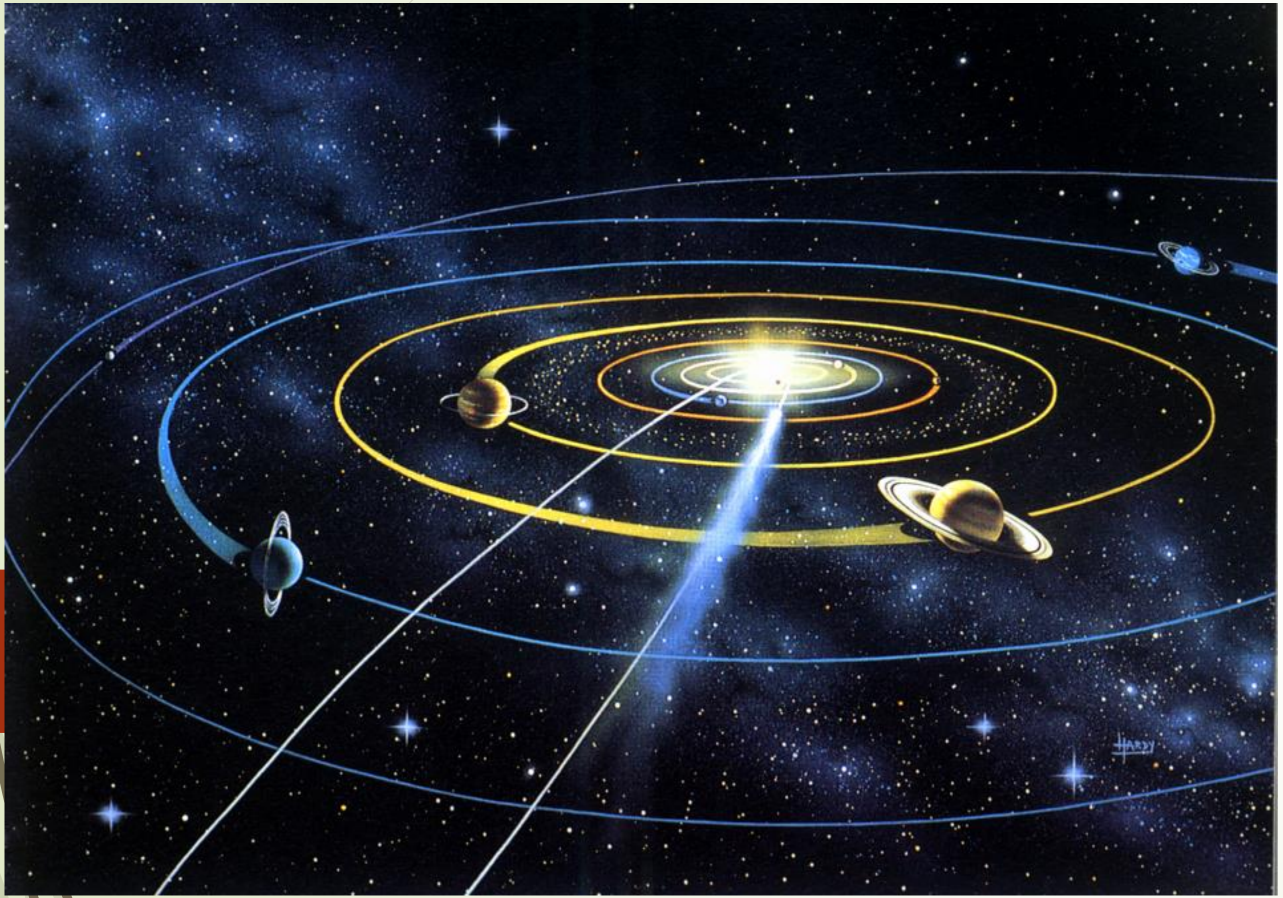
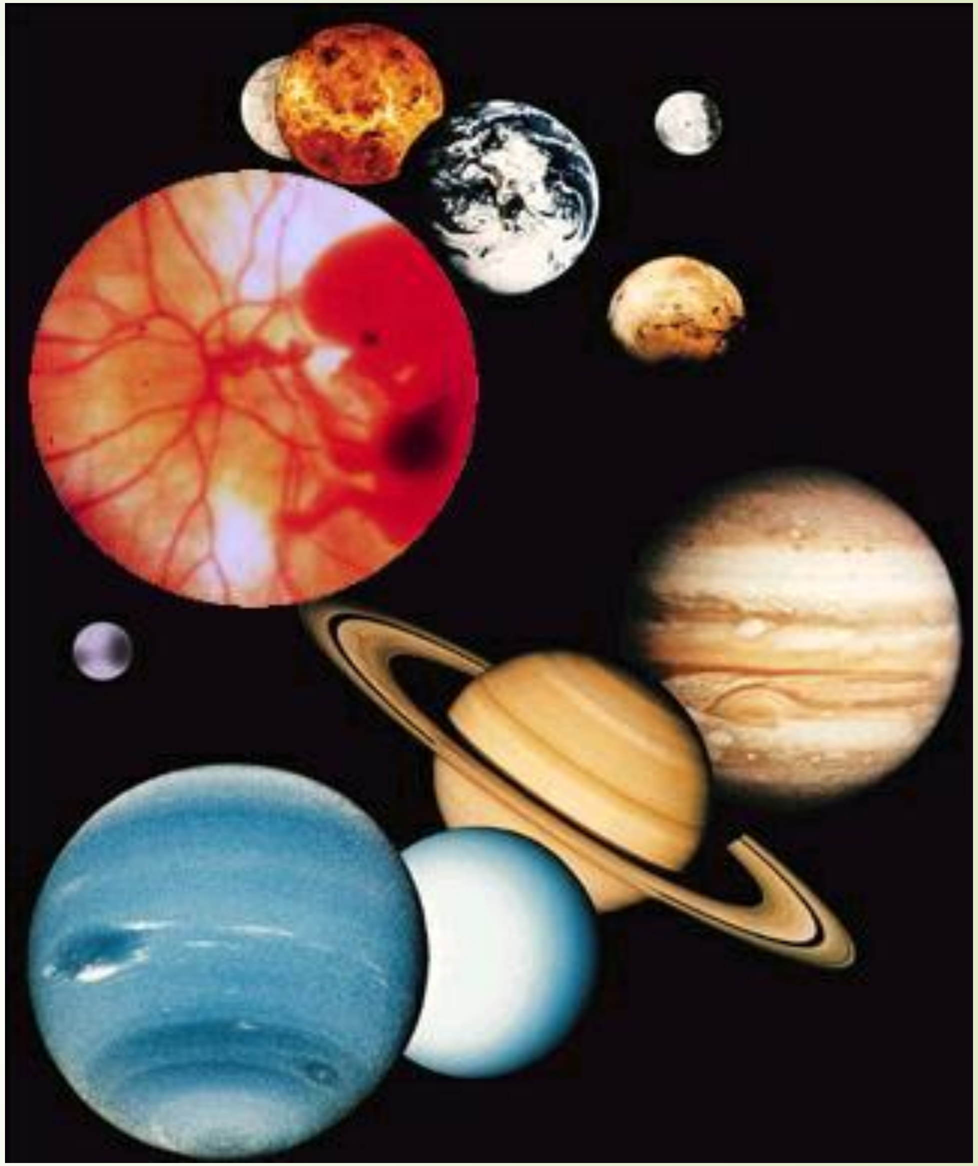
太陽系形成

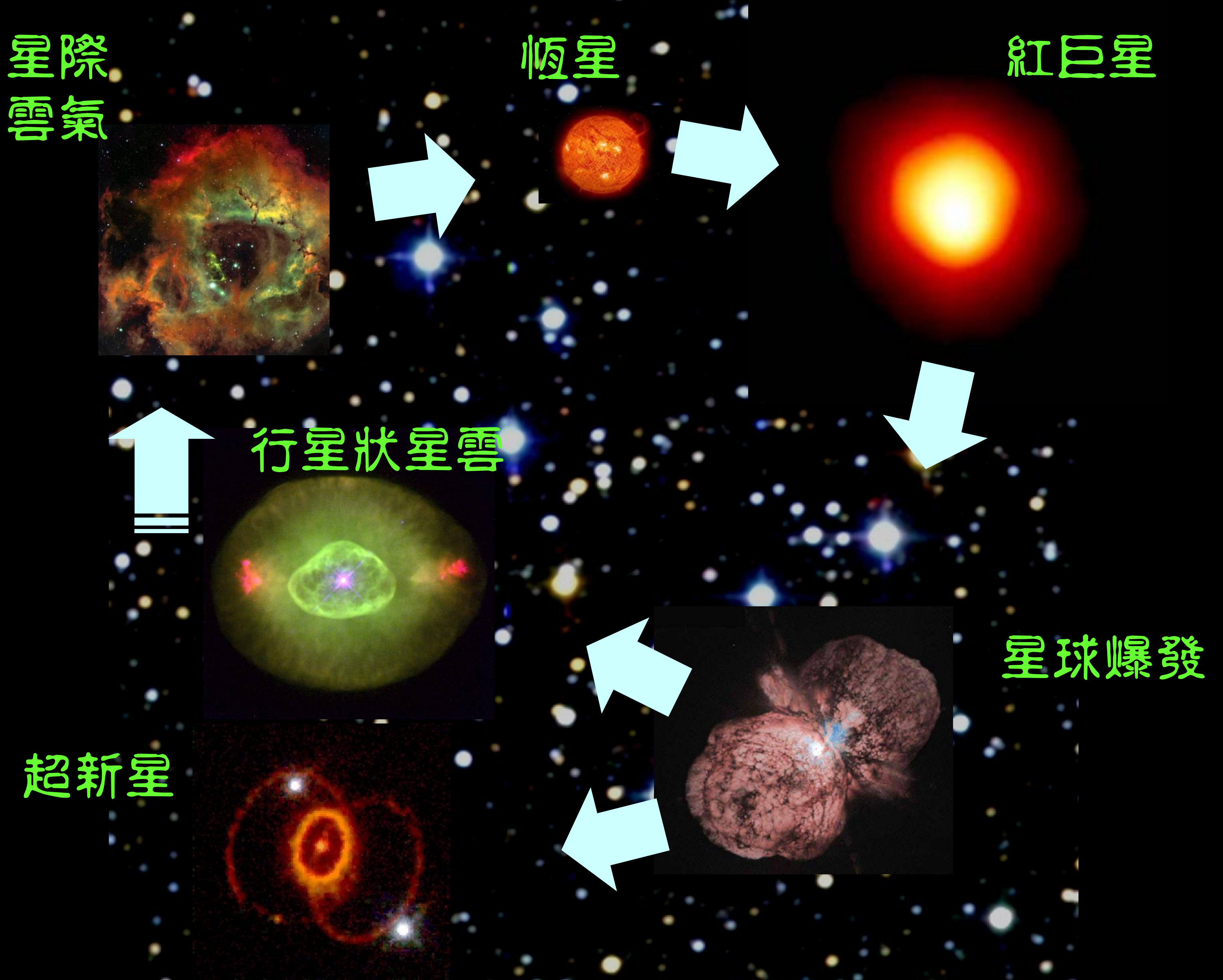


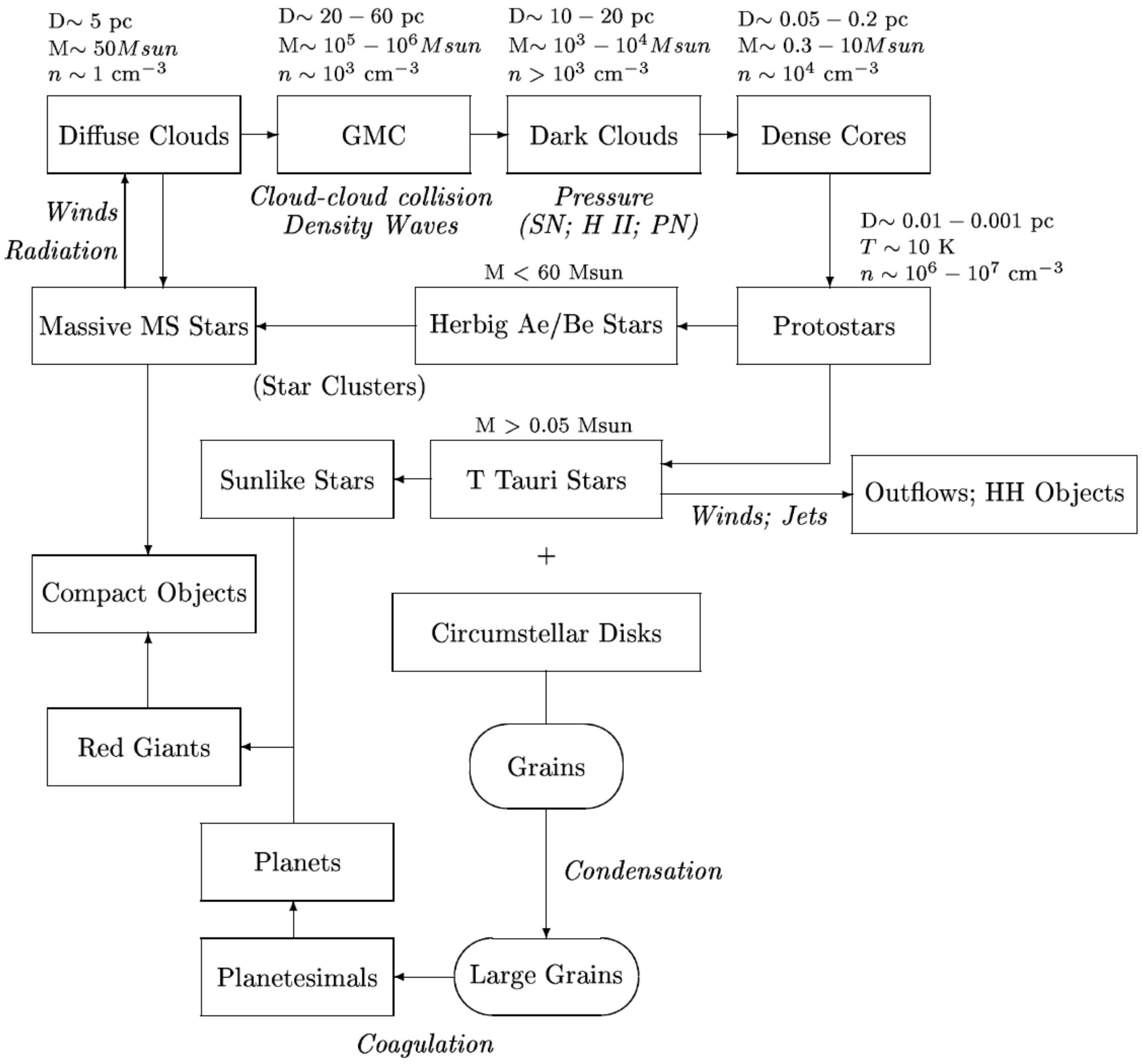


2016.06.27 @NCU Summer Camp

陳文屏 中央大學 天文所、物理系

恒星的生老病死





Galactic Ecology

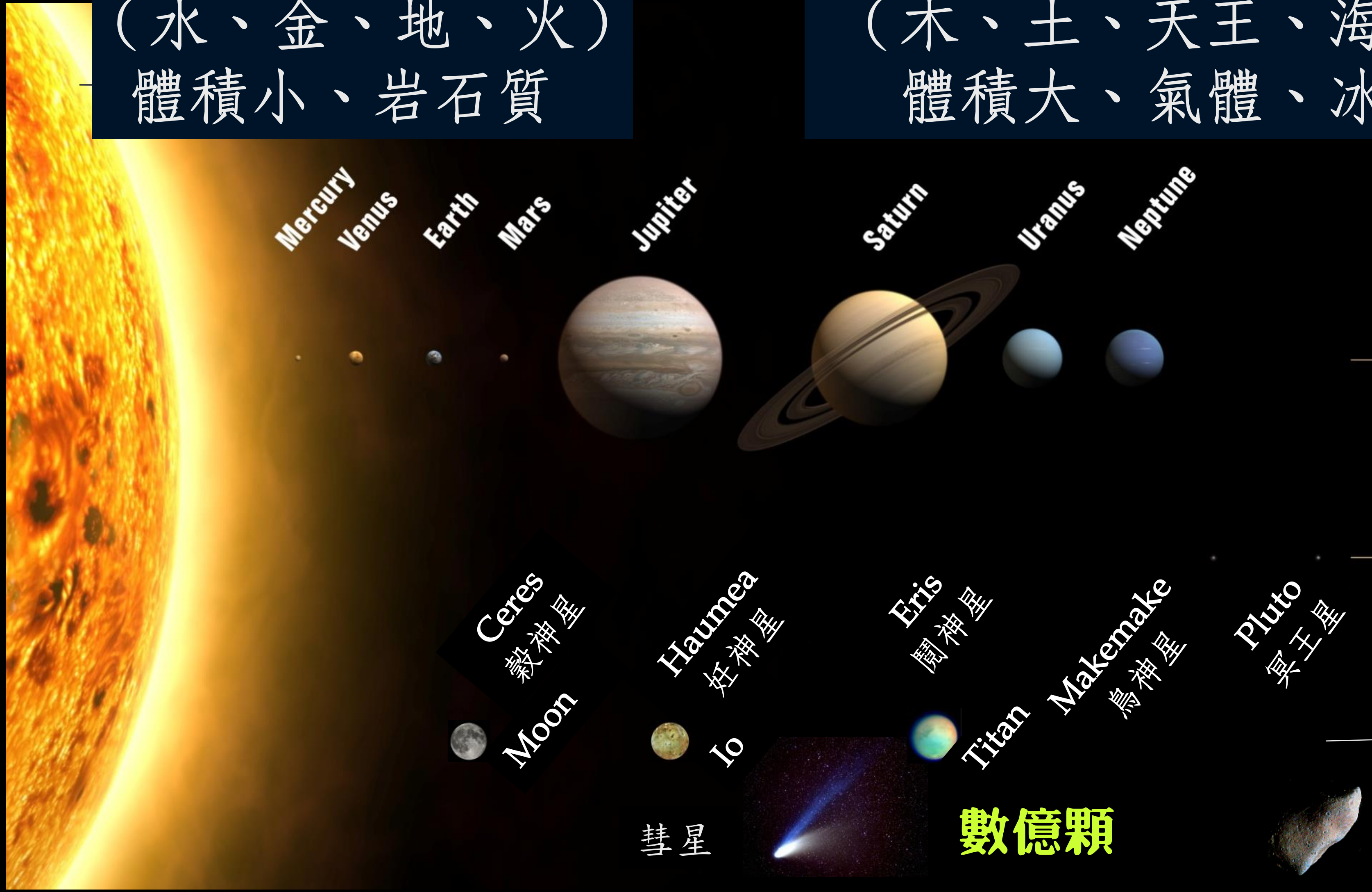
Stars are formed in groups out of dense molecular cloud cores …

whereas planets are formed, contemporaneously, in young circumstellar disks.

太陽系家族之「戶口名簿」

靠內部的行星
（水、金、地、火）
體積小、岩石質

靠外部的行星
（木、土、天王、海王）
體積大、氣體、冰體



行星 八顆

矮行星 五顆 (IAU認可)

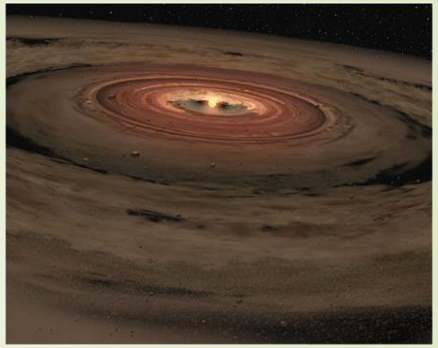
衛星 百來顆

彗星 數億顆

小行星 百萬顆

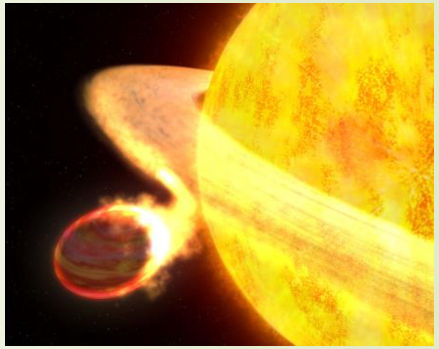
修改自IAU原圖

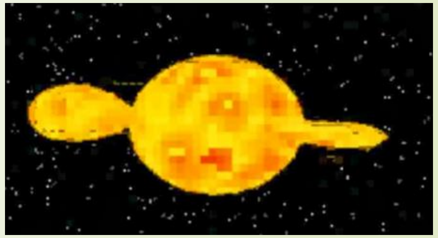
太陽系如何形成？



Cosmogony

- Nebular Hypothesis
  (1755, Immanuel Kant; 1972, Victor Safronov)
- Tidal Theory (1917, James Jeans)
- Fission (1951, Louis Jacot)
- Capture (1964. M. M. Woolfson)





Star Formation

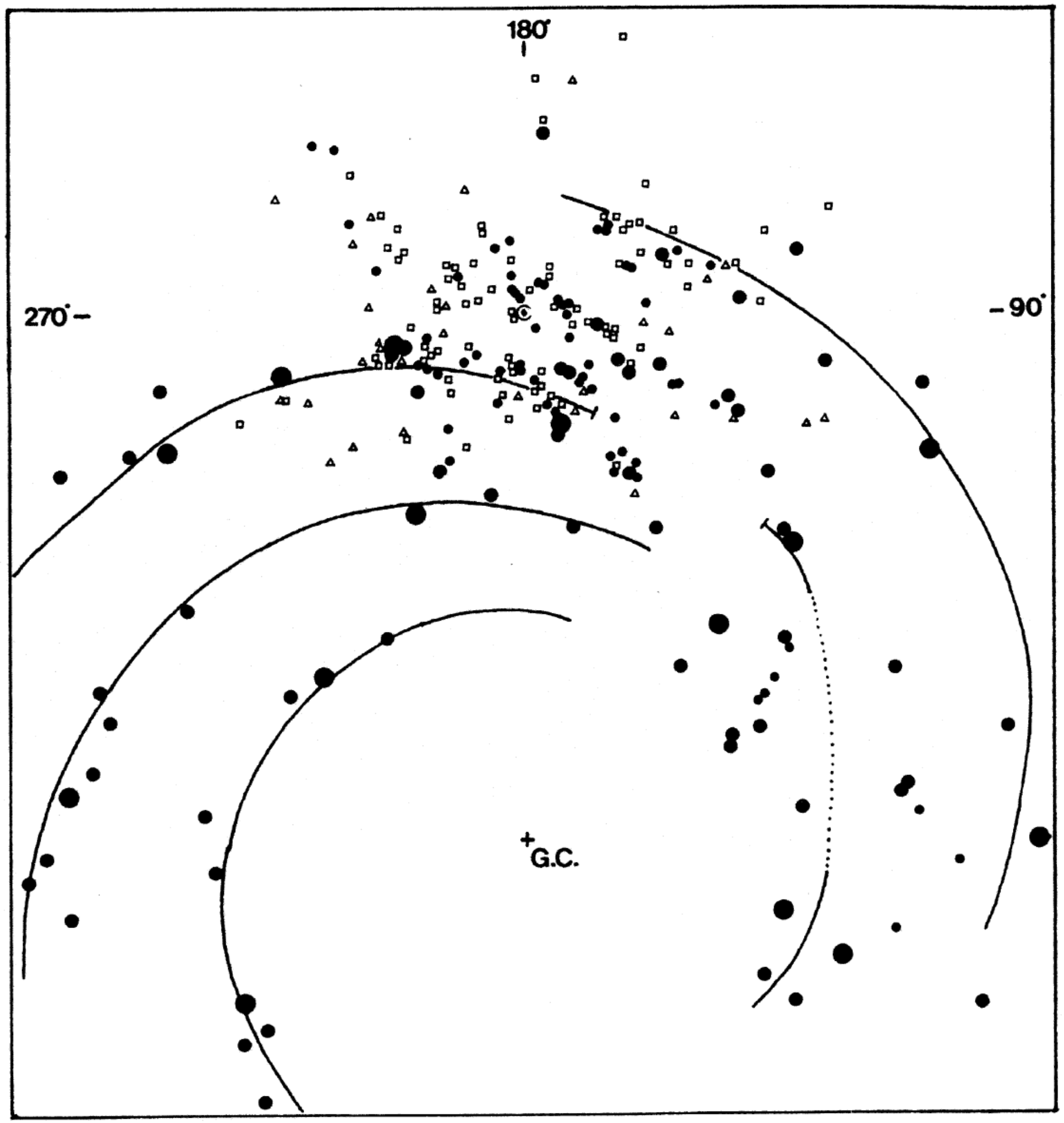
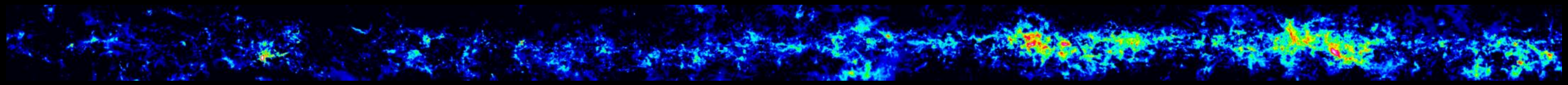
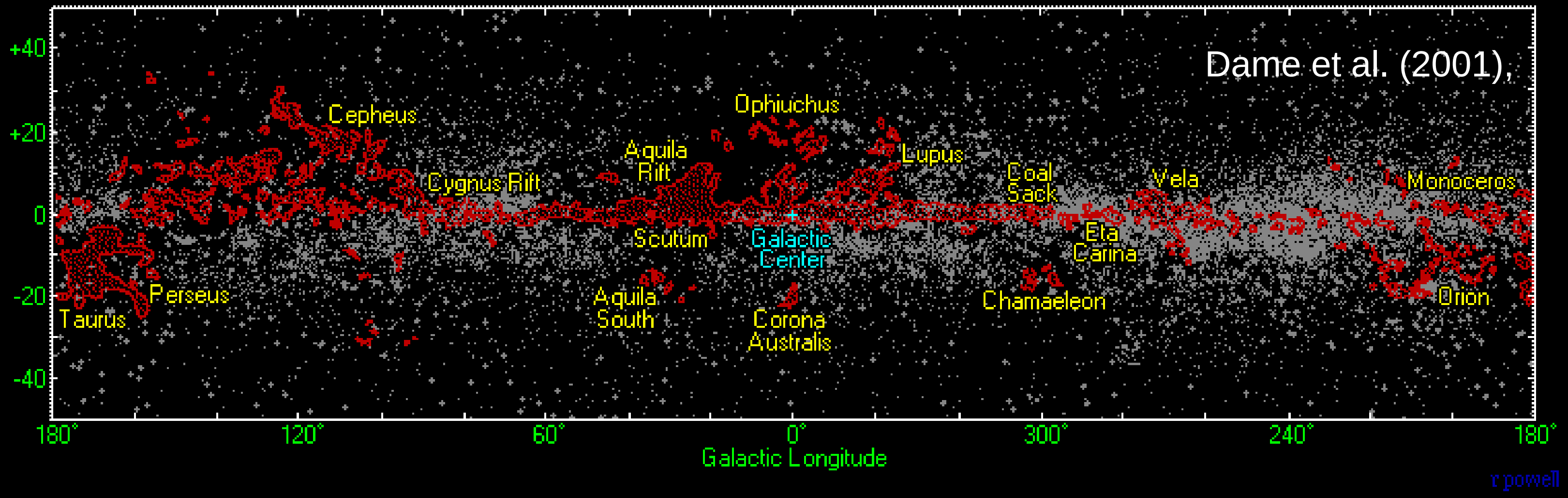


FIGURE 15 The spiral structure of the Milky Way galaxy as inferred from the positions of HII regions (clouds of ionized hydrogen) in the galaxy. The Sun and solar system are located at the upper center, as indicated by the ⊙ symbol. (Reprinted with kind permission from Kluwer Academic Publishers, Forbes and Shuter, in "Kinematics, Dynamics, and Structure of the Milky Way," p. 221, Fig. 3, copyright © 1983.)

Filamentary Molecular Clouds





Molecular clumps/ clouds/condensations

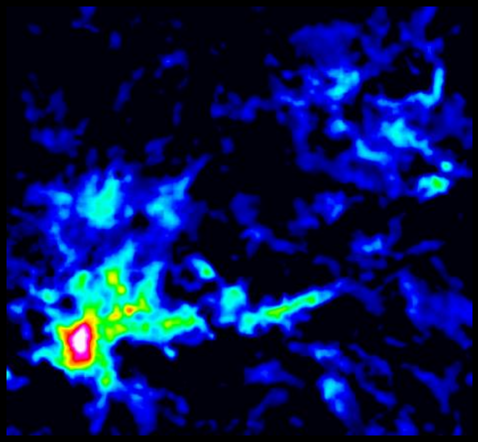
$n \sim 10^3$ cm^{-3}, $D \sim 5$ pc,

$M \sim 10^3\,M_\odot$

Dense molecular cores

$n \geq 10^4$ cm^{-3}, D ~ 0.1 pc,

$M \sim$ 1-2 $M_\odot$



http://www.bu.edu/galacticring/outgoing/PressRelease/

Giant Molecular Clouds

$\mathrm{D}=20\sim100$ pc

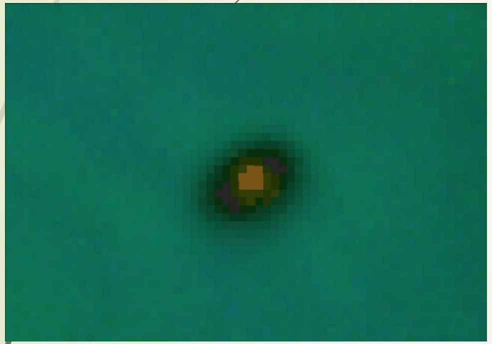
$\mathcal{M} = 10^5 \sim 10^6\ \mathcal{M}_\odot$

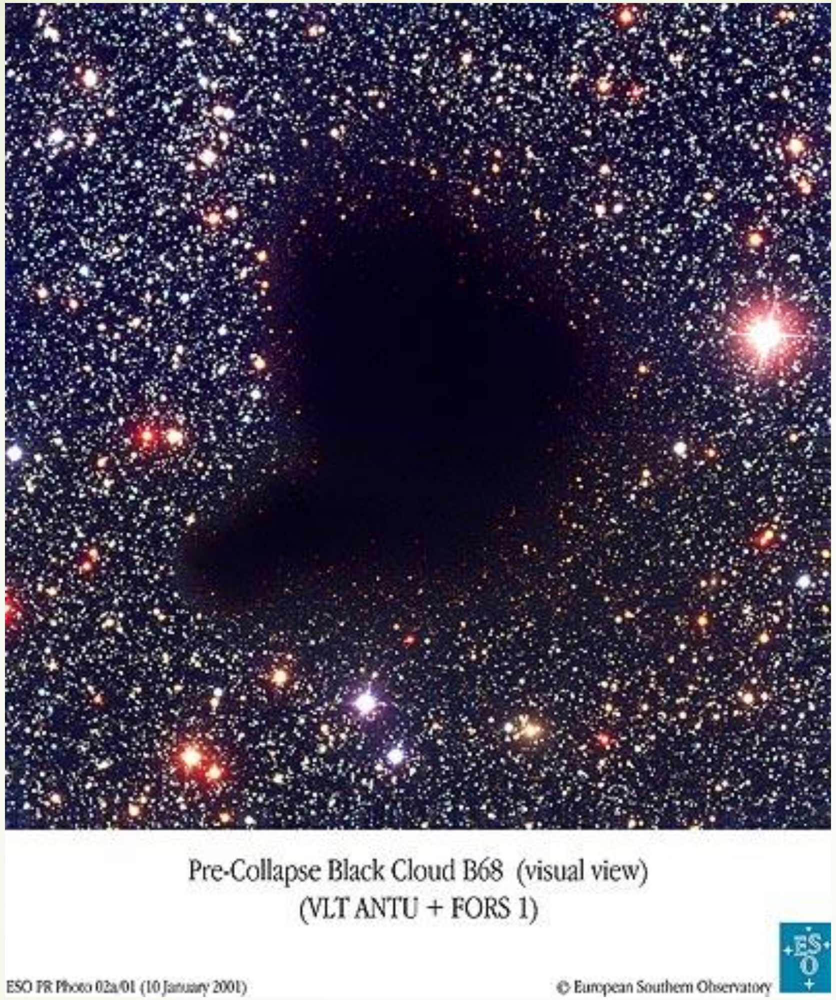
$\rho \approx 10\sim300\ \mathrm{cm}^{-3}$

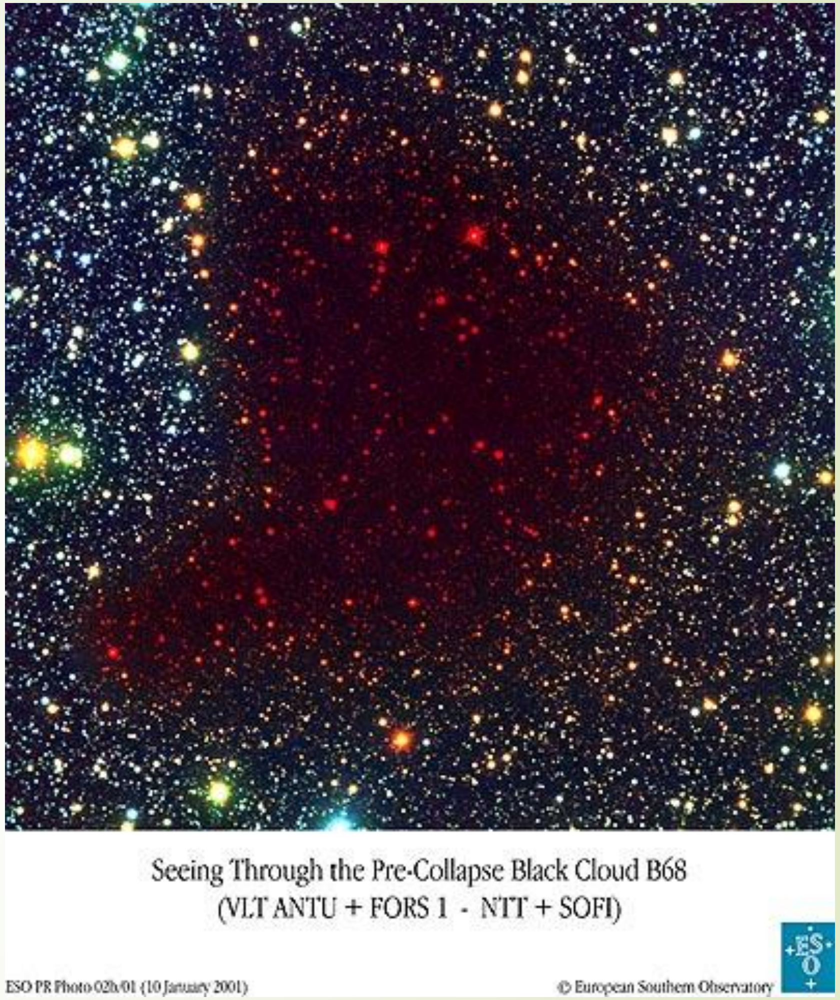
$T \approx 10\sim30$ K

$\Delta v \approx 5\sim15\ \mathrm{km}^{-1}$

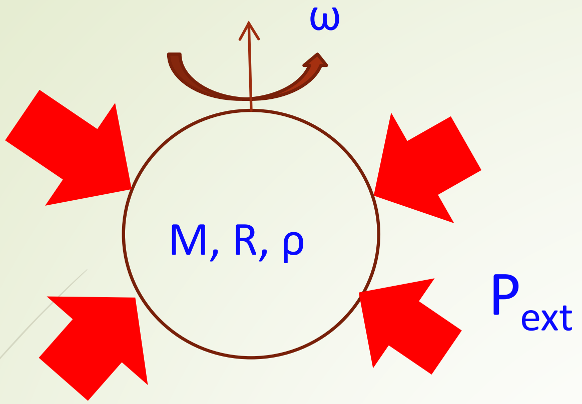

Barnard 72 in Ophiuchus
http://www.robgendlerastropics.com/B72JMM.jpg

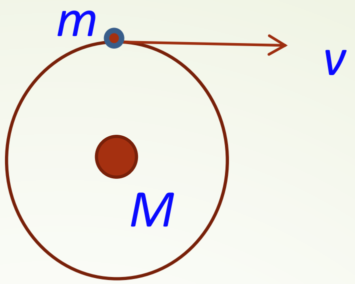






太空中低溫且濃密的雲氣，擋住了後方恆星。雲氣當中高密度而低溫的局部區域，由於萬有引力收縮而形成恆星





$$\frac{GmM}{r^2} = m\frac{v^2}{r}$$

$$2E_K + E_P = 0$$

Virial theorem
活力定理

So for a cloud on the verge of the gravitational collapse

$$2 \cdot \frac{3}{2}\frac{M}{\mu m_H}kT - \frac{3}{5}\frac{GM^2}{R} = 0$$

這是個臨界質量

$$M_J = \rho\left(\sqrt{\frac{\pi}{G\rho}}c_s\right)^3 \approx 4\left(\frac{\rho}{10^{-19}\,\mathrm{g\ cm^{-3}}}\right)^{-1/2}\left(\frac{T}{10\mathrm{K}}\right)^{3/2}$$

雲團的質量大於此便有條件塌縮

This is the Jeans mass. If $M_{cloud} > M_{Jeans}$ ➔ collapse

In reality, thermal pressure + magnetic field + rotation + turbulence, etc.

星星也有生、老、病、死
源於塵土、歸於塵土

星際暗雲 —收縮／旋轉→ 初生星球 ＋ 扁盤 ＋ 剩下的雲氣

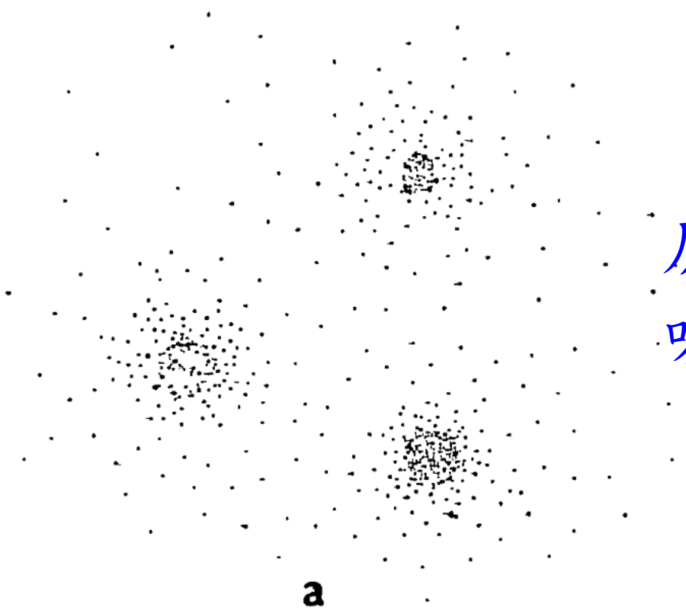
溫度上升、塵消氣散

↓

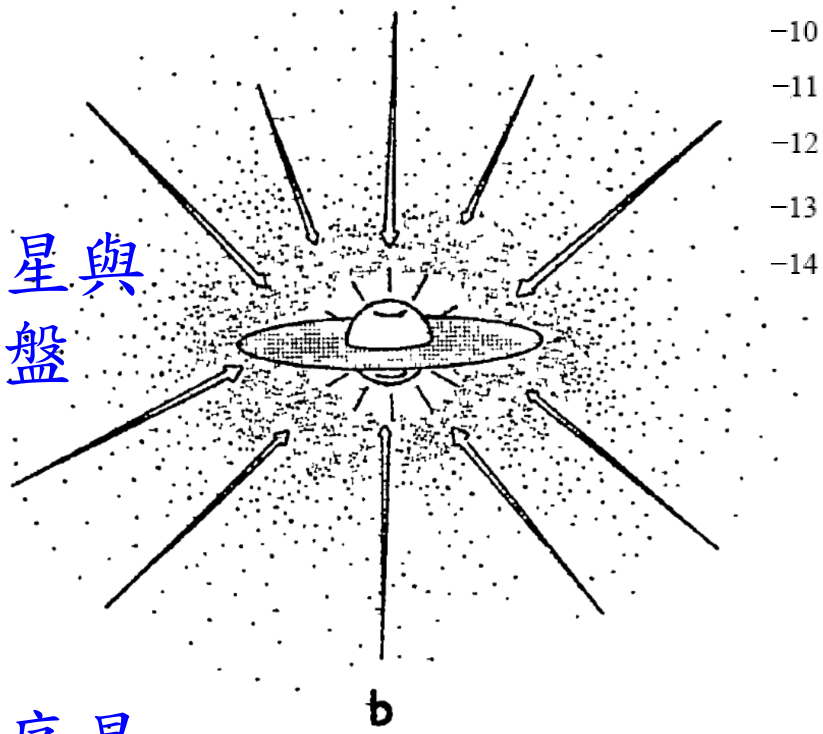
年輕太陽 ＋ 盤狀物質

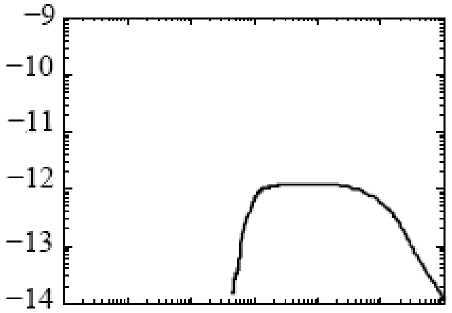
星際塵埃 → 塵塊 → 小行星 → 行星

失去支撐的
分子雲核

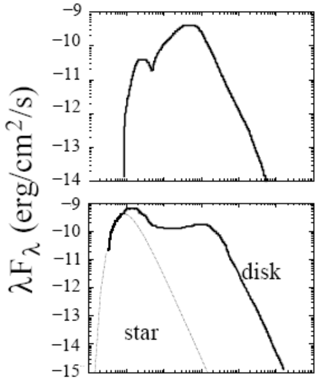


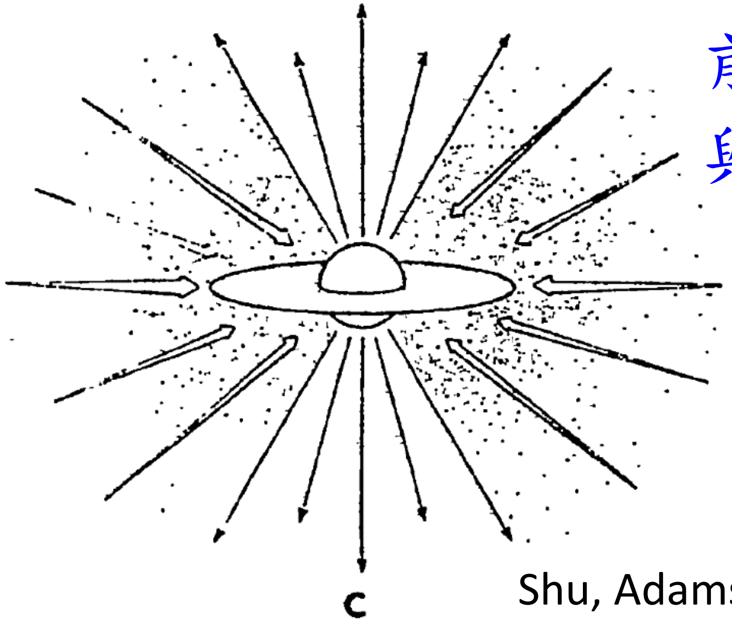
原恆星與
吸積盤



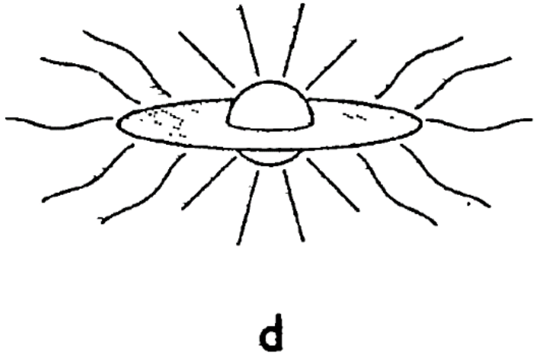


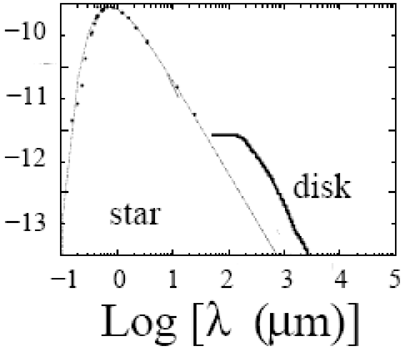
恆星風與
雙極噴流





前主序星
與環星盤





Shu, Adams, & Lizano (1987)

原恆星環星盤 (protostellar/protoplanetary disk)

- 吸積物質，使中央星體長大（物質向內）
- 帶走角動量（角動量向外）
- 盤中塵埃聚集 → 行星

那麼行星系統應該

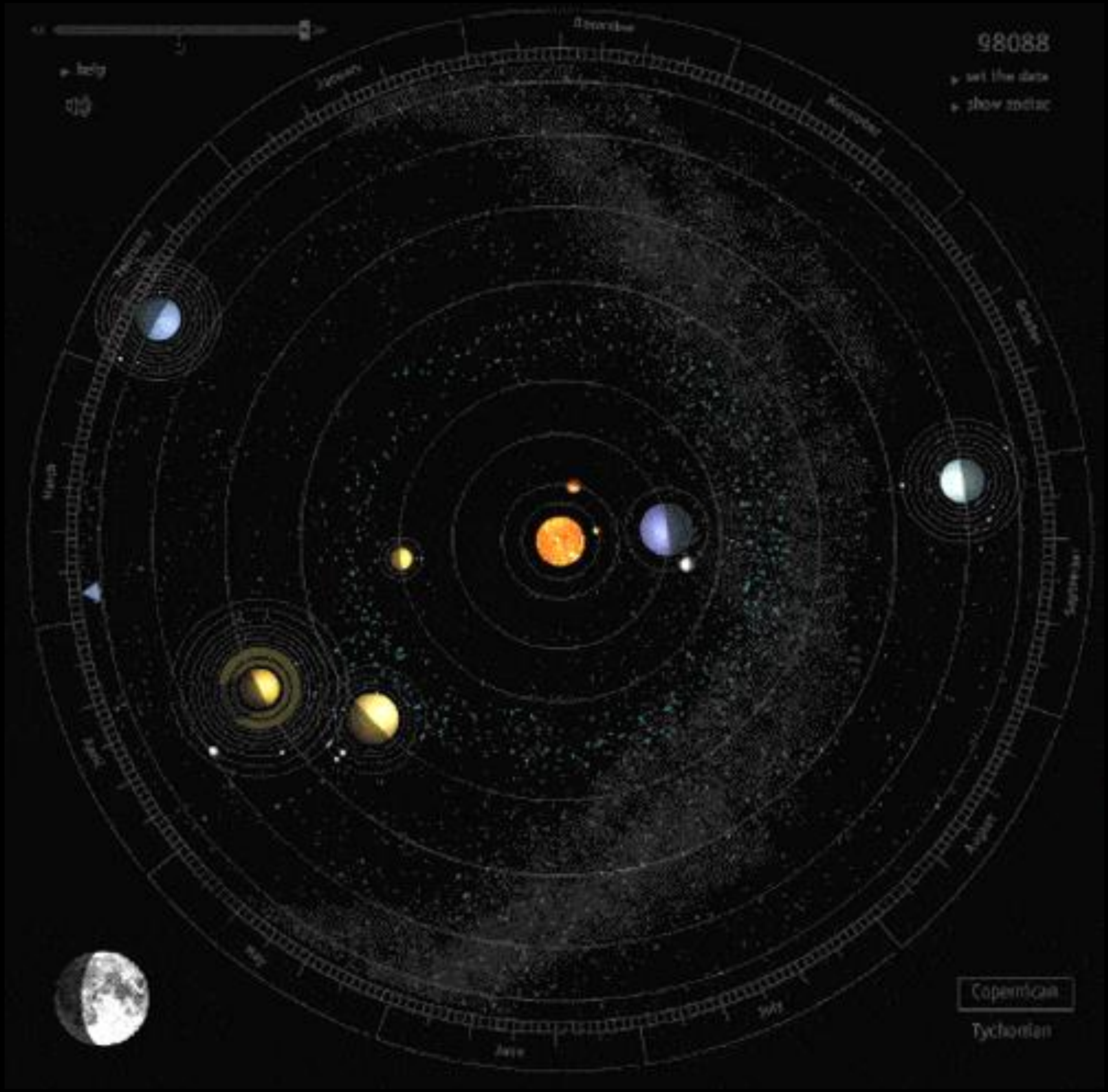
- 分布在平面上
- 公轉（及自轉）方向相同
- 圓形軌道
- 幾乎同時期形成

Solar System Overview

Overview of the Solar System

- ✓ Sun at center, 99.9% mass, 2% angular momentum
- ✓ Three types of planets
  - Inner, small, dense, and rocky (terrestrial) planets (Mercury, Venus, Earth, Mars)
  - Outer, giant, gas (jovian) planets (Jupiter, Saturn)
  - Outermost, icy giant planets (Uranus, Neptune)

- ✓All planets orbit in the same direction, almost in a common plane
- ✓Most planets spin in the same direction as their orbits, with a large range of inclinations
- ✓Giant planets have many moons; large moons orbit in the equatorial plane of their planet
- ✓A swarm of small bodies exist beyond Neptune (Edgeworth-Kuiper belt)



http://infinity-imagined.tumblr.com/post/54065841977/the-gravitational-orbit-of-any-moon-planet-star

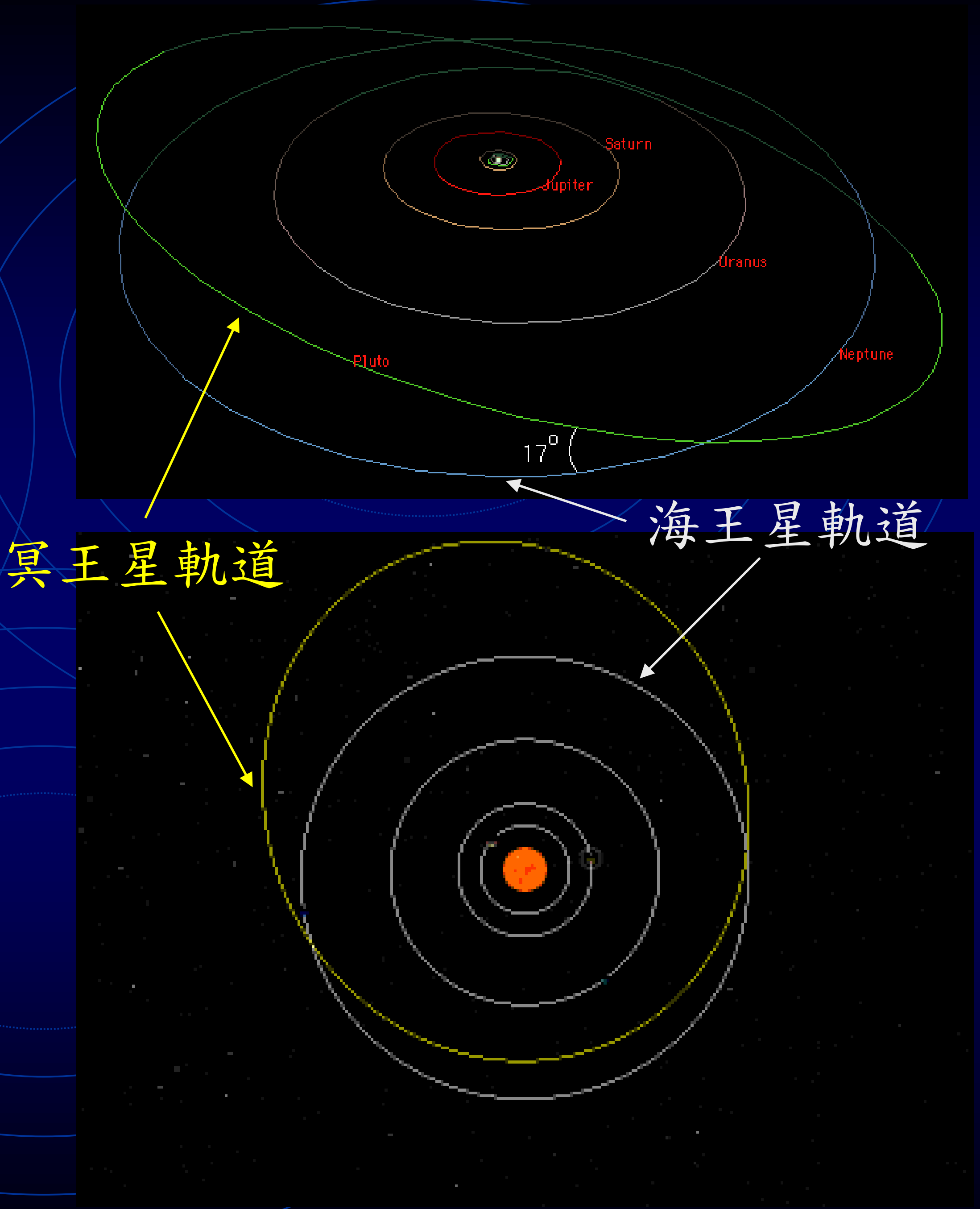
TABLE 1 Orbits of the Planets and Dwarf Planets[a]

Name	Semimajor Axis (AU)	Eccentricity	Inclination (°)	Period (years)
Mercury	0.38710	0.205631	7.0049	0.2408
Venus	0.72333	0.006773	3.3947	0.6152
Earth	1.00000	0.016710	0.0000	1.0000
Mars	1.52366	0.093412	1.8506	1.8808
Ceres[b]	2.7665	0.078375	10.5834	4.601
Jupiter	5.20336	0.048393	1.3053	11.862
Saturn	9.53707	0.054151	2.4845	29.457
Uranus	19.1913	0.047168	0.7699	84.018
Neptune	30.0690	0.008586	1.7692	164.78
Pluto[b]	39.4817	0.248808	17.1417	248.4
Eris (2003 UB_{313})[b]	68.1461	0.432439	43.7408	562.55

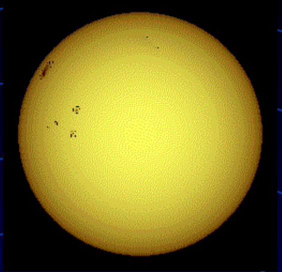
[a] J2000, Epoch: January 1, 2000.
[b] Dwarf planet.

Encyclopedia of the Solar System

行星	軌道傾角（度）	軌道離心率
水星	7.01	0.2056
金星	3.39	0.0068
地球	0	0.0167
火星	1.85	0.0934
穀神星	10.59	0.0758
木星	1.31	0.0483
土星	2.49	0.0560
天王星	0.77	0.0461
海王星	1.77	0.0097
冥王星	17.14	0.2482

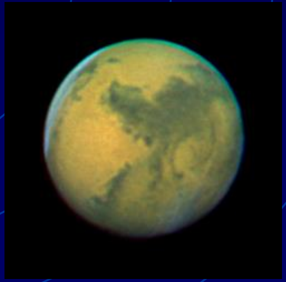


太陽系中各式天體

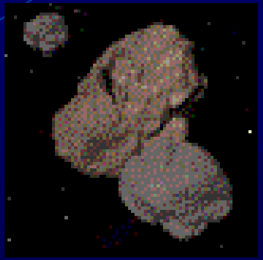
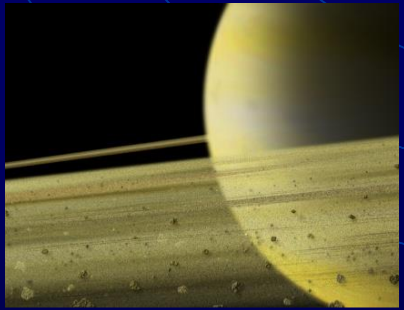



太空雲氣收縮、溫度升高、點燃核子反應 → 太陽

雲氣縮成扁盤狀、盤中灰塵凝集 → 小行星

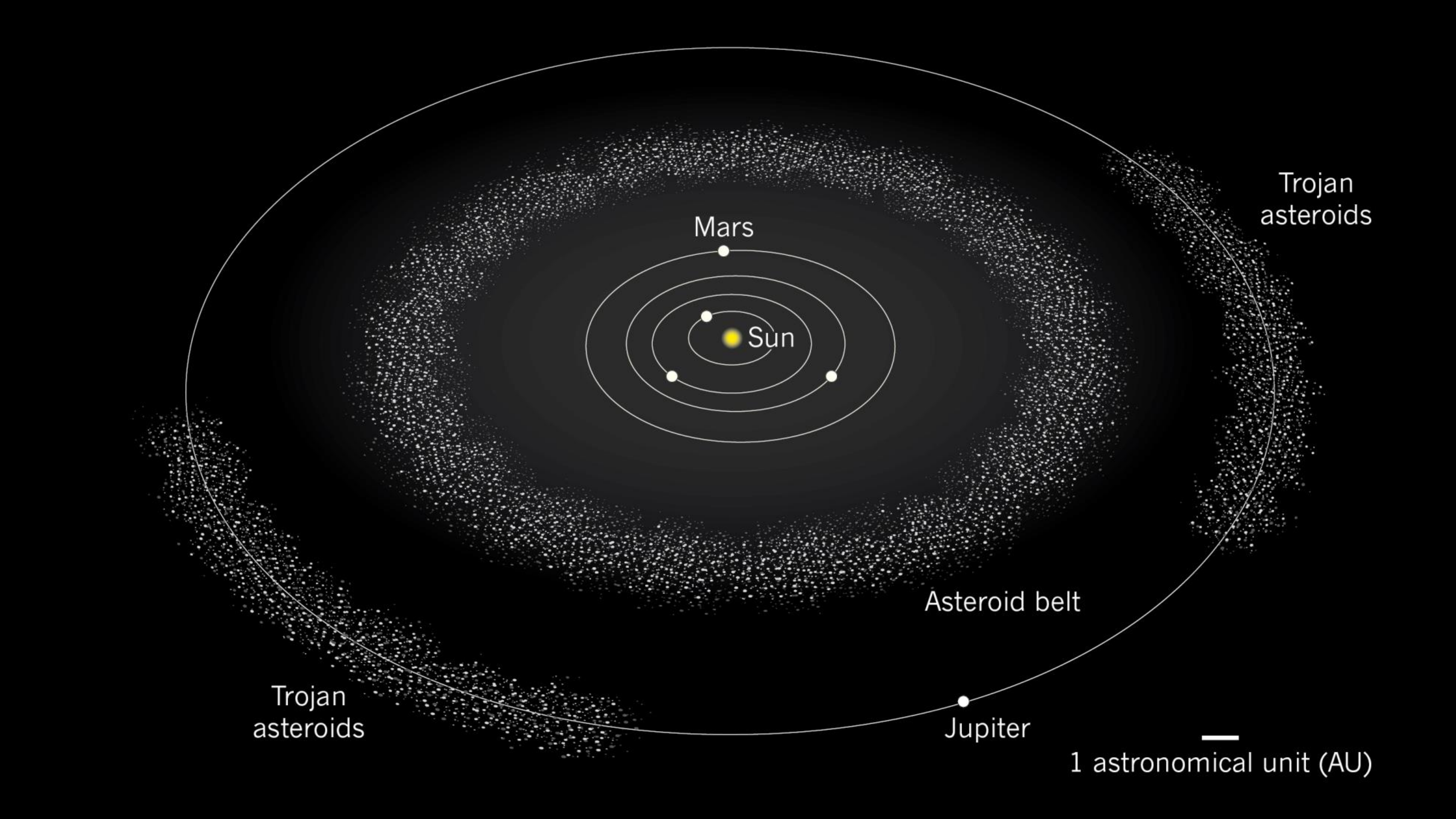
- ✓ 繼續凝集 → 行星
  - ◆ 旁邊扁盤中的灰塵凝集→ 衛星
  - ◆ 不成形 → 外行星的環

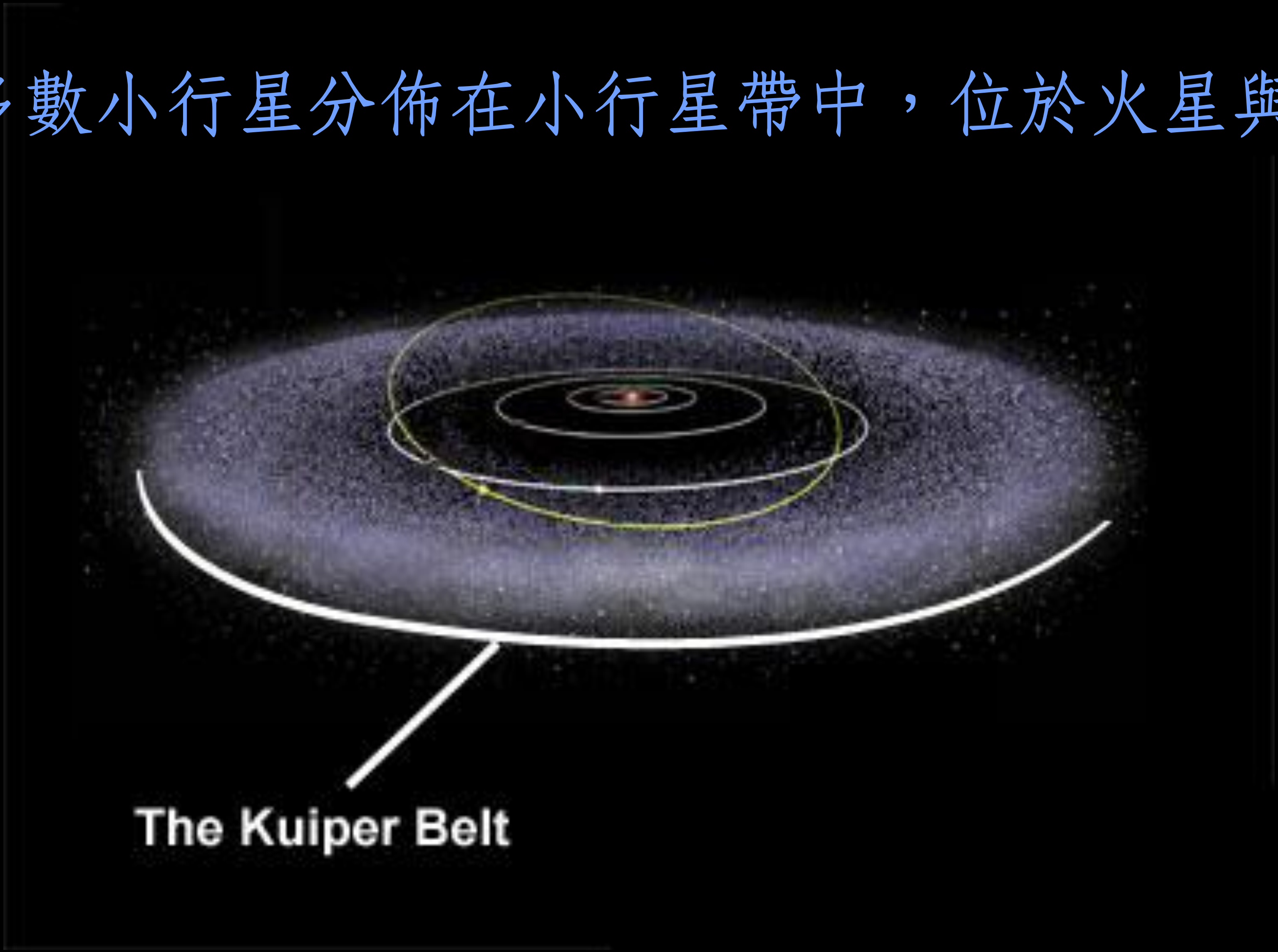

- ✓ 不成形 → 留在原地，小行星帶、古伯帶

  → 被拋到遠方 → 歐特雲中的彗星核

  進入太陽系內圍 → 彗星


Trojan asteroids
Mars
Sun
Asteroid belt
Trojan asteroids
Jupiter
1 astronomical unit (AU)

絕大多數小行星分佈在小行星帶中，位於火星與木星之間

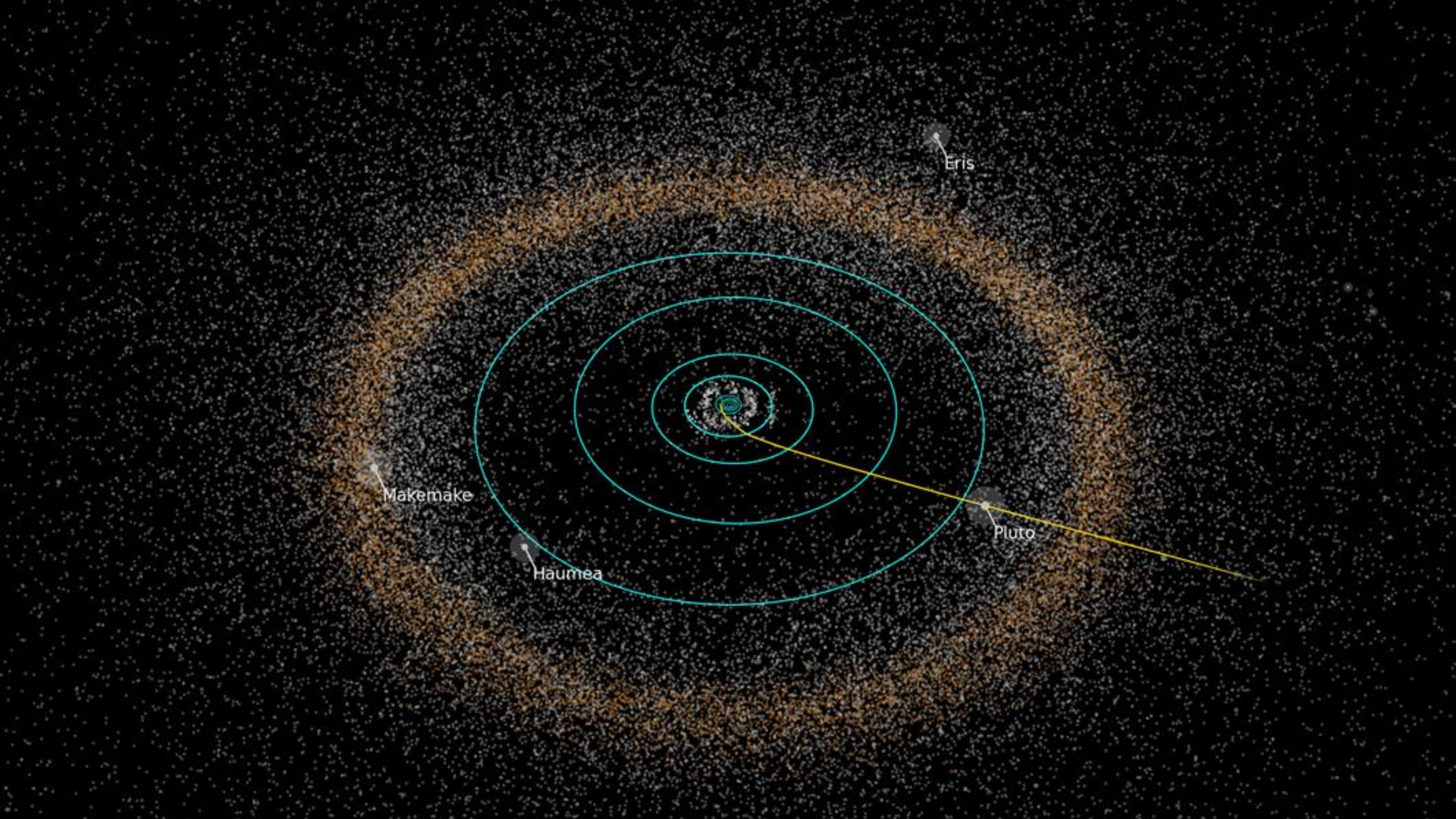


Kuiper belt objects (KBOs)

也叫做

trans-Neptunian objects (TNOs)

海王星之外也有個帶狀區域，稱為「古伯帶」，是製造行星剩下的小天體所在　目前已知超過數千顆


Eris
Makemake
Pluto
Haumea

古伯帶

短週期
(< 200 年）
彗星的故鄉

軌道接近黃道面、
方向有序

歐特雲
(Oort cloud)

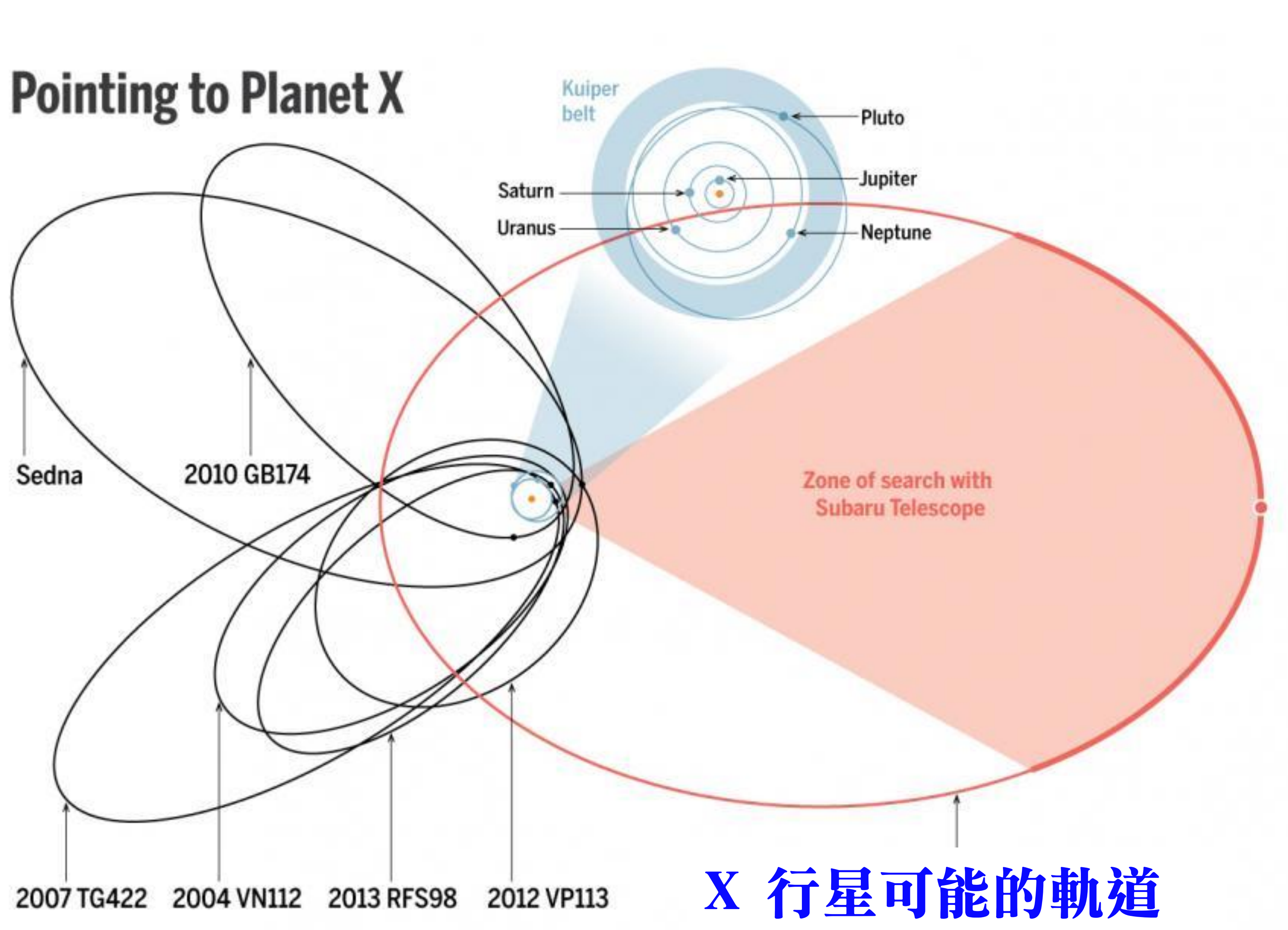
長週期彗星
的故鄉

50,000 ~ 200,000 au
(0.8 ~ 3.2 光年）

軌道狹長、方向凌亂

第九顆行星？

- 太陽系外圍天體的軌道群聚＋電腦模擬
  (2016/02) Konstantin Batygin & Mike Brown (Caltech)
  → **推論**冥王星之外有顆海王星大小的行星
- 繞日週期15,000年，近日點200 au，遠地點 600~1200 au
- 要偵測這樣的天體，亮度不是問題，很多望遠鏡（哈伯、凱克）都做得到，問題是天空很大，要往哪裡找？
- 速霸陸的視野夠大（凱克的75倍）→ 正在搜尋，預計5年內完成，且拭目以待


Pointing to Planet X
Kuiper belt
Pluto
Saturn
Jupiter
Uranus
Neptune
Sedna
2010 GB174
Zone of search with Subaru Telescope
2007 TG422
2004 VN112
2013 RFS98
2012 VP113

X 行星可能的軌道

Planet Formation

✓Planetesimals (1-100 km) --- building blocks of planets

Growth versus destruction

- Gravitational interactions → *Elliptical orbit*
- Physical collisions ←

✓If relative velocity small → coalesced

✓If relative velocity large → shattered

Large bodies: stronger grav. to sweep up debris, resisting shattering, withstanding larger impacts

Terrestrial planets formed by coalescence of rocky materials.

Giant planets formed **cores** by collisional growth as the inner planets

Once the core is large enough → accrete gas (H, He) + ices

→ **Runaway growth**

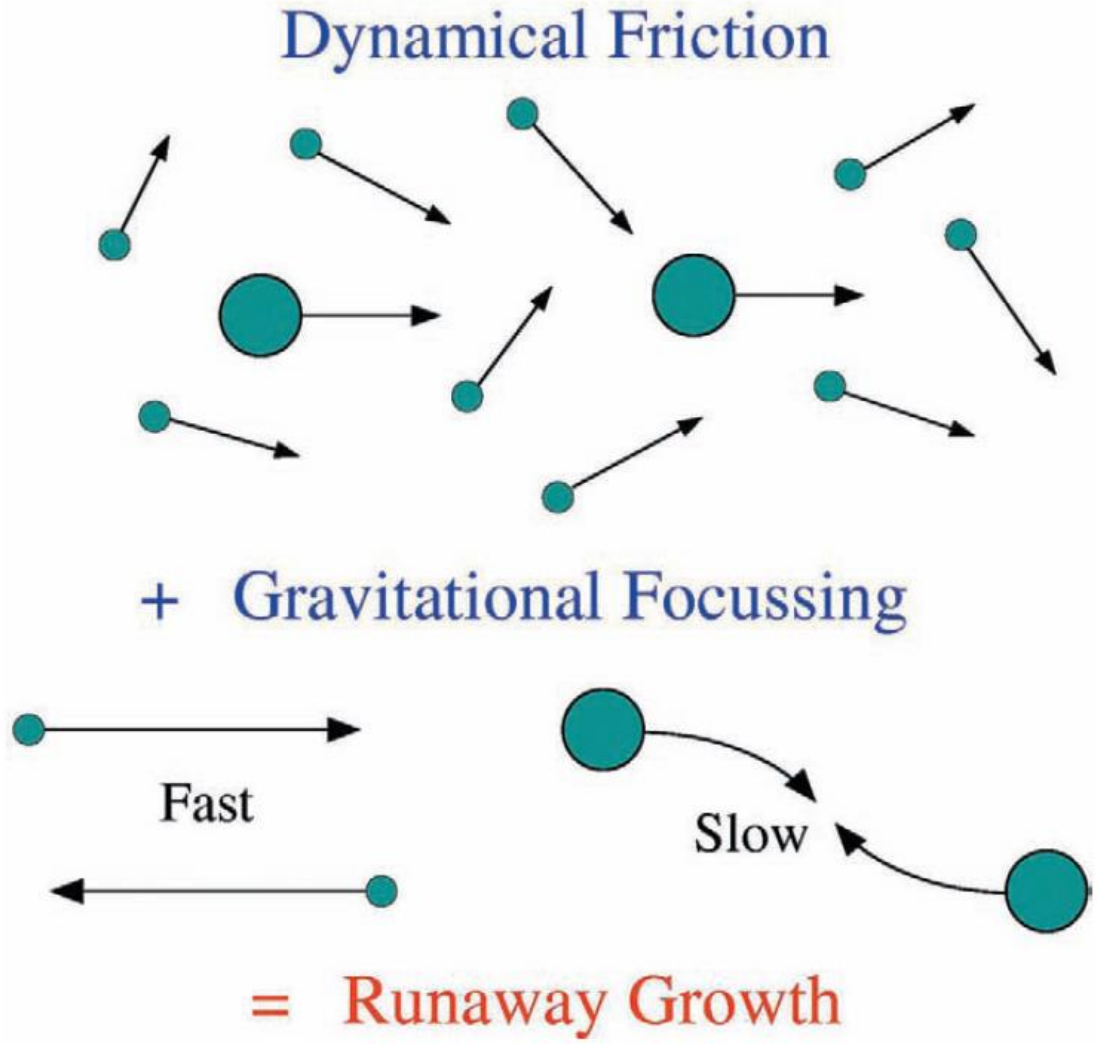


FIGURE 17 Runaway growth of a few large planetesimals takes place due to a combination of dynamical friction (which gives large planetesimals circular and coplanar orbits), and gravitational focusing (which increases the chance of a collision between bodies moving on similar orbits).

Encyclopedia of Solar System

Keplerian orbit → outer, slower, smaller shear force

→ accrete from a larger surr. region

Giant planets formed by runaway accretion of gas and ices.

Supporting evidence: giant planets have excess heavy elements relative to Sun,

Jupiter, Saturn, Uranus/Neptune = 5, 15, 300

... outer orbits had less gas available for accretion.

Timing is critical!

If collisional build-up too long → disk dissipated

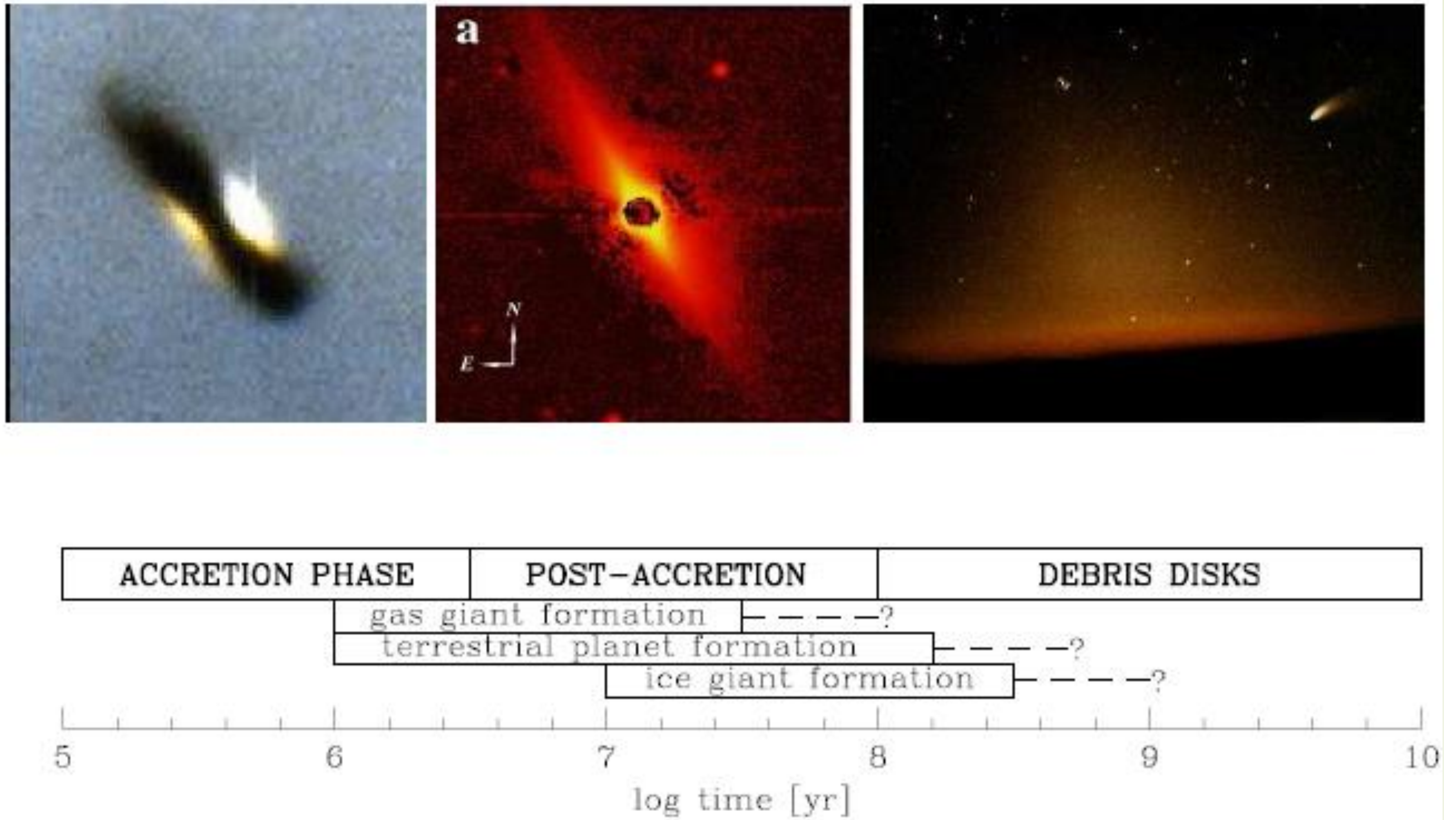
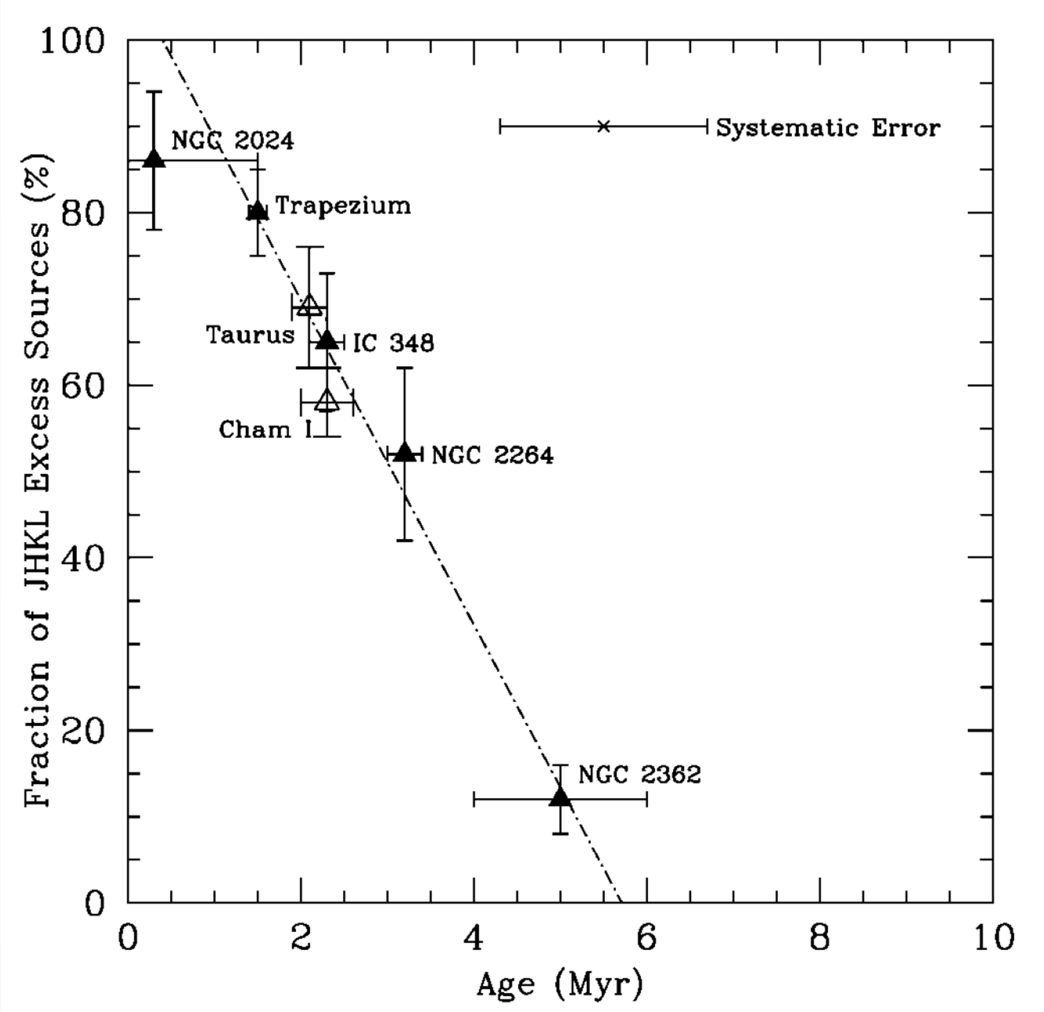


FIGURE 1. *Images of disks at various evolutionary stages scaled to a time line showing our general understanding of the basic phenomena.* Data are courtesy of J. Stauffer and B. Patten (left panel, Ori 114-426 optically thick "silhouette disk" as imaged with HST/WFPC), Kalas & Jewitt 1995 (middle panel, β Pic as imaged by a ground-based coronagraph), and P. Kalas (right panel, our own zodiacal dust disk along with a comet, as photographed from Calar Alto).

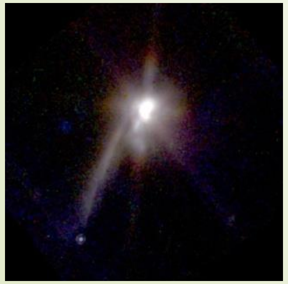
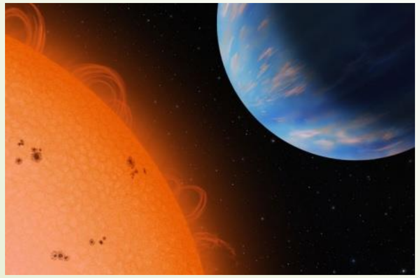
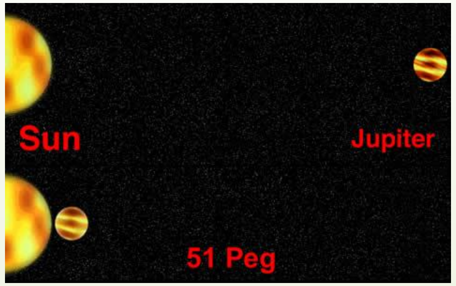
Hillenbrand (2005)

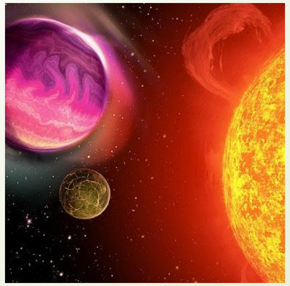
Young circumstellar disks --- where planets are formed out of --- are gone in < 10 Myrs



Haisch, Lada, & Lada (2001)

- Extrasolar planets (exoplanets) ubiquitous
  http://www.exoplanet.eu
- So far some 1000s exoplanets found
- Unlike our Solar System, there are many
  hot Jupiters → selection bias? Super Earths
- terrestrial planets yet to be found with next-generation instruments, e.g., adaptive optics, interferometry on large ground-based telescopes, ELTs




Exoplanets easier to detect at long wavelengths

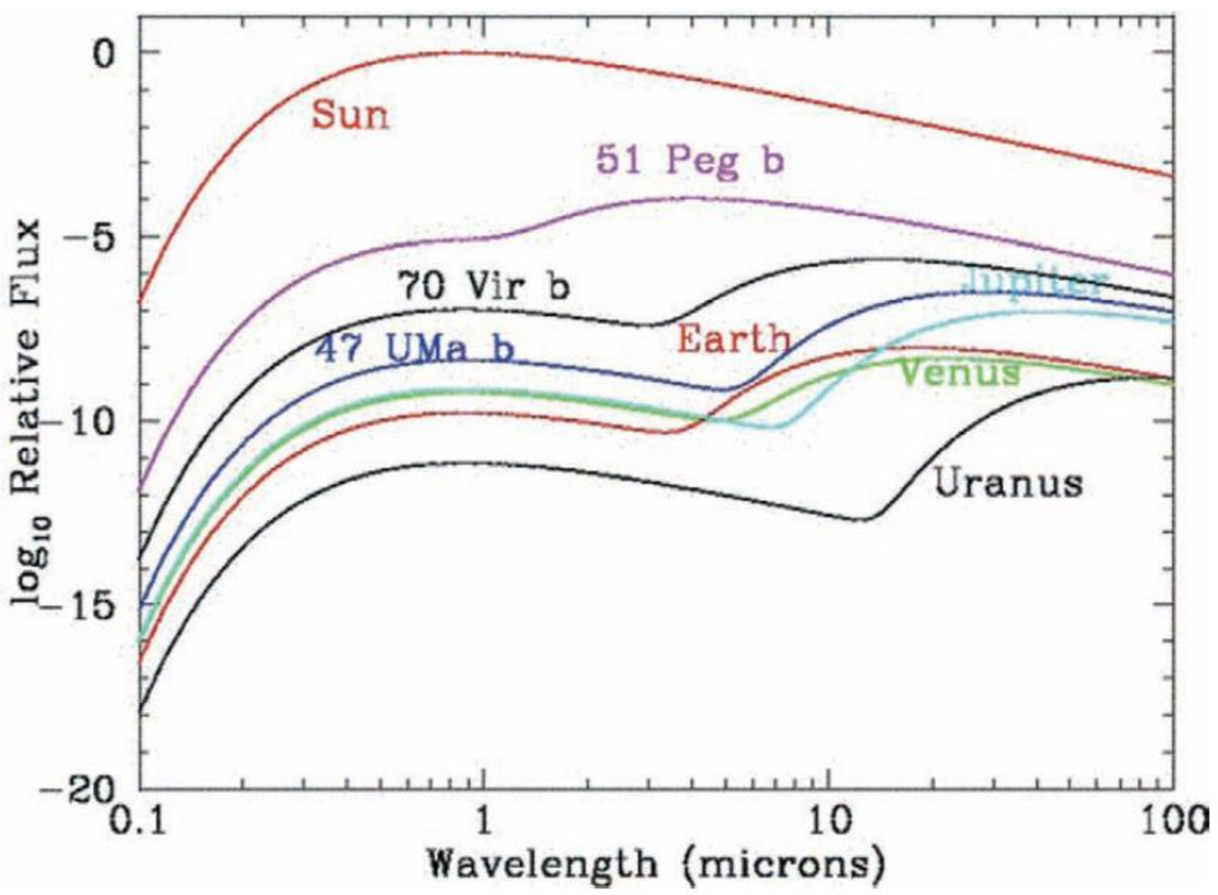
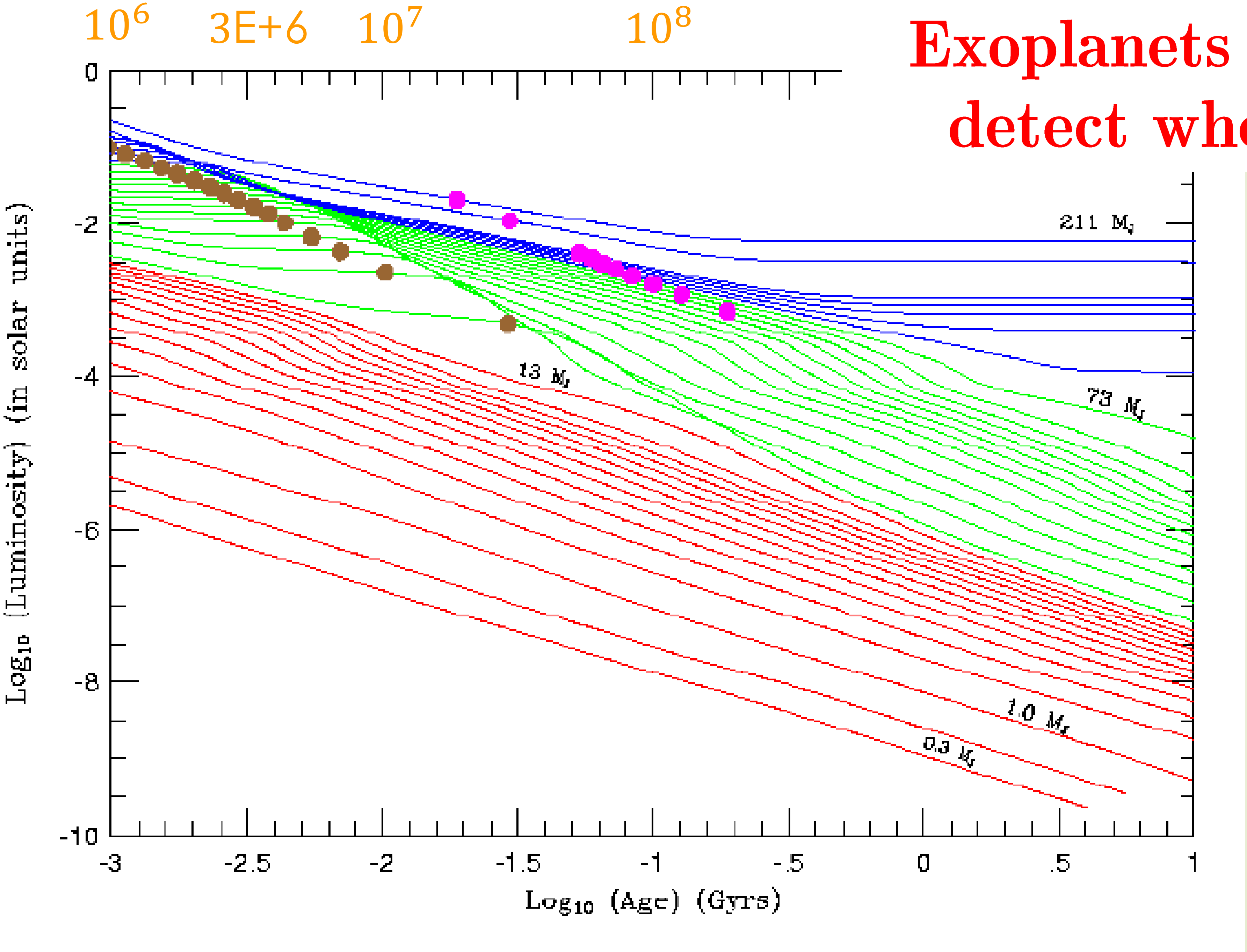


FIGURE 3 The relative flux of planets compared to the Sun's emission as a function of wavelength. Four planets of our solar system and three extrasolar planets (51 Peg b, 70 Vir b, and 47 UMa b) are shown. The difference in flux ranges from 10^{-6} to 10^{-12} in the optical (< 1 μm) and generally improves toward the infrared (> 1 μm), where the planet's thermal emission dominates.

Encyclopedia of Solar System

Exoplanets easier to detect when young



Burrows+01

結論

- 大約46億年前，太空中一團雲氣，由於引力收縮，中央形成太陽
- 環星盤內塵埃凝聚、增大 → 微行星 → 小行星 → 行星

  靠內圍行星　熱、固體、體積小、衛星少

  靠外圍行星　冷、氣體、冰體、體積大、衛星多
- 剩下的小天體 小行星帶、古伯帶

  近地、特洛依、半人馬天體、彗星