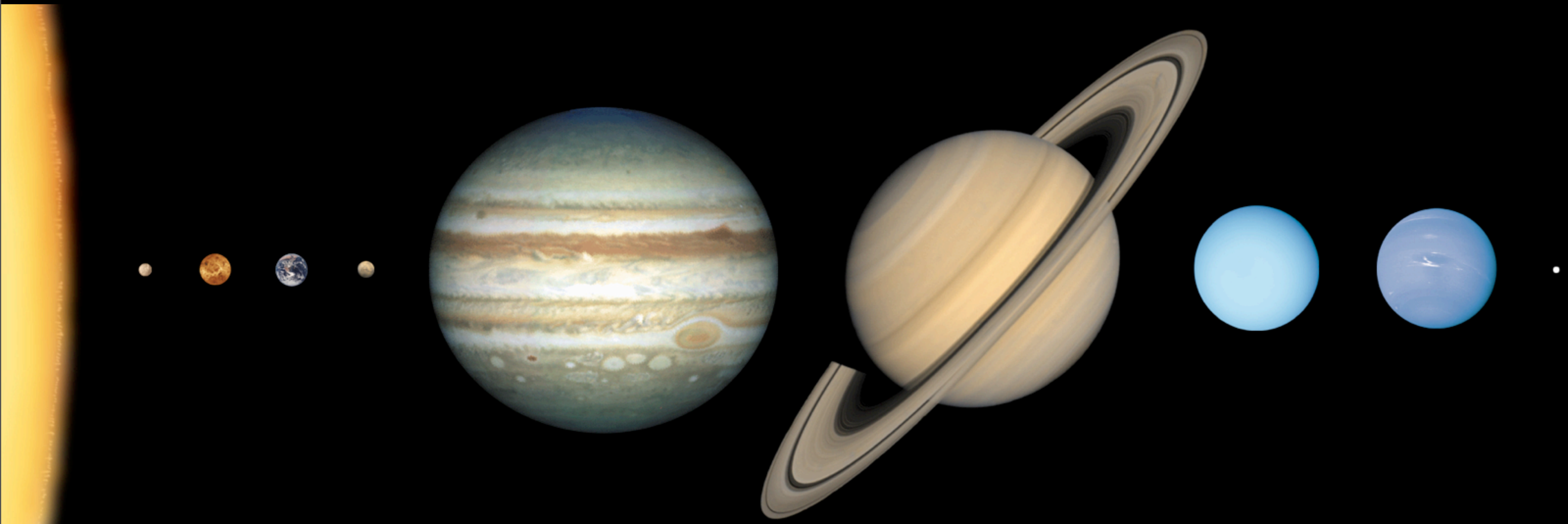
Theory of planet formation



Pre-1995 theory failed to predict:

- high frequency of planets
- existence of planets much more massive than Jupiter
- sharp upper limit of around 15 $M_{Jupiter}$
- giant planets at very small semi-major axes
- high eccentricities
- high obliquities

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Theory reliably predicts:

- planets should not exist

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Theory reliably predicts:

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> "almost every prediction by theorists about planetary formation has been wrong" (Tremaine 2002)

The brown dwarf hypothesis

- **extrasolar "planets" are simply very low-mass stars that form from collapse of multiple condensations in protostellar clouds**
- **good points:**
  - distribution of eccentricities and periods of massive extrasolar planets very similar to distributions for binary stars
- **bad points:**
  - why is there a brown-dwarf desert?
  - how did planets in solar system get onto circular, coplanar orbits?
  - how do you make planets with solid cores, or terrestrial planets?
  - theory suggests that it is hard to make objects as small as Jupiter by fragmentation of a gas cloud
- **maybe the most massive extrasolar planets are made this way**

The encounter hypothesis

- Close encounter with a passing star rips material off the Sun that spreads into a long filament and condenses into planets (Buffon 1745, Jeans 1928, Jeffreys 1929)
- Problems:
  - very rare event: needs impact parameter $< 2\ R_\odot$ so only happens to 1 in 10^8 stars
  - specific angular momentum of order $(GM_\odot R_\odot)^{1/2}$ not $(GM_\odot a_J)^{1/2}$; factor 30 too small (Russell 1935) (not a problem for some extrasolar planets!)
  - 1 Jupiter mass of material requires digging to $R \sim 0.1\ R_\odot$ where temperature $\sim 5 \times 10^5$ K and resulting blob will have positive energy, and cooling time $\sim 10^{10}$ sec. Blob expands adiabatically and disperses (Spitzer 1939)
  - where did Jupiter's deuterium come from?

The “nebular” or “disk instability” hypothesis

- **the Sun and planets formed together out of a rotating cloud of gas (the “solar nebula”)**
- **gravitational instabilities in the gas disk condense into planets** (Kant 1755, Laplace 1796)
- Laplace, Exposition du système du monde (1796):
  - it is astonishing to see all the planets move around the Sun from west to east, and almost in the same plane; all the satellites move around their planets in the same direction and nearly in the same plane as the planets; finally, the Sun, the planets, and all the satellites that have been observed rotate in the direction and nearly in the plane of their orbits...another equally remarkable phenomenon is the small eccentricity of the orbits of the planets and the satellites...we are forced to acknowledge the effect of some regular cause since chance alone could not give a nearly circular form to the orbits of all the planets

The "nebular" or "disk instability" hypothesis

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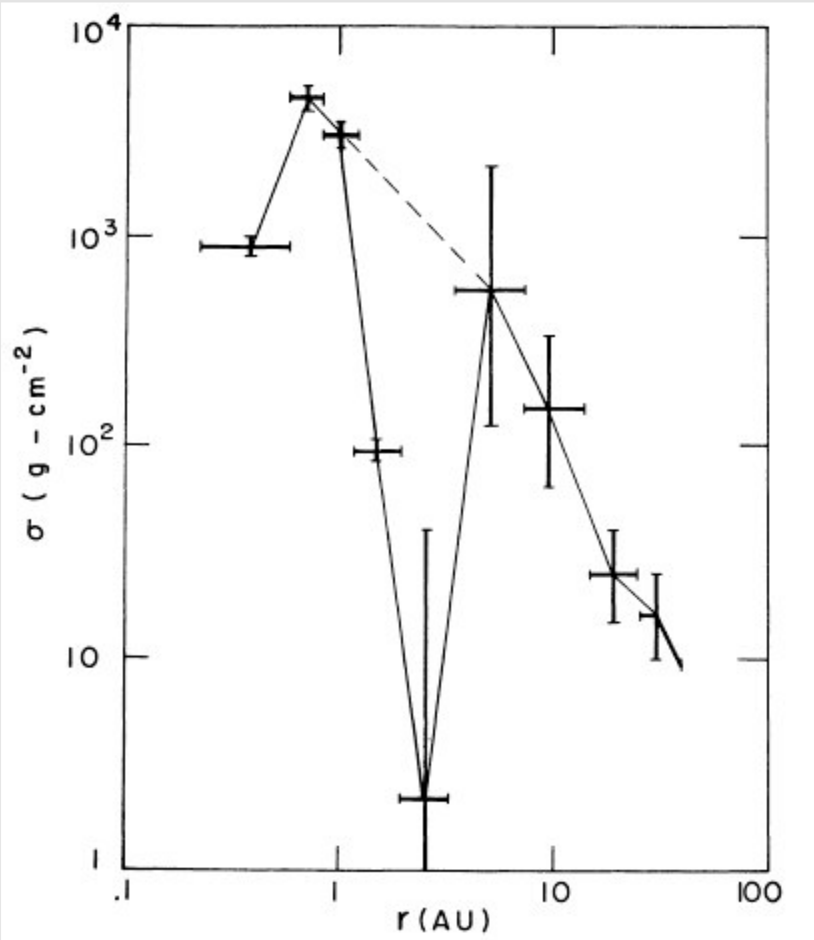
Minimum solar nebula



- add volatile elements to each planet to augment them to solar composition
- spread each planet into an annulus reaching halfway to the next planet
- smooth the resulting surface density:

$\Sigma(r) \approx 3 \times 10^3 \text{ g cm}^{-2} (1 \text{ AU}/r)^{1.5}$

Minimum solar nebula

$$\Sigma(r) \approx 3 \times 10^3 \text{ g cm}^{-2} (1 \text{ AU}/r)^{1.5}$$

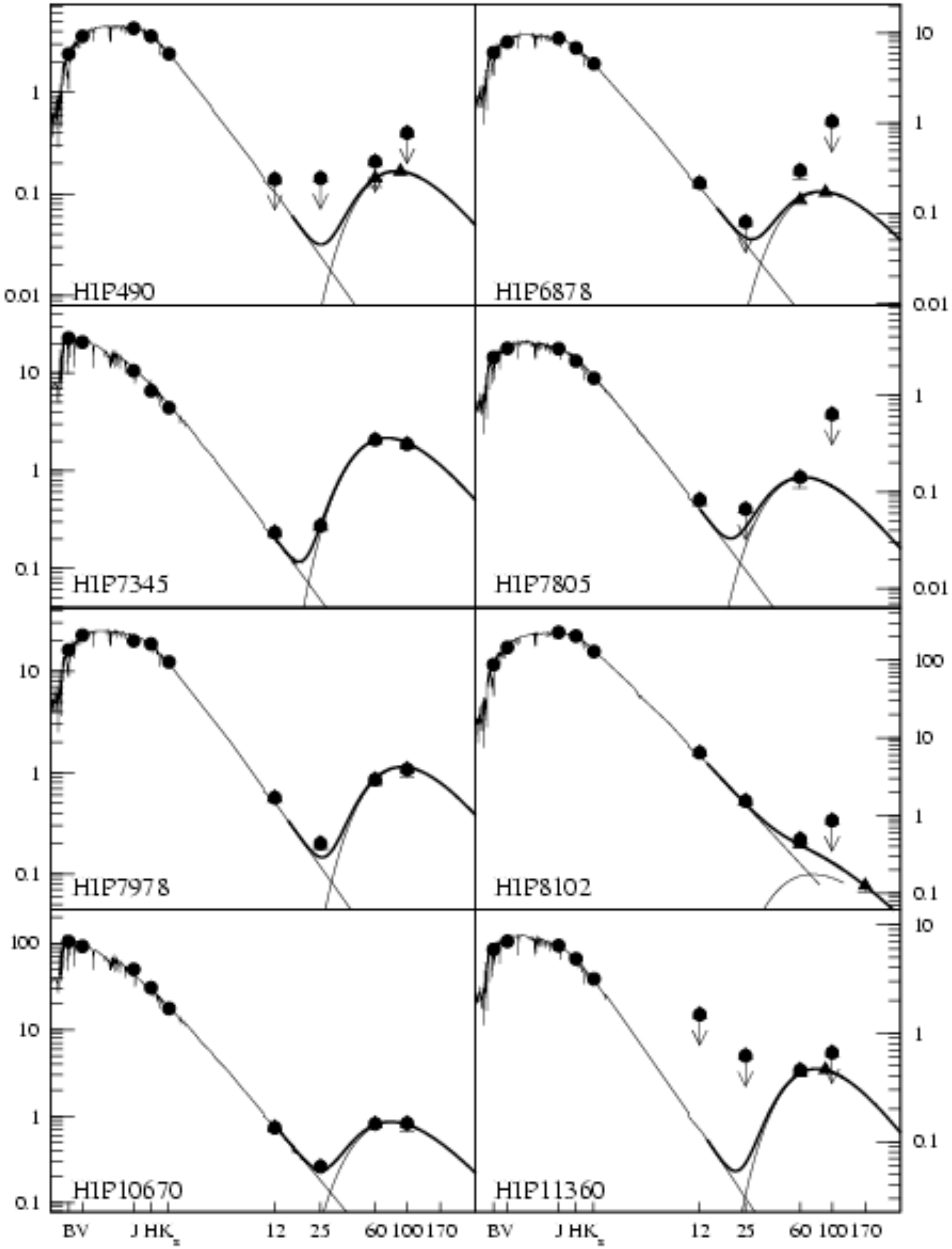
- assume 0.5% metals and divide into $r = 0.1\ \mu$ dust particles with density $\rho = 3$ g cm^{-3}
- geometric optical depth is

$$\tau \approx 4 \times 10^5 \ (1 \text{ AU}/r)^{1.5}$$

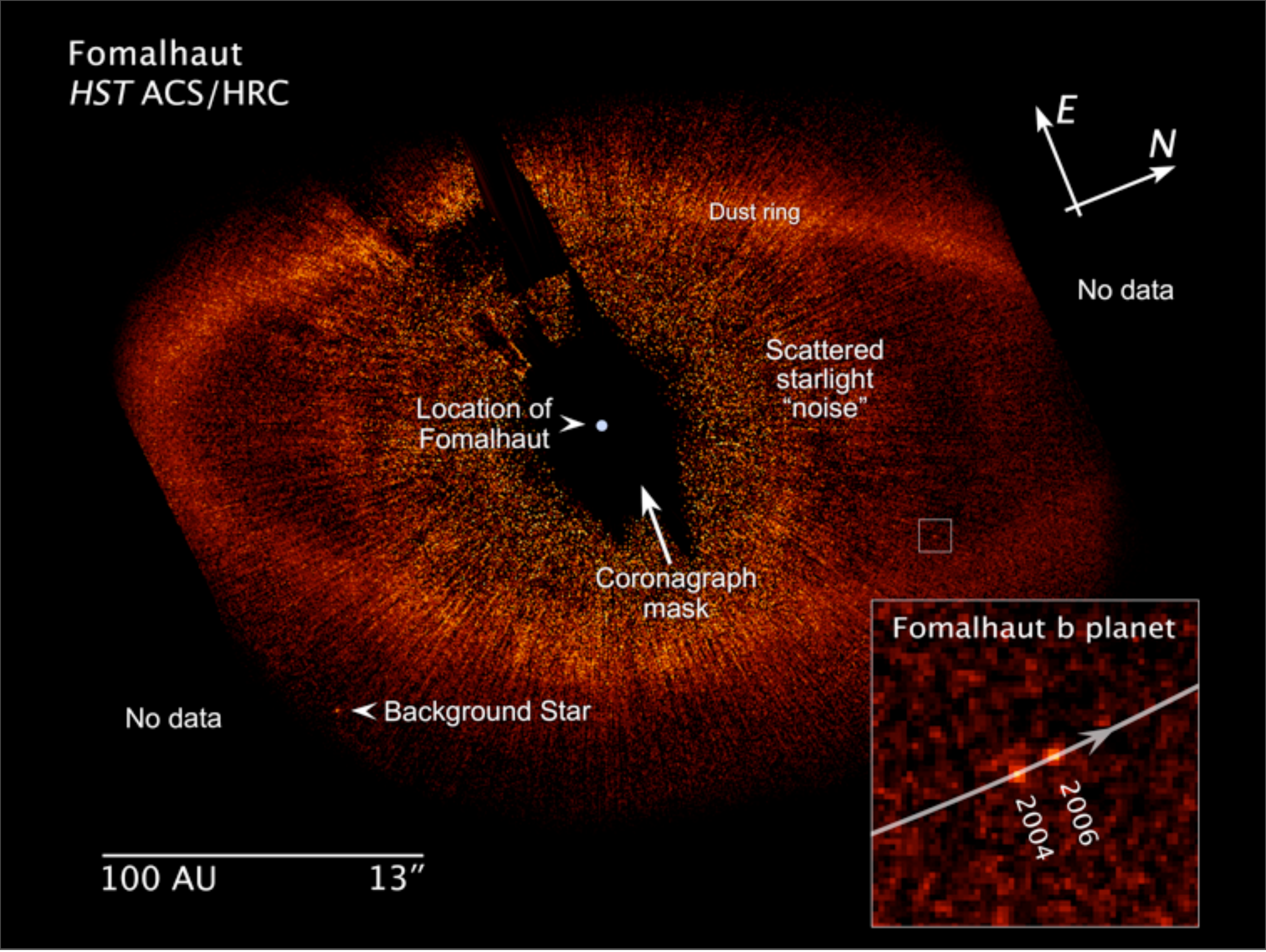
i.e. disk is opaque to very large distances

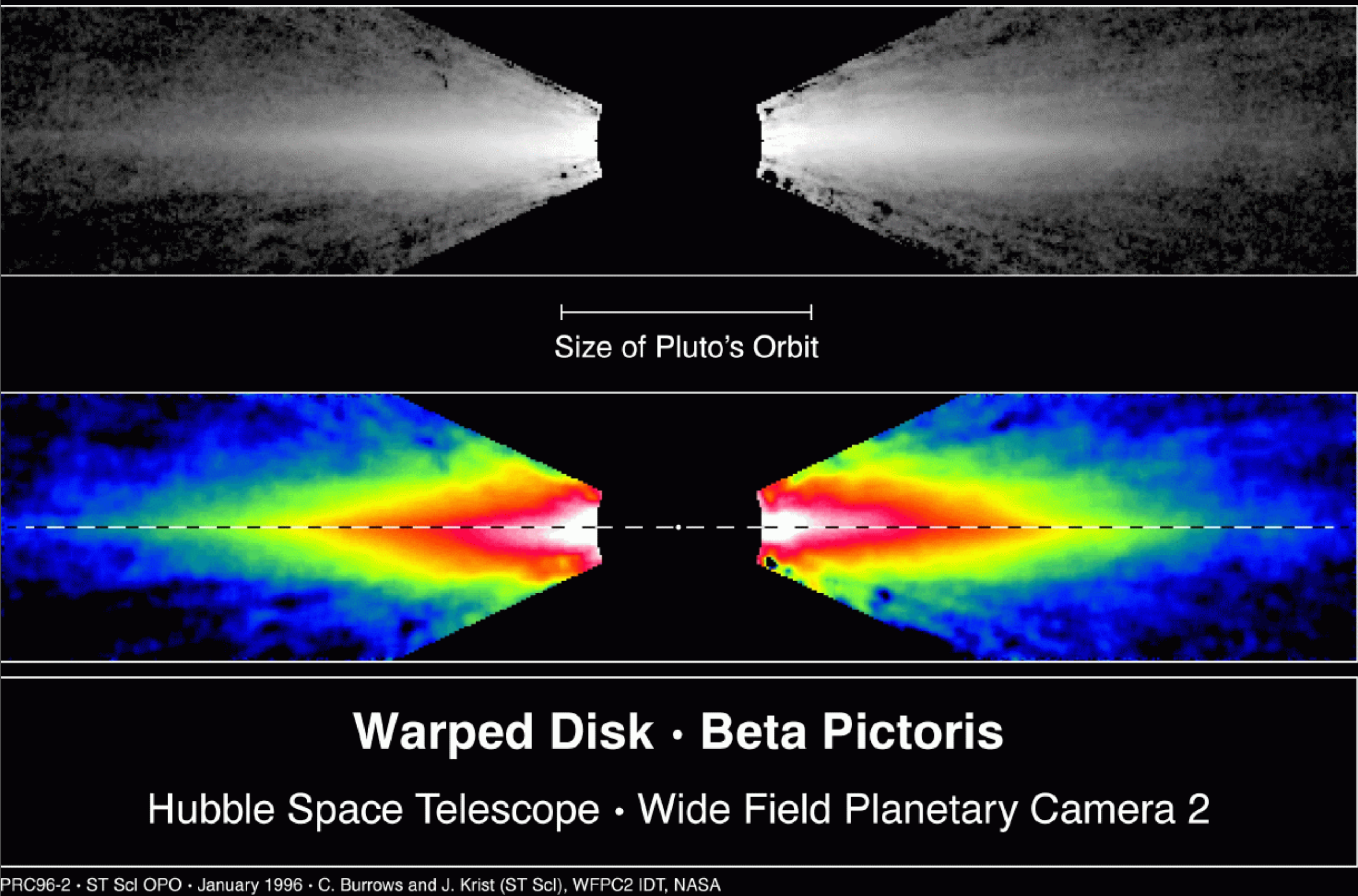
The "nebular" or "disk instability" hypothesis

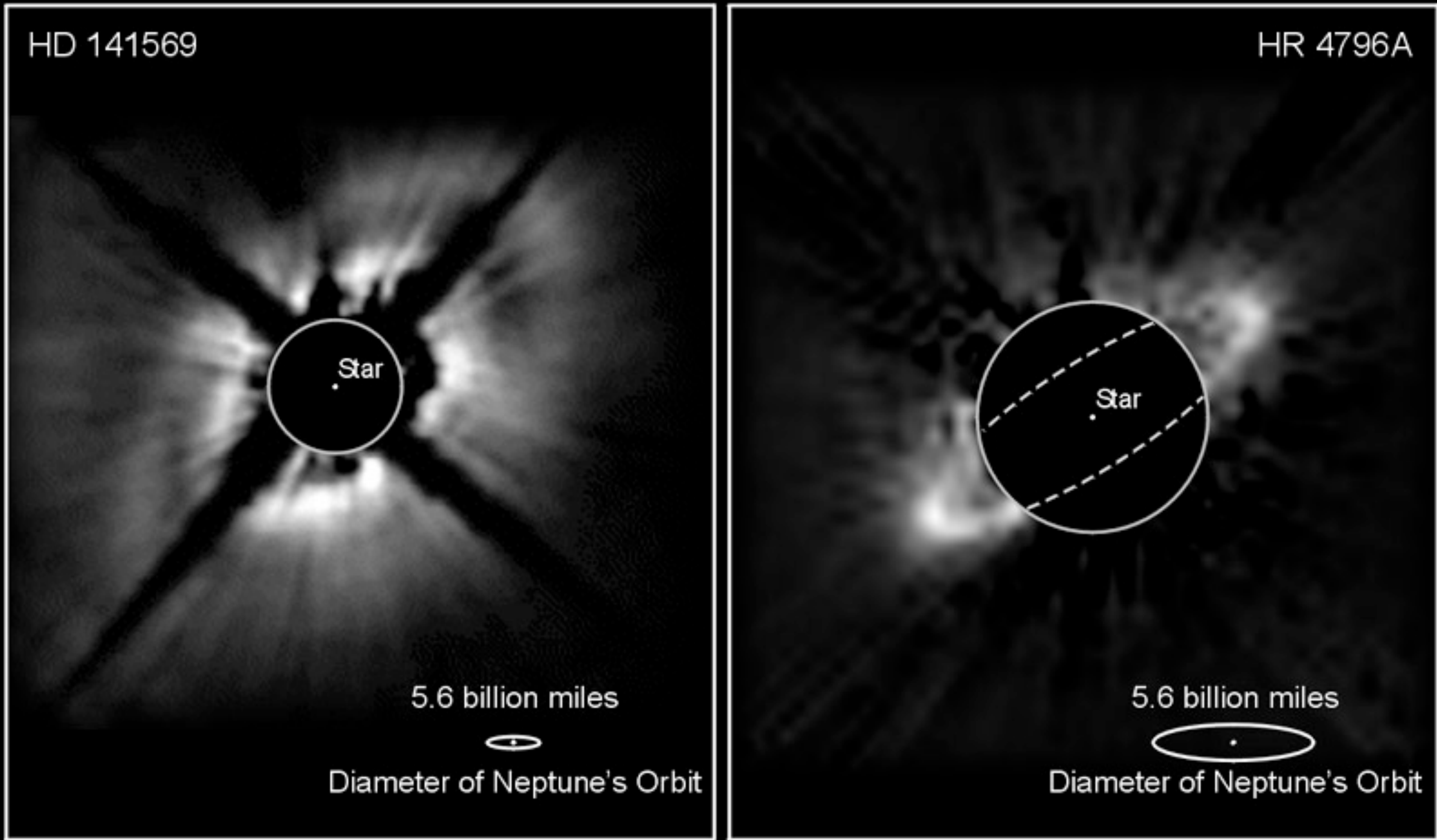
- **the Sun and planets formed together out of a rotating cloud of gas (the "solar nebula")**
- **gravitational instabilities in the gas disk condense into planets** (Kant 1755, Laplace 1796)
- **Good points:**
  - correctly predicted that stars are surrounded by rotating gas disks after they are born



infrared excesses around otherwise normal stars imply the presence of disks


Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet
2004
2006
No data
Background Star
100 AU
13″

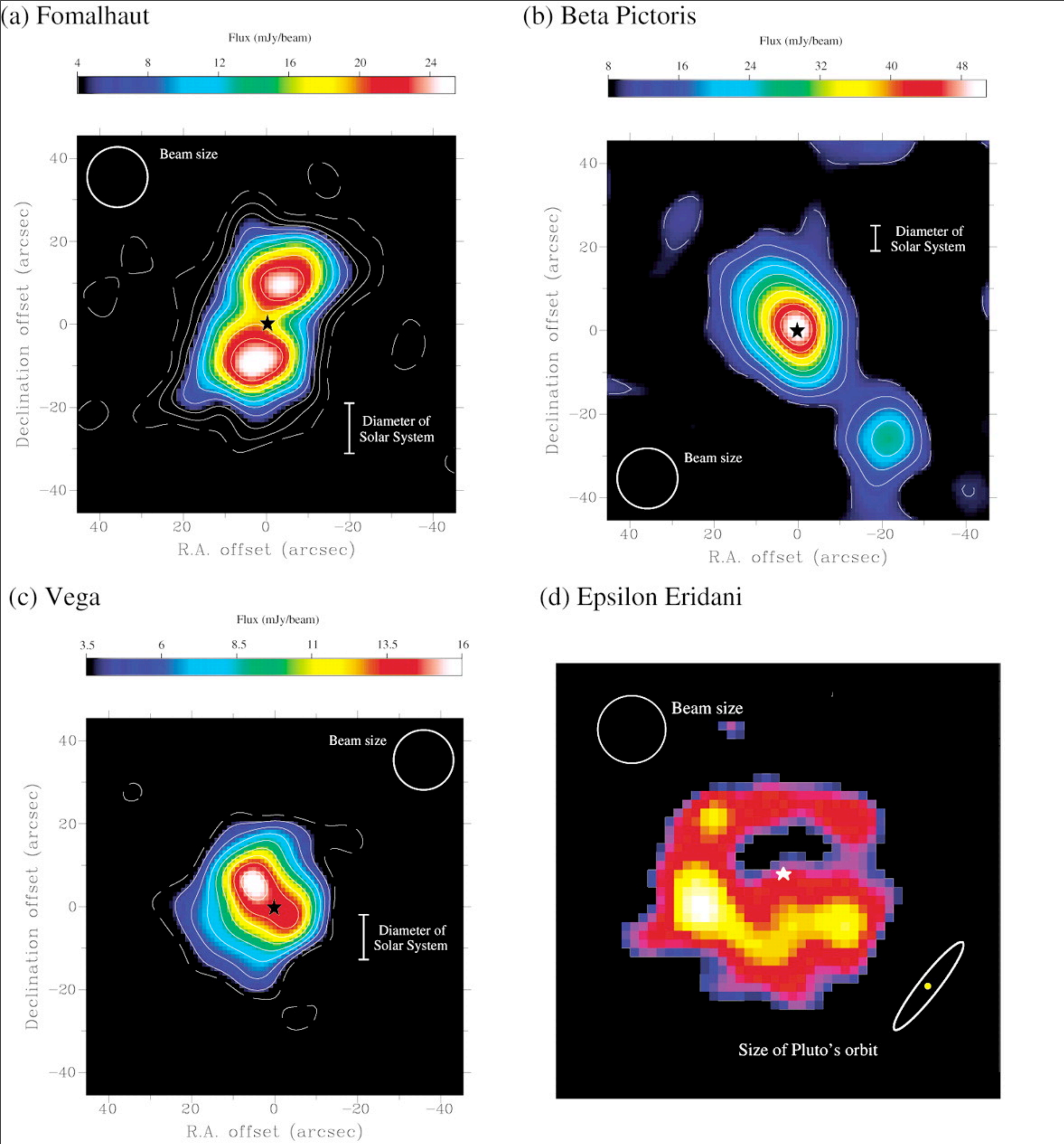

Size of Pluto's Orbit
Warped Disk • Beta Pictoris
Hubble Space Telescope • Wide Field Planetary Camera 2
PRC96-2 • ST ScI OPO • January 1996 • C. Burrows and J. Krist (ST ScI), WFPC2 IDT, NASA



Dust Disks around Stars **HST • NICMOS**

PRC99-03 • STScI OPO • January 8, 1999

B. Smith (University of Hawaii), G. Schneider (University of Arizona), E. Becklin and A. Weinberger (UCLA) and NASA



dust emission at 850 μ from SCUBA on JCMT. From Zuckerman (2001)

Minimum solar nebula

$$\Sigma(R) \approx 3 \times 10^3 \text{ g cm}^{-2} \left(\frac{1\,\text{AU}}{R}\right)^{1.5}.$$

Assume vertical distribution is isothermal,

$$\rho(z) \propto \exp\left(-\frac{\Phi}{kT}\right), \qquad \text{where} \qquad \Phi = -\frac{\mu m_p G M_\odot}{(R^2 + z^2)^{1/2}} \simeq \text{const} + \frac{\mu m_p G M_\odot}{2R^3} z^2$$

where $\mu = 2$ for hydrogen molecules. Thus

$$\rho(z, R) = \rho_0(R) \exp\left[-\frac{z^2}{2h^2(R)}\right],$$

where

$$h^2 = \frac{kTR^3}{\mu m_p G M_\odot} \qquad \text{or} \qquad h = 7.20 \times 10^{11}\,\text{cm} \left(\frac{T}{500\,\text{K}}\right)^{1/2} \left(\frac{R}{1\,\text{AU}}\right)^{3/2} \left(\frac{2}{\mu}\right)^{1/2}.$$

1

Minimum solar nebula

$$\frac{h}{R} = 0.048 \left(\frac{T}{500\,\mathrm{K}}\right)^{1/2} \left(\frac{R}{1\,\mathrm{AU}}\right)^{1/2} \left(\frac{2}{\mu}\right)^{1/2}$$

$$\rho_0(R) = 1.7 \times 10^{-9}\mathrm{g\ cm}^{-3} \left(\frac{500\,\mathrm{K}}{T}\right)^{1/2} \left(\frac{1\,\mathrm{AU}}{R}\right)^{3}.$$

Sound speed : $c = \left(\frac{\gamma k T}{\mu m_p}\right)^{1/2} = 1.70\,\mathrm{km\,s}^{-1} \left(\frac{T}{500\,\mathrm{K}}\right)^{1/2} \left(\frac{2}{\mu}\right)^{1/2}.$

Angular speed: $\Omega = \left(\frac{G M_\odot}{R^3}\right)^{1/2} = \frac{2\pi}{1\,\mathrm{yr}}.$

Mean free path: $\lambda \approx \frac{\mu m_p}{\pi r^2 \rho} \sim 10\,\mathrm{cm}.$

2

Stability of the minimum solar nebula

Consider a disk with surface density Σ, angular speed Ω, and sound speed c, and examine a small patch of size L.

- mass is $M \sim \Sigma L^2$
- gravitational potential energy is $E_G \sim -GM^2/L \sim -G\Sigma^2 L^3$
- energy in rotational motion is $E_R \sim M(\Omega L)^2 \sim \Sigma\Omega^2 L^4$
- internal energy is $E_P \sim Mc^2 \sim \Sigma L^2 c^2$
- stable if $E_G + E_R + E_P > 0$ or

$$-G\Sigma^2 L^3 + \Sigma\Omega^2 L^4 + \Sigma L^2 c^2 > 0, \text{ or}$$

$$-G\Sigma L + \Omega^2 L^2 + c^2 > 0$$

for all L. The quadratic function on the left reaches its minimum at $L=G\sigma/2\Omega^2$, and this is positive if

$$2c\Omega/G\Sigma > 1.$$

Accurate calculations show that gravitational stability requires that Toomre's parameter

$$Q = \frac{c\Omega}{\pi G \Sigma} > 1$$

The nebular hypothesis

For standard parameters at 1 AU, Q= 170

Minimum solar nebula is very stable!

Moreover disk must be able to cool within a few orbital periods or instability leads to heating, not gravitational collapse (Gammie 2001)

Can only work for massive planets, ~ 10 M_J, at large radii, ~ 100 AU (Rafikov 2005)

Also,

- how do you make terrestrial planets, solid cores of giant planets, etc.?
- why the strong correlation with metallicity of the host star?

The planetesimal (Safronov) hypothesis

planets form by multi-stage process:

1. dust grains condense out from cooling gas disk and settle to the disk midplane
2. dust coalesces into small (km-sized) solid bodies (**planetesimals,** i.e. bodies big enough that they are unaffected by gas)
3. planetesimals collide and grow into "planetary cores"
4. cores of intermediate and giant planets accrete gas envelopes before the gaseous disk disperses

requires growth by 45 orders of magnitude in mass through many different physical processes

The planetesimal hypothesis

Problem 1:

- rock and ice grains condense out from cooling gas disk and settle to the disk midplane
- thin solid layer is gravitationally unstable and forms km-sized planetesimals

but

- gas disk rotates slower than Keplerian by about 0.2%. This leads to strong shear at the surface of the particulate disk
- shear induces Kelvin-Helmholtz instability which leads to turbulent velocities of order $v - v_g \sim c^2/\Omega R \sim 5 \times 10^3$ cm s^{-1} which suppresses gravitational instability
- alternative is that particle velocities are turbulent and collisions lead to sticking, but icy or even rocky bodies fracture at these high speeds (~150 km/hr)

The planetesimal hypothesis

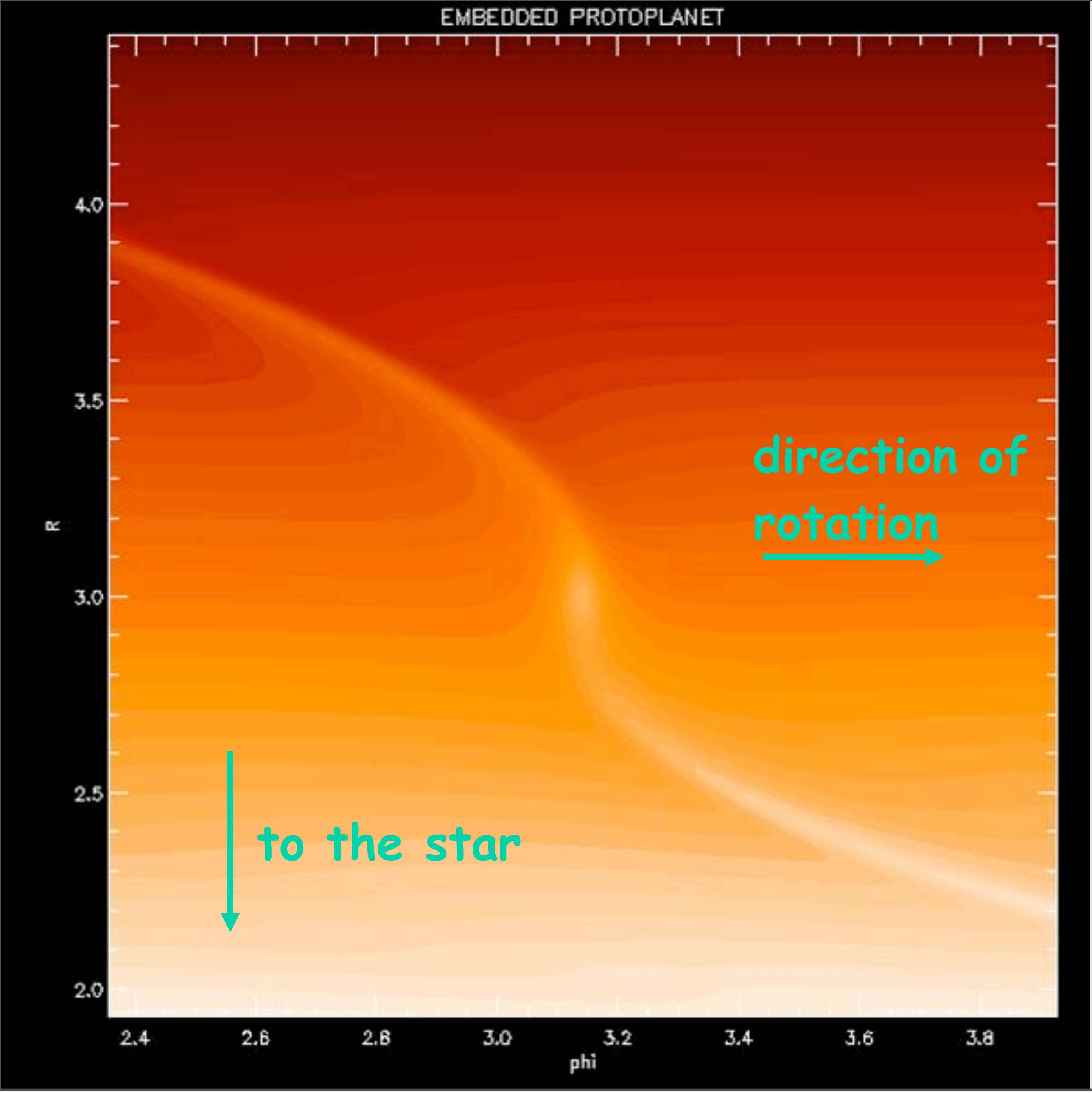
Problem 2:

- gas disk is partially pressure supported so rotates slightly (~0.2%) slower than the thin layer of planetesimals
- planetesimals feel a "headwind" of about 50 m/s at 1 AU
- small particles are entrained in the wind; large particles don't feel the wind; but intermediate-sized particles spiral inwards
- shortest inspiral time is 100 yr from 1 AU for 30 cm particles
- the "meter-size barrier": planetesimals must grow from << 1 m to >> 1 m in less than a century

The planetesimal hypothesis

Problem 3: At $r < 0.1$ AU no elements condense so planetesimals cannot form. So why are there planets there?

- Planets must form at much larger radii and migrate inwards. Two broad classes of migration scenarios:
  - **disk migration**
    - gravitational interactions between a planet and the surrounding gas disk lead to repulsive torques between them
  - **high-eccentricity migration**
    - some process excites planets to high eccentricity and then tidal friction from the host star drains energy from the orbit



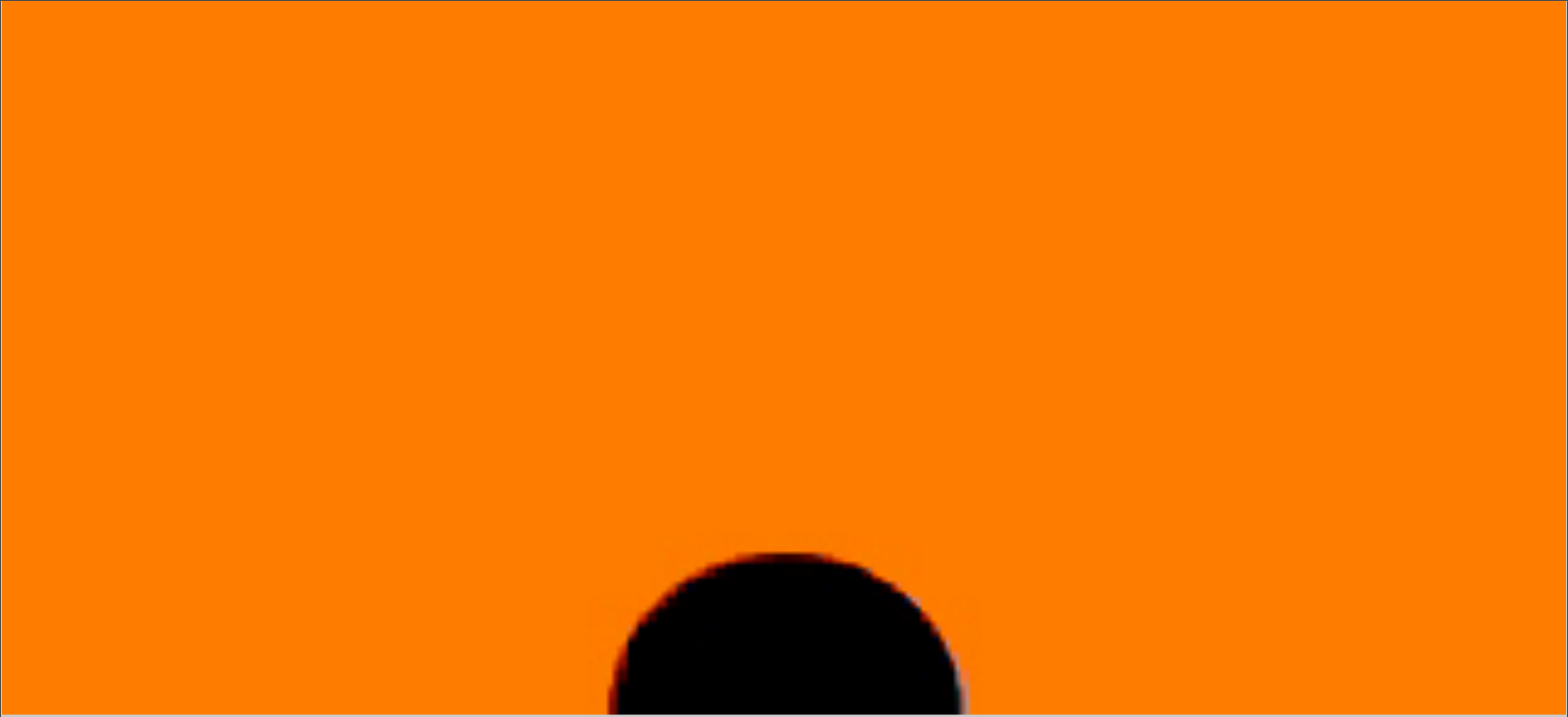
Disk migration

R. Nelson, University of London

Type I migration: low-mass planet only weakly perturbs the disk

- very rapid, ~ 10^4 years for Jupiter
- usually inward

Masset (2002)



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Type II migration: bigger planet opens a gap in the disk

- planet evolves with the disk on the disk's viscous evolution timescale (acts like a disk particle)
- probably ~ 10^5 yr timescale
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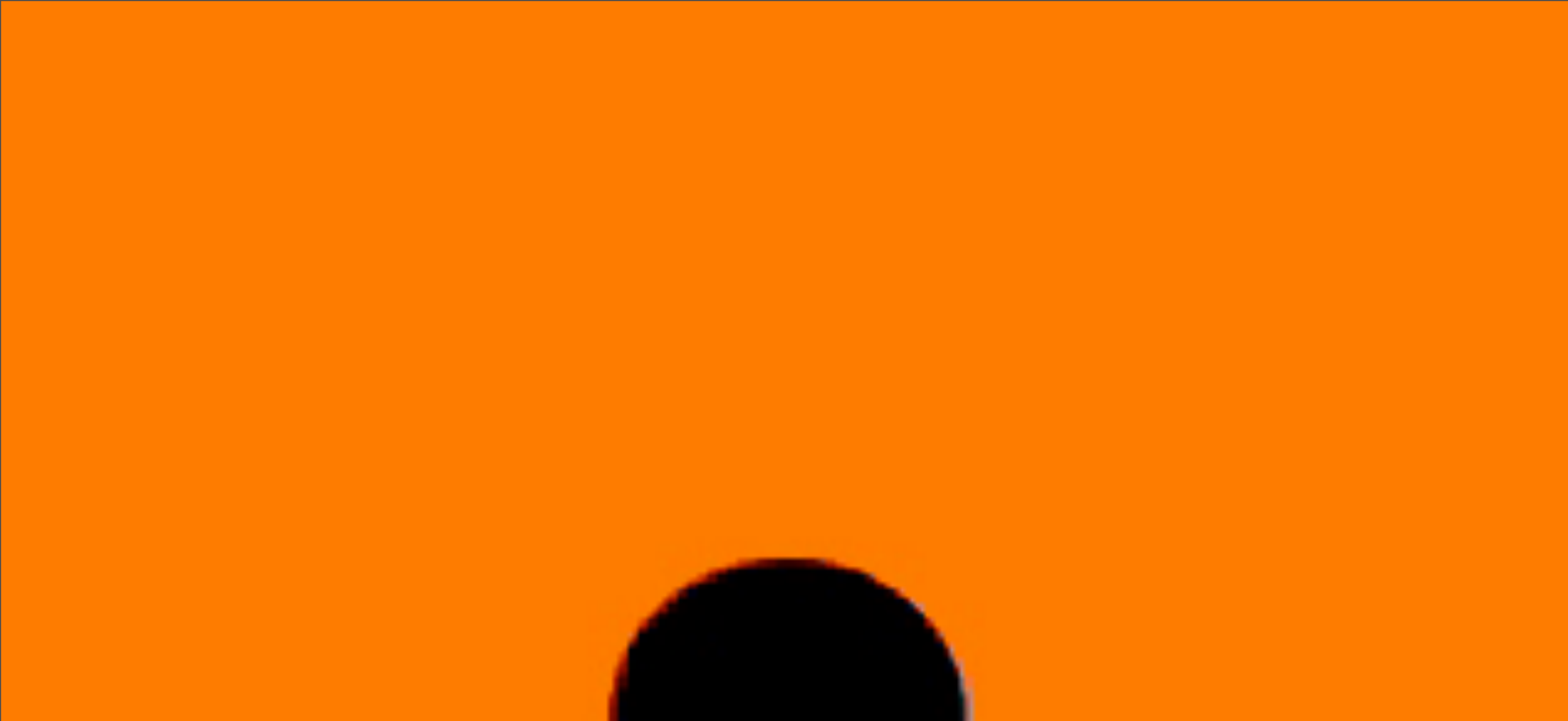

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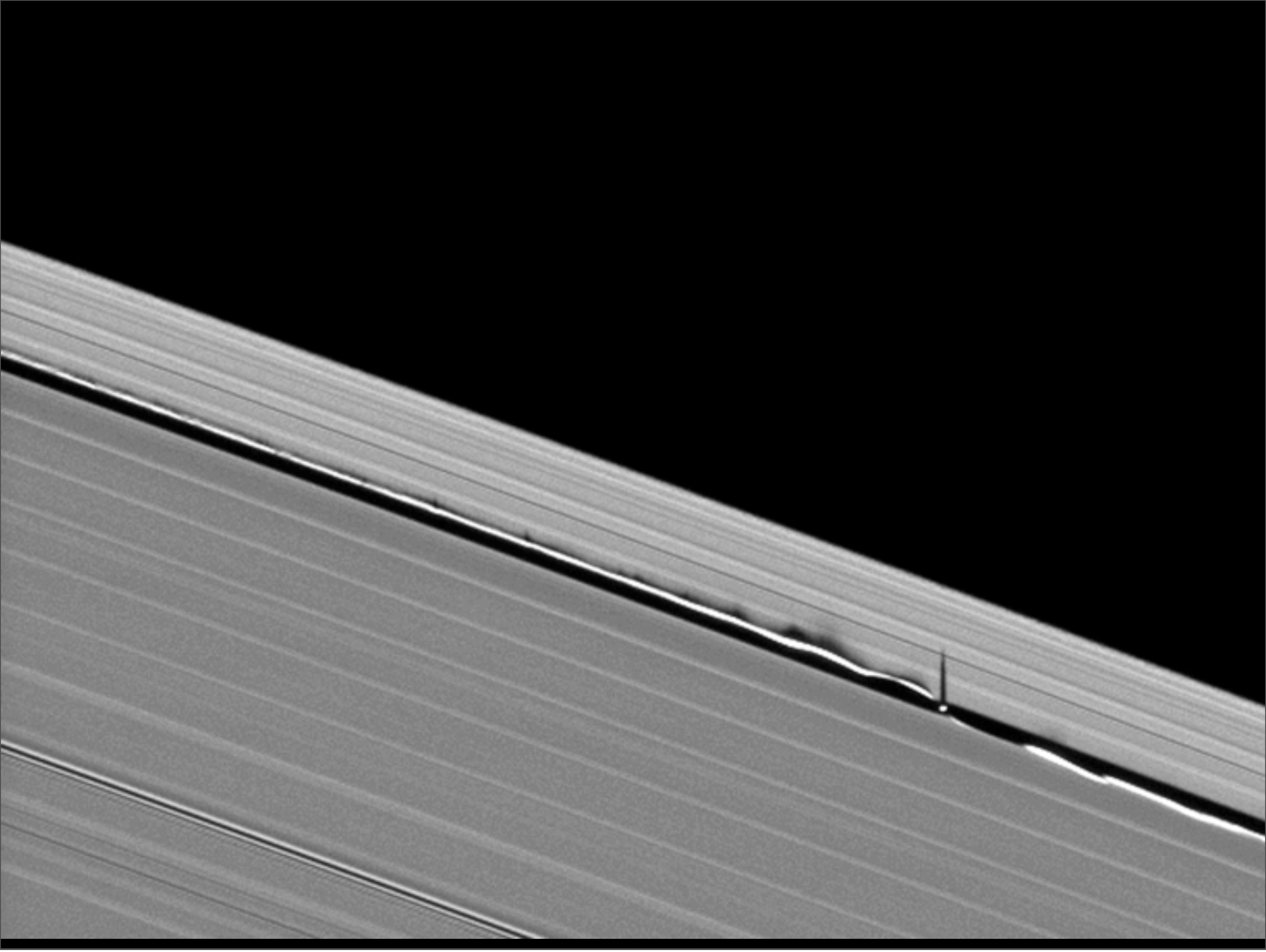
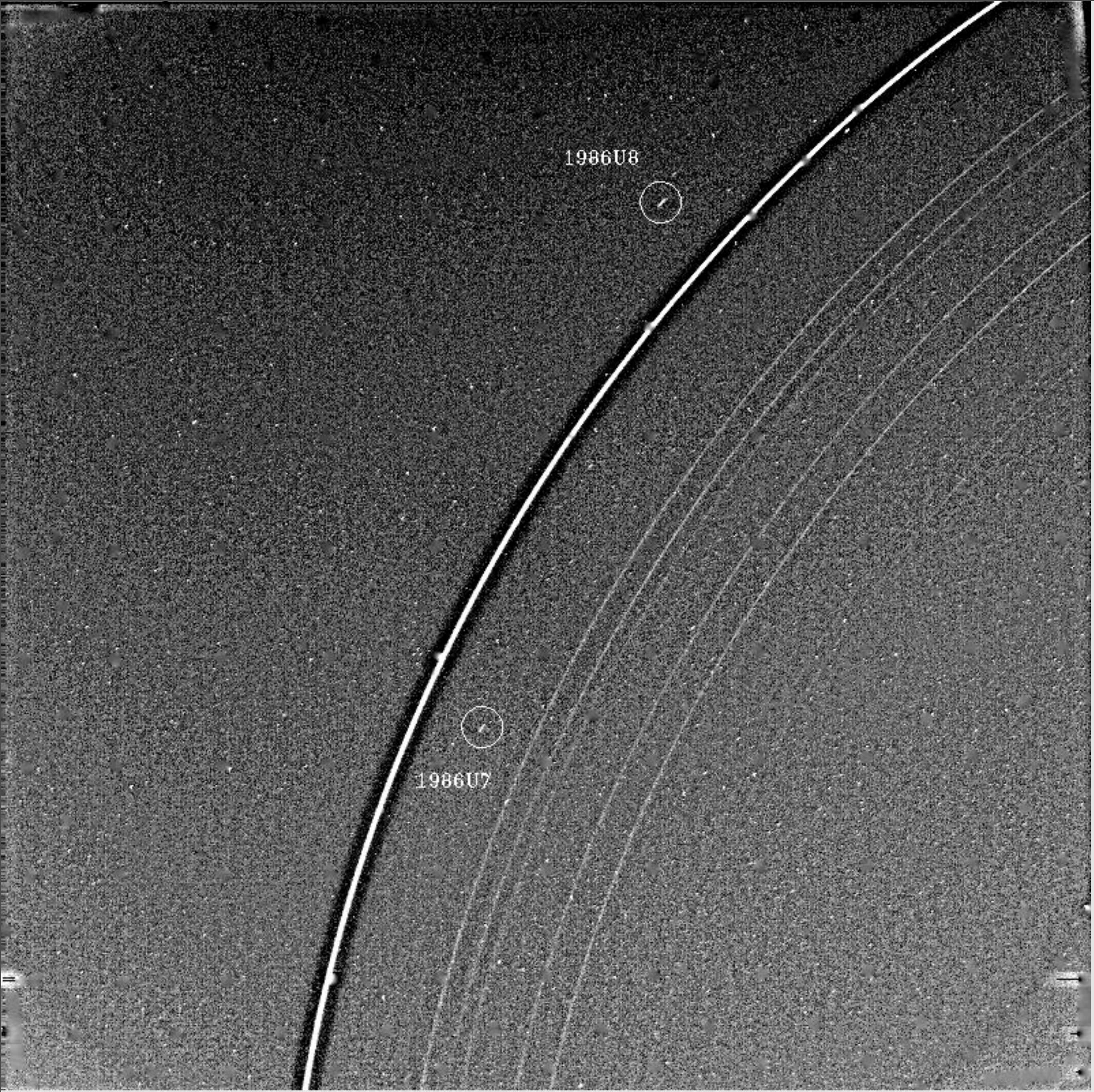
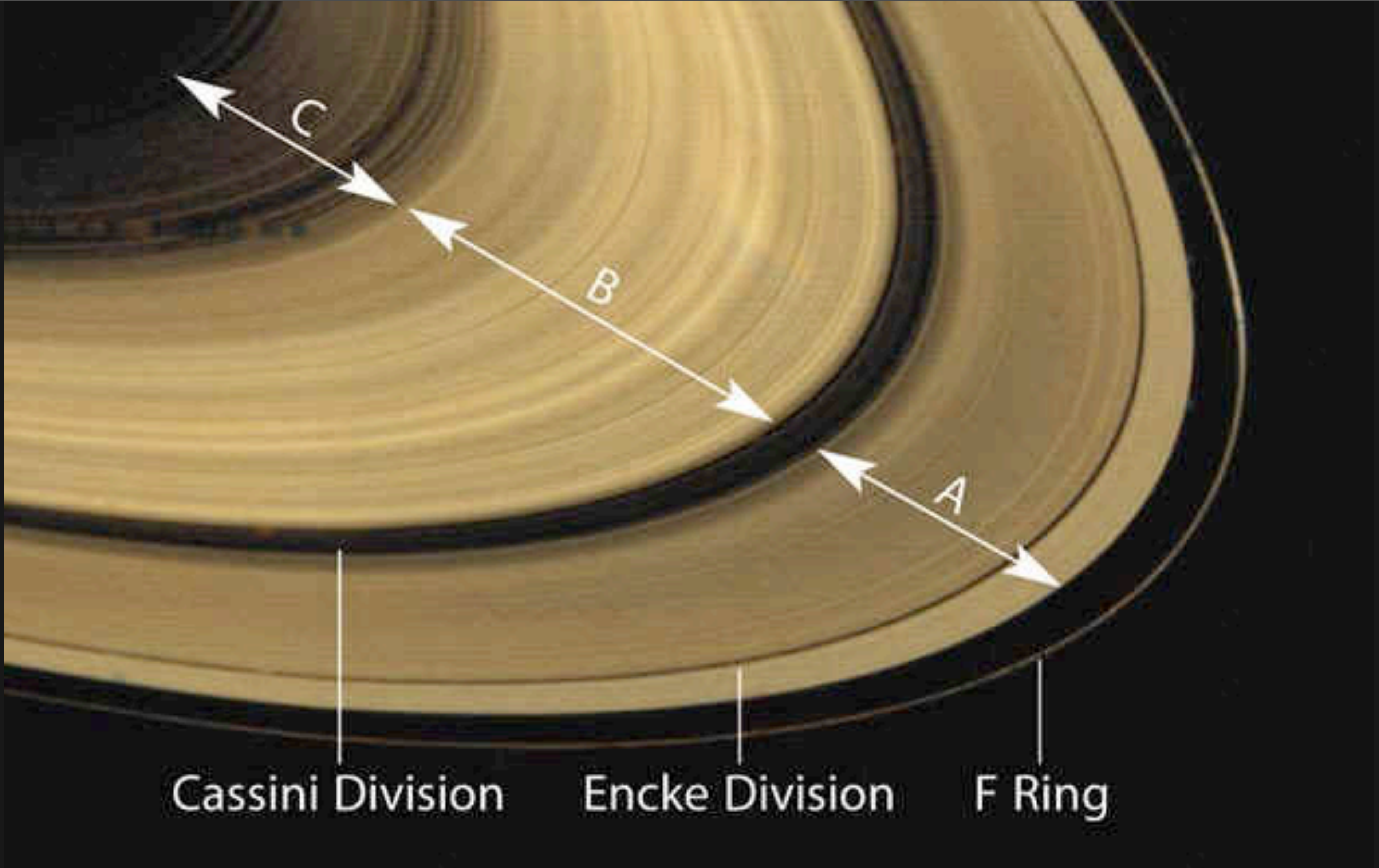


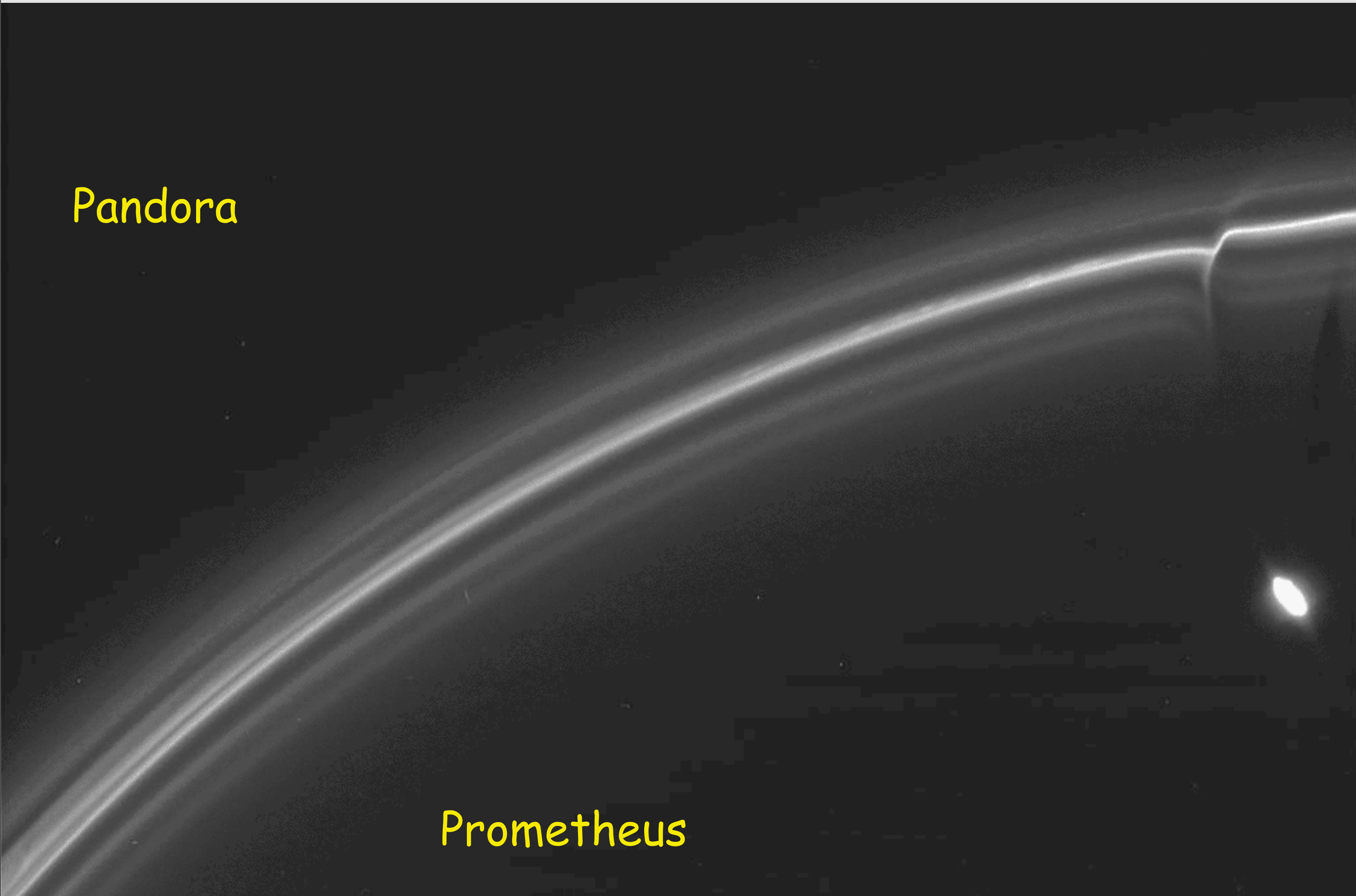


Cordelia and Ophelia at Uranus


C
B
A
Cassini Division
Encke Division
F Ring

Pandora

Prometheus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Types of migration

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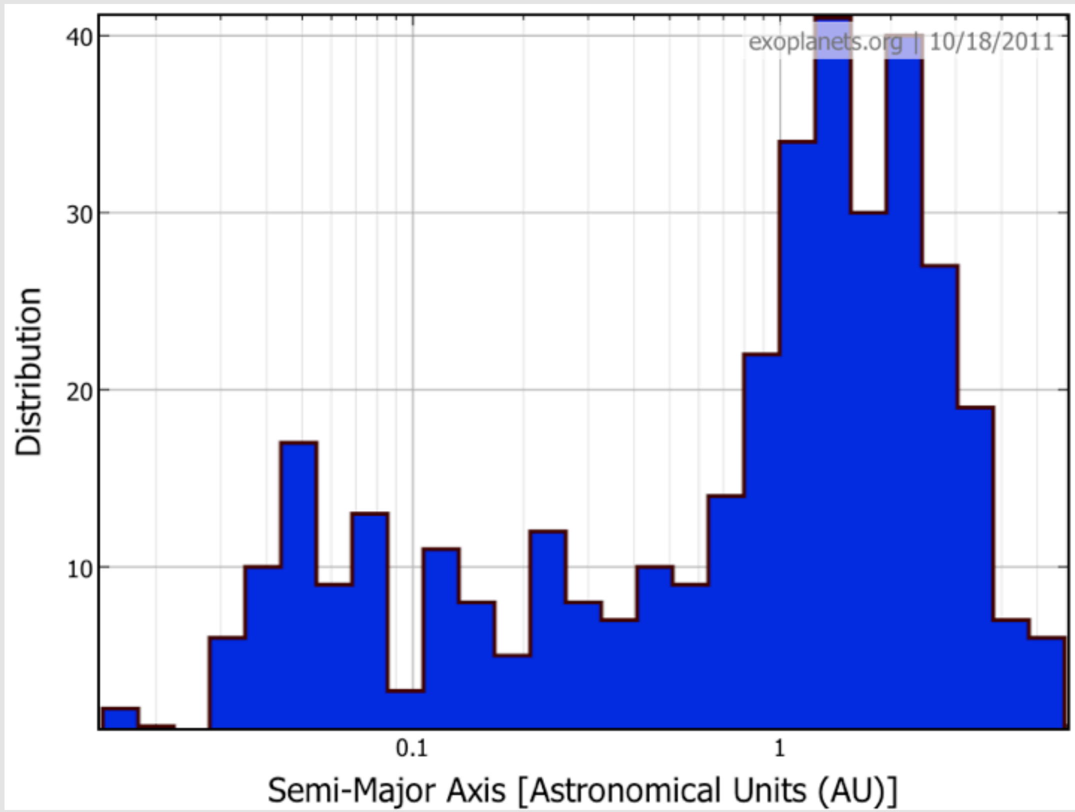
- probably ~ 10^5 yr timescale
- usually inward

Both Type I and Type II migration have timescales much shorter than the age of the protoplanetary gas disk (10^6 – 10^7 yr)

The planetesimal hypothesis

Problem 4: migration from larger radii offers a plausible way to form giant planets at small radii, but:

- why did the migration stop?
- why are the planetary semimajor axes distributed over a wide range?
- why did migration not occur in the solar system?

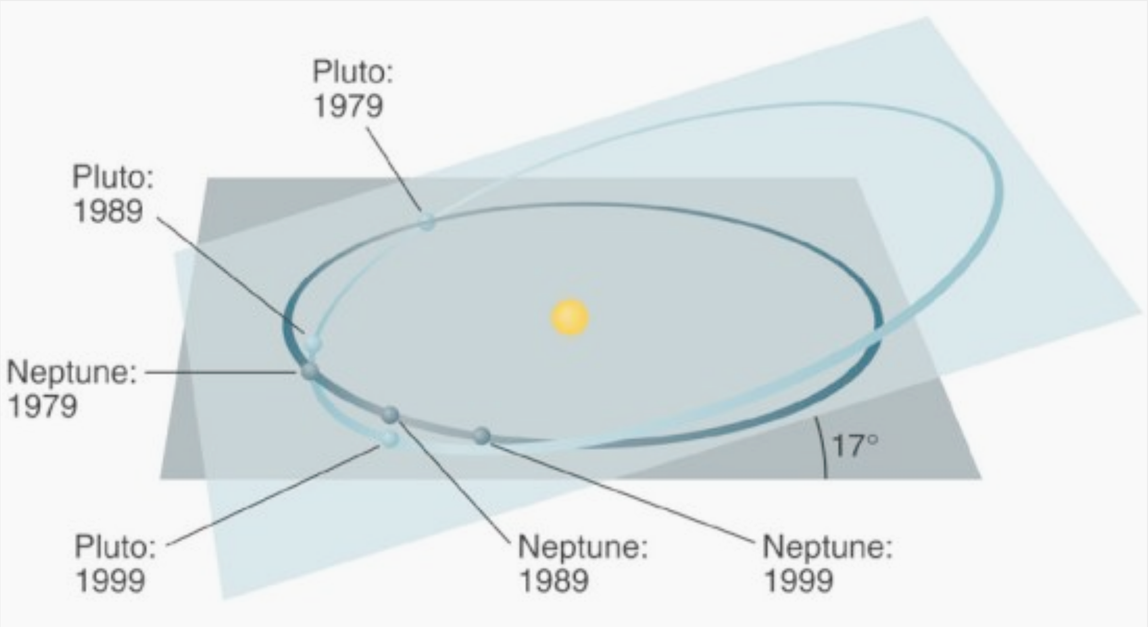


Pluto's peculiar orbit

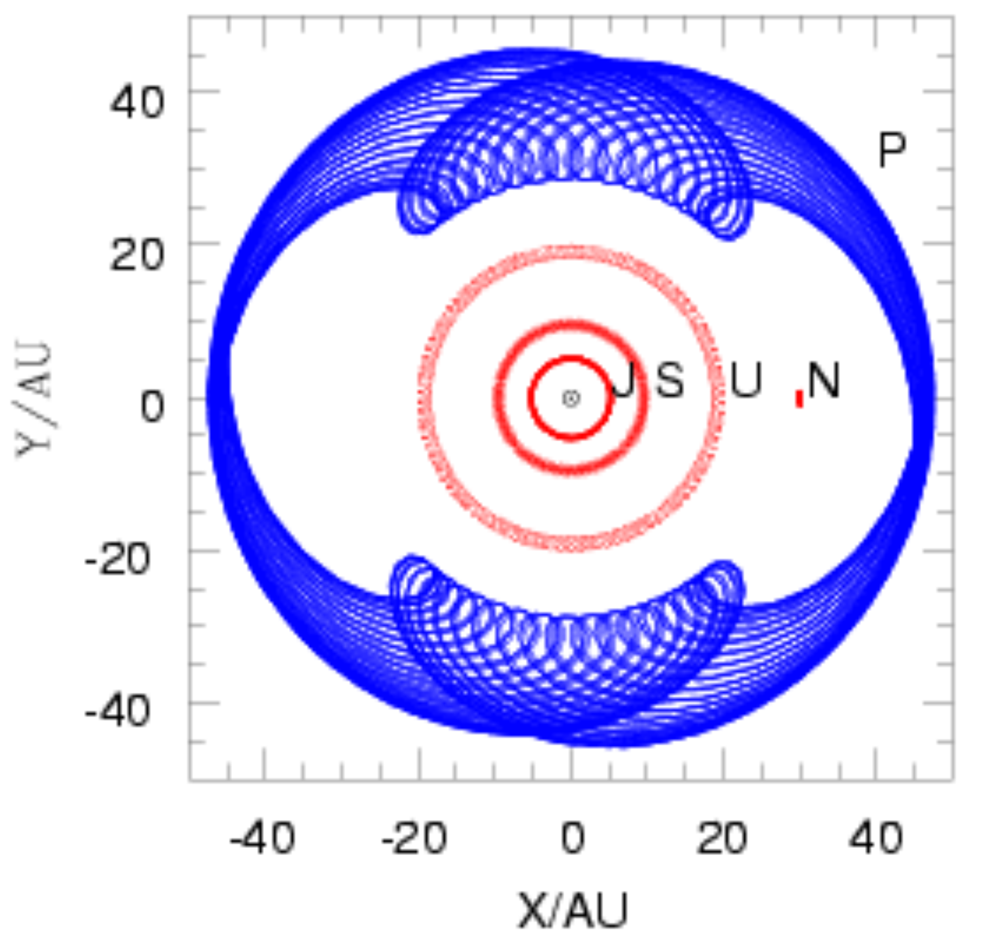
Pluto has:

- the highest eccentricity of any "planet" ($e = 0.250$)
- the highest inclination of any "planet" ($i = 17^{o}$)
- perihelion distance $q = a(1 - e) = 29.6$ AU that is smaller than Neptune's semi-major axis ($a = 30.1$ AU)

How do they avoid colliding?



Pluto's peculiar orbit



Orbital period of Pluto = 247.7 y

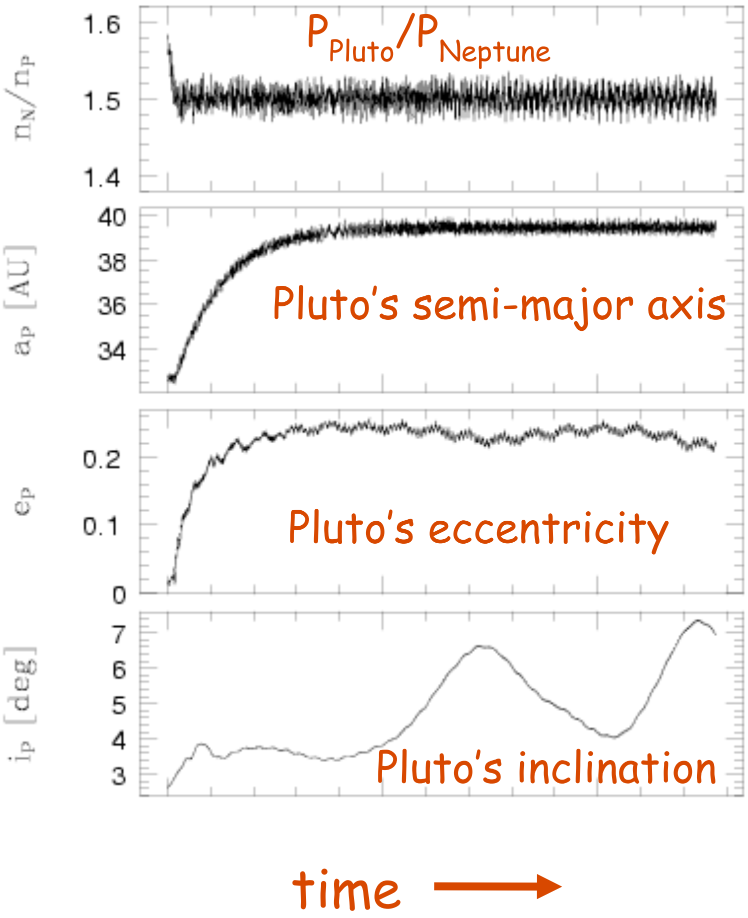
Orbital period of Neptune = 164.8 y

247.7/164.8 = 1.50 = 3/2

Resonance ensures that when Pluto is at perihelion it is approximately 90° away from Neptune

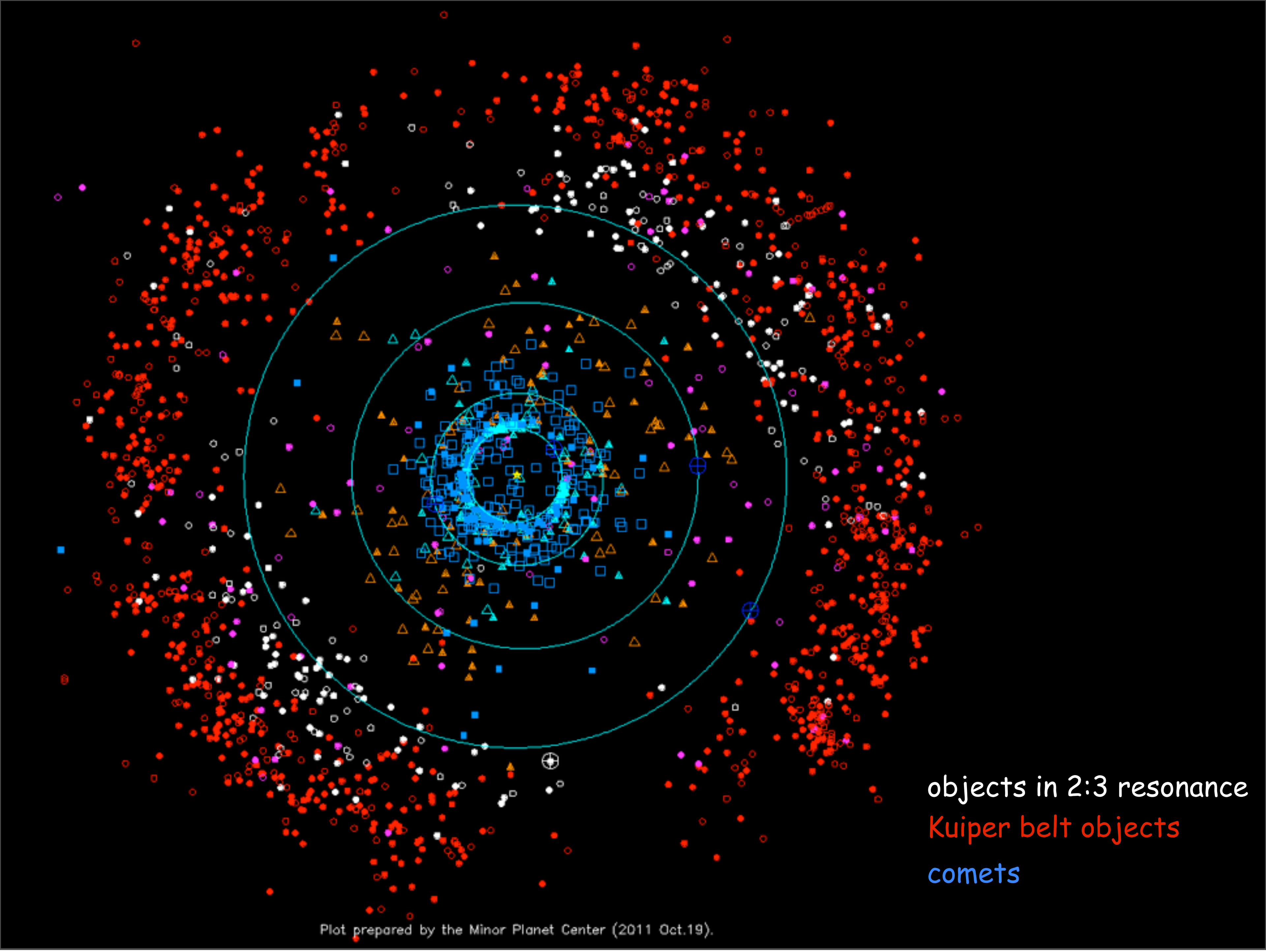
(Cohen & Hubbard 1965)

Pluto's peculiar orbit



- early in the history of the solar system there was debris left over between the planets
- ejection of this debris by Neptune caused its orbit to migrate outwards
- if Pluto were initially in a low-eccentricity, low-inclination orbit outside Neptune it is inevitably captured into 3:2 resonance with Neptune
- once Pluto is captured its eccentricity and inclination grow as Neptune continues to migrate outwards
- other objects may be captured in the resonance as well

Malhotra (1993)


Plot prepared by the Minor Planet Center (2011 Oct.19).
objects in 2:3 resonance
Kuiper belt objects
comets

High-eccentricity migration

- giant planets form, as in the solar system, at 5-10 AU
- some process excites their eccentricities to $e > 0.99$ so pericenter is $q=a(1-e) < 0.1$ AU = 20 $R_\odot$
- tidal friction then damps the eccentricity
- possible processes:
    - close encounters between planets
    - tidal forces from a companion star (Kozai-Lidov oscillations)
    - resonant capture during disk migration
    - secular chaos (as in delivery of meteorites to Earth)

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good points:

- naturally produces high obliquities
- predicts super-eccentric ($e > 0.95$) planets (Socrates et al. 2011)

bad points:

- inefficient: $P(<q) \sim 2q/a$
- planet may not be able to absorb the energy without disrupting

Unresolved questions:

- what determines the mass function of planets?
- how are hot Jupiters formed, and what is the migration mechanism?
- why did Jupiter not migrate?
- what fraction of planetary systems are like the solar system?
- why are the eccentricities of extrasolar planets so large?
- how flat are planetary systems?
- how do planetesimals form?
- how do planetesimals get past the meter-size barrier?
- what fraction of stars have habitable planets?

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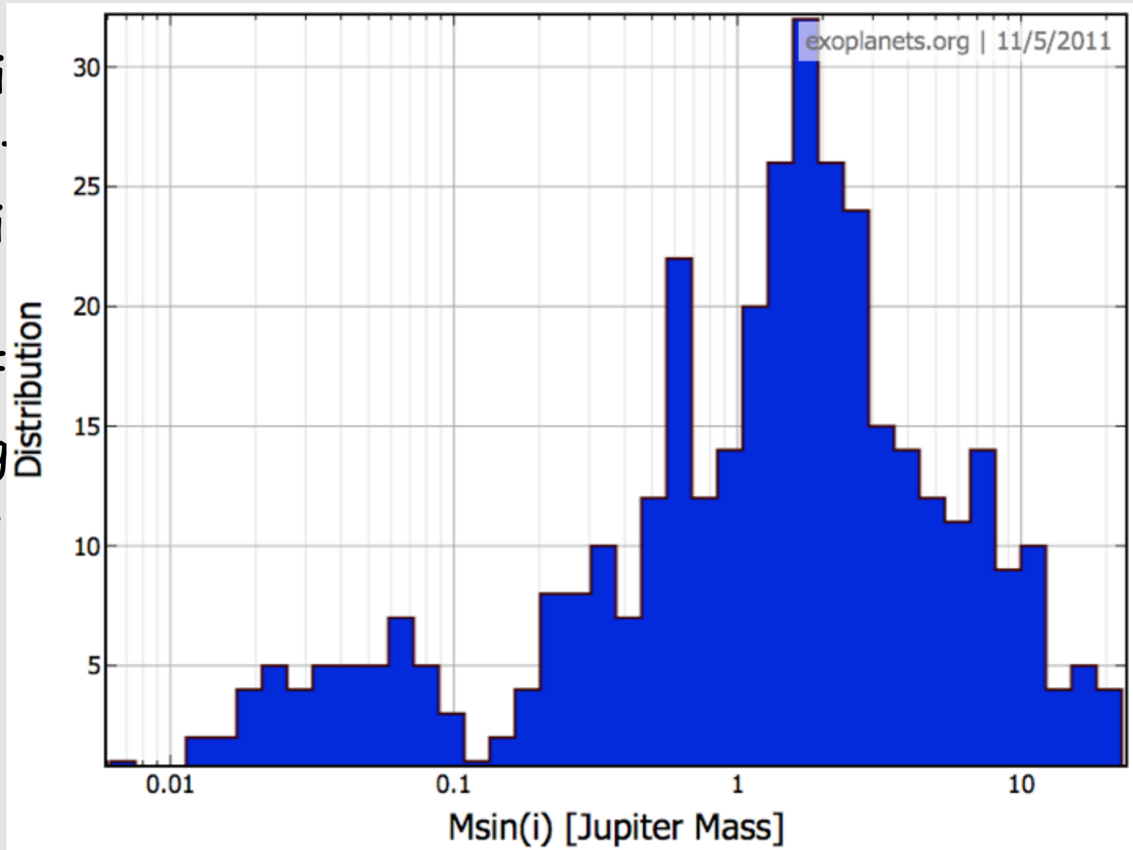

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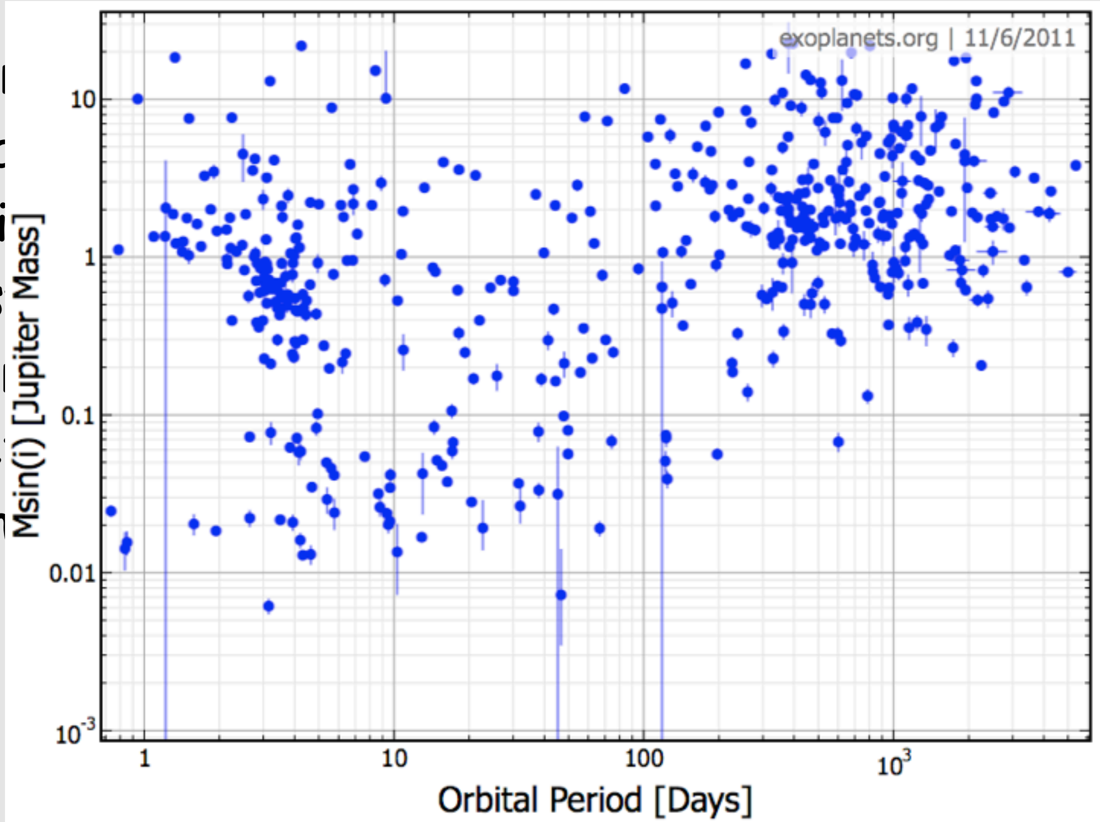

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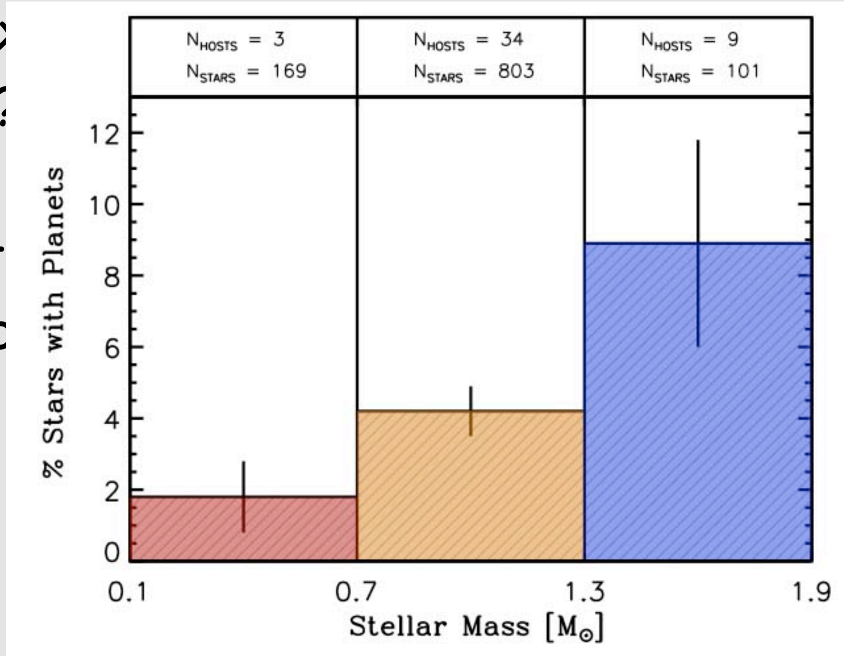

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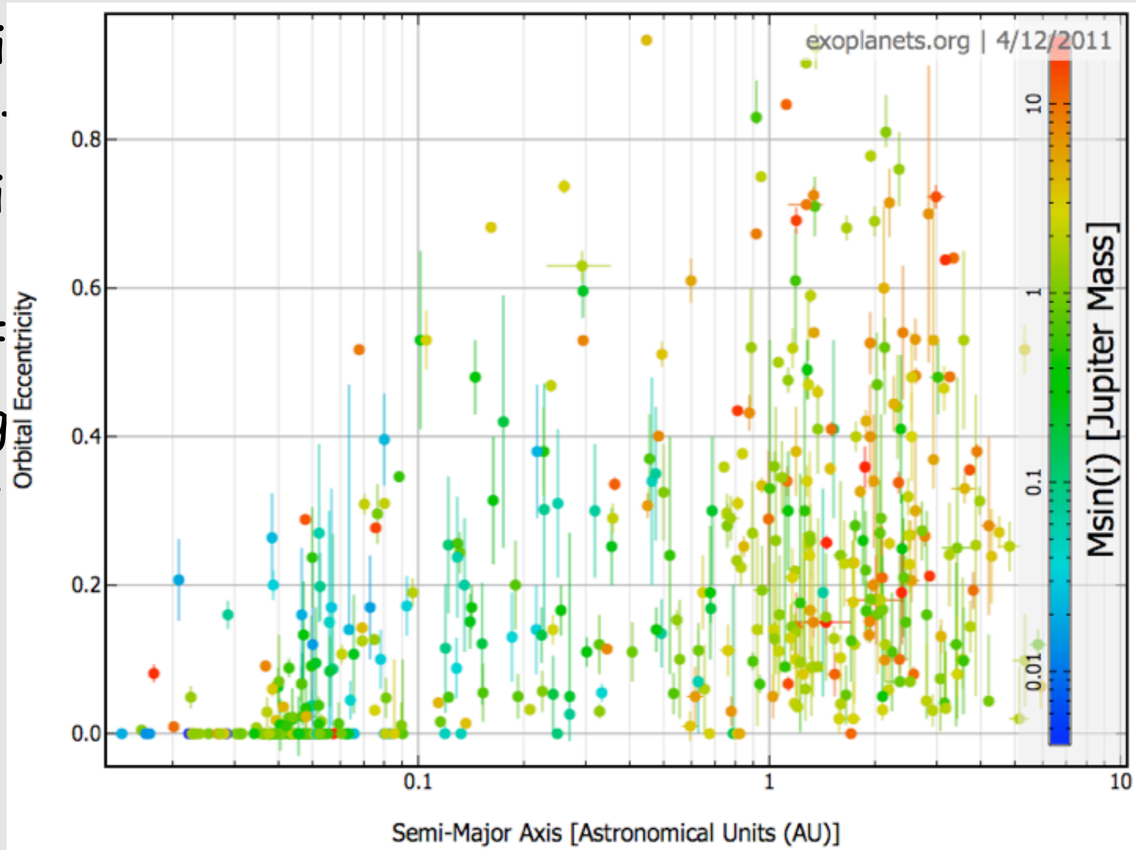

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