College Scholars Seminar

Introduces fields in the sciences to freshman honors students. Faculty members discuss their research, the nature of their fields, and career opportunities. R twice for a maximum of 3 credits. We try to indicate the diversity of opportunity available to *sciency* students in this seminar, especially in areas not typically associated with the hard sciences.

Organizer: Dr. Jim Imamura, Institute of Theoretical Science, 444 Willamette Hall, imamura@uoregon.edu, 541-346-5212.

Seminar meets weekly on Thursday afternoons in Room 203 Condon Hall from 4 pm to 4:50 pm. The course is offered as P*, P/NP is only grading option.

Attendance is mandatory. If a session is missed or will be missed, please inform me with a written note which includes a short explanation or through a conversation with me.

College Scholars Seminar

Speaker Schedule

- March 31, Dr. Jim Imamura, Institute of Theoretical Science
- April 7, Dr. Ray Frey, Physics Department colloquium, LIGO and gravitational radiation, 100 Willamette Hall, 4-5 pm
- April 14, Dr. Hank Childs, Computer and Information Science
- April 21, Dr. Ben Young, Department of Mathematics
- April 28, Dr. Scott Fisher, Department of Physics
- May 5, Dr. Becky Dorsey, Department of Geological Sciences
- May 12, Dr. Kristin Sterner, Department of Anthropology
- May 19, Dr. Stephanie Majewski, Department of Physics
- May 26, Dr. Janis Weeks, Department of Biology
- June 2, Dr. Mark Fonstad, Department of Geography

Formation of Planetary Systems

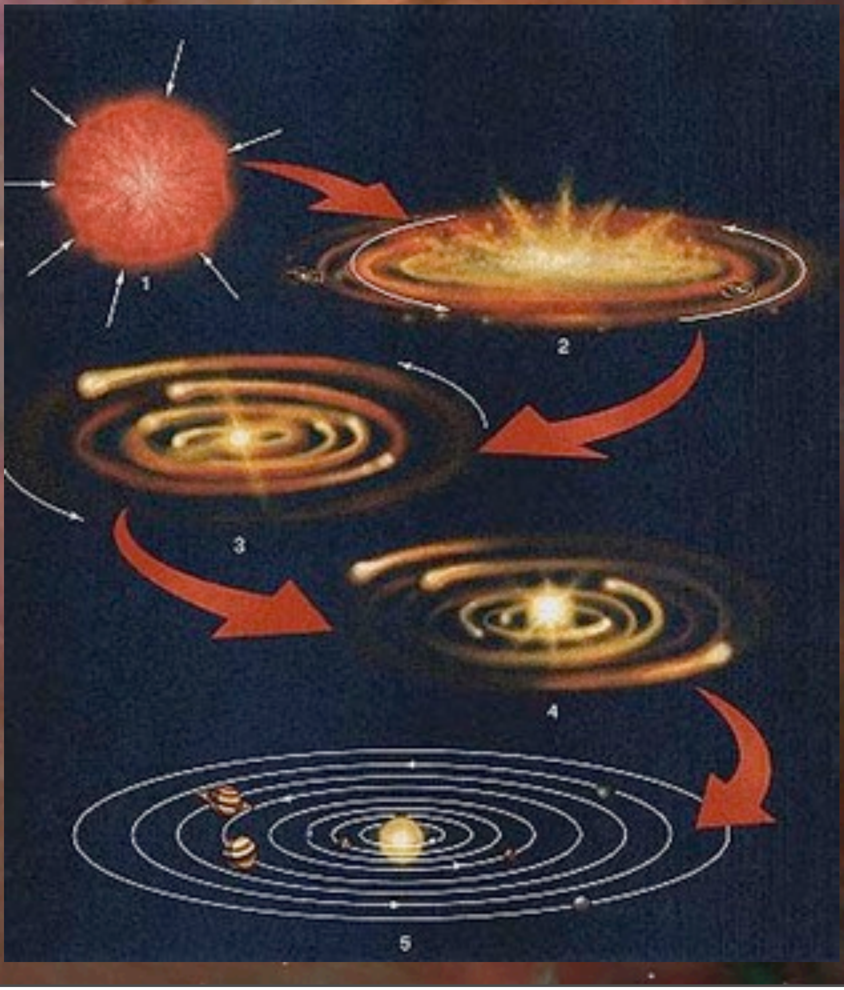
James N. Imamura
Department of Physics
University of Oregon

A fundamental question in astronomy, first posed in ancient times, is that of the origin of the Solar System. Today it is accepted that the collapse of dense cores in giant molecular clouds leads to the formation of stars (e.g., see Armitage 2011). In most proposed scenarios, the cores do not collapse directly to stars, they first pass through an intermediate phase where a nascent star forms surrounded by a circumstellar disk because of the large specific angular momentum of the cloud (e.g., Armitage 2011); the formation of stars and planetary systems results after mass and angular momentum are redistributed within these massive disks (e.g., see Shariff 2009). This scenario had its origins in the 18th century when Swedenborg (1734), Kant (1755) and Laplace (1796) put forth, without observational support, the *Nebular theory* for the formation of the Solar System wherein planets formed in a massive disk orbiting about the young Sun (e.g., Woolfson 1993). Today, although aspects of the process remain elusive, the original vision has been firmly established. The mechanism, however, by which Jupiter-like planets are produced is not settled. Currently, it is thought that Jupiter-like planets form either through: (i) the core-accretion scenario where planet growth starts from the coalescence of dust particles in the disk and concludes with the gravitational capture of gas from the disk; and/or (ii) direct gravitational collapse driven by disk instabilities (e.g., see Armitage 2011). No singular piece of evidence establishes which theory is the most plausible mechanism for the formation of Jovian planets. In my talk, I review observations of planets and planet forming regions, and the current state of modeling of planet formation mechanisms.

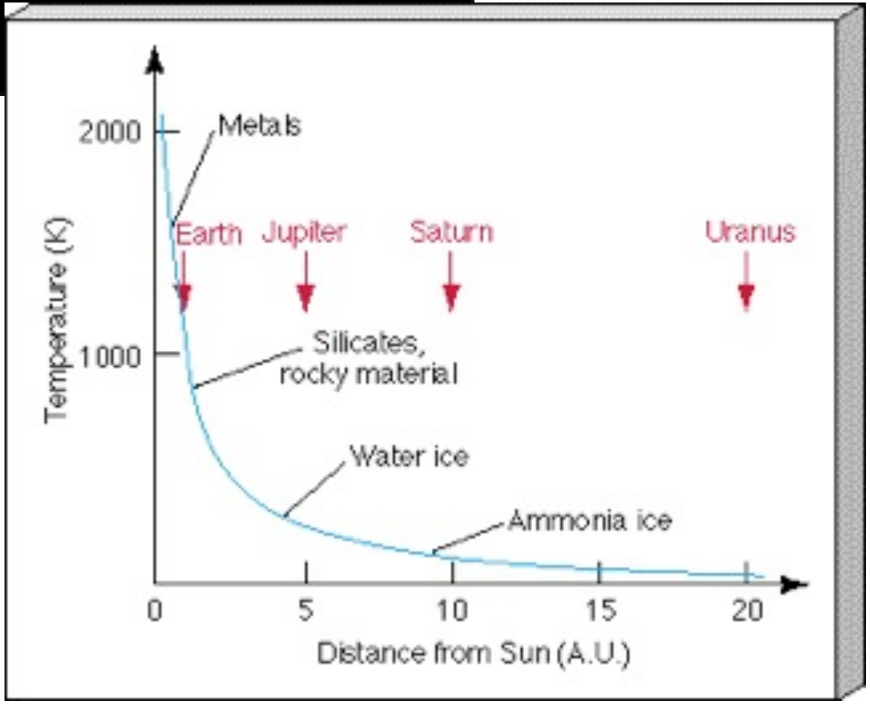
INTRODUCTION

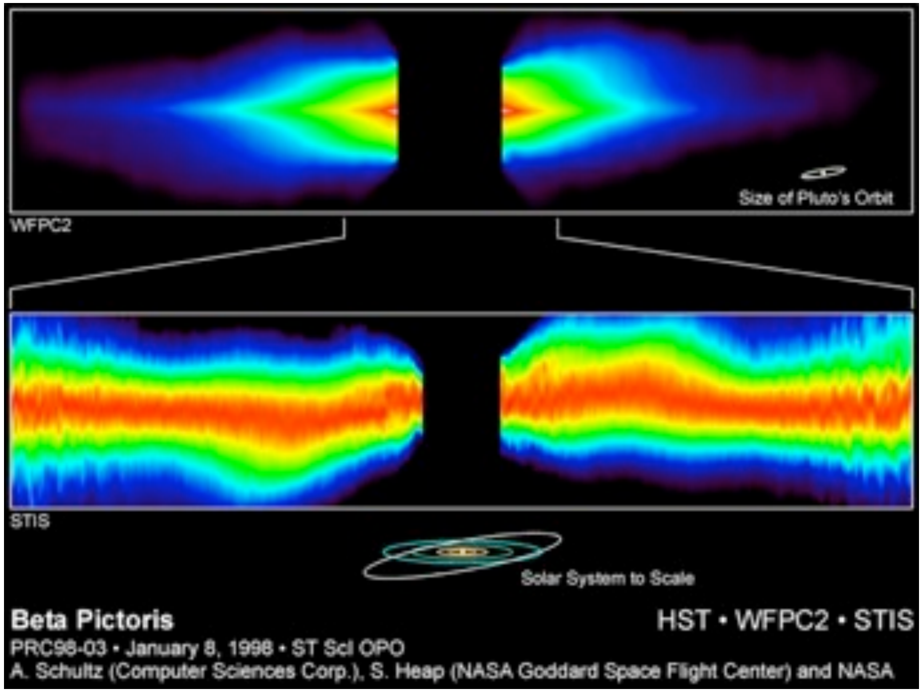
Star and planet formation takes place in Giant Molecular Clouds. Shown is a close-up of the Orion Nebula with nascent protoplanetary disks (propylds) highlighted.

Swedenborg (1734) and Kant (1755) proposed the original Nebular Hypothesis. Laplace (1796) fleshed out the mathematical details.



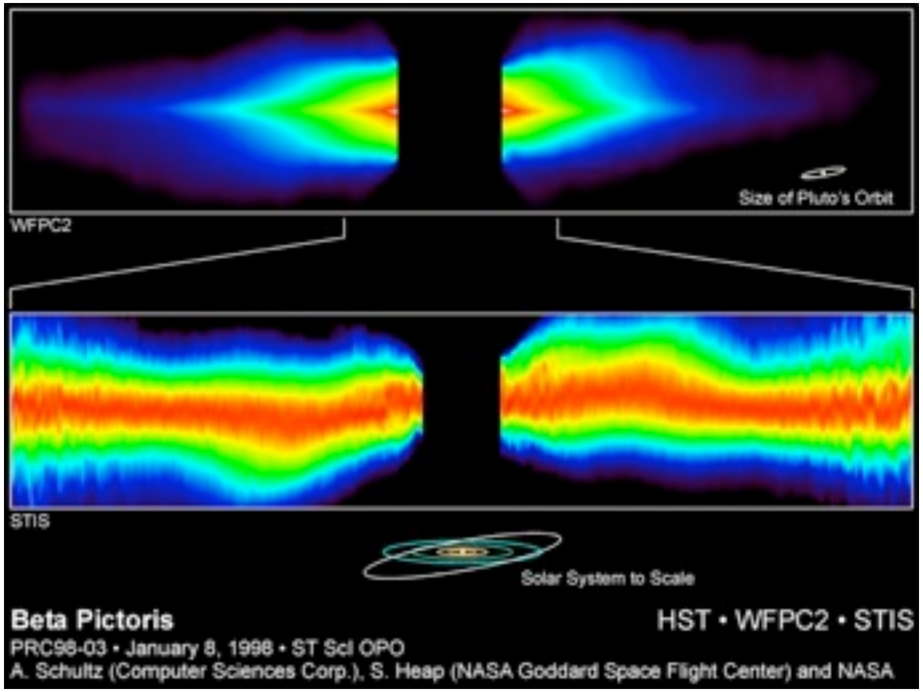
The Solar System contains 8 major planets and 3 dwarf planets, naturally broken into 3 types: (1) Low-mass Terrestrial (solid rocky) planets; (ii) High-mass Jovian (gaseous, h-he) planets; and (iii) rock/ice planets. The breakdown is understood based on the condensation properties of the protoSolar disk and the location of the Snowline.





Today, almost 2,000 extra-Solar planets in ~1,200 planetary systems have been discovered with perhaps as many as 1 Earth-like planet in the *Habitable Zones* of every 5 Sun-like stars!

Our understanding of how planets form is making many strides because of the unprecedented improvements in the observations of protostars and protostellar and protoplanetary disks.



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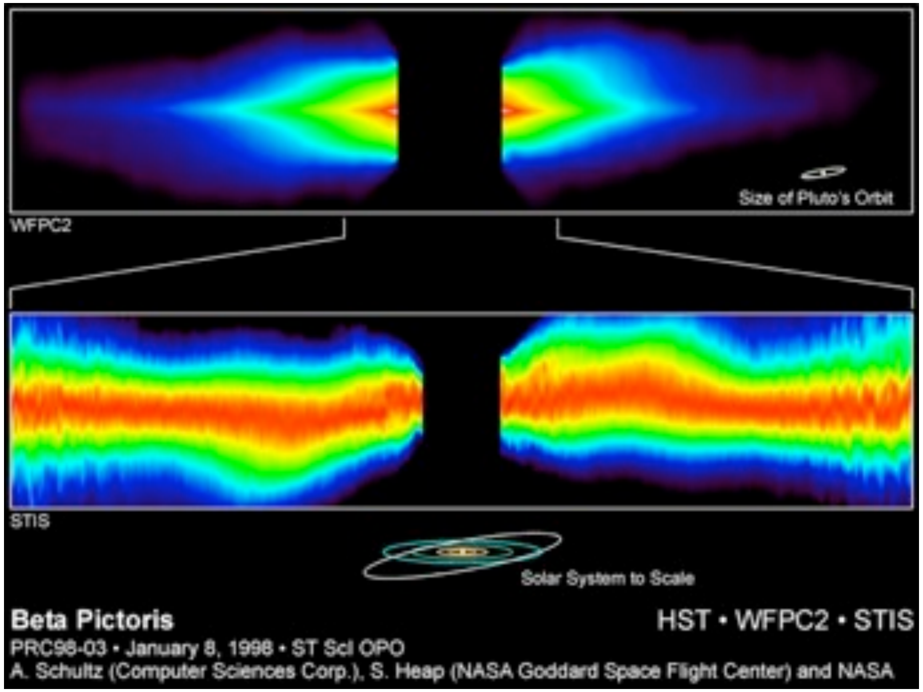
- Planet Hunters: Marcy et al. and Mayor & Queloz and the Kepler satellite team



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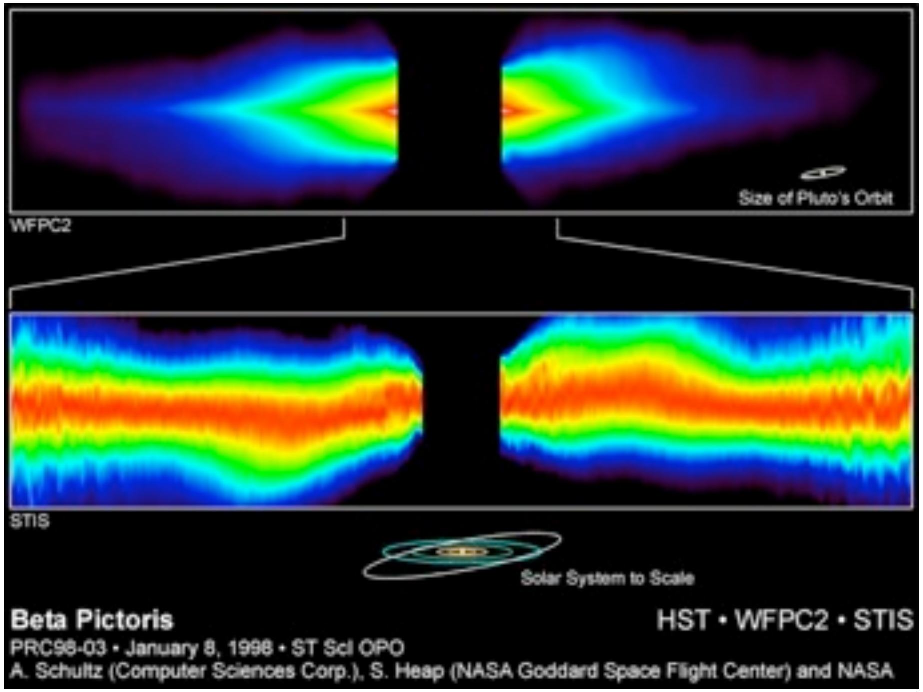
- High-resolution observations of protostellar and protoplanetary disks: Subaru and ALMA



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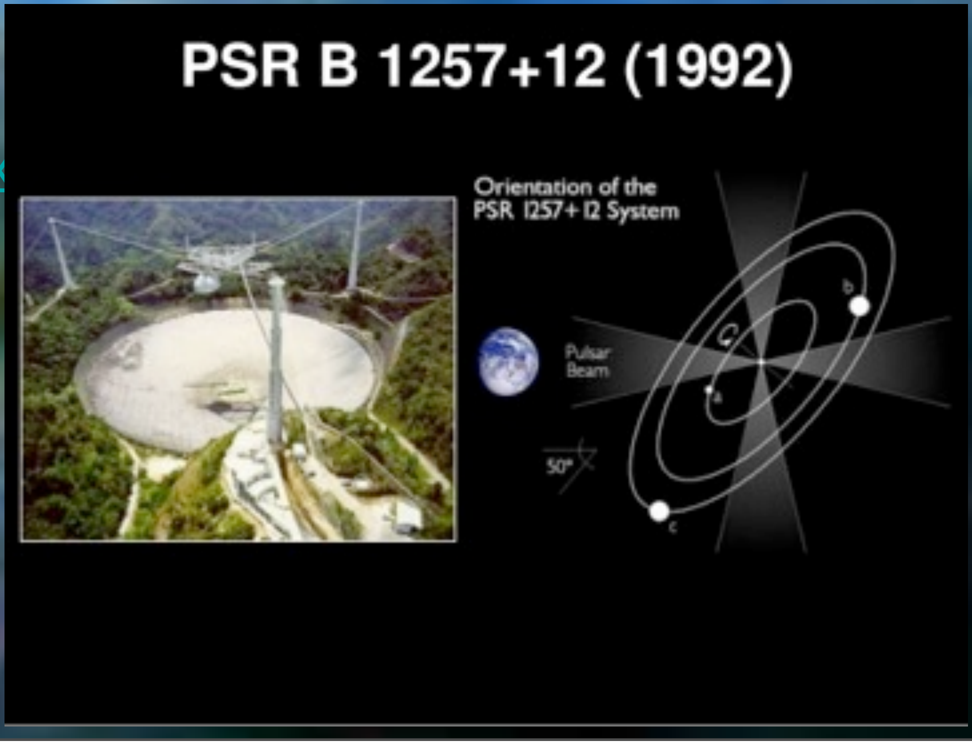
- Planet Hunters: Marcy et al. and Mayor & Queloz and the Kepler satellite team
- High-resolution observations of protostellar and protoplanetary disks: Subaru and ALMA
- HPCC: Planet formation mechanisms

PLANET HUNTERS

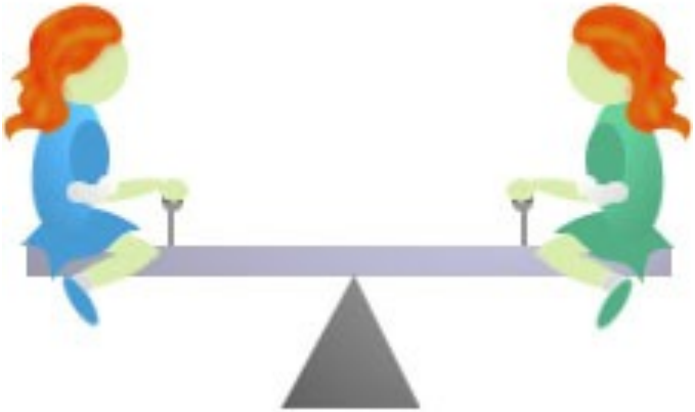
Planet Hunters: Mayor & Queloz, Marcy & Butler

In 1995, Mayor & Queloz and Marcy & Butler started the planetary discovery outburst (using spectroscopic techniques). The last 20 years has seen a dramatic growth in our observational understanding of planets and planet formation.


PSR B 1257+12 (1992)

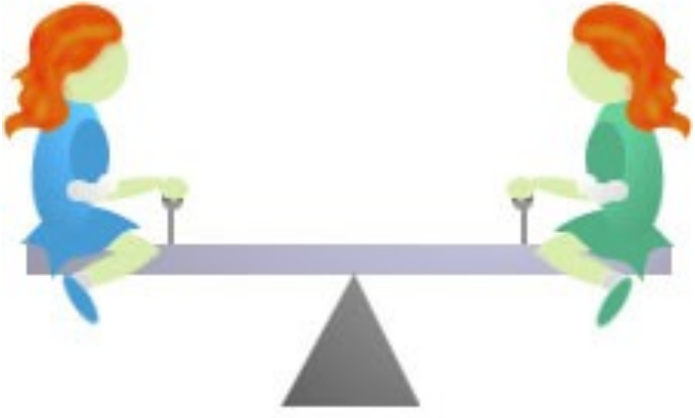
Note: In 1992, radio astronomers Alex Wolszczan and Dale Frail discovered two planets orbiting the *millisecond* pulsar PSR 1257+12, generally considered to be the first definitive detection of extra-Solar planets.

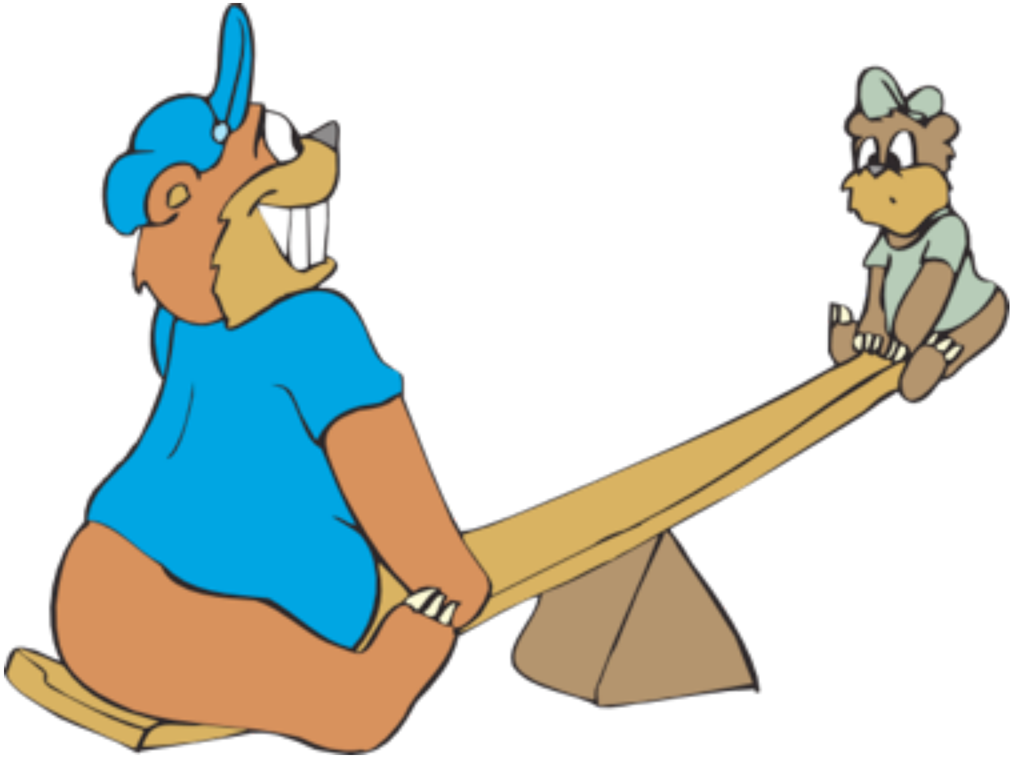
Center-of-Mass (Barycenter)



For a seesaw on which two girls of the same mass are playing, the balance point is midway between the two girls.

Center-of-Mass (Barycenter)





For the case where the riders have different masses, the balance point sits closer to the more massive rider.

What does this have to do with the Solar System? Planets, strictly speaking, do not orbit the Sun. The planets (and Sun) orbit about the balance point (the center-of-mass) of the Solar System: https://phet.colorado.edu/sims/my-solar-system/my-solar-system_en.html

Doppler Shift

For a stationary source of waves, the crests of the wave move away from the source. The distance between the crests defines the wavelength of the wave.

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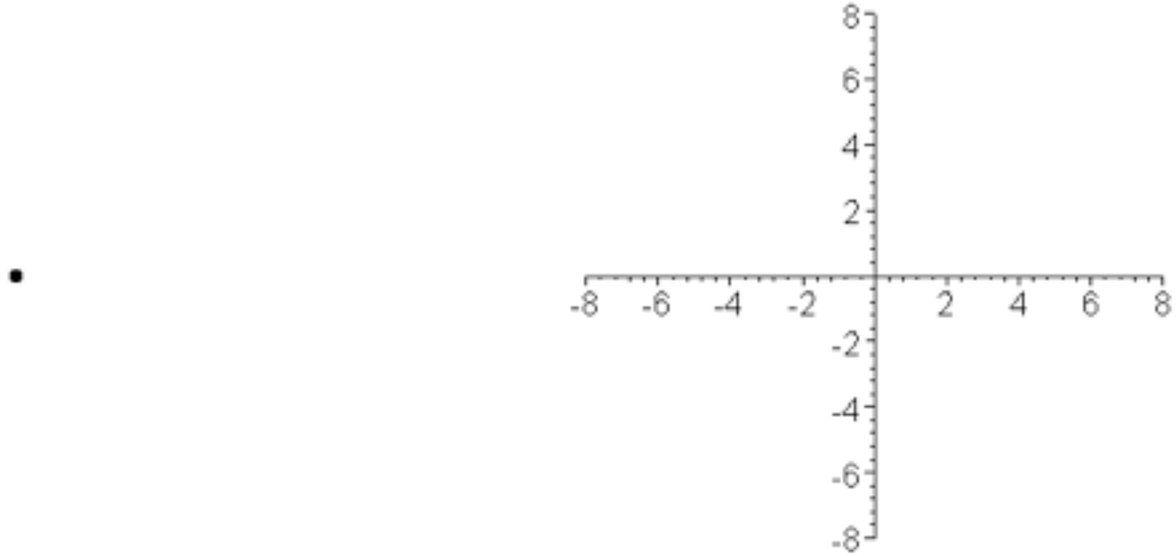
For the case where the source of the waves is in motion, the waves propagate from the instantaneous location of the source. The distance between the crests in the direction of motion is shortened while the distances behind the source of the waves are increased ====> Doppler Shift.

Doppler Shift



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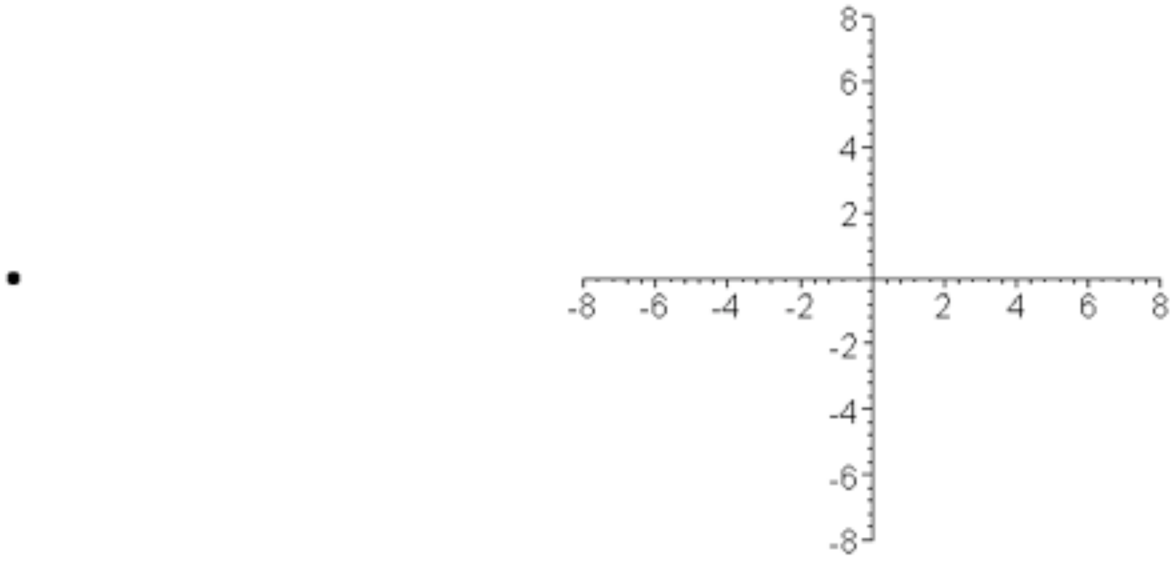
Doppler Shift



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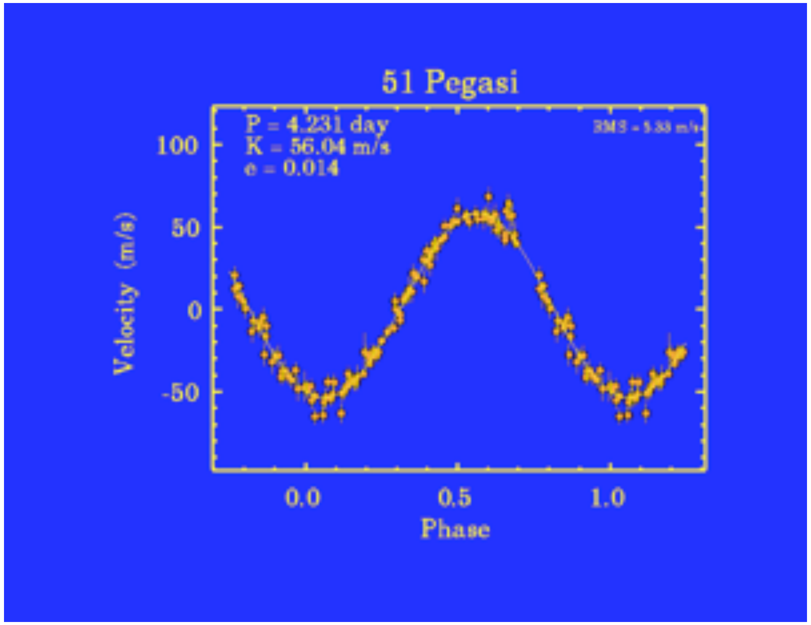
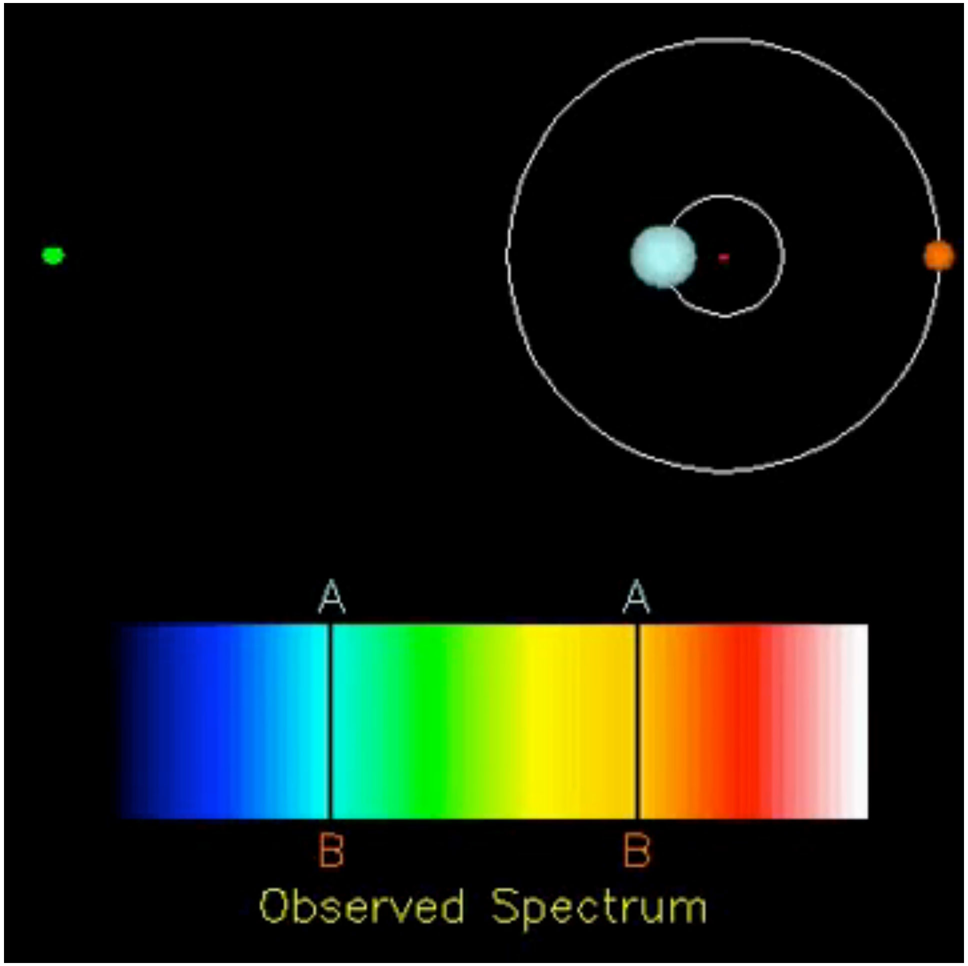
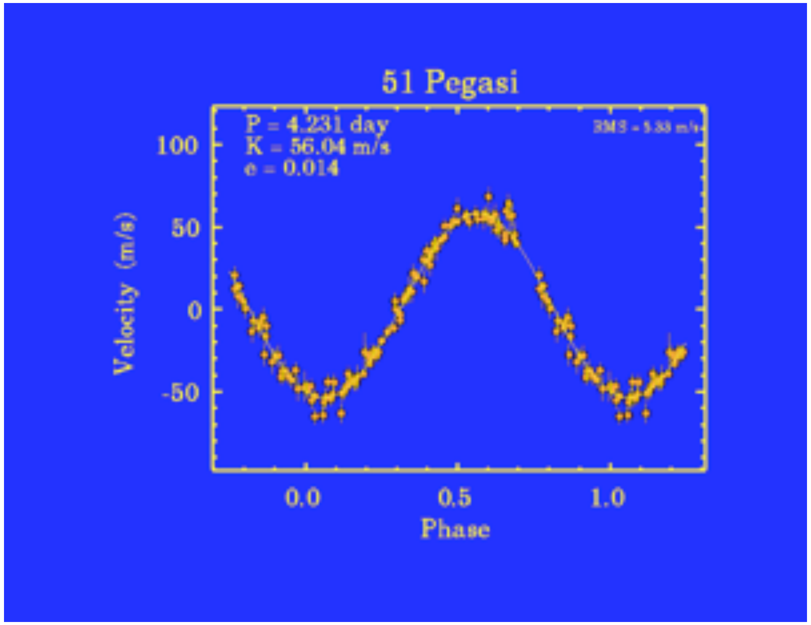
Spectroscopic Searches



The first planets discovered in this manner were around the star 51 Peg by Mayor & Queloz in 1995.

Spectroscopic Searches





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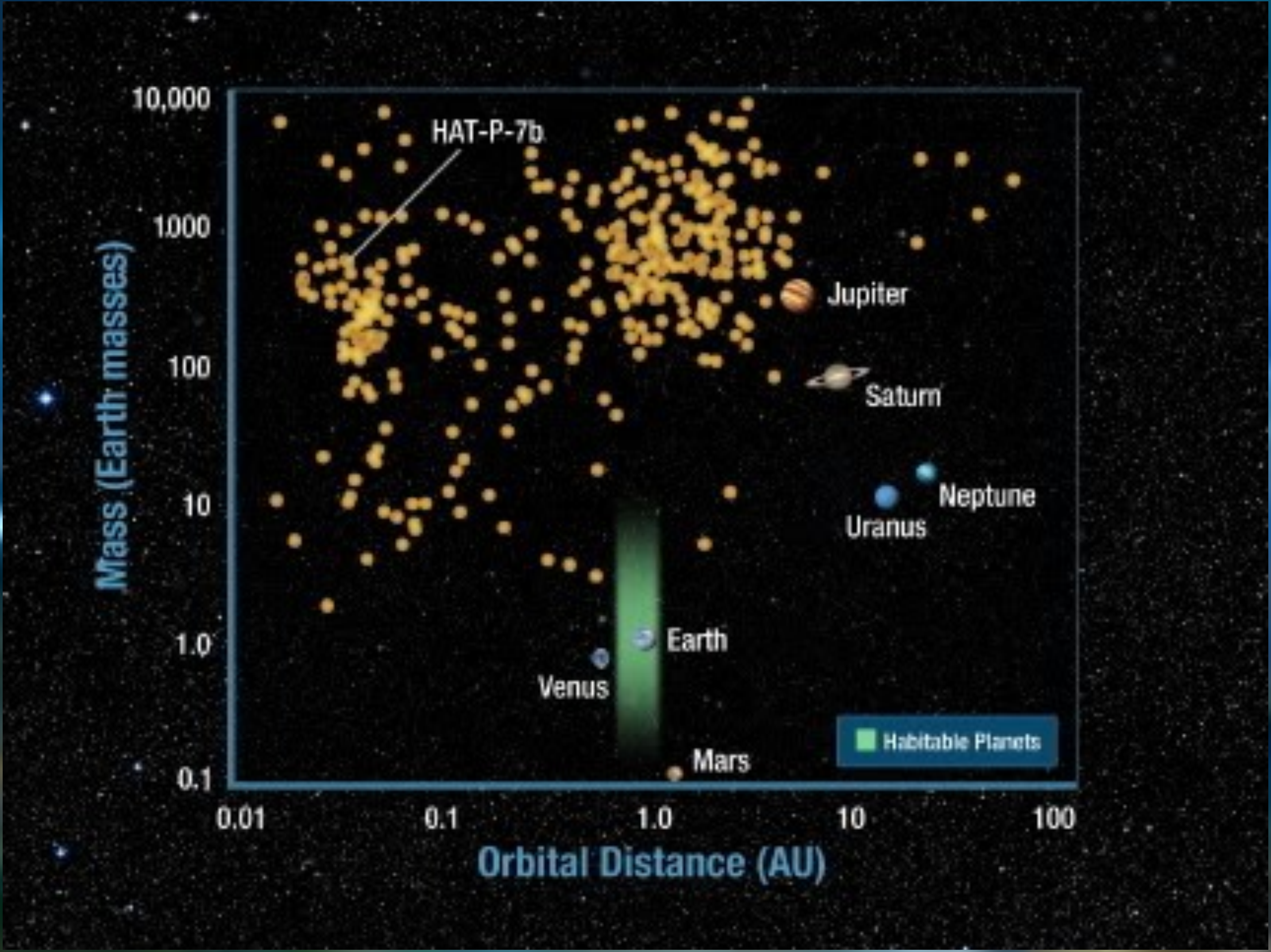
Planet Hunters: Marcy & Butler, Mayor & Queloz



Because discoveries have only been made for 20 years and the technique used by Marcy *et al.* and Mayor *et al.*, most planets are Jupiter-like. Most planets found in this manner were massive, Jovian planets, and most were found within the snowlines of the systems.

Planet Hunter: Kepler

Kepler Satellite

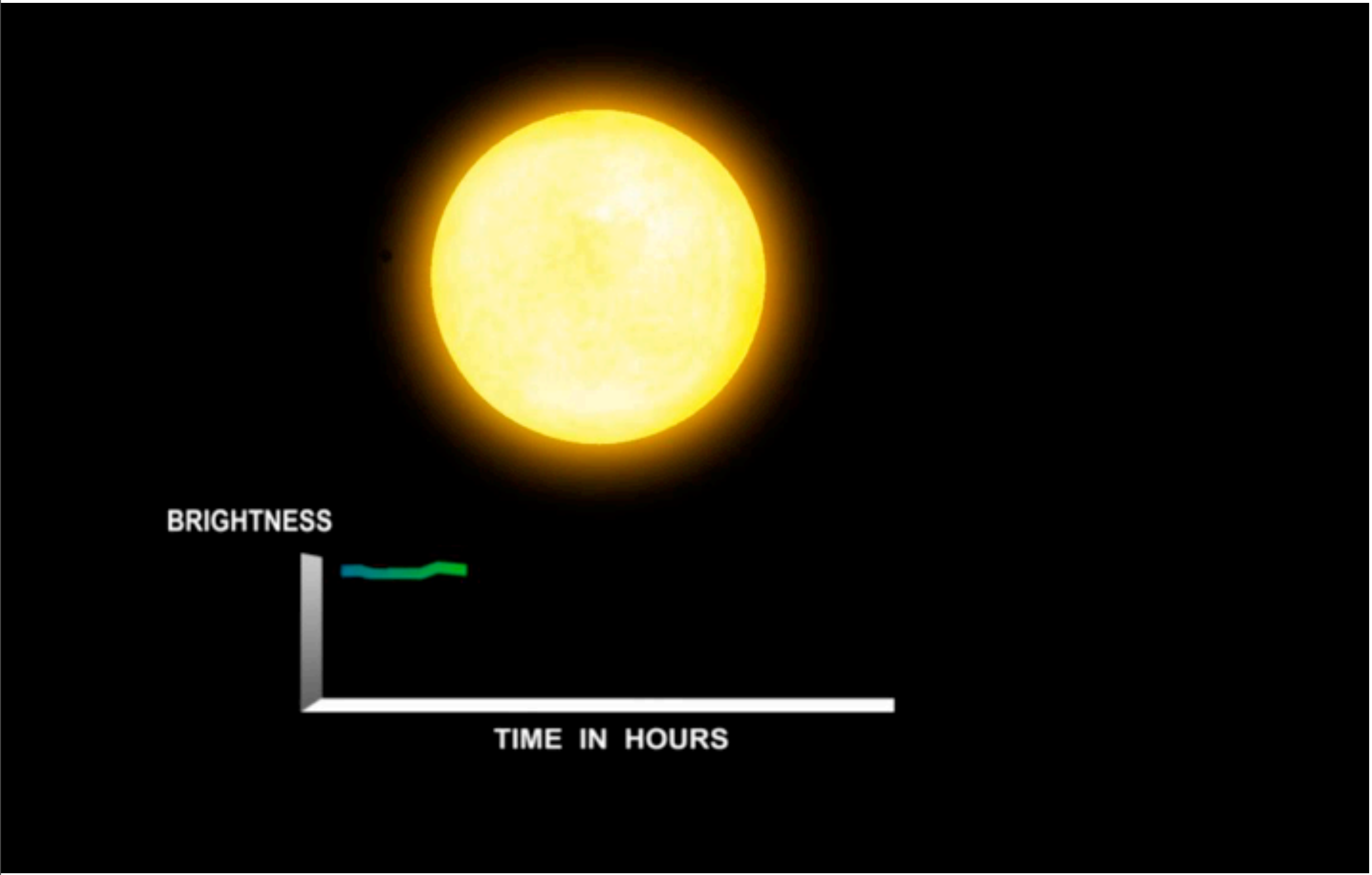
The Kepler spacecraft lifted off March 6, 2009 aboard a Delta II rocket from Cape Canaveral Air Force Station in Florida. Launch occurred at 10:49 p.m. EST.

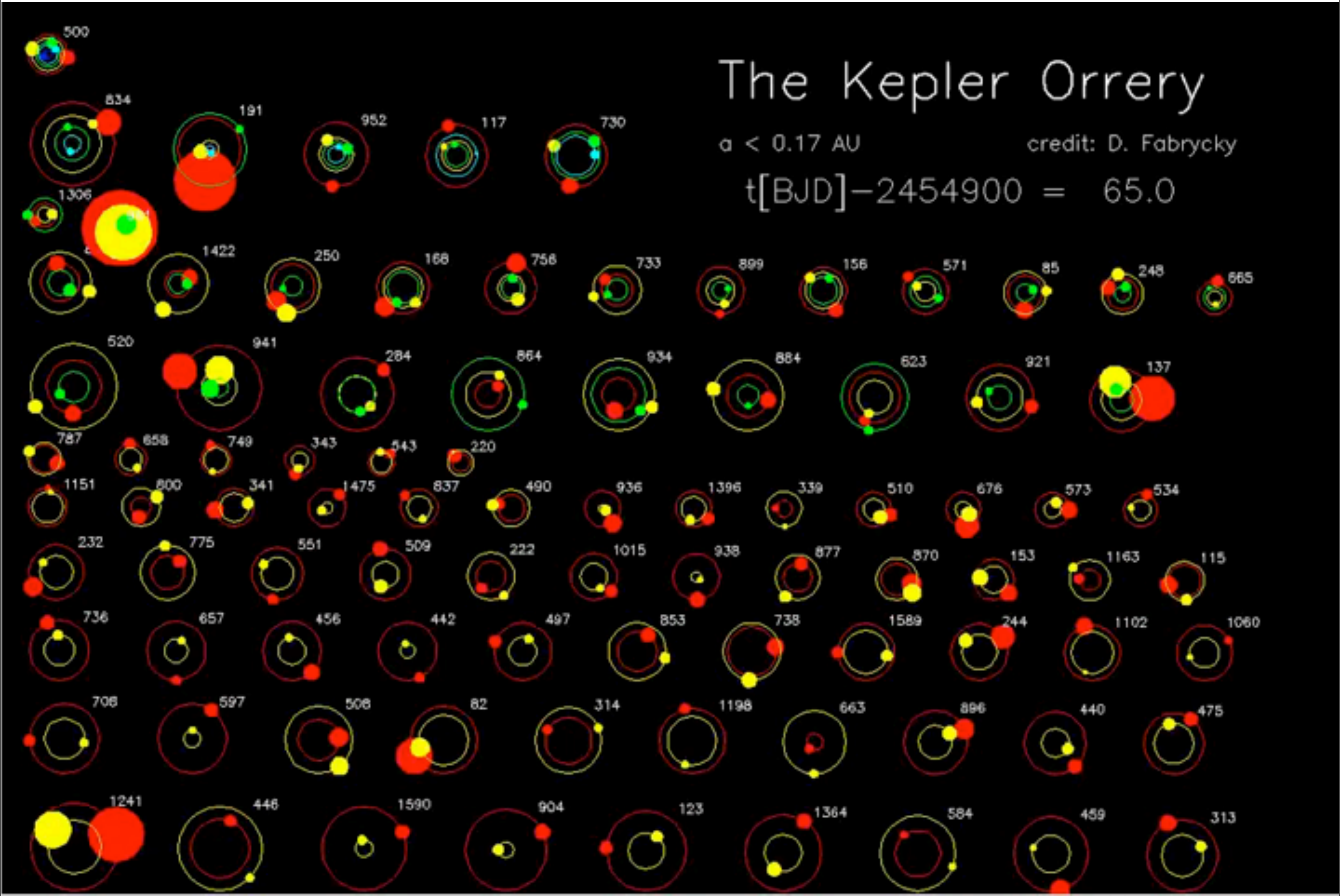
Kepler's Mission

The centuries-old quest for other worlds like our Earth has been rejuvenated by the intense excitement and popular interest surrounding the discovery of more than 1,500 planets orbiting other stars. The Kepler Mission is specifically designed to survey our region of the Milky Way galaxy monitoring over 150,000 stars to discover Earth-size and smaller planet and determine the fraction of the hundreds of billions of stars in our galaxy that might have such planets.

Planetary Transits (eclipses)

Planetary Transits (eclipses)


BRIGHTNESS
TIME IN HOURS


The Kepler Orrery
a < 0.17 AU
credit: D. Fabrycky
t[BJD]−2454900 = 65.0
500
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952
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730
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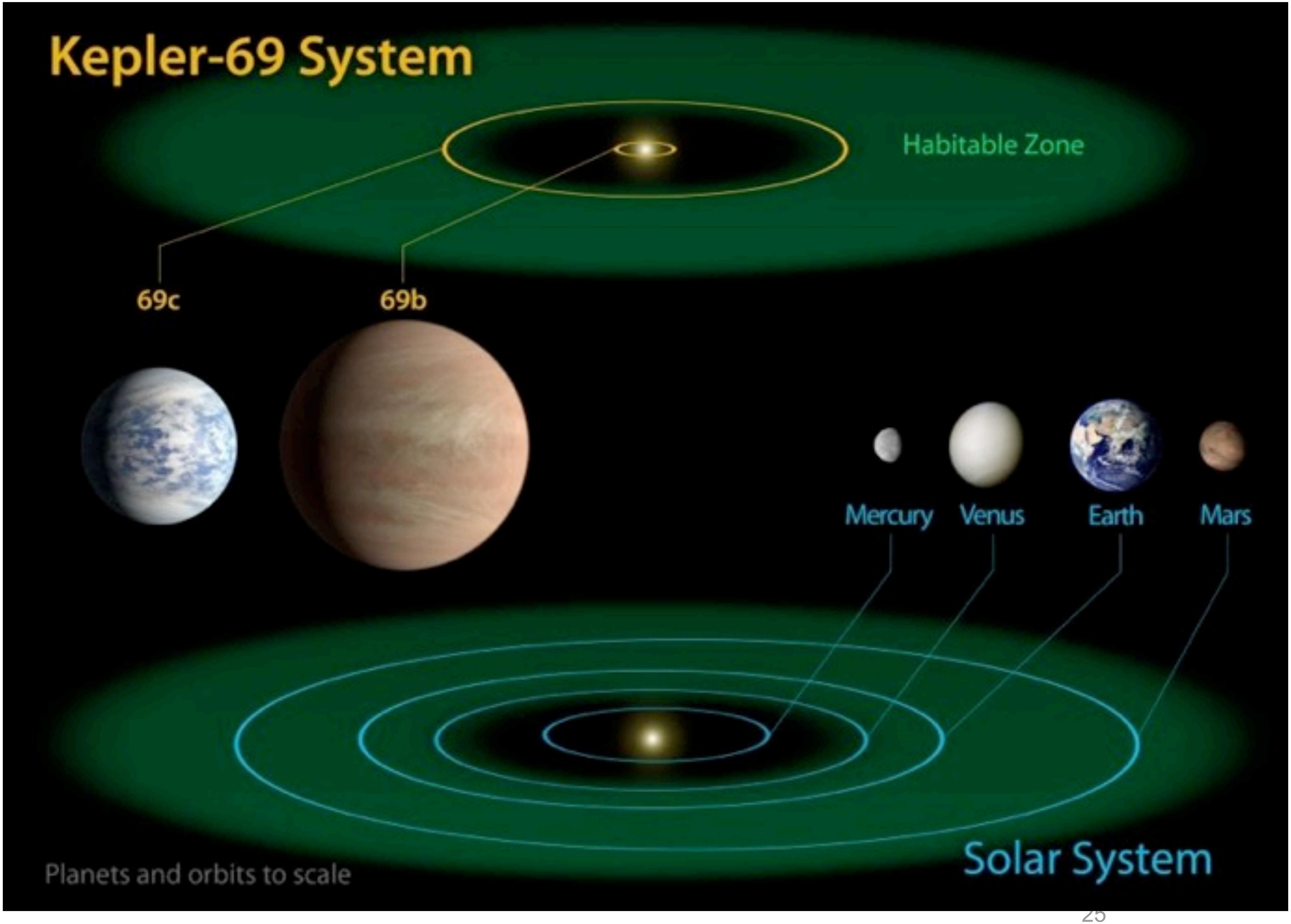
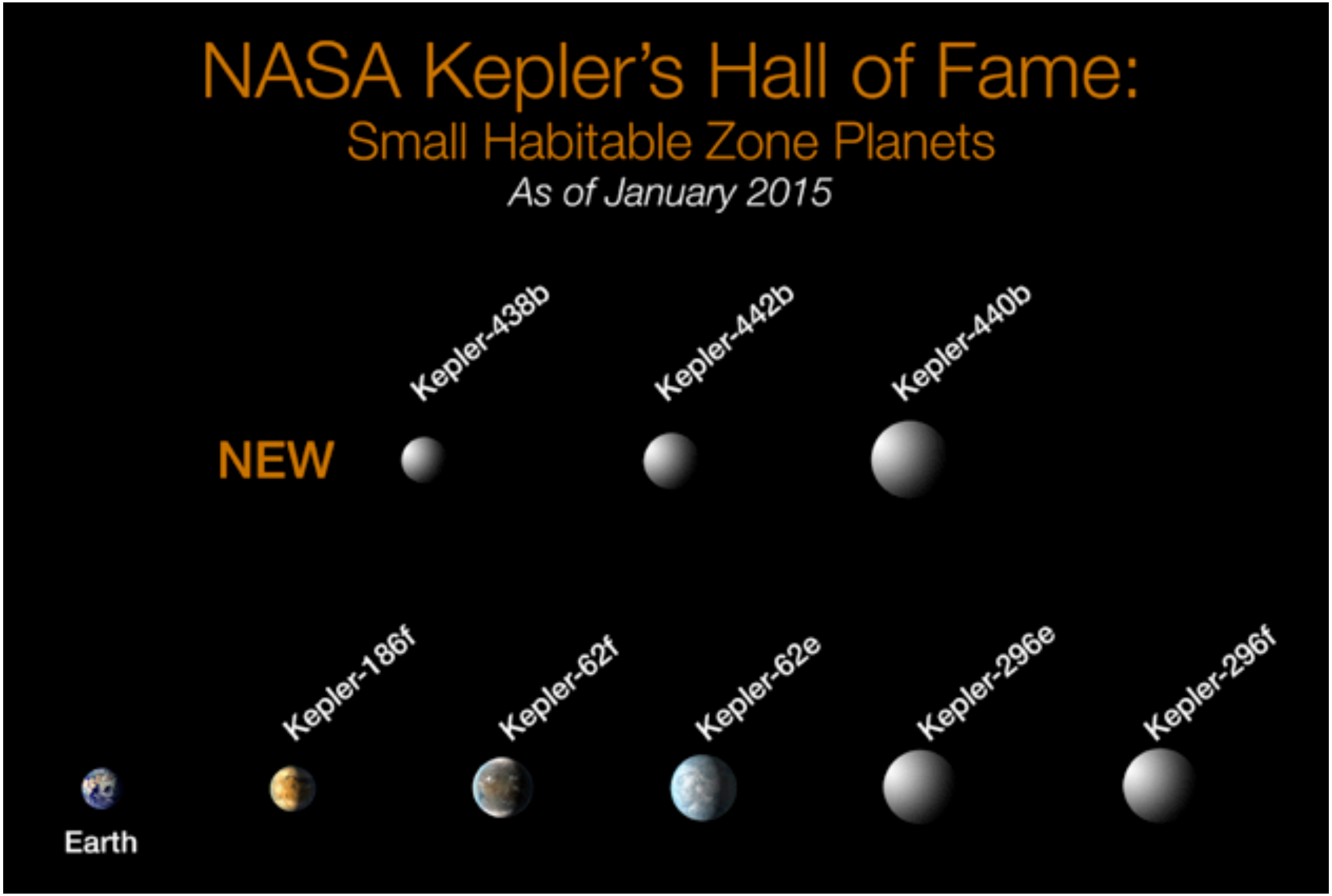
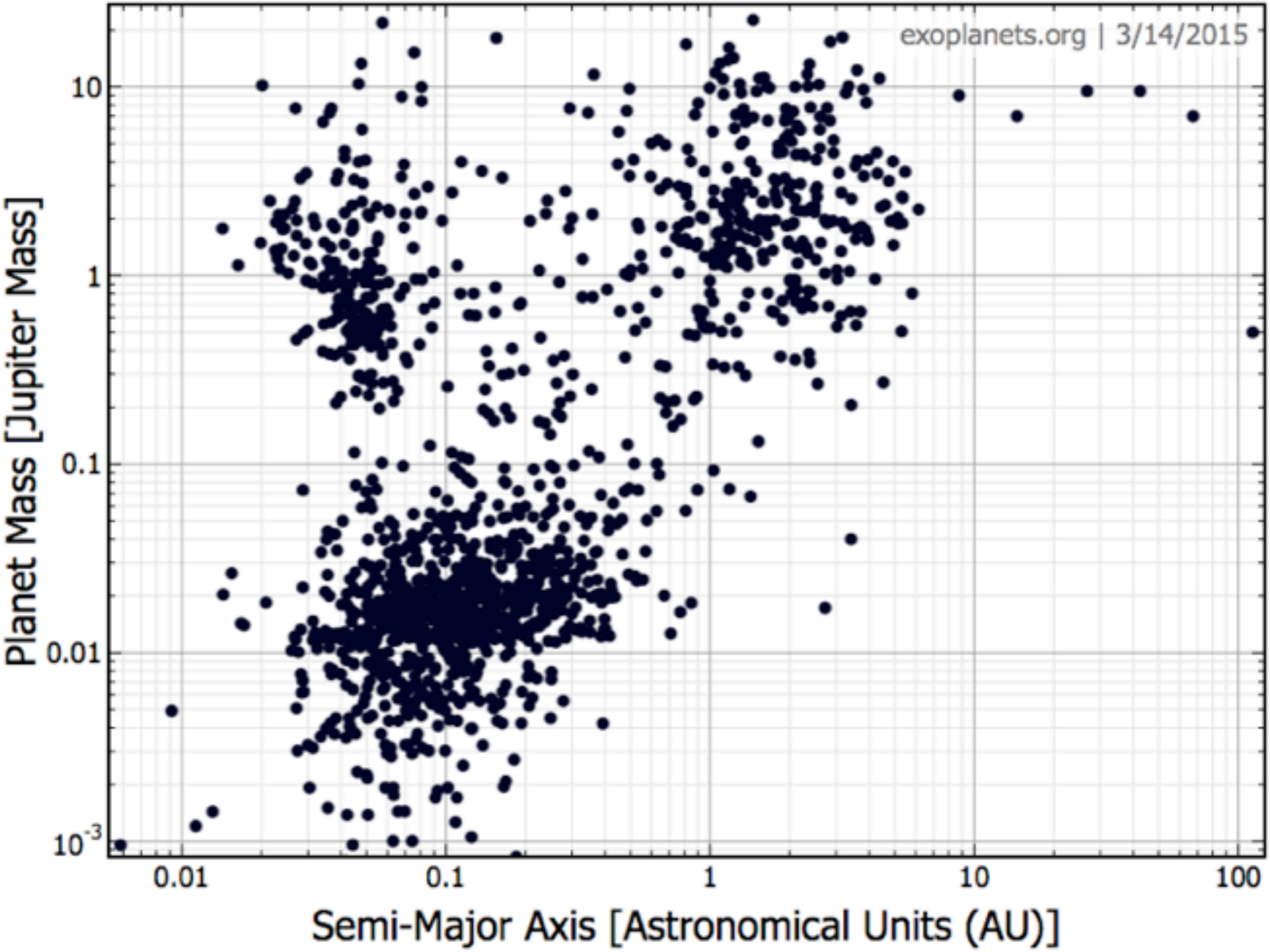

Kepler-69 System
Habitable Zone
69c
69b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale



Kepler has discovered $>$ 1,000 extra-Solar planets with many planets roughly the size of Earth at the right distance from their parent star to support liquid water, that is, *Earth-like planets in the Habitable Zone*.


exoplanets.org | 3/14/2015
Planet Mass [Jupiter Mass]
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10^{-3}
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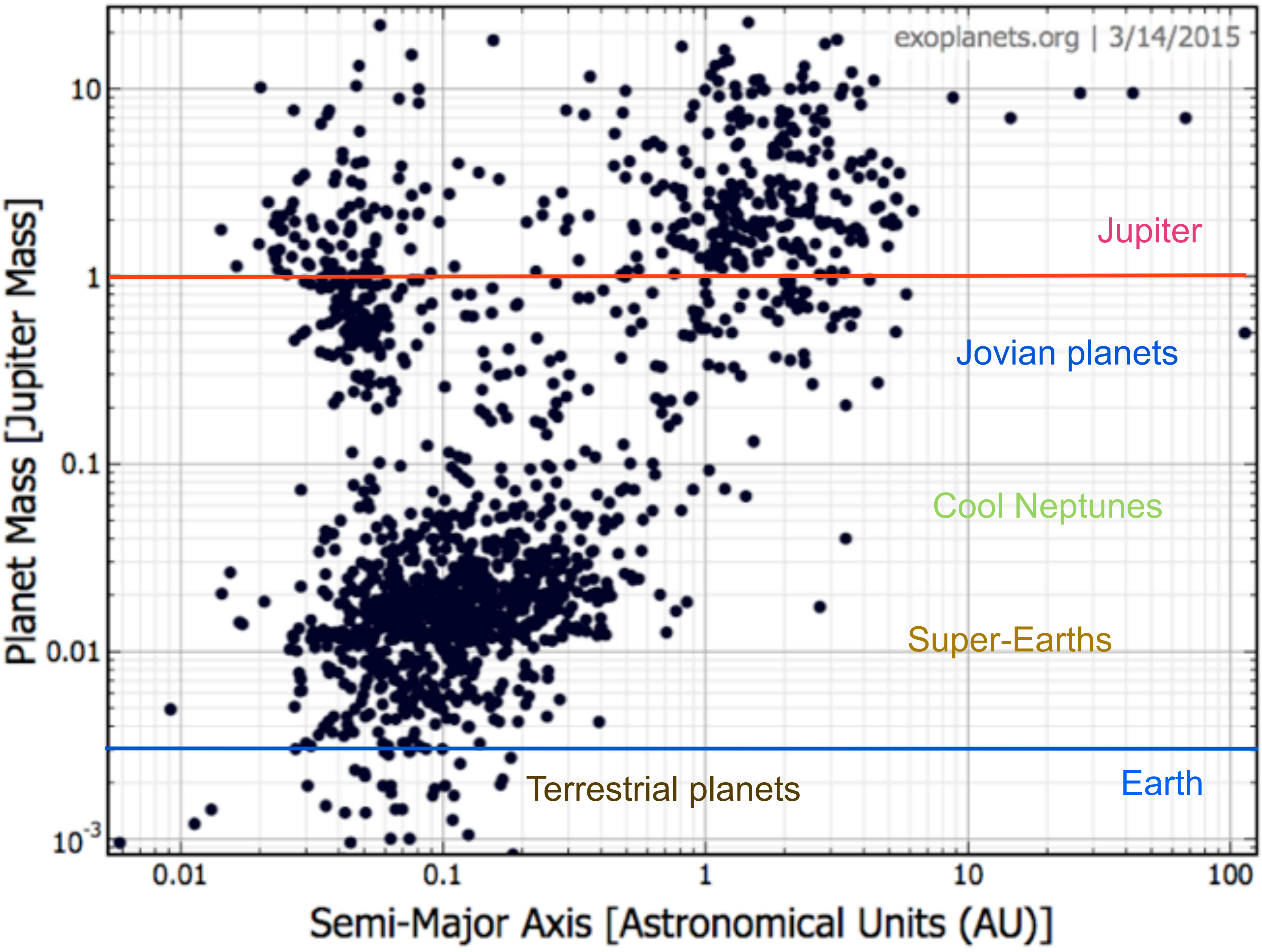
10
100
Semi-Major Axis [Astronomical Units (AU)]


exoplanets.org | 3/14/2015
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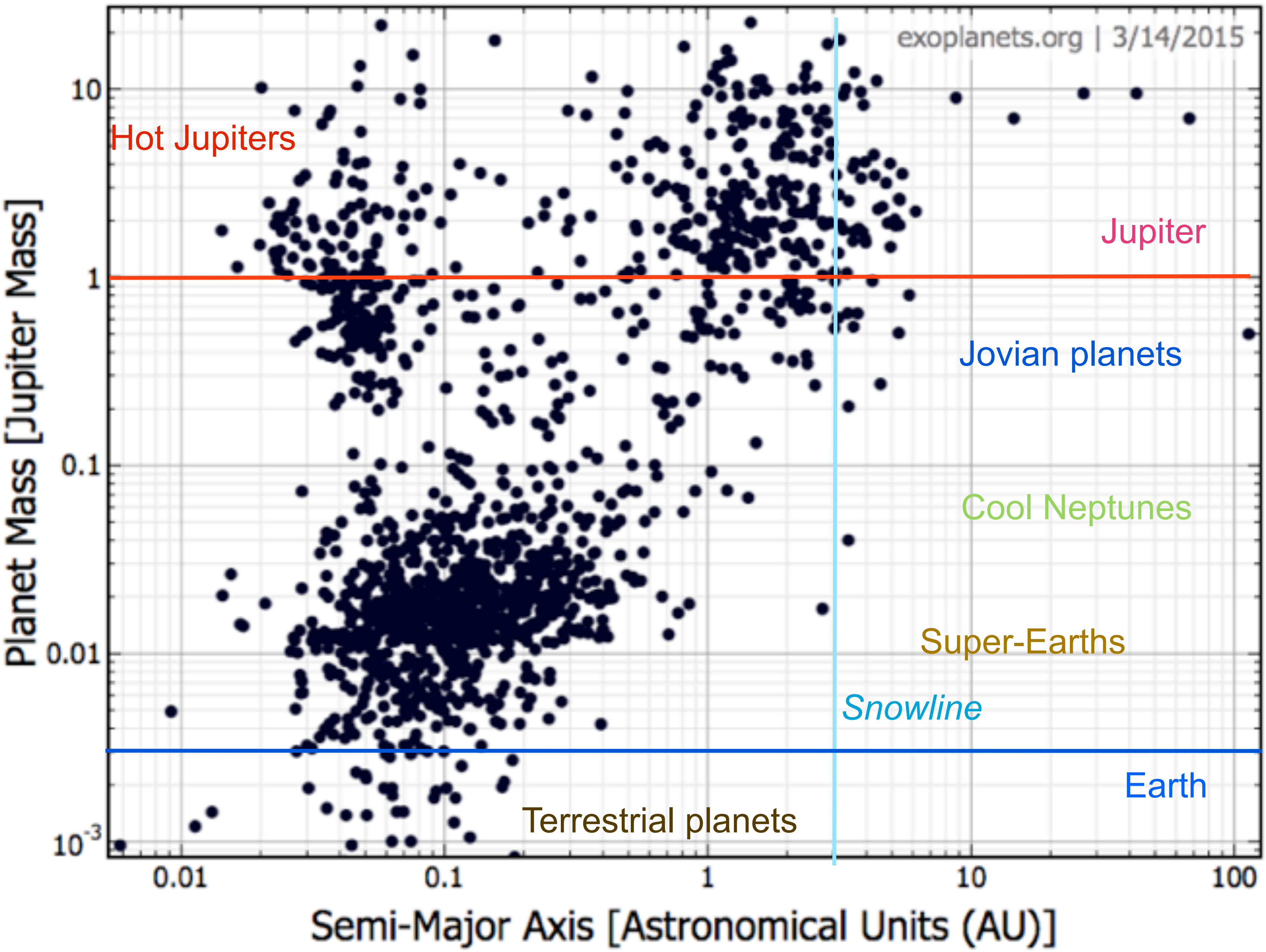
Semi-Major Axis [Astronomical Units (AU)]
Jupiter
Jovian planets
Cool Neptunes
Super-Earths
Earth
Terrestrial planets


exoplanets.org | 3/14/2015
Hot Jupiters
Jupiter
Jovian planets
Cool Neptunes
Super-Earths
Snowline
Earth
Terrestrial planets
Planet Mass [Jupiter Mass]
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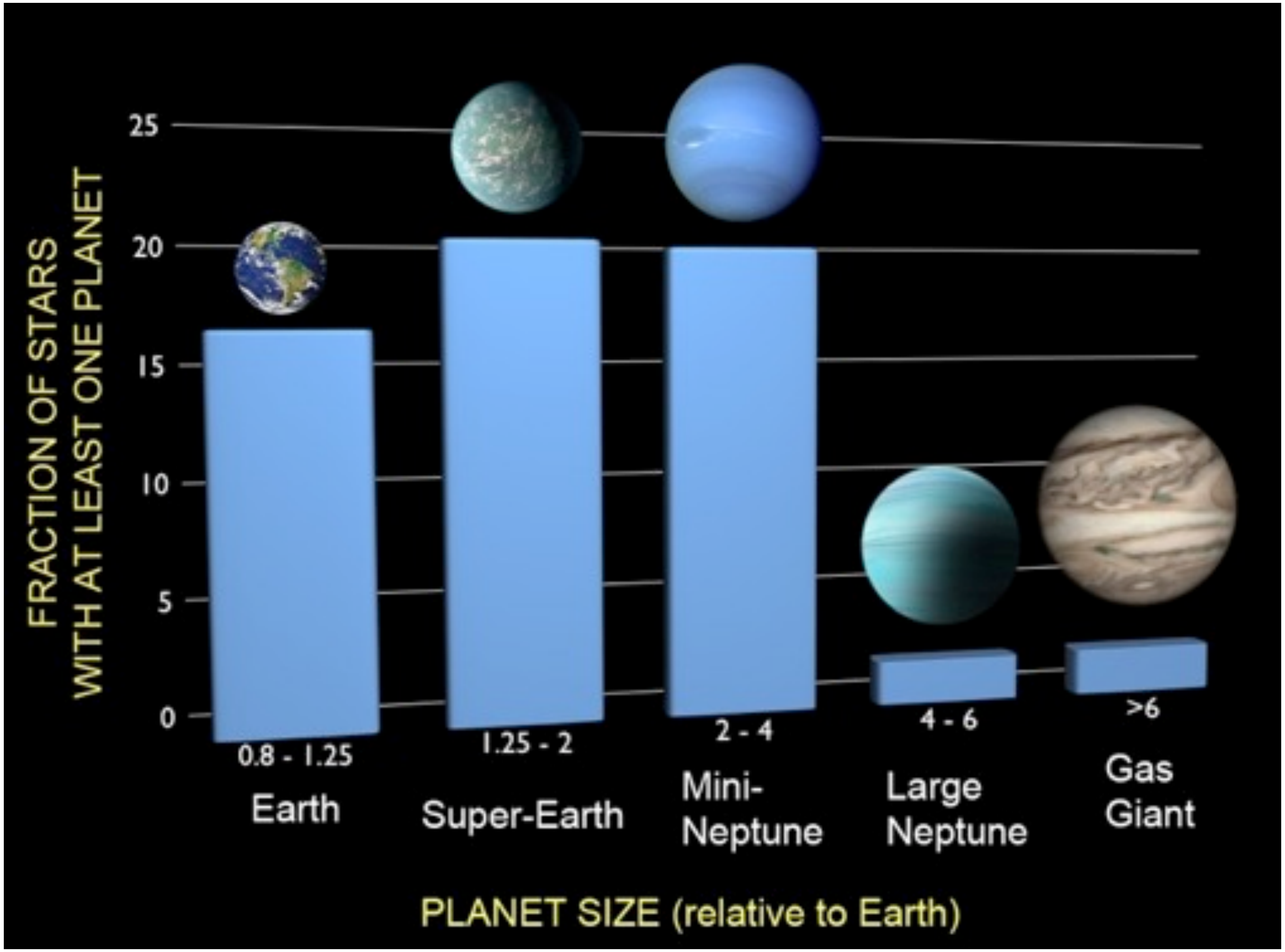
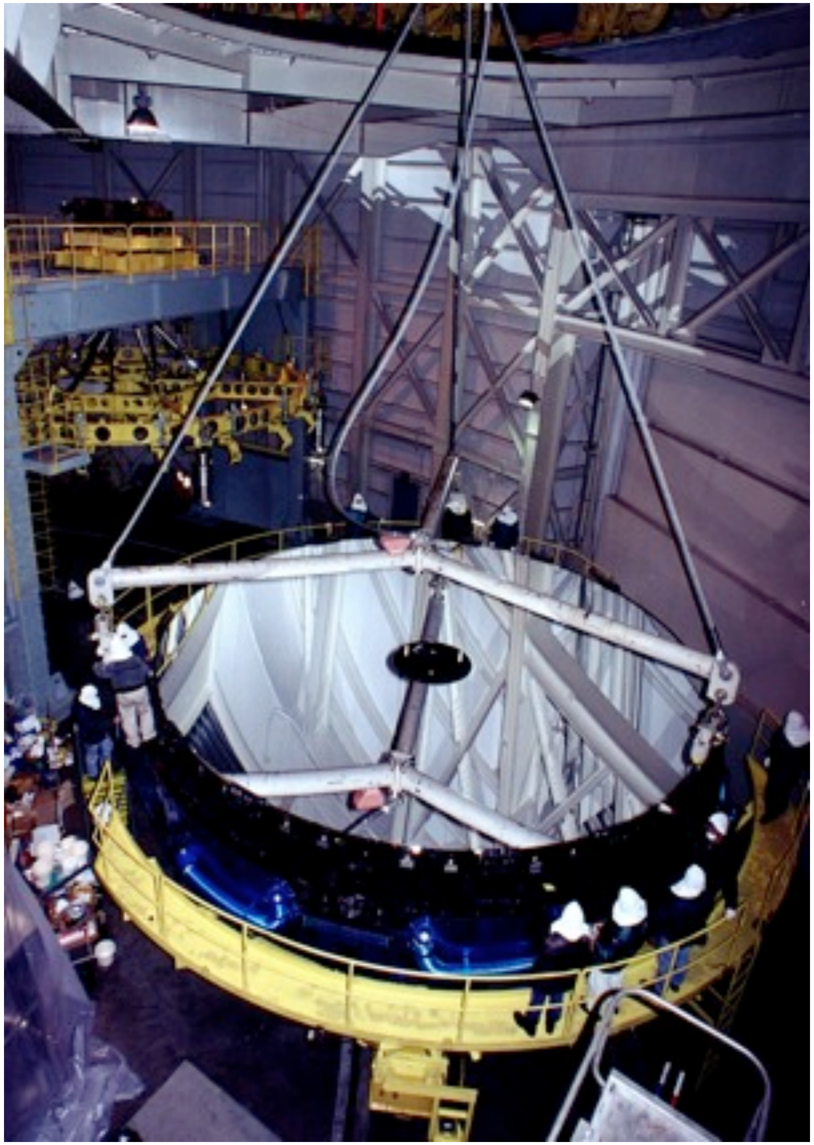
Semi-Major Axis [Astronomical Units (AU)]

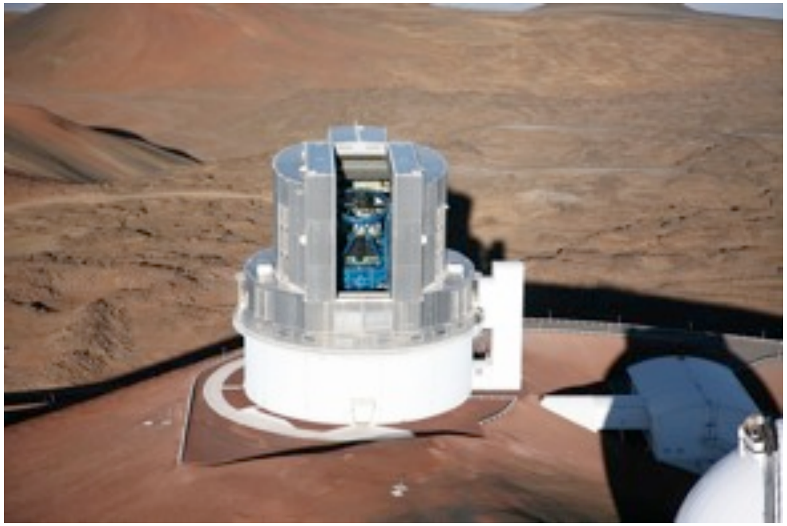


Traditional work suggests that 17–30% of solar-like star have planetary systems. Stars orbited by planets are the rule rather than the exception (Cassan et al. 2012, Nature, 481, 167). Studies of planets with orbits of size 0.5–10 astronomical units. It was found that many stars host Jupiter-mass planets (0.3–10 M_{J}, where $M_{\mathrm{J}} = 318\ M$ and M is Earth's mass) but that cool Neptunes (10–30 M) and super-Earths (5–10 M) are even more common.

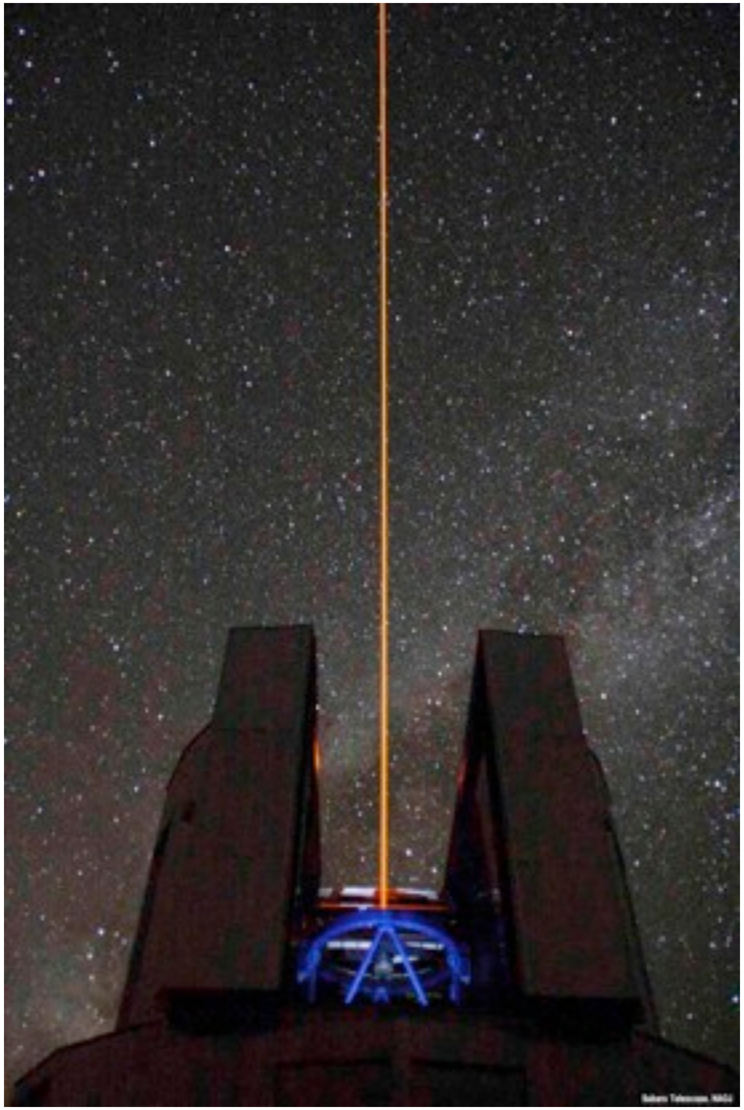
PROTOPLANETARY DISKS

Protoplanetary and Protostellar Disks

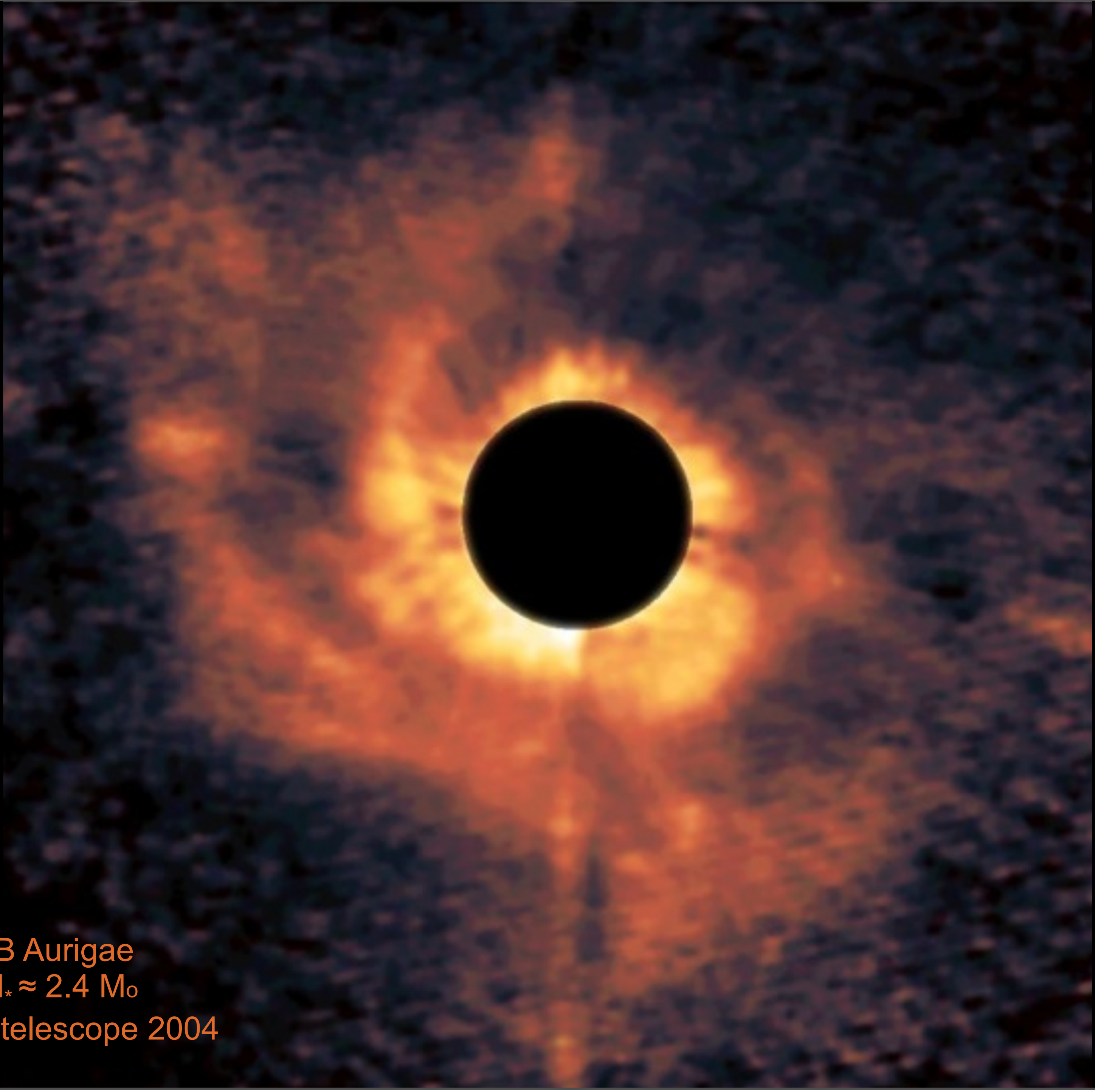




Subaru is an 8.2-m optical-Infrared telescope at the 13,460 ft summit of Mauna Kea. It is one of a new generation of telescopes with its state of the art technologies, an active support system, a dome designed to suppress local atmospheric turbulence, an accurate tracking mechanism using magnetic driving systems, seven observational instruments installed at the four foci, and an auto-exchanger system to use the observational instruments effectively.



Star trails at Mauna Kea with the Subaru telescope and the Keck telescope. The sodium (Na) laser (589 nm) creates an artificial guide star in the sodium layer. This combined with a deformable mirror allows the effects of seeing to be ameliorated and nearly removed under optimal conditions!



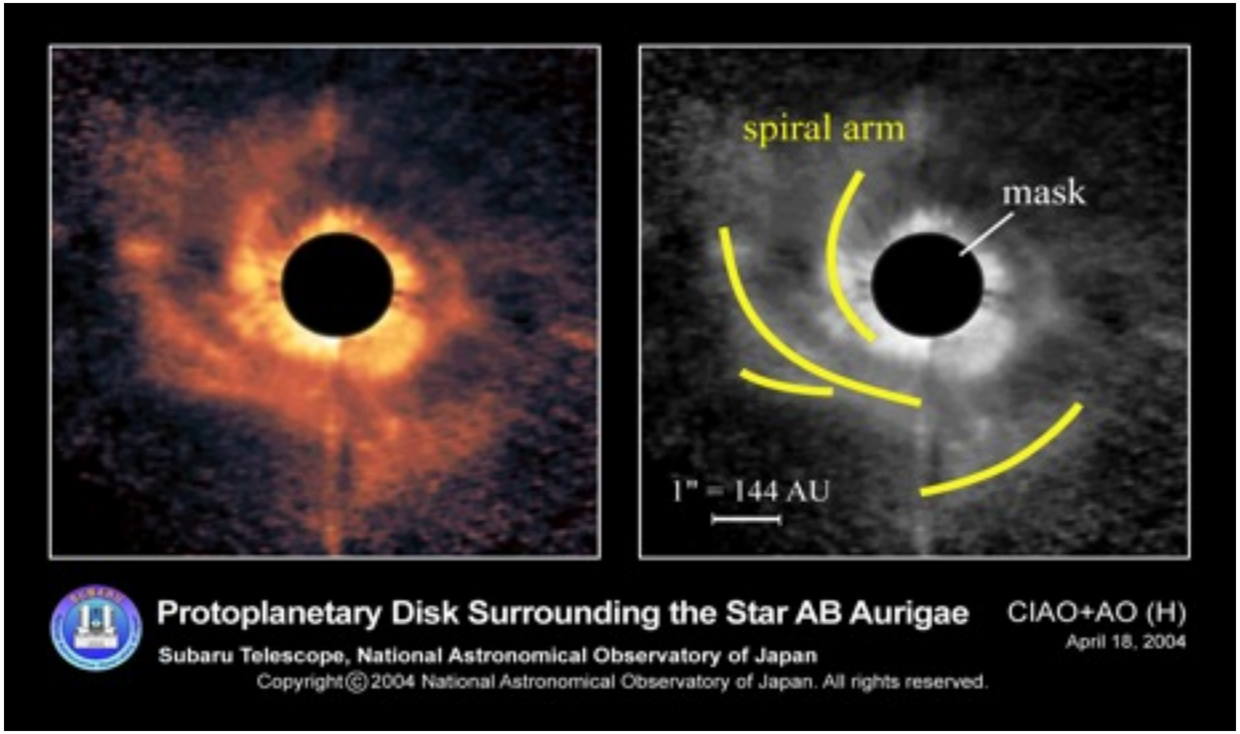
AB Aurigae

$M_* \approx 2.4\ M_\odot$

Subaru telescope 2004

AB Aurigae (AB Aur)

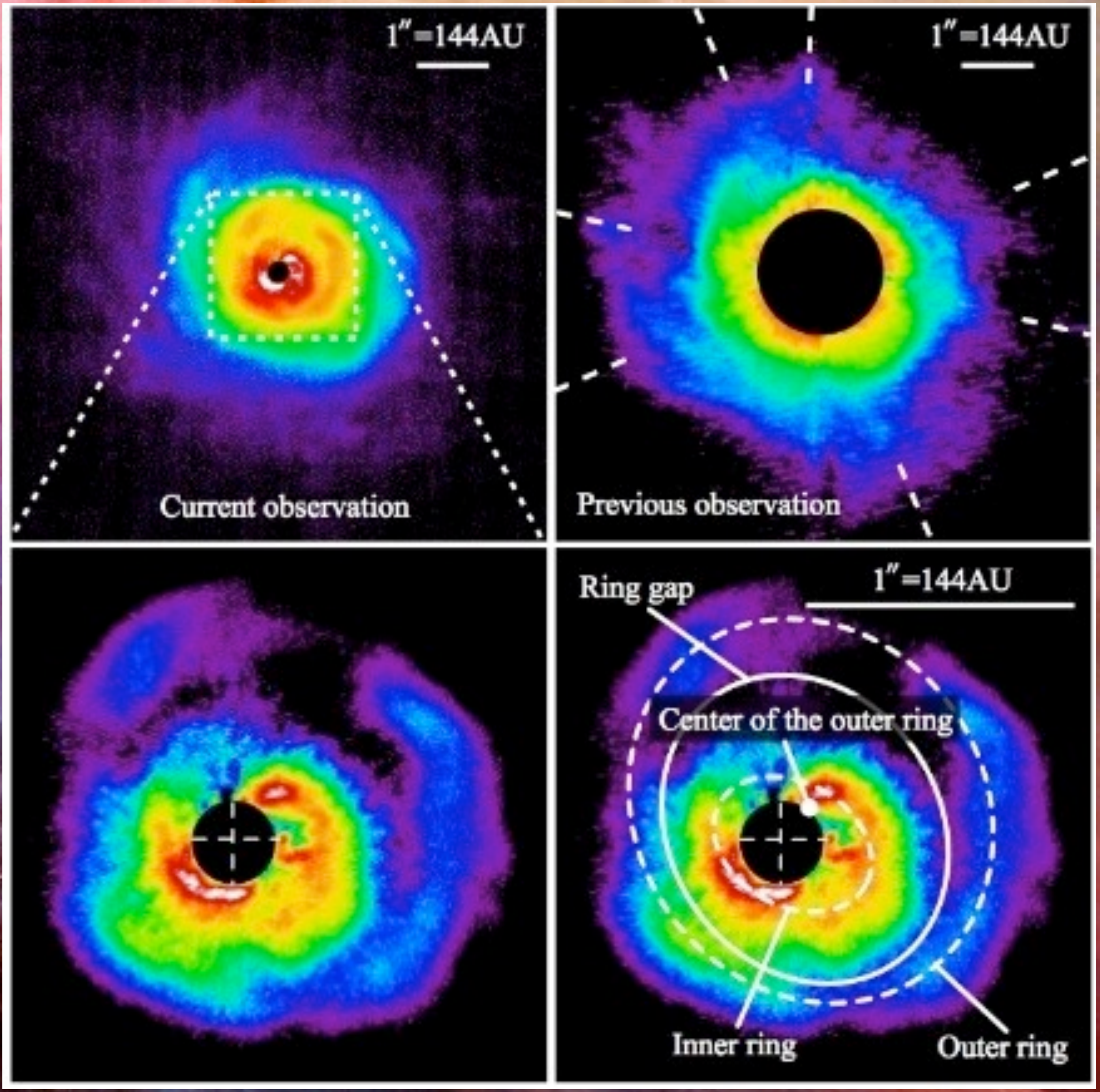
AB Aur contains a 4 My old A0 star, M = 2.4 Solar masses star surrounded by a disk of mass ~ 0.01 to 0.1 Solar masses → star to disk mass ratio 24 -240. Conservatively, based on the inner ring and outer arm structure found by Subaru, r-/r+ < 0.2-0.3. The disk in AB Aur is close to non-self-gravitating and may be subject to strong gravitational instability depending on its angular velocity distribution.



Protoplanetary Disk Surrounding the Star AB Aurigae

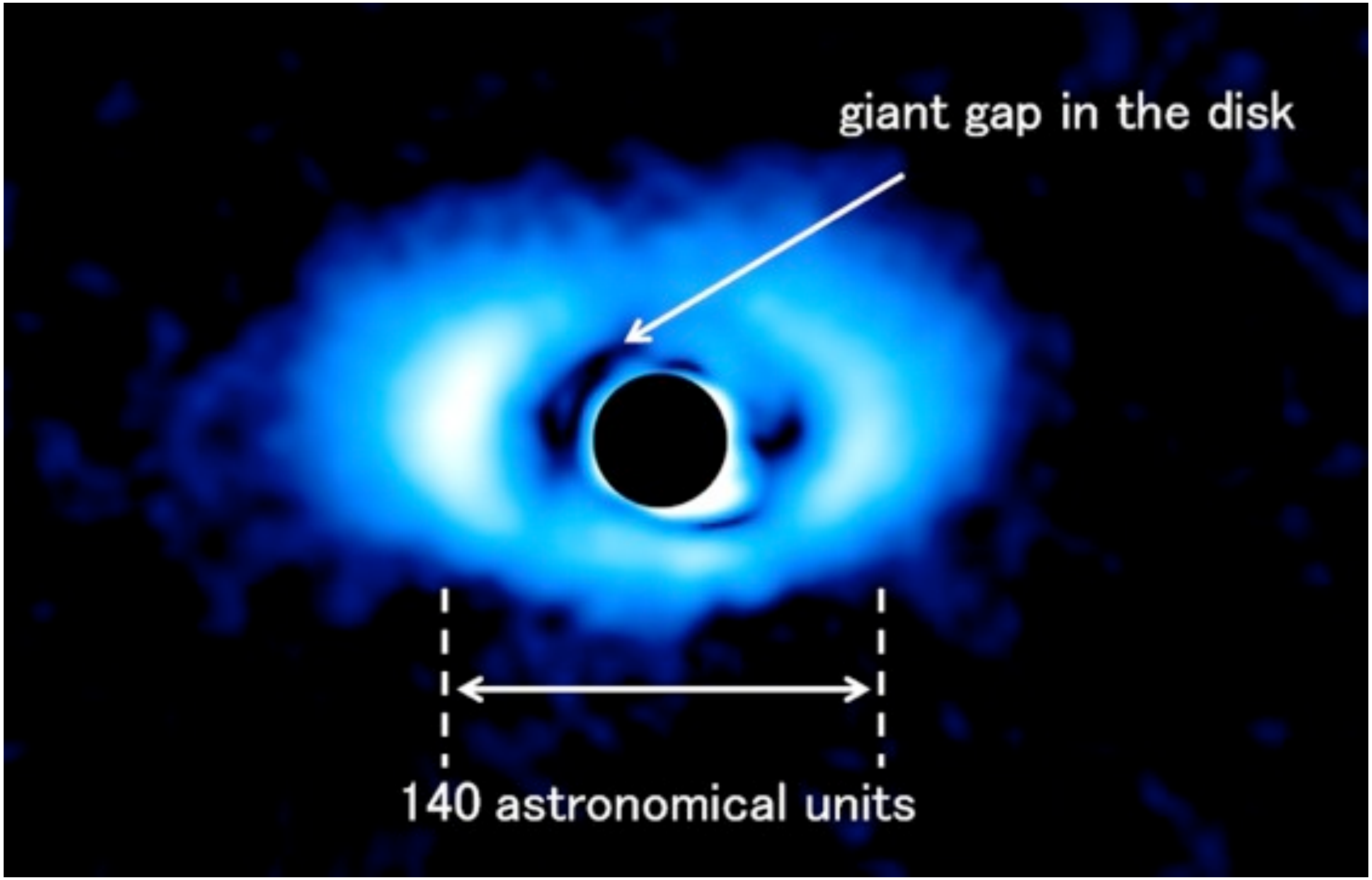
CIAO+AO (H)
April 18, 2004

Subaru Telescope, National Astronomical Observatory of Japan

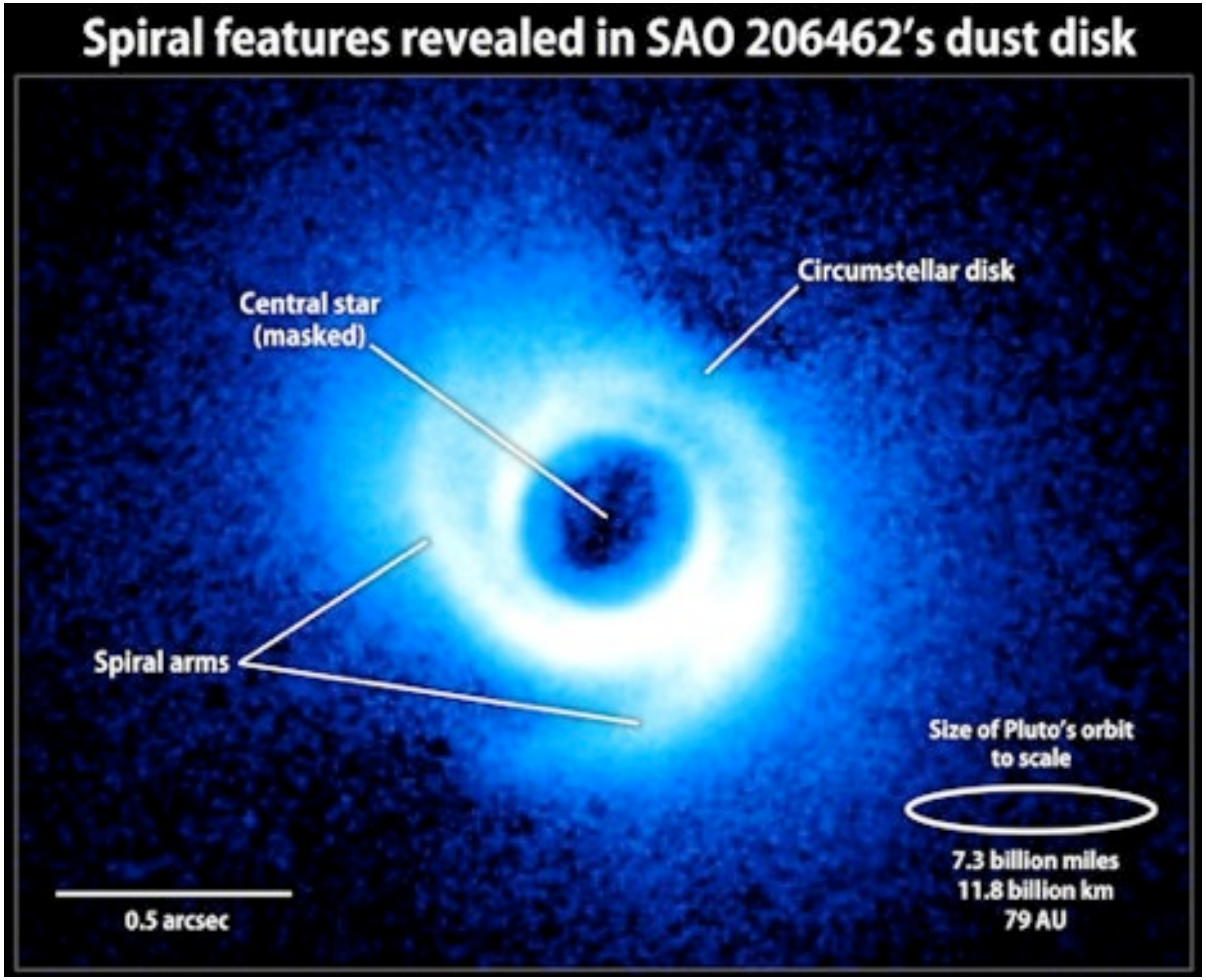


AB Aurigae

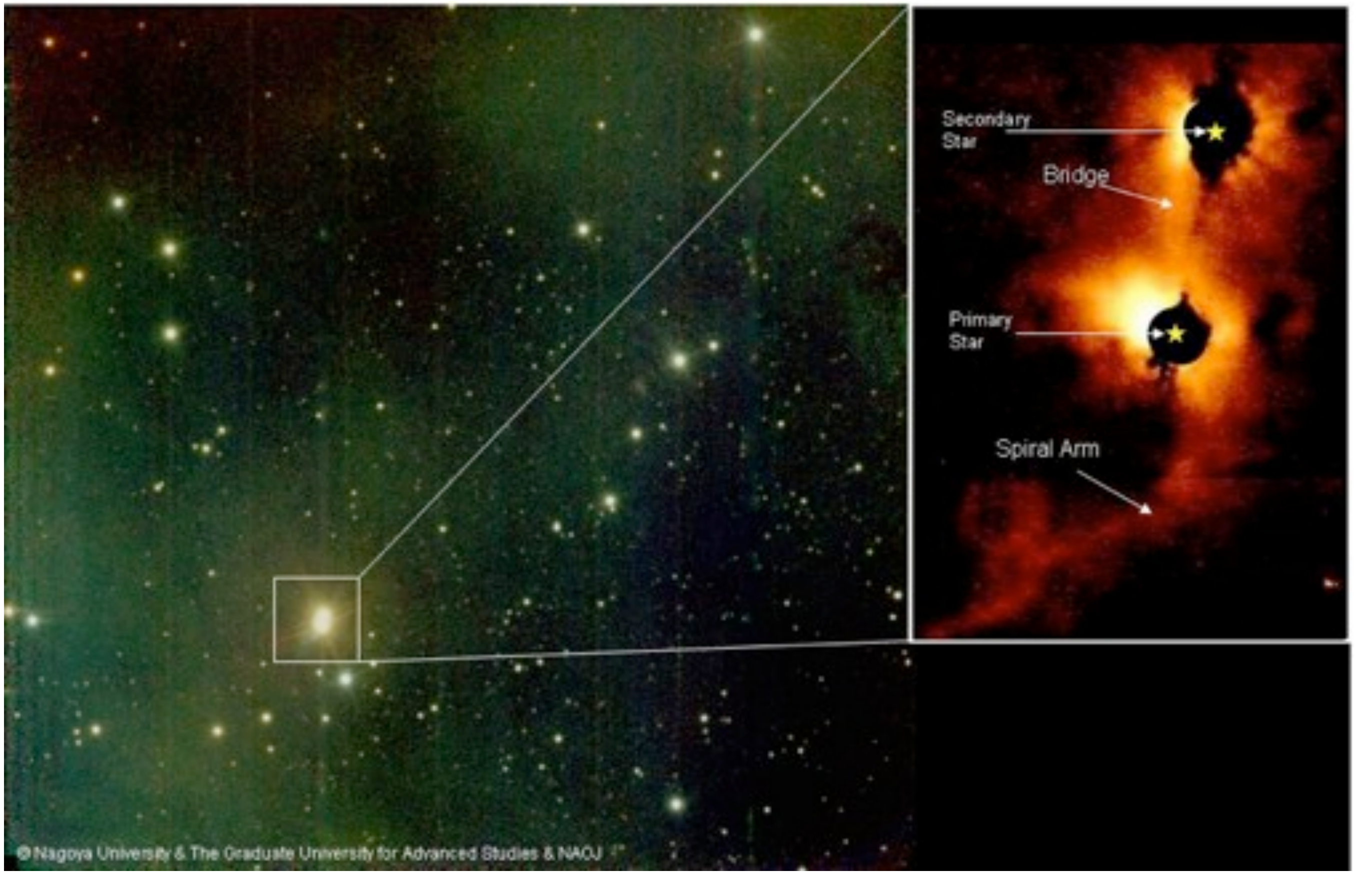
Subaru observations of AB Aurigae revealed an outer spiral arm structure and what was interpreted as a set of smaller inner rings with a gap (Fukagawa *et al*. 2004, Hashimoto *et al*. 2011). The inner structure was interpreted as arising from a planet interacting with the disk. We consider the possibility that the structures are the result of gravitational instability.



HiCIAO mounted on the Subaru Telescope captured this near infrared image of the protoplanetary disk around PDS 70. A software mask blocked out the light in the immediate vicinity of the central star. The colors in the image indicate the luminosity of the infrared light; the white area has stronger infrared radiation while that of the bluer area is weaker.

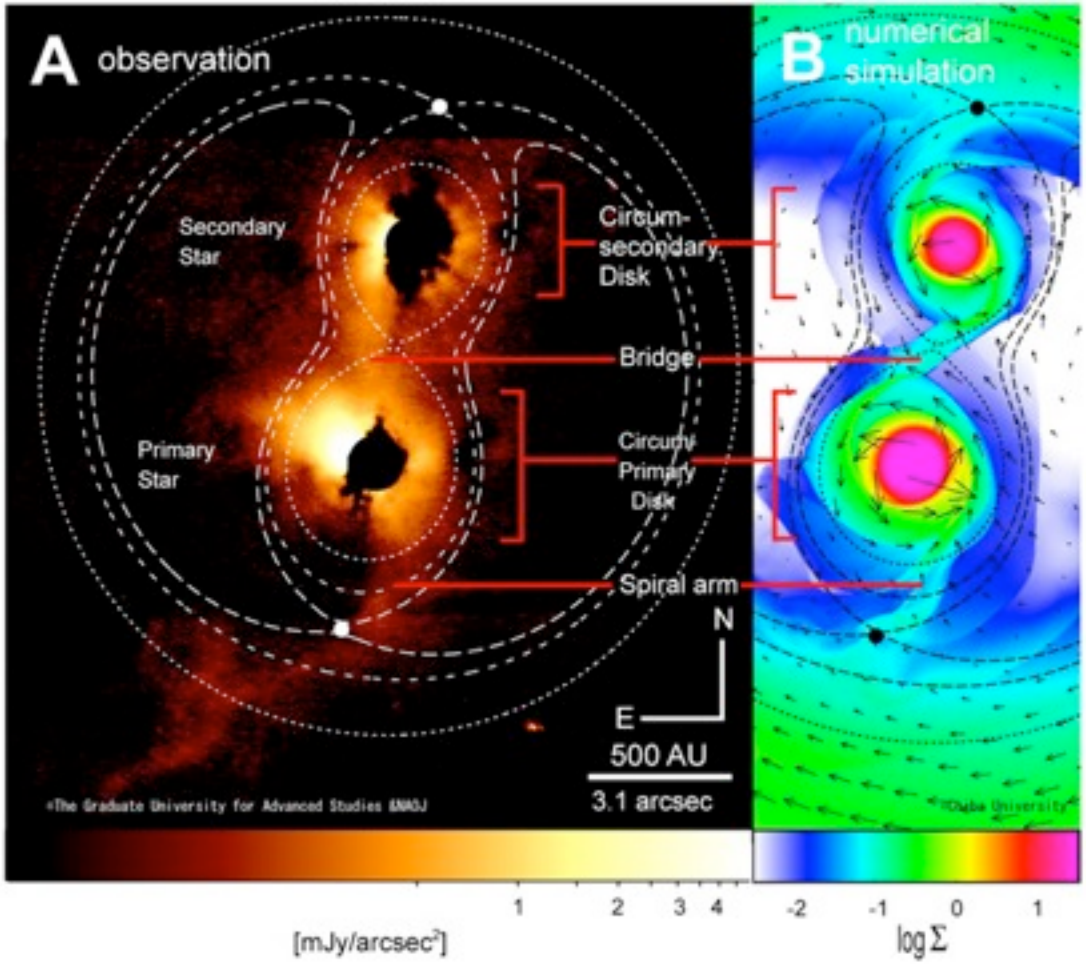


Two spiral arms emerge from the disk around SAO 206462, a young star in the constellation Lupus. This image acquired by the Subaru Telescope and its HiCIAO instrument, is the first to show spiral arms in a circumstellar disk. The disk itself is ~14 billion miles across, about twice the size of Pluto's orbit. (Credit: NAOJ/Subaru).



Wide-field three-color composite image of the environment around the constellation Ophiuchus, where the binary system SR24 is located. (Obtained with the 1.4 m telescope IRSF [Infrared Survey Facility] at the South African Astronomical Observatory [SAAO]) (© The Graduate University for Advanced Studies)

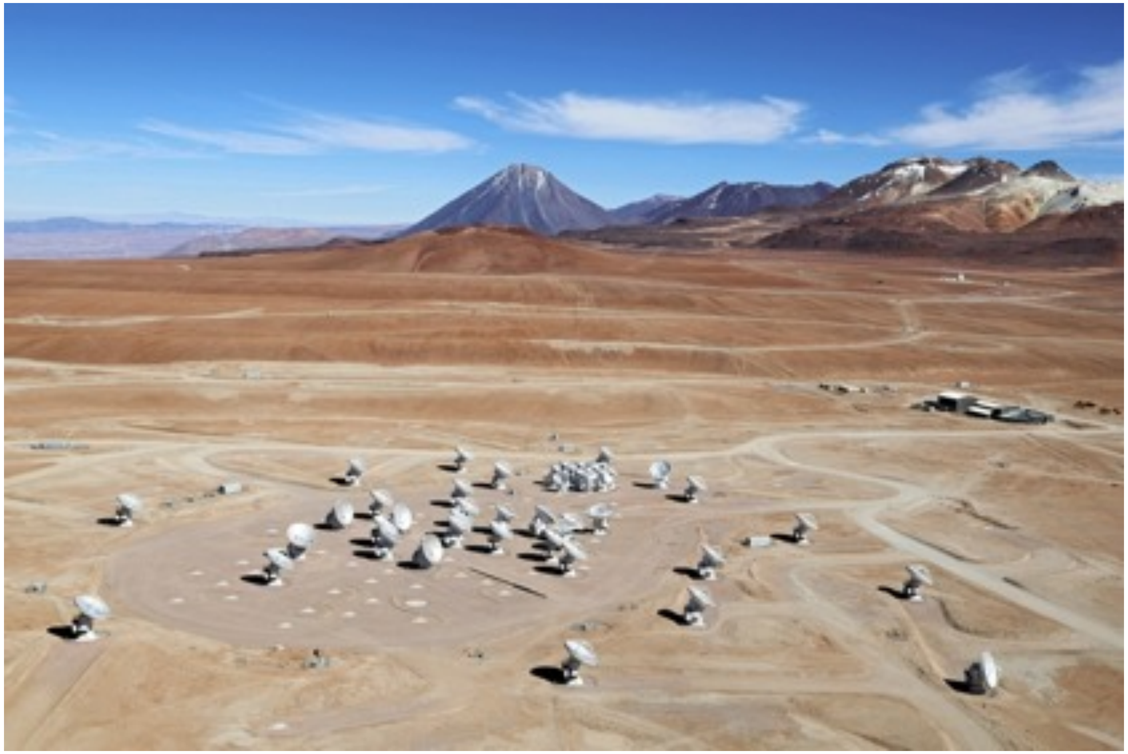
Right inset: Image of the young binary system SR24. Obtained with the 8.2m Subaru Telescope. (© The Graduate University for Advanced Studies)



Left: Observed image of the young binary SR24 (distance: 520 light years). IR image of SR24 and associated disks. The Roche lobe of each star are indicated by dotted lines (for the inner regions) and dashed lines (for the outer regions). (©The graduate University for Advanced Studies & the NAOJ)

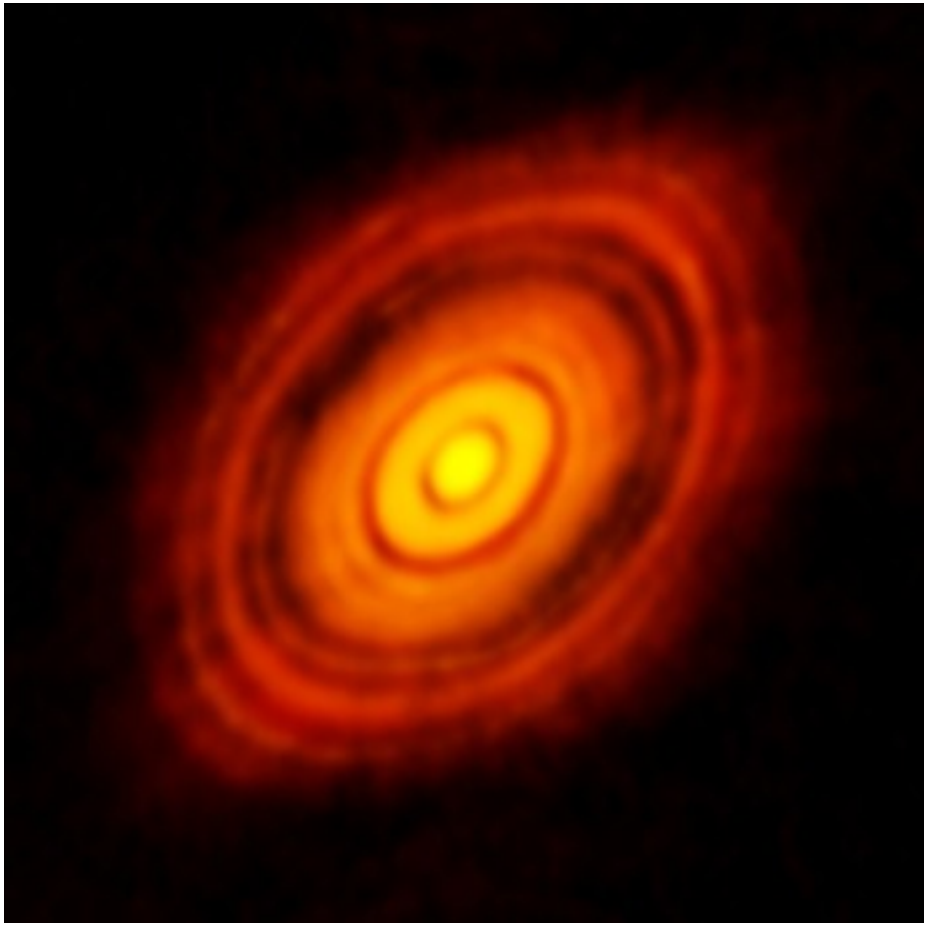
Right: Snapshot of the binary system SR24 based on two-dimensional numerical simulations. The colors designate the distribution of surface densities and the arrows, the distribution of velocity. (© Chiba University)

Atacama Large Millimeter/submillimeter Array (ALMA)



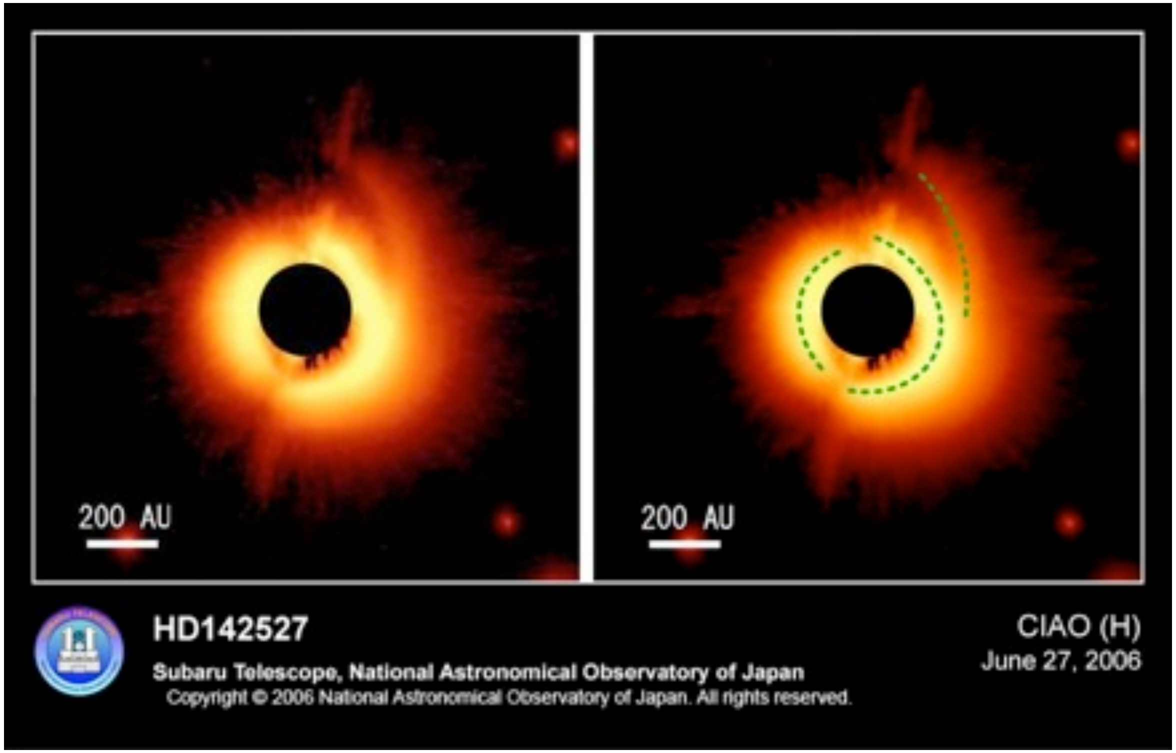
ALMA is a microwave interferometer with 66 parabolic antennae, fifty 12-m antennae, and "Atacama Compact Array (ACA)," four 12-m antennae and twelve 7-m antennae located in the Atacama desrt in northern Chile. The movable antennae are spread over distances of up to 18.5 km achieving resolution equivalent to a telescope 18.5 km in diameter, ALMA attains the world's highest sensitivities and resolutions at millimeter and submillimeter wavelengths.

Protoplanetary Disks: HL Tauri

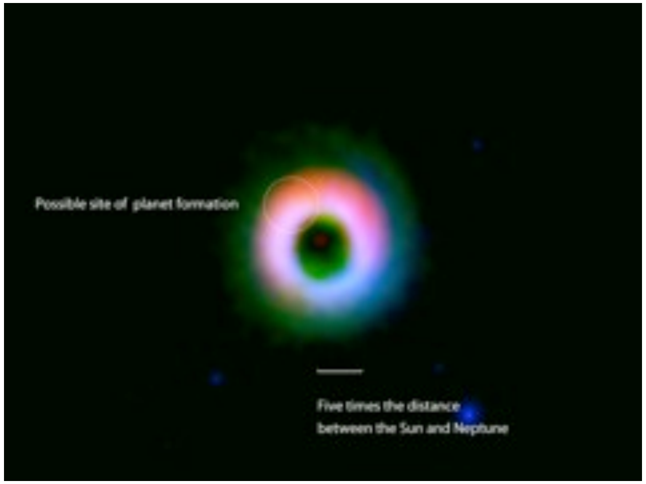


Why does HL Tau's giant disk have gaps? Planets! A mystery is how planets massive enough to create these gaps formed so quickly, since HL Tau is only about one million years old.

The image was taken with ALMA. ALMA imaged the protoplanetary disk, which spans about 170 AU across showing features as small as 5 AU. HL Tau is about 450 light years from Earth.



Subaru HiCIAO observations of HD 142527



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Dust and gas disk around HD142527. The dust and gas distributions observed by ALMA are shown in red and green, respectively. Near-infrared image taken by the NAOJ Subaru Telescope is shown in blue. The image clearly shows that the dust is concentrated in the northern (upper) part of the disk. The circle in the image shows the position of the dust concentration, in which planets are thought to be formed. Credit: ALMA (ESO/NAOJ/NRAO), NAOJ.

PLANETARY FORMATION

TWO PLANET FORMATION SCENARIOS

Accretion model

Gas-collapse model

Orbiting dust grains accrete into "planetesimals" through nongravitational forces.

Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."

Gas-giant planets accrete gas envelopes before disk gas disappears.

Gas-giant planets scatter or accrete remaining planetesimals and embryos.

A protoplanetary disk of gas and dust forms around a young star.

Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.

Dust grains coagulate and sediment to the center of the protoplanet, forming a core.

The planet sweeps out a wide gap as it continues to feed on gas in the disk.

Core-accretion: the coalescence model where dust particles (several microns) collide and stick together and form large objects called planetesimals, which then continue to grow until they reach 100 kilometers in size, whereupon they start to capture other planetesimals gravitationally and become protoplanets. Finally, Jupiter-like planets capture gas from the protoplanetary nebula. This process is slow taking perhaps 10 million years with a crucial point of the location of the *snowline*.

Gravitational Instability: the disk becomes unstable to fragmentation and clumping, driven by gravity (perhaps through Jeans-like instabilities). This process is quick, taking place on time scales as short as hundreds to thousands of years.

Which to Choose?

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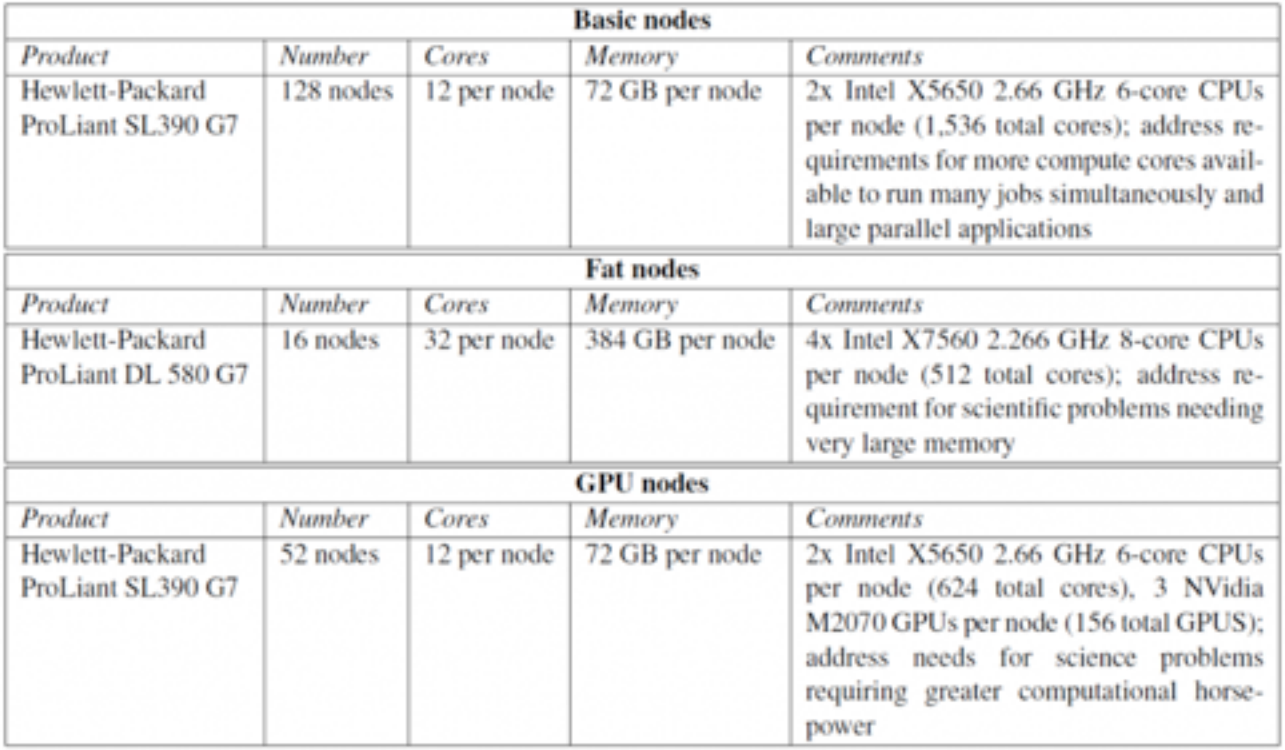
In light of these issues, we pursue the scenario where Jupiter-like planets form from gravitational instabilities.

ACISS: University of Oregon’s supercomputer offers the most powerful computing resources available on campus. ACISS provides scientists with thousands of processing cores, high-performance computational accelerators, hundreds of terabytes of storage space, and high-speed integrated network interfaces. The project was funded by a $1.97 million National Science Foundation grant awarded under the American Recovery and Reinvestment Act of 2009, Principal Investigator Allen Malony.

ACISS: Univ of Oregon HPCC



Basic nodes

Product	*Number*	*Cores*	*Memory*	*Comments*
Hewlett-Packard ProLiant SL390 G7	128 nodes	12 per node	72 GB per node	2x Intel X5650 2.66 GHz 6-core CPUs per node (1,536 total cores); address requirements for more compute cores available to run many jobs simultaneously and large parallel applications

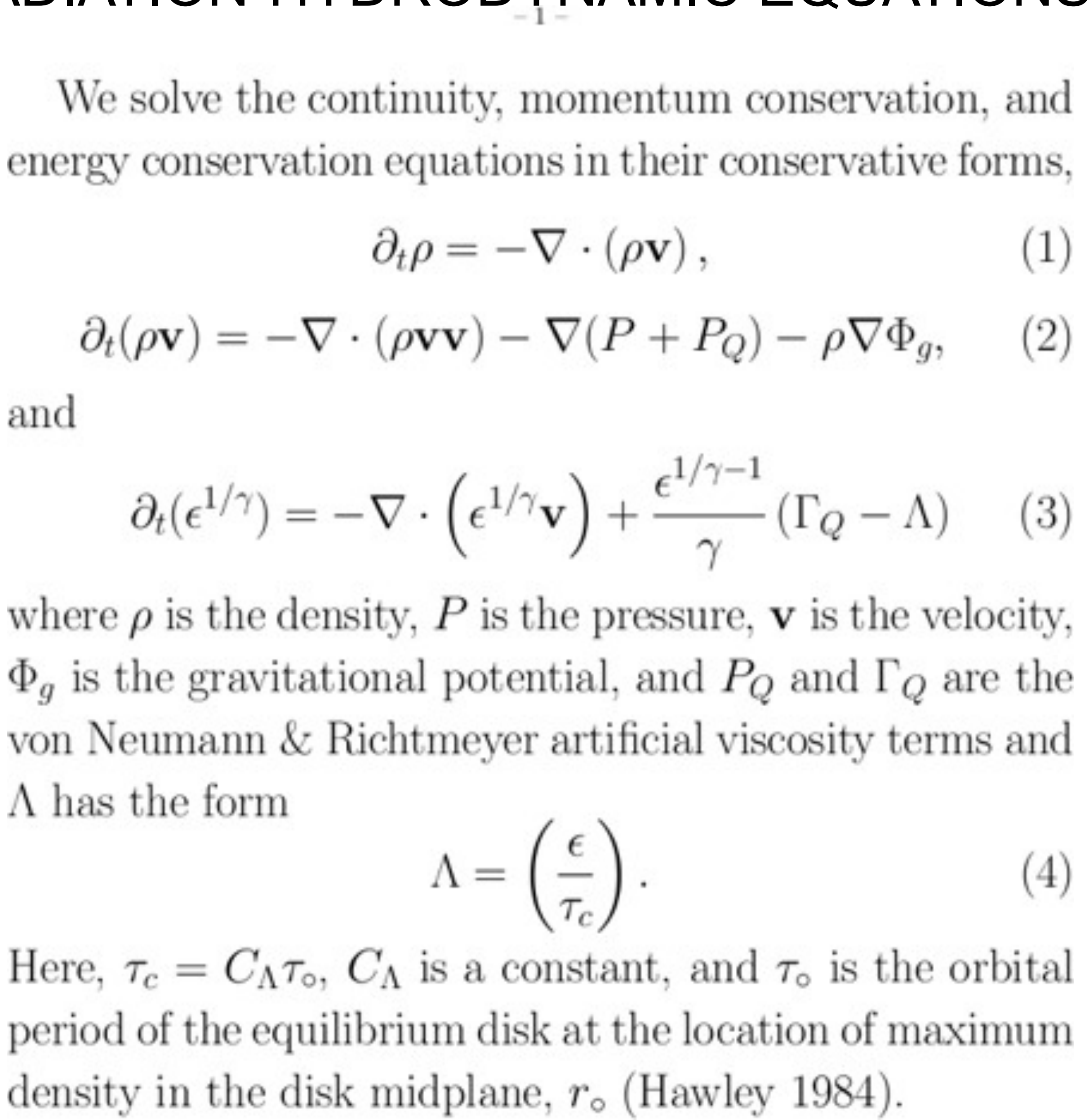
Fat nodes

Product	*Number*	*Cores*	*Memory*	*Comments*
Hewlett-Packard ProLiant DL 580 G7	16 nodes	32 per node	384 GB per node	4x Intel X7560 2.266 GHz 8-core CPUs per node (512 total cores); address requirement for scientific problems needing very large memory

GPU nodes

Product	*Number*	*Cores*	*Memory*	*Comments*
Hewlett-Packard ProLiant SL390 G7	52 nodes	12 per node	72 GB per node	2x Intel X5650 2.66 GHz 6-core CPUs per node (624 total cores), 3 NVidia M2070 GPUs per node (156 total GPUS); address needs for science problems requiring greater computational horsepower

RADIATION-HYDRODYNAMIC EQUATIONS



We solve the continuity, momentum conservation, and energy conservation equations in their conservative forms,

$$\partial_t \rho = -\nabla \cdot (\rho \mathbf{v}) \, , \tag{1}$$

$$\partial_t(\rho \mathbf{v}) = -\nabla \cdot (\rho \mathbf{v}\mathbf{v}) - \nabla(P + P_Q) - \rho \nabla \Phi_g, \tag{2}$$

and

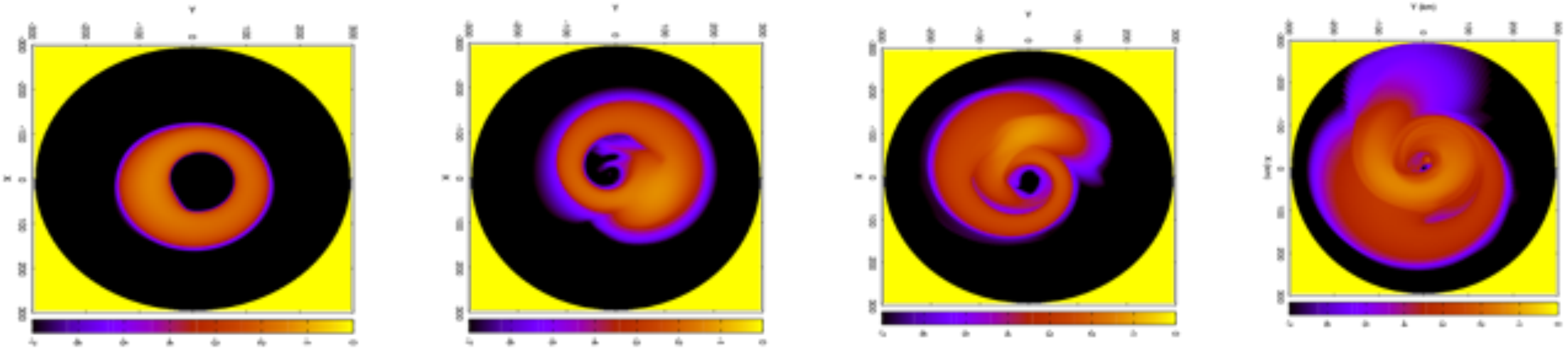
$$\partial_t(\epsilon^{1/\gamma}) = -\nabla \cdot \left(\epsilon^{1/\gamma}\mathbf{v}\right) + \frac{\epsilon^{1/\gamma-1}}{\gamma}(\Gamma_Q - \Lambda) \tag{3}$$

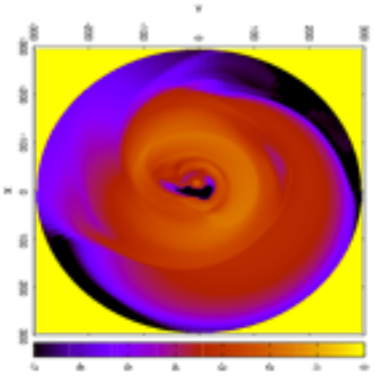
where ρ is the density, P is the pressure, $\mathbf{v}$ is the velocity, Φ_g is the gravitational potential, and P_Q and Γ_Q are the von Neumann & Richtmeyer artificial viscosity terms and Λ has the form

$$\Lambda = \left(\frac{\epsilon}{\tau_c}\right) . \tag{4}$$

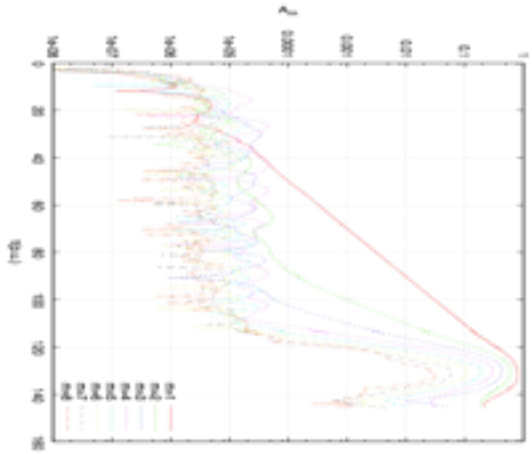
Here, $\tau_c = C_\Lambda \tau_\circ$, C_Λ is a constant, and $\tau_\circ$ is the orbital period of the equilibrium disk at the location of maximum density in the disk midplane, $r_\circ$ (Hawley 1984).

I Mode Simulation with Weak Cooling





The system is dominated by a one-armed spiral. A smooth trailing arm develops; it does not lead to fragmentation. The structures are shown at times $t = 6.8, 7.2, 7.6, 8$, and $8.4\ t_o$, where $t_o = 17.18$.



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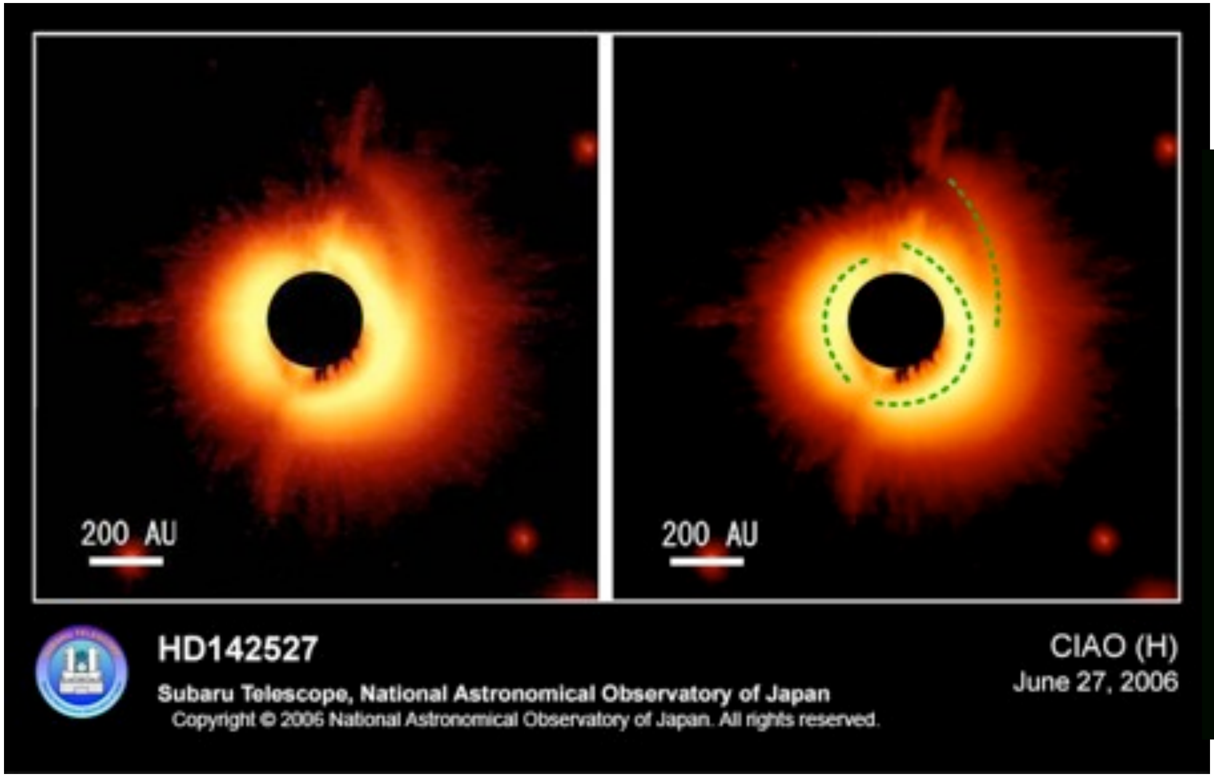
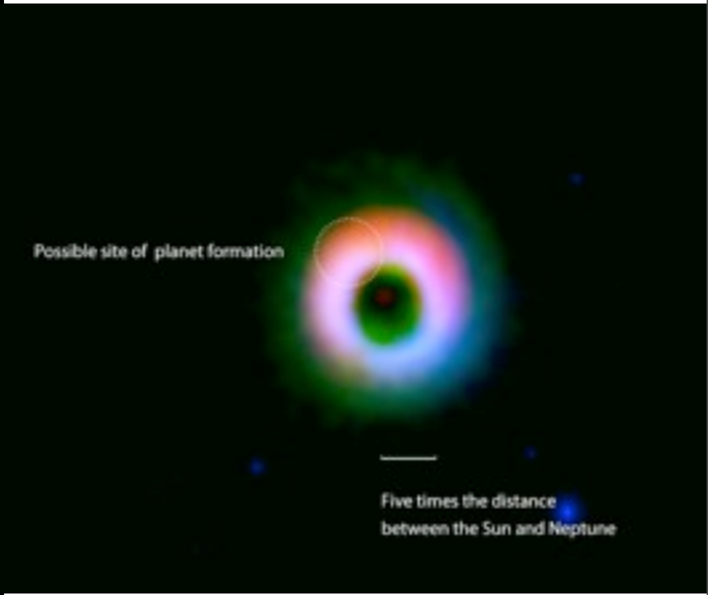
Subaru HiCIAO observations of HD 142527





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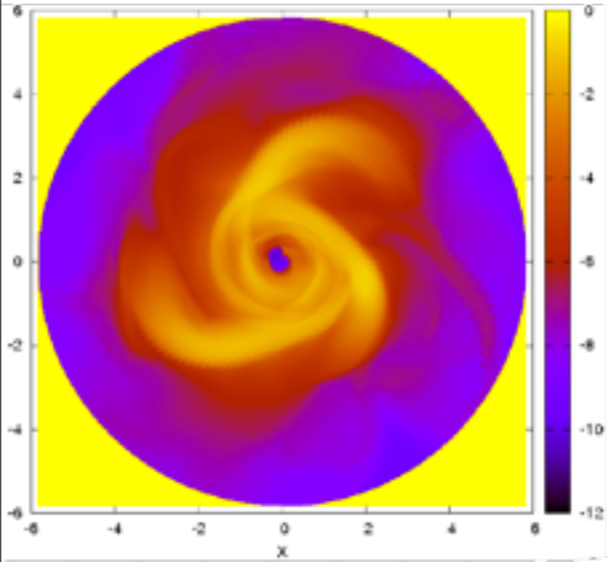
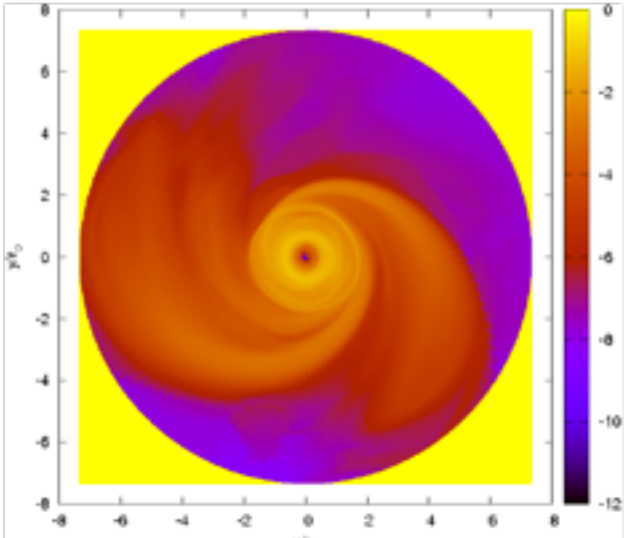
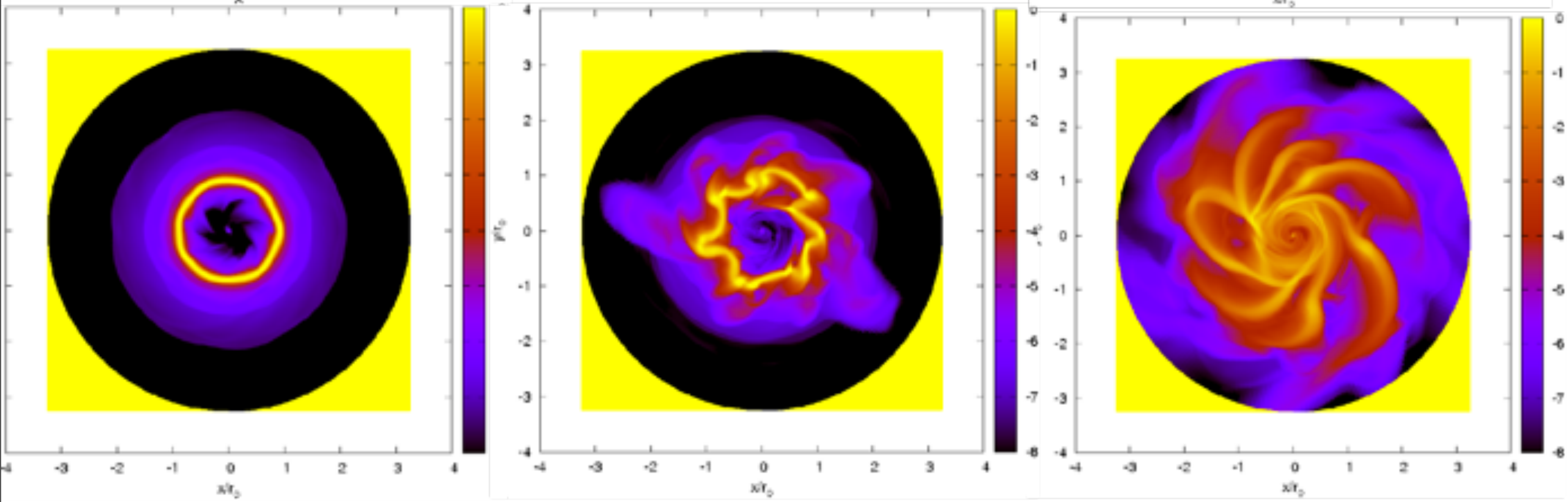
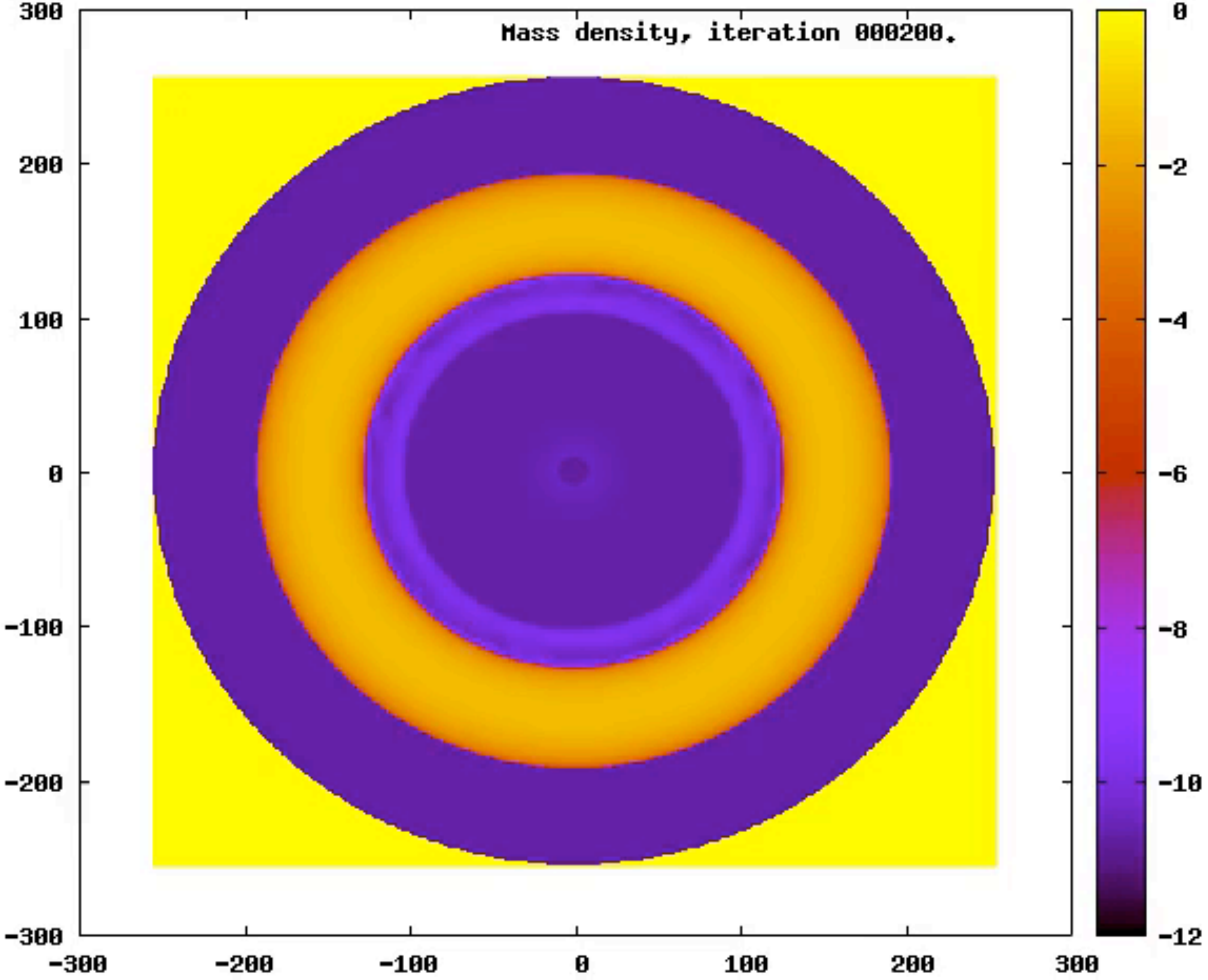
I Mode Simulation with Dust Emission



Simulations for the previous system, but with dust emission. The upper two figures are moderate cooling $t_c = 5\ t_o$. The bottom row is for strong cooling, $t_c = 0.5\ t_o$.






Mass density, iteration 000200.
300
200
100
0
-100
-200
-300
-300
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100
200
300
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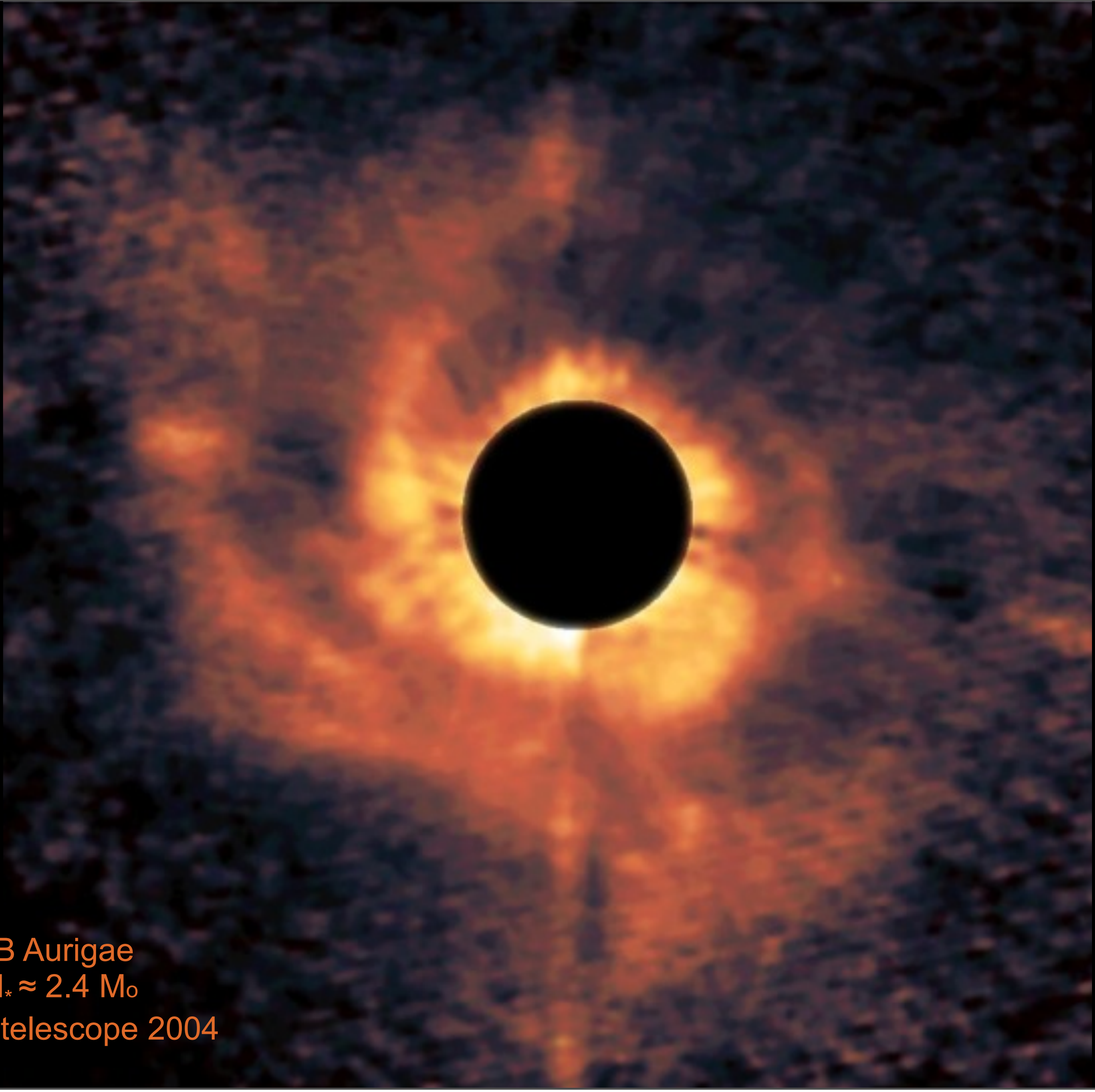
-2
-4
-6
-8
-10
-12

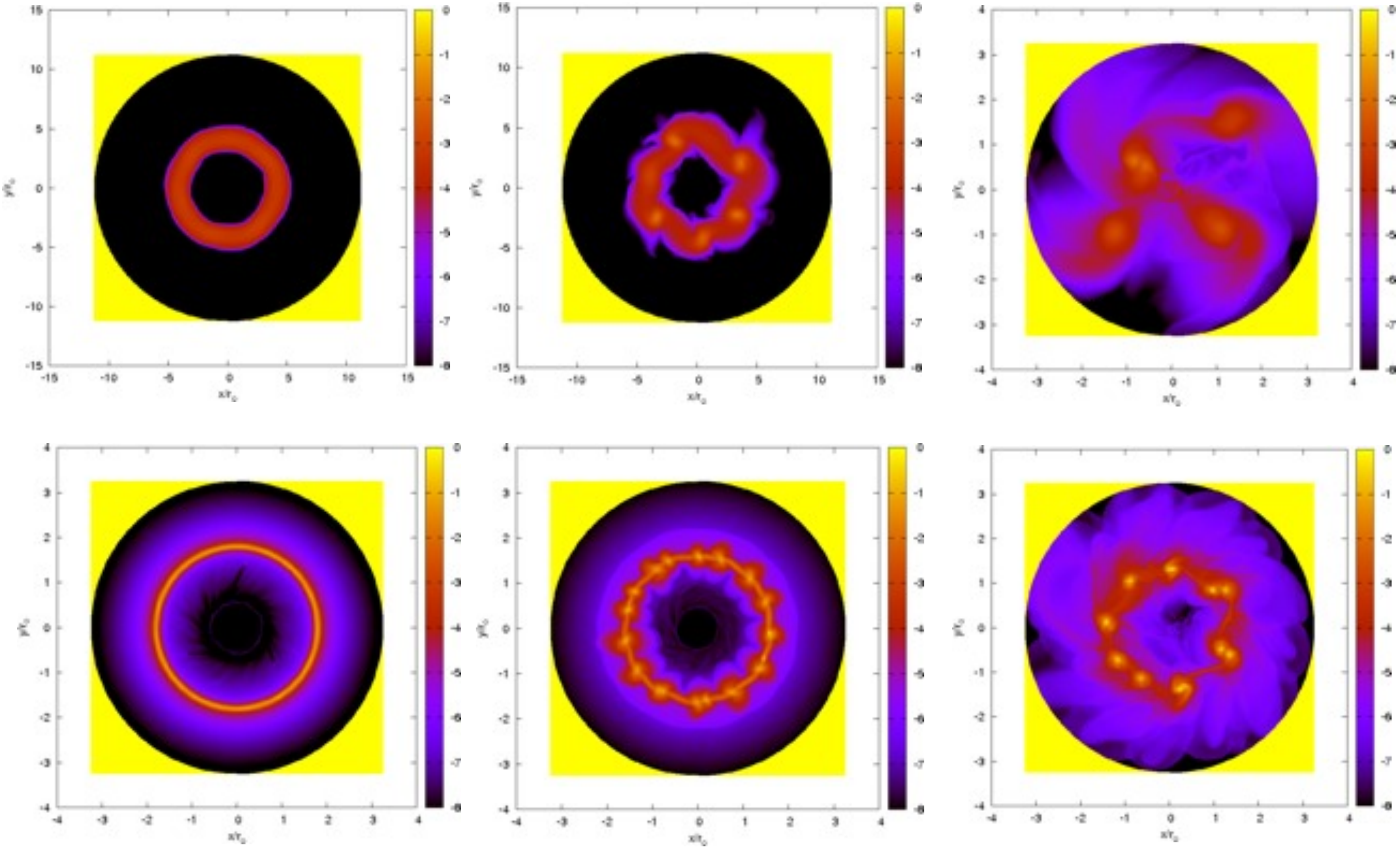


AB Aurigae

$M_* \approx 2.4\ M_\odot$

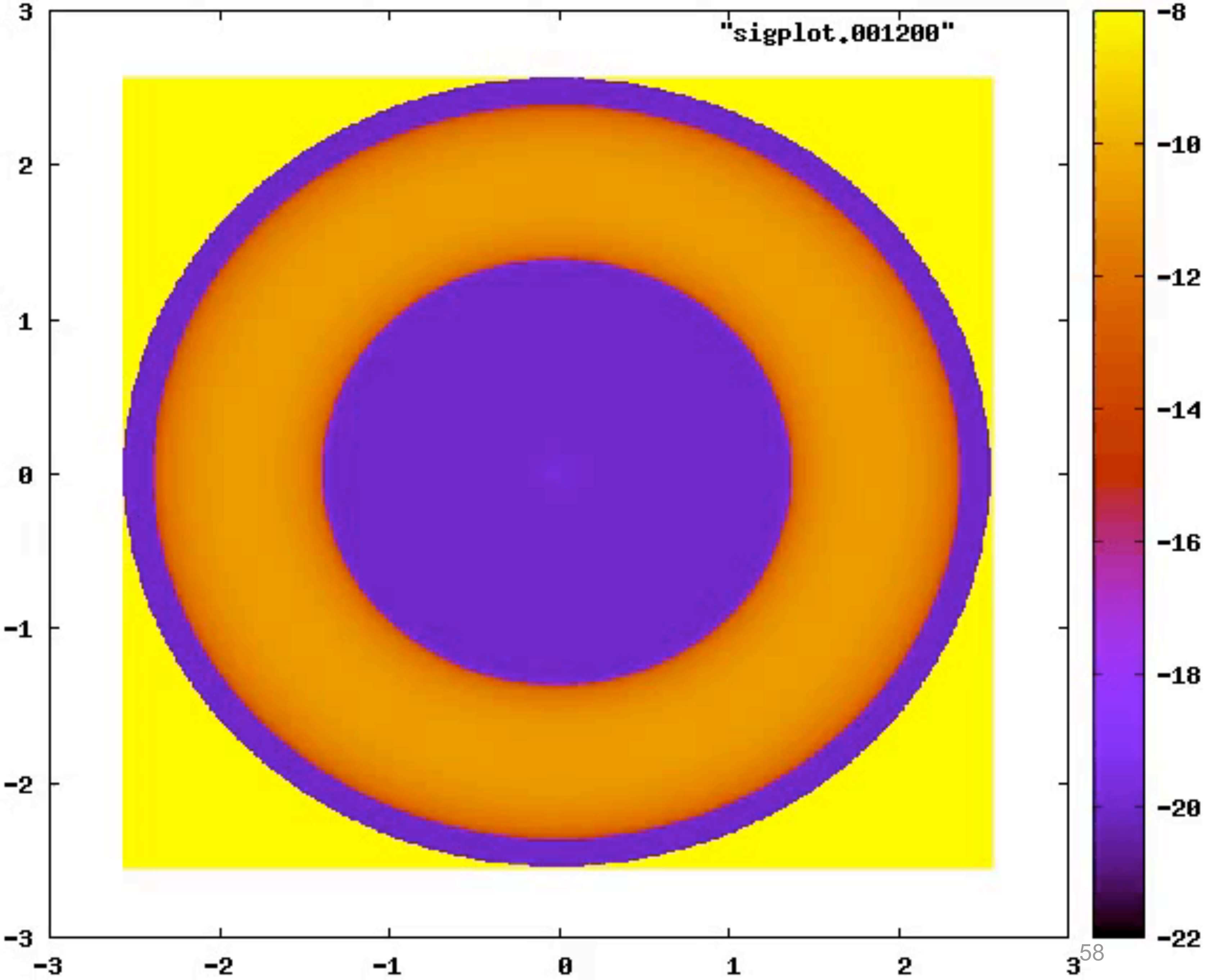
Subaru telescope 2004

J Mode Without and With Dust Emission



The disk clumped and fragmented into multiple bodies in both simulations. The disks were massive compared to the central star for these simulations.

60


"sigplot.001200"
3
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1
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-1
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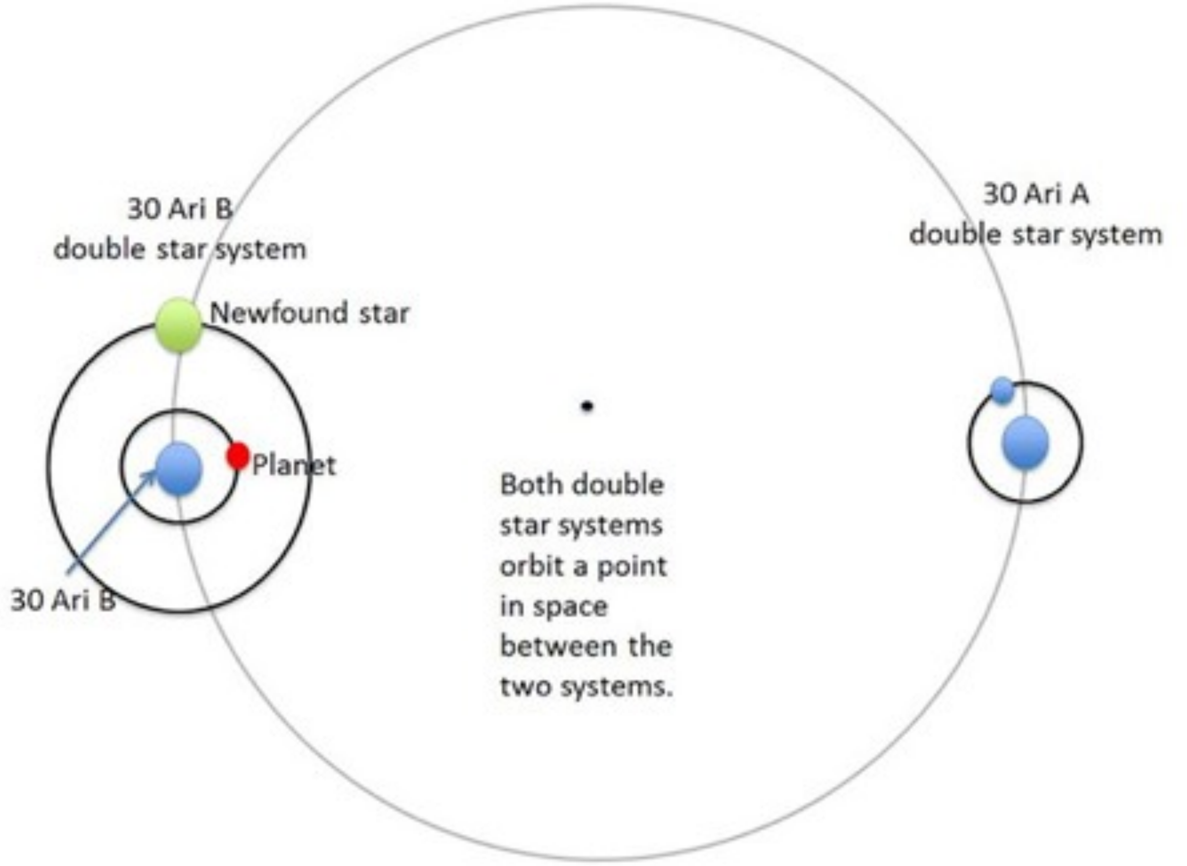
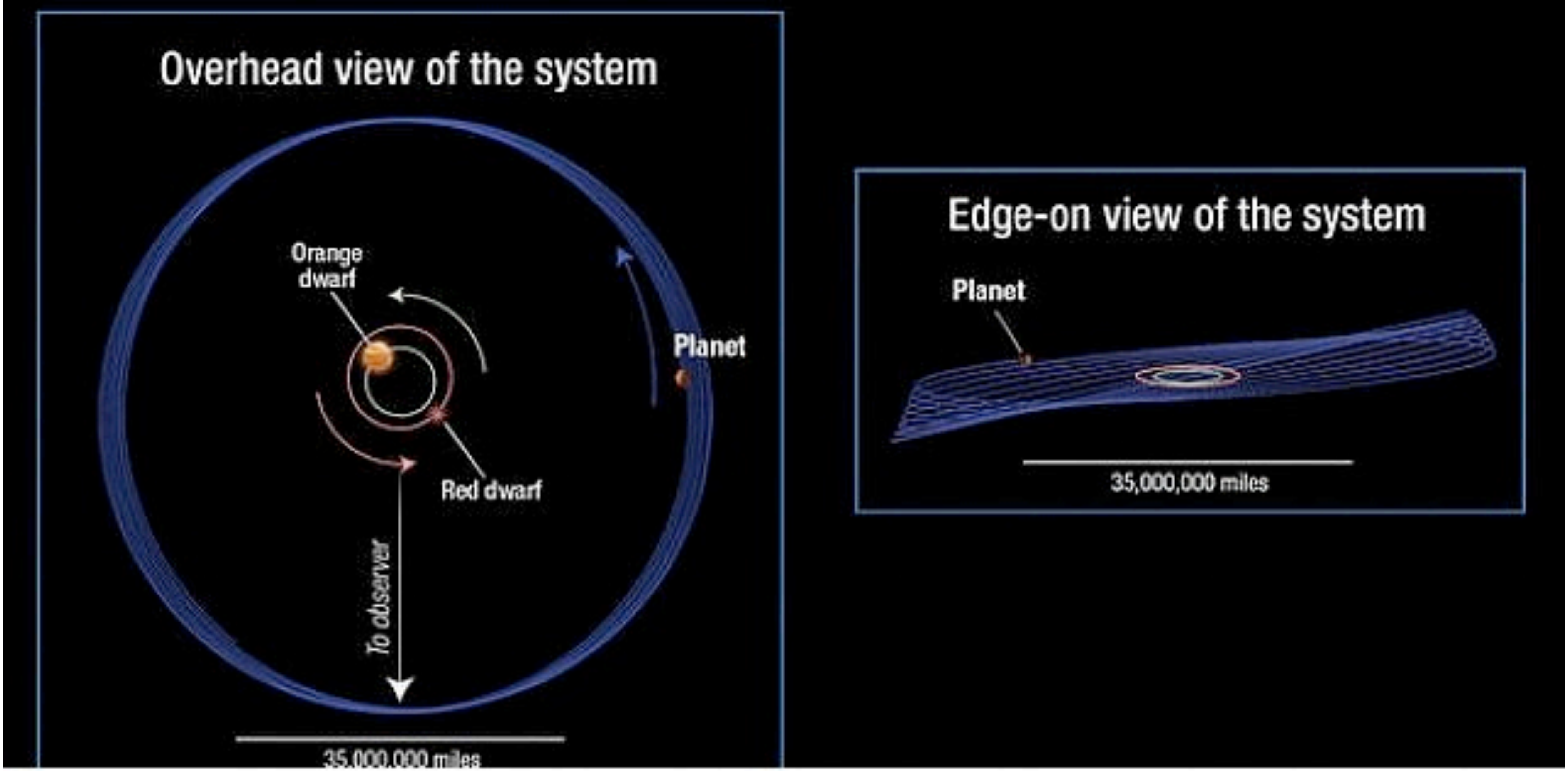


Quadruple Star System - 30 Ari

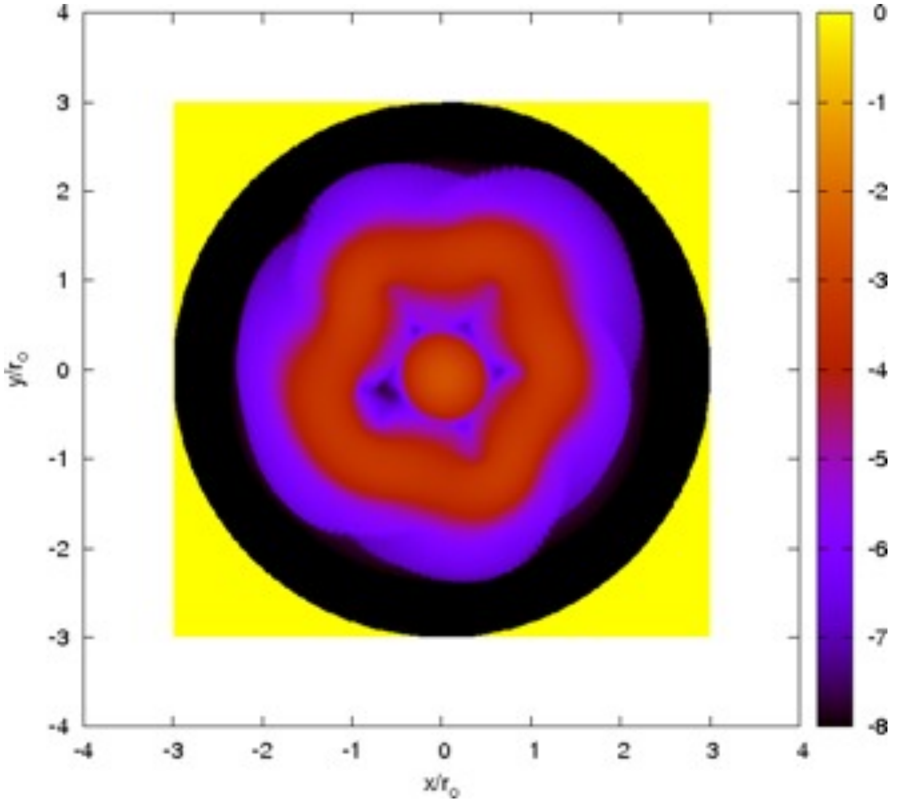
30 Ari, consists of two doubles, 30 Ari B and 30 Ari A. A Jovian planet (red) orbits in 30 Ari B about once a year. Observations led by JPL, identified the fourth star (green). The three others stars and the planet were know previously. This is the second quadruple system found to host a planet. The first, KIC 4862625, was discovered by a citizen science project that scours Kepler data to seek extra-Solar planets. With two systems out of 1,500 exoplanets discovered, hints that planet formation can occur in unlikely places.

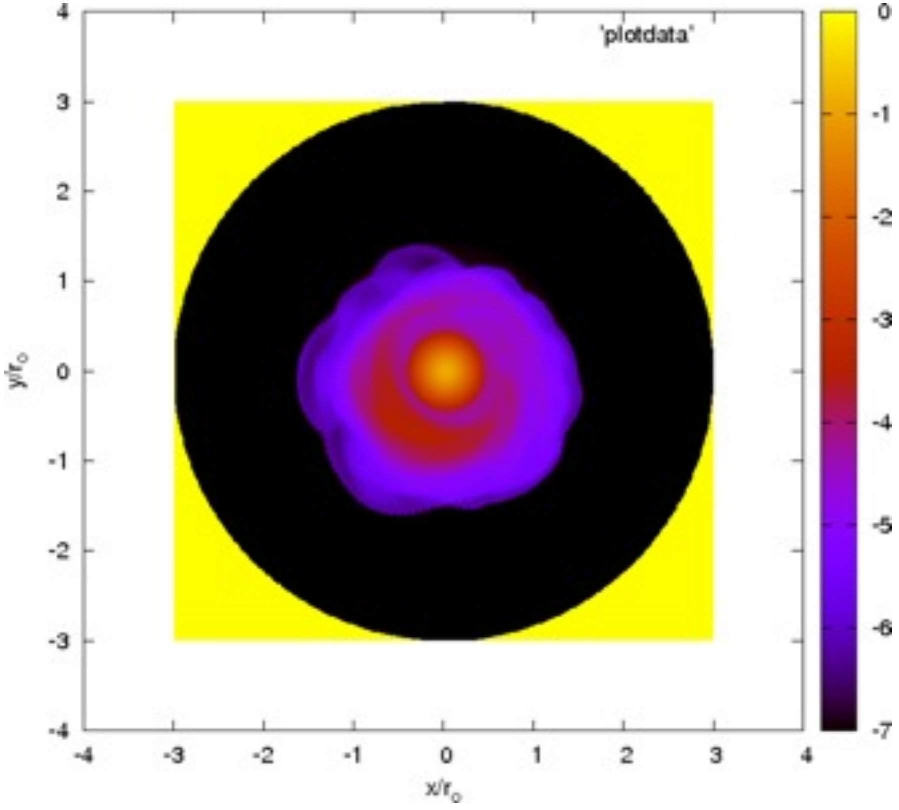
Kepler-413b Binary System



Kepler-413b is a circumbinary planet, 20 % the mass of Jupiter, in the constellation Cygnus orbiting stars Kepler-413 A and Kepler-413 B, K and M dwarfs, respectively. The stars orbit each other with orbital period of 10.1 days. Kepler-413b has an orbit of size 0.35 AU, orbital period of 66.262 d, and a variable orbital inclination of ~2.5 degrees. Kepler has found seven planets in ~1,000 eclipsing binaries searched.

Resolved Star: J Mode and I Mode Simulations without Cooling





Currently, we are extending our program to include *large* stars as a means to make circumbinary planetary systems. No luck yet.

Take-Aways

Nearly 2,000 extra-Solar planets in ~1,200 planetary systems have been discovered with as many as 1 Earth-like planet in the *Habitable Zone* of every 5 Sun-like stars!

Between 1/6-th to 1/3-rd of stars that can have planets appear to have planetary systems.

Contrary to our Solar System, super-Earths and cool Neptunes dominate observed systems.

The understanding of how planets form is making great strides because of the interplay between the unprecedented improvements in observations of protostars and protoplanetary disks, and advances in modeling because of rapid advances in computer techonology.*

*We thank the National Science Foundation, National Aeronautics and Space Administration, the University of Oregon and Kobe University for support during the course of our research.