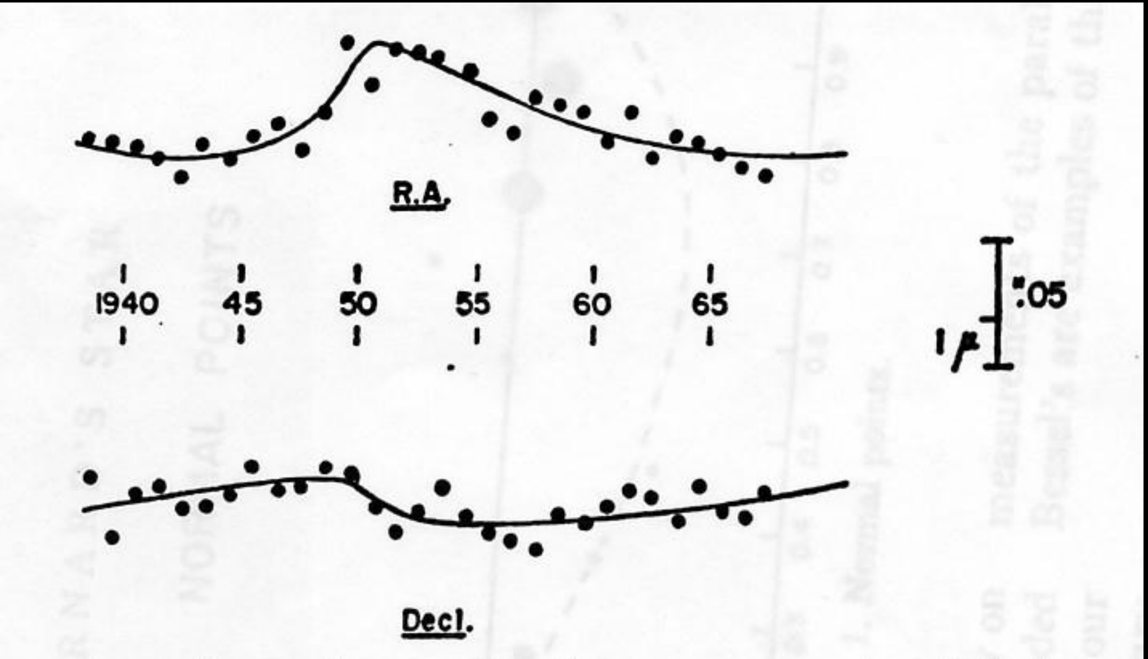


FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

Improper motions

The first exoplanet – NOT!

Peter van de Kamp – with data from the Sproul Observatory – found a planet

1.6 Jupiter masses
P ~ 24 – 25 yr

But the "wobble" in the astrometry corresponded to the schedule of maintenance and replacement of the telescope lens

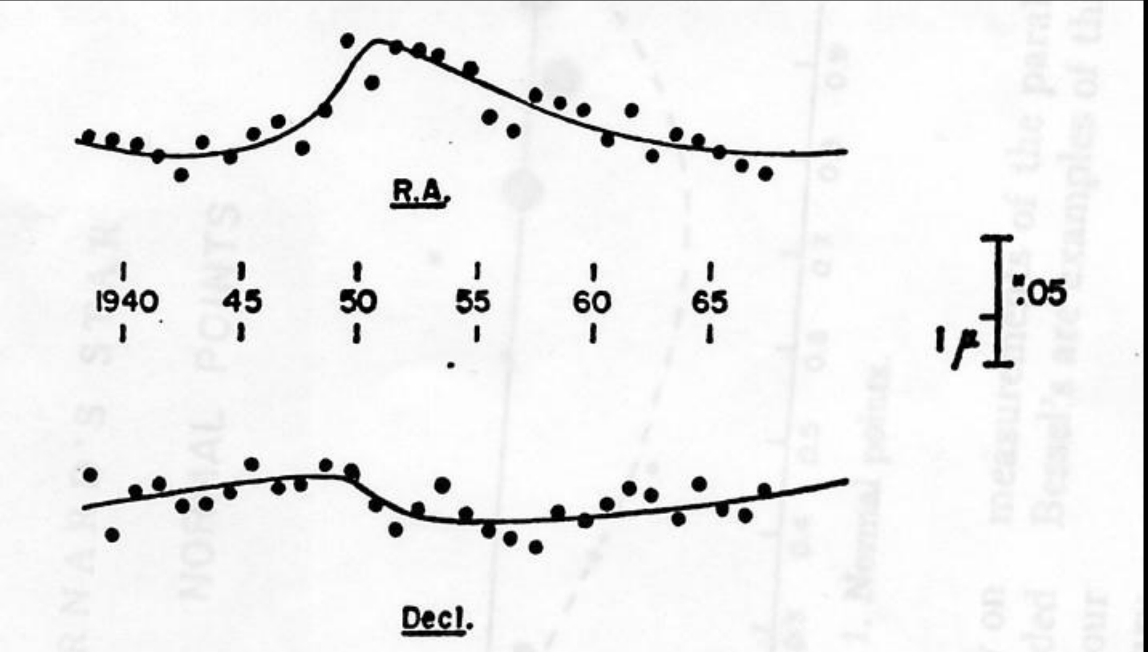


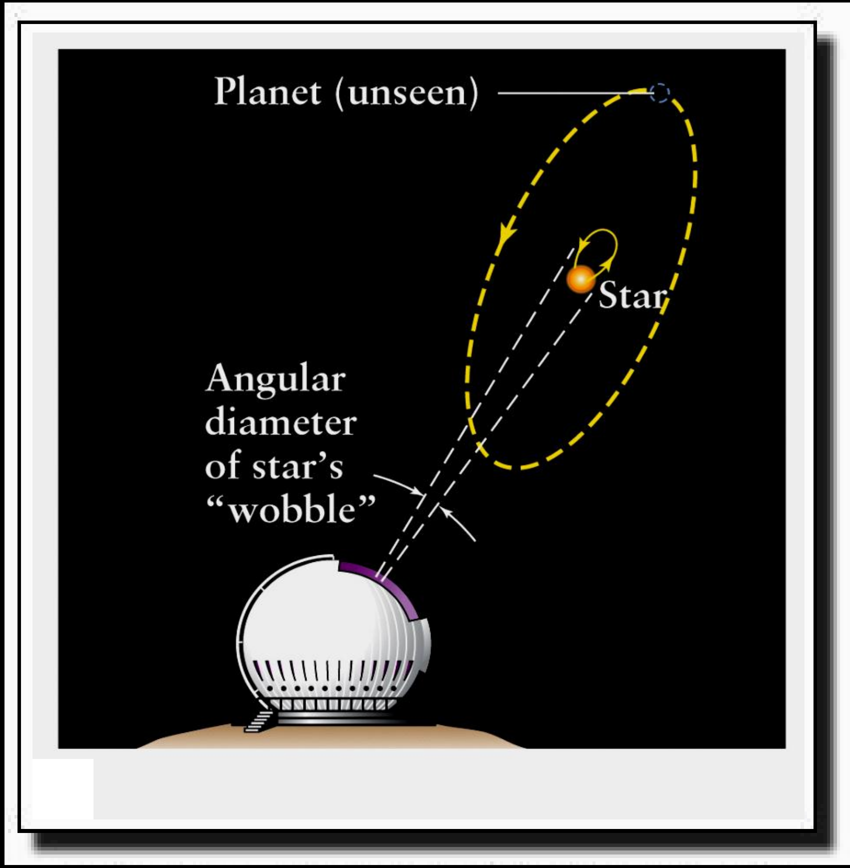
FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

Other planetary systems

Searching for exoplanets

We must rely on indirect techniques

A star and planet orbit around a common *centre of mass* which is much closer to the centre of the star because it is much more massive



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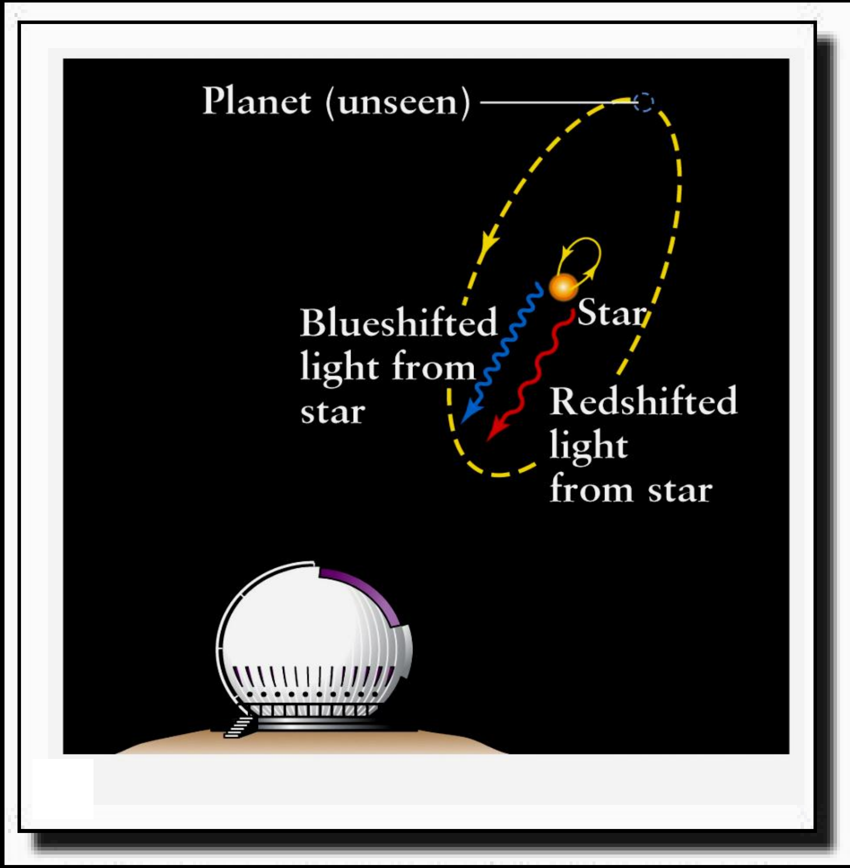
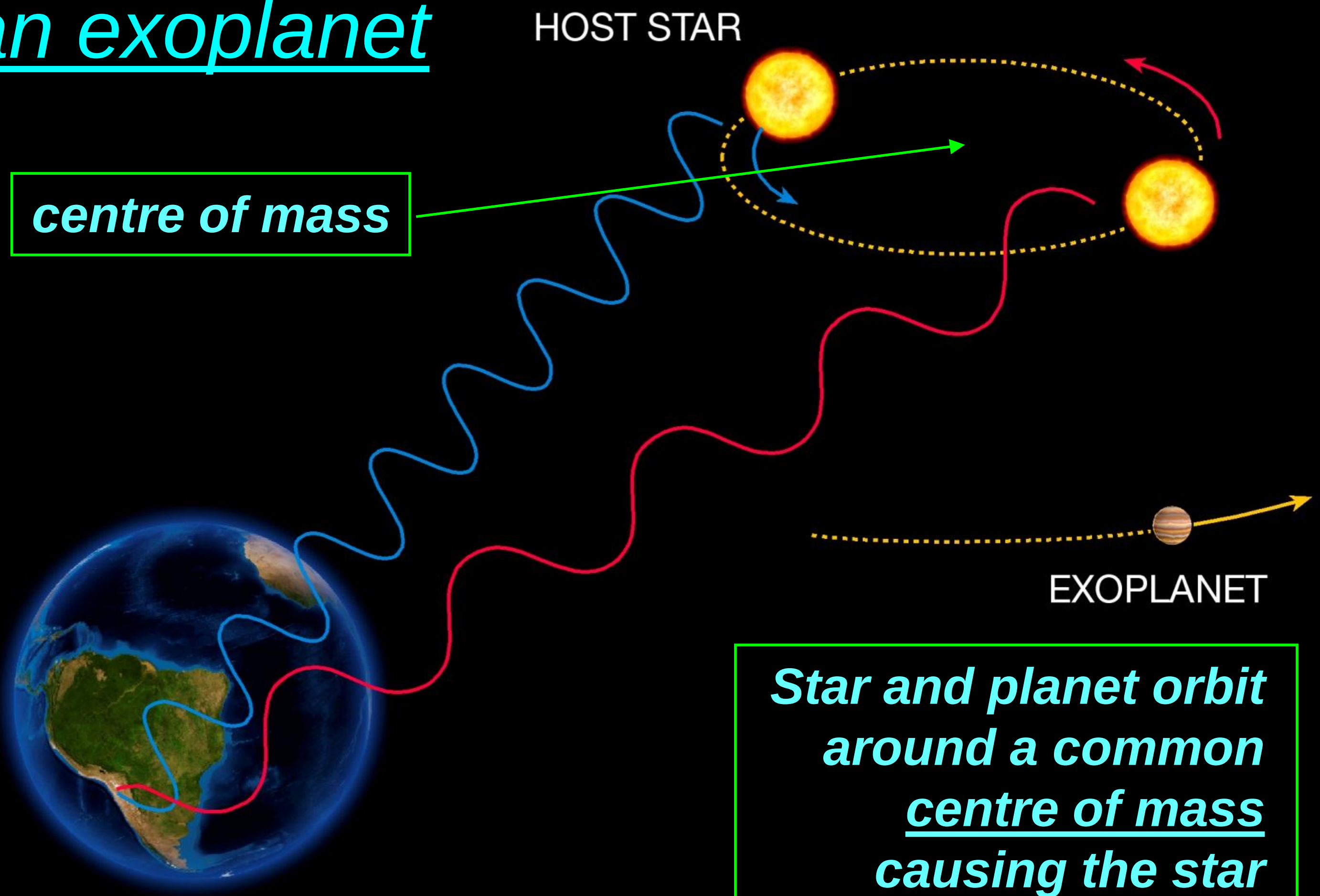


But the motion of the wobbling star can be measured through the *Doppler Effect* if the planet is massive enough

Other planetary systems

Detecting an exoplanet

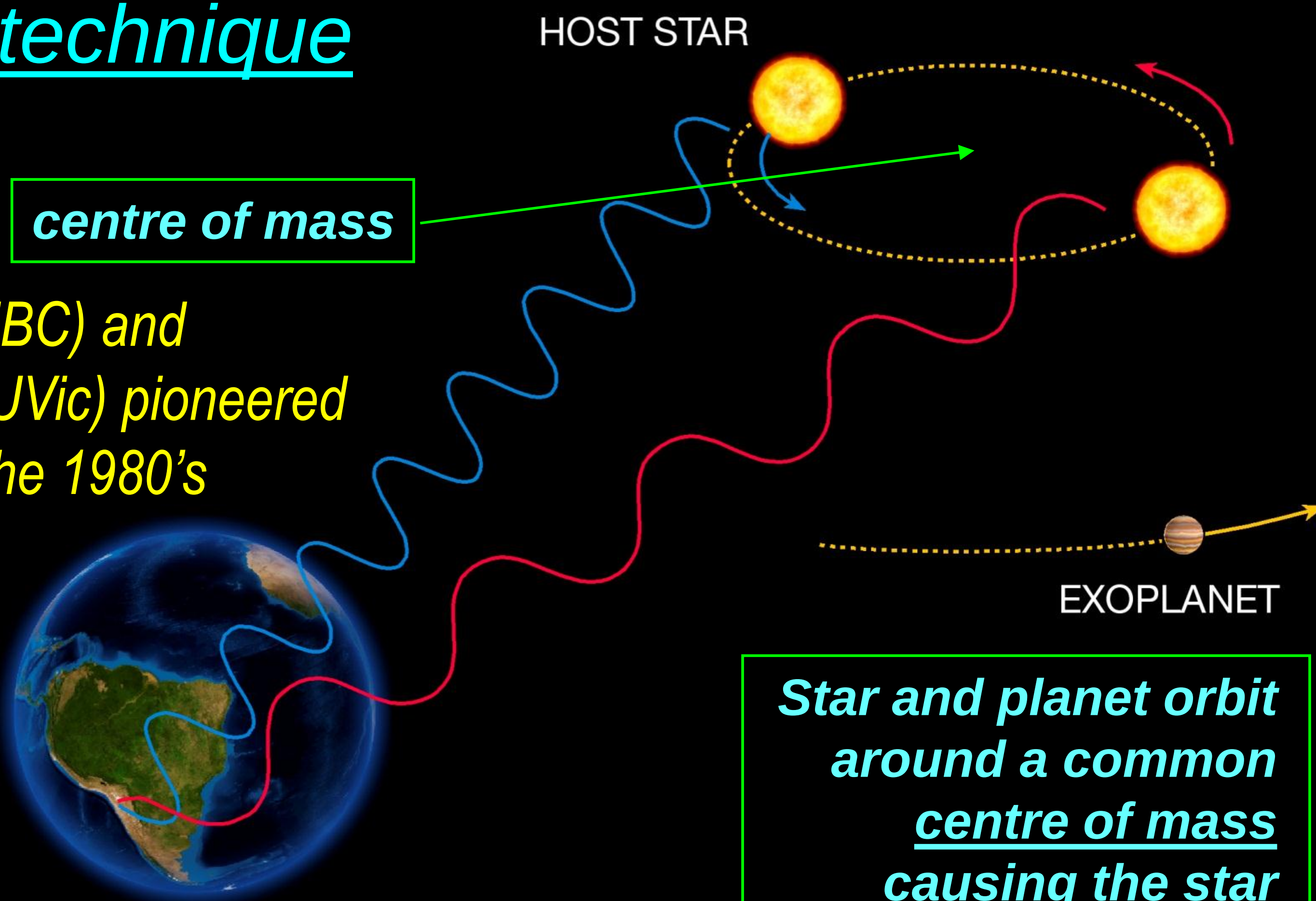
centre of mass



Star and planet orbit around a common <u>centre of mass</u> causing the star to 'wobble' with the same period as the unseen planet

Other planetary systems

A BC-born technique



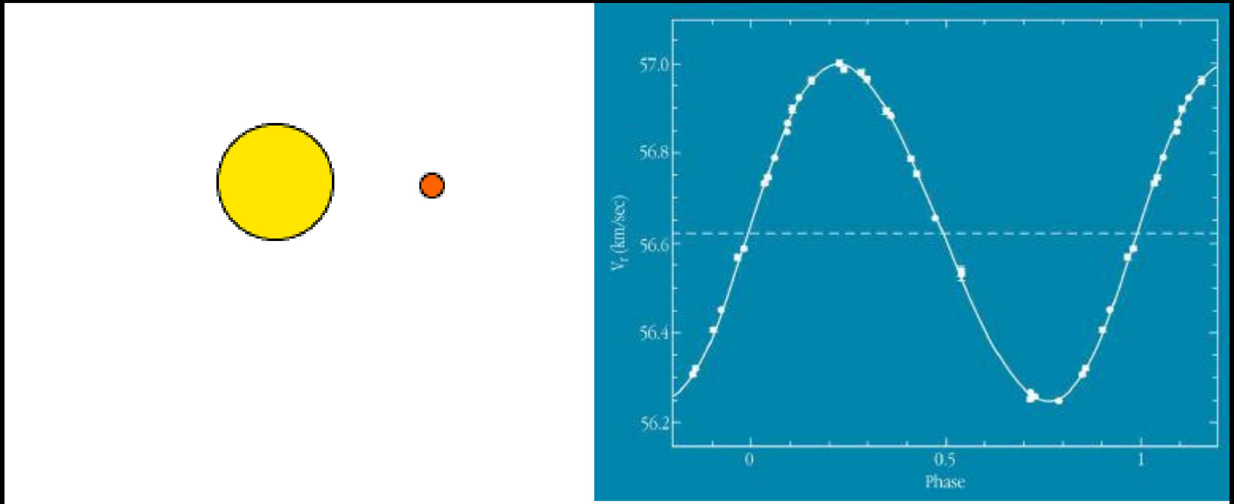
Gordon Walker (UBC) and Bruce Campbell (UVic) pioneered this technique in the 1980's

UBC Astronomy Professor Emeritus Gordon Walker

Star and planet orbit around a common centre of mass causing the star to 'wobble' with the same period as the unseen planet

Other planetary systems

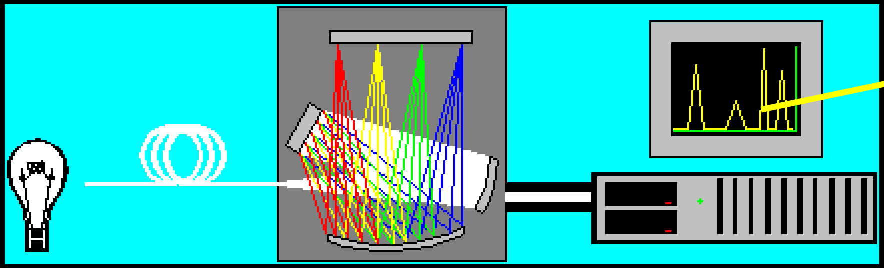
© Nick Strobel
astronomynotes.com

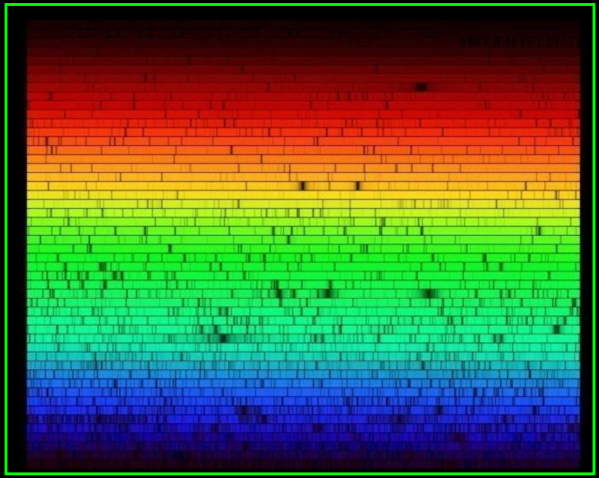


What is happening

What we see

spectrum

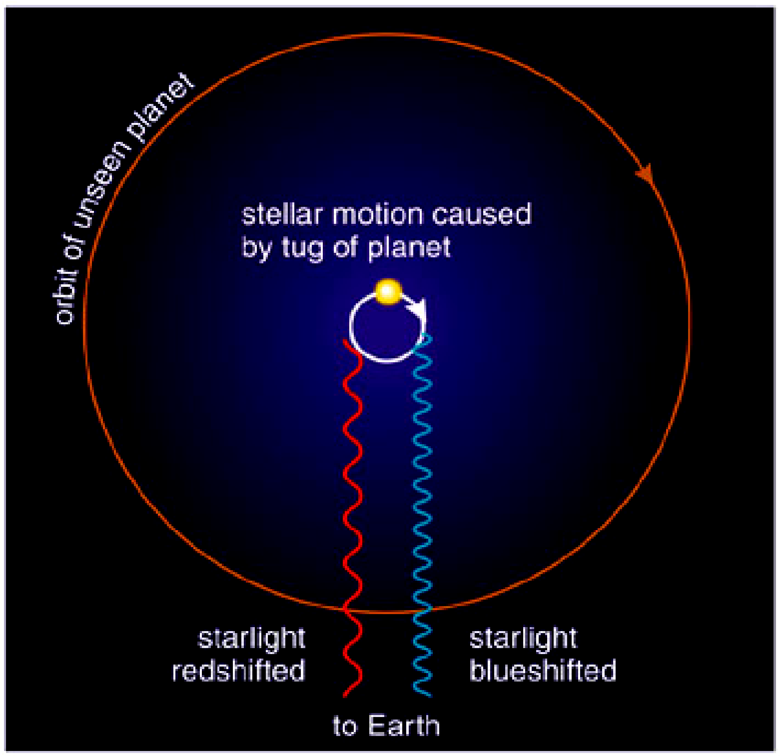




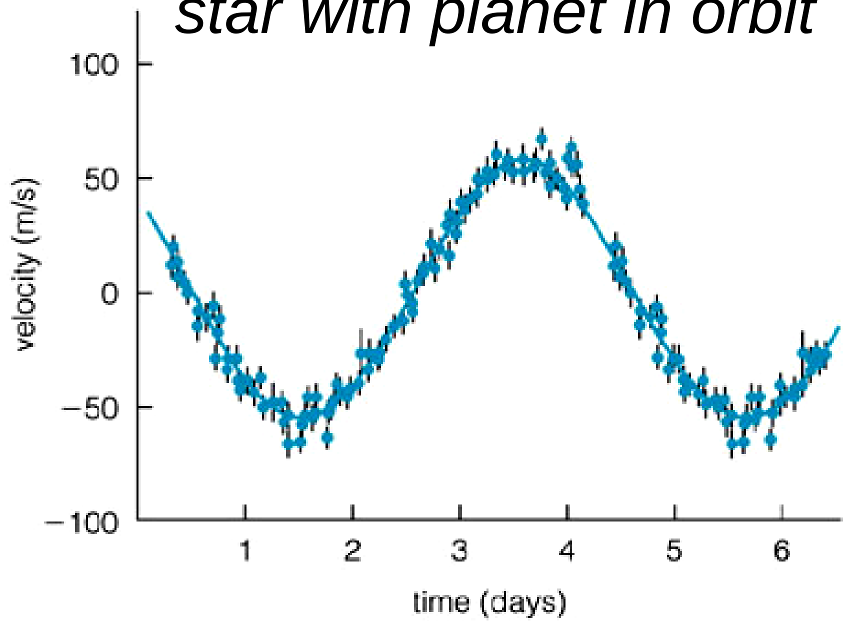
Other planetary systems

Finding exoplanets

Most of the planets around other Sun-like stars have been discovered through Doppler surveys



radial velocity (RV) curve of star with planet in orbit

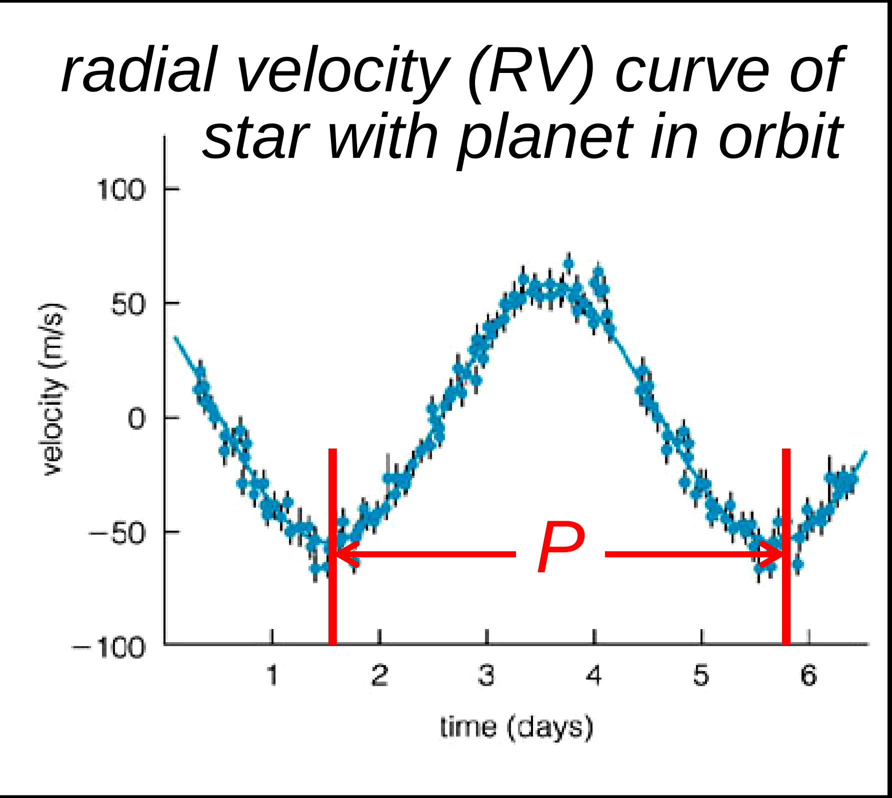


Other planetary systems

The semi-major axis of an exoplanet orbit

That's the easiest thing to derive from the RV curve …

… using Kepler's Third Law and the measured period



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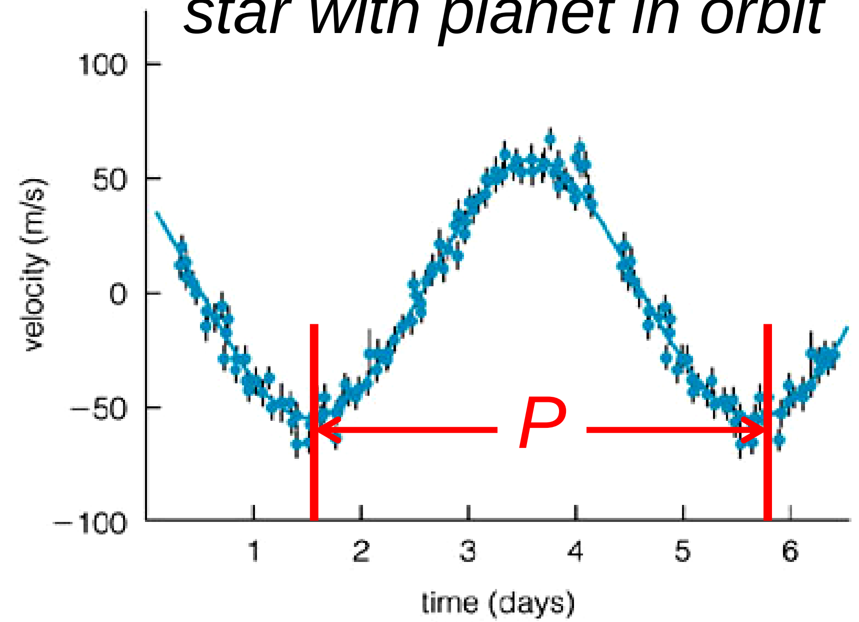
$$P^2 = \frac{4\pi^2}{G(M_{star} + m_{planet})} a^3$$

You estimate the star's mass M_{star} from its spectrum (and luminosity, if known)

radial velocity (RV) curve of star with planet in orbit



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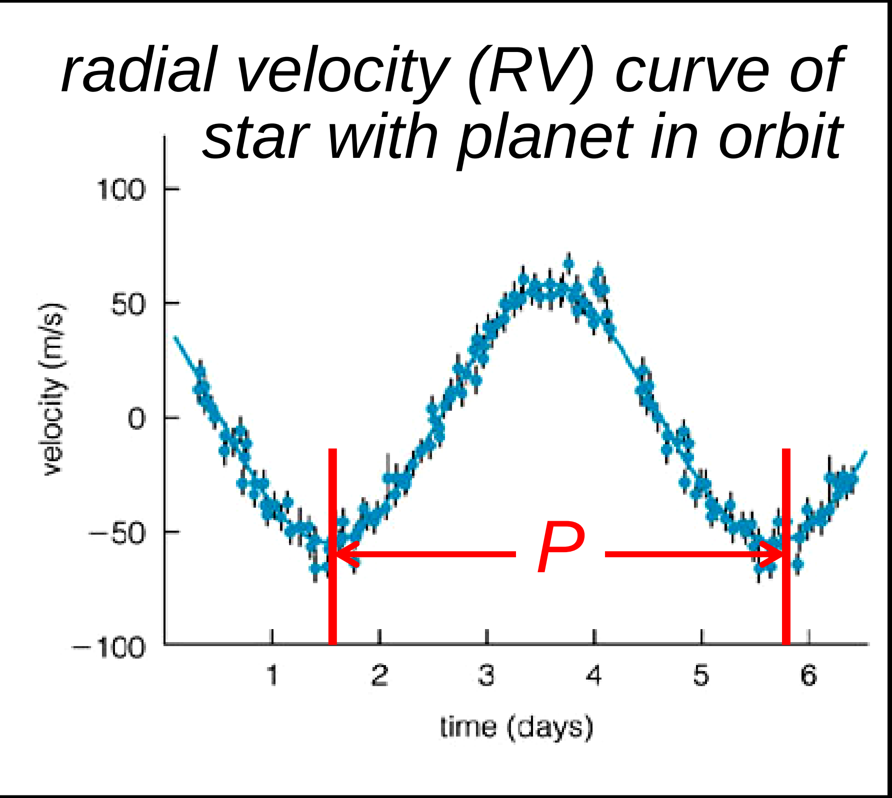


You estimate the star's mass M_{star} from its spectrum (and luminosity, if known)

$$M_{star} >>> m_{planet}$$

so $M_{star} + m_{planet} \sim M_{star}$

Other planetary systems

The semi-major axis of an exoplanet orbit

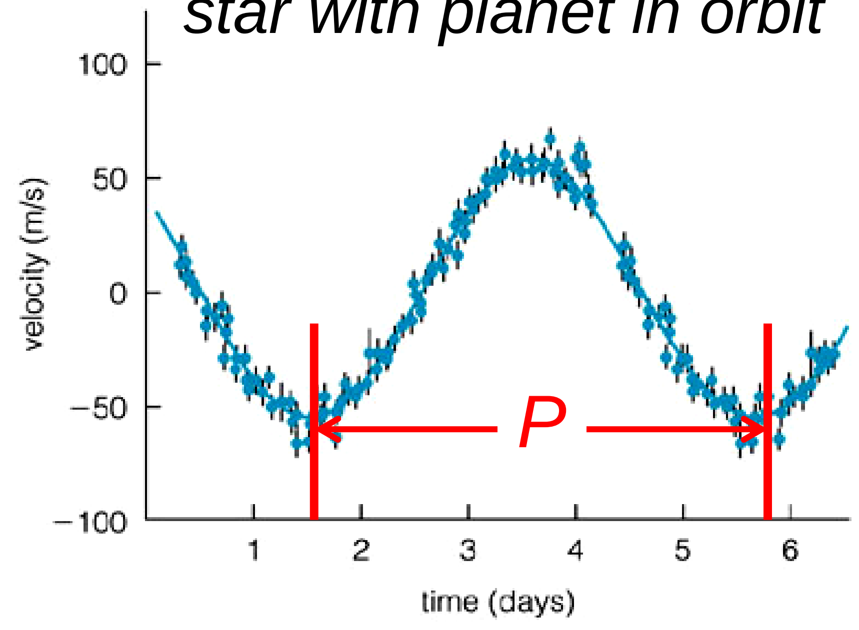
Kepler's Third Law simplifies to the following …

$$P^2 = \frac{4\pi^2}{G\,M_{star}}\,a^3$$

… and then solve for the semi-major axis *a*

since the period of the star's orbit around the centre of mass is the same as the period of the planet's orbit

radial velocity (RV) curve of star with planet in orbit



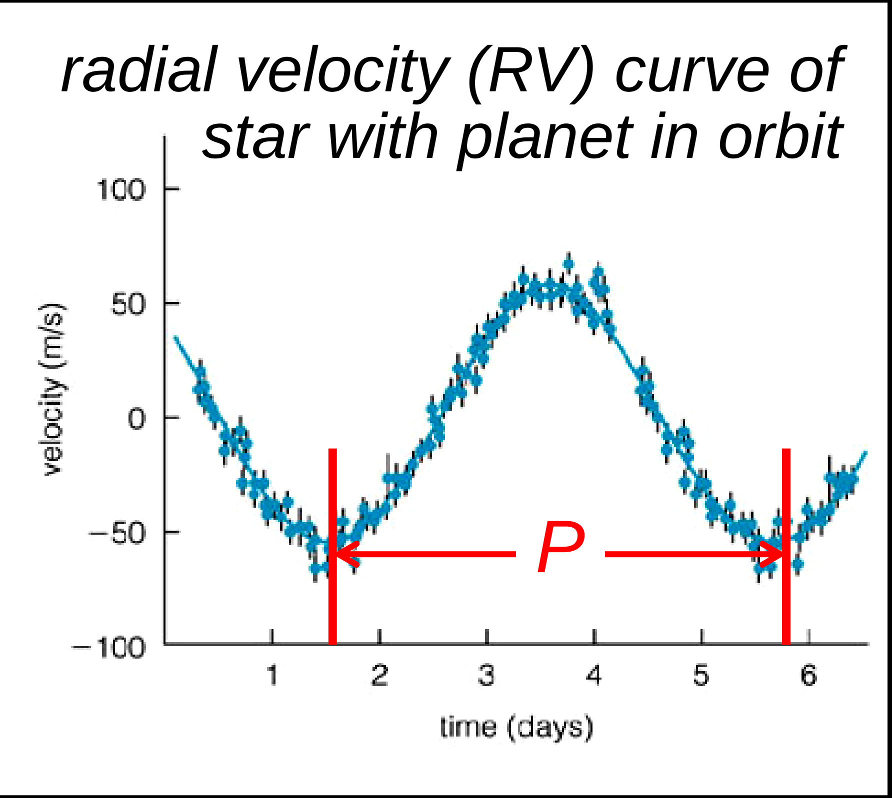
Other planetary systems

The mass of an exoplanet

The velocity *v* of the exoplanet depends on the gravitational force, which results in the centripetal acceleration in the orbit

$$\frac{m_{pl}\, v_{pl}^2}{r} = \frac{G M_{star}\, m_{pl}}{r^2}$$

so $$v_{pl} = \sqrt{\frac{G M_{star}}{r}}$$



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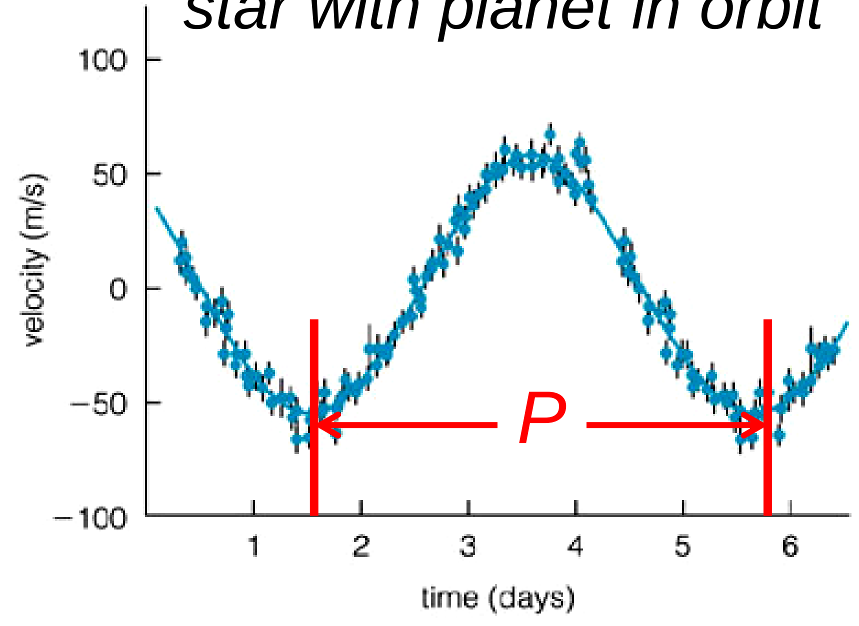
For a circular orbit $r = a$

radial velocity (RV) curve of star with planet in orbit



Other planetary systems

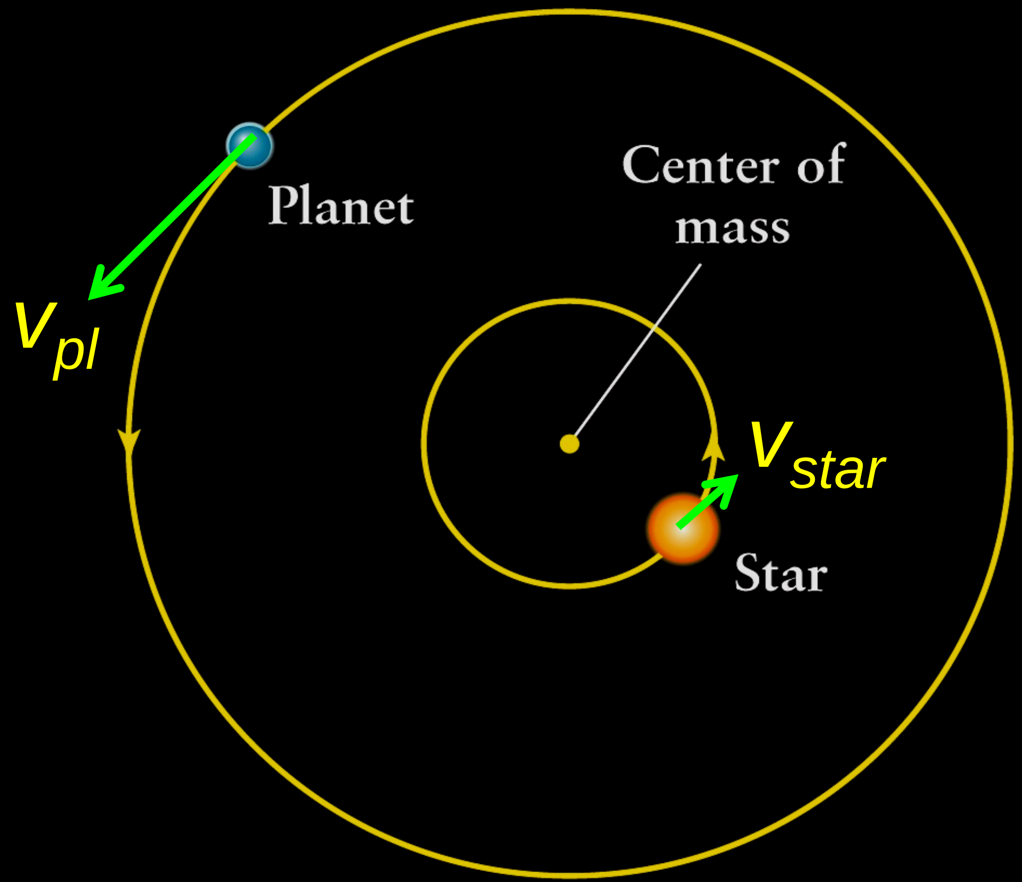
The mass of an exoplanet

Momentum
is conserved
in this system

so

$$m_{pl}\, v_{pl} = M_{star}\, v_{star}$$

$$m_{pl} = M_{star} \frac{v_{star}}{v_{pl}}$$



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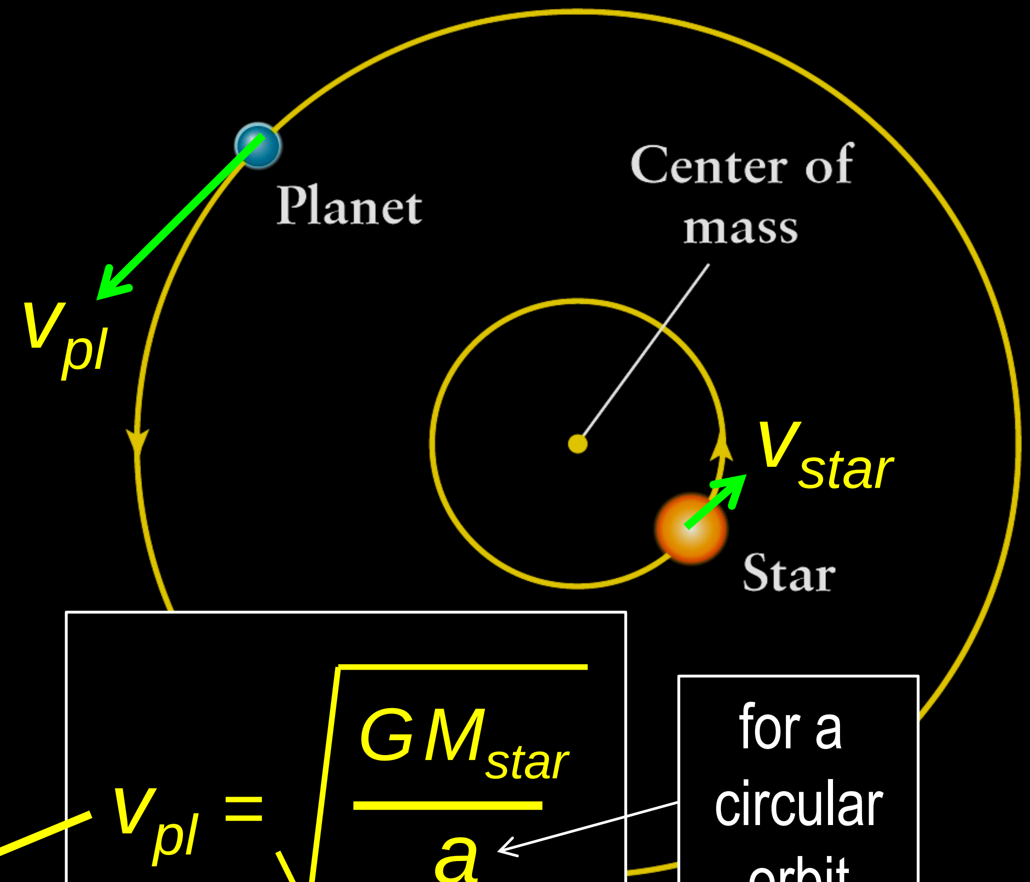


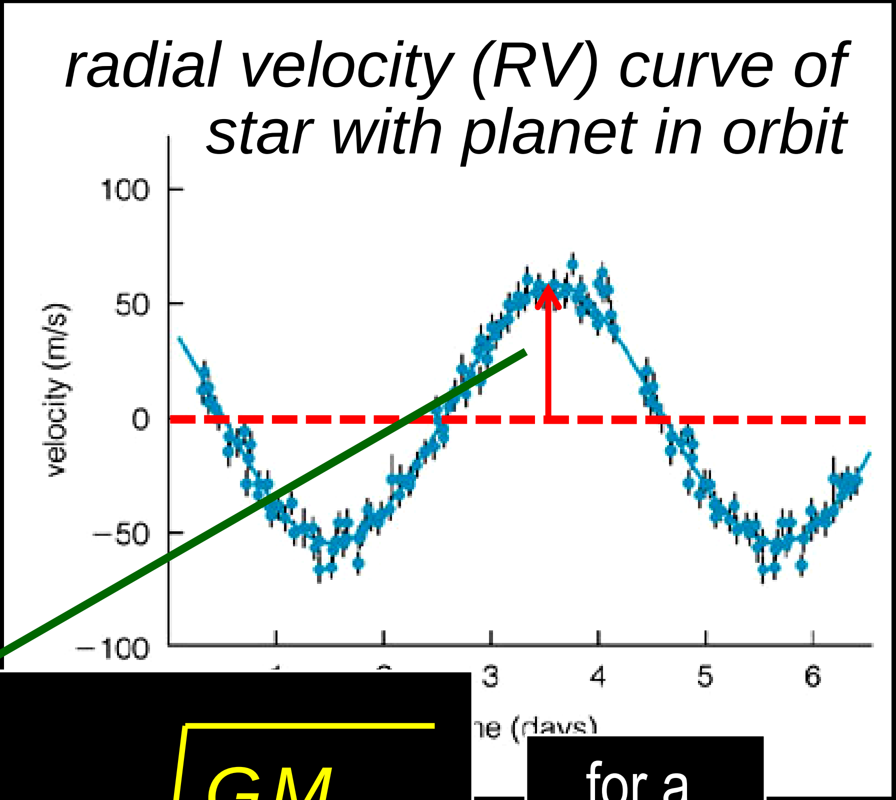
$$m_{pl} = M_{star} \frac{v_{star}}{v_{pl}}$$

$$v_{pl} = \sqrt{\frac{G M_{star}}{a}}$$

for a circular orbit

Other planetary systems

The mass of an exoplanet



$$m_{pl} = M_{star} \frac{v_{star}}{v_{pl}}$$

$$v_{pl} = \sqrt{\frac{G M_{star}}{a}}$$

for a circular orbit

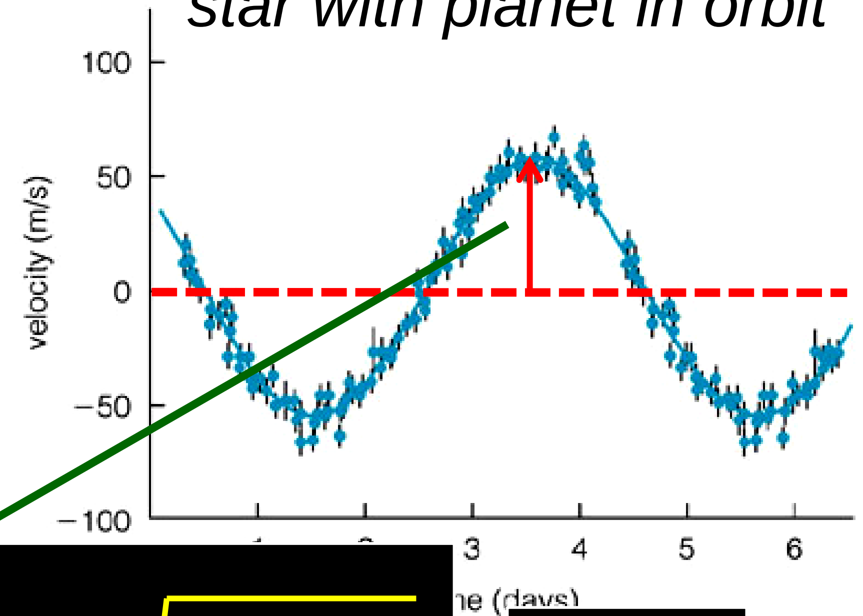
Other planetary systems

The minimum mass of an exoplanet

We don't in general know the inclination *i* of the orbital plane so the amplitude of the RV curve doesn't give us v_{star} but instead $v_{star} \sin i$

So we don't get the mass m_{pl} but instead $m_{pl} / \sin i$

radial velocity (RV) curve of star with planet in orbit



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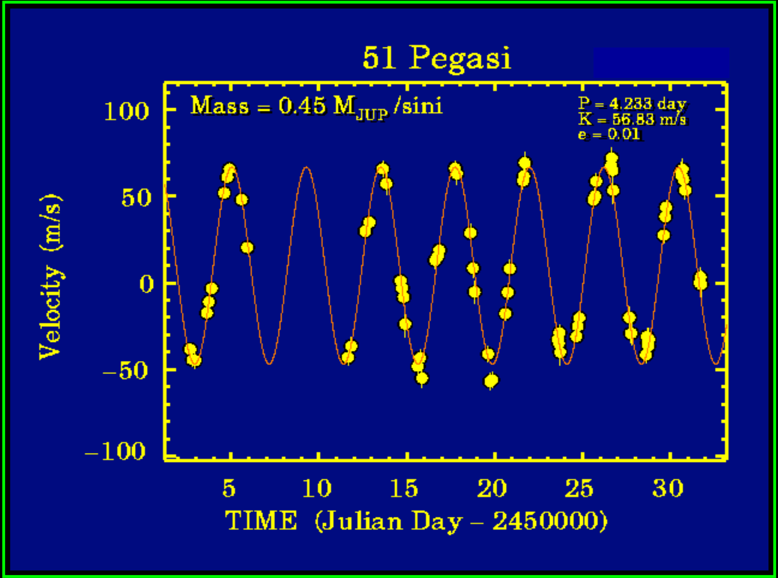
for a circular orbit

Other planetary systems

“Hot Jupiter”

The first exoplanet around a Sun-like star was discovered in 1994 by Swiss astronomers *Michel Mayor* & *Didier Queloz* with sensitive Doppler velocity measurement techniques pioneered at UBC and UVic



Other planetary systems

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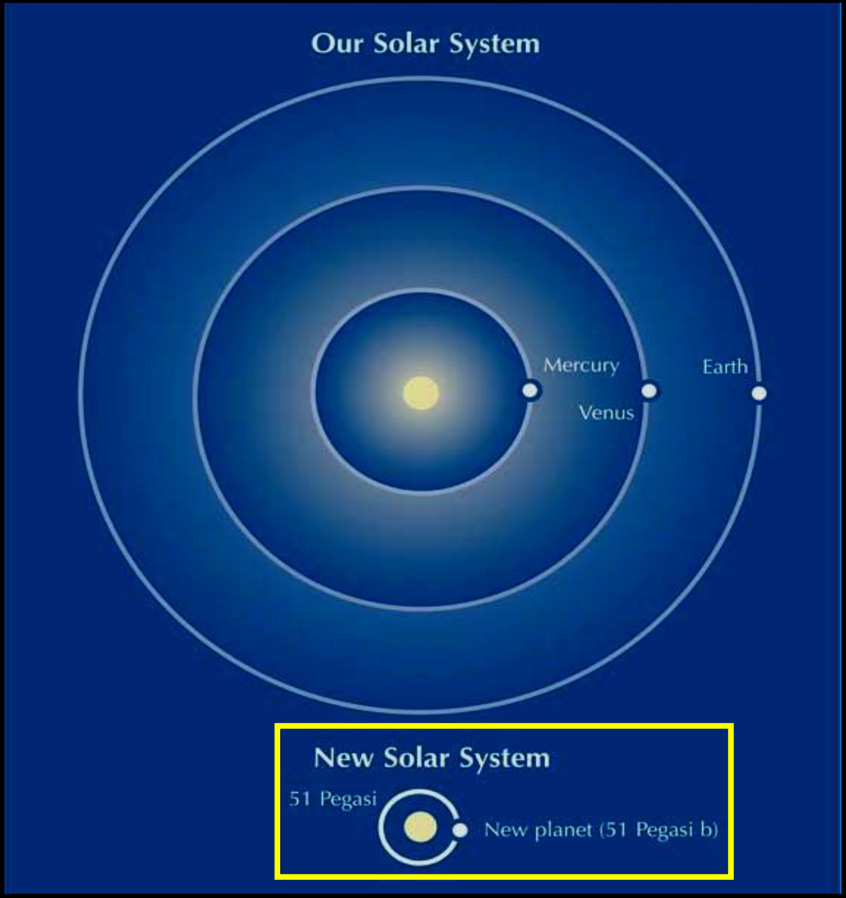
51 Pegasi was a surprise. The planet’s mass is at least <u>½ that of Jupiter</u> but its semi-major axis is only <u>1/20 AU</u>



Other planetary systems

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Other planetary systems

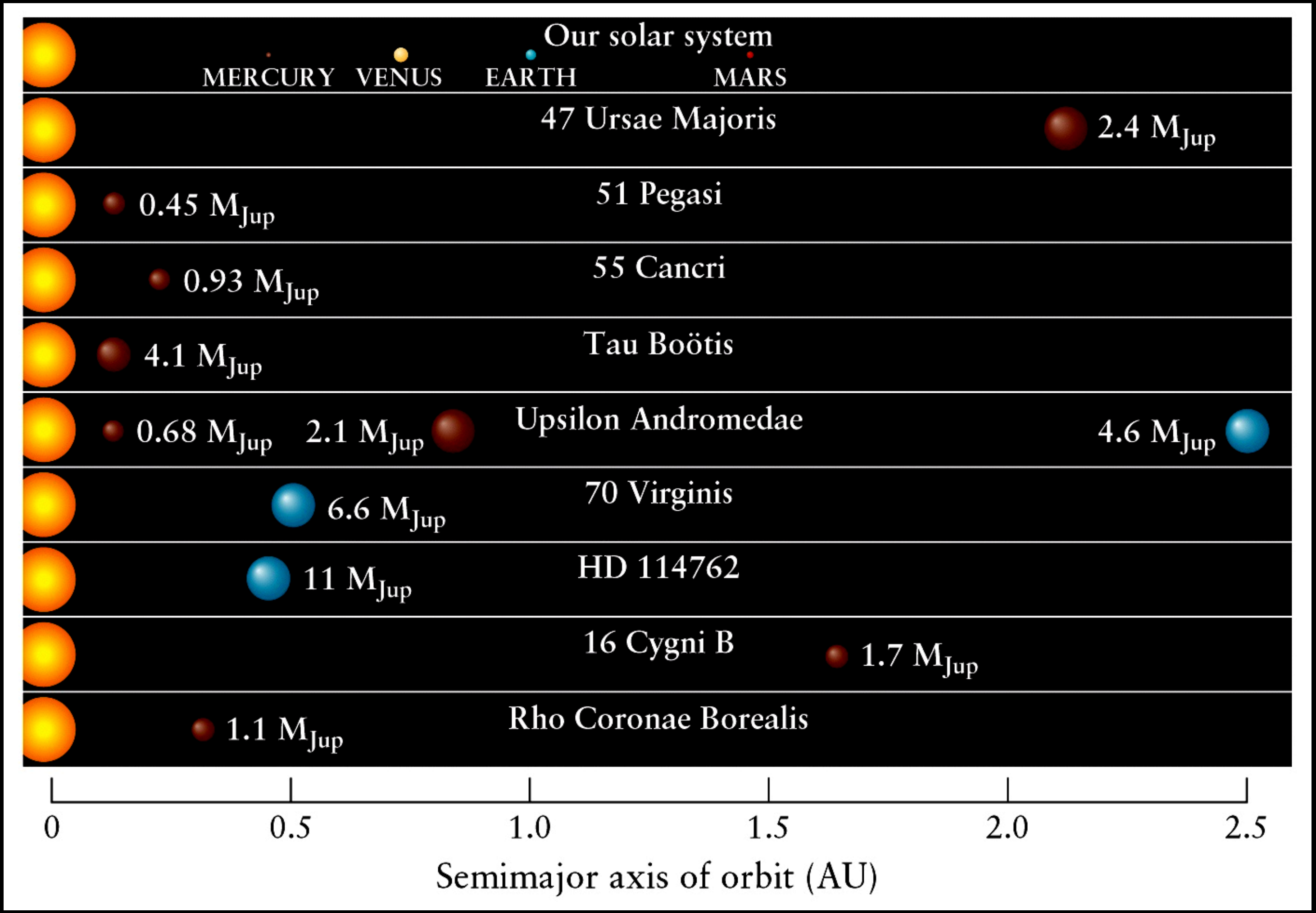
"Hot music?"

51PEG

A NEW BREED OF ELECTRONIC ROCK

Other planetary systems

More exoplanets



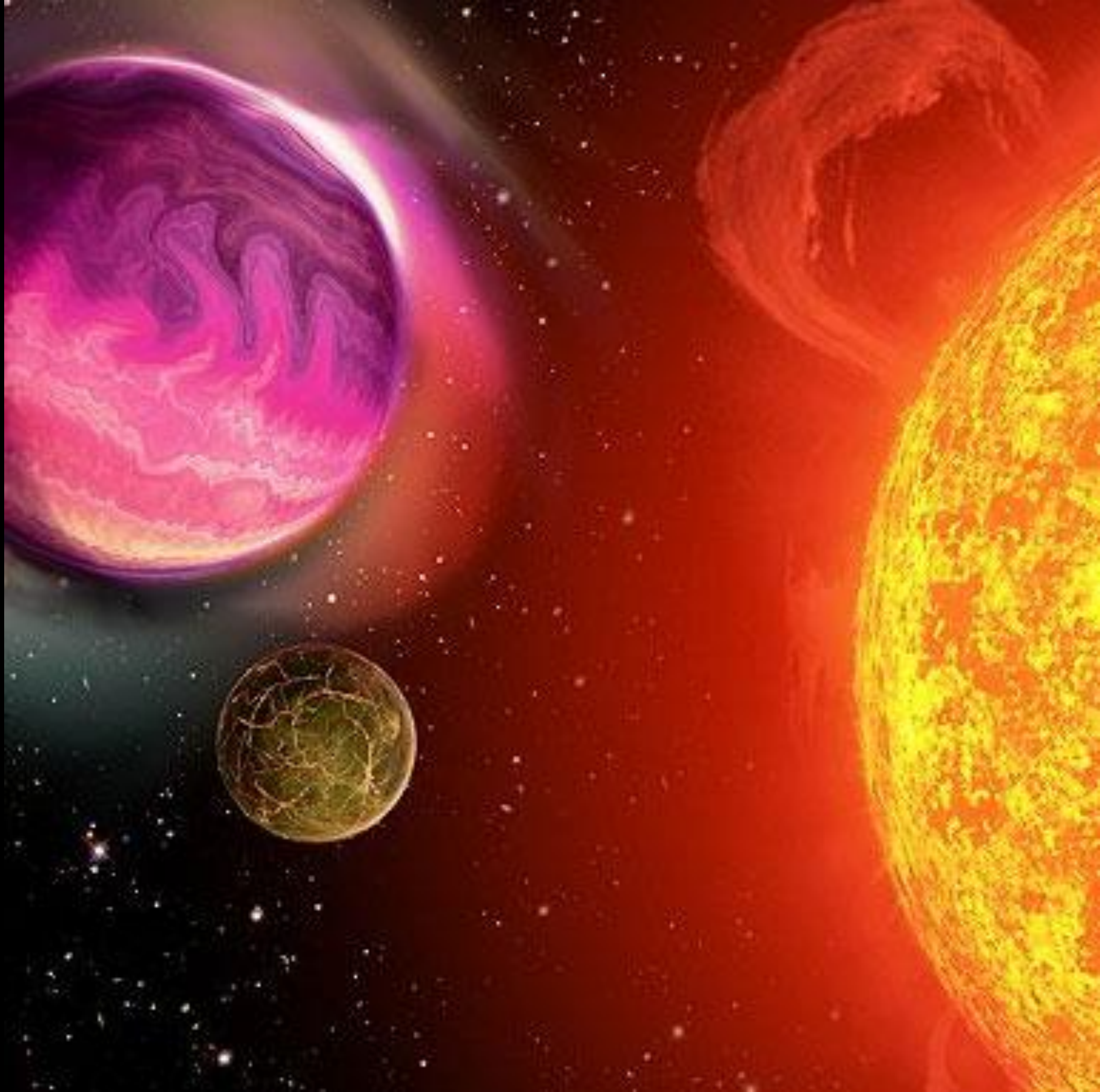
Other planetary systems

More obscure bands

47 UMa

Reggae, World Rhythms and More

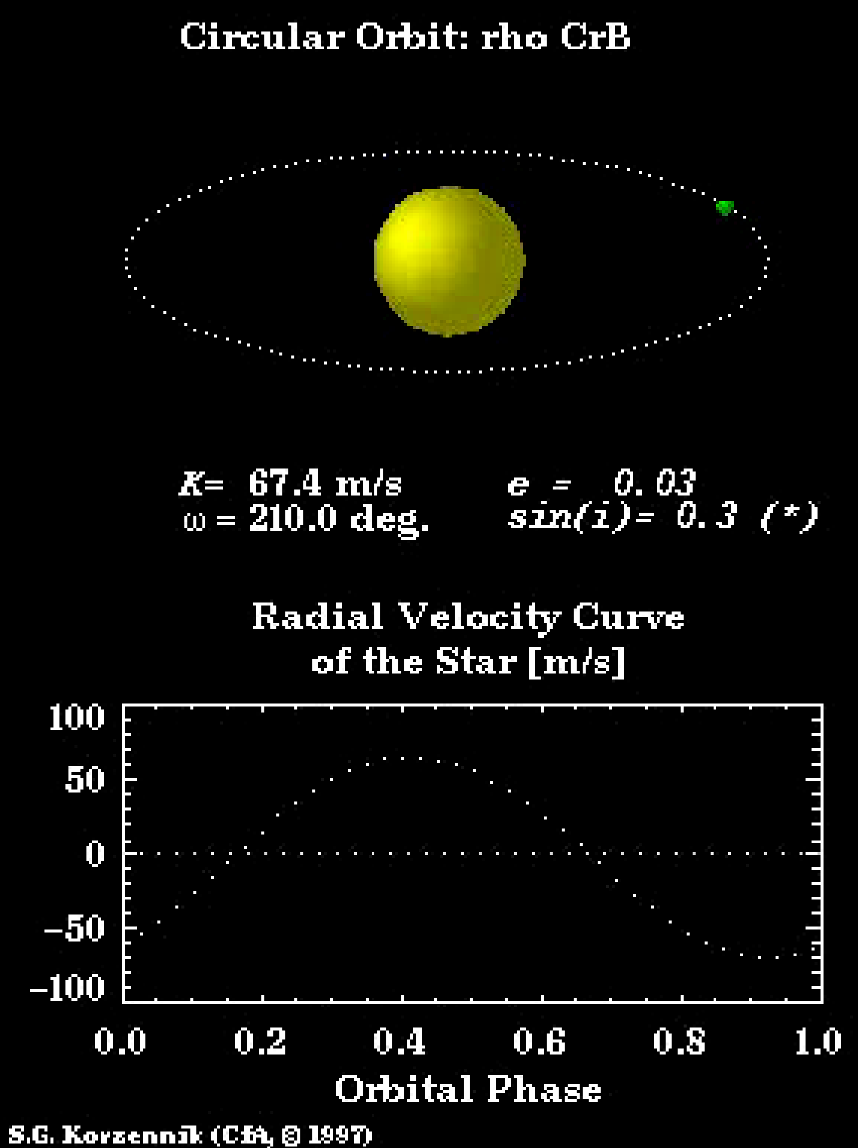
Any questions?



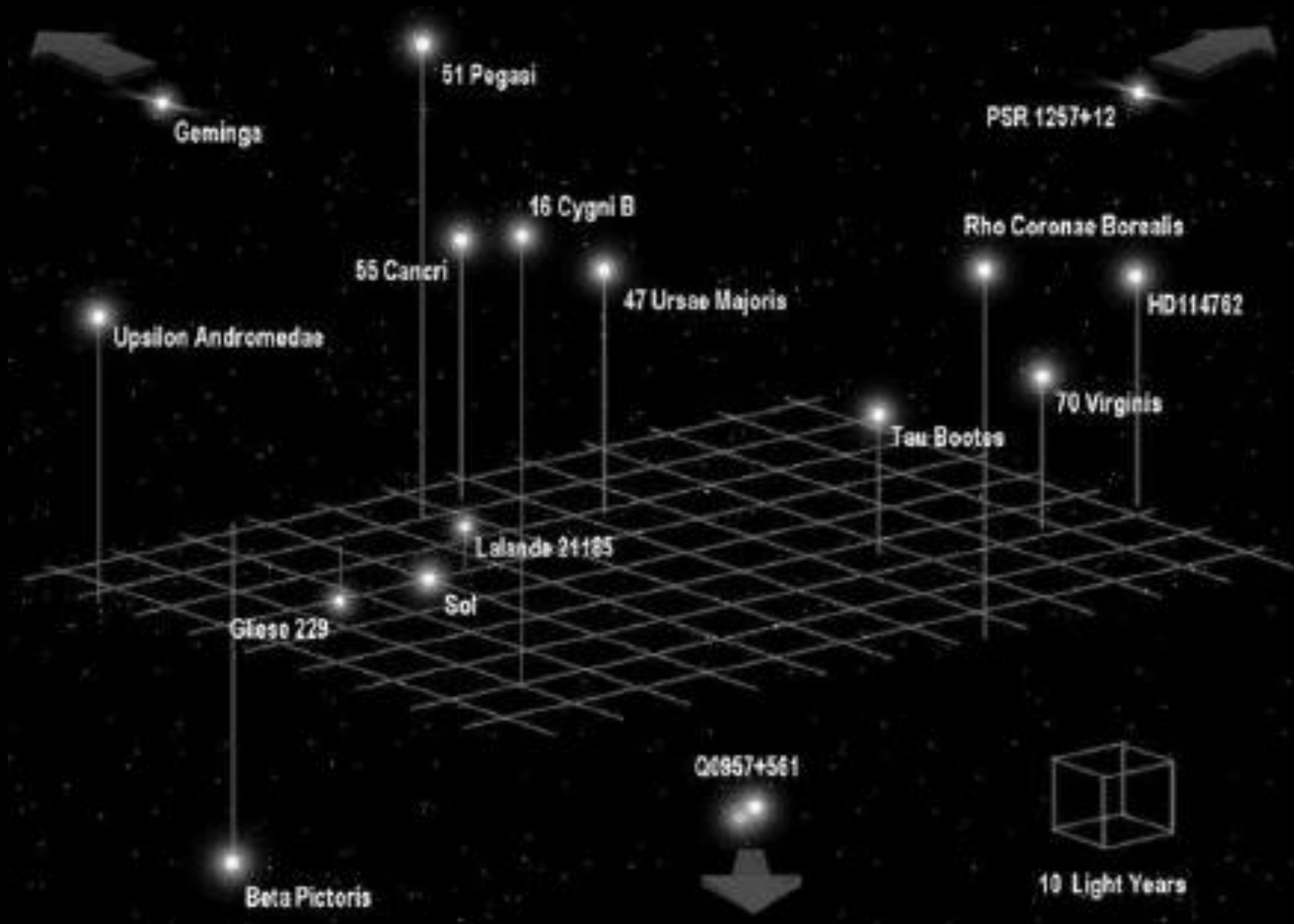
Other planetary systems

More exoplanets

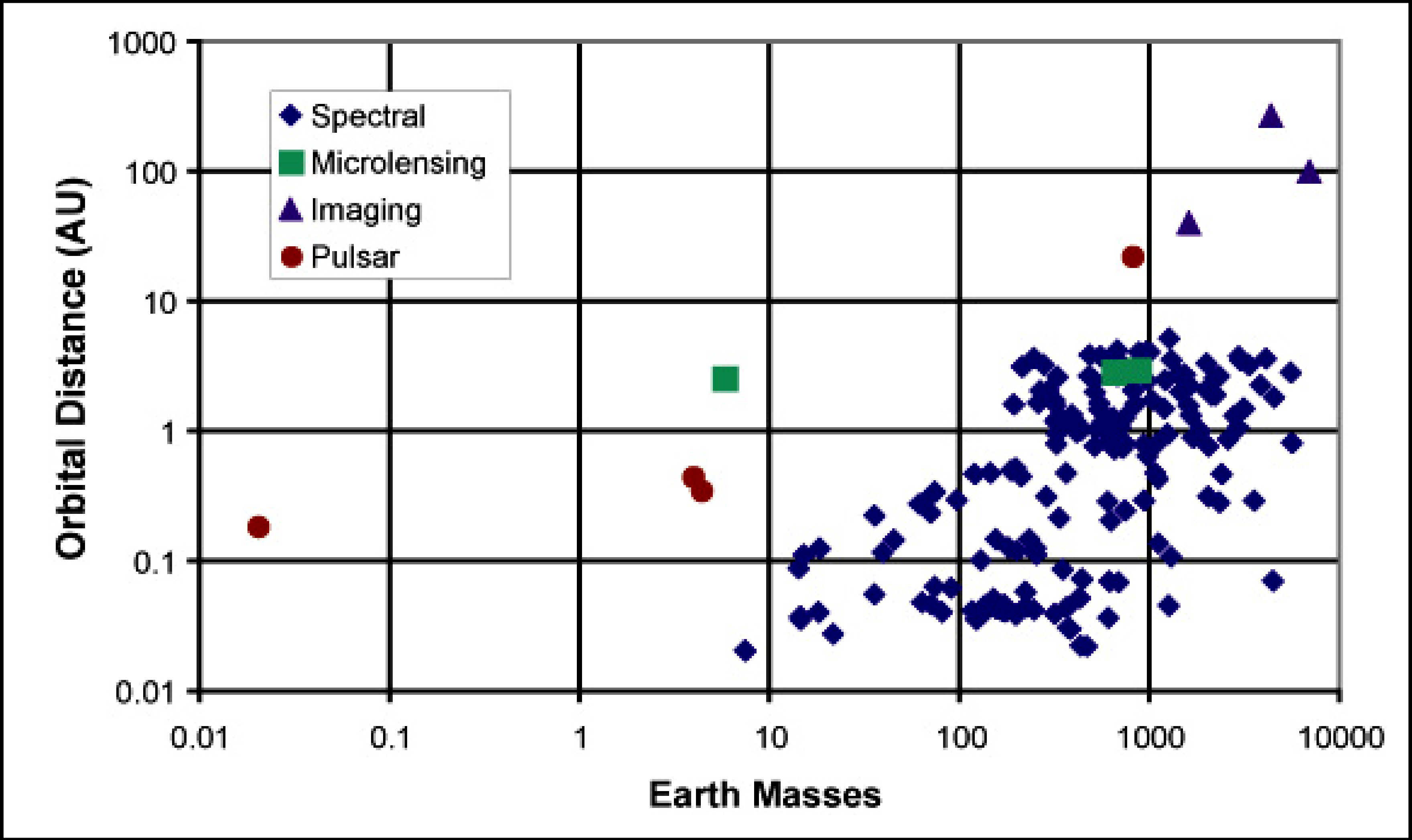
There are currently
429 exoplanets
as of this morning
known around other
Sun-like and red dwarf stars
mostly discovered through
the wobble of each star
seen through the star's
changing radial velocity
because of the Doppler shift



Other planetary systems

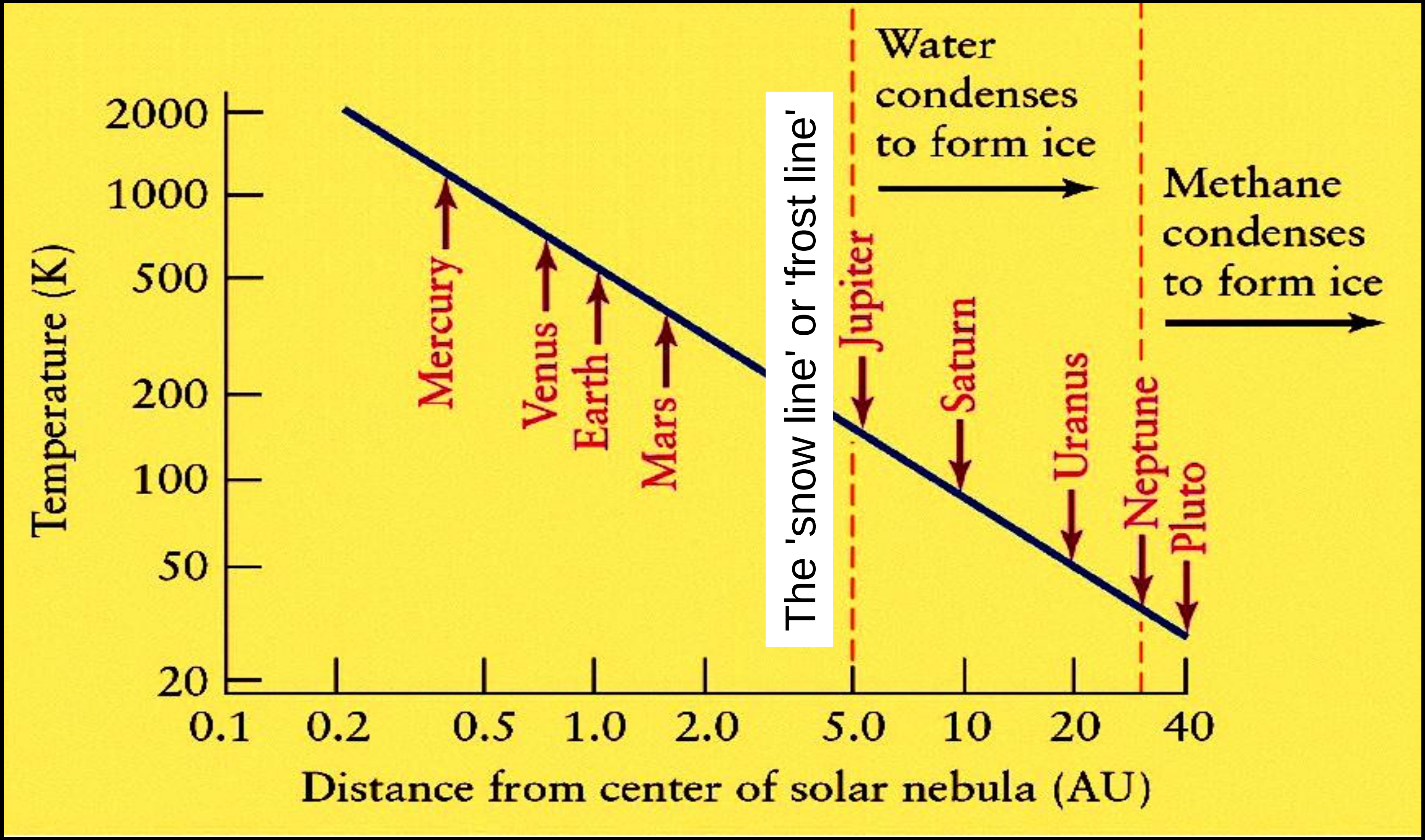


Other planetary systems



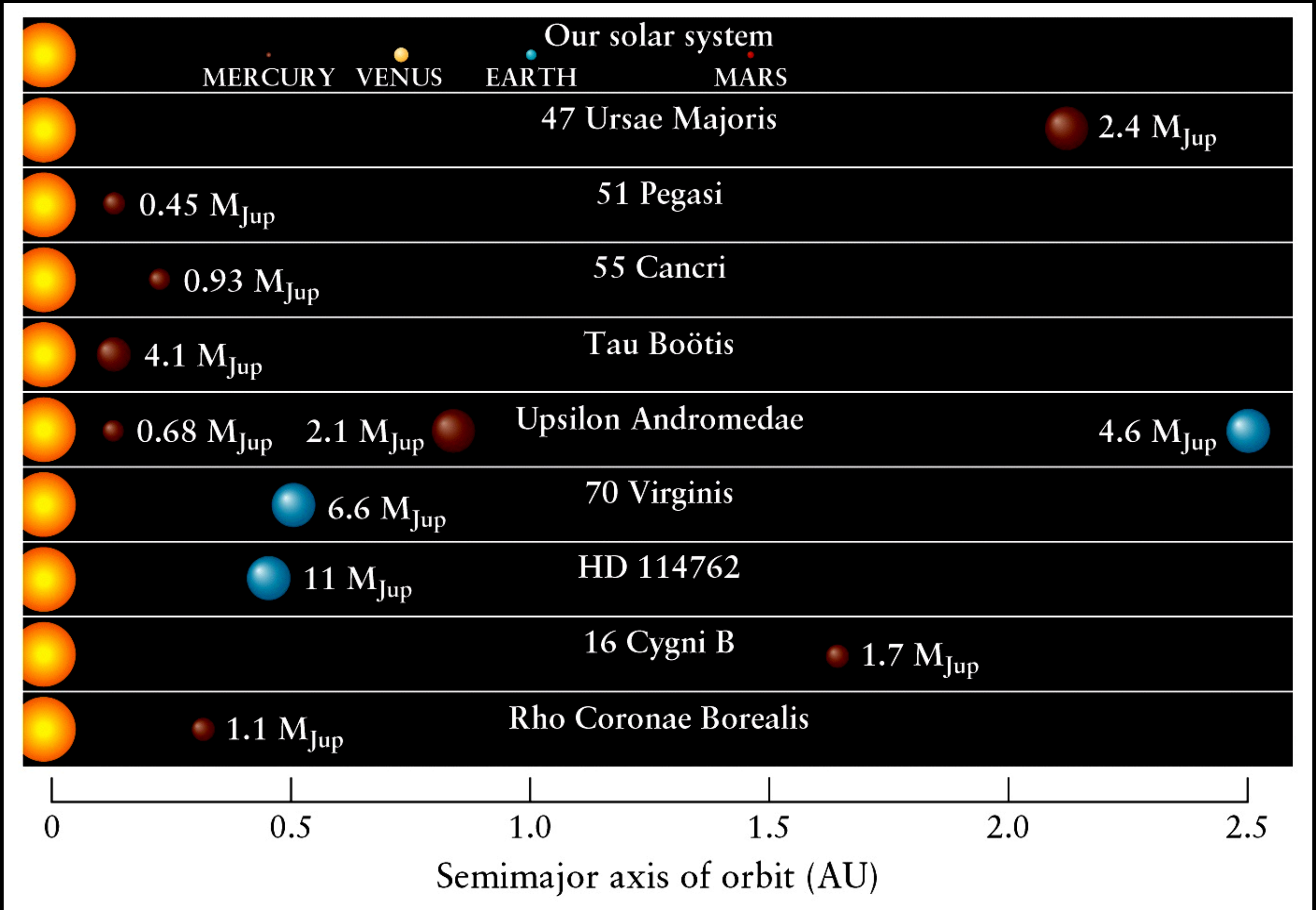
Other planetary systems

Condensation in the protoplanetary nebula



Other planetary systems

How do you form a hot Jupiter?

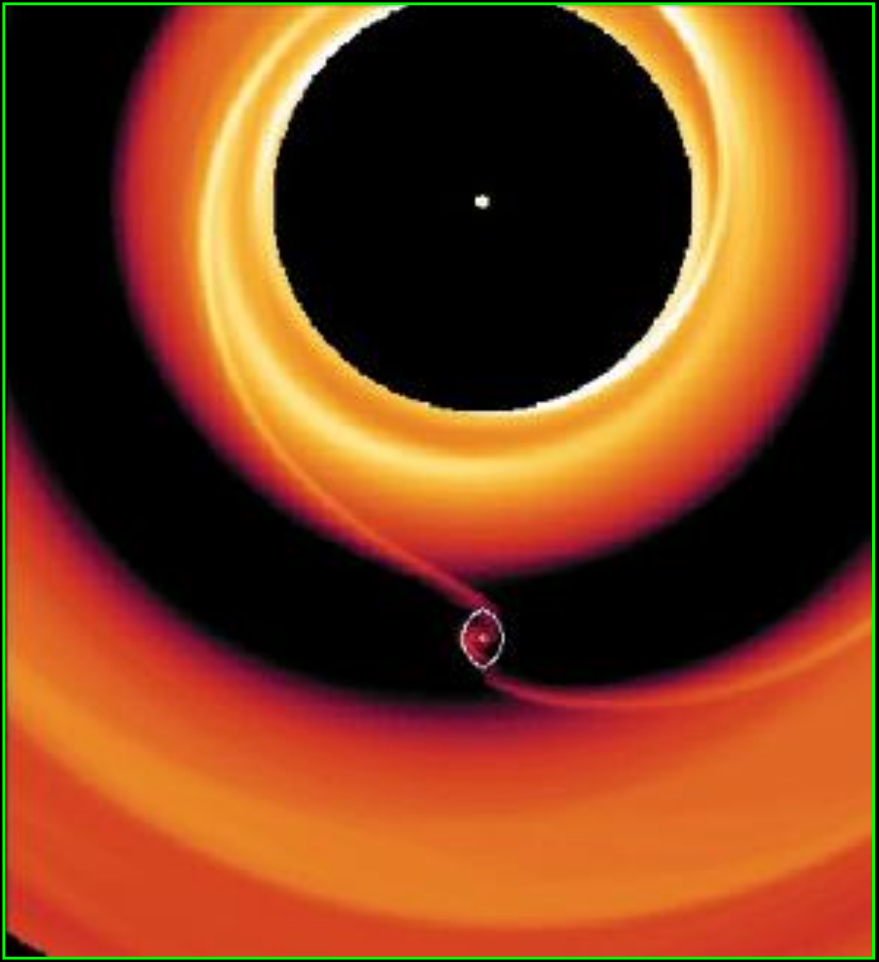


Other planetary systems

Planetary migration

Tidal interactions between the forming planet and the gas and dusk in the protoplanetary disk can cause the planet to slowly spiral towards the star

A gas giant can form near 5 AU (like Jupiter in our Solar System) and then migrate inward, pushing the inner parts of the disk to fall into the star



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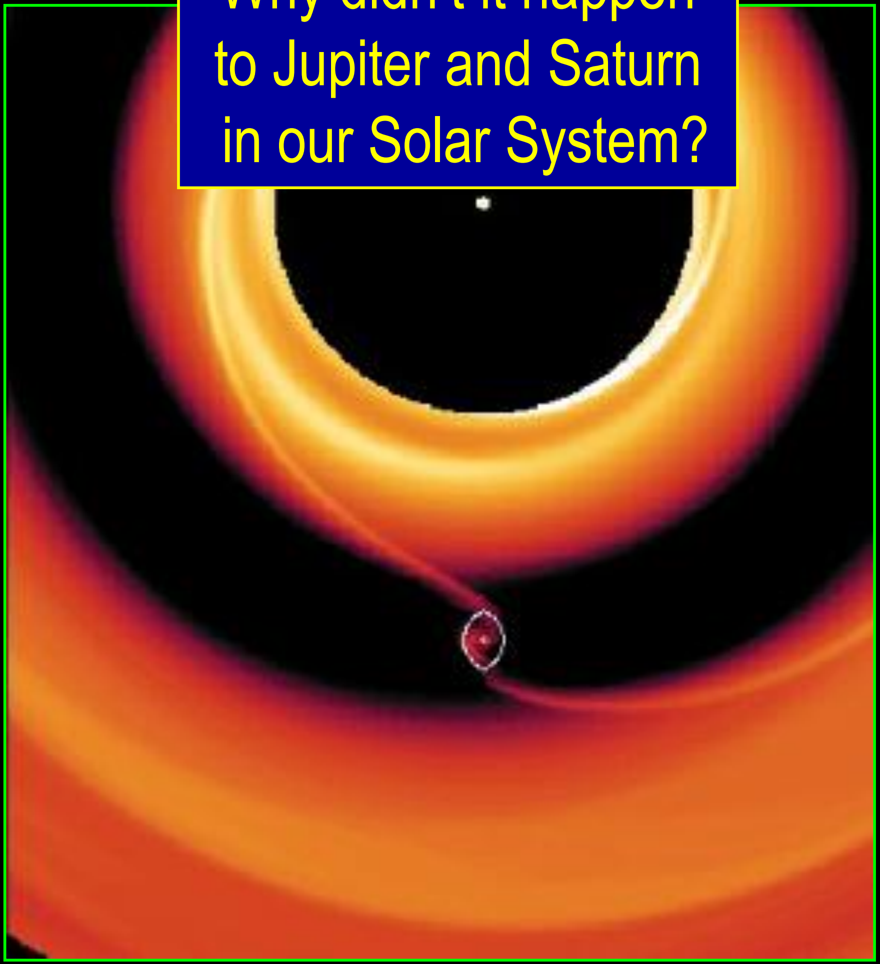
Why didn't it happen to Jupiter and Saturn in our Solar System?



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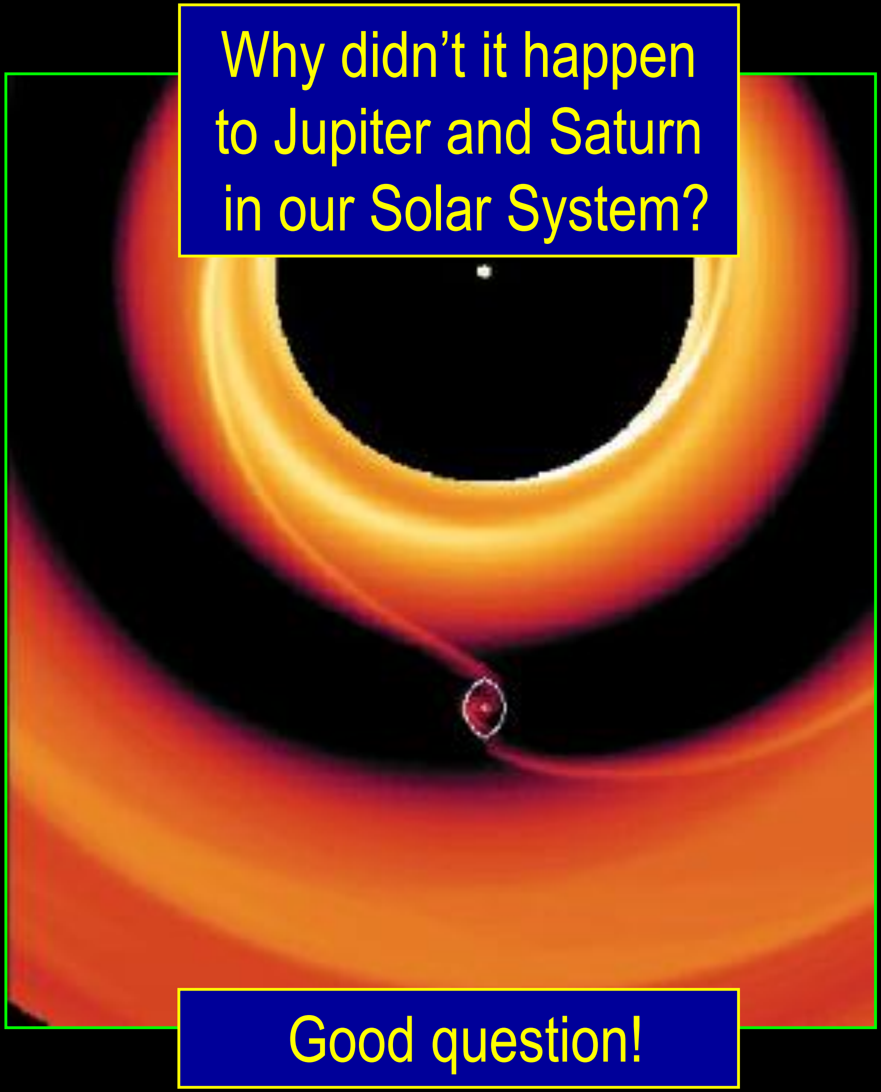


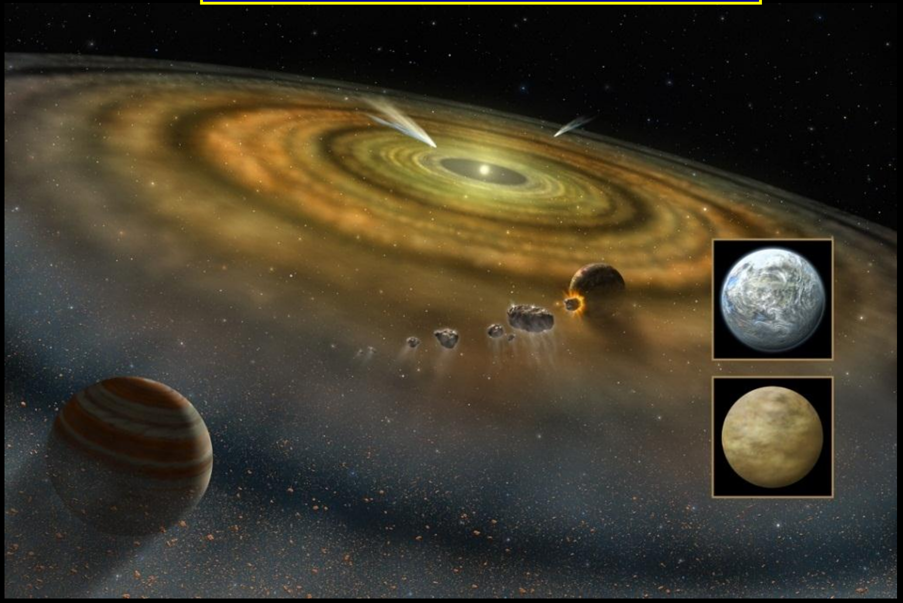
Other planetary systems

Planetary migration

It may be a matter of timing

The giant planets in other systems may have formed while there was still a dense disk of gas & dust with which they could tidally interact and be dragged inward

Why didn't it happen to Jupiter and Saturn in our Solar System?



Other planetary systems

Planetary migration

It may be a matter of timing

In our Solar System
the protoplanetary disk may
have been cleared by the
strong early solar wind just
as the Jovian planets
had condensed

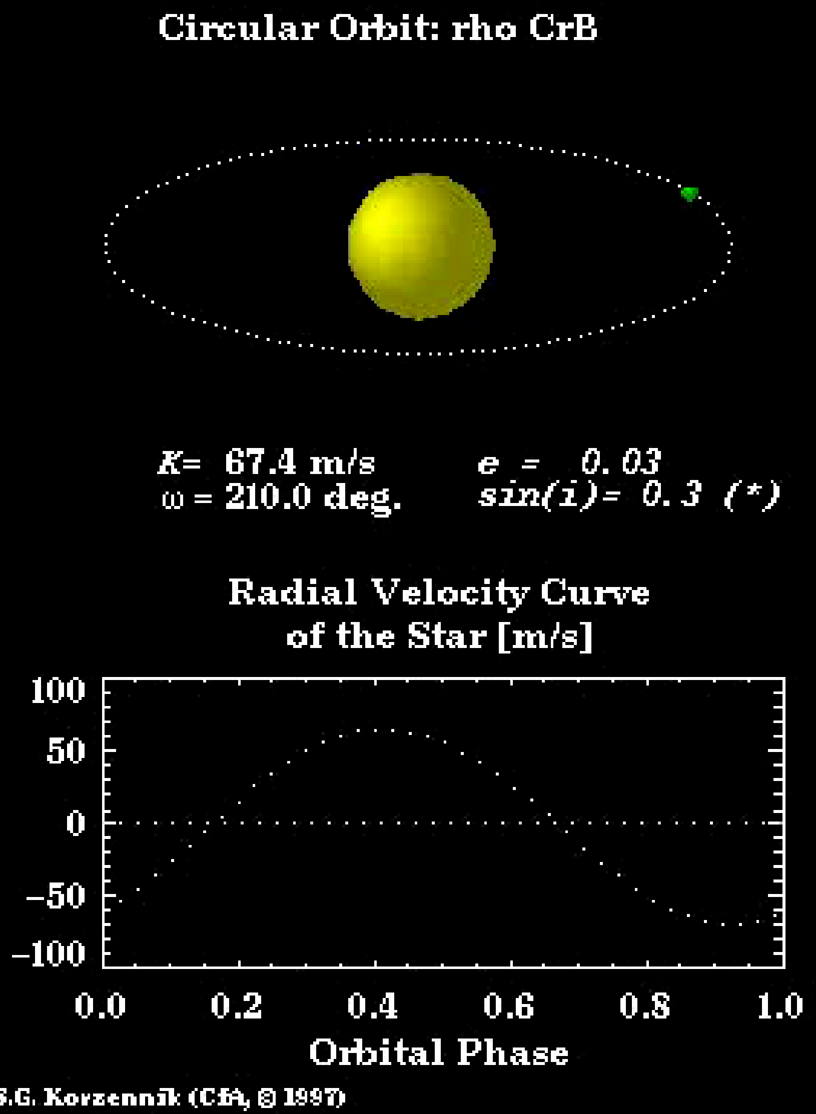
Why didn't it happen
to Jupiter and Saturn
in our Solar System?

There would have been no tidal interaction to trigger migration

Other planetary systems

Exoplanet orbits

The "hot Jupiters" (which have the smallest orbits) tend to have low eccentricities *e ~ 0* (almost circular orbits)



Other planetary systems

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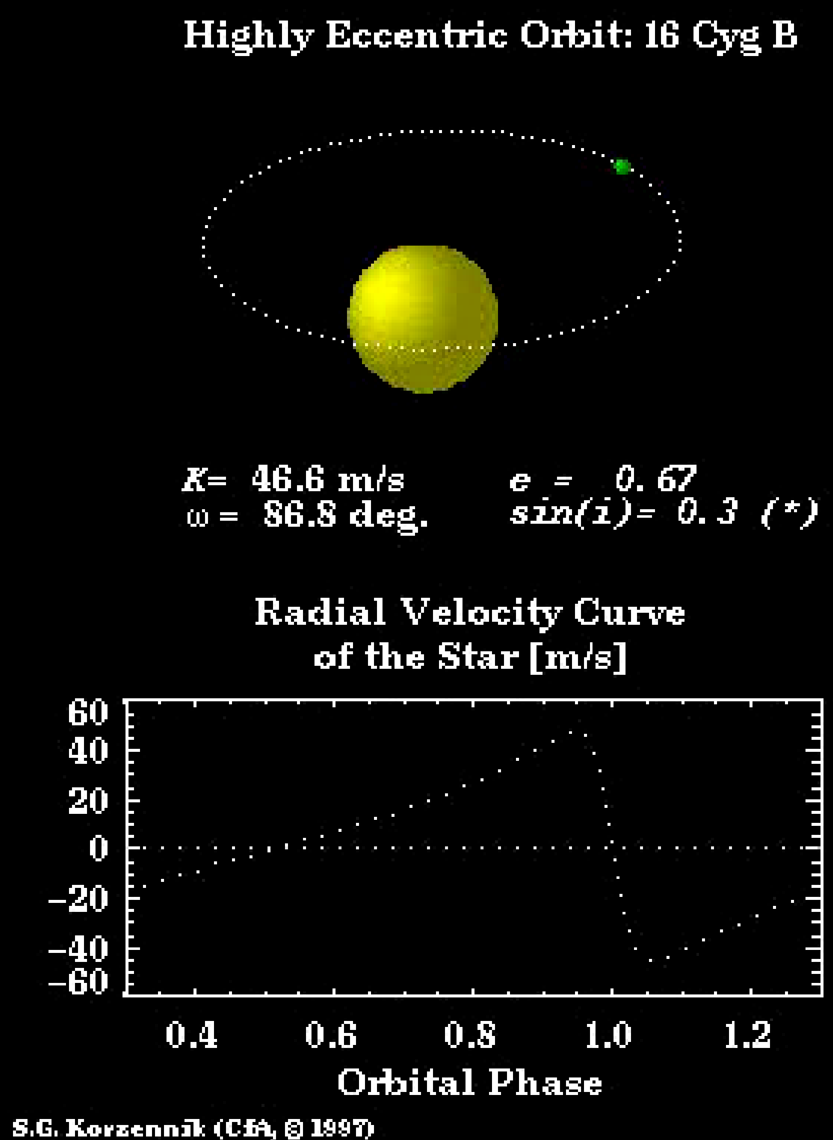


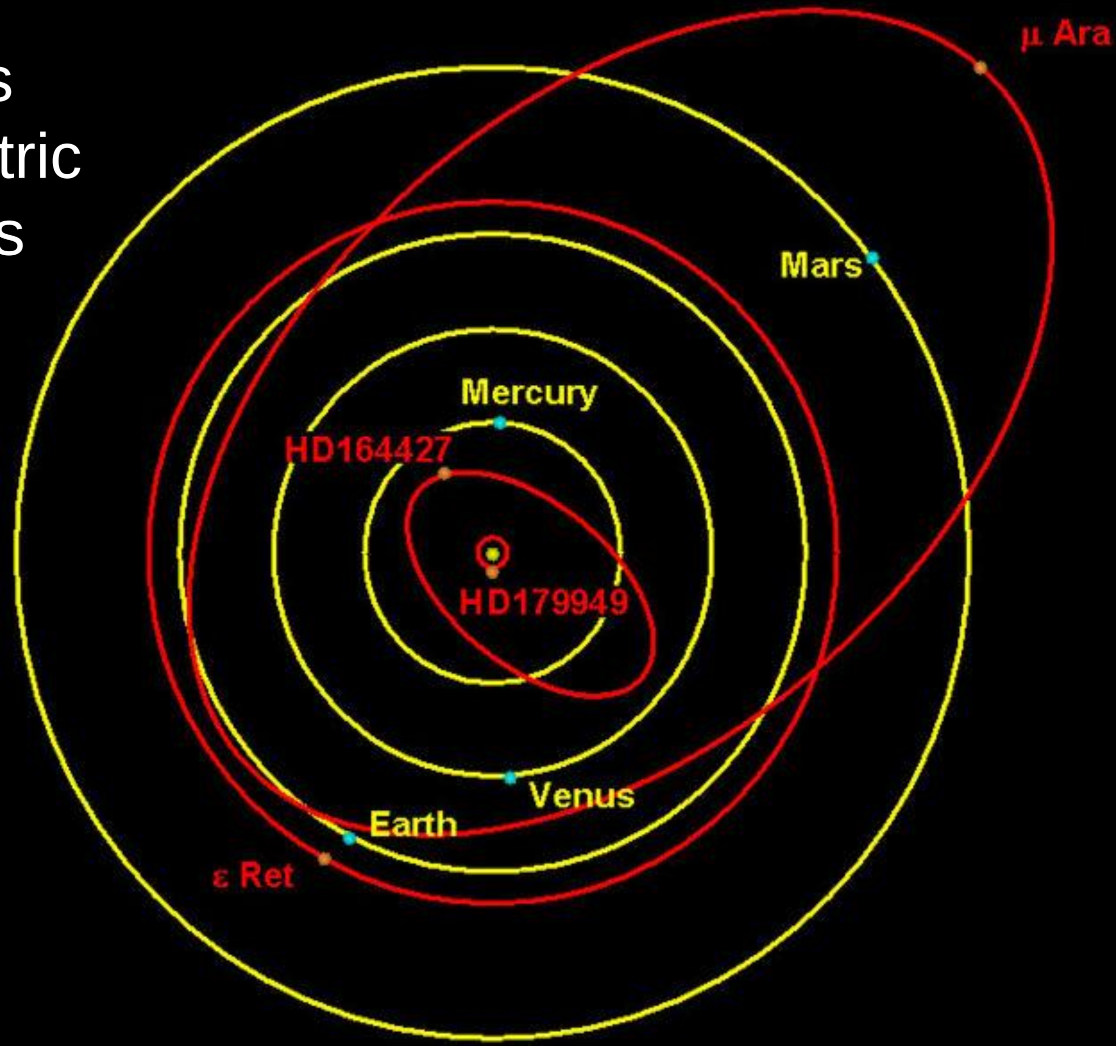
But many exoplanets have highly eccentric orbits

e.g., 16 Cygni Bb *e = 0.67*

Other planetary systems

Orbital eccentricities

Many of the exoplanets found have very eccentric orbits unlike the planets in our Solar System



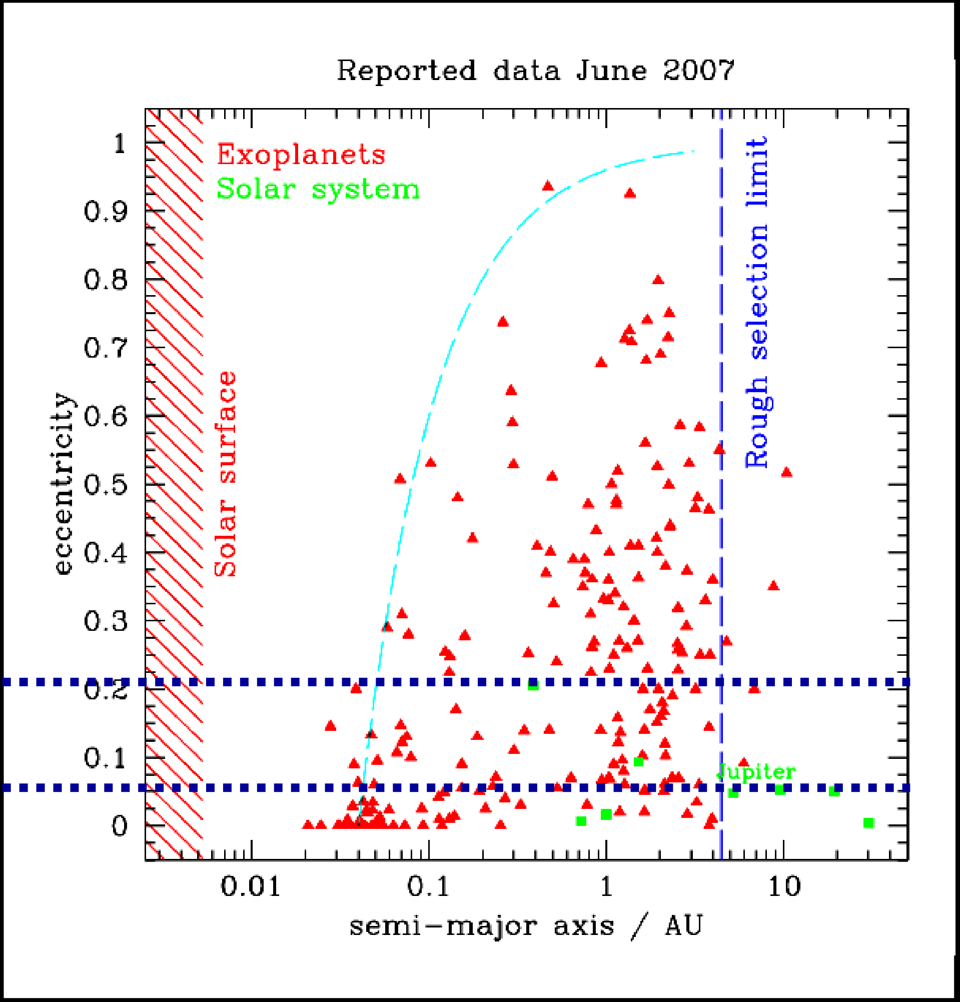
Other planetary systems

Orbital eccentricities

Many of the exoplanets found have very eccentric orbits unlike the planets in our Solar System

largest eccentricity of a planet in Solar System (Mercury)

6 of 8 planets in Solar System have eccentricities less than this



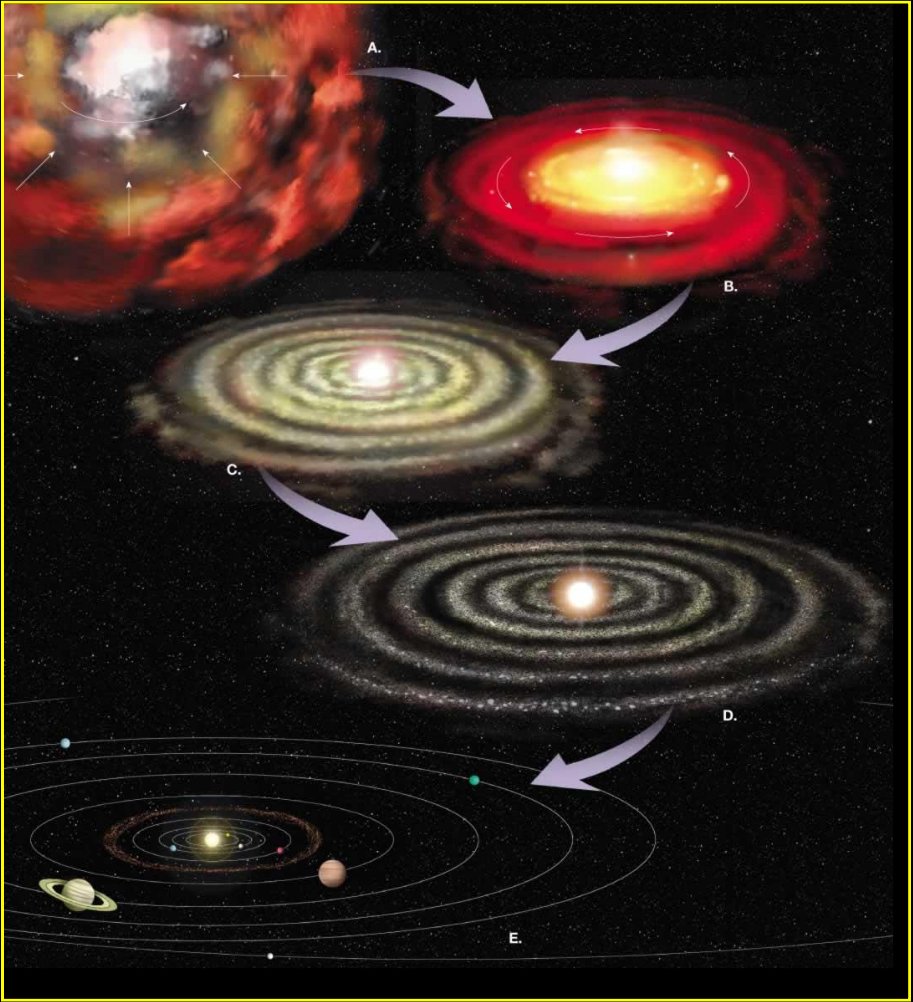
Other planetary systems

Opening our eyes to new perspectives

Planetary astrophysics is finally becoming a statistical science with a sample larger than one

There are “selection effects” in our current sample of exoplanets, biased towards giant planets in small orbits

But there are hints that our Solar System may not be as “typical” as astronomers had assumed for many decades

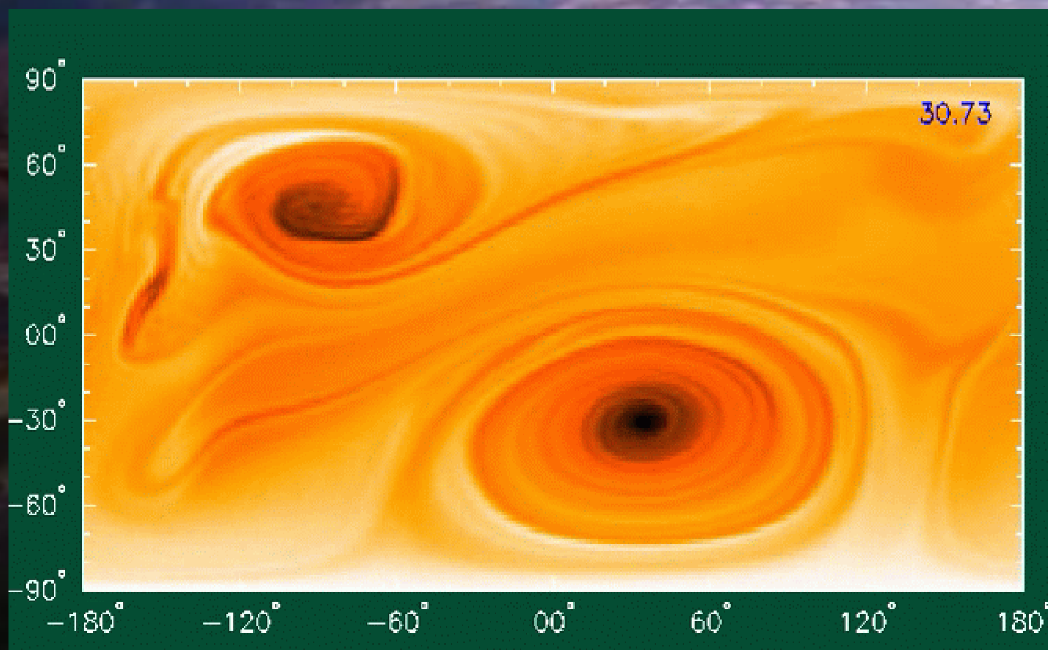



Alien worlds
artist's conception


Alien worlds like Pandora
Cameron’s conception

Alien worlds like Pandora

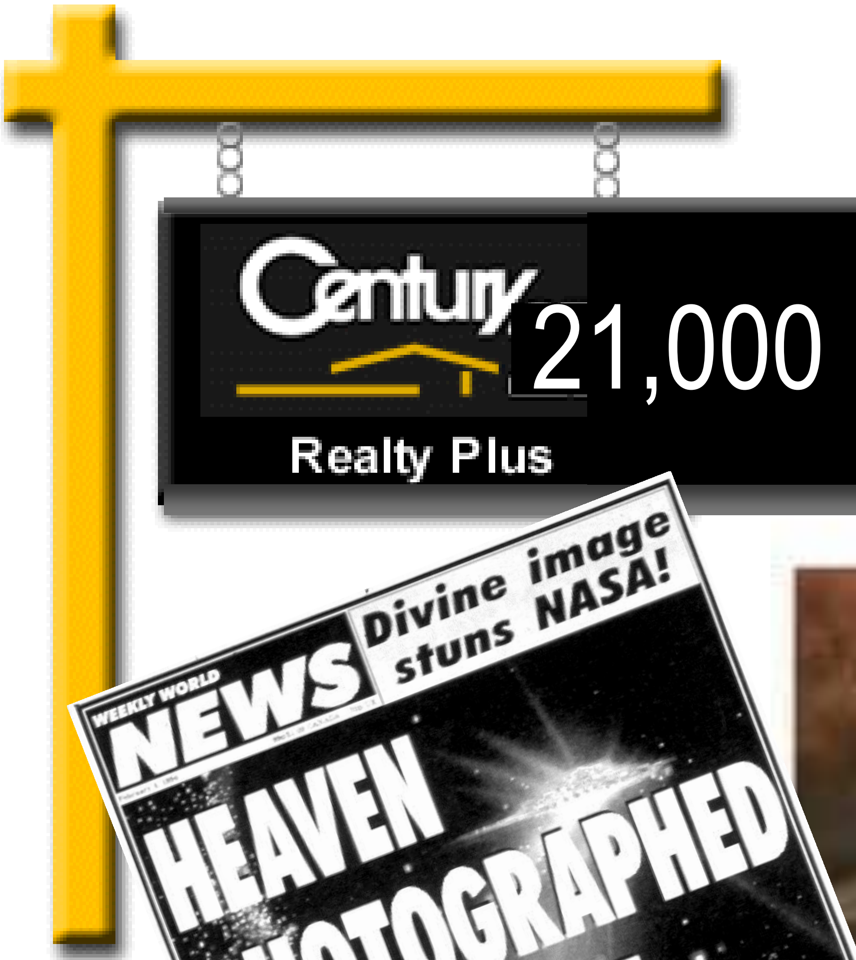
Cameron's conception



Alien worlds


Alien real estate

I've become a
real estate agent
to science fiction writers




WEEKLY WORLD NEWS

Divine image stuns NASA!

HEAVEN PHOTOGRAPHED BY HUBBLE TELESCOPE

'We found where God lives,' says scientist