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. Office Hours, Tu 10-noon, Th noon-2 pm.

Seminar meets weekly on Thursday afternoons in Room 121 McKenzie 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.

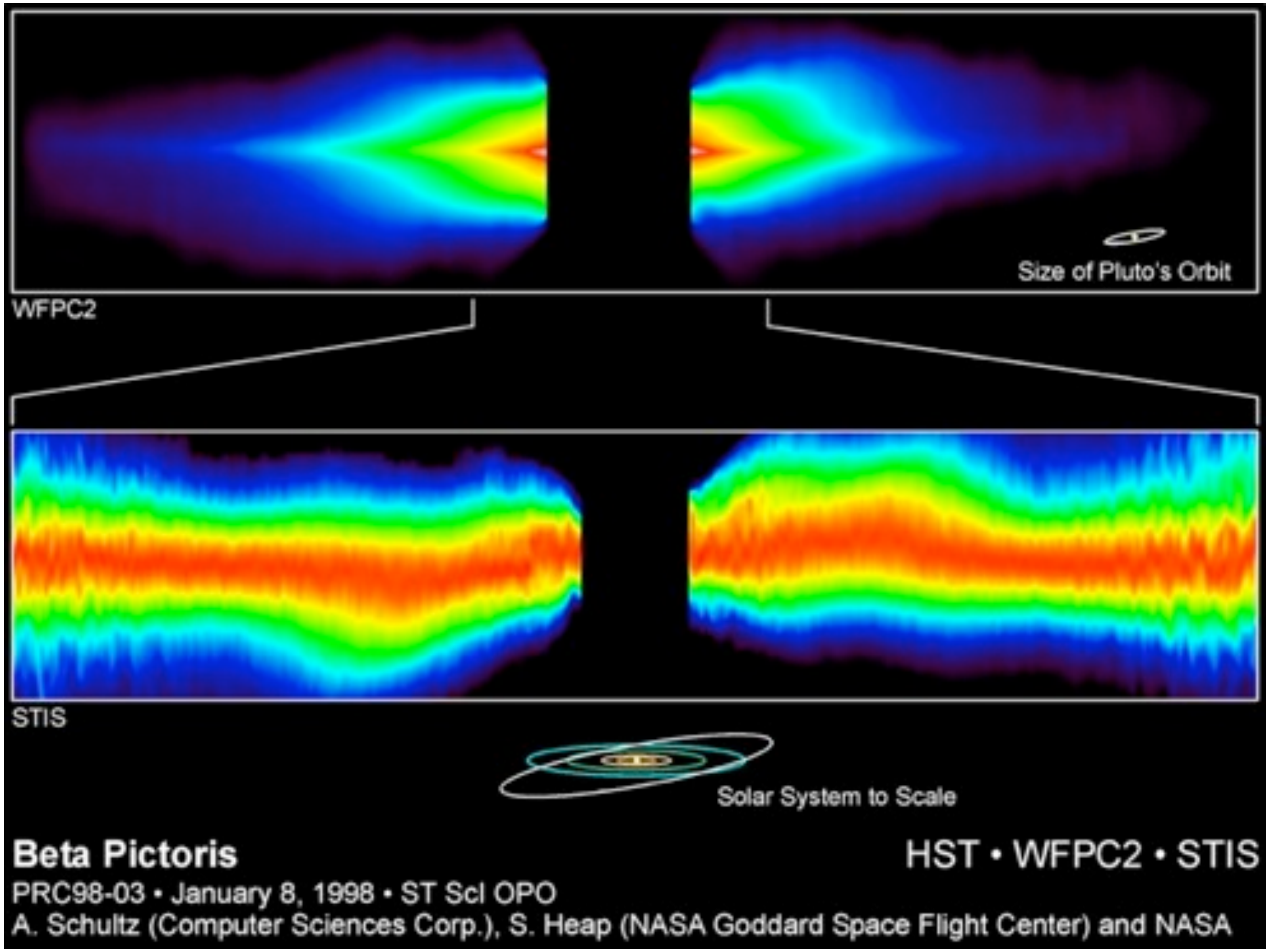
College Scholars Seminar

Speaker Schedule

- April 3, Dr. Jim Imamura, Institute of Theoretical Science
- April 10, Dr. Marina Guenza, Department of Chemistry
- April 17, Dr. Tom Grennbowe, Department of Chemistry
- April 24, Dr. William Harbaugh, Department of Economics
- May 1, Dr. Scott Fisher, Department of Physics
- May 8, Dr. Greg Bothun, Department of Physics (tentative)
- May 15, Dr. Alan Rempel, Department of Geology
- May 22, Dr. Jim Isenberg, Department of Mathematics
- May 29, Dr. Josh Snodgrass, Department of Anthropology
- June 5, Dr. Ben McMorran, Department of Physics

Planet Formation in Massive Disks

James N. Imamura
Department of Physics
University of Oregon



Beta Pictoris

PRC98-03 • January 8, 1998 • ST ScI OPO

A. Schultz (Computer Sciences Corp.), S. Heap (NASA Goddard Space Flight Center) and NASA

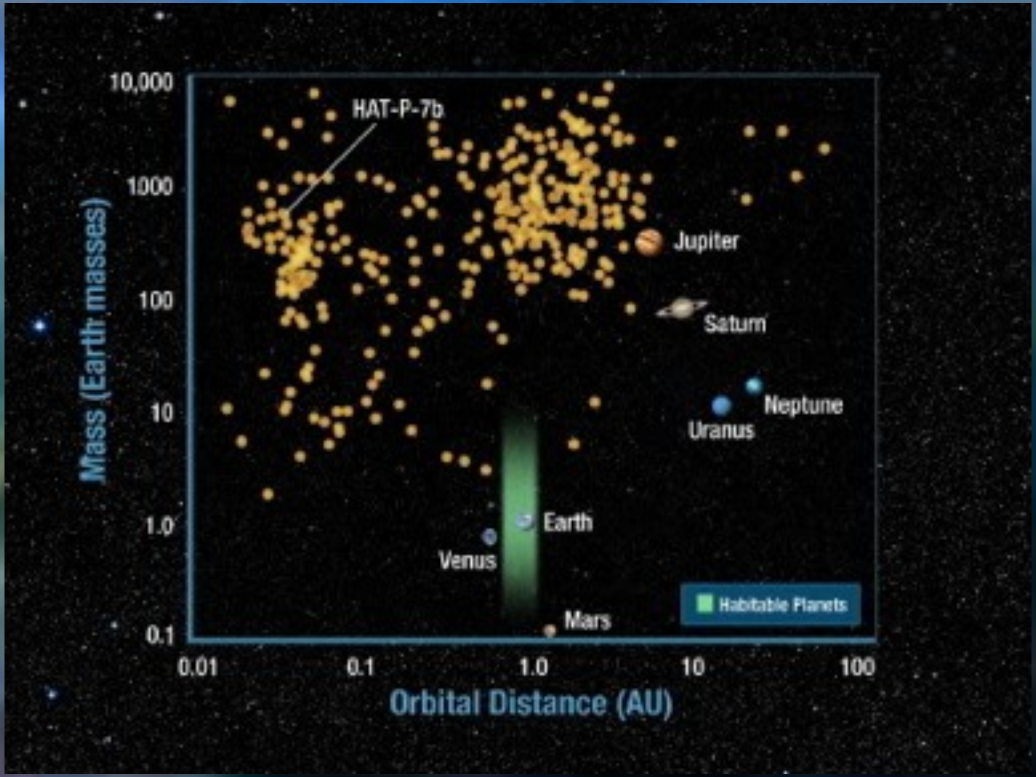
Physical Problem: Star and Disk formation

- Clouds with high specific angular momenta ~ 10^{21} cm^2/s , spin up and flatten as they collapse
- Material near the spin axis has little angular momentum and so falls inward, forming a central object with a few percent of the mass of the cloud. The rest of the cloud settles into a massive circumstellar disk (e.g., Kratter *et al*. 2011).
- Viscous interactions cause the disk matter to flow inward and accrete onto the star while planets form from the dust and gas through the core-accretion model or gravitational intabilities.

http://www.spitzer.caltech.edu/images

Planet Hunters: Marcy, Mayor et al.

In the mid-1990s, Mayor et al. and Marcy et al. started the planetary discovery outburst (using spectroscopic techniques).



Today, over 700 extra-Solar planets have been discovered. Because discoveries have only been made for 15 years, most planets are Jupiter-like.

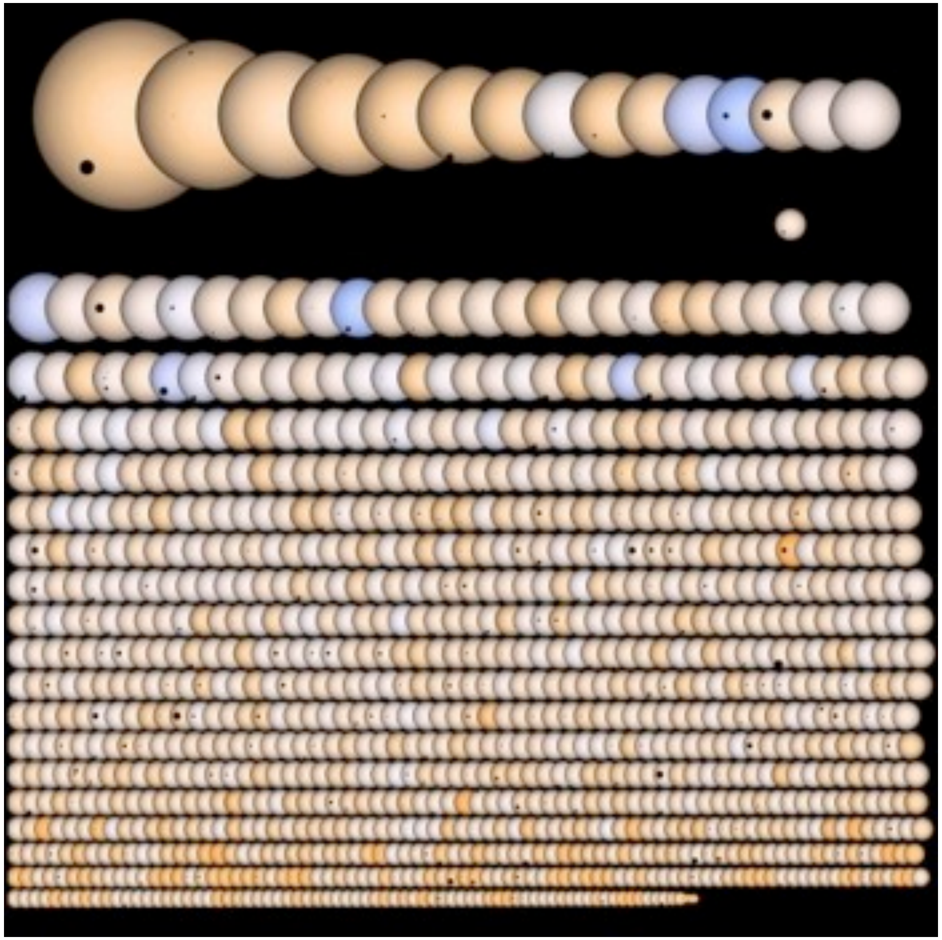
Planet Hunter: Kepler

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.

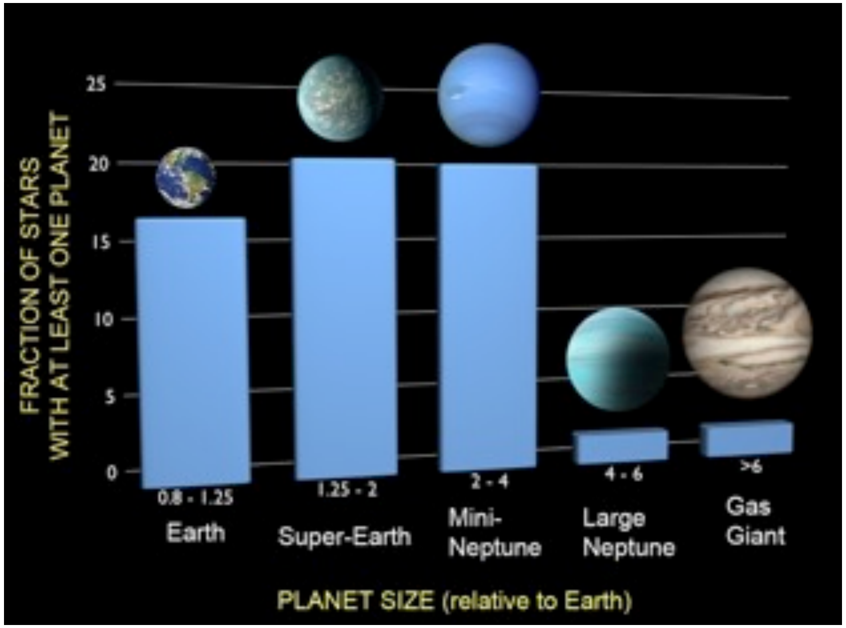
Kepler's Mission

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

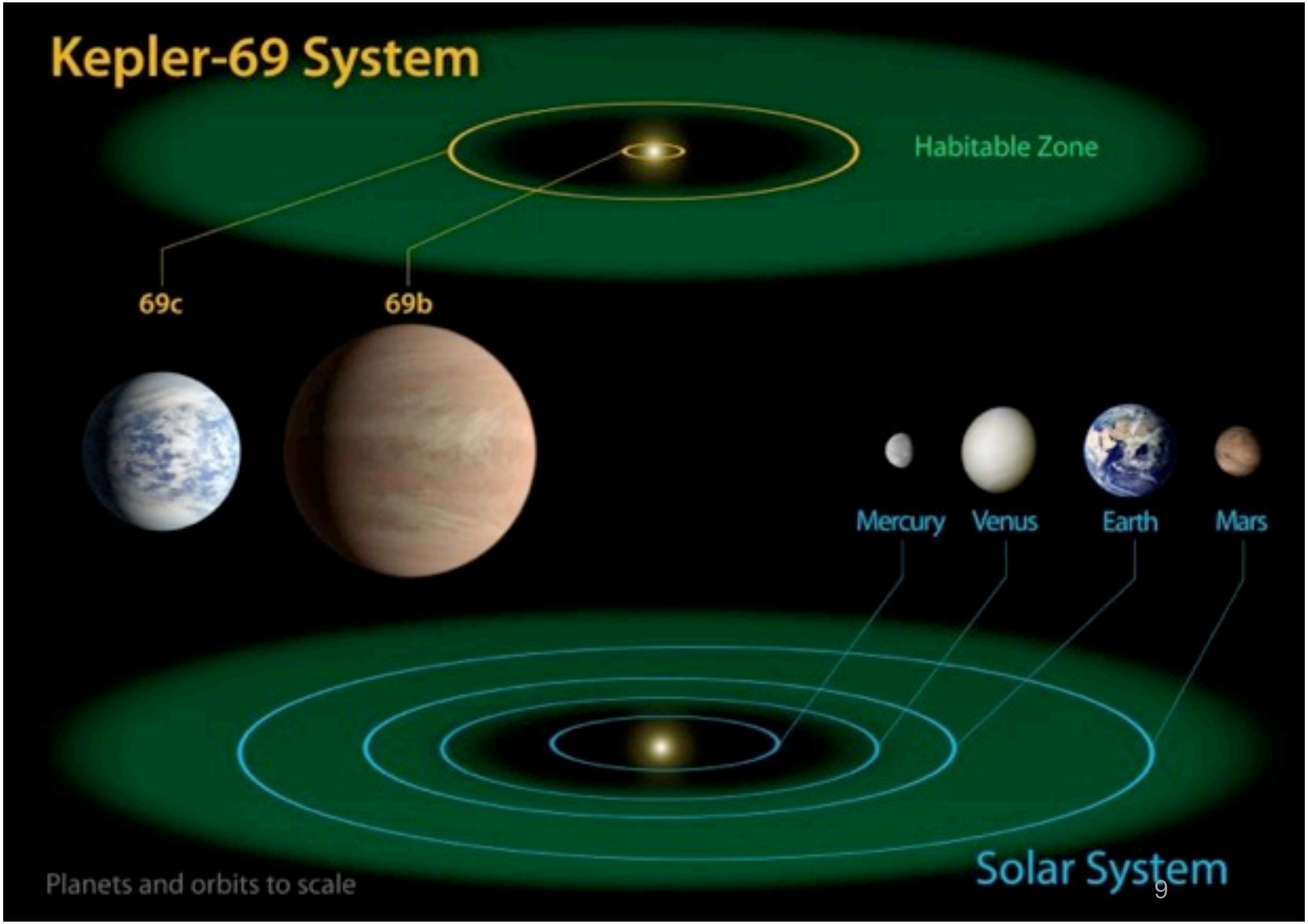
Kepler Satellite



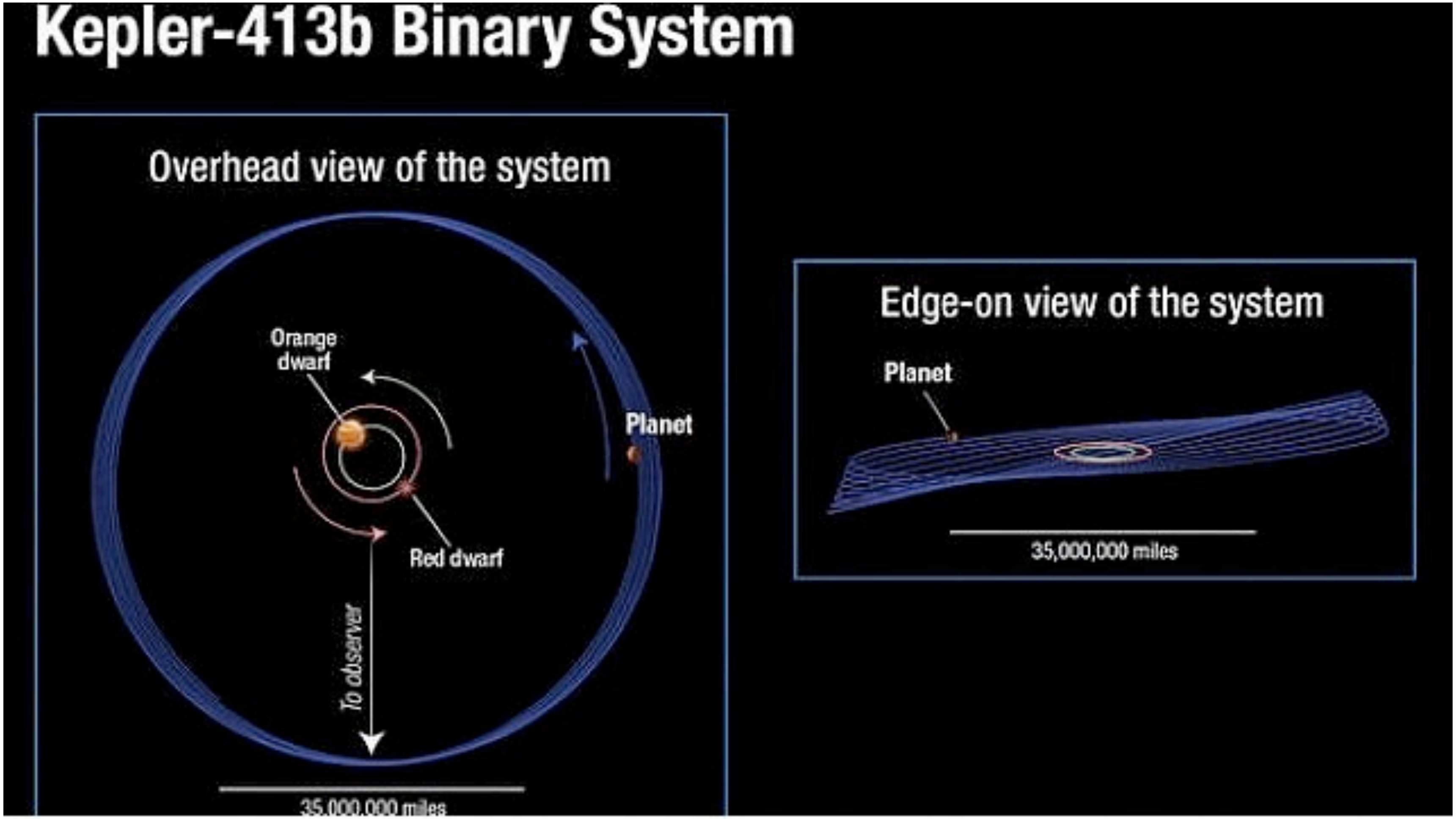
Kepler has discovered > 700 extra-Solar planets with as many as 1 in five stars having a planet roughly the size of Earth at the right distance from their parent star to support liquid water, that is, *Earth-like planets in the Habitable Zone*.



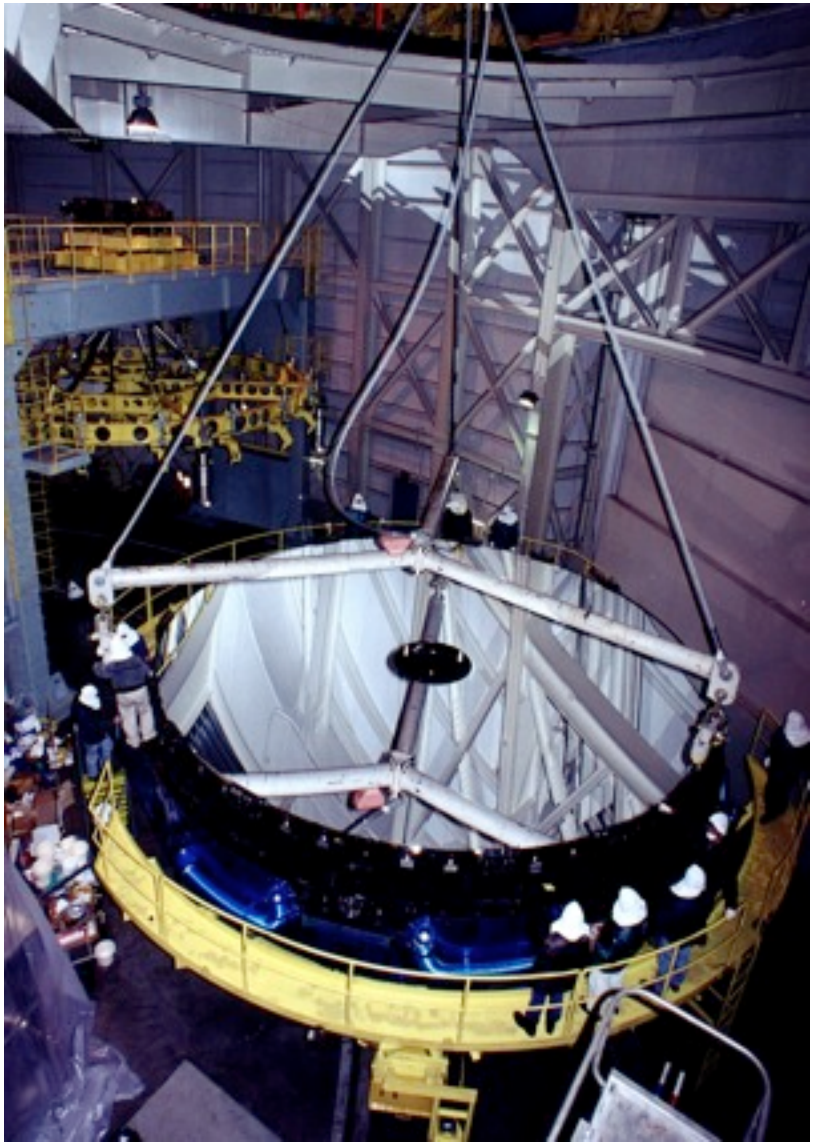
Traditional work suggests that 17–30% of solar-like star have planetary systems. Recent gravitational microlensing studies which probe planets in large orbit. A set of such planets are at least as numerous as the stars in the Milky Way. “Astatistical analysis of microlensing data (gathered in 2002–07) that reveals the fraction of bound planets 0.5–10 au (Sun–Earth distance) from their stars. We find that of stars host Jupiter-mass planets (0.3–10 M_J, where $M_J = 318\,M$ and M is Earth’s mass). Cool Neptunes (10–30 M) and super-Earths (5–10 M) are even more common: their respective abundances per star are and . We conclude that stars are orbited by planets as a rule, rather than the exception,” Cassan et al. 2012, Nature, 481, 167

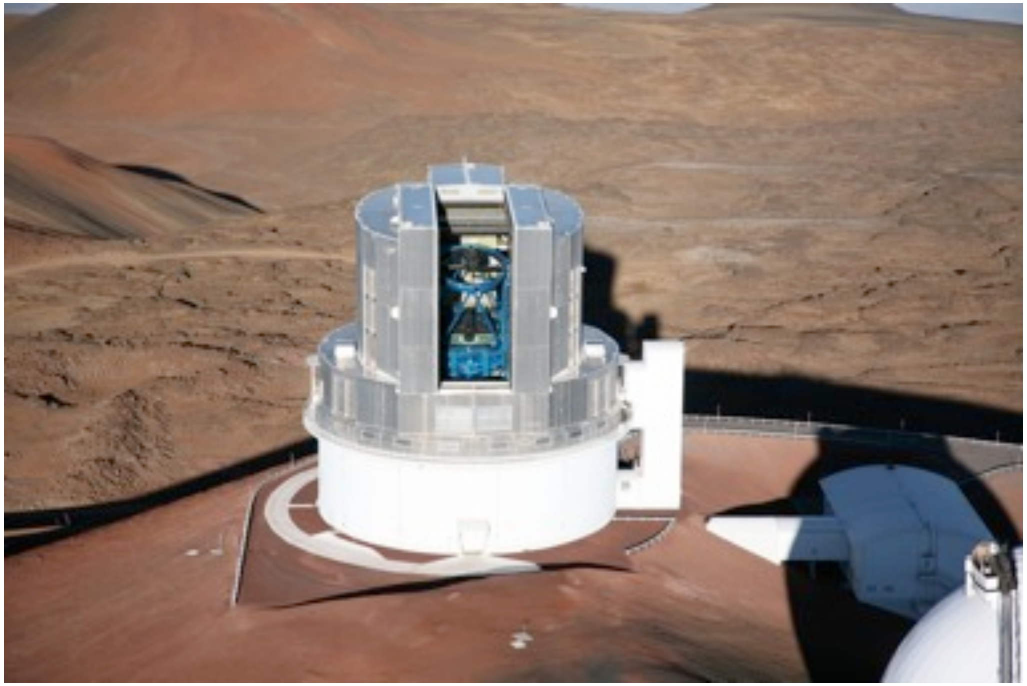

Kepler-69 System
Habitable Zone
69c
69b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

Tatooine

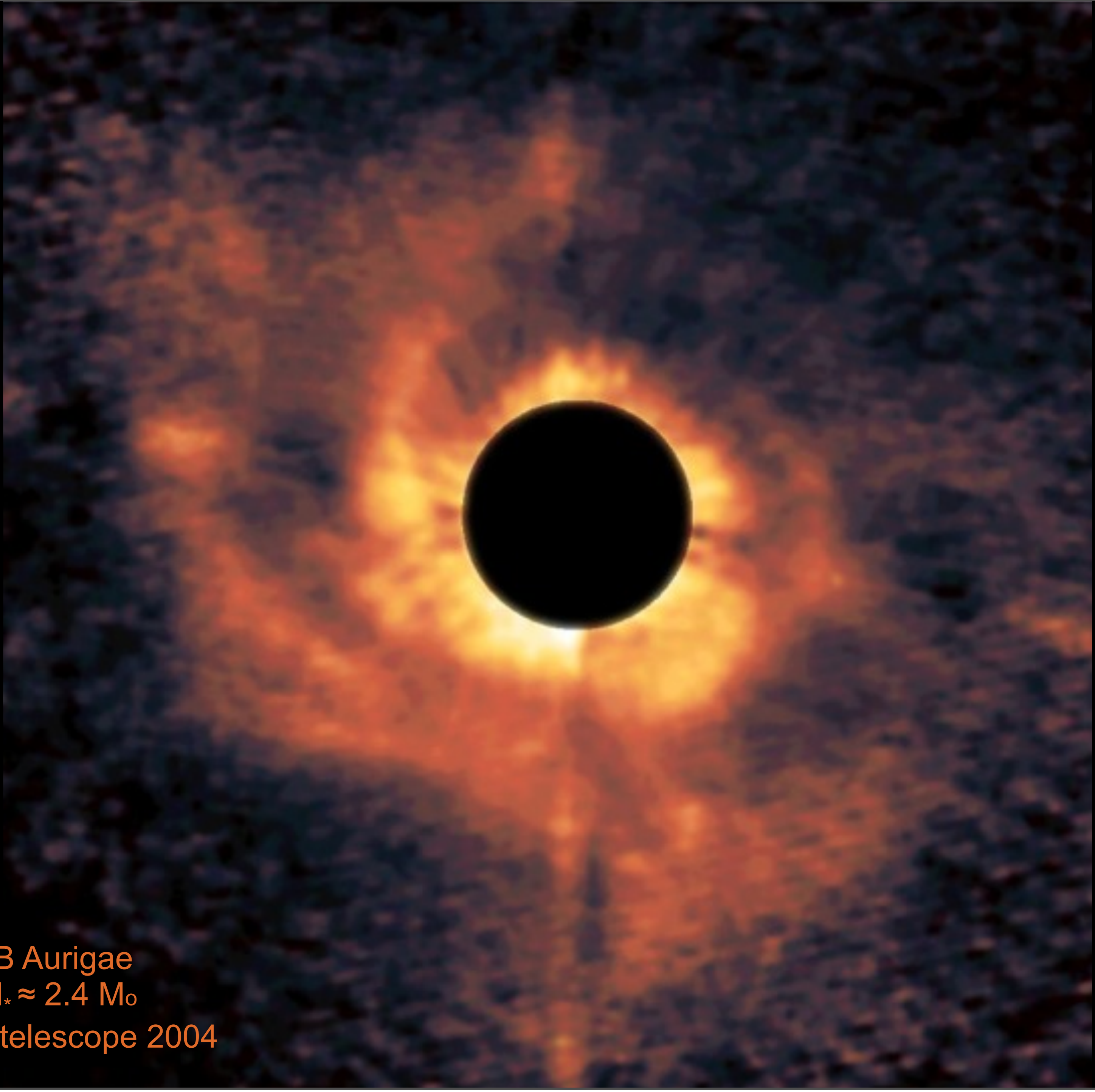

Kepler-413b Binary System
Overhead view of the system
Orange dwarf
Planet
Red dwarf
To observer
35,000,000 miles
Edge-on view of the system
Planet
35,000,000 miles

Protoplanetary and Protostellar Disks





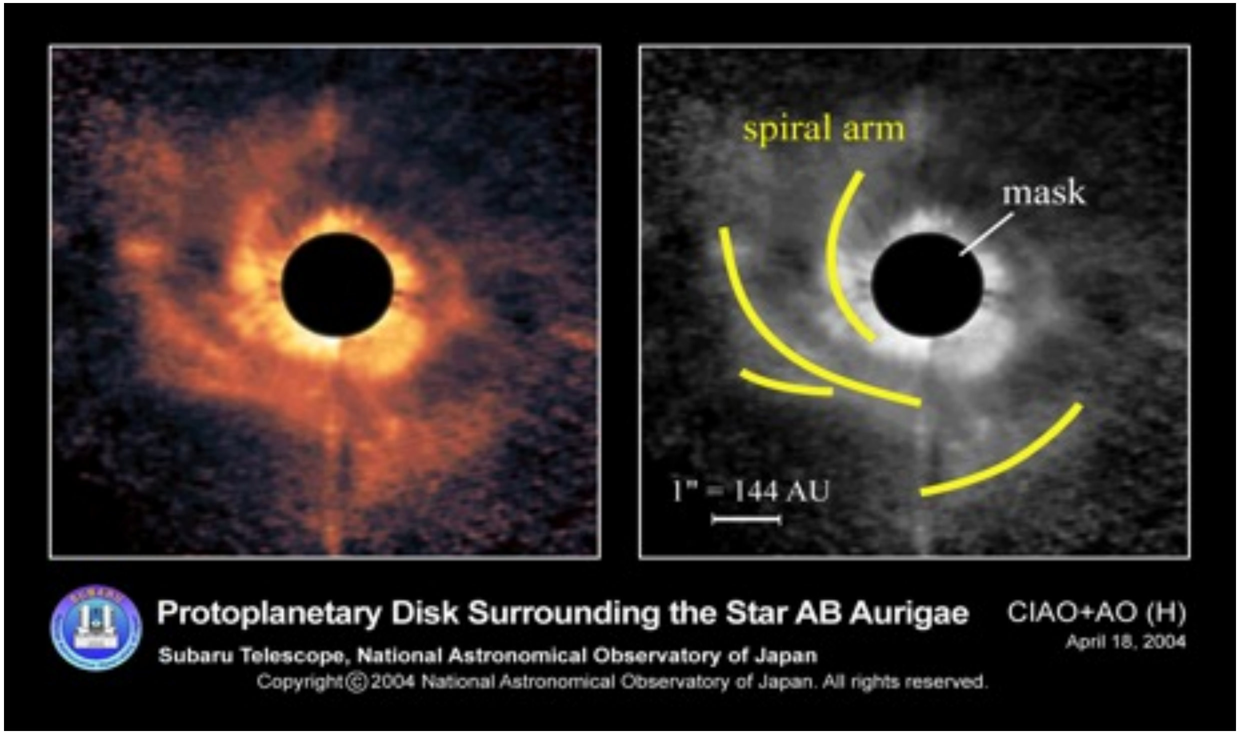
Subaru Telescope, NAOJ

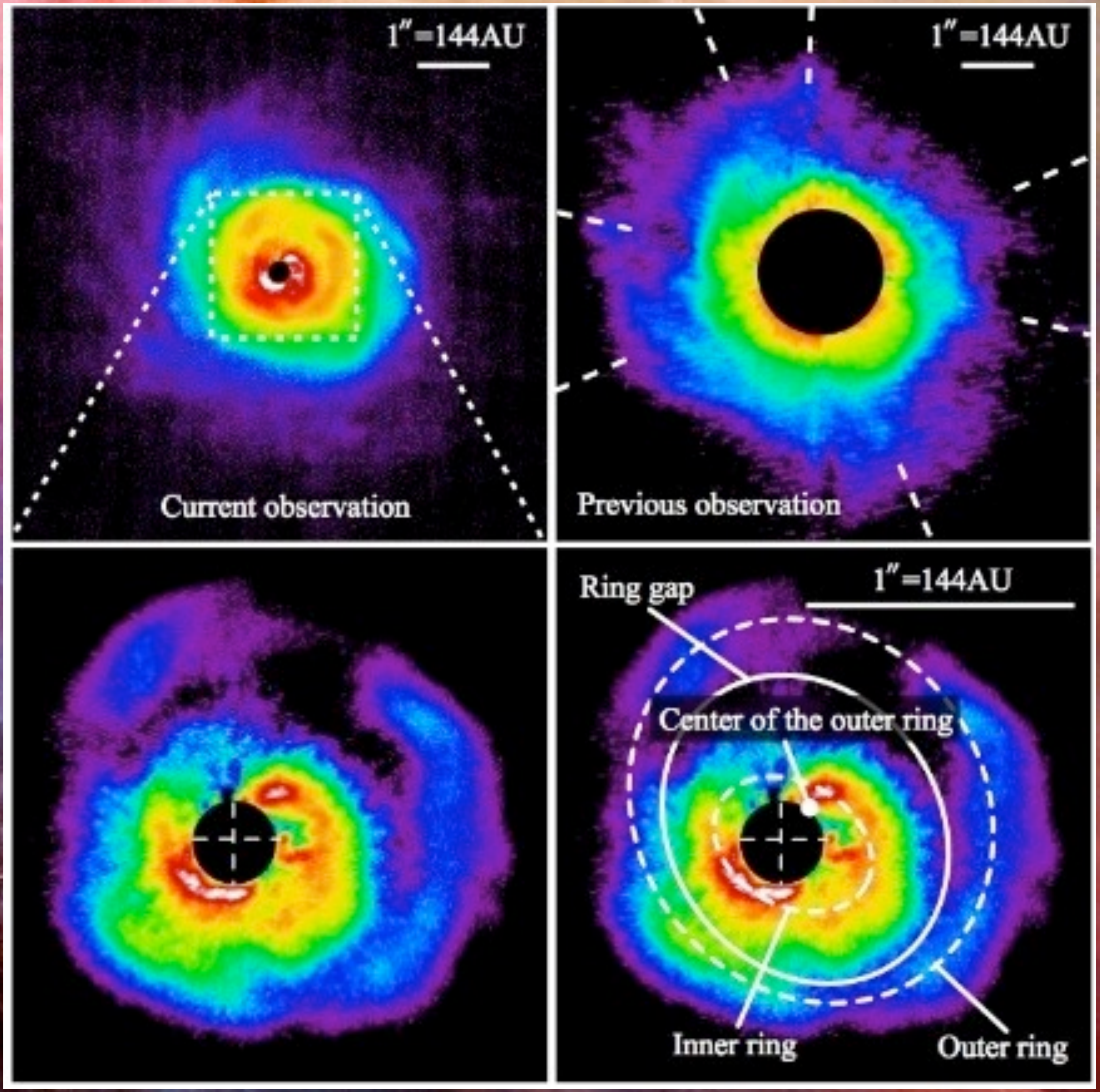


AB Aurigae
$M_* \approx 2.4\ M_\odot$
Subaru telescope 2004

AB Aurigae (AB Aur)

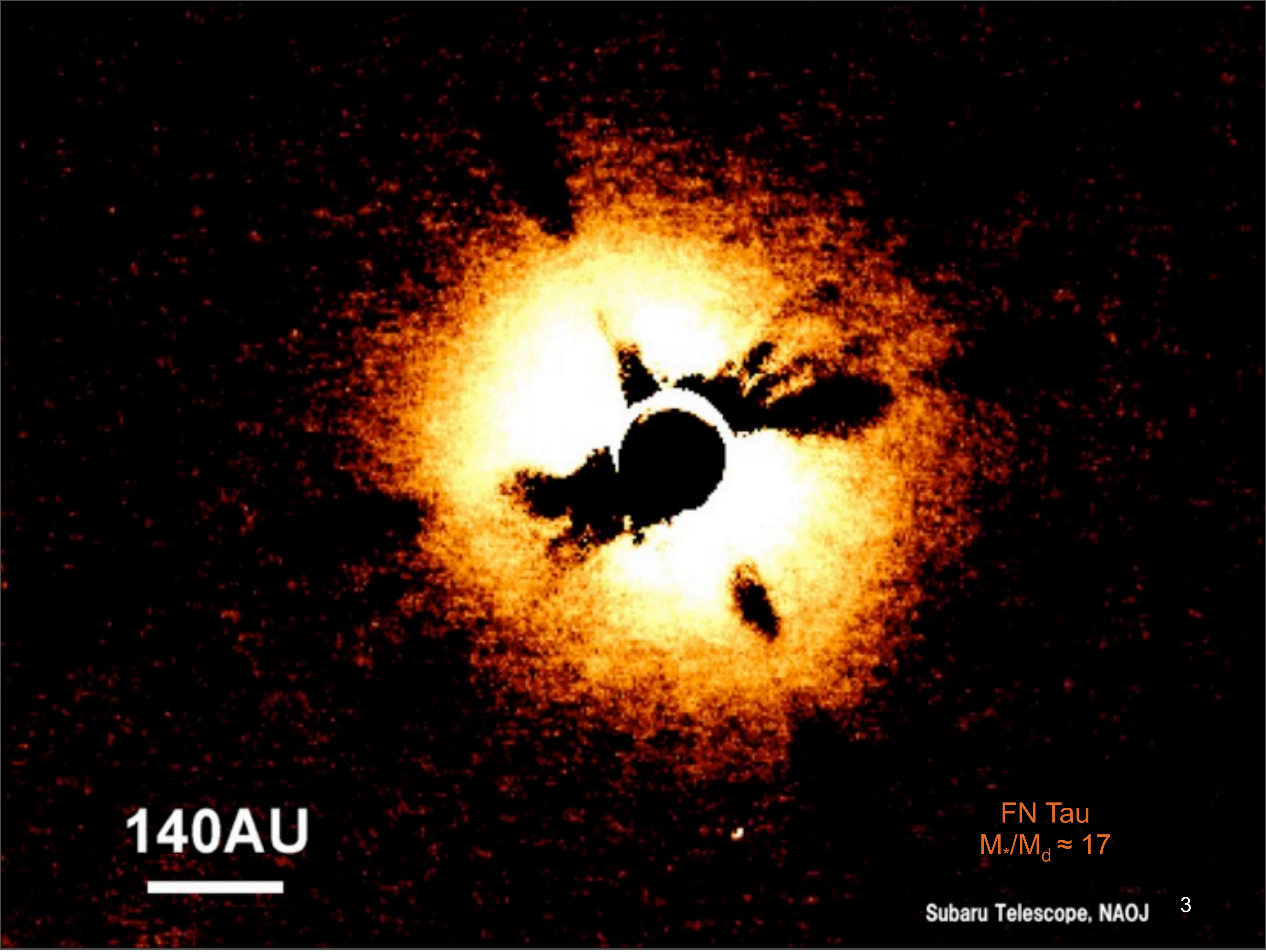
AB Aur contains a 4 My old A0 star, $M = 2.4$ Solar masses star surrounded by a disk of mass ~ 0.01 to 0.1 Solar masses -→ star to disk mass ratio 24 -240. Conservatively, based on the inner ring and outer arm structure found by Subaru, $r-/r+ < 0.2-0.3$. The disk in AB Aur is close to non-self-gravitating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



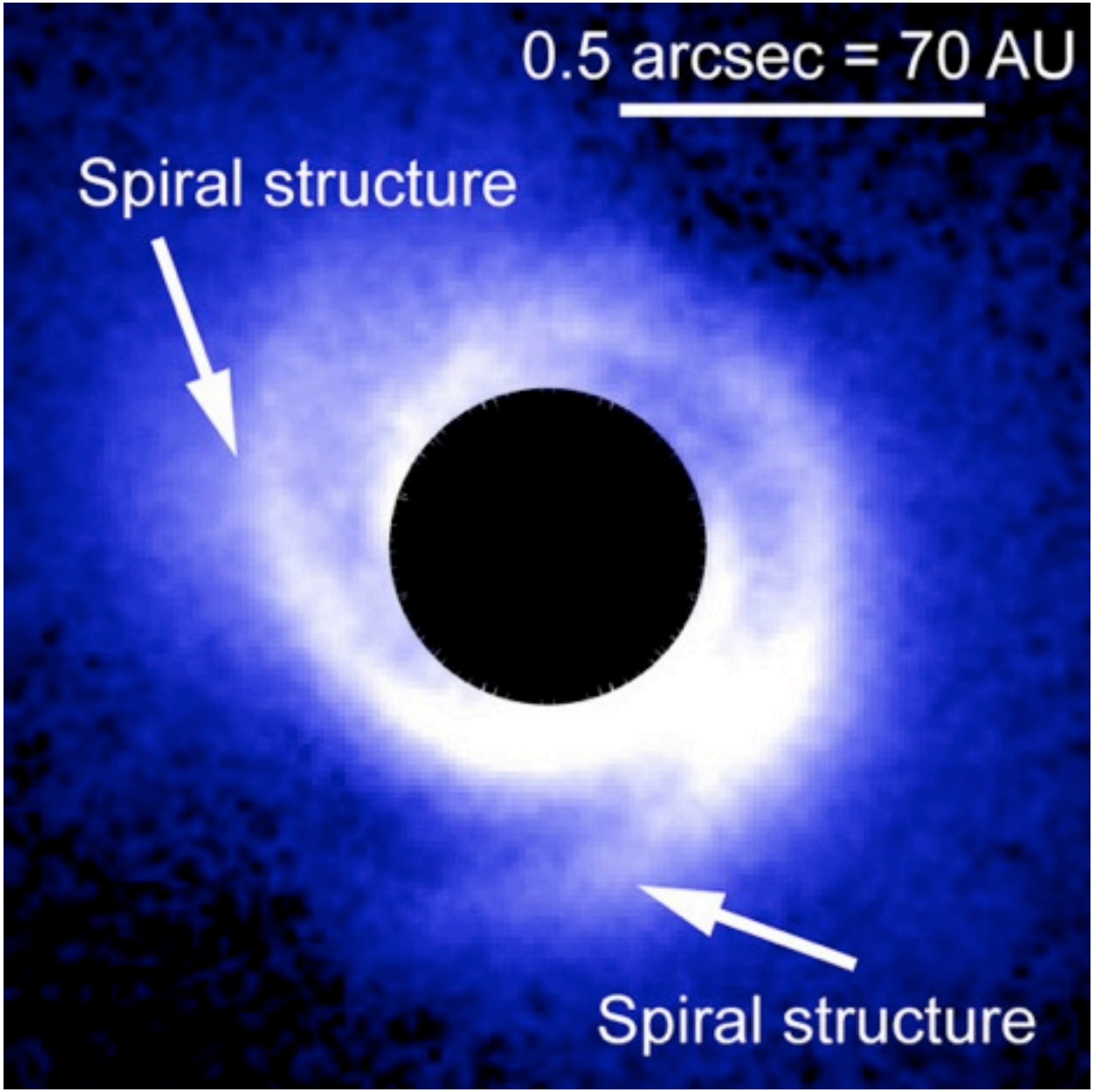


AB Aurigae

Subaru observations of AB Aurigae revealed an outer spiral arm structure and what was interpreted as a set of smaller radii 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.



FN Tau
$M_*/M_d \approx 17$



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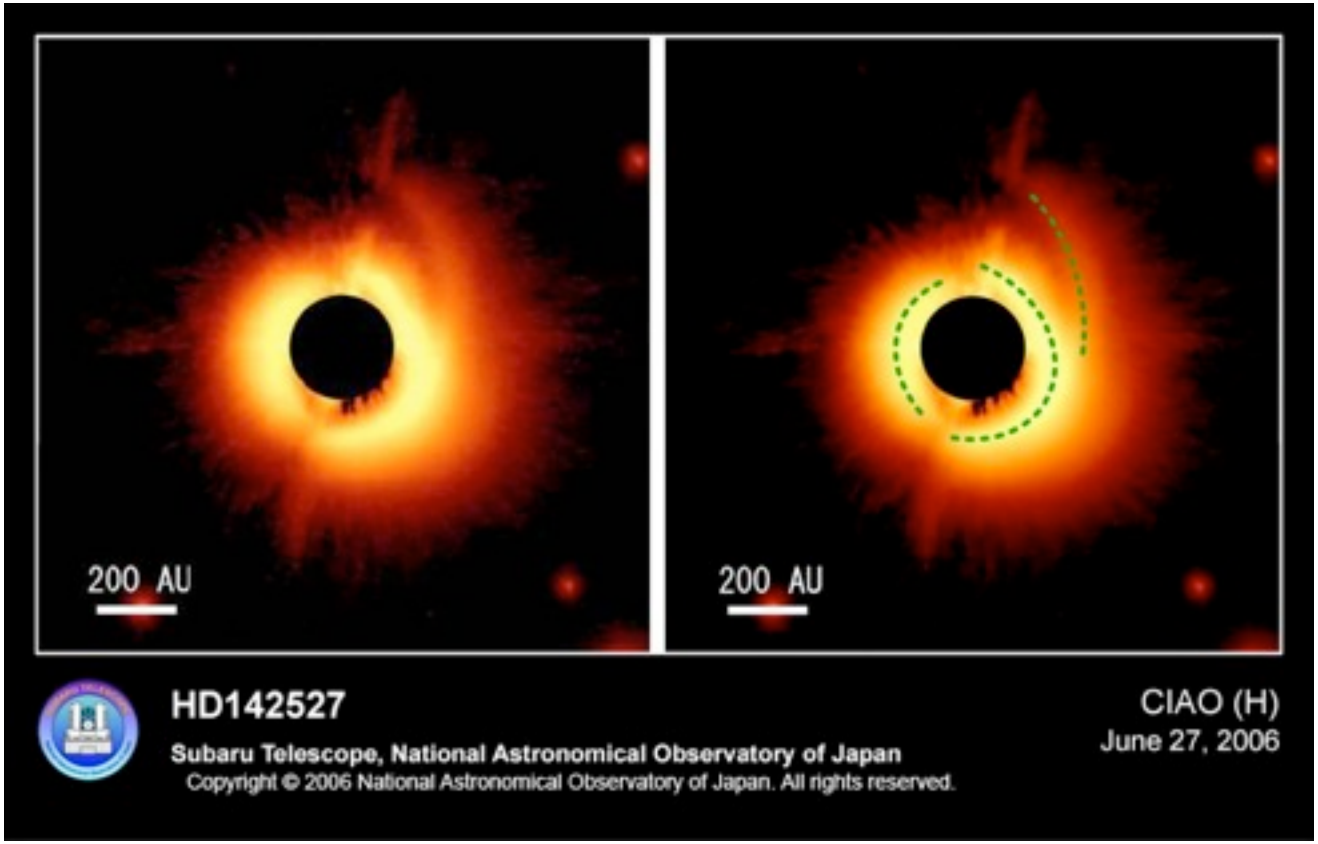
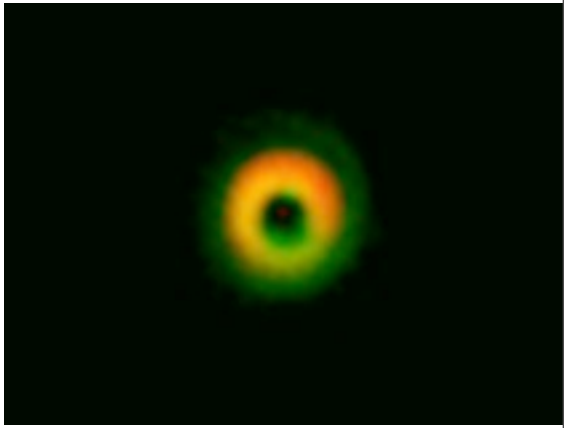
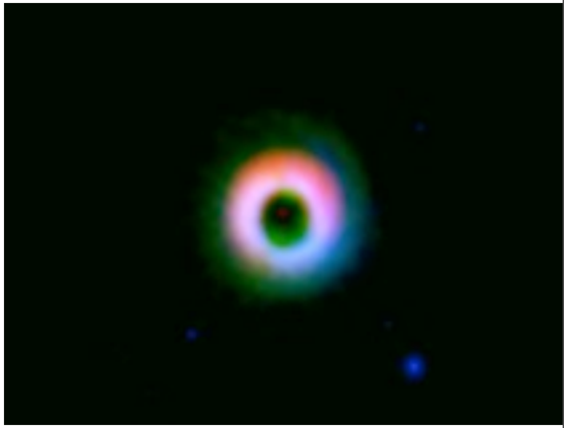


Subaru CIAO observations of disk in HD 142527



ALMA observations of HD 142527



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

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

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

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

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

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

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

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

Planet formation:

Earth-like Planets: 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.

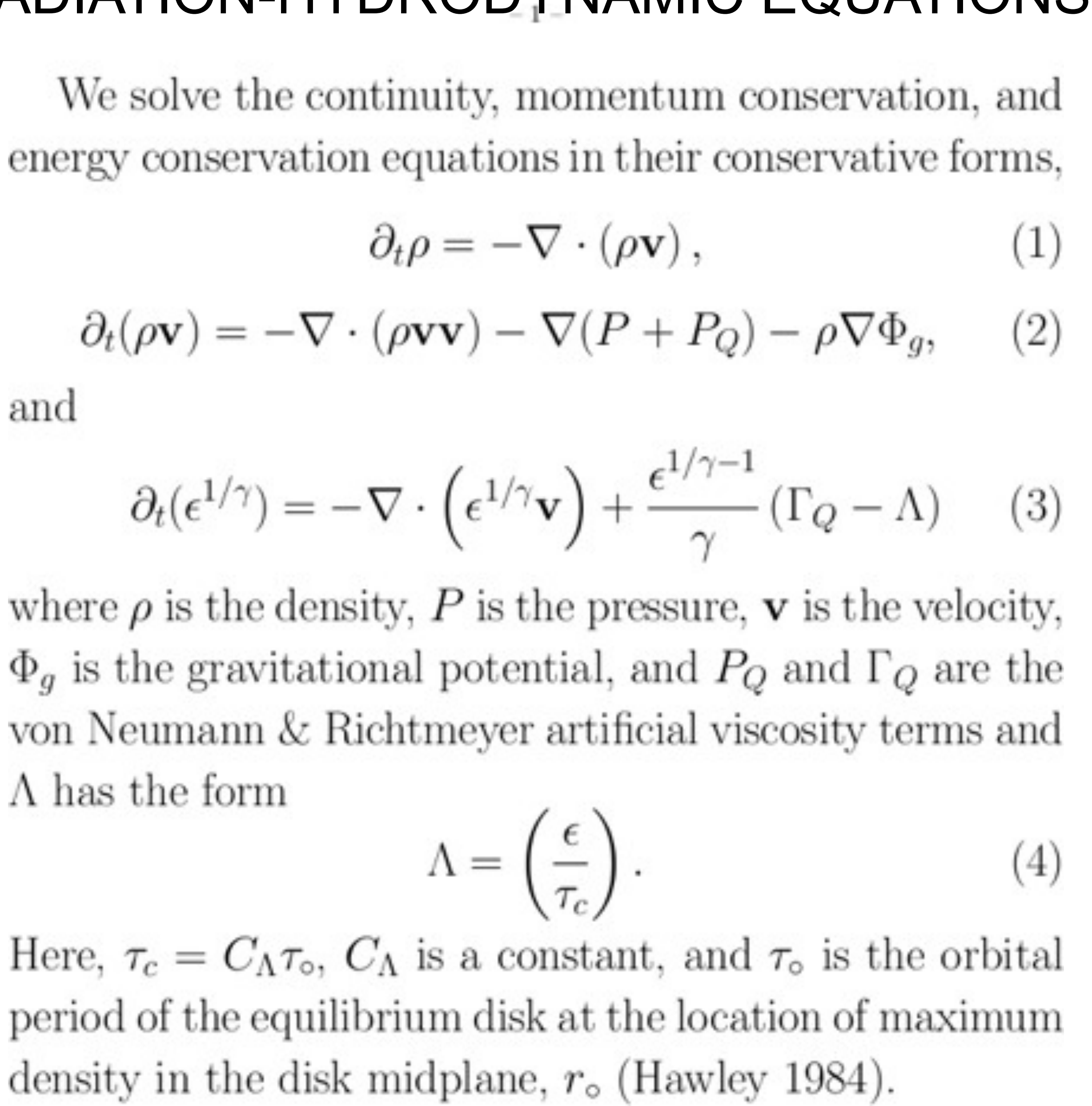
Jupiter-like Planets: the cores of Juper-like planets form as in the Earth-like planet scenario, but after the protoplanet stage they become massive enough to gravitationally capture gas from the protoplanetary nebula, the **core-accretion scenario**. A crucial point in this model is the location of the *snowline*. This is commonly accepted model for the formation of the Jupiter-like planets.

Issues

- Planetary migration ===> protoplanetary cores migrate out of the planet forming region on timescales of millions of years, close to the time needed to form Jupiter–like planets, <10 My
- Jupiter–like planets are found >50–100 A.U. from their stars ===> such regions have densities too low to lead to planet formation

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

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).

Nonaxisymmetric Instabilities in Disks

- Previous studies (plus many other unmentioned ones)
  - Papaloizou & Pringle (1984, 1987)
    - Slender annuli and rings
  - Goldreich, Goodman & Narayan (1986)
    - Slender, incompressible tori
    - Thin ribbon approximation
  - Kojima (1986, 1989)
    - Non-self-gravitating disks
  - Adams, Ruden & Shu (1989), Heemskerk *et al.* (1992), Noh, Vishniac & Cochran (1992), Taga & Iye (1998)
    - m=1 mode, central star motion, thin disks
  - Andalib, Tohline & Christodoulou (1998)
    - Slender incompressible tori (ICTs)
  - Hachisu & Tohline (1992), Woodward, Tohline & Hachisu (1994)
    - Nonlinear study of self-gravitating disks
  - Shariff (2009)
    - Review of current work, observation
    - Magnetic effects, radiation transport

Imamura group: Hadley & Imamura 2011, Hadley et al. 2012,2014a,b, Tumblin et al. 2012, Dumas et al. 2014

Linear Evolution Equations (Initial Value Problem)

$$\partial_t \delta\rho = -im\Omega\delta\rho - \frac{1}{\varpi}\rho_0\delta v_\varpi - \delta v_\varpi \partial_\varpi \rho_0 - \delta v_z \partial_z \rho_0$$
$$- \rho_0\left(\partial_\varpi \delta v_\varpi + \frac{im}{\varpi}\delta v_\phi + \partial_z \delta v_z\right)$$

$$\partial_t \delta v_\varpi = -im\Omega\delta v_\varpi + 2\Omega\delta v_\phi - \gamma\frac{P_0}{\rho_0^2}\partial_\varpi \delta\rho$$
$$-(\gamma - 2)\frac{\delta\rho}{\rho_0^2}\partial_\varpi P_0 - \partial_\varpi \delta\Phi$$

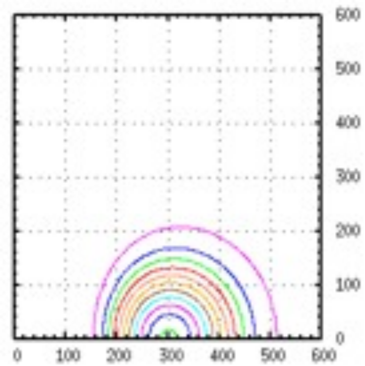
$$\partial_t \delta v_\phi = -im\Omega\delta v_\phi - \frac{1}{\varpi}\partial_\varpi\left(\Omega\varpi^2\right)\delta v_\varpi - \frac{im}{\varpi}\frac{P_0}{\rho_0^2}\delta\rho - \frac{im}{\varpi}\delta\Phi$$

$$\partial_t \delta v_z = -im\Omega\delta v_z - \gamma\frac{P_0}{\rho_0^2}\partial_z\delta\rho - (\gamma - 2)\frac{\delta\rho}{\rho_0^2}\partial_z P_0 - \partial_z\delta\Phi$$

Mode types

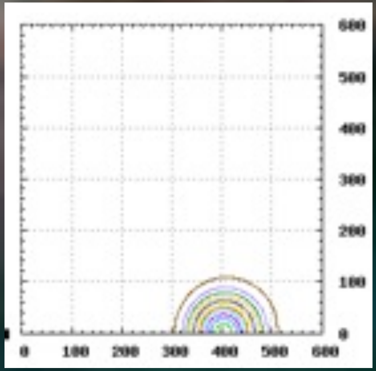
Equilibrium mass density contours

I^+



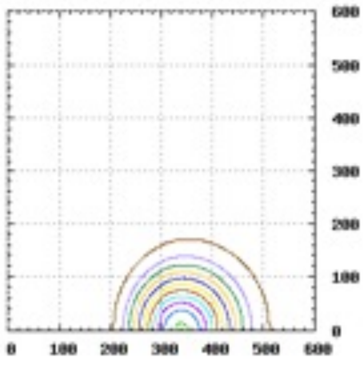
$q = 1.5$, $r_-/r_+ = 0.30$ $M_*/M_d = 0.0$

I^-



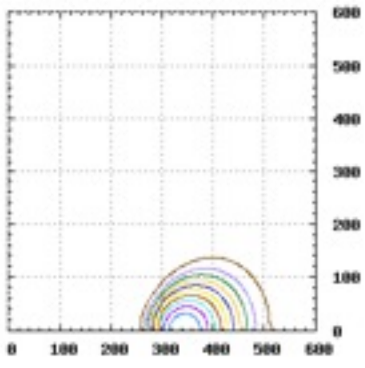
$q = 1.5$, $r_-/r_+ = 0.60$ $M_*/M_d = 0.1$

J



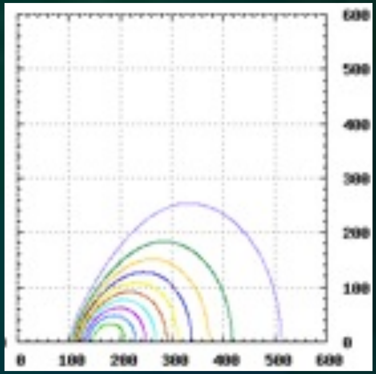
$q = 1.5$, $r_-/r_+ = 0.40$ $M_*/M_d = 0.0$

P



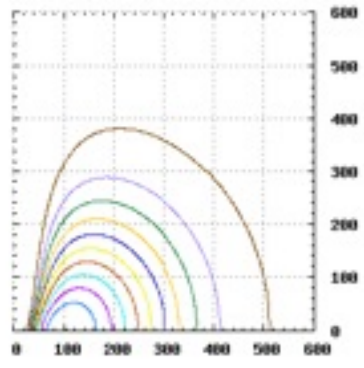
$q = 2.0$, $r_-/r_+ = 0.50$ $M_*/M_d = 100.0$

Edge



$q = 2.0$, $r_-/r_+ = 0.20$ $M_*/M_d = 100.0$

A

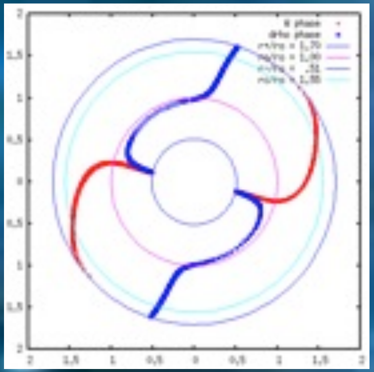


$q = 1.75$, $r_-/r_+ = 0.05$ $M_*/M_d = 0.1$

Mode types

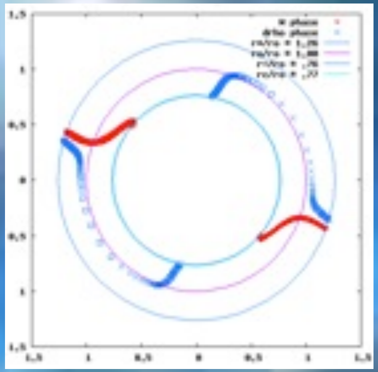
Eigenfunction phases

I^+



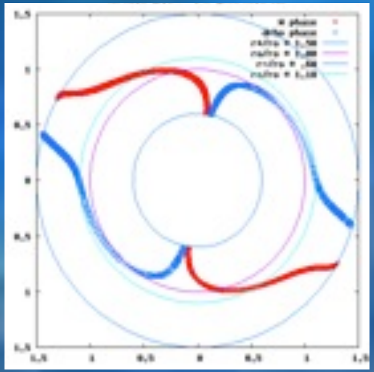
$q = 1.5$, $r_-/r_+ = 0.30$ $M_*/M_d = 0.0$

I^-



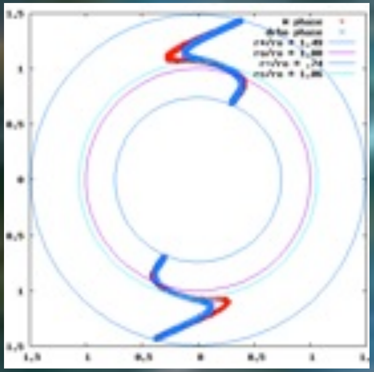
$q = 1.5$, $r_-/r_+ = 0.60$ $M_*/M_d = 0.1$

J



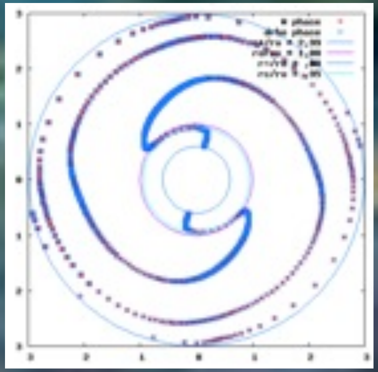
$q = 1.5$, $r_-/r_+ = 0.40$ $M_*/M_d = 0.0$

P



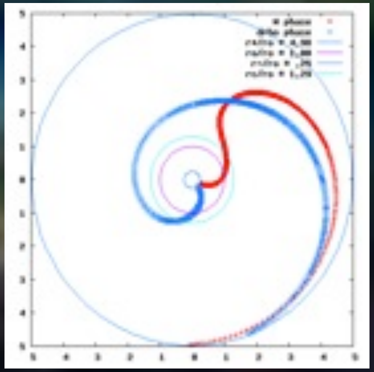
$q = 2.0$, $r_-/r_+ = 0.50$ $M_*/M_d = 100.0$

Edge



$q = 2.0$, $r_-/r_+ = 0.20$ $M_*/M_d = 100.0$

A



$q = 1.75$, $r_-/r_+ = 0.05$ $M_*/M_d = 0.1$

Hill Sphere

The difficulty faced when forming planets from gravitational instabilities is the tidal force arising from the protostar.

Tidal Force:

$$a_t \sim 2\delta r\ GM_c/r^3$$

where δr is the distance from the center of the clump, r is the clump distance from the star, G is the gravitational constant, and M_c is the mass of the protostar.

The clump is held together by:

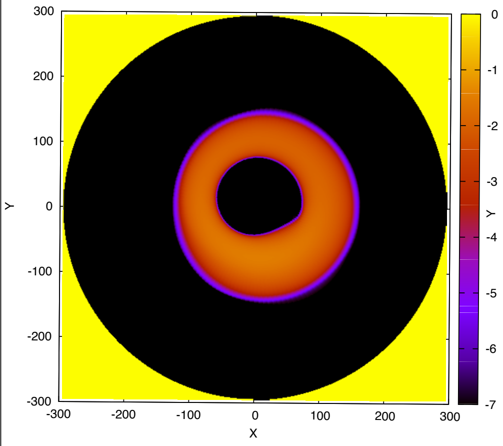
$$a_c \sim -Gm_c/\delta r^2$$

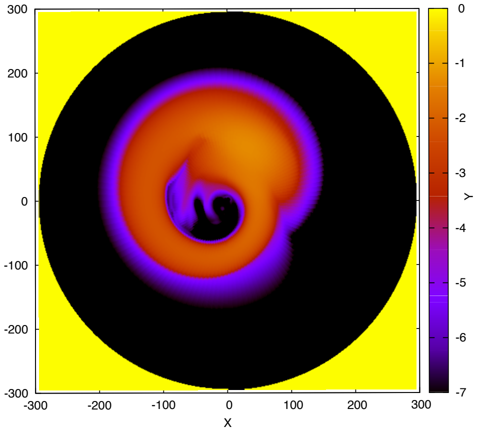
where m_c is the mass of the clump.

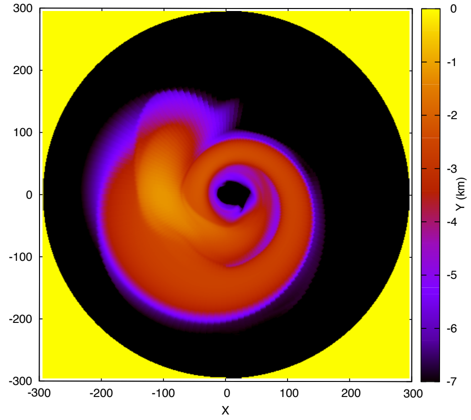
The clump collapses if $a_c + a_t < 0$ or if

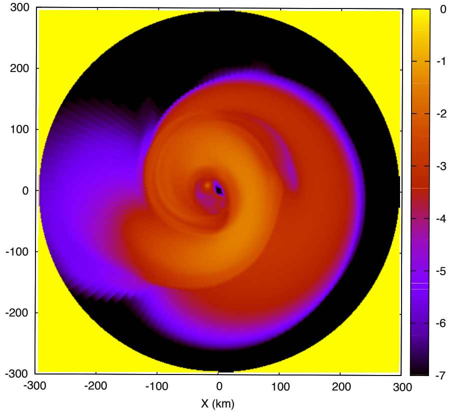
$$\delta r^3 < 0.5\ (m_c/M_c)\ r^3$$

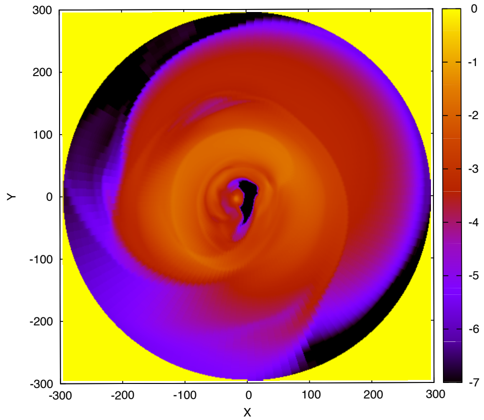
I Mode Simulation with Weak Cooling



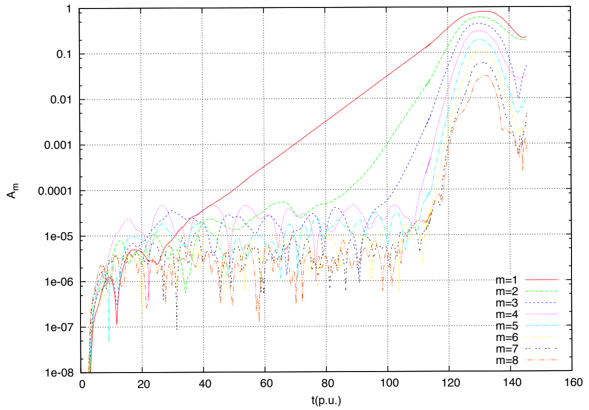


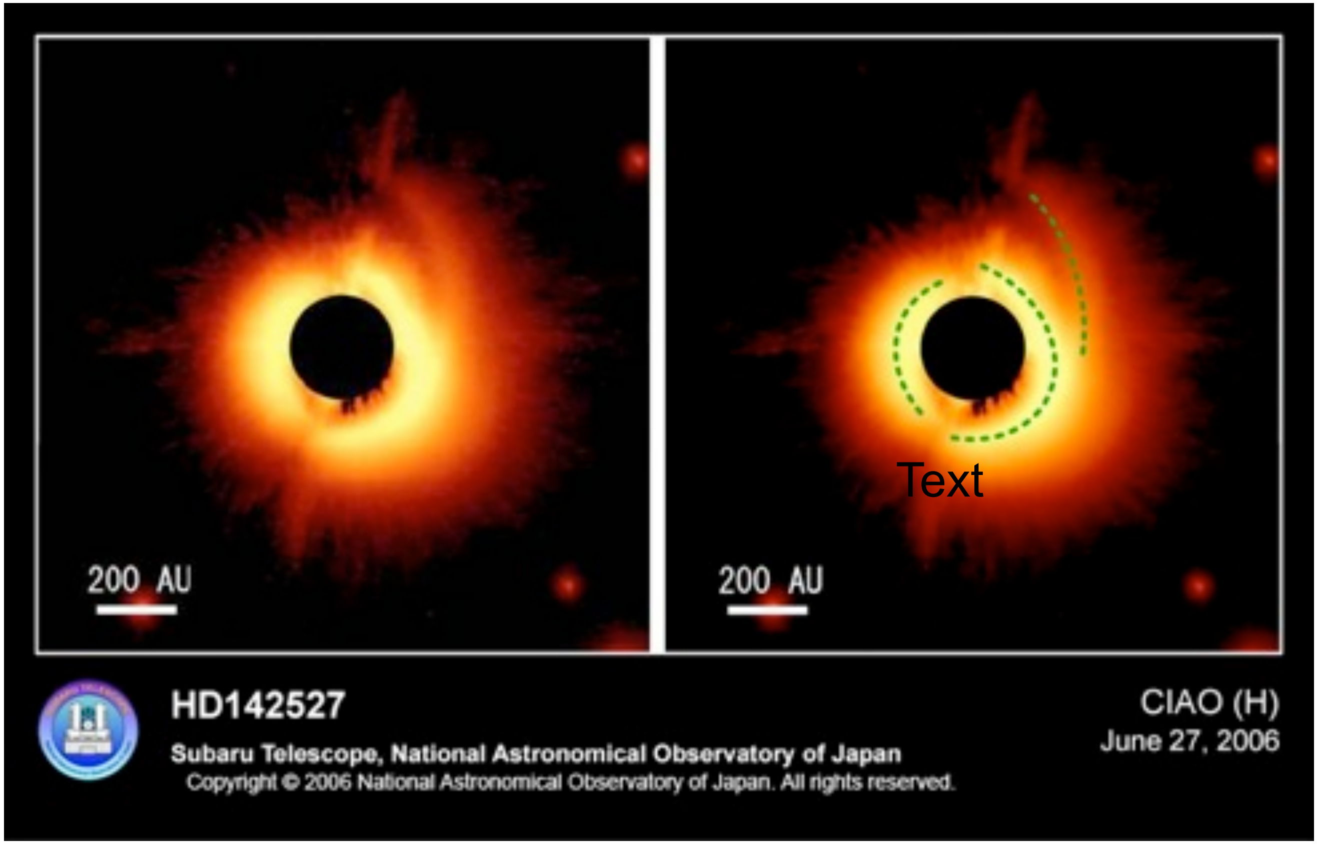




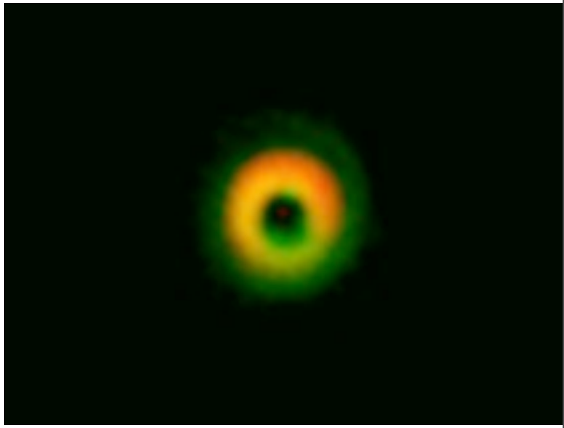


The system is dominated by an m = 1 I mode. A smooth trailing arm develops; it does not lead to fragmentation. The structures are shown at times t = 6.8, 7.2, 7.6, 8, and 8.4 t_o, where t_o = 17.18.

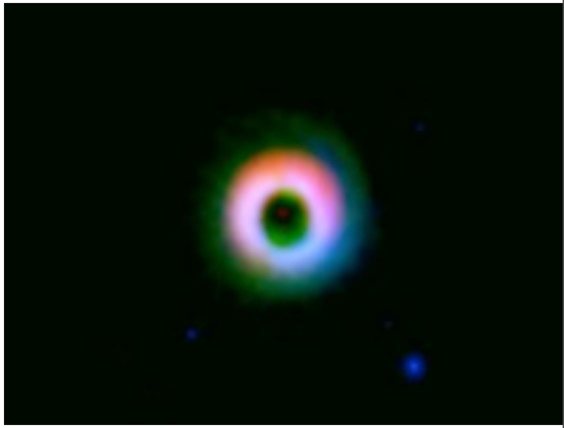




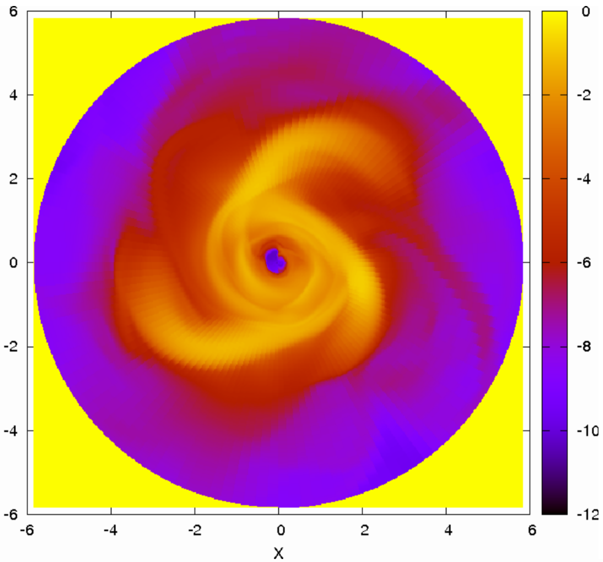
Subaru CIAO observations of disk in HD 142527



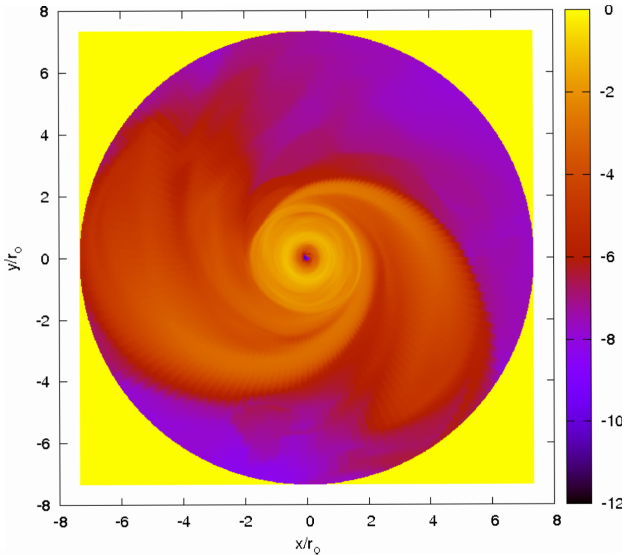
ALMA observations of HD 142527

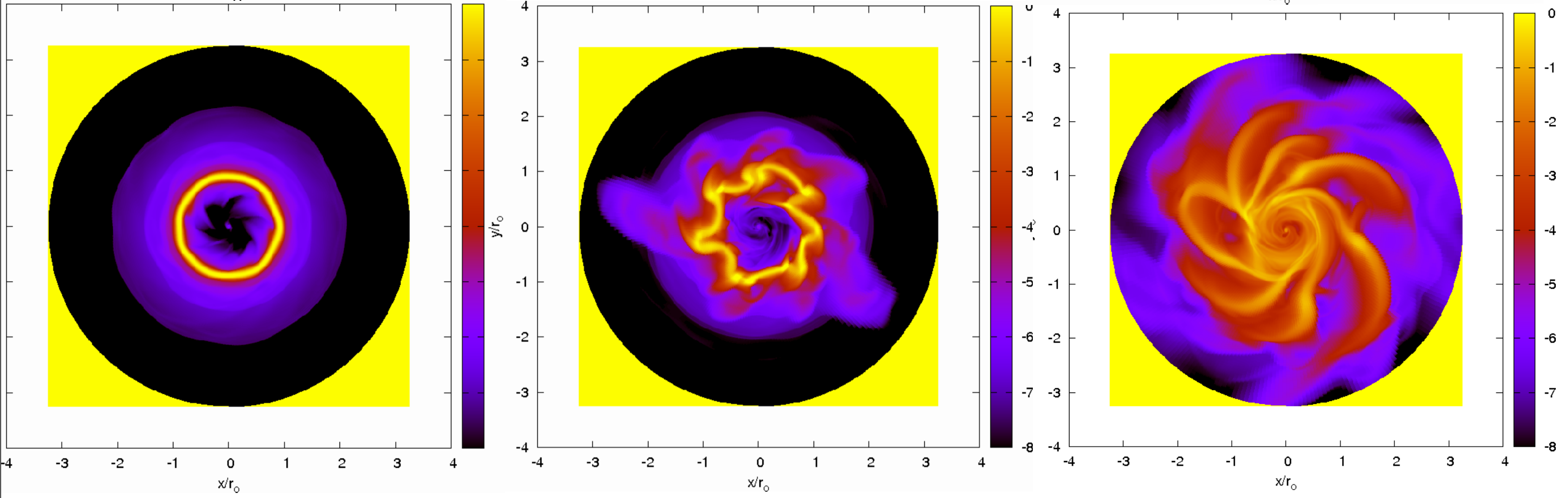


I Mode Simulation with Cooling

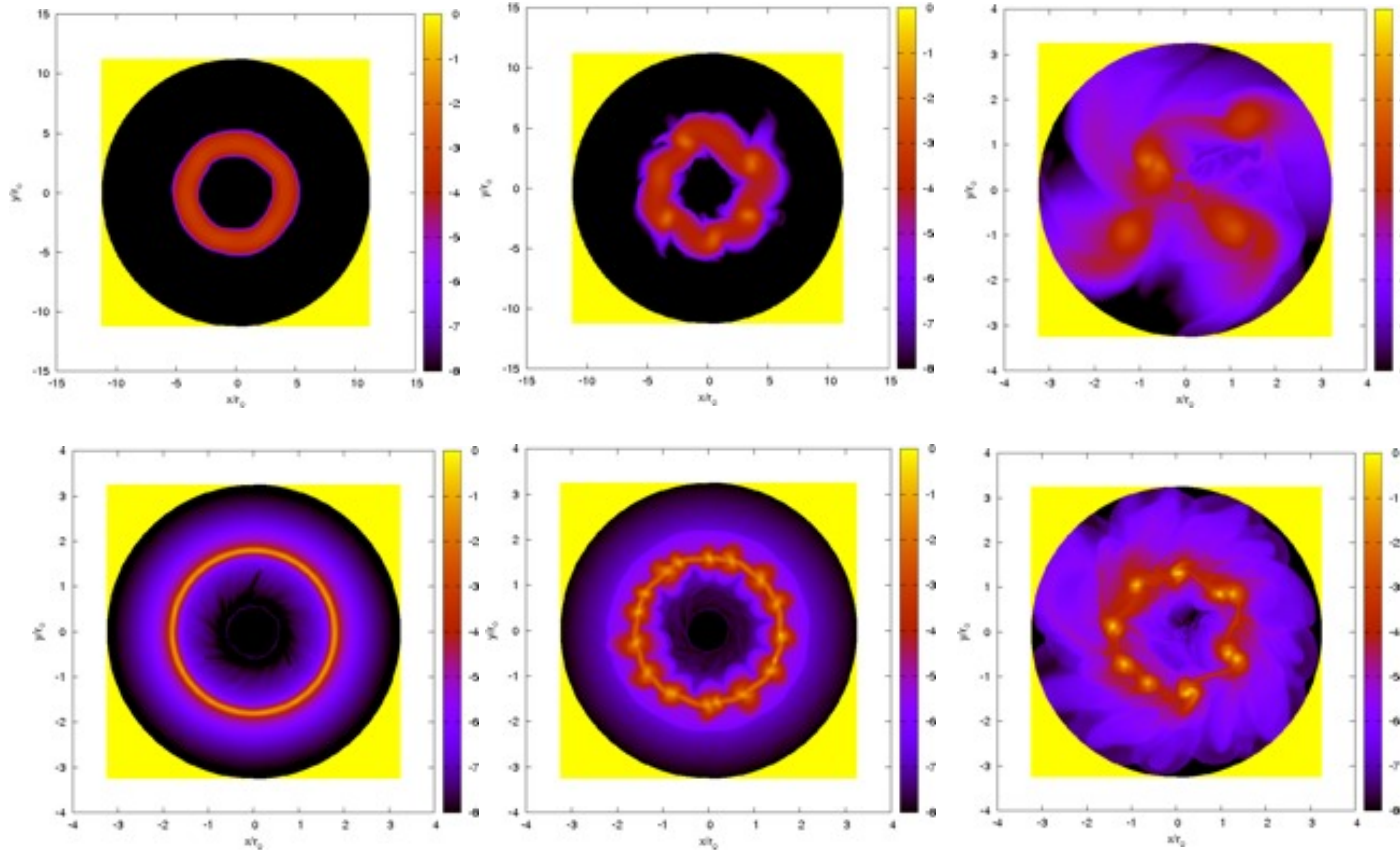


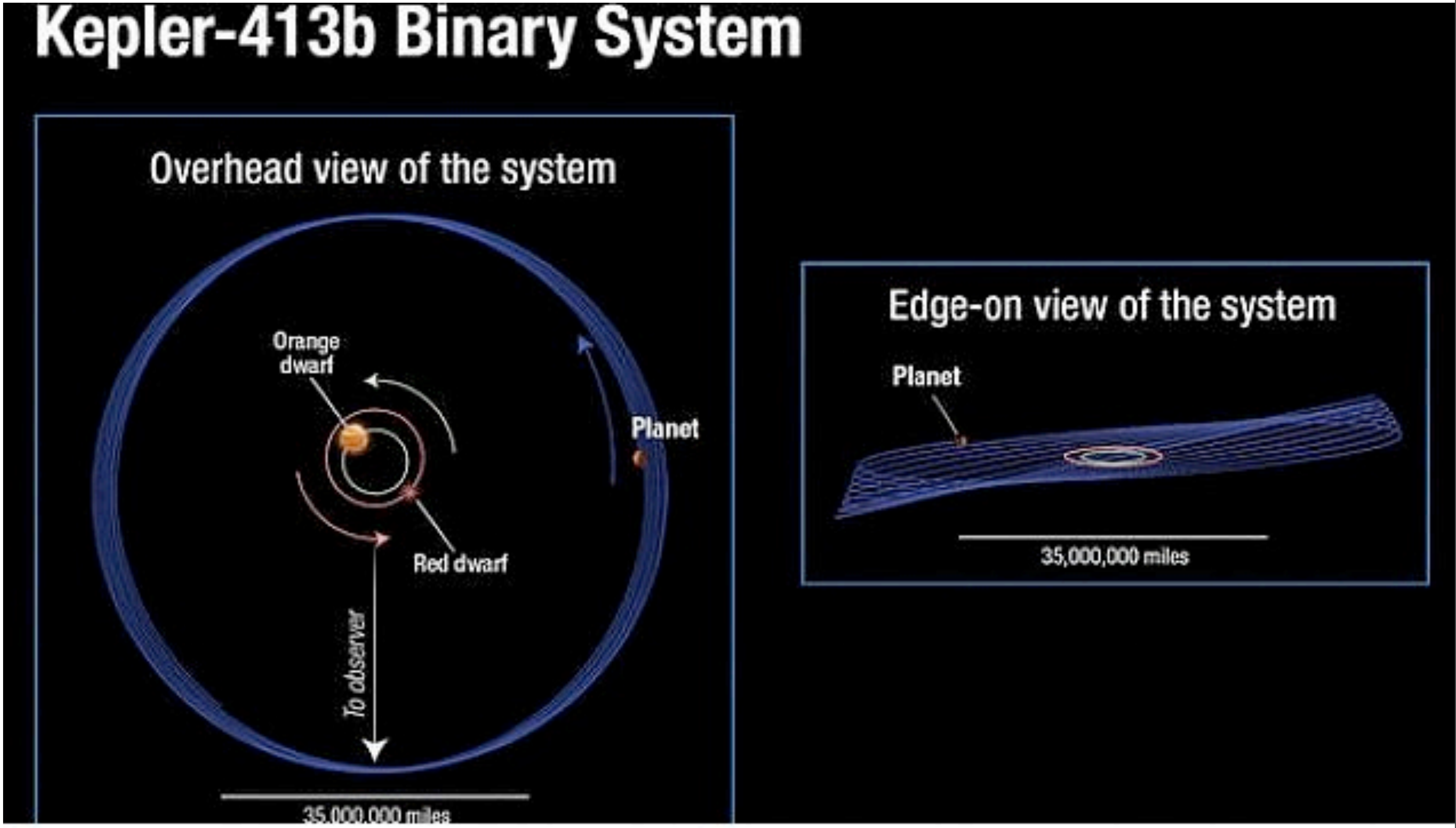
Simulations for the previous system, but with cooling. The upper two figures are moderate cooling $t_c = 5\ t_o$. The bottom row is for strong cooling, $t_c = 0.5\ t_o$.





J Mode Without and With Cooling




Kepler-413b Binary System
Overhead view of the system
Orange dwarf
Planet
Red dwarf
To observer
35,000,000 miles
Edge-on view of the system
Planet
35,000,000 miles

Resolved Star: J Mode and I Mode Simulations without Cooling