EXOPLANETS

P L A N E T S

Where do we come from?

Where do we come from?

PLANET FORMATION

Where do we come from?

PLANET FORMATION

Are we alone?

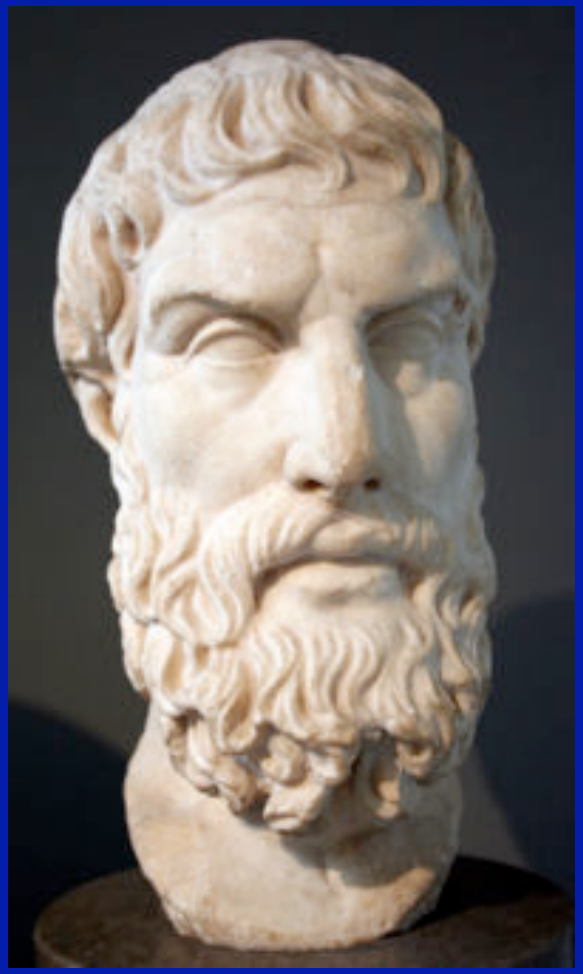
Where do we come from?

PLANET FORMATION

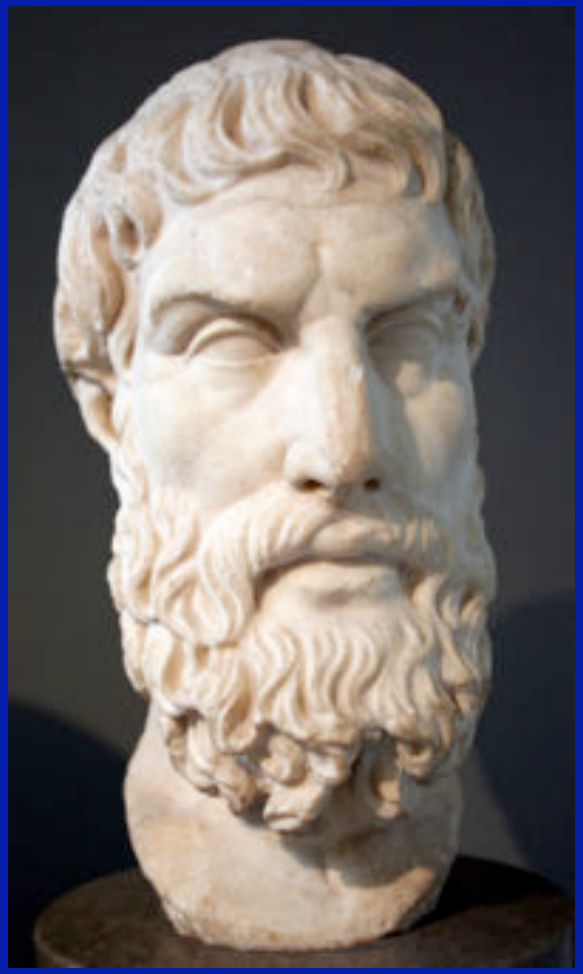
Are we alone?

EXOBIOLOGY

Epicurus (ca 300 BC)

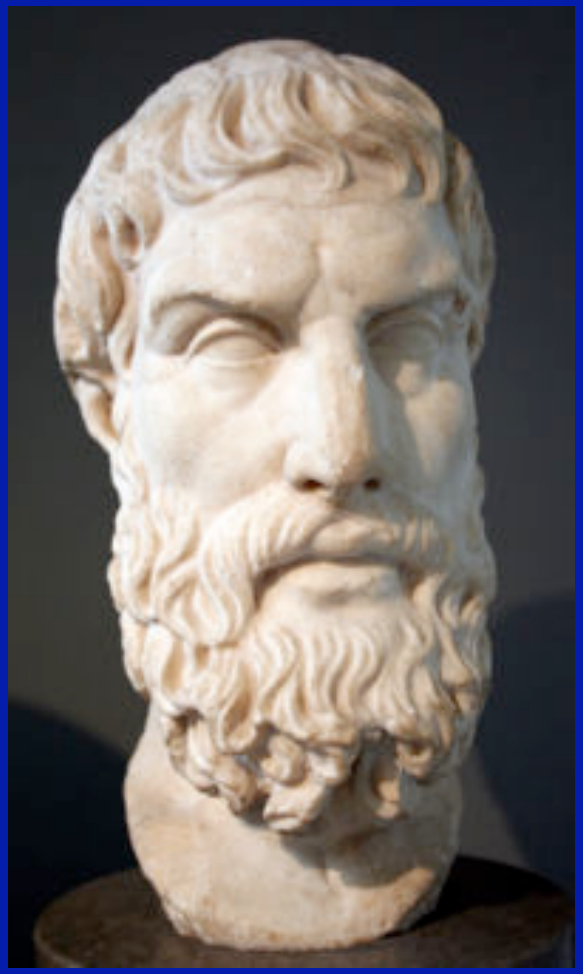


Epicurus (ca 300 BC)



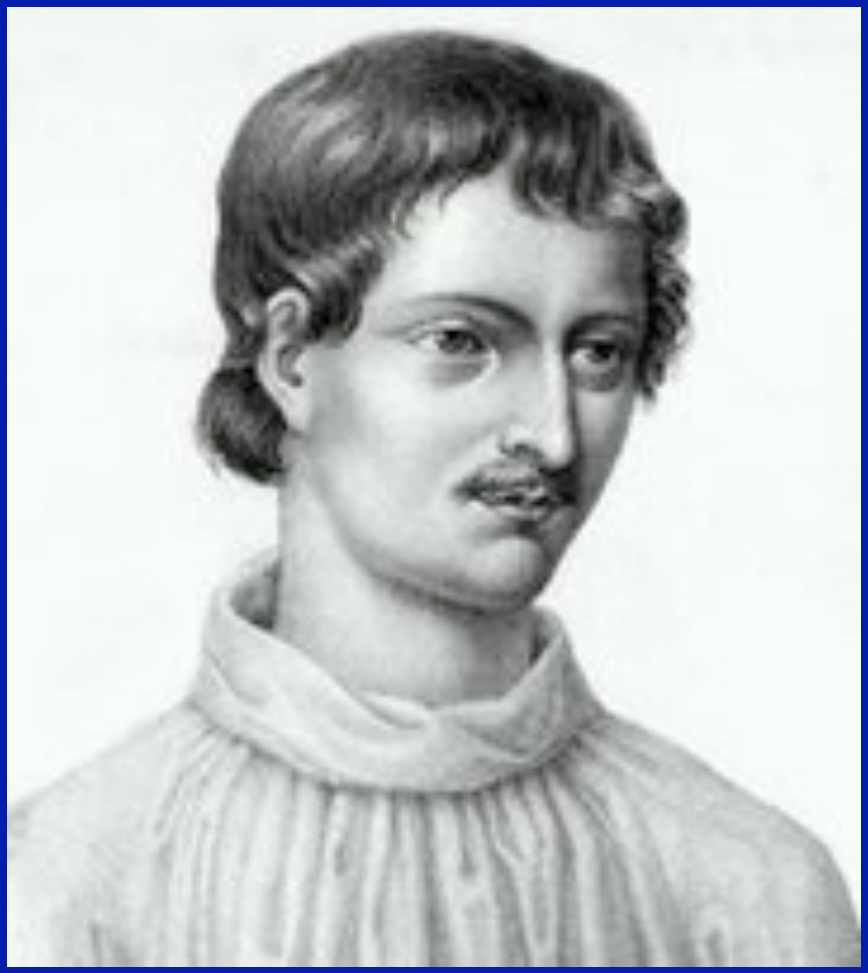
Moreover, there is an infinite number of worlds, some like this world, others unlike it. For the atoms being infinite in number, as has just been proved, are borne ever further in their course. For the atoms out of which a world might arise, or by which a world might be formed, have not all been expended on one world or a finite number of worlds, whether like or unlike this one. Hence there will be nothing to hinder an infinity of worlds.

Epicurus (ca 300 BC)

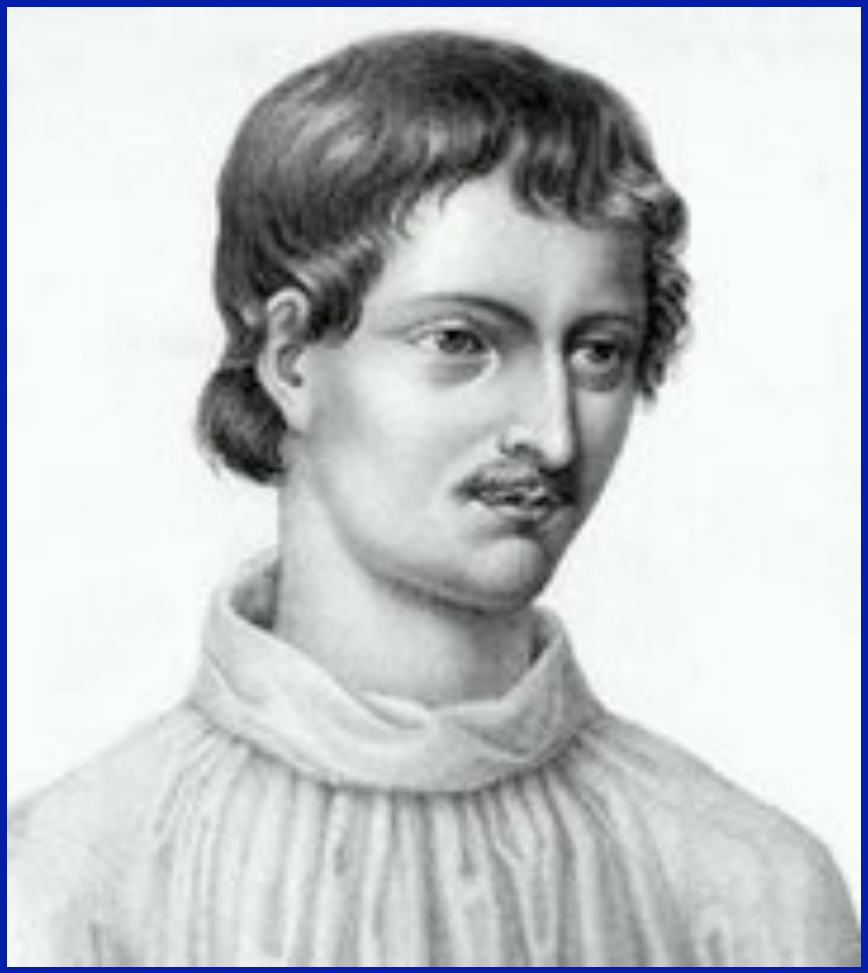


And further, we must not suppose that the worlds have necessarily one and the same shape. For nobody can prove that in one sort of world there might not be contained, whereas in another sort of world there could not possibly be, the seeds out of which animals and plants arise and all the rest of the things we see.

Giordano Bruno (late 1500s)

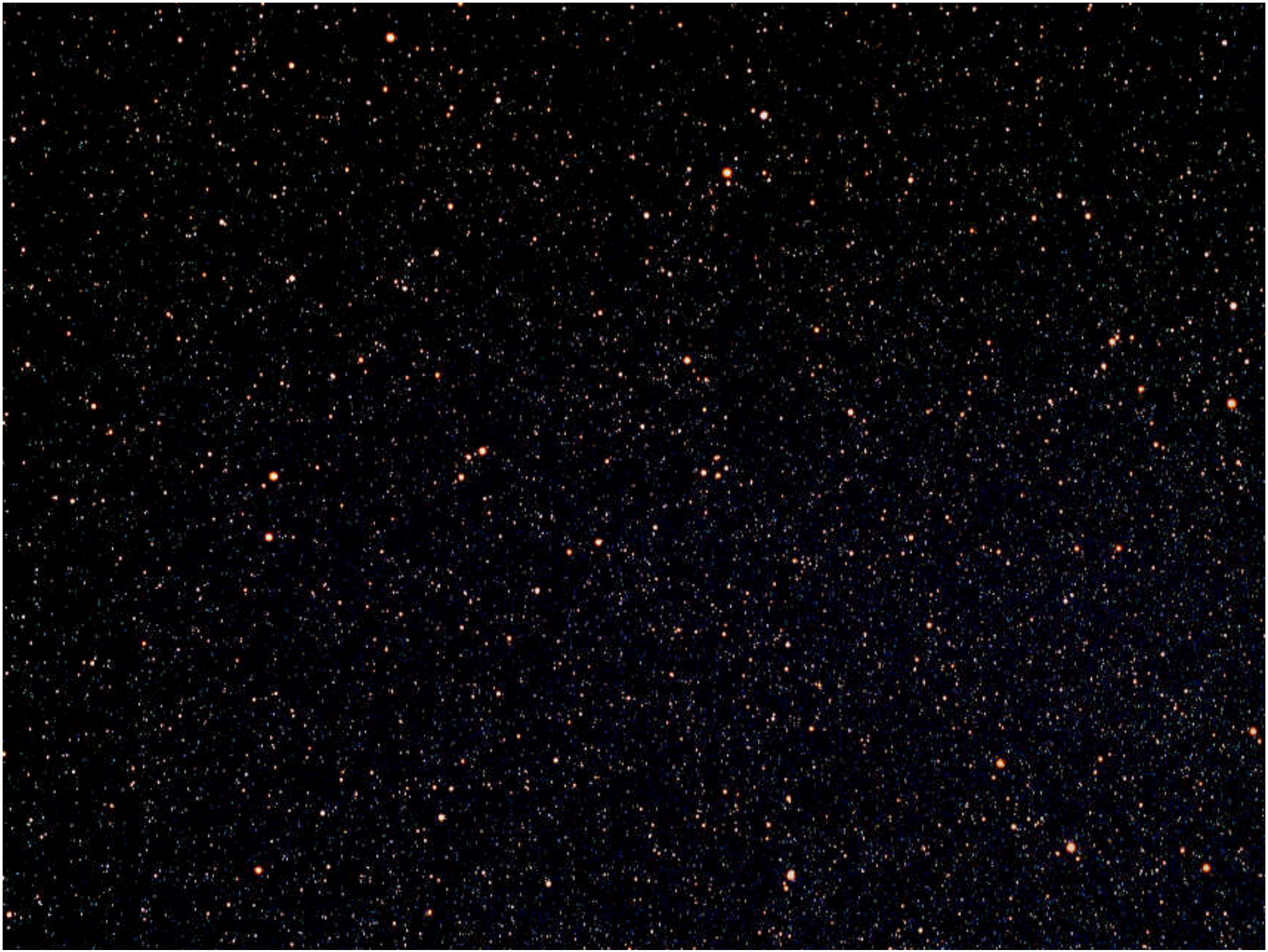


Giordano Bruno (late 1500s)

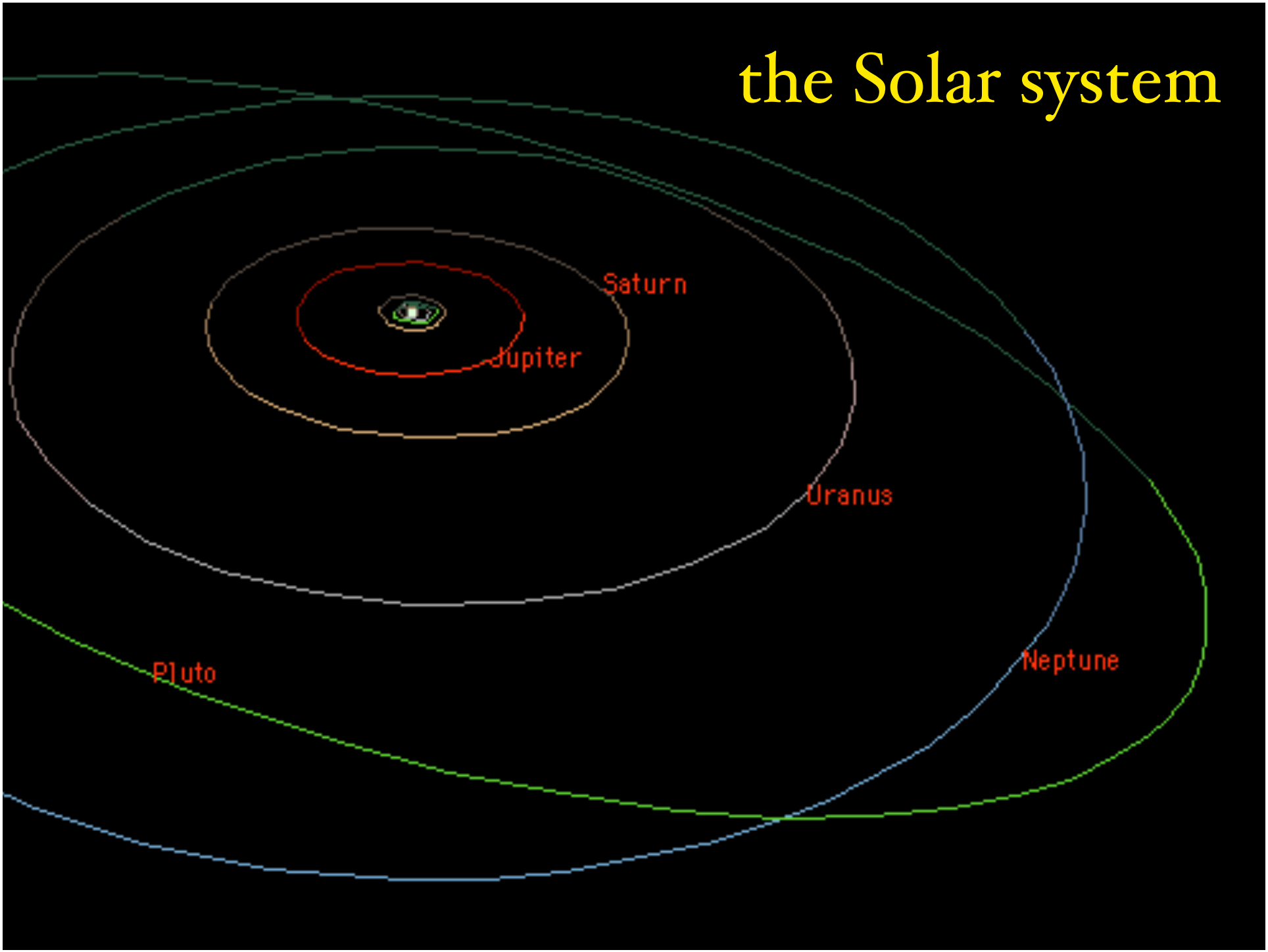


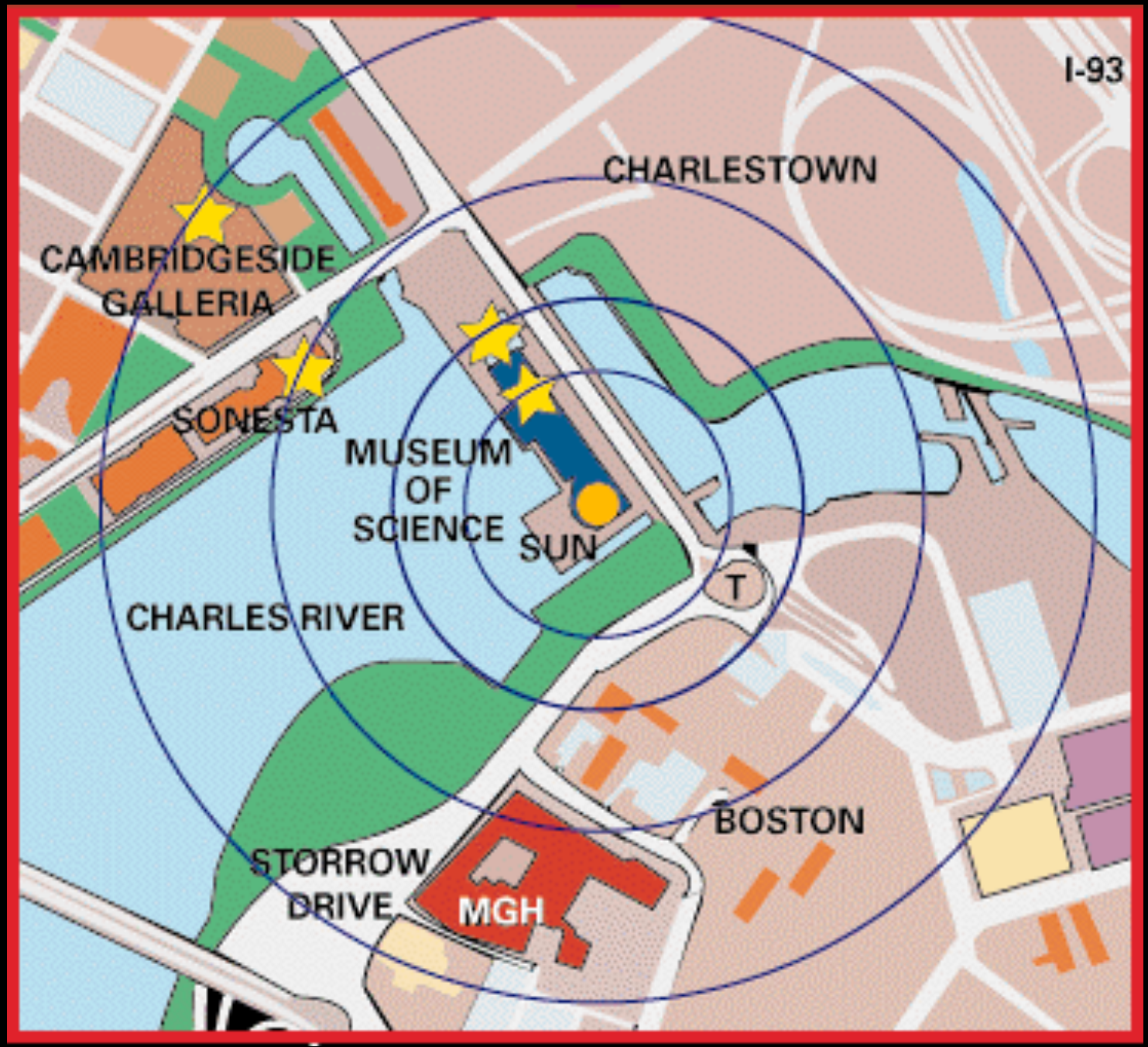
Giordano Bruno (late 1500s)

Burned at the stake in the year 1600, in the Piazza di Campo de' Fiori, Rome



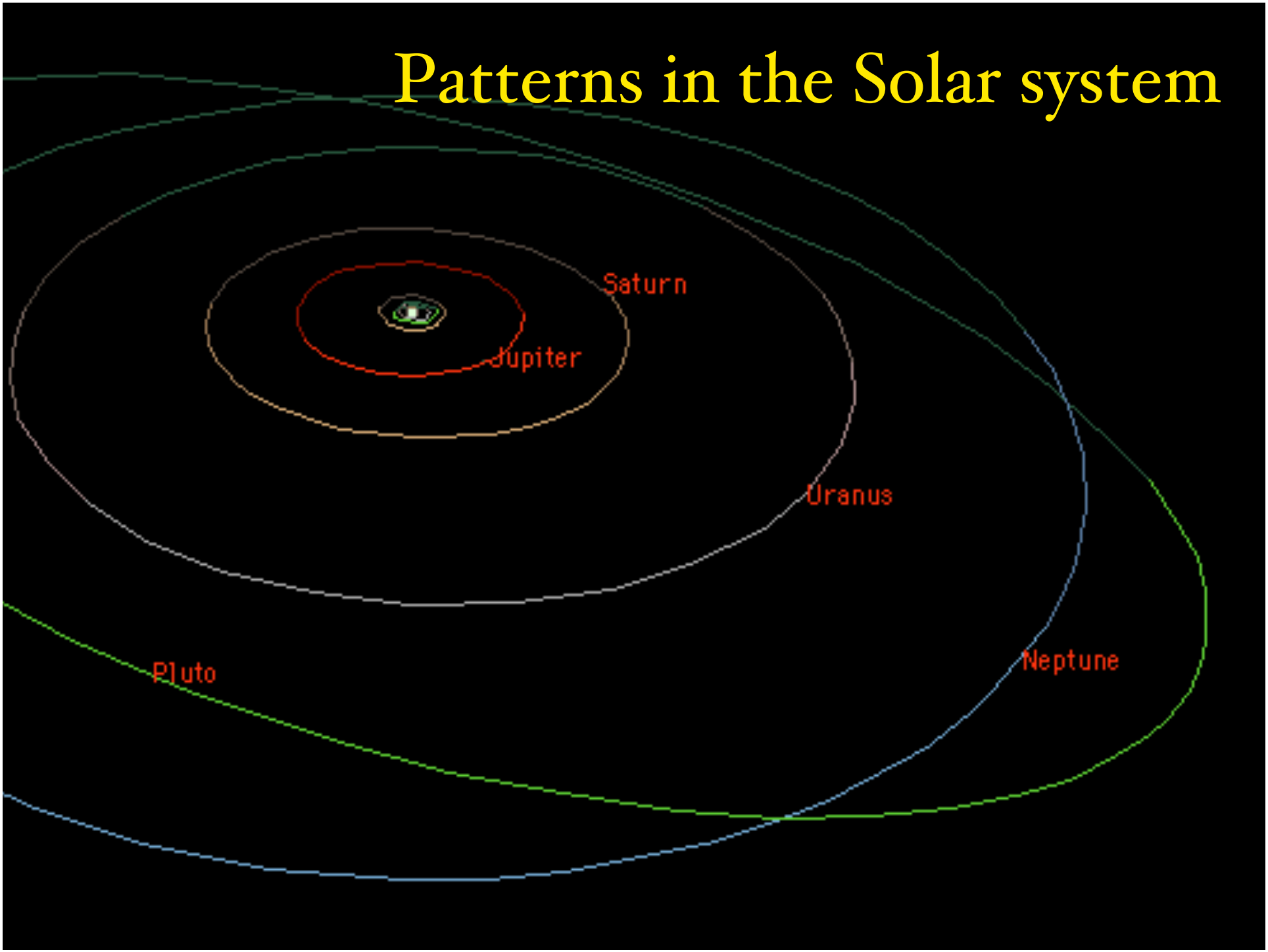
the Solar system




I-93
CHARLESTOWN
CAMBRIDGESIDE
GALLERIA
SONESTA
MUSEUM
OF
SCIENCE
SUN
T
CHARLES RIVER
BOSTON
STORROW
DRIVE
MGH

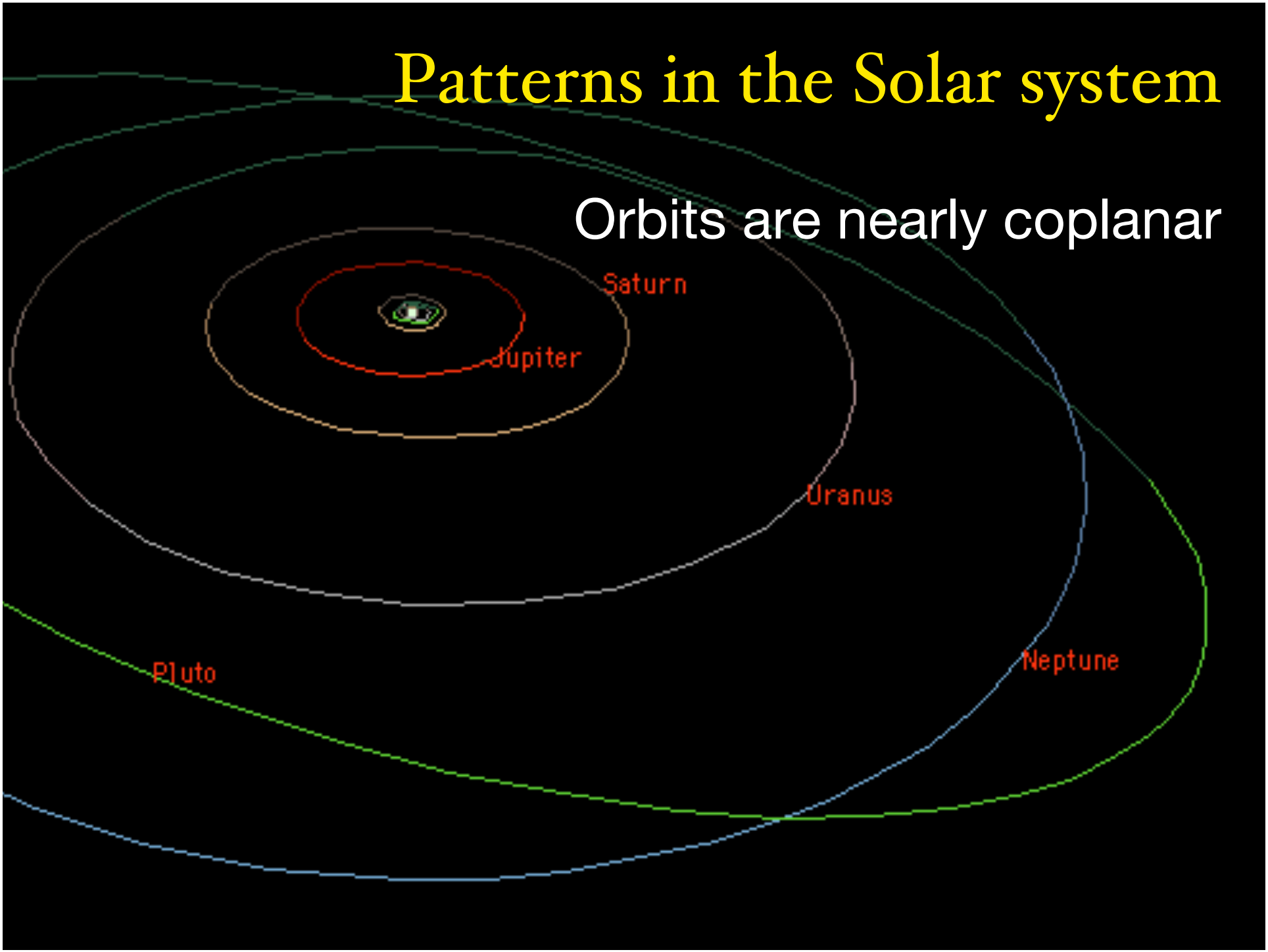
WAKEFIELD
WOBURN
SAUGUS
MELROSE
LEXINGTON
MEDFORD
REVERE
WALTHAM
CAMBRIDGE
BOSTON
NEWTON
BROOKLINE
DORCHESTER
NEEDHAM
QUINCY
MILTON
DEDHAM

Patterns in the Solar system



Patterns in the Solar system

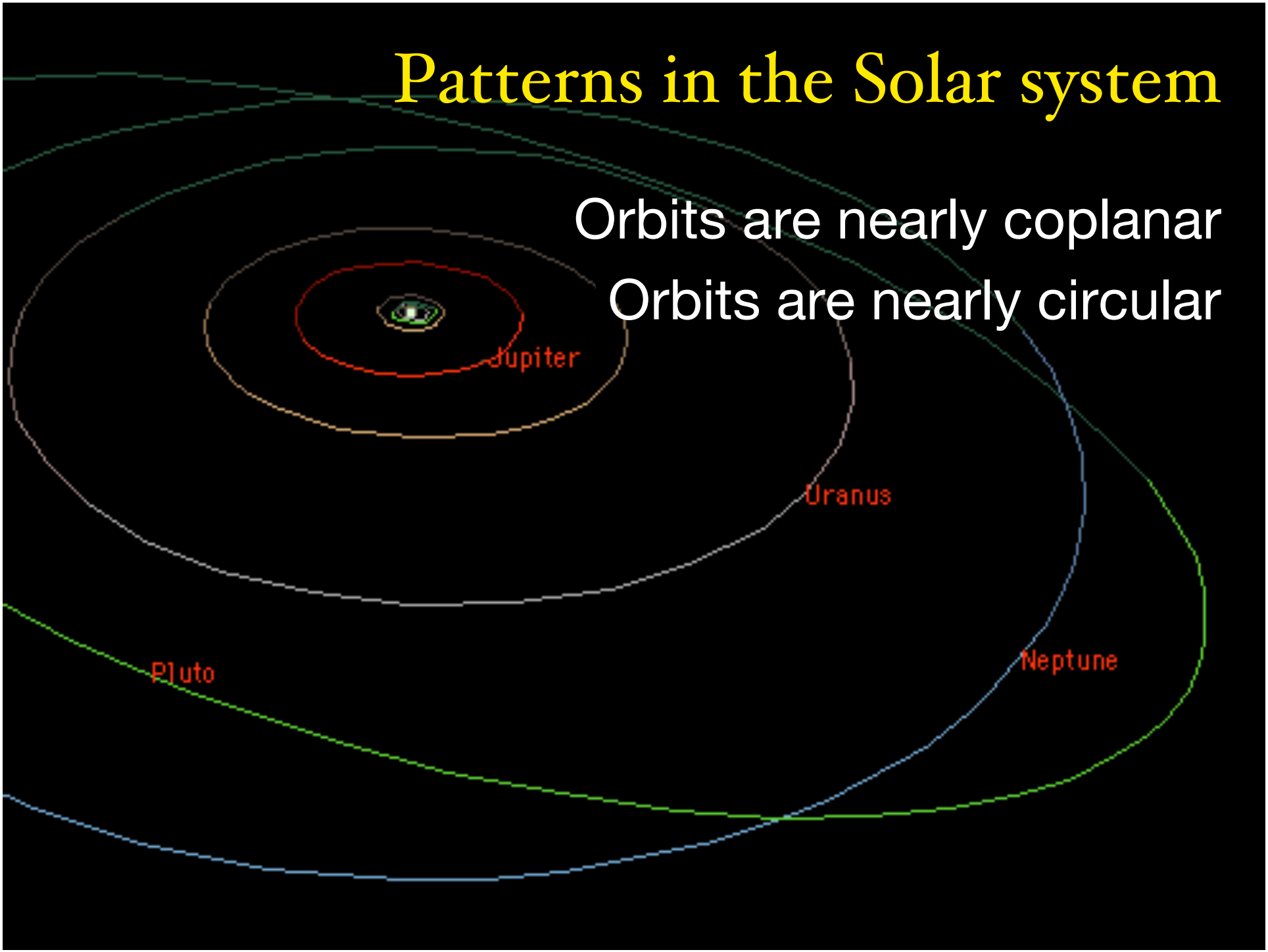
Orbits are nearly coplanar



Patterns in the Solar system

Orbits are nearly coplanar

Orbits are nearly circular

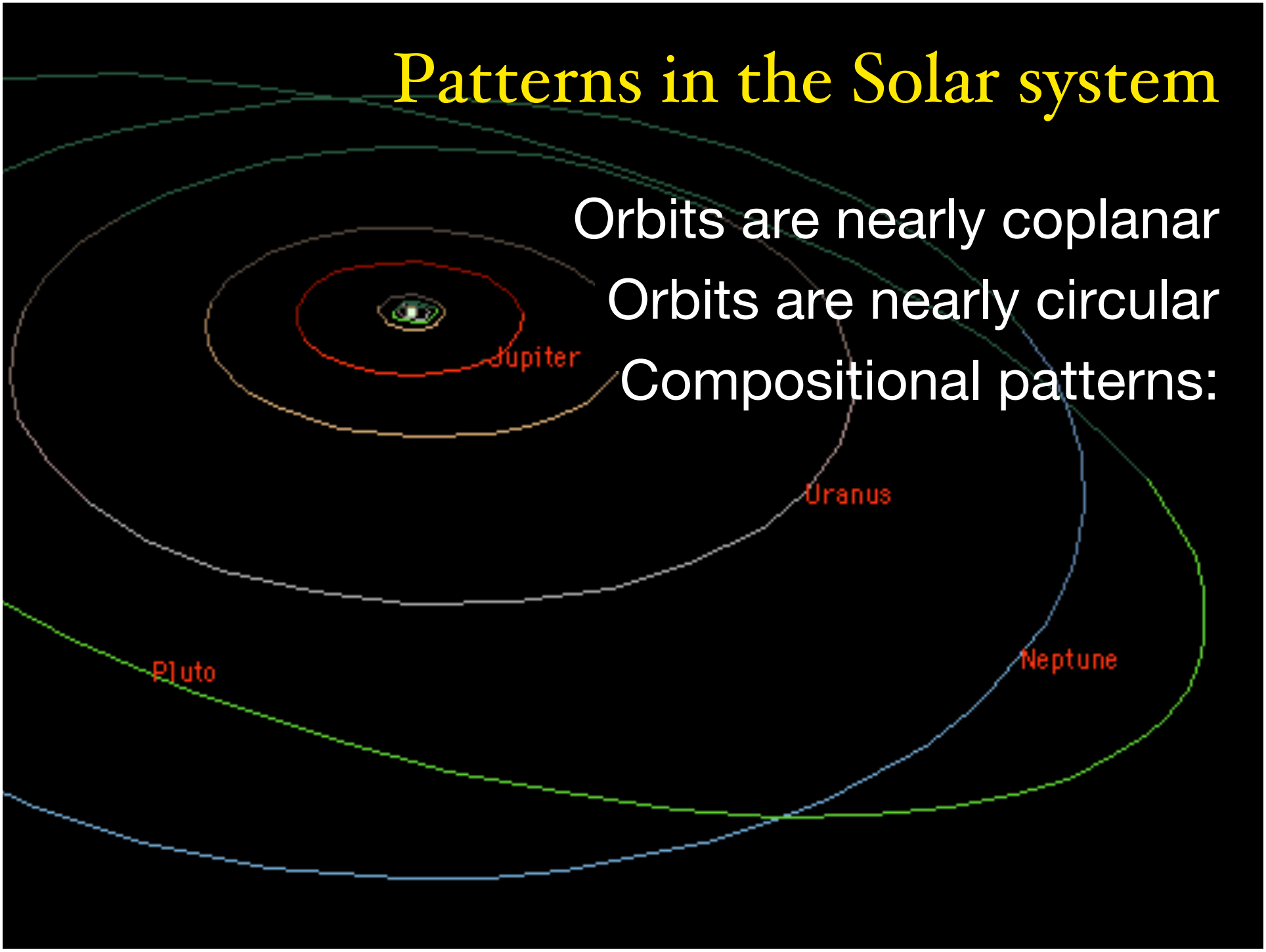


Patterns in the Solar system

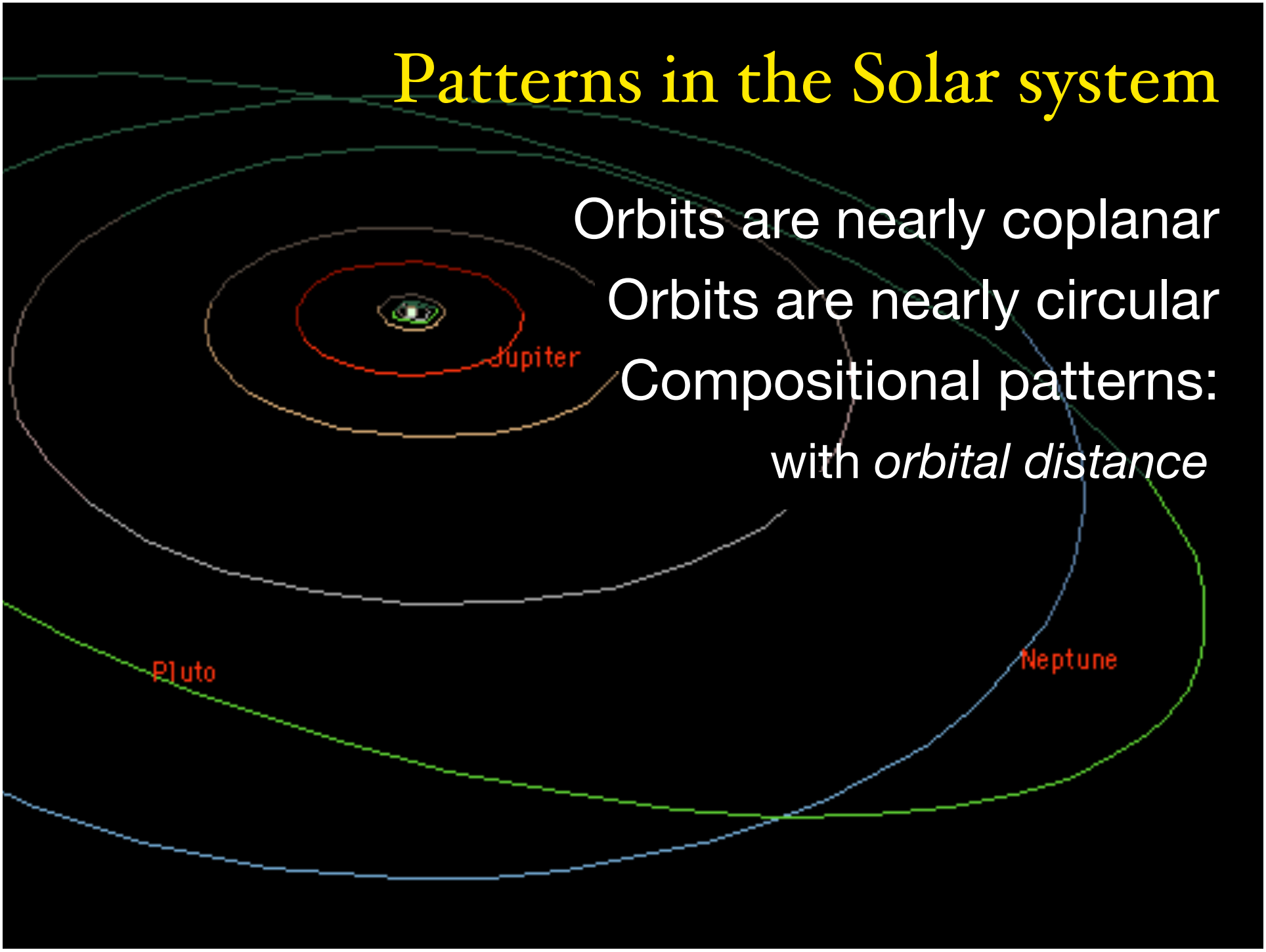
Orbits are nearly coplanar

Orbits are nearly circular

Compositional patterns:



Patterns in the Solar system



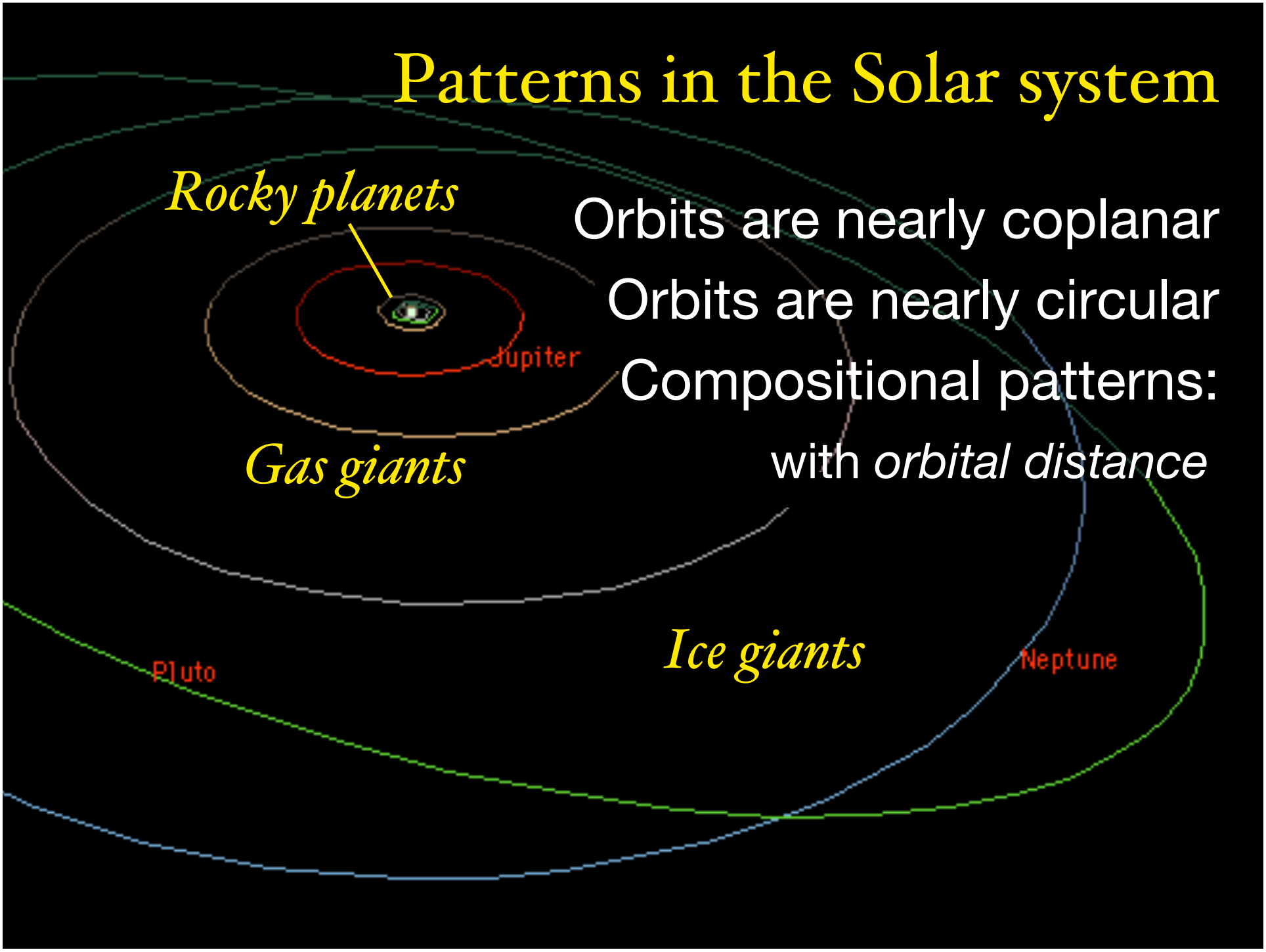
Orbits are nearly coplanar

Orbits are nearly circular

Compositional patterns:

with *orbital distance*

Patterns in the Solar system



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Compositional patterns:

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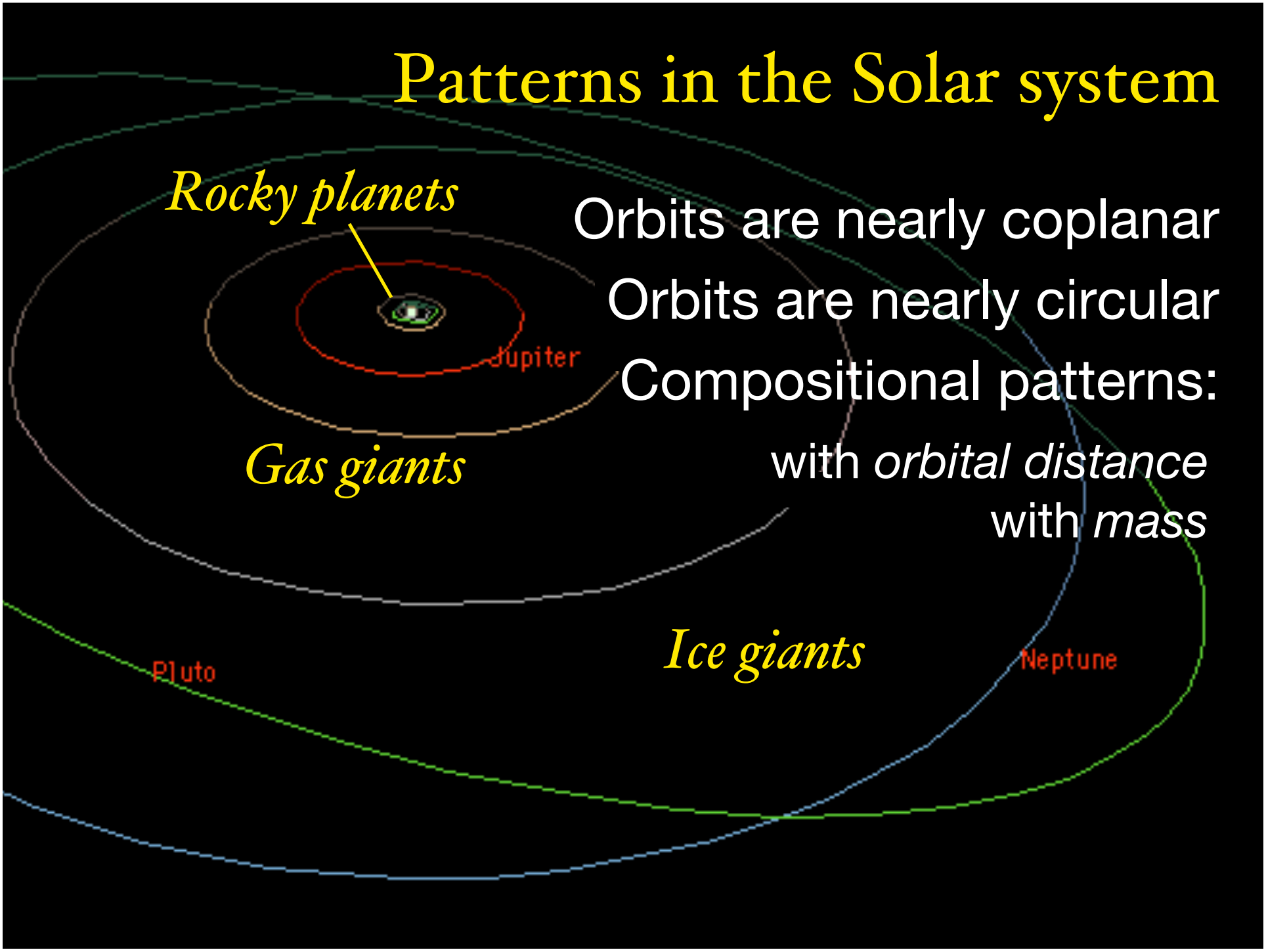
Patterns in the Solar system



Orbits are nearly coplanar

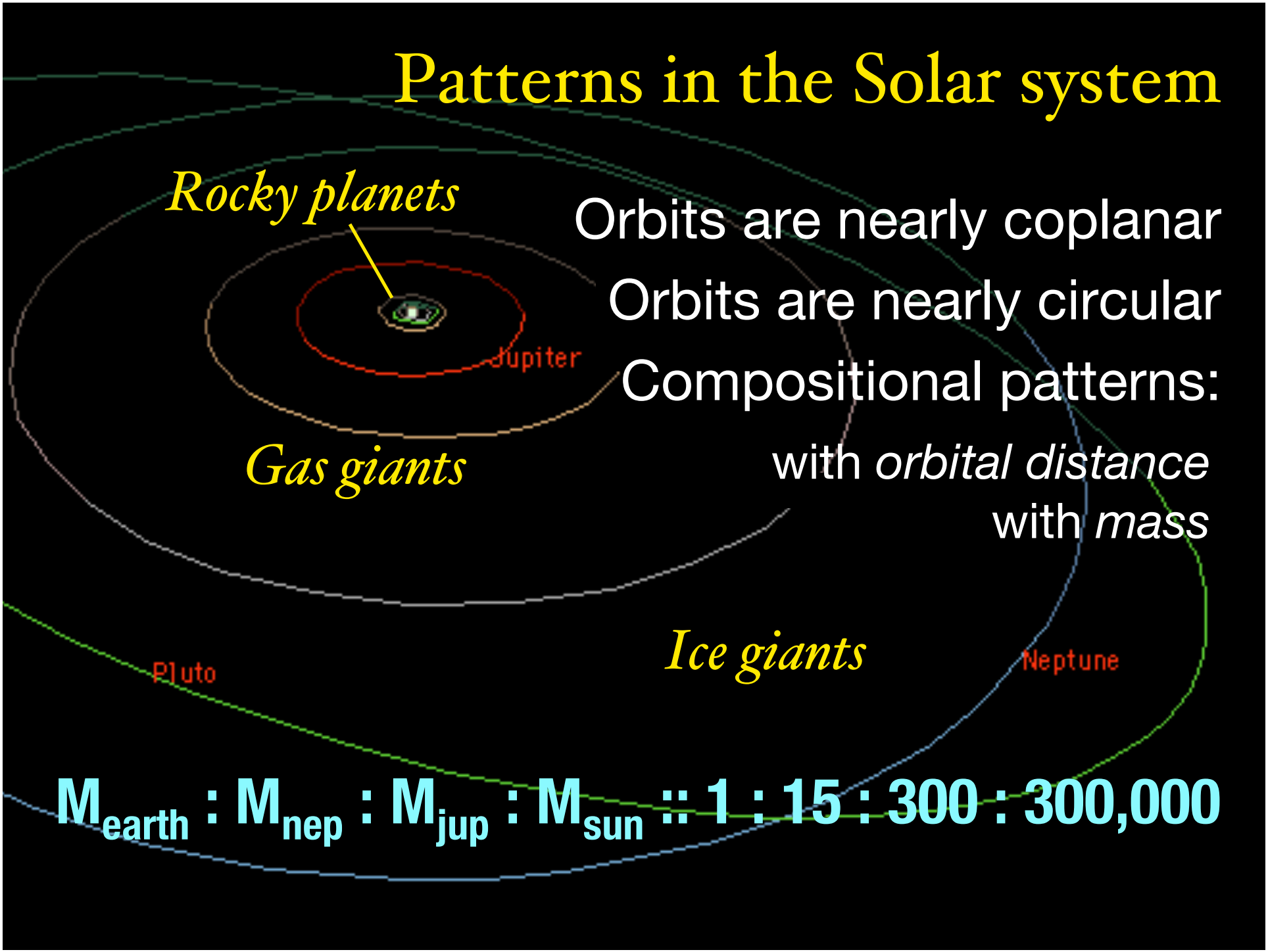
Orbits are nearly circular

Compositional patterns:

with *orbital distance*

with *mass*

Patterns in the Solar system



Orbits are nearly coplanar

Orbits are nearly circular

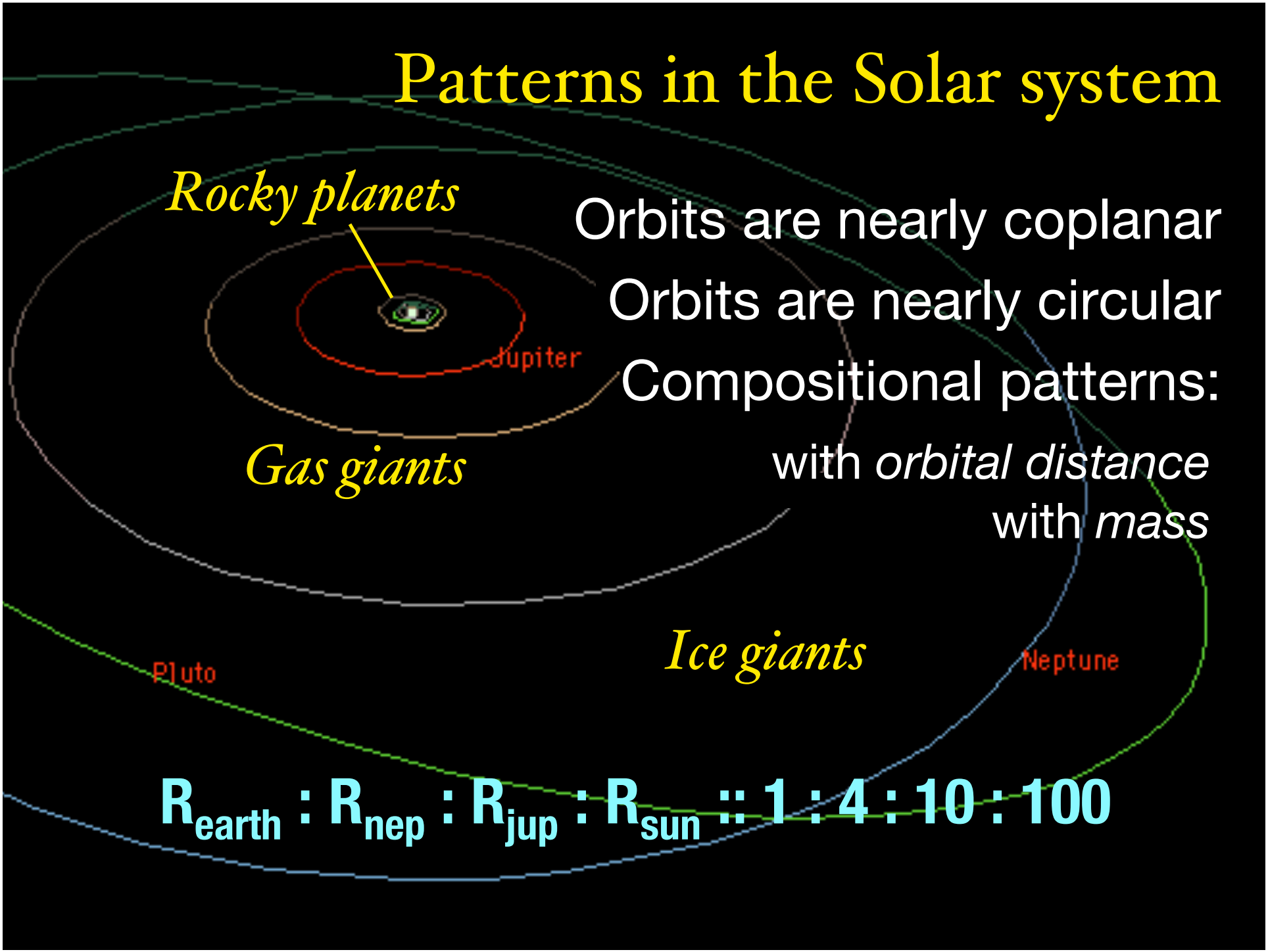
Compositional patterns:

with *orbital distance*

with *mass*

$M_{earth} : M_{nep} : M_{jup} : M_{sun} :: 1 : 15 : 300 : 300{,}000$

Patterns in the Solar system



Orbits are nearly coplanar

Orbits are nearly circular

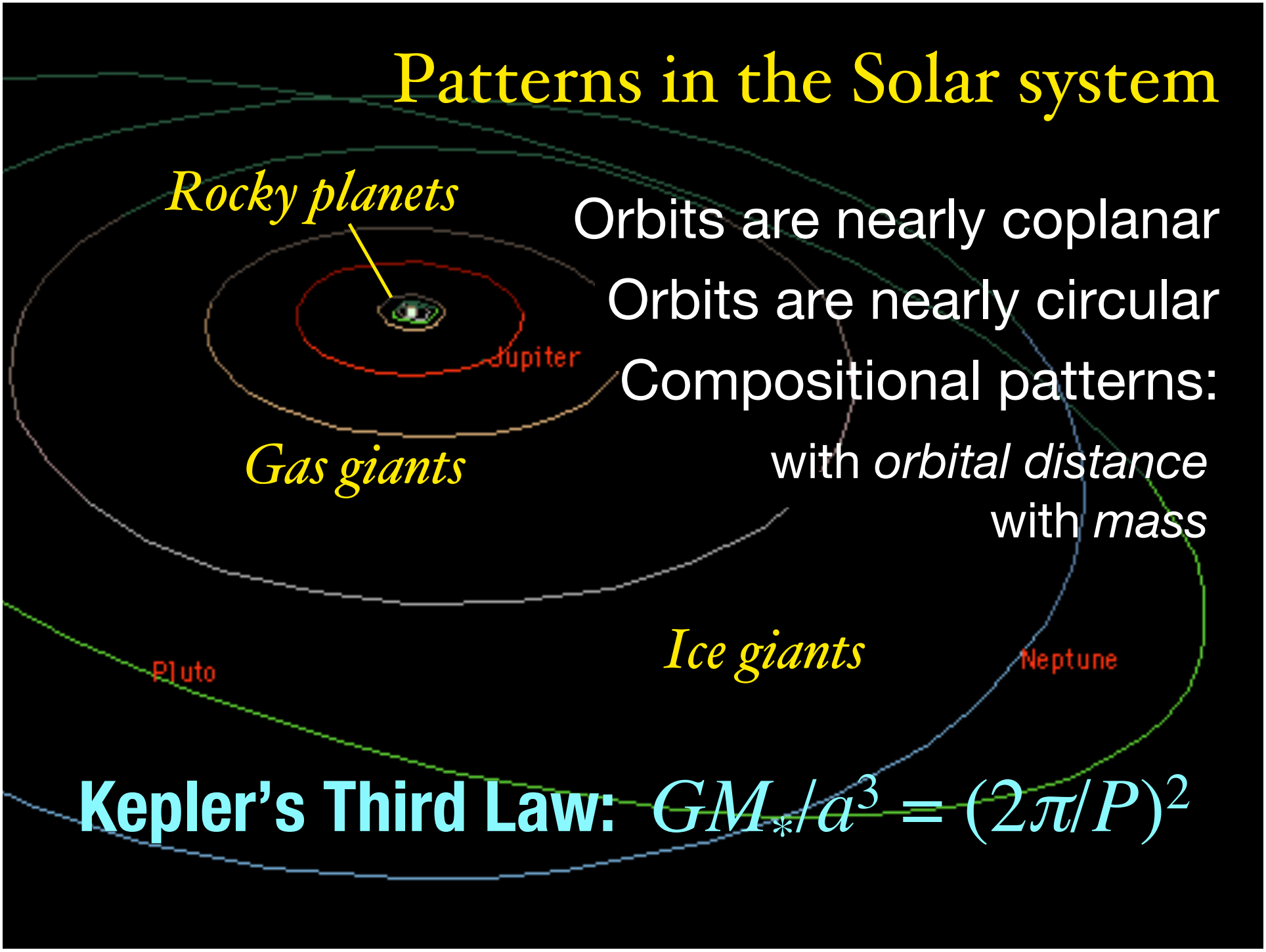
Compositional patterns:

with *orbital distance*

with *mass*

$R_{earth} : R_{nep} : R_{jup} : R_{sun} :: 1 : 4 : 10 : 100$

Patterns in the Solar system



Orbits are nearly coplanar

Orbits are nearly circular

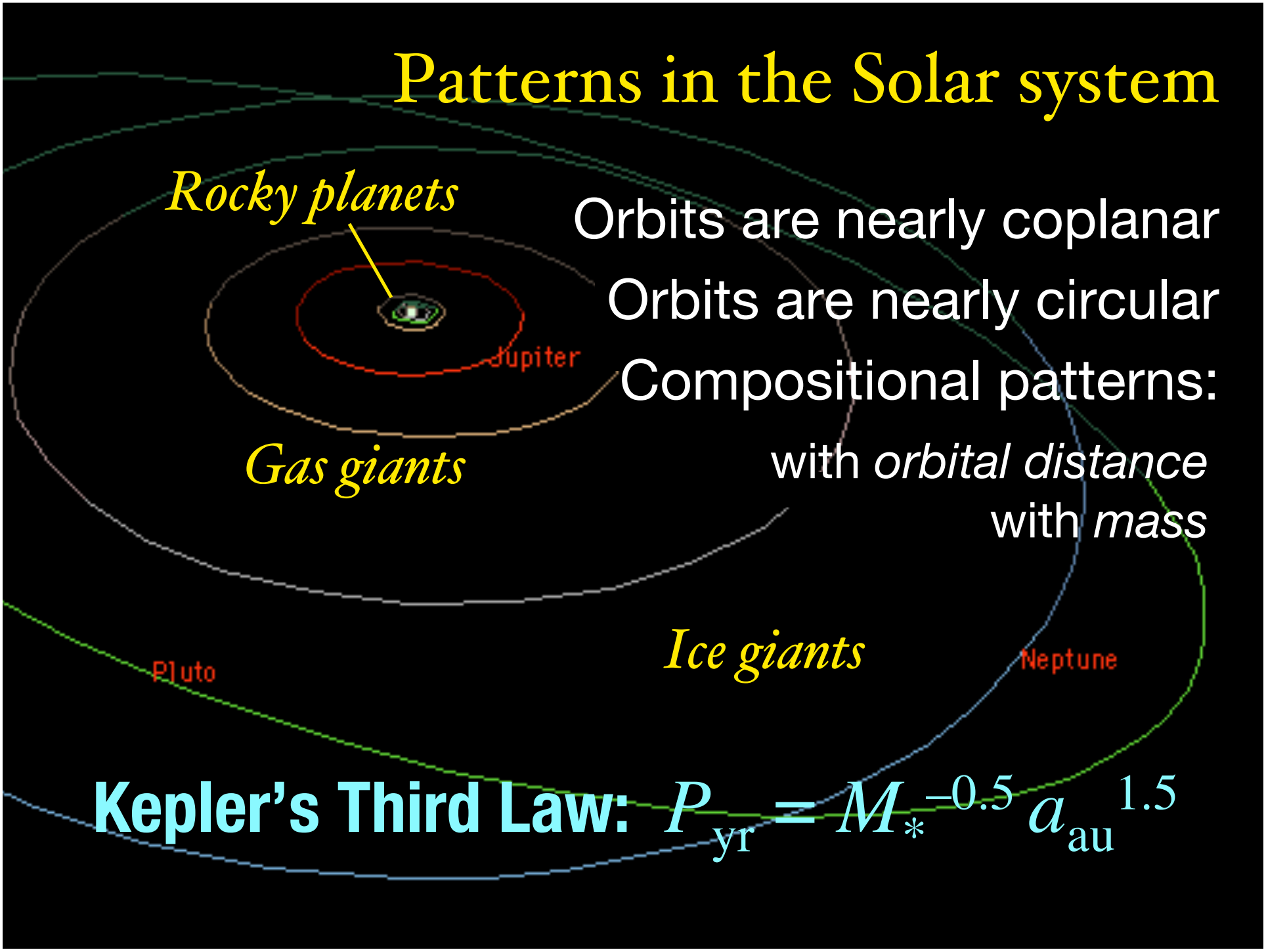
Compositional patterns:

with *orbital distance*

with *mass*

Kepler's Third Law: $GM_*/a^3 = (2\pi/P)^2$

Patterns in the Solar system



Orbits are nearly coplanar

Orbits are nearly circular

Compositional patterns:

with *orbital distance*

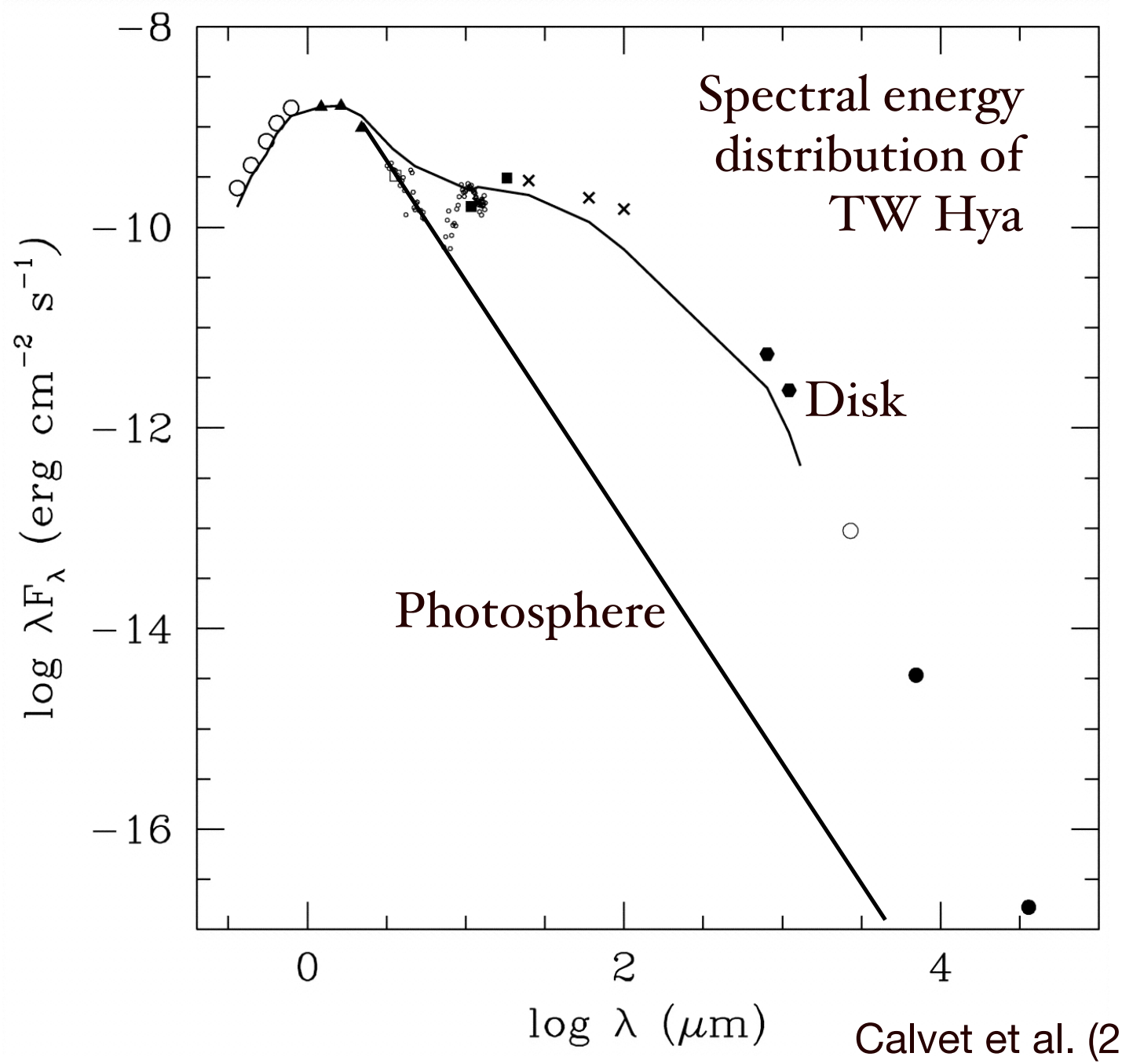
with *mass*

Kepler's Third Law: $P_{\mathrm{yr}} = M_{*}^{-0.5} a_{\mathrm{au}}^{1.5}$

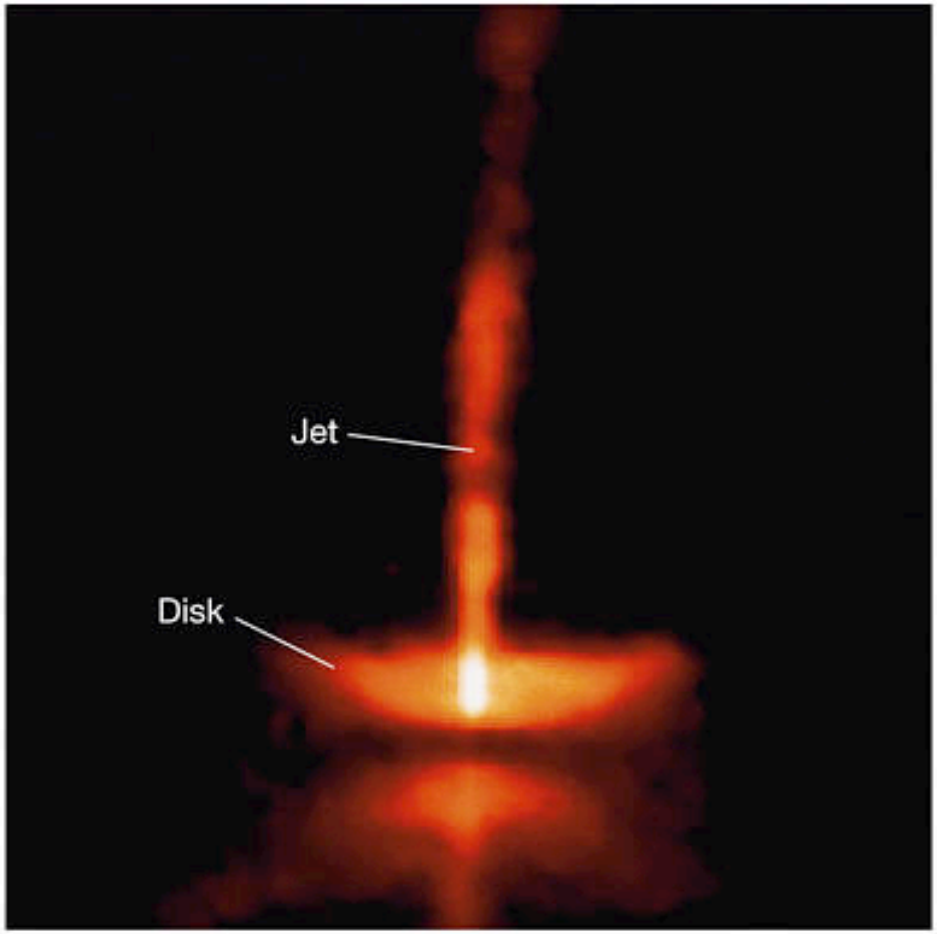
The Kant-Laplace hypothesis

Immanuel Kant (1724-1804)

Pierre-Simon Laplace (1749-1827)



Calvet et al. (2002)



(a)

(b)

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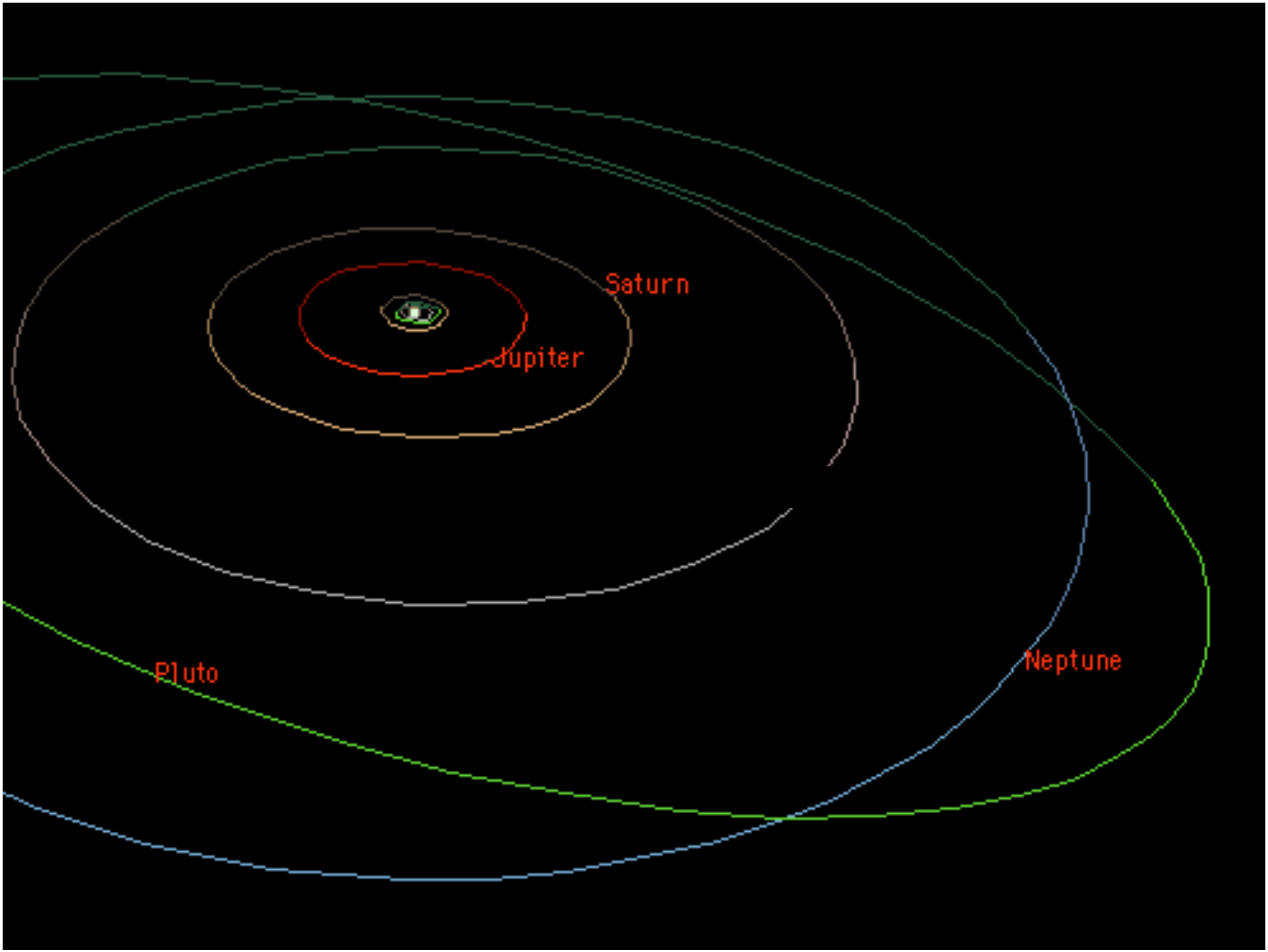
Protoplanetary Disks
Orion Nebula

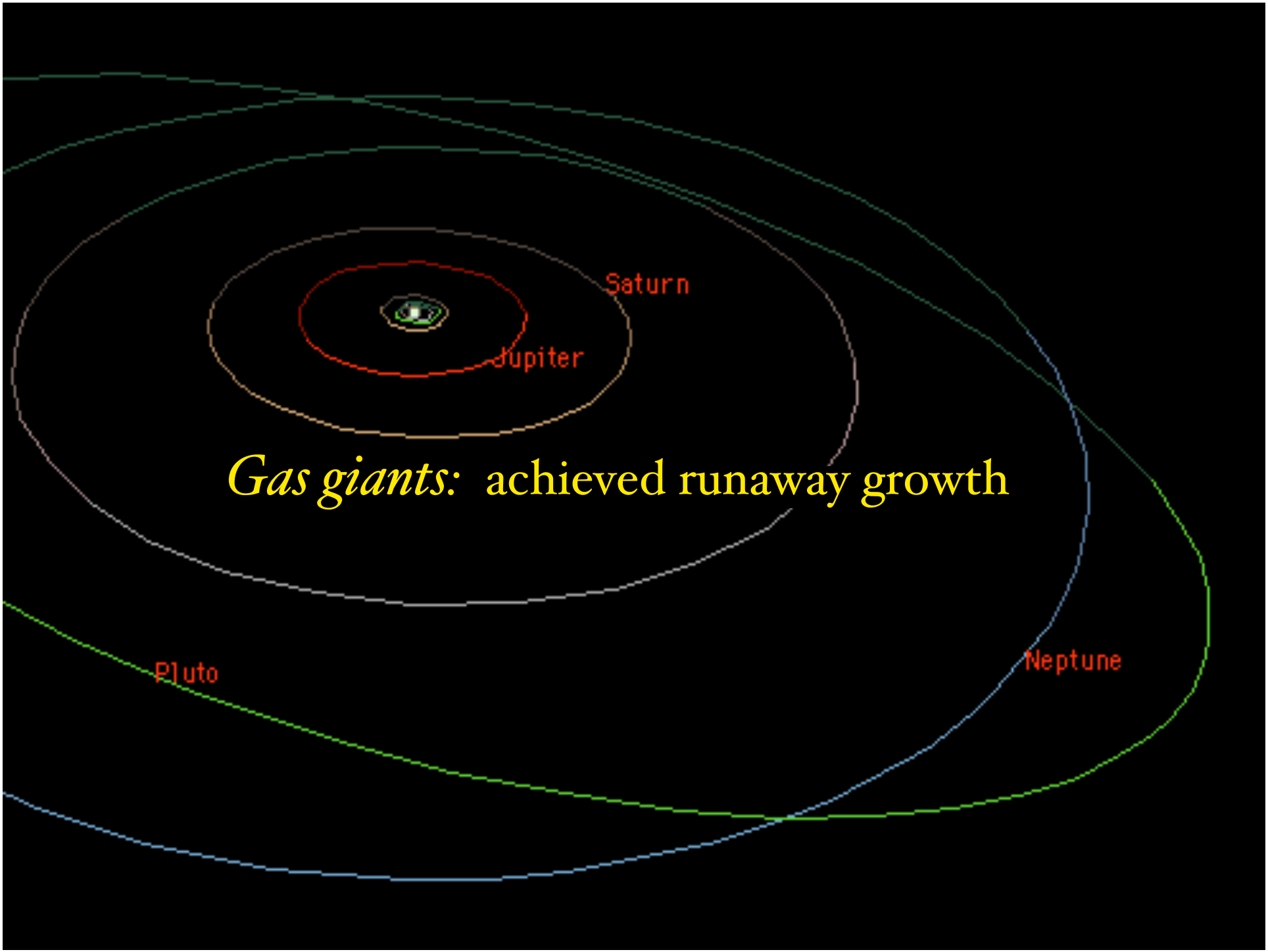
HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

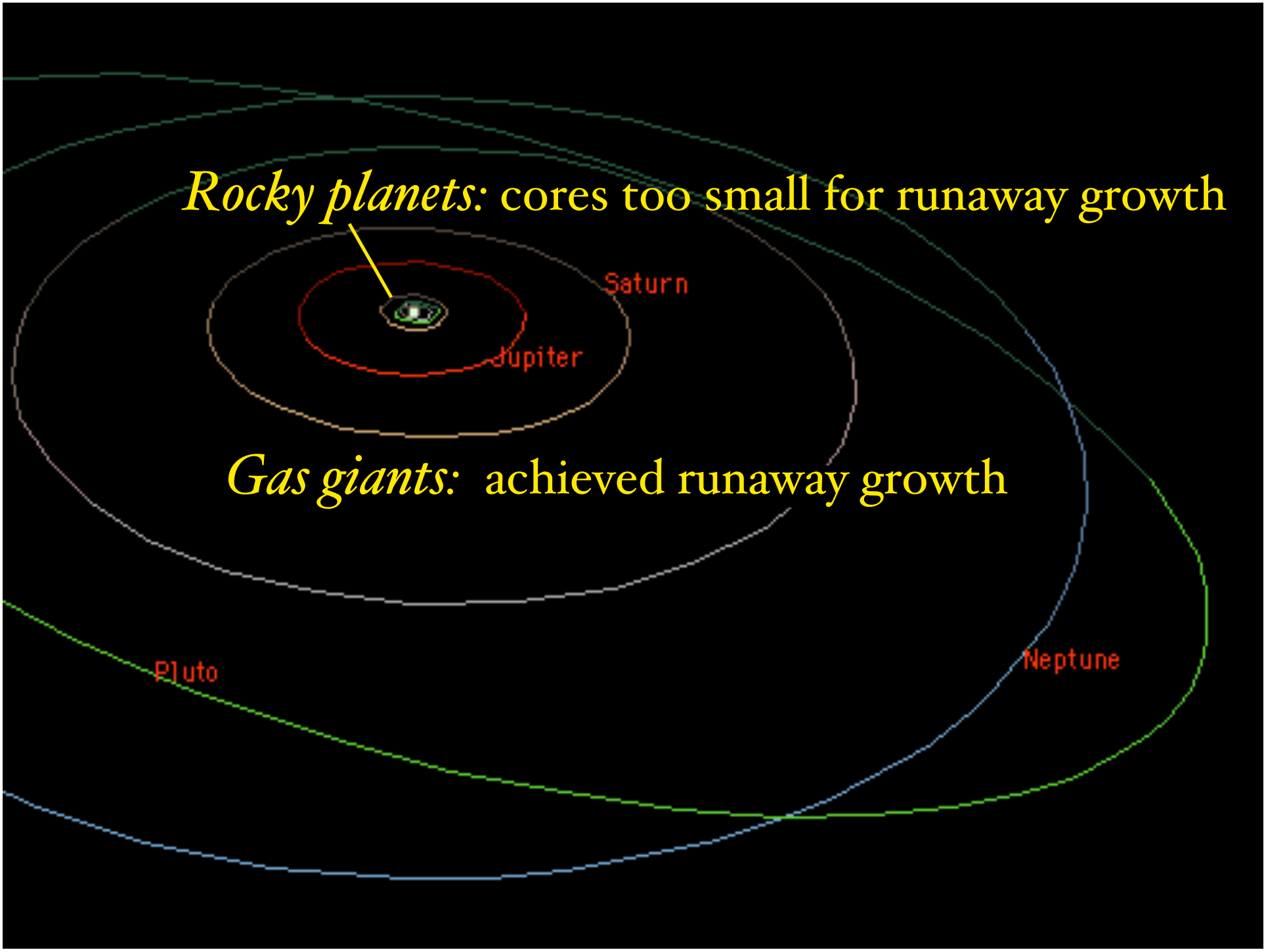
Core-nucleated growth

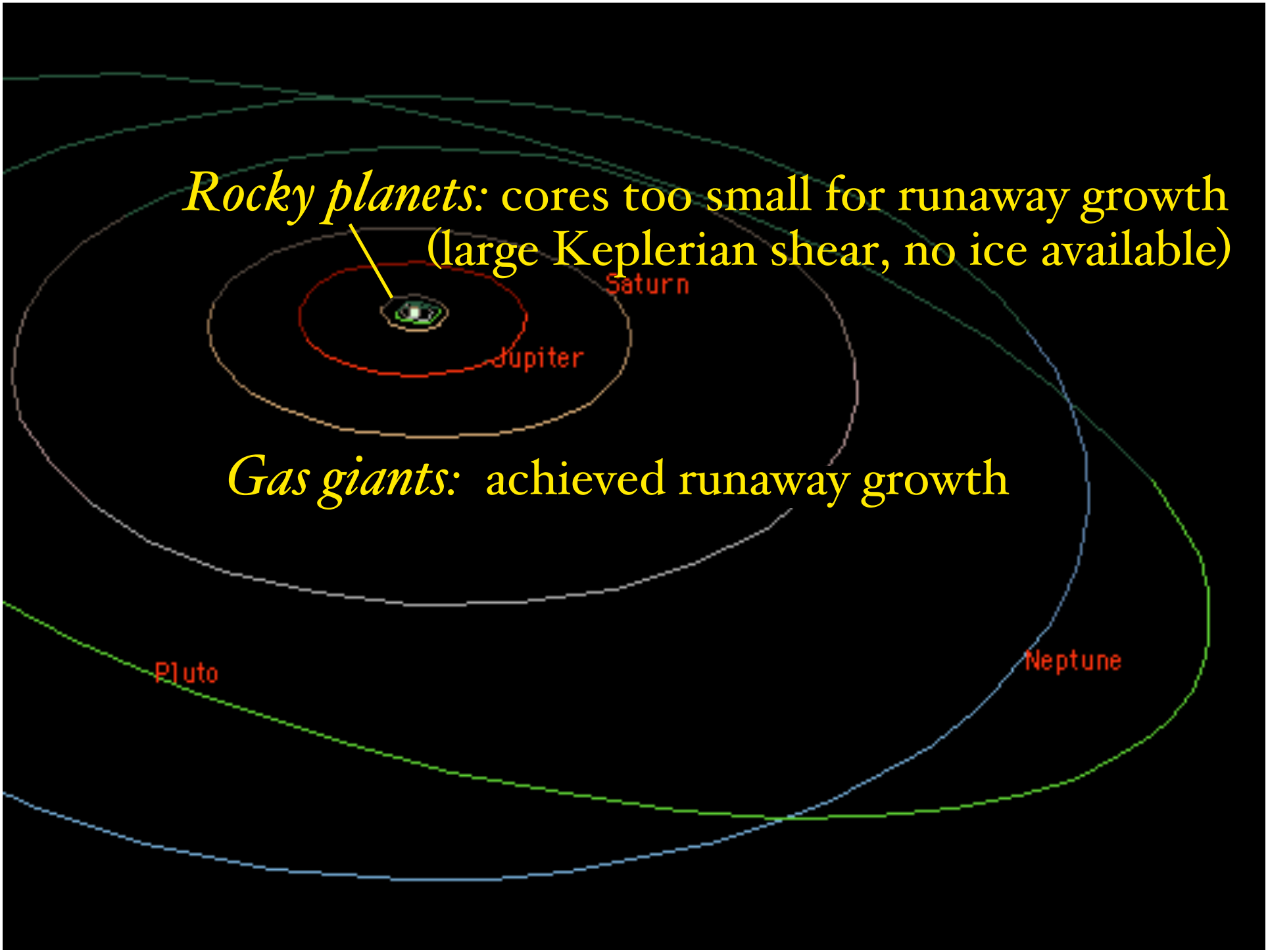
- Dust settles to midplane
- Agglomerates into ~1km objects (somehow)
- Growth through gravitationally-focused collisions
- Begin accreting gas at ~1 M_E
- Runaway accretion of gas when core reaches ~10 M_E


Saturn
Jupiter
Pluto
Neptune



Gas giants: achieved runaway growth


Rocky planets: cores too small for runaway growth
Saturn
Jupiter
Gas giants: achieved runaway growth
Pluto
Neptune


Rocky planets: cores too small for runaway growth
(large Keplerian shear, no ice available)
Saturn
Jupiter
Gas giants: achieved runaway growth
Pluto
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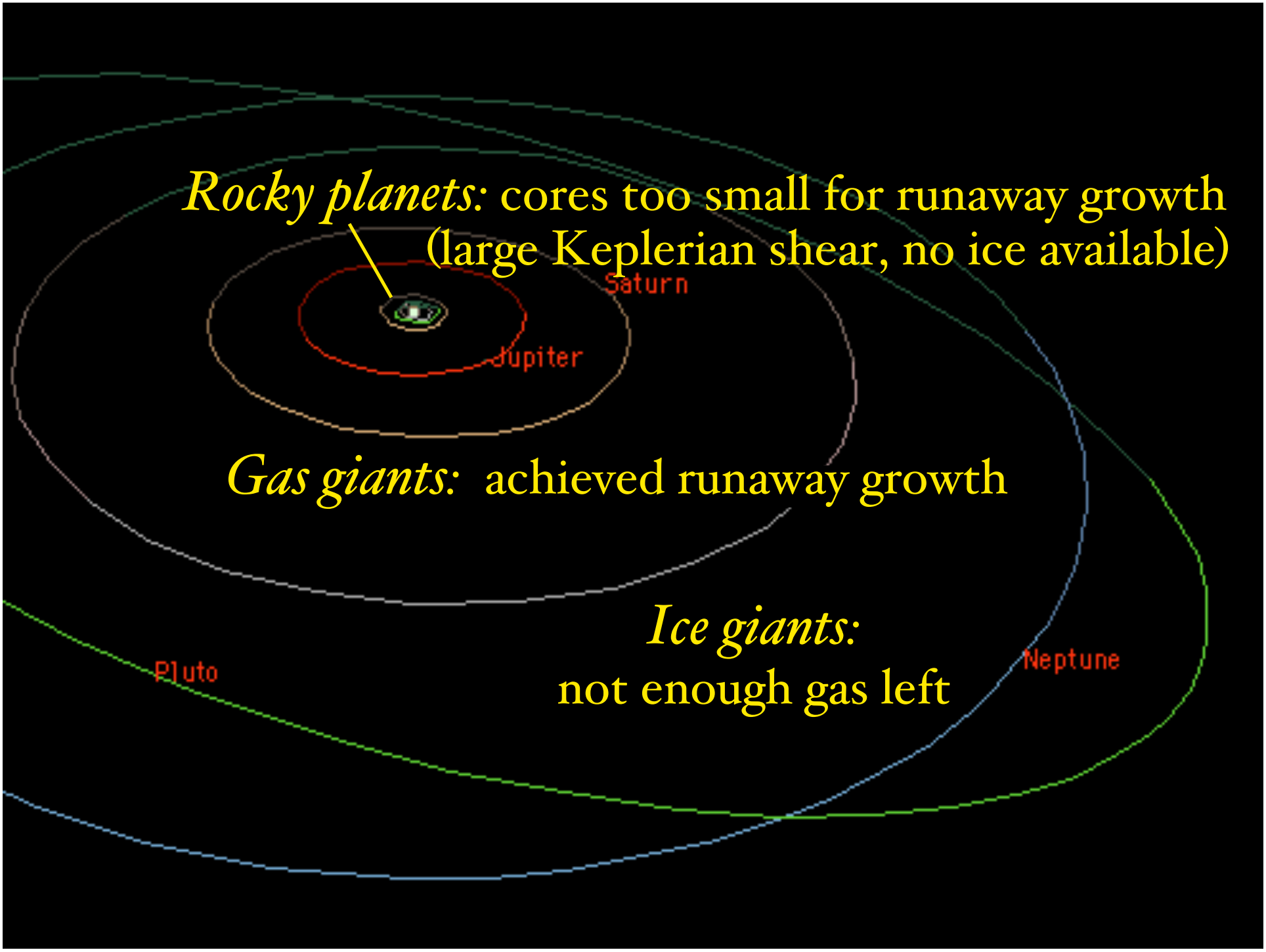
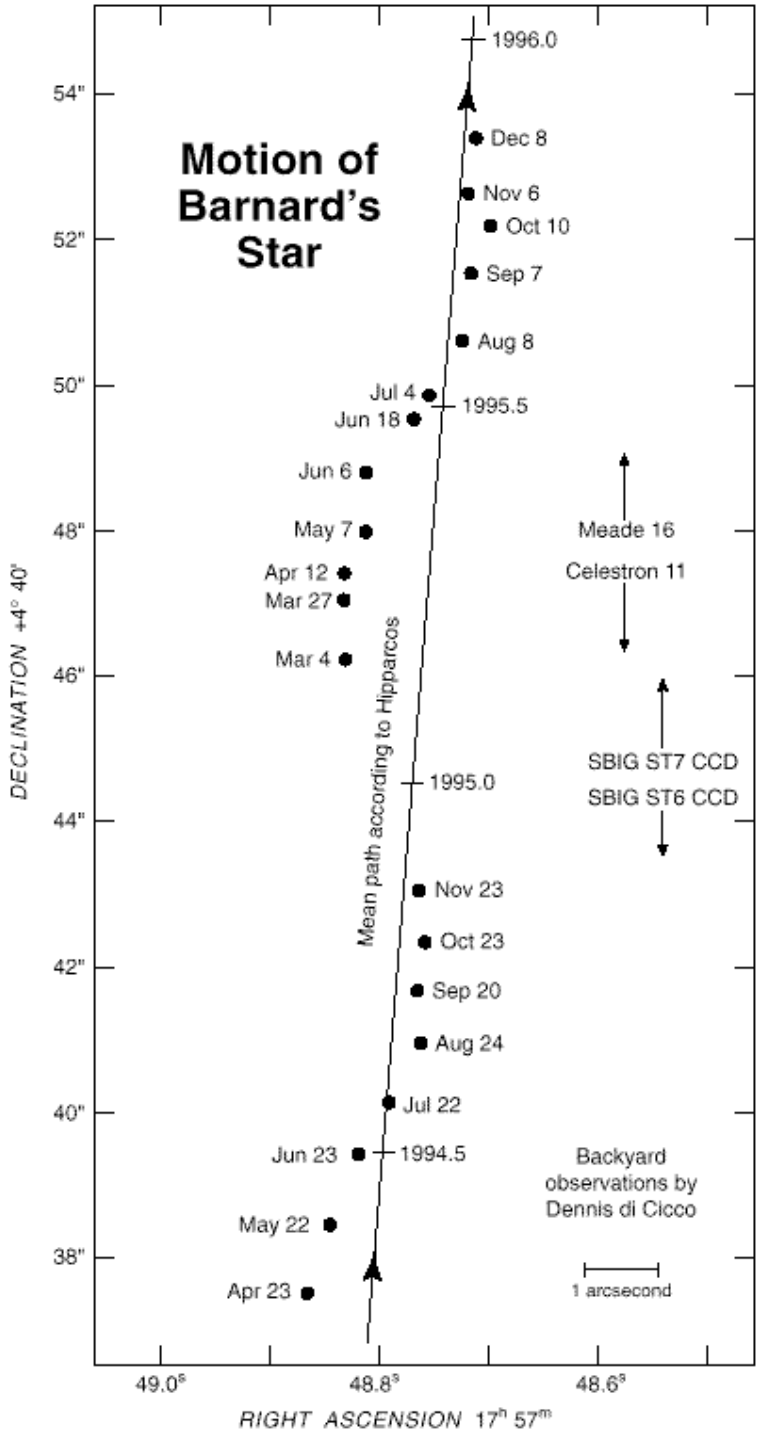
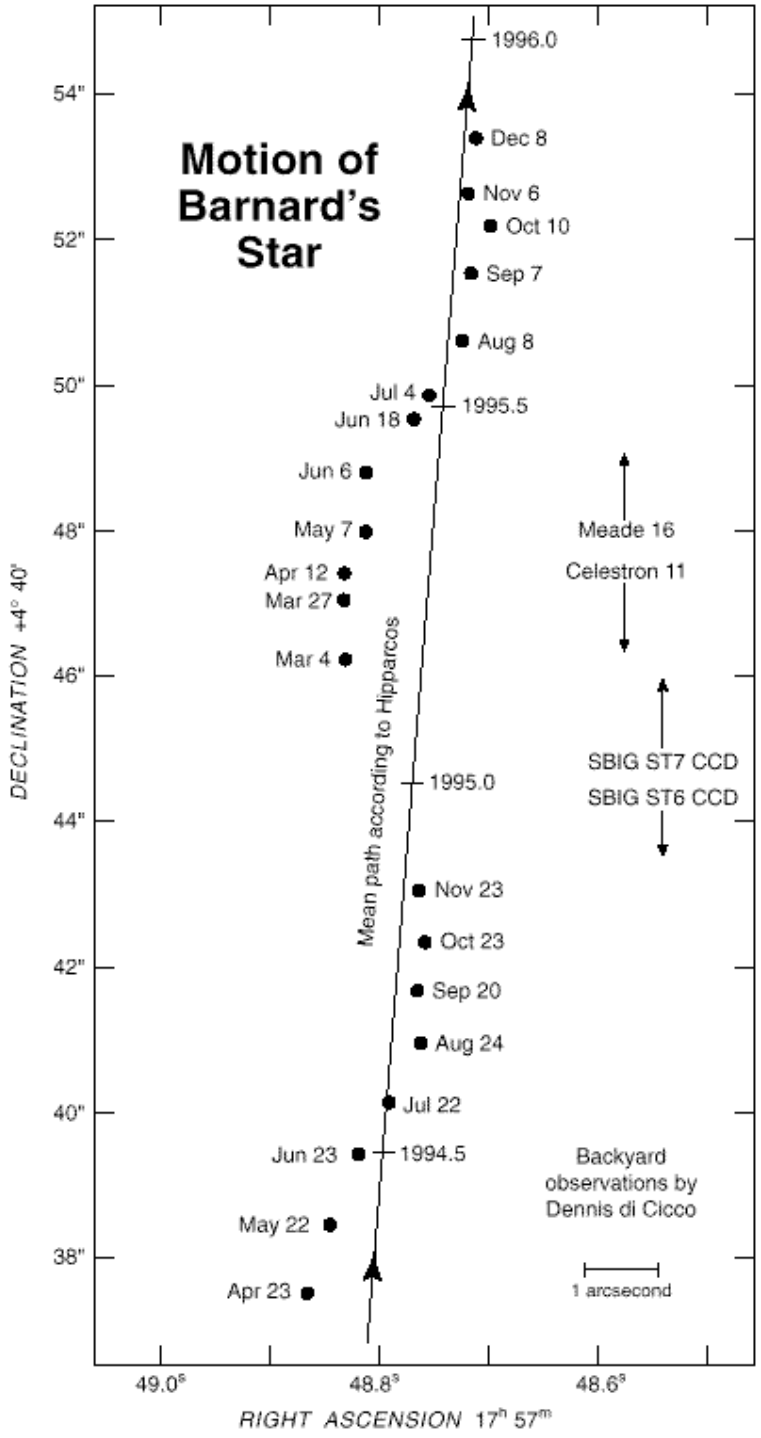

Rocky planets: cores too small for runaway growth
(large Keplerian shear, no ice available)
Saturn
Jupiter
Gas giants: achieved runaway growth
Ice giants:
not enough gas left
Pluto
Neptune

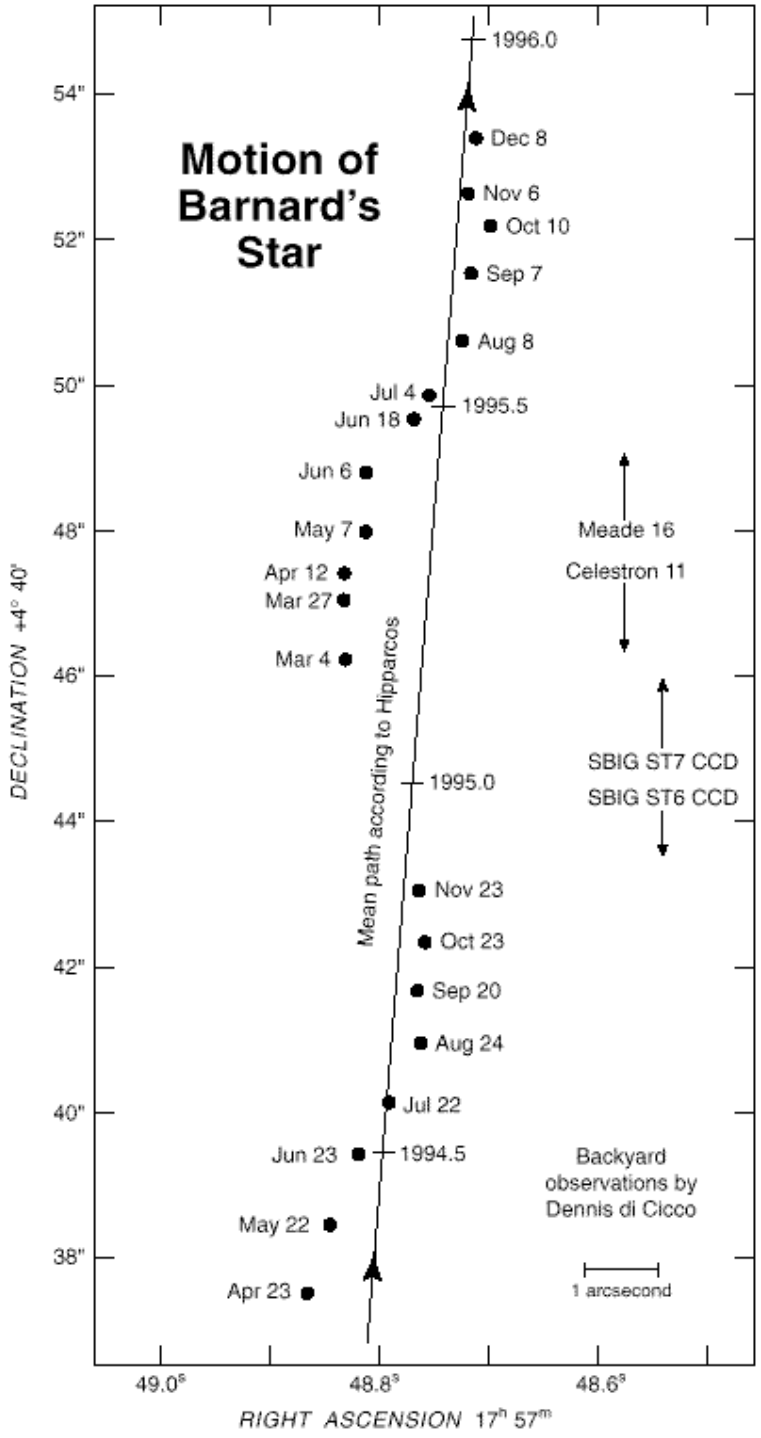


False start: Barnard's star



False start: Barnard's star

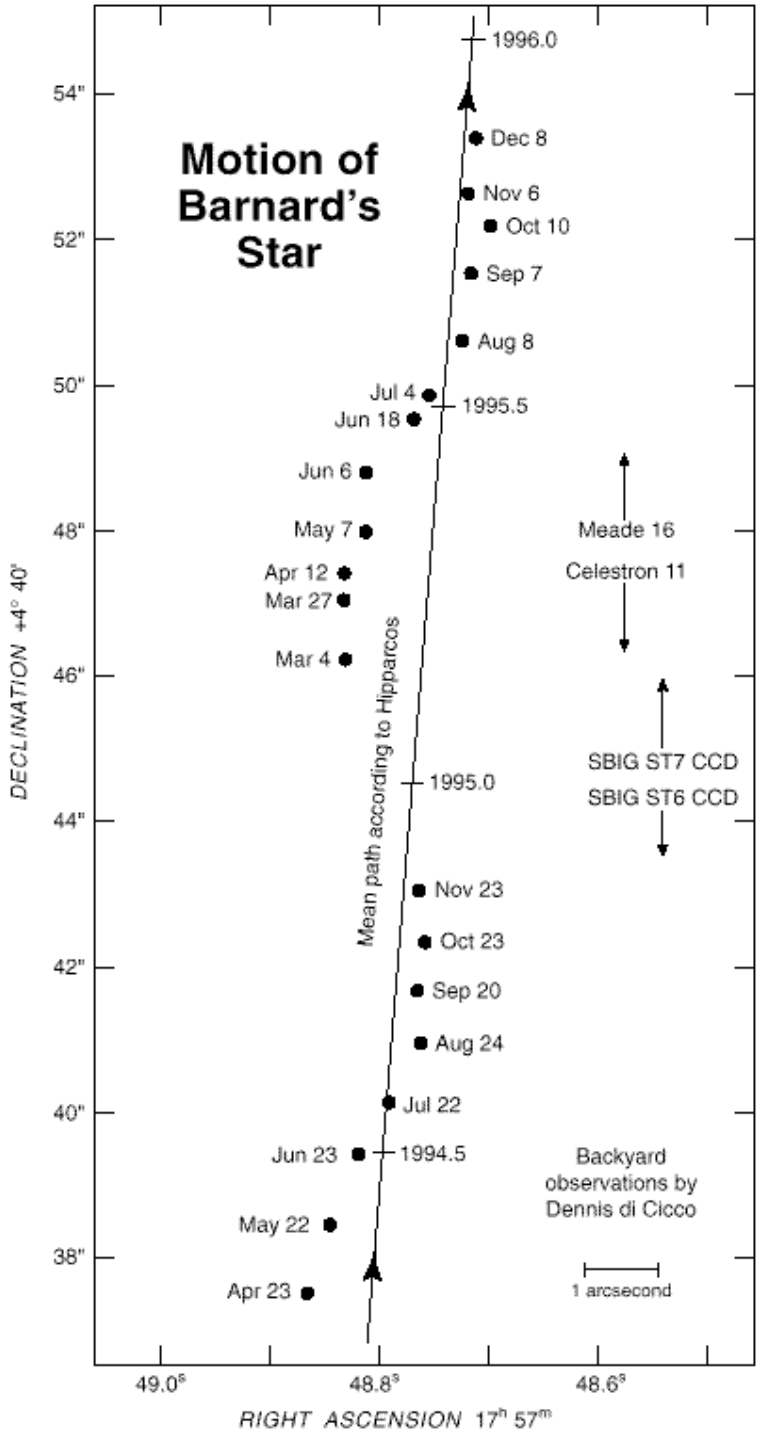
M dwarf



False start: Barnard's star

M dwarf

2nd closest system



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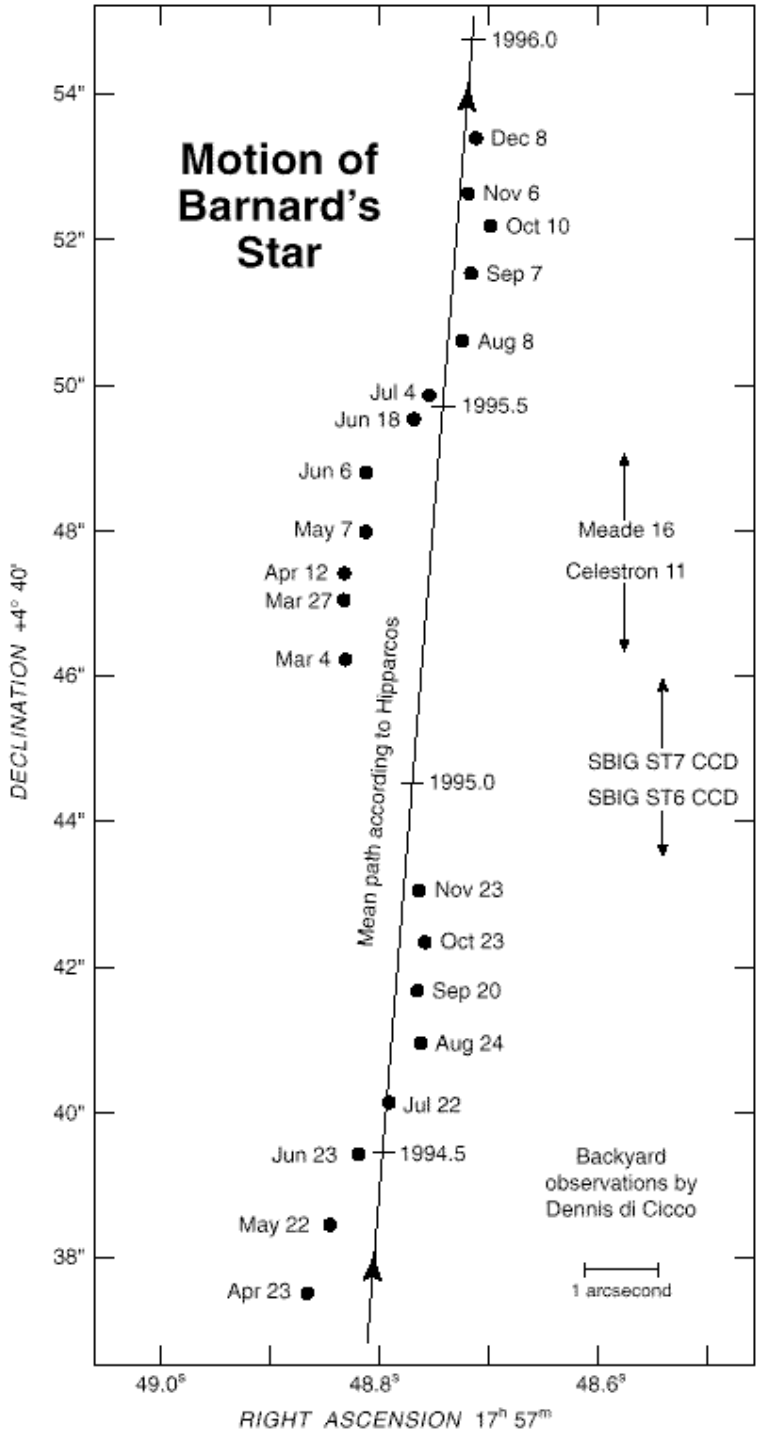
M dwarf

2nd closest system

Peter van de Kamp (1963):



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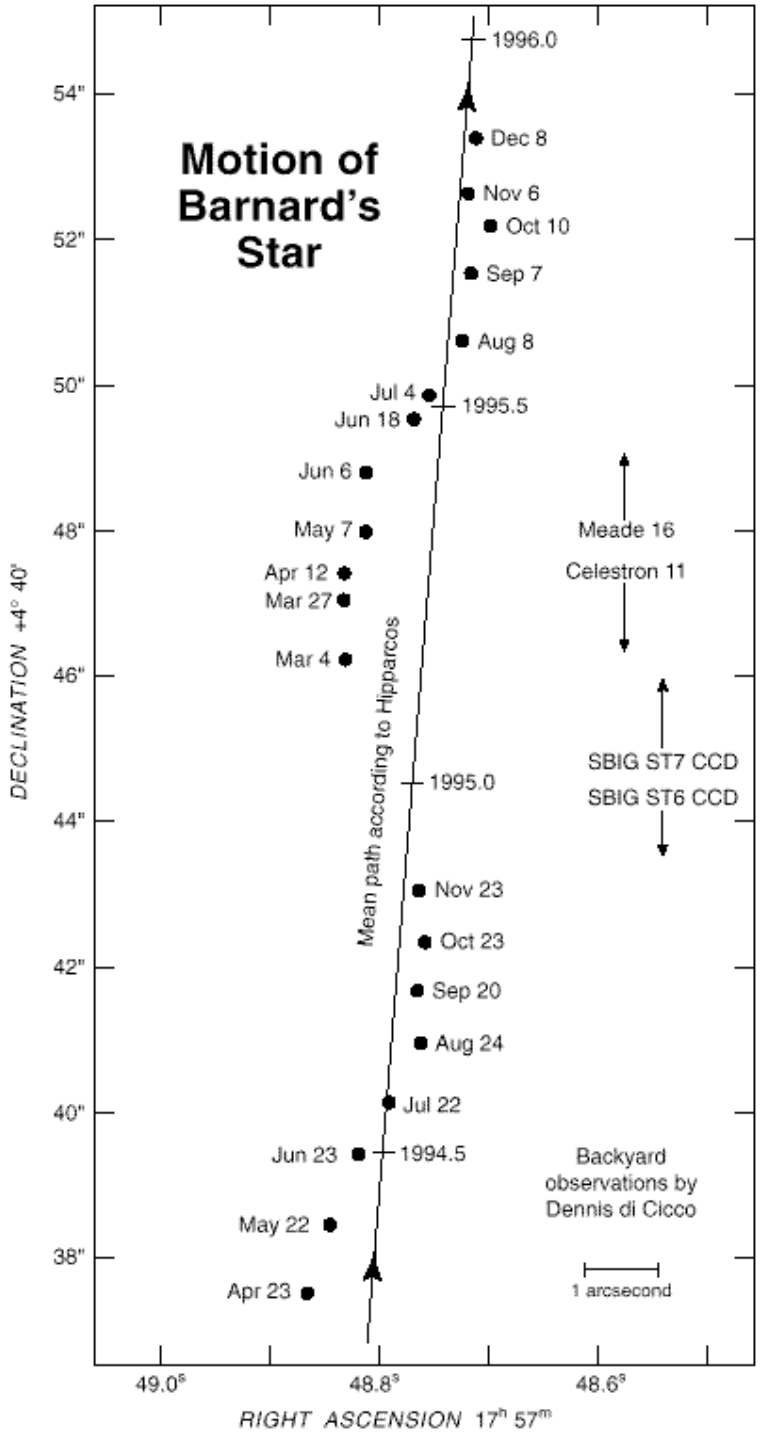
Peter van de Kamp (1963):

Jupiter-mass planet



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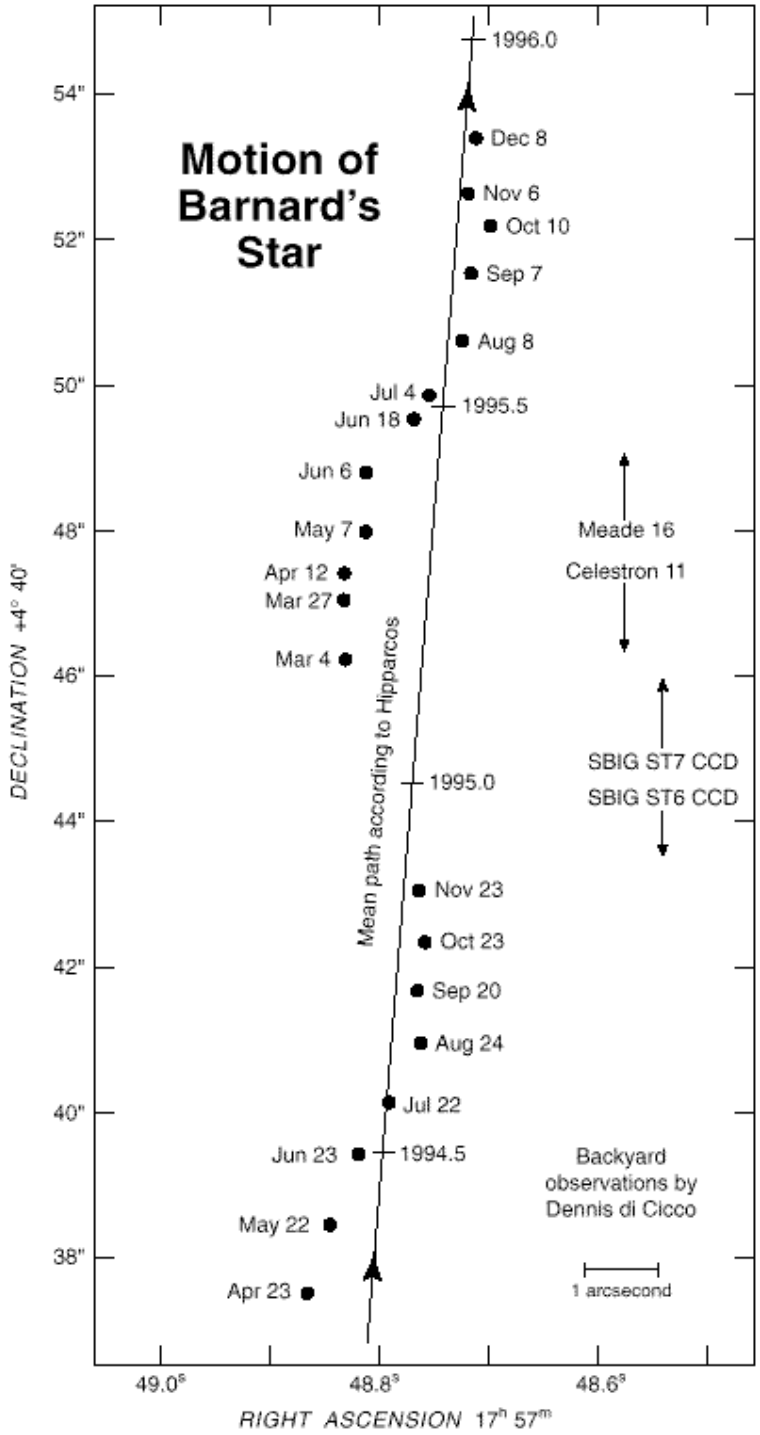
Jupiter-mass planet

25 year period



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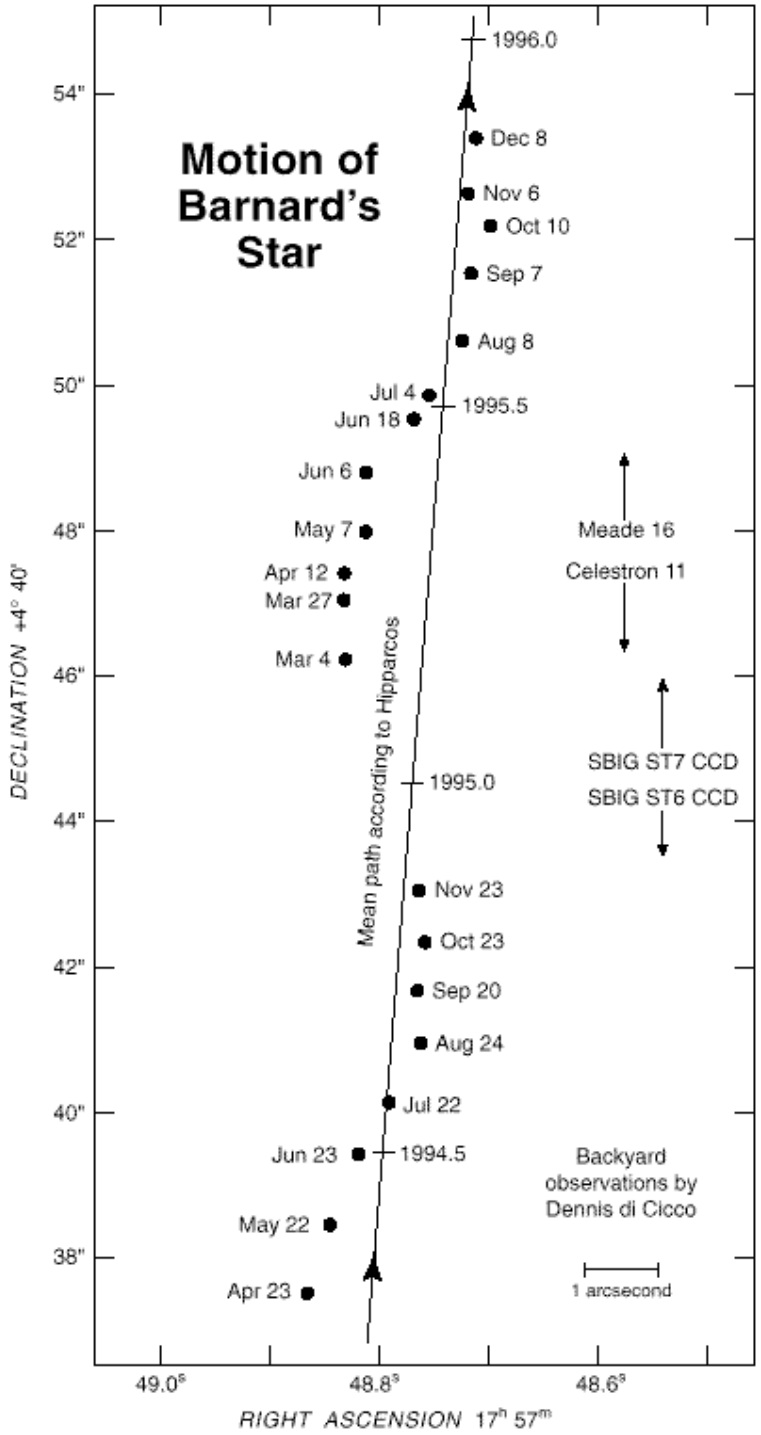
2nd closest system

Peter van de Kamp (1963):

Jupiter-mass planet

25 year period

Eccentric orbit



False start: Barnard's star

M dwarf

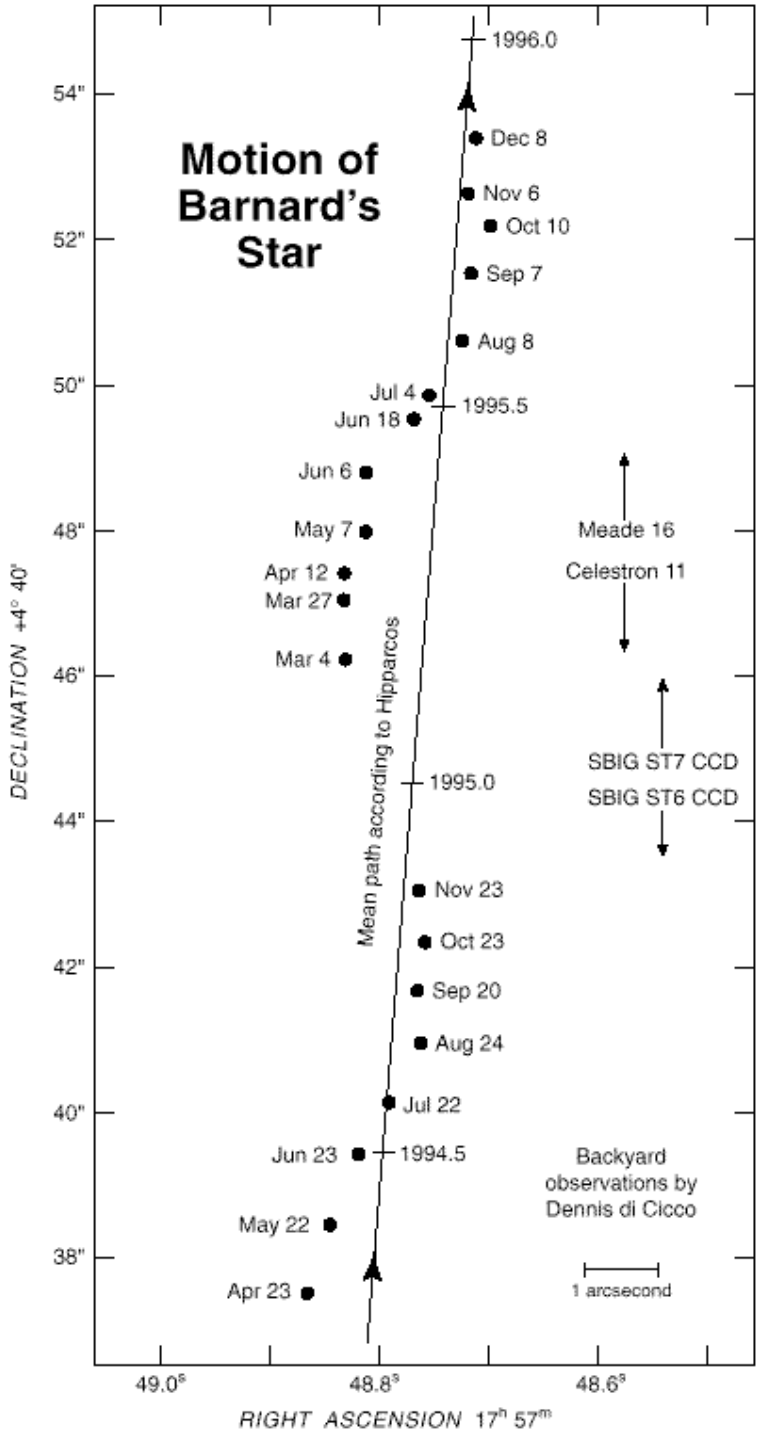
2nd closest system

Peter van de Kamp (1963):

2 Jupiter-mass planets

12, 26 year periods

Circular orbits



False start: Barnard's star

M dwarf

2nd closest system

Peter van de Kamp (1963):

- ***2 Jupiter-mass planets***
- ***12, 26 year periods***
- ***Circular orbits***

Bogus

True start
(but only in retrospect!)

Latham et al. 1989,
***Nature*, 339, 38**

"The unseen companion of HD114762 - A probable brown dwarf"

True start
(but very weird!)

Wolszczan & Frail 1992,
***Nature*, 355, 145**

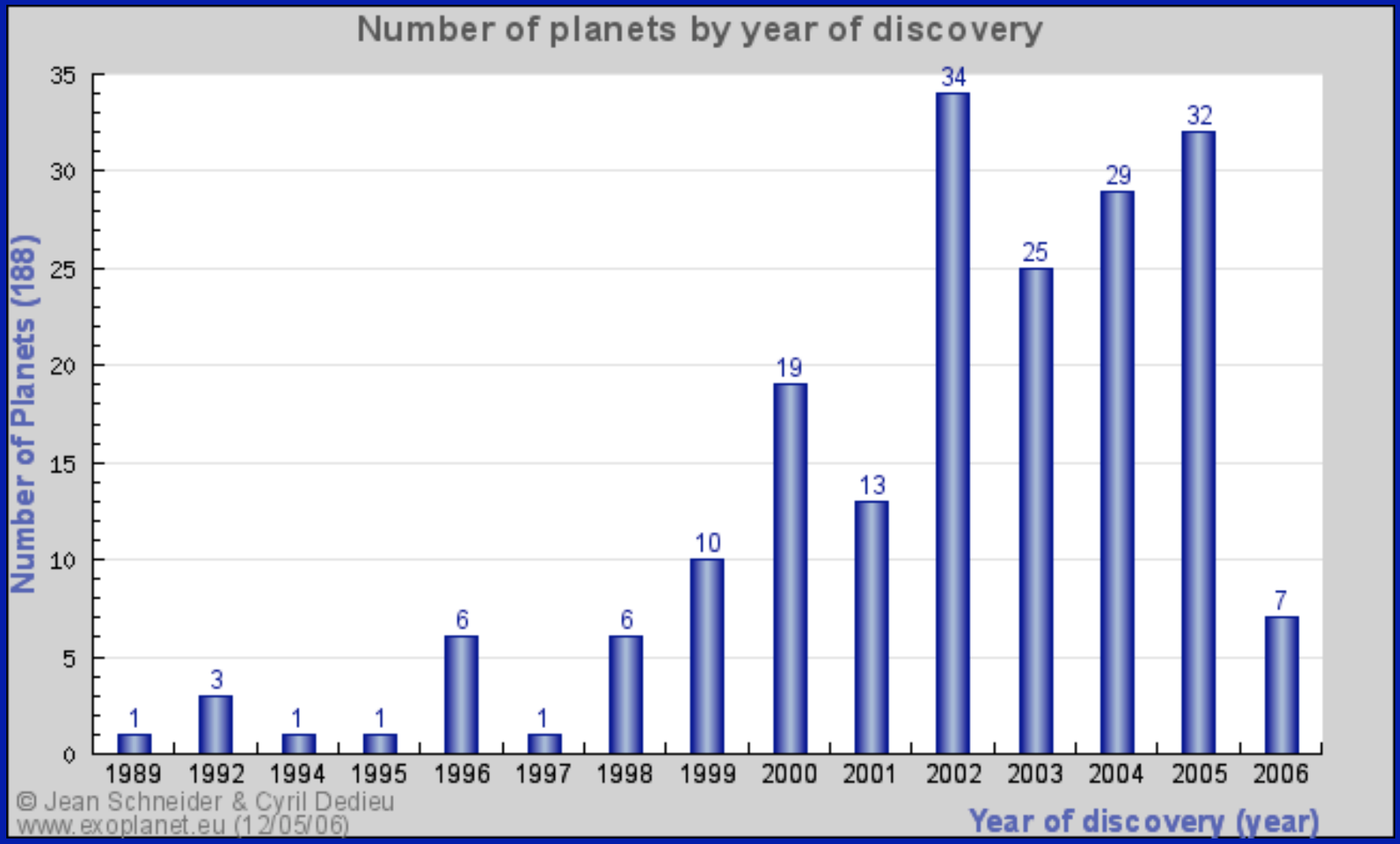
"A planetary system around the millisecond pulsar PSR1257+12"

True start

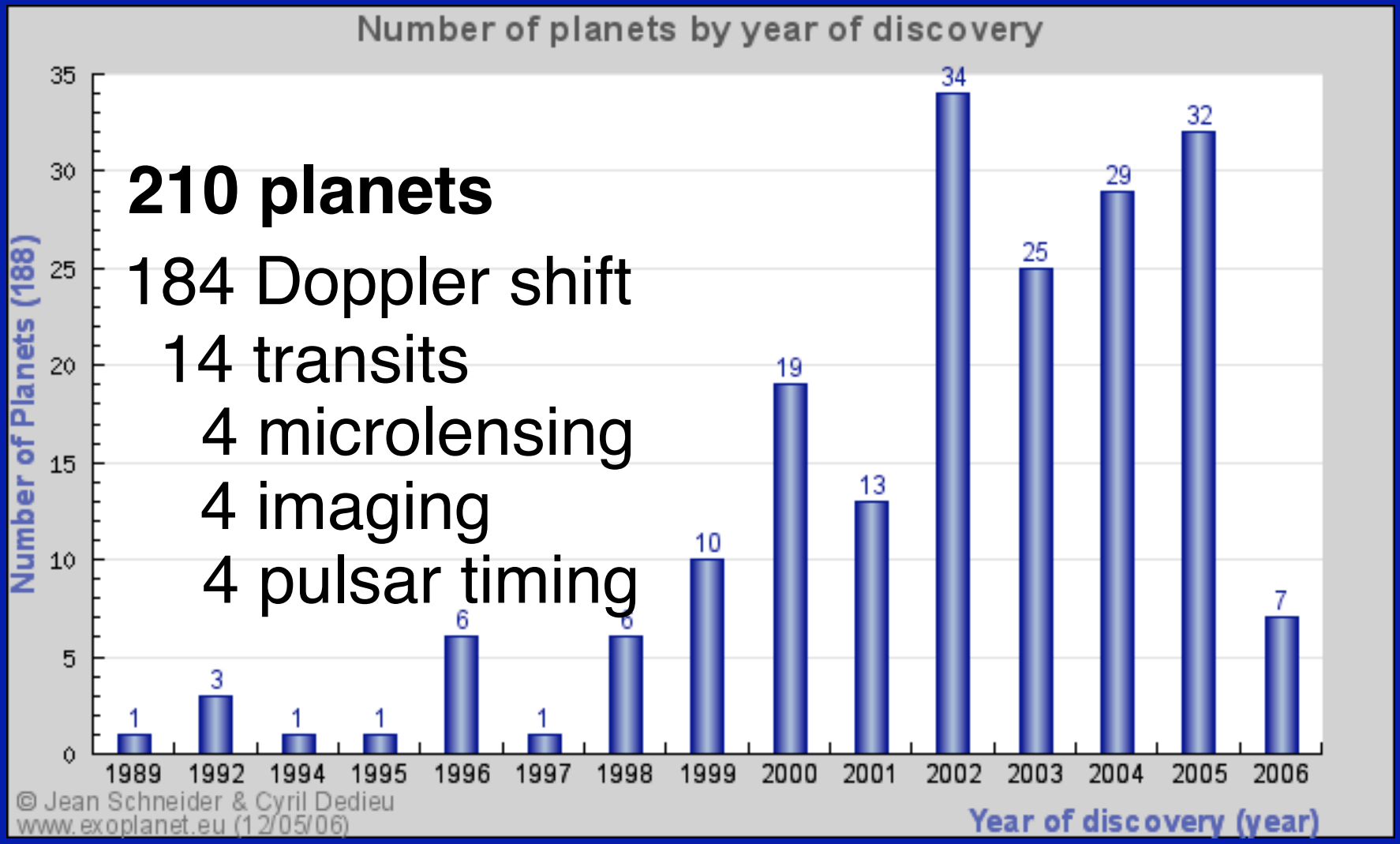
Mayor & Queloz 1995,
***Nature*, 378, 355**

“A Jupiter-mass companion
to a solar-type star”

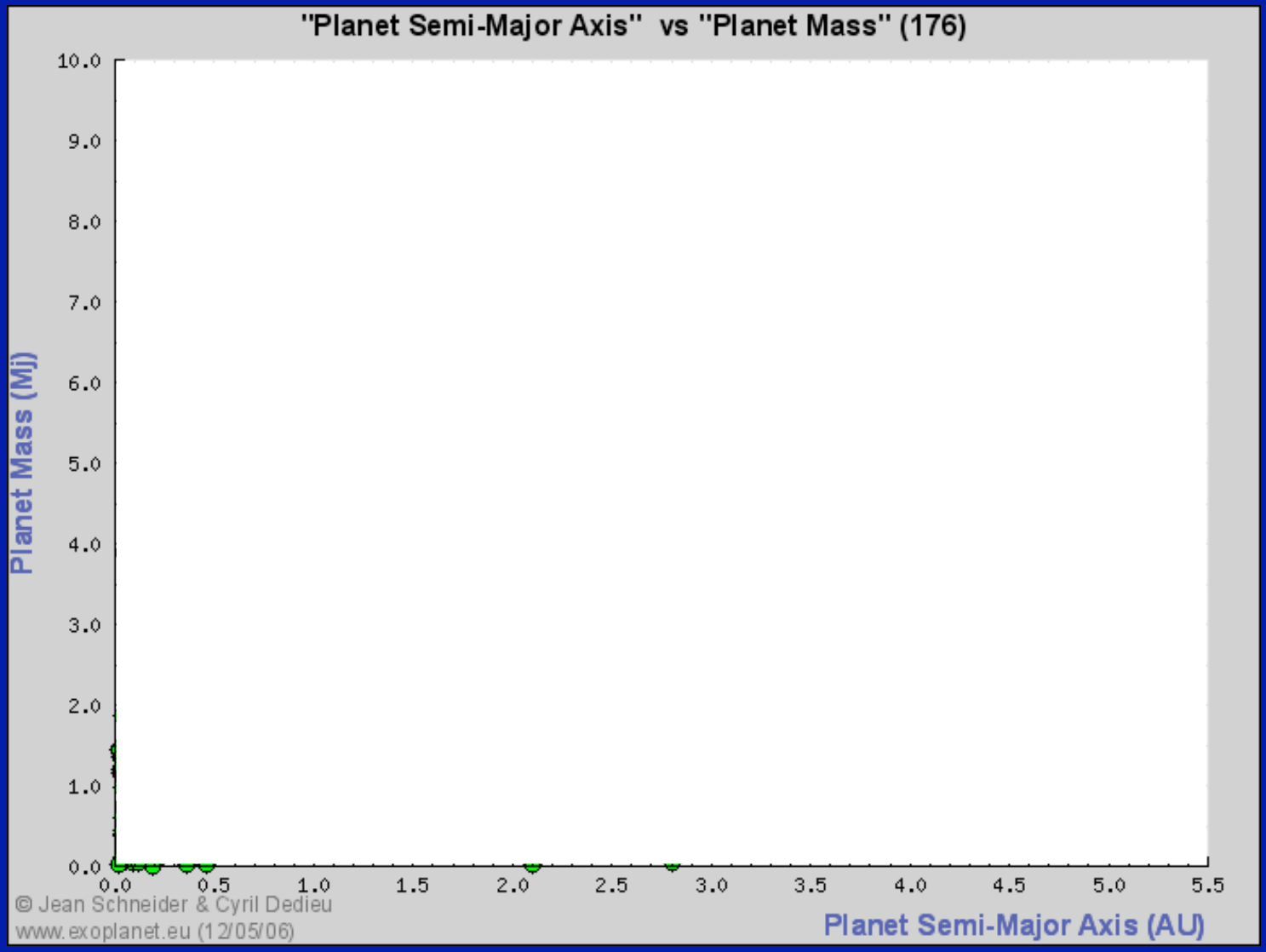
Exoplanet discoveries



Exoplanet discoveries



Exoplanet discoveries



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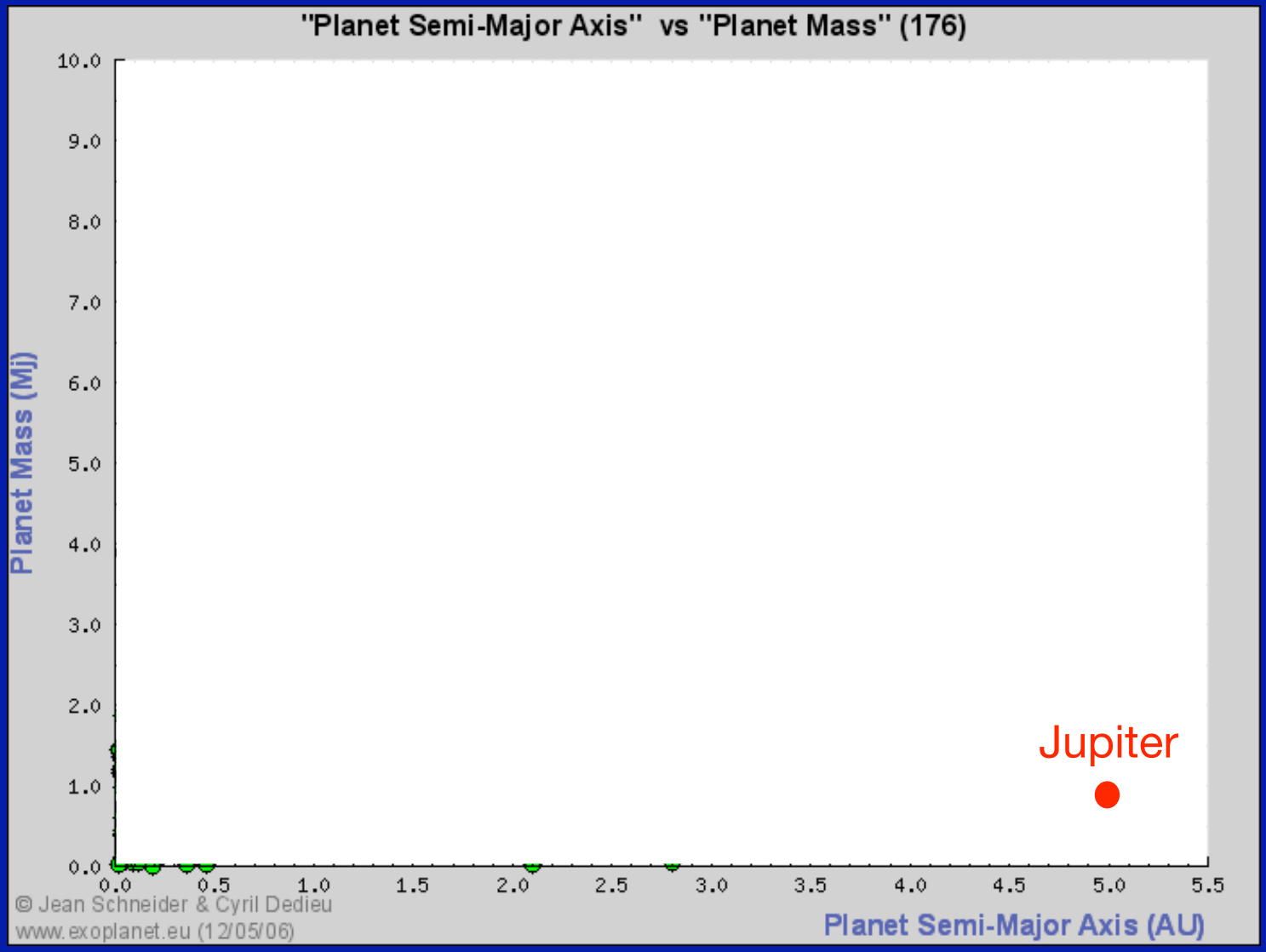

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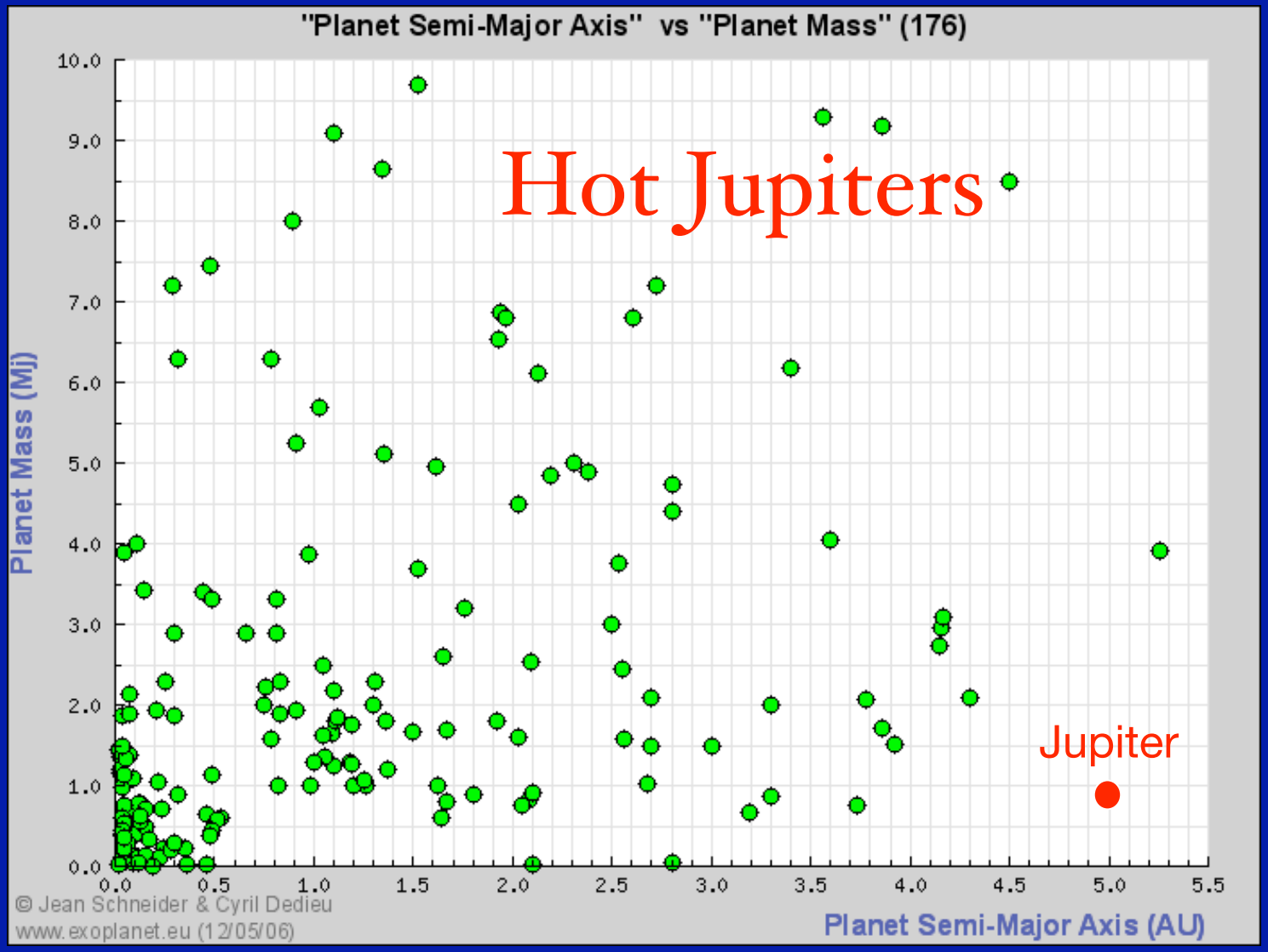
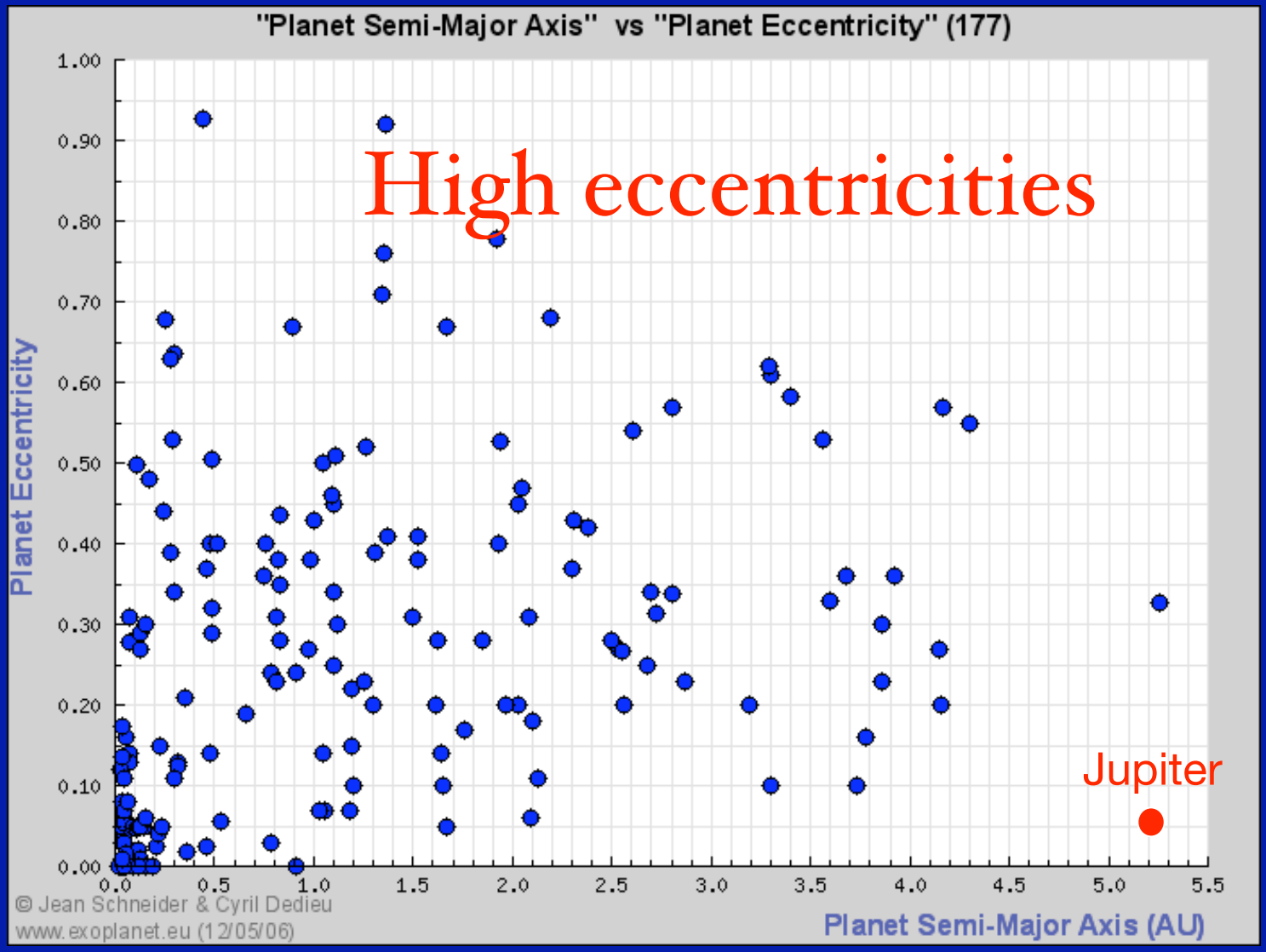


Exoplanet discoveries



HD 80606: P = 112 days, e = 0.927

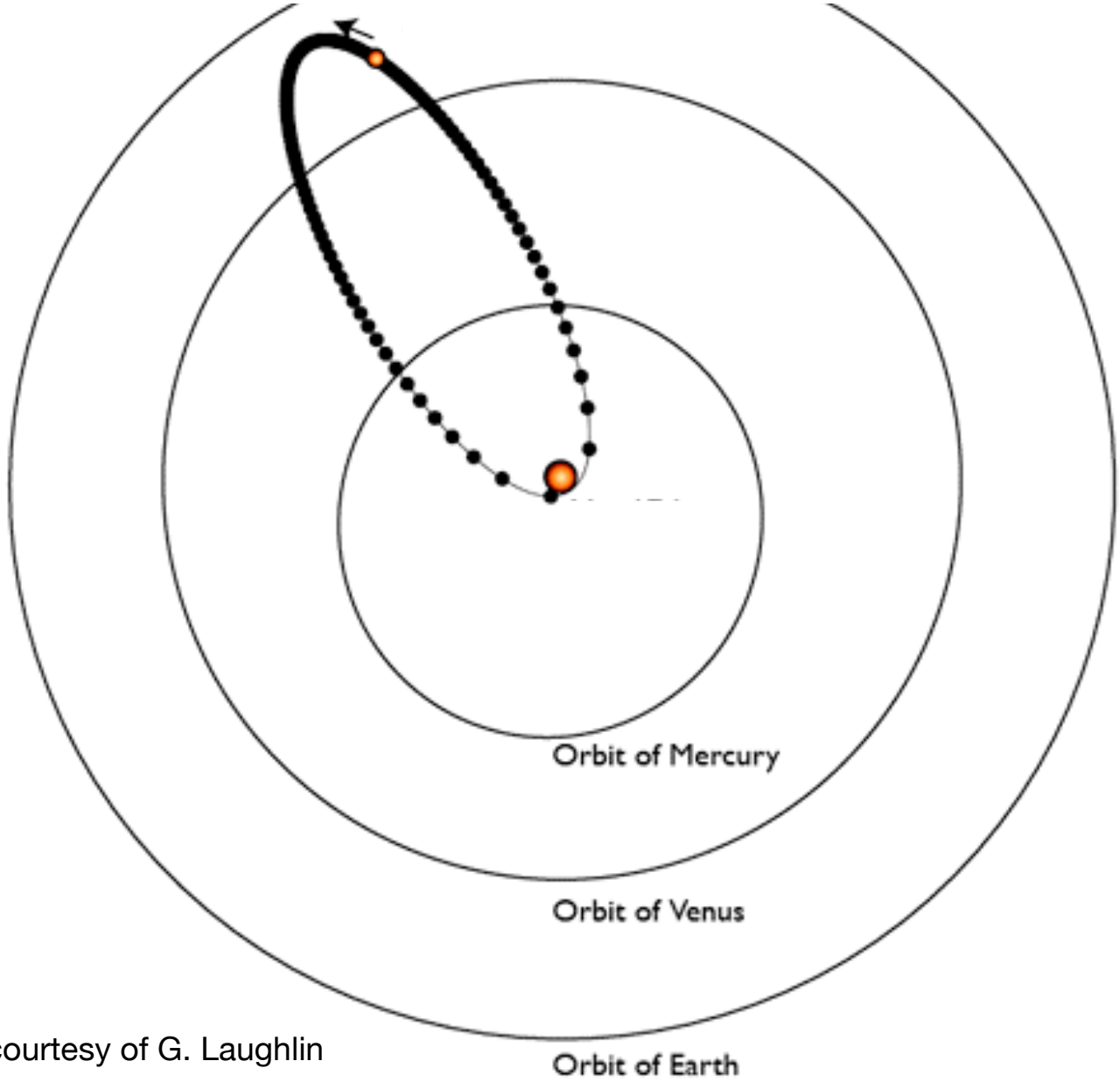
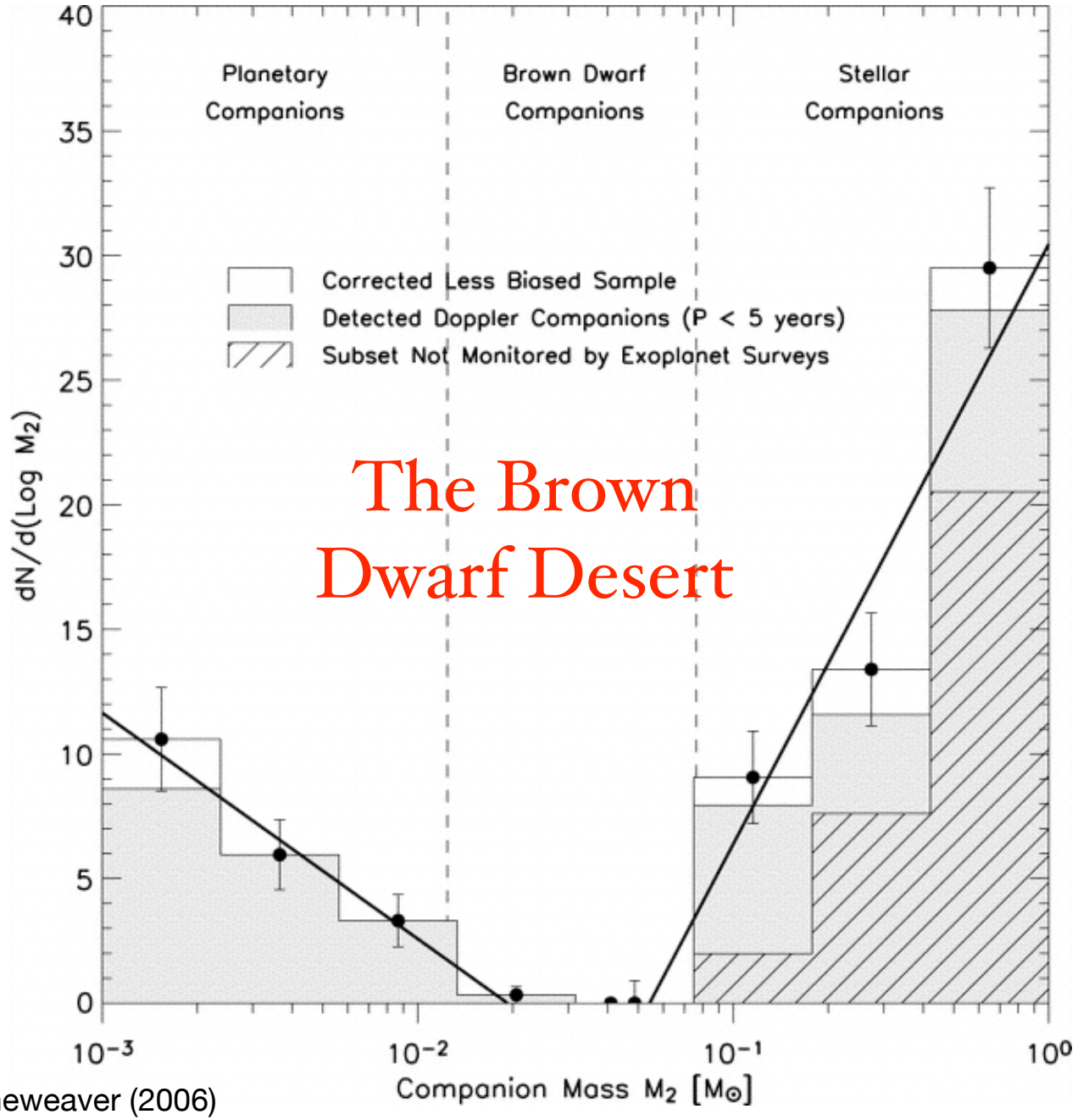


Illustration courtesy of G. Laughlin



Grether & Lineweaver (2006)

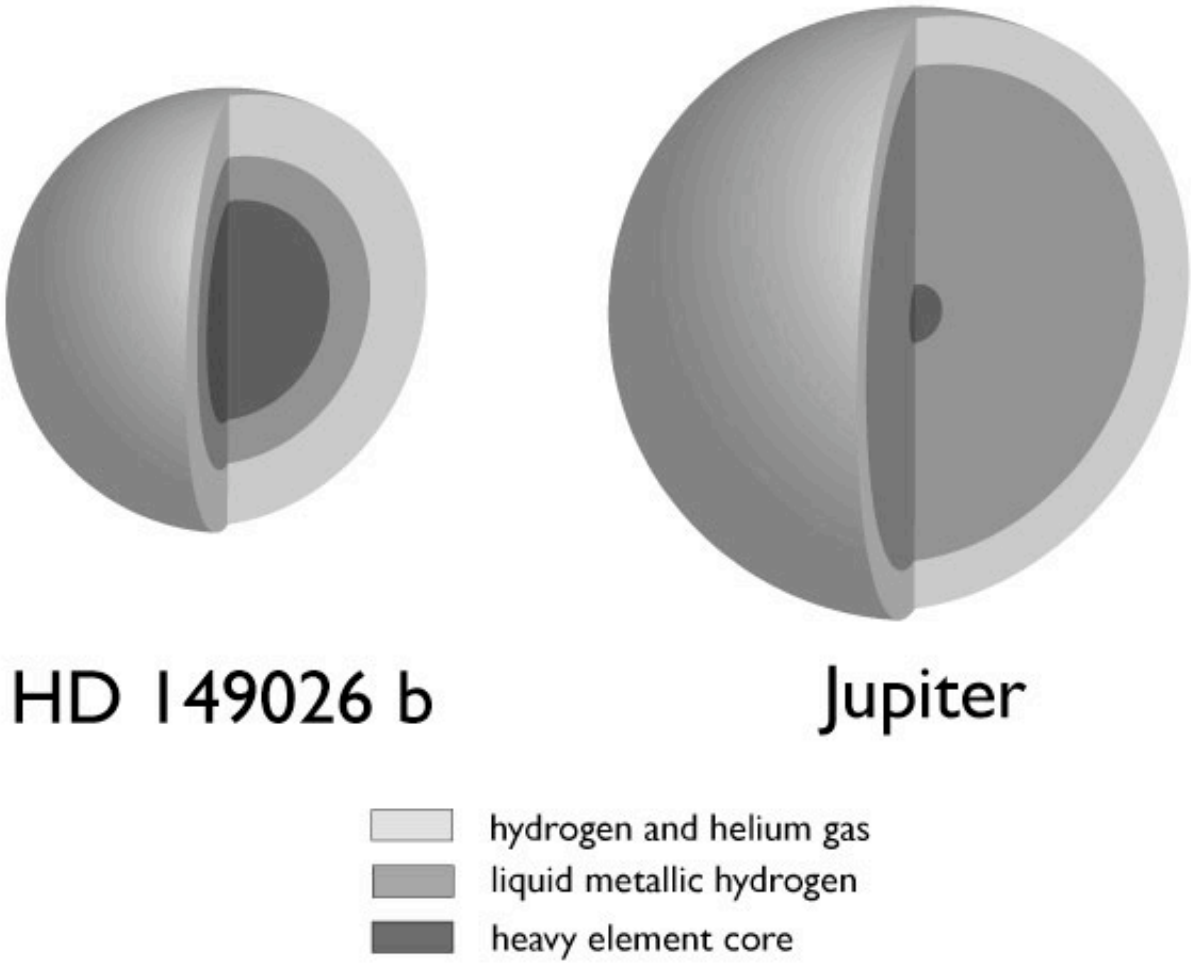


Illustration courtesy of G. Laughlin