Formation of Solar Systems

Jay Gallagher

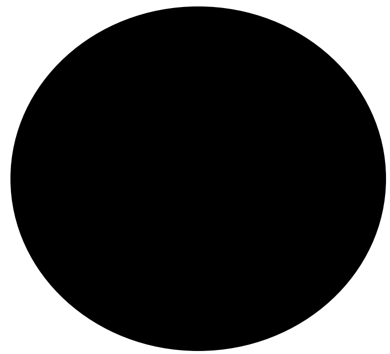
Horsehead Nebula

Hubble Heritage

NASA, NOAO, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-12

Gravitational Collapse

Consider a spherical isolated cloud



$$\Omega \approx -\frac{3GM^2}{5r} \qquad T = \frac{3}{5}\int P\,dV$$

$2T + \Omega = 0$ virial theorem equilibrium

< 0 collapse

Gravitational Collapse

$$\frac{\partial^2 \rho_1}{\partial t^2} = c_s^2 \nabla^2 \rho_1 + 4\pi G \rho_0 \rho_1$$

$$c_s^2 = {kt}/{\mu m_H} \quad \text{isothermal sound speed}$$

$$\Rightarrow \lambda_J = \sqrt{{\pi k T}/{\mu m_H G \rho_0}} \quad \text{Jeans length}$$

$$\Rightarrow M_J \cong \lambda_J^3 \rho_0 \quad \text{Jeans mass}$$

Dense ISM cloud has $\mathrm{n} \approx 100 - 1000\, cm^{-3}$ $T \approx 30K$

$$\Rightarrow \lambda_J \approx 4\, pc; \quad M_J \approx 600 \text{ solar masses}$$

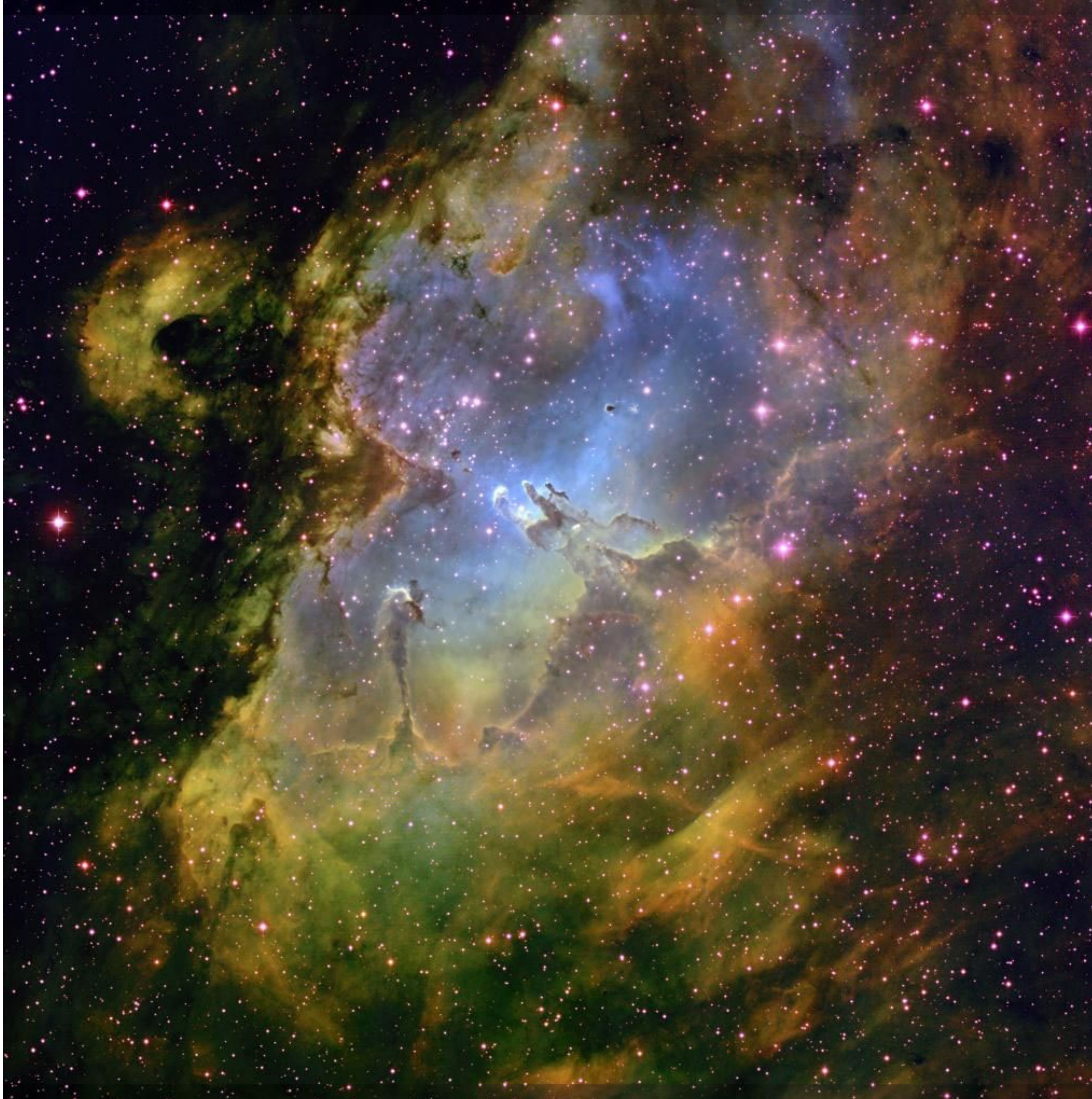
Gravitational Collapse

Stars form by FRAGMENTATION vs. monolithic collapse of interstellar clouds!

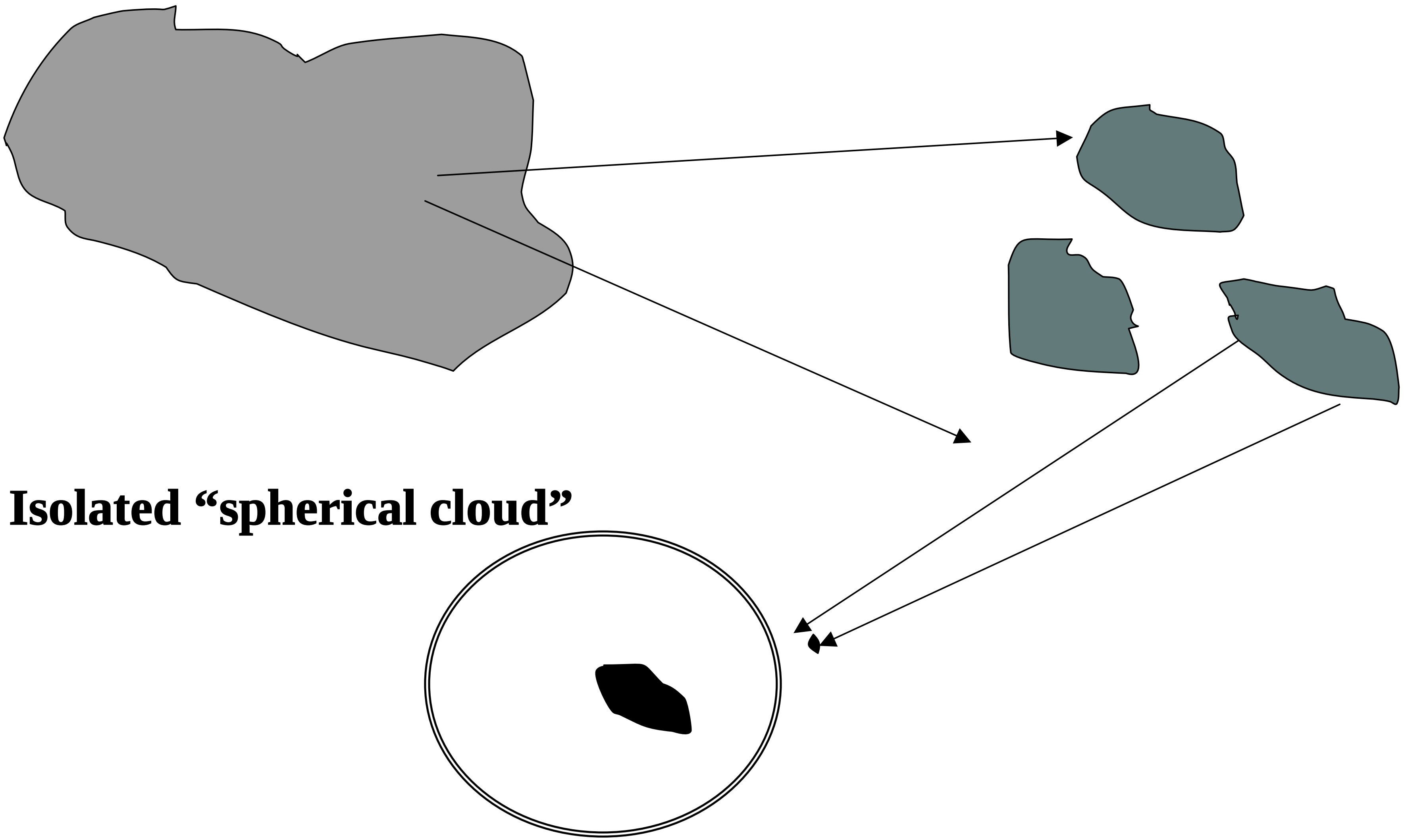
As density increases, new instability can form substructure

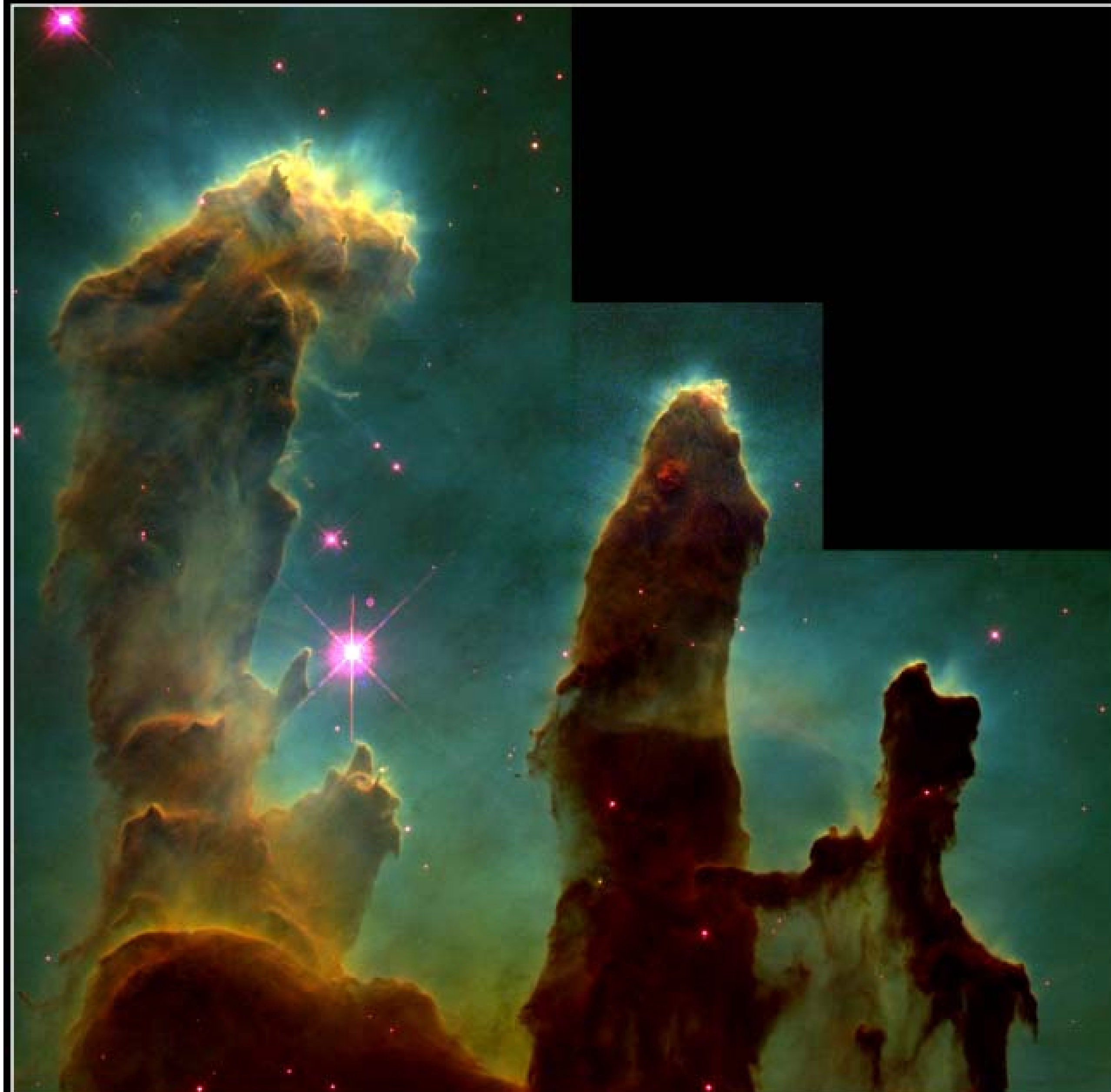
$\Rightarrow \quad \rho_1 \rightarrow new\, \rho_0$ and smaller fragment collapses

$$\tau_{\rm ff} \approx \left(\frac{(32 G \rho_0)}{3\pi} \right)^{-1/2} \approx 3 \times 10^6\, yr \text{ for our IS cloud}$$



Gravitational Collapse



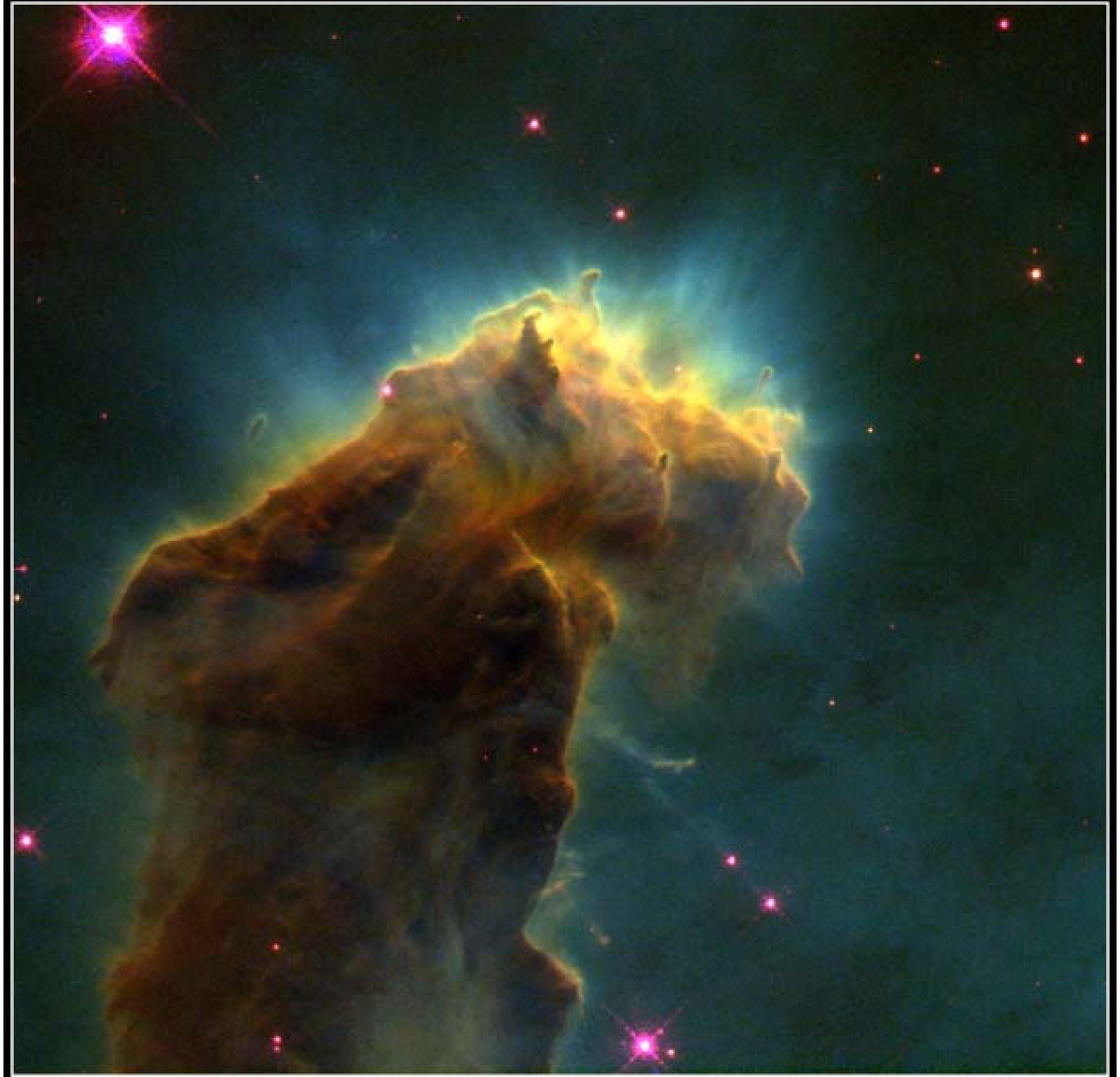


Gaseous Pillars · M16

HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995

J. Hester and P. Scowen (AZ State Univ.), NASA



Star-Birth Clouds • M16 HST • WFPC2

PRC95-44b • ST ScI OPO • November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

Thackeray's Globules in IC 2944

Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC02-01

Gravitational Collapse

What sets the RATE of collapse?

Must radiate energy to make $|\Omega|$ larger.

$$L = -\frac{d\Omega}{dt} \approx \frac{3GM^2}{r} \bullet \frac{dr/dt}{r}$$

e-folding Kelvin-Helmholtz time scale

$$t_{kh} \approx \frac{3GM^2}{rL}$$

$$\approx 20\left(\frac{M}{Msun}\right)\left(\frac{\mathrm{Lsun}}{\mathrm{L}}\right)\left(\frac{\mathrm{Rsun}}{\mathrm{r}}\right)\mathrm{Myr}$$

Gravitational Collapse

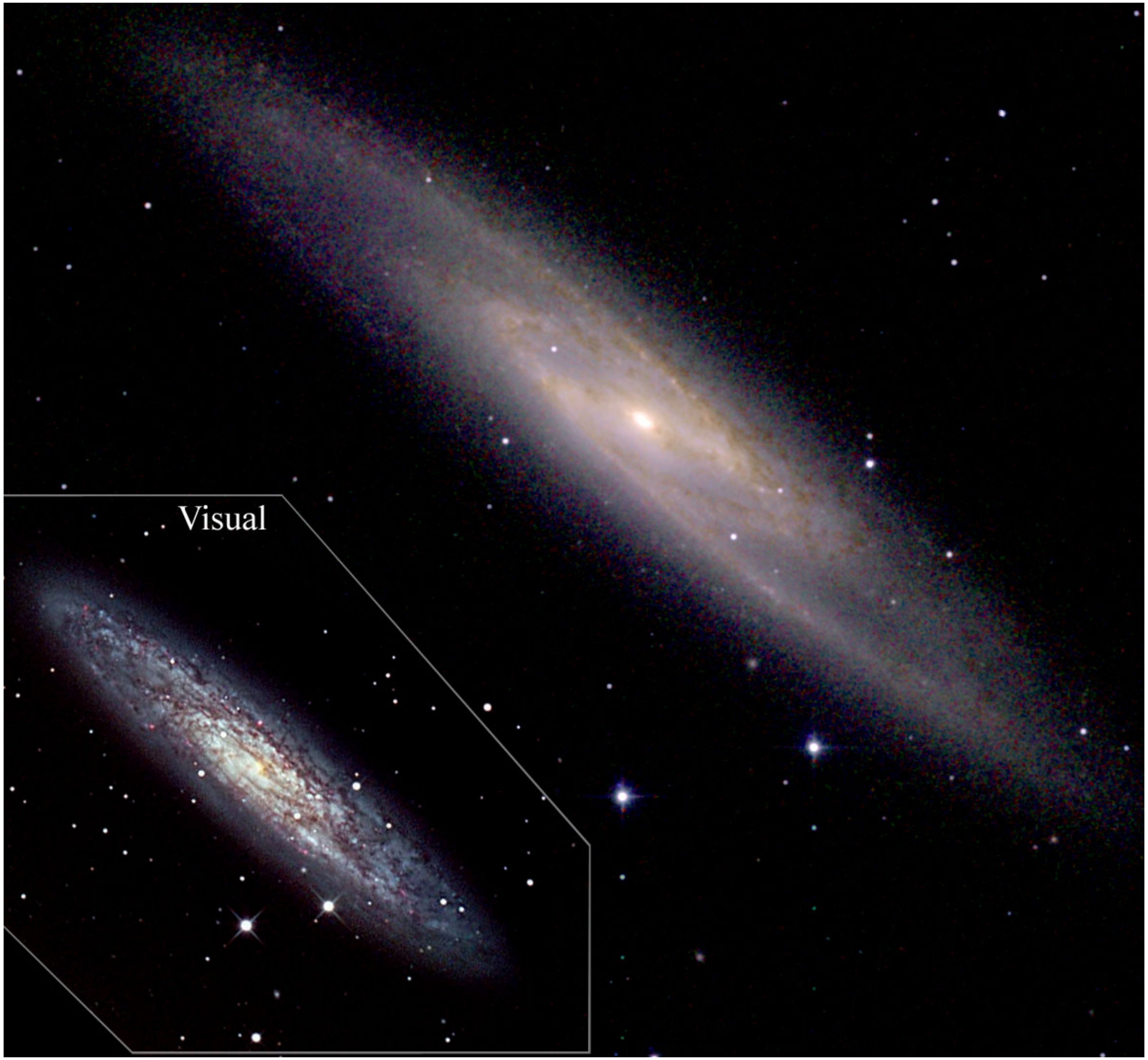
Rate of collapse depends on luminosity L that in turn depends on ability of protostar to transport heat from interior:

Early phases-convection-rapid energy trnasport-fast collapse (<1 Myr)

Later phases, radiation, approaches Kelvin-Helmholtz time scale as nuclear burning begins

Total formation time to nuclear burning star <25 Myr for solar mass star

Angular Momentum



Angular Momentum

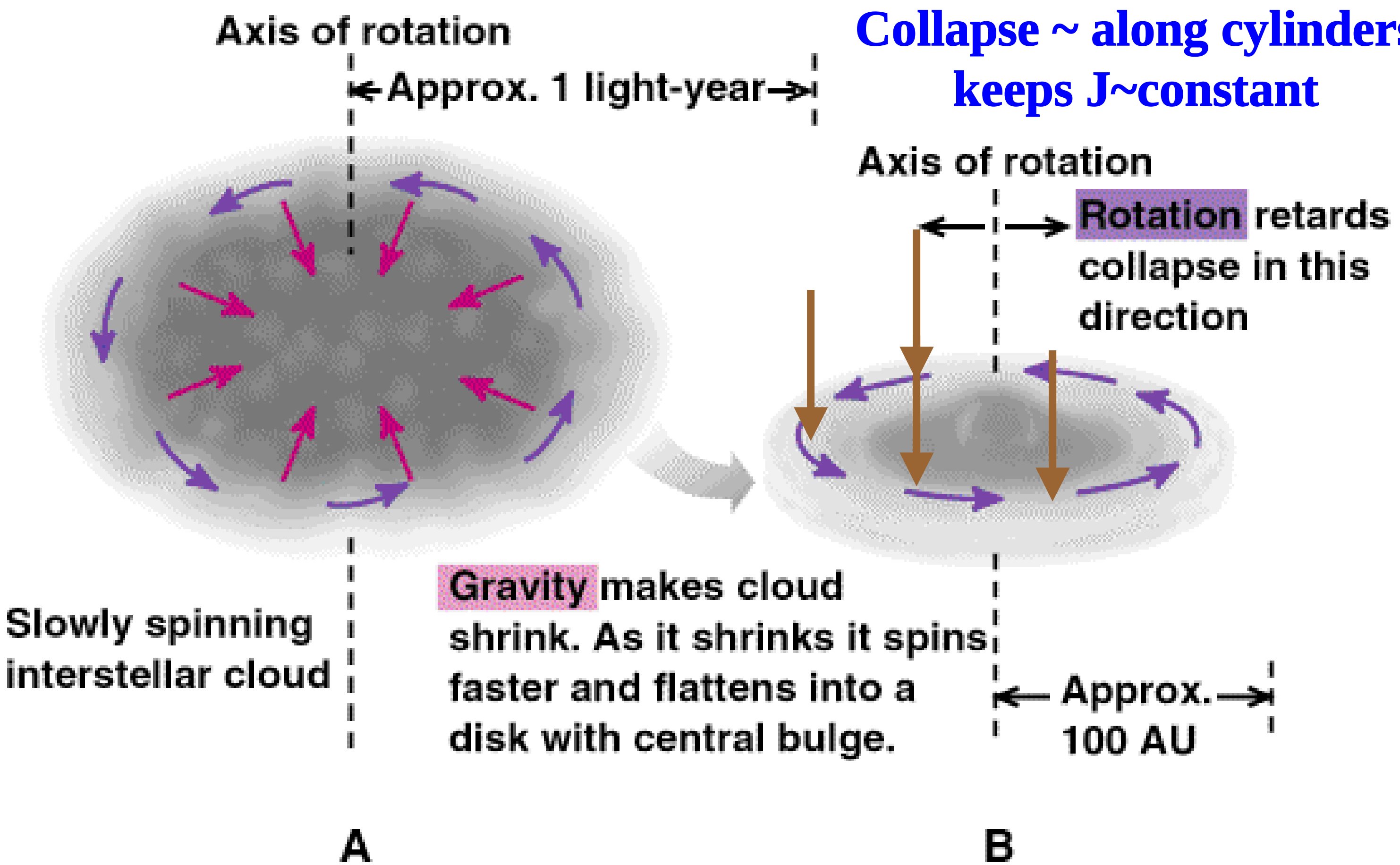
$$J = m v_{\text{tangental}} r$$

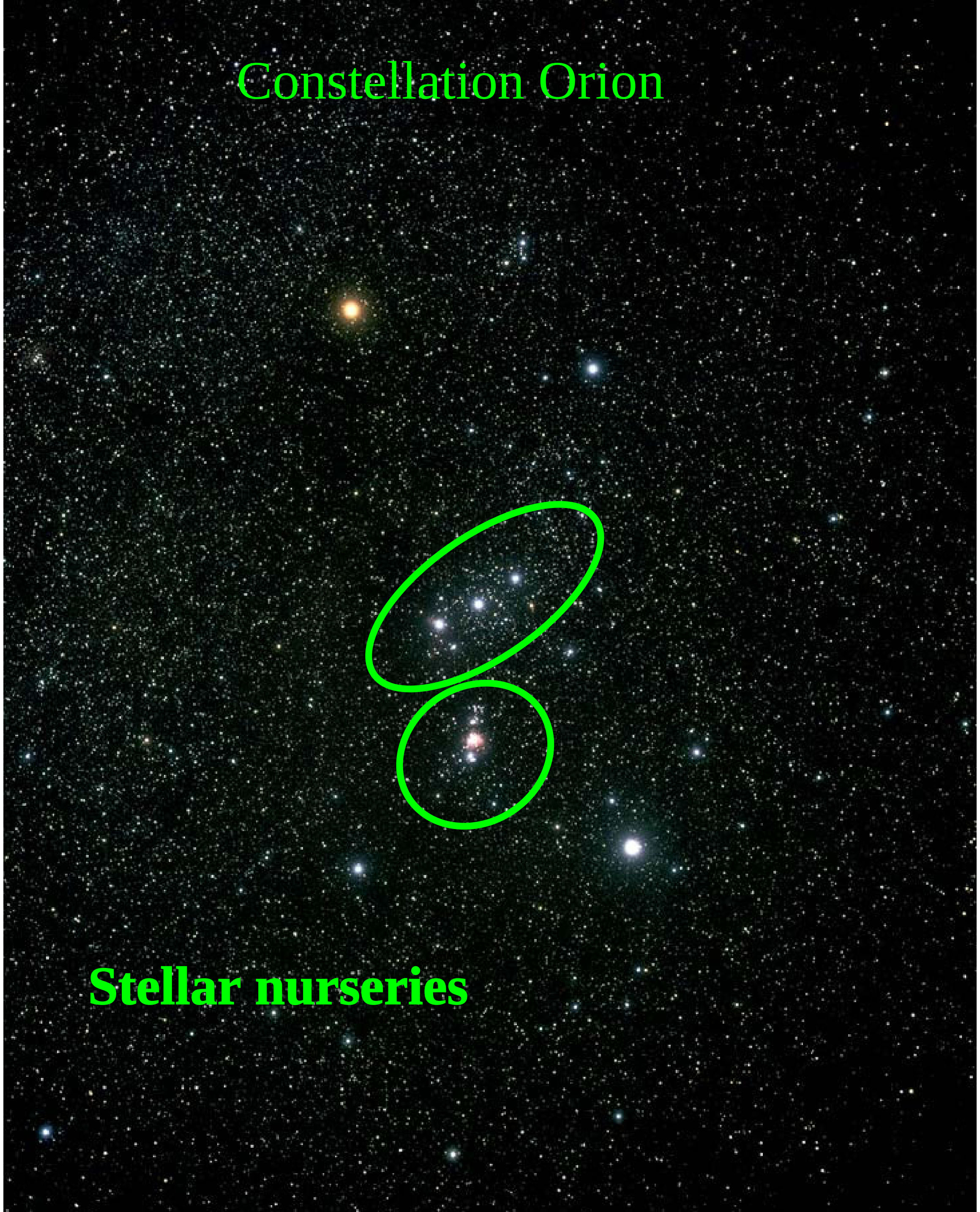
All protostellar systems will be rotating; higher angular momentum material collapses along cylinders to conserve J

Protostars surrounded by DISKS-- sites of PLANET FORMATION

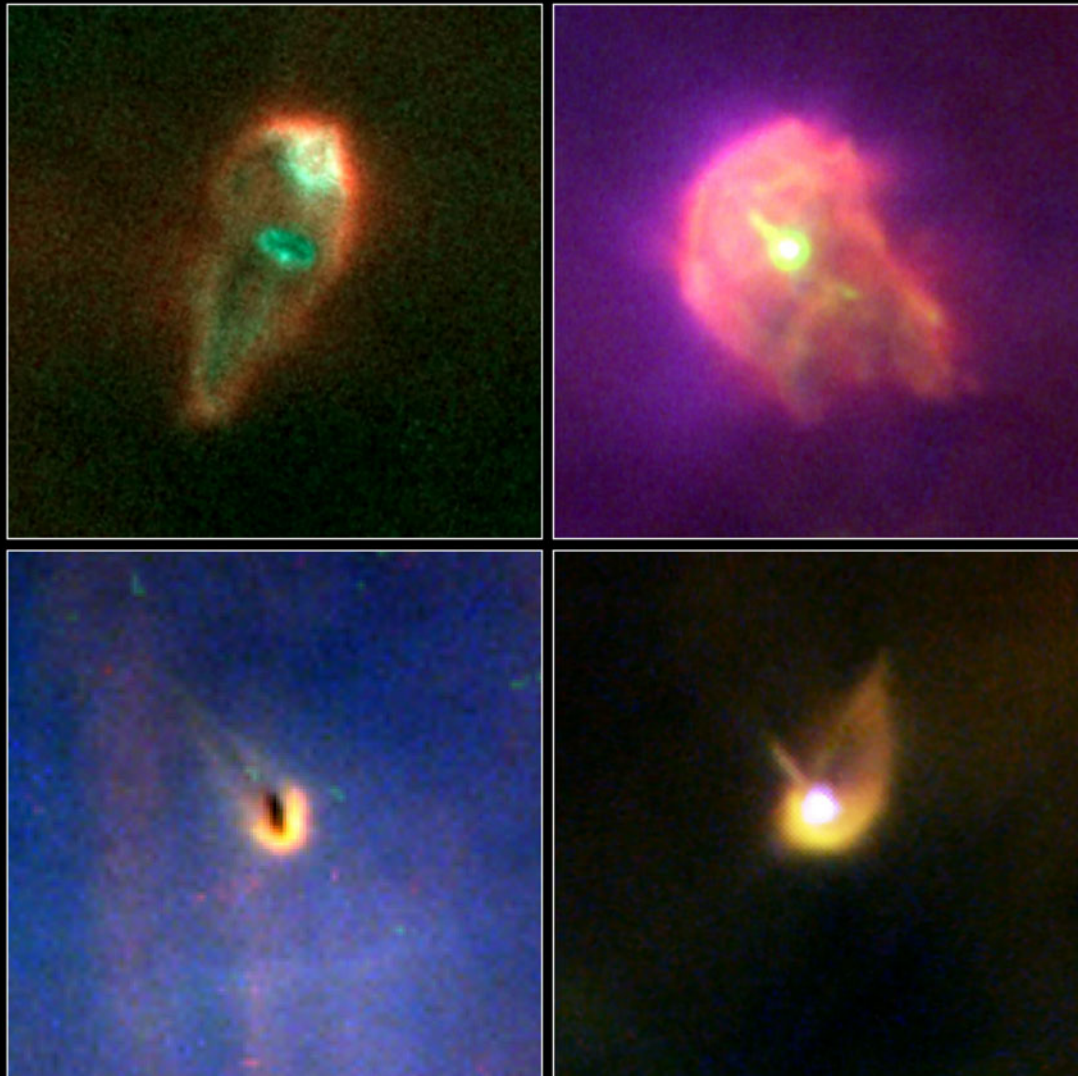
Collapse and Flattening of an Interstellar Cloud to Form Solar Nebula

Collapse ~ along cylinders keeps J~constant



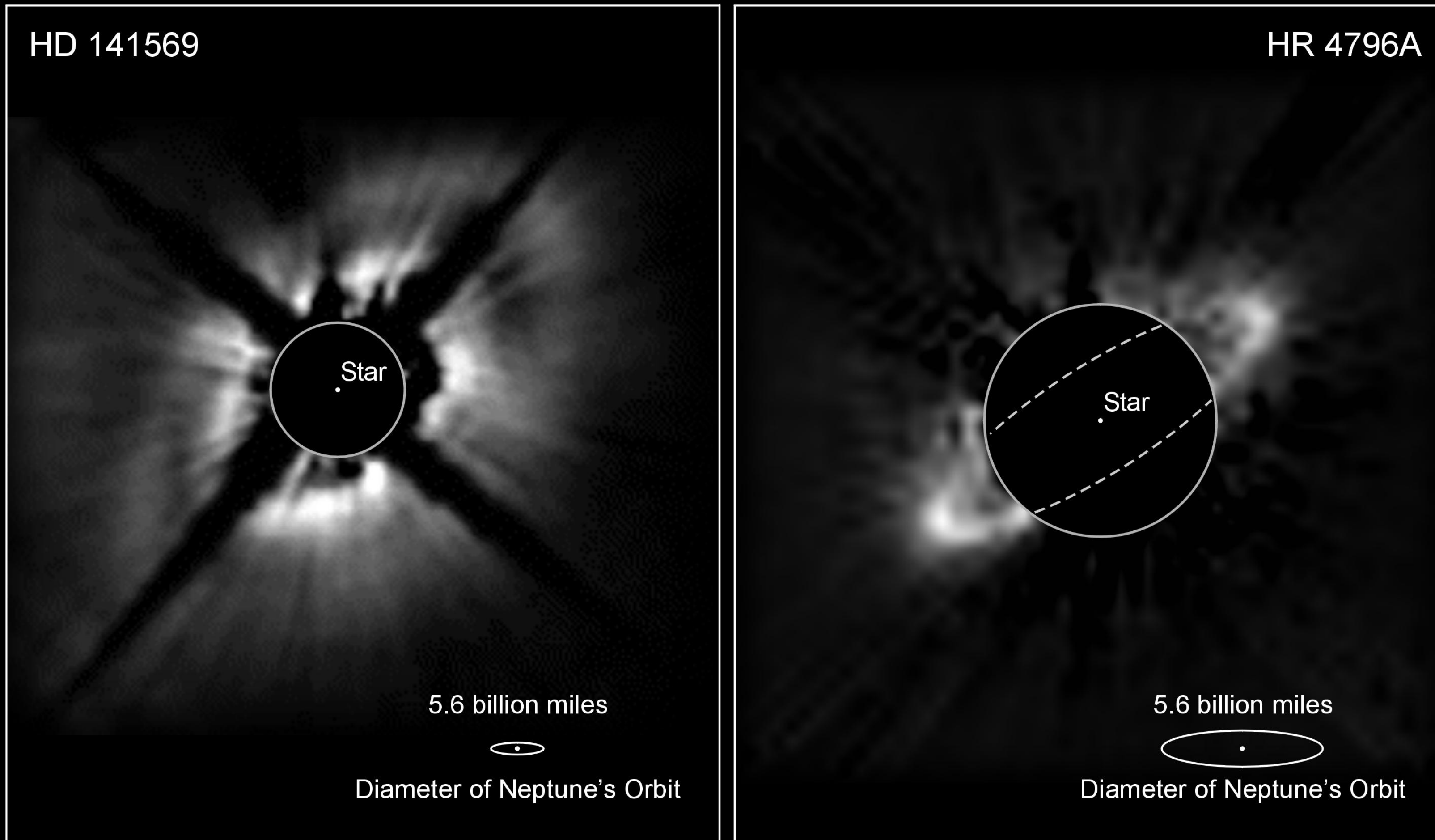

Constellation Orion
Stellar nurseries

Orion Nebula--Young Stellar Region; Age <3 Myr



Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

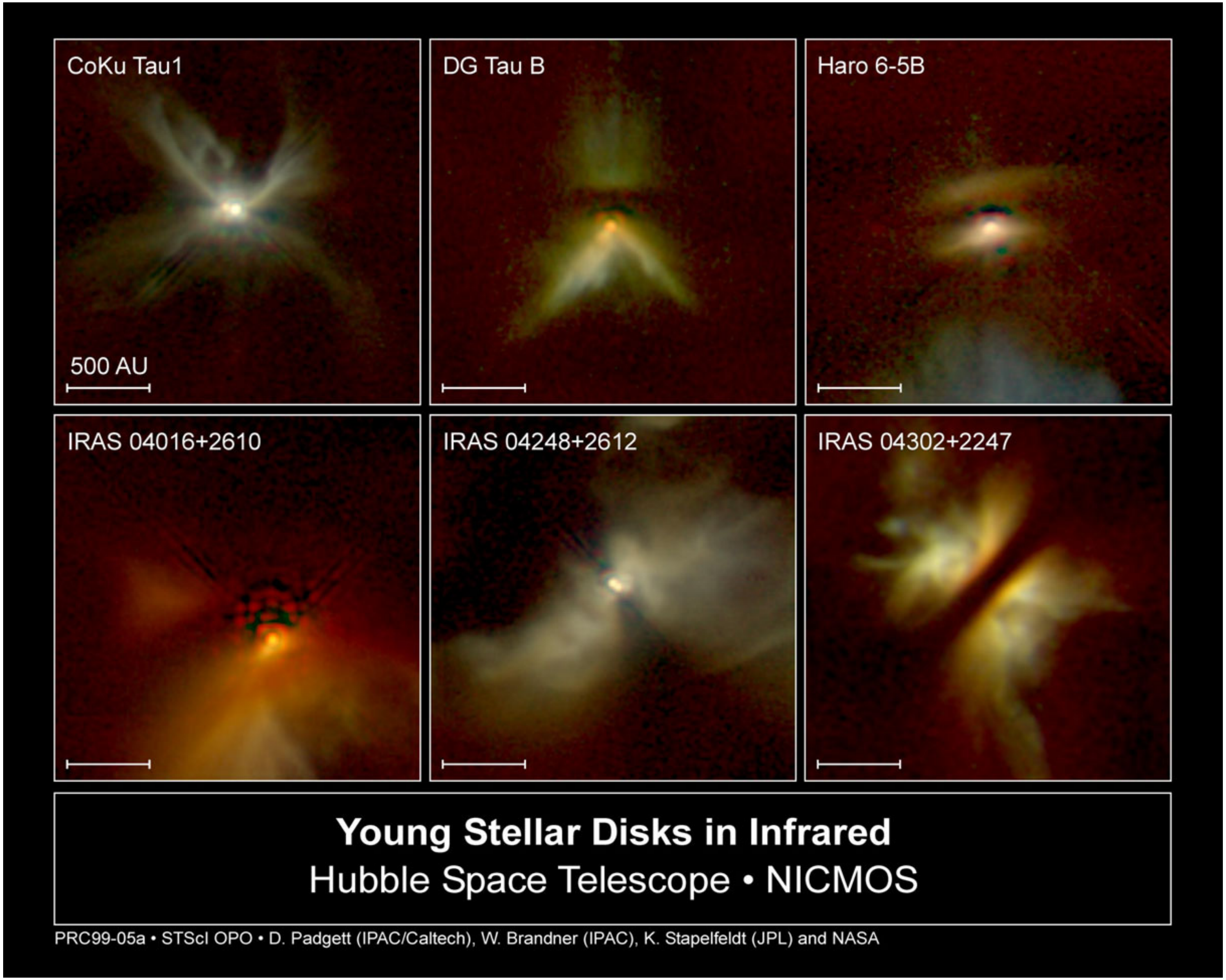
NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
STScI-PRC01-13



Dust Rings around Stars

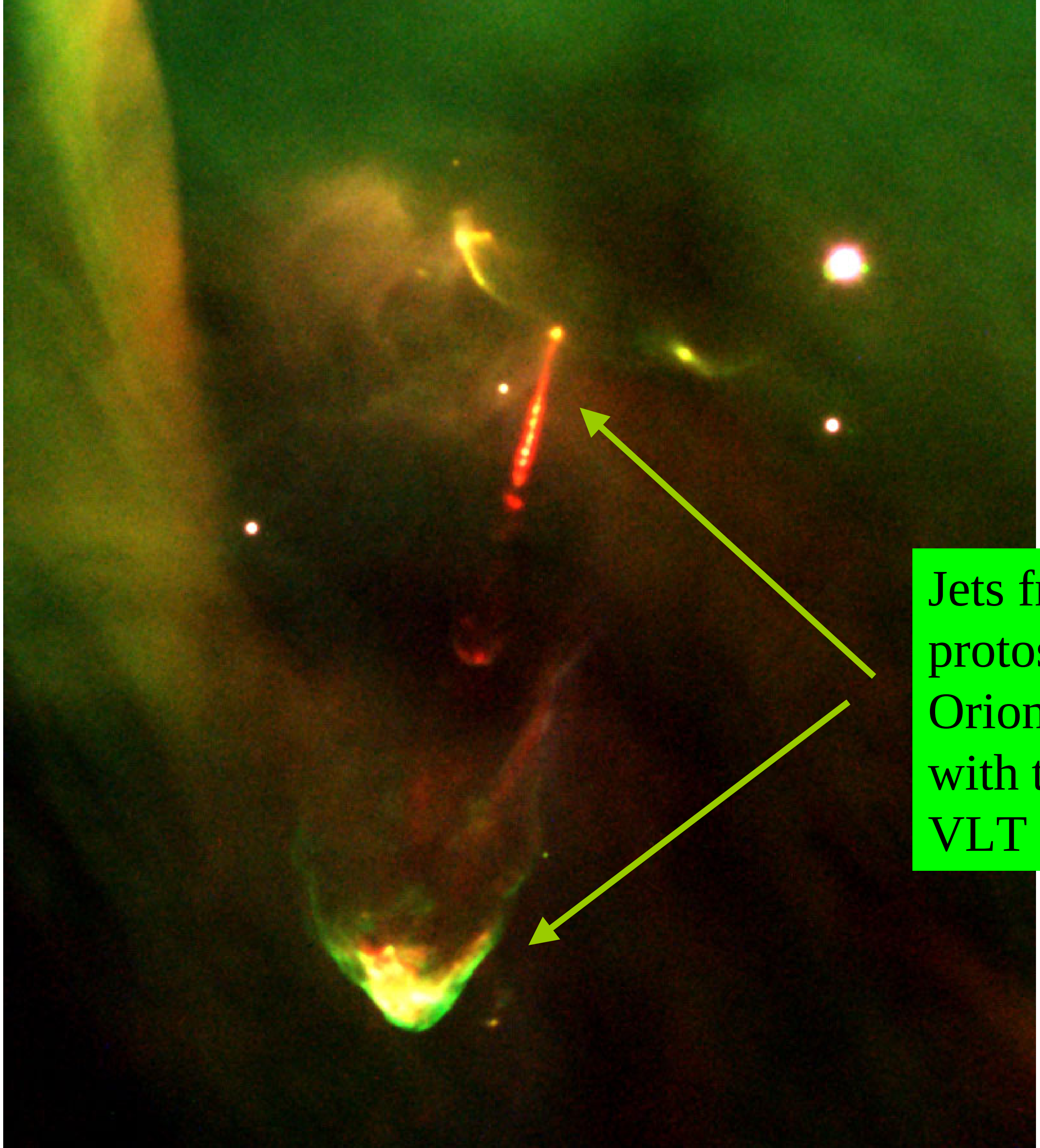
Hubble Space Telescope • NICMOS

PRC99-03 • STScI OPO • B. Smith (University of Hawaii), G. Schneider (University of Arizona), E. Becklin and A. Weinberger (UCLA) and NASA

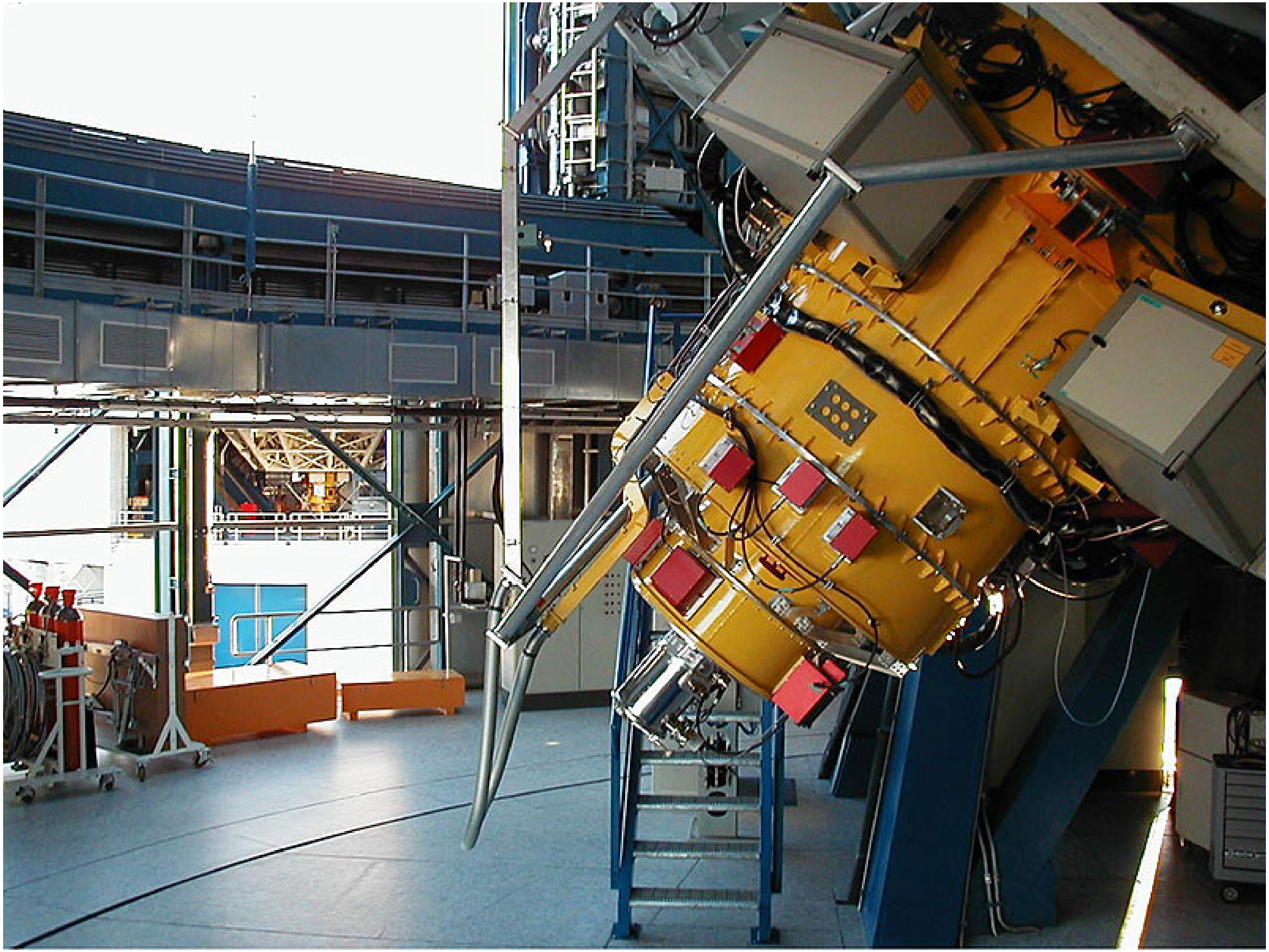

CoKu Tau1
500 AU
DG Tau B
Haro 6-5B
IRAS 04016+2610
IRAS 04248+2612
IRAS 04302+2247
Young Stellar Disks in Infrared
Hubble Space Telescope • NICMOS
PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Multiple observations support presence of disks around lower mass protostars and "young stellar objects" (YSOs).

If planets form in circumstellar disks, then planet formation may be common.

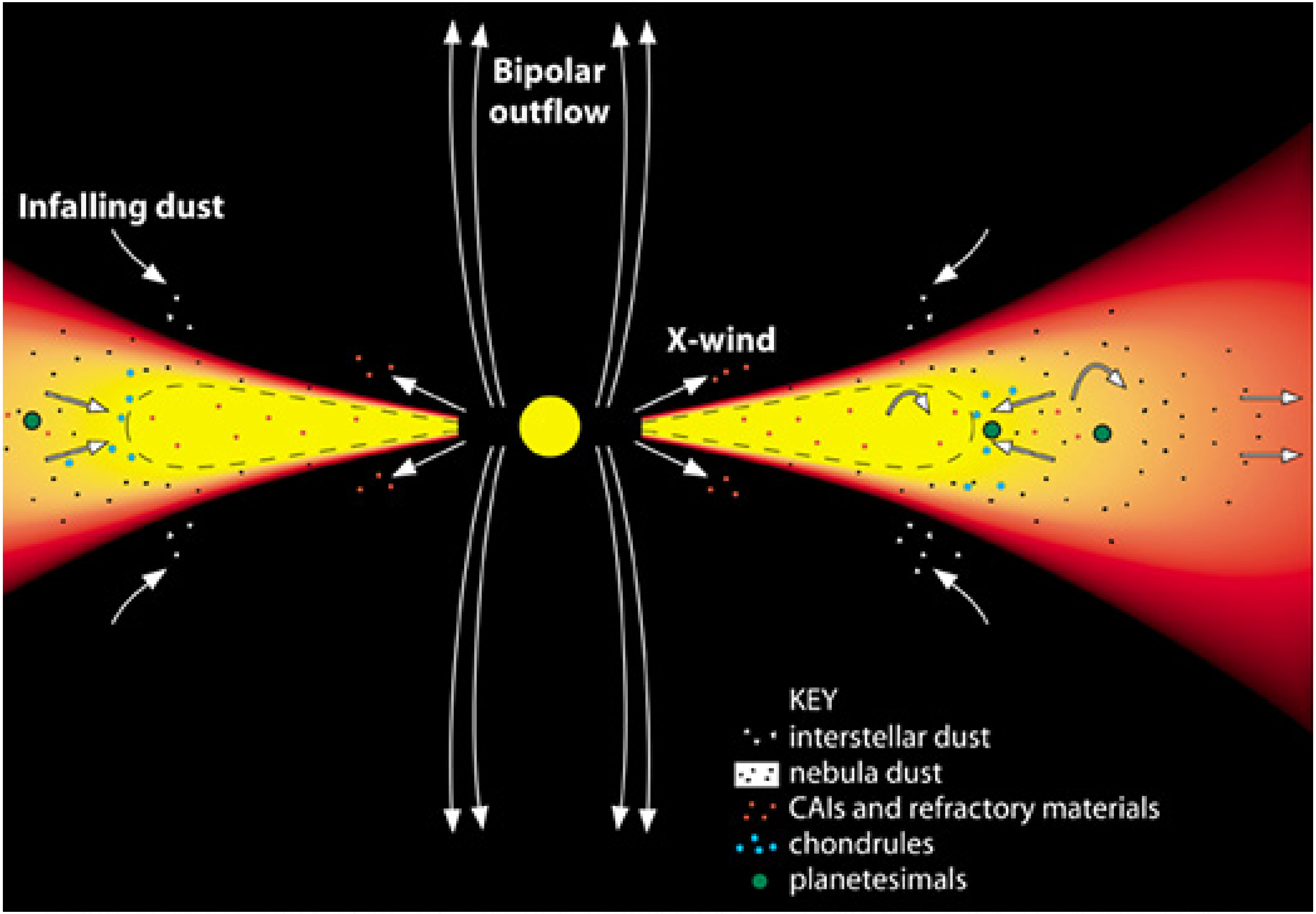


Jets from protostar in Orion taken with the VLT

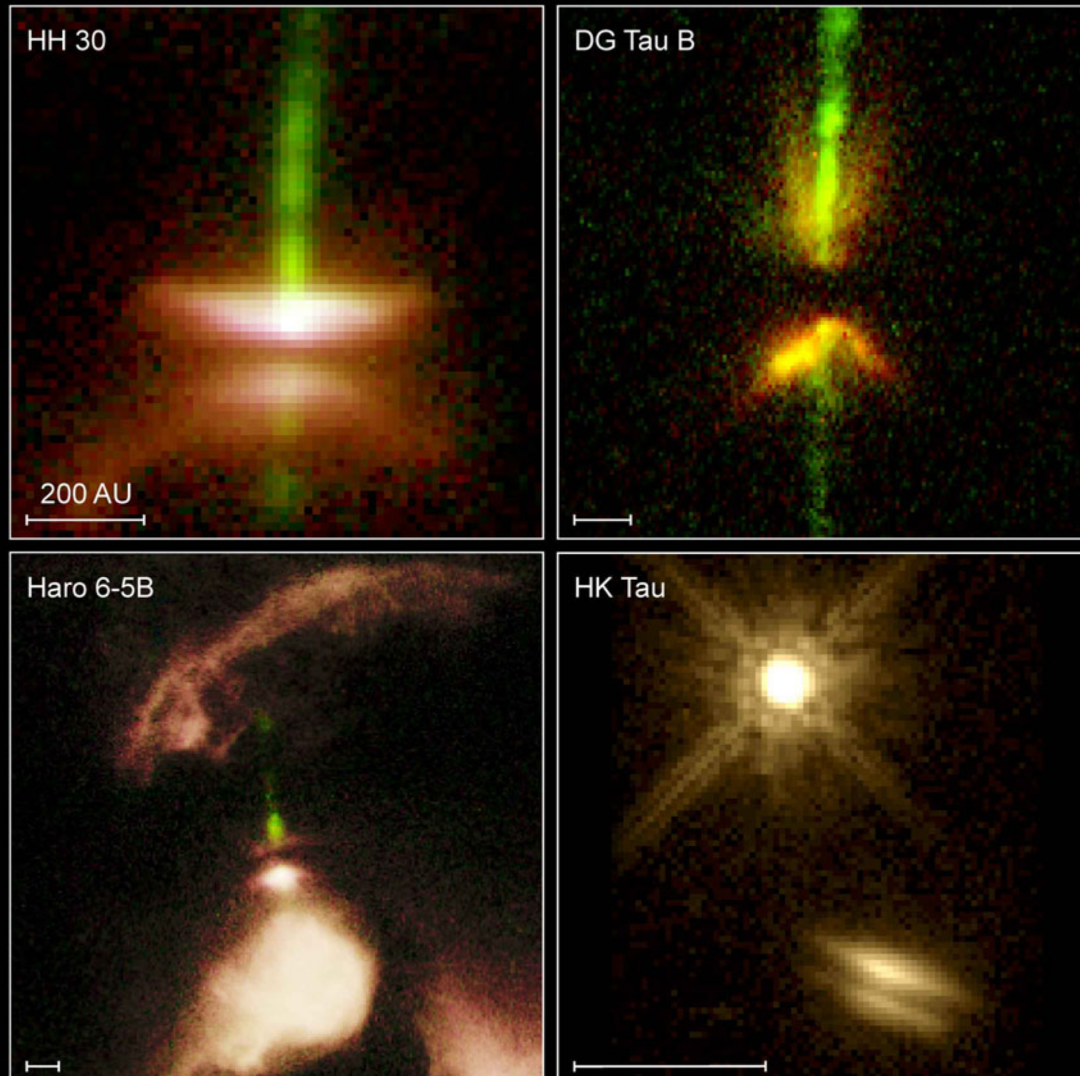


The FORS Twins at VLT ANTU and KUEYEN

ESO PR Photo 40a/99 (17 November 1999)



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

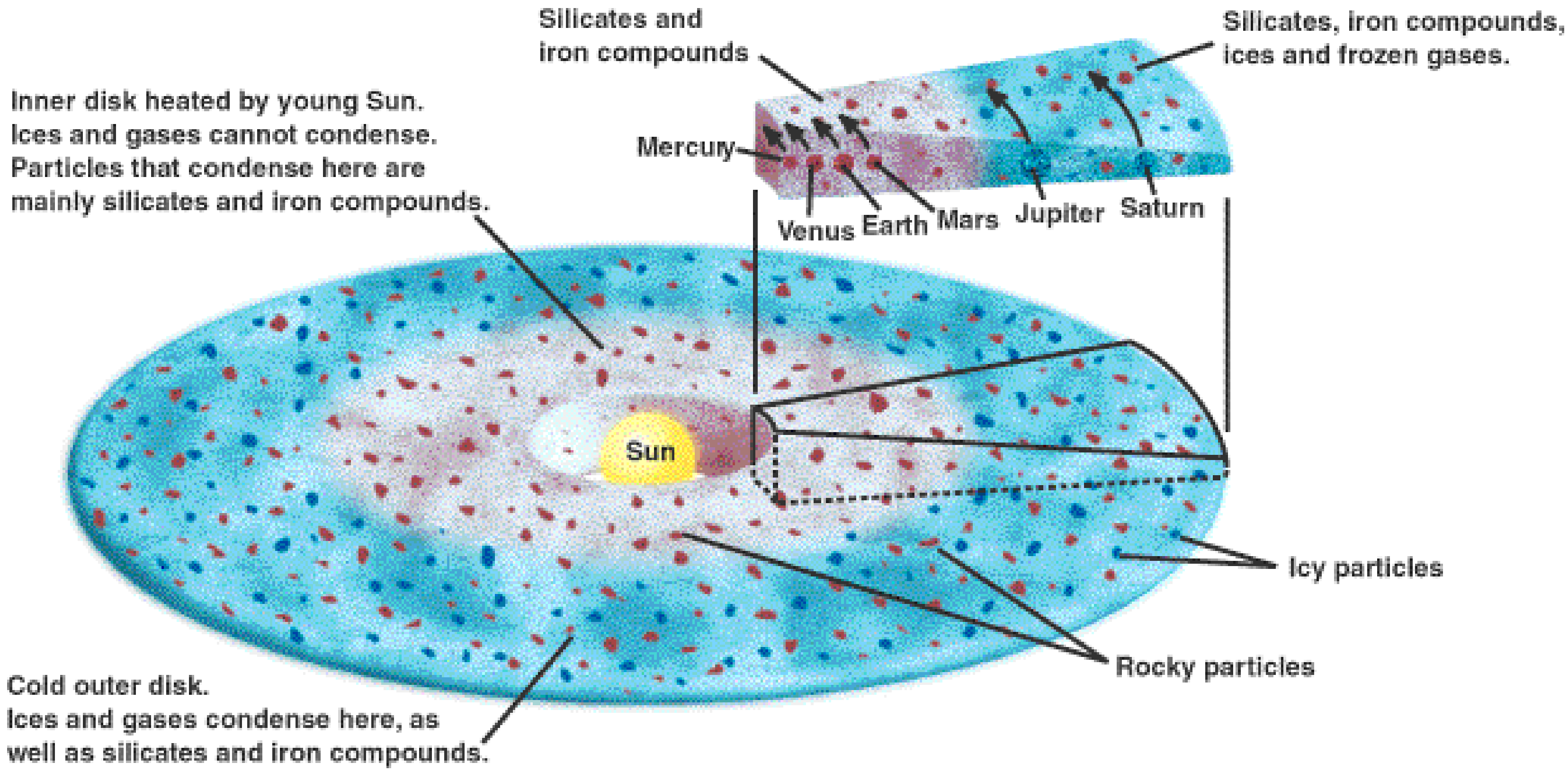


Disks around Young Stars

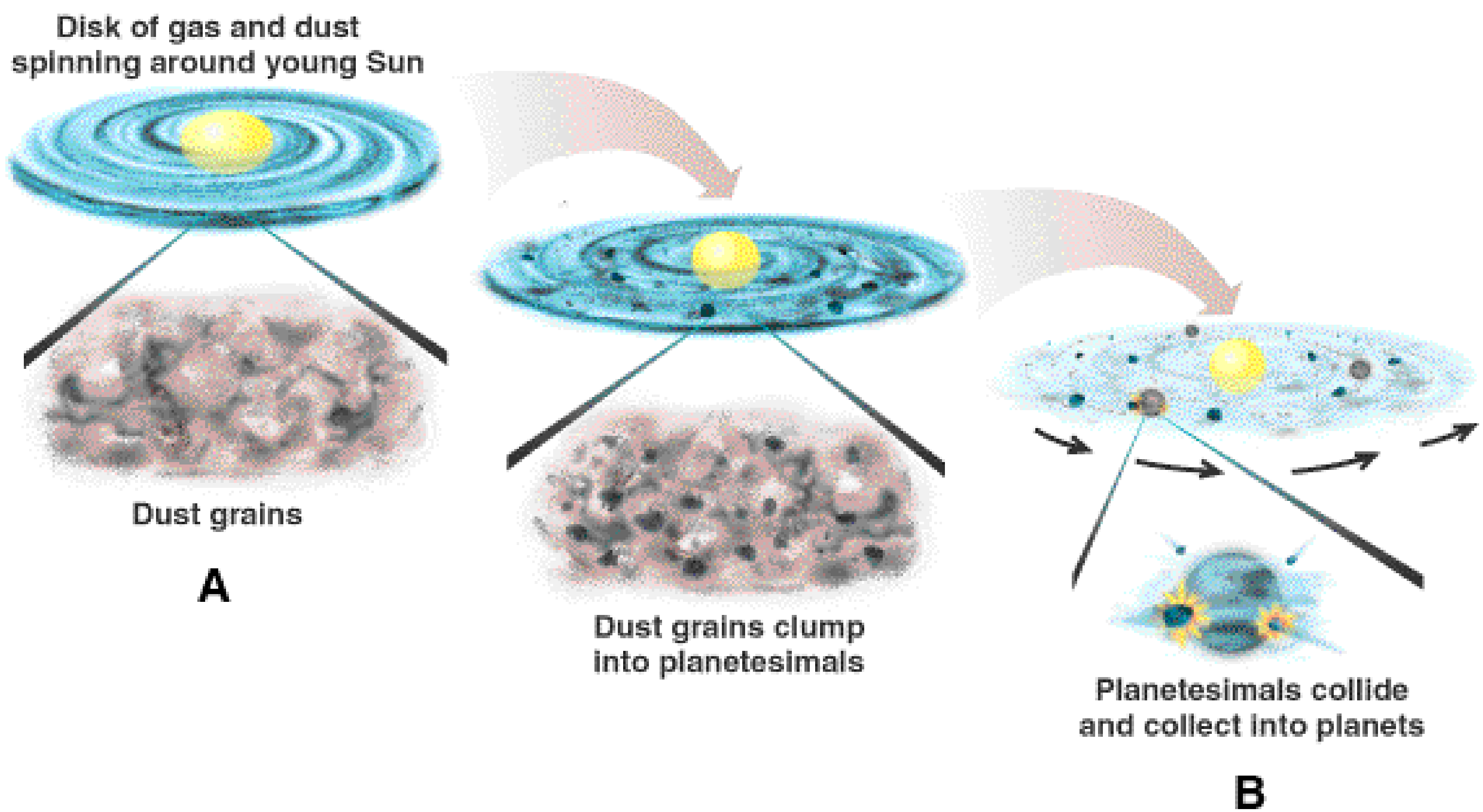
Hubble Space Telescope • WFPC2

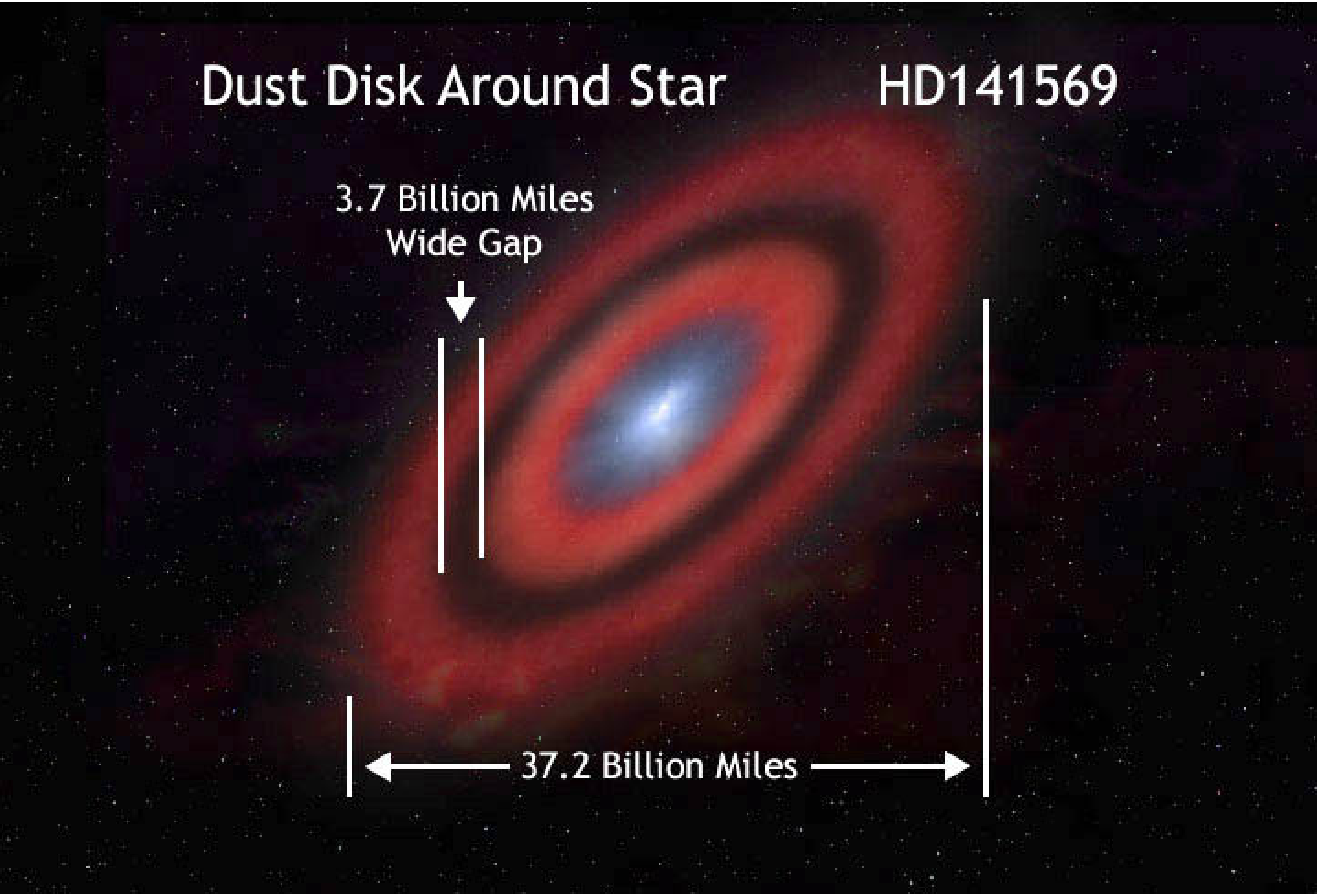
PRC99-05b • STScI OPO • C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

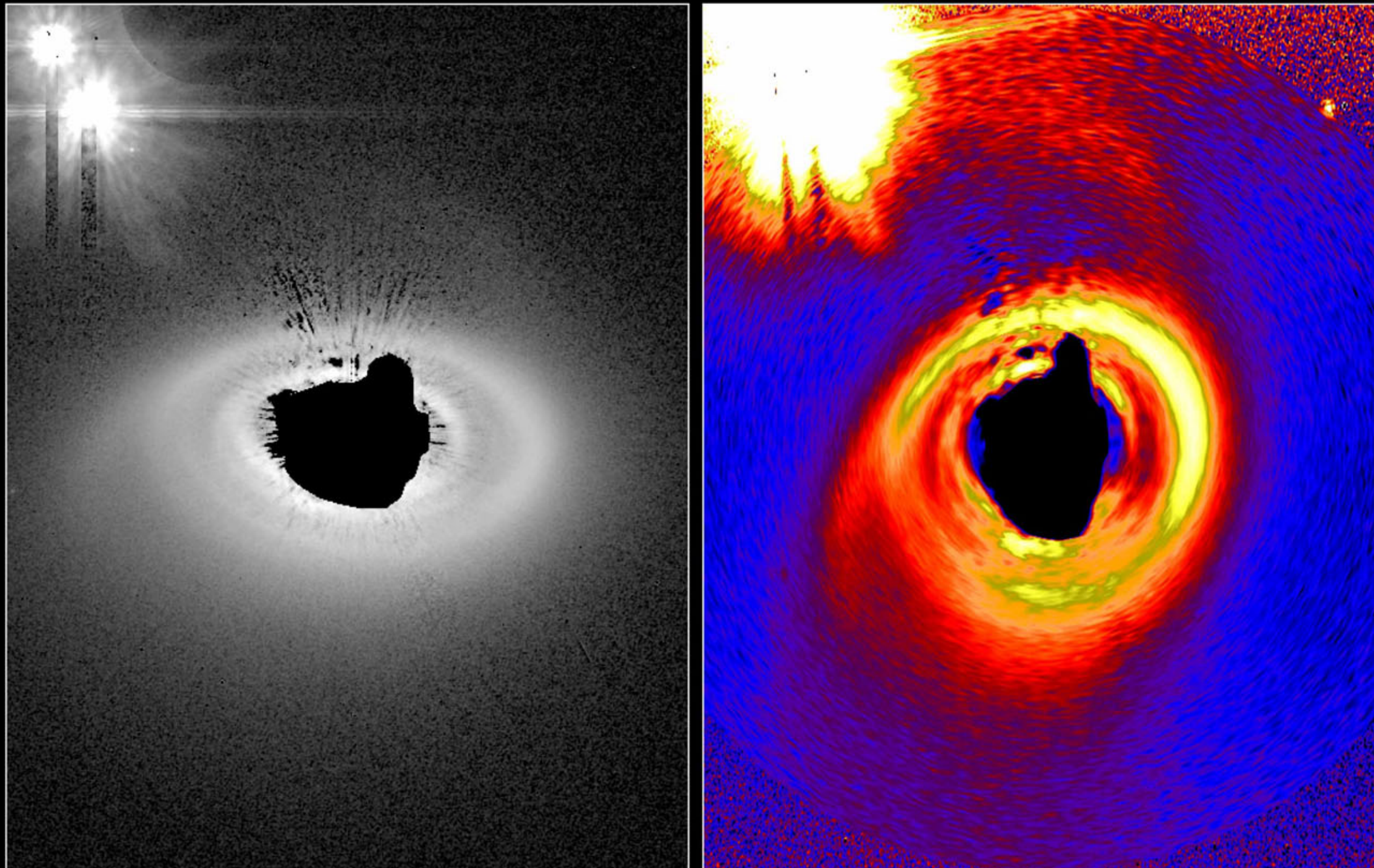
Formation of Icy and Rocky Planetesimals



Planet Building



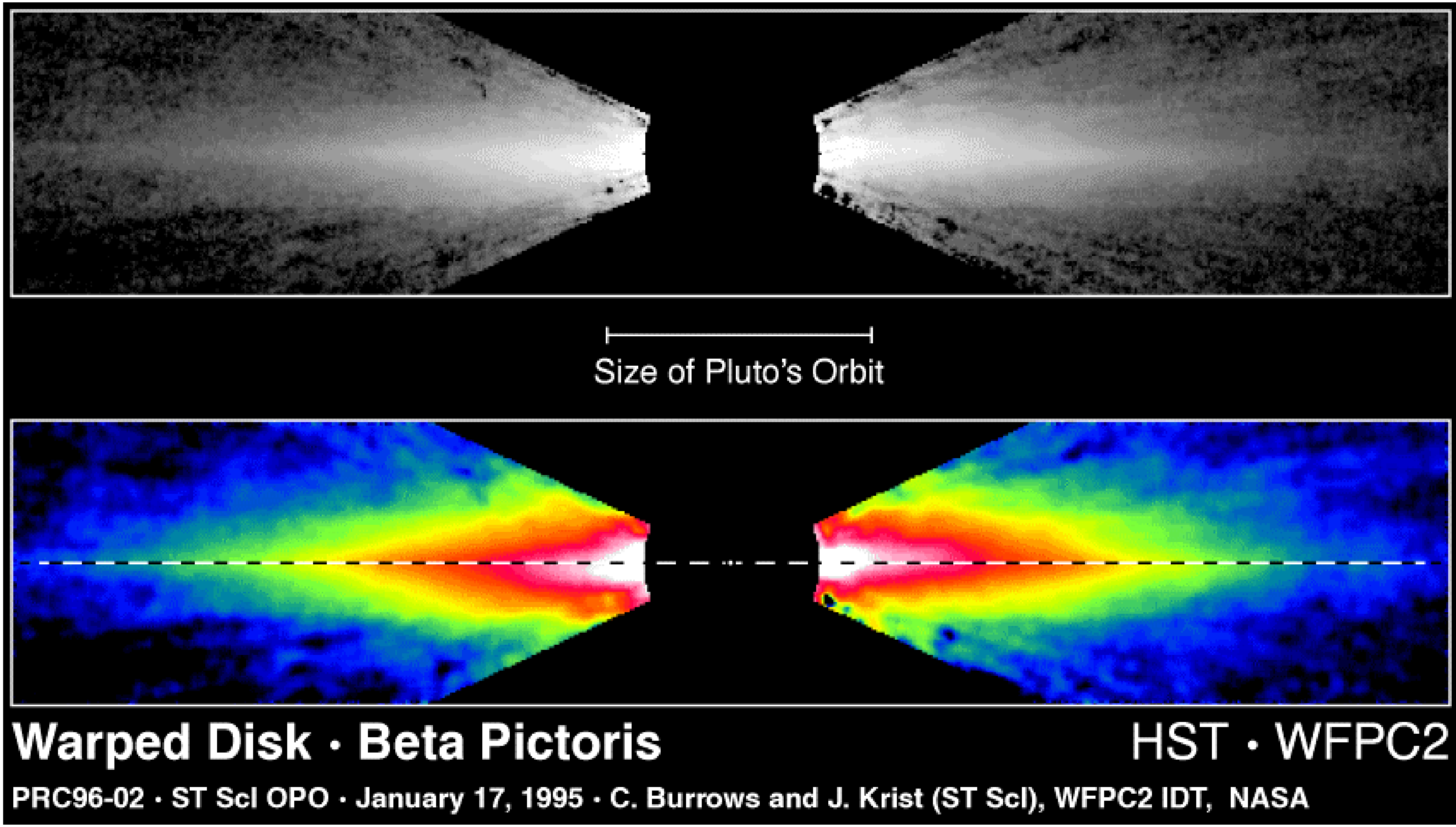

Dust Disk Around Star
HD141569
3.7 Billion Miles
Wide Gap
37.2 Billion Miles



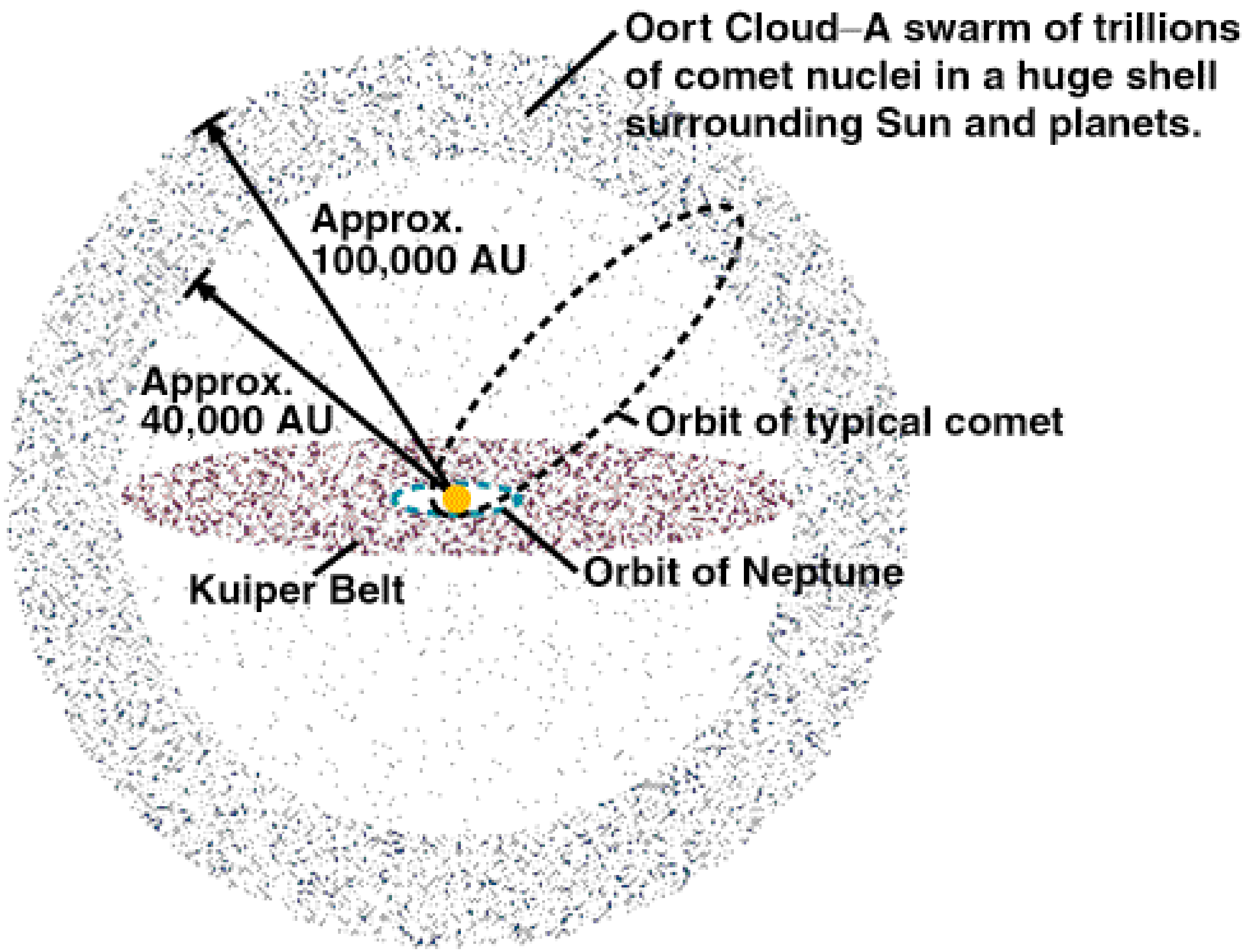
HD 141569 Circumstellar Disk

Hubble Space Telescope ▪ ACS HRC Coronagraph

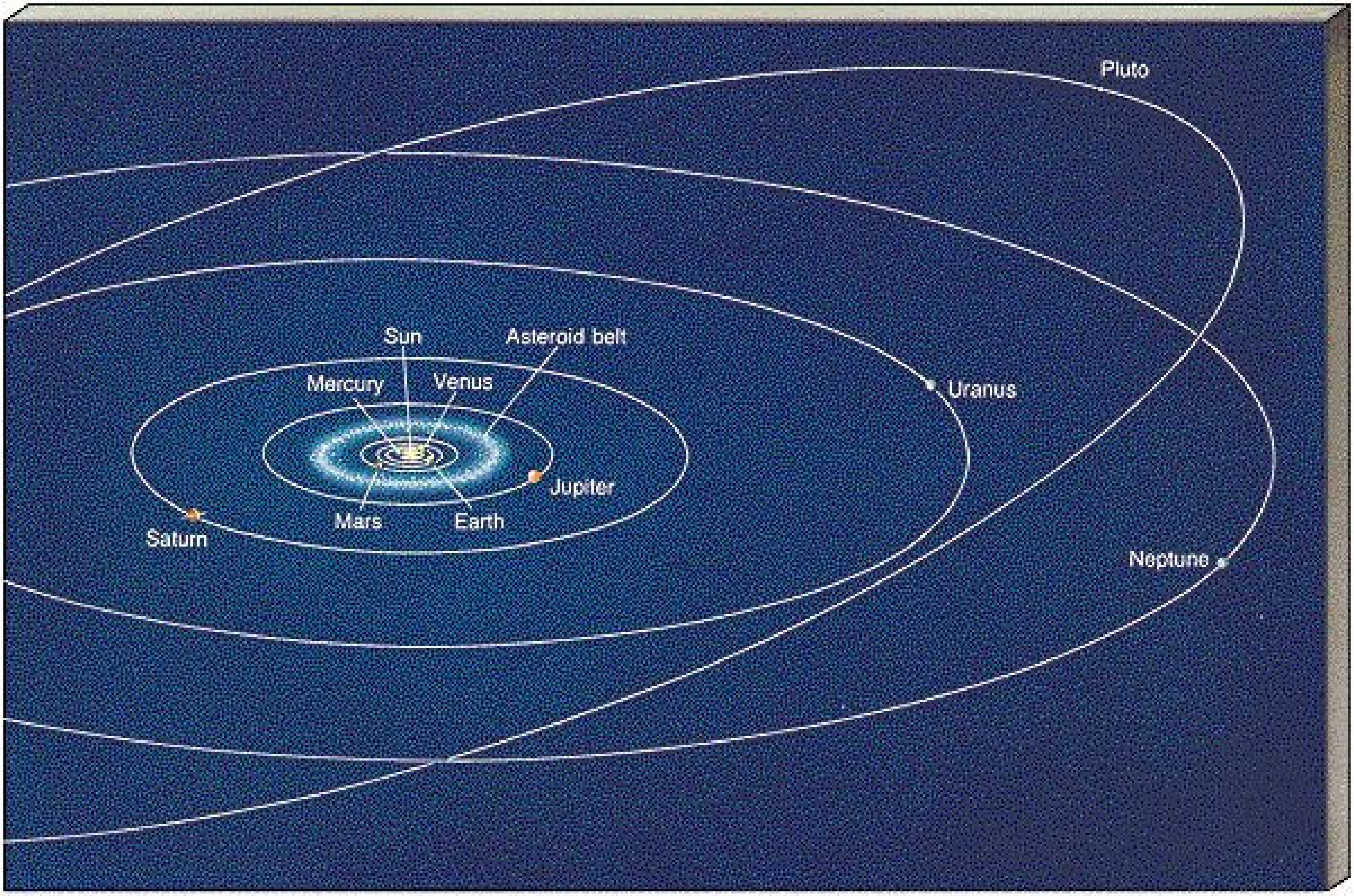
NASA, M. Clampin (STScI), H. Ford (JHU), G. Illingworth (UCO/Lick Observatory),
J. Krist (STScI), D. Ardila (JHU), D. Golimowski (JHU), and the ACS Science Team ▪ STScI-PRC03-02


Size of Pluto's Orbit
Warped Disk • Beta Pictoris
HST • WFPC2
PRC96-02 • ST ScI OPO • January 17, 1995 • C. Burrows and J. Krist (ST ScI), WFPC2 IDT, NASA

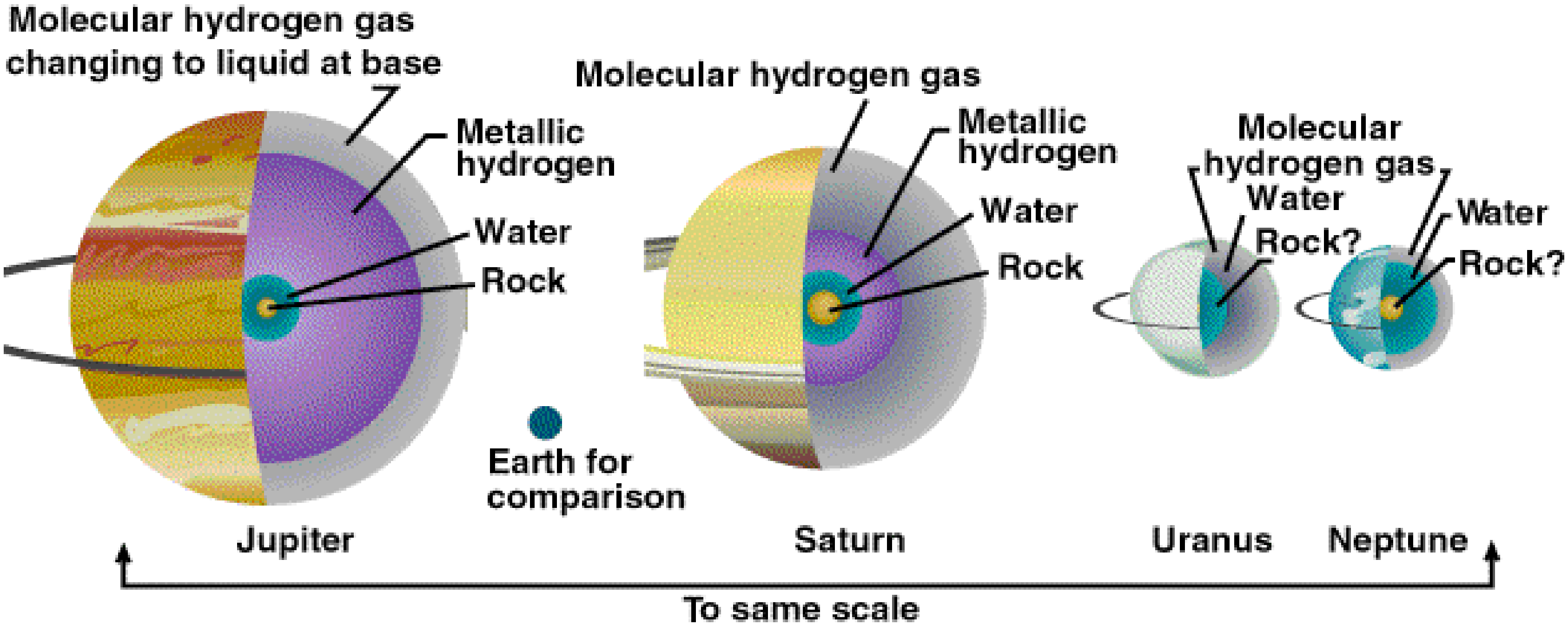
Oort Cloud and Kuiper Belt



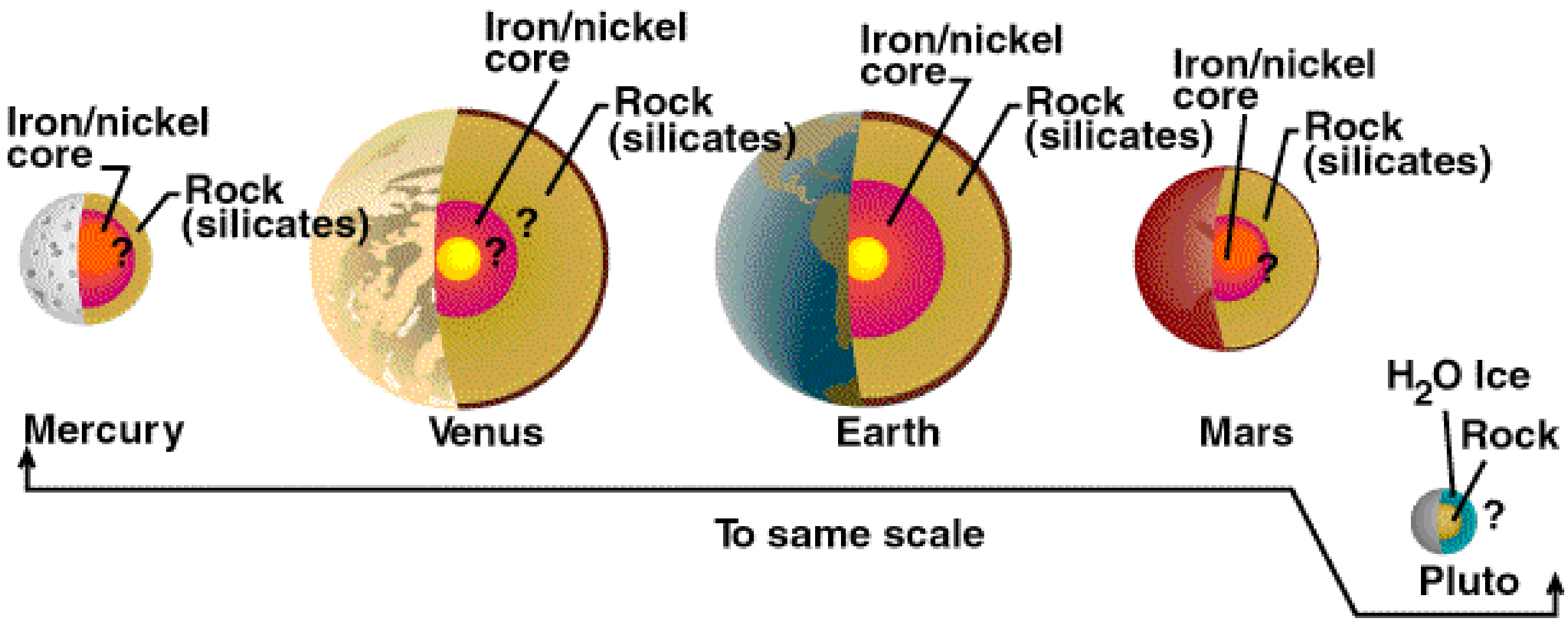
Solar system--remnants of a disk: ~coplanar, all planets orbit in same direction



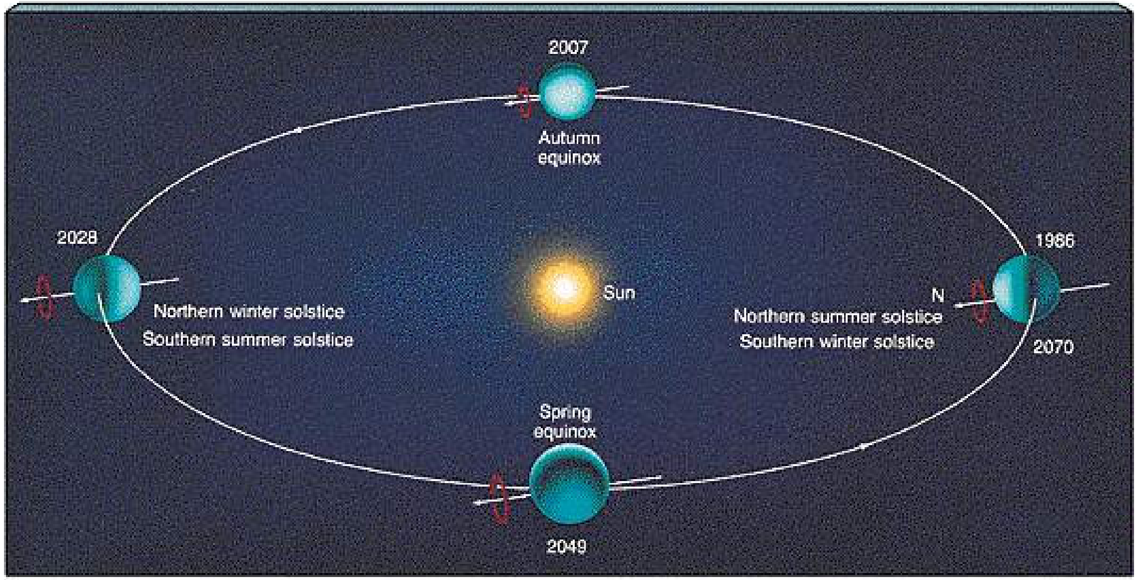
Cut Aways of Planets



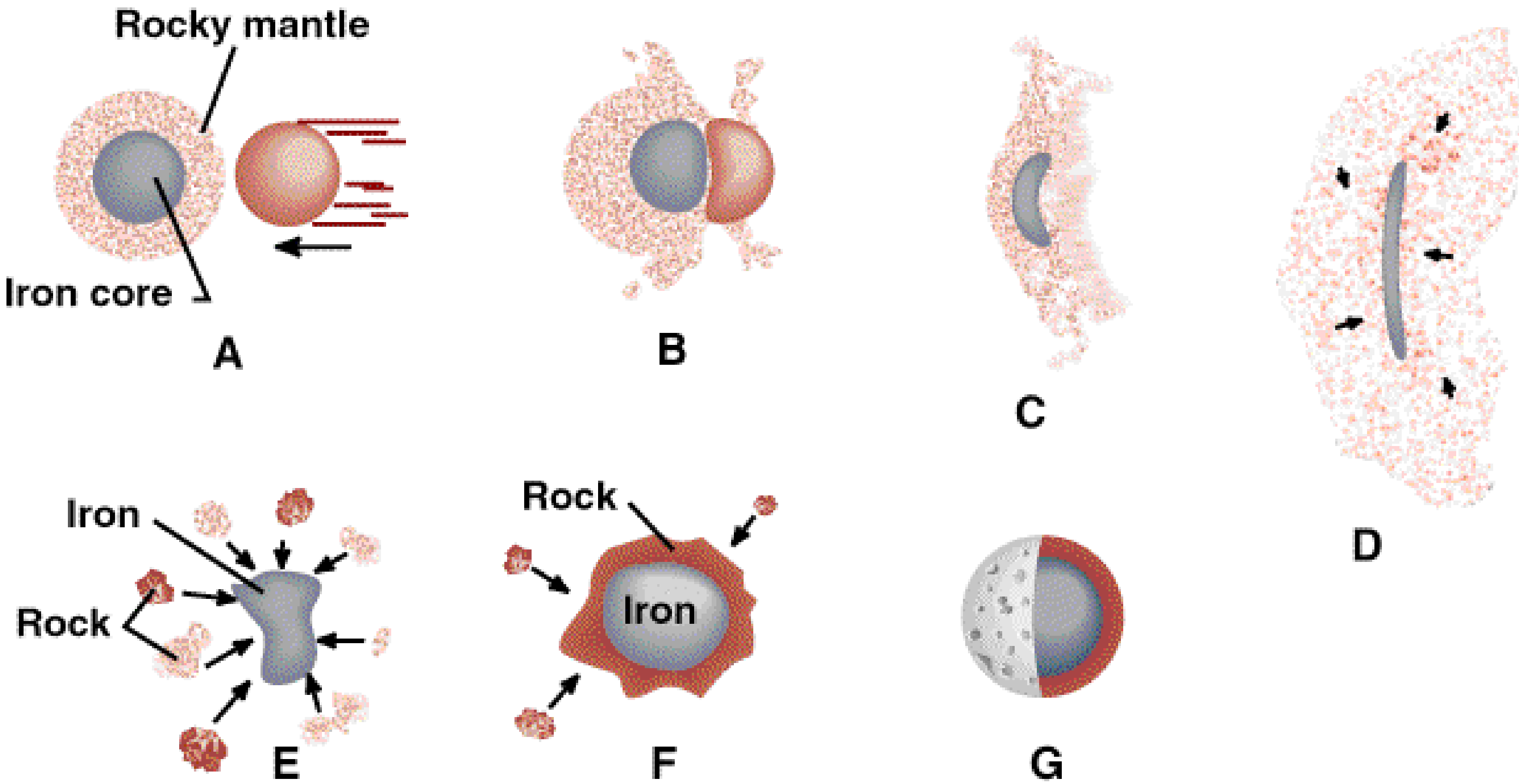
Cut Aways of Planets



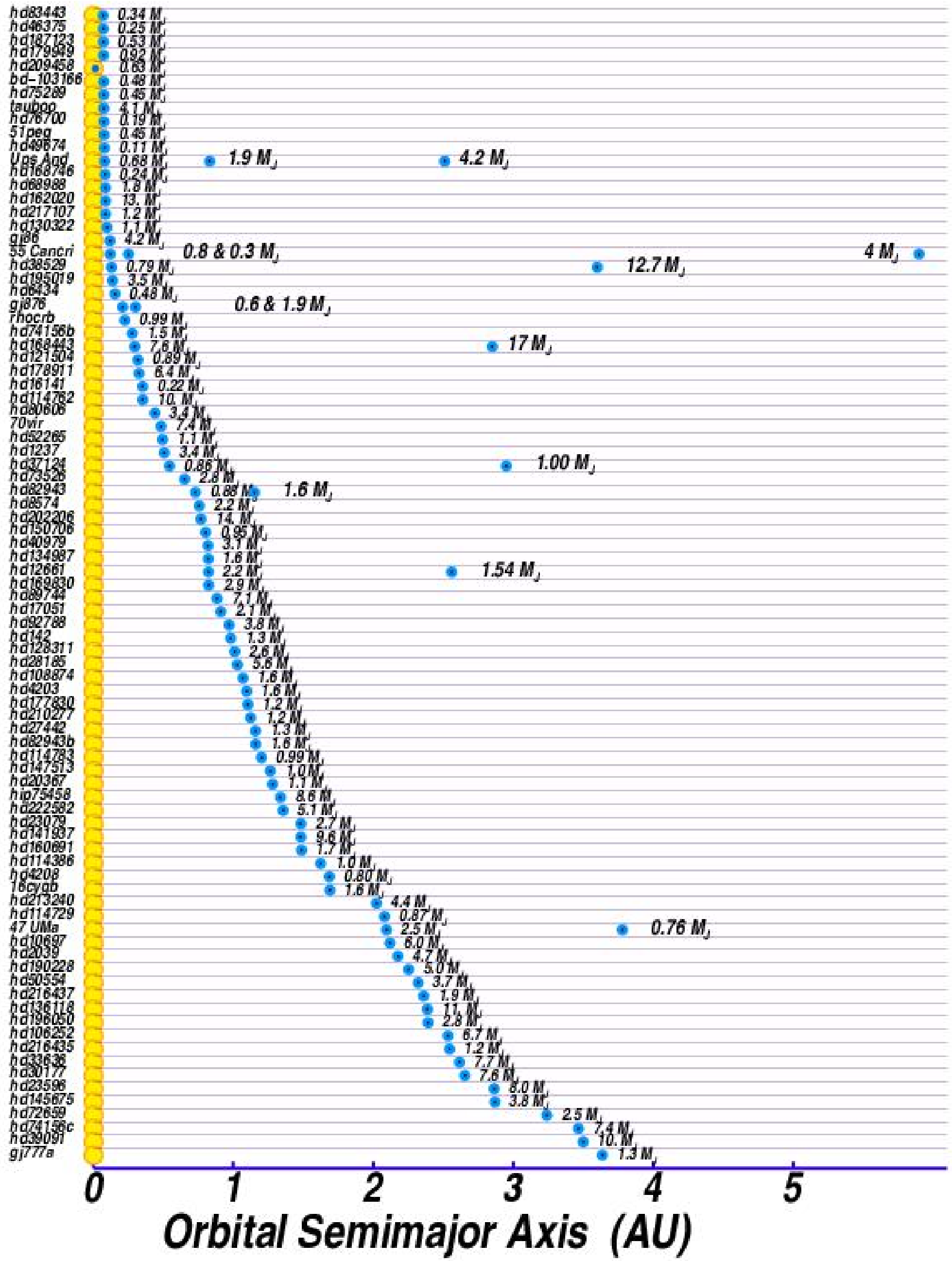
Tilted spin axis --> collisions!



Computer Simulation: The Stripping of Mercury's Crust by Impact



Is the solar system REALLY a typical planetary system?



hd83443 0.34 MJ
hd46375 0.25 MJ
hd187123 0.53 MJ
hd179949 0.92 MJ
hd209458 0.63 MJ
bd-103166 0.48 MJ
hd75289 0.45 MJ
tauboo 4.1 MJ
hd76700 0.19 MJ
51peg 0.45 MJ
hd49674 0.11 MJ
Ups And 0.68 MJ 1.9 MJ 4.2 MJ
hd168746 0.24 MJ
hd68988 1.8 MJ
hd162020 13. MJ
hd217107 1.2 MJ
hd130322 1.1 MJ
gj86 4.2 MJ
55 Cancri 0.8 & 0.3 MJ 4 MJ
hd38529 0.79 MJ 12.7 MJ
hd195019 3.5 MJ
hd6434 0.48 MJ
gj876 0.6 & 1.9 MJ
rhocrb 0.99 MJ
hd74156b 1.5 MJ
hd168443 7.6 MJ 17 MJ
hd121504 0.89 MJ
hd178911 6.4 MJ
hd16141 0.22 MJ
hd114762 10. MJ
hd80606 3.4 MJ
70vir 7.4 MJ
hd52265 1.1 MJ
hd1237 3.4 MJ
hd37124 0.86 MJ 1.00 MJ
hd73526 2.8 MJ
hd82943 0.88 MJ 1.6 MJ
hd8574 2.2 MJ
hd202206 14. MJ
hd150706 0.95 MJ
hd40979 3.1 MJ
hd134987 1.6 MJ
hd12661 2.2 MJ 1.54 MJ
hd169830 2.9 MJ
hd89744 7.1 MJ
hd17051 2.1 MJ
hd92788 3.8 MJ
hd142 1.3 MJ
hd128311 2.6 MJ
hd28185 5.6 MJ
hd108874 1.6 MJ
hd4203 1.6 MJ
hd177830 1.2 MJ
hd210277 1.2 MJ
hd27442 1.3 MJ
hd82943b 1.6 MJ
hd114783 0.99 MJ
hd147513 1.0 MJ
hd20367 1.1 MJ
hip75458 8.6 MJ
hd222582 5.1 MJ
hd23079 2.7 MJ
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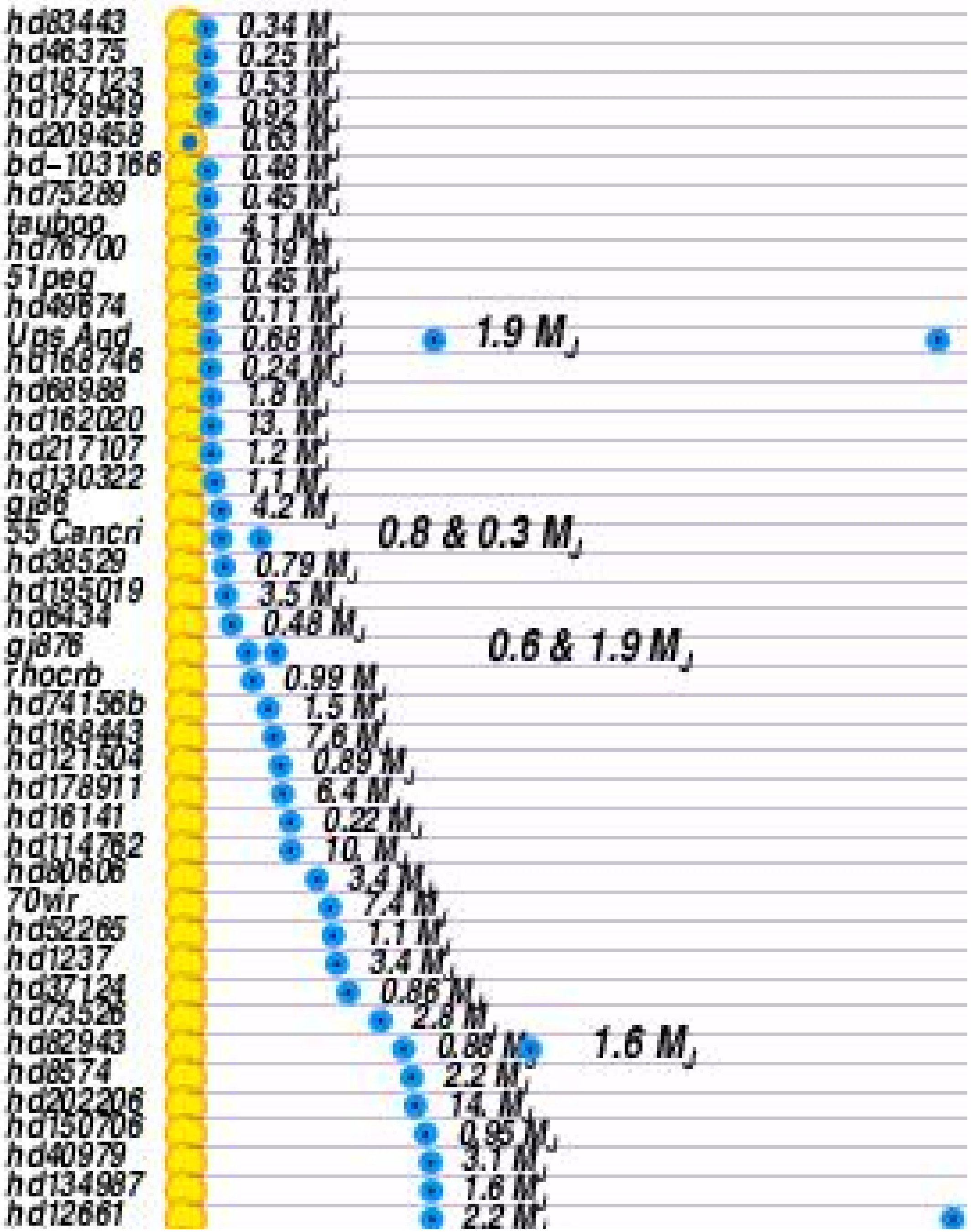
hd2039 4.7 MJ
hd190228 5.0 MJ
hd50554 3.7 MJ
hd216437 1.9 MJ
hd136118 11. MJ
hd196050 2.8 MJ
hd106252 6.7 MJ
hd216435 1.2 MJ
hd33636 7.7 MJ
hd30177 7.6 MJ
hd23596 8.0 MJ
hd145675 3.8 MJ
hd72659 2.5 MJ
hd74156c 7.4 MJ
hd39091 10. MJ
gj777a 1.3 MJ
0
1
2
3
4
5
Orbital Semimajor Axis (AU)



hd83443 0.34 MJ
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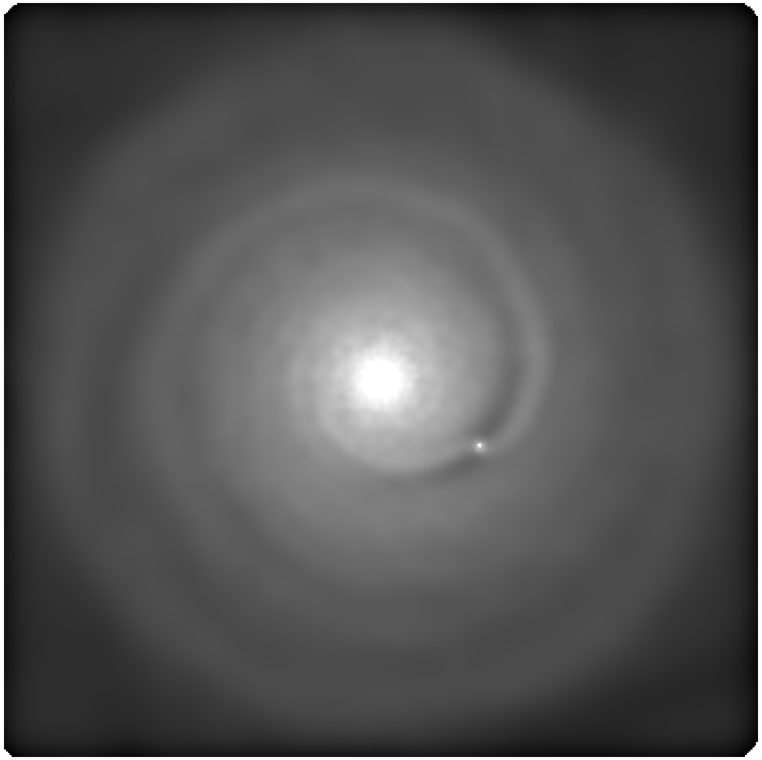
hd82943 0.88 MJ 1.6 MJ
hd8574 2.2 MJ
hd202206 14. MJ
hd150706 0.95 MJ
hd40979 3.1 MJ
hd134987 1.6 MJ
hd12661 2.2 MJ

Is the solar system REALLY a typical planetary system?

Not clear--giant planets can exist near their stars

Interactions within disks may lead to PLANET MIGRATION where giant planets move inwards



Solar systems are not unusual and are natural side-products of star formation.

BUT frequency of solar systems like ours with terrestrial planets remains to be determined