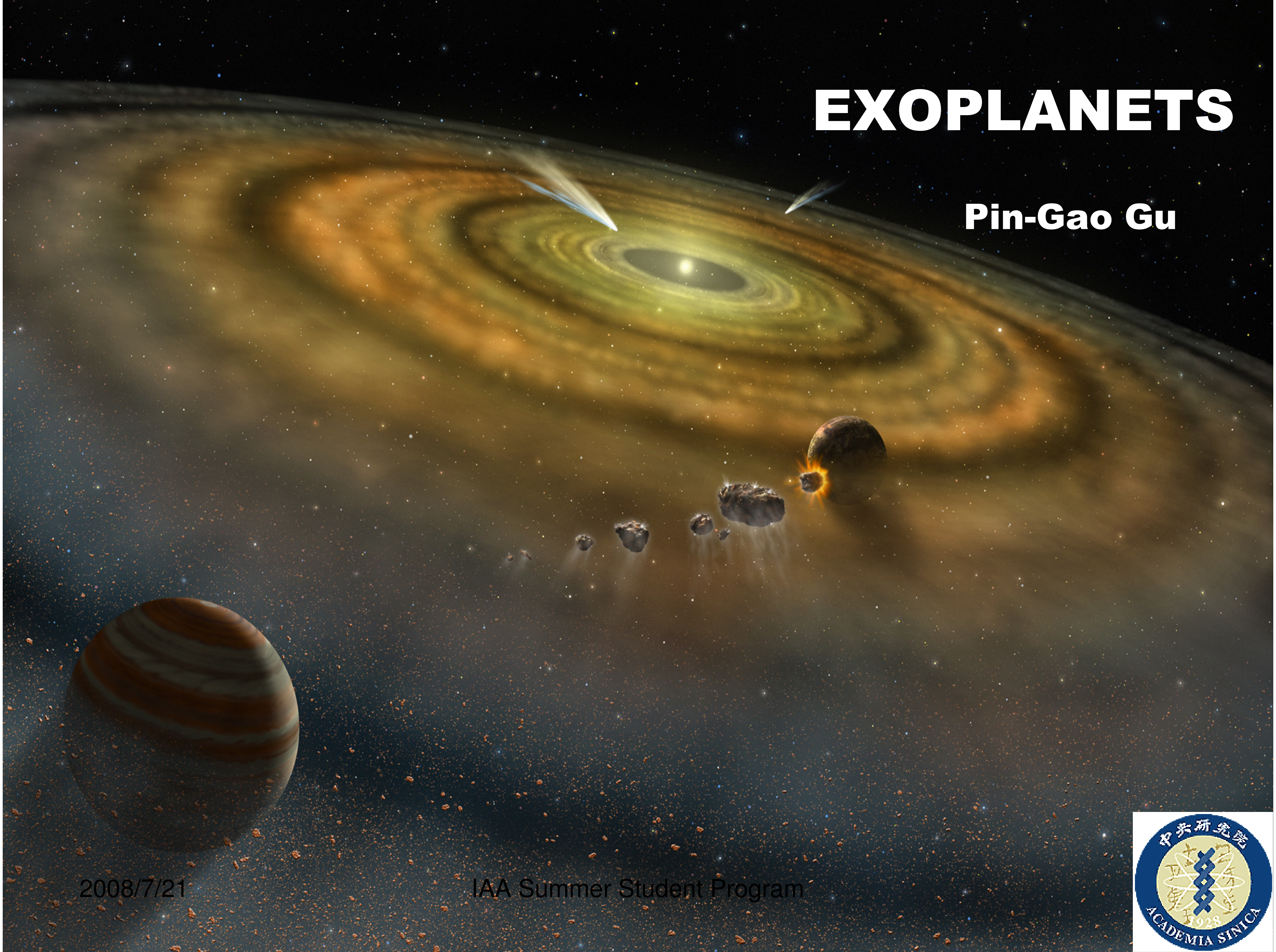
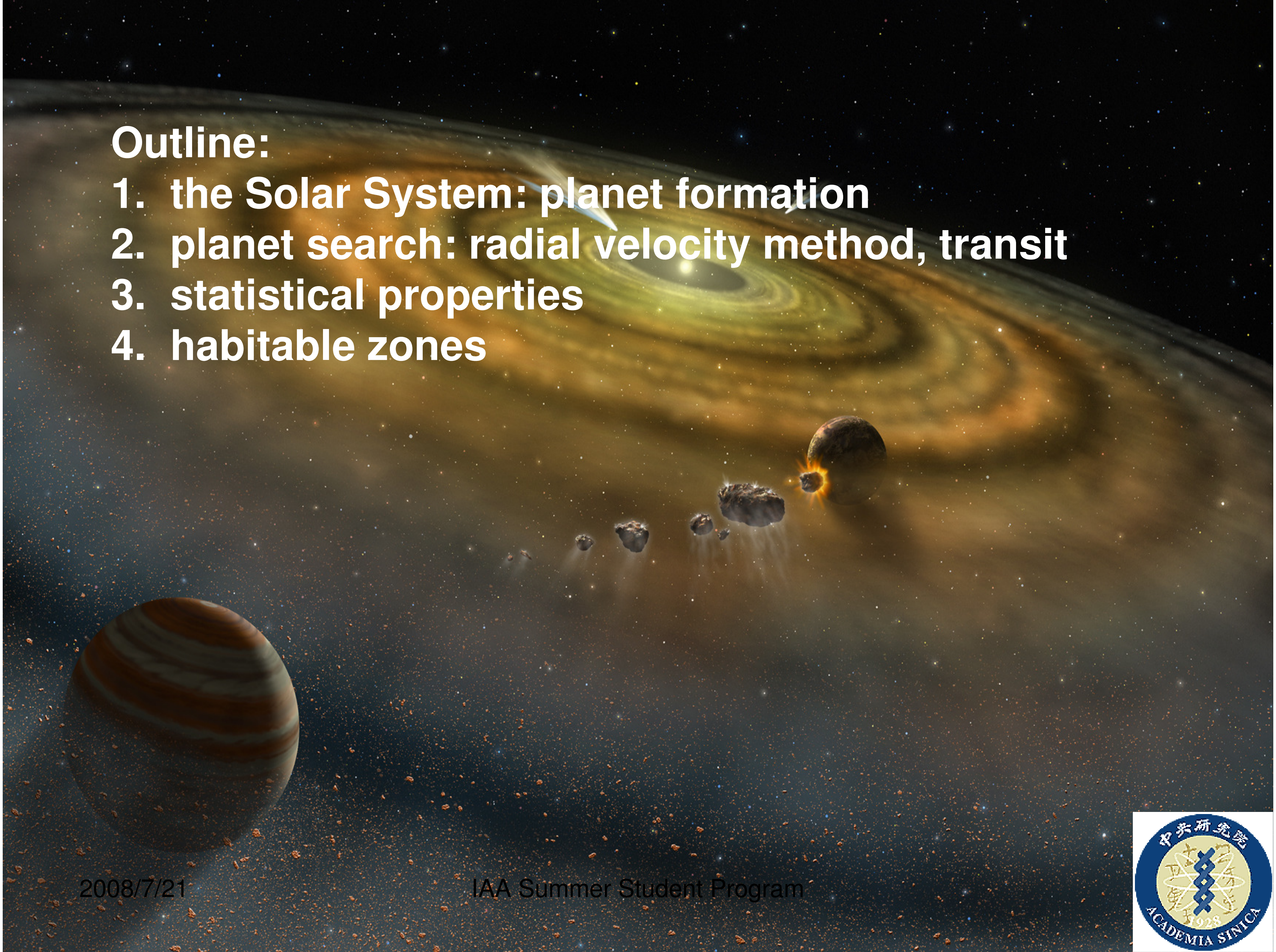


EXOPLANETS

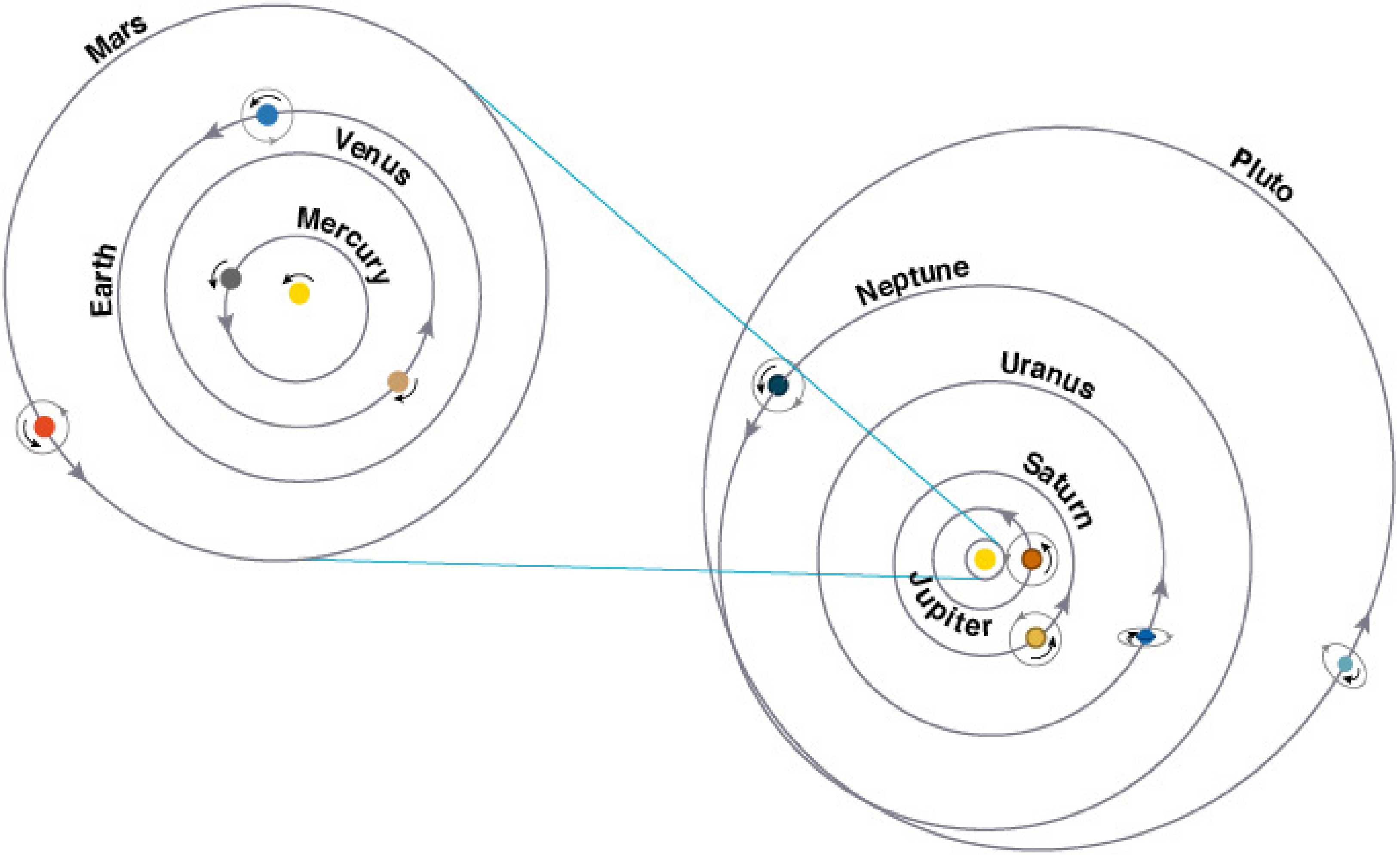
Pin-Gao Gu



Outline:

1. the Solar System: planet formation
2. planet search: radial velocity method, transit
3. statistical properties
4. habitable zones

Planets Revolve in Mostly Circular Orbits in Same Direction as Sun Spins



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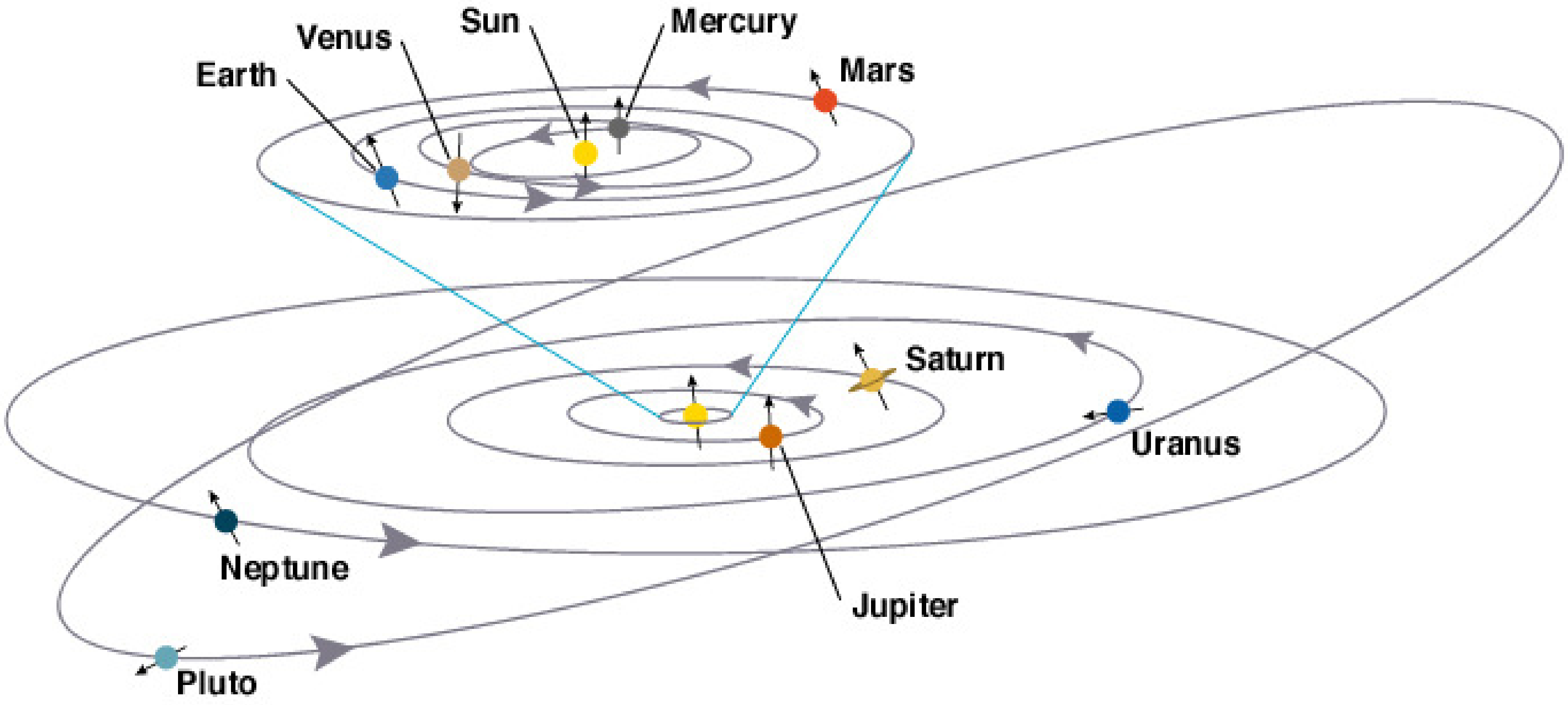
Planetary Orbits Nearly Lie in a Single Plane with Exception of Pluto & Mercury



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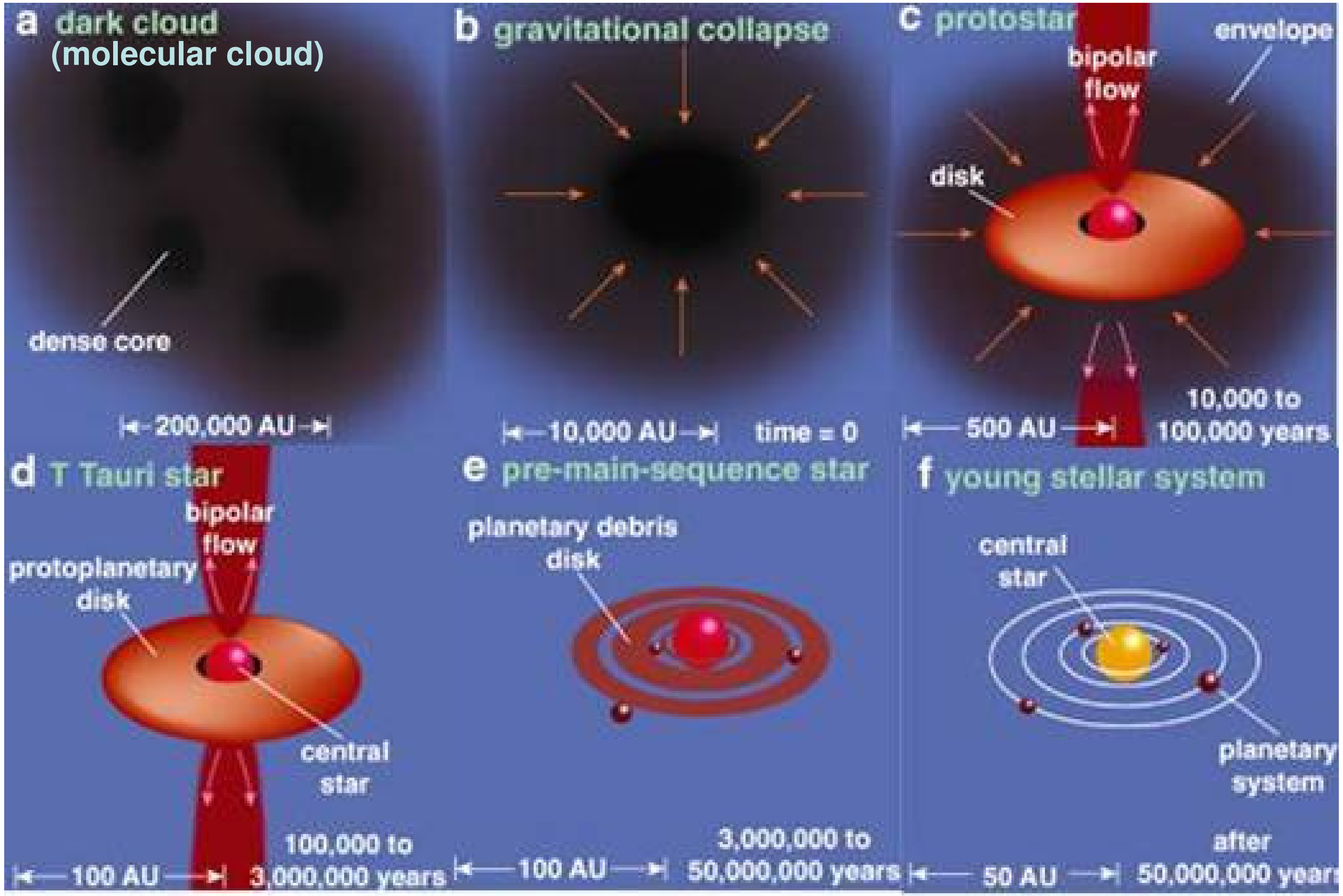
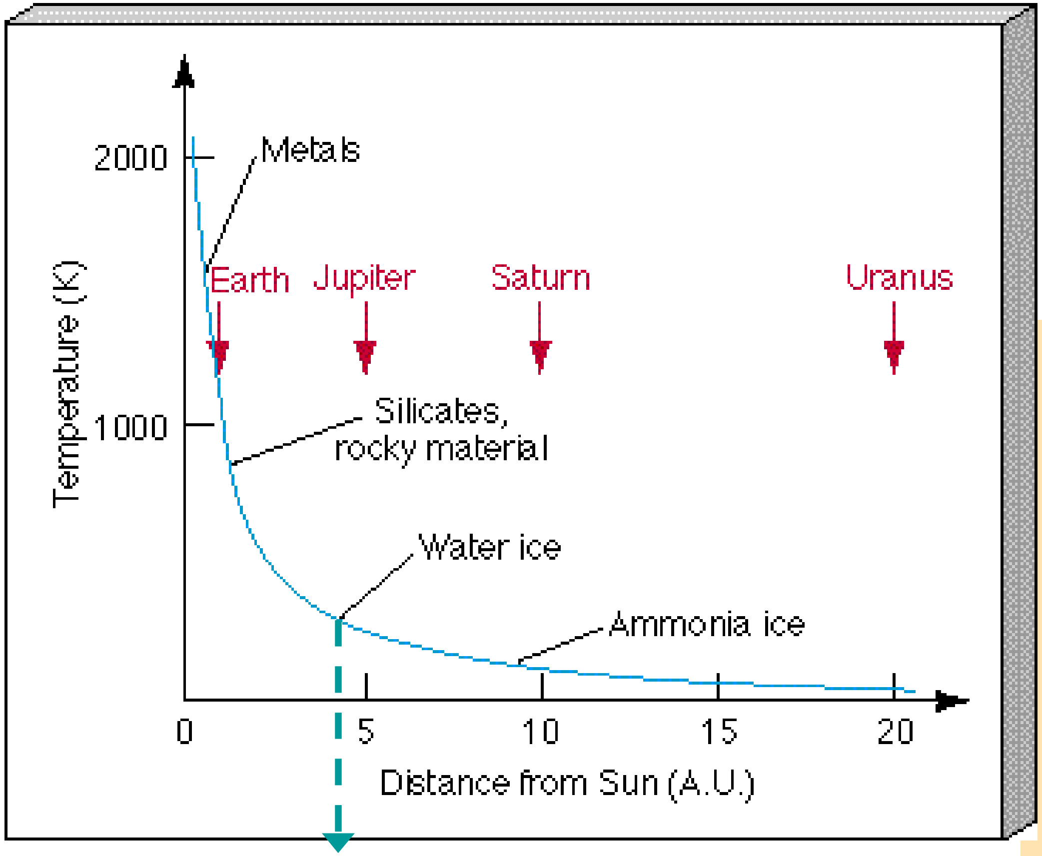
Formation of a solar-like star and possibly planets



http://ssc.spitzer.caltech.edu/documents/compendium/galsci/

AU = astronomical unit = distance between Sun & Earth

Condensation Sequence



snow line

http://ircamera.as.arizona.edu/astr_250/Lectures/Lec_21sml.htm
http://inverse.astro.uwo.ca/ast21/slides20/slide2.html

Planets form in a proto-planetary (proto-stellar) disk around a proto-star. What is the disk structure? → What is the planet made of?

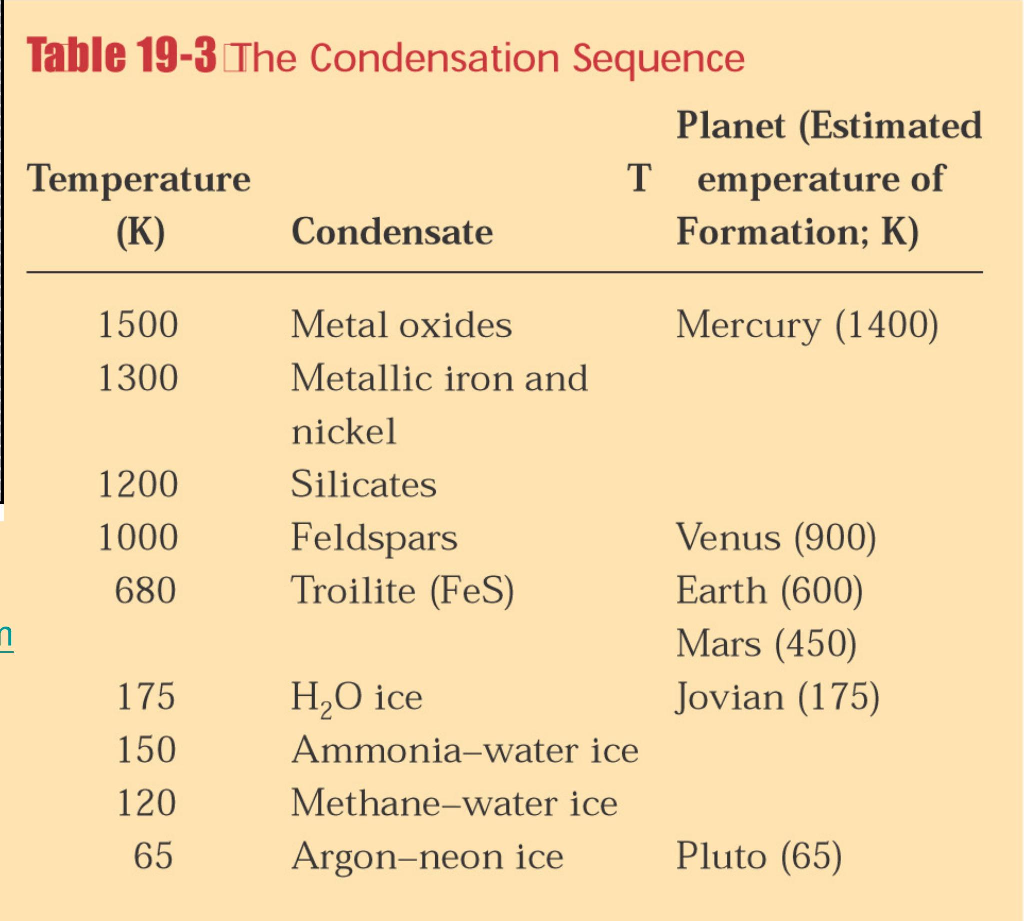


Table 19-3 The Condensation Sequence

Temperature (K)	Condensate	Planet (Estimated Temperature of Formation; K)
1500	Metal oxides	Mercury (1400)
1300	Metallic iron and nickel	
1200	Silicates	
1000	Feldspars	Venus (900)
680	Troilite (FeS)	Earth (600) Mars (450)
175	H_2O ice	Jovian (175)
150	Ammonia–water ice	
120	Methane–water ice	
65	Argon–neon ice	Pluto (65)

Minimum-mass Solar Nebula Model (Weidenschilling 1977; Hayashi 1981)

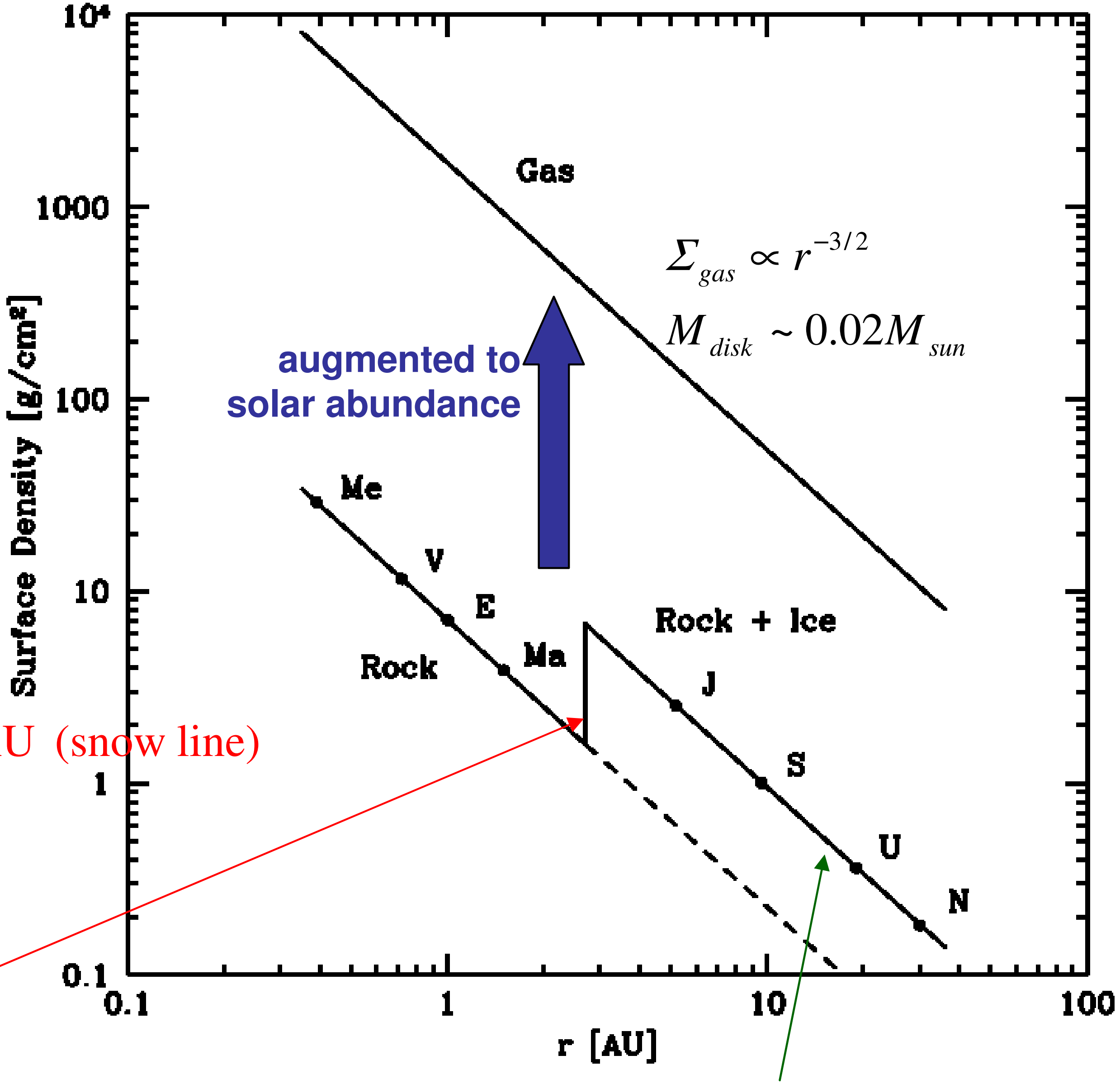
$$T = 280\left(\frac{r}{1\,\mathrm{AU}}\right)^{-1/2}\left(\frac{L_*}{L_{Sun}}\right)^{1/4}\mathrm{K}$$

$$T_{ice} \approx 170\mathrm{K} \Rightarrow r_{ice} \approx 2.7\left(\frac{L_*}{L_{Sun}}\right)^{1/2}\mathrm{AU}\ \ (\text{snow line})$$

$$\Sigma_d = f_d \eta_{ice} 10\left(\frac{r}{1\,\mathrm{AU}}\right)^{-3/2}\ \mathrm{g/cm^3}$$

$\eta_{ice} = 1$ when $r < r_{ice}$

$\eta_{ice} \approx 3 \sim 4$ when $r > r_{ice}$



$\Sigma_{gas} \propto r^{-3/2}$

$M_{disk} \sim 0.02 M_{sun}$

augmented to solar abundance

Assume J, S, U, N each contributes 15 earth masses.

Disk Masses

Beckwith & Sargent 1996

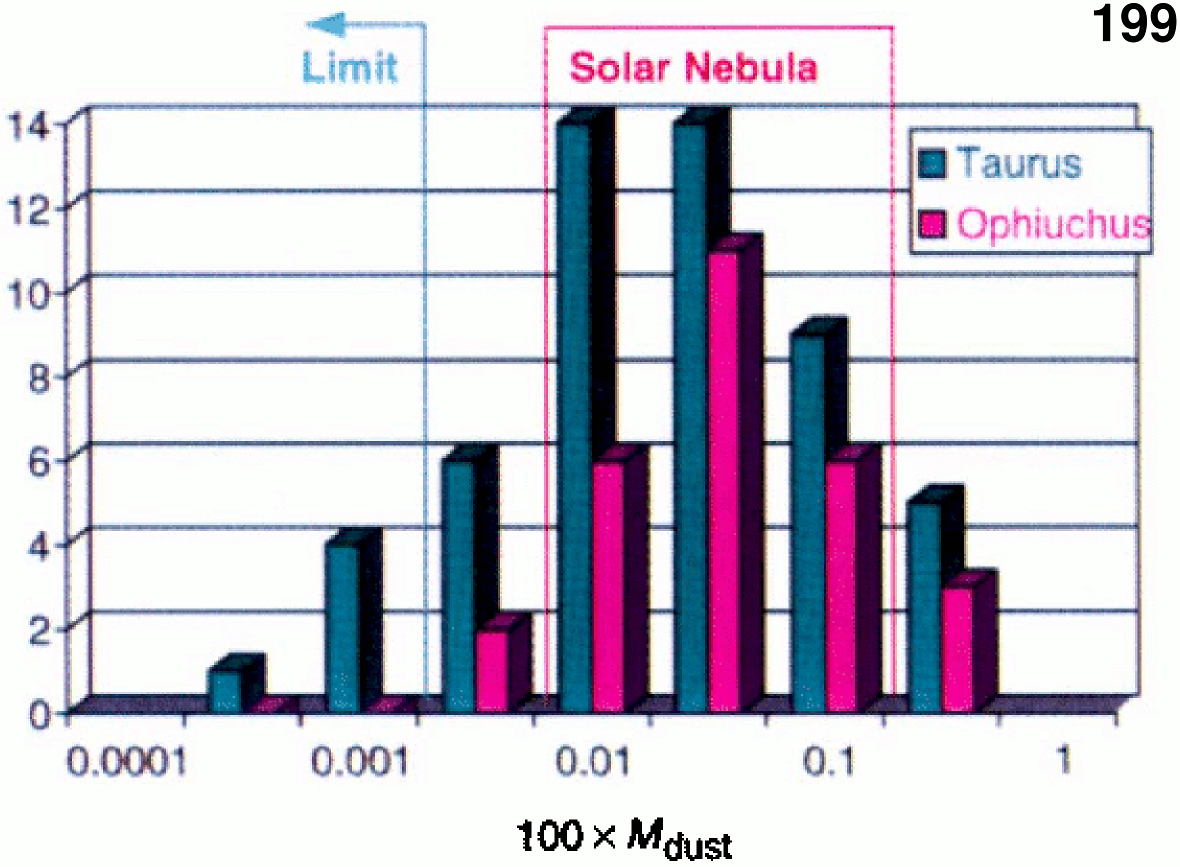


FIG. 5 Distribution of disk gas masses 100 × M_{dust} (in solar masses) for two samples of stars in the dark clouds in Taurus[15,35] and Ophiuchus[36]. The red box denotes the range of estimates for the mass of the primitive solar nebular before the planets were created. 'Limit' refers to the smallest mass than can be reliably observed.

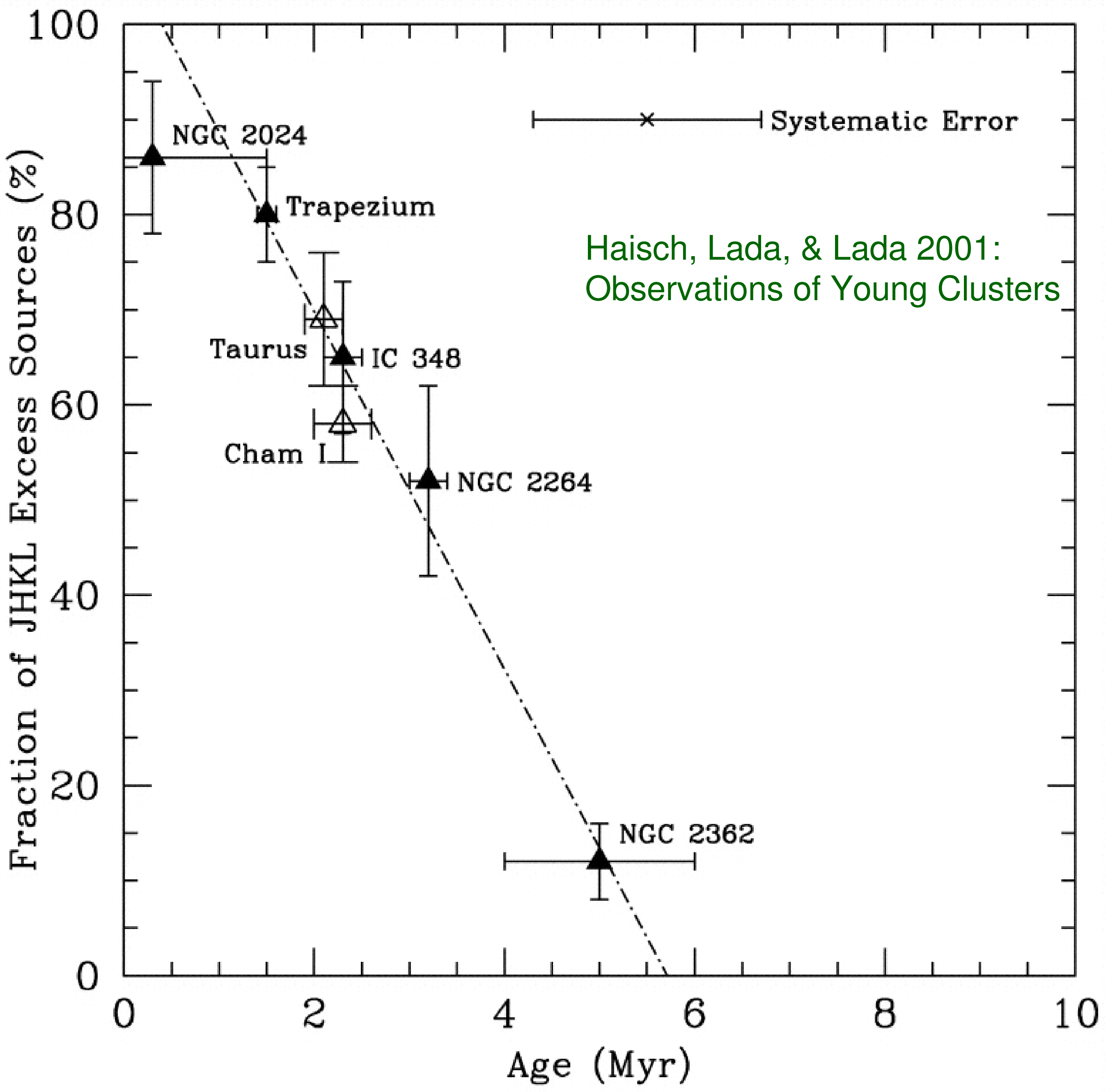
Depletion of protostellar disks

Near-Infrared excess comes from micron-sized, hot (about 900K) dust grains.

This may imply that planets form in ~ a few million years.

c.f. solar-type stars spend Gyrs on main sequence.

Causes: accretion, evaporation?



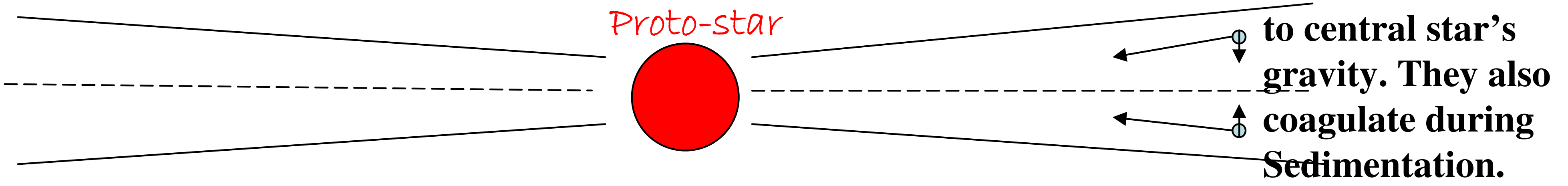
Haisch, Lada, & Lada 2001: Observations of Young Clusters

Disk as a planet factory

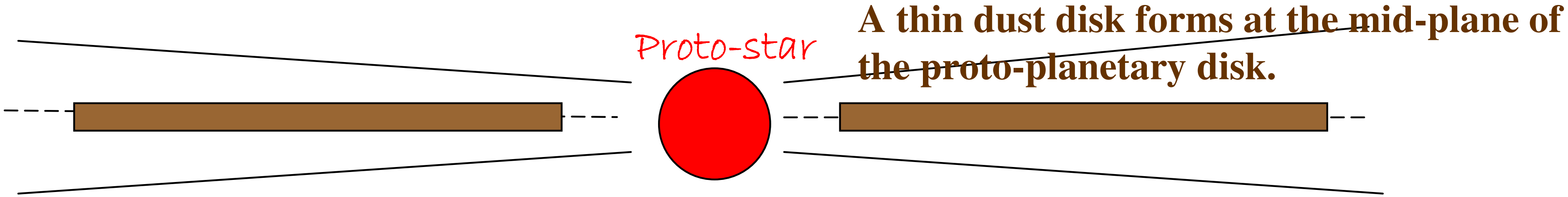
- In a proto-planetary disk: dust grains (micron-sized, coupled with gas) → planetesimals (km-sized, decoupled from gas & move in a Keplerian orbit) → planets, asteroids, comets, interplanetary dusts (debris disk)
- Other possibilities: giant planets form like stars via gravitational collapse in a molecular cloud (free-floating planets) or in a disk?

micron-sized dusts (塵埃) → km-sized planetesimals (星子)

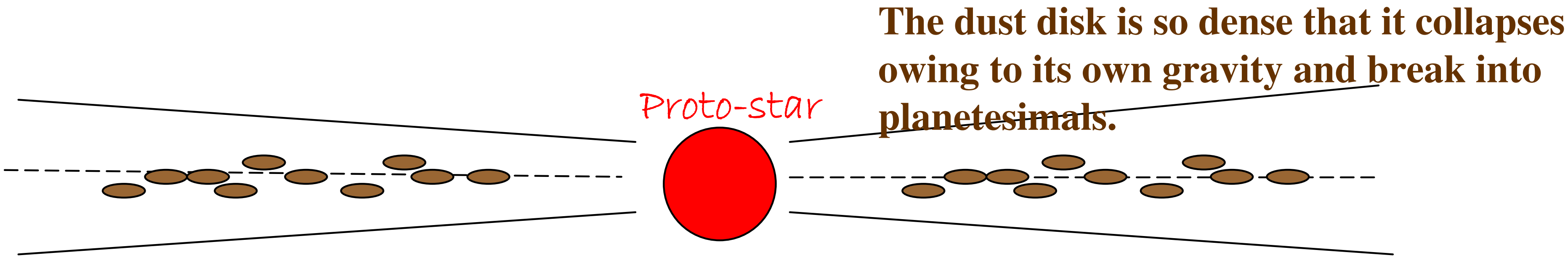
not well understood, but here is one popular scenario:



Dusts sediment due to central star’s gravity. They also coagulate during Sedimentation.



A thin dust disk forms at the mid-plane of the proto-planetary disk.



The dust disk is so dense that it collapses owing to its own gravity and break into planetesimals.

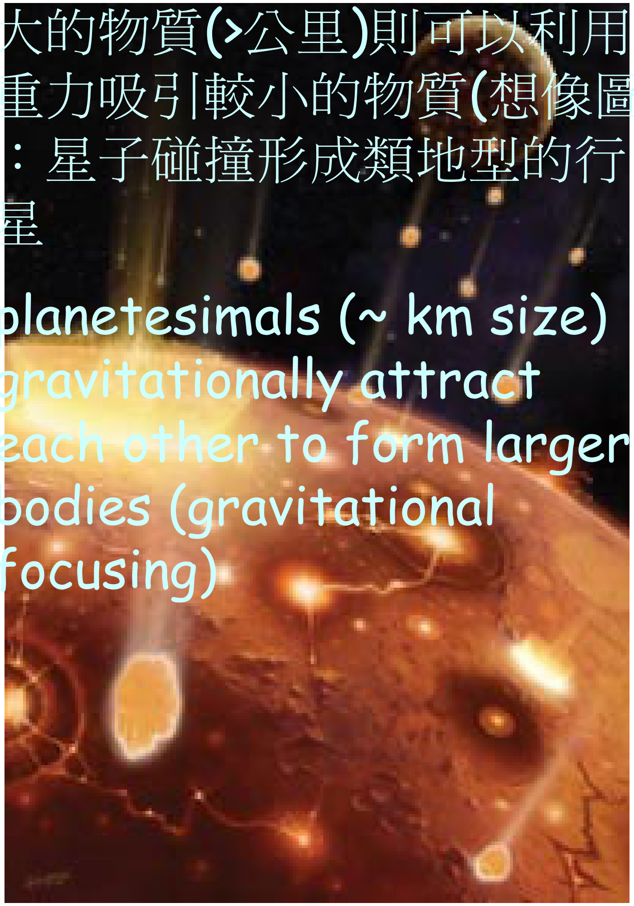
行星系統的形成：由小而大 (planet formation: small → large)

小物質相撞結合成大物質(想像圖)

正誕生的恆星

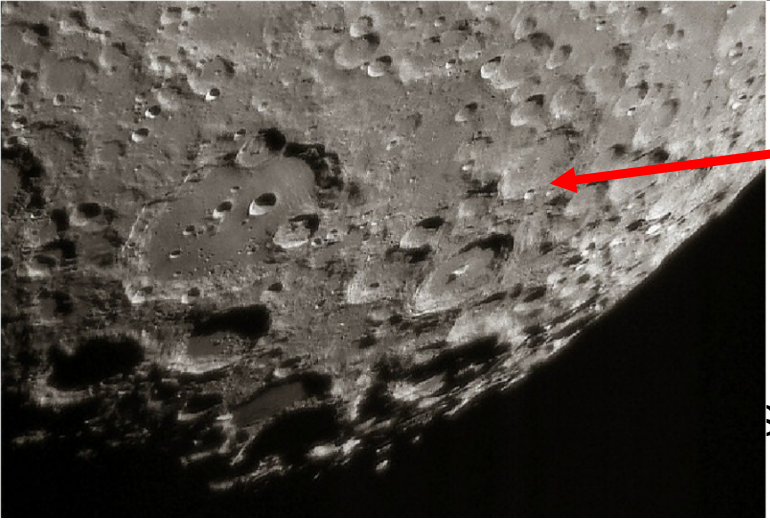
Young star at the center of a nascent disk

微米塵埃 (micron size)
→ 公分 (cm size)
→公里 km size (星子 planetesimal：小行星 asteroid、慧星 comet)



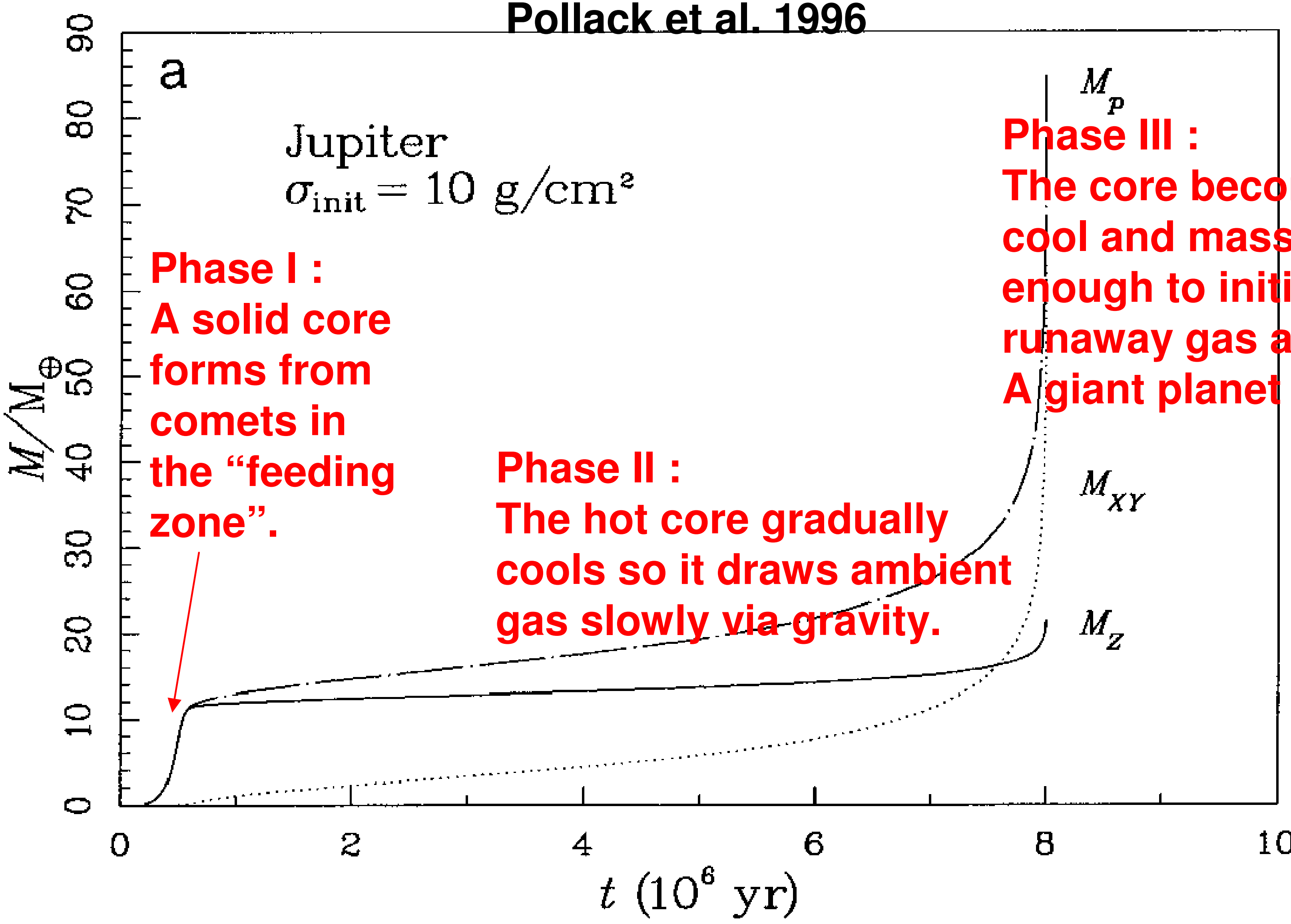
大的物質(>公里)則可以利用重力吸引較小的物質(想像圖)：星子碰撞形成類地型的行星

planetesimals (~ km size) gravitationally attract each other to form larger bodies (gravitational focusing)



證據：
月球隕石坑大部分在38億年前形成
proof: most of the moon craters formed 3.8 billion years ago.

Formation of a giant planet



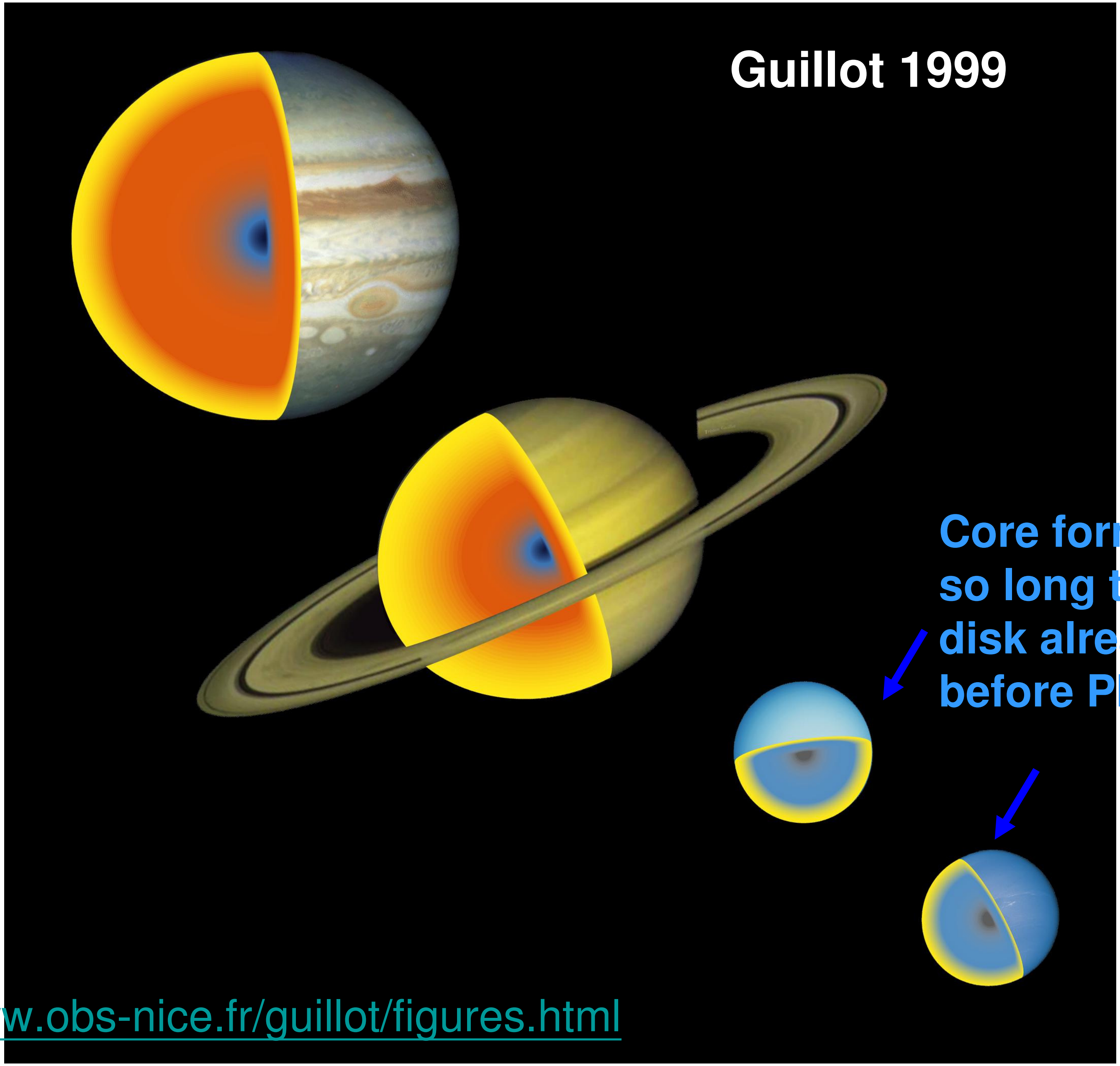
Pollack et al. 1996

Phase I :
A solid core forms from comets in the “feeding zone”.

Phase II :
The hot core gradually cools so it draws ambient gas slowly via gravity.

Phase III :
The core becomes cool and massive enough to initiate a runaway gas accretion. A giant planet forms.

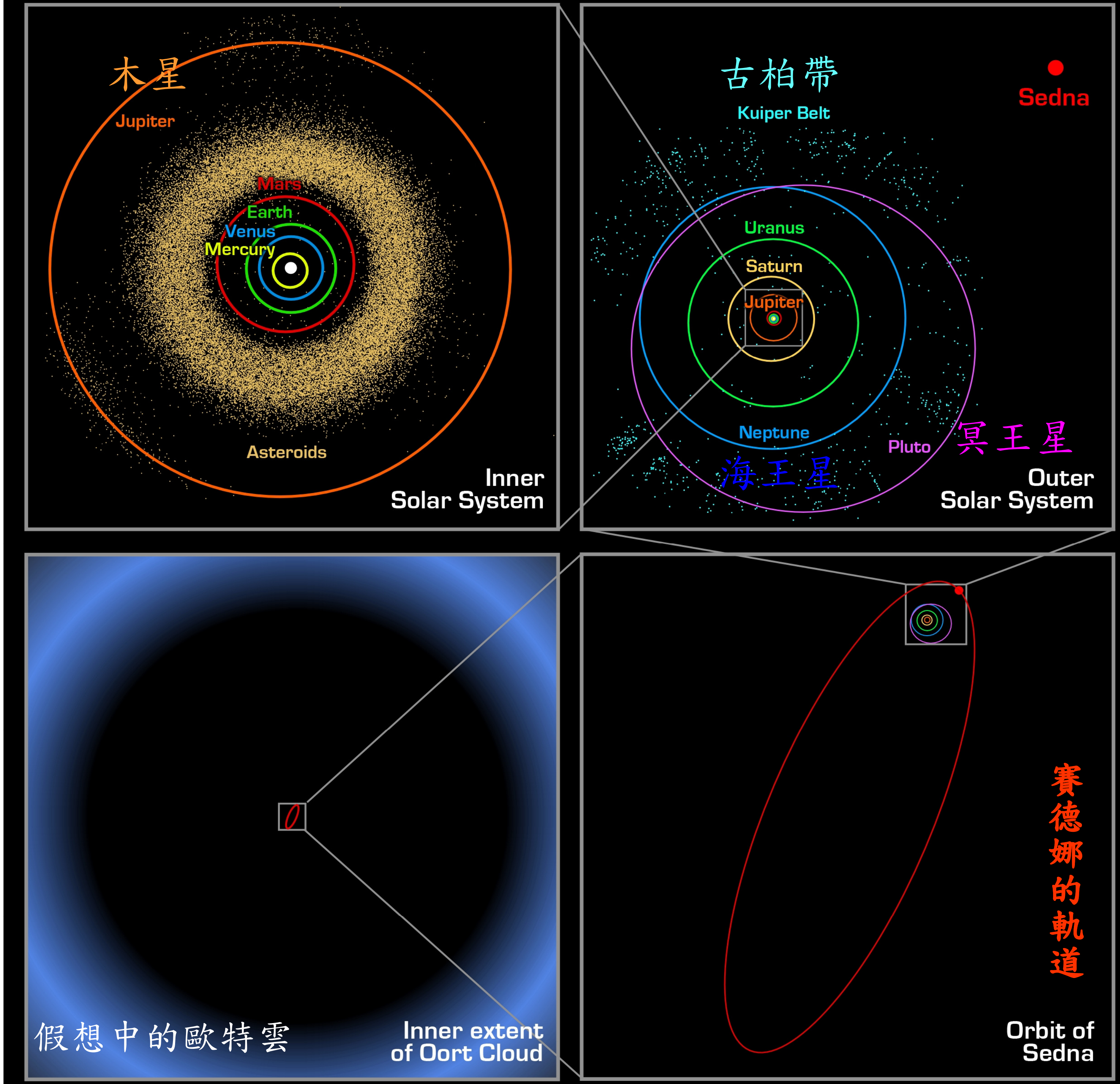
Interior structure of giant planets in the Solar System



Core formation takes so long that the gas disk already depletes before Phase III.

http://www.obs-nice.fr/guillot/figures.html

古柏帶 (Kuiper Belt):

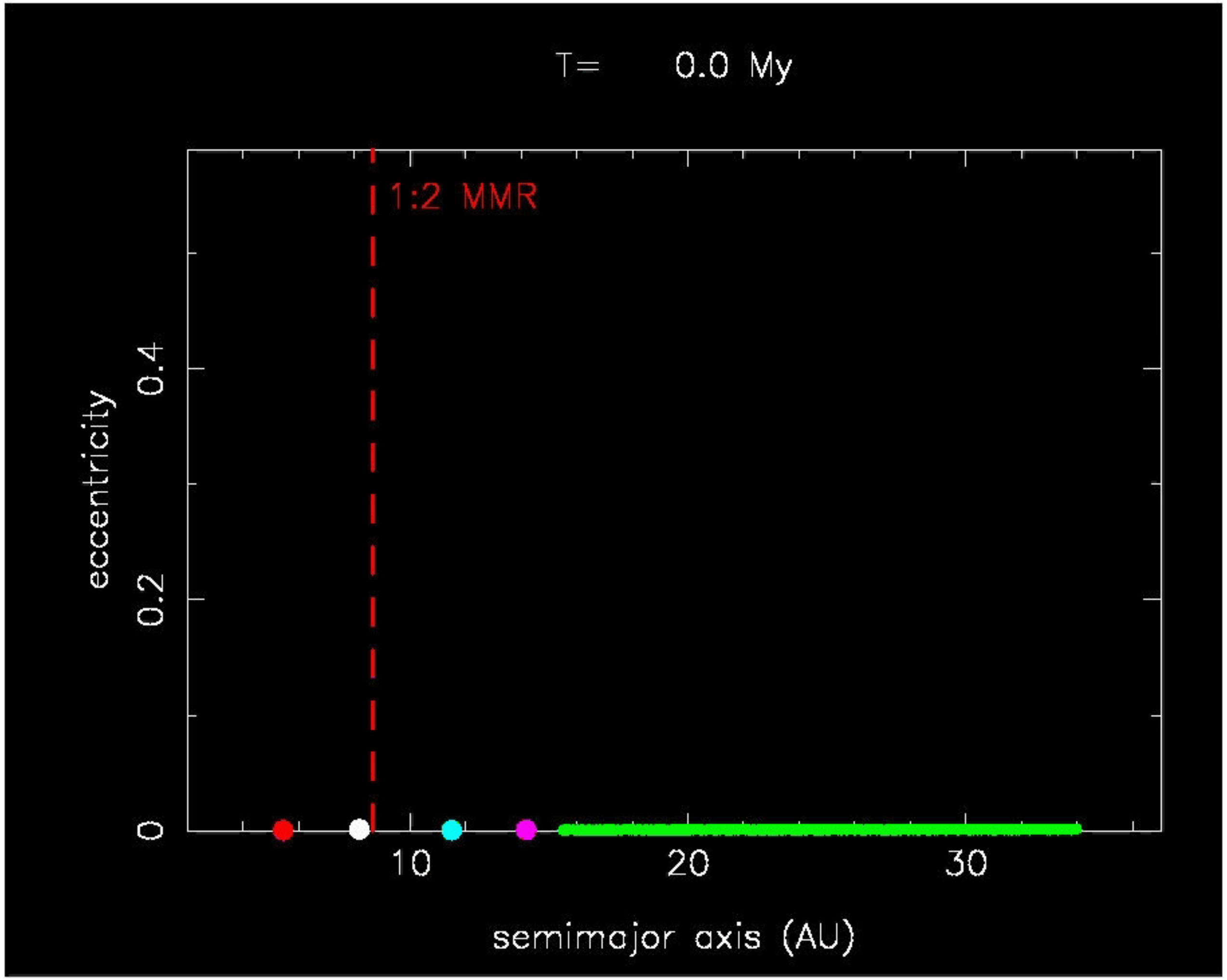


remnant of planetesimals which even fail to form a core. Kuiper predited that the Kuiper Belt Objects are the source of short-period comets. In other words, comets preserves the pristine materials in the early Solar System.

圖片來源:
http://www.gps.caltech.edu/~mbrown/

Planet migration in a planetesimal disk

- Plutino (3:2 orbital resonance with Neptune)
- Last heavy bombardment



Morbidelli's Simulation (direction of migration: distrib of panetesimals, transfer planetesimals among planets, massive planet Jupiter acts as a sink of planetesimals)

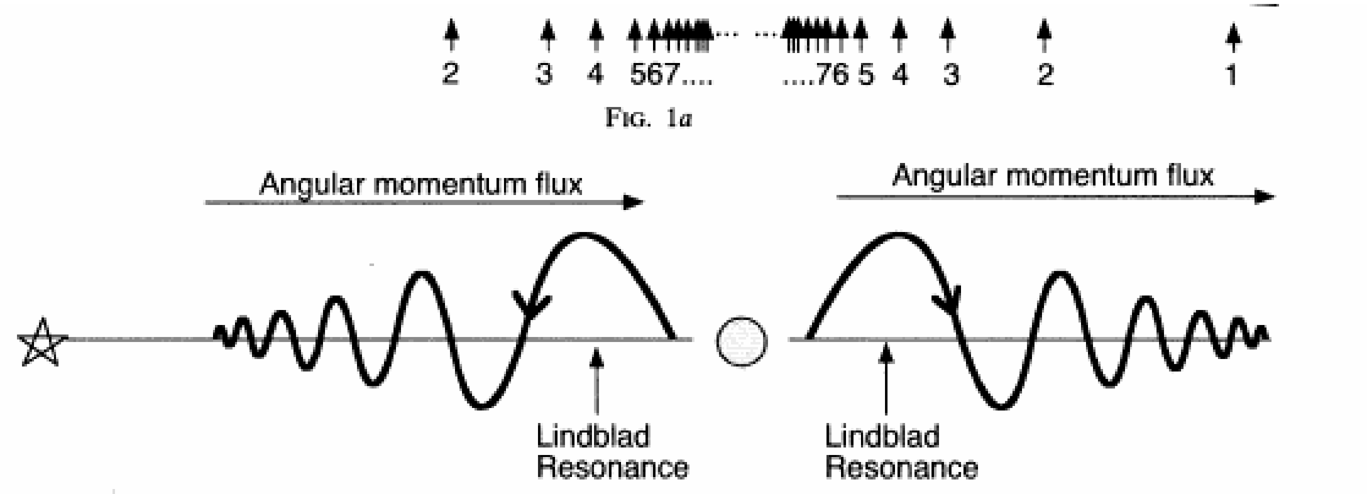
Formation of Oort cloud Objects with the aid of galactic tides on a very long timescale?

different minimum mass nebula model

However, this model requires an outer truncation of a planetesimal disk at ~ 35 AU. (c.f. Thommes)

Planet Migration in a gaseous disk

Type I (for earth-Neptune mass planets):



Linblad resonances $\kappa = m(\Omega - \Omega_p)$,
where κ **is the disk natural frequency (epicyclic frequency),** $(\Omega - \Omega_p)$ **is the planet forcing frequency viewed by the disk gas, and** m **is an integer.**

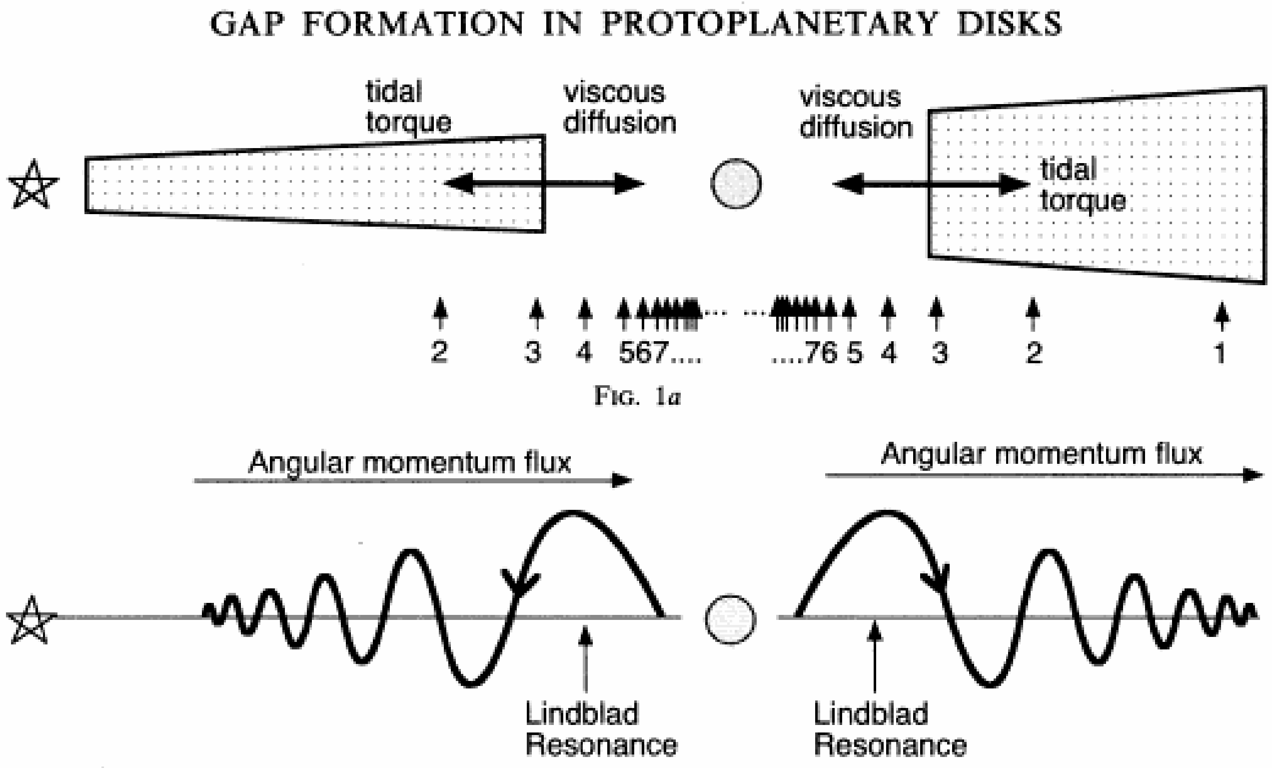
Outer Linblad resonances are closer to the planet than Inner Linblad resonances → inward migration

Problem: inward migration time scale << disk lifetime

However, type I migration might be slowed down in some disk conditions (e.g. turbulent disk, adiabatic horseshoe orbit, steep change of radial density such as ice line and disk edge).

Planet Migration in a gaseous disk

Type II (for giant planets):



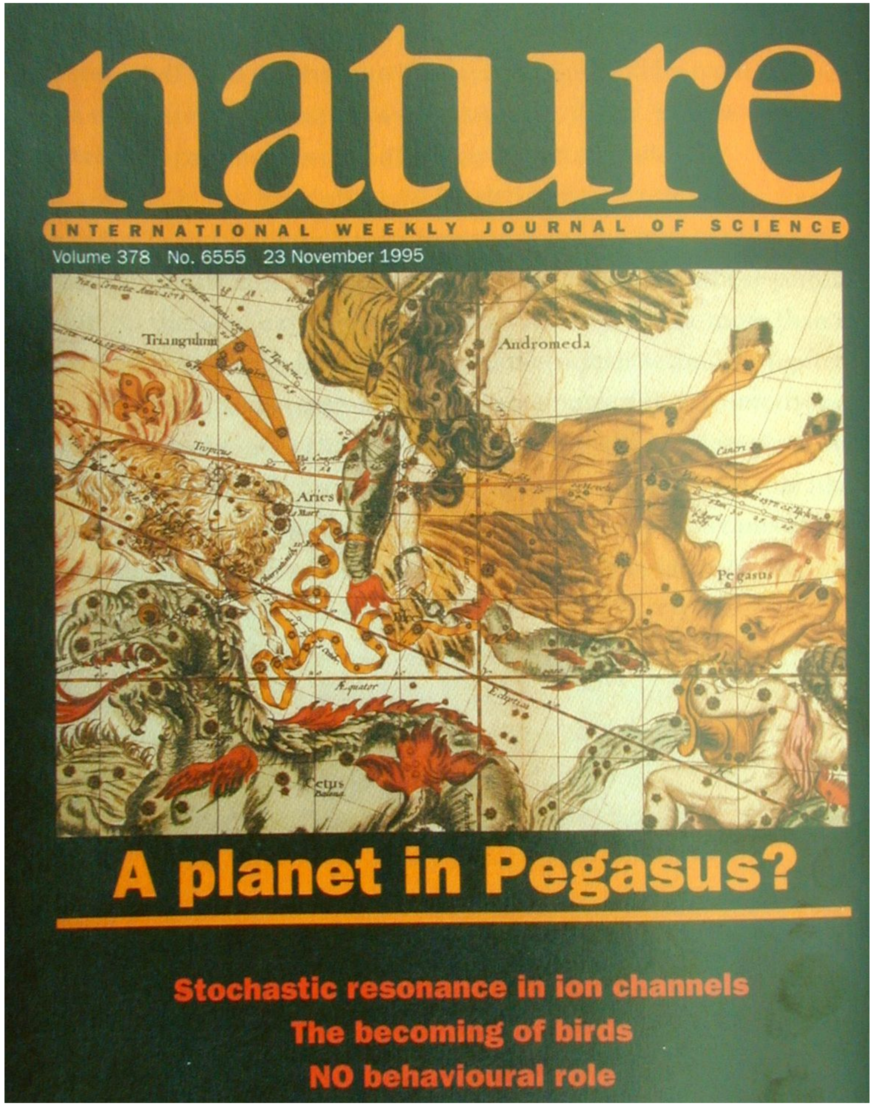
GAP FORMATION IN PROTOPLANETARY DISKS

FIG. 1*a*

Linblad resonances $\kappa = m(\Omega - \Omega_p)$

A giant planet opens a gap. The interaction is not so strong → the giant planet becomes part of the disk → inward migration time scale ~ disk diffusion time scale~ disk lifetime

First Planet discovered around a Sun-like star
(Mayor & Queloz 1995)



nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 378 No. 6555 23 November 1995

A planet in Pegasus?

Stochastic resonance in ion channels

The becoming of birds

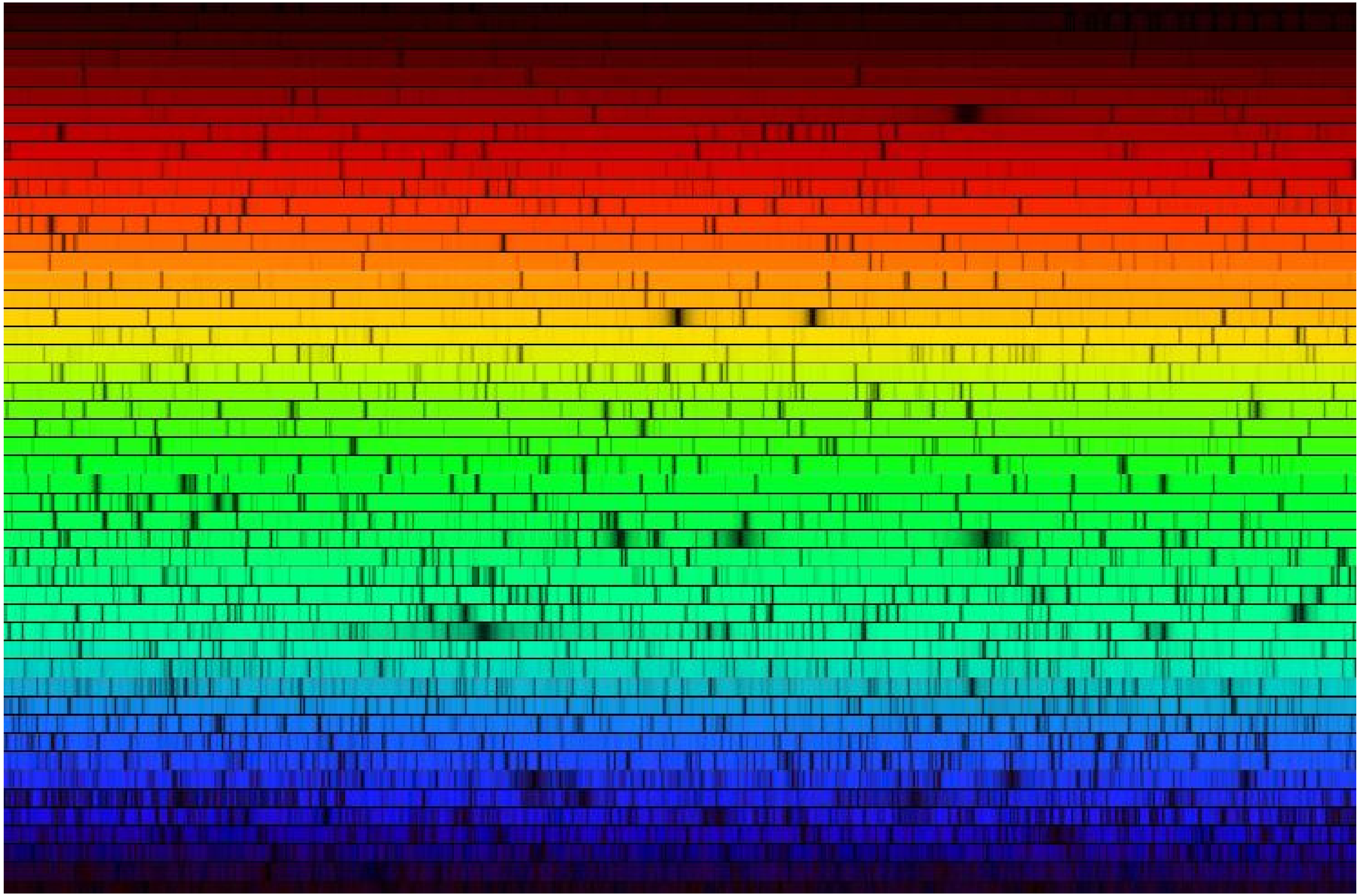
NO behavioural role

51 Pegasi
(50 ly away)

Can you see the planet?

Solar Spectrum

absorption lines: light of specific freq absorbed by elements in cool atmosphere



Planet search：radial velocity method

search strategy

☐ sun-like stars

☐ not in close binaries

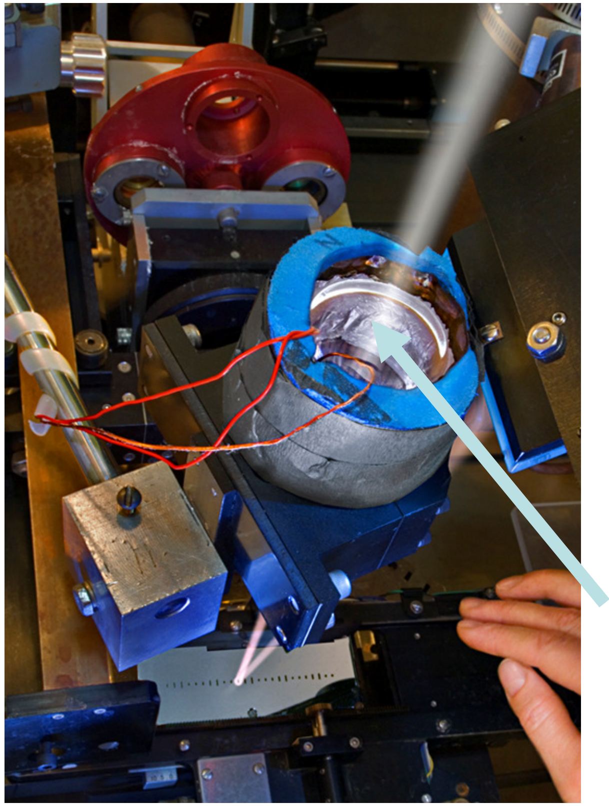
animation:

Doppler shift $\Delta\lambda / \lambda \approx v/c$

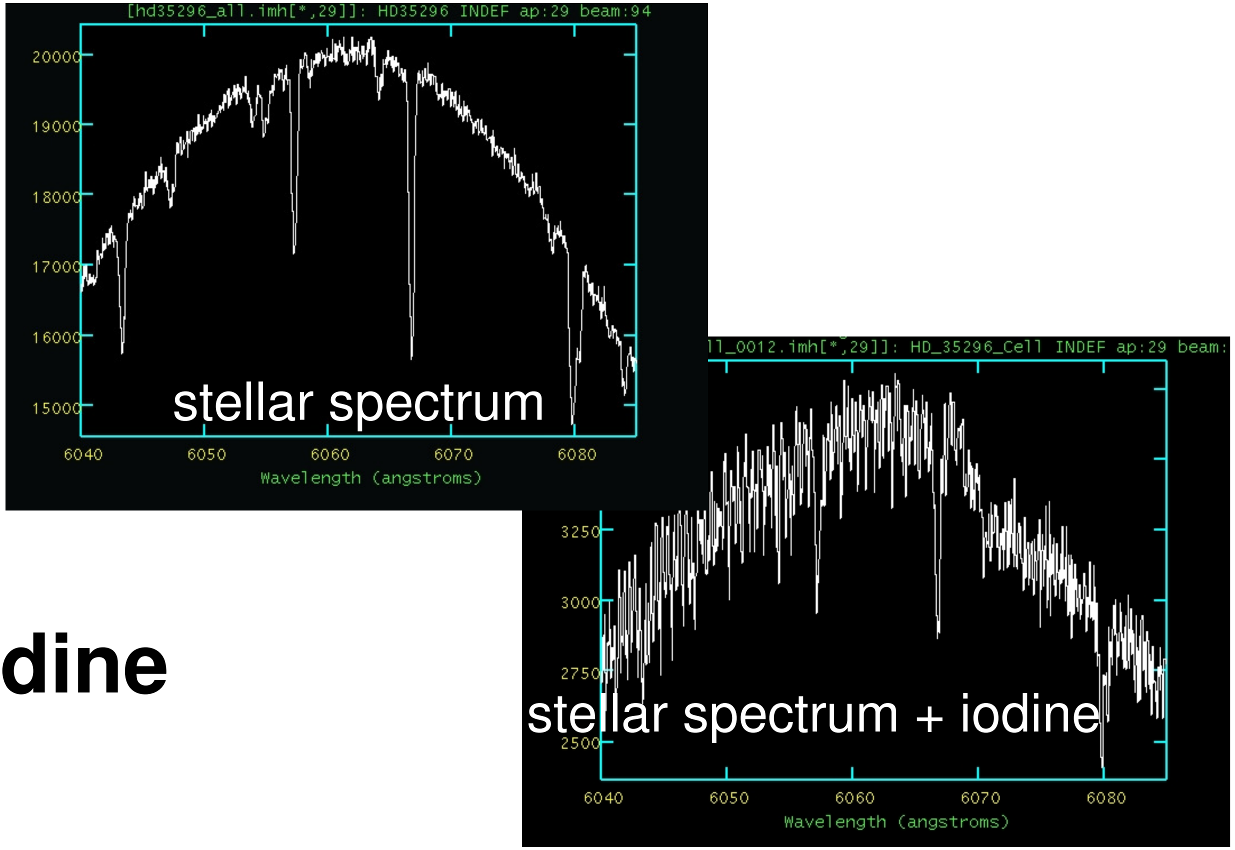
c.f. Jupiter → $V_{Sun} = 3$ m/s

Earth → $V_{Sun} = 0.01$ m/s

current record： $V_{star} \lesssim 1$ m/s



iodine



Hertzprung-Russell Diagram

Tells us about
the evolution
of a star, a nuclear
process depending
on the stellar mass.

Radial-velocity search focuses mainly on nearby FGKM stars on the main-sequence.

Searches around sub-giants and G-giants are also underway.

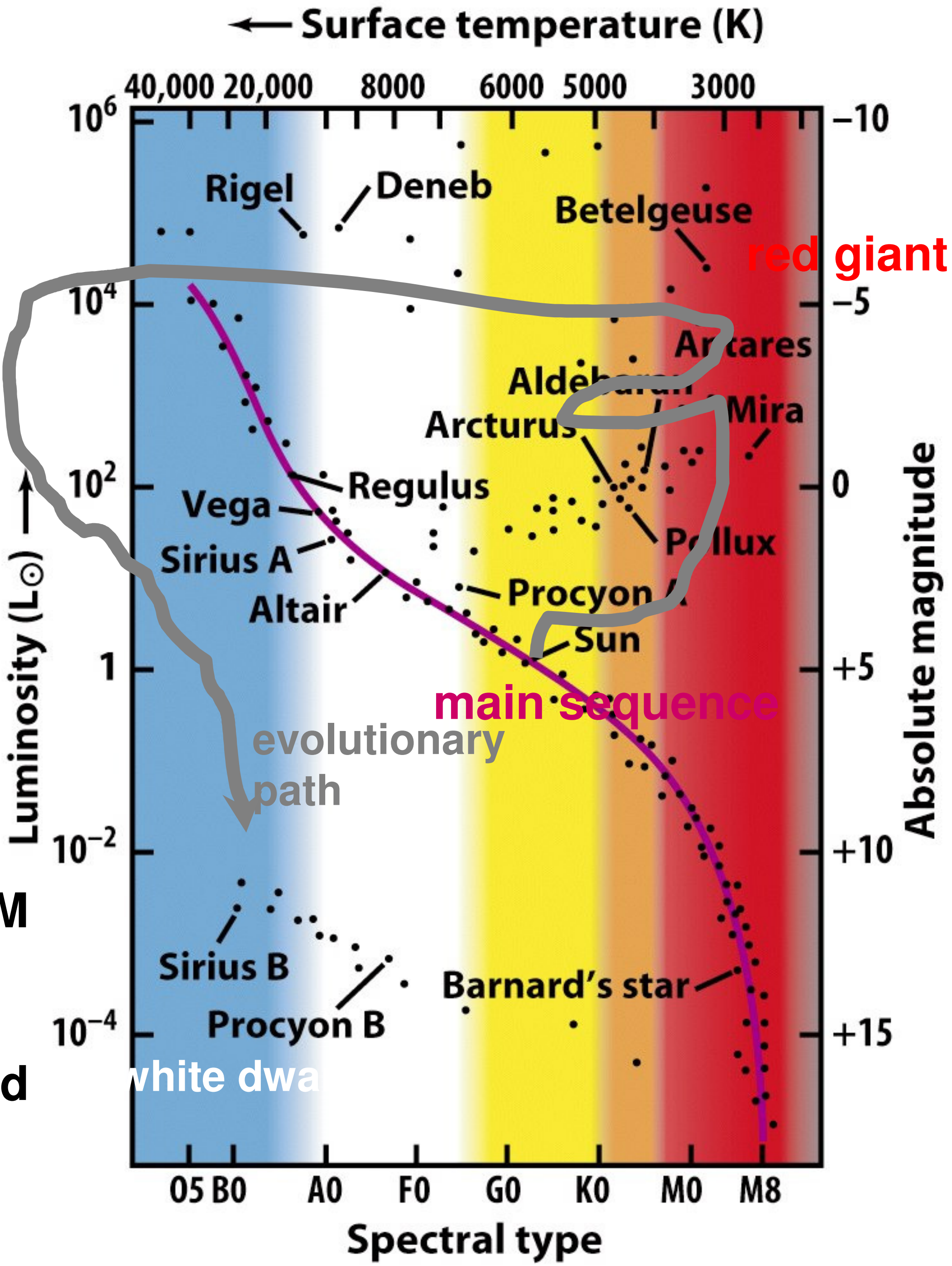
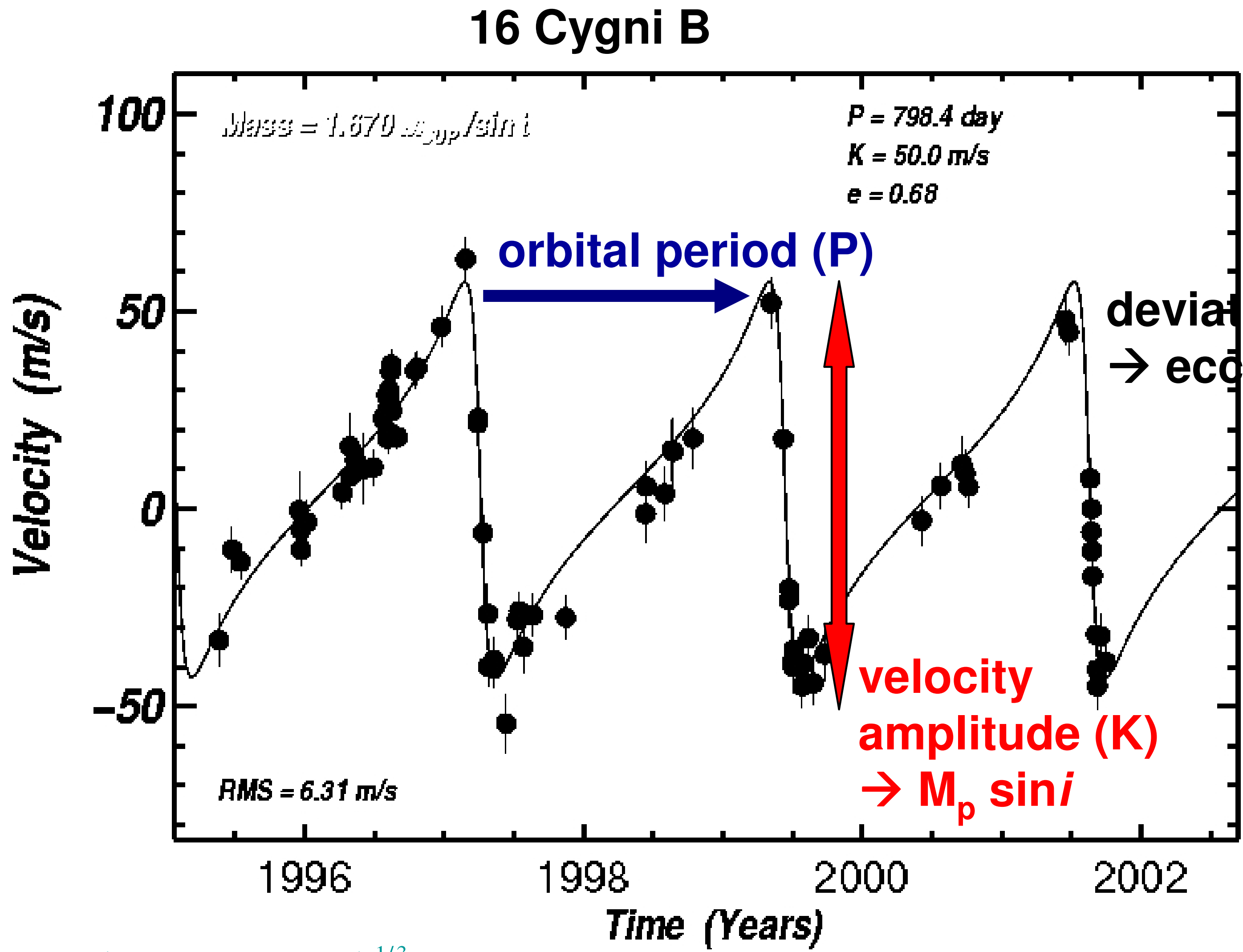


Figure 11-7
Discovering the Universe, Seventh Edition
© 2006 W. H. Freeman and Company

Radial Velocity Curve



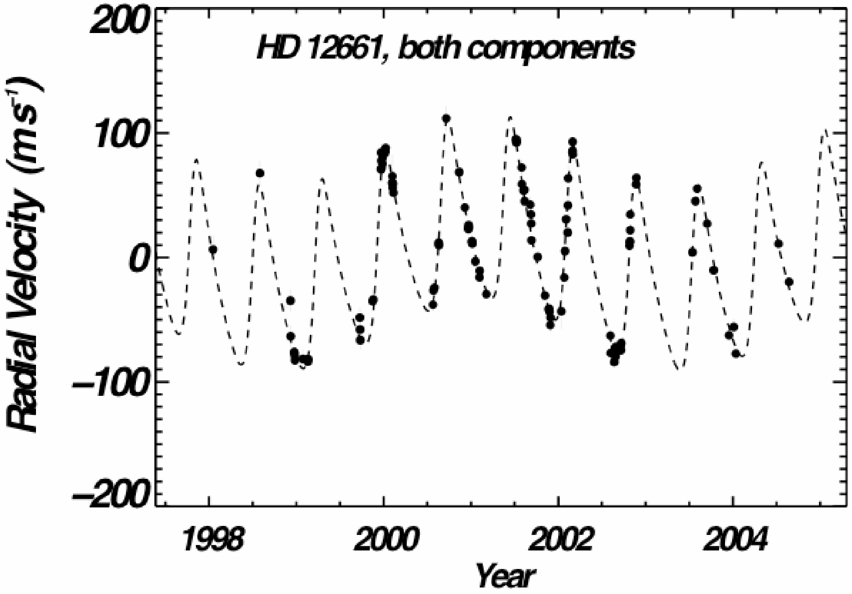
orbital period (P)

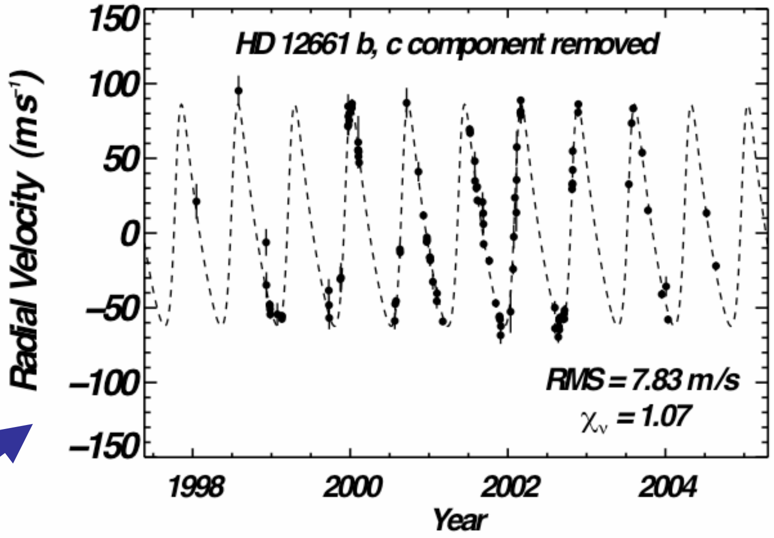
deviate from sinusoidal → eccentricity (e)

velocity amplitude (K) → $M_p \sin i$

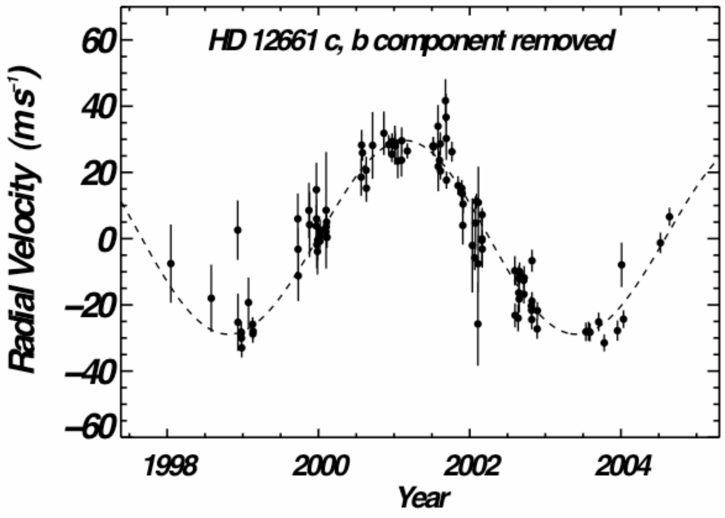
$$K = \frac{M_p \sin i}{M_* + M_p}\left(\frac{2\pi G(M_* + M_P)}{P}\right)^{1/3}\left(1-e^2\right)^{-1/2}, \text{ where } i \text{ is the inclination angle } (=0^\circ : \text{face on}; =90^\circ : \text{edge on}).$$

Evidence for A Multi-Planet System





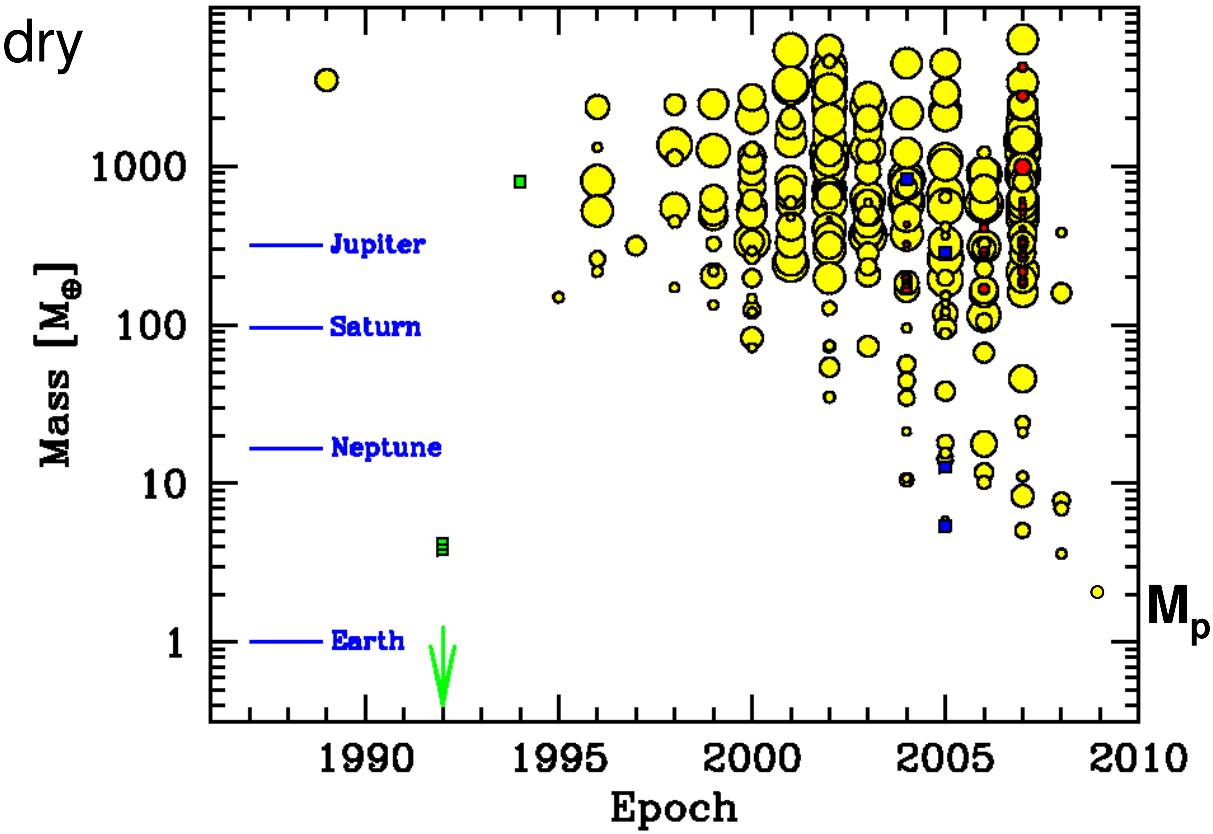
262d
$2.5M_{Jup}$



4.6y
$1.9M_{Jup}$

Discovery History

Mayor & Udry
2008



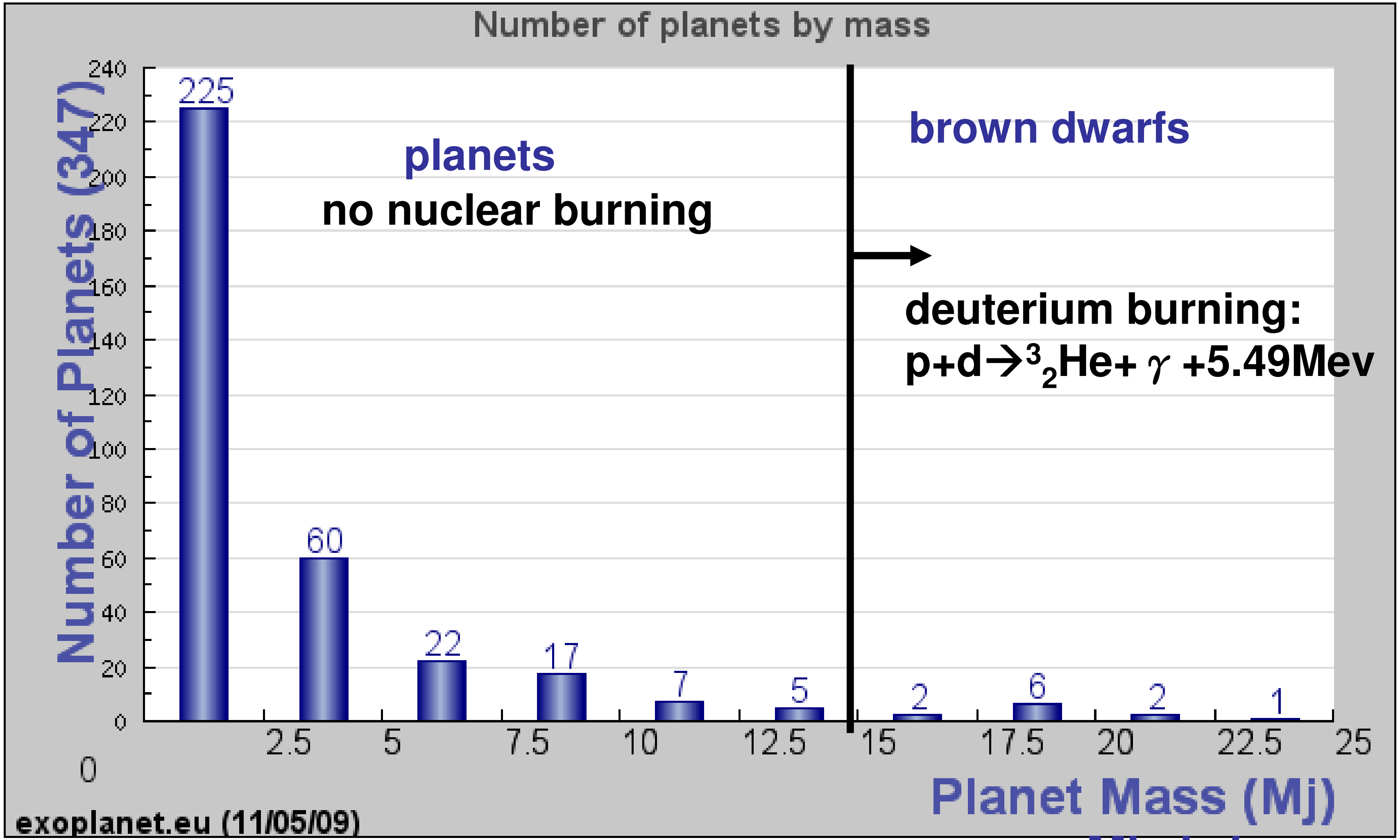
more than 300 exoplanets have been discovered

$M_p\sin i = 1.9\ M_\oplus$

Figure 1. Masses of detected exoplanets as a function of the year of discovery. The planets orbiting a neutron star (1992) or detected by microlensing (~2005) are represented by squares, transiting planets by dark filled circles, and the most numerous exoplanets discovered by Doppler spectroscopy by open circles having radii proportional to their orbital eccentricities. The lower envelope illustrates the continuous progresses of the spectrograph sensitivity. Since a few years, we have entered the era of super-Earth detections

Brown dwarf desert

Different formation mechanism between planets & brown dwarfs around FGKM dwarf stars?



exoplanet.eu (11/05/09)

planets

no nuclear burning

brown dwarfs

deuterium burning:

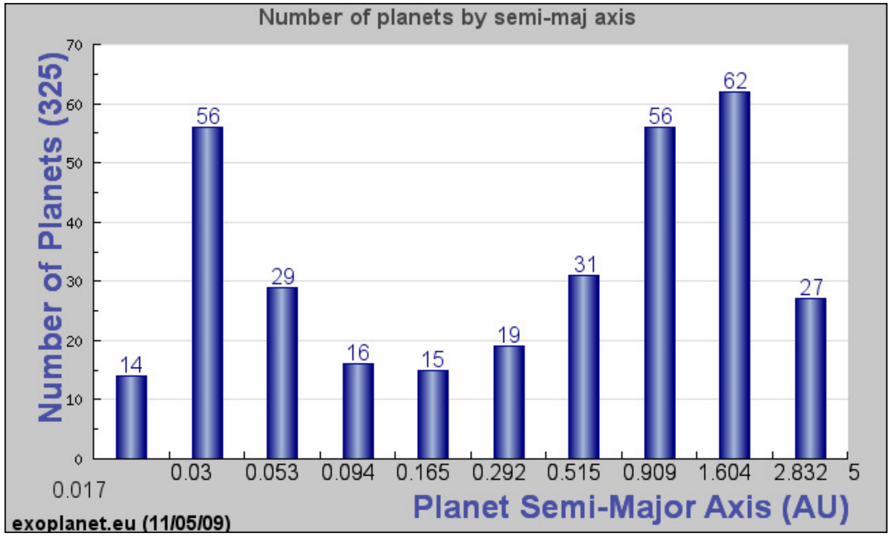
$p+d \rightarrow {}^{3}_{2}He + \gamma$ +5.49Mev

Planet Mass (Mj)

Mj sin*i*

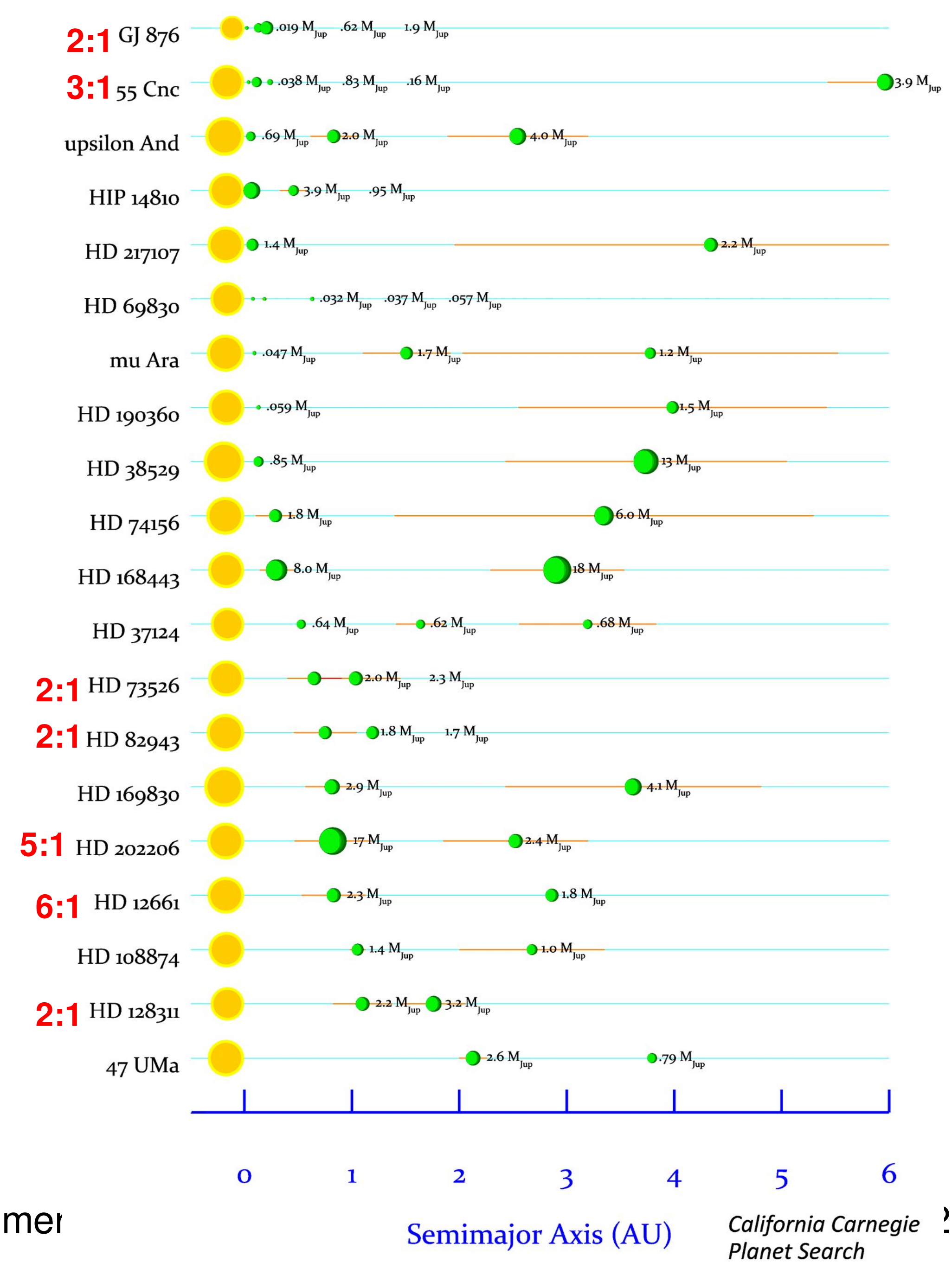
Evidence hints the migration theory

most are Jupiter-mass planets



exoplanet.eu (11/05/09)

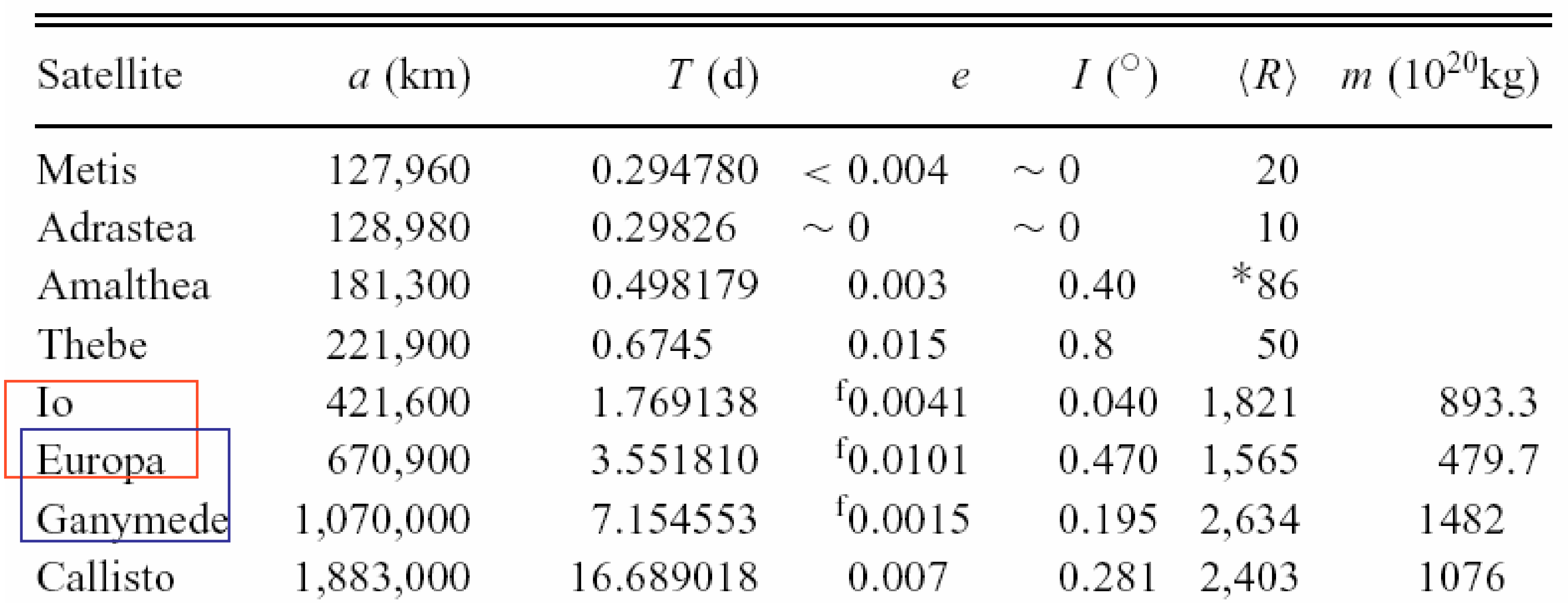
Some of the known multi-planet systems



California Carnegie Planet Search

Is our solar system special?
It takes time to know…

The Jupiter System



Satellite	a (km)	T (d)	e	I (°)	$\langle R \rangle$	m (10^{20}kg)
Metis	127,960	0.294780	< 0.004	~ 0	20	
Adrastea	128,980	0.29826	~ 0	~ 0	10	
Amalthea	181,300	0.498179	0.003	0.40	*86	
Thebe	221,900	0.6745	0.015	0.8	50	
Io	421,600	1.769138	^{f}0.0041	0.040	1,821	893.3
Europa	670,900	3.551810	^{f}0.0101	0.470	1,565	479.7
Ganymede	1,070,000	7.154553	^{f}0.0015	0.195	2,634	1482
Callisto	1,883,000	16.689018	0.007	0.281	2,403	1076

2:1

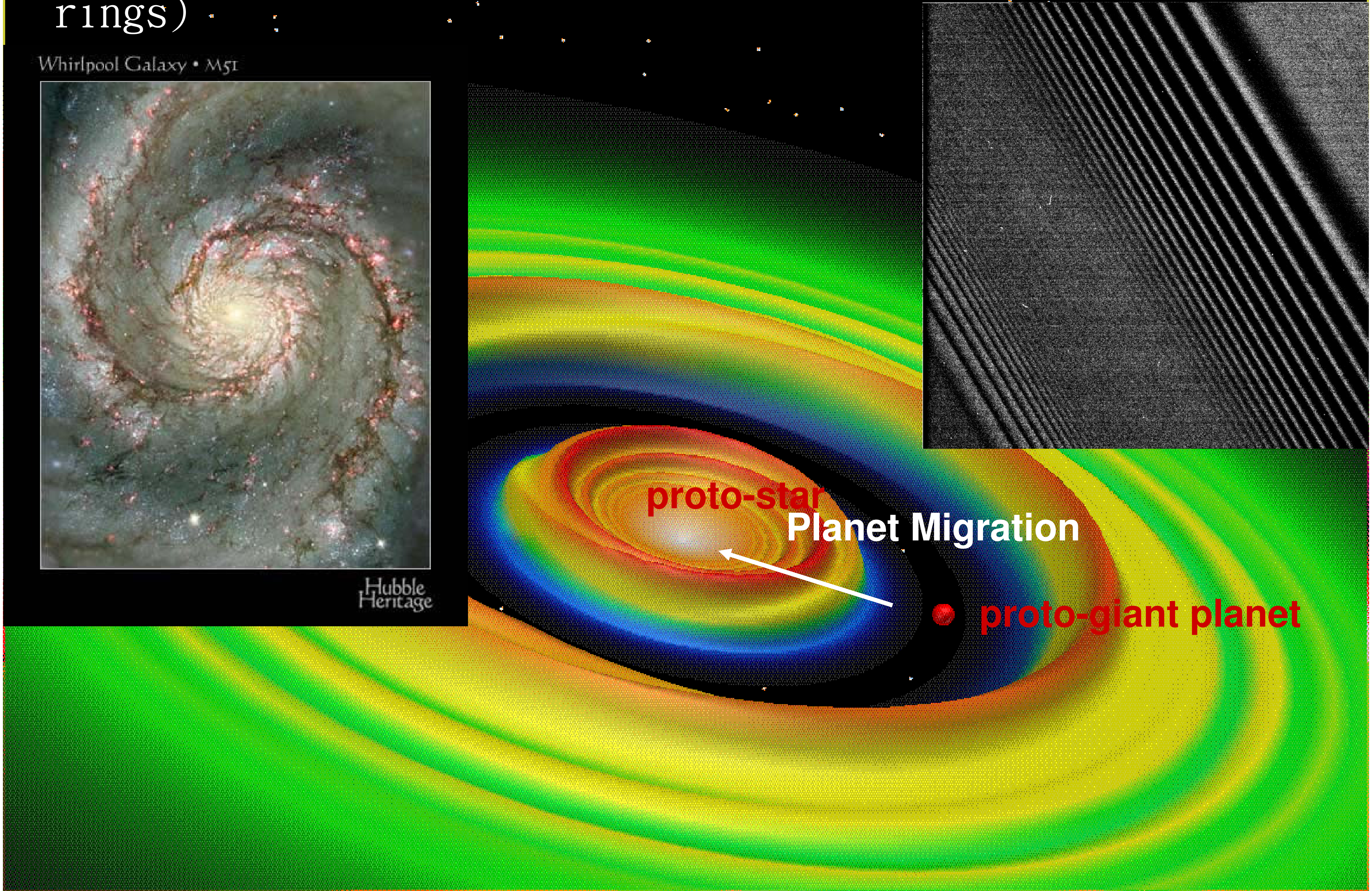
2:1

Io and Europa have a period ratio close to 2:1

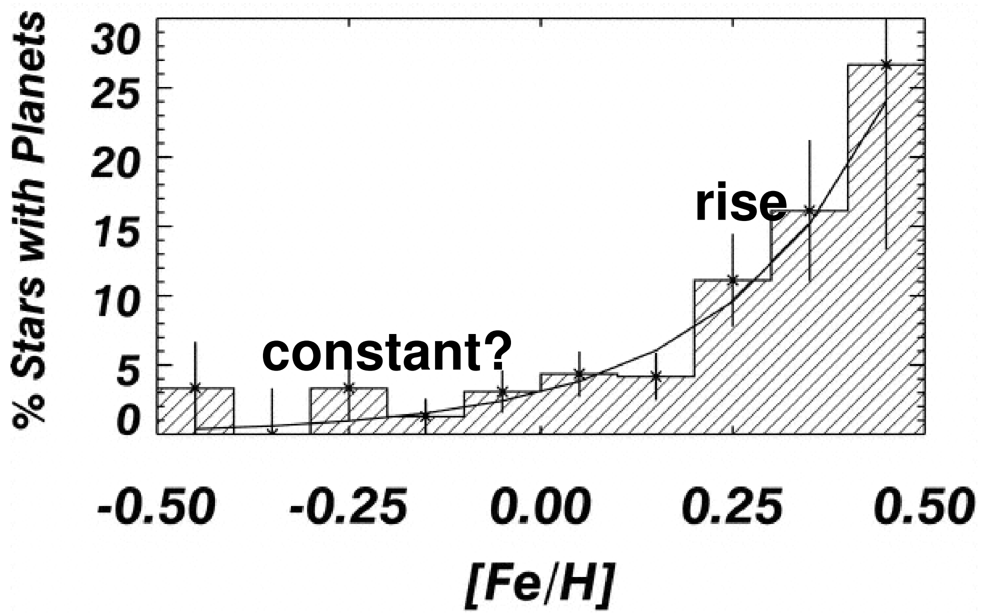
Europa and Ganymede have a period ratio close to 2:1

tidal evolution → differential orbital migration → capture into resonance

Geoff Bryden's simulation : density waves in proto-planetary disk (cf. spiral galaxies, waves in Saturn rings)

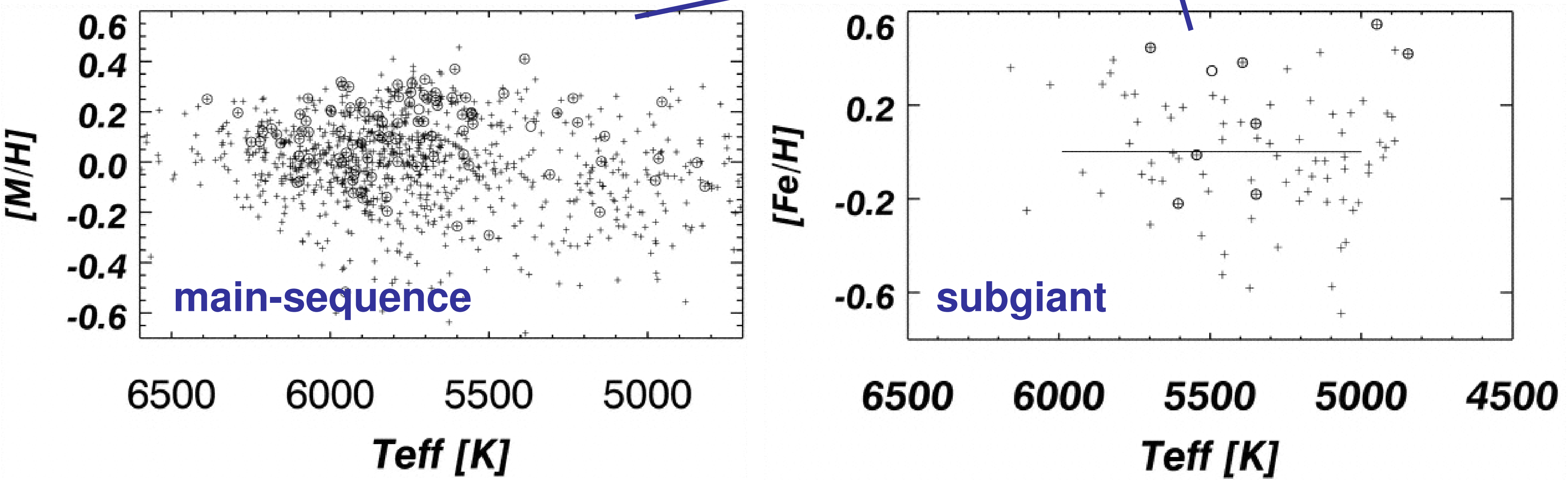


Stellar Metallicity & Planet (Fischer & Valenti 2005)



Stars with giant planets form preferentially in a high metallicity molecular cloud (related to gas/dust ratio).

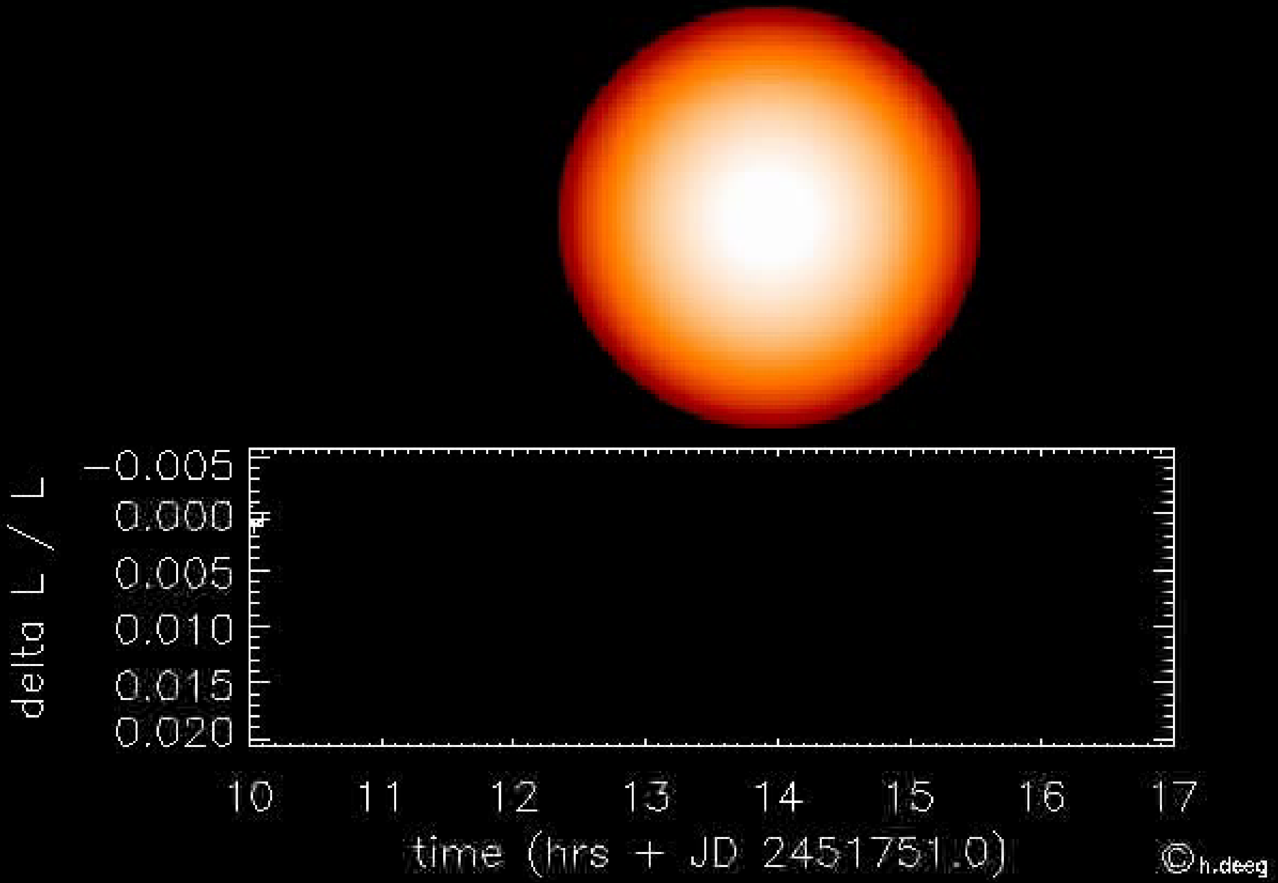
Contamination is not favored.



Planet Search: Transit

can’t resolve →

what you see →

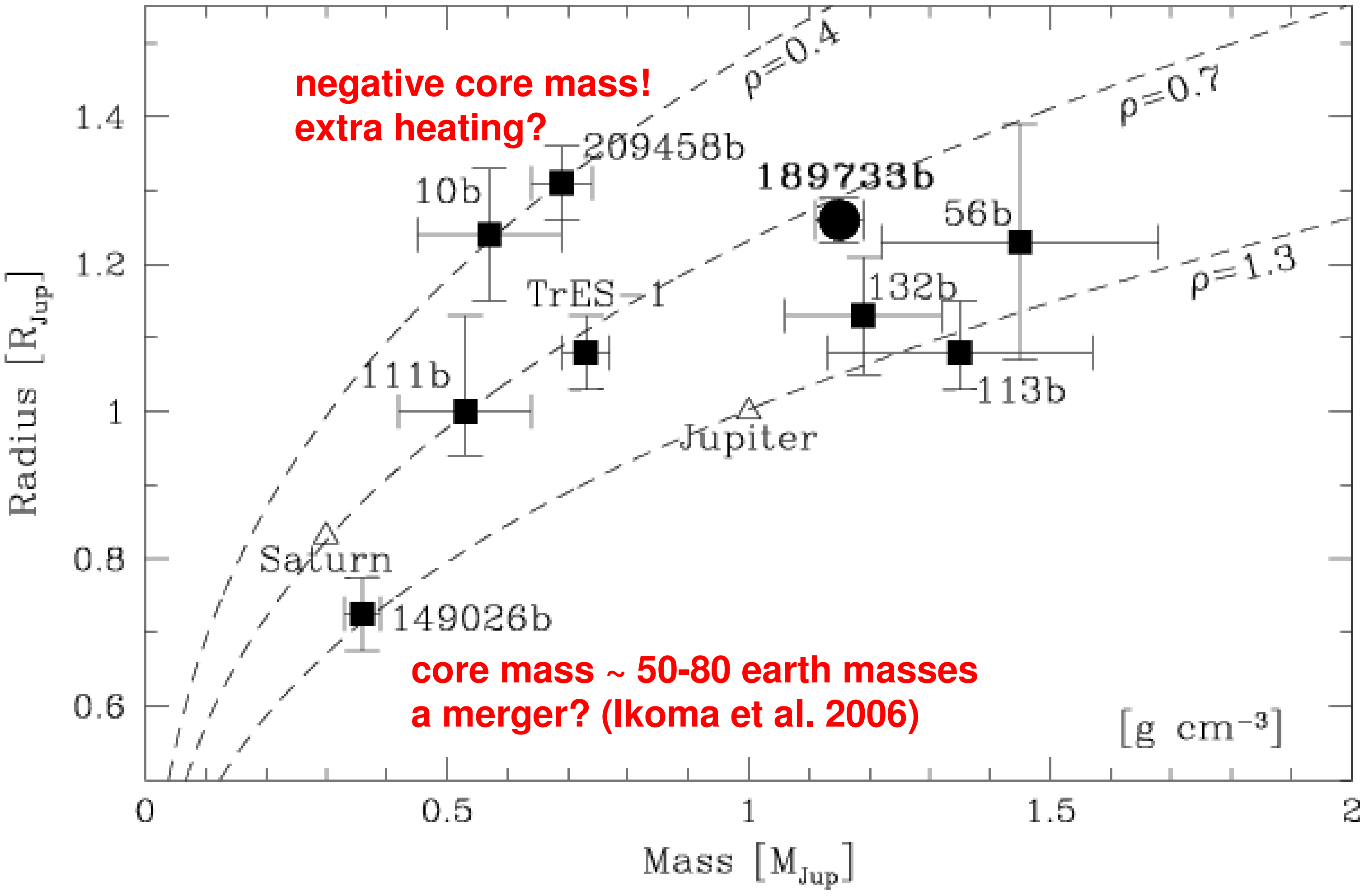


http://www.iac.es/proyect/tep/transitanim.html

Transiting Planets → Mass-Radius relation

Bouchy et al. 2005

Is there a core at center of a giant planet?

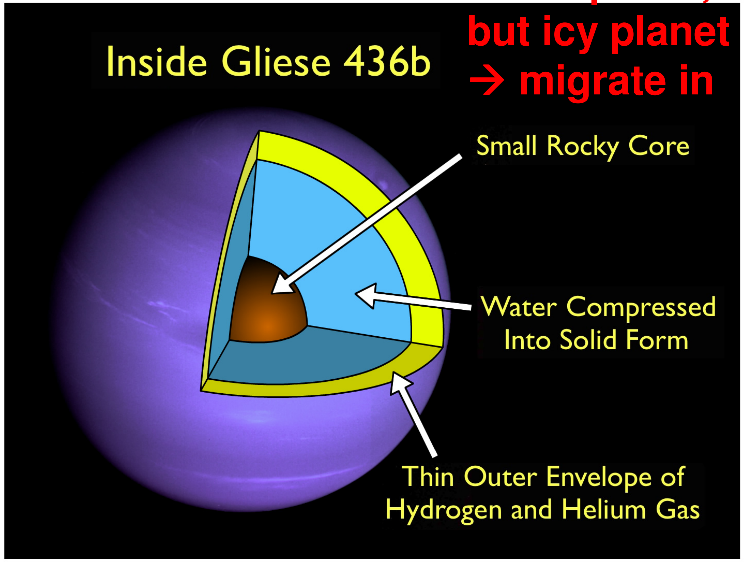


negative core mass!
extra heating?

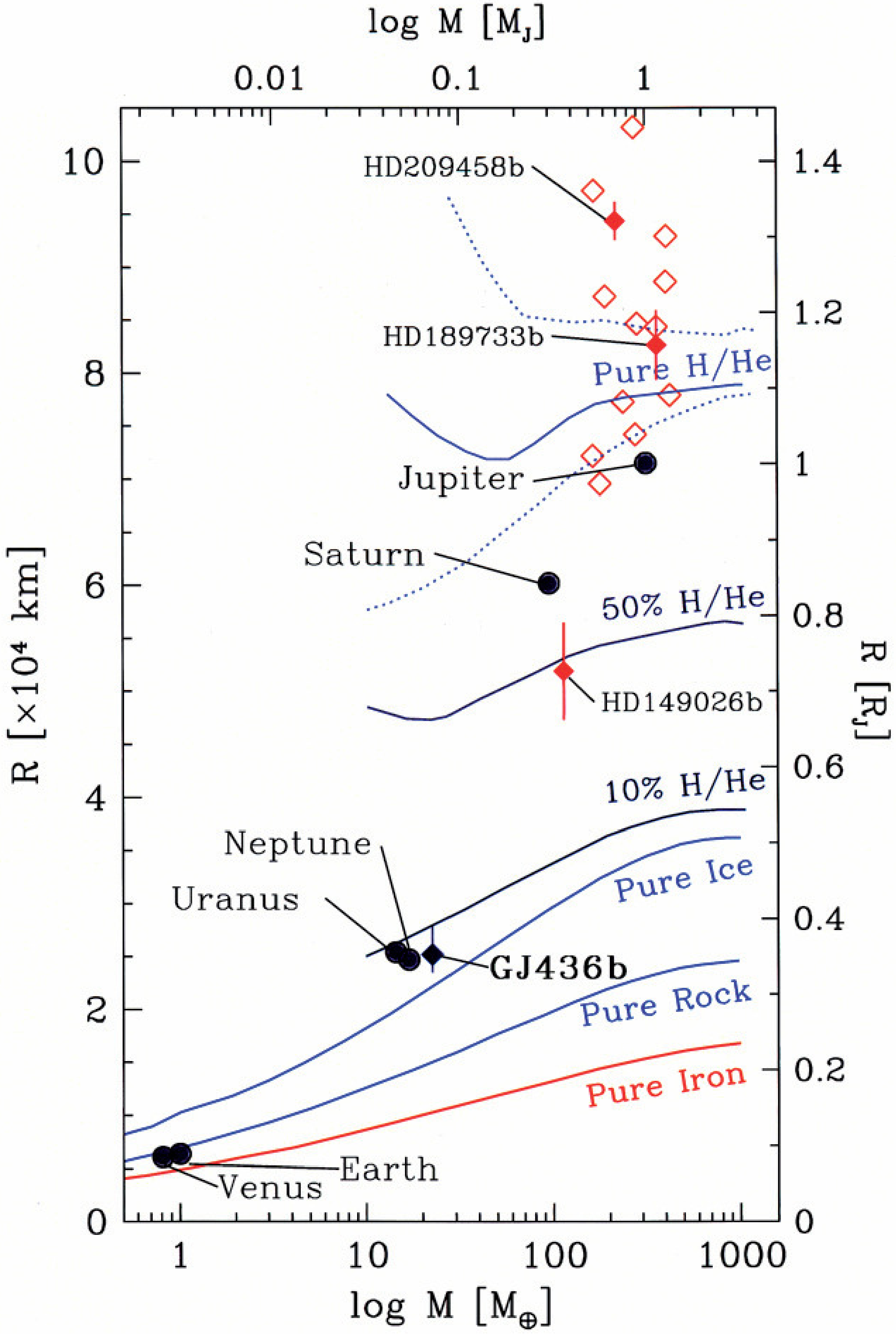
core mass ~ 50-80 earth masses
a merger? (Ikoma et al. 2006)

Transiting Planets → Mass-Radius relation → composition

Gillon et al. 2007
Fortney et al. 2007



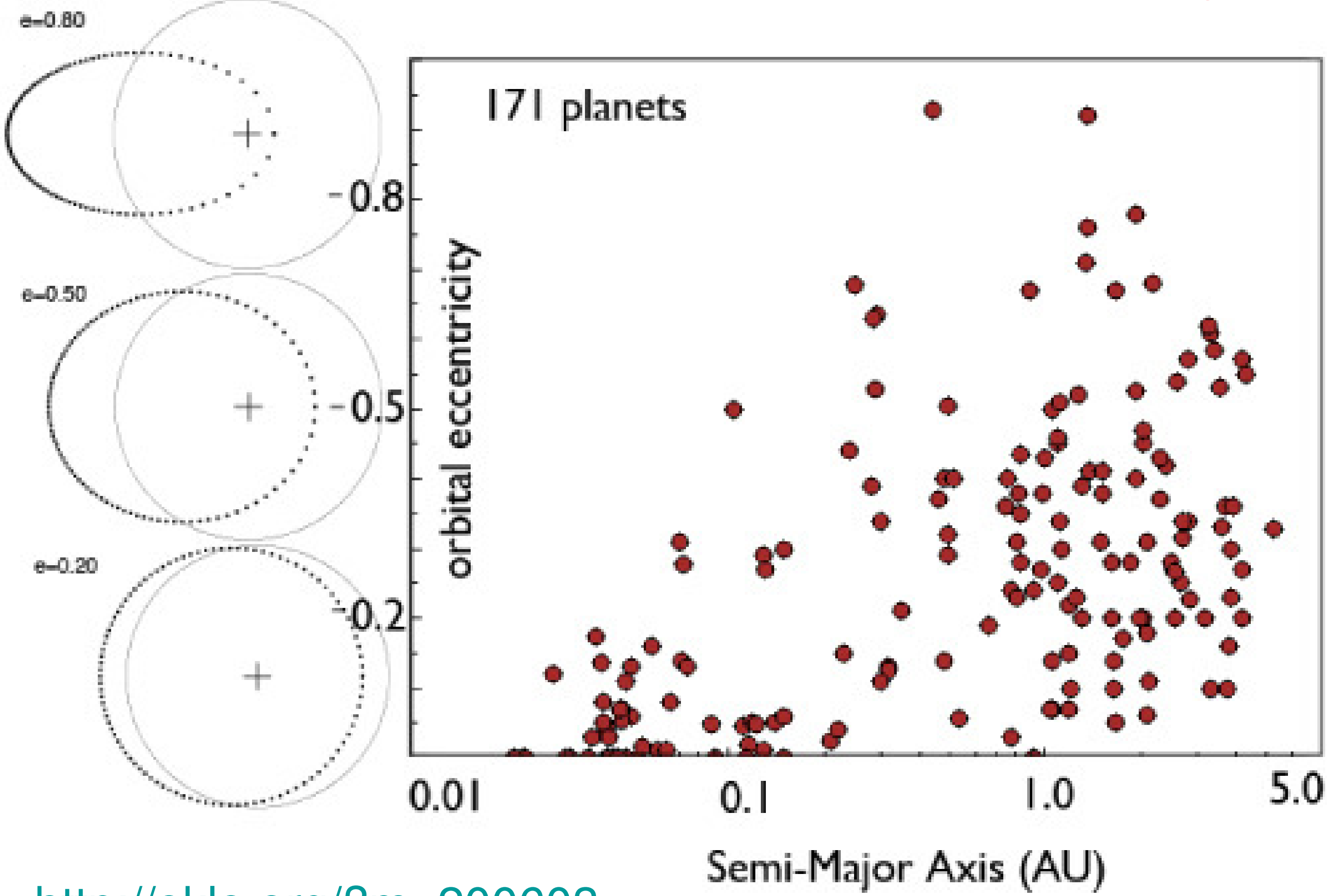
hot neptune, but icy planet → migrate in



elliptical orbits

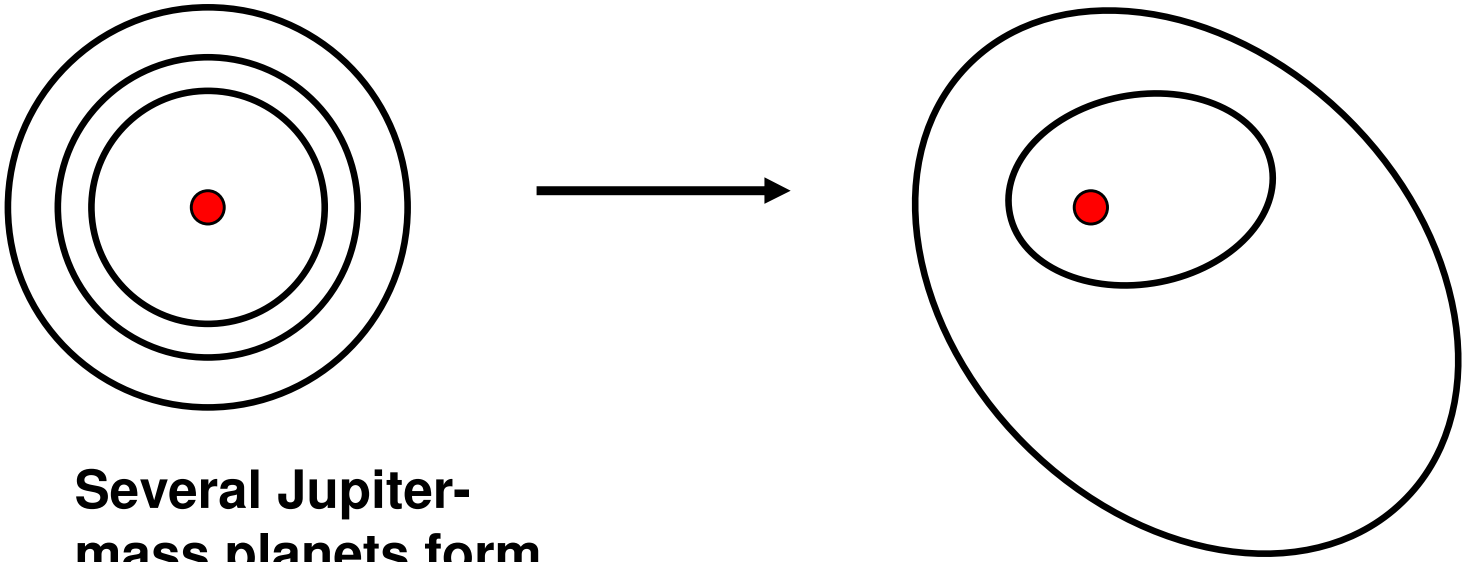
Why is there a broad distribution?

Difficult to deliver comets (ie water source) to the Earth (Raymond et al. 2004)？



http://oklo.org/?m=200603

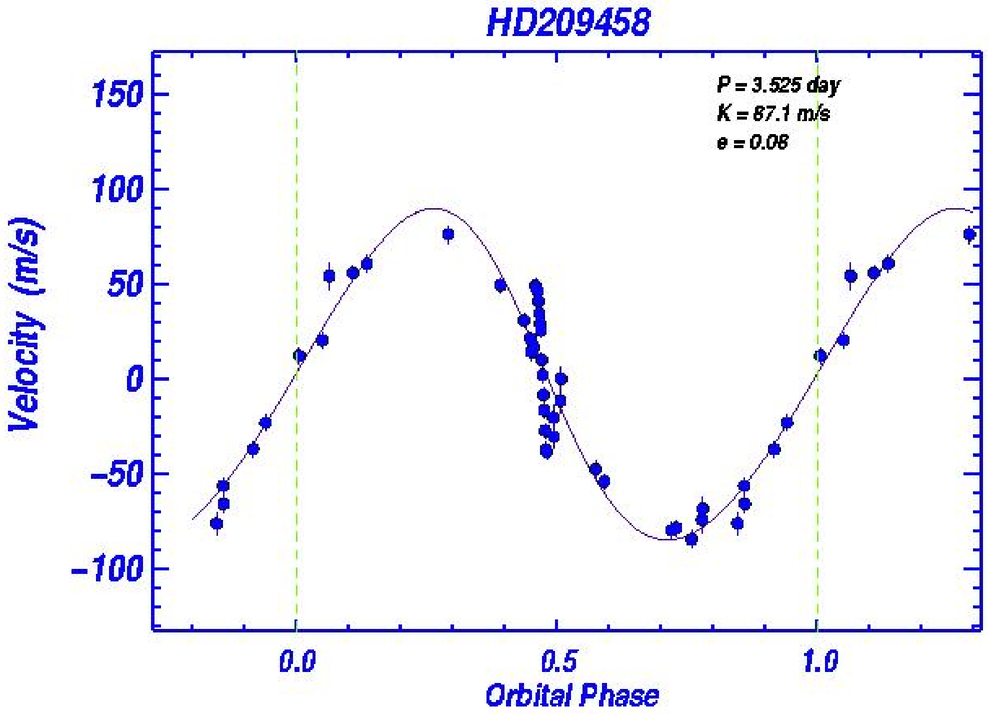
One scenario to form elliptical orbits

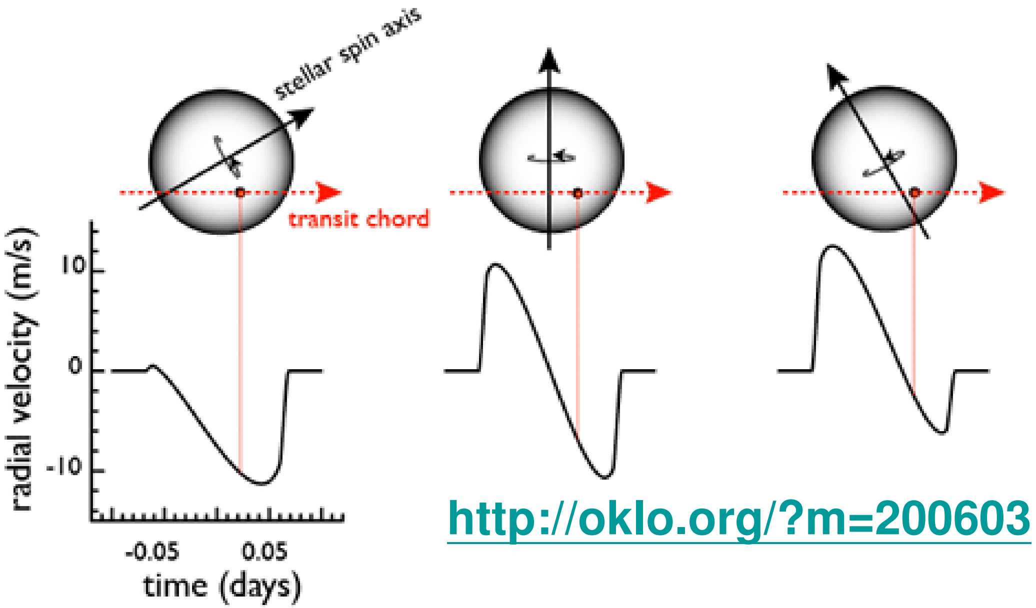


Several Jupiter-mass planets form in a proto-planetary disk

After gravitational interactions

Orbital & Spin direction





http://oklo.org/?m=200603

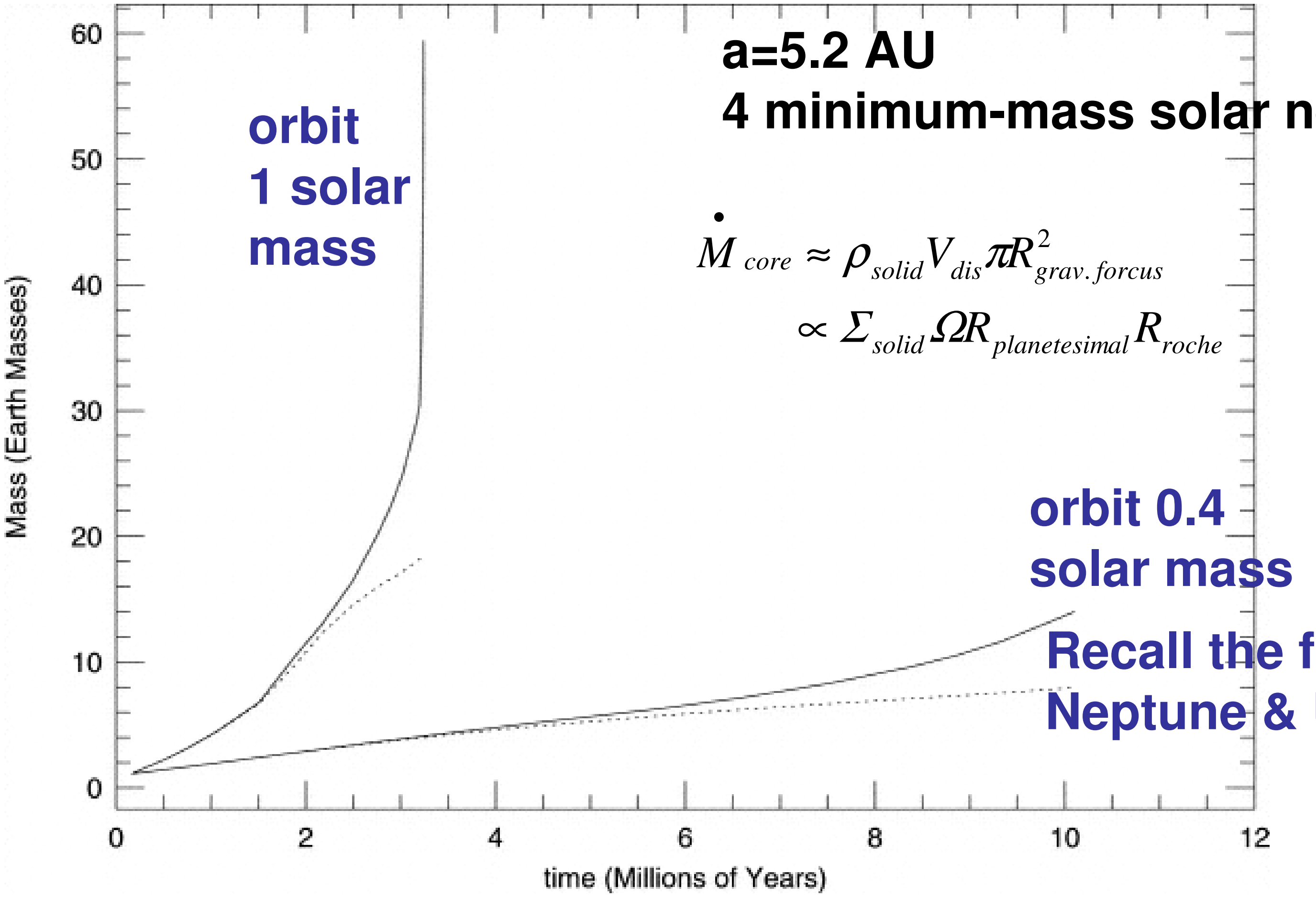
Winn et al. 2005 estimate the angle between stellar spin axis and the planet orbital axis
λ =4.4° ±1.4°

Statistical studies of λ in the future can prove/disprove planet-planet interactions which may be needed for eccentricity distribution.

Radial velocity anomaly due to the Rossiter-McLaughlin effect: a special result for a transiting planet

Giant planet formation around M dwarfs

Laughlin et al. 2004



a=5.2 AU
4 minimum-mass solar nebula

$$\dot{M}_{core} \approx \rho_{solid} V_{dis} \pi R^2_{grav.forcus}$$
$$\propto \Sigma_{solid} \Omega R_{planetesimal} R_{roche}$$

orbit
1 solar
mass

orbit 0.4
solar mass

Recall the formation of
Neptune & Uranus

Giant planet around intermediate-mass stars

Sato et al. 2007, Lovis & Mayor 2007: search for planets around evolved intermediate-mass stars (retired A stars: G-type giants) in open clusters. They rotate slowly and contain more lines: good for the radial-velocity method.

Statistical analysis criteria:

- **$M_p > 5\ M_{jupiter}$**
- **0.5 AU < a < 2.5 AU**

0 planets out of 300 M dwarfs (0%)
14 planets out of 3000 solar-type stars (0.5%)
5 planets out of 200 intermediate-mass stars (2.5%)

Issues:

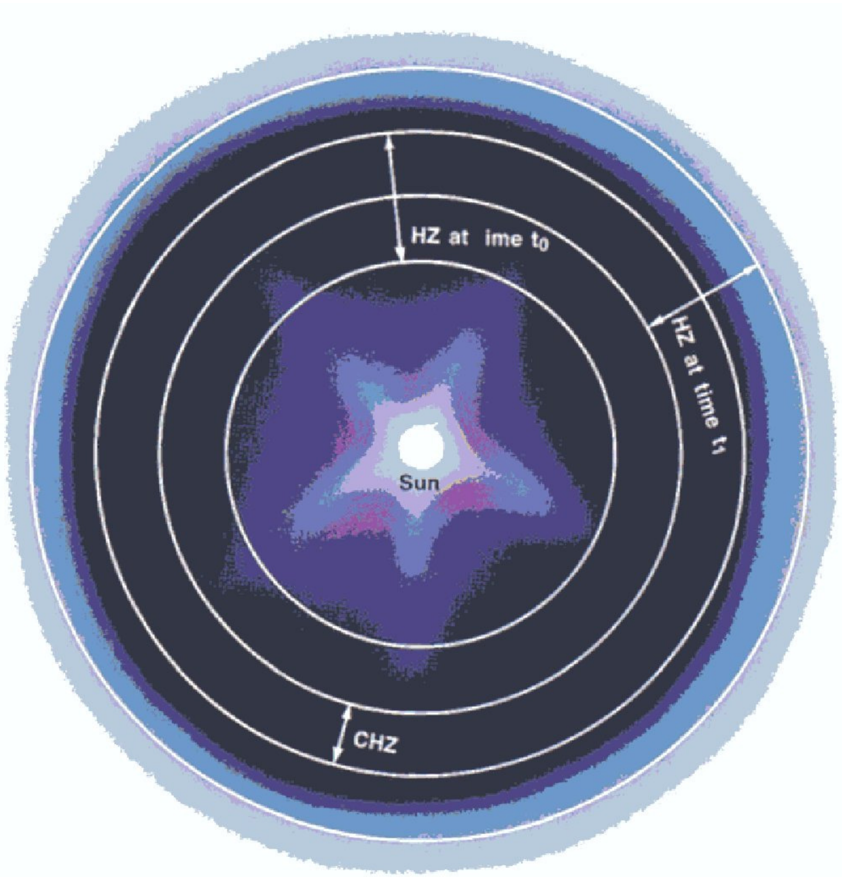
- **massive stars → massive disks → many massive giant planets?**
- **But another thought: massive stars → short-lived disks → low frequency of planets?**
- **How about planet formation around very early-type (O & B) stars?**

habitable zone：

an orbital zone where liquid water can exist on terrestrial planets

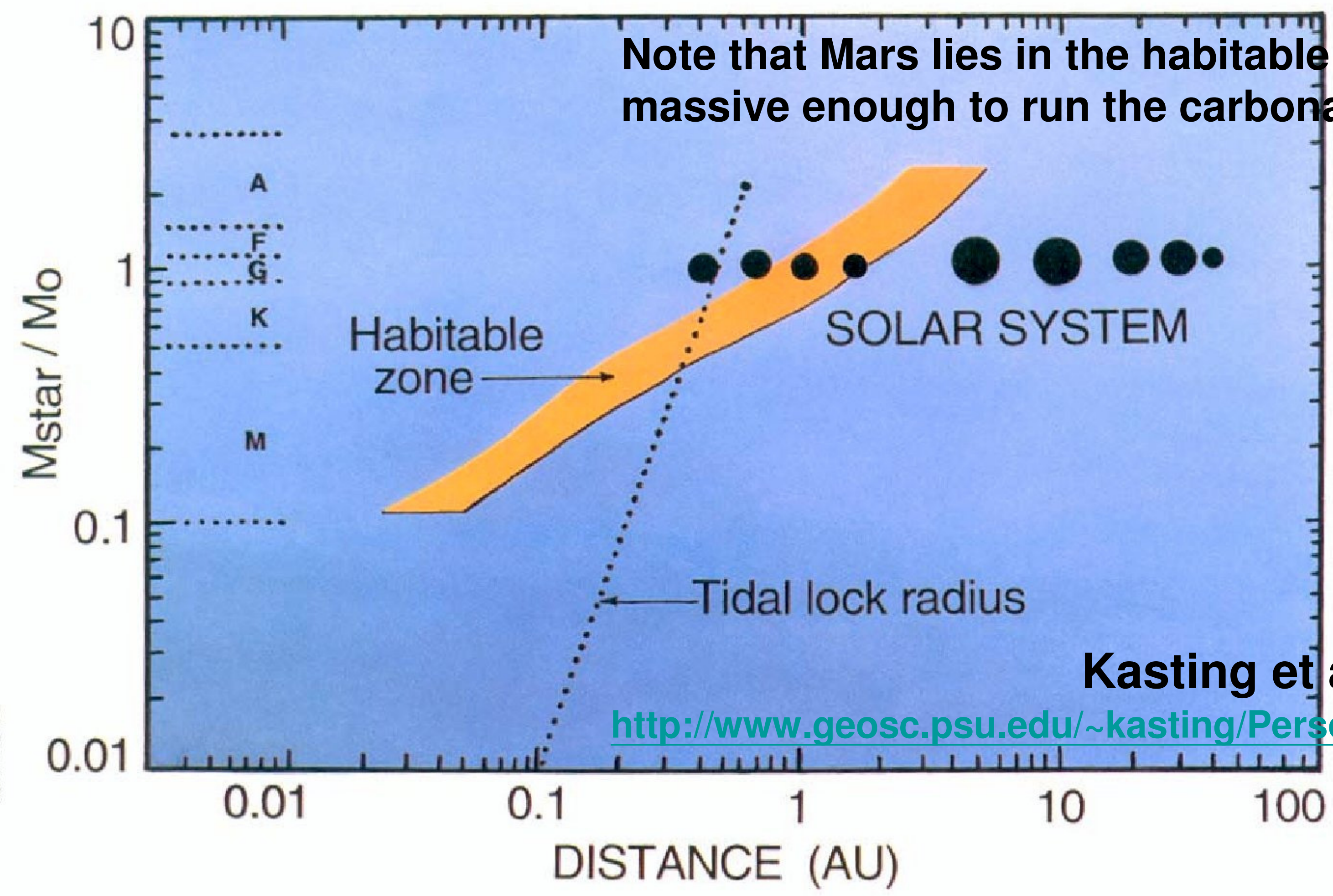
Consider what would happen if we move the Earth inward/outward from the current location. Here are the results from James Kasting:

- inner edge of habitable zone (~0.95 AU): oceans evaporate due to the runaway moisture greenhouse effect (water vapor is a greenhouse gas + extended troposphere → wet stratosphere)
- outer edge of habitable zone (~1.7 AU): carbonate-silicate cycle stabilizes cold climate but CO2 condensation lowers the greenhouse effect.



Continuously habitable zone (CHZ): the region
In which a planet could remain habitable for a long period of time (~ several billion years)

Habitable Zone & Spectral types



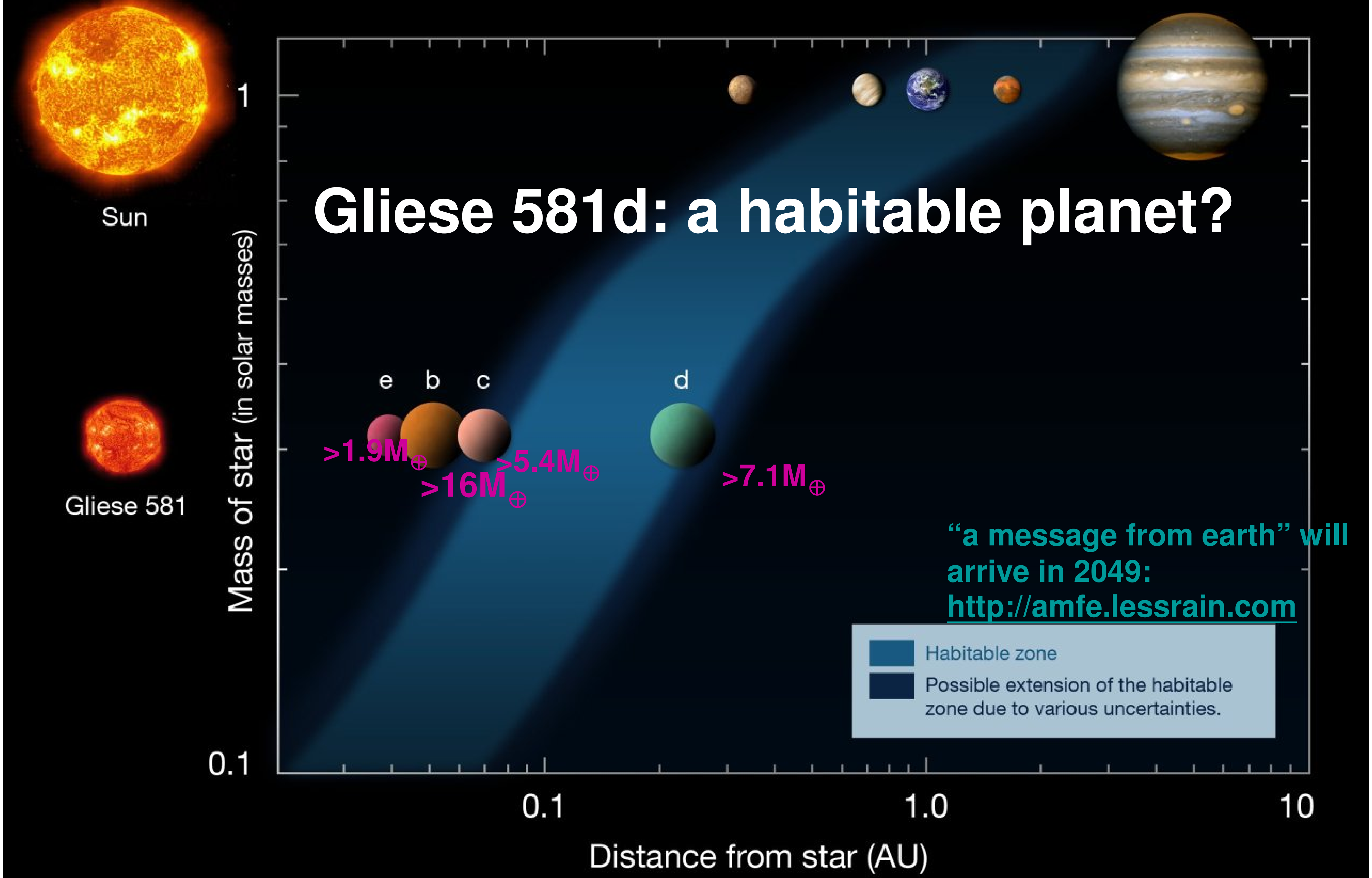
Note that Mars lies in the habitable zone but it is not massive enough to run the carbonate-silicate cycle.

Kasting et al. 1993

http://www.geosc.psu.edu/~kasting/PersonalPage/Kasting.htm

Other issues:
F and A stars: high stellar UV radiation. Short main-sequence lifetimes
K and M stars: tidal locking, stellar flares

Gliese 581d: a habitable planet?



“a message from earth” will arrive in 2049: http://amfe.lessrain.com

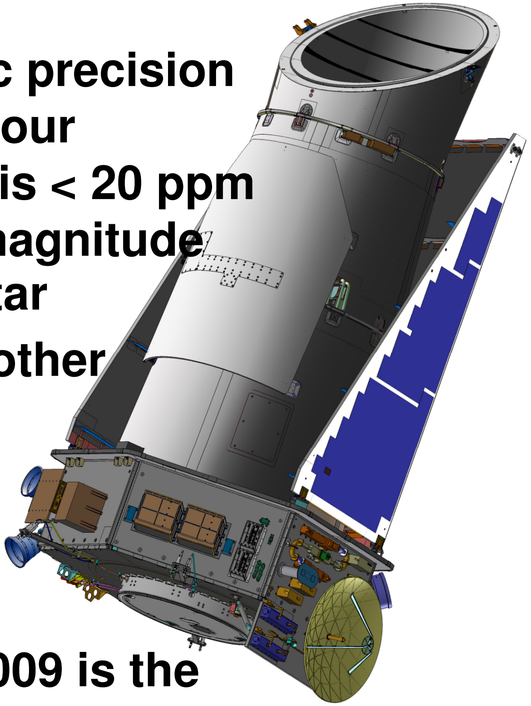
http://www.eso.org/public/outreach/press-rel/pr-2009/pr-15-09.html

KEPLER 1-m (2009)

NASA space mission monitor ~ 10^5 sun-like stars for 3.5 years.

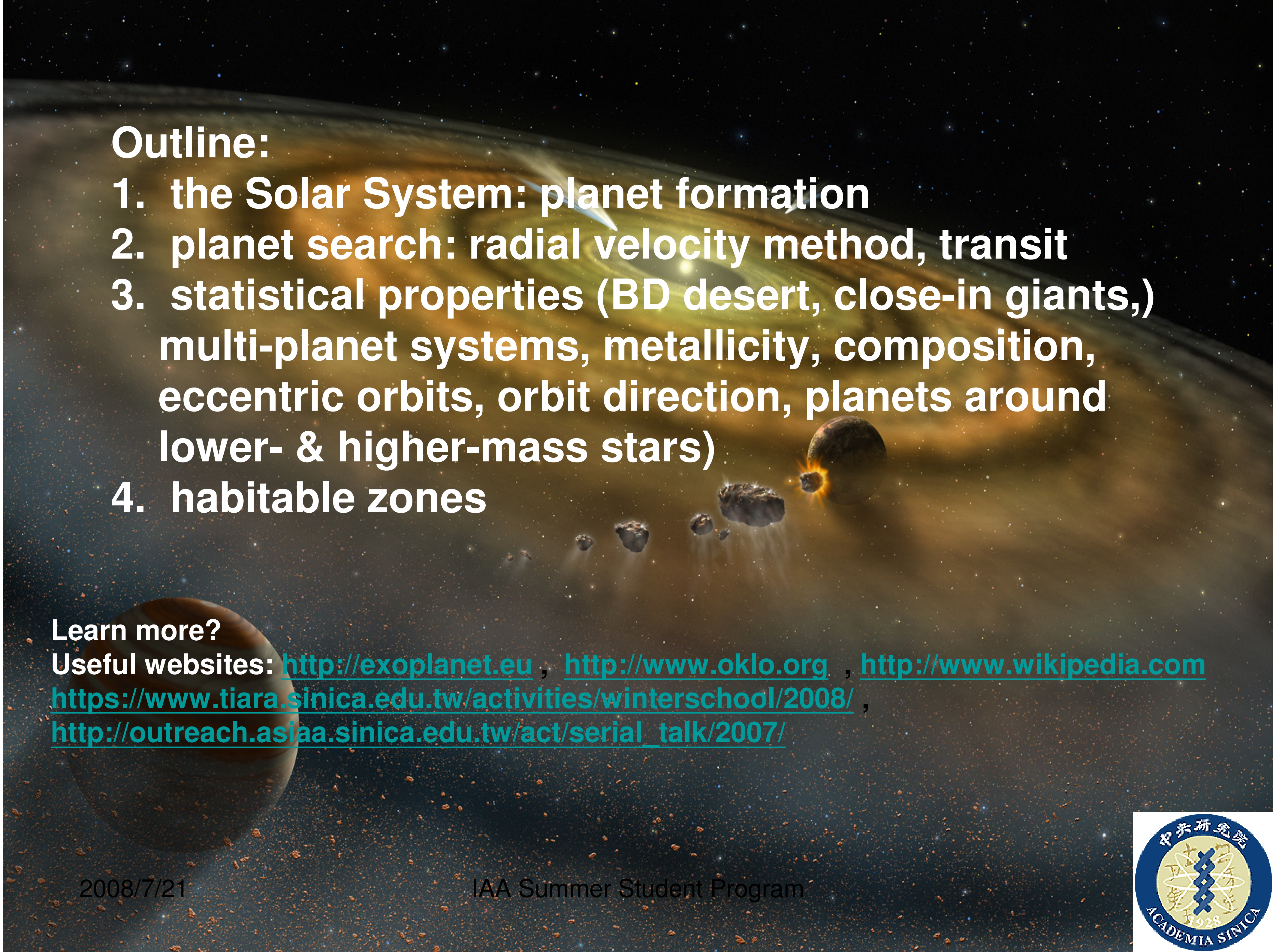
photometric precision over a 6.5 hour integration is < 20 ppm for a 12th magnitude solar-like star

→Look for other earths!



Remark: 2009 is the International Year of Astronomy

http://kepler.nasa.gov/



Outline:

1. the Solar System: planet formation
2. planet search: radial velocity method, transit
3. statistical properties (BD desert, close-in giants,) multi-planet systems, metallicity, composition, eccentric orbits, orbit direction, planets around lower- & higher-mass stars)
4. habitable zones

Learn more?

Useful websites: http://exoplanet.eu , http://www.oklo.org , http://www.wikipedia.com
https://www.tiara.sinica.edu.tw/activities/winterschool/2008/ ,
http://outreach.asiaa.sinica.edu.tw/act/serial_talk/2007/