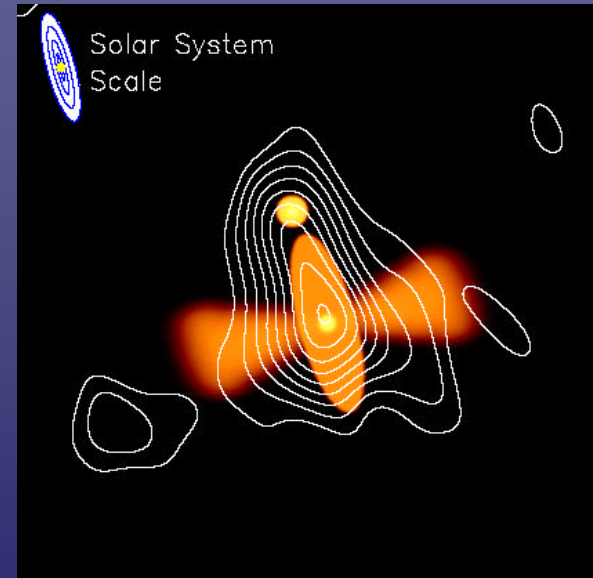
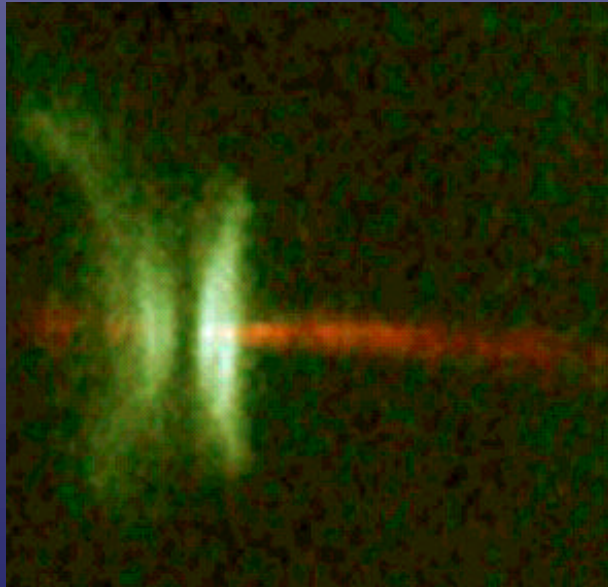


# Accretion Disks around Stars and the Process of Planet Formation



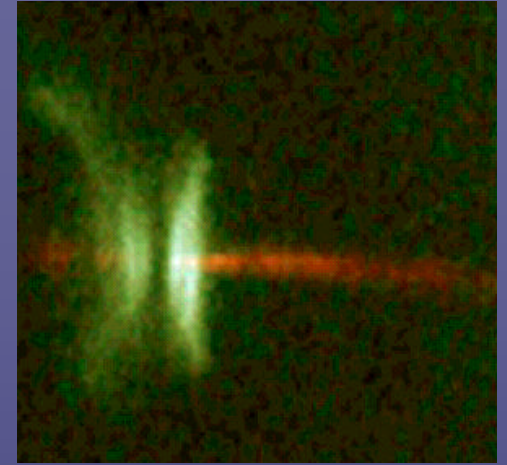
## National Radio Astronomy Observatory



The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.



# How Stars & Planets Form



- I. Stars form from disks of gas & dust. This process is regulated by ejecting gas in “jet-like” outflows.
- II. Planets form later from the remnants of the disk. Planets may only form when conditions around the star are “just right.”
- III. Planets have been detected around other stars. Current detection methods are limited to finding large gaseous planets like Jupiter.

# Introduction: The Formation Process

For a “T-Tauri” star – how our Solar System formed

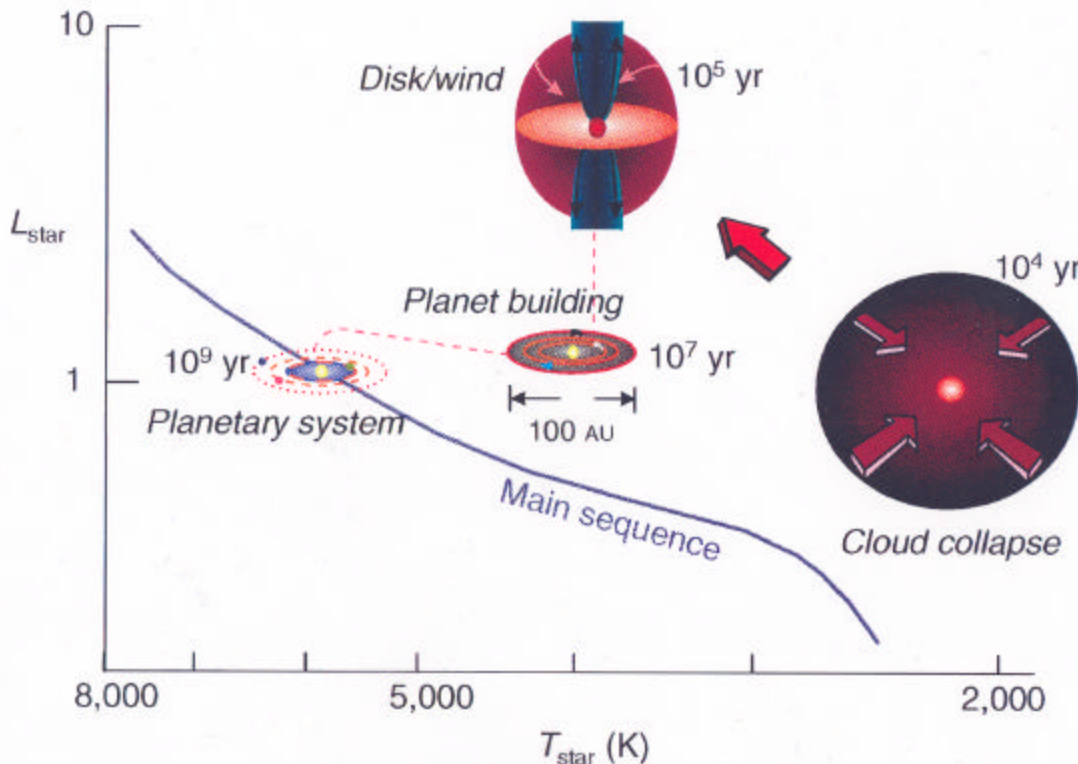


Fig. 2. Beckwith & Sargent, *Nature*, 383, 139-144.

## Scales:

Earth sun distance = 1 AU,  
Astronomical Unit (6 lt minutes)

Size of our Solar System  
= 80 AU (8 lt hours)

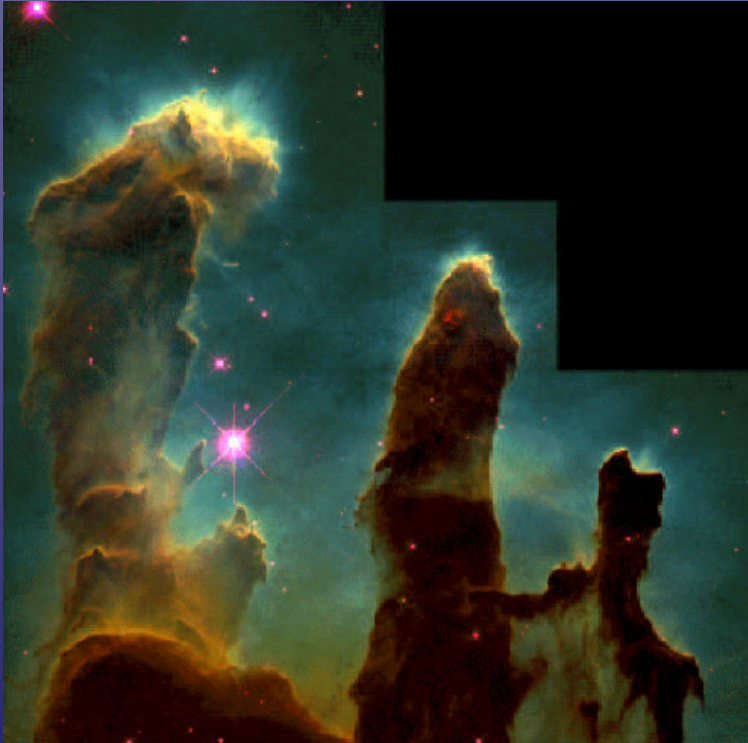
Size of typical accretion  
disks = 100 AU

Size of typical outflow = 1  
parsec (pc) = 3.26 lt yrs =  
200,000 AU

Closest star to Sun = 4.3 lt  
yrs = 1.3 pc ( $\alpha$  Centauri)

# The Star Forming Environment

The Eagle Nebula, Hester et al. (1995)



Thackeray's Globule in IC 2944, Reipurth et al. (2002)

Stars form within dense interstellar clouds of gas & dust that obscure our view at visible wavelengths.



The Horsehead Nebula, HST Heritage project

# Accretion/Outflow

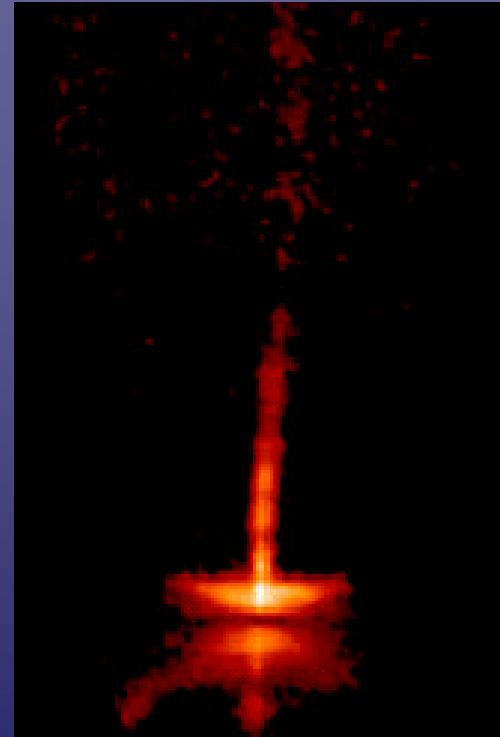
HH 111



**Forming stars  
and disks**

HH 111. IR &  
visible light  
(HST) showing  
jet & nebula  
above edge-on  
accretion disk  
(Reipurth et al.  
1997, Reipurth &  
Bally 2001).

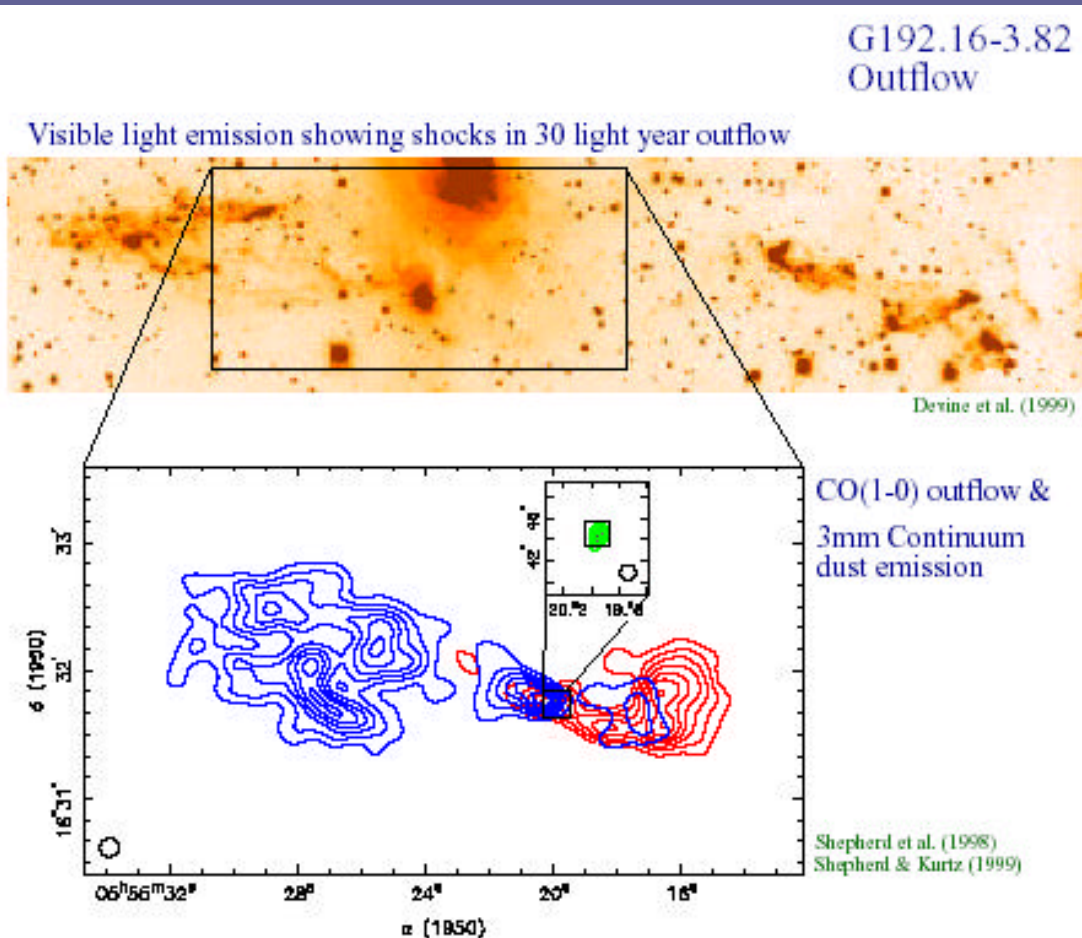
HH 30



HH 30: visible light (HST R  
band) showing jet & reflected  
light from surface of flared disk  
(Watson et al. 2000).



# G192.16-3.82: The outflow



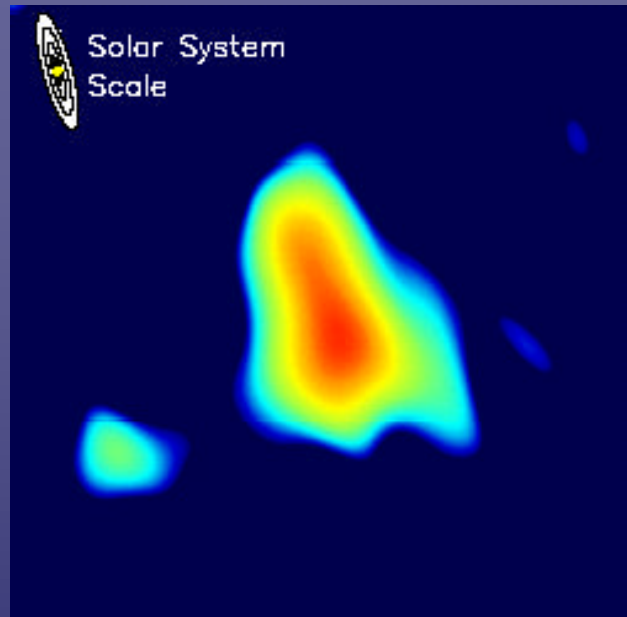
Shocks in [SII] emission.  
Outflow escapes cloud,  
extends more than 10 pc  
from end-to-end.  
 $D = 2$  kpc (7000 lt yrs)

Red & blue-shifted  
CO(J=1-0) emission  
imaged with the Owens  
Valley Millimeter Array,  
 $100 M_{\text{sun}}$  outflow material

Mass outflow rate:  
 $\sim 6 \times 10^{-4} M_{\text{sun}}/\text{yr}$

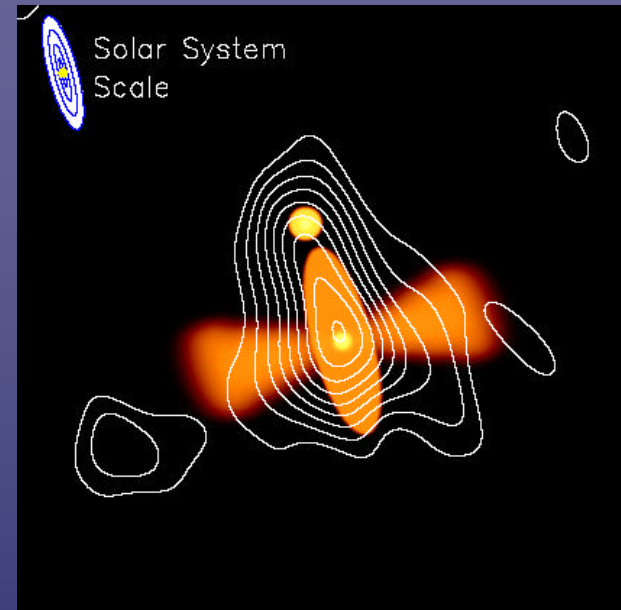
→ Mass accretion rate  
likely to be greater than  
 $\sim 10^{-3} M_{\text{sun}}/\text{yr}$

# G192.16-3.82 – Inner Accretion Disk



Very Large Array + Very Long Baseline Array  
Pie Town Antenna observations of inner-most region surrounding massive protostar (40 AU resolution at 2 kpc (7000 lt yrs).

7 mm (43 GHz) continuum emission from ionized gas and warm dust  
(Shepherd et al. 2001).



**Contours:** observations

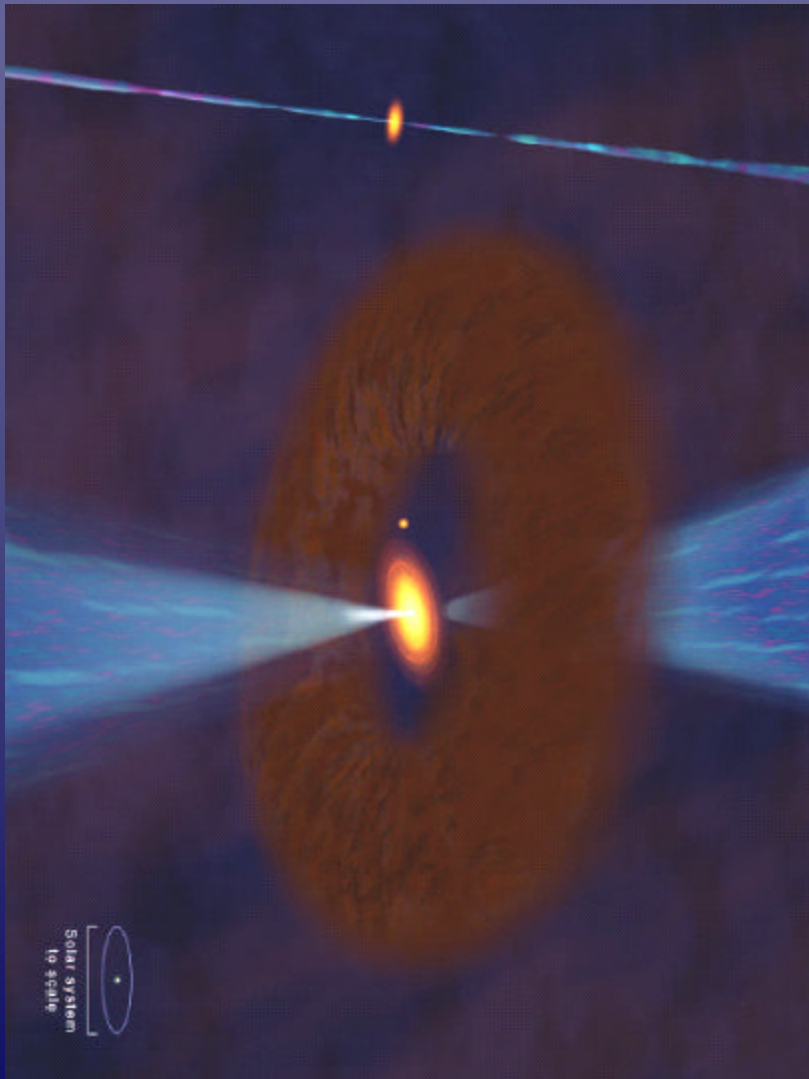
**Color:** model of accretion disk, central star, outflow, & companion protostar:

8  $M_{\text{sun}}$  protostar

3-20  $M_{\text{sun}}$  disk

Outflow with  $40^\circ$  opening angle.

# G192.16-3.82 – Artist view



Massive protostar with 130 AU diameter accretion disk and wide-angle outflow.

Close binary companion, 100 AU separation – truncating inner disk?

Circumbinary torus – inferred from water maser emission.

Well-collimated jet (mixed thermal and synchrotron emission) , actual location of protostar producing jet is unknown.

Credit: B. Starosta, NRAO/AUI/NSF



# Accretion Disks: Solar Type Stars

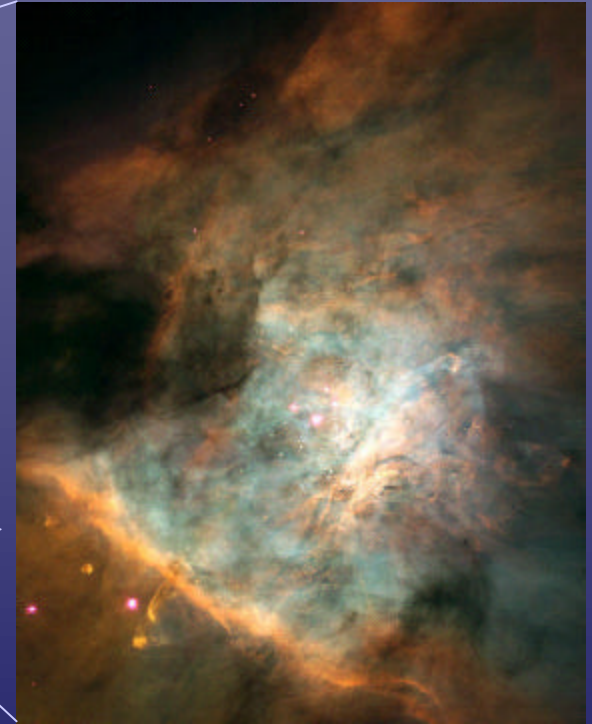
Akira Fujii



David Malin



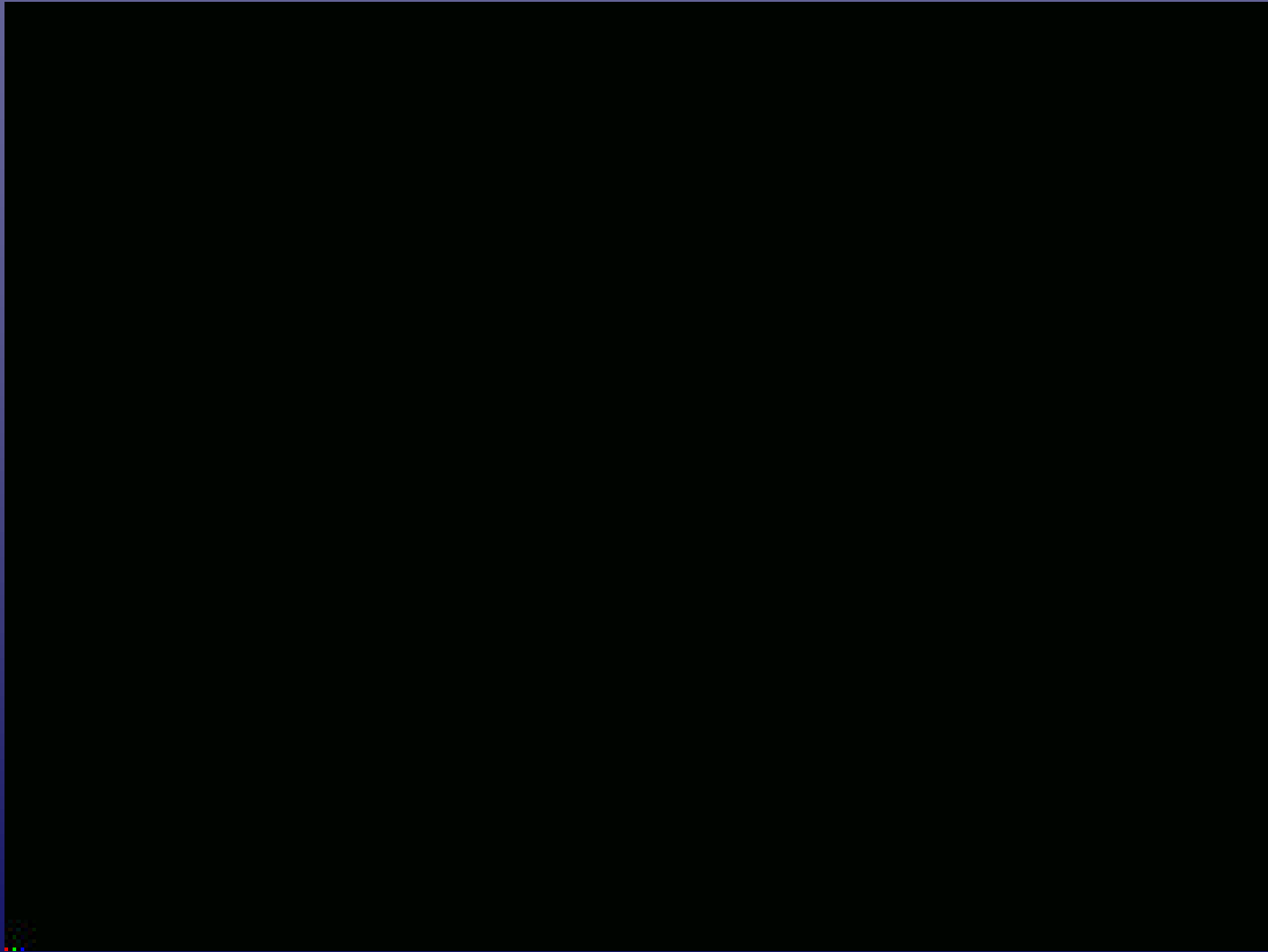
HST image (O'Dell 1995)



**Consider nearest massive  
star forming region: Orion**

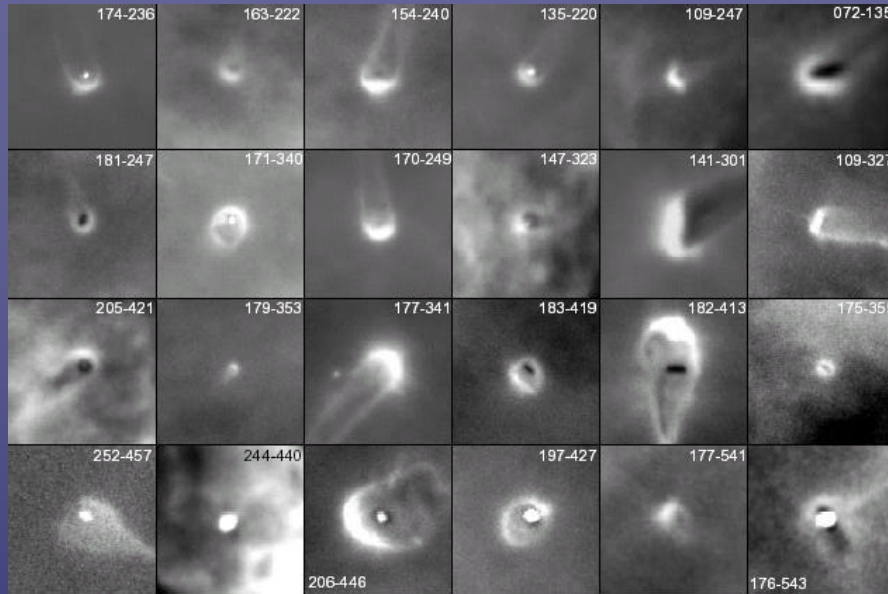
Visible nebula created by reflected light from “Trapezium Cluster” of hot, massive stars. Low-mass stars are still forming near massive stars.

# The 3-D Structure of Orion



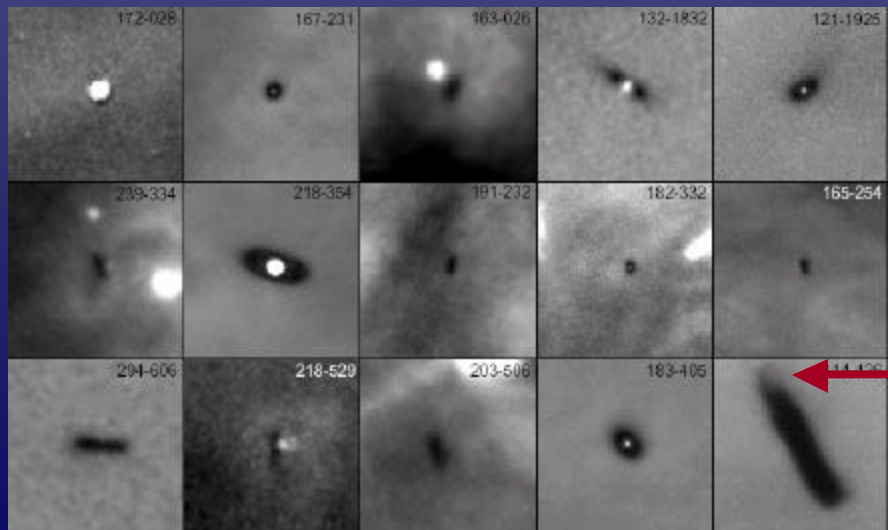
Simulation developed by San Diego Supercomputing Center & Hayden Planetarium

# Disks in the Orion Nebula



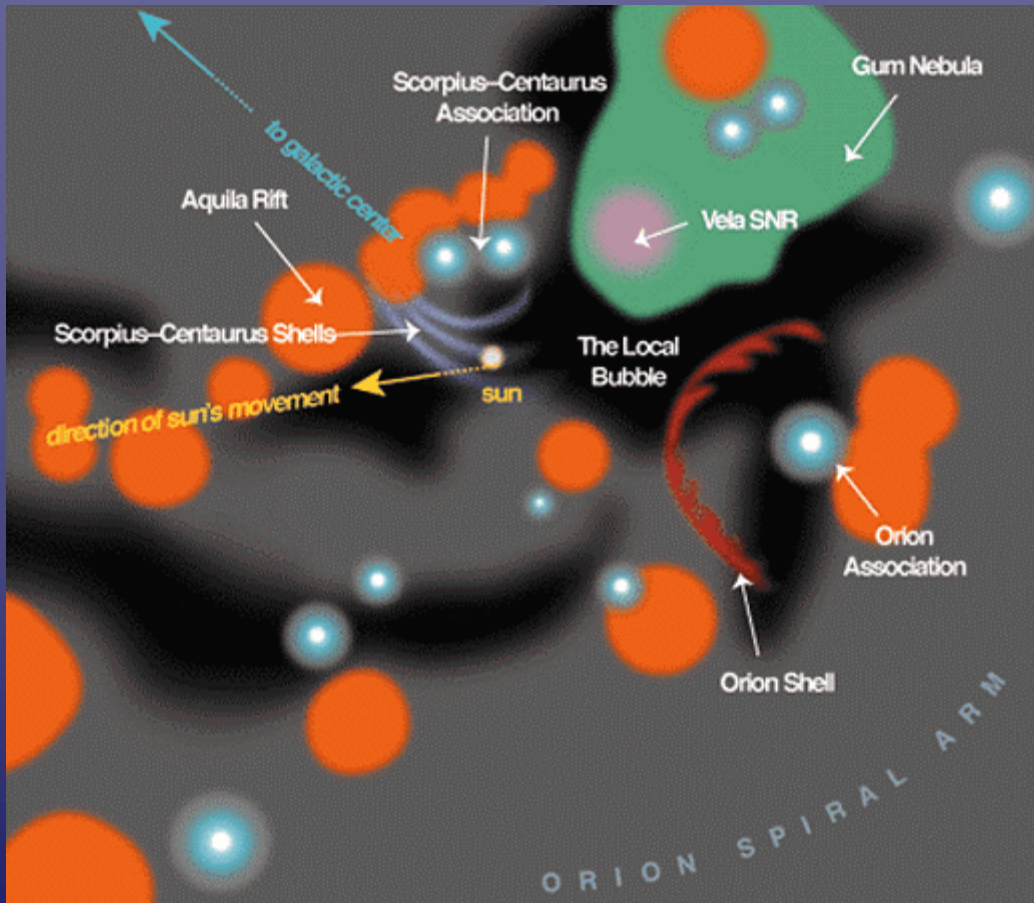
Irradiated by the Trapezium stars (left) & in silhouette against bright nebular emission (bottom).

Bally, O'Dell, McCaughrean 2000



Translucent edge in disk: Measured opacity at 3 wavelengths → large grains (cm sized – protoplanetary?) (Bally et al. 2002)

# The Solar Neighborhood



- Star forming regions
- Hot interstellar medium (low density)
- Ionized gas (HII region) from massive star winds & supernovae

Sun about to pass through “local interstellar cloud” within “local bubble.”

Sun may have been formed in a massive star forming region (Gum Nebula?), perhaps ejected.

→ Star/disks in Orion could show history of our Sun.

Credit/copyright:

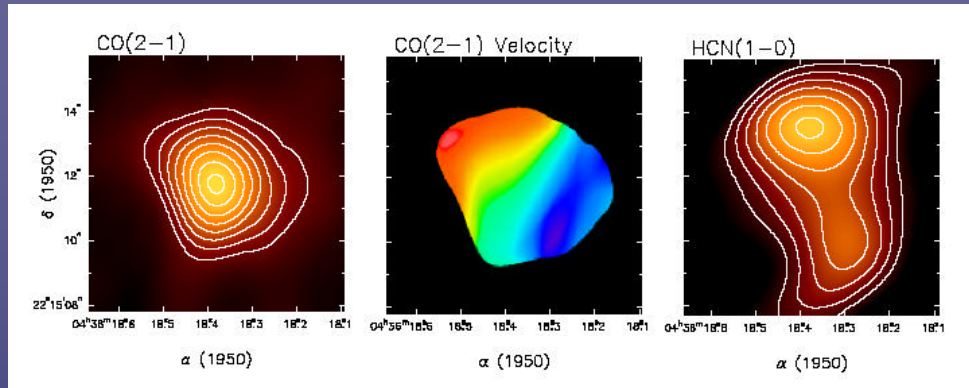
Huff & Frisch (Astronomy  
Picture of the Day 12apr00)

450 pc  
1500 Lt yrs



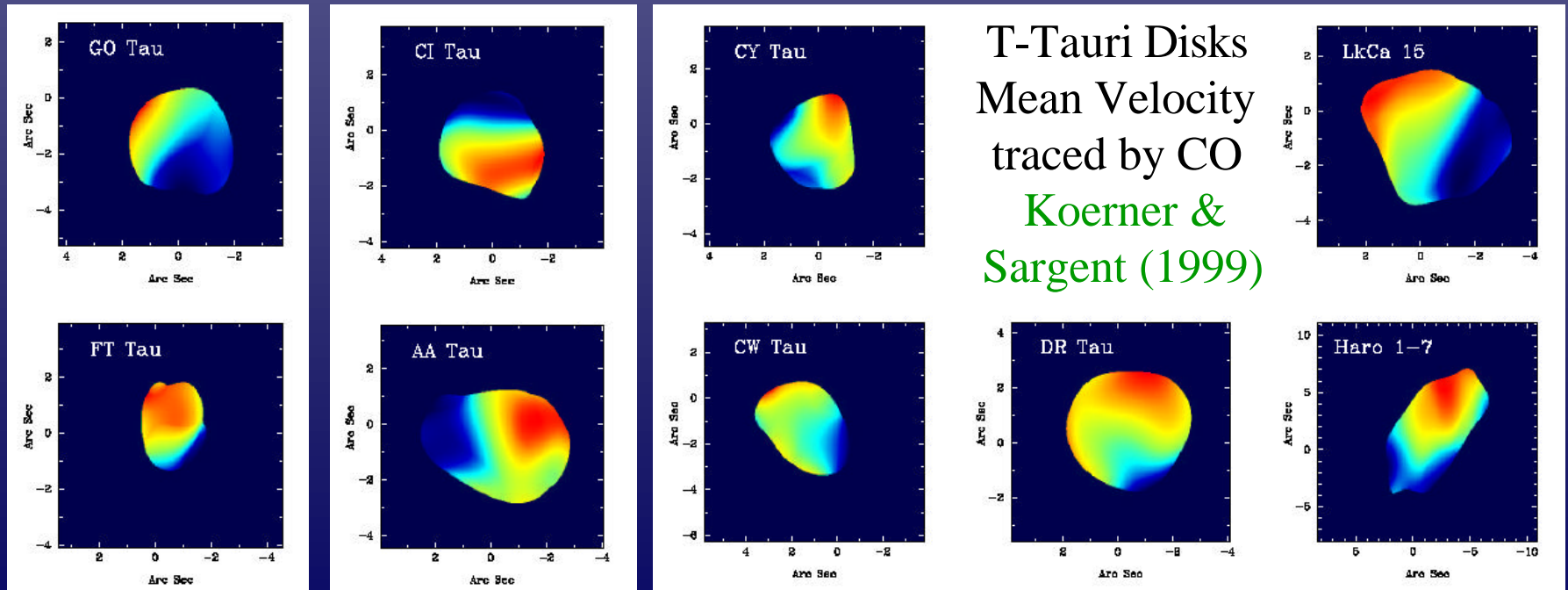
# Accretion Disk Velocity Structure

## LkCa 15 disk



The disk velocity in LkCa 15 traced by CO and chemistry traced by HCN, Owens Valley Interferometer (Qi et al. 2001)

Disk sizes  $\sim 100$  AU,  $M_d \sim .03 M_{\text{sun}}$  (Sargent et al. 1986, Dutrey et al. 1997, Looney et al. 2000)





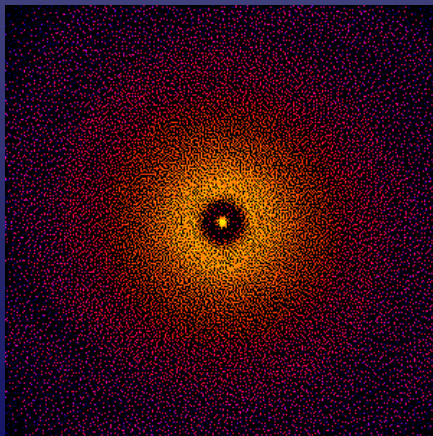
# Debris Disks

Debris disks are remnant accretion disks with little or no gas left (just dust & rocks), outflow has stopped, the star is visible.

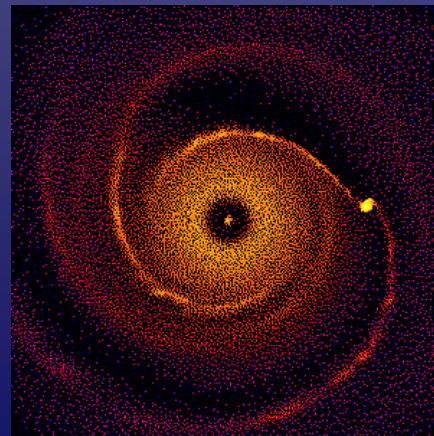
**Theory:** Gas disperses, “planetesimals” form (100 km diameter rocks), collide & stick together due to gravity forming protoplanets (Wetherill & Inaba 2000).

Protoplanets interact with dust disks: tidal torques cause planets to migrate inward toward their host stars. Estimated migration time  $\sim 2 \times 10^5$  yrs for Earth-size planet at 5 AU (Hayashi et al. 1985).

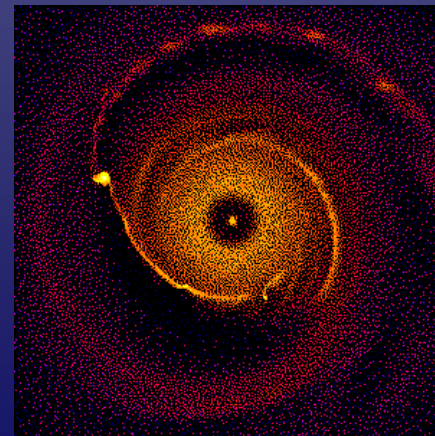
Perturbations caused by gas giants may spawn smaller planets (Armitage 2000):



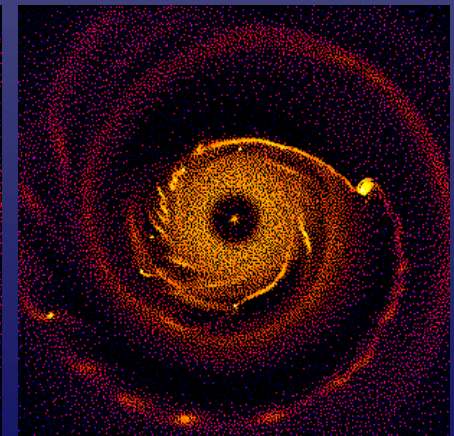
Start with a stable disk around central star.



Jupiter-sized planet forms & clears gap in gas disk.

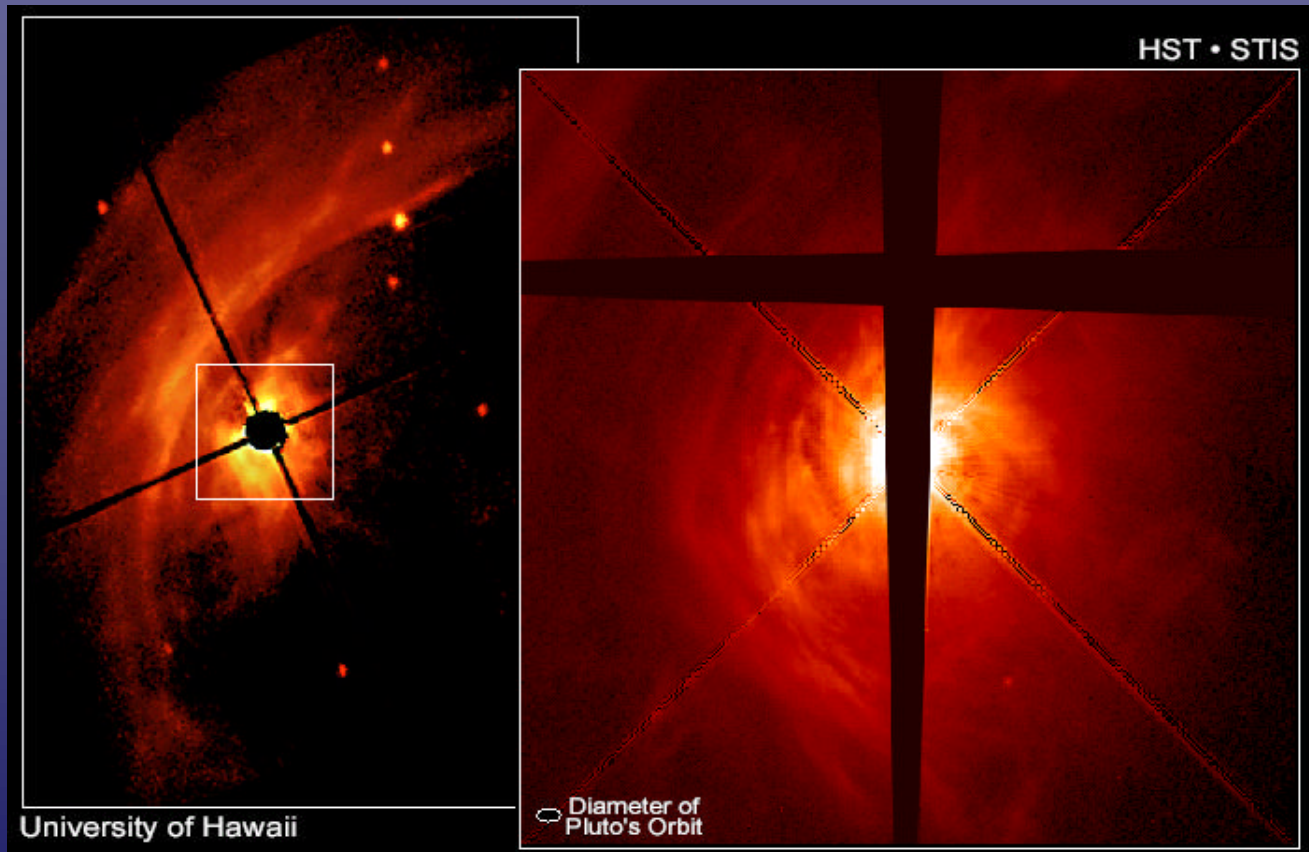


Planet accretes along spiral arms, arms become unstable.



Disk fragments into more planetary mass objects.

# Debris Disks – Outer Disk



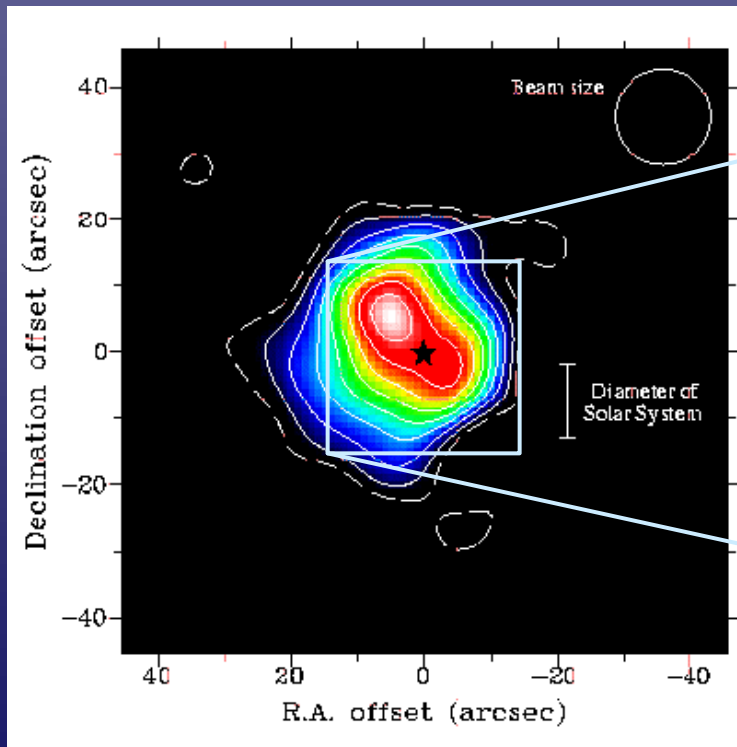
AB Aurigae outer debris disk nearly face on – see structure & condensations (possible proto-planet formation sites? Very far from star) .

(Grady et al. 1999)

# Debris Disks – Near Solar System Size

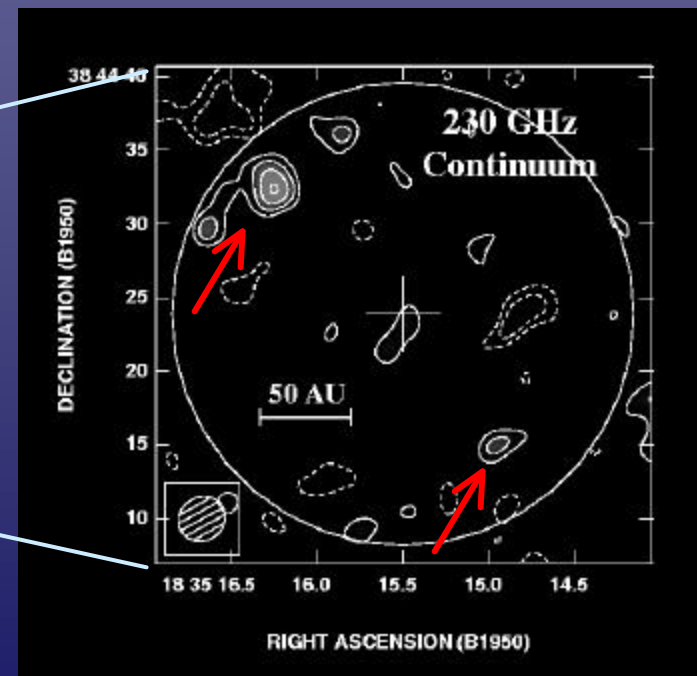
SCUBA/JCMT & OVRO Imaging of Vega  
(7.8 pc/25 lt yrs from earth)

$\lambda = 0.85 \text{ mm}$



Holland et al. (1998)

$\lambda = 1.3 \text{ mm}$



Koerner, Sargent, & Ostroff (2001)

Semi-major axis of Pluto = 40 AU

# Evidence for Extra-Solar Planets

Two detection methods available to infer existence of planets around **solar type stars**:

- Measure star wobbles due to gravitational tug of planet on star
- Image perturbations in debris disks

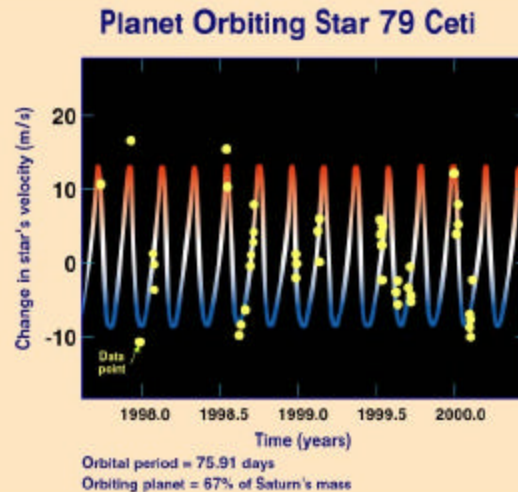
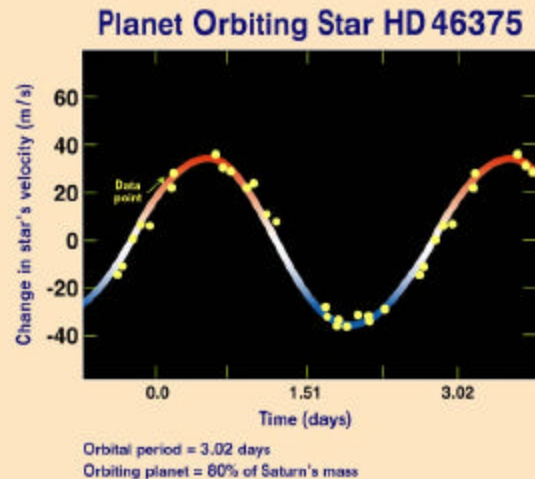
Methods preferentially detect large planets near the star (e.g. Jupiter-sized planets less than 1 AU from star). We cannot detect Earths yet.

Recently, an additional method has become possible to probe other characteristics of the planet:

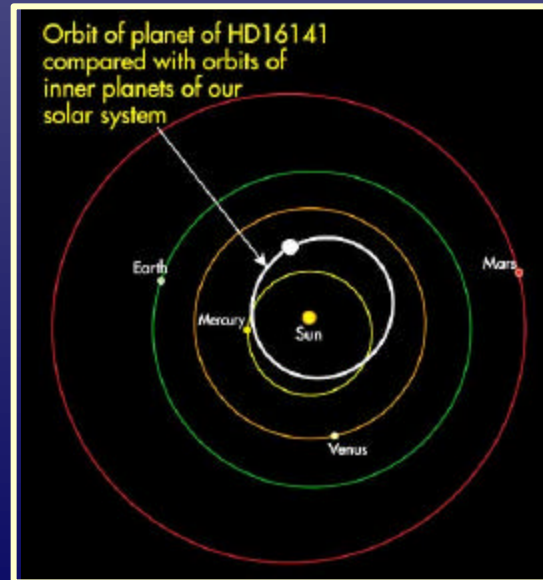
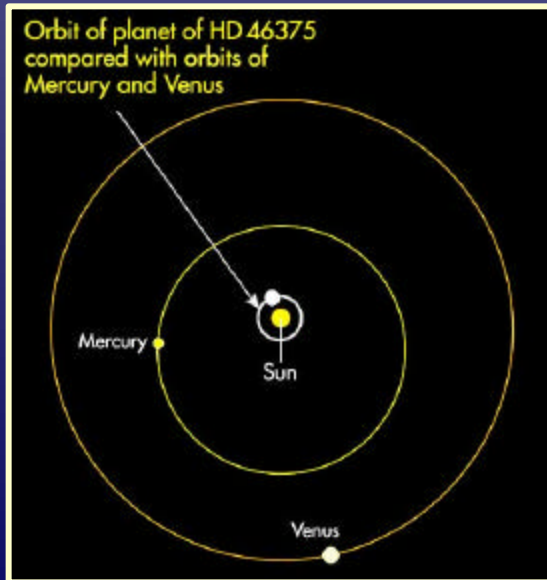
- Monitor known planetary systems for star transit events



# Extra-Solar Planets – “Star Wobbles”



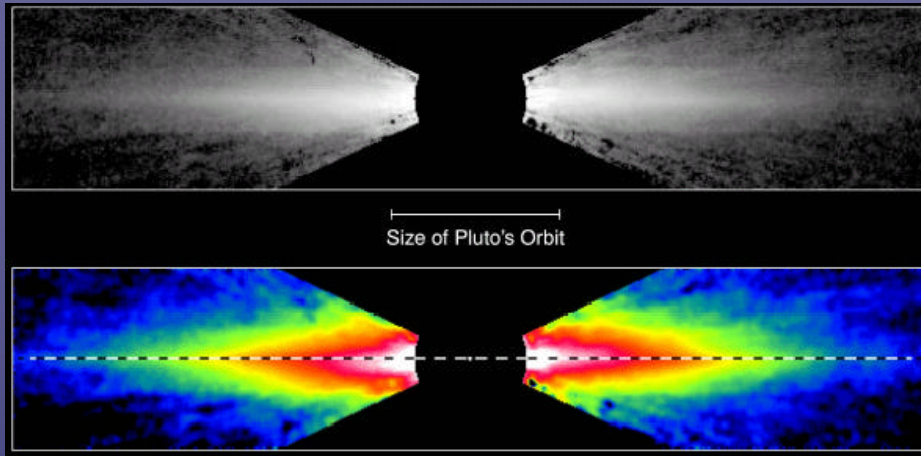
Measures lower limit on mass:  
 $M \sin(i)$  where  
 $i = \text{unknown}$   
inclination of orbit &  $M =$   
mass of planet  
(Marcy 2000)



More than 70  
gas giant planets  
discovered so far.



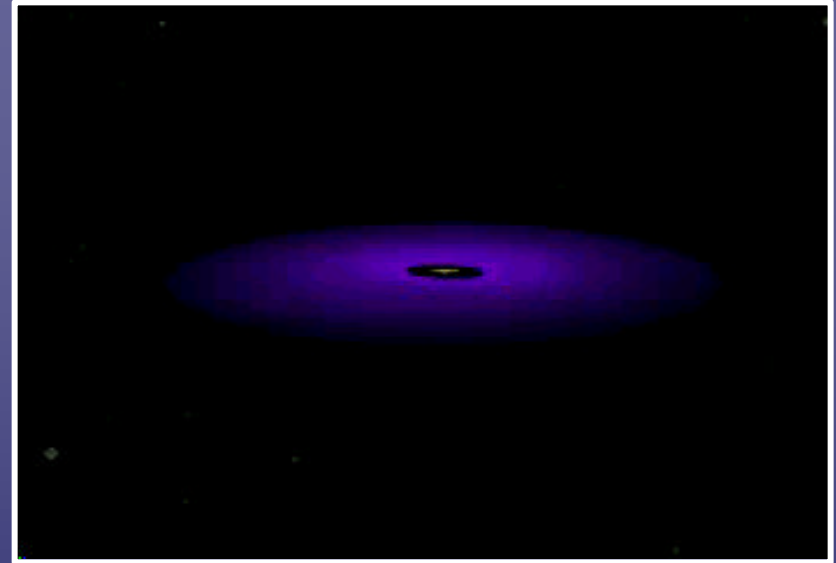
# Extra-Solar Planets: Disk Perturbations - 1



Beta Pictorus (100 million years old) debris disk: Inner debris disk orbits in a different plane than outer disk.

Dust particles collide & get blown out by radiation pressure or accrete onto star → warp should not last less than 10 Myrs.

Something must continuously twist the disk. A Jupiter-sized planet in an inclined orbit could do this. (Burrows, Krist 1996)

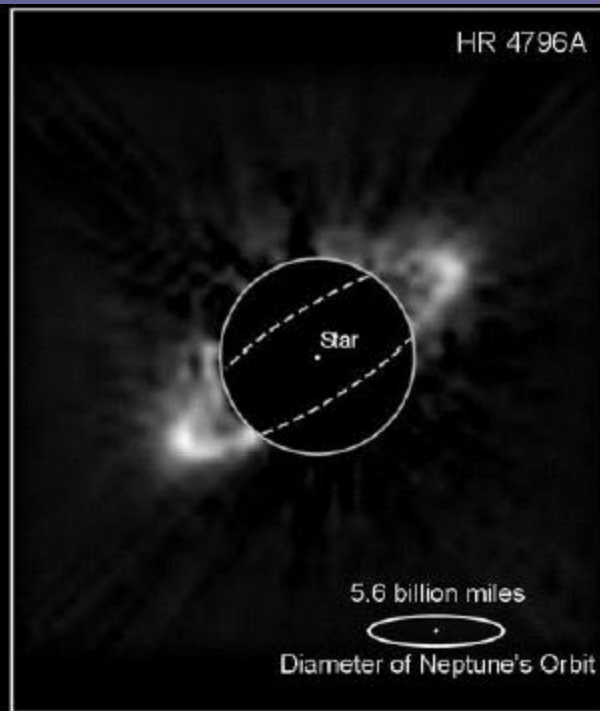
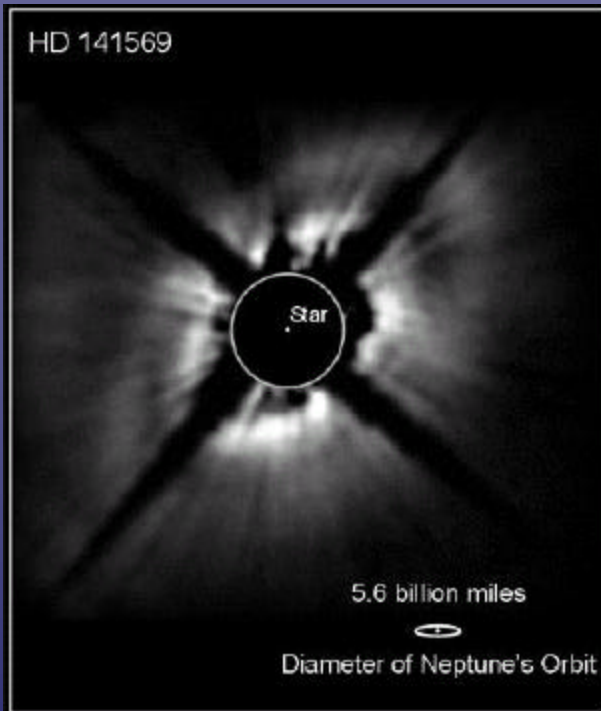


**Simulation** (Burrows, Krist 1996)

**Zoom in:** A Jupiter-mass planet in Jupiter orbit. Planet orbit is in disk plane, no warp seen.

**Zoom out:** planet is now inclined  $3^\circ$  with respect to outer disk plane. Inner disk is now warped.

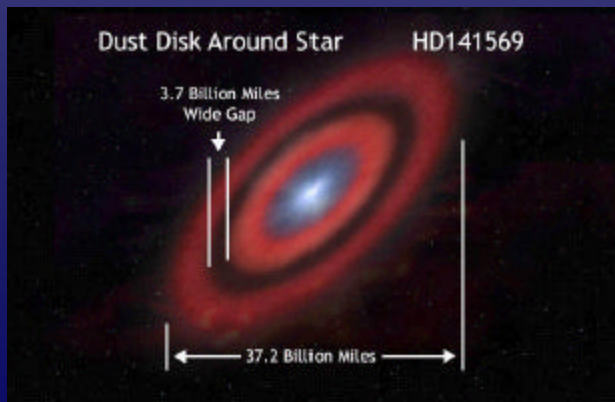
# Extra-Solar Planets: Disk Perturbations - 2



Dust rings around stars – something is clearing dust out regions of debris disk: most likely explanation: planet/protoplanet.

Weinberger, Becklin, Schneider (1999)

Schneider et al. (1999)



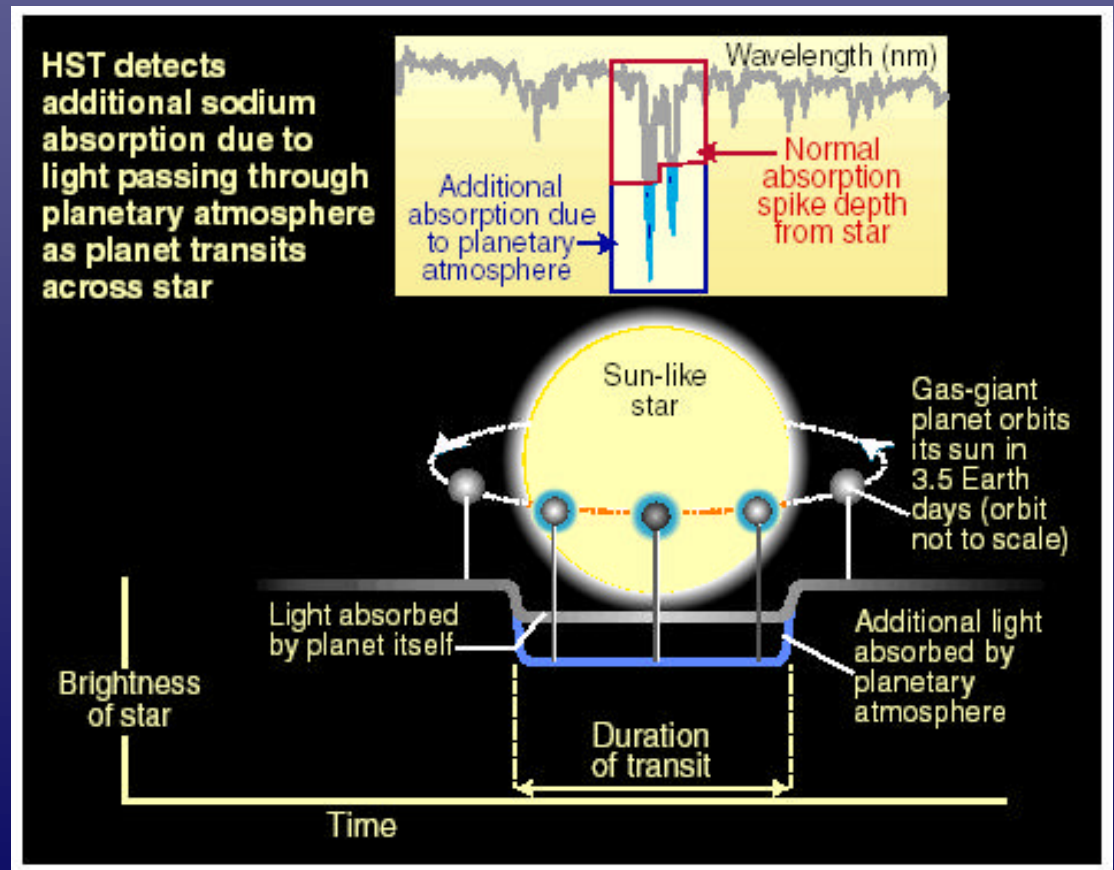
# Extra-Solar Planets – Planet Transit

When planet passes in front of parent star, starlight is dimmed & some light must pass through planetary atmosphere.

Spectral signature of atmosphere in planet around HD 209458 measured:

Using HST Space Telescope Imaging Spectrograph (STIS), Charbonneau et al (2001) measured absorption of starlight by sodium in planet's atmosphere.

The detection opens new frontier to find chemical elements such as oxygen, the signature of life, on other planets.



# Where Do We Go From Here?

Refine current methods & build new instruments such as:


**Very Large Telescope Interferometer (VLTI) with Phase-Referenced Imaging & Micro-arcsecond Astrometry (PRIMA)** – Array of mid-IR (10-20 $\mu$ m) telescopes being built in Chile, PRIMA available in 2005. Will be able to solve for inclination of planet orbit ( $M_p \sin(i) \rightarrow M_p$ ).

**Atacama Large Millimeter Array (ALMA)** – World wide project to be completed in 2010. Will study *how* planets form by imaging accretion & debris disks, trace disk velocity structure, image proto-Jupiter planets, map gaps in disks where planets may be forming. ALMA will be able to detect minute motions in stars (via astrometry), even those still deeply embedded in obscuring gas and dust  $\rightarrow$  can search for newly formed planetary systems.

**Space Interferometry Mission (SIM)** – scheduled for launch in 2009, using optical interferometry, SIM will determine stellar positions & distances 100s of times better than now possible  $\rightarrow$  can search for Earth-sized planets.

**Terrestrial Planet Finder (TPF)** – Will be designed to image planetary systems & debris disks. TPF will be either a coronagraph, a large-baseline interferometer operating in the infrared, or perhaps a combination of the two architectures. Final selection of a TPF architecture will occur in 2006.

# Summary

- Stars form within dense clouds of molecular gas from disks of gas & dust. Disks regulate accretion onto the star & act as a launching point for the outflow.
- Planets form later from the remnants of the disk (debris disk).
-  Planets have been detected around “solar-type” stars but we have not imaged a planet yet. Current detection methods are limited to finding large gaseous planets like Jupiter.
- The next generation of telescopes will have the sensitivity & resolving power to detect Earth-sized planets and allow us to study how they are formed.



# More information about planets and the search for life

Here be Dragons: The Scientific Quest for  
Extraterrestrial Life

By Koerner & LeVay

Oxford University Press 2000