WHERE DO WE SEARCH FOR LIFE IN THE UNIVERSE?

What makes the Earth unique?

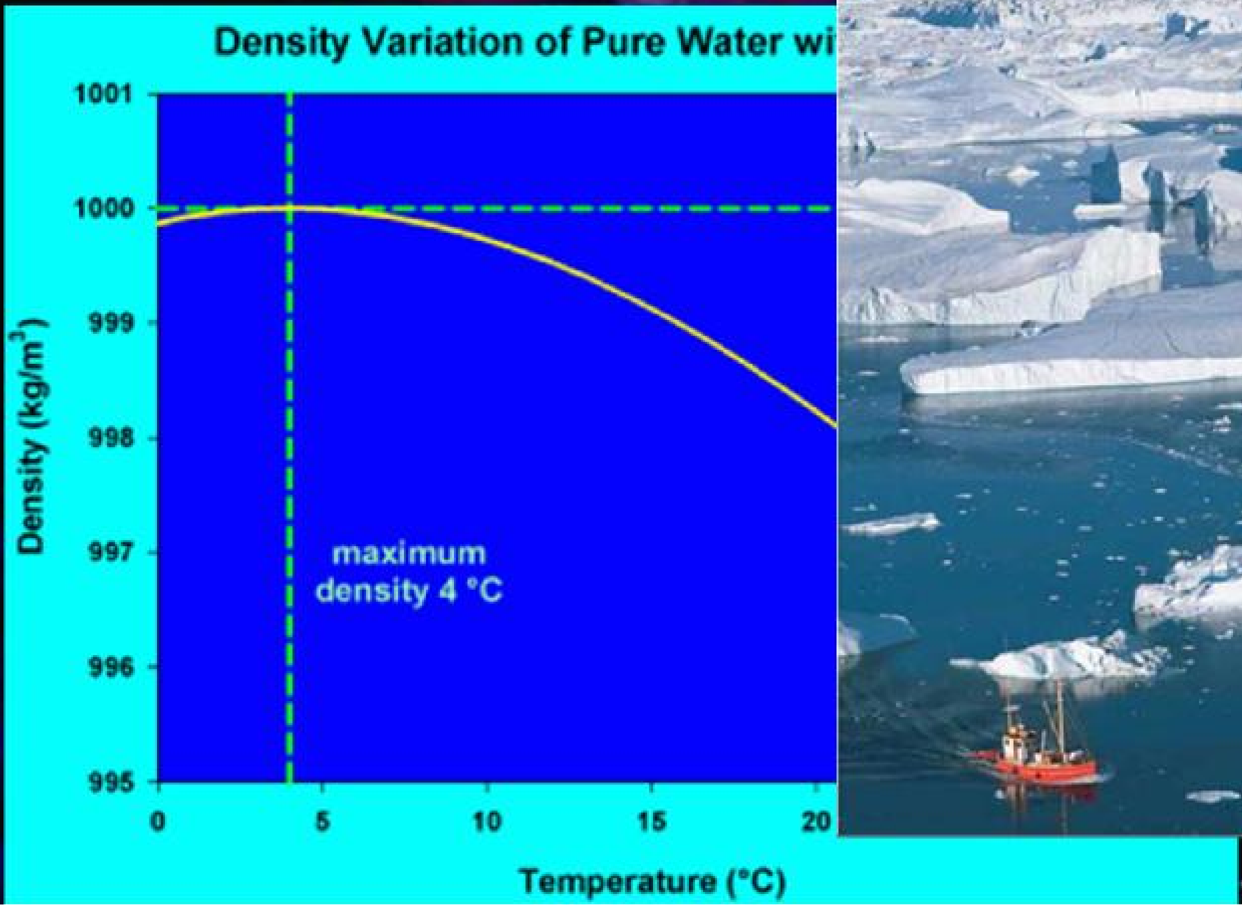
- Source of “heavy elements”
- Distance from the Sun (The Habitable Zone)
- Planetary Mass (Escape Velocity)
- Solid Body (Provides a stable surface)
- Possession of a relatively large natural satellite

The Role of H_2O As a Solvent

- Provides a fluid for nutrients to float in.
- Has the ability to dissolve other chemical compounds.
- Requires a temperature between 0 - 100°C to remain liquid
- Helps regulate the temperature in cells.
- High heat capacity (minimizes the effect of sudden heat changes)
- High heat of vaporization

(Ammonia & Methyl Alcohol are comparable but not as versatile)

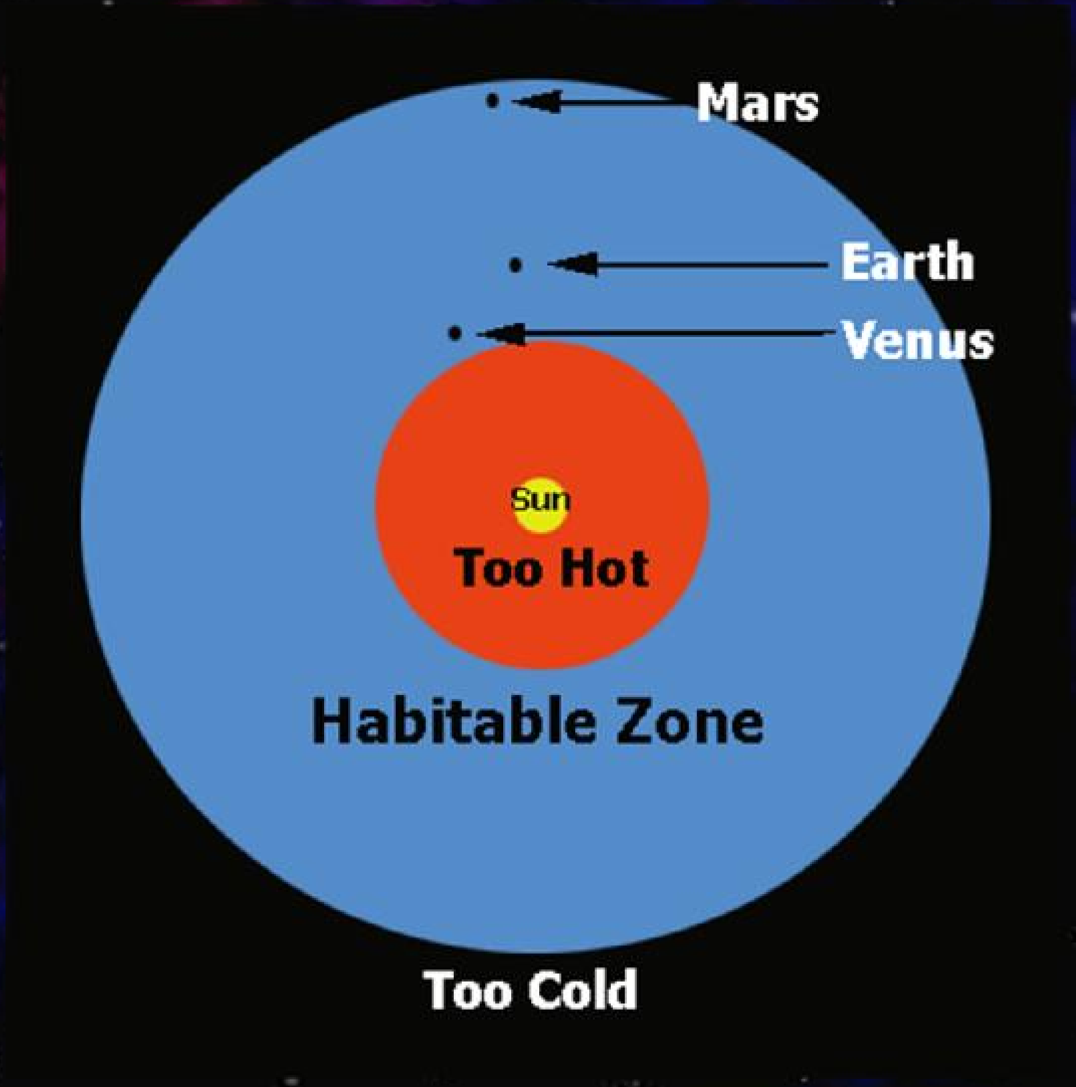
The Role of H_20 As a Solvent



The Role of H_20 As a part of the mantle/crust

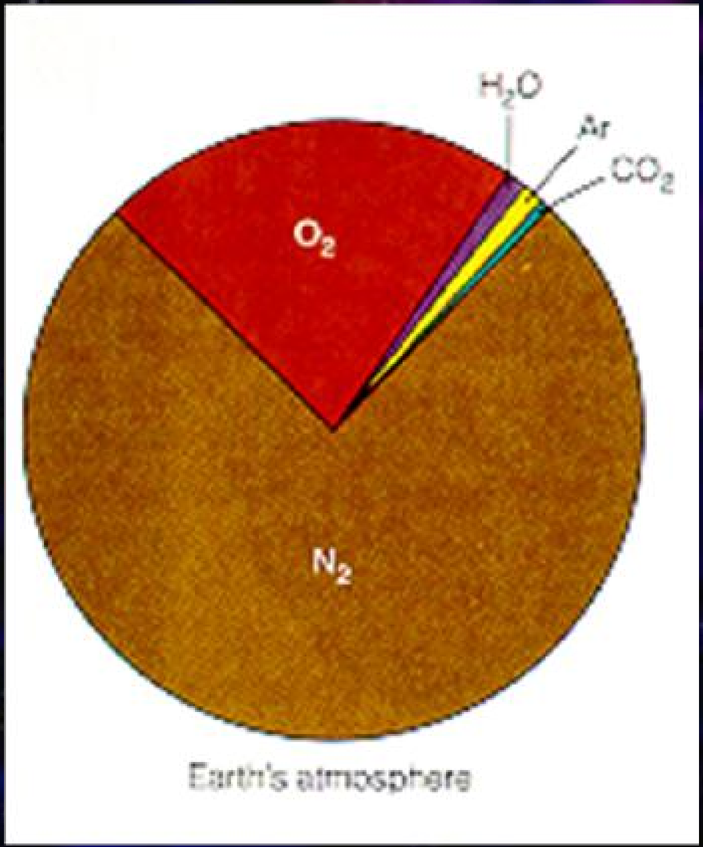
- Becomes a hydrated part of mineral structure
- Dramatically lowers melting point of rock
- Lowers viscosity of lava (flows more easily)
- Anywhere from 0.5 to 2.5 times surface water volume locked up
- Elasticity of crust greatly augmented: leads to crust being readily deformed
- Lubricates movements of plates on the mantle
- Venus does not have hydrated minerals, rock melts much higher, crust and mantle much stiffer-no tectonics!!

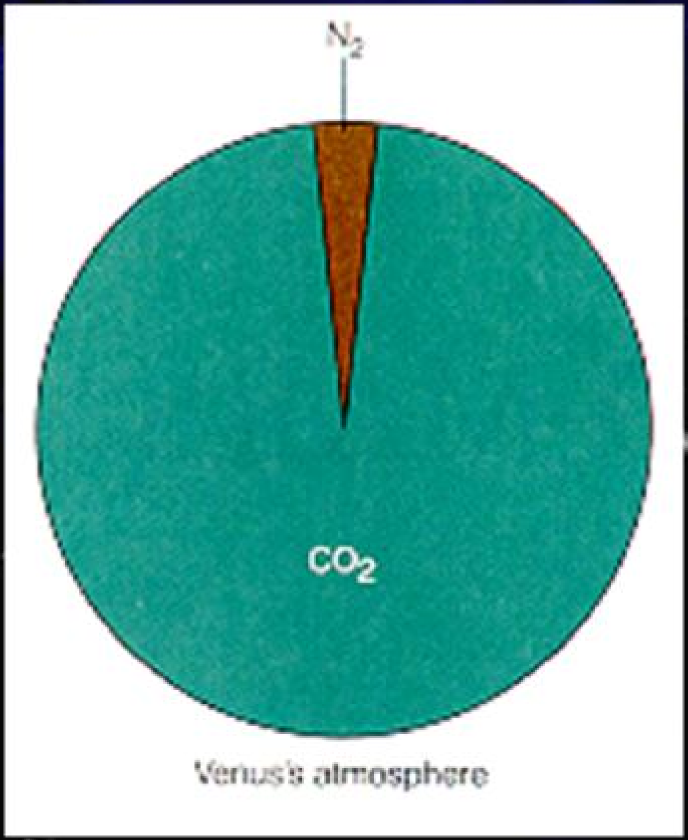
The Habitable Zone
(0.85 – 2.0 AU's)



The Distance From the Sun

Case 1: Too Close (runaway greenhouse effect)

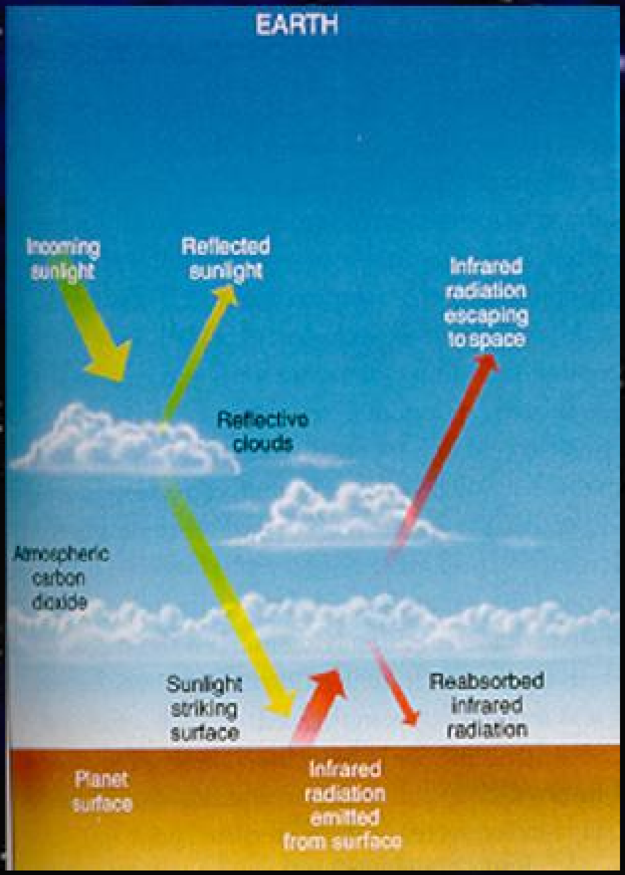




The Distance From the Sun

Case 1: Too Close (runaway greenhouse effect)

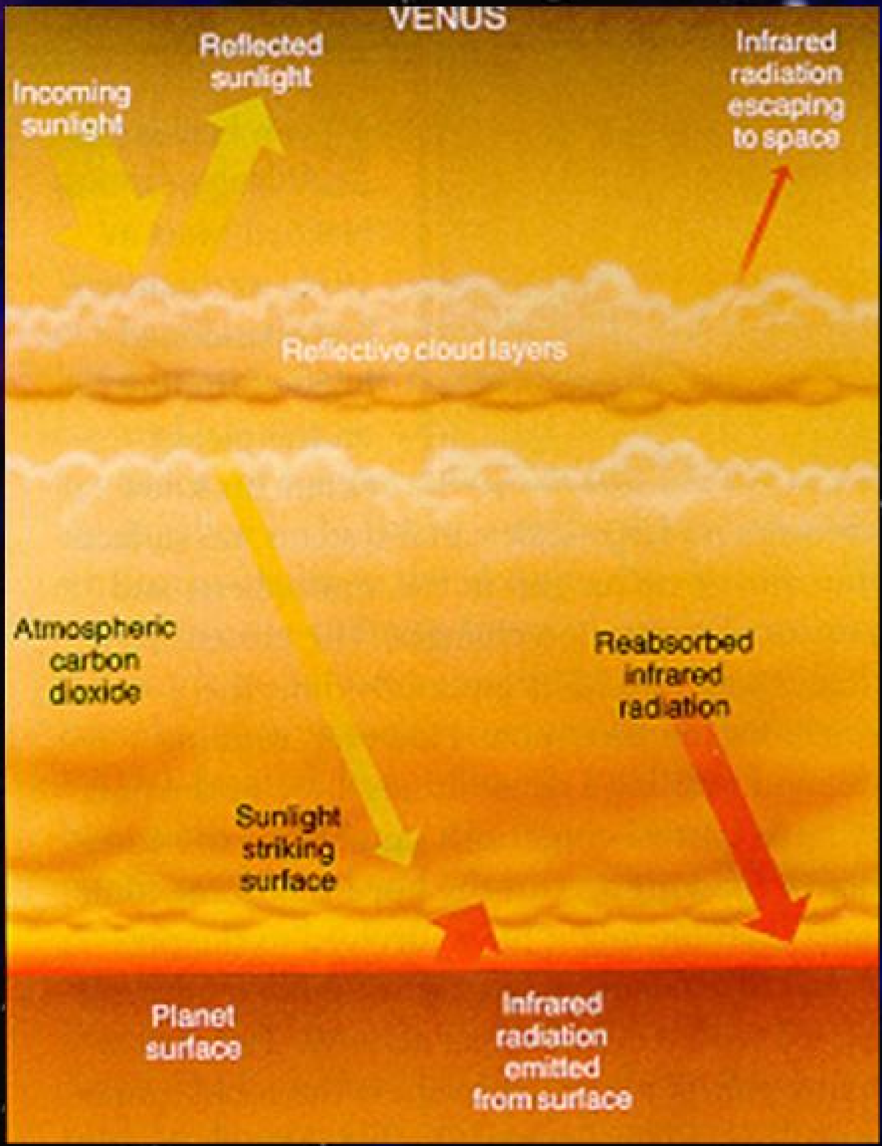
- Start with oceans of water and moderate temperatures
- CO_2 is naturally dissolved in oceans and chemically combined in rocks



The Distance From the Sun

Case 1: Too Close (runaway greenhouse effect)

- Create modest additional heating
- Increased evaporation from oceans & release of CO_2 from rocks
- Increase in atmospheric water vapor & CO_2 amplifies existing greenhouse effect causing increased evaporation and outgassing causing additional heating….



The Distance From the Sun
Case 2: Too Far (runaway refrigerator effect)

- Start with oceans of water and moderate temperatures
- Reduced amount of incoming solar energy cools atmosphere and oceans
- Polar caps increase in size

The Distance From the Sun
Case 2: Too Far (runaway refrigerator effect)

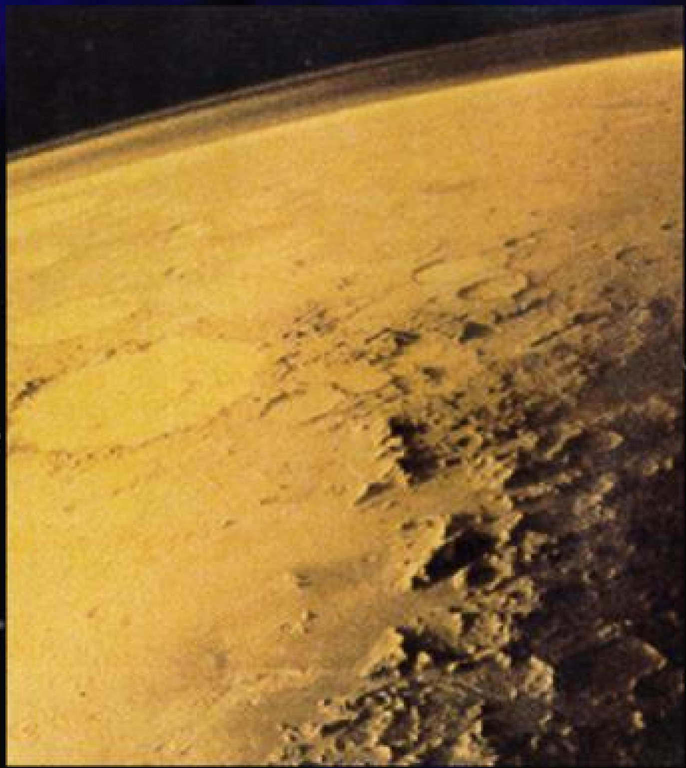
- Leaves less water vapor in atmosphere
- Increases reflectivity of surface which in turn cools atmosphere
- Temperatures drop causing a further increase in polar caps which in turn leaves less water vapor in atmosphere….

Localized Habitable Zones: Natural satellites orbiting unsuitable worlds

Planetary Mass (Escape Velocity)

- Smaller mass planets cannot retain their atmosphere

$$v = \sqrt{\frac{2GM}{R}}$$



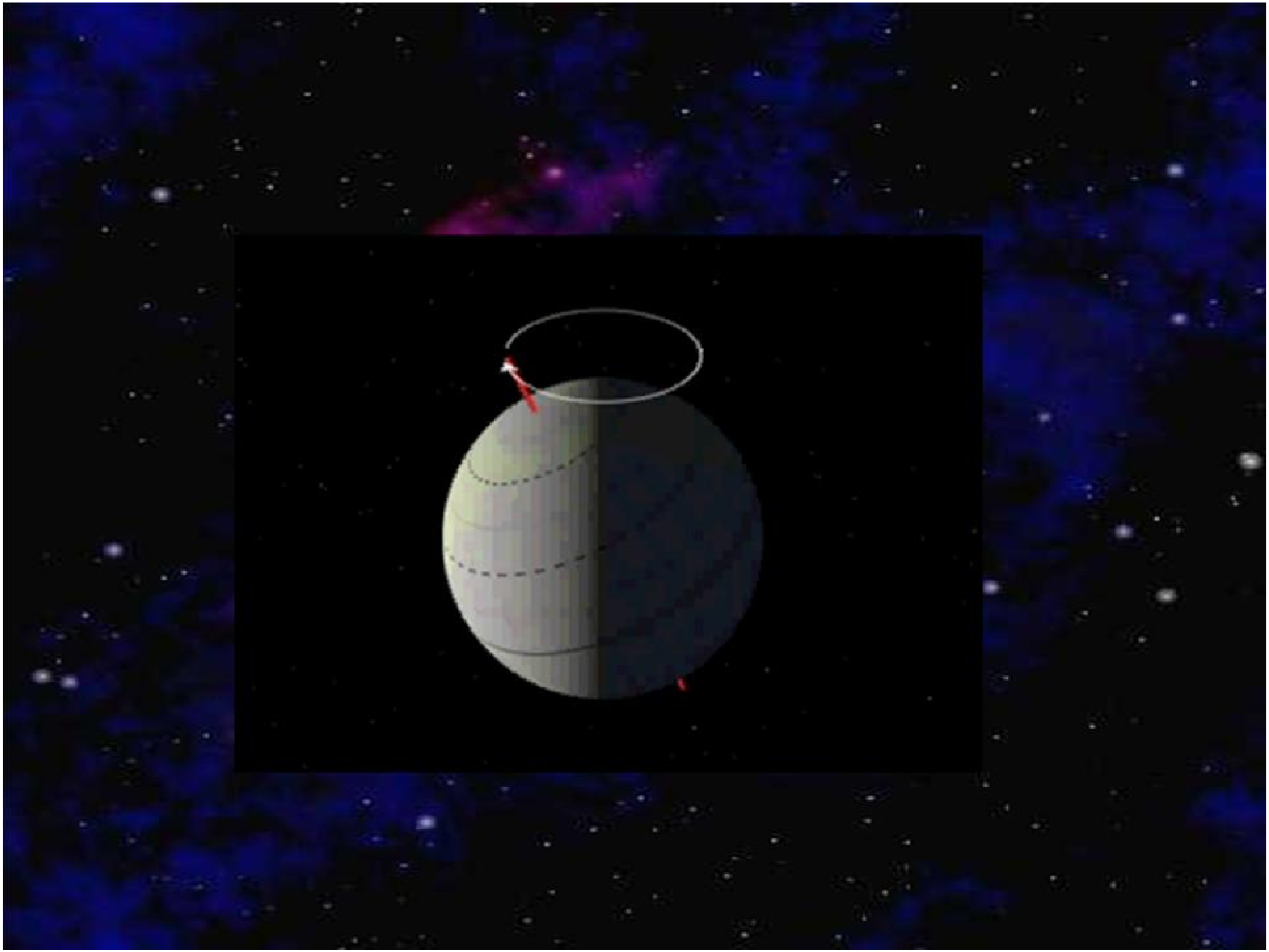
Larger Mass Planets

- Larger mass planets cannot lose their hydrogen
- Presence of hydrogen affects initial chemistry of life

Intermediate Mass Planets

- Outgas longer than small mass planets
- Can retain a sizeable atmosphere
- Survive impacts while retaining their atmosphere
- Plate tectonics

Possession of a Relatively Large Natural Satellite



Are these Earth-like conditions common throughout the galaxy?

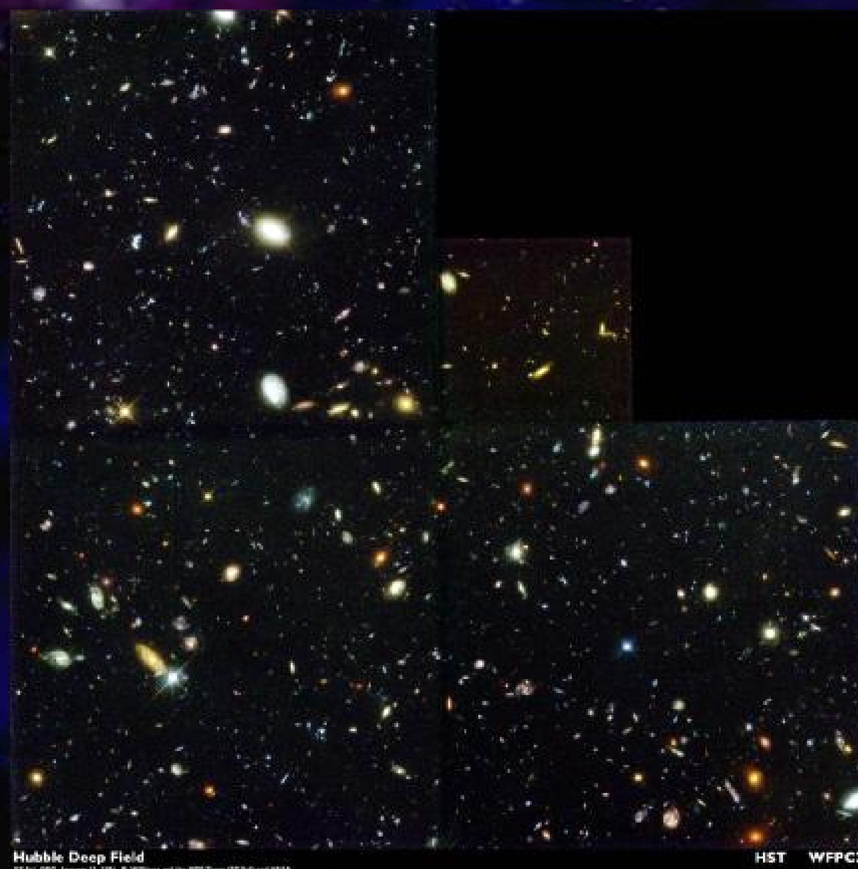
In our solar system:

- 1 out of 9 worlds
- Nearly 3 out of 9 worlds

FOOD FOR THOUGHT...

- The existence of a planet identical to Earth does not guarantee life will develop.
- Life does not necessarily require an Earth-like planet to flourish.

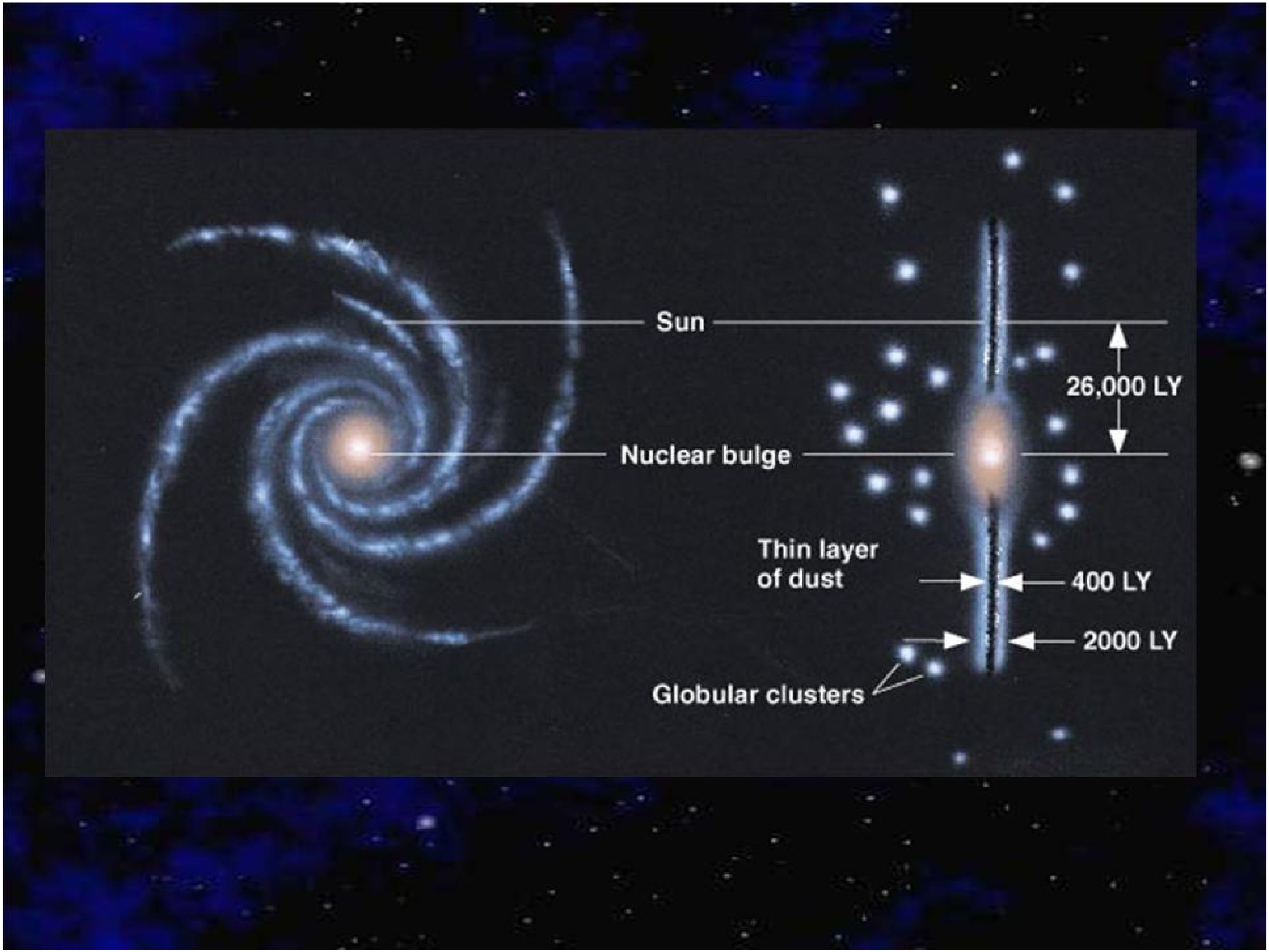
WHERE DO WE SEARCH FOR LIFE IN THE UNIVERSE?



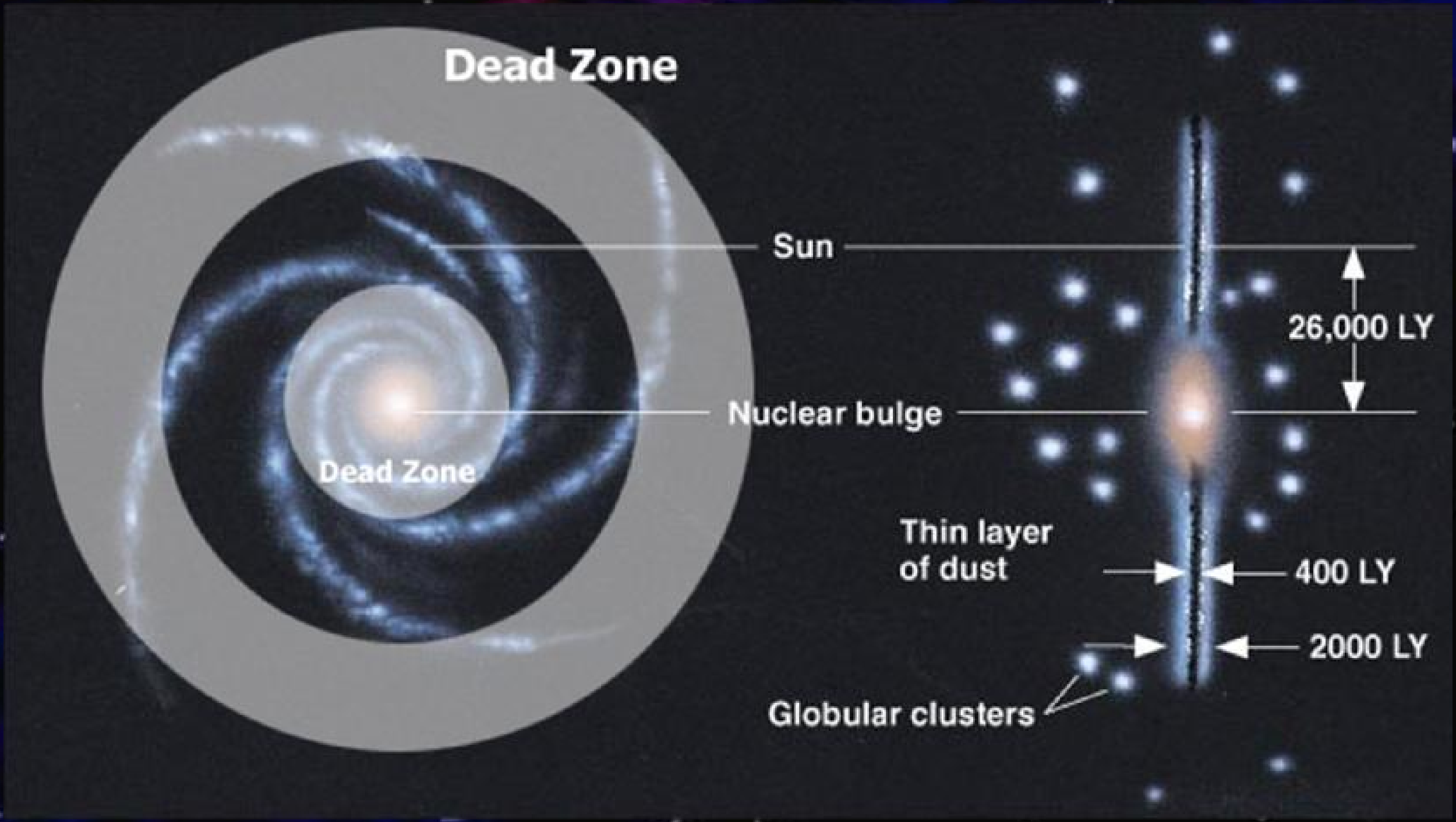
Which Stars Deserve Our Attention?

- Spectral Types
- Multiple Star Systems
- Stellar Populations

Perhaps it is better to eliminate stars rather than to include them?


Sun
26,000 LY
Nuclear bulge
Thin layer
of dust
400 LY
2000 LY
Globular clusters

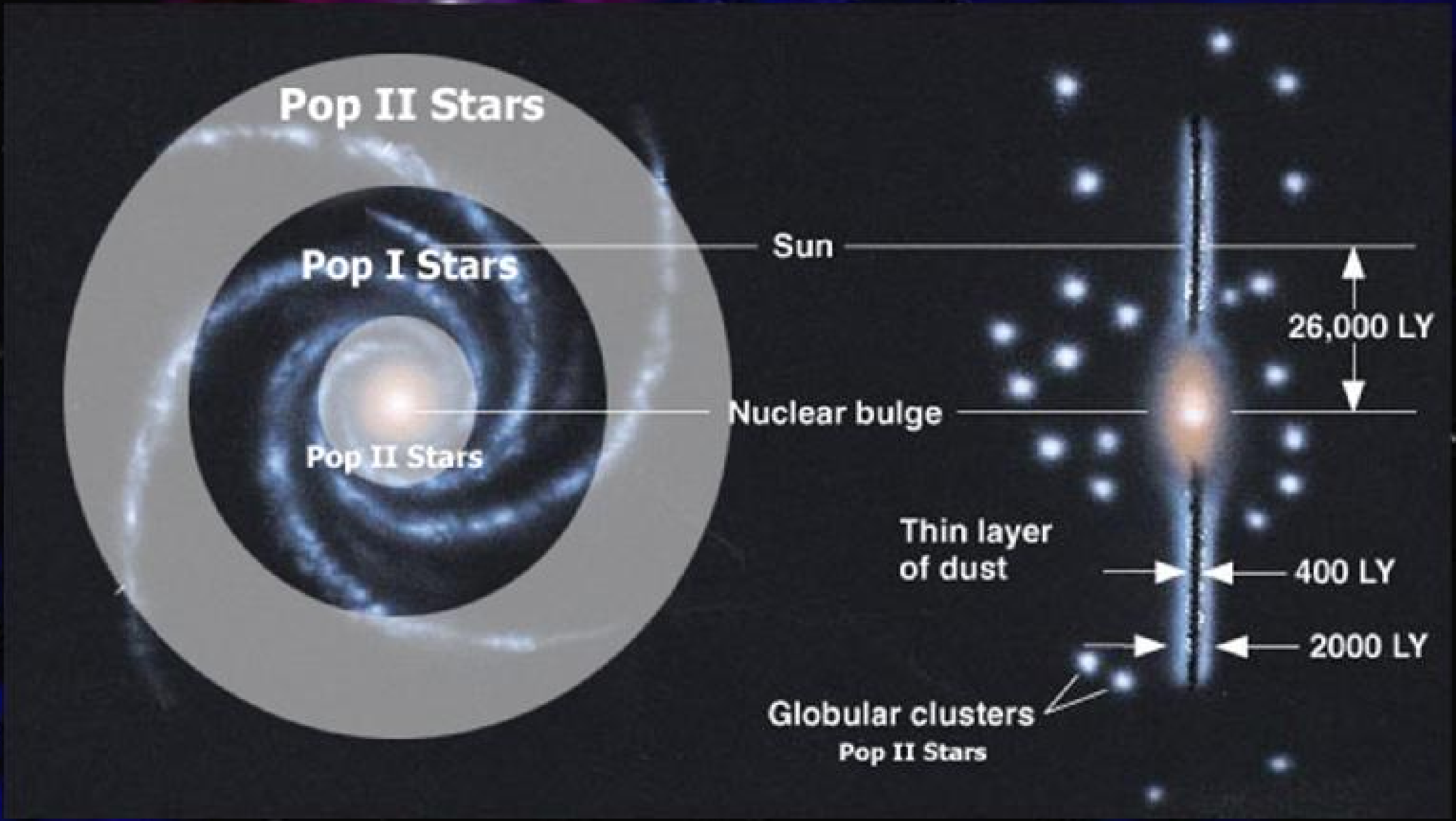
Galactic Dead Zones



Stellar Populations

Populations are based upon stellar metallicity

- Population I stars have “high” metallicity
- Population II stars have “low” metallicity

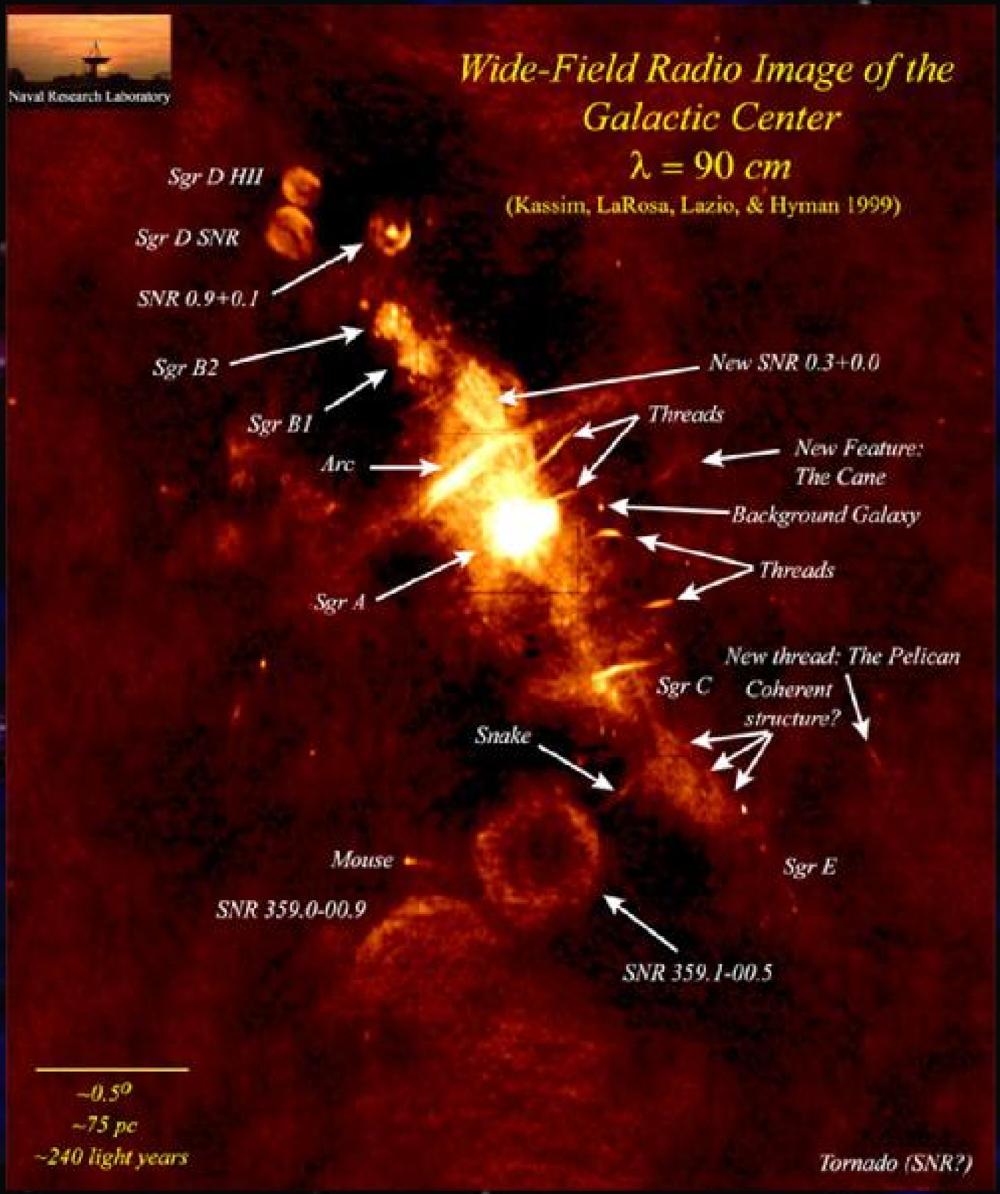


Galactic Dead Zones

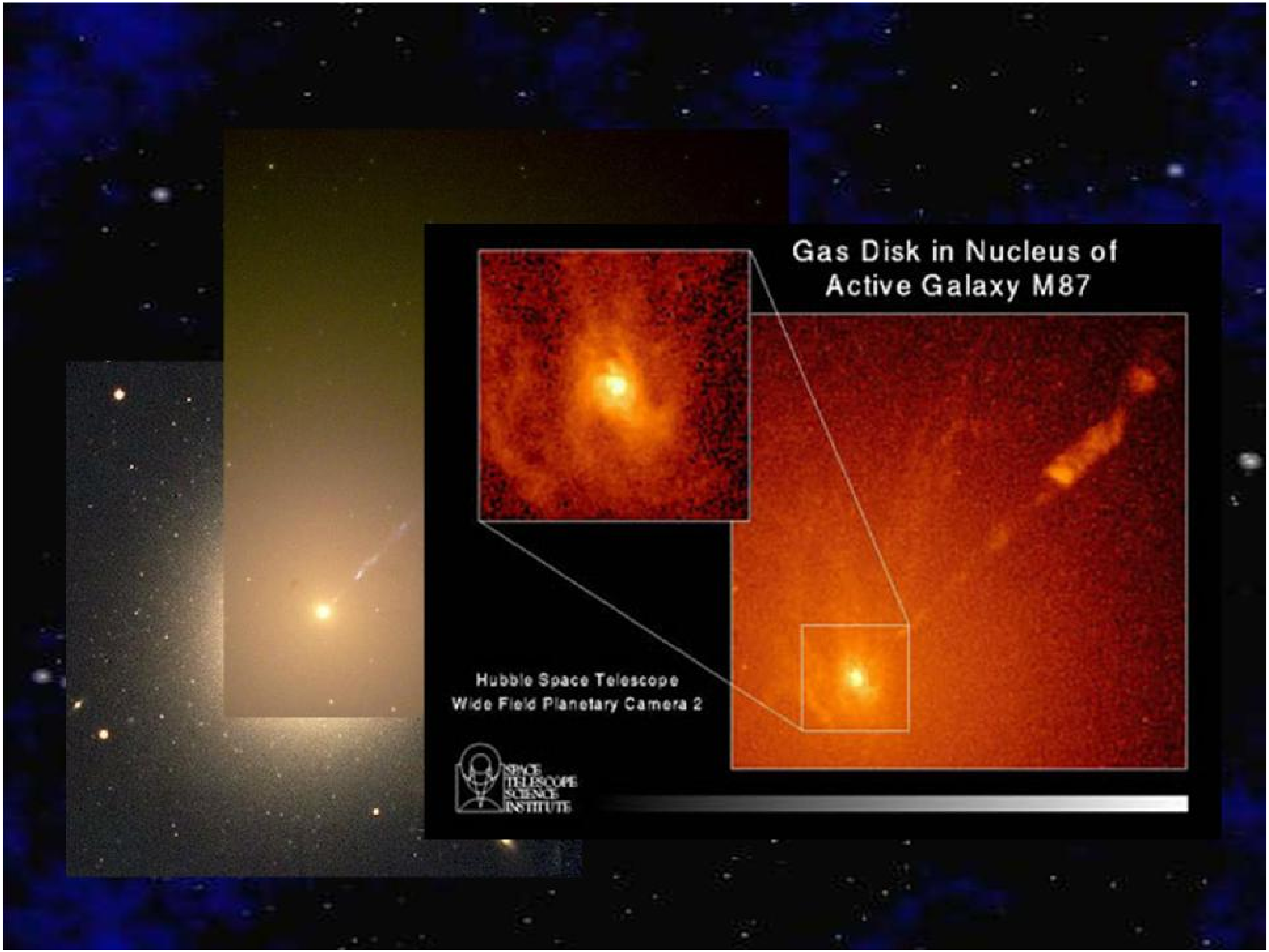
- Stars in the galactic nucleus are metal poor (Pop II)
- Stars in the galactic halo are mostly metal poor (Pop II)
- Stars in the galactic outskirts are metal poor (Pop II)
- Studies show that extrasolar planets tend to belong to Pop I stars

Xray image of galactic center

Radio image of galactic center

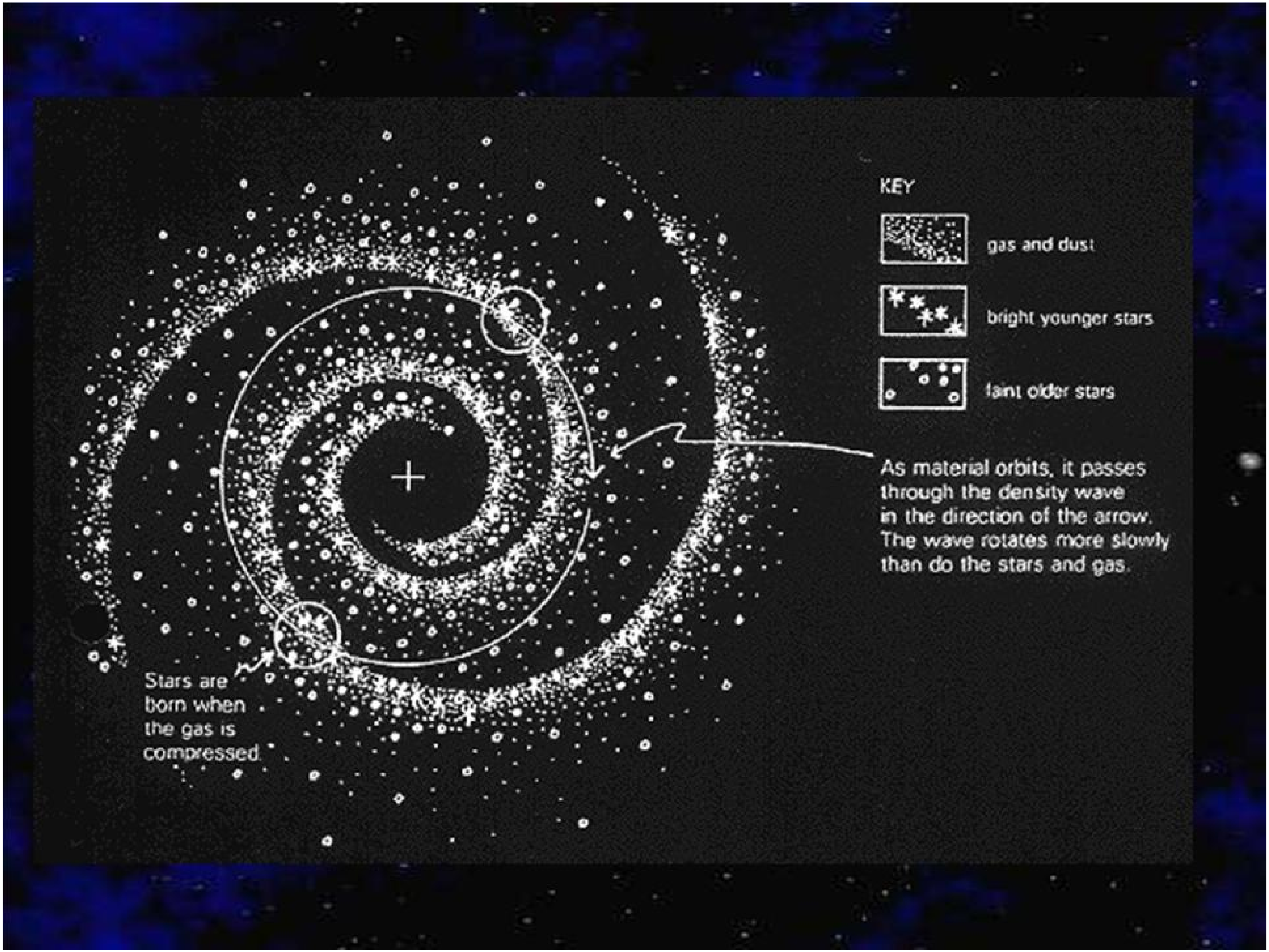


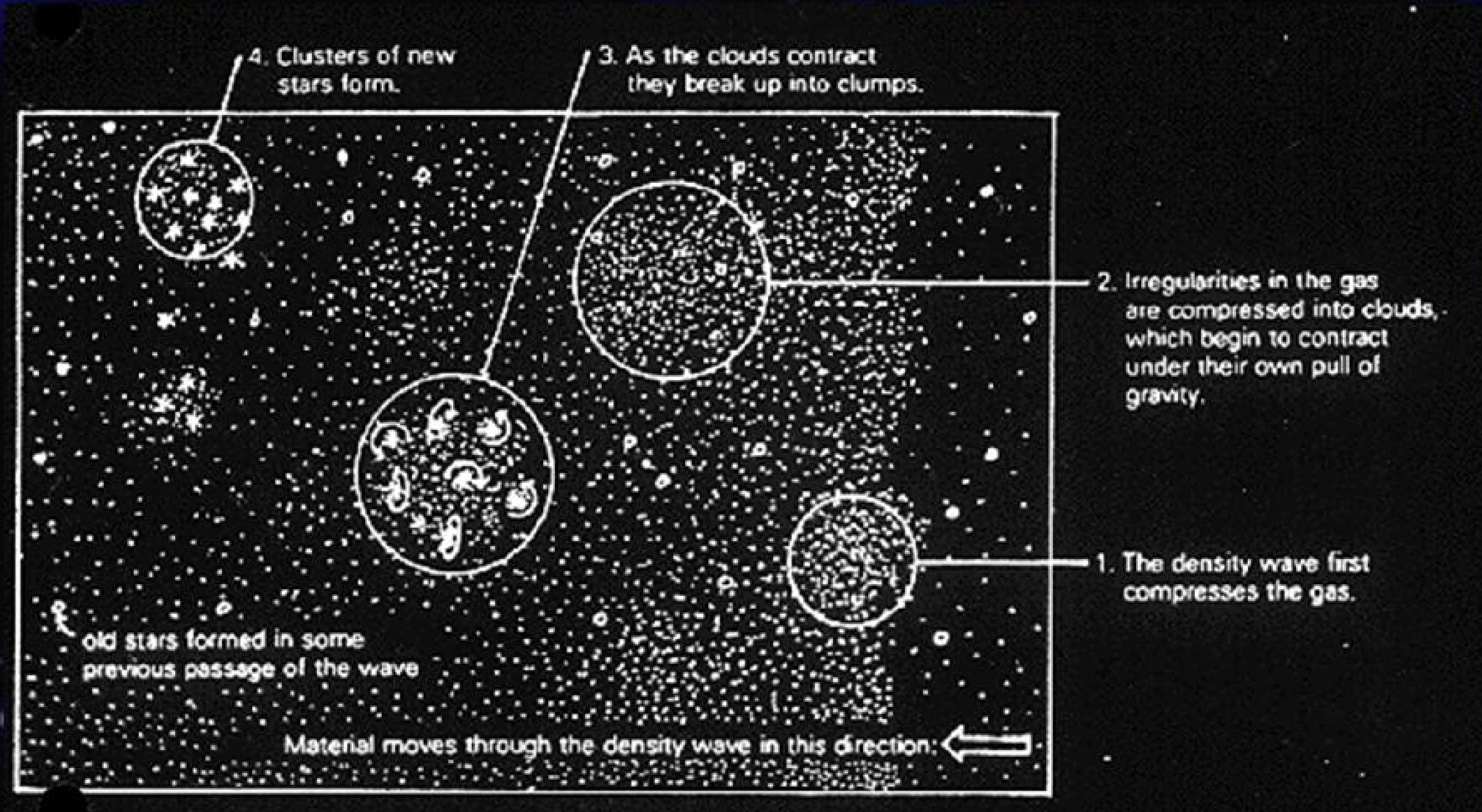
Supermassive Black Holes


Gas Disk in Nucleus of
Active Galaxy M87
Hubble Space Telescope
Wide Field Planetary Camera 2
SPACE
TELESCOPE
SCIENCE
INSTITUTE

Galactic Danger Zones: Nucleus

- Numerous supernova remnants
- Supermassive black hole
- Flooded with high energy photons
- Highly energized gasses
- Gravitationally “disturbed” by crowded conditions

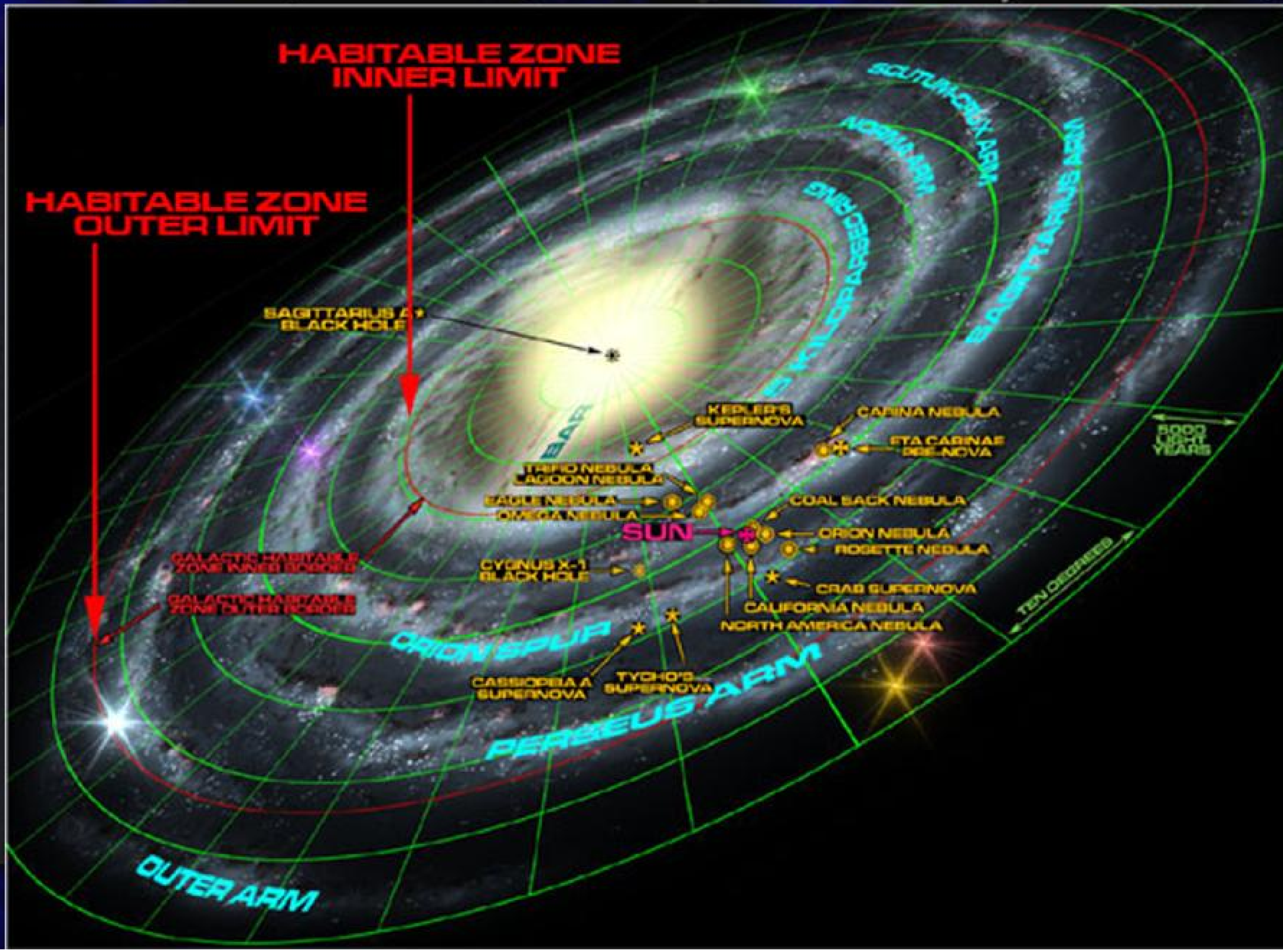

KEY
gas and dust
bright younger stars
faint older stars
As material orbits, it passes
through the density wave
in the direction of the arrow.
The wave rotates more slowly
than do the stars and gas.
Stars are
born when
the gas is
compressed.


4. Clusters of new stars form.
3. As the clouds contract they break up into clumps.
2. Irregularities in the gas are compressed into clouds, which begin to contract under their own pull of gravity.
1. The density wave first compresses the gas.
old stars formed in some previous passage of the wave
Material moves through the density wave in this direction:

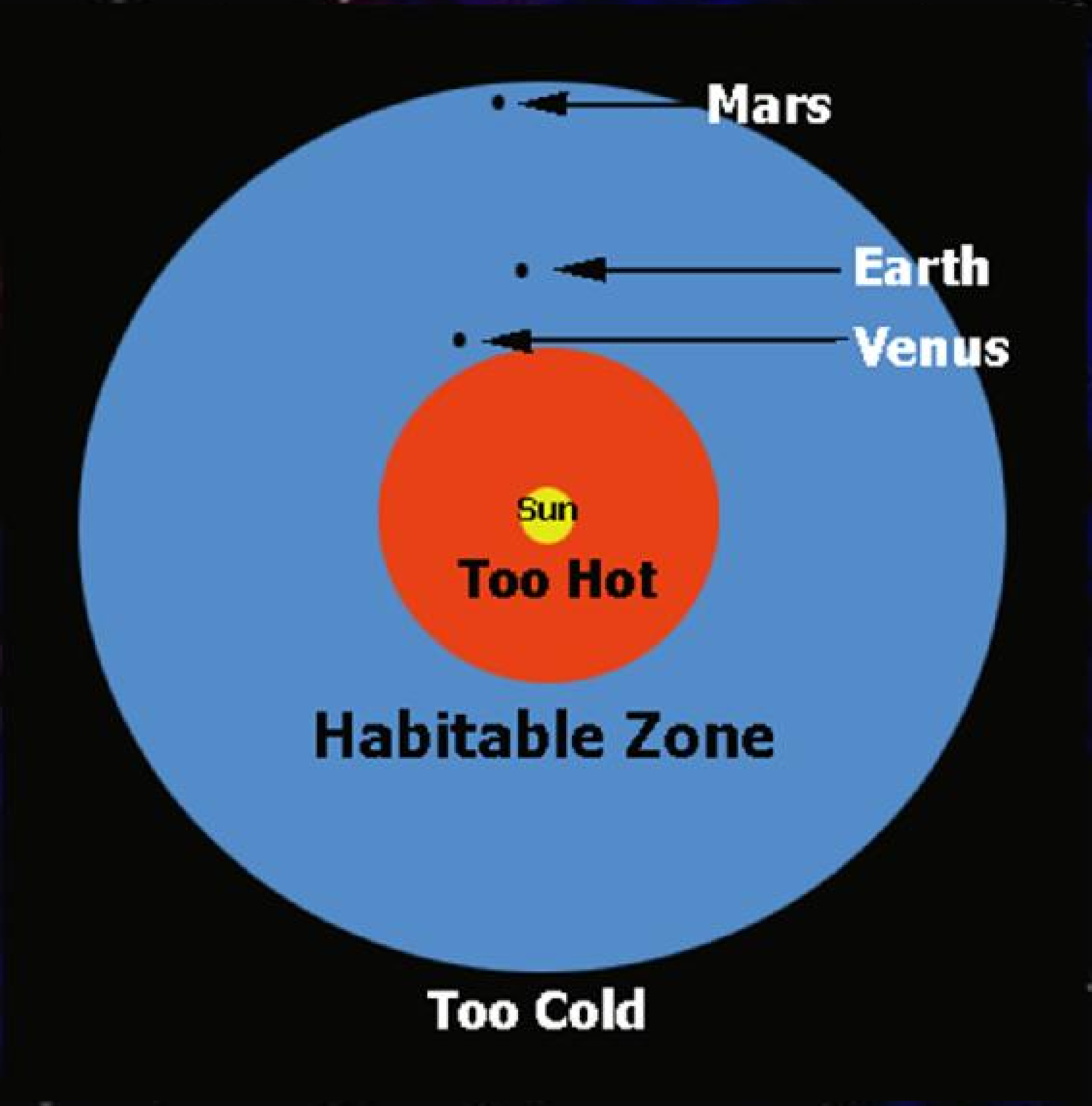
Galactic Danger Zones: Spiral Arms

- Gravitationally perturbed
- Interstellar cloud chaos
- Sun avoids spiral arms
- Sun has nearly circular orbit around galaxy
- Sun has a “synchronized” rotation with spiral arm

Galactic Habitable Zone

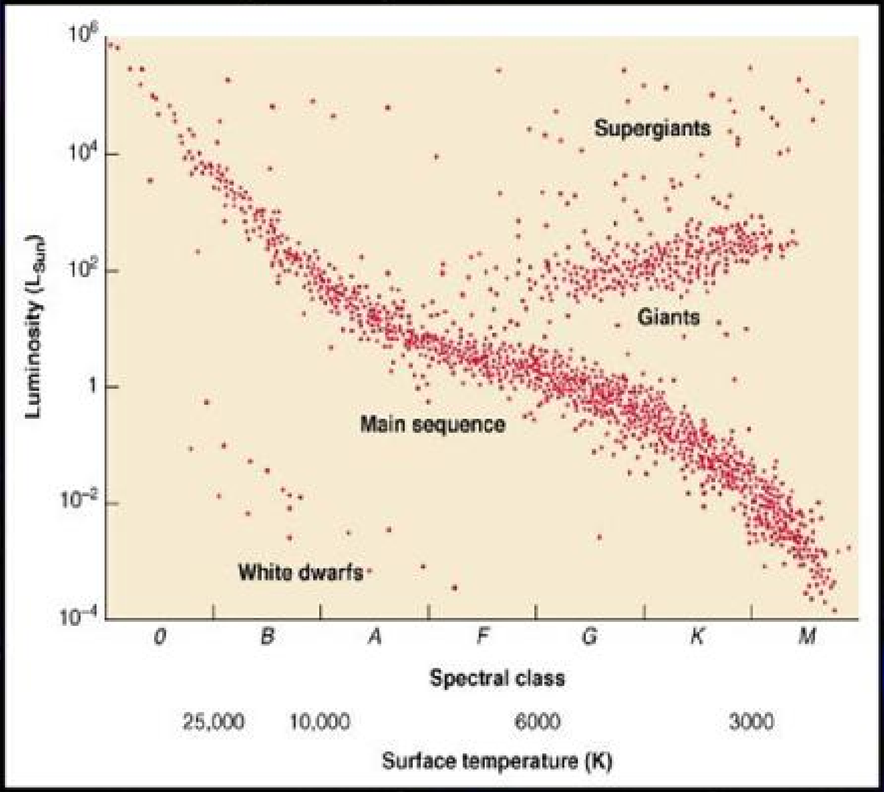


Stellar Habitable Zones



Spectral Types

- Stellar Lifetimes
- Sizeable Habitable Zone

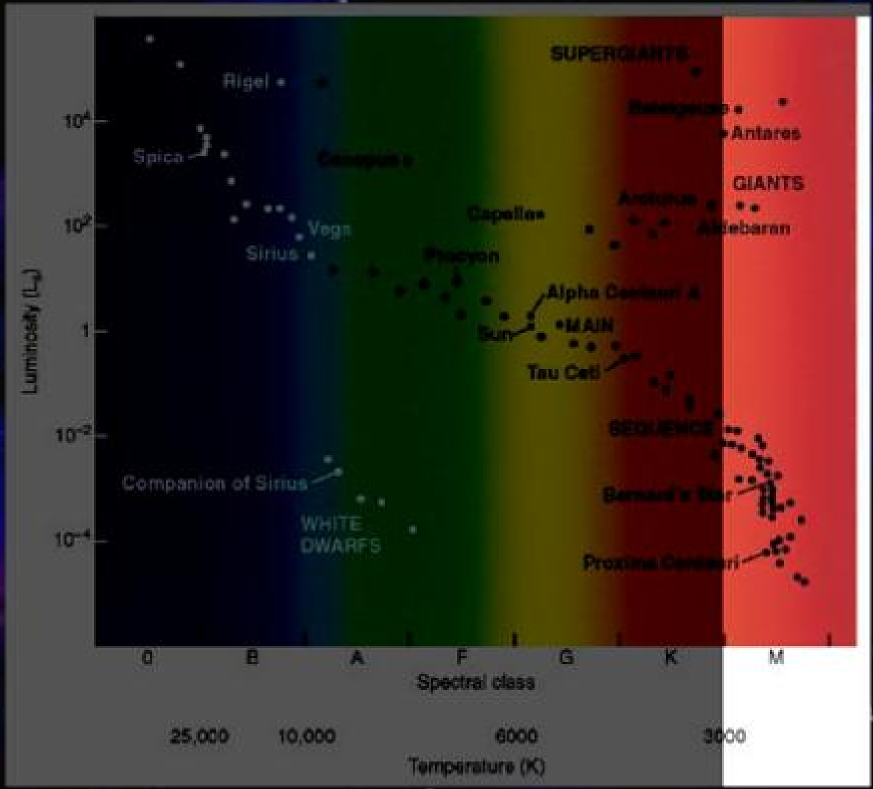


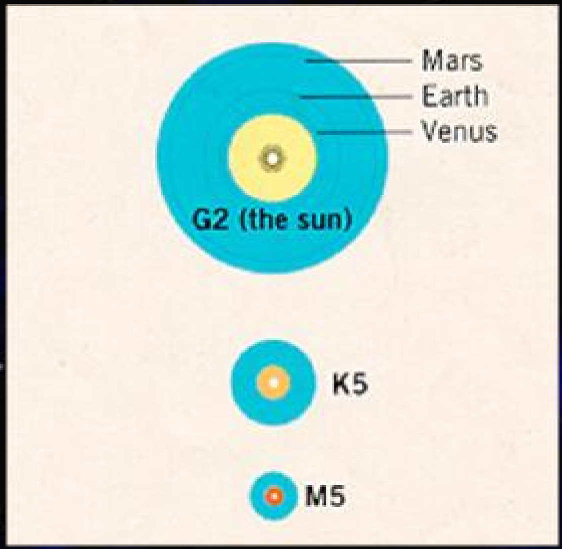
Low Mass Stars

- Very long stellar lifespan
- Habitable Zone is too small
- Risks tidal locking with planet

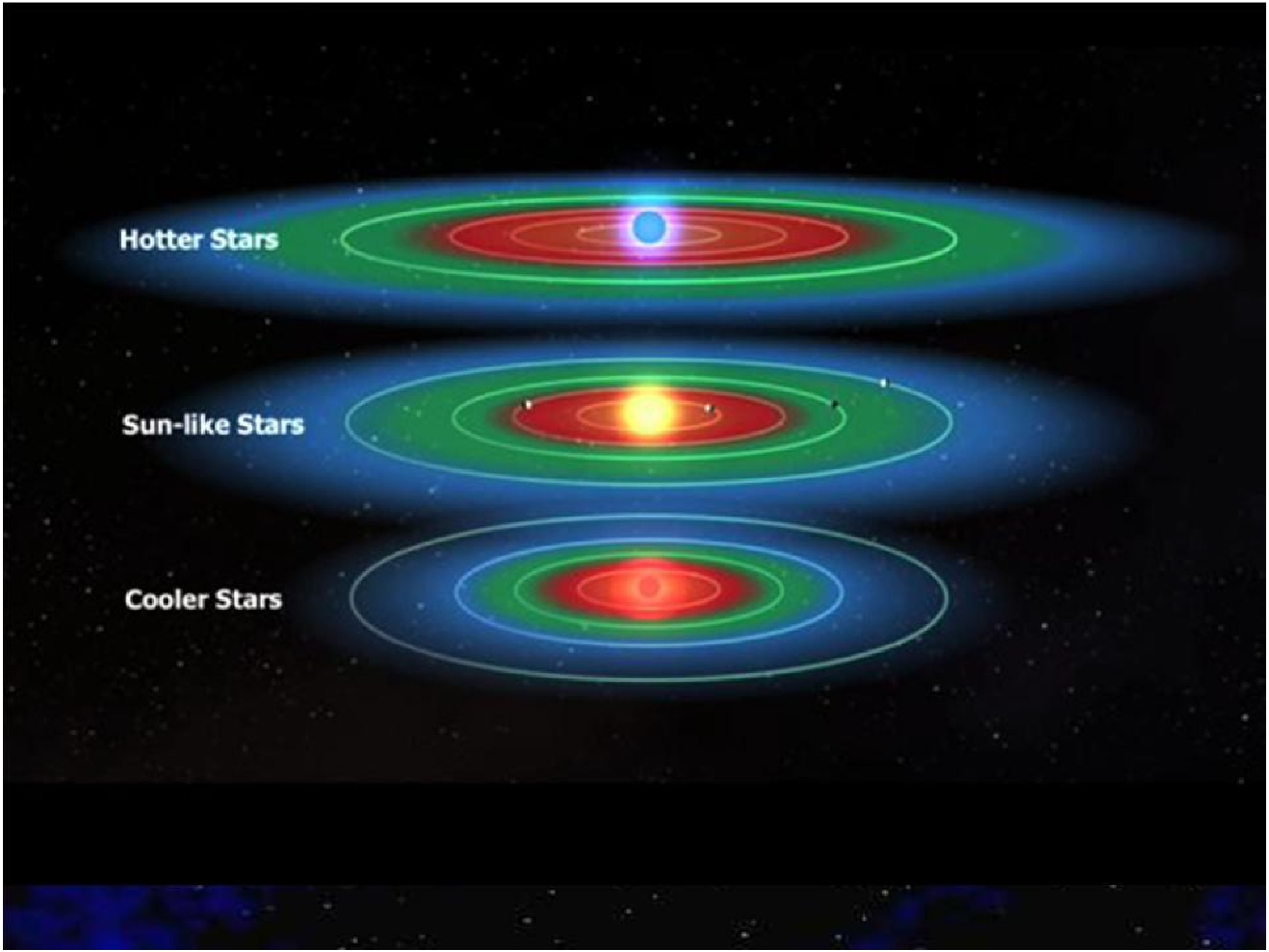
Alternation of conditions probably necessary to help the initial chemistry of life

- Freezing / thawing
- Wet / dry



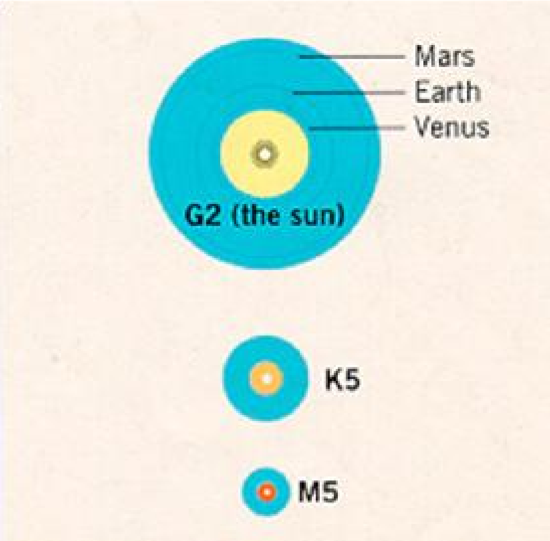


$$t_{\text{lock}} \approx 6 \frac{a^6 R \mu}{m_s m_p^2} \times 10^{10} \text{ years},$$


Hotter Stars
Sun-like Stars
Cooler Stars

Low Mass Stars

$$t_{\mathrm{lock}} \approx 6\frac{a^6 R\mu}{m_s m_p^2} \times 10^{10}\ \mathrm{years},$$



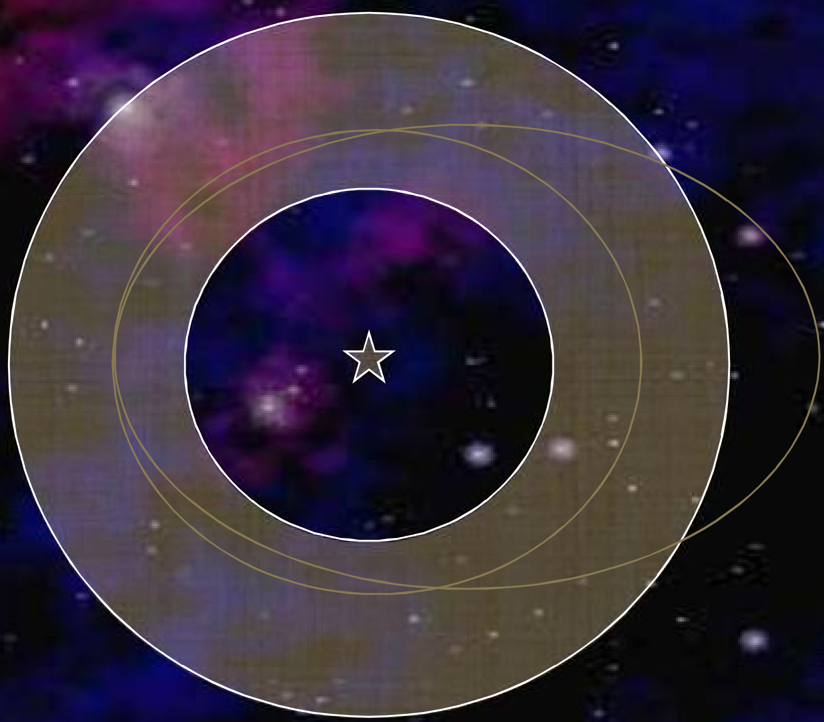
Semi-Major axis, a	a^6	Relative time to Tidal Lock
1	1	10000000000
0.9	0.531441	5314410000
0.8	0.262144	2621440000
0.7	0.117649	1176490000
0.6	0.046656	466560000
0.5	0.015625	156250000
0.4	0.004096	40960000
0.3	0.000729	7290000
0.2	0.000064	640000

Not absolute:

Mercury, 3:2 spin orbit resonance made possible by relatively large e.

Venus, 3:2 spin orbit resonance with Earth, every 3 Venus rotations = 2 Earth years

Circular versus more elliptical orbit



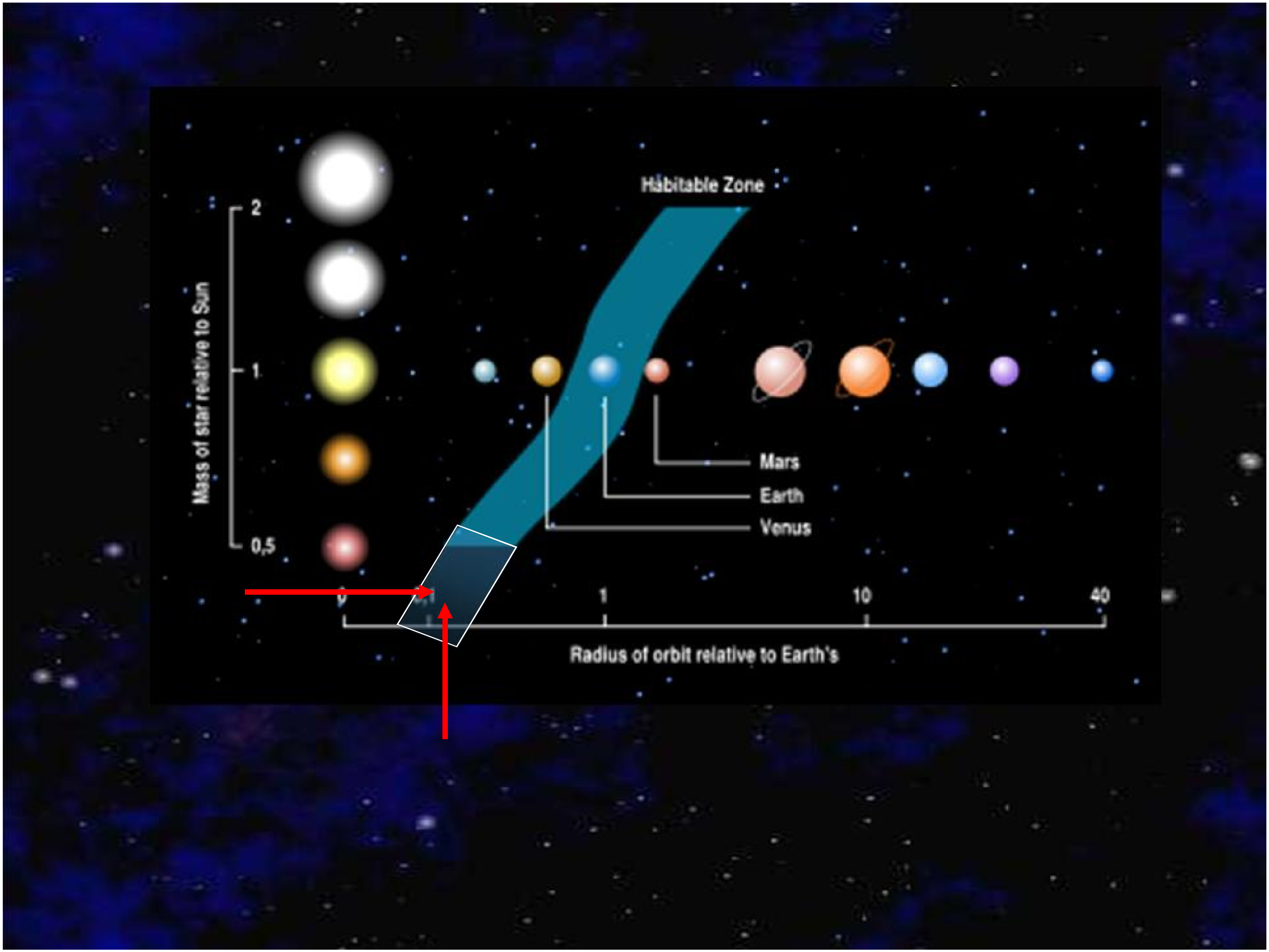
Scientists find most Earth-like planet yet

Models predict planet should be either rocky or covered with oceans

Gliese 581

50% larger than earth, 5 times the mass
150 lb person would weight 333 lbs
Temperature: 32-104^{o}F

6,000,000 miles from M type star
13 days to complete orbit


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

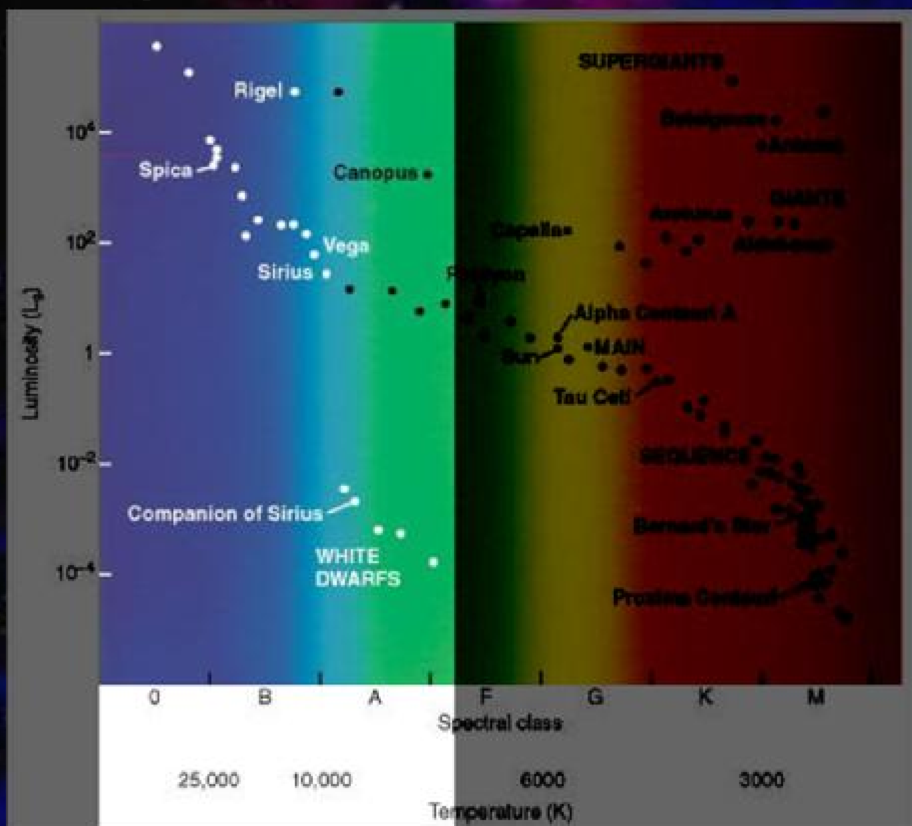
Elimination of Low Mass Stars

If we eliminate all stars that have a luminosity that is less than 1% of the Sun's, then we eliminate nearly 75% of all stars in the Milky Way!

- 225 billion stars eliminated
- 75 billion stars left

High Mass Stars

- Large Habitable Zone
- Nasty forms of EM energy
- Lifespan too short



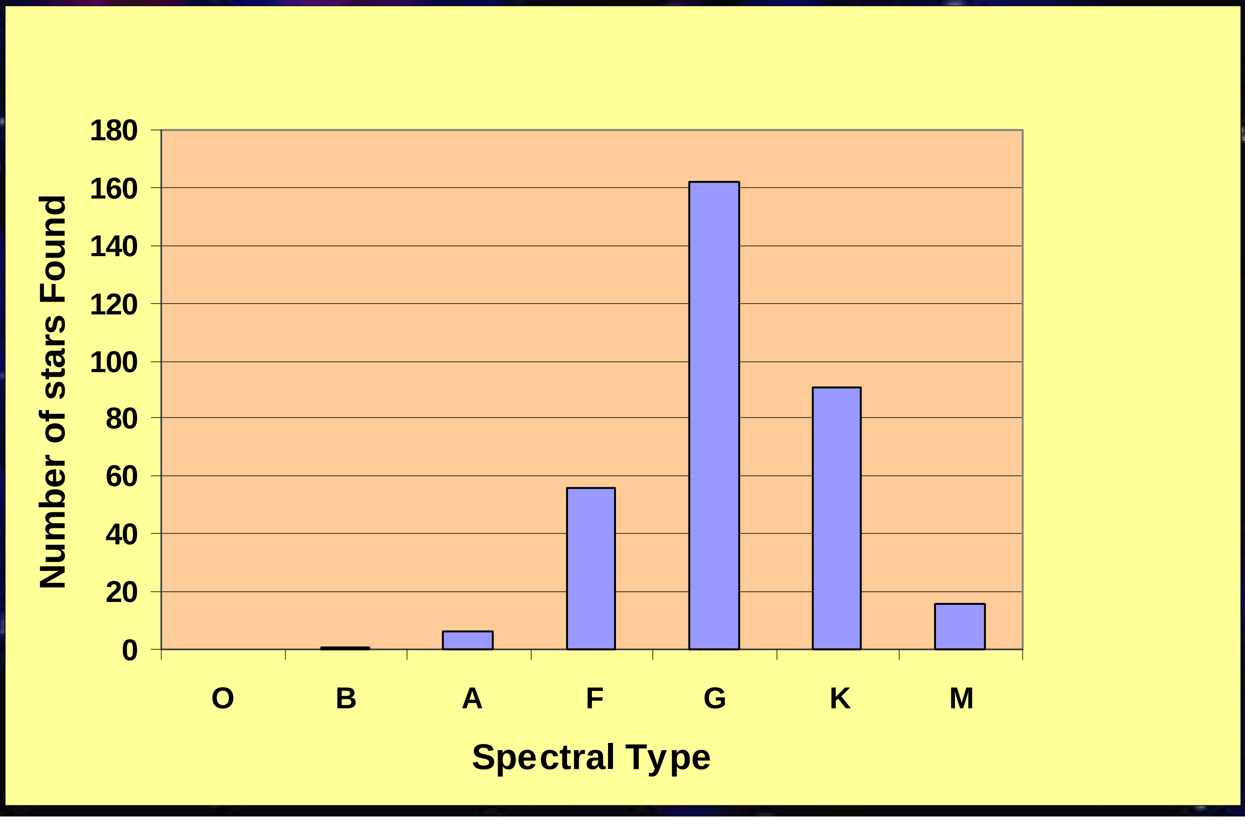
Elimination of High Mass Stars

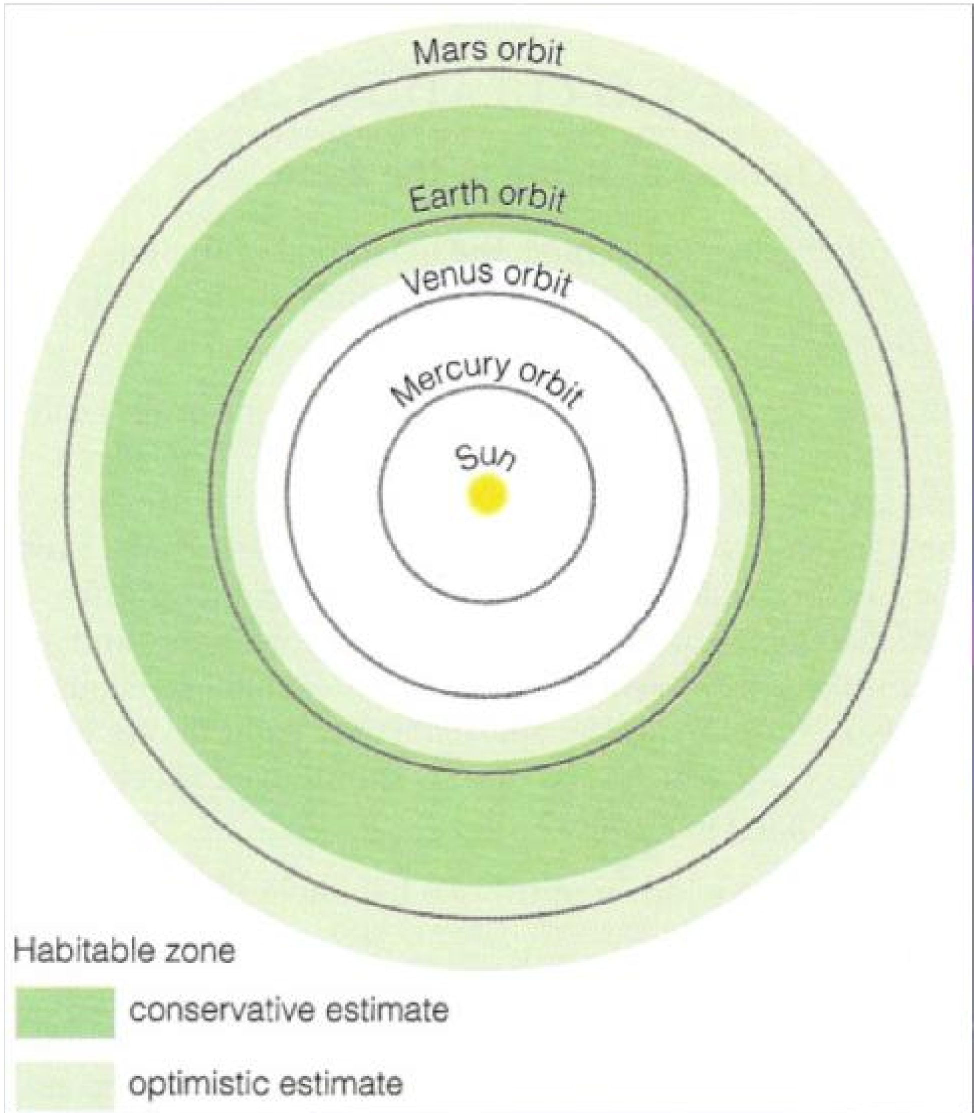
Roughly 1% of all Milky Way stars are considered high mass stars that do not meet certain minimum criteria

- 3 billion stars eliminated
- 72 billion stars left

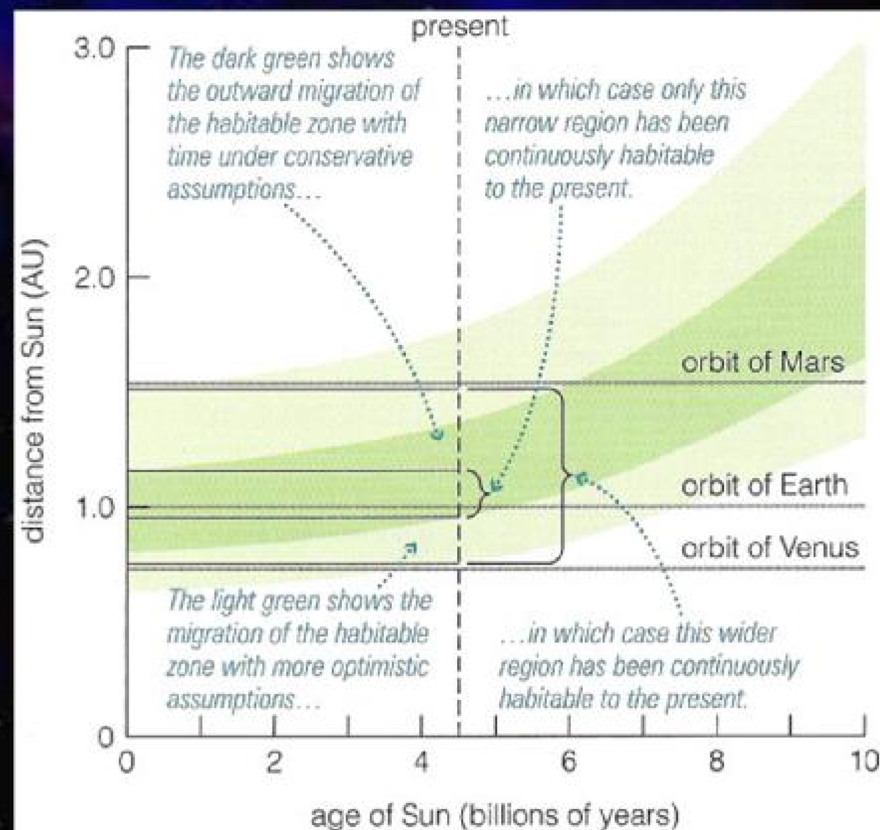
Which Spectral Types Deserve Consideration?

F5 – K8

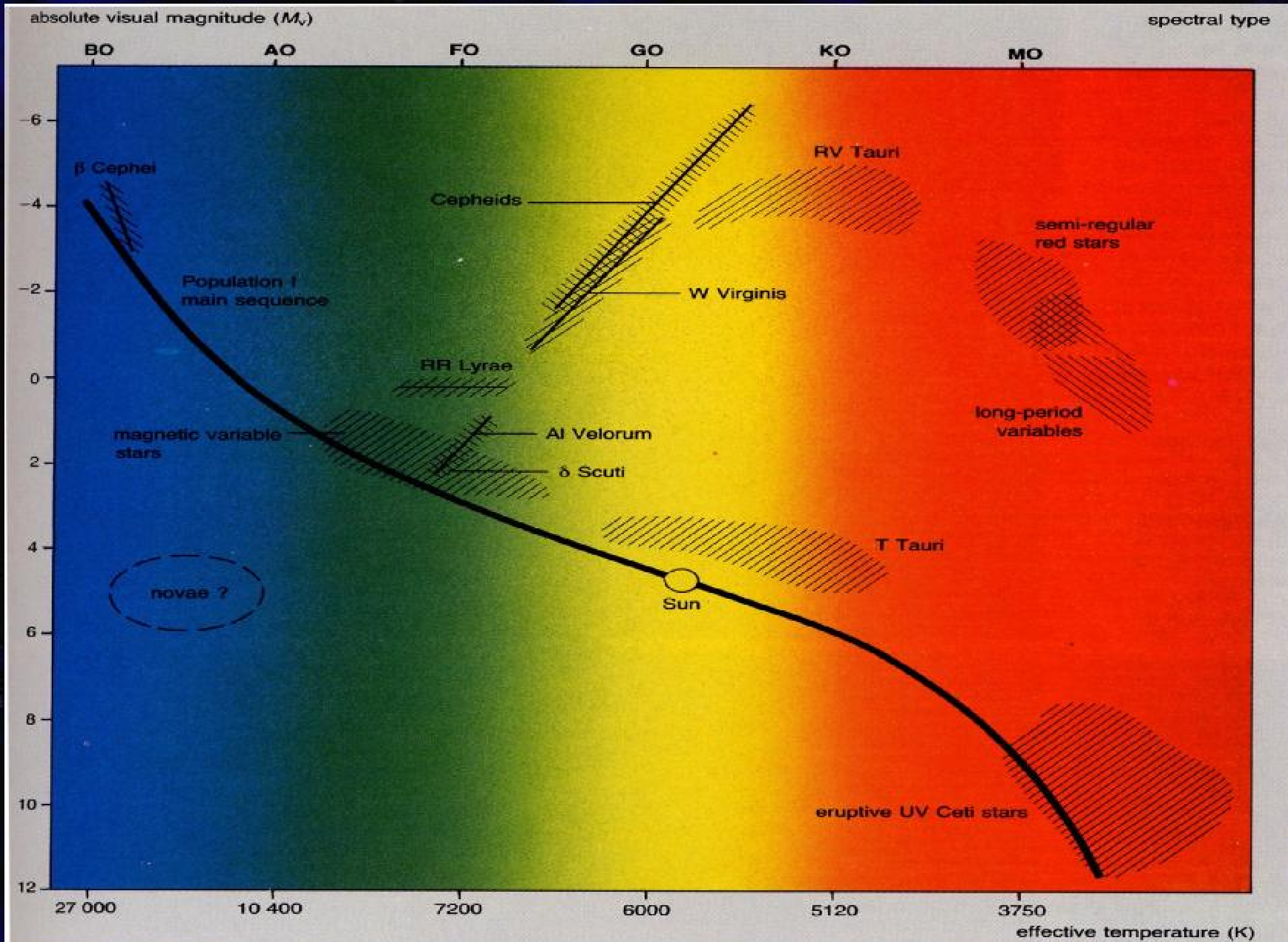




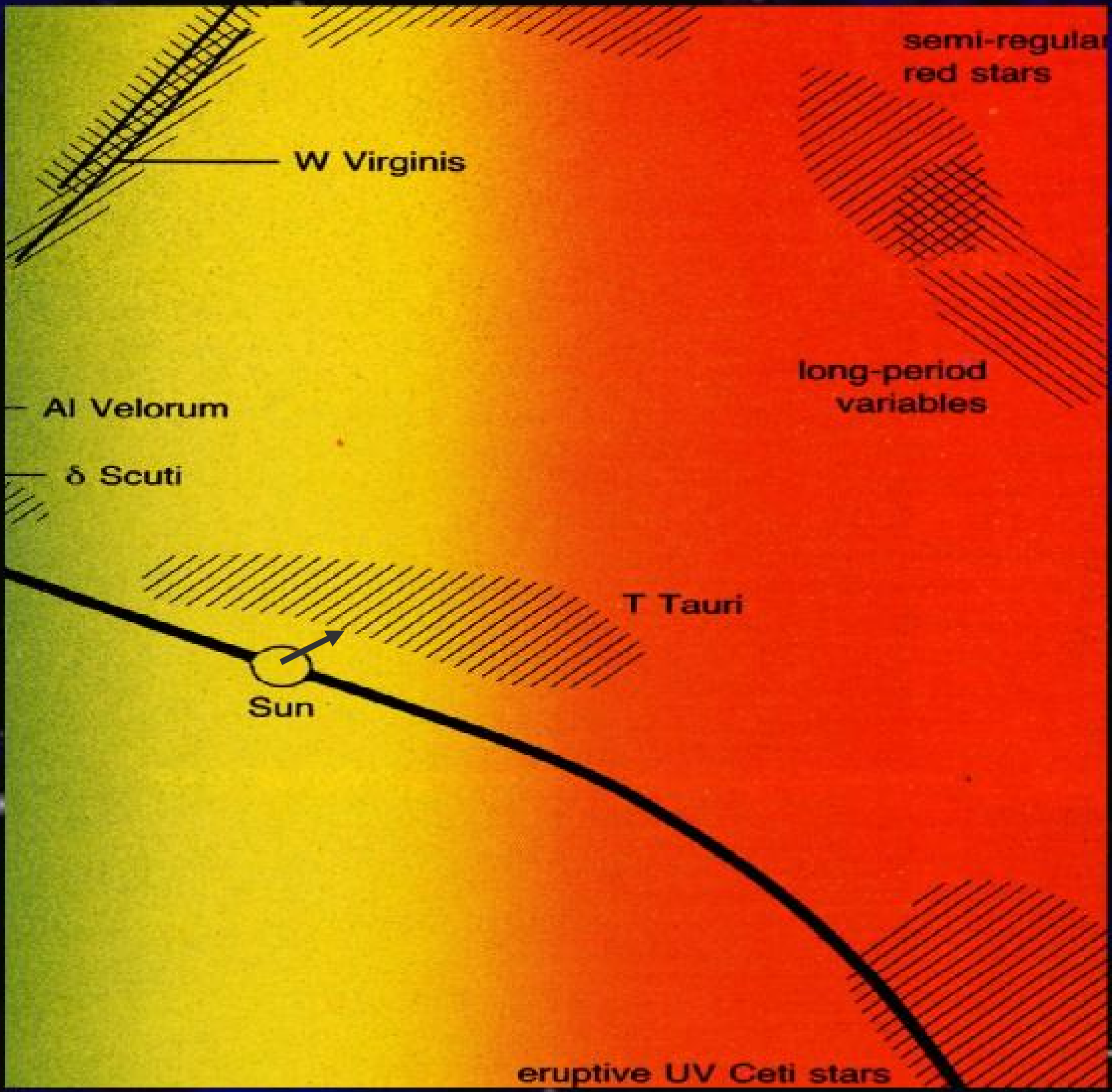
Mars orbit
Earth orbit
Venus orbit
Mercury orbit
Sun
Habitable zone
conservative estimate
optimistic estimate



present
3.0
2.0
1.0
0
distance from Sun (AU)
The dark green shows the outward migration of the habitable zone with time under conservative assumptions…
…in which case only this narrow region has been continuously habitable to the present.
orbit of Mars
orbit of Earth
orbit of Venus
The light green shows the migration of the habitable zone with more optimistic assumptions…
…in which case this wider region has been continuously habitable to the present.
0
2
4
6
8
10
age of Sun (billions of years)

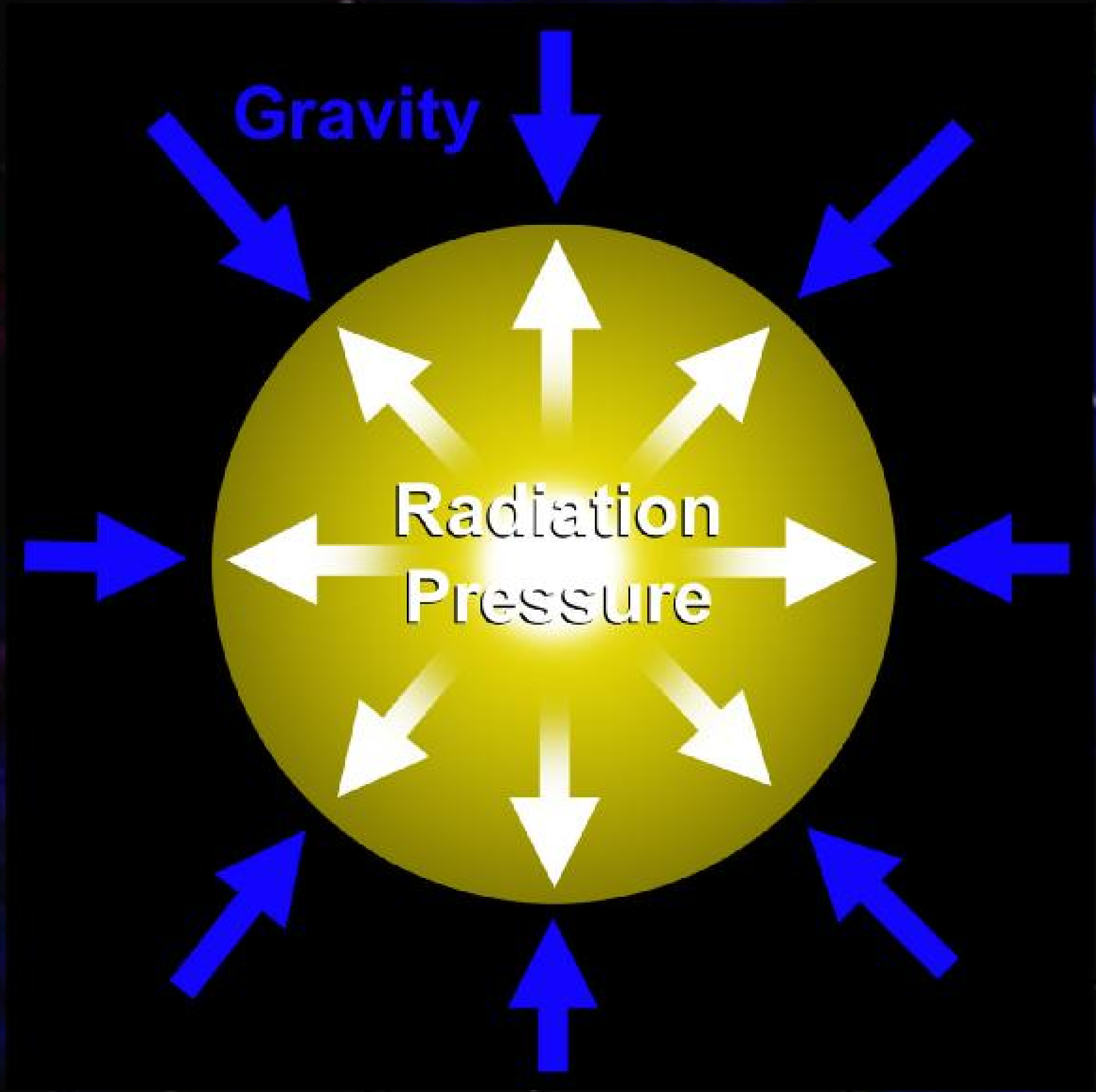

absolute visual magnitude (M_v)
spectral type
BO
AO
FO
GO
KO
MO
-6
-4
-2
0
2
4
6
8
10
12
β Cephei
Cepheids
RV Tauri
semi-regular red stars
Population I main sequence
W Virginis
RR Lyrae
long-period variables
magnetic variable stars
AI Velorum
δ Scuti
T Tauri
novae ?
Sun
eruptive UV Ceti stars
27 000
10 400
7200
6000
5120
3750
effective temperature (K)

The sun and all stars gradually move off the MS

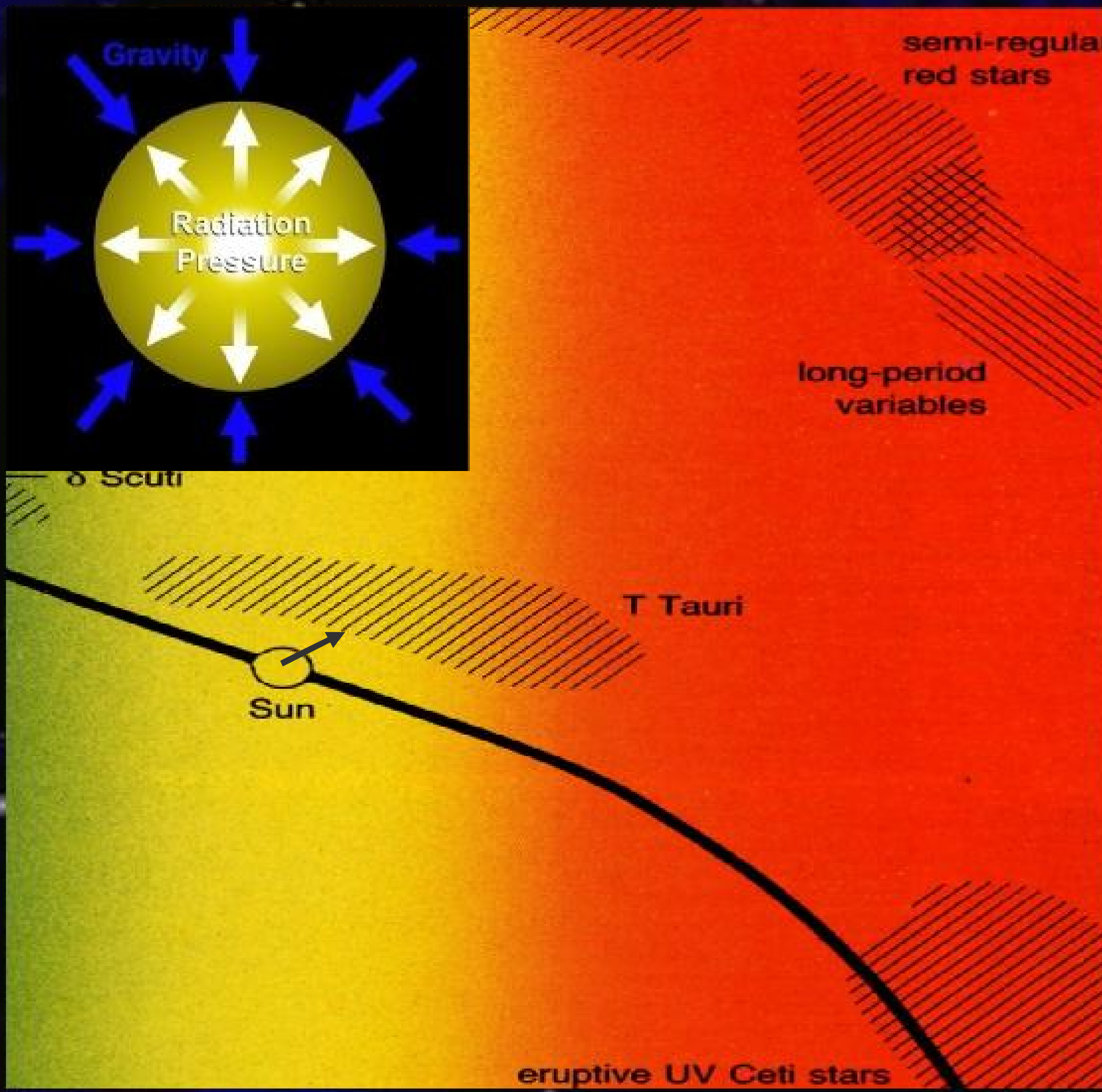


Why is this?

Hydrostatic Equilibrium



The sun and all stars gradually move off the MS



Why is this?

PV=nRT

n=particle density

4H ⟶ He

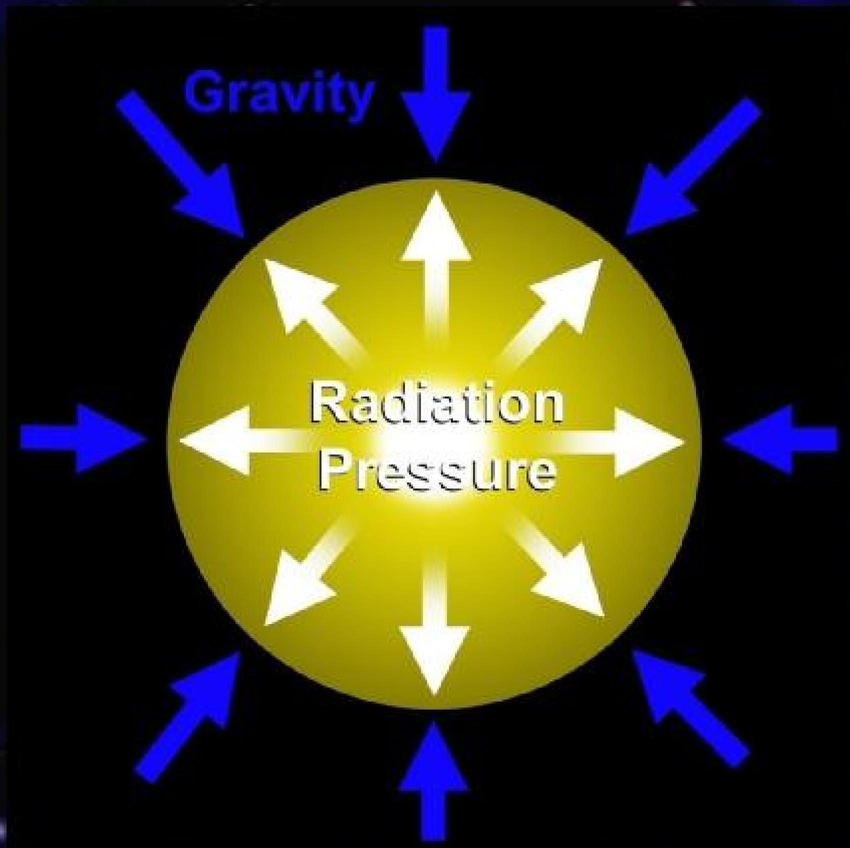
So...n is decreasing

P and V in core are not decreasing

To compensate, T must increase

Energy production ~ T^4

The sun and all stars gradually move off the MS

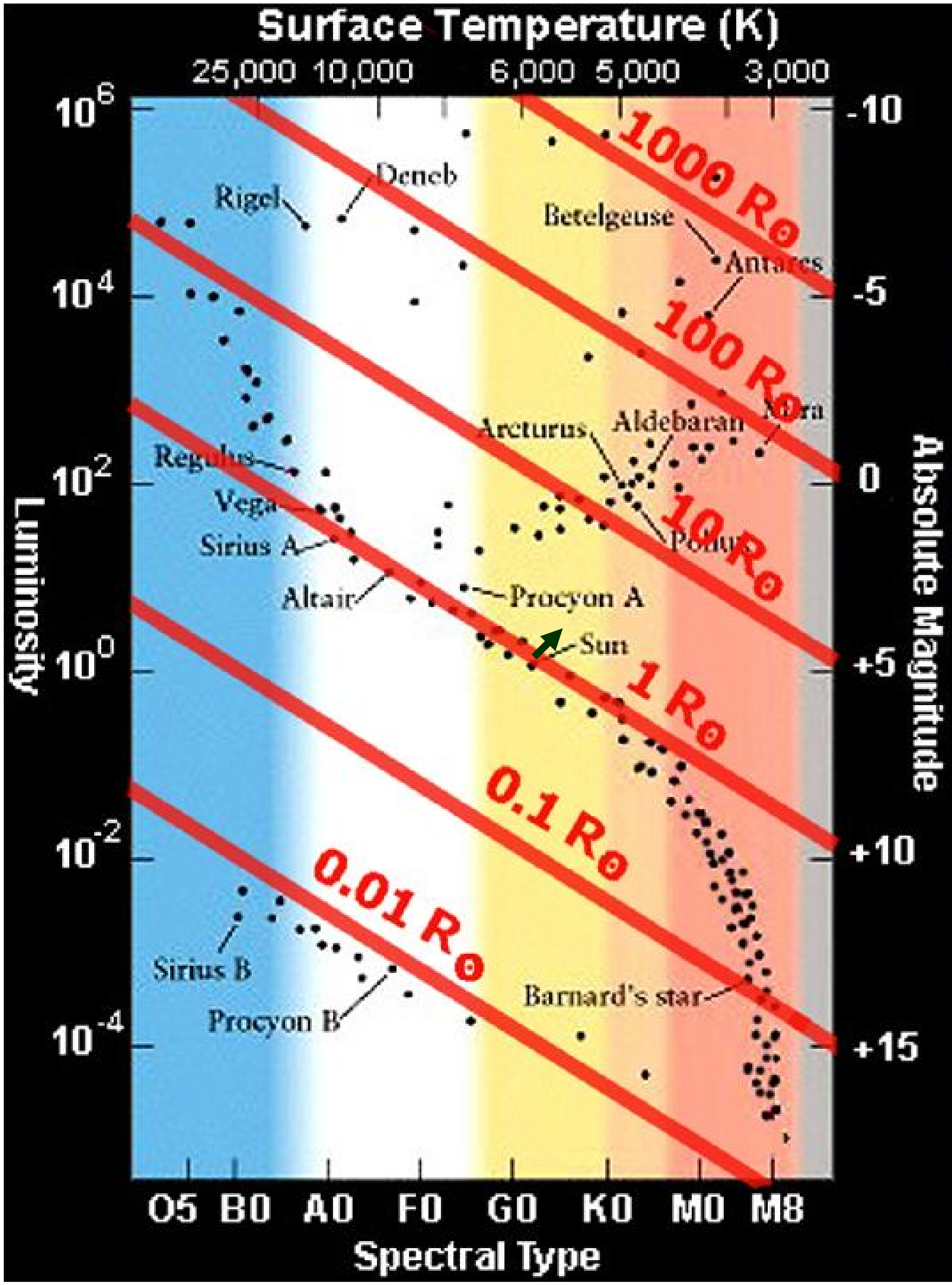


PV=nRT

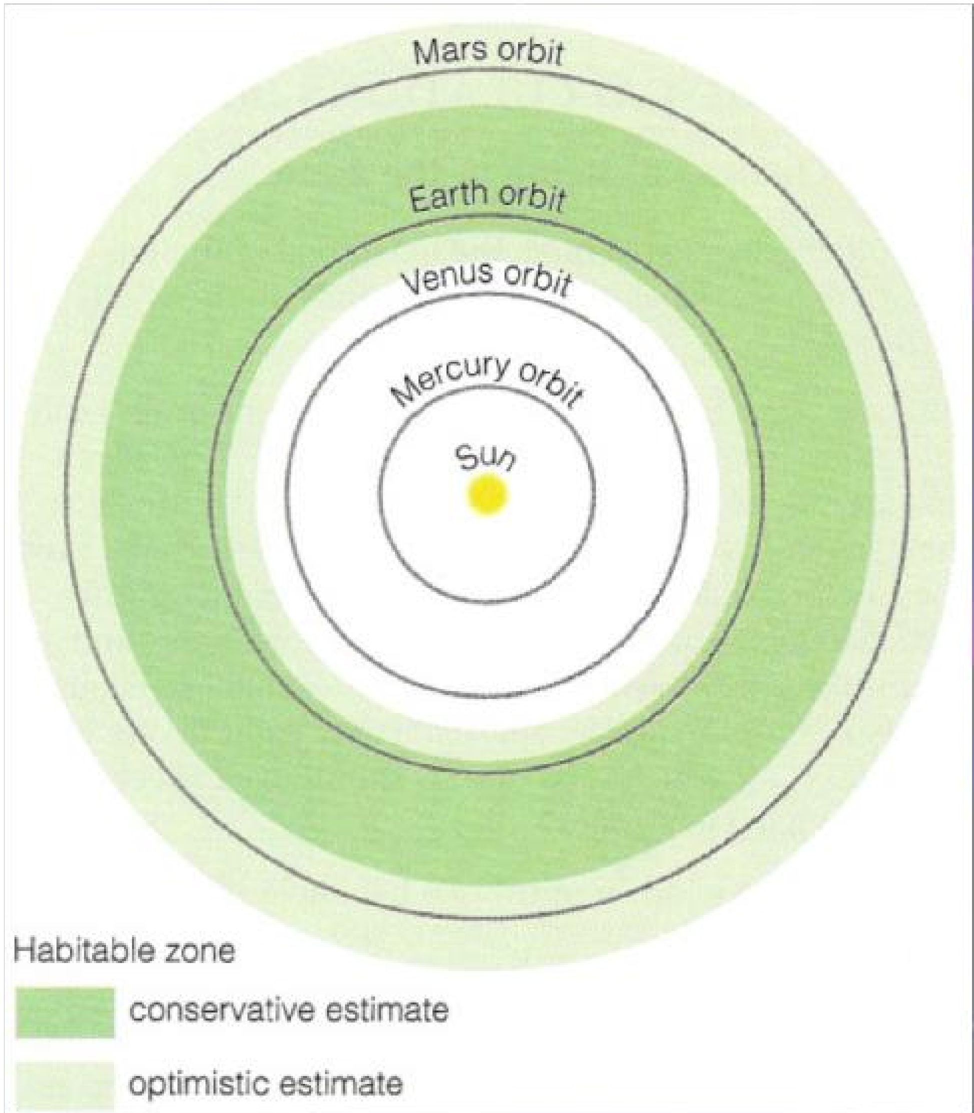
Energy production ~ T^4

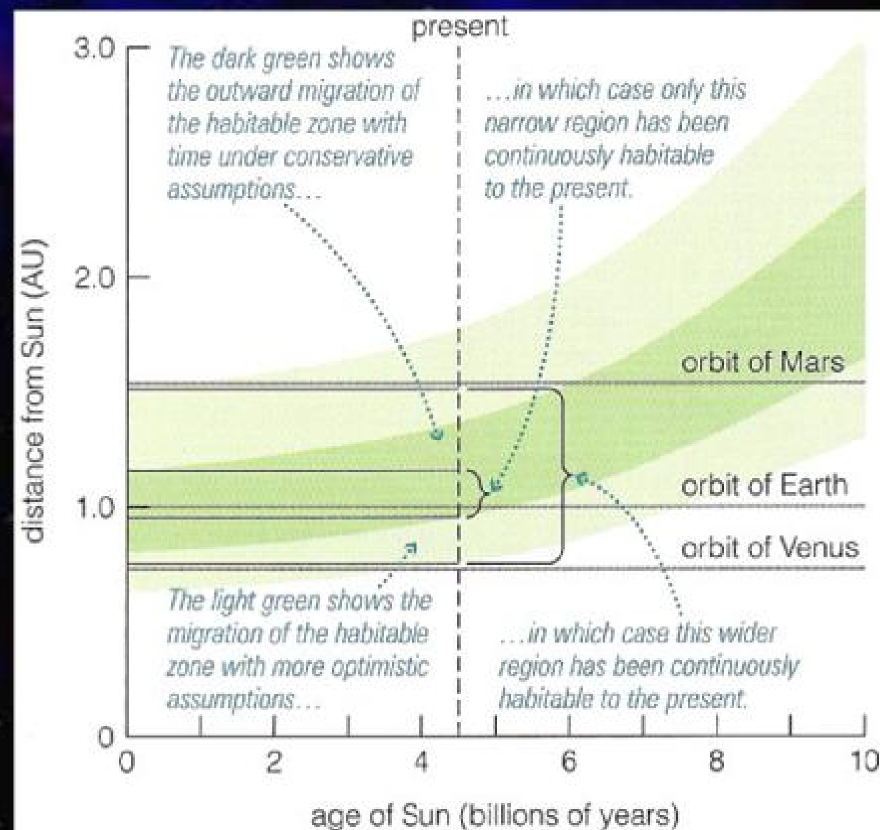
Increases P leading to increase in stellar diameter

$$L = 4pR^2 sT^4$$



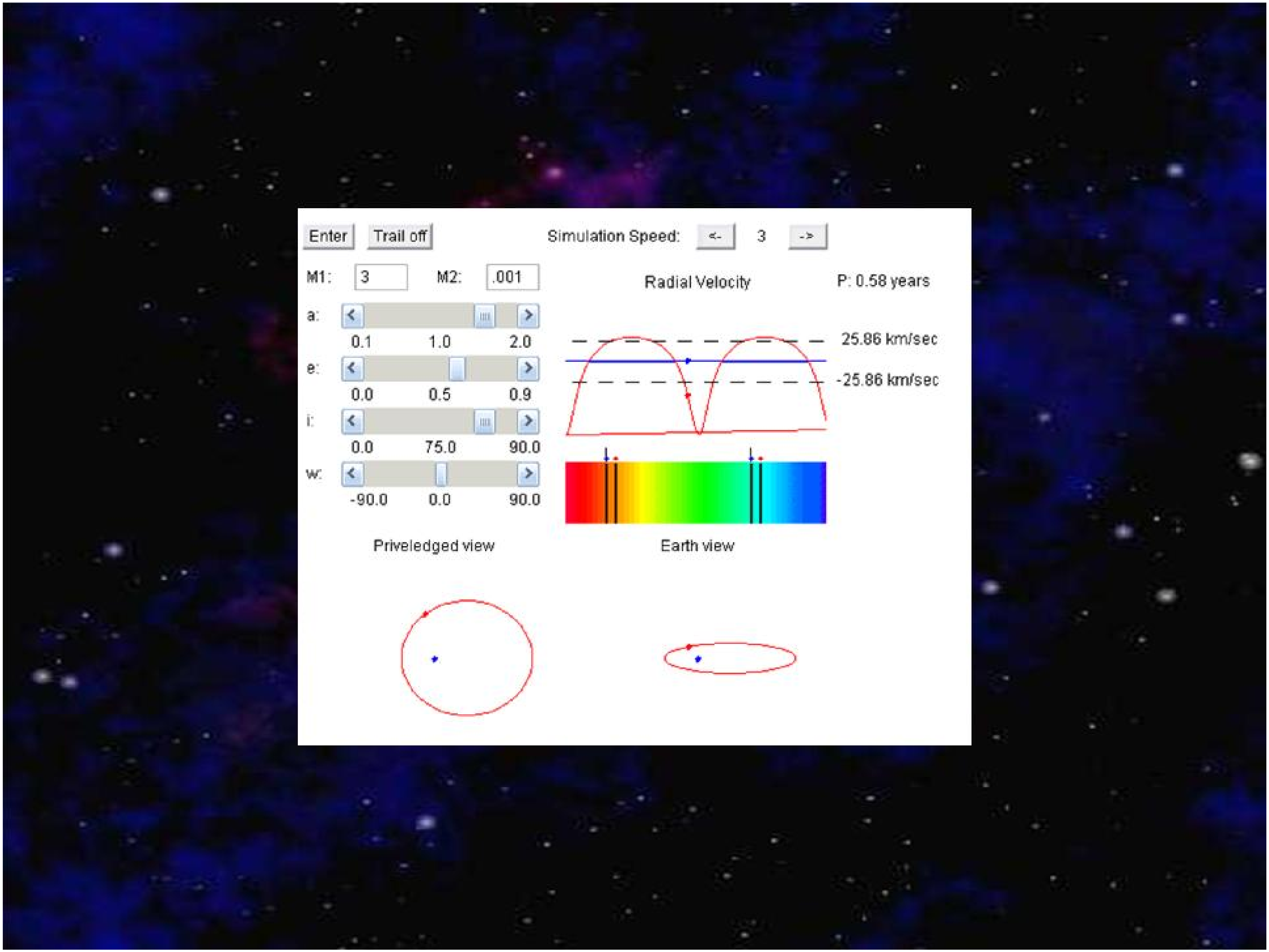
All this results in gradual expansion of habitable zone outward.


Mars orbit
Earth orbit
Venus orbit
Mercury orbit
Sun
Habitable zone
conservative estimate
optimistic estimate

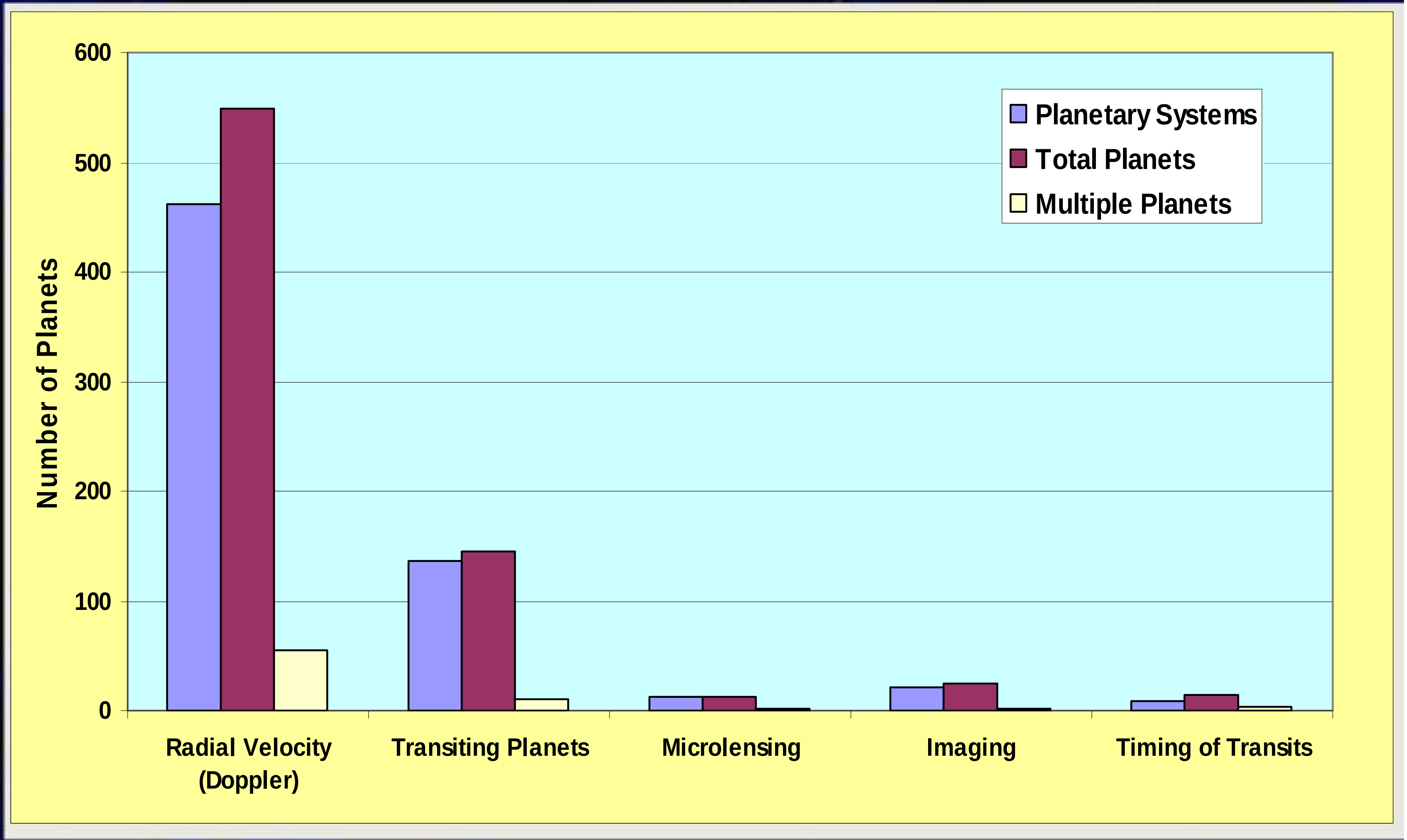

present
The dark green shows the outward migration of the habitable zone with time under conservative assumptions…
…in which case only this narrow region has been continuously habitable to the present.
The light green shows the migration of the habitable zone with more optimistic assumptions…
…in which case this wider region has been continuously habitable to the present.
orbit of Mars
orbit of Earth
orbit of Venus
distance from Sun (AU)
3.0
2.0
1.0
0
0
2
4
6
8
10
age of Sun (billions of years)

Which Neighboring Stars Should We Consider?

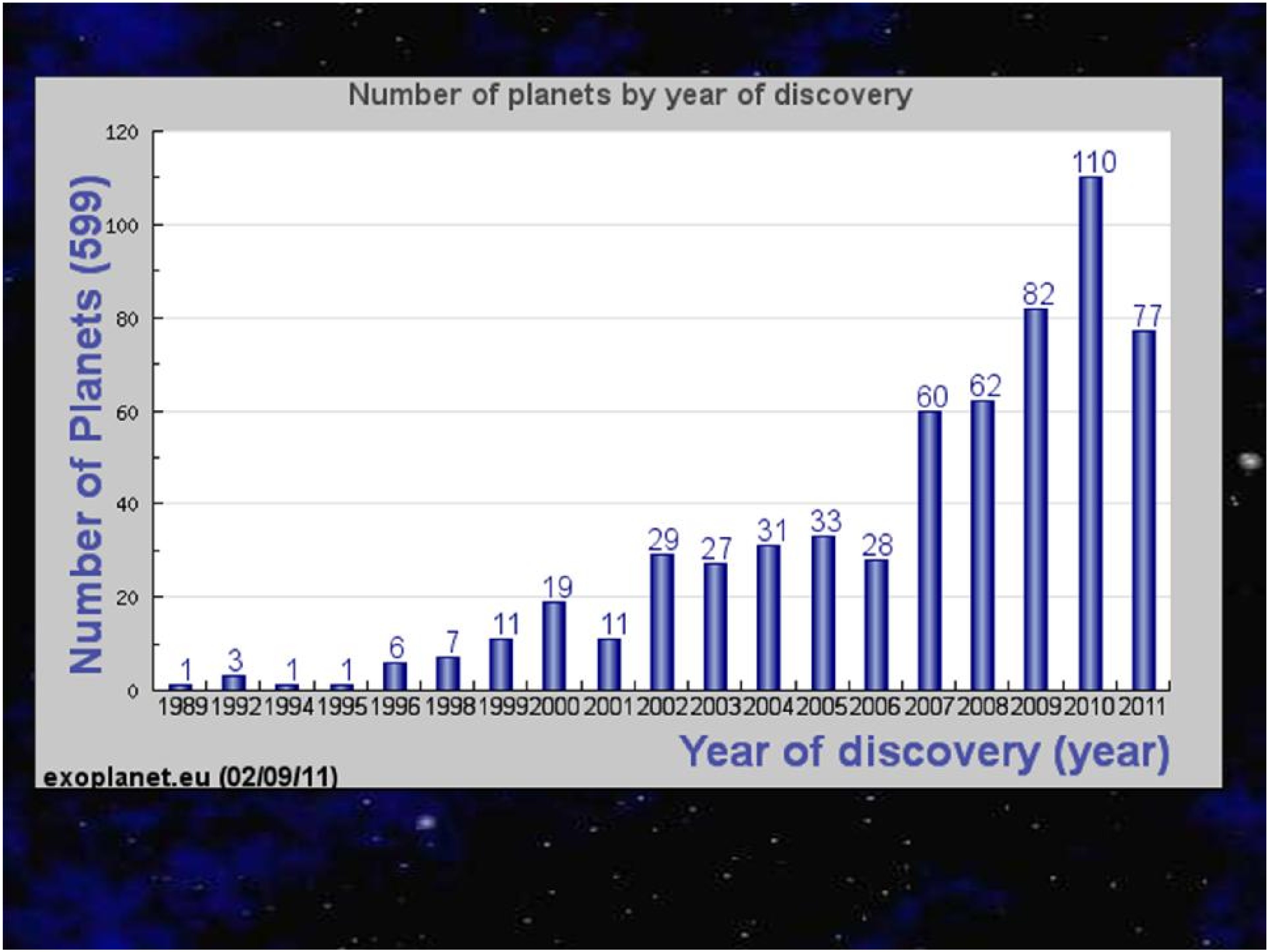
- Spectral Type F5 – K8
- Stellar Metallicity?
- Eliminate Multiple Star Systems?
- Consider Stellar Luminosity (not too high, not to low)
- Consider Stellar Mass (not to high, not too low) F5-K8



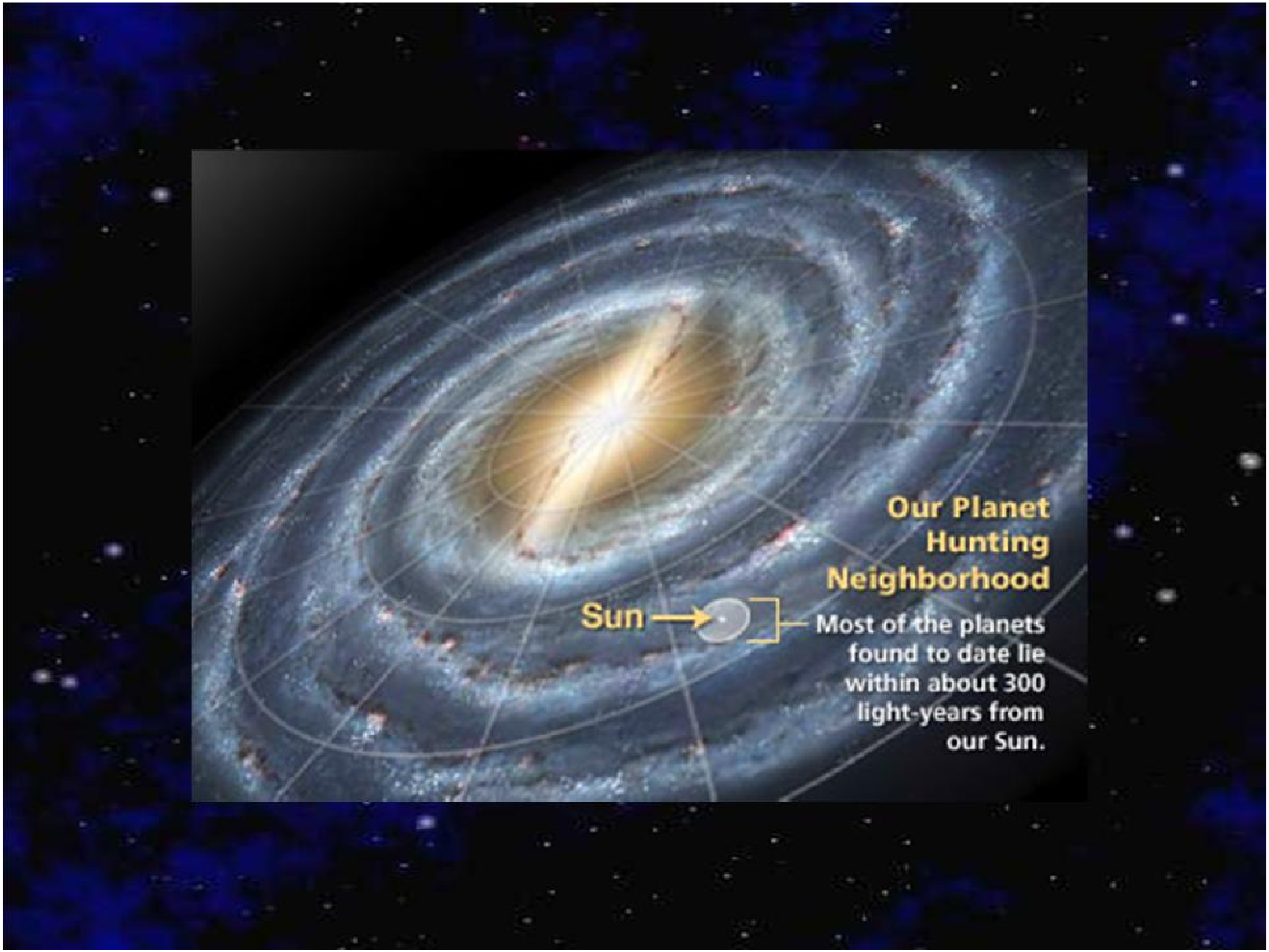
Enter
Trail off
Simulation Speed:
<-
3
->
M1:
3
M2:
.001
Radial Velocity
P: 0.58 years
a:
0.1
1.0
2.0
25.86 km/sec
e:
-25.86 km/sec
0.0
0.5
0.9
i:
0.0
75.0
90.0
w:
-90.0
0.0
90.0
Priveledged view
Earth view



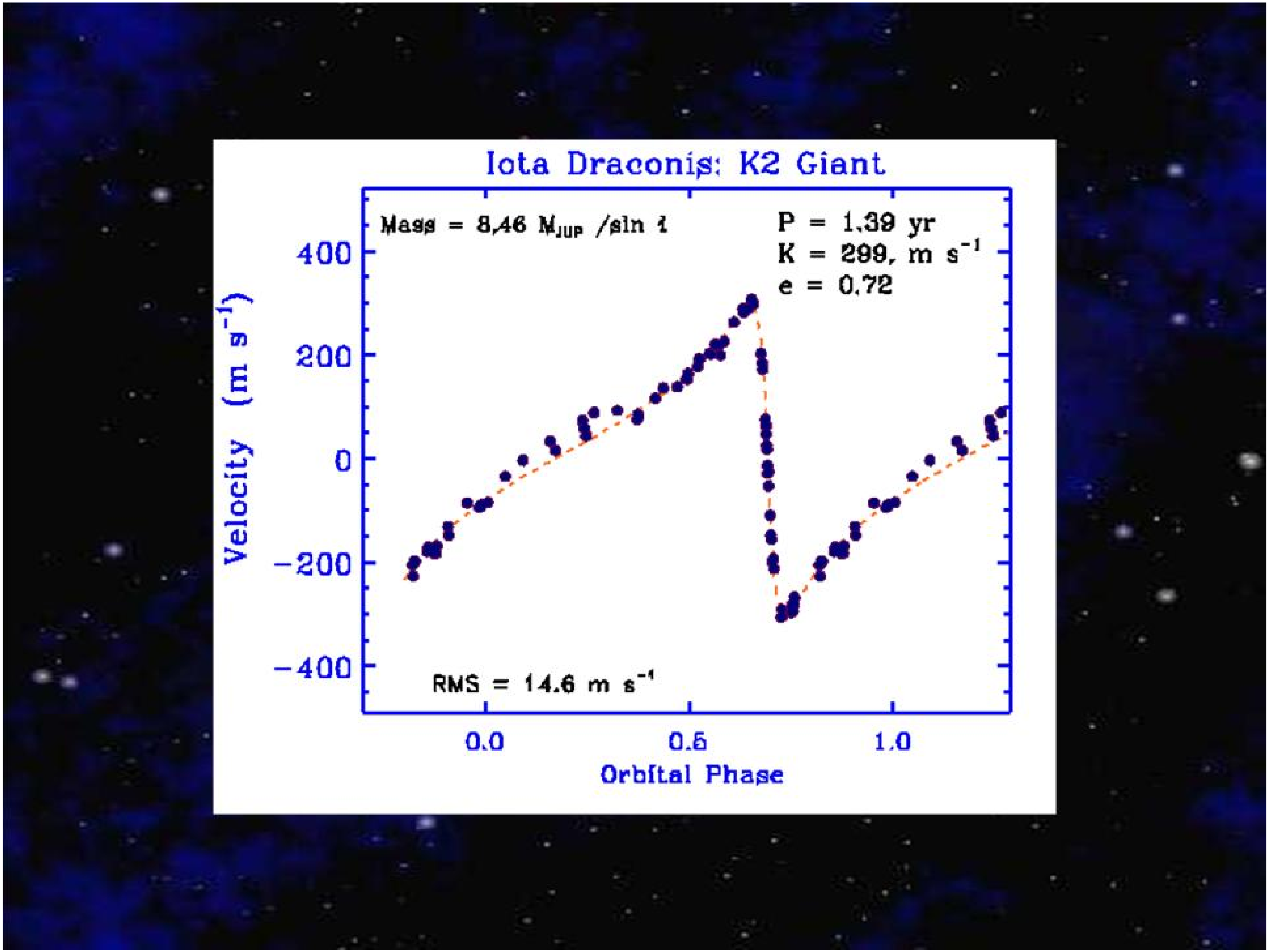
Number of Planets
600
500
400
300
200
100
0
Planetary Systems
Total Planets
Multiple Planets
Radial Velocity (Doppler)
Transiting Planets
Microlensing
Imaging
Timing of Transits



Number of planets by year of discovery
Number of Planets (599)
120
100
80
60
40
20
0
1
3
1
1
6
7
11
19
11
29
27
31
33
28
60
62
82
110
77
1989
1992
1994
1995
1996
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year of discovery (year)
exoplanet.eu (02/09/11)

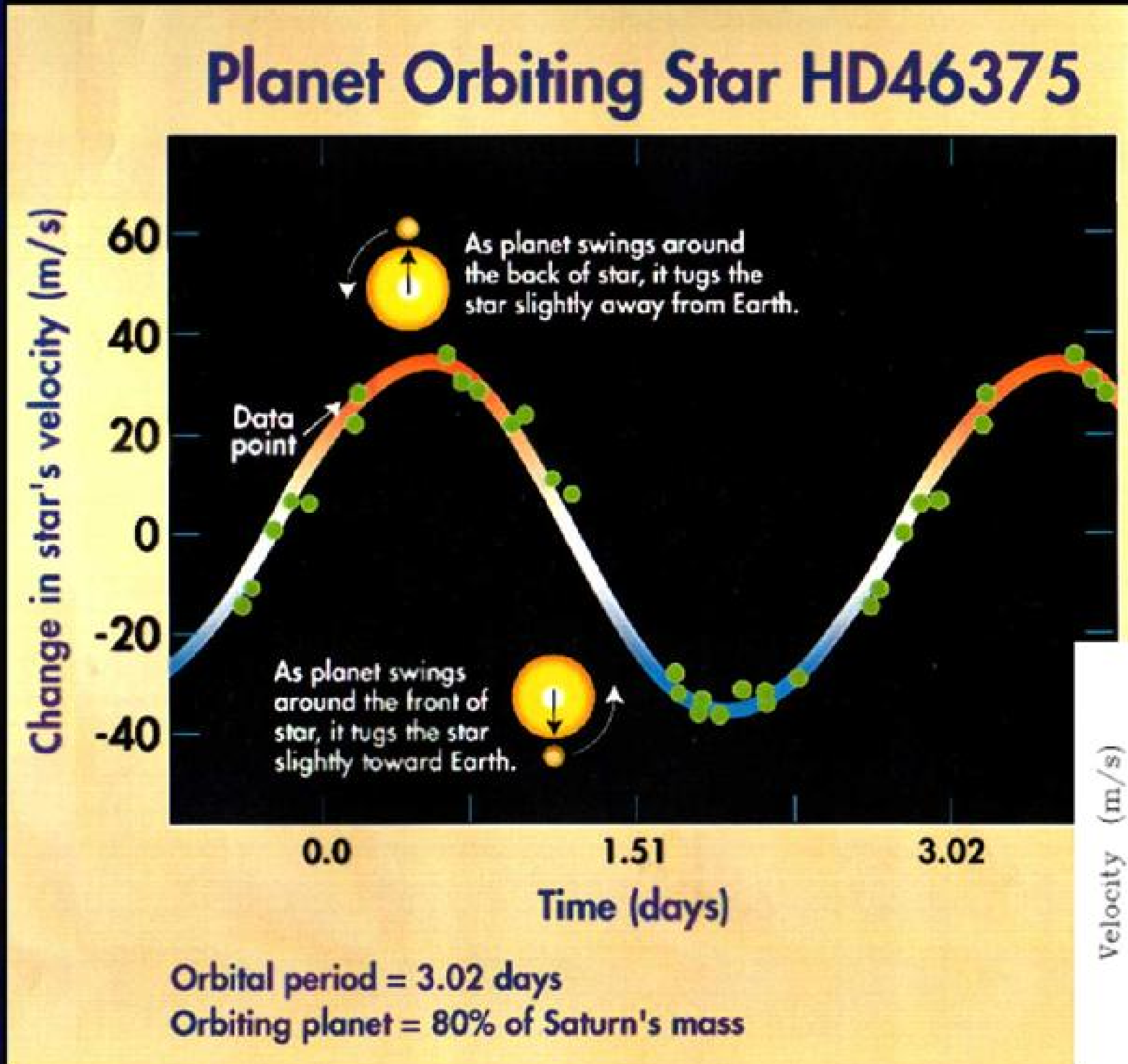


Our Planet Hunting Neighborhood
Sun
Most of the planets found to date lie within about 300 light-years from our Sun.

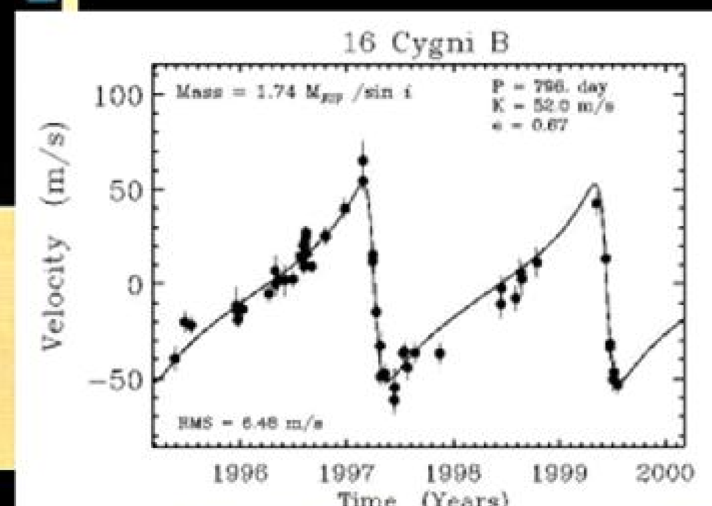


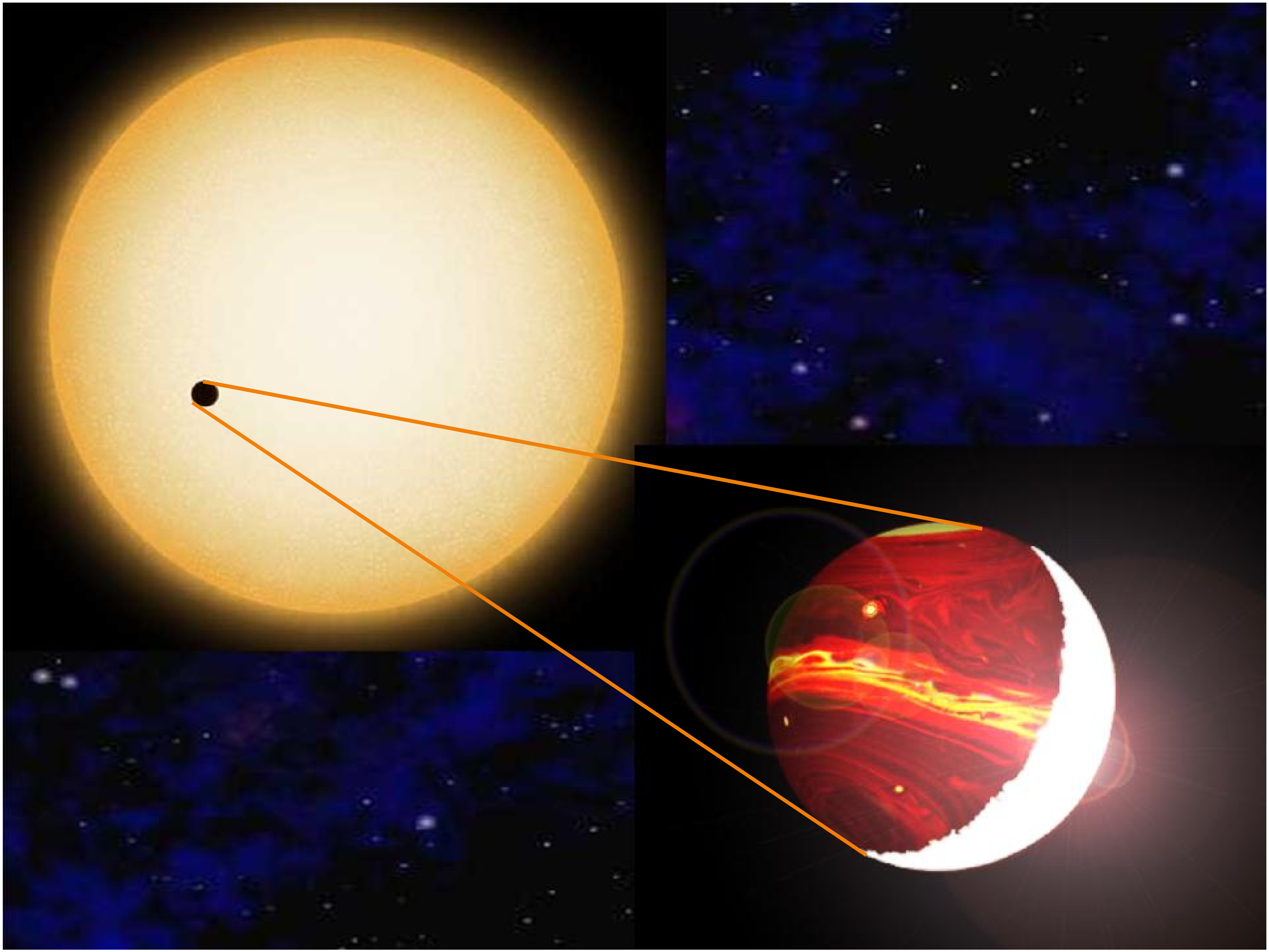
Iota Draconis: K2 Giant
Mass = 8.46 M_JUP /sin i
P = 1.39 yr
K = 299. m s^-1
e = 0.72
RMS = 14.6 m s^-1
Velocity (m s^-1)
400
200
0
−200
−400
0.0
0.5
1.0
Orbital Phase

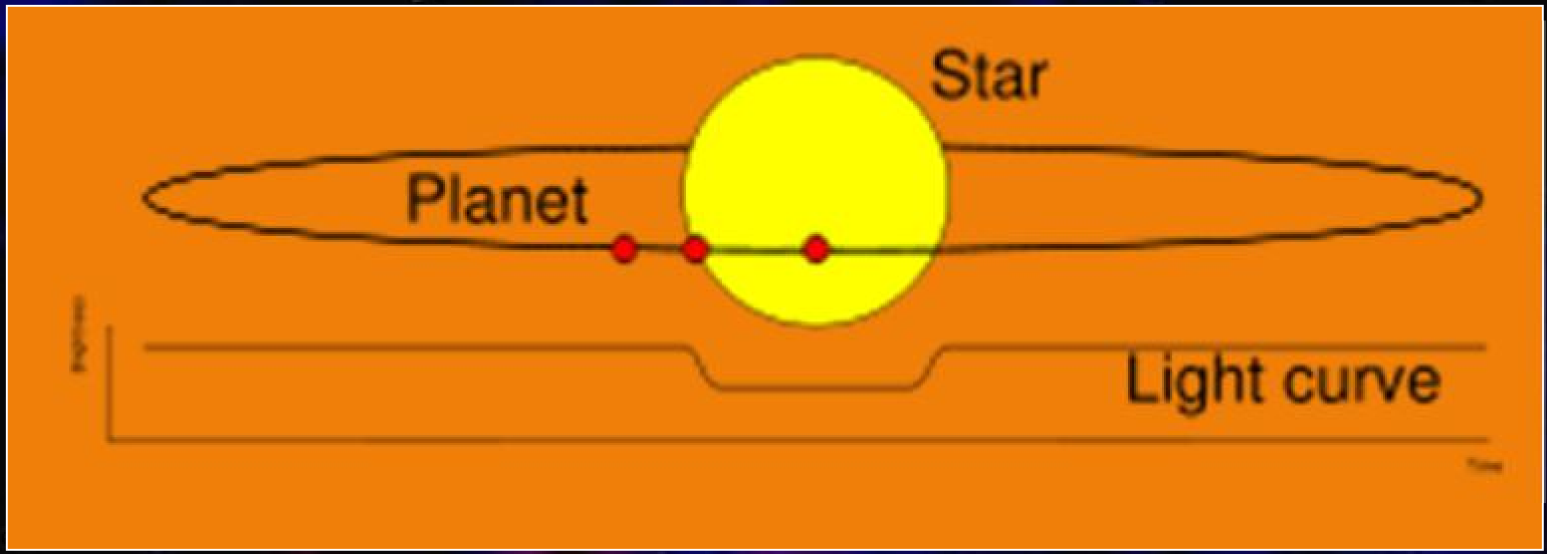
Doppler shift planet discovery



The "wobble" method gets the orbital period, semi-major axis, and a lower limit on the mass of the planet. This has detected down to 7 Earth-mass planets very close in, (but favors gas giant planets).






Star
Planet
Light curve

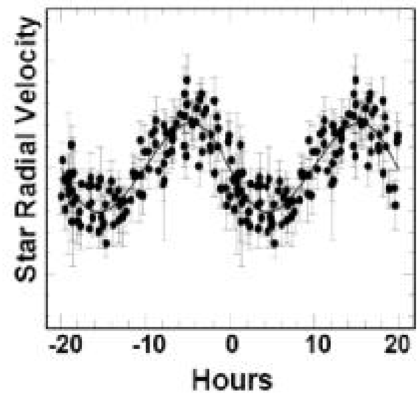
First Rocky Exoplanet Detected

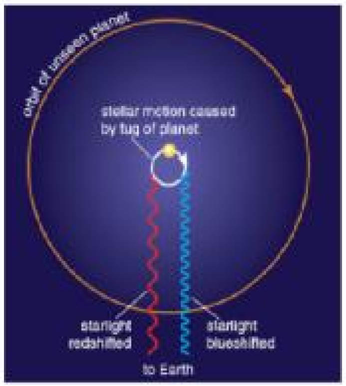
- Most known exoplanets are large and have low densities - similar to jovian planets in our solar system
- A space telescope recently discovered a planet with radius only 70% larger than Earth's
- Groundbased observations show the planet's mass is less than 5 times Earth's
- Together, the observations reveal that the planet's density is similar to Earth's - the first confirmation of a "rocky" exoplanet

Artist's conception of the view of the rocky planet's parent star (Corot-7) from above the surface of the planet (Corot-7b). Image from ESO / L. Calcada.

How Can We Find a Planet's Density?

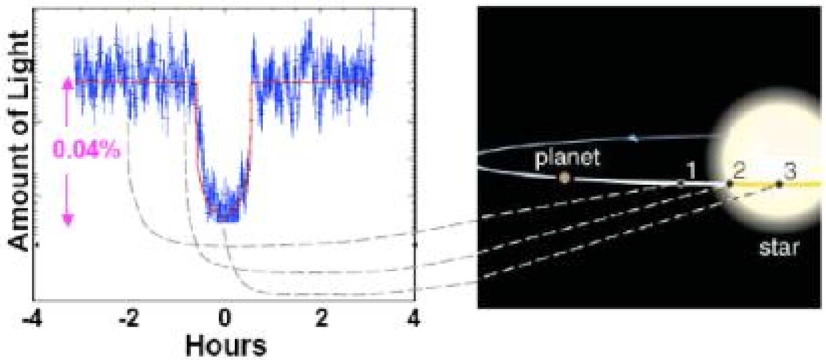
- Density = Mass / Volume
- The planet's mass was determined using the *radial velocity method:*
  The planet gravitationally 'tugs' on the star, shifting the wavelength of light the star emits back and forth. The amount of shift indicates the planet's mass.





Changes in the measured wavelengths of star light are caused by a planet with mass ~5 times Earth's.

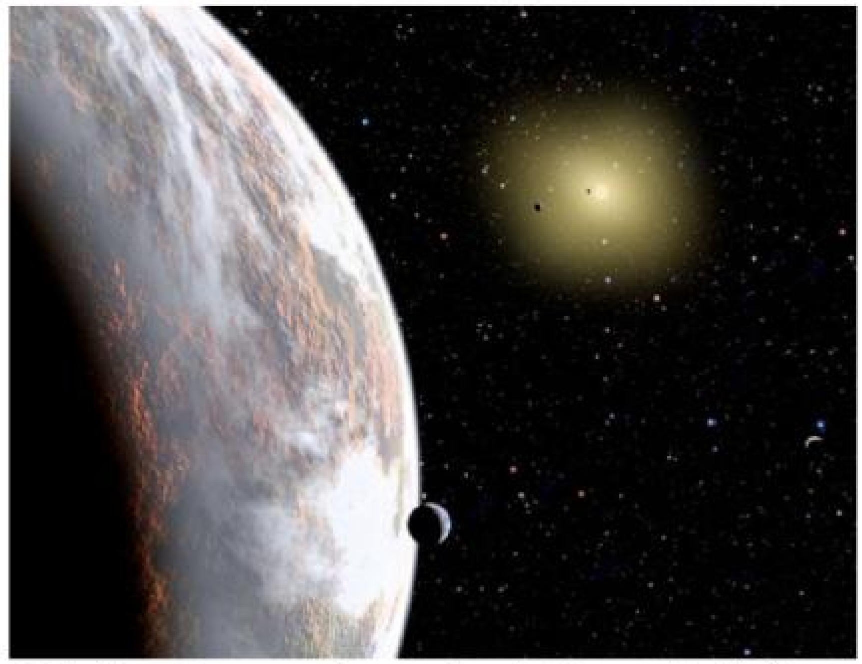
- Volume = $4/3\ \pi\ R^3$
- The planet's size was determined using the *transit method:*
  The amount of light measured from a star decreases when a planet passes in front. The amount of decrease indicates the planet's size.



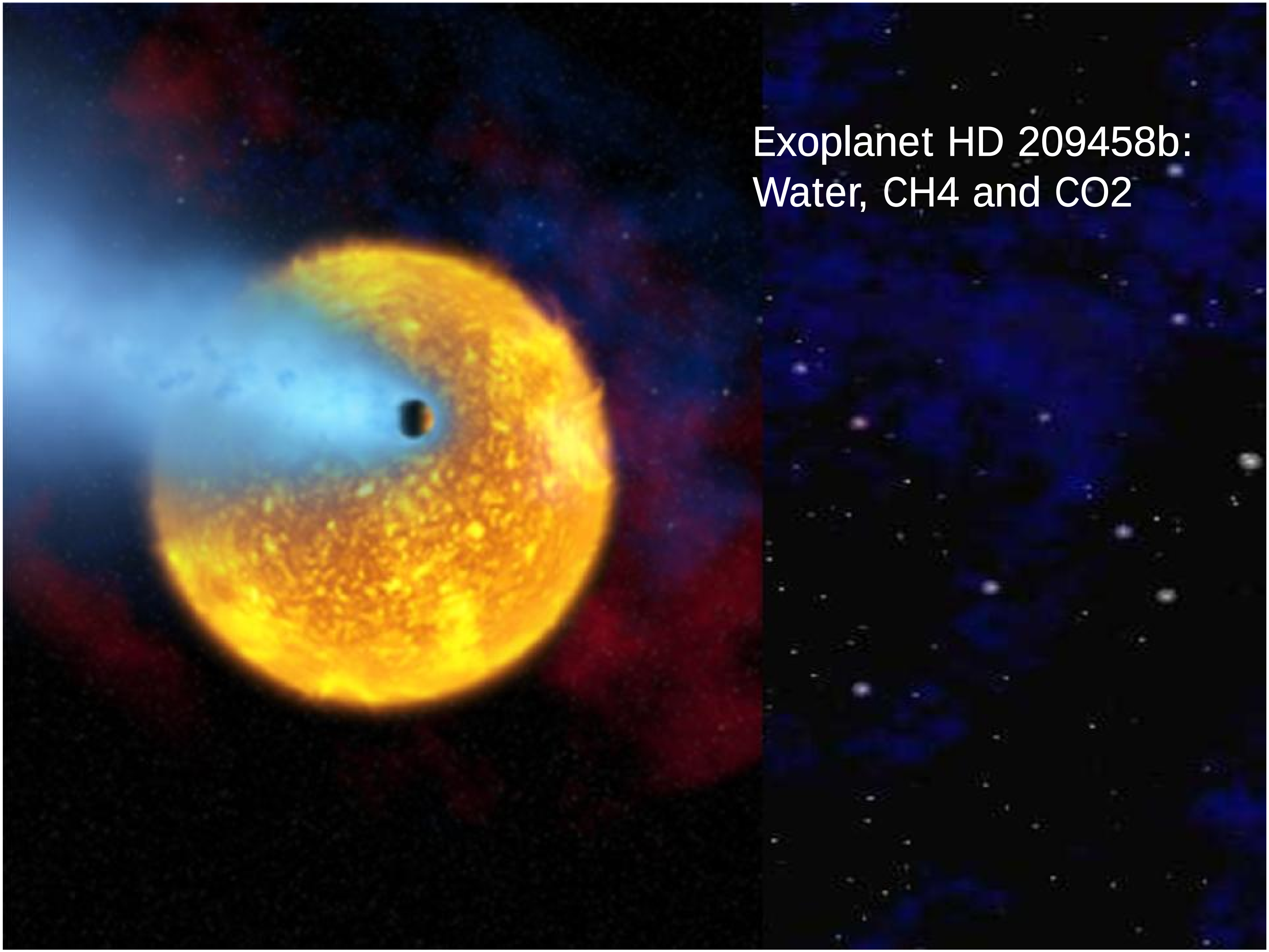
Periodic decreases in light from the star are caused by a planet with diameter 1.7 times Earth's passing in front.

The Big Picture

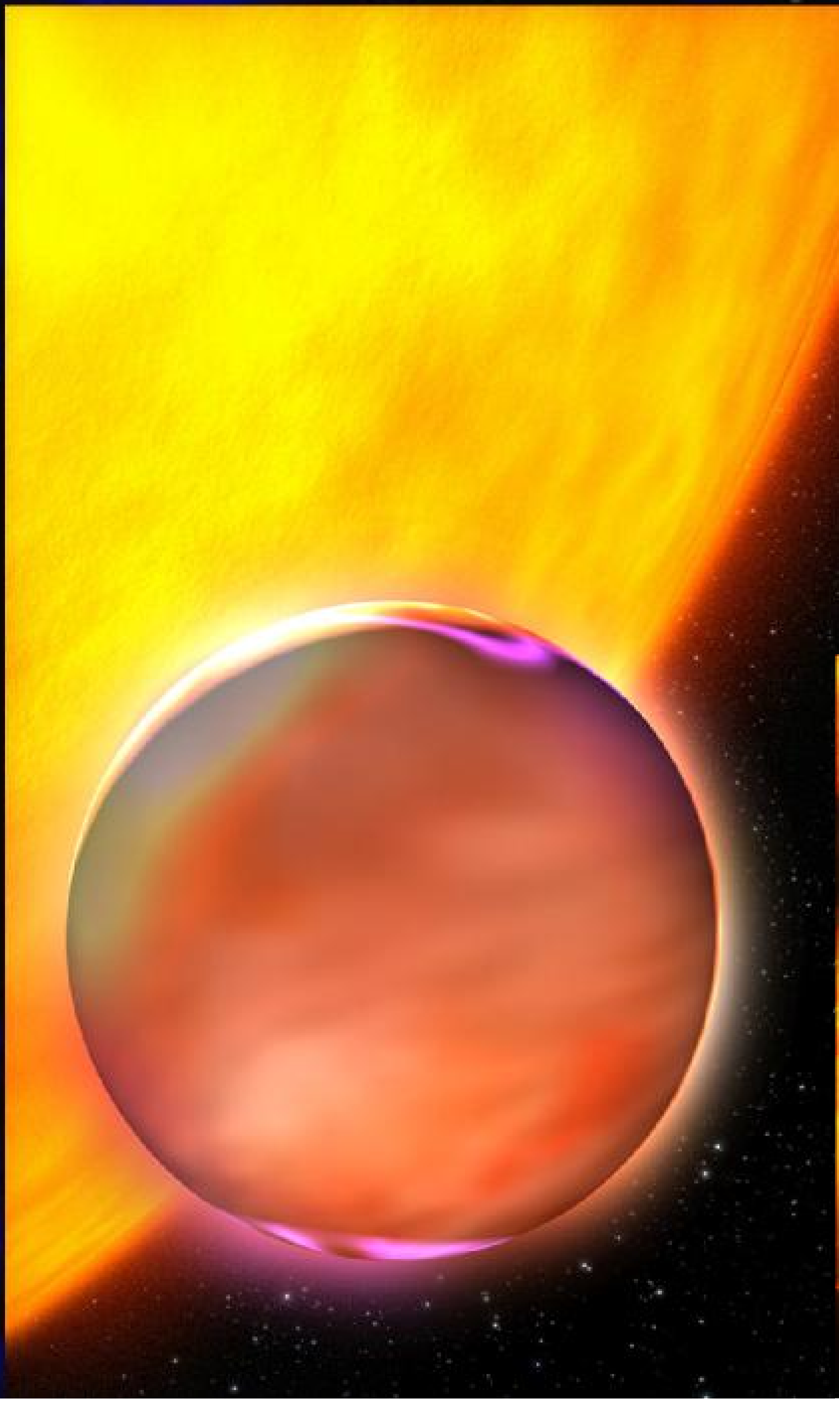
- After discovering hundreds of exoplanets resembling our jovian planets, astronomers have found the most Earth-like planet to date
- Although planet Corot-7b's density is close to Earth's, differences abound: it orbits its star in ~20 hours (faster than any known exoplanet) - so close that its rocky surface may be molten
- With the existence of Earth-like planets now demonstrated, astronomers have reason to hope that the Kepler mission will discover more



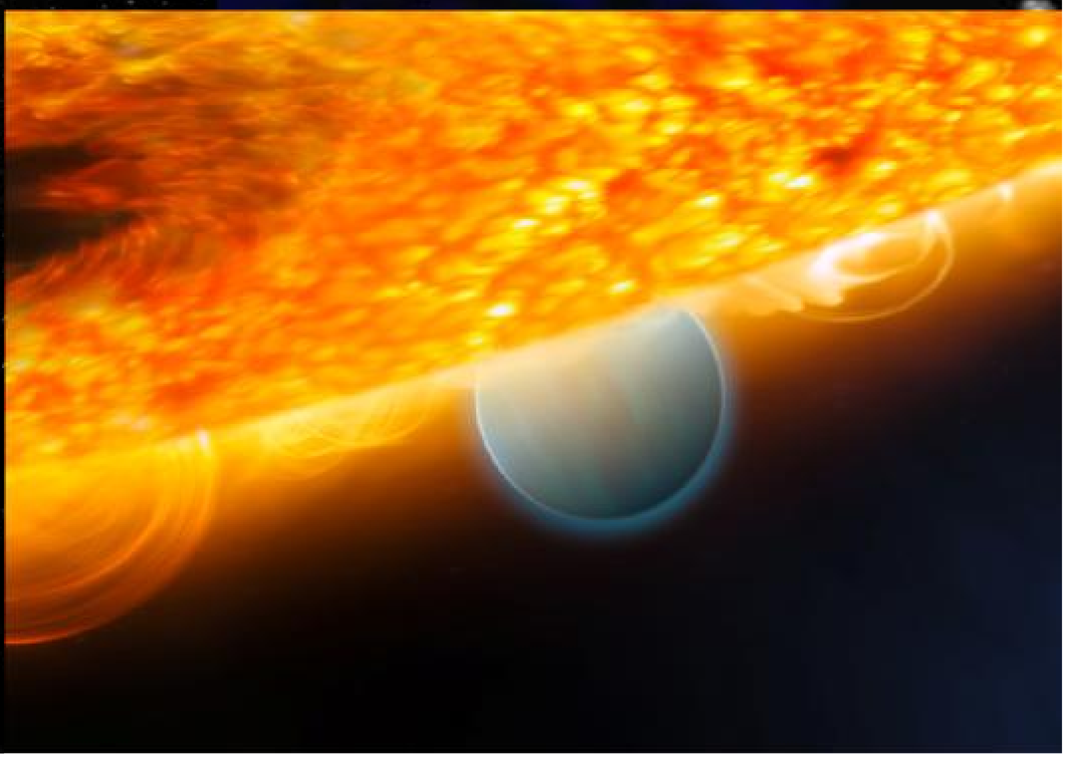
Detection of more rocky exoplanets ('Super-Earths') like those in this artist's depiction should come rapidly, thanks to dedicated space telescopes and improving ground-based detection capabilities. Image from D. Aguilar, Harvard Smithsonian CfA.


Exoplanet HD 209458b:
Water, CH4 and CO2

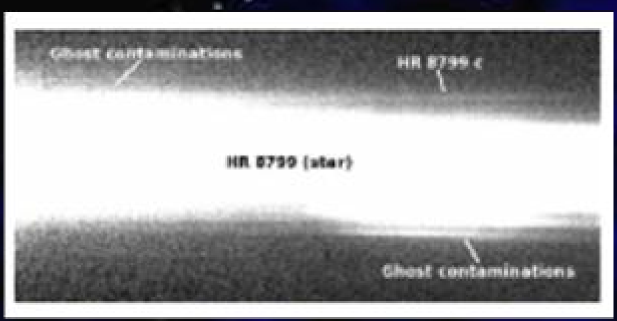
2007, K and Na in atmosphere:
hazes and dust

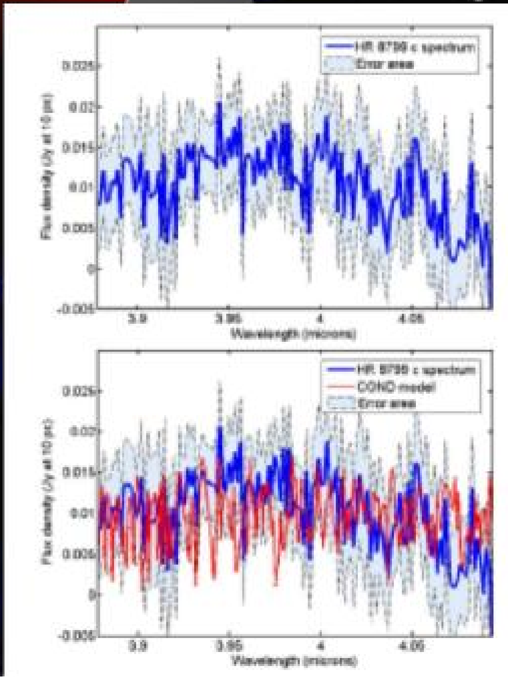


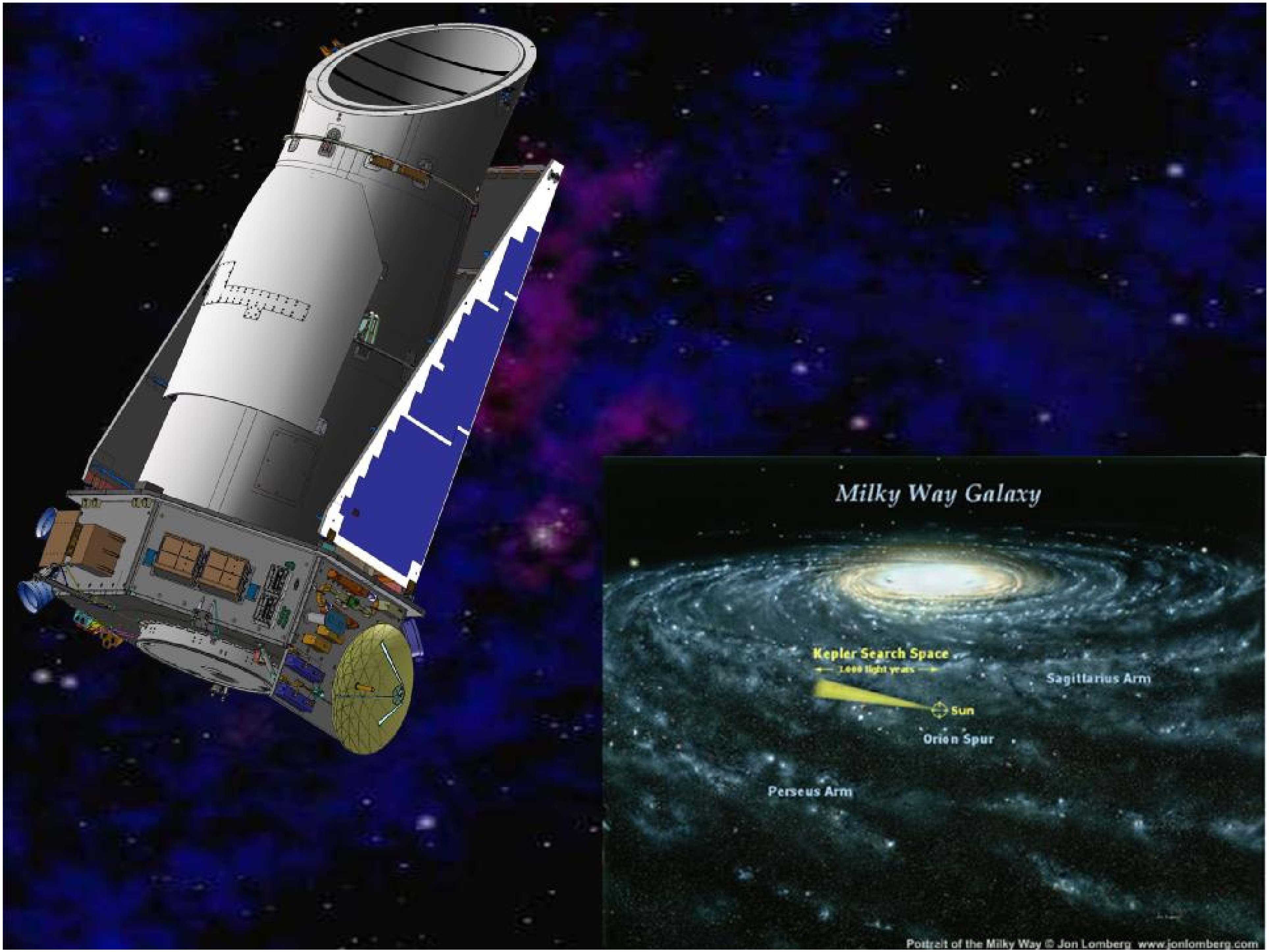
2009, CO_2 in atmosphere:

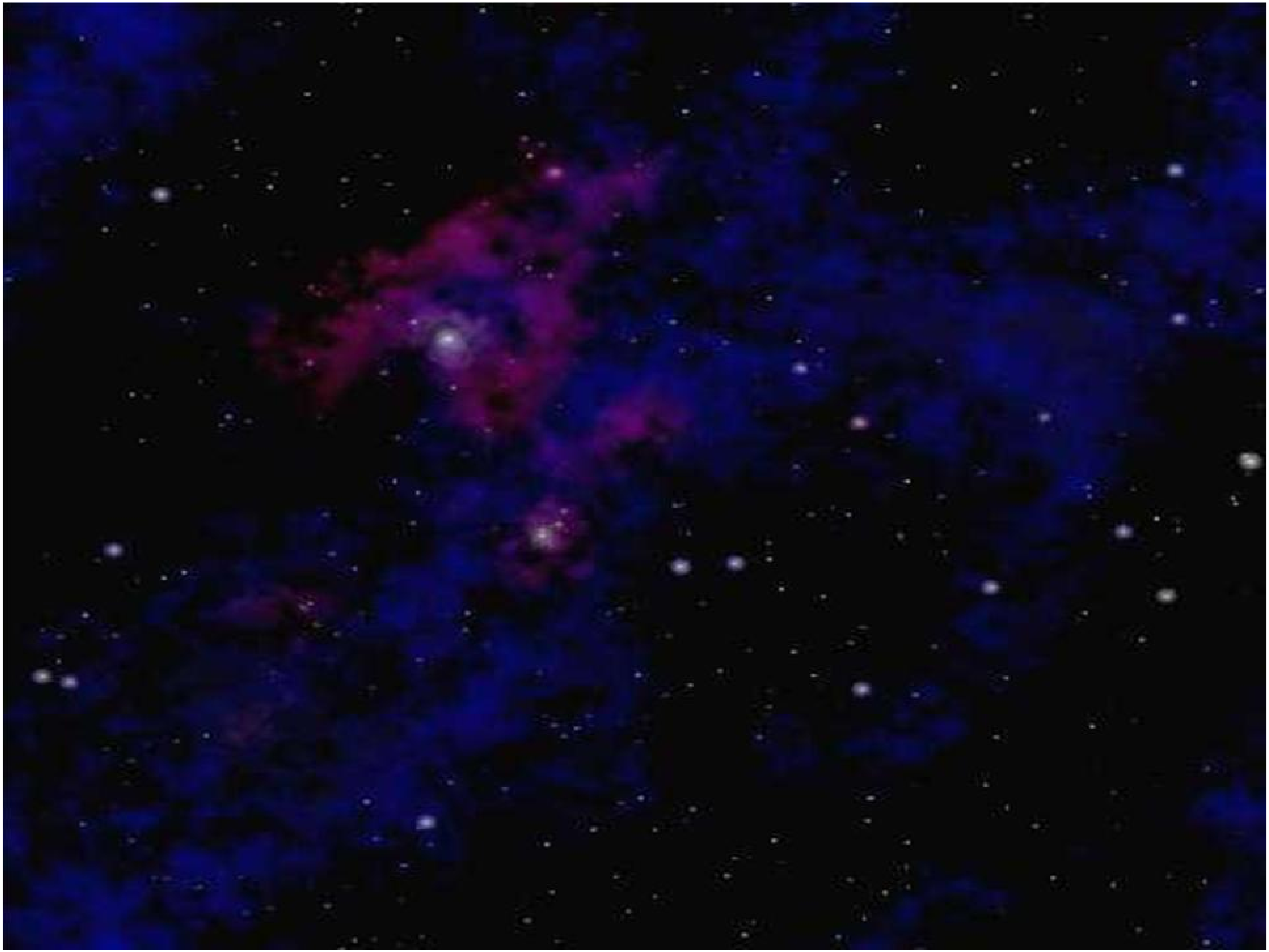


2010, first ever direct spectrum of exoplanet

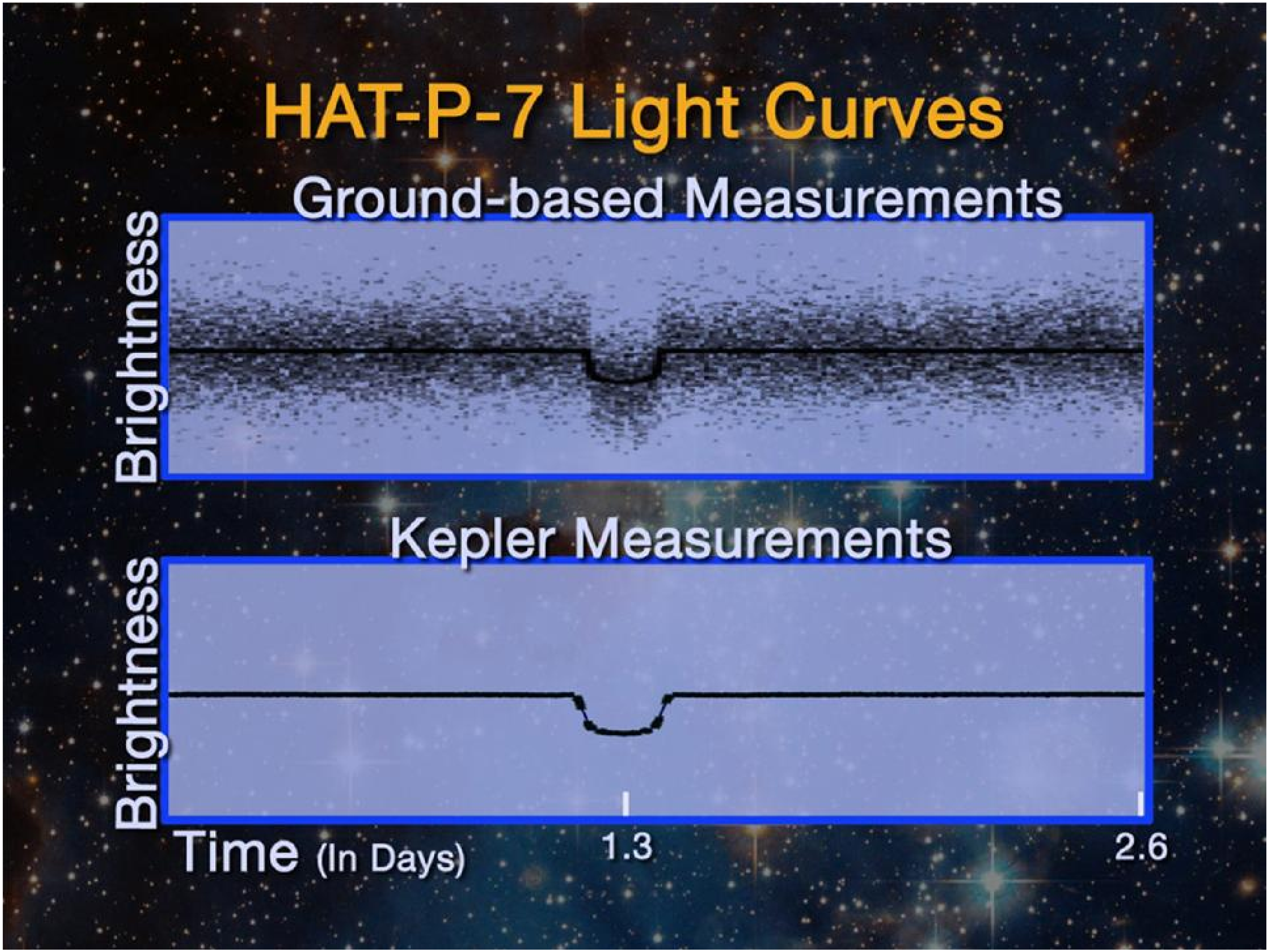


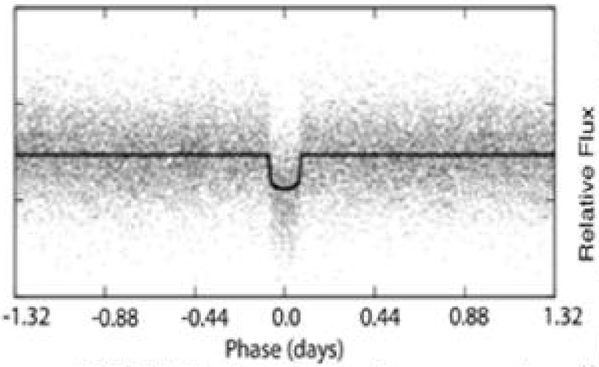



Milky Way Galaxy
Kepler Search Space
Sun
Sagittarius Arm
Orion Spur
Perseus Arm
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

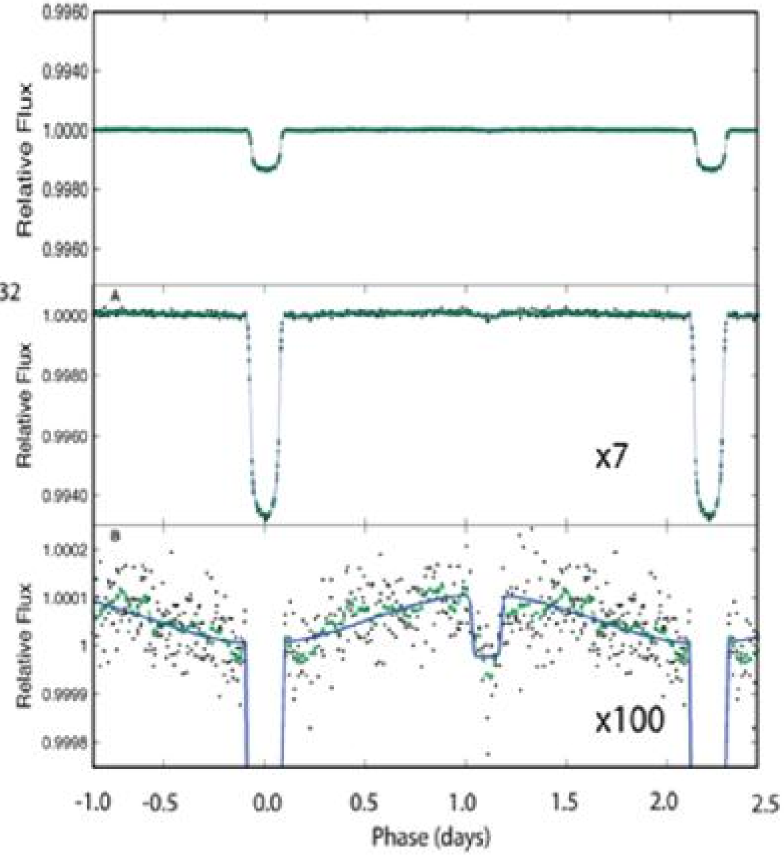



Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA


HAT-P-7 Light Curves
Ground-based Measurements
Brightness
Kepler Measurements
Brightness
Time (In Days)
1.3
2.6



HAT-P-7b data from the ground



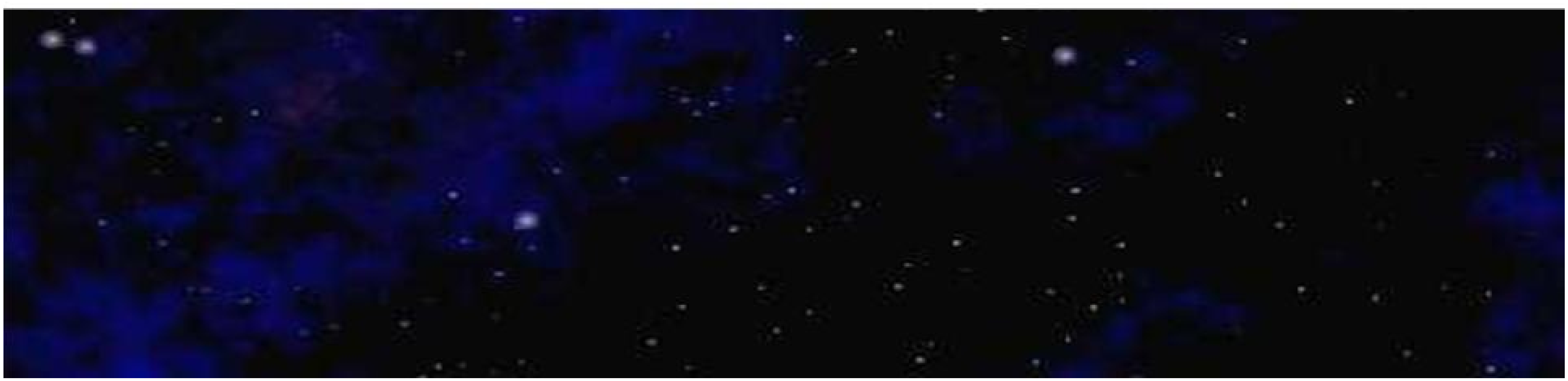
Kepler Commissioning data

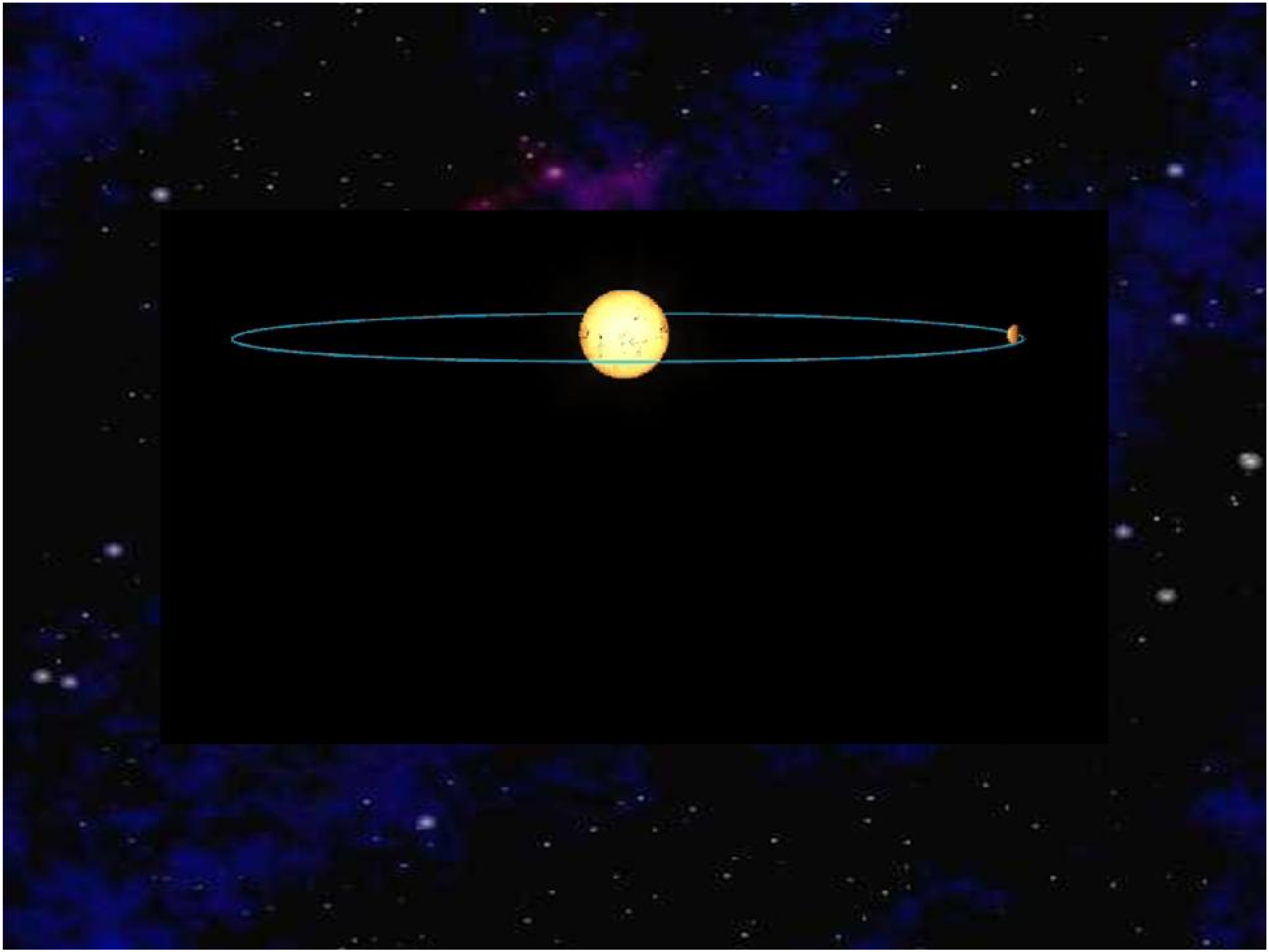
Measurement scatter is within the line thickness.

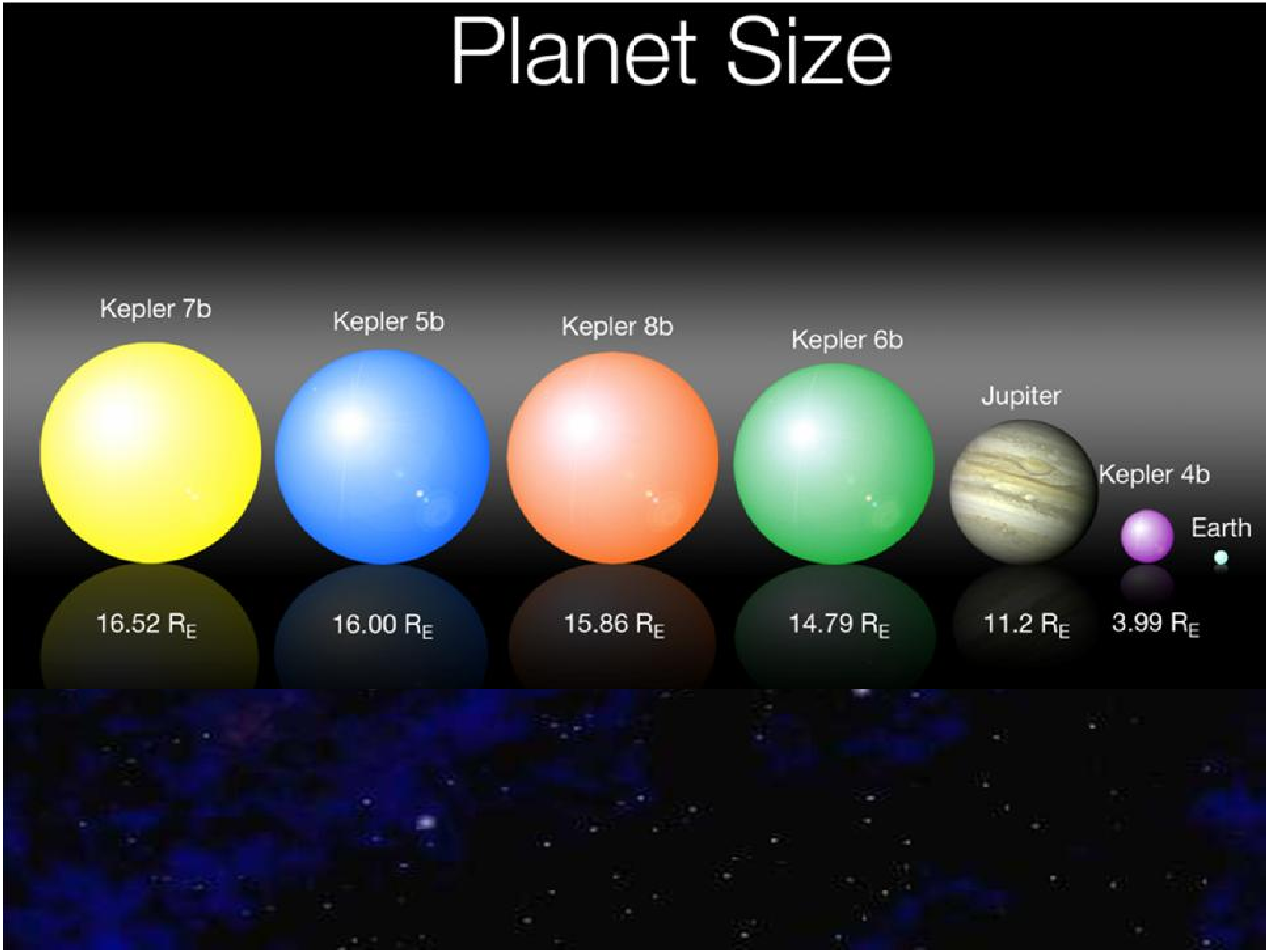
Magnification by 7 shows transits + occultation

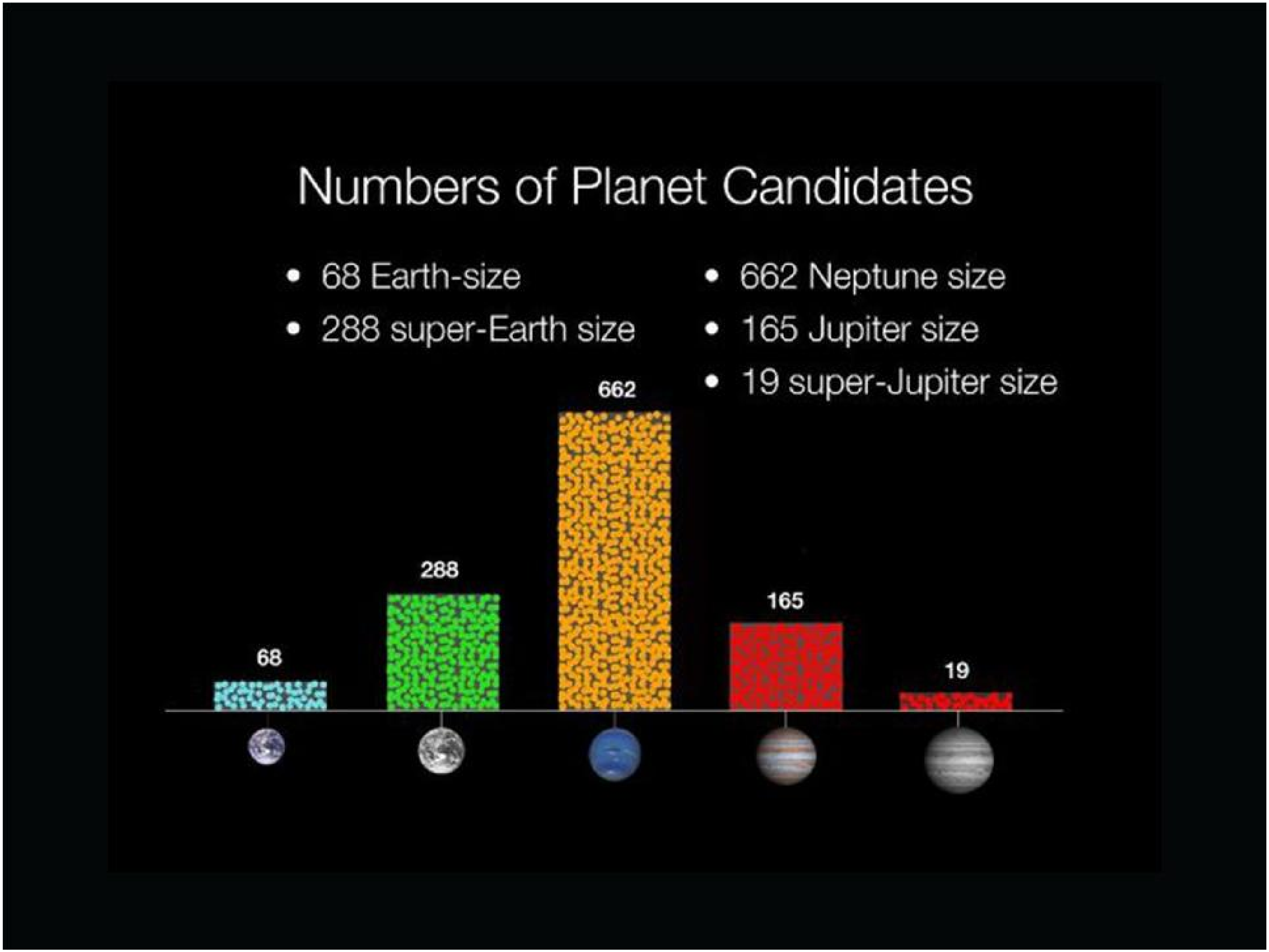
Occultation is the size of a transit by Earth-size planet.

Rise in light between transits is discovery of light from the planet itself.



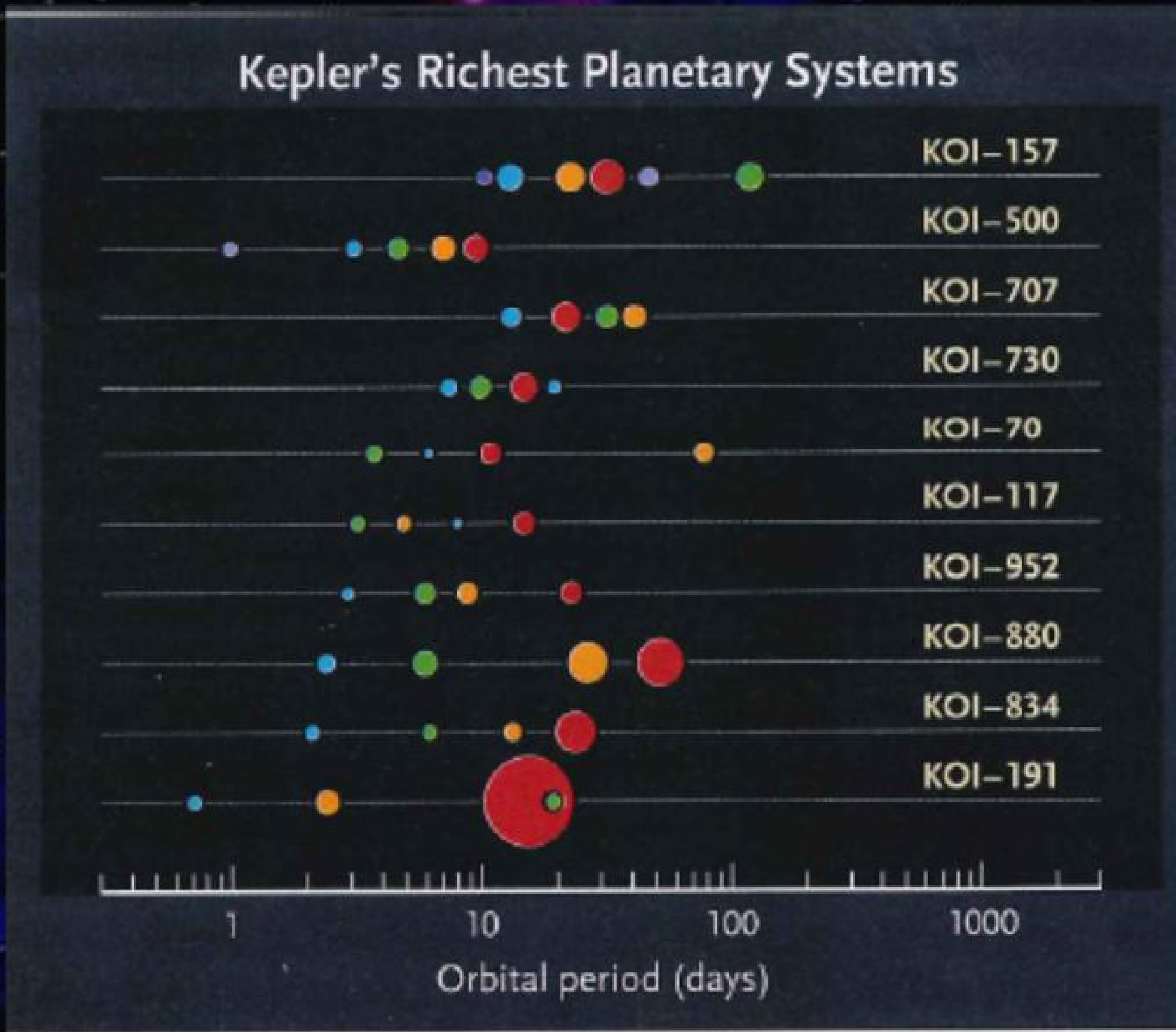


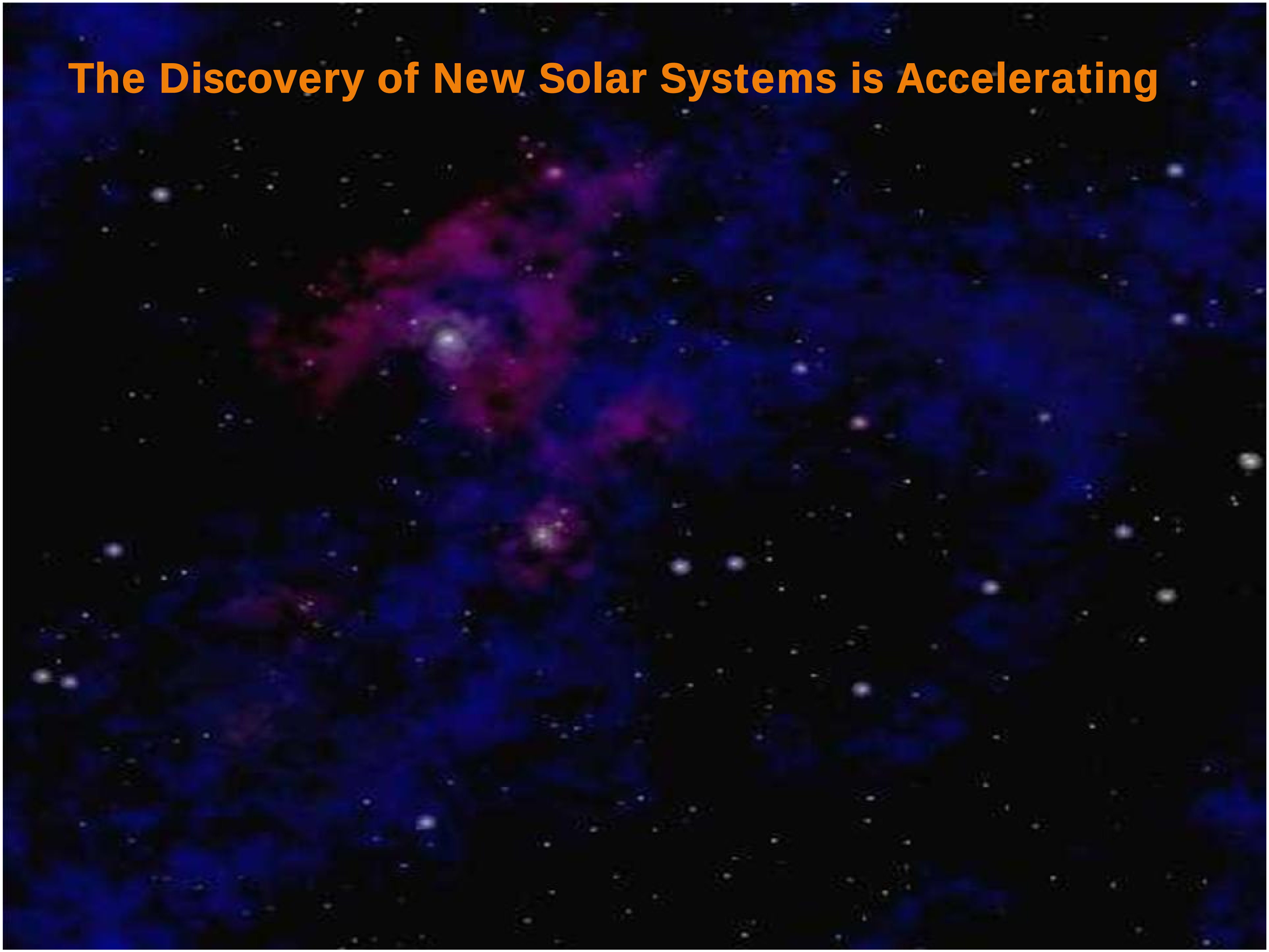

Planet Size
Kepler 7b
Kepler 5b
Kepler 8b
Kepler 6b
Jupiter
Kepler 4b
Earth
16.52 R_E
16.00 R_E
15.86 R_E
14.79 R_E
11.2 R_E
3.99 R_E

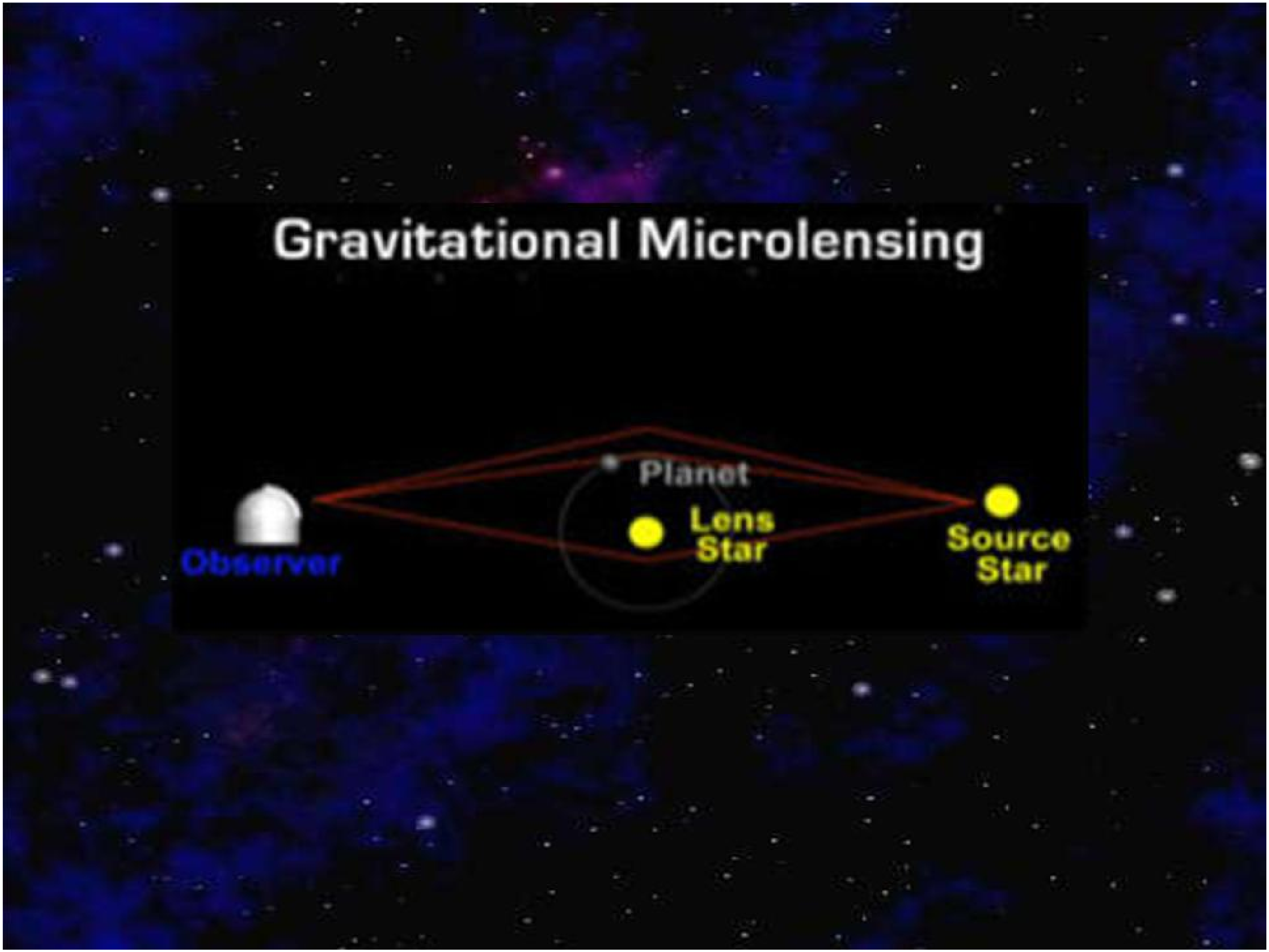


Numbers of Planet Candidates
• 68 Earth-size
• 288 super-Earth size
• 662 Neptune size
• 165 Jupiter size
• 19 super-Jupiter size
68
288
662
165
19

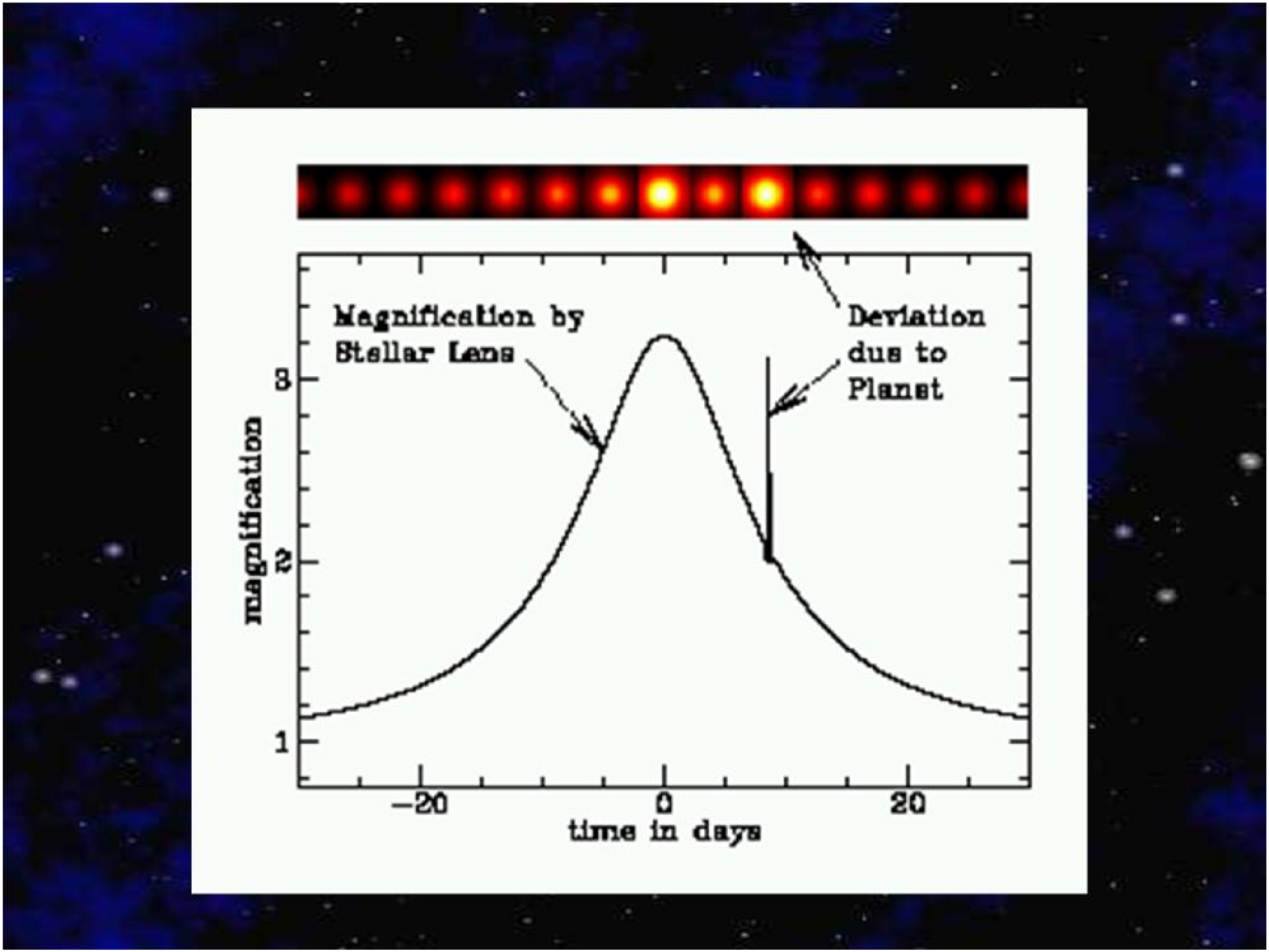
The Discovery of New Solar Systems is Accelerating




The Discovery of New Solar Systems is Accelerating



Gravitational Microlensing
Planet
Observer
Lens
Star
Source
Star



Magnification by
Stellar Lens
Deviation
due to
Planet
magnification
1
2
3
-20
0
20
time in days

Plural worlds. The Kepler space telescope (below) has already spotted hundreds of candidate planets around other stars.

Alien Planets Hit the Commodities Market

There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. —*Giordano Bruno, 1584*

FOR HOLDING FIRM TO THIS IDEA OF PLURAL worlds, Giordano Bruno spent 7 years in a dungeon; then, on 17 February 1600, he was led to a public square in Rome and burned at the stake. If Bruno had had the power to summon the future, his best shot at survival might have been to show his inquisitors the Web page of the Extrasolar Planets Encyclopedia, circa 2010. Evidence from the year 2000, when the planets in the encyclopedia numbered a mere 26, might not have done the trick. But the latest tally, 505 and counting, surely would have stayed their torches.

In the past decade, astronomers have discovered so many planets outside of the solar system that only the weirdest of them now make the mainstream news—such as WASP-17, a giant planet discovered in August 2009, which orbits "backward," or counter to the spin of its parent star. A software application for iPhones and iPads keeps track of exoplanet discoveries; the score crossed 500 as this article was being written. Hundreds more may soon follow as astronomers pursue some 700 candidates that NASA's Kepler space telescope detected in the first few months after its launch in March 2009.

Although most of the planets discovered so far are gas giants, an analysis of the Kepler data has convinced researchers that smaller Earth-like planets abound in the universe and that improved detection capabilities in the coming years will turn up scores of them just in our galactic backyard. This insight has opened up the possibility of detecting life elsewhere in the universe within the lifetimes of young astronomers entering the field, if not sooner. Meanwhile, the sizes and orbits of planets already discovered are revolutionizing researchers' understanding of how planetary systems form and evolve.

The discovery of exoplanets began as a trickle in the previous decade, starting with the detection of "51 Pegasi b" in 1995 by a Swiss team led by Michel Mayor, followed the next year by the discoveries of five planets by U.S. astronomers Geoffrey Marcy, Paul Butler, and their colleagues. By 2001, several other teams had joined the quest, and the pace of discovery quickened.

The oldest and most popular technique for finding planets has been the use of Doppler spectroscopy—the blue-ward or red-ward shift in the light of a star as it wobbles under the gravitational tug of its orbiting planet. In 1999, astronomers also began detecting exoplanets by the transit technique, watching for a star to dim slightly as its planet travels across its face. Transits have yielded the discovery or confirmation of more than 100 planets to date.

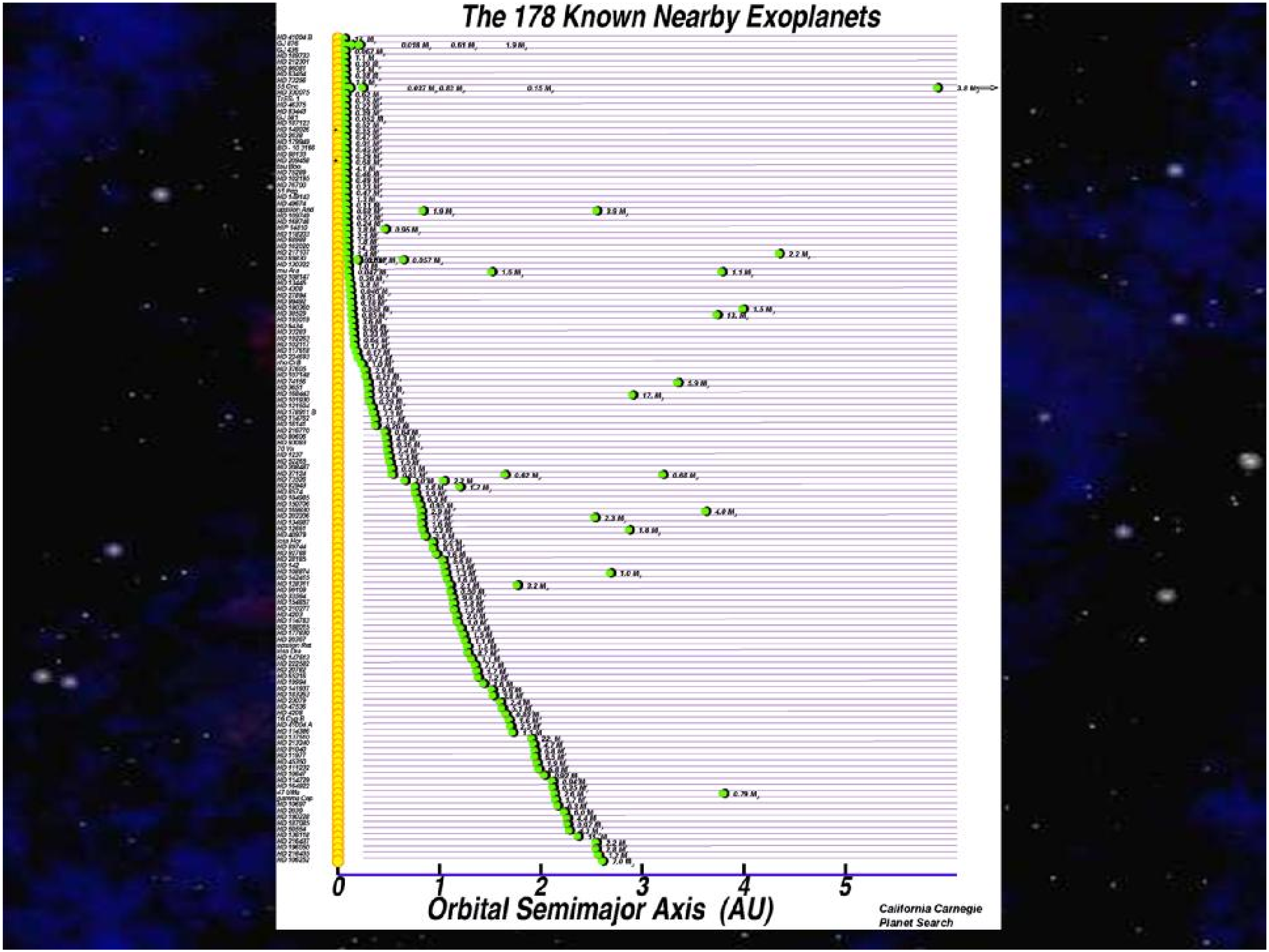
Since 2001, planet-hunters have added two more techniques to their toolbox. One is microlensing, in which a star briefly brightens as the gravity of another star in the foreground bends its light; changes in the brightening can reveal a planet orbiting the foreground star. Researchers led by Ian Bond of the Royal Observatory, Edinburgh, in the United Kingdom announced the first discovery of a planet through microlensing in 2004; the technique has led to 10 more finds since.

In 2008, astronomers published the first direct images of exoplanets: tiny pinpricks of light close to a nearby star. With advances in adaptive optics, the technology that corrects for the blurring effect of the atmosphere on ground telescopes, and the development of better coronagraphs—devices that help block out the direct light from a star—astronomers hope to image many more planets directly.

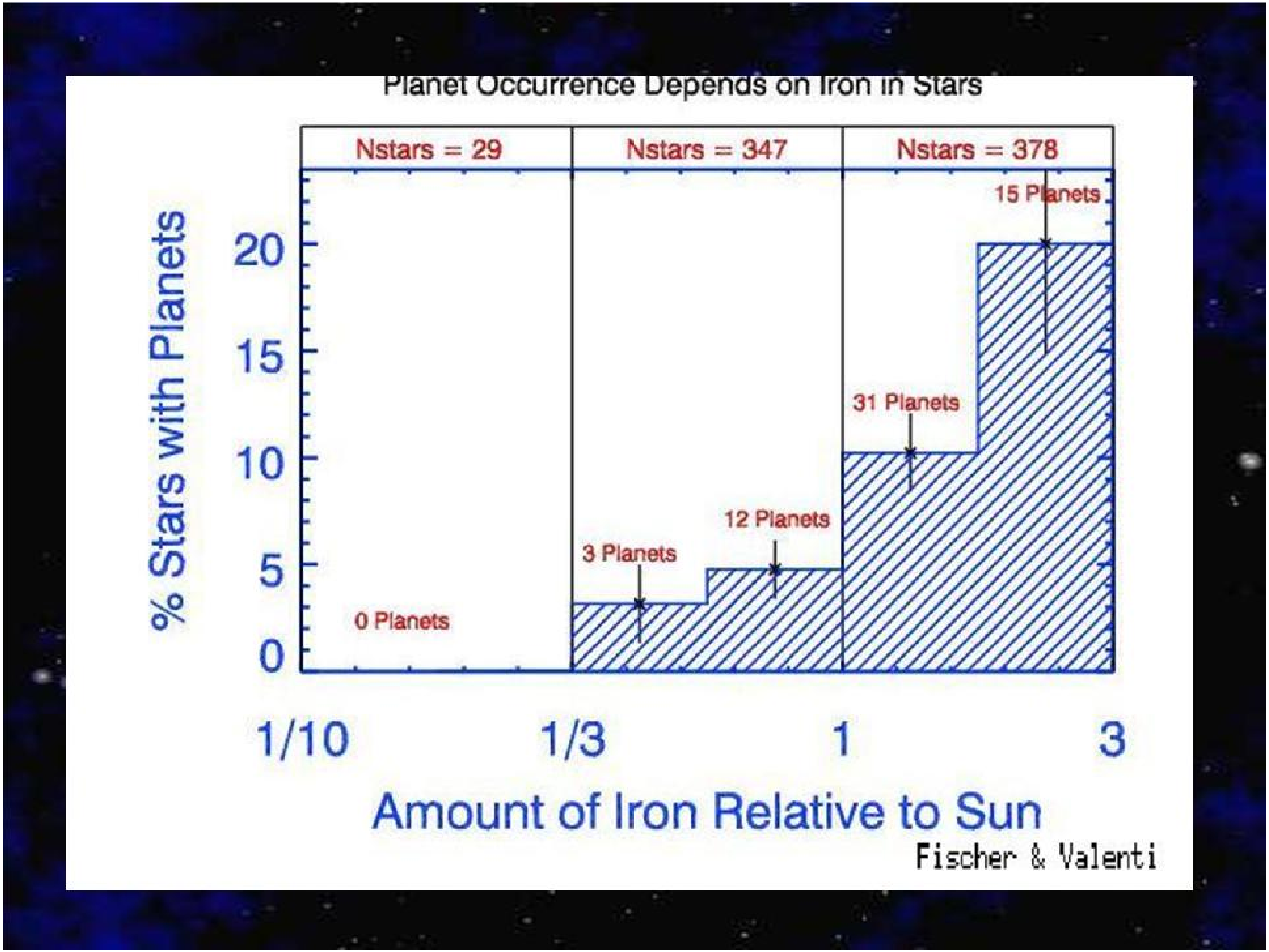
The diversity of planetary systems discovered to date has forced astronomers to revise their theories of how these systems arise and develop. The discovery of hot Jupiters orbiting very close to their parent star suggests that gas giants—thought to form far out from the star—can migrate inward over time. And the discovery of planets dancing around their stars in tilted or even retrograde orbits suggests that planets can be wrenched from their original birthplaces into odd orbits that astronomers could not have predicted.

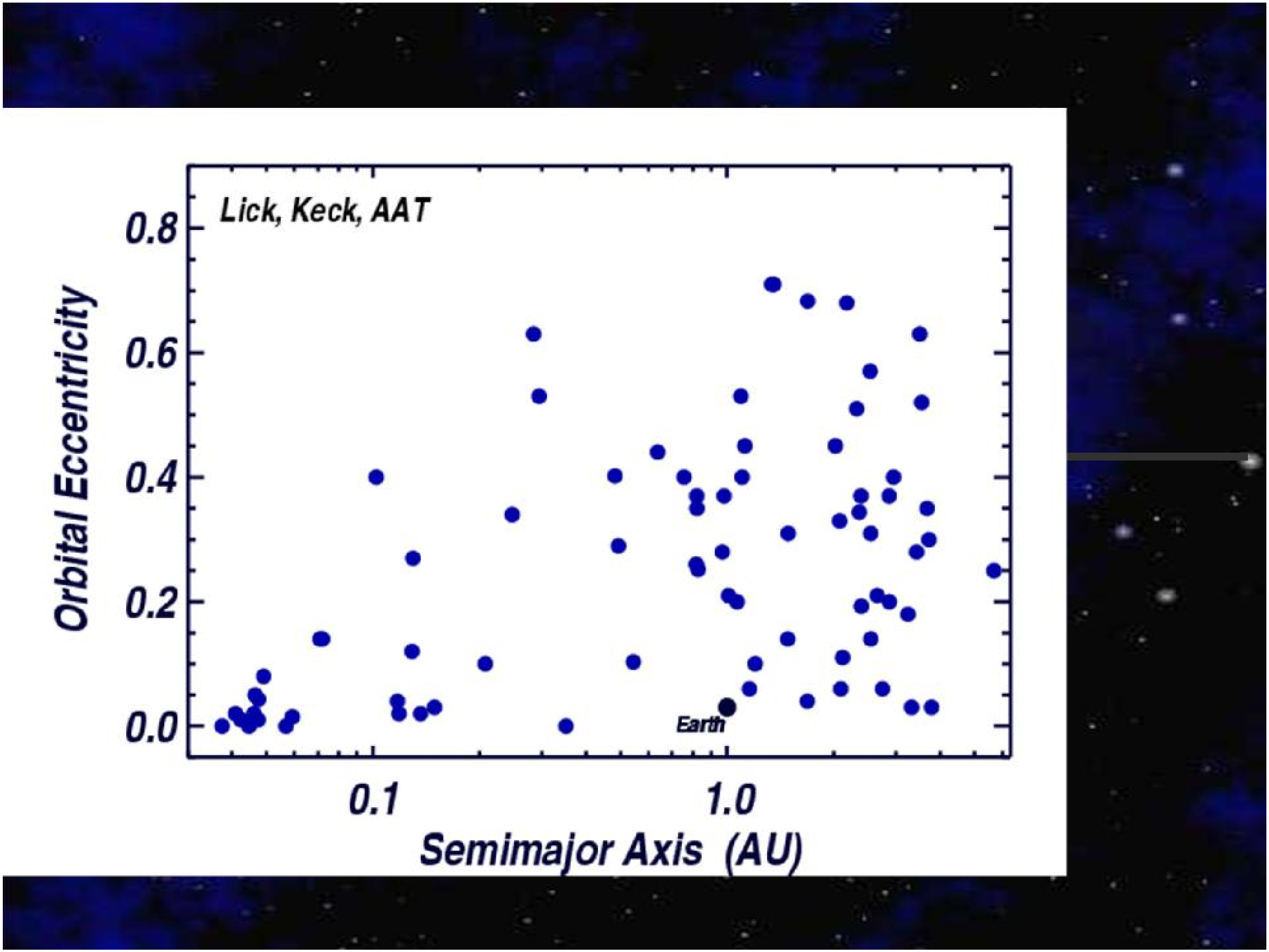
Astronomers expect Kepler to find several Earth-like planets in the next few years. Already, researchers are planning new ground- and space-based instruments to take spectra of the atmospheres of some of those habitable planets. Those atmospheres may bear signatures of life, such as oxygen, which researchers believe can be produced only by biological processes. If and when that happens, it would be the ultimate vindication of Bruno's fatal vision of a cosmos teeming with worlds.

–YUDHIJIT BHATTACHARJEE



The 178 Known Nearby Exoplanets
0
1
2
3
4
5
Orbital Semimajor Axis (AU)
California Carnegie
Planet Search


Planet Occurrence Depends on Iron in Stars
Nstars = 29
Nstars = 347
Nstars = 378
15 Planets
31 Planets
12 Planets
3 Planets
0 Planets
% Stars with Planets
20
15
10
5
0
1/10
1/3
1
3
Amount of Iron Relative to Sun
Fischer & Valenti

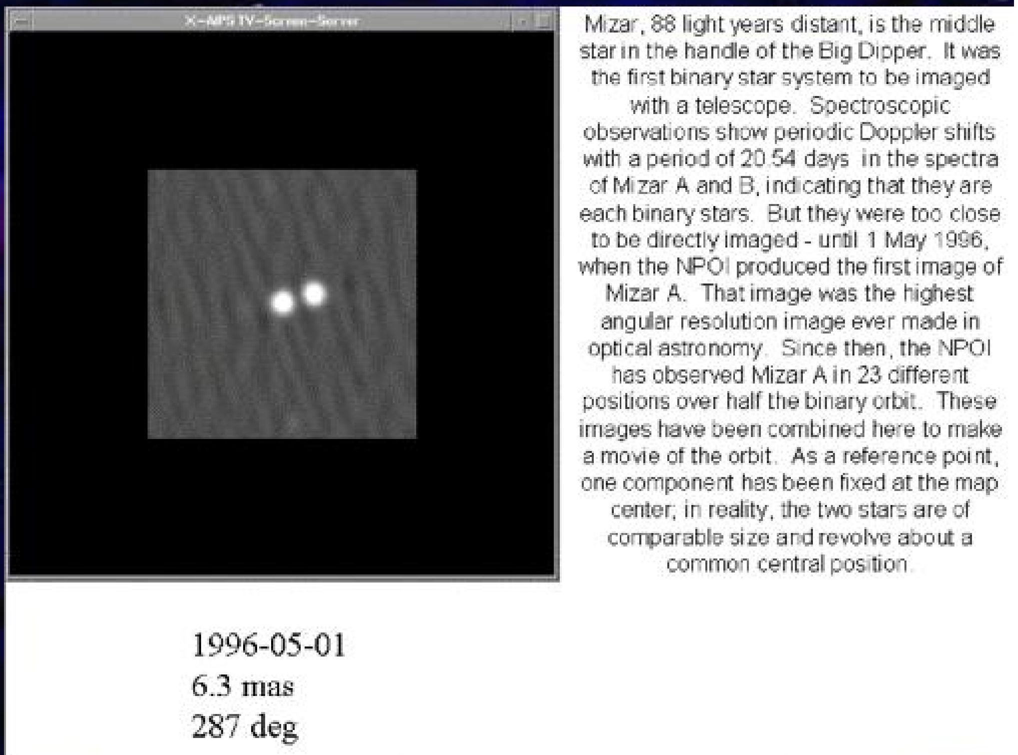


Lick, Keck, AAT
Orbital Eccentricity
0.8
0.6
0.4
0.2
0.0
Earth
0.1
1.0
Semimajor Axis (AU)

Multiple Star Systems

Generally thought to be unsuitable for planets

- Gravity prevents planetary formation
- Gravity makes stable orbits impossible

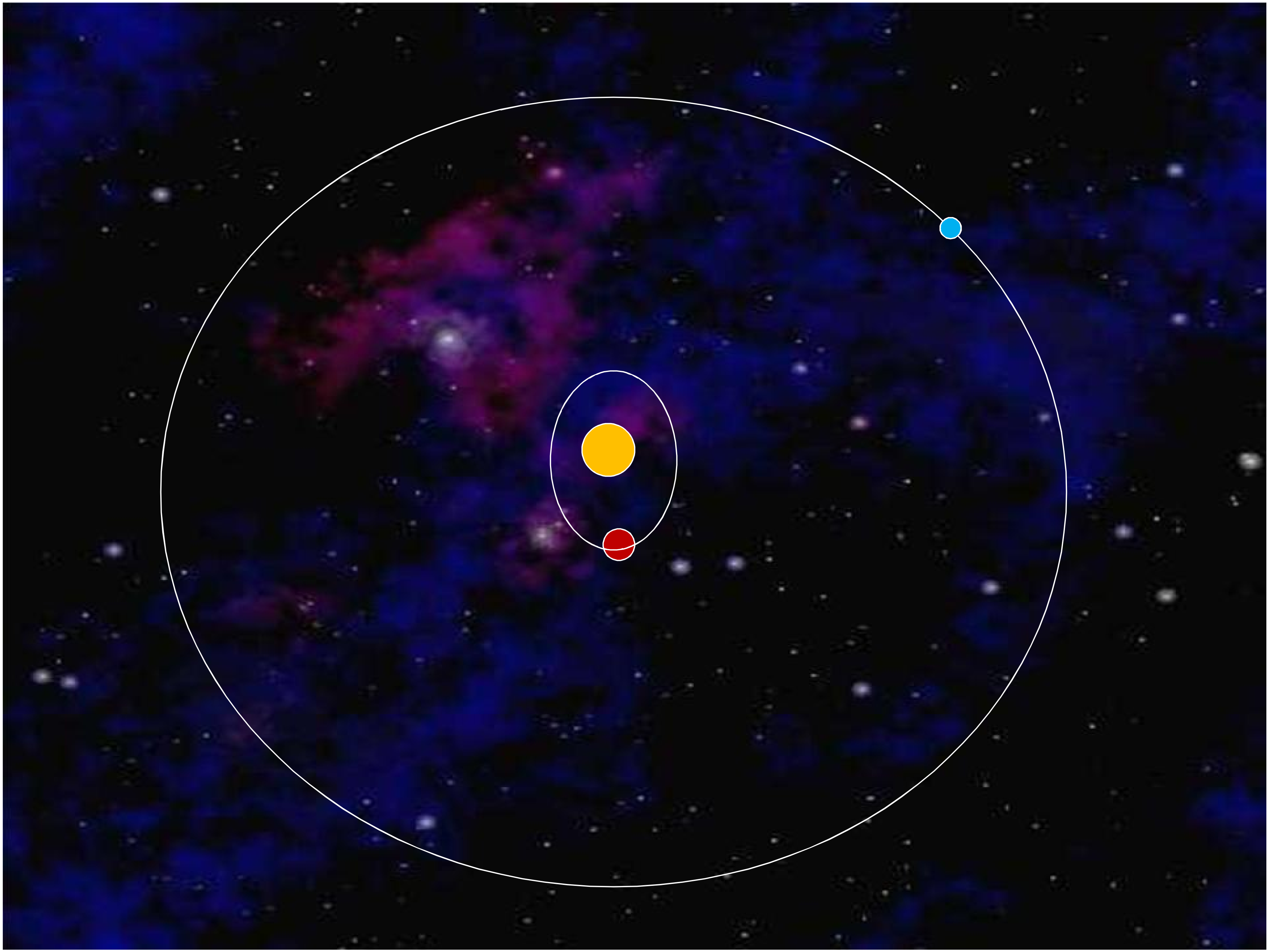


Multiple Star Systems (cont'd)

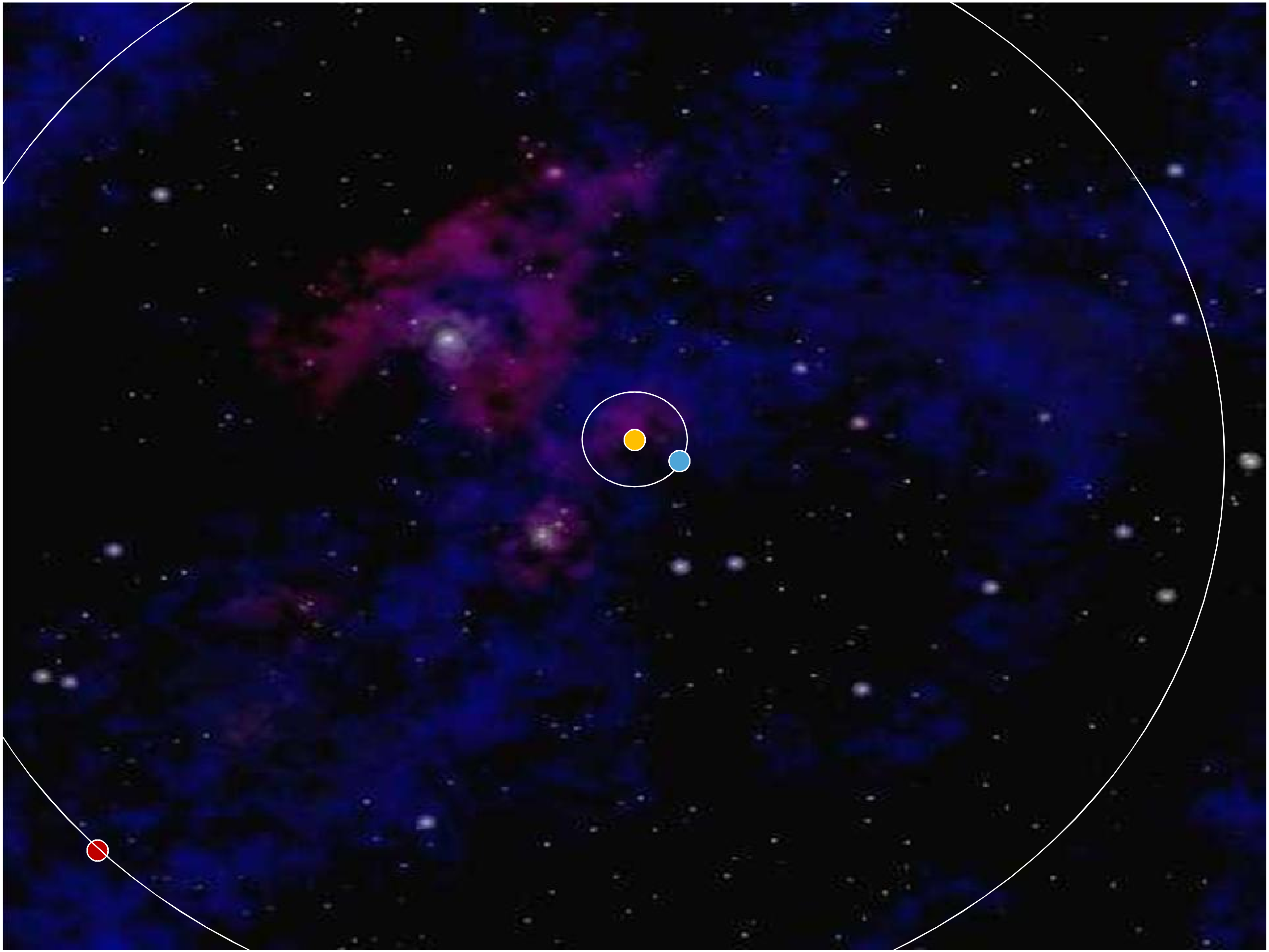
Perhaps planets possible if:

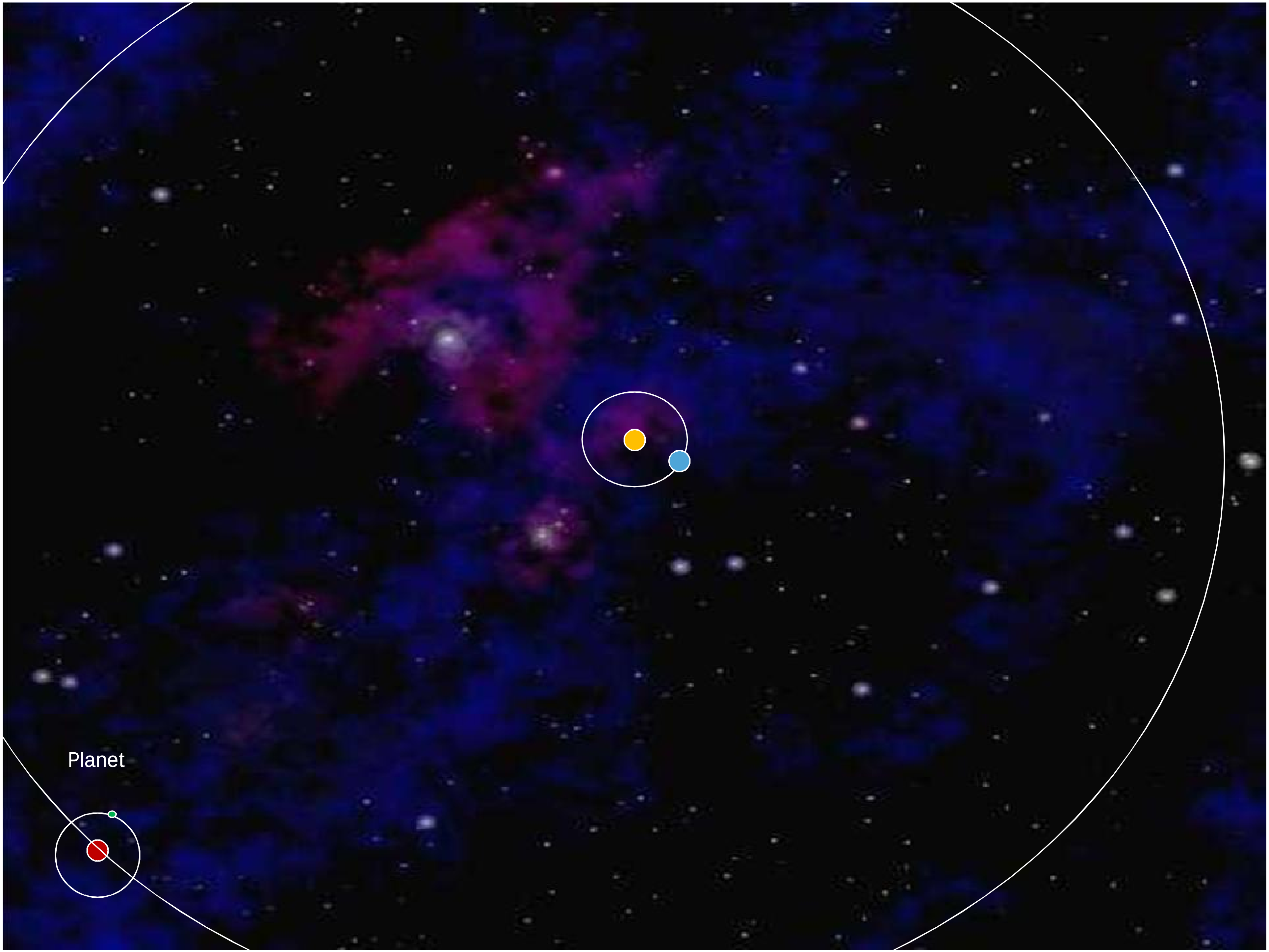
- Planets orbit close to one member of system
- Planets orbit at a large distance from both members

Multiple Star Systems (cont'd)



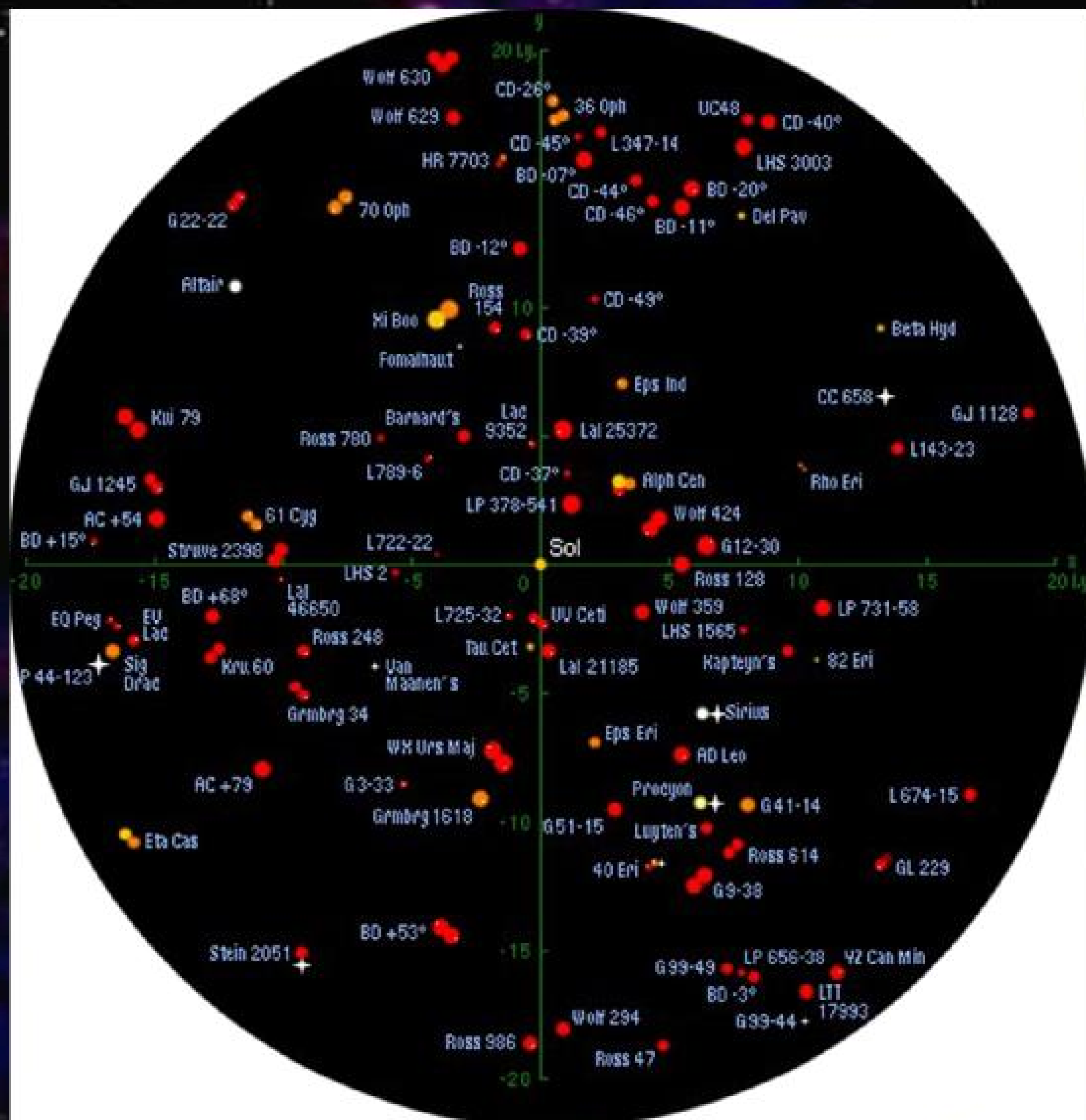
Multiple Star Systems (cont'd)




Planet

Multiple Star Systems (cont'd)

The Sun’s Neighborhood



Is a Search Worth It?

- Is the chemistry of Life common in the Universe?
- Are Earth-like conditions common?
- Are their other “suitable stars” in our galaxy?
- Do extrasolar planets exist?
- Is the existence of life elsewhere in the galaxy beyond the realm of possibility?

Search Strategies

- How do we conduct the search?
- What should we be looking for?
- What are we going to find?