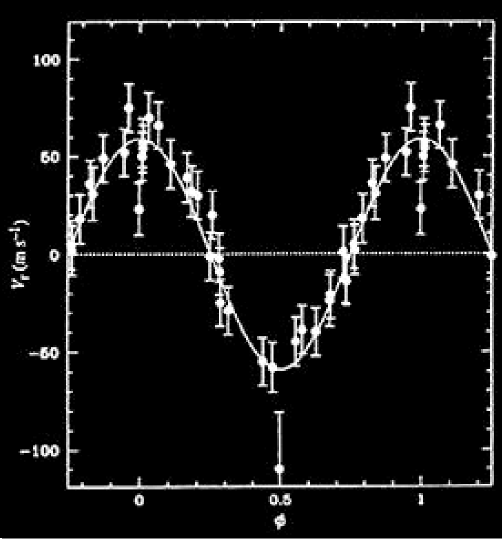
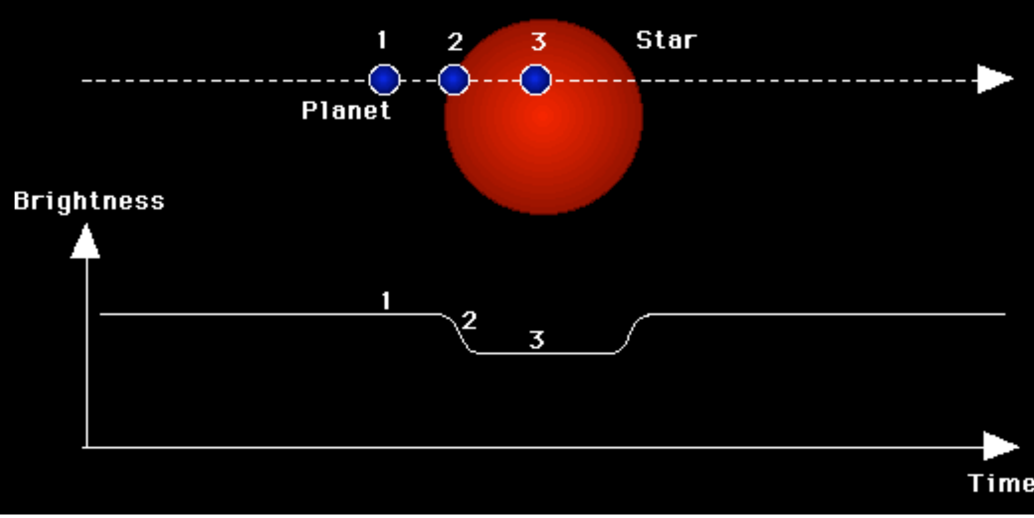
What **Exoplanets** tell us about **Planet Formation**

Jack J. Lissauer

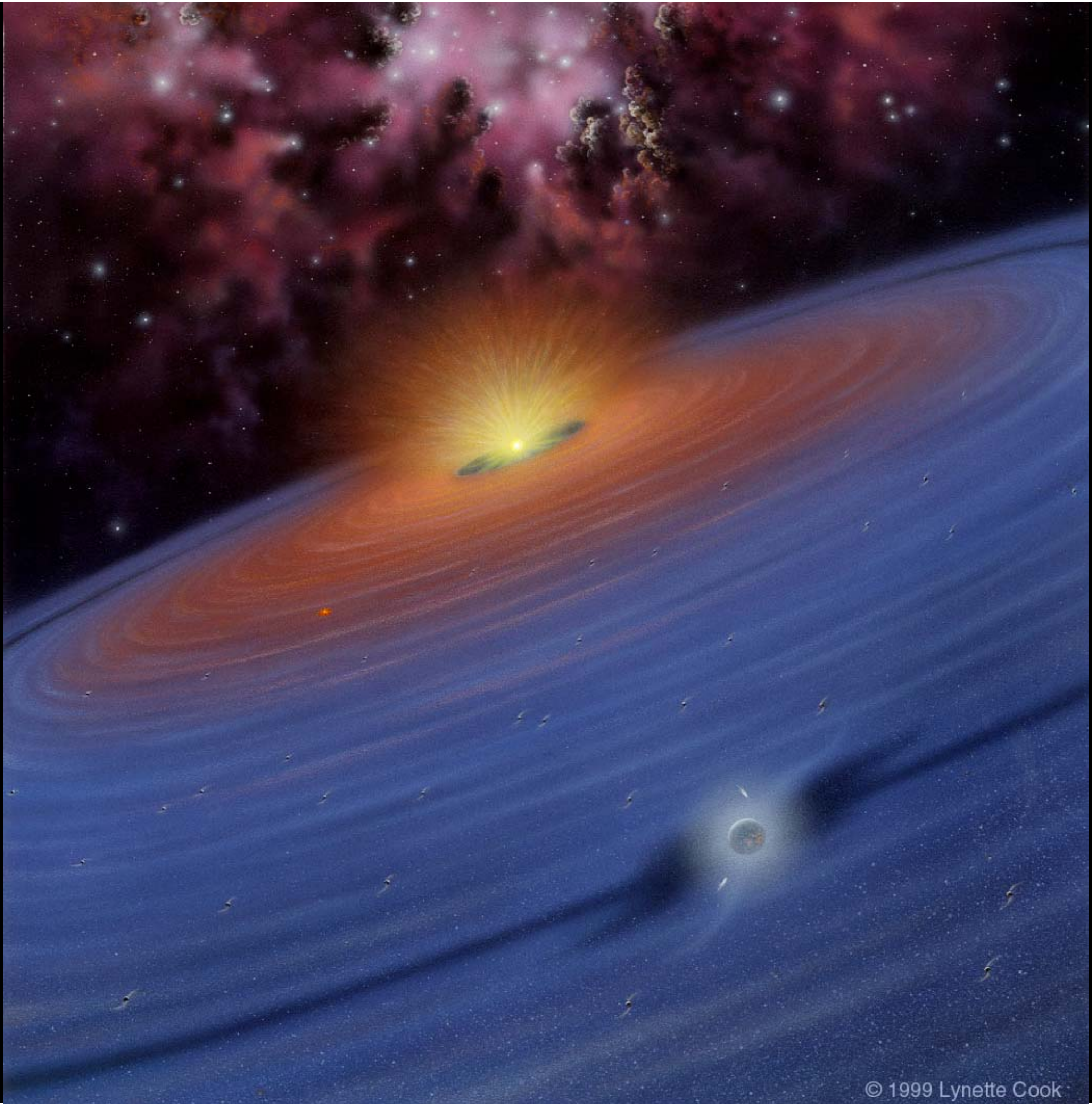
NASA - Ames Research Center

Boulder, CO - 2007 January





- **Overview**
- **Observations: Our Solar System**
  - Dynamics
  - Planetary composition
  - Meteorites
  - Geology
- **Models: Solar Nebula & Planetesimals**
  - Protoplanetary Disks
  - Solid body growth
  - Accumulation of giant planet gaseous envelopes
- **Observations: Exoplanets**
  - **Radial velocity**
  - **Transits**
  - **Microlensing, pulsar timing, other**
- **Implications, New Models & Conclusions**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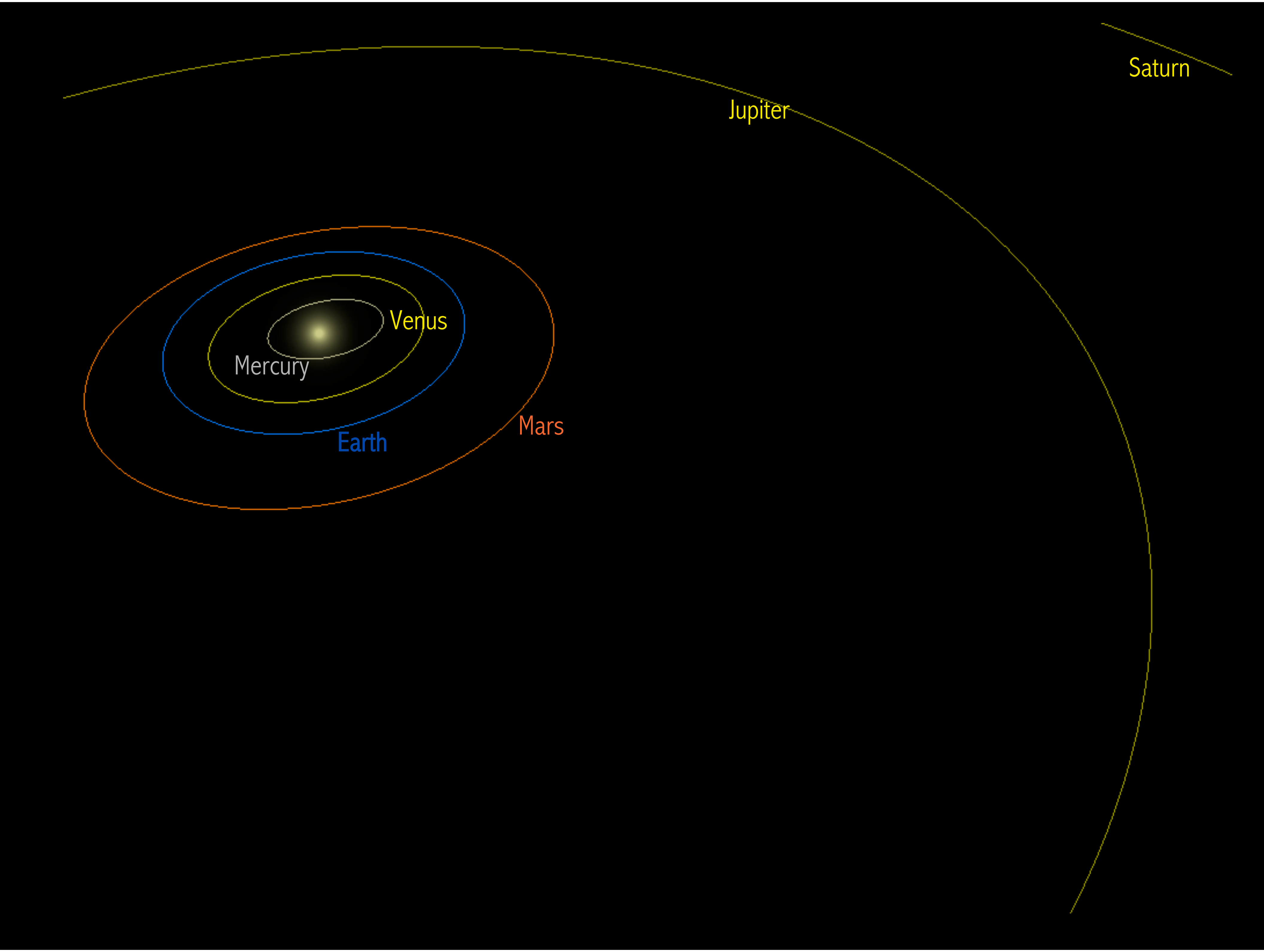
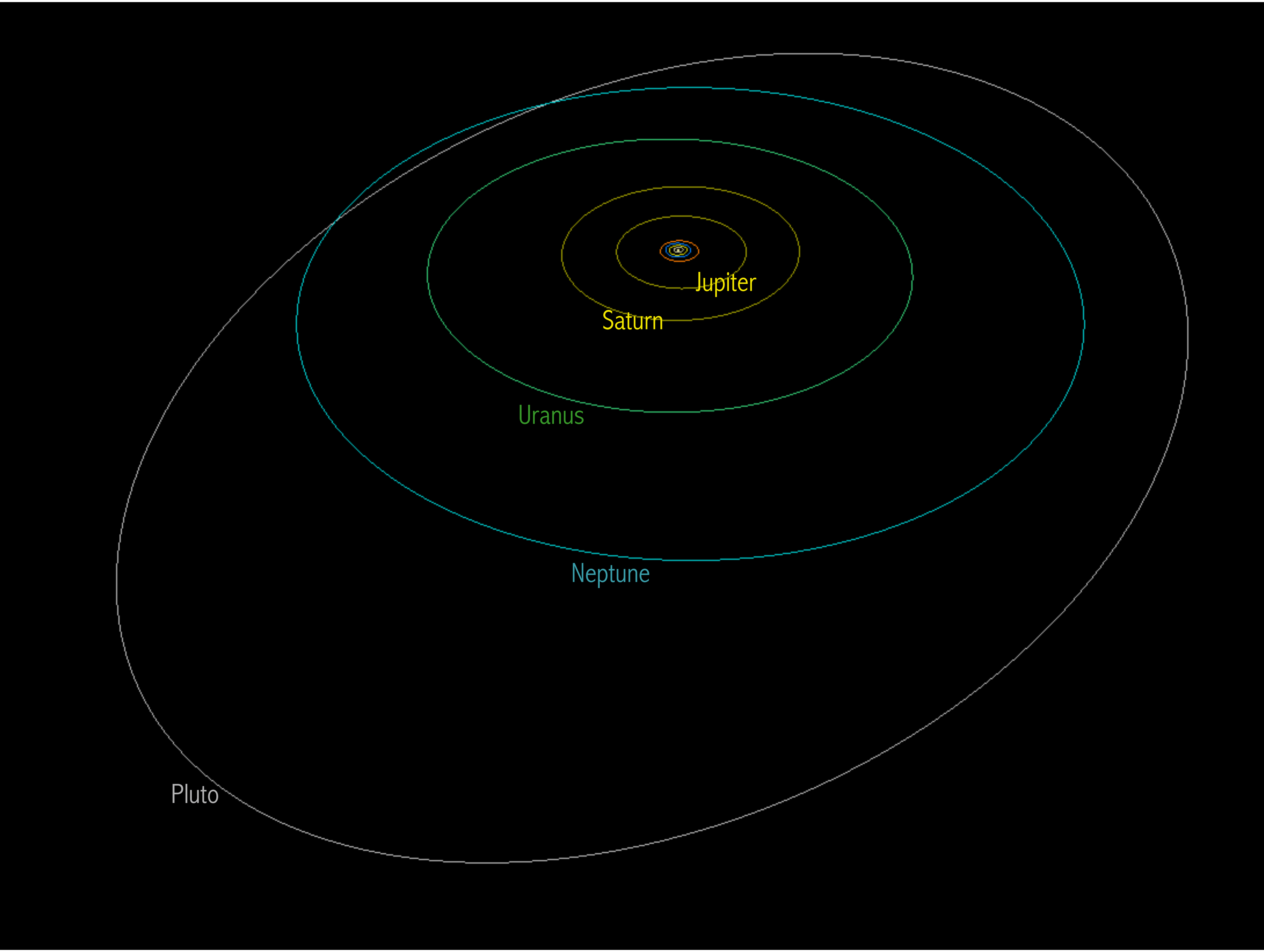
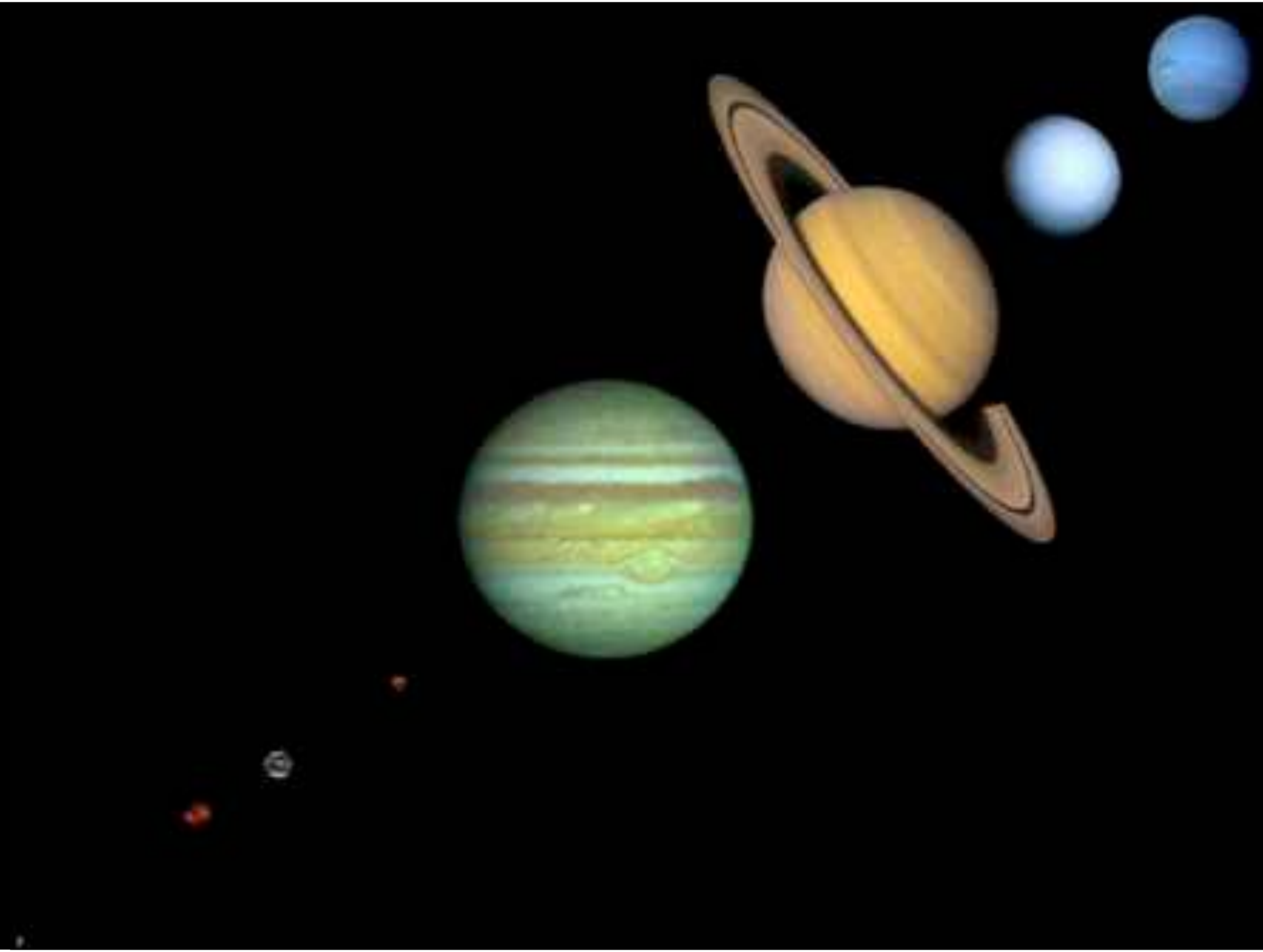
Our Solar System

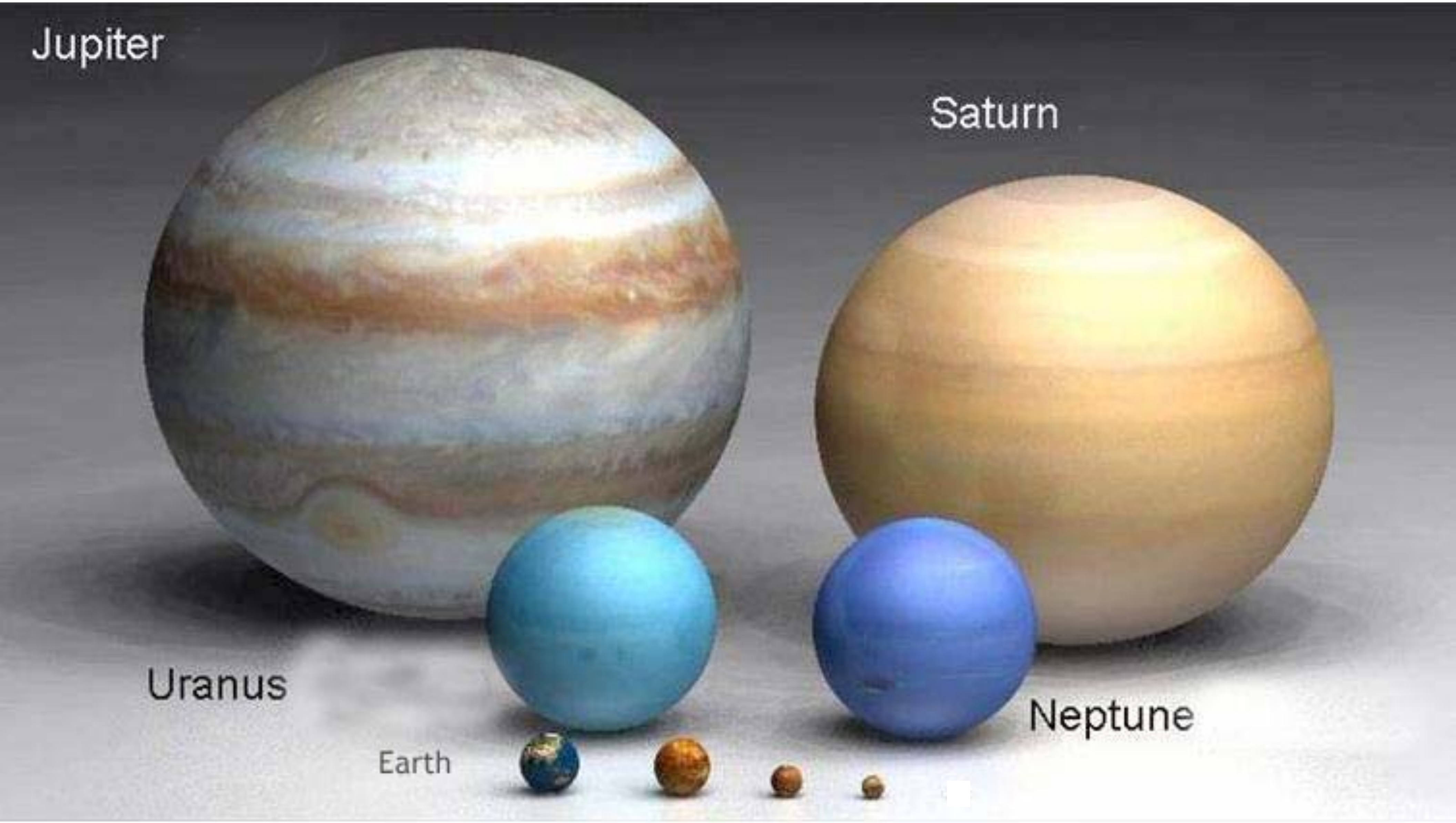
- **Dynamics**
  - Planetary orbits nearly circular & coplanar
  - Spacing increases with distance from Sun
  - All giant planets have satellite systems
  - Planetary rings close to planets
  - Many rotations per orbit unless tidally slowed
- **Compositions**
  - Largest bodies most gas-rich
  - Rocky bodies near Sun, icy bodies farther out
  - Elemental/isotopic abundances similar (except volatiles)
  - Meteorites - active heterogeneous environment
- **Planetary Geology: Cratering Record**
  - Far more small bodies in 1st 800 Myr than today

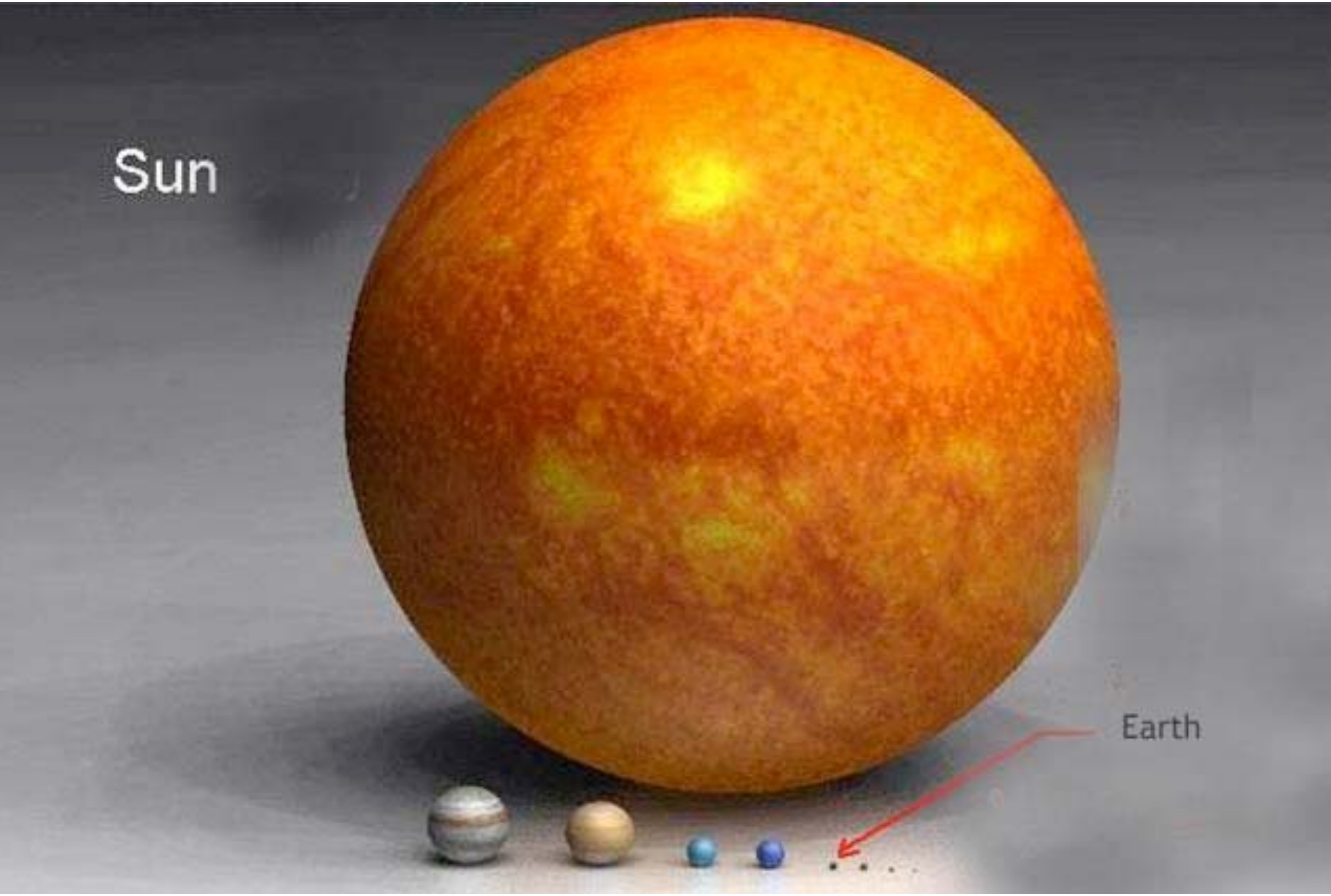


Saturn
Jupiter
Venus
Mercury
Earth
Mars


Jupiter
Saturn
Uranus
Neptune
Pluto




Jupiter
Saturn
Uranus
Neptune
Earth


Sun
Earth

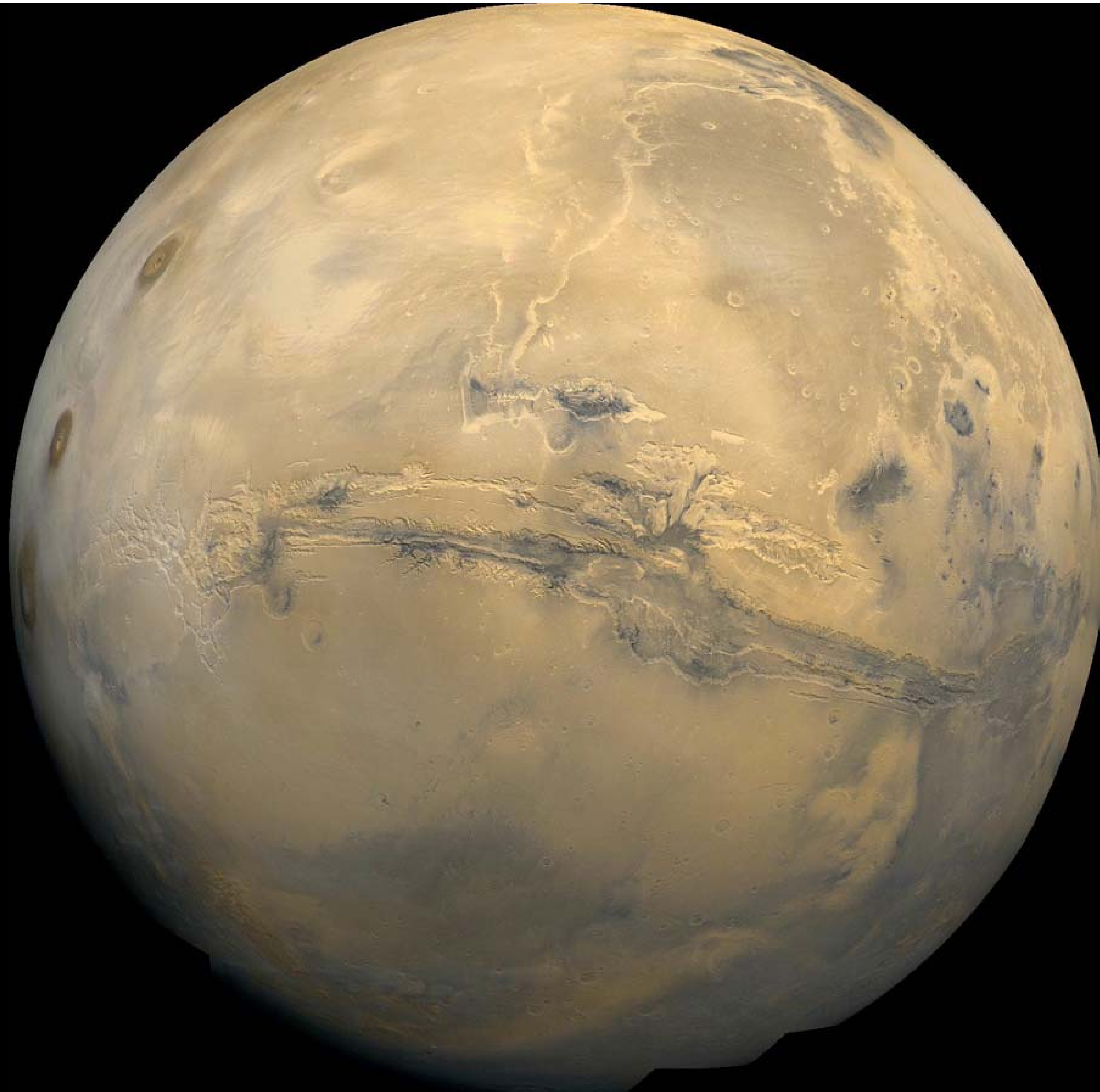
Mercury

Mariner 10 mosaic

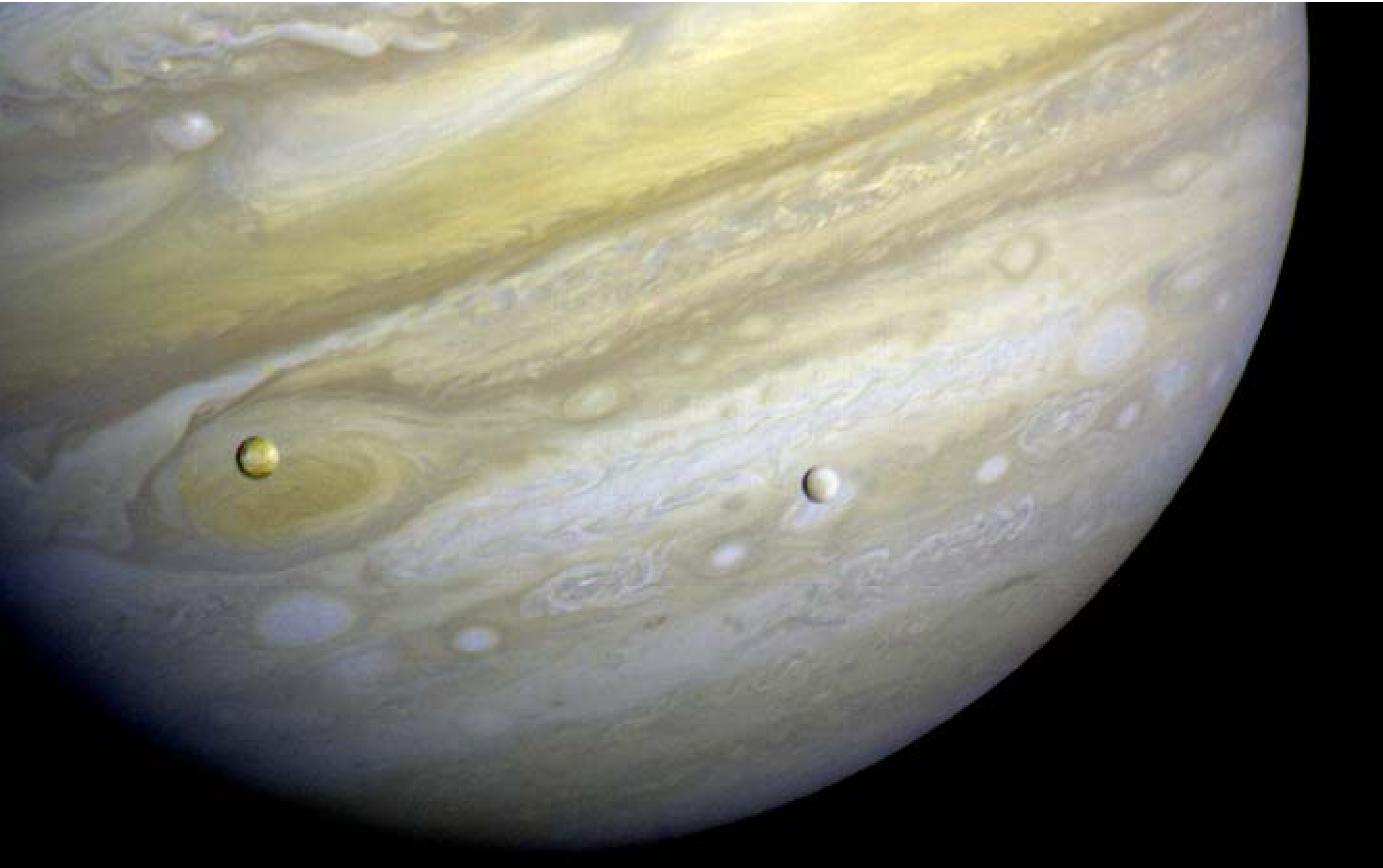
Venus

Violet light - Galileo spacecraft image

Earth



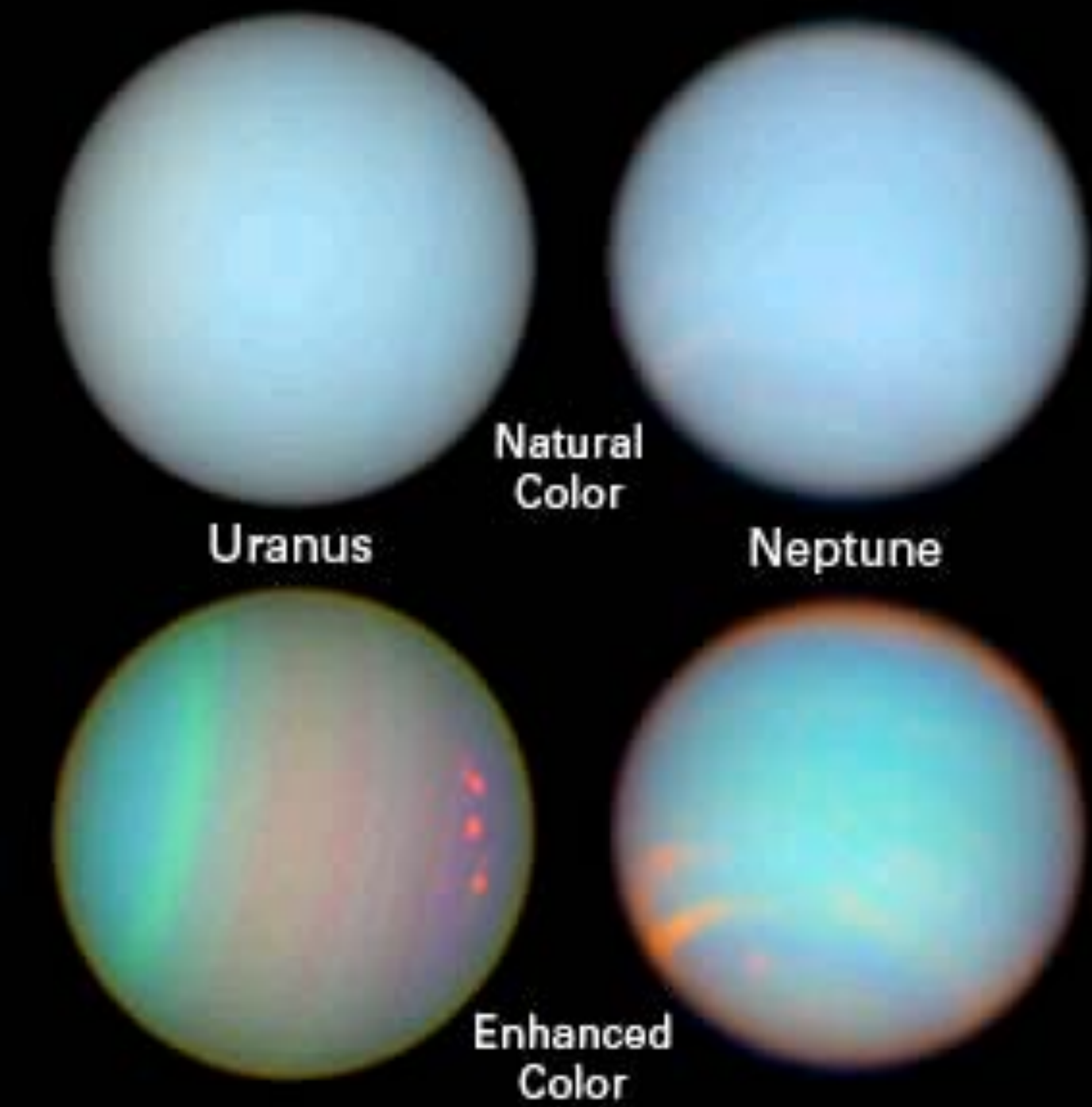
Mars



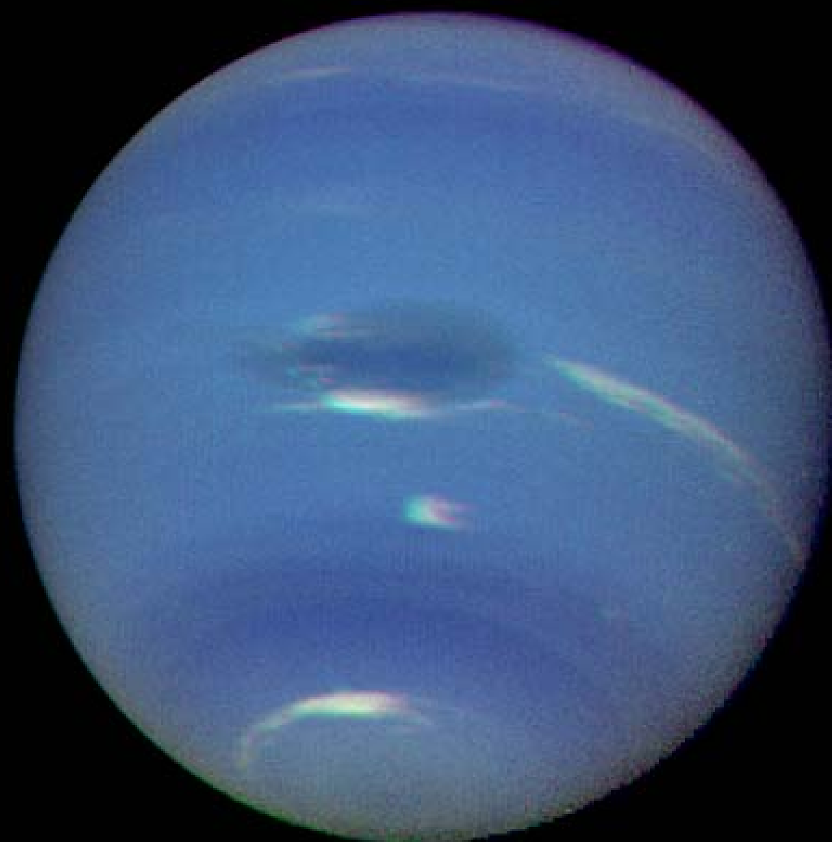
Jupiter, Io & Europa


Saturn
Hubble
Heritage

HST/ACS images 2003



Neptune - Voyager

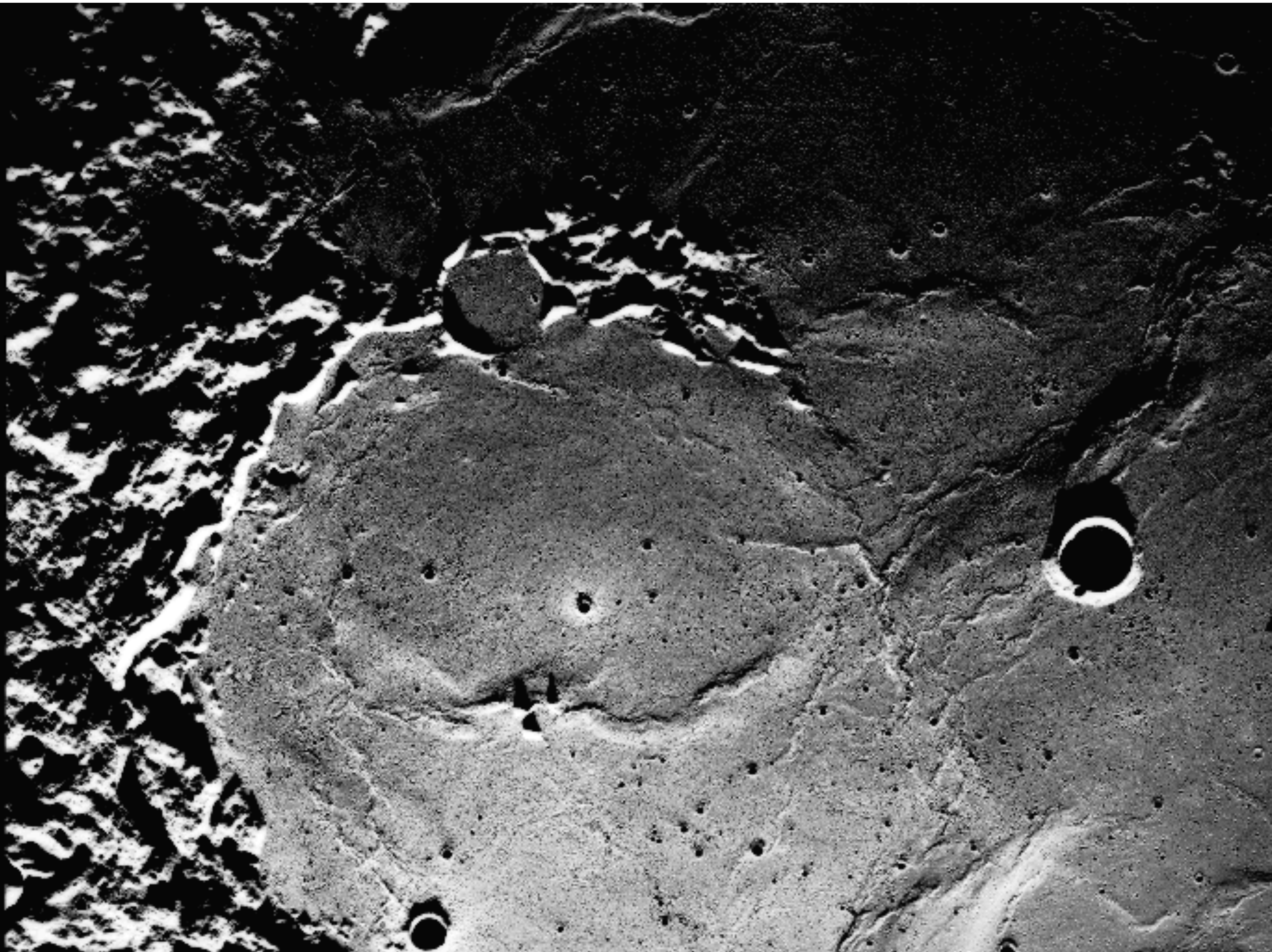



Murchison (Australia) **CM2 Carbonaceous Chondrite** Fall 1969 Sep 28
Photo: Jackie Beckett
© AMNH 2003
0
1
cm
4
5

Allende CV3 Carbonaceous Chondrite Meteorite

Close-up view.
This piece is 39 mm long.

Note CAIs & chondrules.

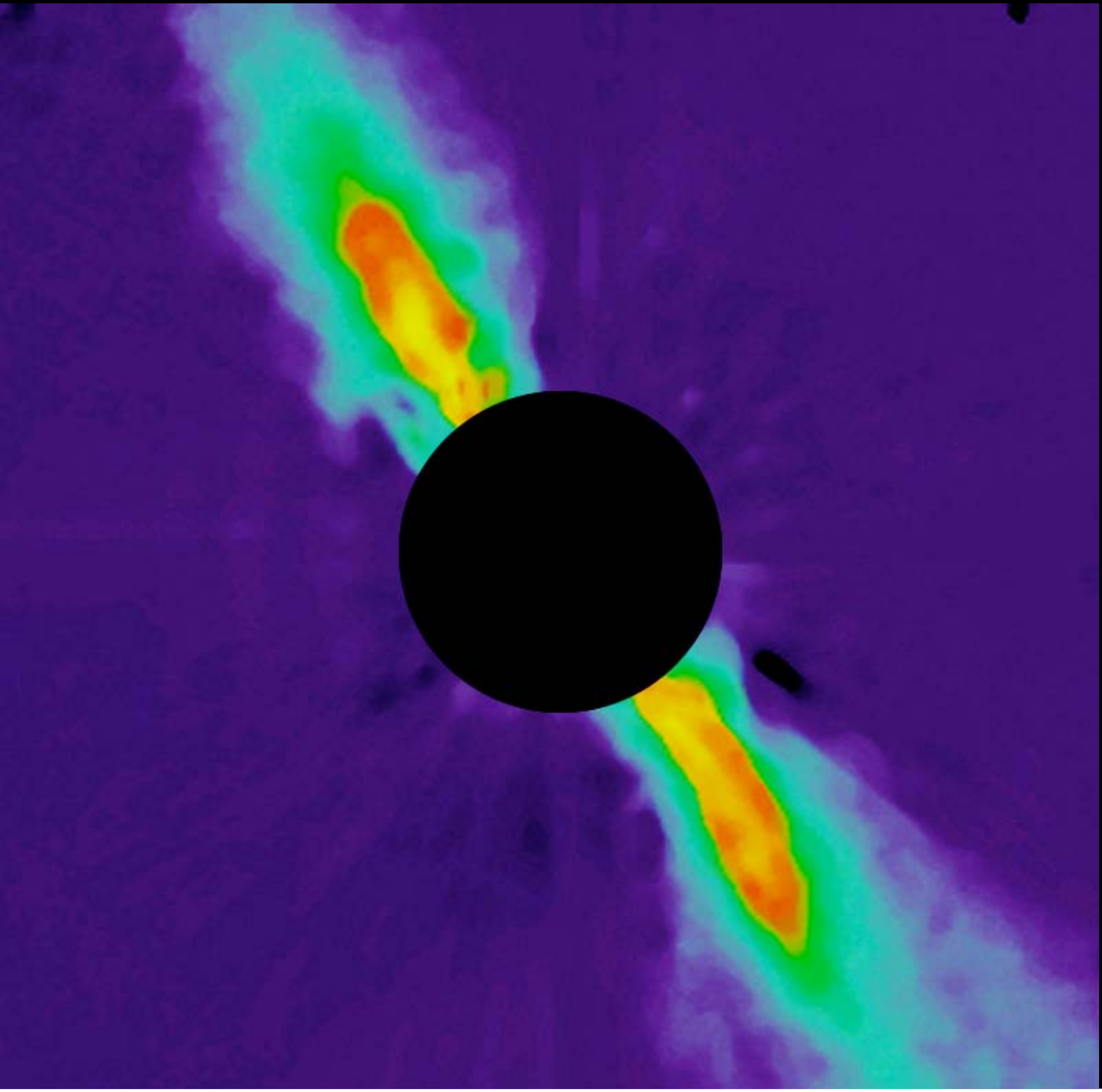


Circumstellar Disks

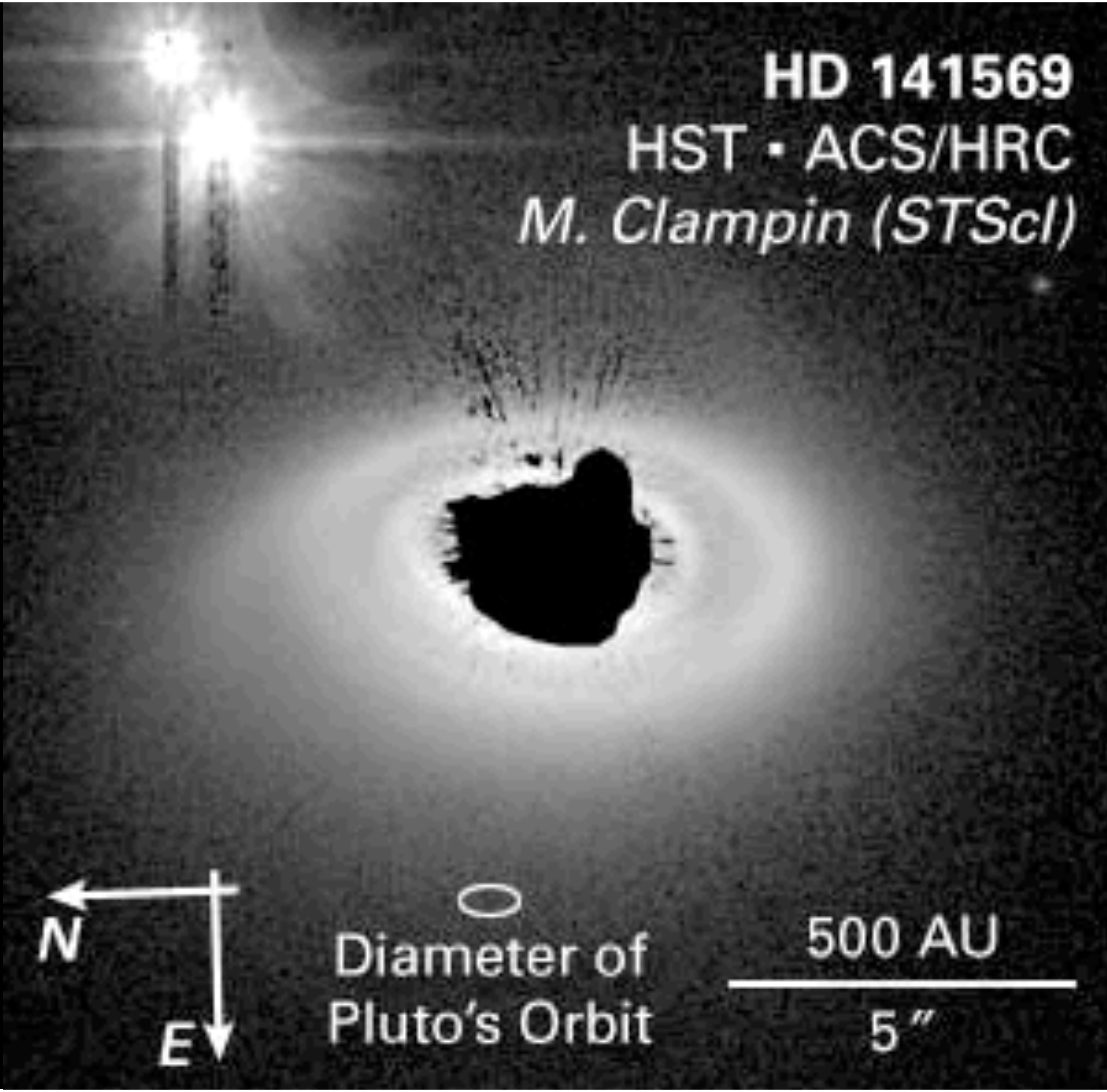
- Young Stars
  - Evidence: IR excesses, rotation curves, proplyd images
  - Radii tens to hundreds of AU (even larger for massive stars)
  - Typical mass ~ 0.01 - 0.1 M_{Sun}
  - Lifetime (dust) < 10 Myr
  - Some show evidence for gaps, inner holes
- Main Sequence Stars
  - Second generation debris disks - unseen parent bodies
  - Low mass, gas poor
  - More prominent around younger stars
  - Some show evidence for gaps, inner holes

Proplyds in Orion

β Pictoris Circumstellar Dust Disk at 1.2 μm



Mouillet et al. 1997, *MNRAS* **292,** 896.
β Pic 1.2 μm ADONIS, Chile.


HD 141569
HST • ACS/HRC
M. Clampin (STScI)
N
E
Diameter of
Pluto's Orbit
500 AU
5″

Solar Nebula Theory

(Kant 1755, LaPlace 1796)

The Planets Formed in a Disk in Orbit About the Sun

Explains near coplanarity and circularity of planetary orbits

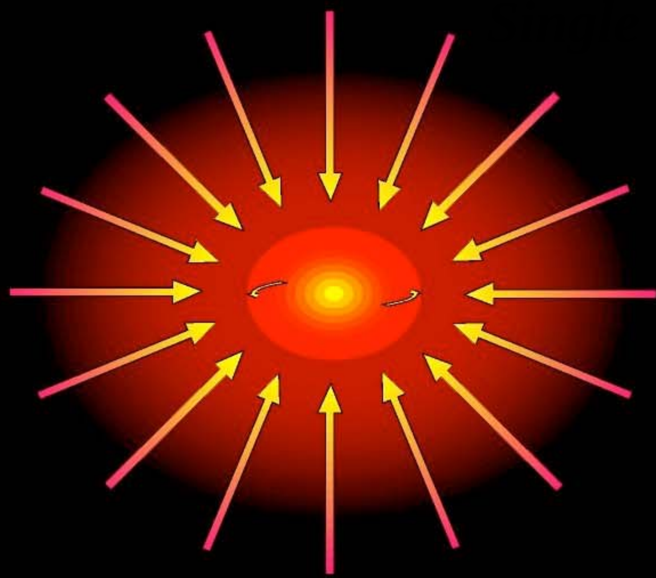
Disks are believed to form around most young stars

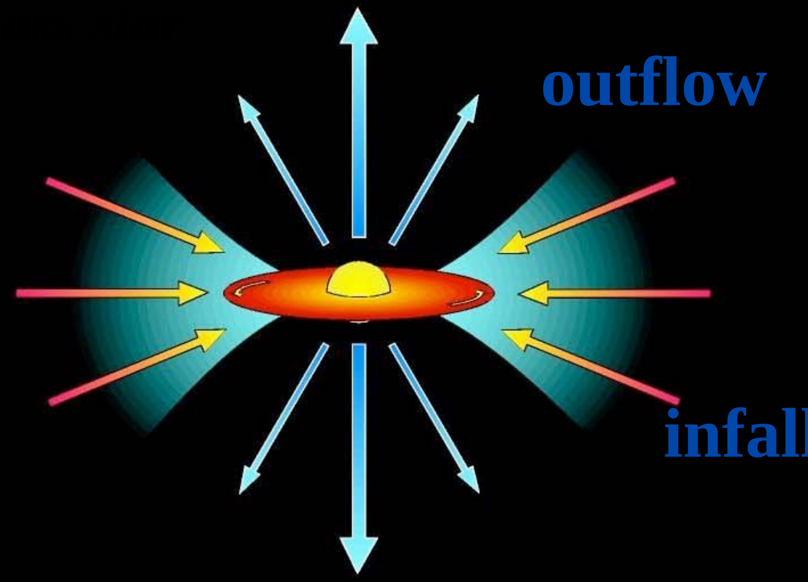
Theory: Collapse of rotating molecular cloud cores

Observations: Proplyds, β Pic, IR spectra of young stars

Predicts planets to be common, at least about single stars

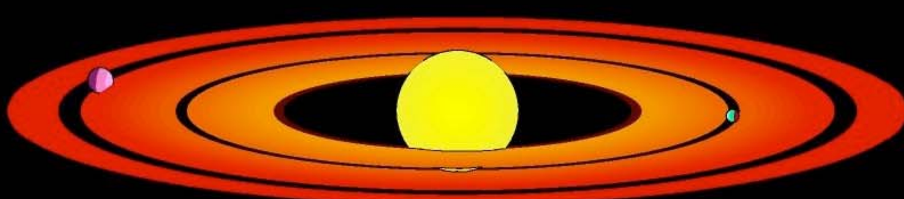
Scenario for star- and planet formation

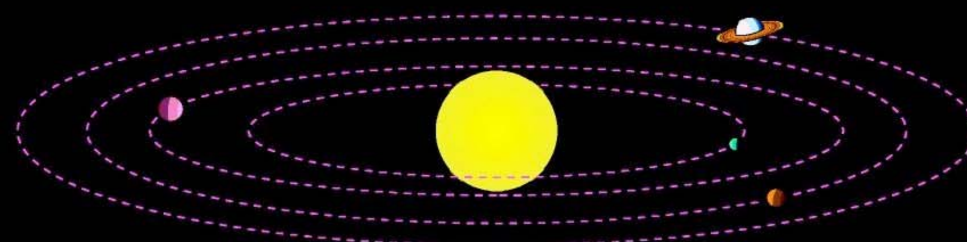




Cloud collapse

Protostar with disk t=10^5 yr





Formation planets t=10^6-10^7 yr

Planetary system t>10^8 yr

Planetesimal Hypothesis

(Chamberlain 1895, Safronov 1969)

Planets Grow via Binary Accretion of Solid Bodies

Massive Giant Planets Gravitationally Trap
H_2 + He Atmospheres

Explains planetary composition vs. mass

General; for planets, asteroids, comets, moons

Can account for Solar System; predicts diversity

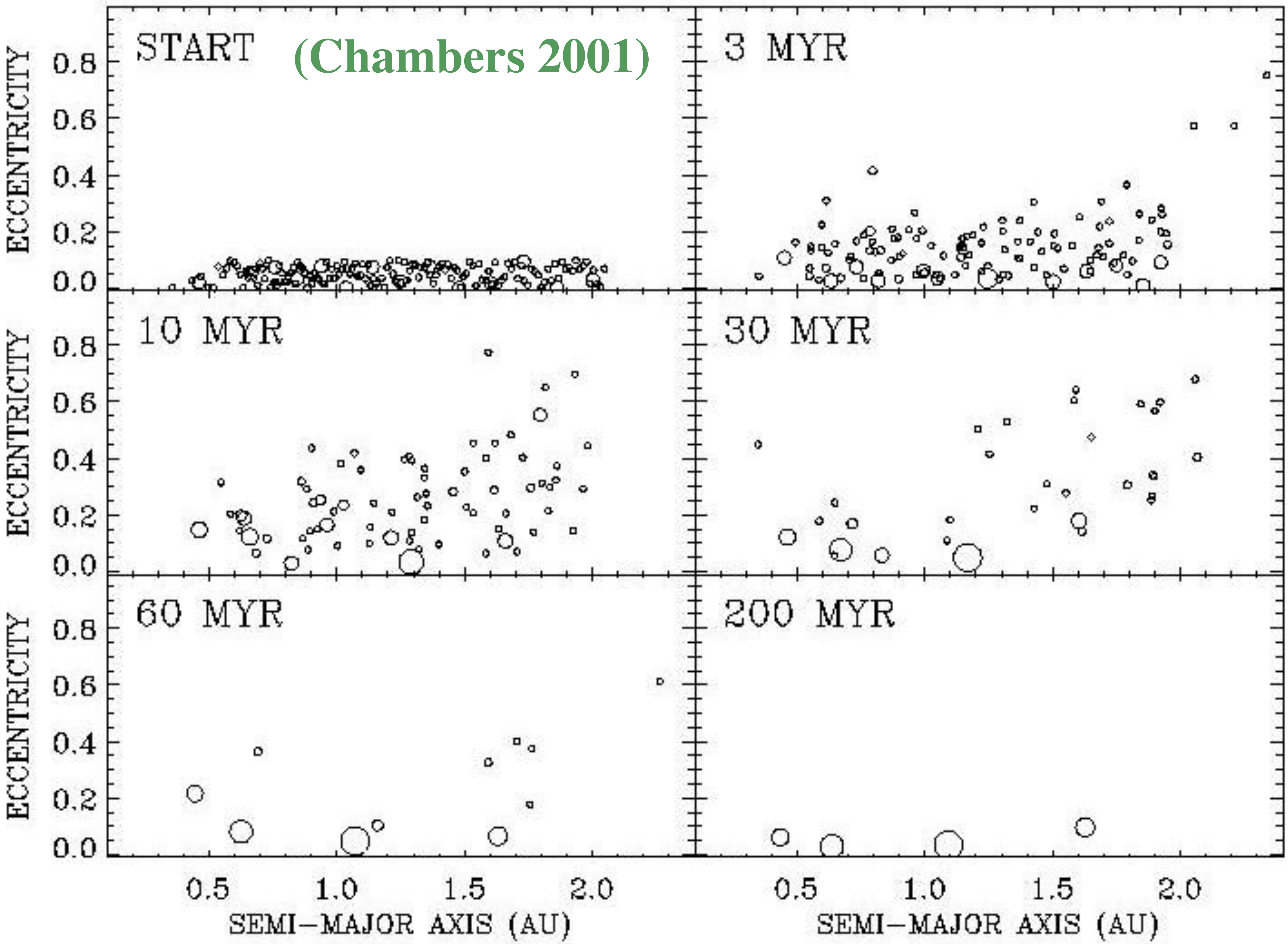
Dust -> Terrestrial Planets

μm - cm: Dust settles towards midplane of disk; sticks, grows. Chondrule & CAI formation??

cm - km: Two possibilities: continued sticking or gravitational instabilities

km - 10,000 km: Binary collisions - runaway growth; isolation; giant impacts

Terrestrial Planet Growth Sun-Jupiter-Saturn



Terrestrial Planets: Masses & Orbits

Mergers continue until stable configuration reached

Fewer planets usually more stable, even though planets are larger

Resonances (commensurabilities in orbital periods) destabilize system

Stable configurations need to last billions of years

Giant impacts & chaos imply diversity

Terrestrial Planet Growth

Mergers continue until stable configuration reached

Runaway/oligarchic stages ~ 10^5 years

High velocity stage ~ 10^8 years

These processes take longer at greater distances from star

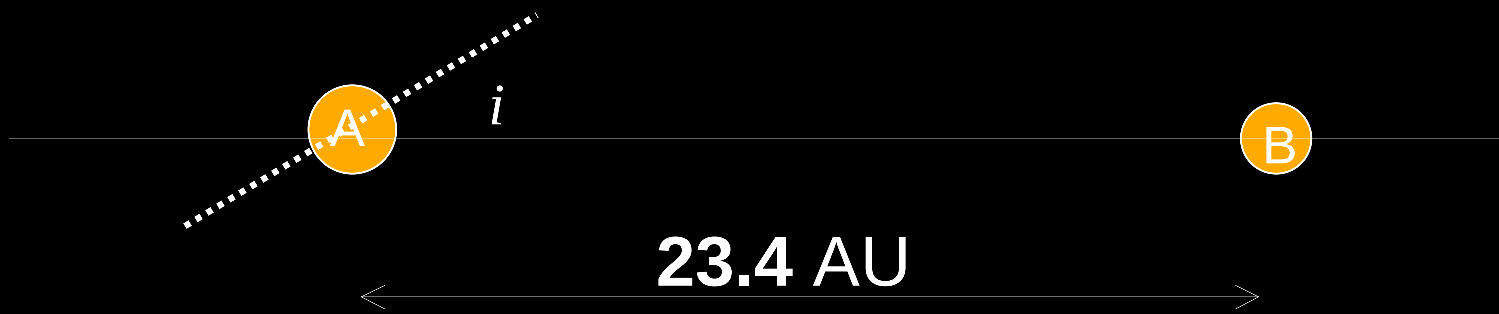
Planet Formation in **Binary Star** Systems

> 50 % stars are in multiple star systems

> 20 planets known in multiple star systems

What is the effect of a **stellar companion** on the planet formation processes?

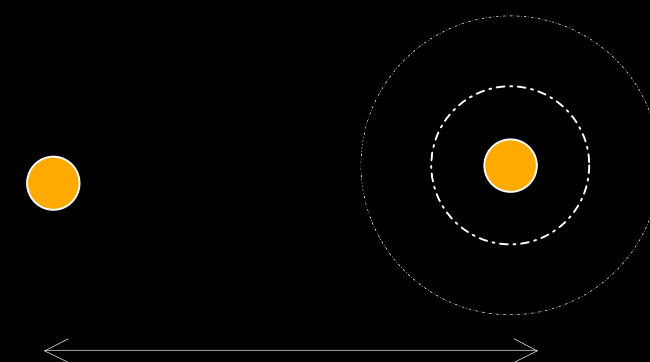
α Centauri System



G2 star
M = **1.1** Msun

K1 star
M = **0.91** Msun

"Wide-Binary"

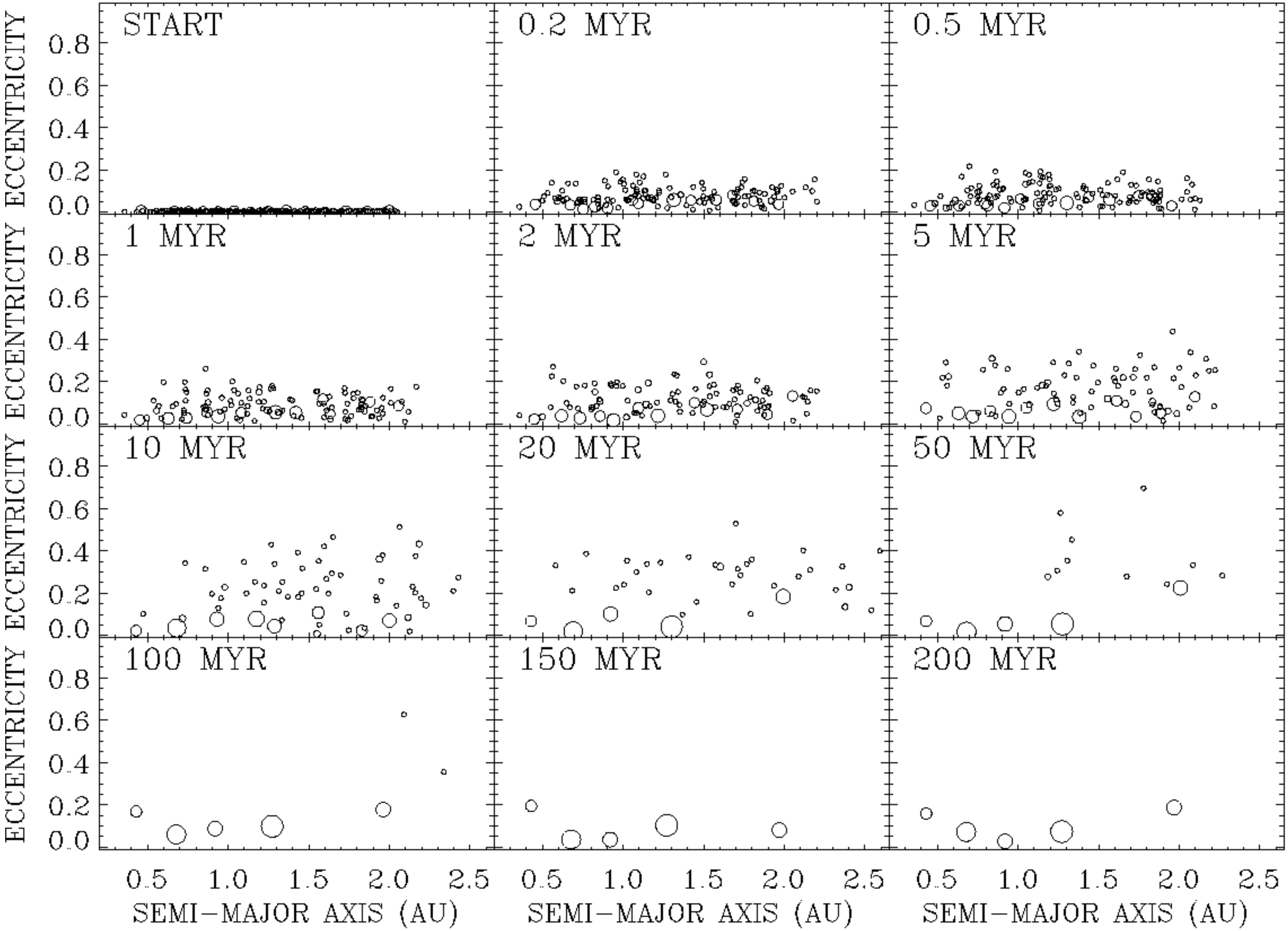


- Disk inclined to binary orbit:

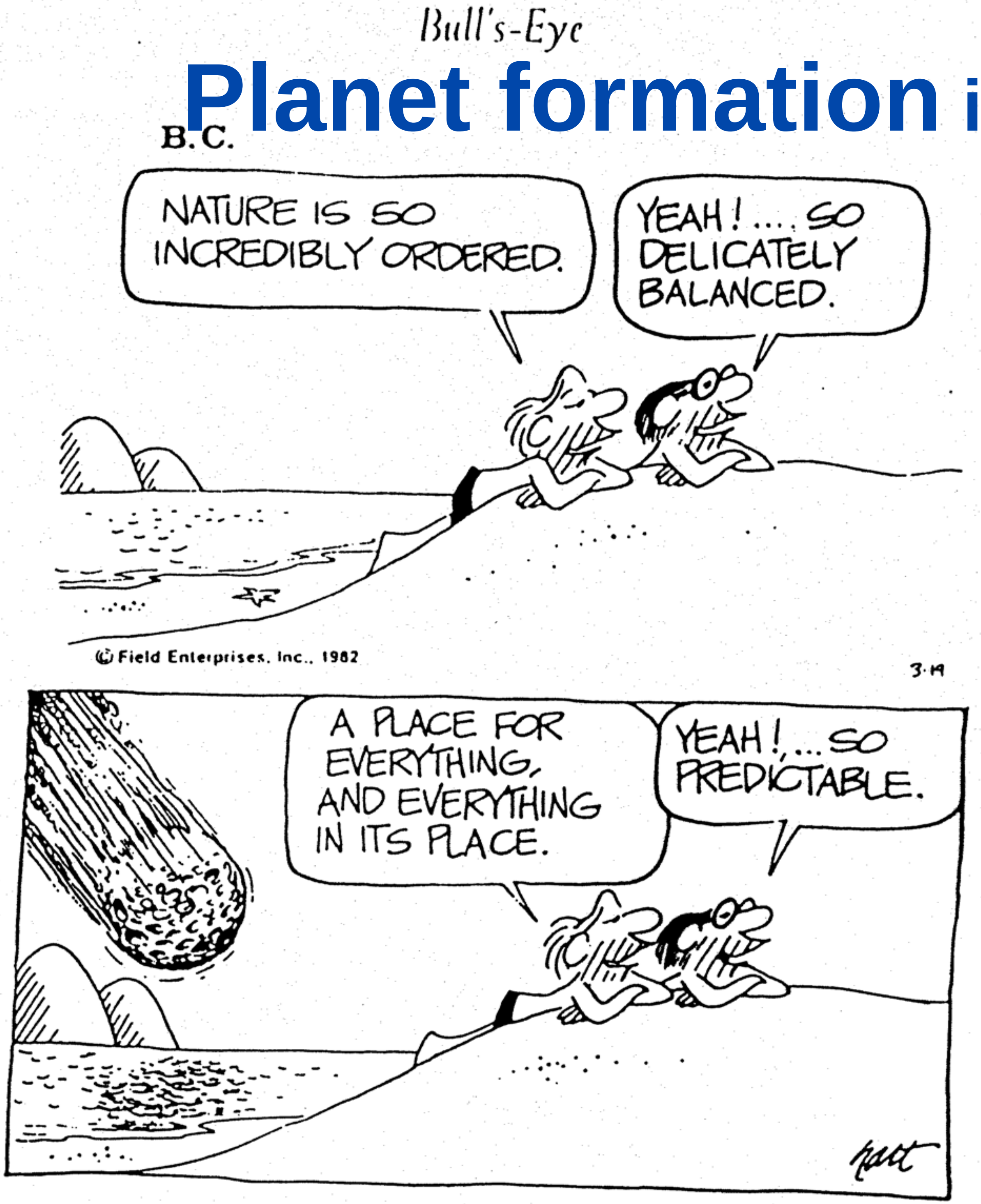
  i = 0°, 15°, 30°, 45°, 60°, 180°

- Integration time = 200 Myr - 1 Gyr

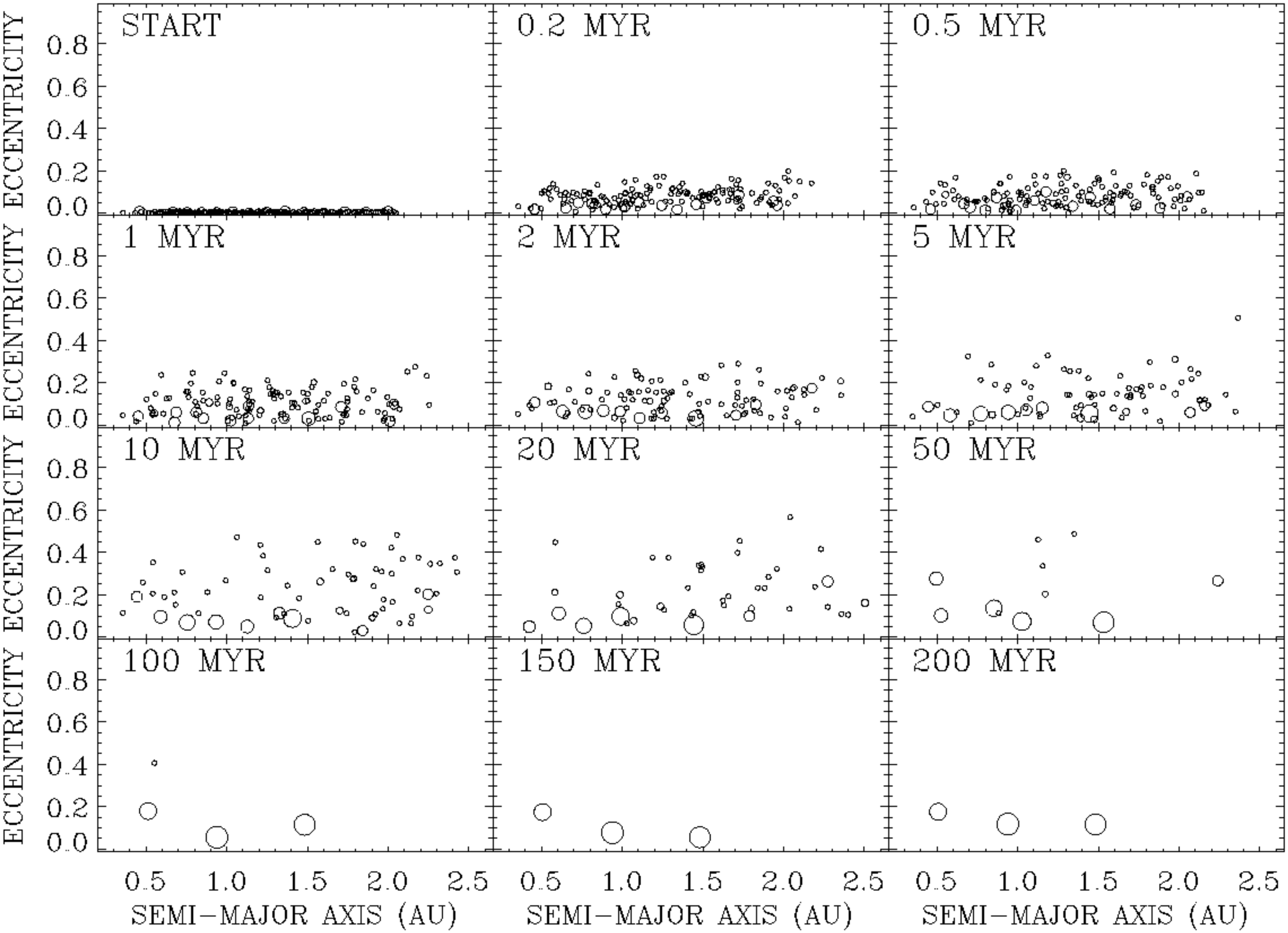
RUN 1 (i=0°) α Cen a_B = 23.4 AU



Planet formation is chaotic, so many numerical experiments are needed to get statistically valid results.



RUN 2 (i=0°) α Cen a_B = 23.4 AU



Theories of Giant Planet Formation

Core-nucleated accretion: Big rocks accumulated gas

Fragmentation during collapse: Planets form like stars

Gravitational instability in disk: Giant gaseous protoplanets

Theories of Giant Planet Formation

Core-nucleated accretion: Big rocks accumulated gas

One model for rocky planets, jovian planets, moons, comets…

Explains composition vs. mass

Detailed models exist

Takes millions of years

Fragmentation during collapse: Planets form like stars

Gravitational instability in disk: Giant gaseous protoplanets

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Fragmentation during collapse: Planets form like stars

Rapid

Binary stars are common

Mass gap

Requires $M > 7\ M_J$

Separate model for solid bodies; no model for Uranus/Neptune

Gravitational instability in disk: Giant gaseous protoplanets

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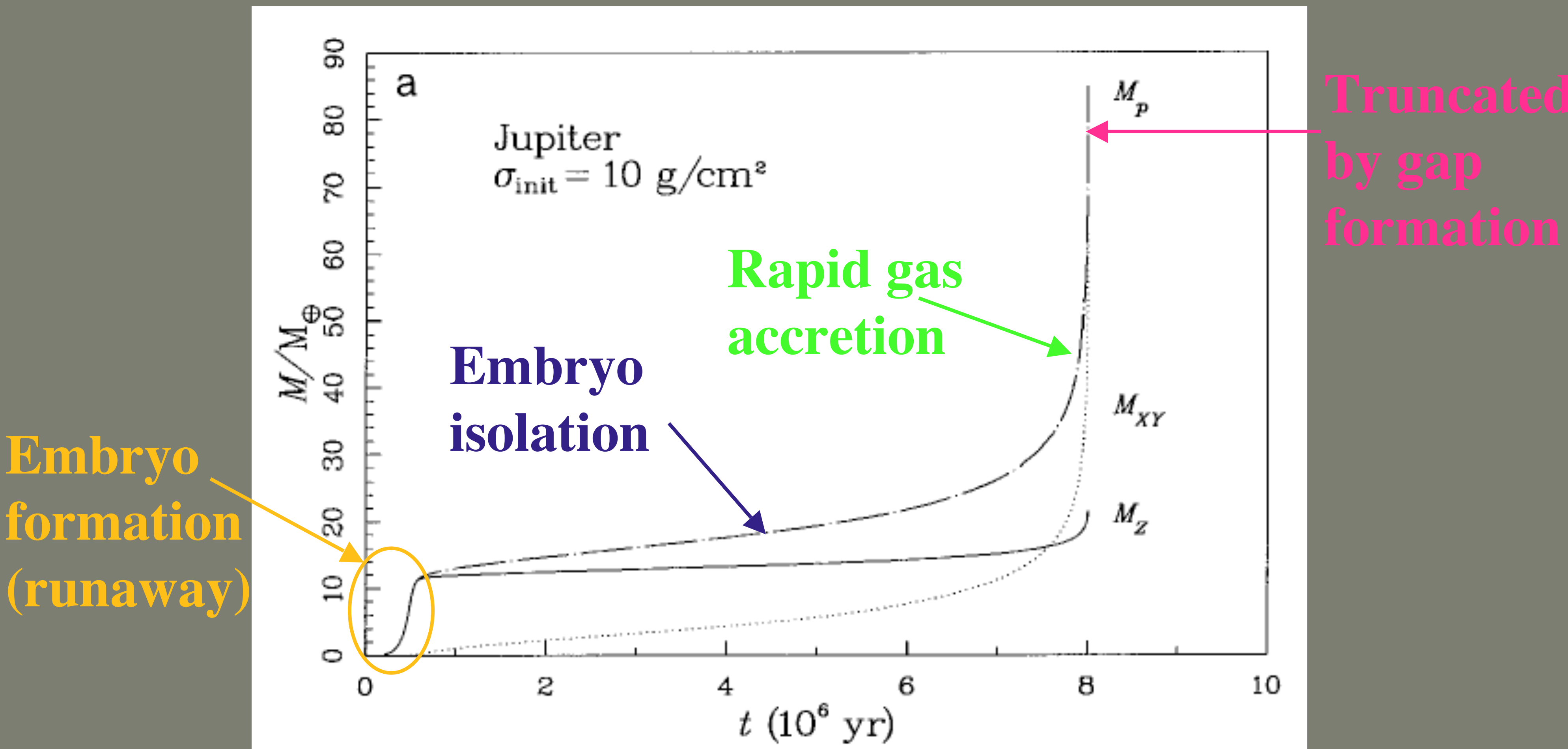
Gravitational instability in disk: Giant gaseous protoplanets

Rapid growth, but cooling rate limits contraction

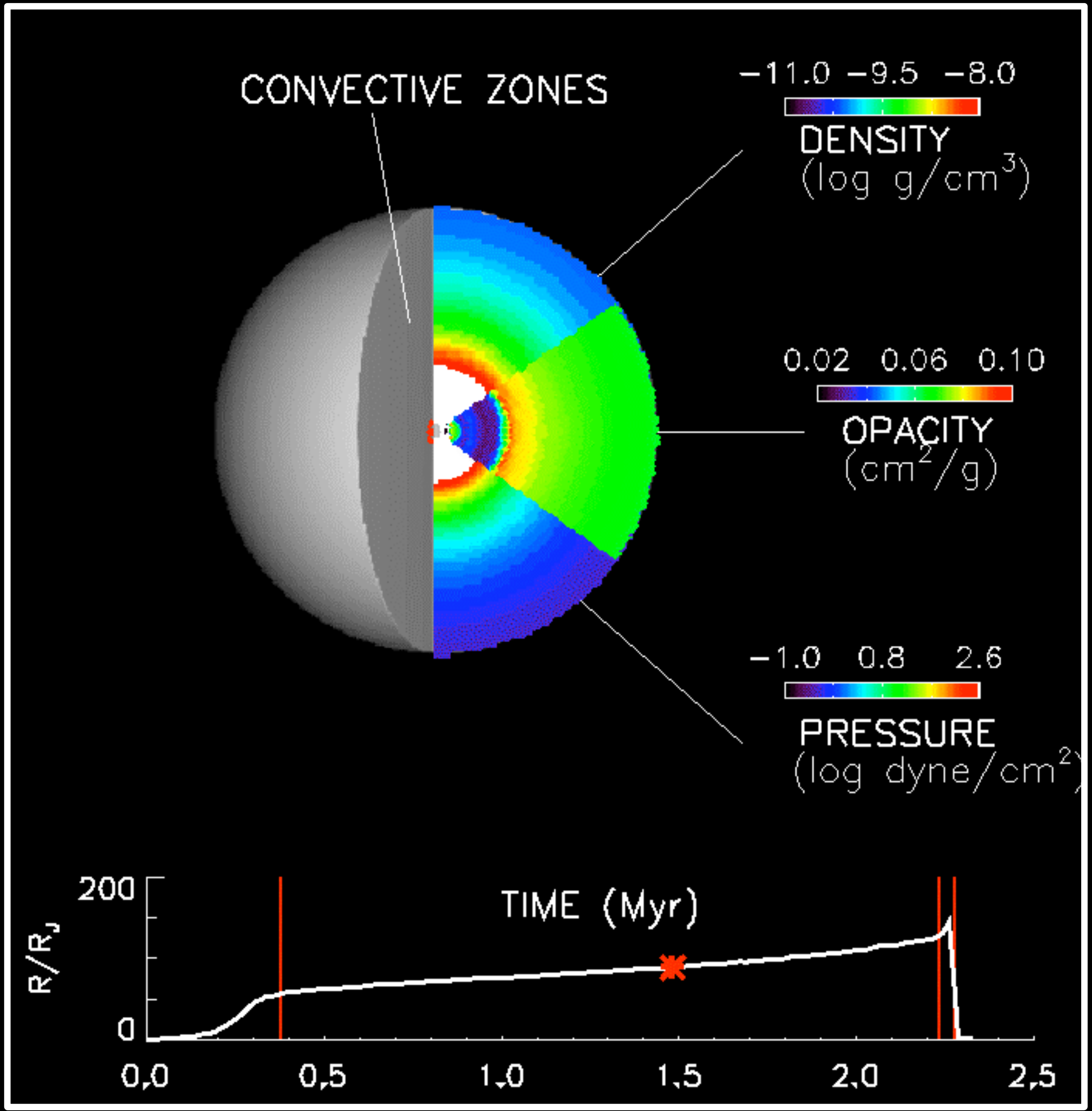
Requires unphysical initial conditions (density waves stabilize)

Separate model for solid bodies; no good model for Uranus/Neptune

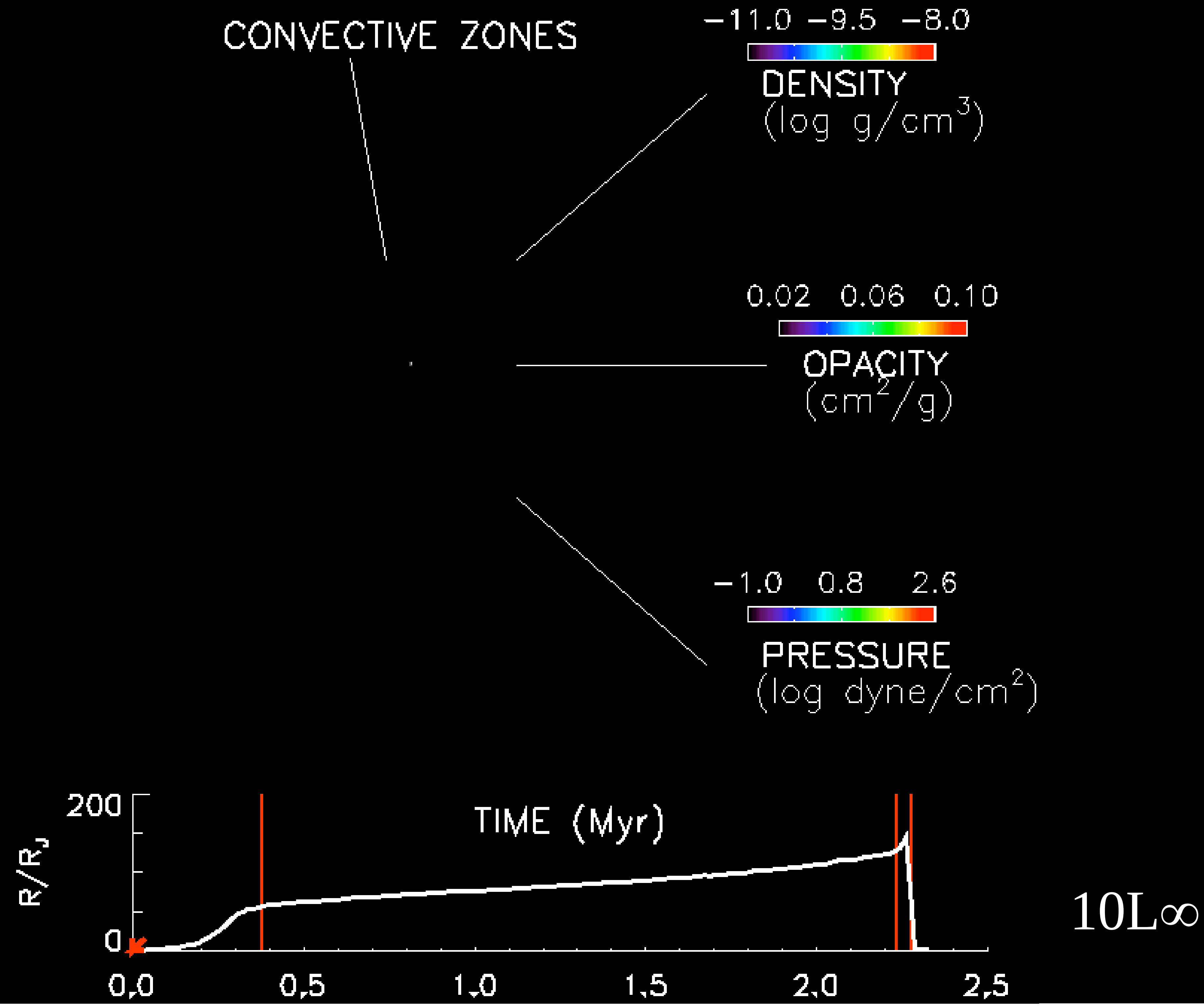
Nucleated Instability model ("Standard" Case)



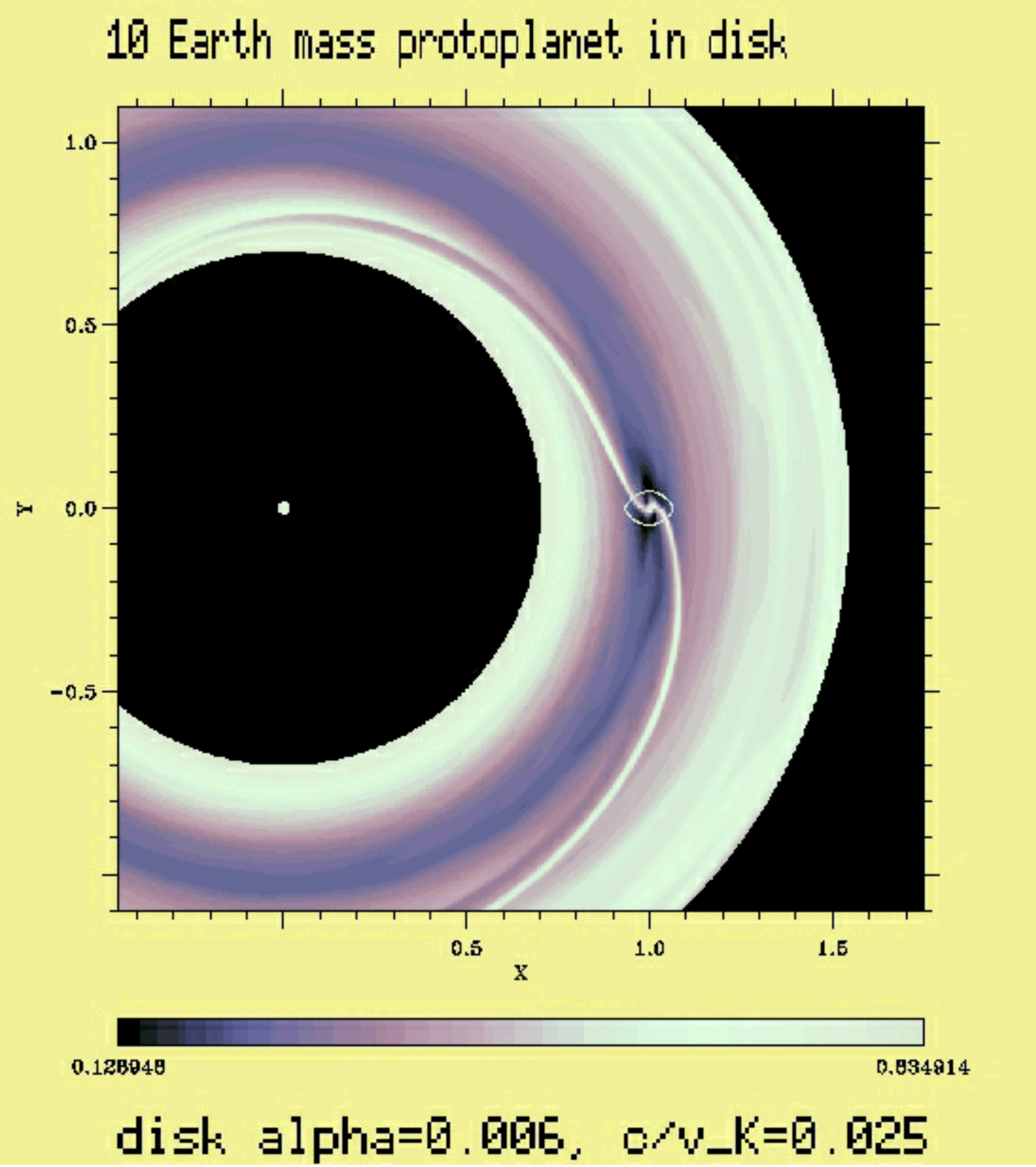
Pollack *et al*, 1996



10L∞ simulation of the evolution of Jupiter



CONVECTIVE ZONES
−11.0 −9.5 −8.0
DENSITY
(log g/cm³)
0.02 0.06 0.10
OPACITY
(cm²/g)
−1.0 0.8 2.6
PRESSURE
(log dyne/cm²)
200
0
R/R_J
TIME (Myr)
0.0 0.5 1.0 1.5 2.0 2.5
10L∞



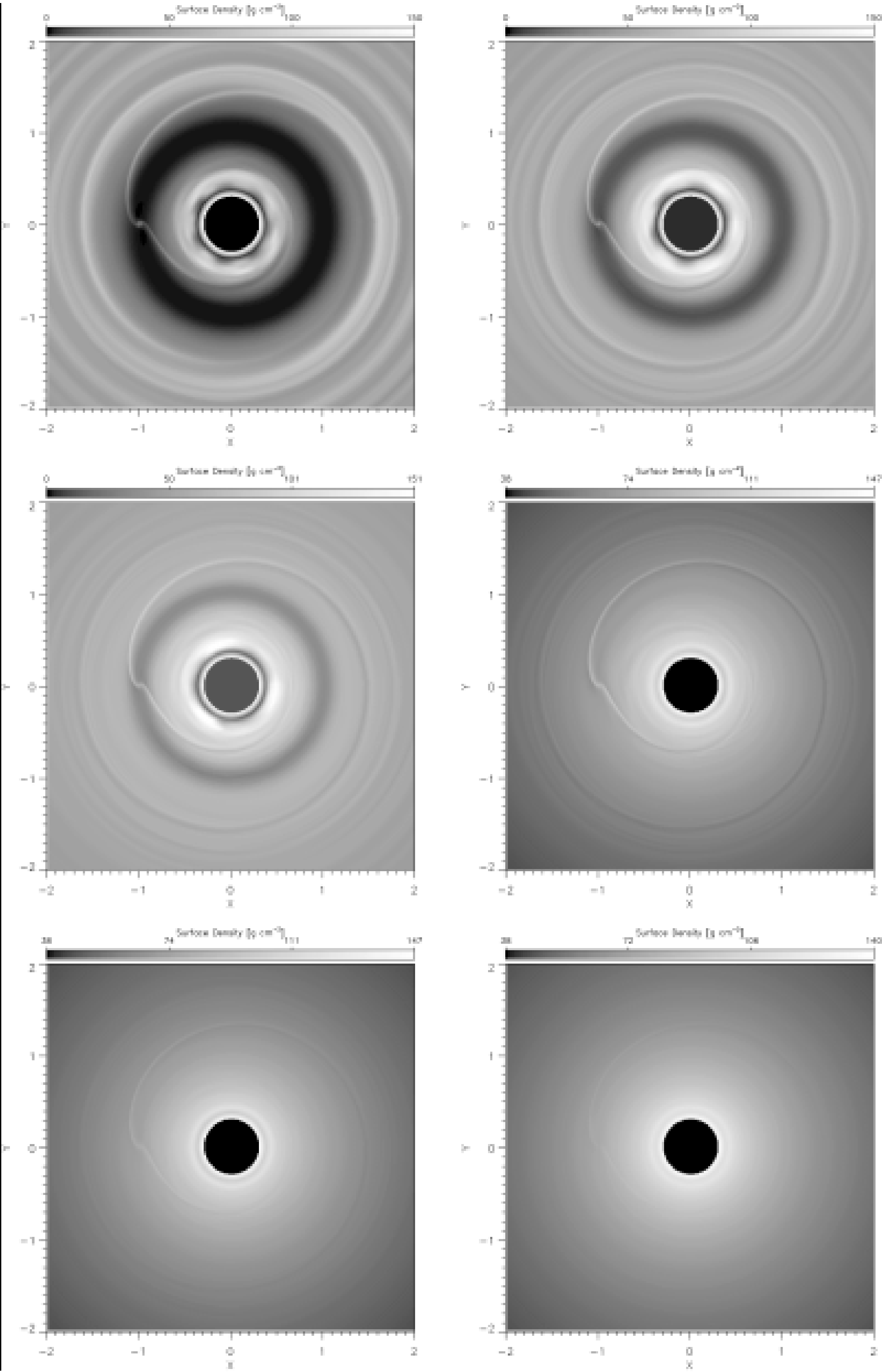
Planet's gravity affects disk.

Computer simulation by P. Artymowicz

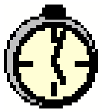
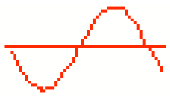
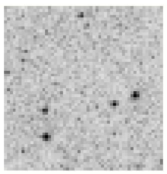
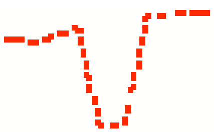
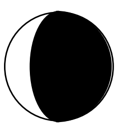
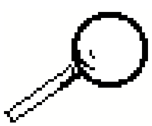
Gas Flow Near Planet

(Bate et al. 2003)

- Planet masses are 1, 0.3, 0.1, 0.03, 0.01, 0.003 M_J

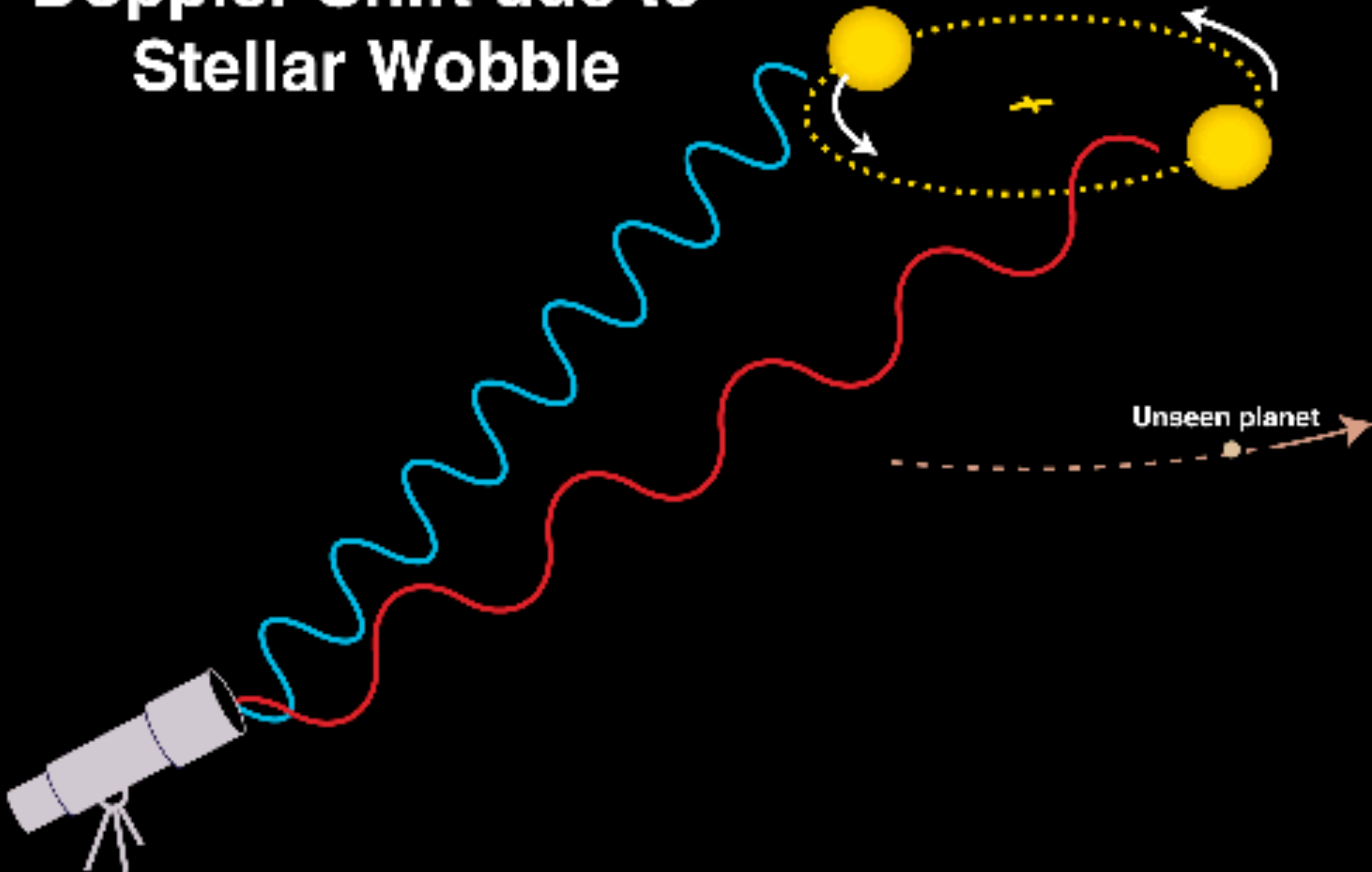


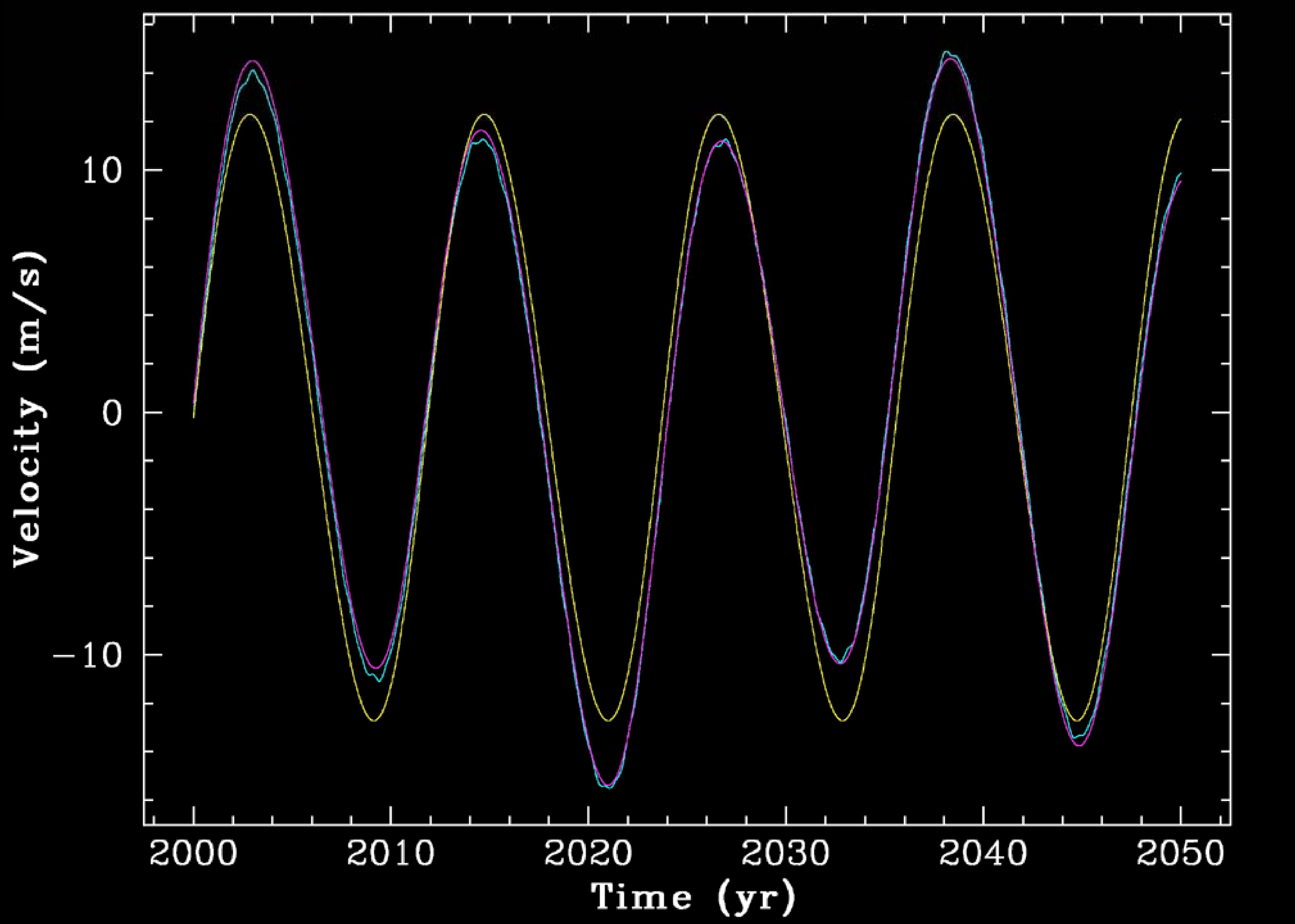
TECHNIQUES FOR FINDING EXTRASOLAR PLANETS

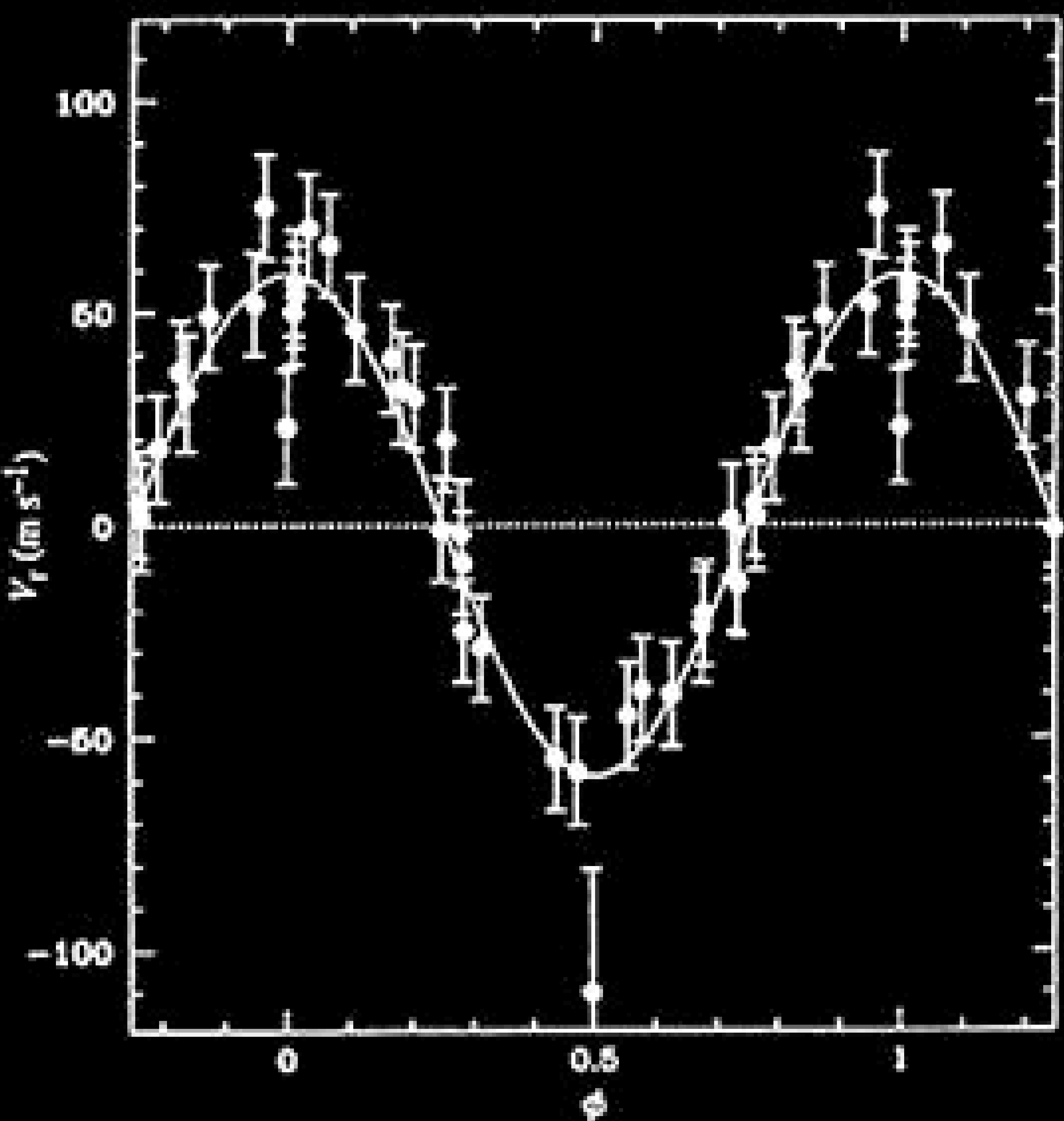

Method	Yield	Mass Limit	Status
Pulsar Timing	m/M ; τ	Lunar	PSR B1257+12 (3)
Radial Velocity	$m \sin i$; τ	super-Earth	Successful (>200)
Astrometry	m ; τ ; D_S ; a		
Ground: Single Telescope		Jupiter	Ongoing
Ground: Interferometer		sub-Jupiter	In development
Space: Single Telescope		sub-Jupiter	Upper limits
Space: Interferometer		Uranus	Being studied
Transit Photometry	R ; τ ; $\sin i=1$		
Ground		sub-Jupiter	Several detections, confirmations
Space		Mars	Planned ***Kepler***
Reflection Photometry(??):	A ; R ; τ		
Space		Saturn	Ongoing *MOST*
Microlensing:	$f(m,M,r,D_S,D_L)$		
Ground		super-Earth	A few detections
Direct Imaging	A ; R ; τ ; D_S ; a ; M		
Ground		Saturn	Possible detection
Space		Earth	Being studied

Doppler Shift due to Stellar Wobble





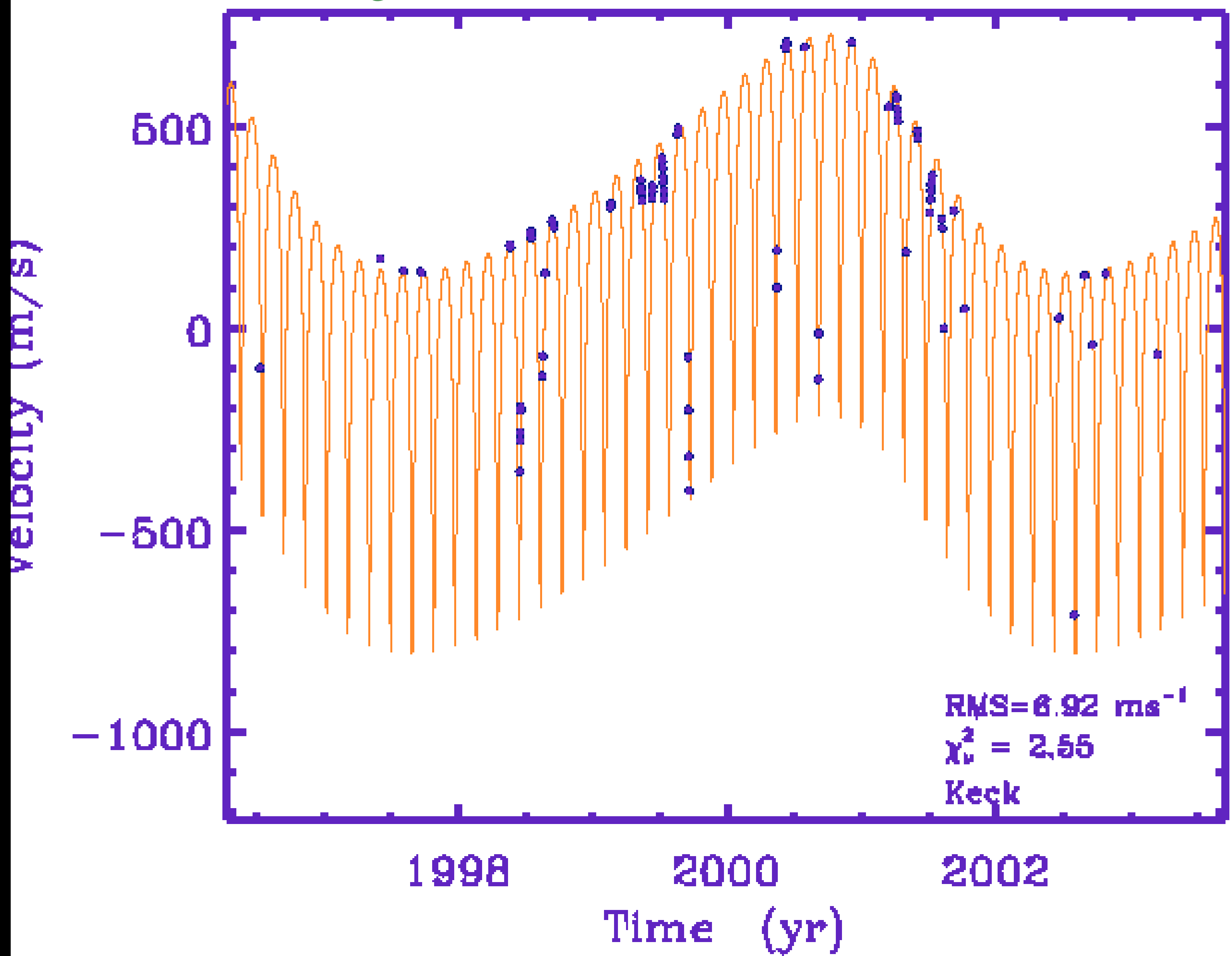
Velocity (m/s)
10
0
−10
2000
2010
2020
2030
2040
2050
Time (yr)

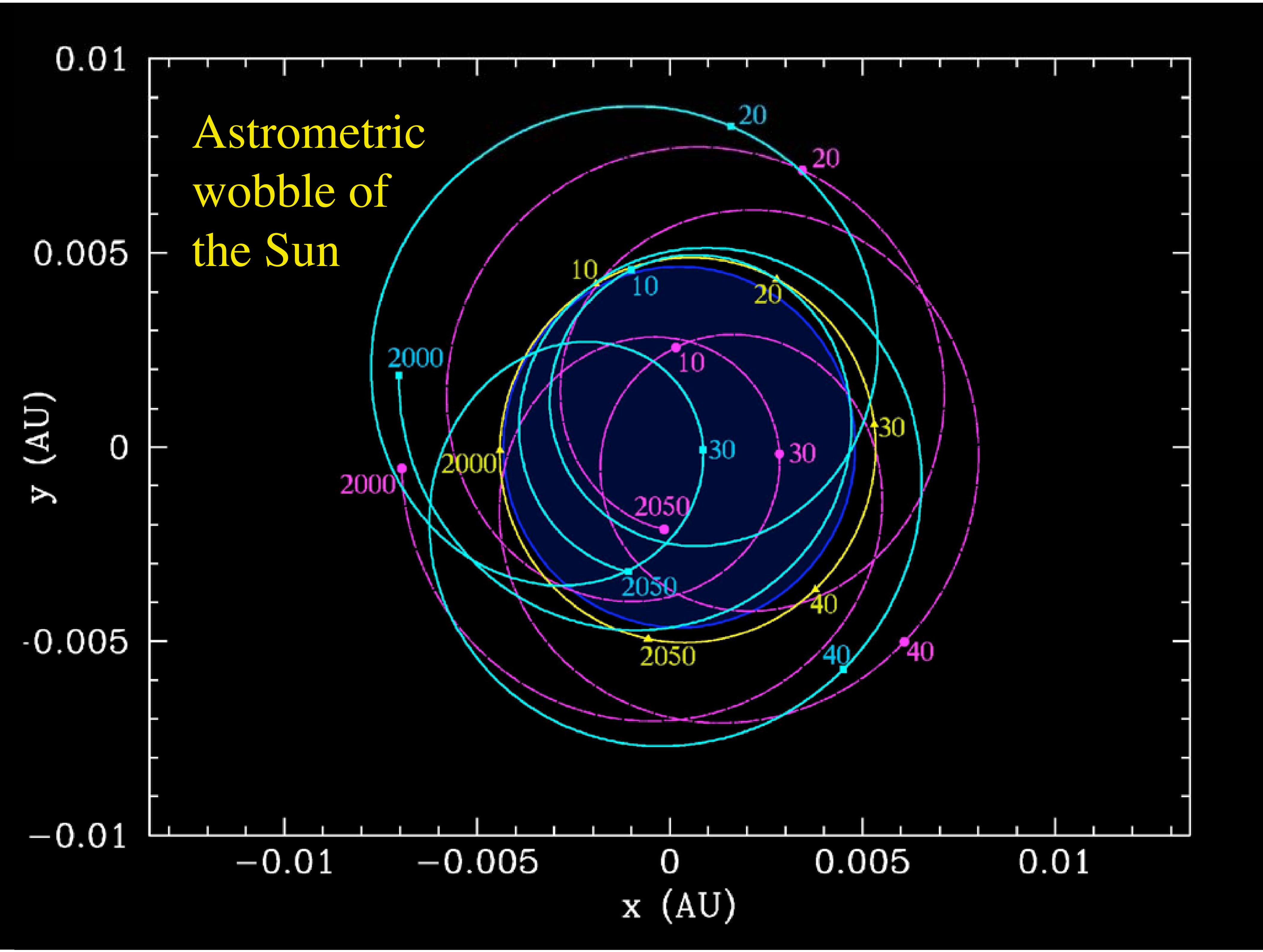


Radial velocity
of **51 Pegasi**

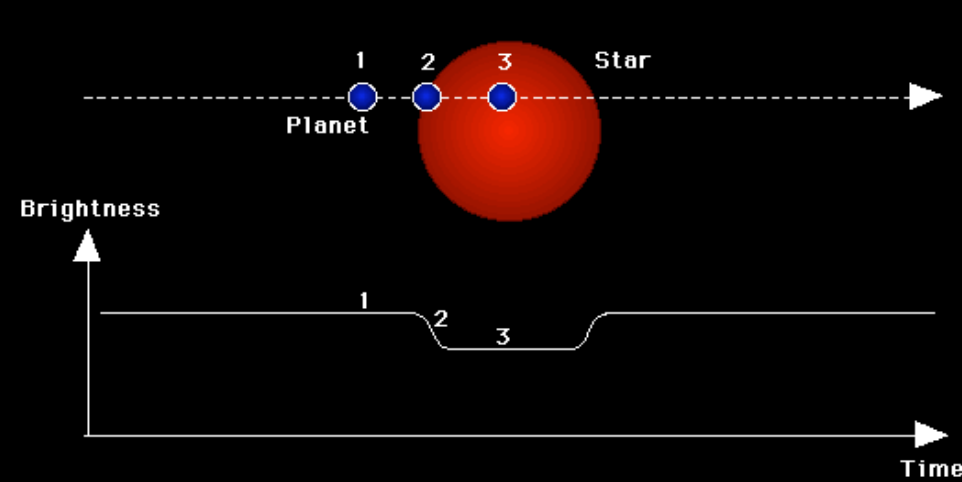
Mayor & Queloz
1995

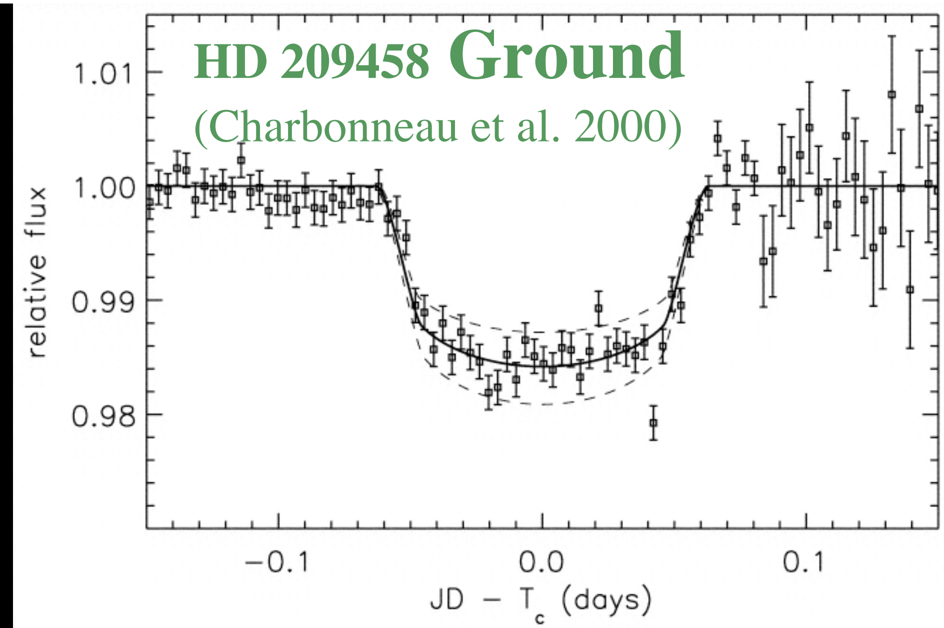
California-Carnegie team HD168443

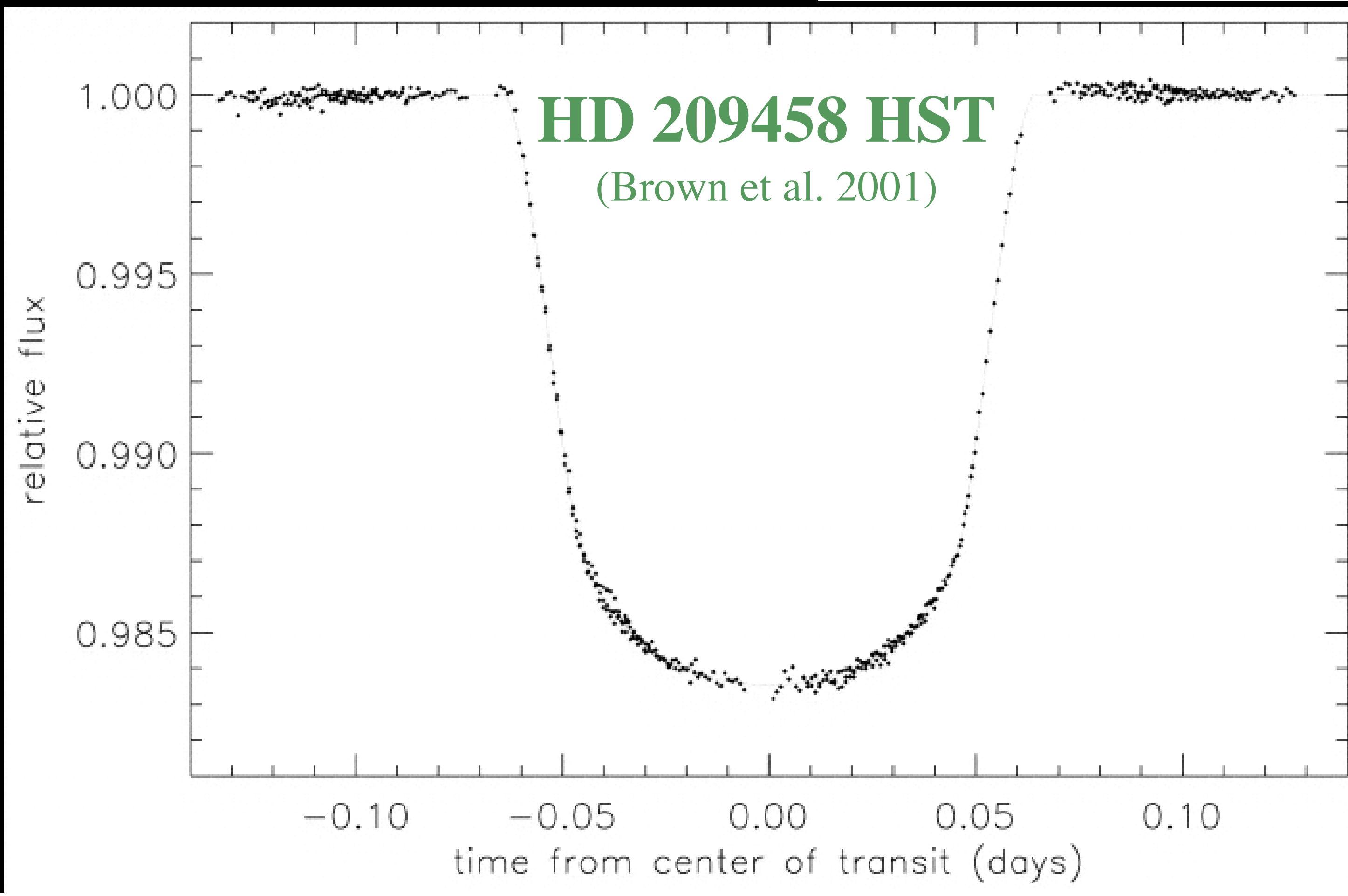


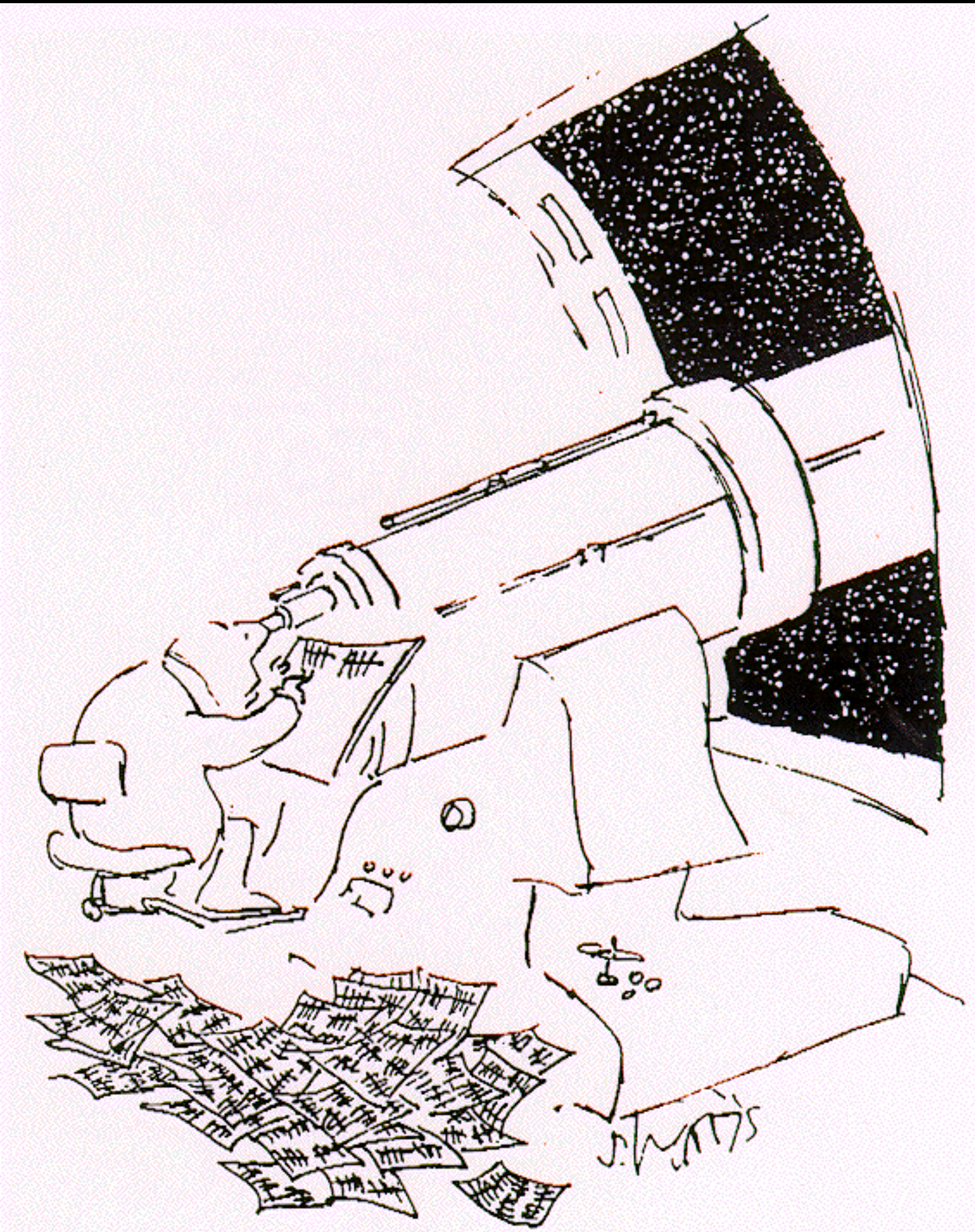

Astrometric wobble of the Sun
0.01
0.005
0
-0.005
−0.01
y (AU)
−0.01
−0.005
0
0.005
0.01
x (AU)
2000
10
20
30
40
2050
2000
10
20
30
40
2050
2000
10
20
30
40
2050

Transit Photometry









How Many Known Extrasolar Planets?

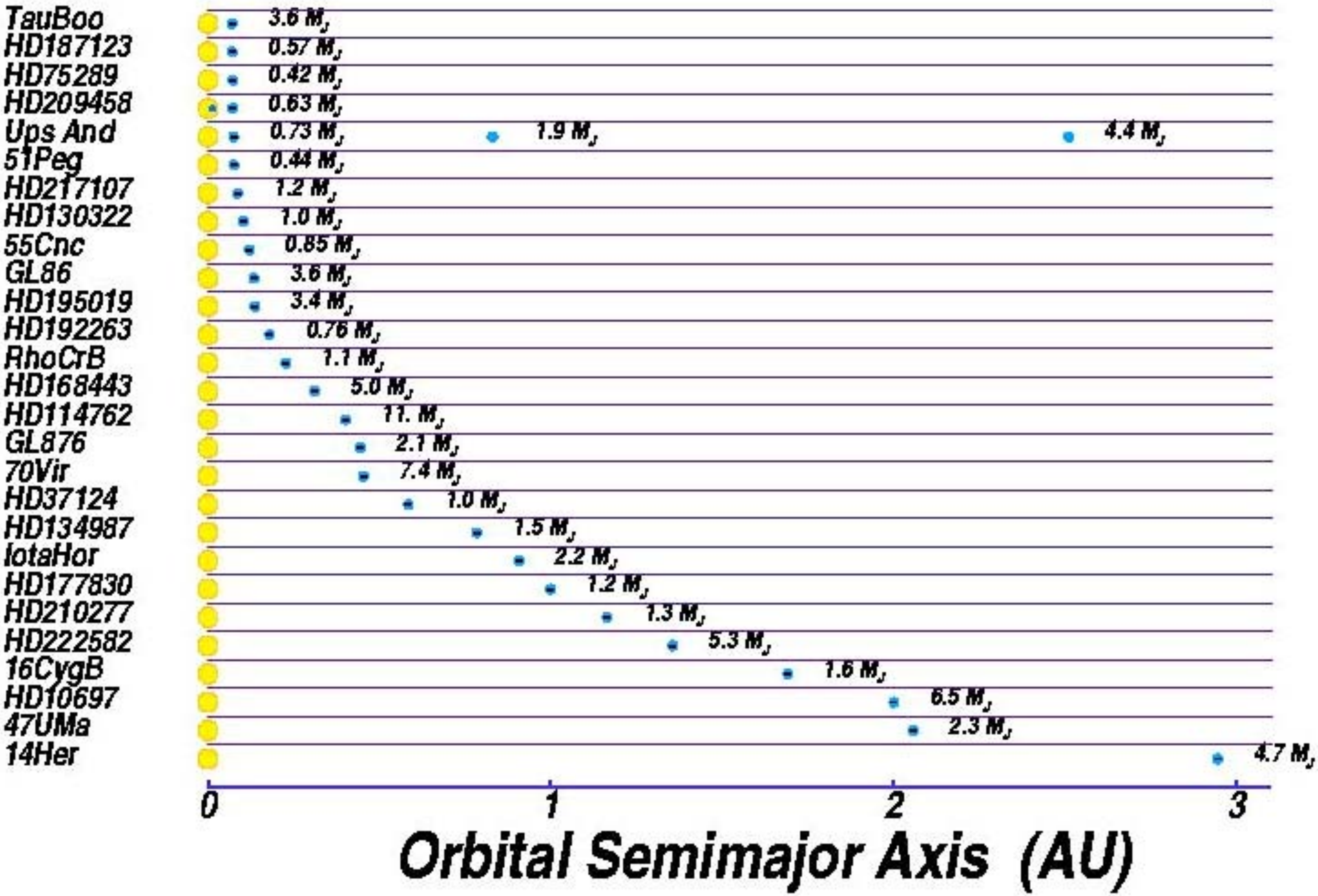
"What's one and one and one and one and one and one and one and one and one and one and one?"

"I don't know," said Alice. "I lost count."

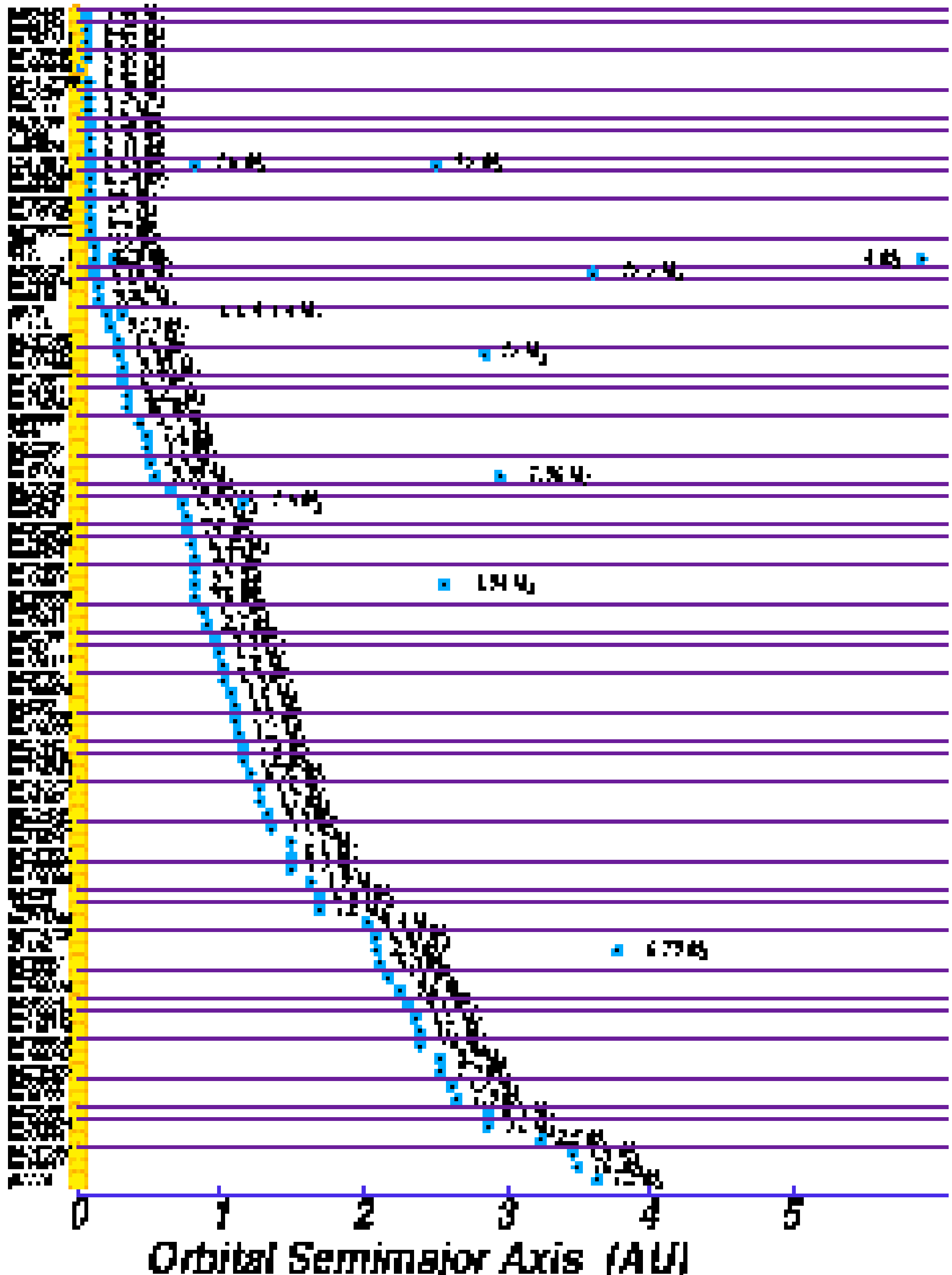
"She can't do addition," said the Red Queen.

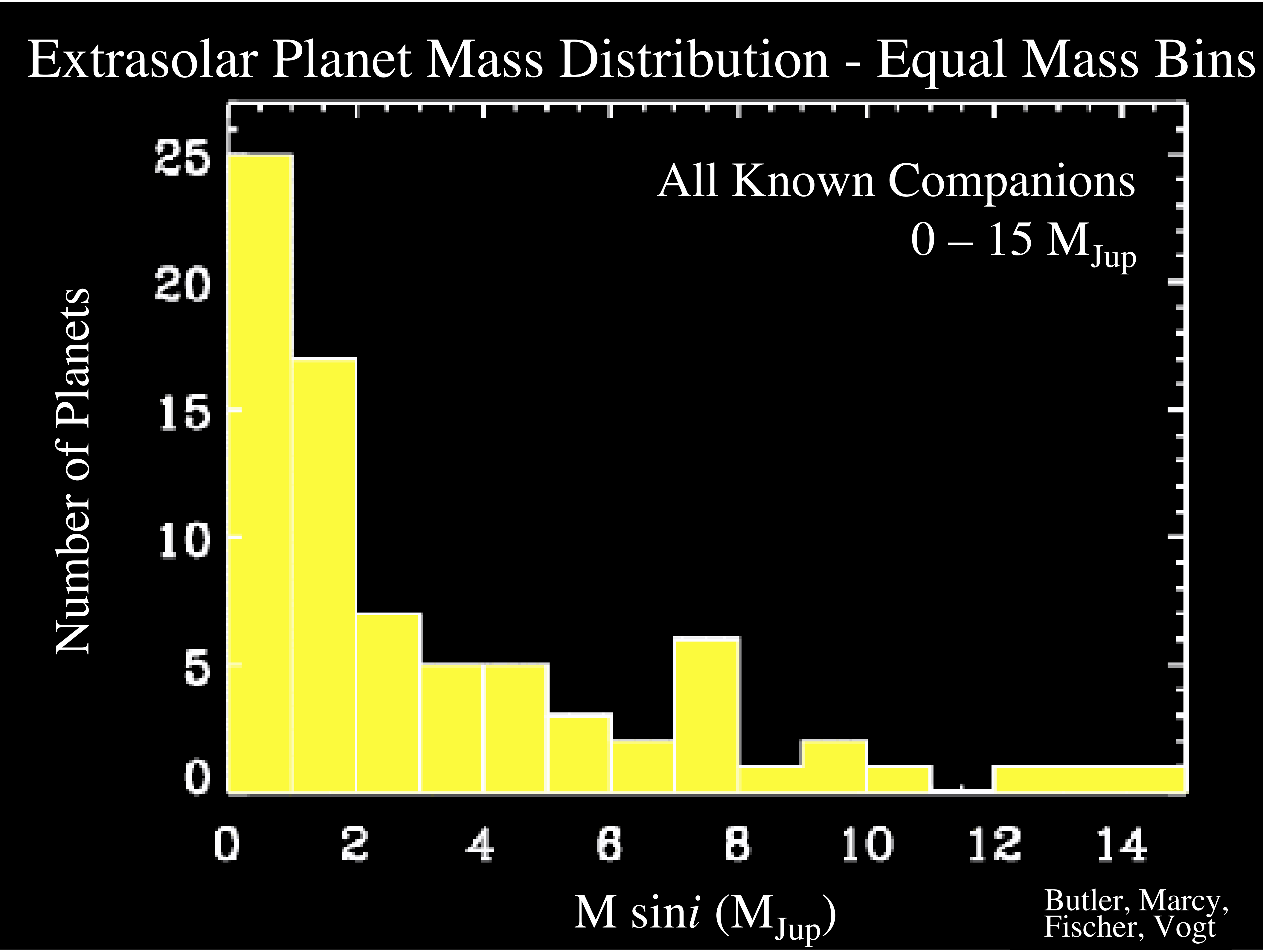
Lewis Carrol,
Alice in Wonderland

First 29 Exoplanets Orbiting Normal Stars

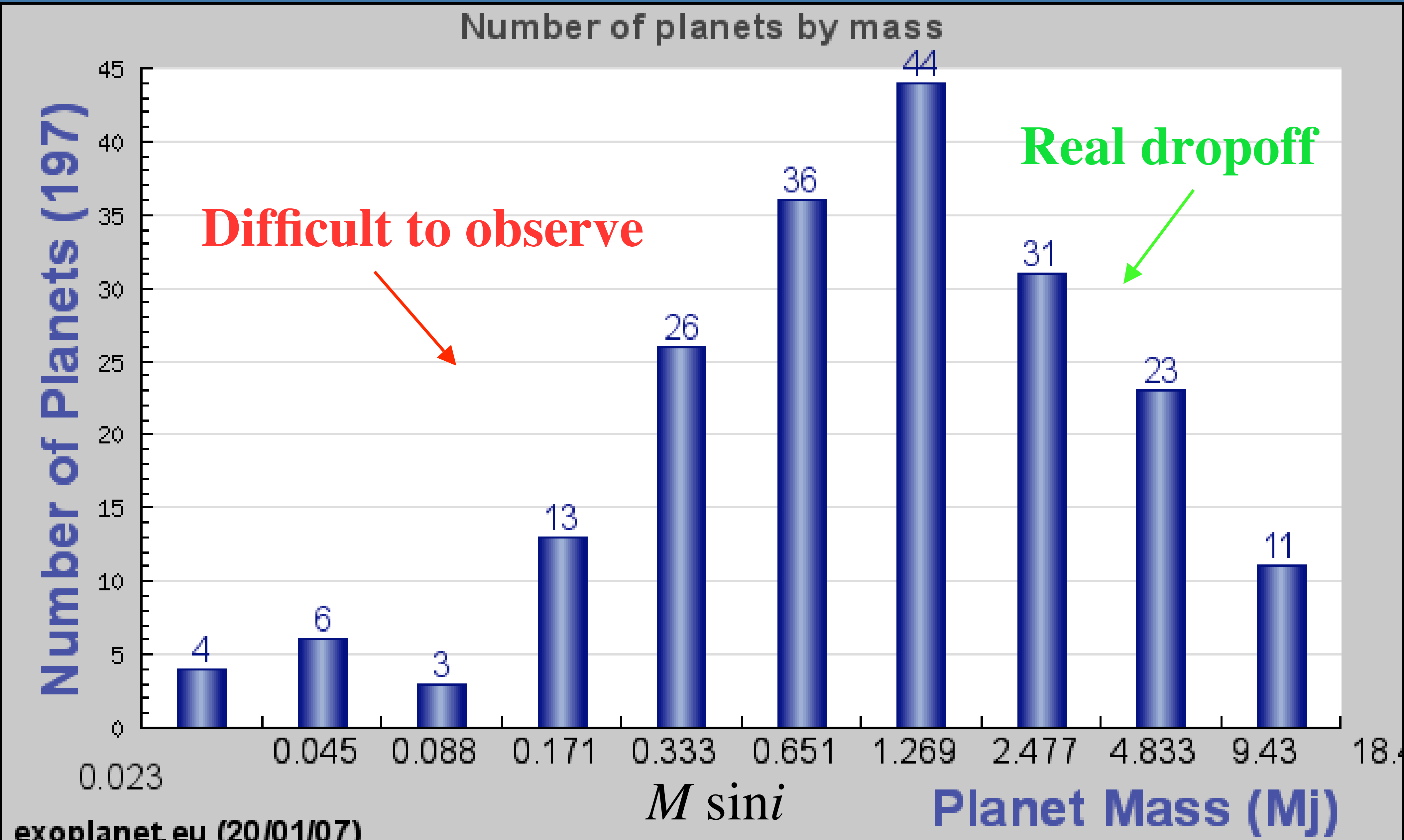


All Exoplanets Known Around Nearby Stars January 2007





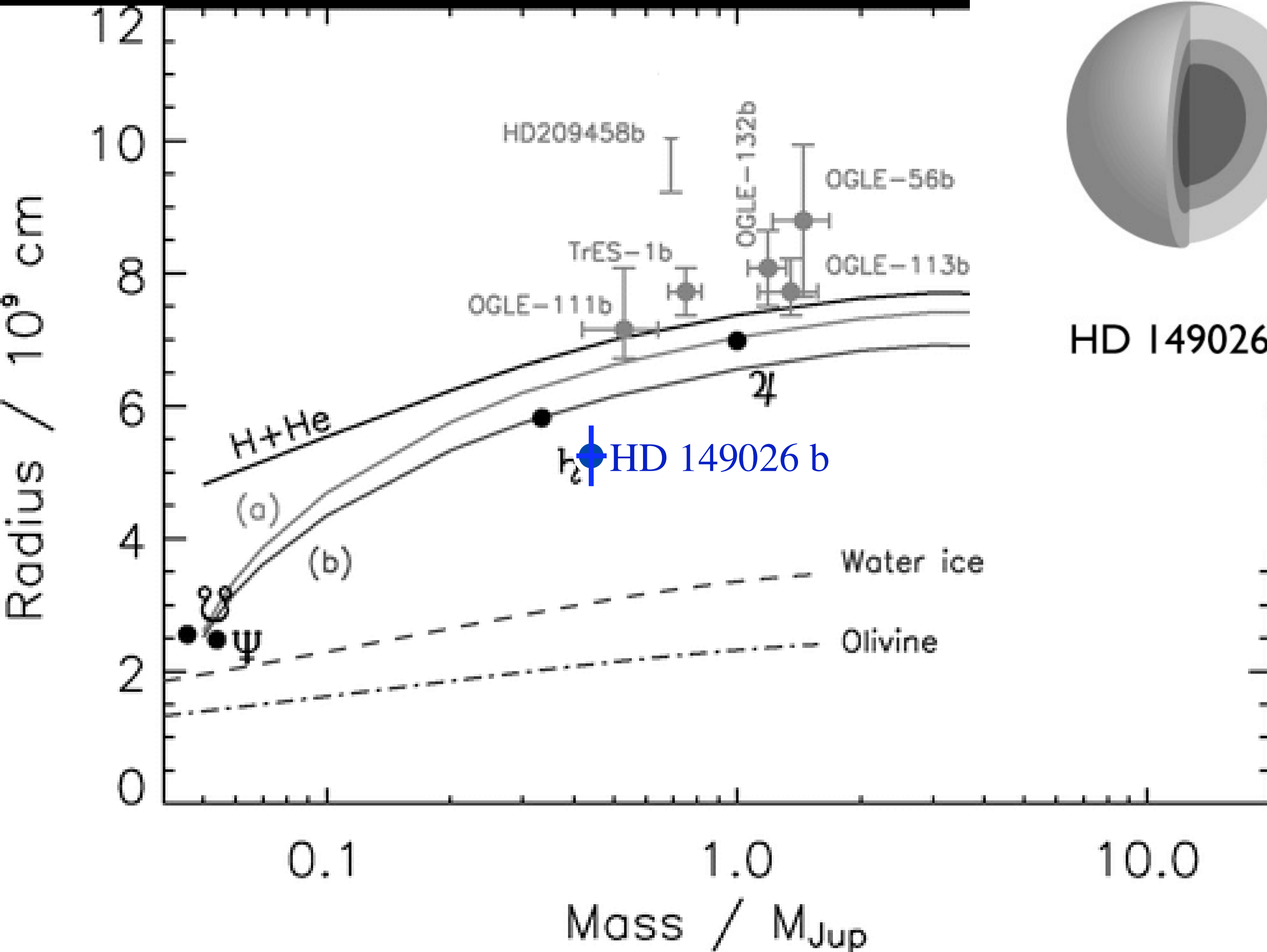
Extrasolar Planet Mass Distribution - Equal Mass Bins
All Known Companions
0 – 15 M_Jup
Number of Planets
M sin*i* (M_Jup)
0
5
10
15
20
25
0
2
4
6
8
10
12
14
Butler, Marcy,
Fischer, Vogt

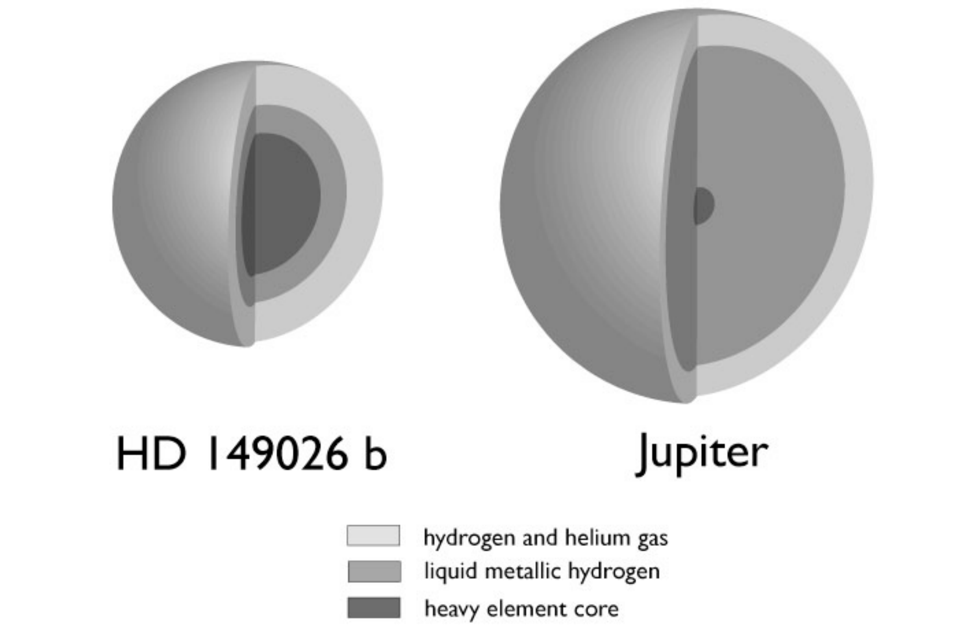


Number of planets by mass
Number of Planets (197)
45
40
35
30
25
20
15
10
5
0
4
6
3
13
26
36
44
31
23
11
Difficult to observe
Real dropoff
0.023
0.045
0.088
0.171
0.333
0.651
1.269
2.477
4.833
9.43
M sini
Planet Mass (Mj)
exoplanet.eu (20/01/07)

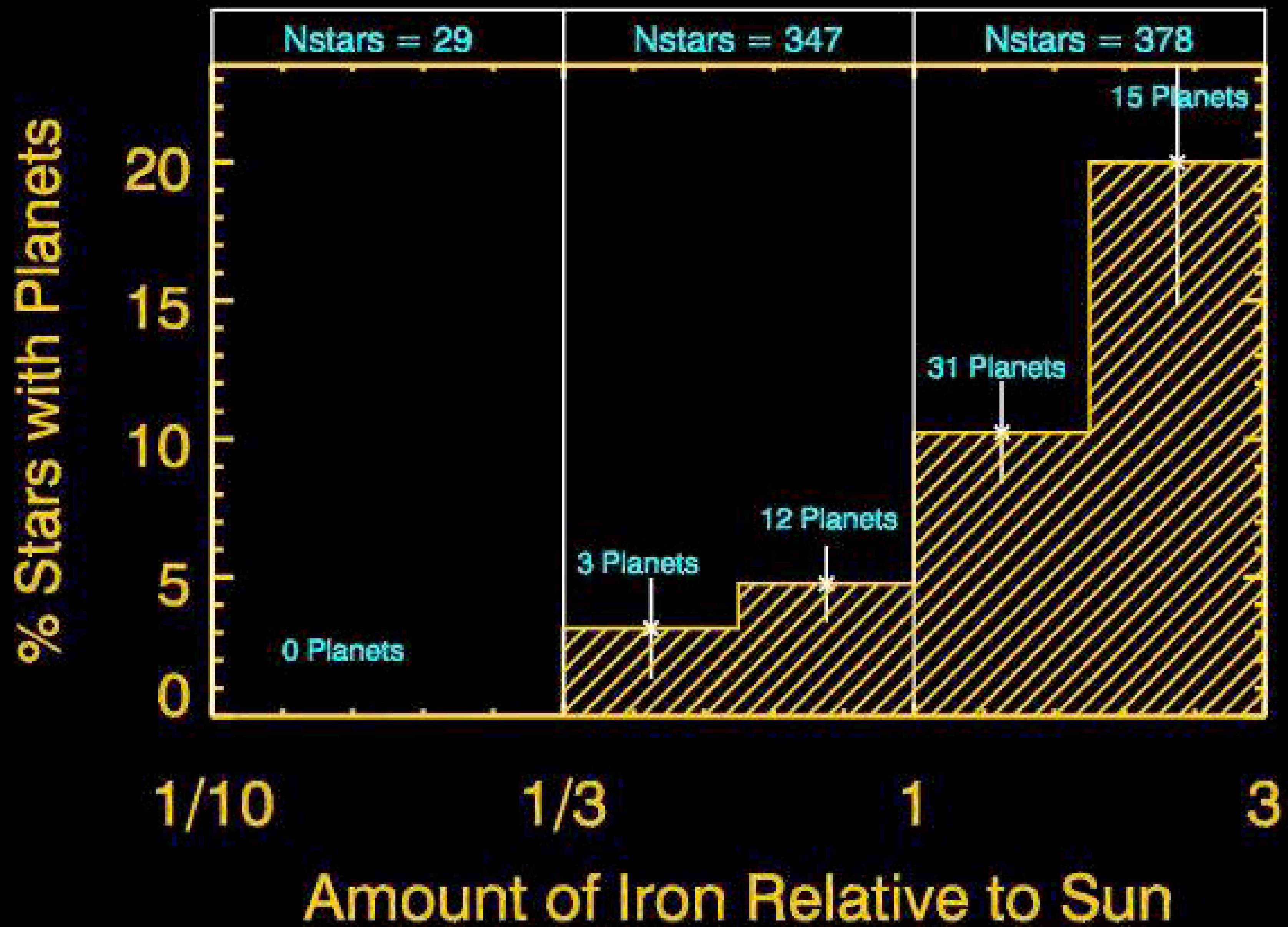
Giant Planets: Radius *vs.* Mass

All Solar System planets denser than solar composition (>98% H + He), as is HD 149026 b





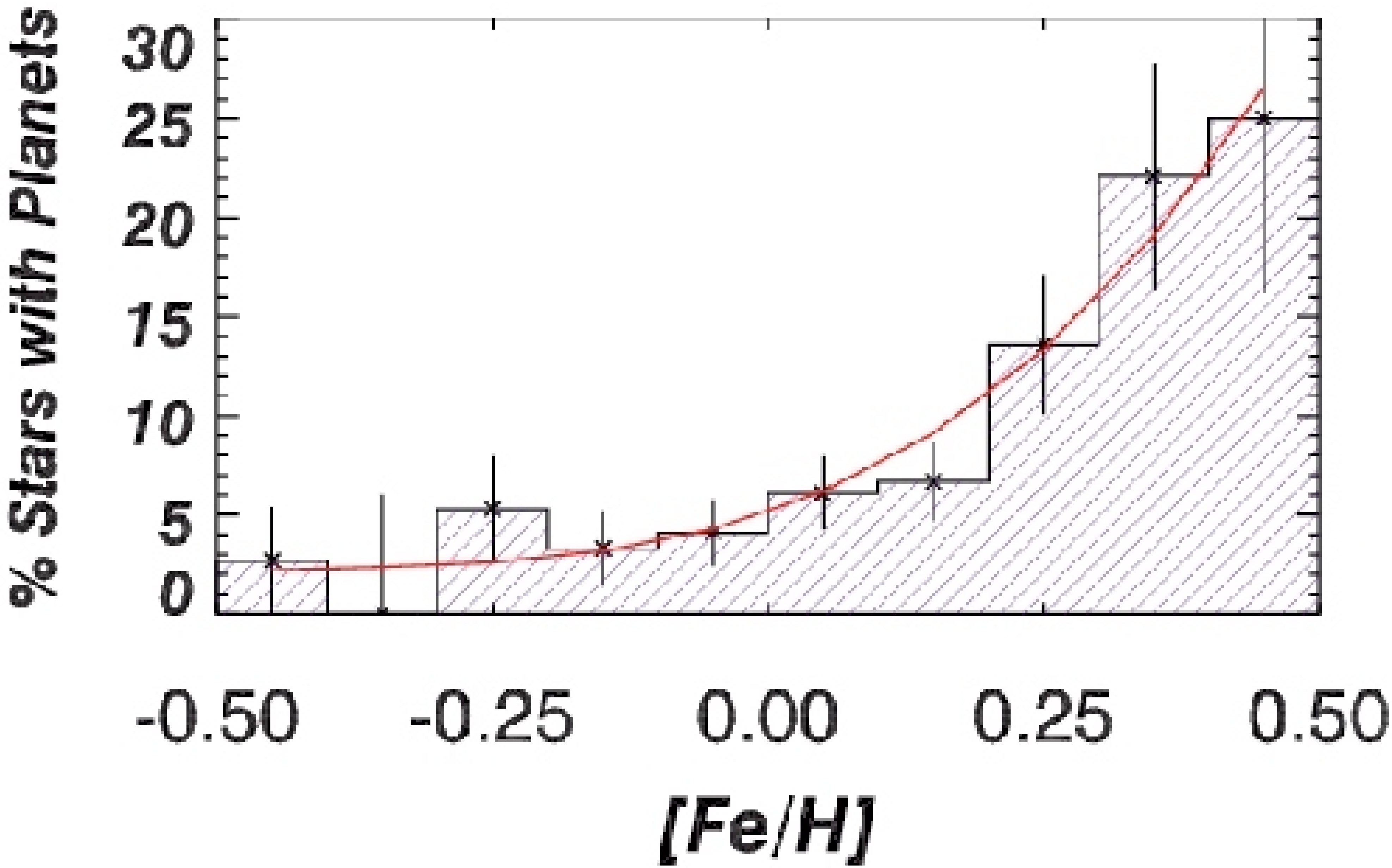
Planet Occurrence Depends on Iron in Stars



Includes all planets found by California/Carnegie team (7/03).

Detected Planets vs. Stellar Metallicity

Fischer & Valenti (2005)



GJ 876 Planetary System

Lynette Cook

Extrasolar Planets: Key Findings

- ~ 1% of sunlike stars have planets more massive than Saturn within 0.1 AU
  - Several of these planets are known to be gas giants
  - Models suggest these planets migrated inwards
- ~ 7% of sunlike stars have planets more massive than Jupiter within 2 AU
  - Some of these planets have very eccentric orbits
- At least a few % of sunlike stars have Jupiter-like (0.5 - 2 M_J, 4 AU < a < 10 AU) companions, but > 20% do not
- Small planets are more common than more massive ones
- More (giant) planets around stars with more metals

Orbital Evolution

- **Disk-planet interactions**
  - No gap: Migration relative to disk (Type 1)
  - Gap: Moves with disk (Type 2)
  - Faster near star - need stopping mechanism
- **Planet-planet scattering**
  - Produces eccentric orbits
  - Planets well-separated
  - Some planets ejected

Conclusions

- Planet formation models are developed to fit a very diverse range of data
  - Meteorites, planetary orbits, composition, circumstellar disks, exoplanets
- Although known exoplanets greatly outnumber planets within our Solar System, little is known about them
- Exoplanets have provided first-order information about planetary growth
  - Inner giant planets imply that migration is important
  - Planet-metallicity correlation implies (most if not all) giant planets formed via core-nucleated accretion
- Future data will soon provide more significant constraints
  - Planets observed using multiple techniques (e.g., Doppler & transits)
  - More multiple planet systems
  - Terrestrial planets (*Kepler*)