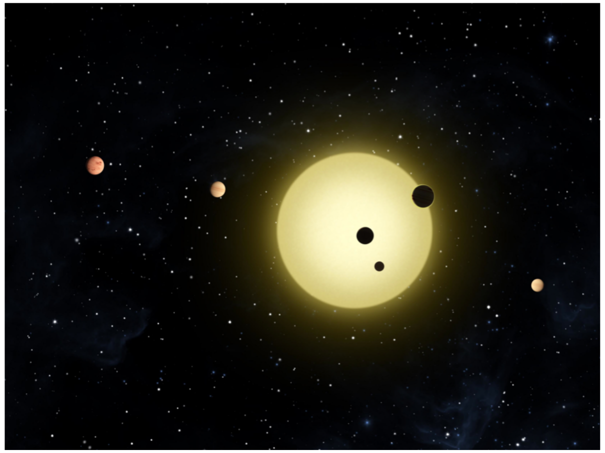
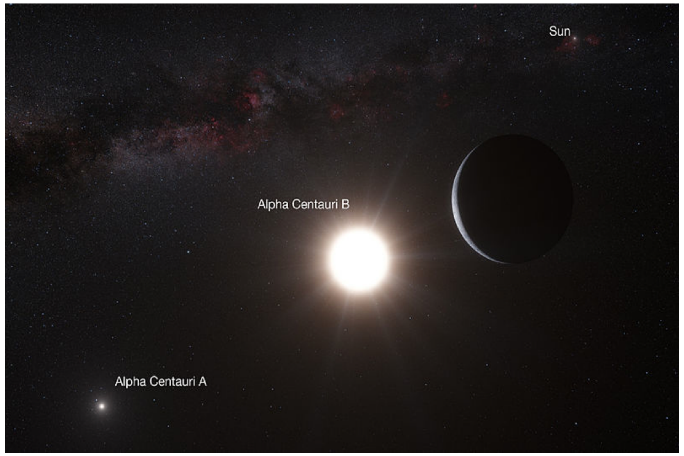
Introduction to exoplanetology

Michaël Gillon (*michael.gillon@uliege.be*)
Olivier Absil (*olivier.absil@uliege.be*)





Introduction to exoplanetology

SPAT0063-1
20hr + 10hr practical work; 4 credits

Venue
R26 classroom, B6d building
Tuesdays from 9h to 11h
Feb 8-15, March 8-15-22-29, Apr 19-26, May 3-10 (May 17 = back-up date)

Broadcast ▶Teams (connection details to be sent by the Lecturer)
Recordings ▶ Uliege podcast uliege repository
Slides ▶ http://www.astro.ulg.ac.be/~gillon/MG_Main_Fr/Cours.html

Lecturers:
Dr. Michaël Gillon (ExoTIC, michael.gillon@uliege.be, B5c, -1/1)
Dr. Olivier Absil (PSILab, olivier.absil@uliege.be, B5c, +2/19)

Assistants for practical work:
Mrs Mathilde Timmermans (ExoTIC, mathilde.timmermans@doct.uliege.be, B5c, -1/2)
Dr. Francisco Pozuelos (ASTA + ExoTIC, fpozuelos@uliege.be, B5c, +1/15)

Introduction to exoplanetology

80% of final score: oral examen about content of the lecture

Knowledge of general concepts and facts (surrounded in red)

Important formula are also surrounded in red, e.g.

$$\boxed{Q = \frac{\sigma_c \Omega}{\pi G \Sigma_p} < 1}$$

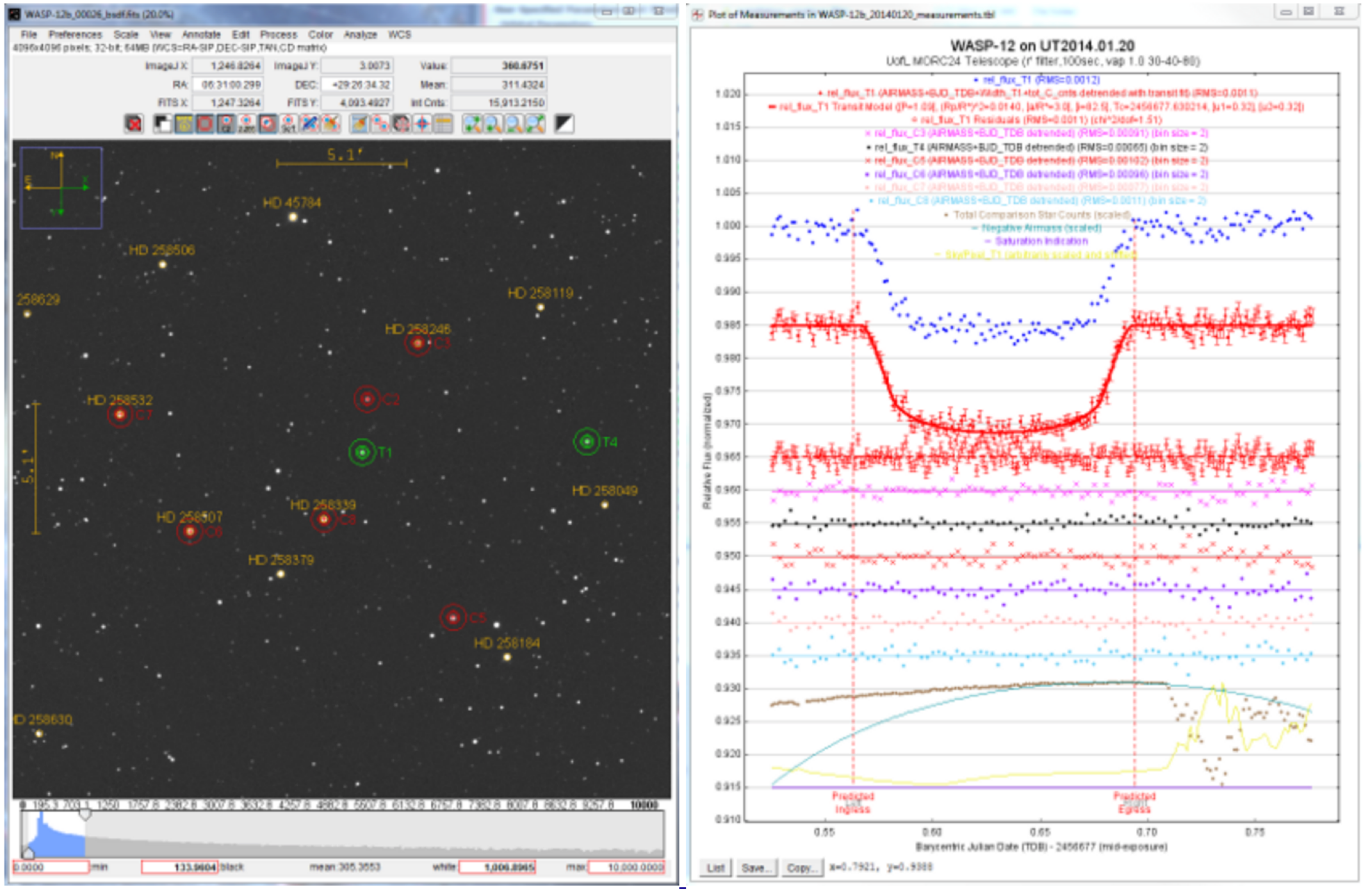
20% of final score: practical work report

See talk by M. Timmermans & F. Pozuelos

Introduction to exoplanetology

<u>Preparing the practical work: installation of the AstroImageJ pipeline</u>

https://www.astro.louisville.edu/software/astroimagej/



Problem? contact Francisco Pozuelos

Introduction to exoplanetology

Course schedule

8/2 - General introduction + introduction to practical work

15/2 - Formation of the solar system + introduction to AstroImageJ

8/3 - Planetary dynamics

15/3 - Indirect detection methods (RVs, astrometry, timings, microlensing)

22/3 - Transits part 1

29/3 - Transits part 2

19/4 - Direct imagery part 1

26/4 – Direct imagery part 2

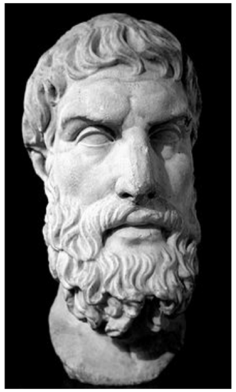
3/5 – Protoplanetary disks

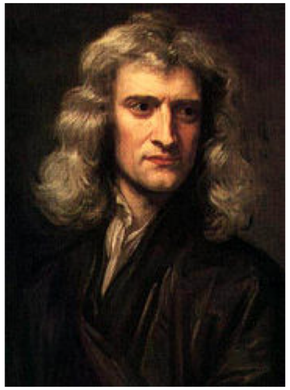
10/5 – Structure and atmospheric models + habitability

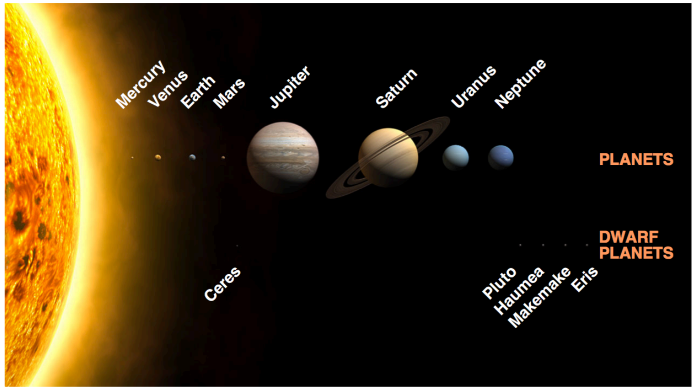
17/5 – Back-up date

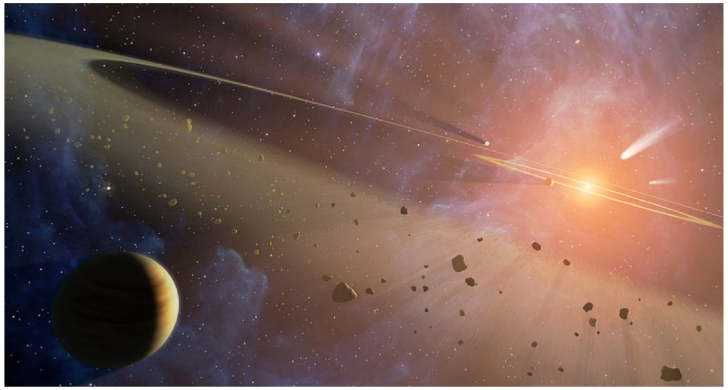
Introduction to exoplanetology. I.

Introduction and historical perspectives – definitions









Michaël Gillon (*michael.gillon@uliege.be*)

At the dawn of astronomy: wandering stars

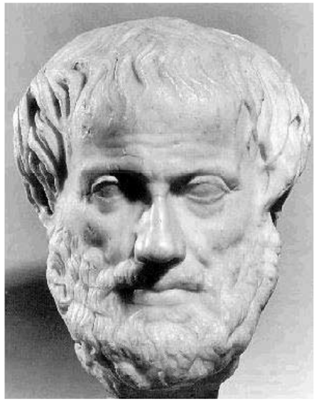
Five naked-eye “stars” show a complex movement (even retrograde) relative to the celestial sphere

Mars, Mercury, Jupiter, Venus & Saturn

= planets

Origin: *planêtês astêrês* (grec) = « wandering stars »

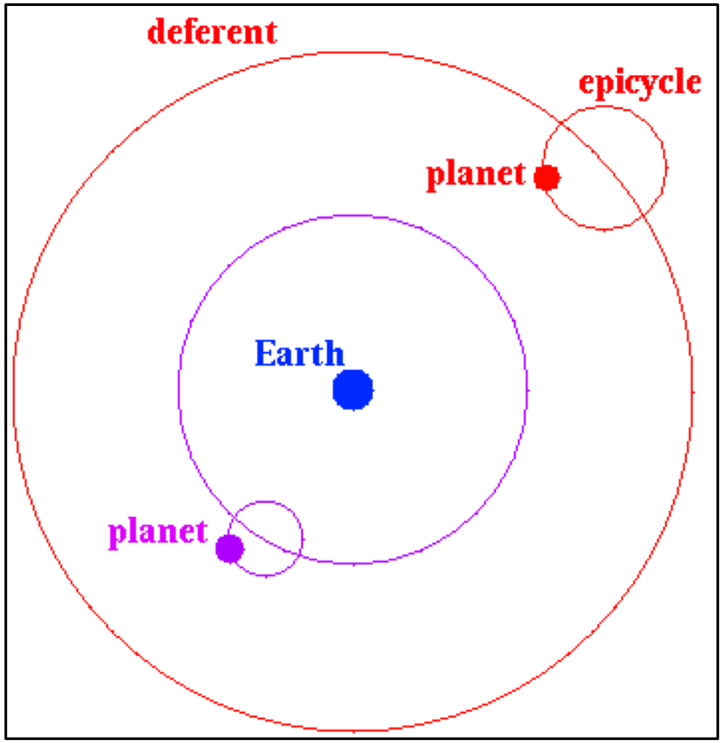
The geocentric models of the Universe



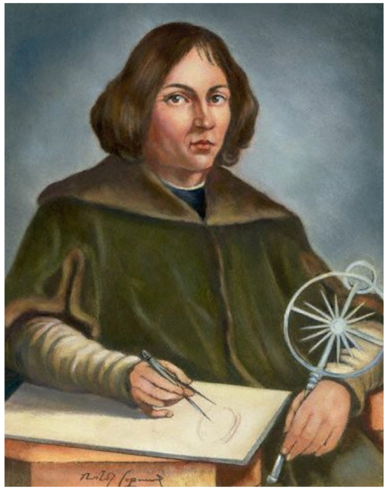
Aristotle
(384 -322 BC)

Hipparchus
(190 -120 BC)

Ptolemy
(90-168)



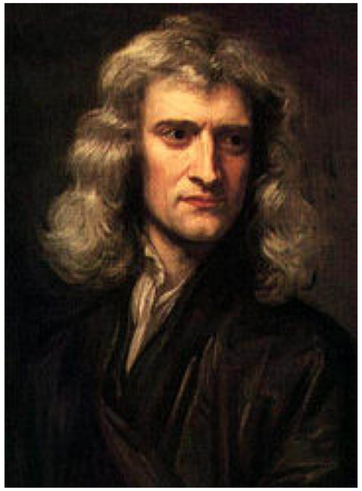
The Copernican Revolution



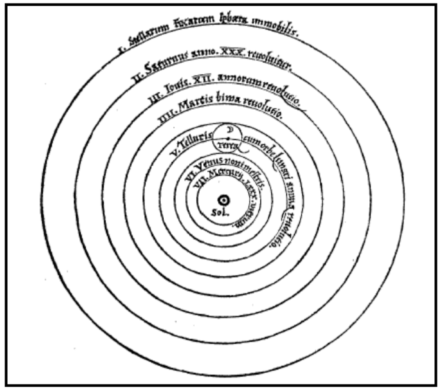
Copernicus
(1473-1543)

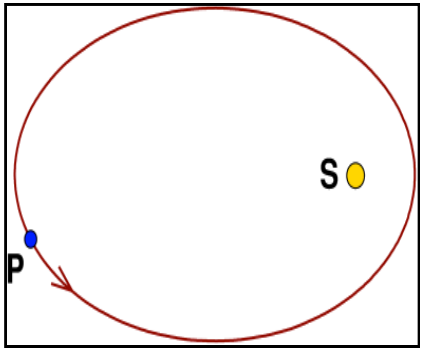
Galileo
(1564-1642)

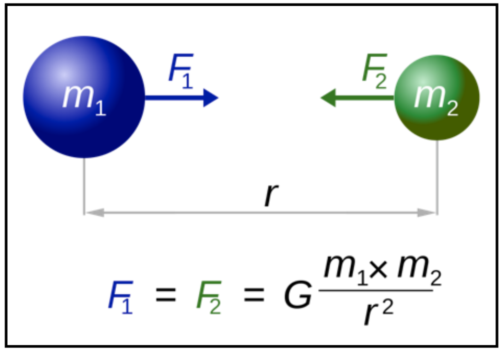
Kepler
(1571-1630)



Newton
(1643-1727)







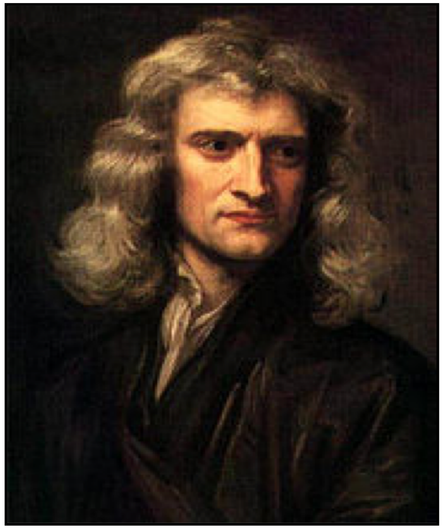
Stars: suns circled by planets?

« There are countless suns and countless earths all rotating round their suns in exactly the same way as the seven planets of our system»

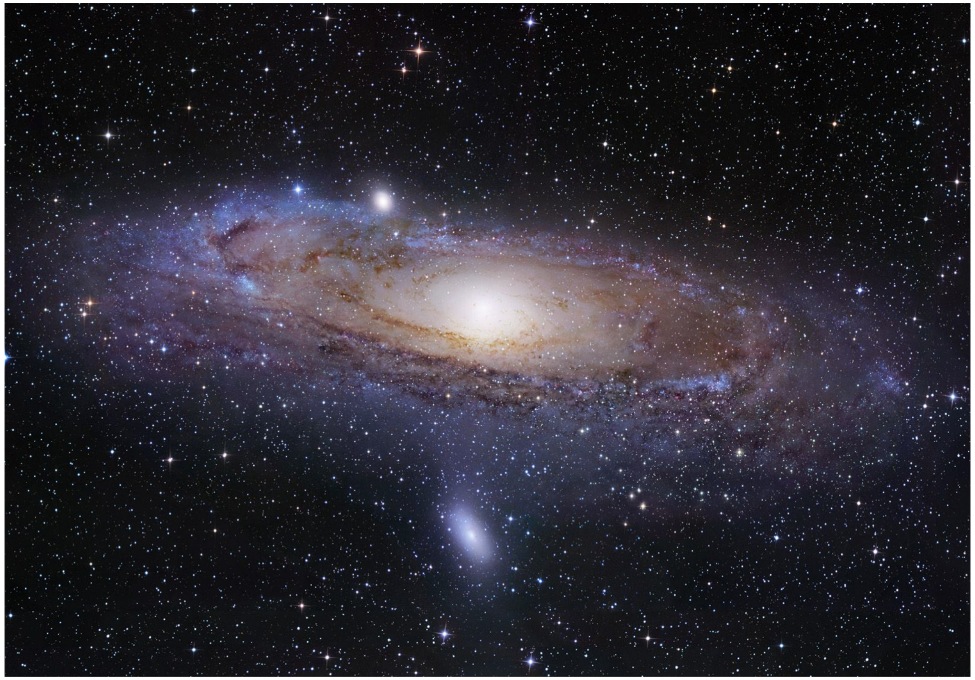
Giordano Bruno
(1548 -1600)

« And if the fixed stars are the centers of similar systems, they will all be constructed according to a similar design and subject to the dominion of One. »

Isaac Newton
(1643-1727)

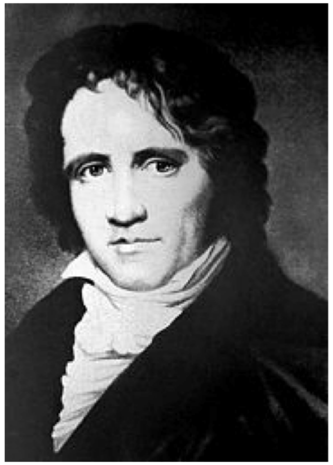


The Sun is one star among billions

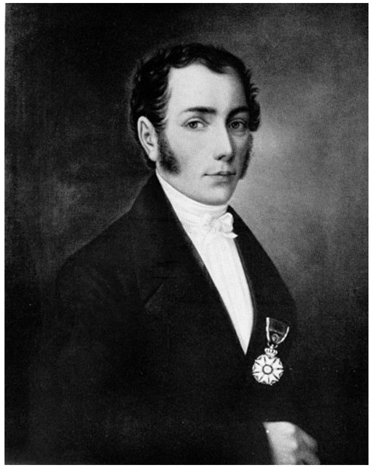


Galileo
(1564-1642)

Thomas Wright
(1711 -1786)

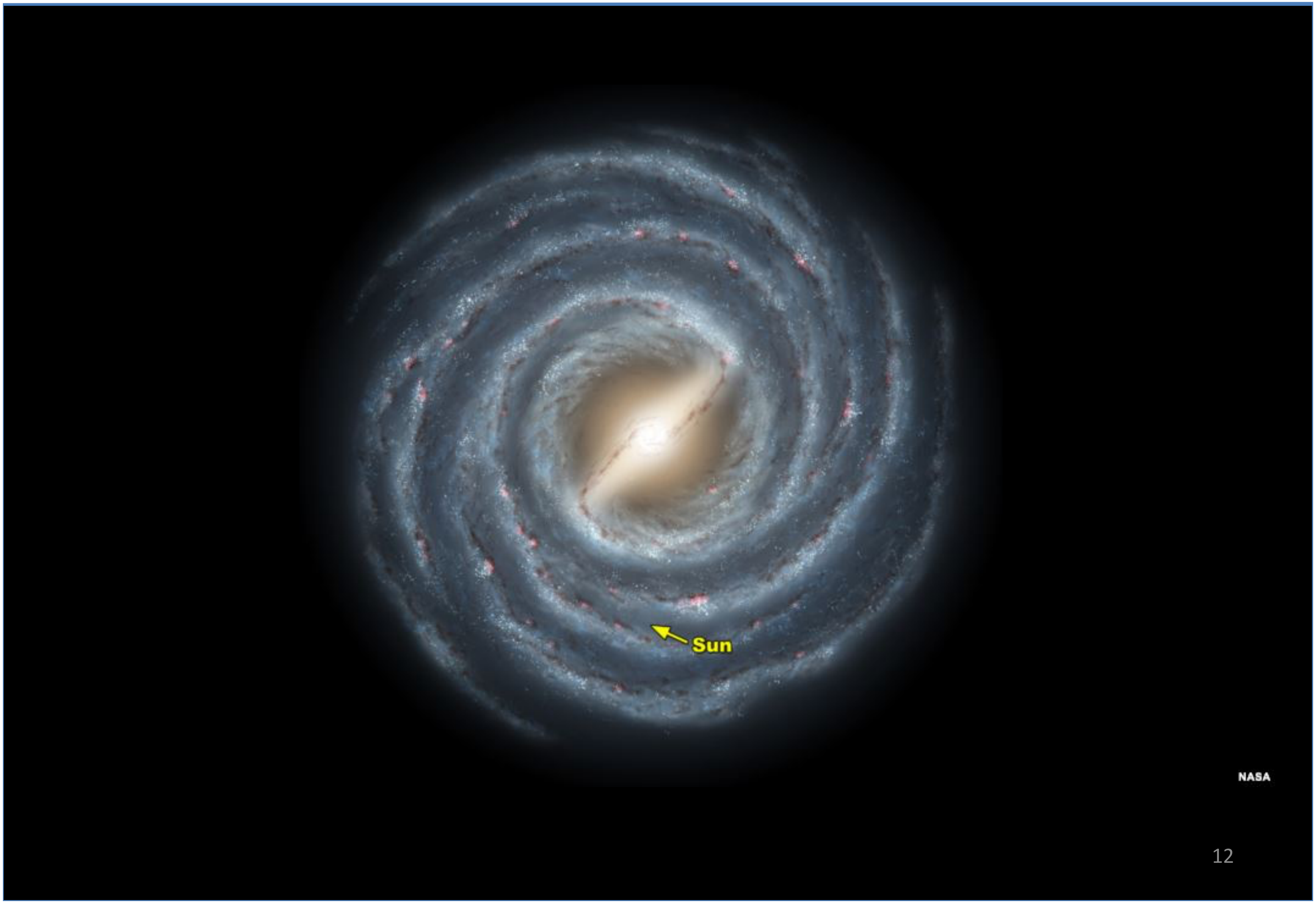


Friedrich W. Bessel
(1784 -1846)



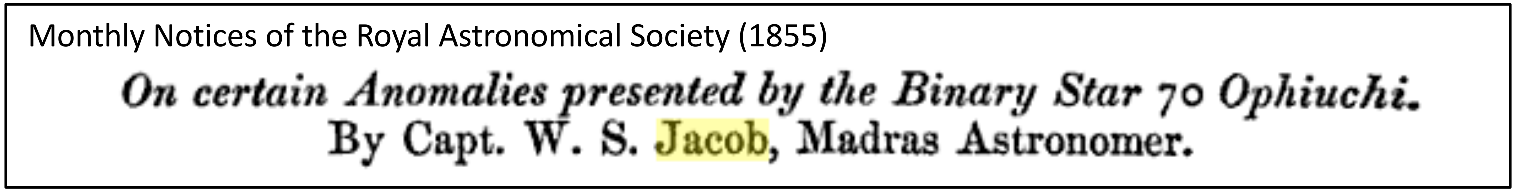
Joseph von Fraunhofer
(1787 -1827)

The Sun is one star among billions



The first searches for exoplanets

- **70 Opiuchi – binary star at 17 light-years**



Monthly Notices of the Royal Astronomical Society (1855)

On certain Anomalies presented by the Binary Star 70 Ophiuchi.
By Capt. W. S. Jacob, Madras Astronomer.

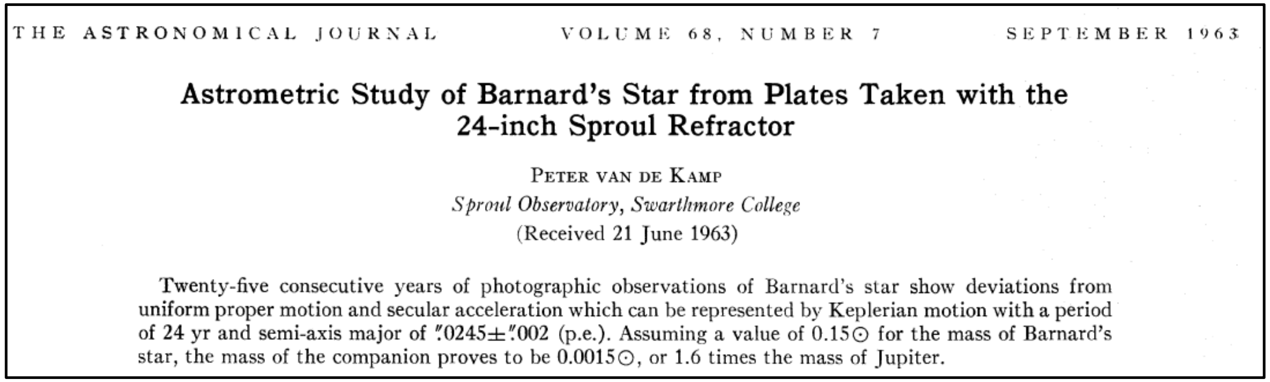
First claim of exoplanet detection … in 1855!

Orbital period = 16 years

Other claims for the same system: Thomas J.J. See (1899) & Dirk Reuyl (1943)

- **Other stars: Barnard's star, Lalande 21185, 61 Cygni, etc**

Peter van de Kamp
(1901-1995)



THE ASTRONOMICAL JOURNAL VOLUME 68, NUMBER 7 SEPTEMBER 1963

Astrometric Study of Barnard's Star from Plates Taken with the
24-inch Sproul Refractor

Peter van de Kamp
Sproul Observatory, Swarthmore College
(Received 21 June 1963)

Twenty-five consecutive years of photographic observations of Barnard's star show deviations from uniform proper motion and secular acceleration which can be represented by Keplerian motion with a period of 24 yr and semi-axis major of $''.0245 \pm ''.002$ (p.e.). Assuming a value of $0.15\odot$ for the mass of Barnard's star, the mass of the companion proves to be $0.0015\odot$, or 1.6 times the mass of Jupiter.

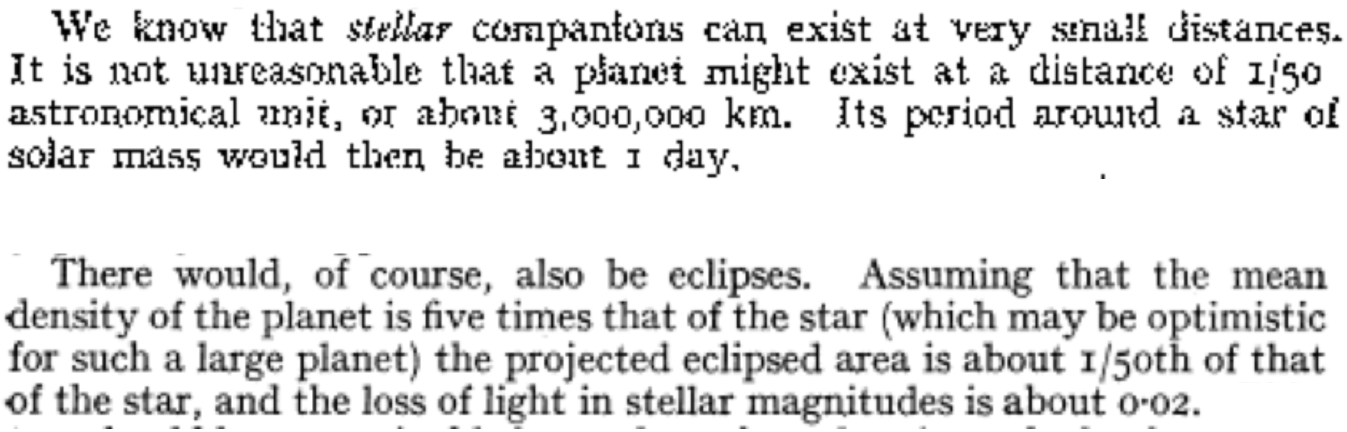
All these detections were disproven

Otto Struve, the visionary

(1897-1963)

Proposal for a project of high-precision stellar radial velocity work

The Observatory, Vol. 72, p. 199-200 (1952)



We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02.

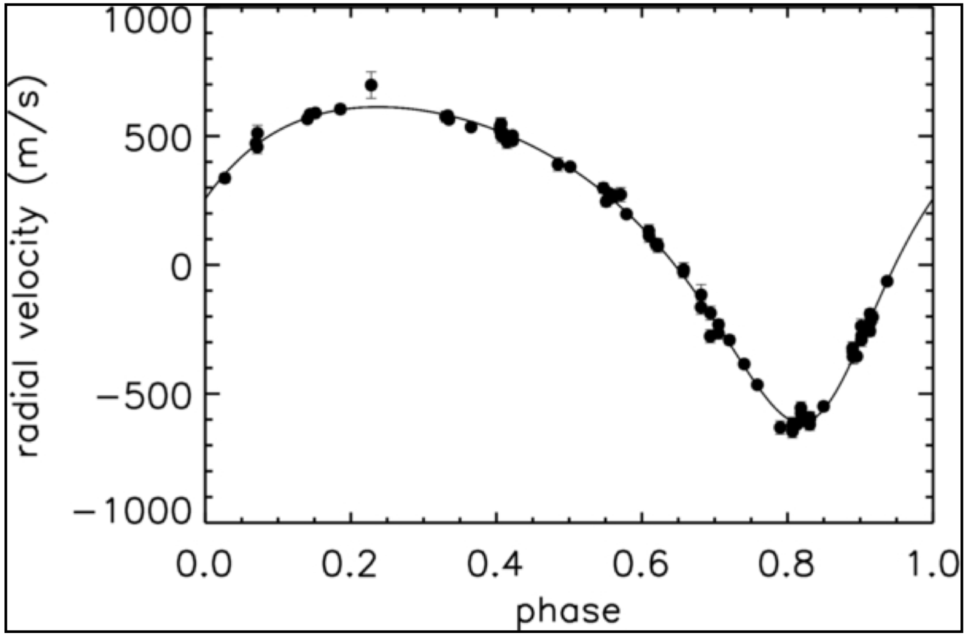
Struve proposed in 1952 to use the radial velocity and transit methods to detect short-period exoplanets

1989: almost there!

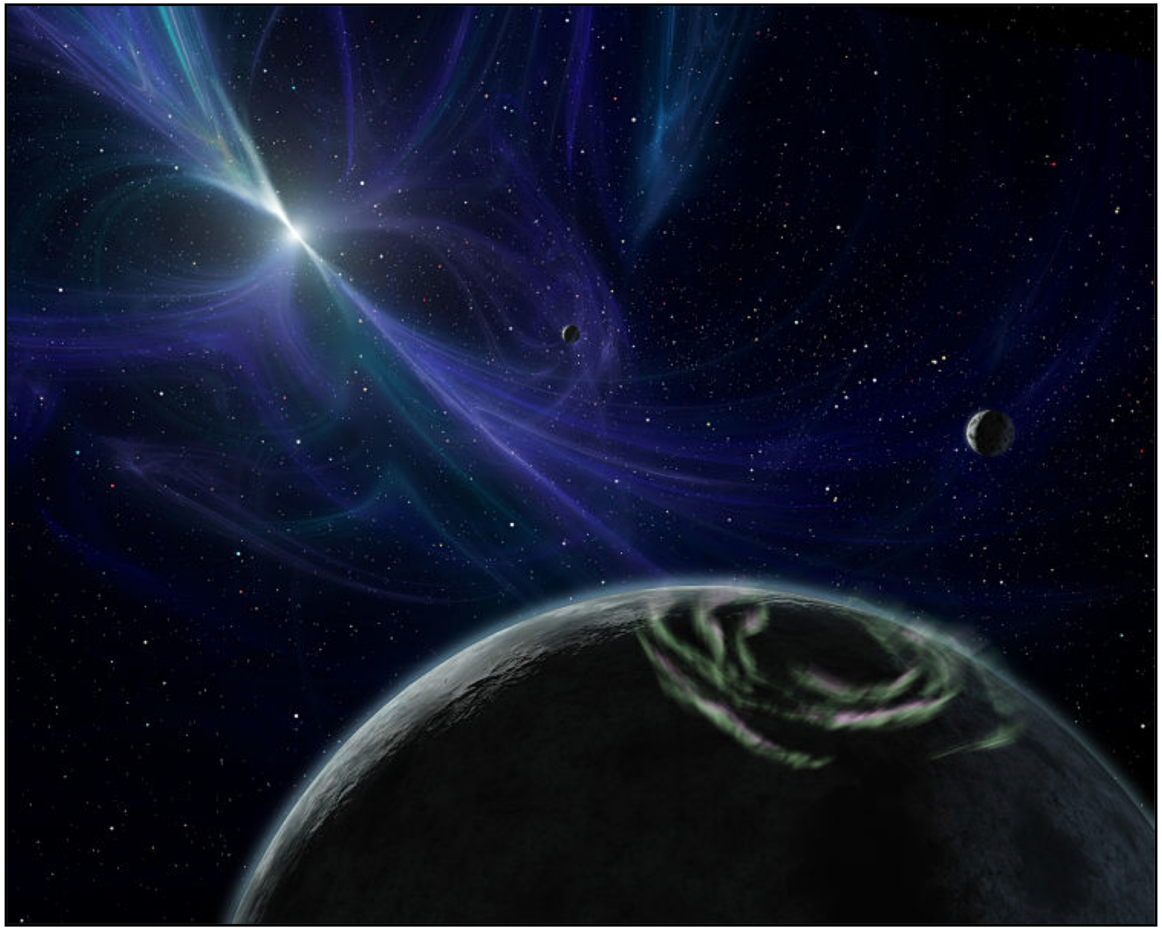
HD114762
132 light-years
Coma Berenices

David Latham (Harvard)

Orbital period = 84 days
Minimal mass = 11 $M_{Jupiter}$
HD114762b
Classified as brown dwarf



1992: the first exoplanets!



Millisecond pulsar
PSR1257+12

Virgo constellation

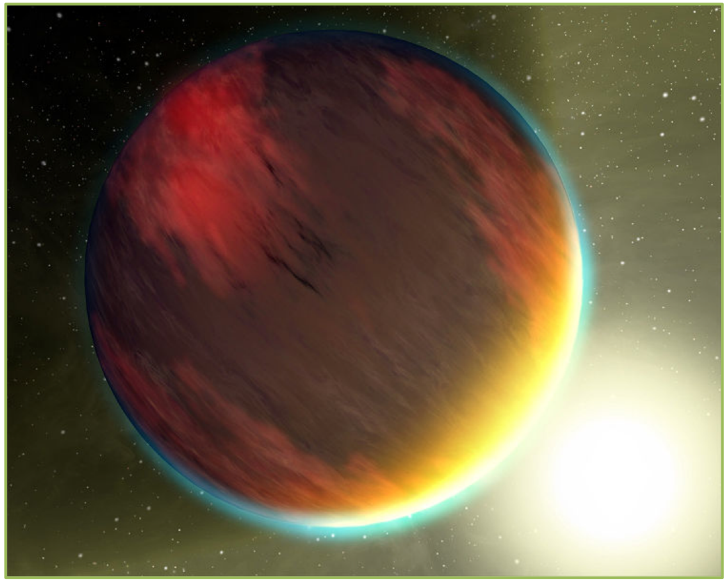
Wolszczan & Frail

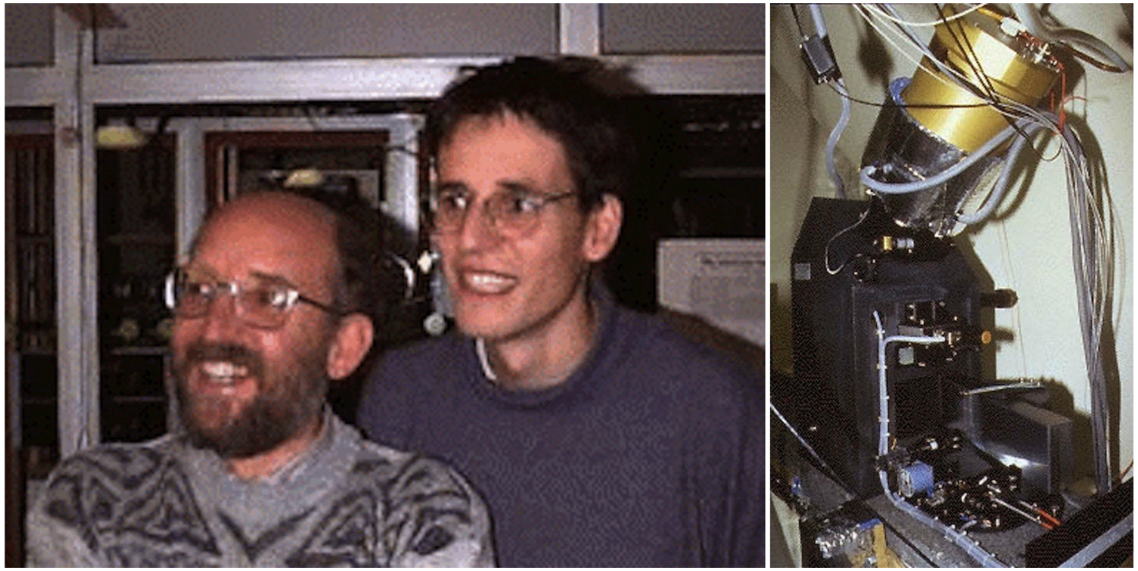
Radio observations (Arecibo)

2 planets ≥ 3 M_{Earth}

Second generation planets?

1995: the first exoplanet around a Sun-like star



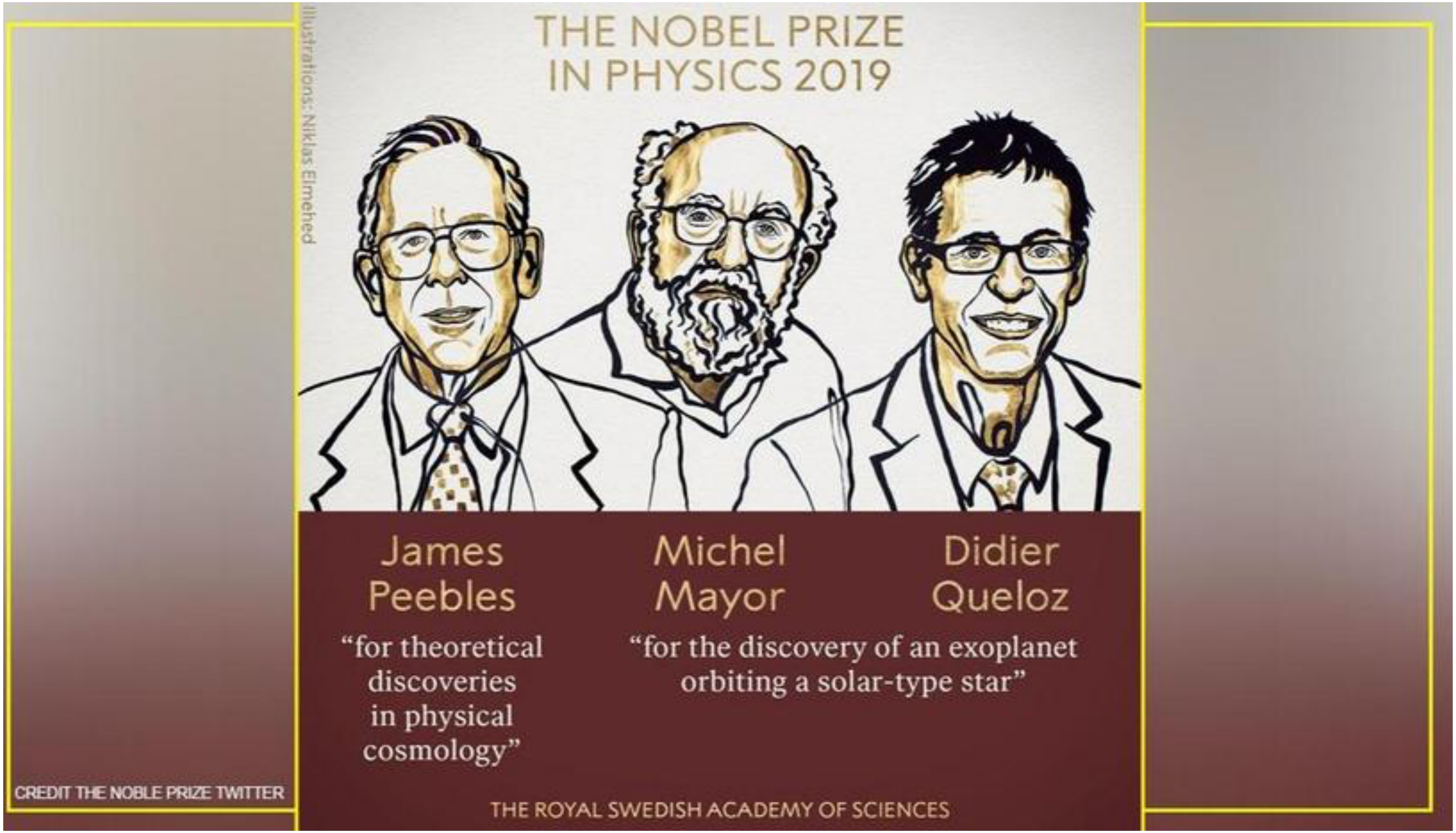


51 Pegasi b :

- $M \geq 0.5\ M_{\text{Jupiter}}$
- $P = 4.2$ days
- $a = 0.053$ *au*

Michel Mayor & Didier Queloz
(Geneva Observatory)
ELODIE spectrograph at Observatoire de Haute-Provence (France)

1995: the first "genuine" exoplanet



Illustrations: Niklas Elmehed

THE NOBEL PRIZE
IN PHYSICS 2019

James
Peebles

"for theoretical
discoveries
in physical
cosmology"

Michel
Mayor

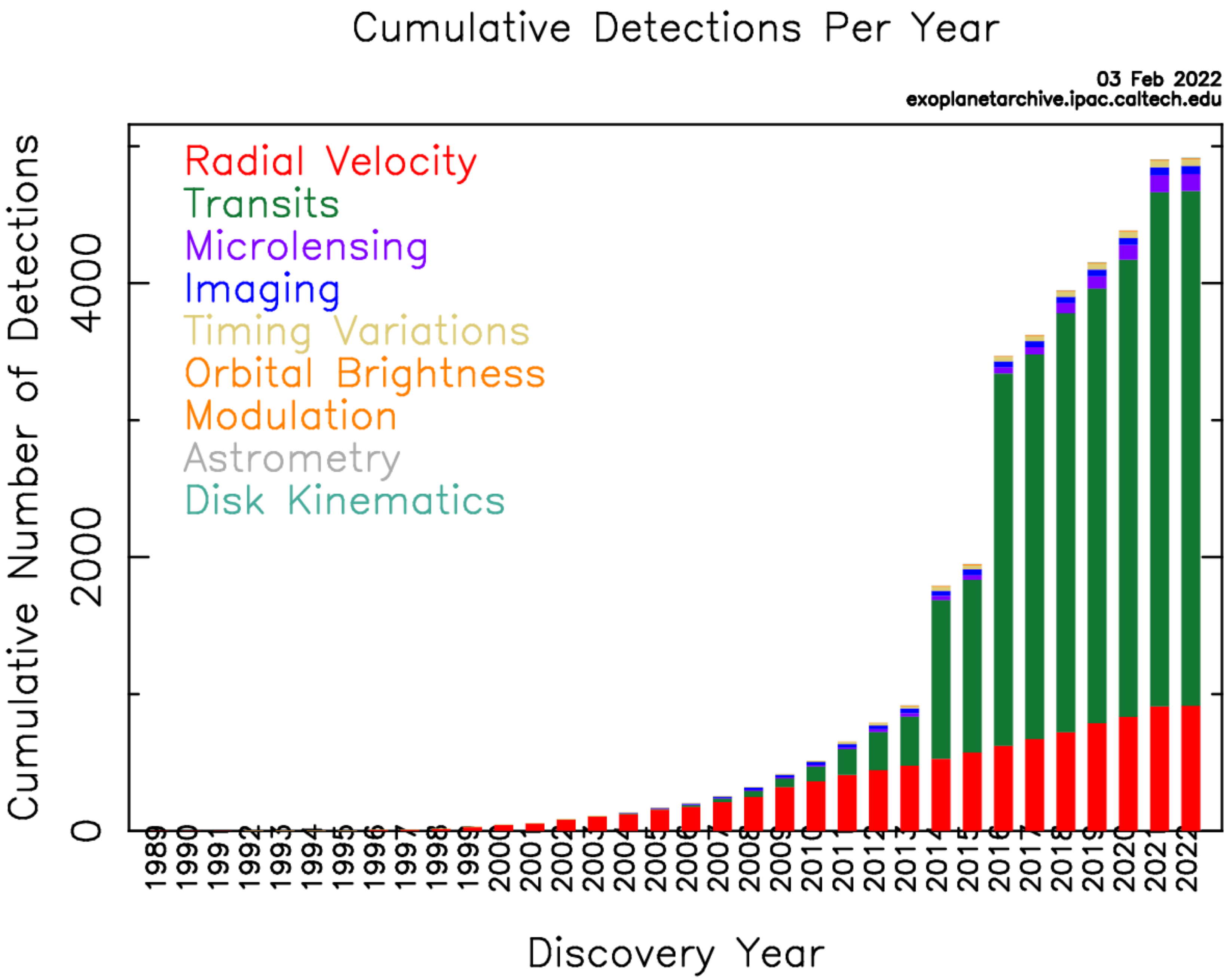
Didier
Queloz

"for the discovery of an exoplanet
orbiting a solar-type star"

THE ROYAL SWEDISH ACADEMY OF SCIENCES

CREDIT THE NOBLE PRIZE TWITTER

The exoplanet era



Planet and exoplanet: IAU definitions

Definition of a planet by the International Astronomical Union (IAU) – 2006 :

Celestial body which

(1) is in orbit around the Sun

(2) has sufficient mass to assume hydrostatic equilibrium (a nearly round shape), and

(3) has « cleared the neighbourhood » of its orbit

If only (1) and (2) fulfilled: dwarf planet (ex. Pluto, Eris, Ceres)

Planet and exoplanet: IAU definitions

Exoplanet: Working definition by the IAU – 2003:

Object with a mass below 13 Jupiter masses (M_J) that orbits one or several stars (or stellar remnants)

13 $M_J \approx$ limiting mass for thermonuclear fusion of deuterium. Between 13 M_J and 0.07 $M_\odot$ (limiting mass for fusion of ^{1}H): **brown dwarf**

Free-floating objects with $M < 13\ M_J$: sub-brown dwarf

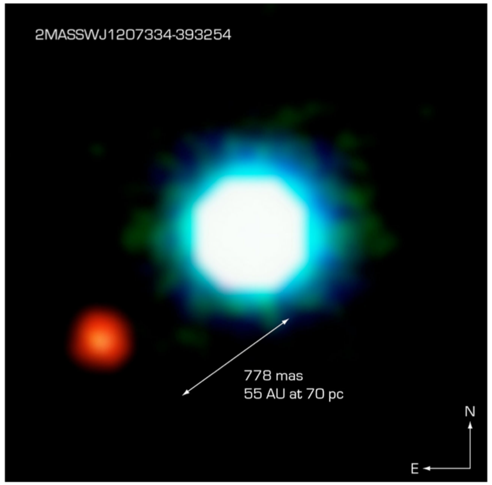
(Exo)planet: practical definition

(Exo)planet = object
(1) formed within a circumstellar disk
(2) having a sufficient mass to assume hydrostatic equilibrium (a nearly round shape),
(3) having « cleared the neighbourhood » of its orbit

➔an ejected planet remains a planet
➔an object of 20 M_J formed within a disk is a planet

Brown dwarf? Object formed like a star, by gravitational collapse of a patch of molecular cloud, and with $M < 0.07\ M_\odot$

Brown dwarfs of $M < 13\ M_J$ = **sub-brown dwarf**
ex: 2M1207b with $M = 8 \pm 2\ M_J$

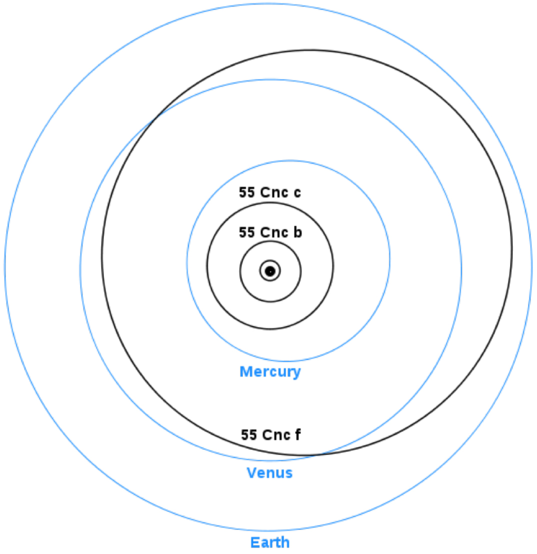


Crédit: ESO

Exoplanet: naming convention

Example: star = 55 Cnc

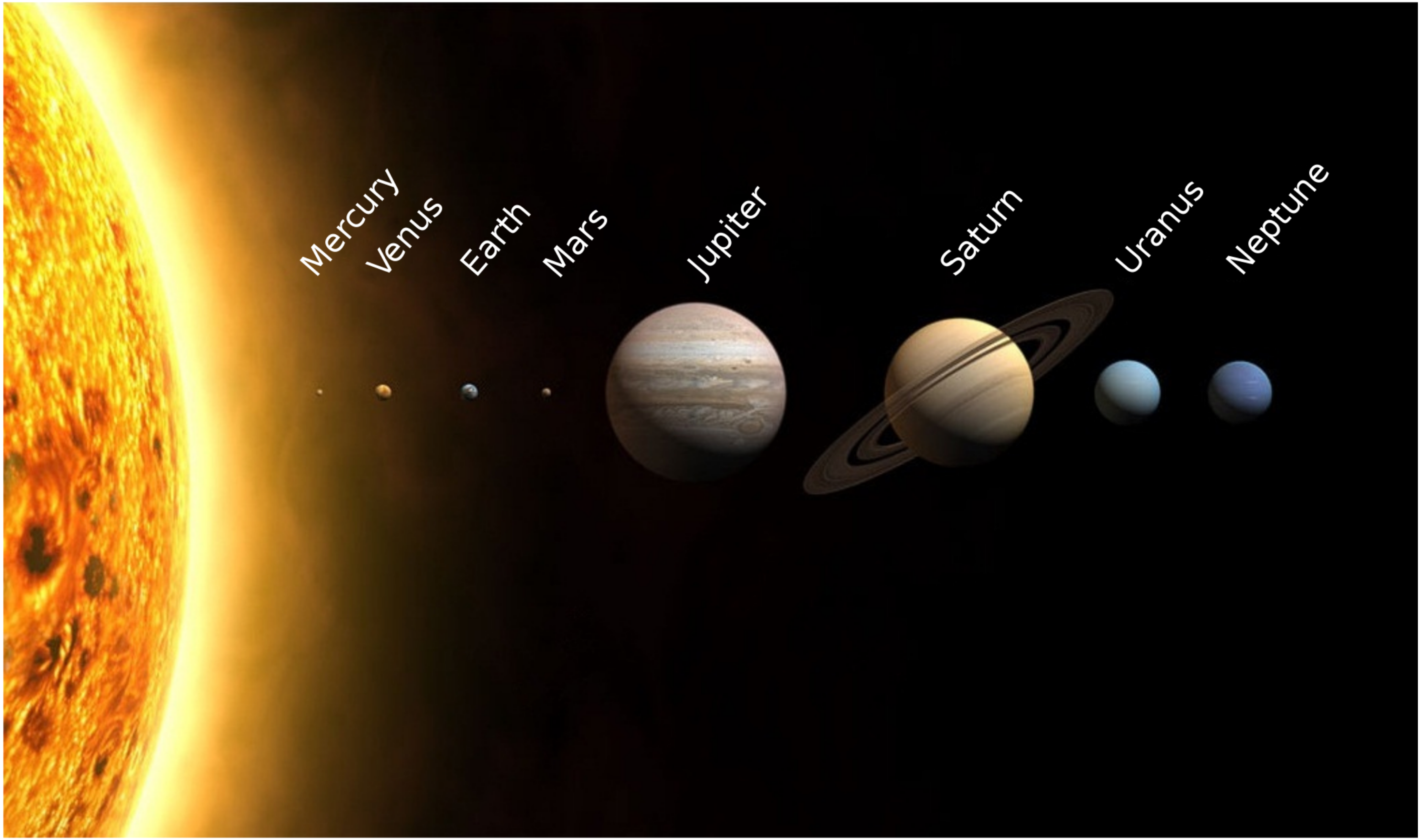
1996 – 1 planet detected -> 55 Cnc b
2002 – 2 planets detected
with P = 44 days -> 55 Cnc c
and with P = 5000 days -> 55 Cnc d
2004 – 1 planet detected -> 55 Cnc e
2007 – 1 planet detected -> 55 Cnc f



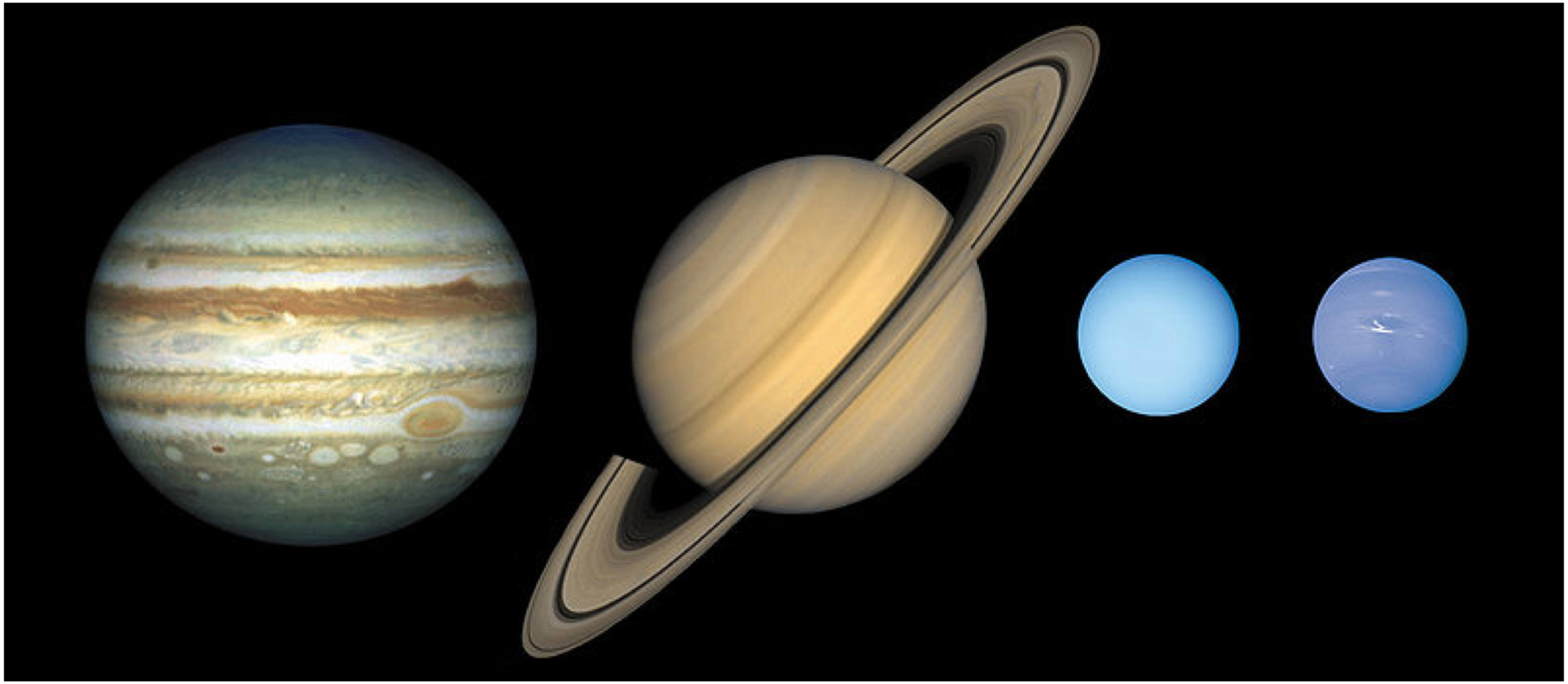
Multiple stellar system? -> e.g. 55 Cnc A b

Circumbinary planet? -> Kepler-16(AB)b

Our own planetary system



Types of planets: the giant planets

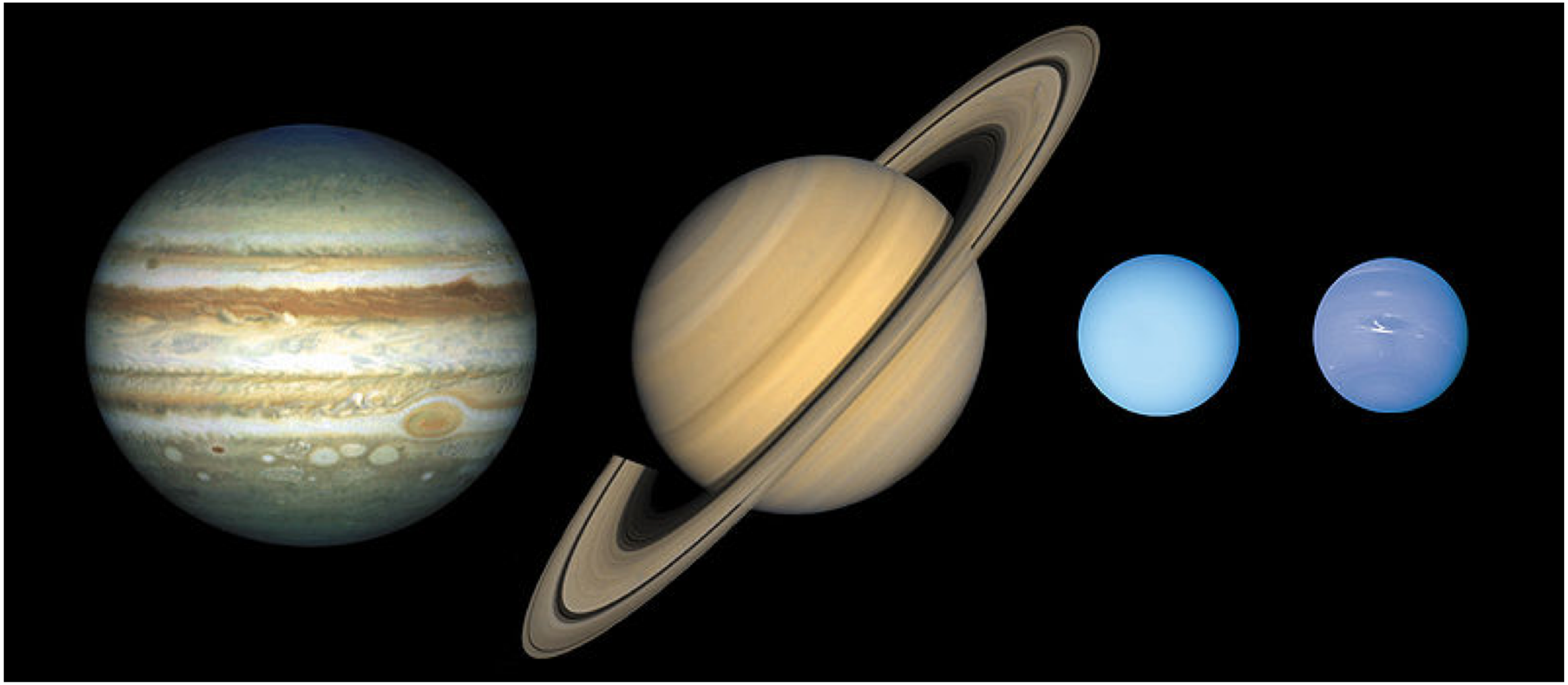


Jupiter Saturn Uranus Neptune

Gas giants

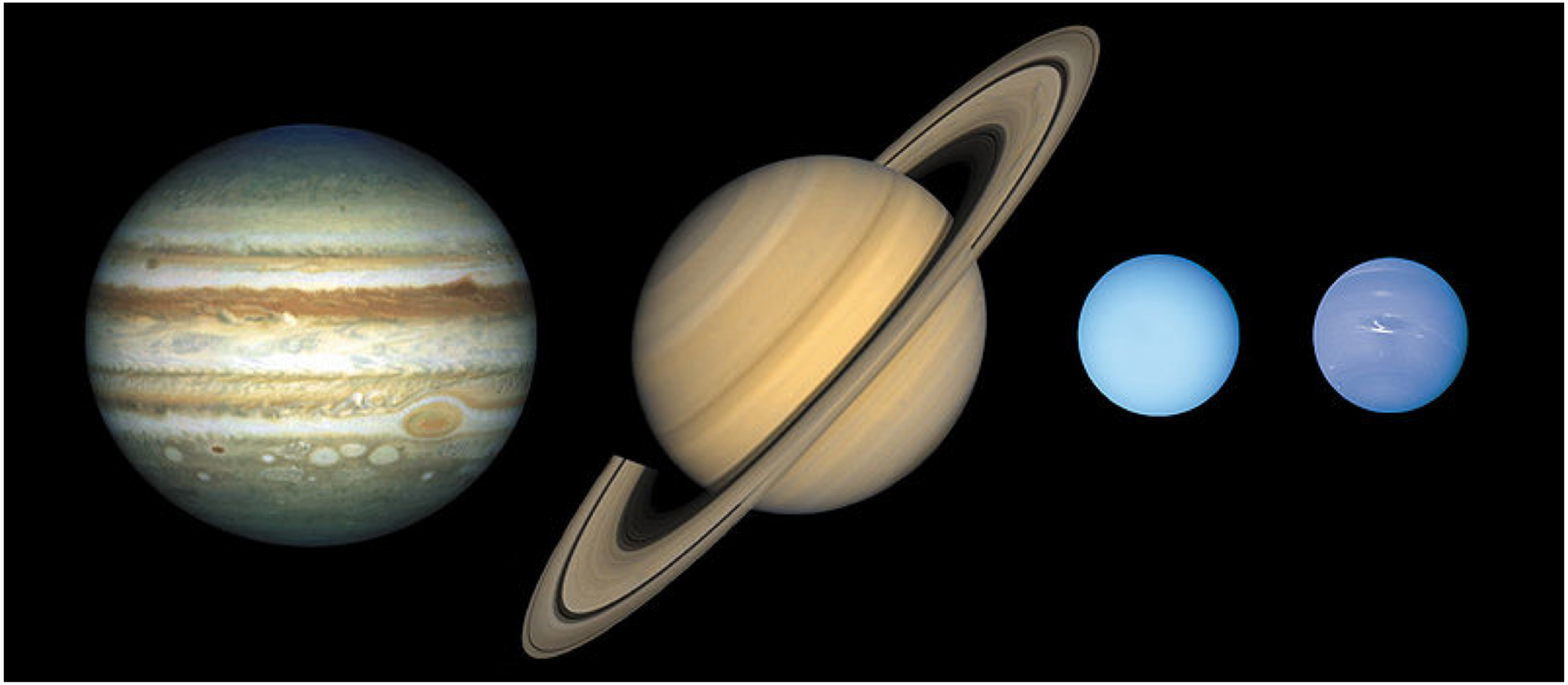
Ice giants

Types of planets: the giant planets



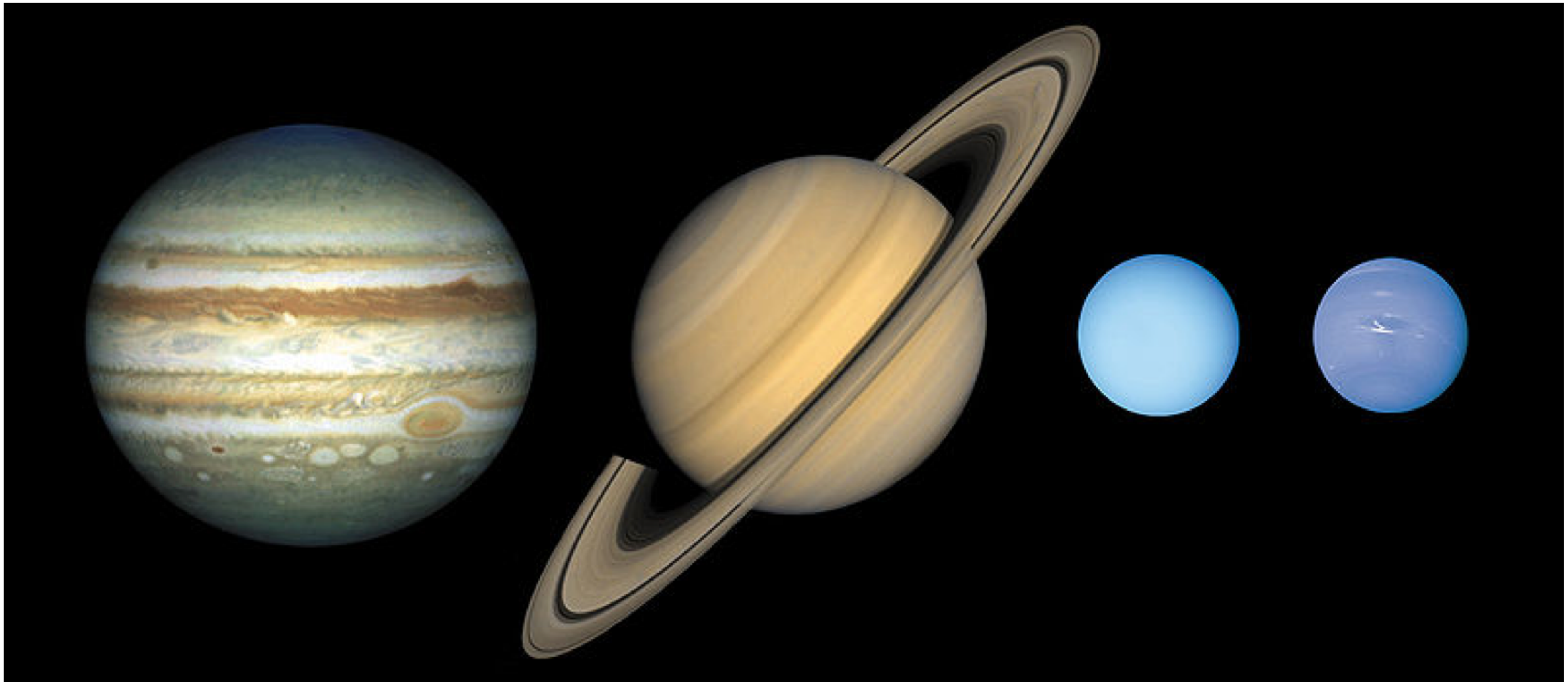
	Jupiter	Saturn	Uranus	Neptune
Mass (M_{Earth})	318	95	14.5	17
Radius (R_{Earth})	11.2	9.5	4	3.8

Types of planets: the giant planets



	Jupiter	Saturn	Uranus	Neptune
a	5.2 au	9.5 au	19.2 au	30.1 au
Orbital Period	11.9 yr	29.5 yr	84 yr	165 yr

Types of planets: the giant planets



	Jupiter	Saturn	Uranus	Neptune
$T_{\mathrm{equilibrium}}$	109K	80K	58K	46K
$T_{\mathrm{effective}}$	124K	95K	59K	59K
Bond albedo	0.34	0.34	0.30	0.29

The equilibrium temperature of a planet

Estimate of the effective temperature for a planet neglecting its own luminosity, i.e. its own internal energy
= ***effective temperature of an isothermal planet in equilibrium with the radiative energy from the host star***

Equilibrium equation: $$4\pi R_p^2 F_{S,p} = (1 - A_B) F_{S,*} \left(\frac{R_*}{a}\right)^2 \pi R_p^2 + \cancel{L_{p,\mathrm{int}}}$$

Emitted energy Received energy Internal energy

A$_B$ = Bond Albedo = fraction of the incoming stellar light scattered back to space

Stefan-Boltzmann's law: $$F_S = \sigma_R T_{eff}^4$$

$$\Rightarrow \quad \boxed{T_{eq} = T_{eff,*} \sqrt{\frac{R_*}{a}} \left[\frac{1}{4}(1 - A_B)\right]^{\frac{1}{4}}}$$

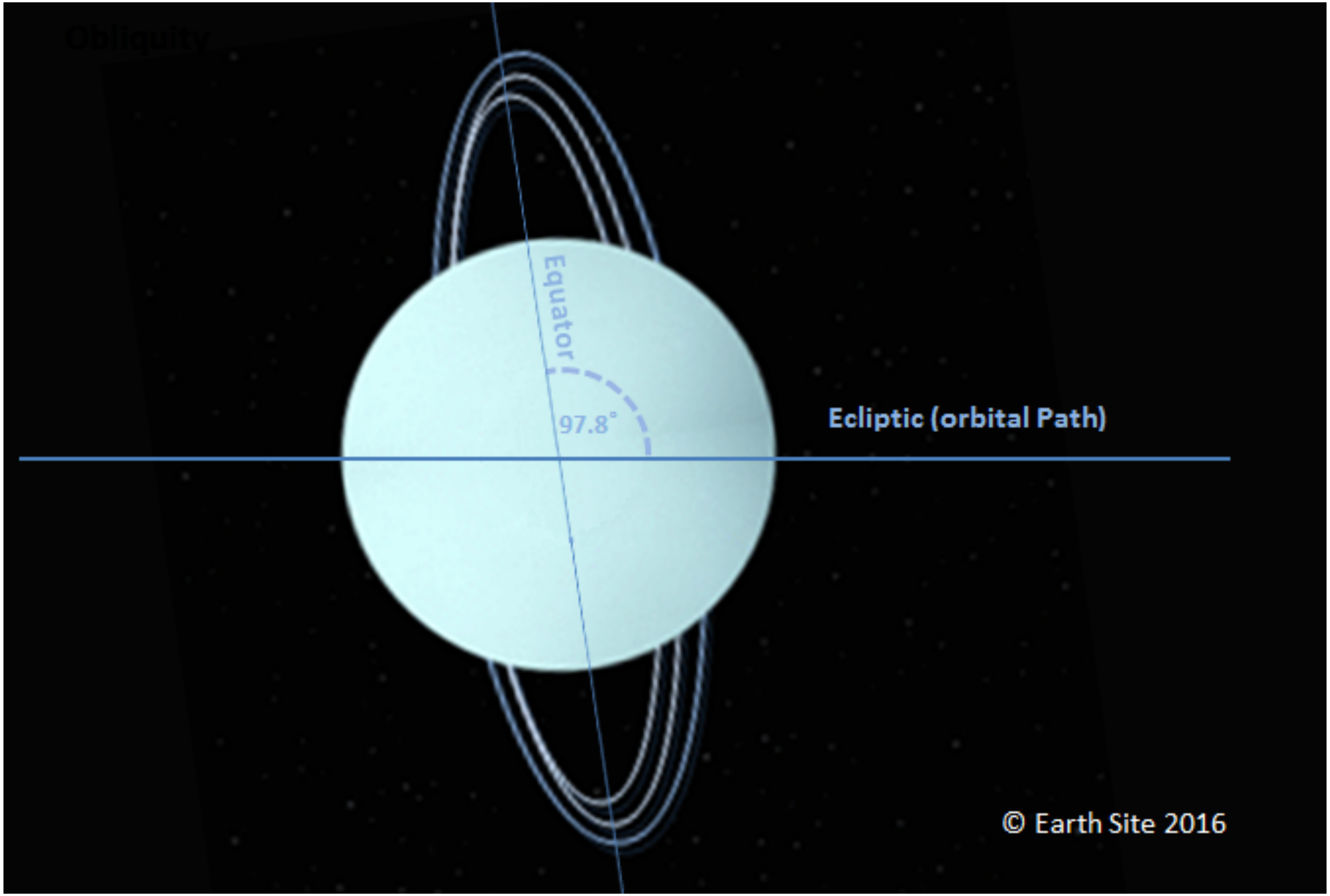
The effective temperature of a planet

Temperature of a black-body emitting the same amount of radiative energy than the planet, i.e. having the same luminosity.

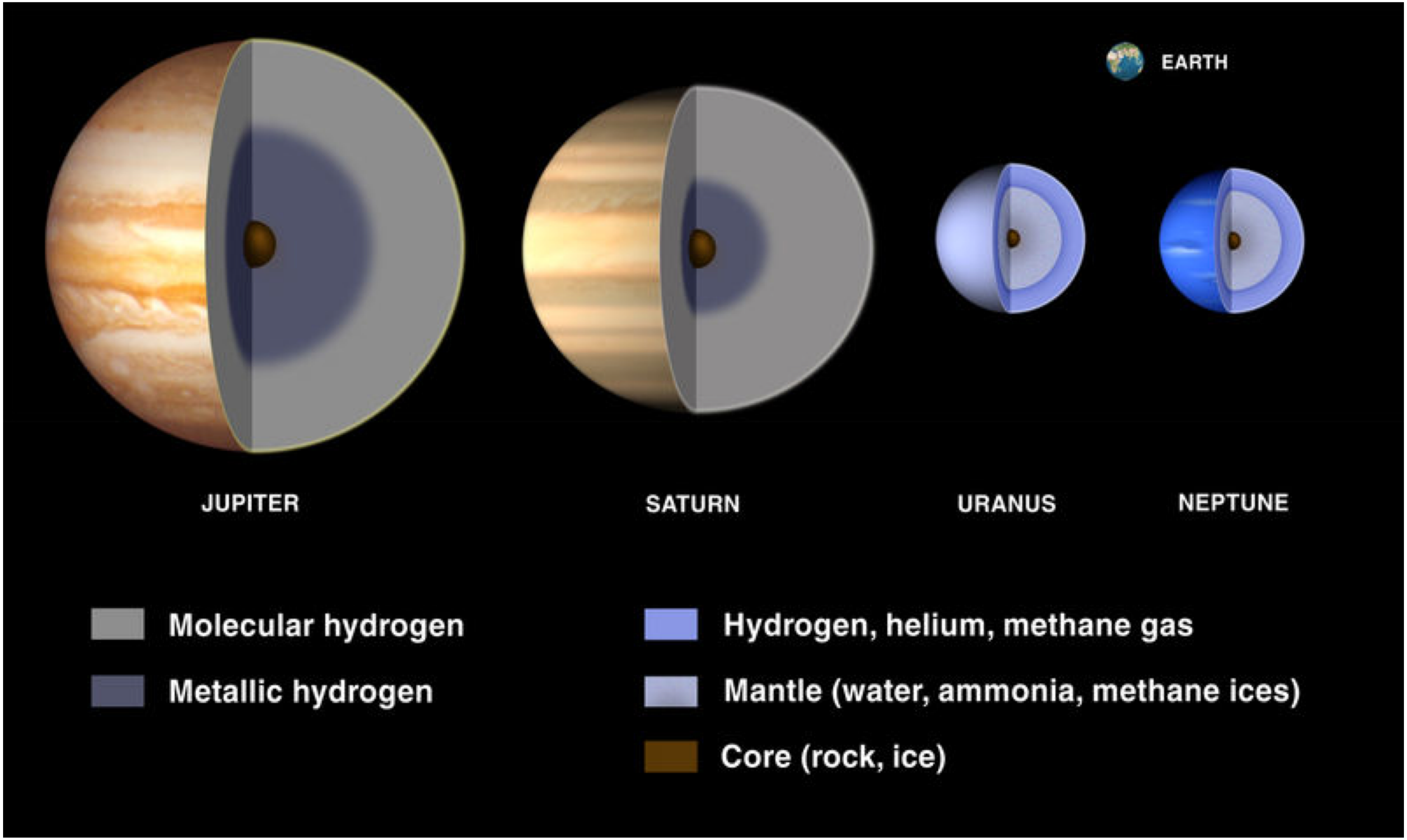
$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$$

Difference between T_{eff} and T_{eq} : internal energy of the planet

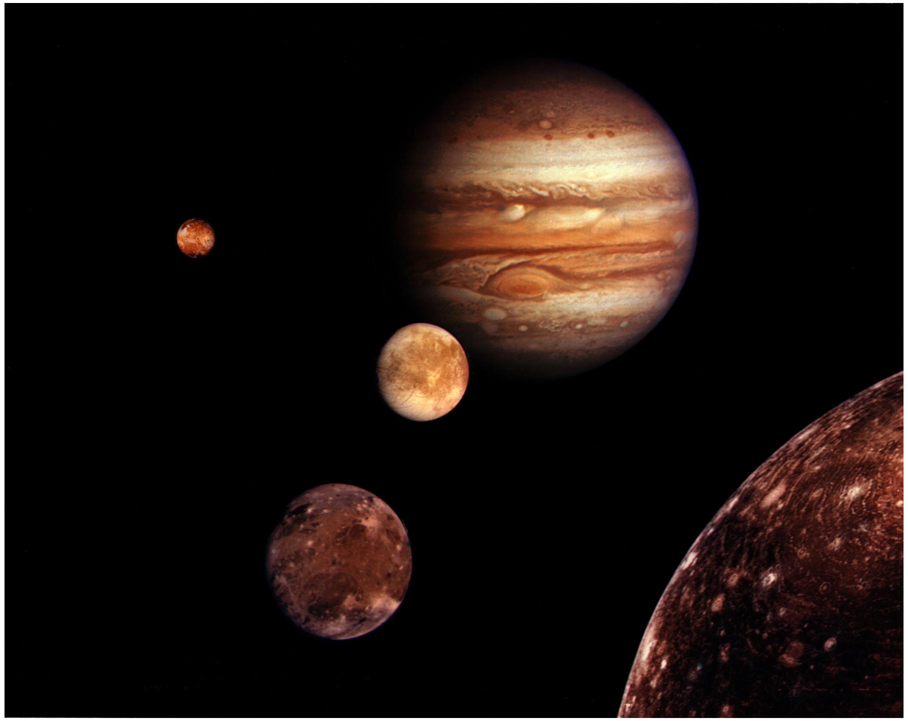
Uranus’ high obliquity

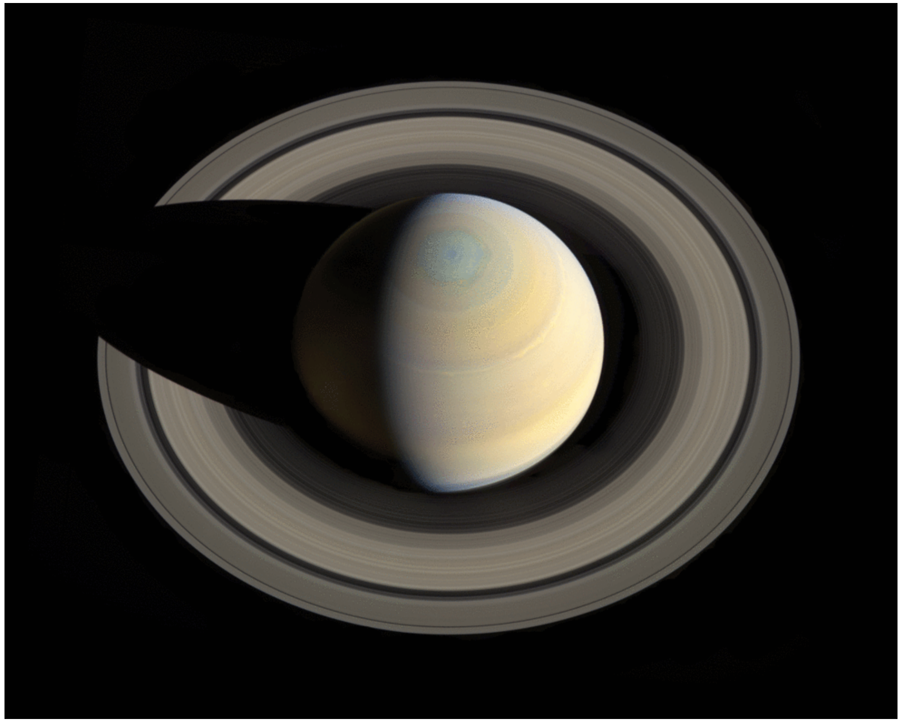


The giant planets: internal structure



Moons and rings



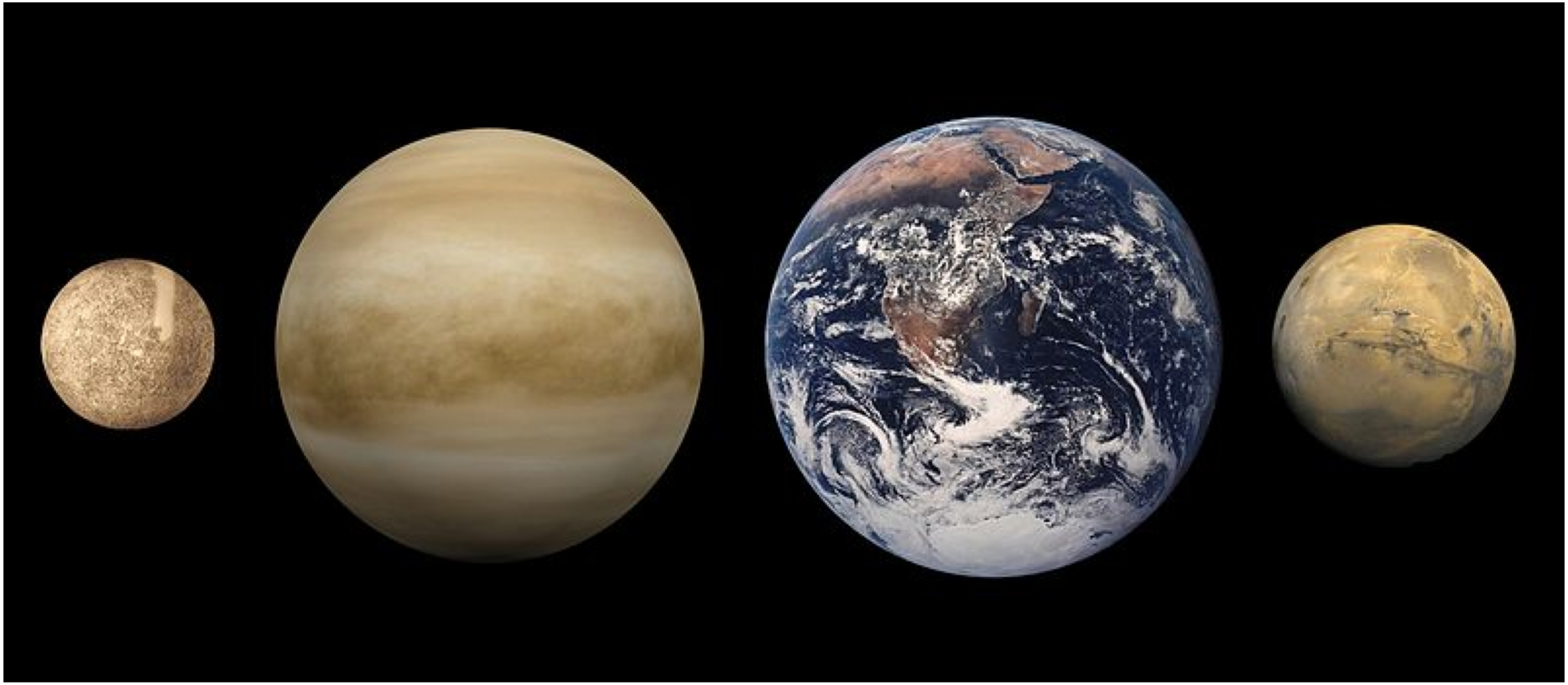


Number of moons

Jupiter: 80
Saturn: 83
Uranus: 27
Neptune: 14

The four giant planets have rings made of dust and moonlets

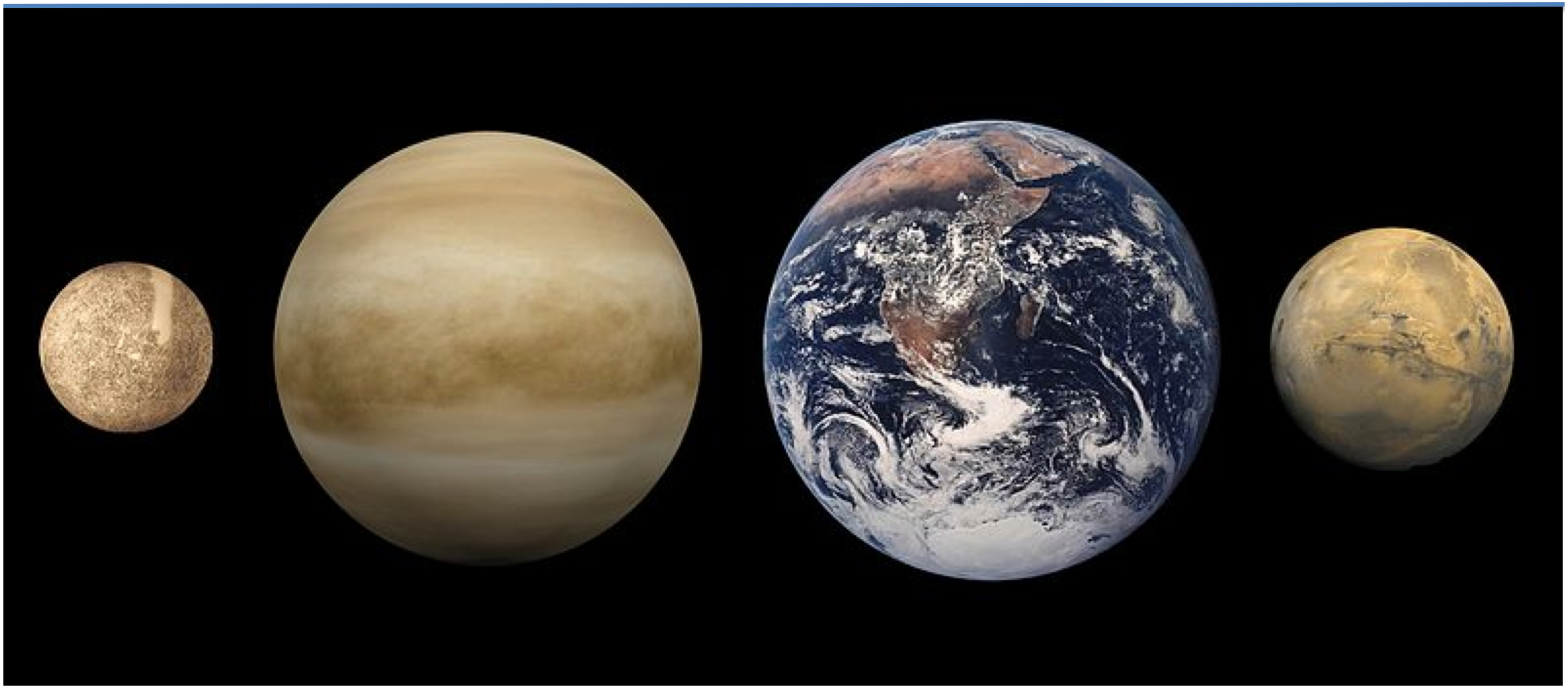
Type of planets: terrestrial (or telluric) planets



Mercury Venus Earth Mars

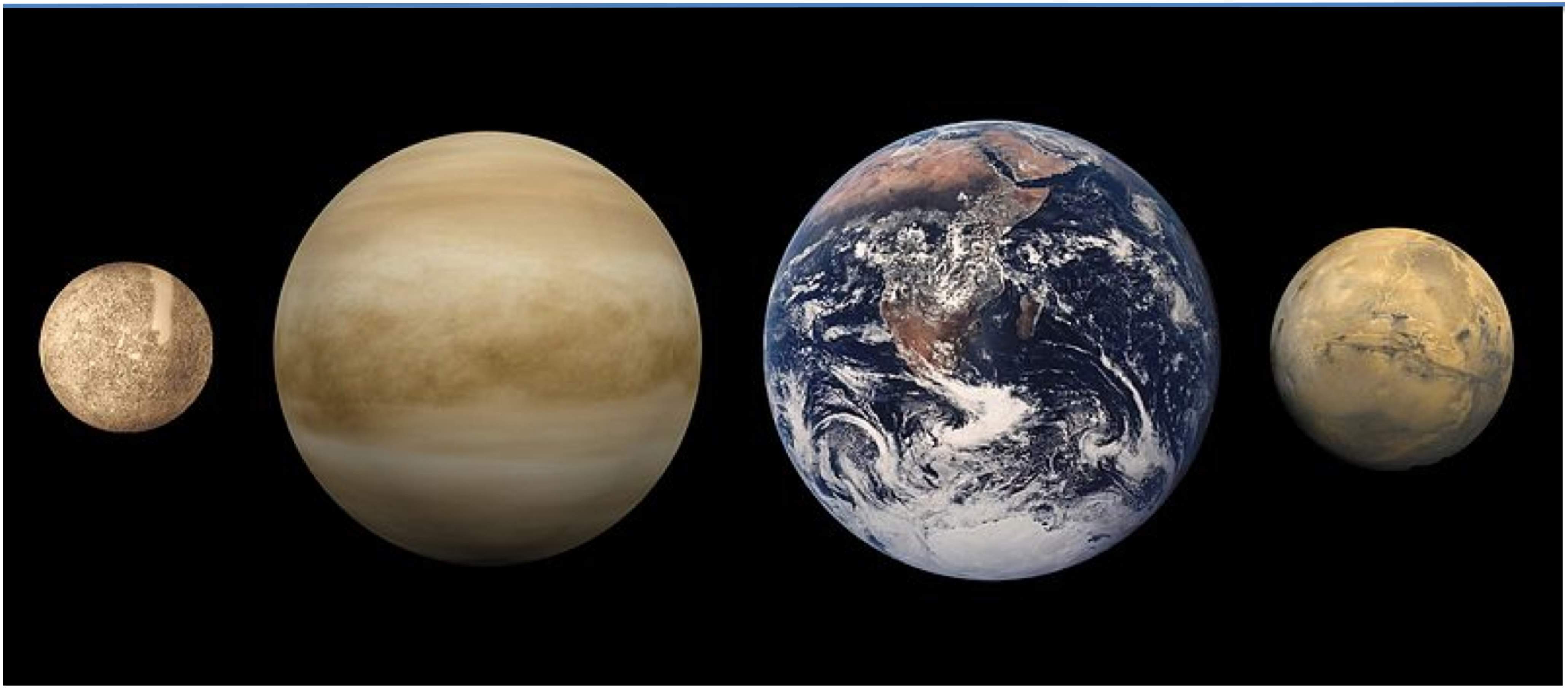
Telluric: from latin *tellus* = earth, ground

Type of planets: terrestrial (or telluric) planets



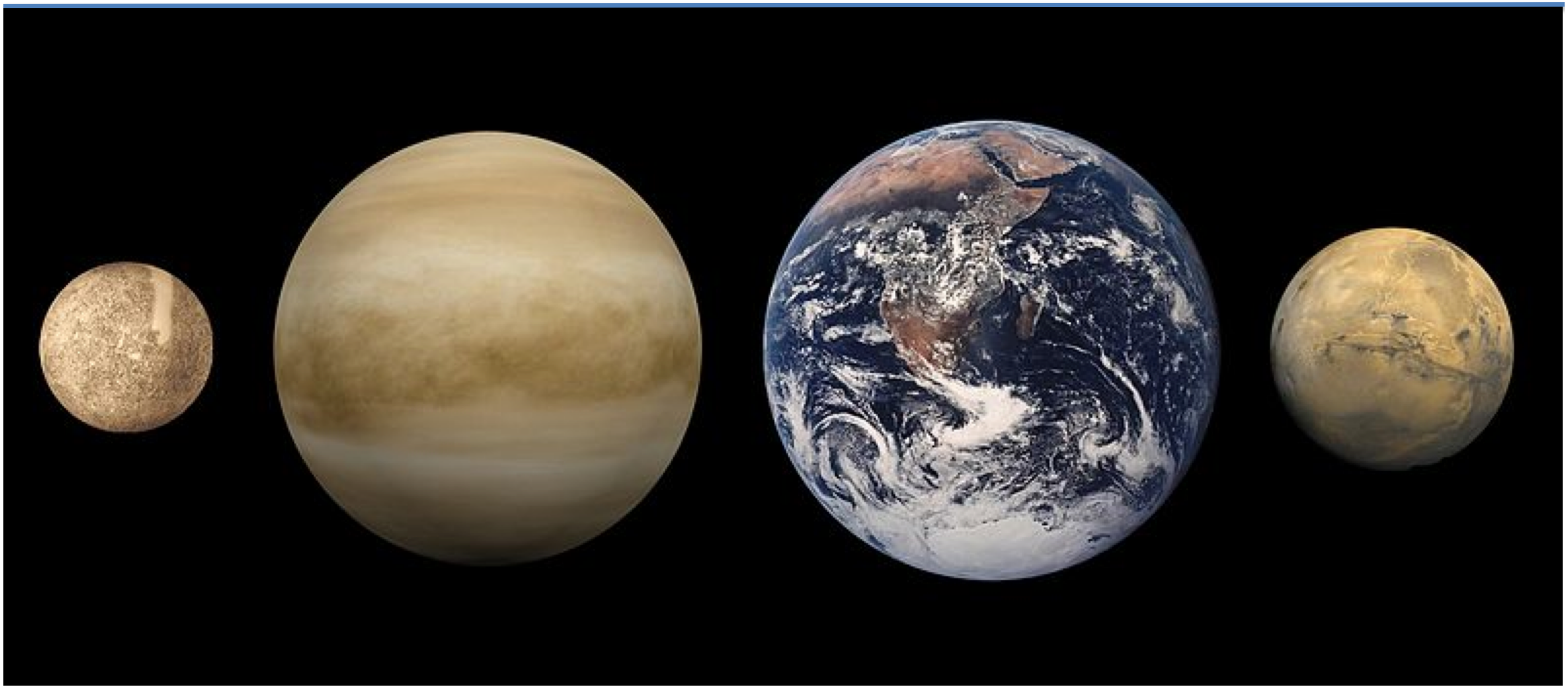
	Mercury	**Venus**	**Earth**	**Mars**
Mass (M_{Earth})	0.055	0.82	$6\ 10^{24}$ kg	0.11
Radius (R_{Earth})	0.38	0.95	6370 km	0.53

Type of planets: terrestrial (or telluric) planets



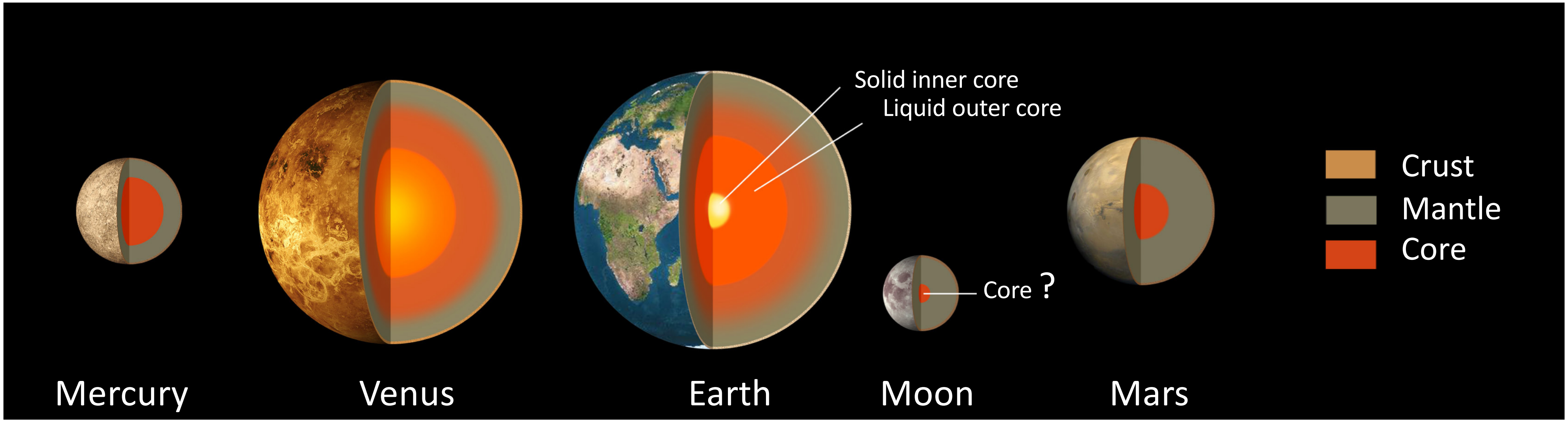
	Mercury	**Venus**	**Earth**	**Mars**
a (au)	0.39	0.72	1.5 10^8 km	1.52
Period (day)	88	225	365	687

Type of planets: terrestrial (or telluric) planets



	Mercury	Venus	Earth	Mars
$T_{equilibrium}$	434K	230K	253K	209K
$T_{effective}$	435K	230K	255K	212K
Bond albedo	0.12	0.75	0.37	0.25

The terrestrial planets: internal structure



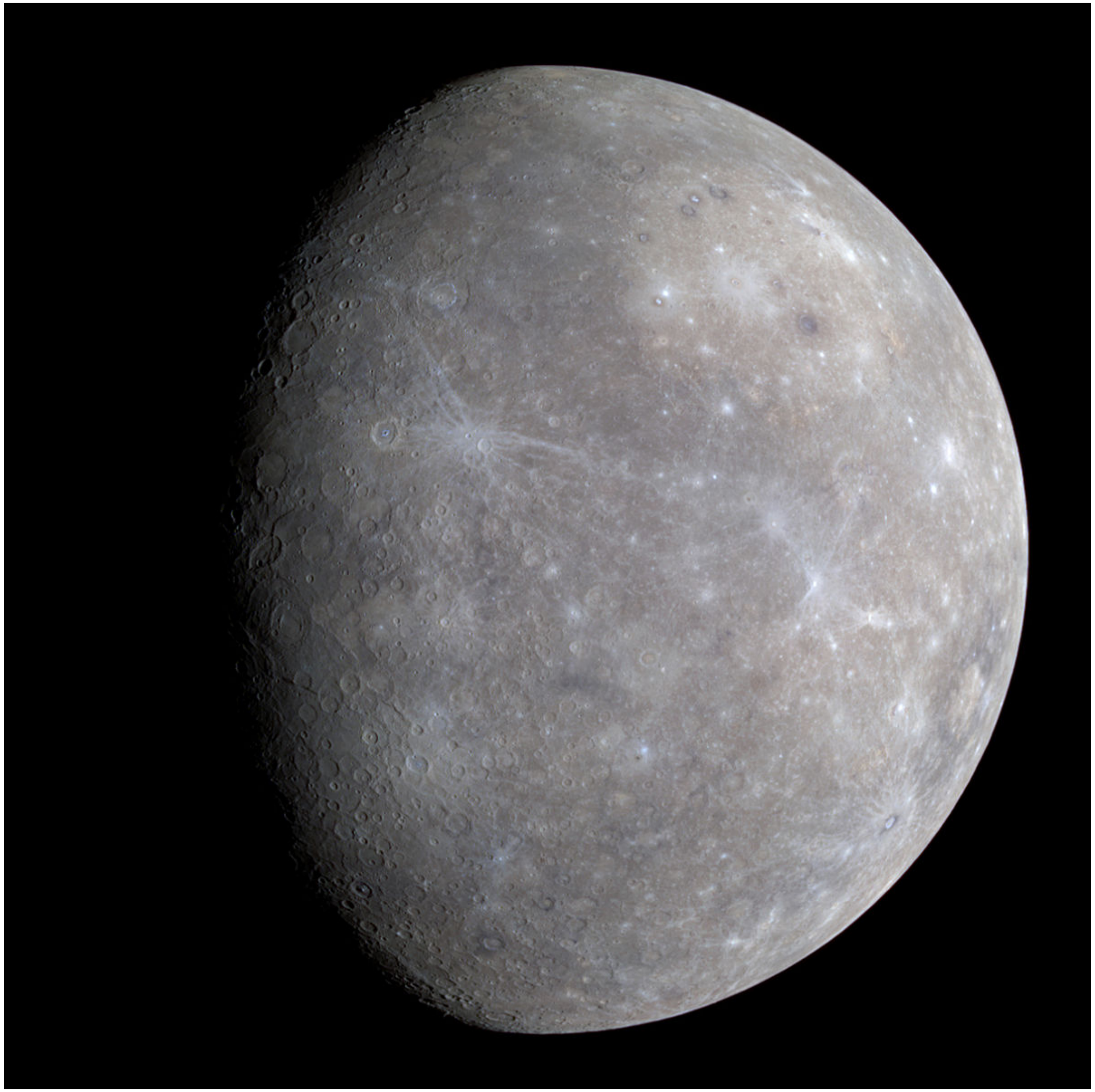
Differentiation in several layers:

Core = metal (mostly Fe, + Ni). Liquid, but possible solid part.

Mantle = densest silicates (olivine, pyroxene). Solid state but viscous. Possible convection if T large enough.

Crust = superficial outer part of the mantle, solid and composed of the least dense silicates (e.g. basalt, granite)

Mercury is basically a big ball of iron

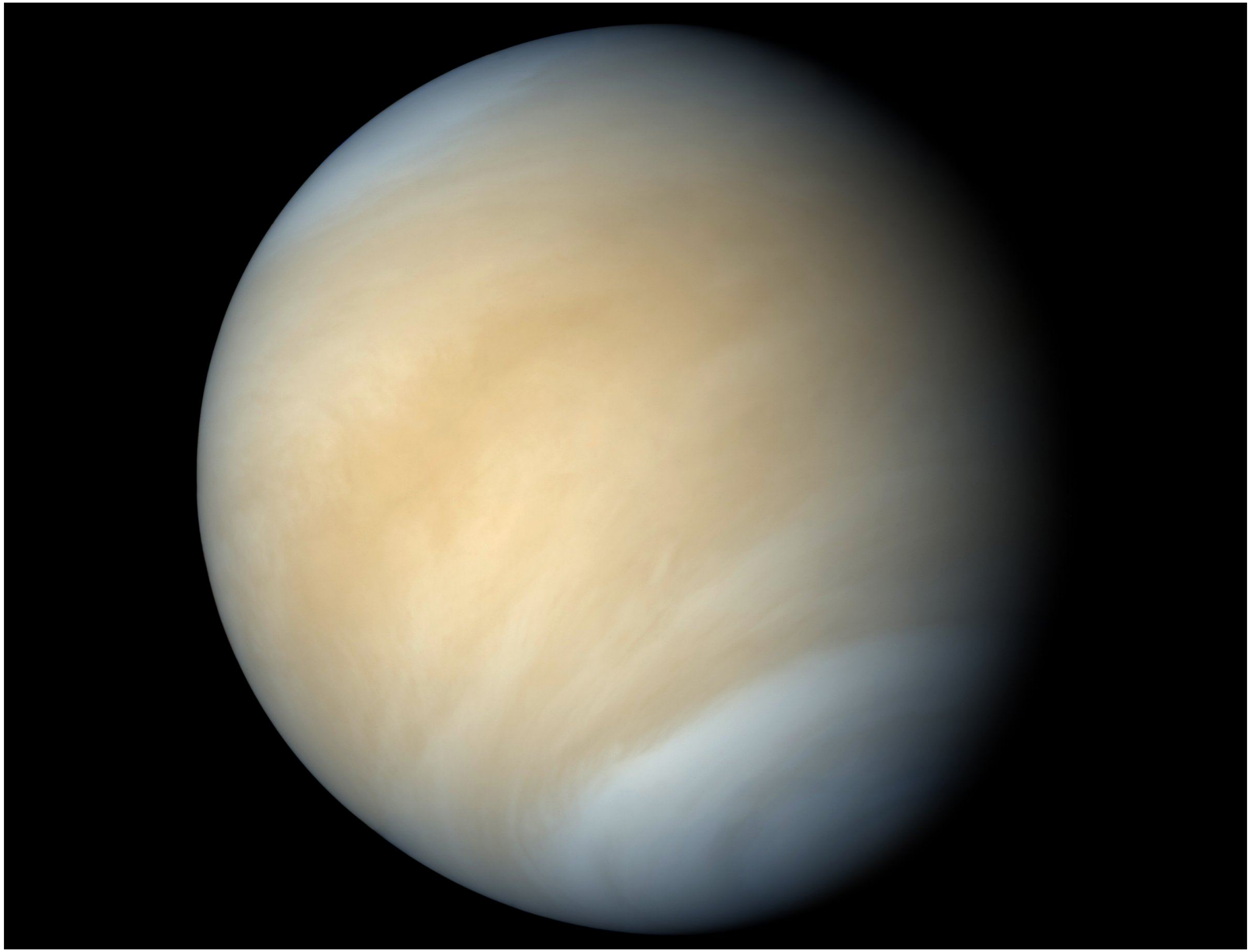


No atmosphere

Orbital eccentricity of 0.21

3:2 spin-orbit resonance

Venus: a slowly rotating Earth-like planet with a very dense CO_2-rich atmosphere

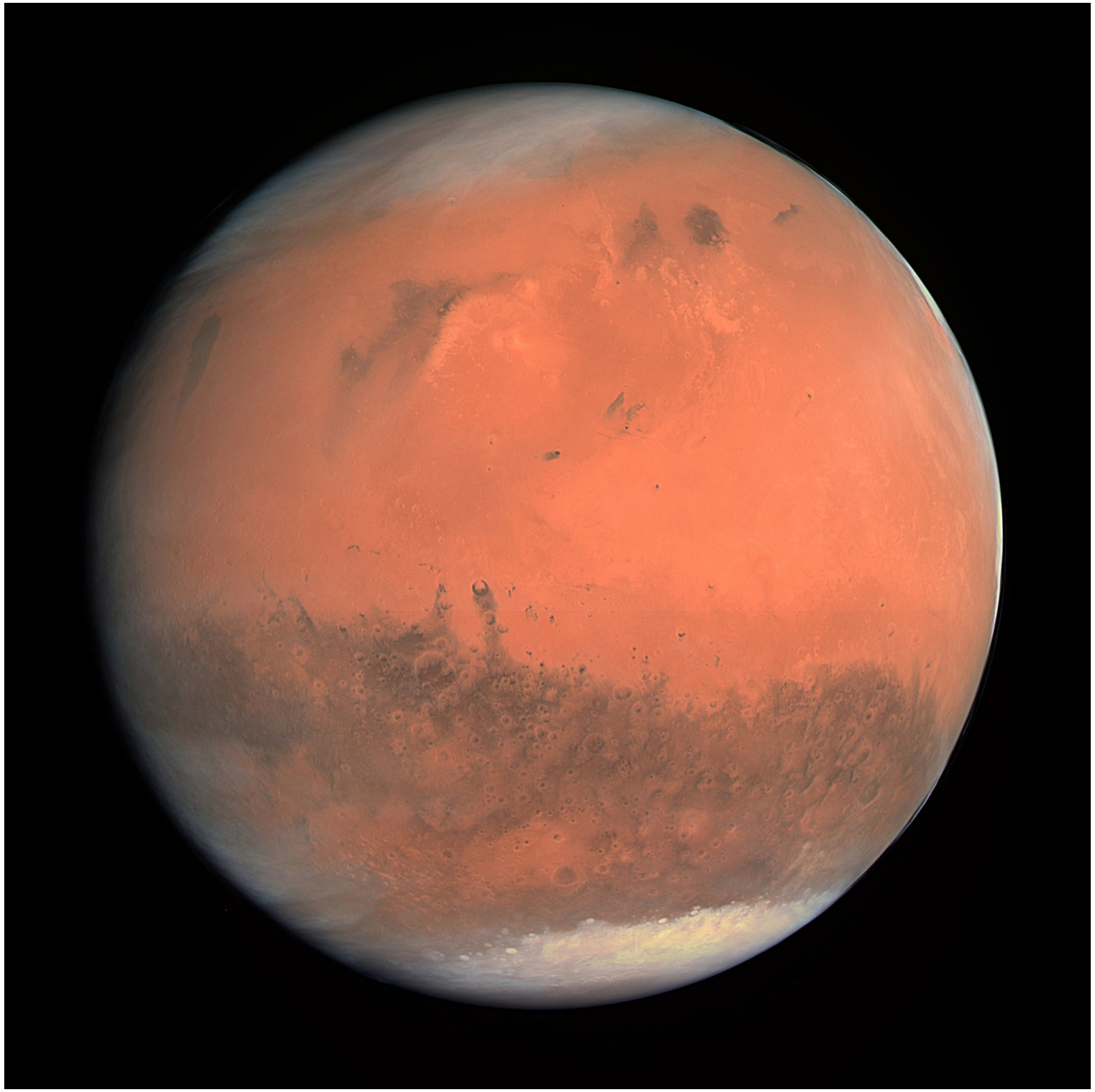


Retrograde rotation
in 243 days

Earth: an inhabited terrestrial planet with a big moon

Moon/Earth mass ratio = 1.2%
Radius: 27% of Earth’s

Mars: a small desert world with a scarce CO_2-dominated atmosphere



The solar system

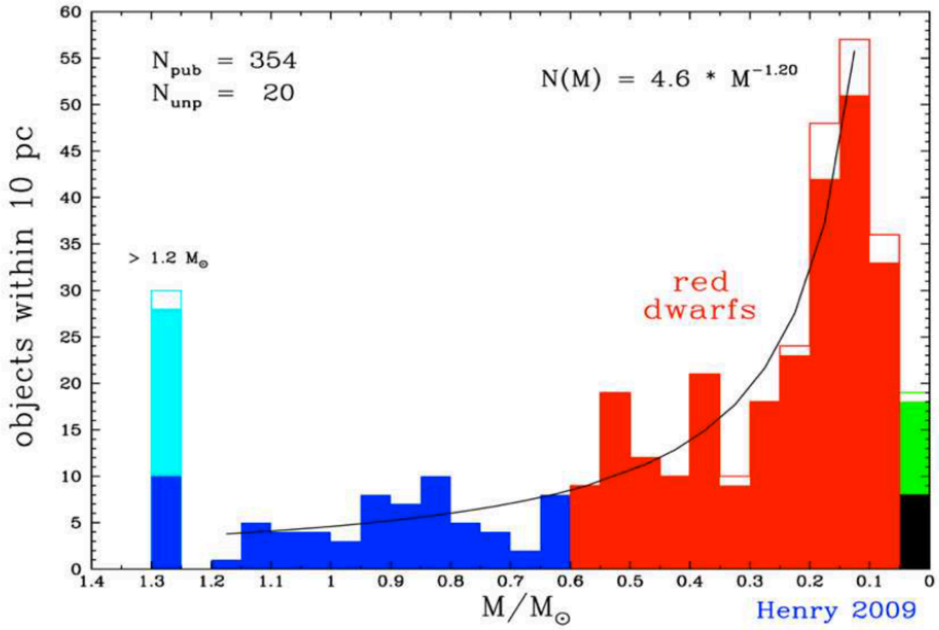
1. Our star

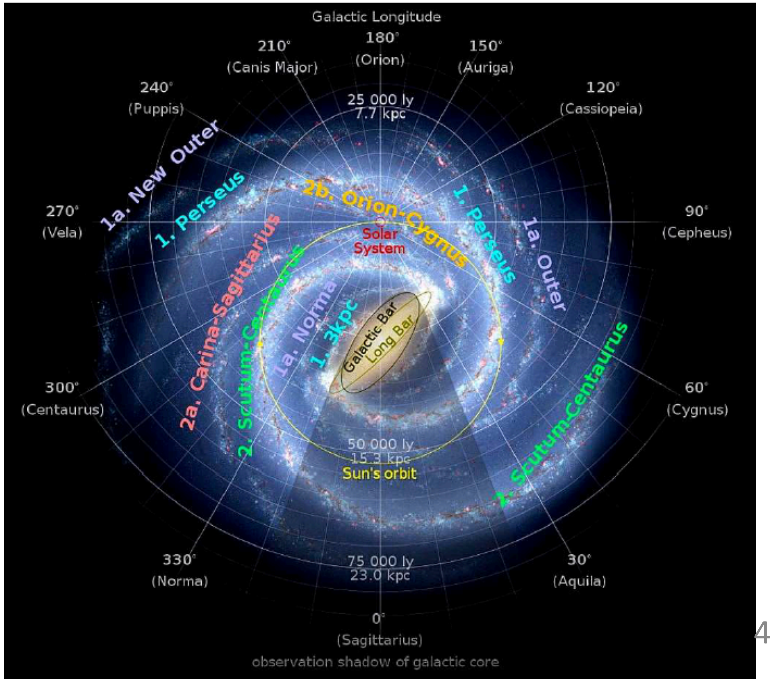
Spectral type G2 - $T_{eff} \sim 5770K$
5 % of G-type stars in the Galaxy

99.8 % of the mass of the solar system

8500 parsec from the galactic center
15 parsec from the galactic equator
Orion's arm
Galactic rotation: 220 Myr

P_{spin} = 27 days
Age = 4.56+-0.02 Gyr (meteorites)
Magnetic cycle of 11yr period





The solar system

2. Planets

< 0.2 % of the mass of the solar system
But 98 % of its angular momentum

In order of distance:

- terrestrial planets
- gas giants
- ice giants

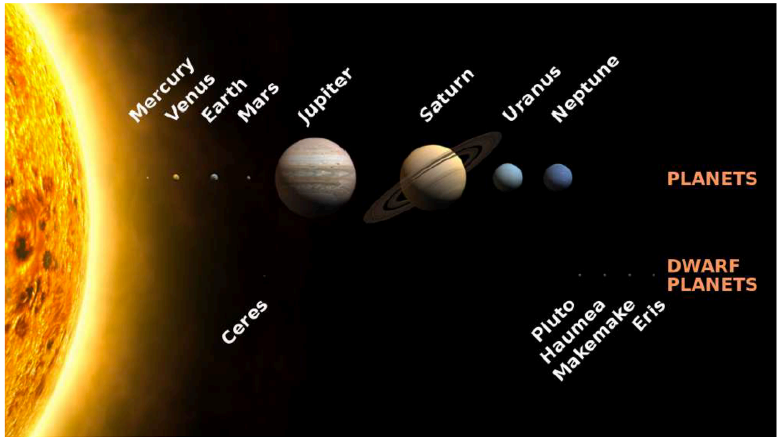
$e \sim 0°$, $i \sim 0°$

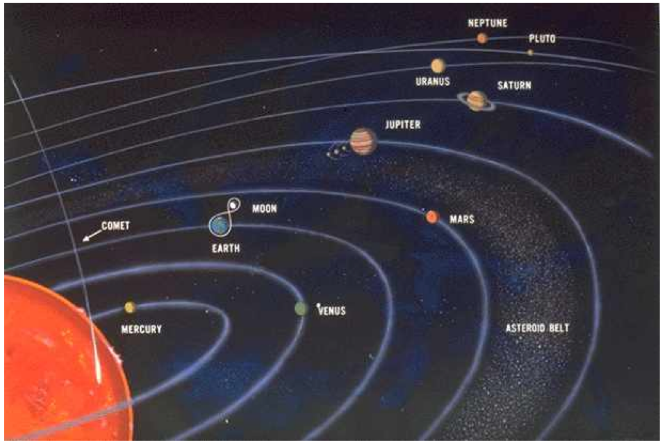
Prograde orbits

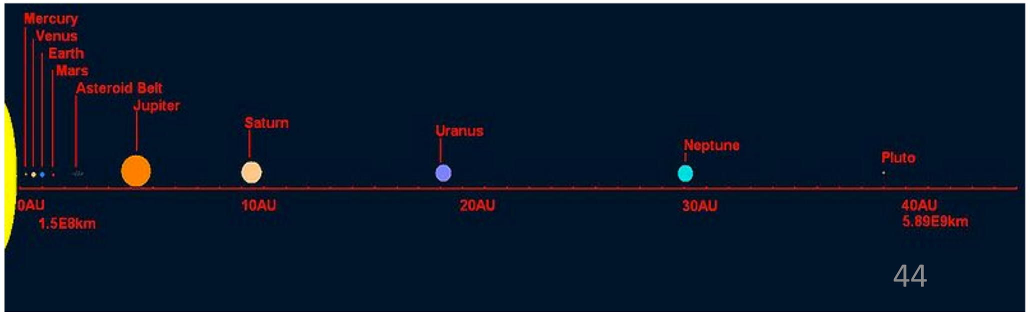
~ 7° misalignement between ecliptics and solar equator

6 planets out of 8 have an obliquity < 30°

Bode's law: $a^n = 0.4 + 0.3 \times 2^n$



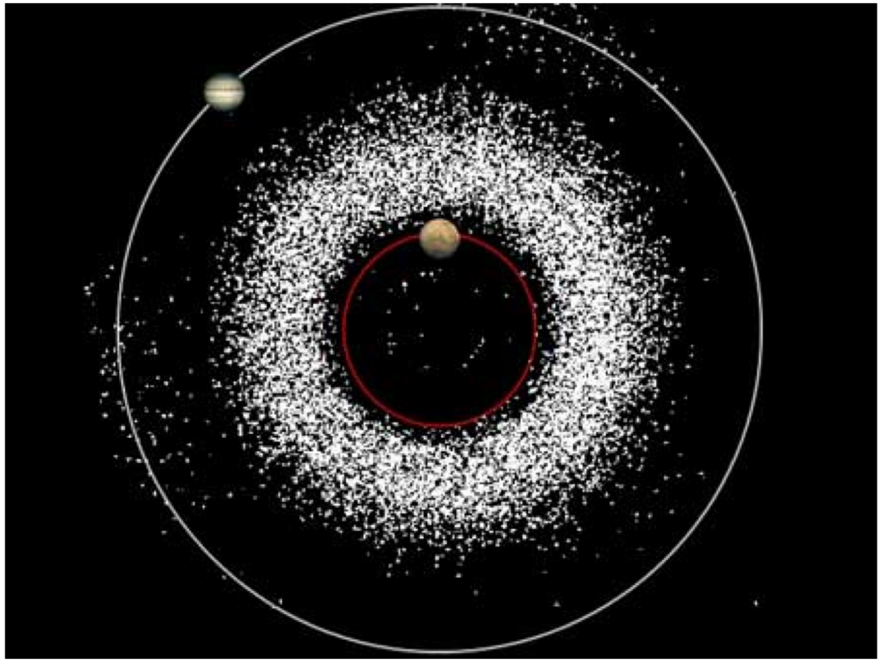


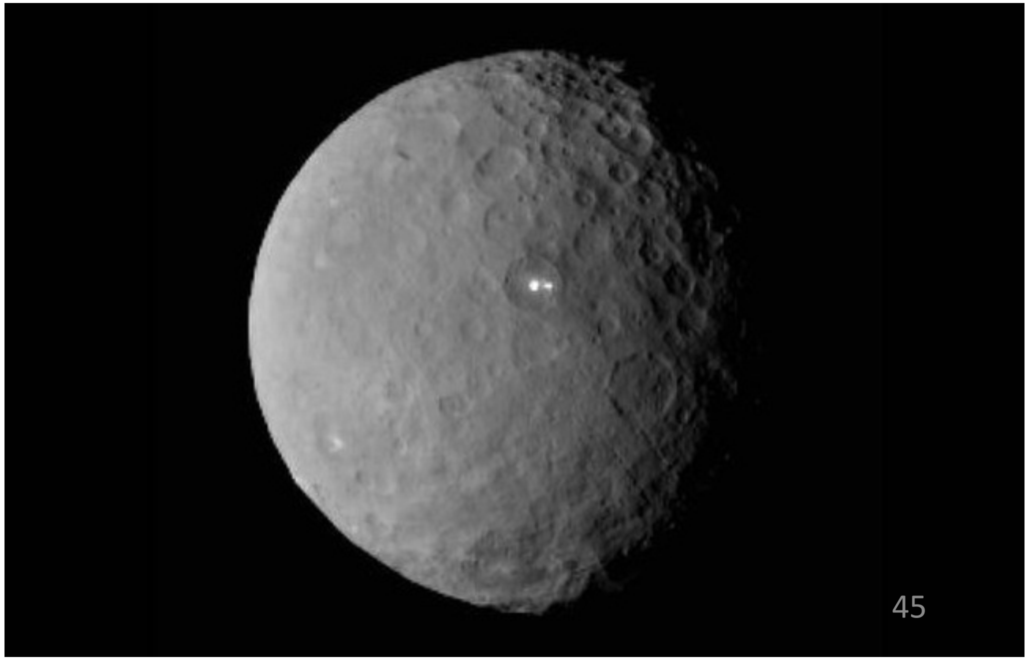


The solar system

3. Small bodies: asteroids, comets, dwarf planets…

Asteroid belt: hundreds of thousands of asteroids.
Total mass: 0.05% M_{Earth}
1/3 of this mass = dwarf planet Ceres (a = 2.8 au, R = 480 km)
Low inclinations (<i> = 15°) and eccentricities
Orbital resonances with Jupiter (Kirkwood gaps)
Most meteorites come from the asteroid belt
3 main types of material: metal-rich (M), silicate-rich (S) and carbon-rich (C)

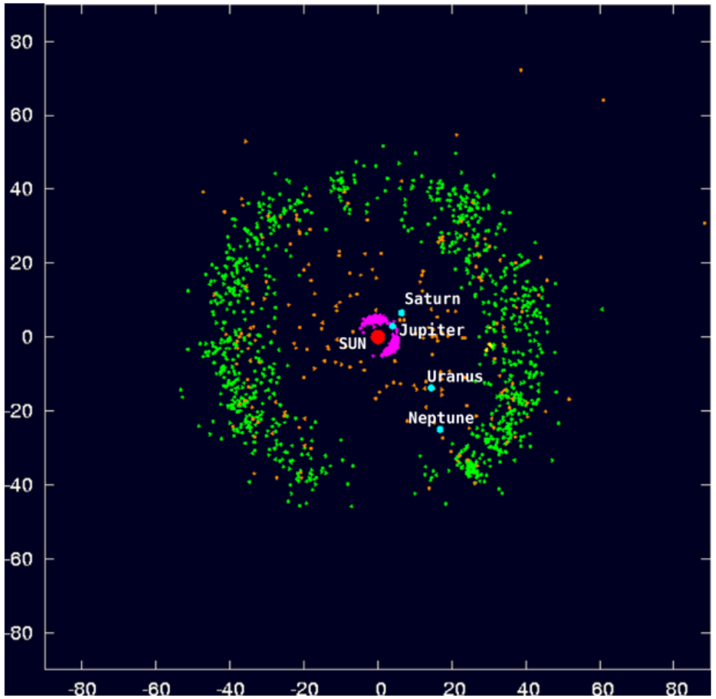




The solar system

3. Small bodies: asteroids, comets, dwarf planets…

Kuiper belt : 30 to 50 au. ~10^9 bodies, a majority being ice-rich.
Most of them have a small eccentricity and inclination.
3:2 resonance with Neptune -> Plutinos.



Kuiper belt

Centaurs (between Jupiter & Neptune)

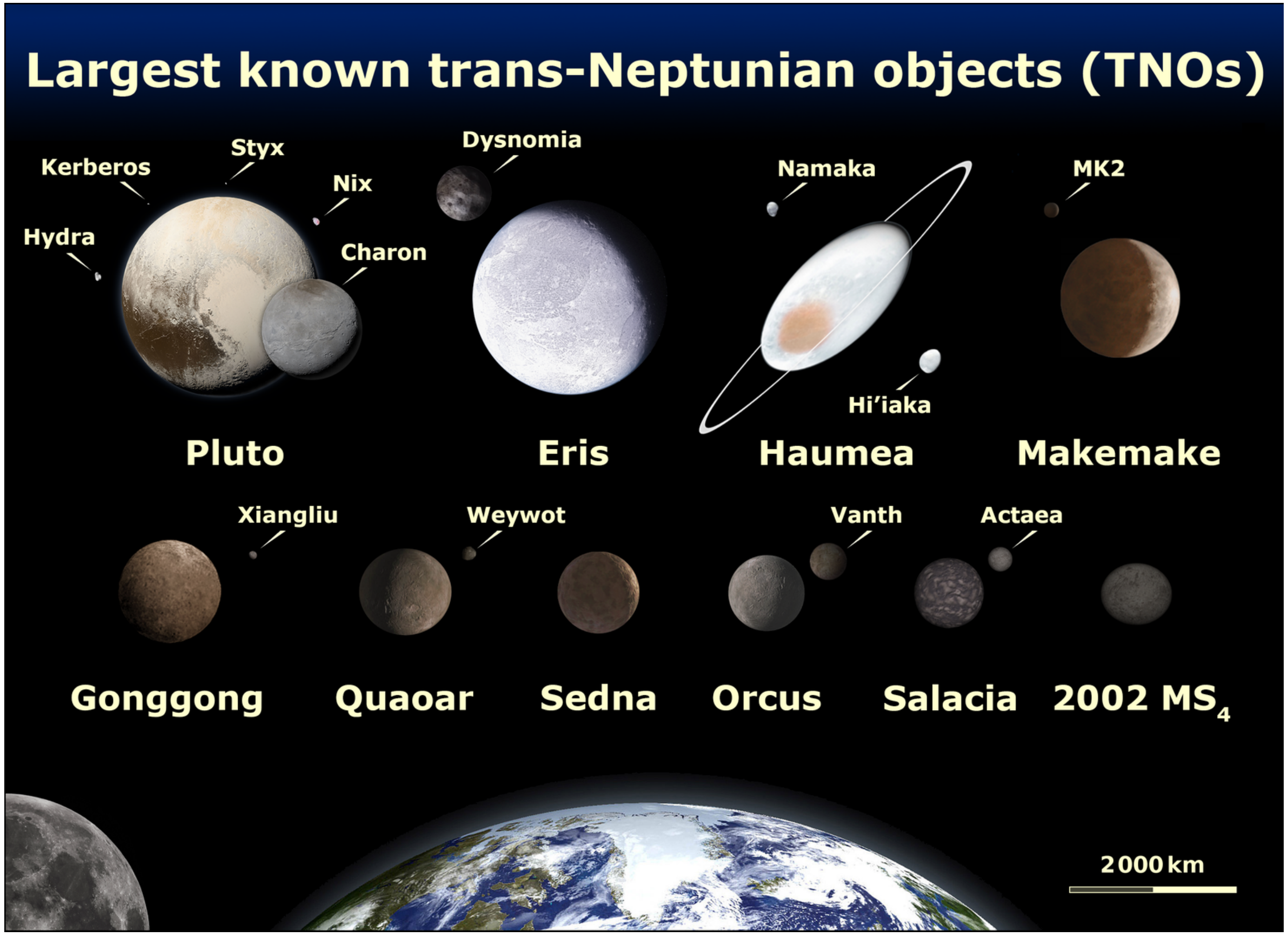
Trojans (Jupiter)

Scattered disk: overlap with the Kuiper belt, but composed of objects with more eccentric and inclined orbits. Origin of short-period comets. Perihelion > 30 au, aphelion to ~ 1000 au (Sedna; P ~ 11000 yr).

The solar system

3. Small bodies: asteroids, comets, dwarf planets…

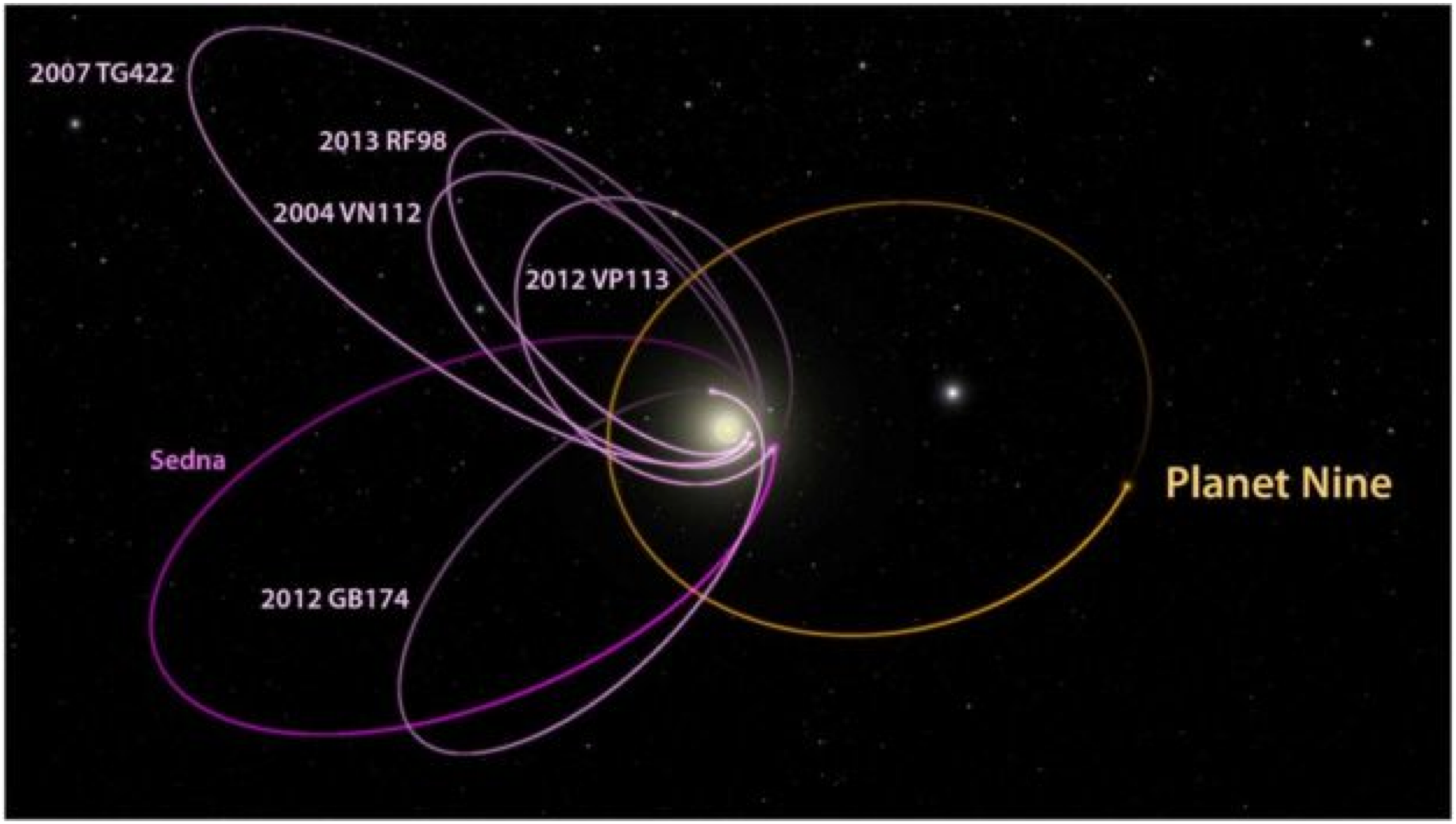
Trans-Neptunian Objects (TNOs): many recent detections. Some orbit farer than the Kuiper belt (Eris, Sedna).



The solar system

3. Small bodies: asteroids, comets, dwarf planets…

Some TNOs' orbits suggest a still undetected ninth planet…

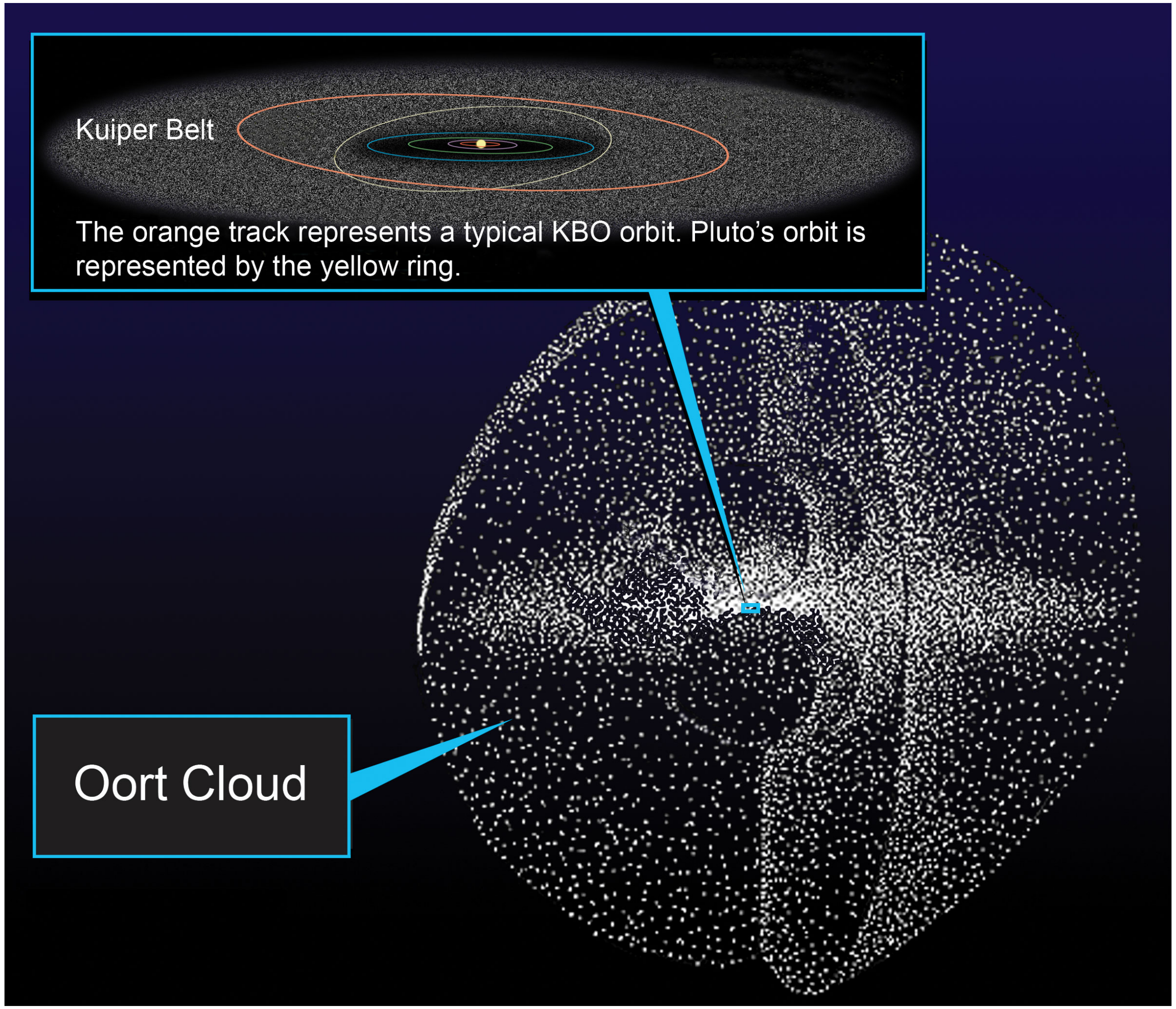


Batygin & Brown (2016)

The solar system

3. Small bodies: asteroids, comets, dwarf planets…

Oort cloud: between 10,000 and 50,000 au (0.8 light-years). ~10^{12} comets. Quasi-isotropic distribution. Source of the long-period comets.

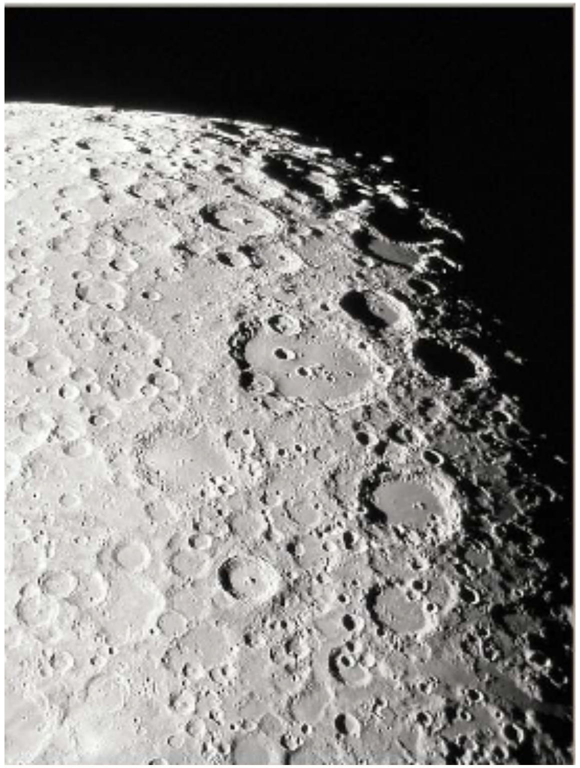


The orange track represents a typical KBO orbit. Pluto’s orbit is represented by the yellow ring.

The solar system

4. Miscellaneous

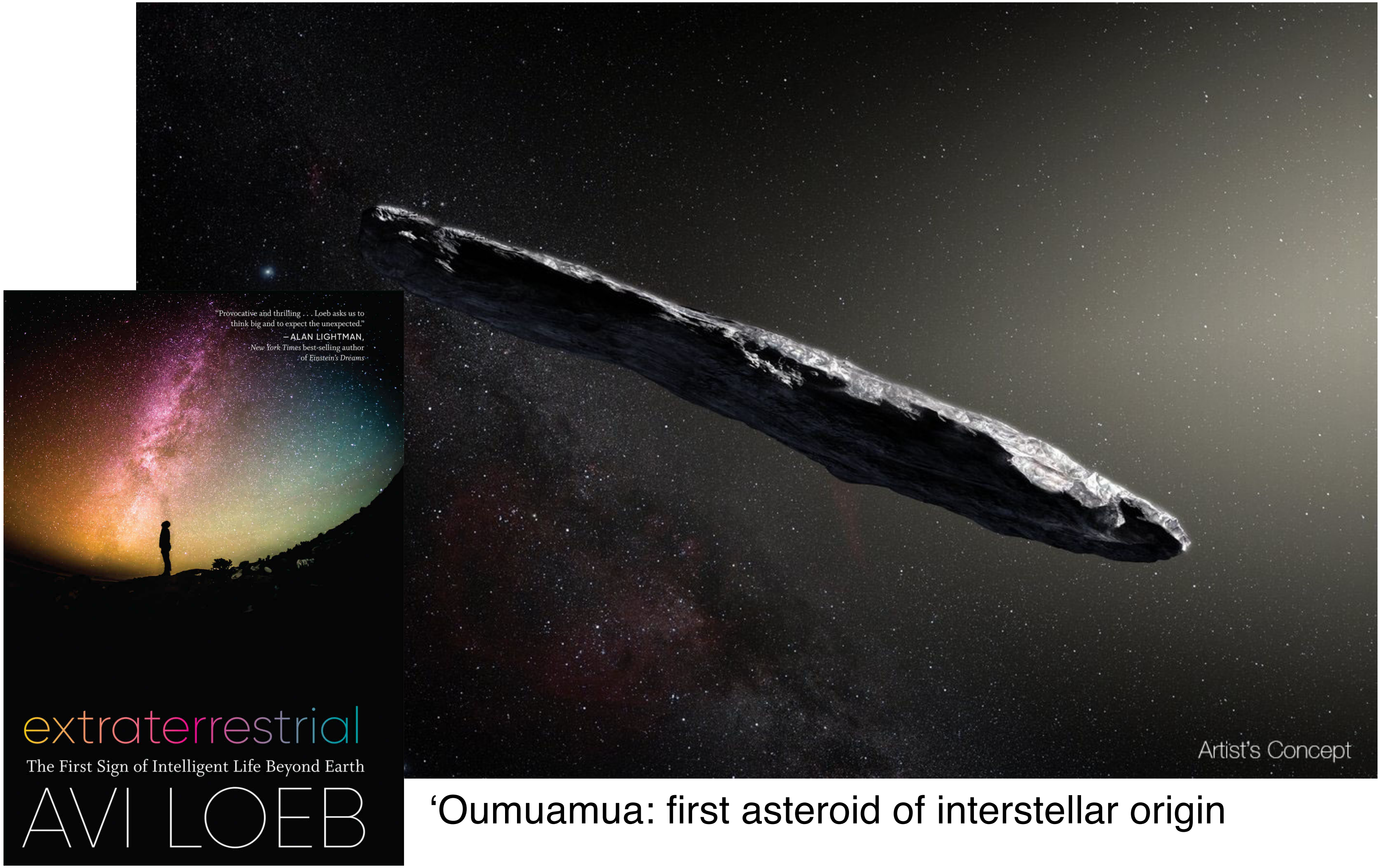
Chondritic meteorites -> chondrules
= traces of **hyper-fast heating** (< 1 min)



Impact marks on the least geologically active bodies suggest a massive bombardment during the first Gyr of the solar system.

The solar system

4. Miscellaneous

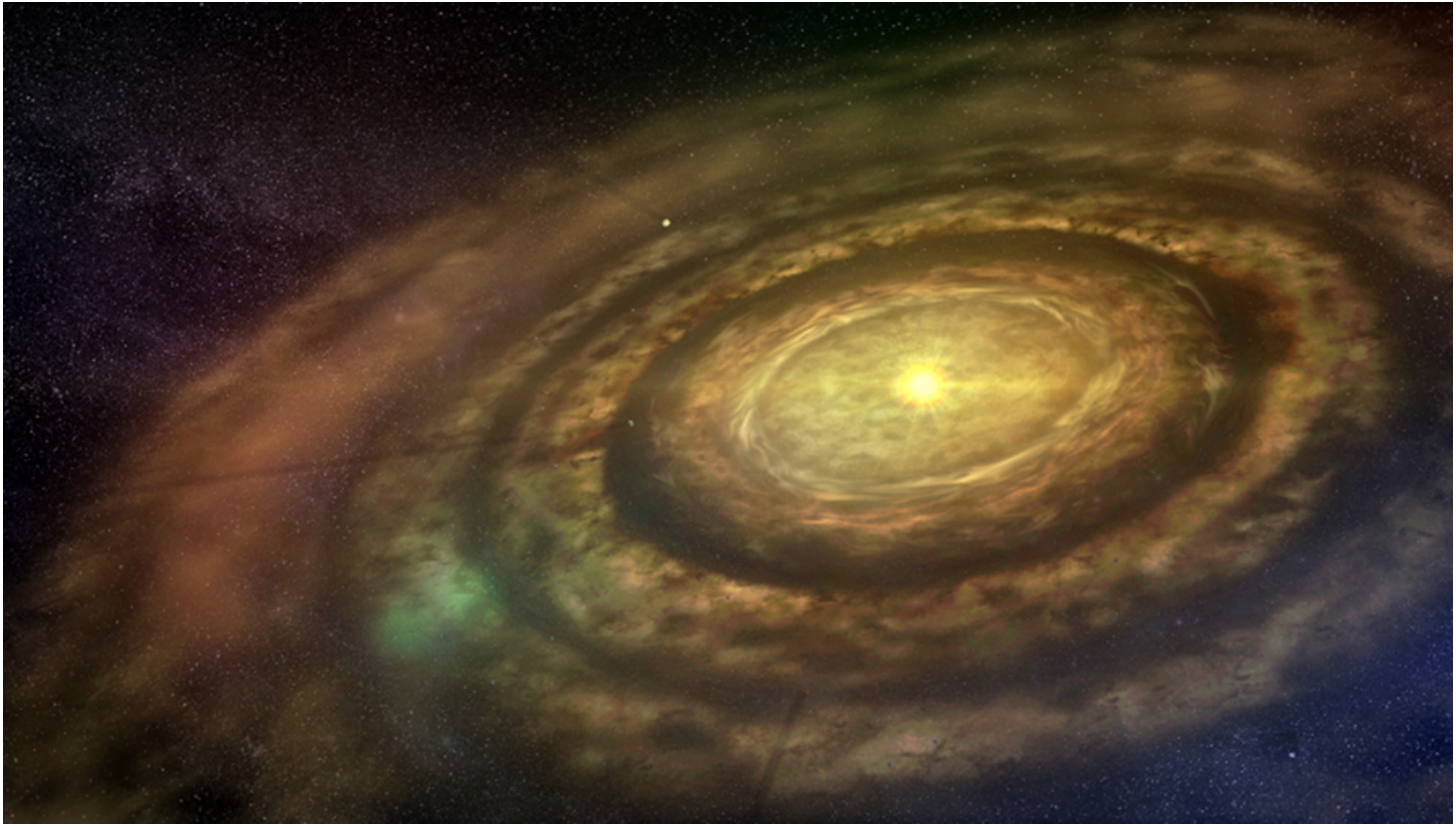


"Provocative and thrilling . . . Loeb asks us to think big and to expect the unexpected."
—ALAN LIGHTMAN,
New York Times best-selling author
of *Einstein's Dreams*

extraterrestrial
The First Sign of Intelligent Life Beyond Earth
AVI LOEB

'Oumuamua: first asteroid of interstellar origin

Formation of the solar system

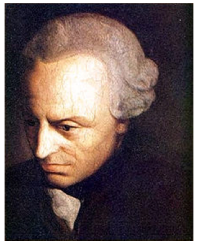


The nebular hypothesis

1734

Swendenborg

1755

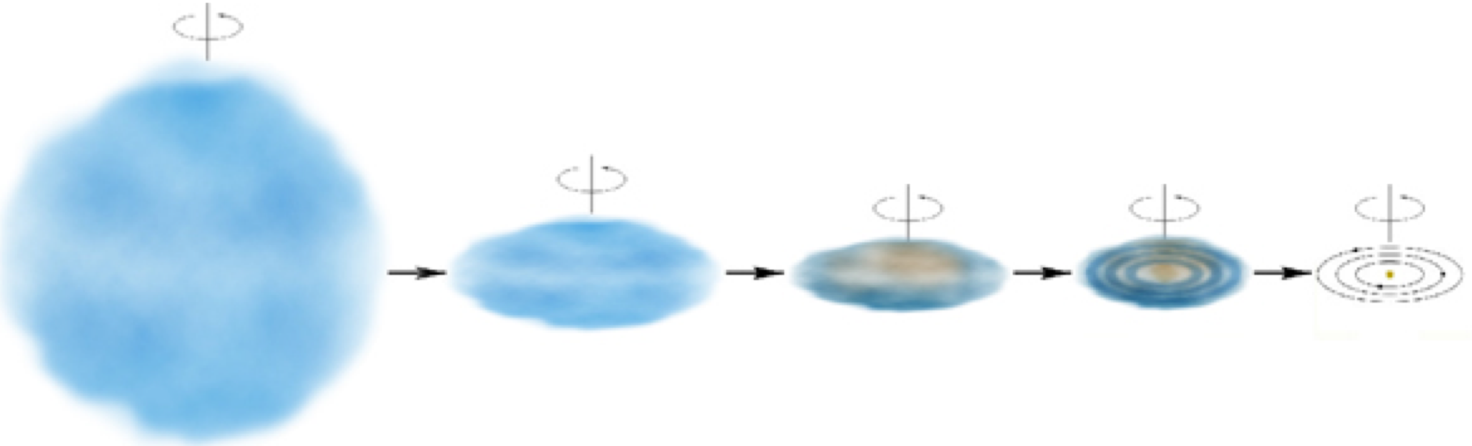


Kant

1796

Laplace

Paradigm until the end of the 19th century

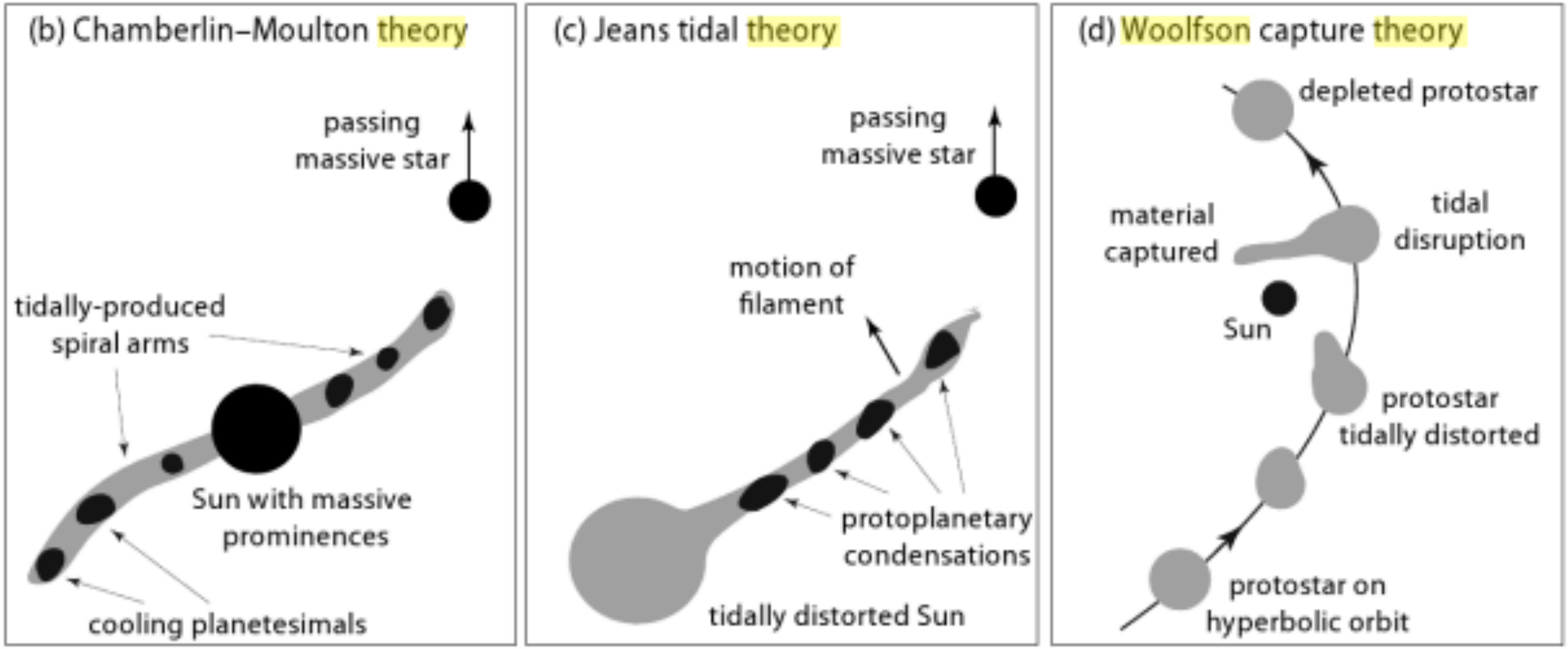


Planets form by gravitational instability (Kant) or by condensation of rings left by the Sun when it contracted (Laplace).

Problems:

- Angular momentum of the Sun should be much higher.
- Can not explain the formation of terrestrial planets nor Uranus and Neptune.

The encounter hypotheses



Perryman (2011)

Requires an impact parameter < 2 $R_\odot$ -> 1/10^8 stars -> **planets should be very rare!**

Problems:

- Jupiter should have an orbital angular momentum of the order of $(GM_\odot R_\odot)^{1/2}$ and not $(GM_\odot a_J)^{1/2}$ -> too big of a factor 30 *(Russell 1935).*

- Adiabatic expansion and dispersion of the filaments *(Spitzer 1939).*

- Non-solar composition of planets!

The core accretion model (Safronov 1969)

Starts from the nebular hypothesis: the Sun in formation surrounded by a disk of gas and dust.

Seven steps process:

1. In sufficiently cold zones of the disk, dust condense and settle in the median plane.

2. The dust particles form by coagulation objects with sizes of the order of km, **the planetesimals** (1-2 Myr).

3. Planetesimals grow by collision and accretion. The most massives acquire sufficient gravity to deflect and attract lighter ones: **« runaway growth »**. At some point, the lighter ones start to accrete more than the most heavy ones: **« oligarchic growth »**.

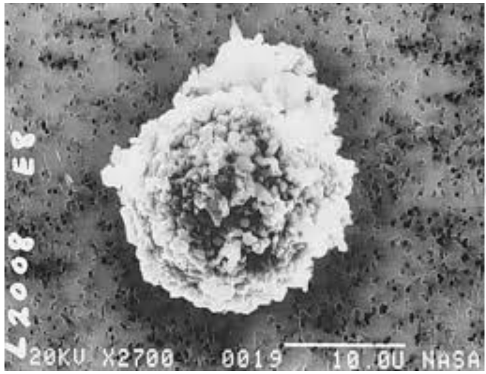
4. The first objects to reach the size of Mars (**planetary embryos**) dominate the dynamic evolution of the system (2-3 Myr).

5. On much longer timescales, planetary embryos eventually collide and form larger bodies, the **terrestrial planets** (10-100 Myr) and the **cores of giant planets** (5-10 Myr).

6. The cores of giant planets slowly **accrete the surrounding gas.**

7. Beyond the mass of 10-20 M_{Earth} the hydrostatic equilibrium of the shell is lost and the gas giant planets enter in **runaway accretion** until dispersion of the disc (10-15 Myr).

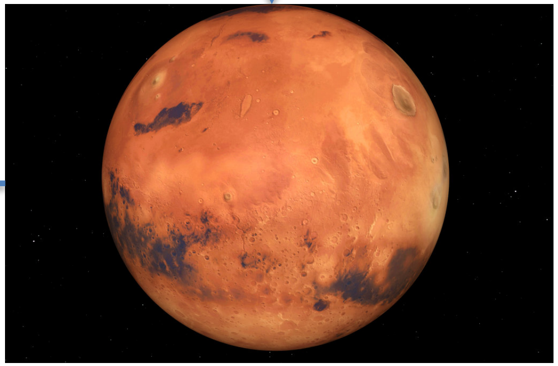
The core accretion model



dust

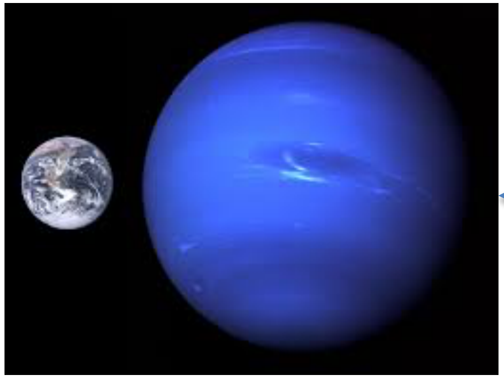
Planetesimal
(1-2 Myr)

Runaway and oligarchic growth



Planetary embryos
(2-3 Myr)

Terrestrial planets (10-100 Myr)
+ core of giants (5-10 Myr)



Gaz accretion
(< 10-15 Myr)

Basic model of the solar disk: Minimal Mass Solar Nebula (MMSN)

(Weidenschilling 1977, Hayashi 1981)

- Adding volatile elements to planets to reach a solar composition (100:1)

- Distributing the mass of each planet in a ring extending halfway to the nearest planets

- Smoothing the resulting surface density:

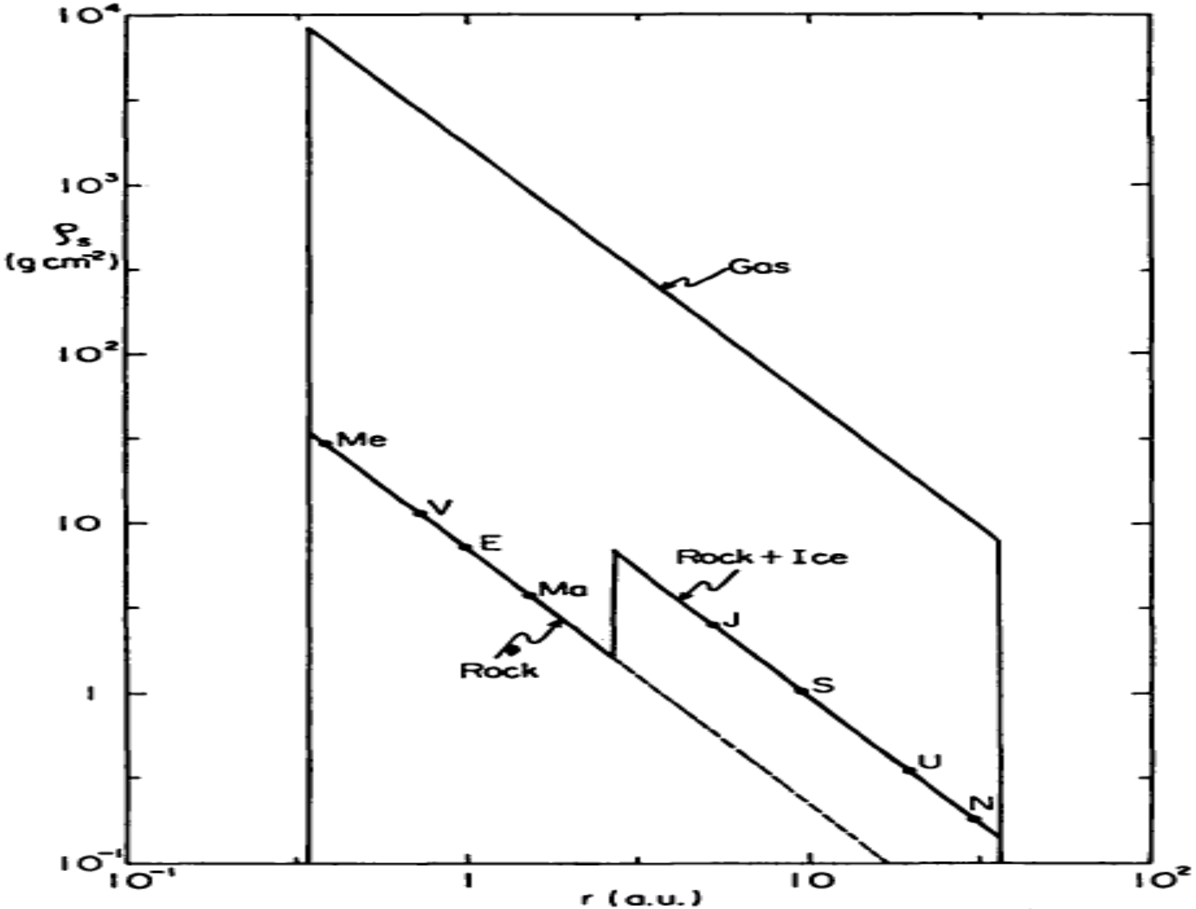
$$\Sigma(r) \approx 3 \times 10^{3}\, g.cm^{-2} \left(\frac{1au}{r} \right)^{1.5}$$

Basic model of the solar disk: Minimal Mass Solar Nebula (MMSN)

- Effect of temperature: **ice line** (~2.7 au, 170K)

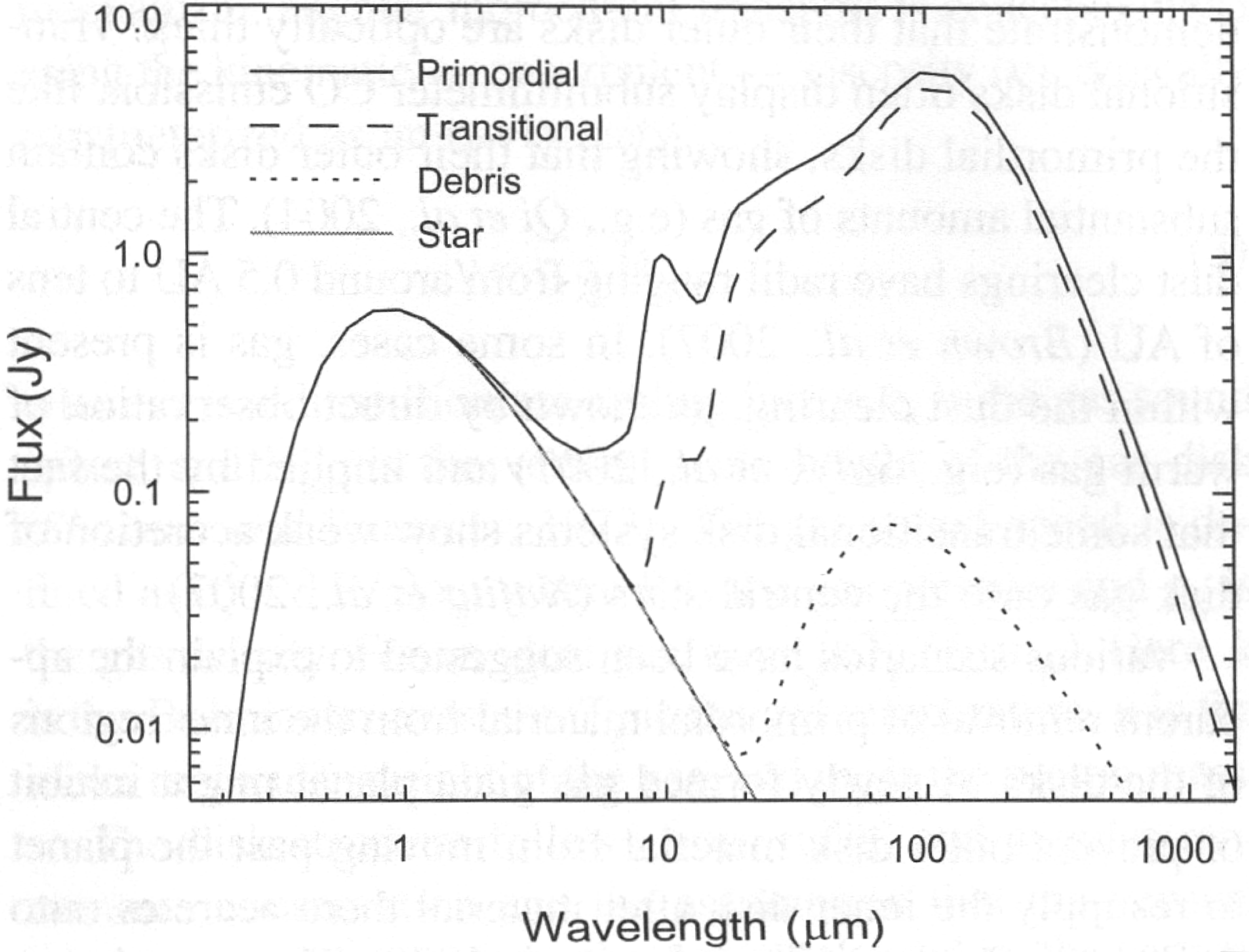
ζ =dust/gas = 1/60 (T<170K)
= 1/240 (T>170K) -> dust density 4 times smaller

-> mass of MMSN ~0.013 $M_\odot$



Hayashi (1981)

Protoplanetary disks: spectral energy distributions

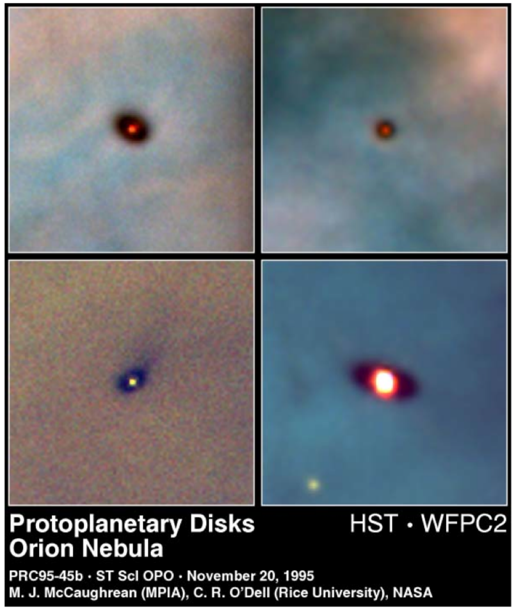


Roberge & Kamp (2010)

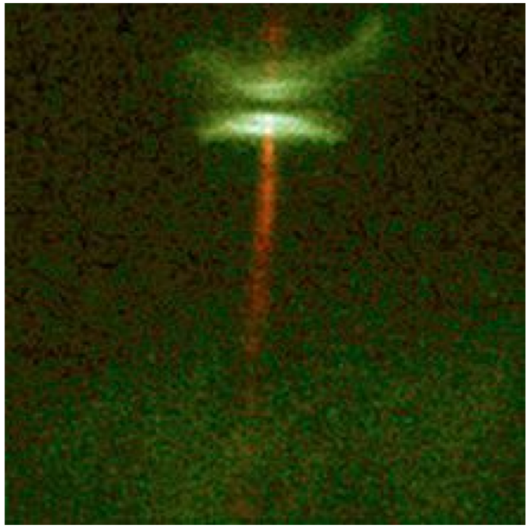
Protoplanetary disks: images

Orion nebula: proplyds

C.R. O'Dell/Rice University; NASA

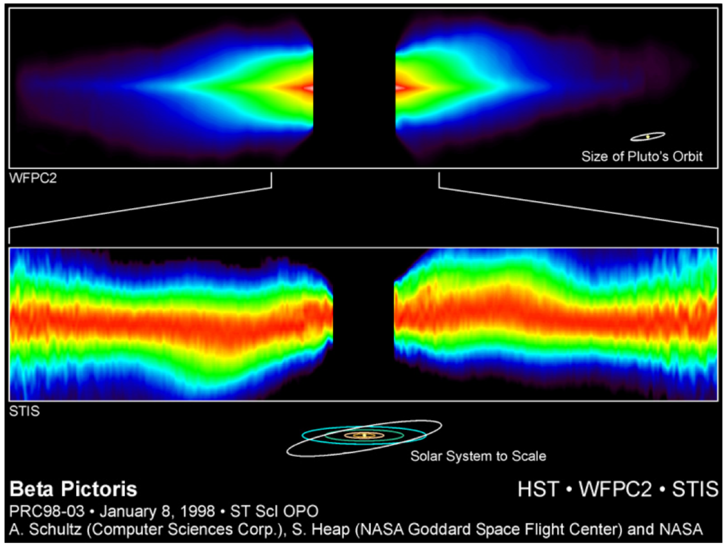


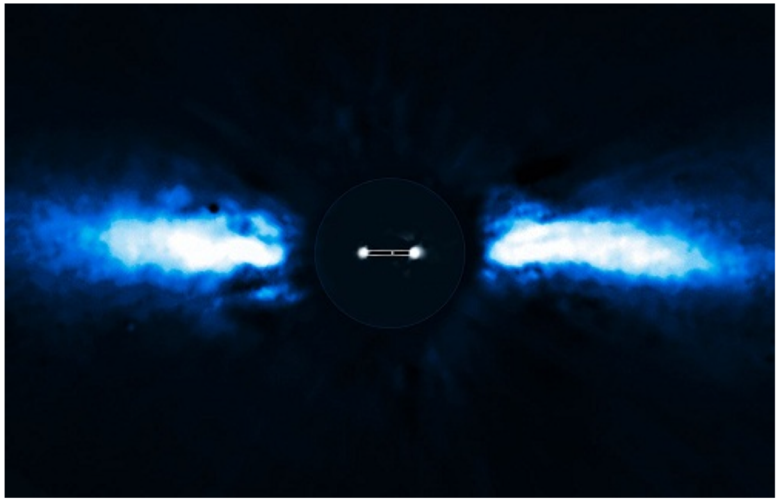
HH30: primordial disk



NASA

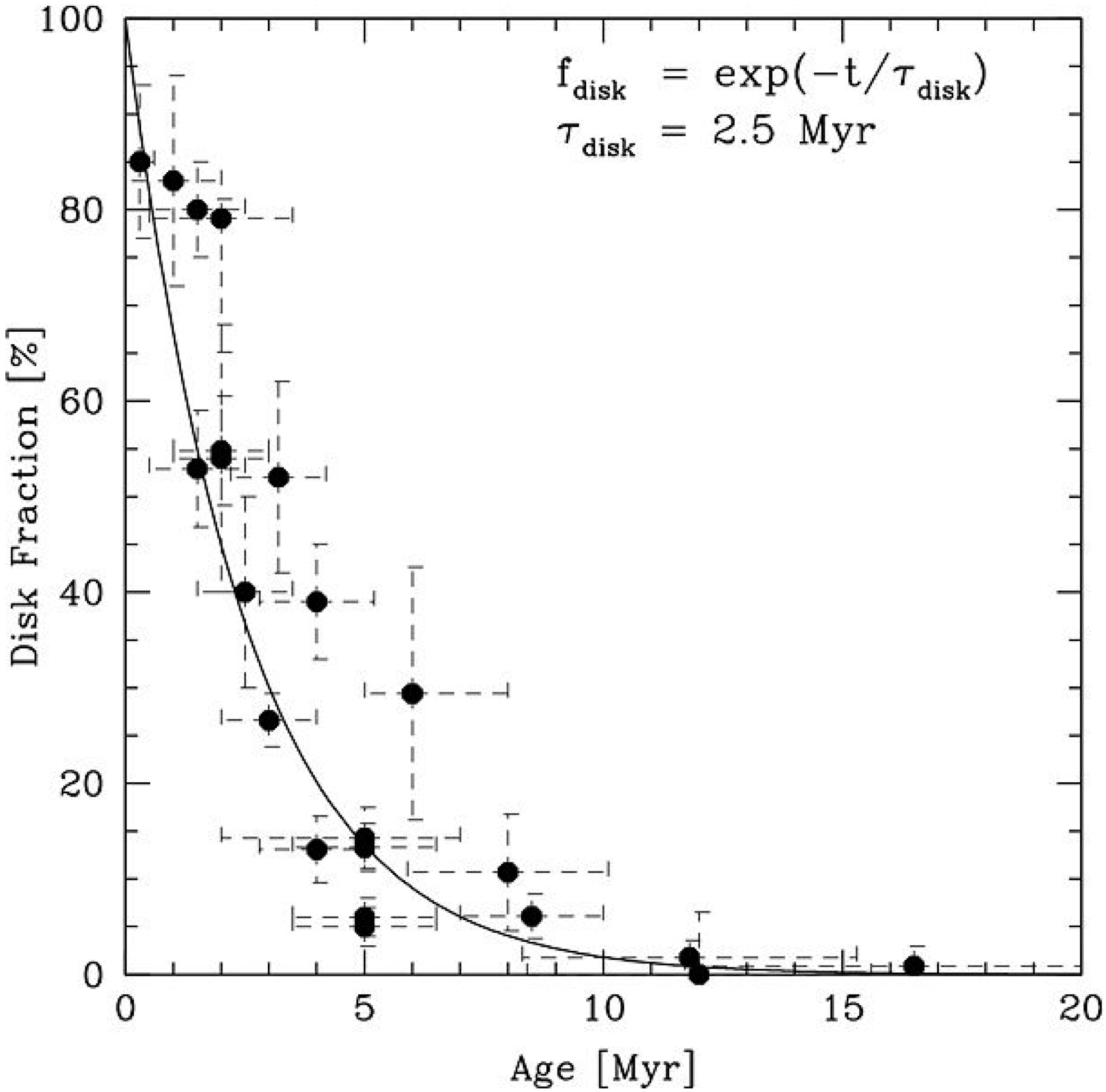
Beta Pictoris: debris disk





ESO/A.M. Lagrange

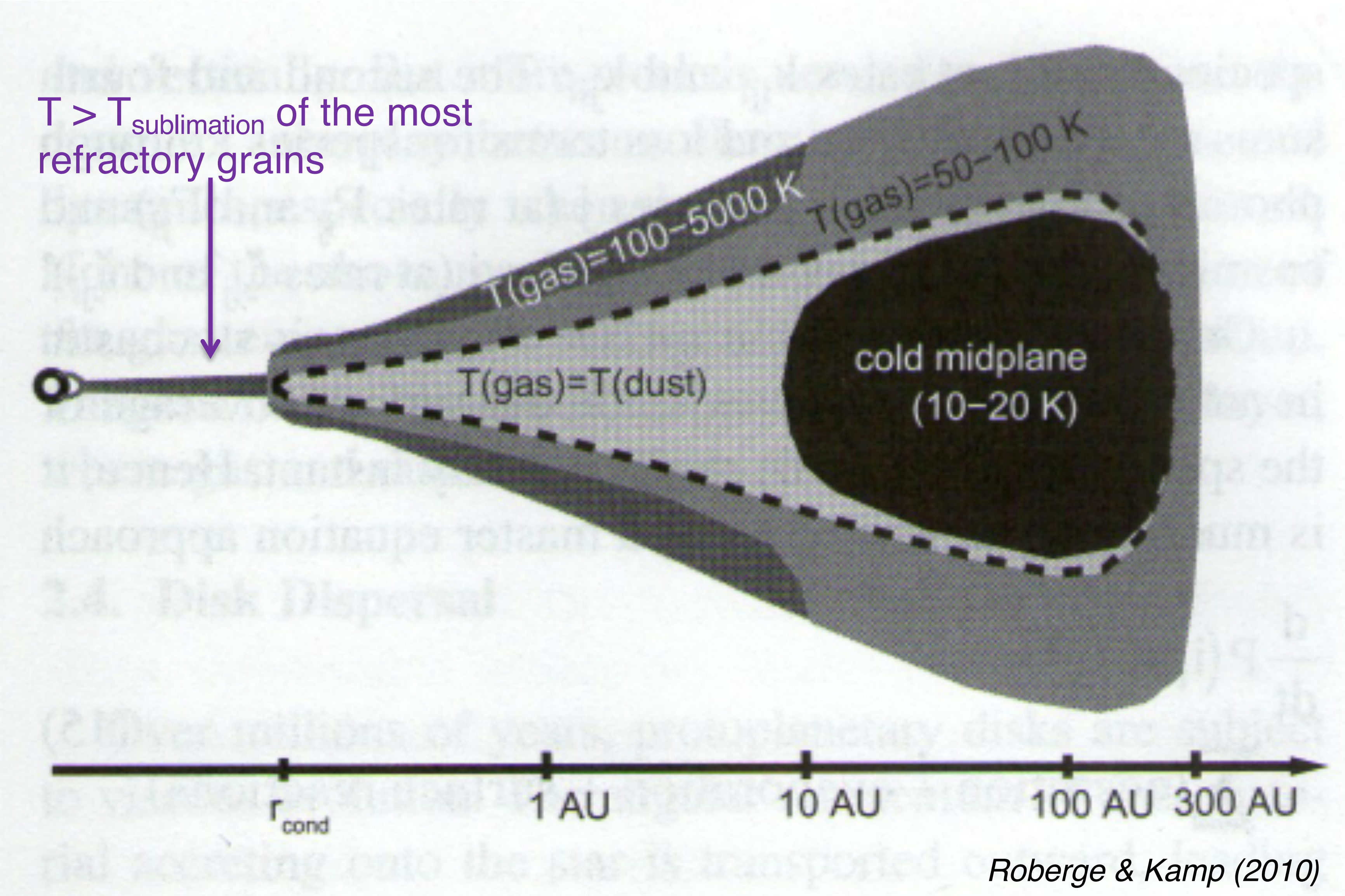
Protoplanetary disks: lifetime of the gaz



Mamajek (2009)

Protoplanetary disks: structure

← Viscosity: spreading of the disk to a few hundreds au + accretion →

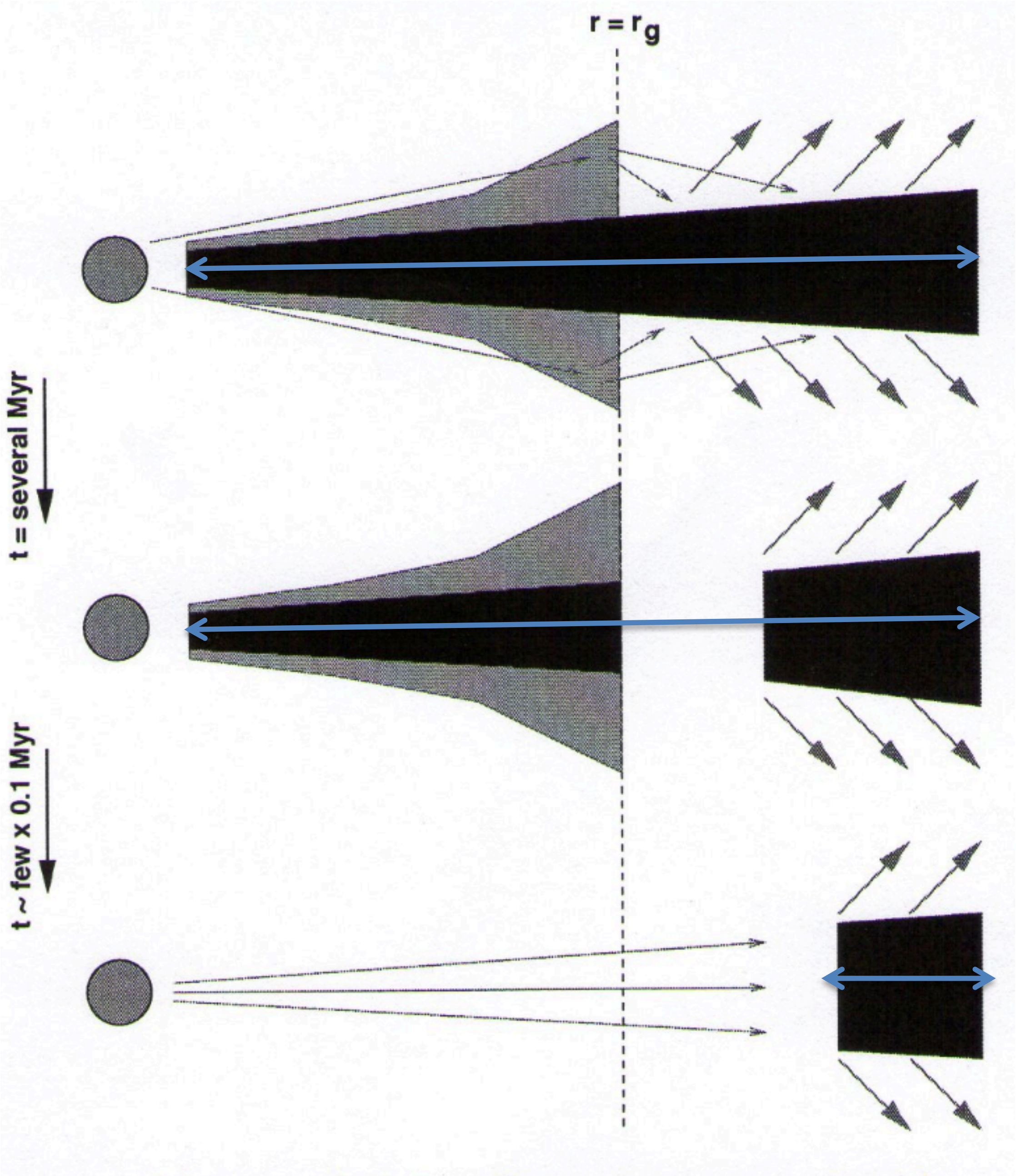


T > $T_{sublimation}$ of the most refractory grains

Roberge & Kamp (2010)

« flaring disk »

Protoplanetary disks: gas dispersal



UV with E > 13.6 eV ionize and heat the gas.
Beyond r_g, $v > v_{escape}$

X-rays are important too

Models reproduct well the observed lifetimes

$r_g \approx 10$ au

Ejection + accretion

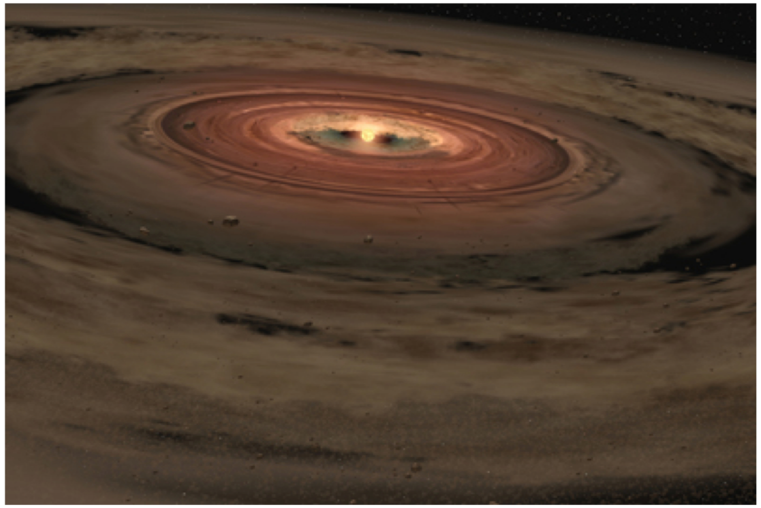
Phase I: dust dynamics

Dust particles of a few 10μm pre-exist or condense from the cooling protoplanetary disk

- Fe, silicates, Ni in the **inner solar system**;
- Water, ammonia, and methane ices in the **outer solar system**.

Maximum growth rate dR_p/dt ~ cm/yr

Dust settle in the median plane at a rate determined by the competition between **the vertical gravity and the gas drag.**



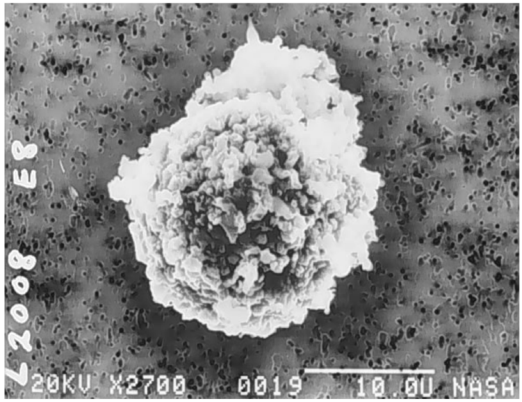
Dust particles reach R_p ~10 cm in ~10 yrs before settling in the disk midplane.

Phase II: planetesimals formation

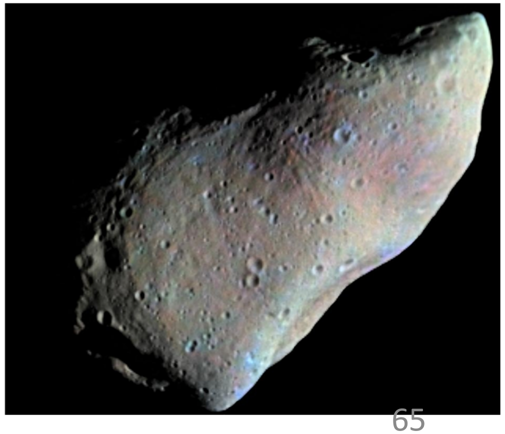
Centrifugal force acting on gas is balanced by solar gravity AND gas pressure.

Therefore the rotation of the gas is slightly slower (0.2%) than for a Keplerian orbit, resulting in **drag force** on solid particules.

Theoretical estimates indicate that dust particles (<1cm) are driven by the wind, and the largest (> 10m) bodies are not affected. But the ‘pebbles’ and ‘boulders’ (1cm to 10m) should be strongly affected and spiral towards the star at speeds up to 1 au / (100-1000 years).



Phase II = planetesimals formation
Jump from cm to km within 1000 years!



Phase II: planetesimals formation

1000 years to pass the critical threshold from < 1 cm to > 1 m

1. **Growth by grains collisions?**

Many lab experiments, with mixed results. The most refractory dust particles do not aggregate very well, and the richest in ice fracture ...
+ The largest inclusions in meteorites have only a few cm ...

2. Gravitational instability (Goldreich-Ward mechanism)?

Median dust disk becomes gravitationally unstable when

$$\boxed{Q = \frac{\sigma\,\Omega}{\pi G \Sigma} < 1}$$

With Σ = surface density of dust, σ is the speed deviation, and Ω is orbital frequency.

Turbulence tends to increase σ and decrease Σ. Formation of planetesimals in the lowest-turbulence zones of the disk, followed by a very efficient **accretion of pebbles** onto the first planetesimals.

Phase III: planetesimals growth

Starting from ~10^{10} bodies with radii ~1-10 km, and neglecting the gas, we let these bodies interact through gravity. A growth by collisional accretion is assumed.

The orbit of a planetesimal is perturbated if, during a conjonction, another planetesimal enters its **Hill radius $r_H = a(M_p/3M_*)^{1/3}$.**

The zone $|\Delta a| < r_H$ represent the **feeding zone** of a planetesimal. When it has accreted all the material available in its feeding zone = $4\pi\Sigma a r_H$, the process stops and the planetesimal has become a **planetary embryo**. Its mass is then:

$$M_{pe} \approx 0.2 * M_{Mars} \left(\frac{\Sigma}{10\,g.cm^{-2}}\right)^{\frac{3}{2}} \left(\frac{a}{1au}\right)^{3}$$

At 1 au, and assuming $\rho = 5.52\ g/cm^3$ -> **$R \sim 0.25\ R_{Earth}$**

Phase III: planetesimals growth

The largest planetesimals have a significant gravitational field and deflect the trajectory of the passing smaller bodies, which increases their cross section by a factor (1 + Θ), where Θ is the number of Safronov:

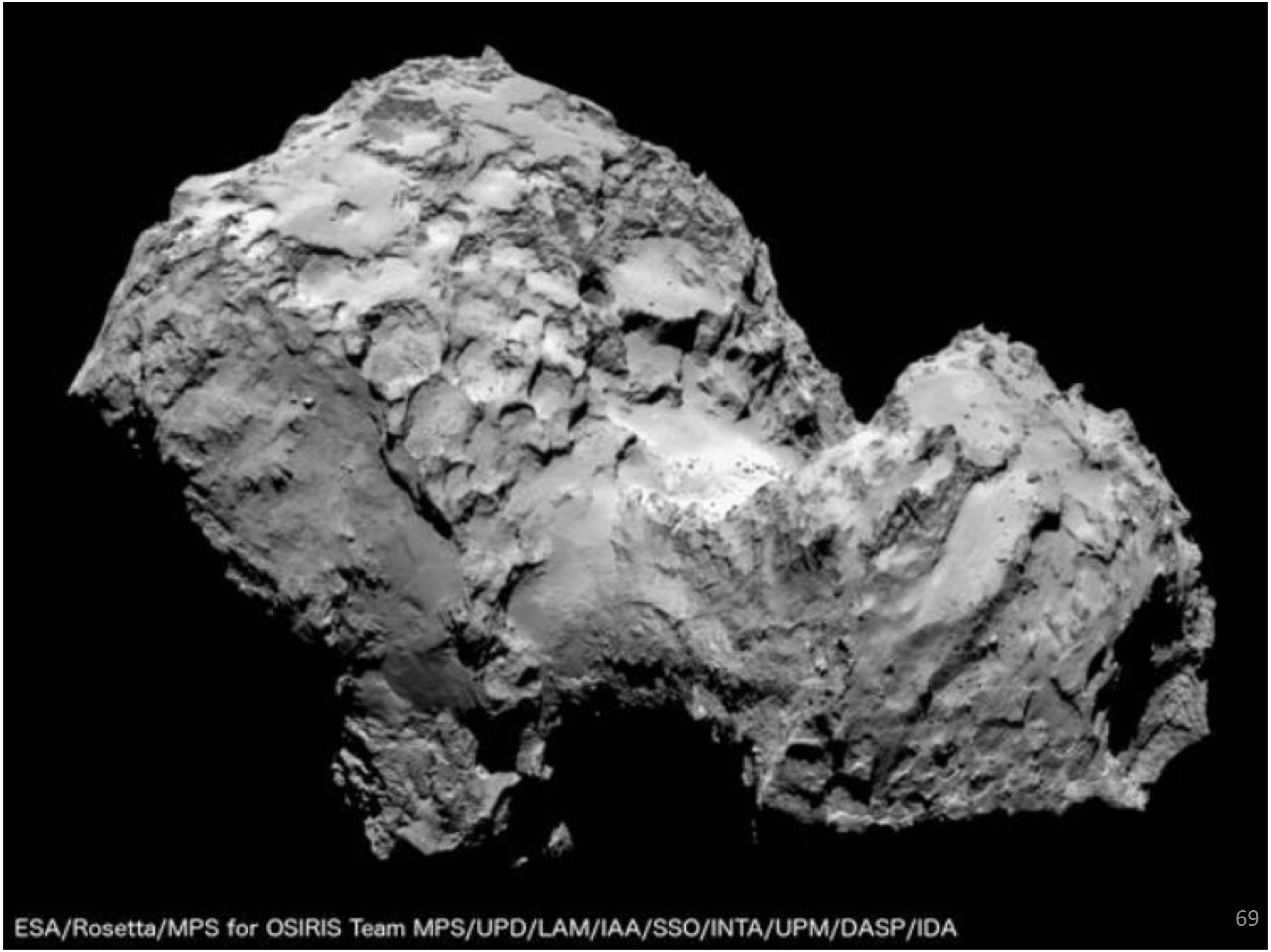
$$\Theta = \frac{2GM_p}{R_p v_{rel}^2} = \frac{v_{escape}^2}{v_{rel}^2}$$

This is the phenomenon of «**gravitational focusing**».

Interaction: big bodies maintain circular orbits (dynamic friction), while smaller ones get more and more eccentric orbits. This increases their chance of colliding with a big body. As every big-small collision leads to an increase of the big's mass, the net result is a « **runaway growth**, i.e. a much larger growth for the big bodies.
Growth times vary as $M^{-1/3}$

Accretion does not only involve « sticky » collisions , but also and mainly gravitational captures **-> loose structure of planetesimals.**

Phase III: planetesimals growth



ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Phase IV and V: planetary embryos

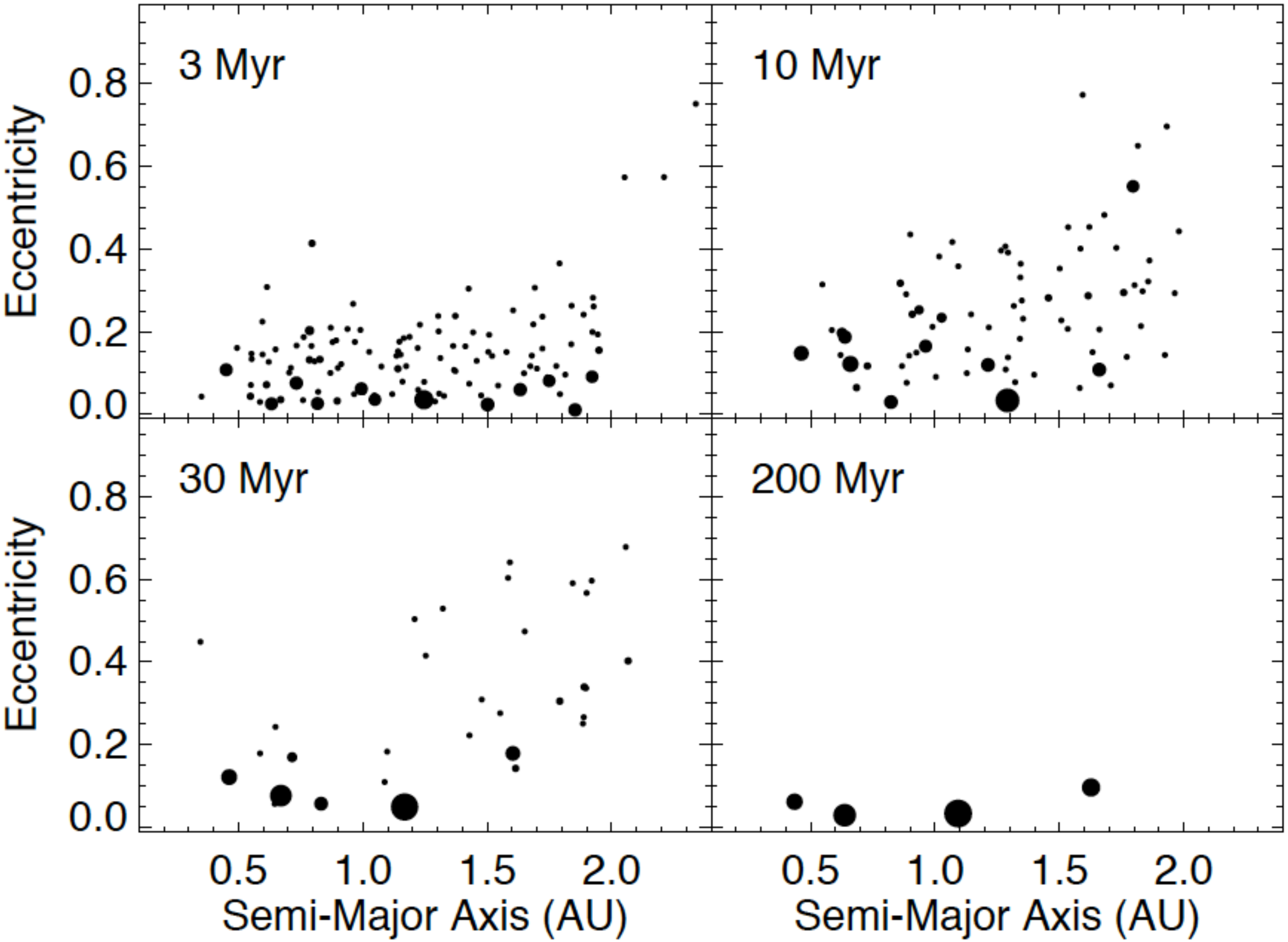
The **runaway growth** is followed by the **oligarchic growth** where depletion of small bodies and their more and more eccentric orbits in the vicinity of the biggest ones (planetary embryos) decrease the probability of accretion. **Growth times then vary as $M^{1/3}$, the largest bodies thus having the slowest evolution.**

When planetary embryos acquire a mass comparable to that of Mars, they begin **to accrete the surrounding gas**. Their atmosphere will then slow the planetesimals and increases the cross-section.

The interaction of the embryos with the gaseous disk will reduce their eccentricity and inclination, and also potentially leads to semi-major axis changes (**type I migration**). Combined with embryos-embryos, embryos-planetesimals interactions, it gives a stochastic nature to this phase.

At the dispersal of the gaseous disk, at a few Myr, there are ~**100 planetary embryos in the terrestrial zone**. Their mutual perturbations lead to collisions, responsible for the transition to the planet stage. Growth time is 10^7-10^8 years (**phase V**).

Phase IV & V: planetary embryos

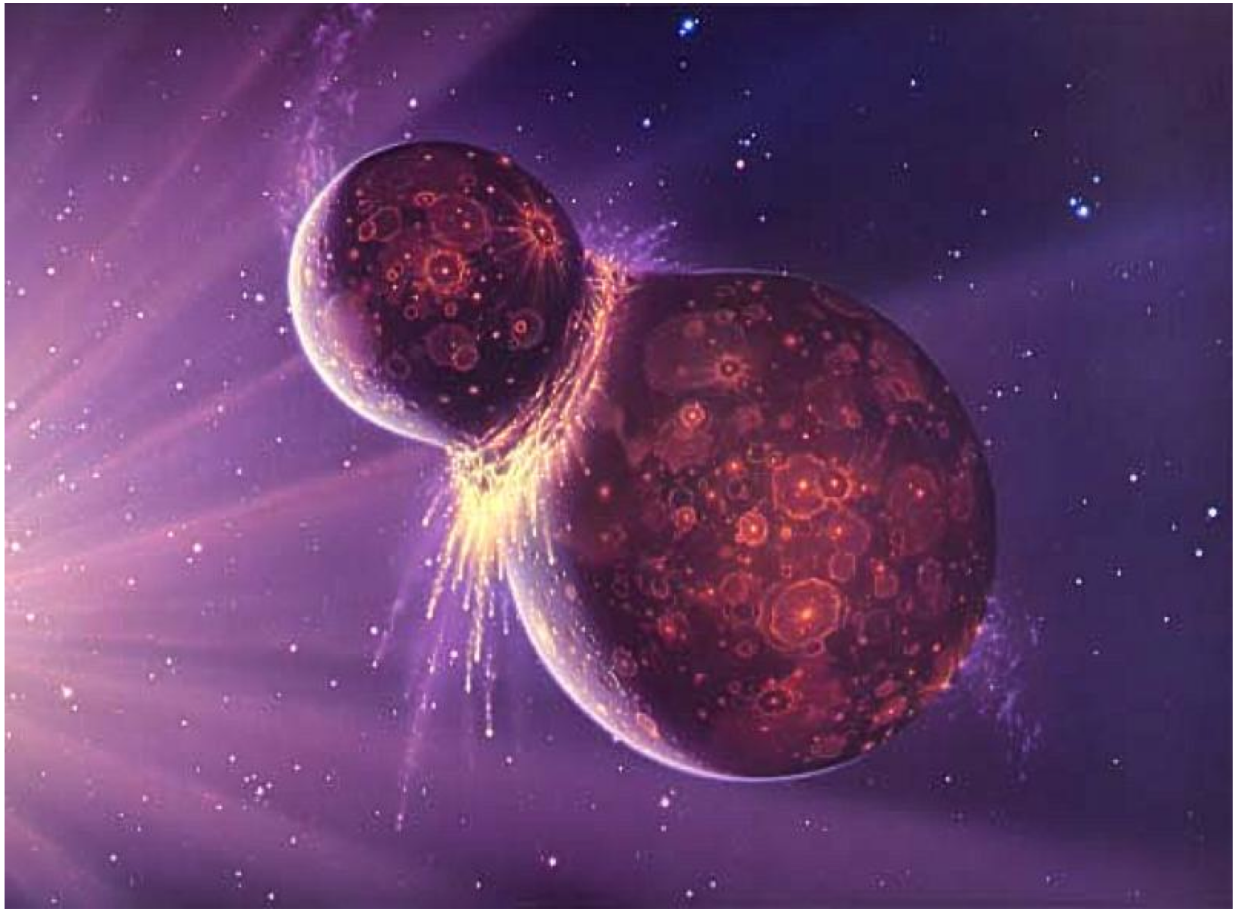


Chambers (2010)

Formation of the Moon

Impact between proto-Earth and a planetary embryo (called **Theia**)
A few dozens of Myr after the start of the formation of the Solar System
Fractions of the mantles of proto-Earth and Theia are ejected around the proto-Earth
Coalescence within 1 century

Canup & Asphaug (2001)



Accretion is still going on…

Phase VI: gas accretion

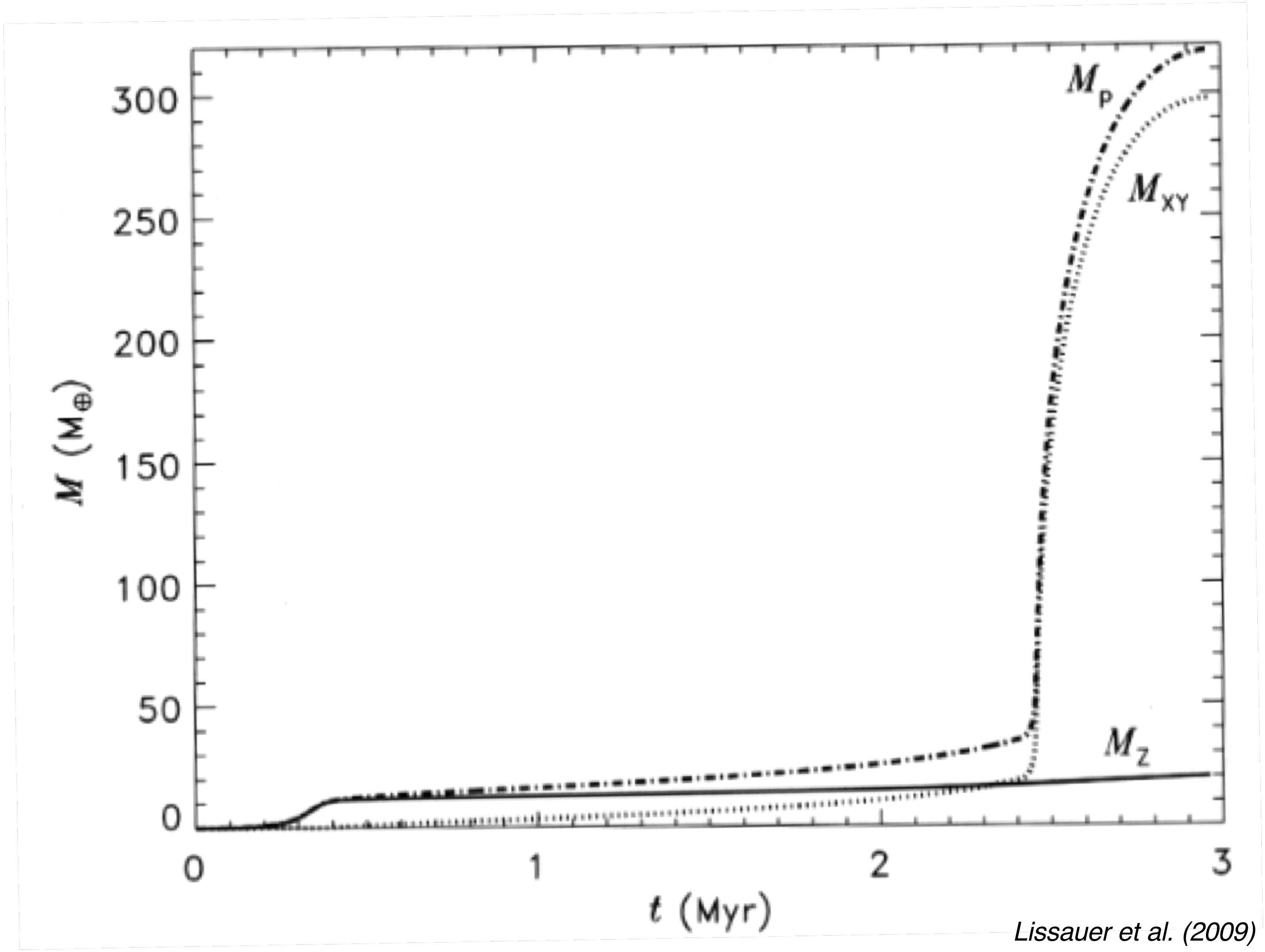
Condition: thermal energy of the gas gets smaller than its gravitational energy connecting it to the planetary embryo.

At a few au, a mass of 0.01M_{Earth} is enough to accrete the gas of the disk

At first, the atmosphere is optically thin, so the thermal energy due to impacts is effectively irradiated, and the atmosphere cools and contracts. It will then become optically thicker and both denser and hotter than the gas disk, which leads to a pseudo-hydrostatic equilibrium, stopping the gas accretion -> **quasi-static contraction, with very slow accretion rates.**

Once reached a critical mass ~10-20 M_{Earth}, hydrostatic equilibrium is no longer possible, gravity outweighs the pressure and **accretion runs away**. The protoplanet then will accrete all gas on its orbit, creating a hole in the disc.

Phase VI: gas accretion



Lissauer et al. (2009)

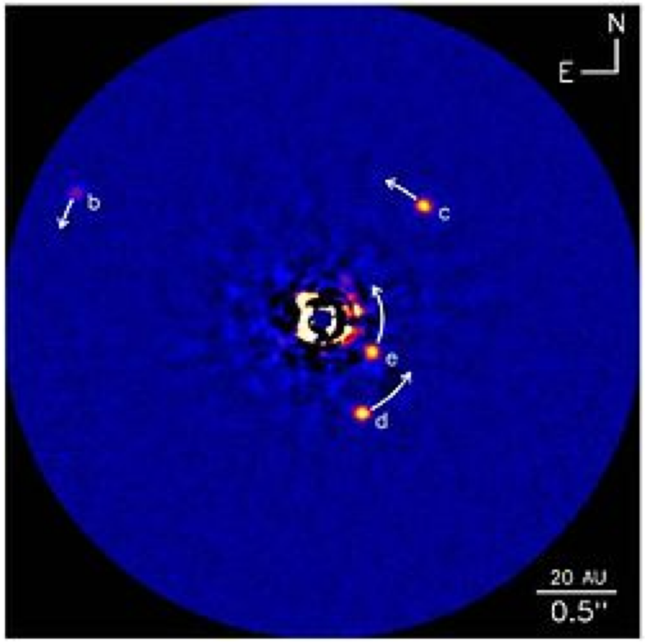
Alternative model: formation of giant planets by gravitational instability of the disk

The gaseous disk becomes gravitationaly unstable if the Toomre parameter

$$Q = \frac{\sigma_c \Omega}{\pi G \Sigma_g} < 1$$

with here Σ_g instead of Σ_d, and σ_c = speed of sound $\sim \sqrt{\frac{P}{\rho}}$

Massive and cold disk areas: OK for external parts of a massive disk?



HR8799: A-type star of ~30 Myr
$1.47 \pm 0.30\ M_{sun}$
$[Fe/H] = -0.47 + -0.10$

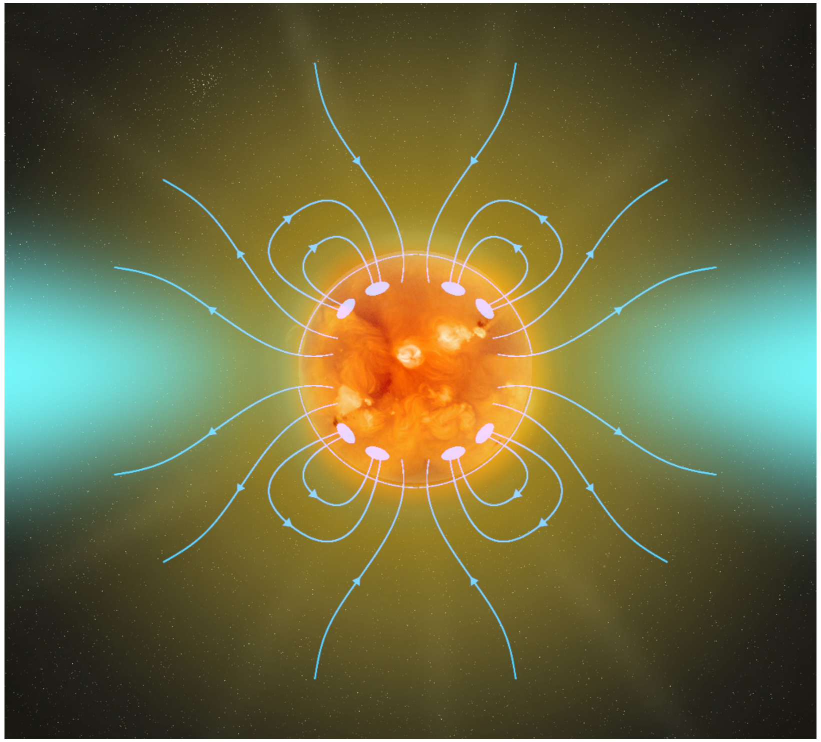
4 planets of several jovian masses at 15, 24, 38, 68 au.

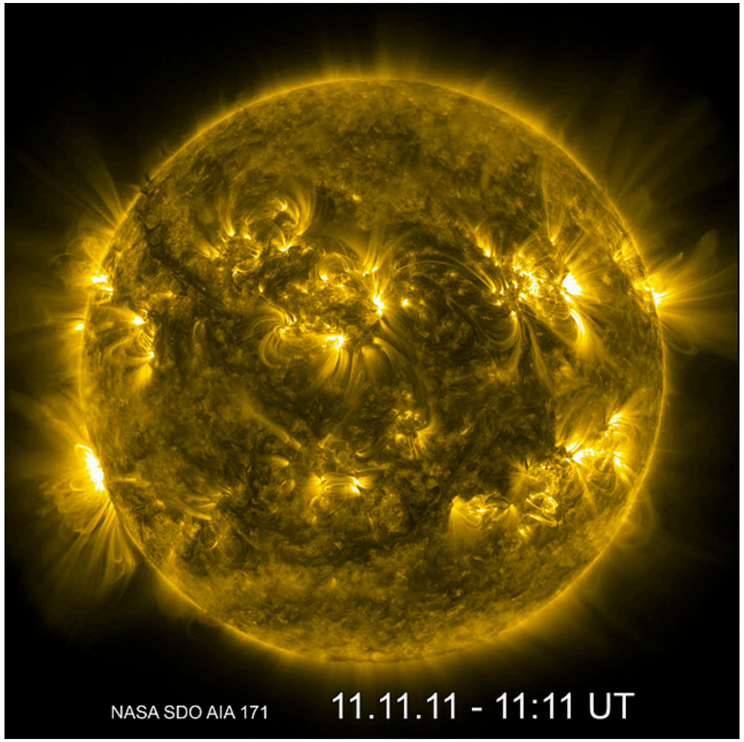
Boss (2011) showed that these planets could have formed by gravitational instability.

And how to explain the Sun’s low angular momentum?

Magnetic braking

The magnetic field lines rotate together with the Sun as a solid object. Ionized material carried along the field lines will at some point escape the magnetic field lines and thus take away the Sun's angular momentum

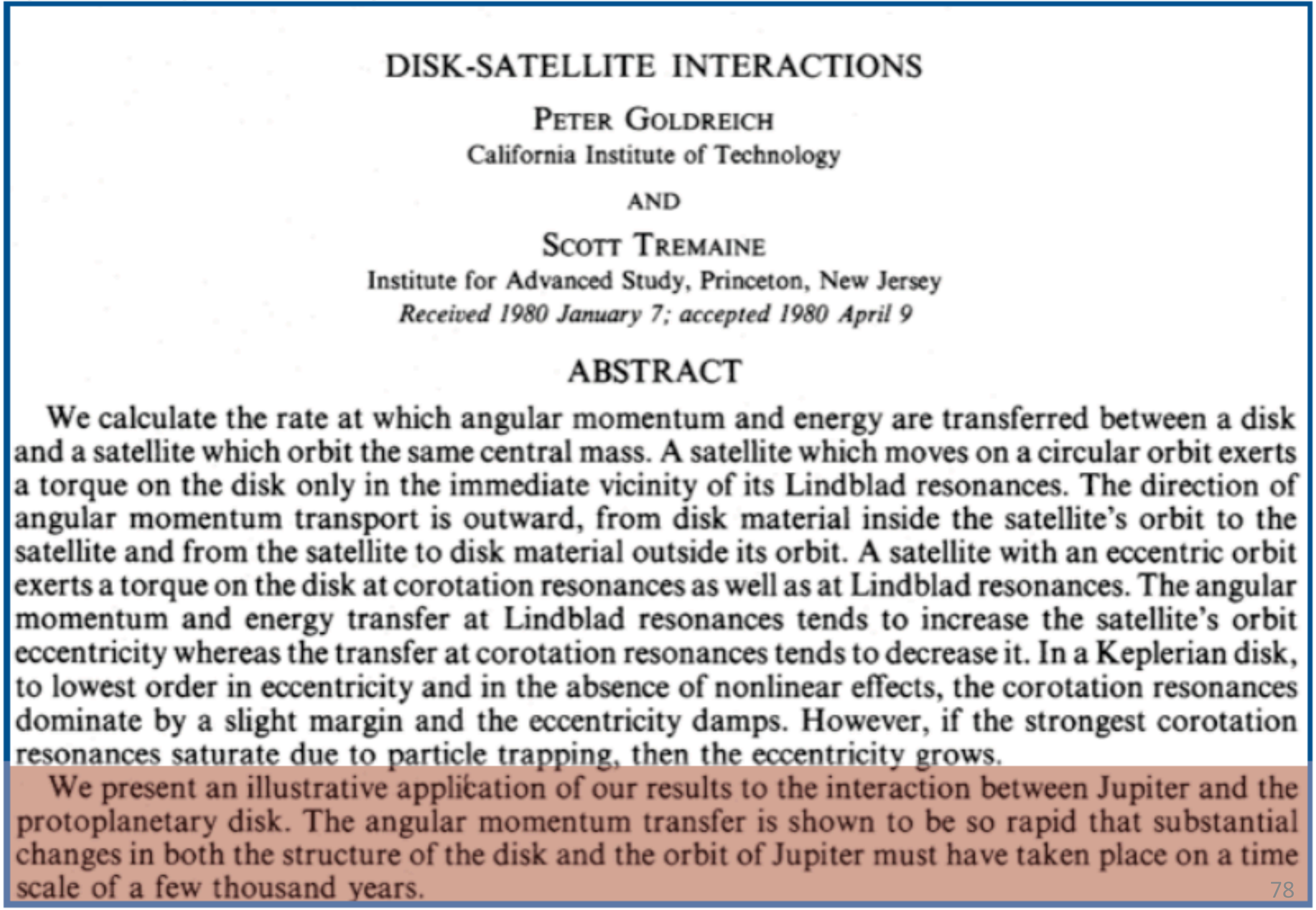




Ionized plasma on magnetic field lines extending of a few solar radius from the Sun have enough kinetic energy to break away from the magnetic field.

Migrations

ApJ, 241, 425 (October 1, 1980)



DISK-SATELLITE INTERACTIONS

PETER GOLDREICH
California Institute of Technology

AND

SCOTT TREMAINE
Institute for Advanced Study, Princeton, New Jersey

Received 1980 January 7; accepted 1980 April 9

ABSTRACT

We calculate the rate at which angular momentum and energy are transferred between a disk and a satellite which orbit the same central mass. A satellite which moves on a circular orbit exerts a torque on the disk only in the immediate vicinity of its Lindblad resonances. The direction of angular momentum transport is outward, from disk material inside the satellite's orbit to the satellite and from the satellite to disk material outside its orbit. A satellite with an eccentric orbit exerts a torque on the disk at corotation resonances as well as at Lindblad resonances. The angular momentum and energy transfer at Lindblad resonances tends to increase the satellite's orbit eccentricity whereas the transfer at corotation resonances tends to decrease it. In a Keplerian disk, to lowest order in eccentricity and in the absence of nonlinear effects, the corotation resonances dominate by a slight margin and the eccentricity damps. However, if the strongest corotation resonances saturate due to particle trapping, then the eccentricity grows.

We present an illustrative application of our results to the interaction between Jupiter and the protoplanetary disk. The angular momentum transfer is shown to be so rapid that substantial changes in both the structure of the disk and the orbit of Jupiter must have taken place on a time scale of a few thousand years.

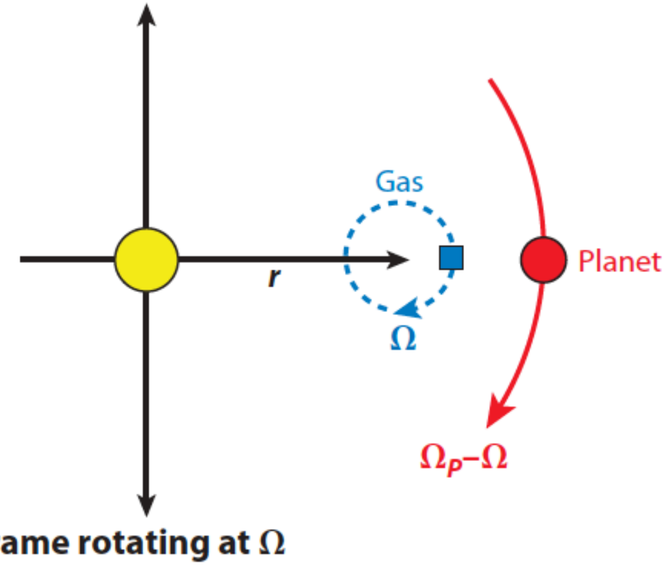
Migrations

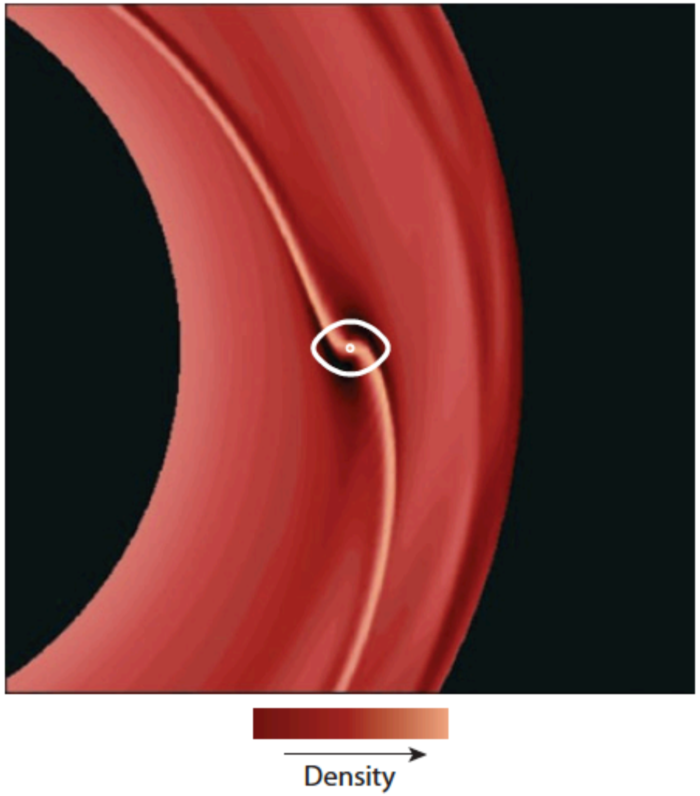
I. Migration by interaction with the gaseous disk. Type I

Concerns low-mass planets, whose effects on the gaseous disk are only important at **Lindblad resonances.**

$$P_g = P_p\,(m \pm 1)/m$$

m=integer





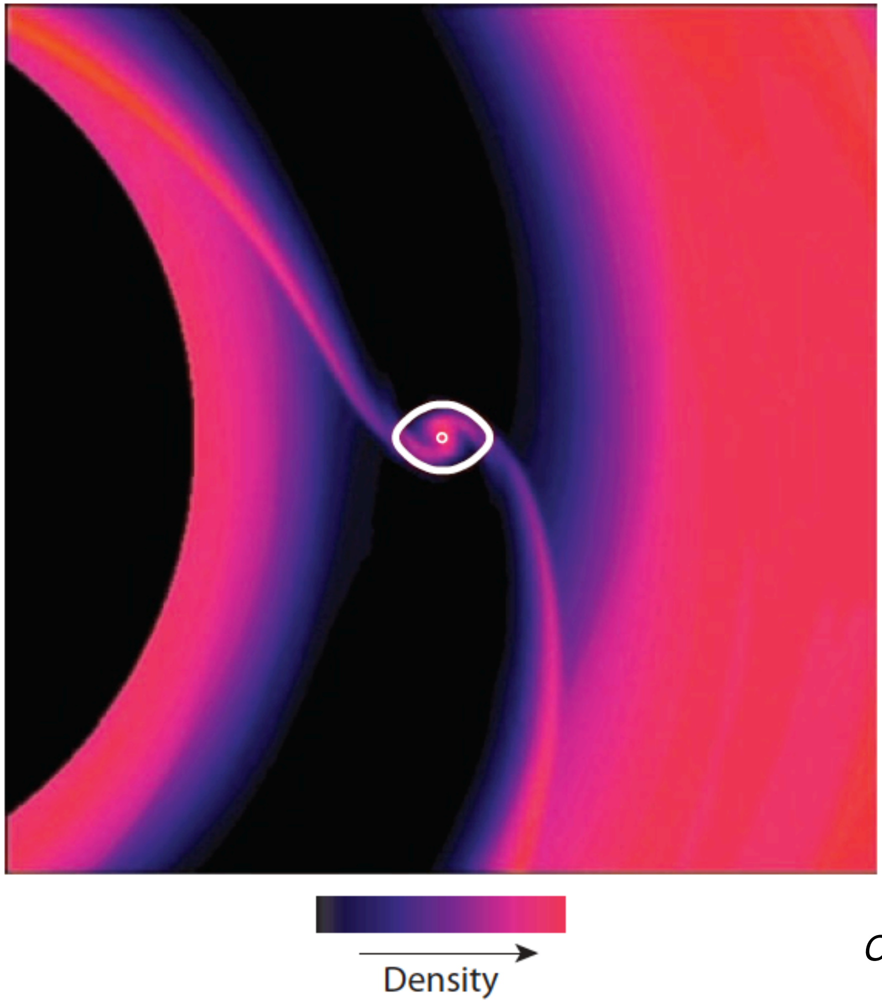
Chambers (2009)

Excited disturbances (**density waves**) typically causing rapid internal migration and a decrease of *i* and *e*.

Migrations

I. Migration by interaction with the gaseous disk. Type II

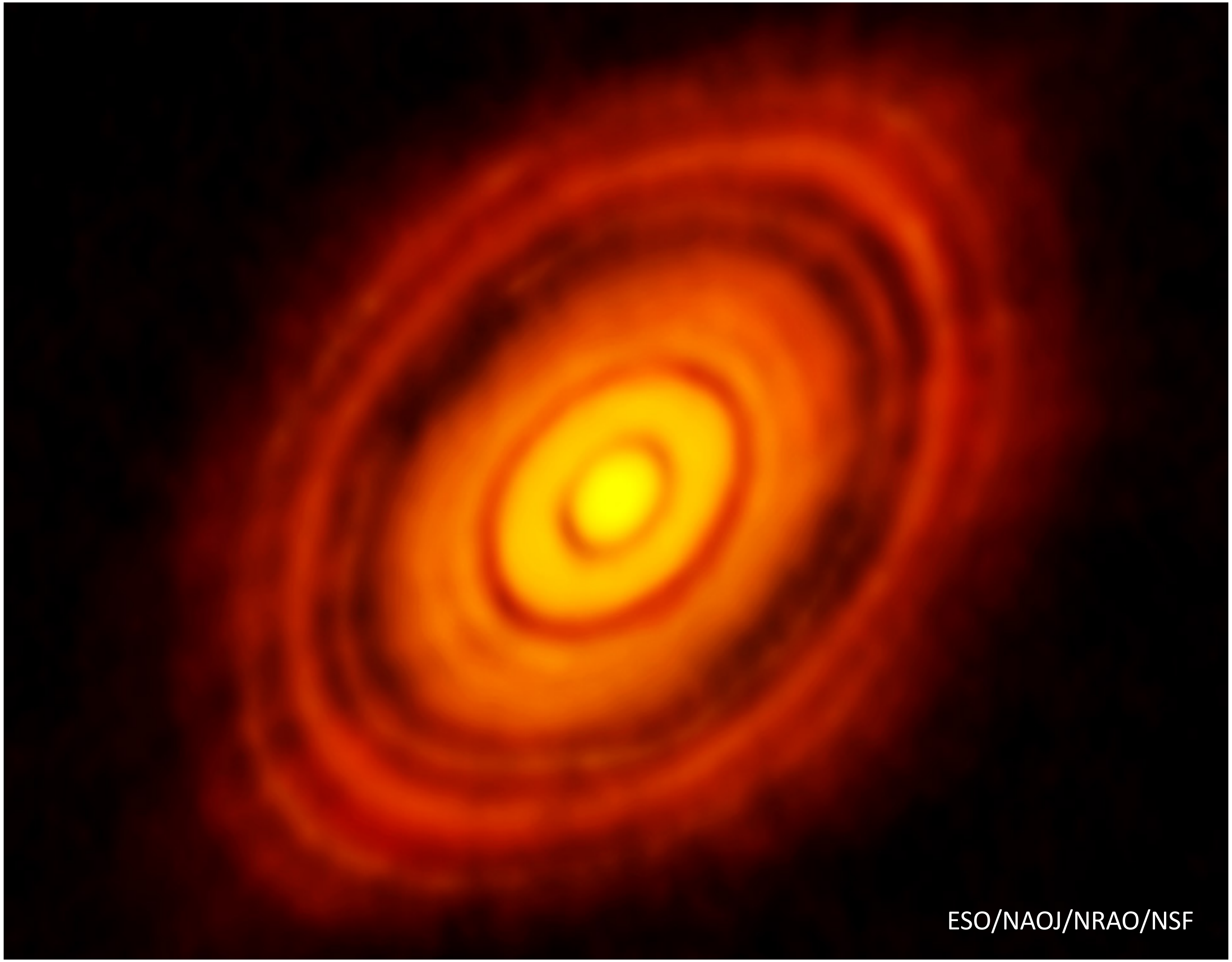
Concerns the massive planets, whose effects on the gas disk are very important. The torque created by the planet creates **a hole in the disc**. **The planet is dynamically linked to the evolution of the viscous gaseous disk -> migration**



Chambers (2009)

Migrations

The disk of the young star HL Tauri (0.5 Myr) as seen by ALMA (Nov 2014)

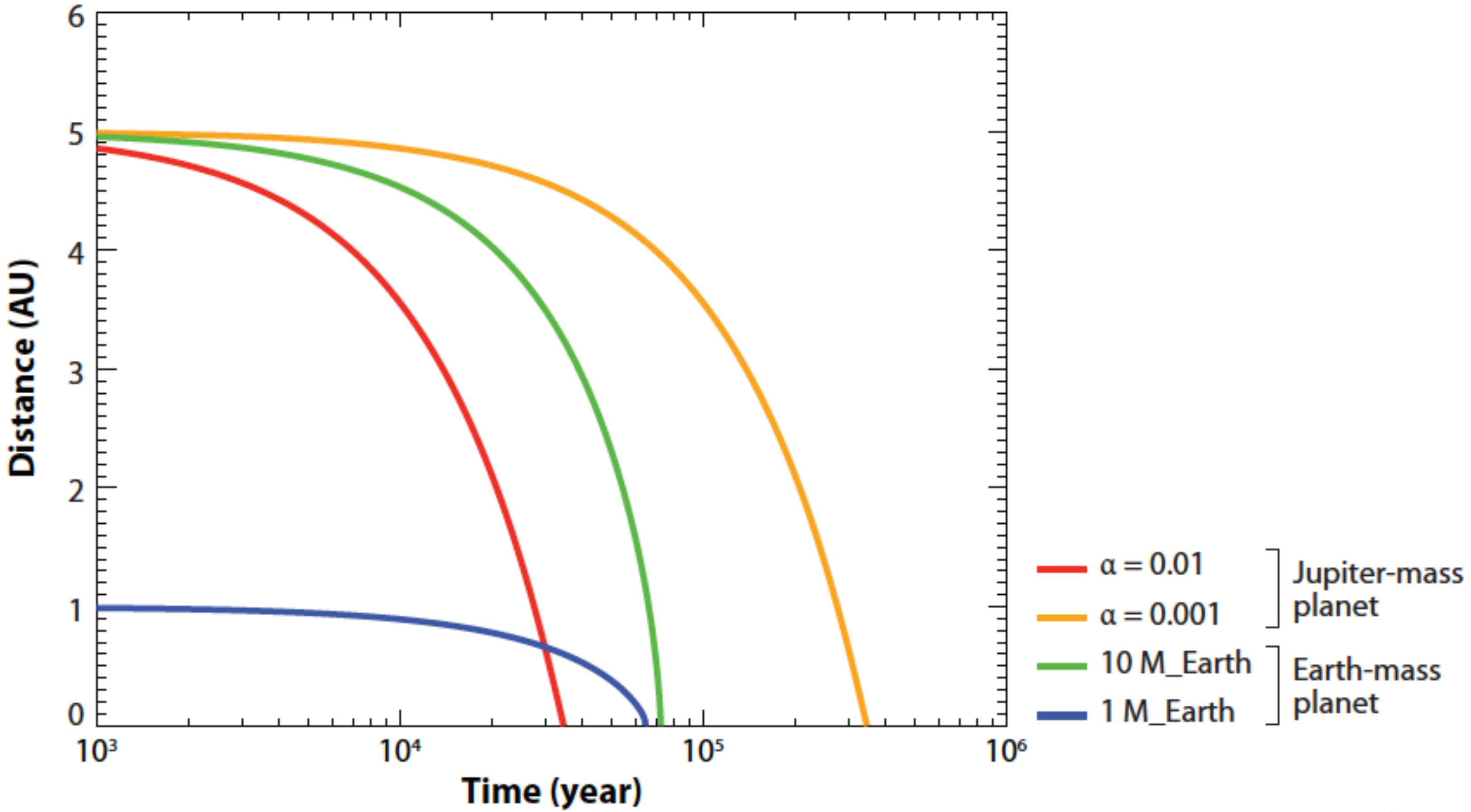


ESO/NAOJ/NRAO/NSF

Migrations

I. Migration by interaction with the gaseous disk

Simulations with vertically isothermal disk



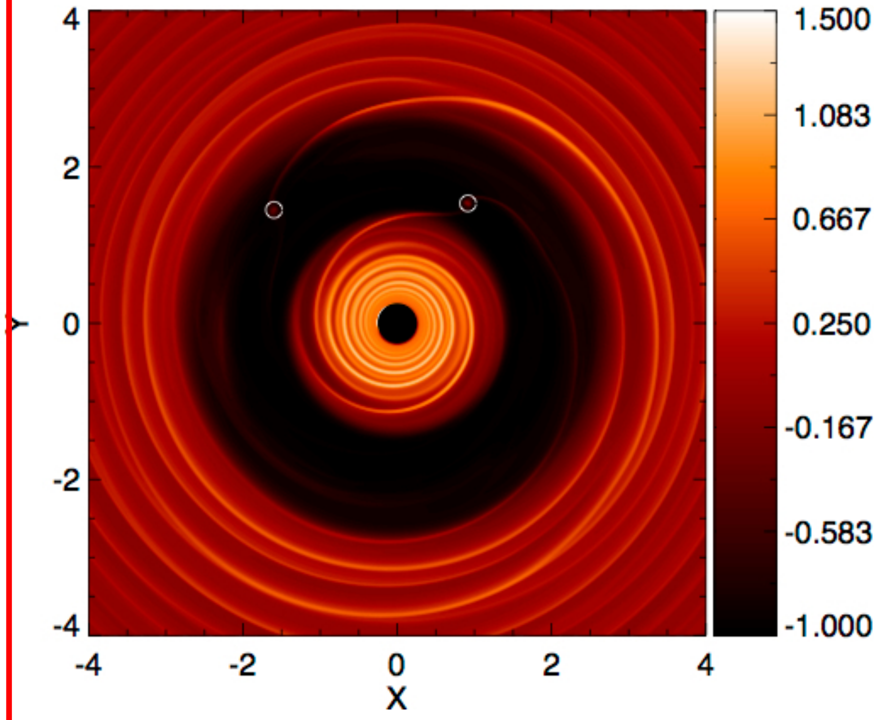
Chambers (2009)

Strong effect of opacity, disk structure, and magnetic field on the direction and amplitudes of migrations

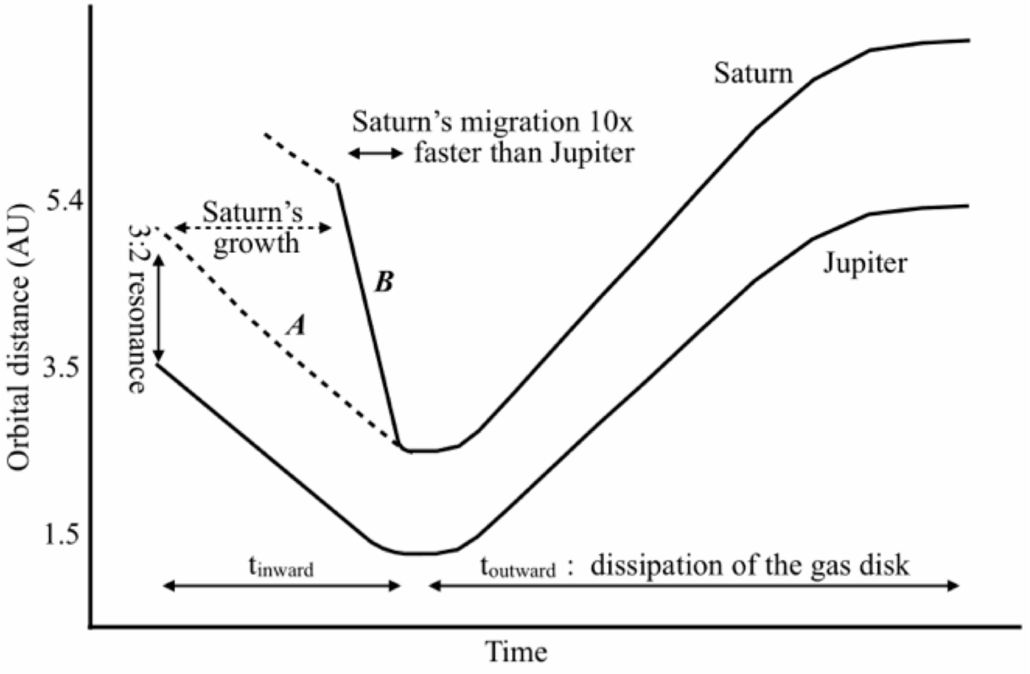
Migrations

I. Migration by interaction with the gaseous disk in the solar system? The « Grand Tack » model

Just formed at 3.5 au, Jupiter enters in inwards type II migration. Saturn does it too a little later and "catches up" Jupiter in 3:2 resonance.
Due to their configuration with respect to the gas disk, they migrate together outwards until depletion of the gas disk.



Pierens & Raymond (2011)

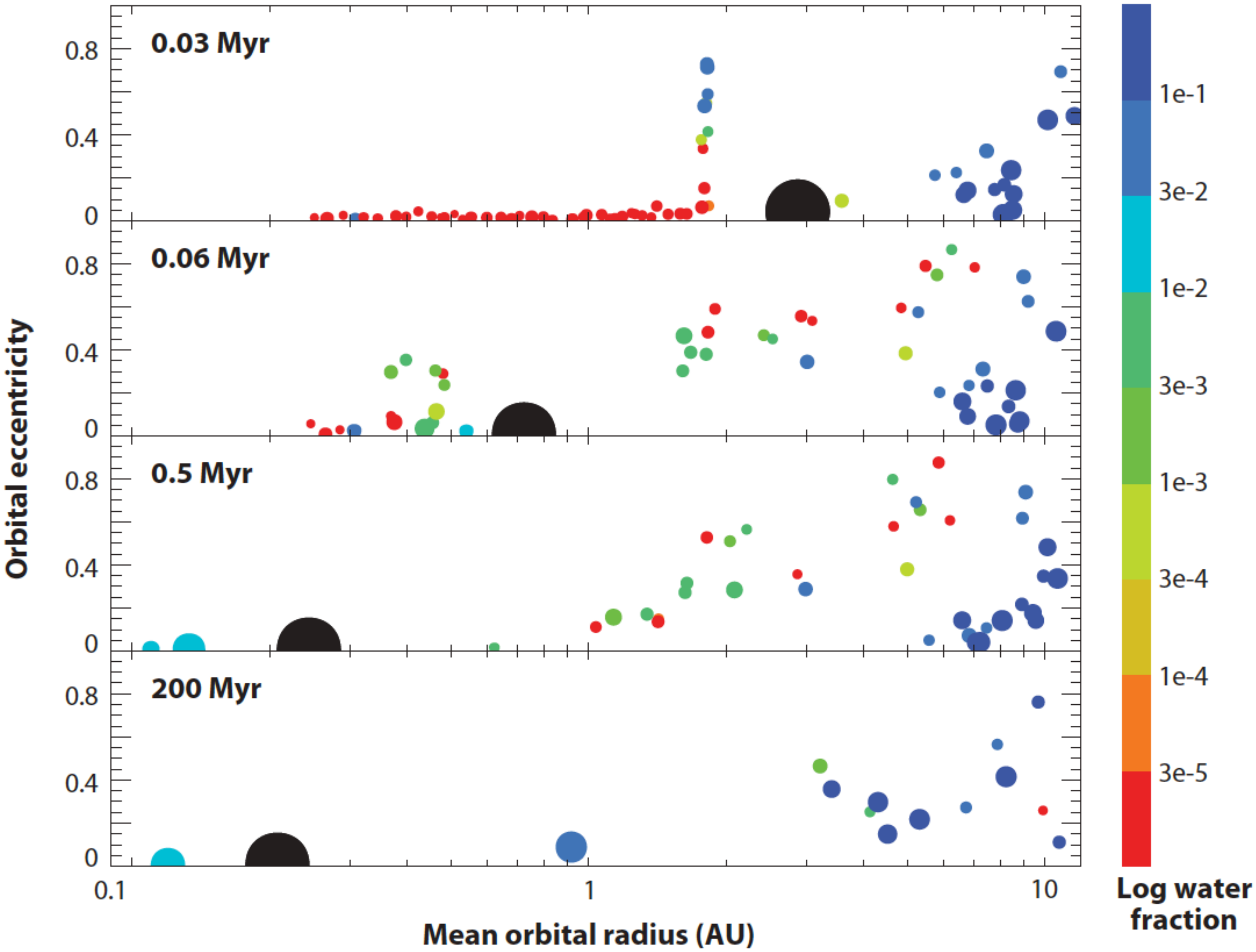


Walsh et al. (2011)

Explains the small mass of Mars, and the origin of water on Earth

Migrations

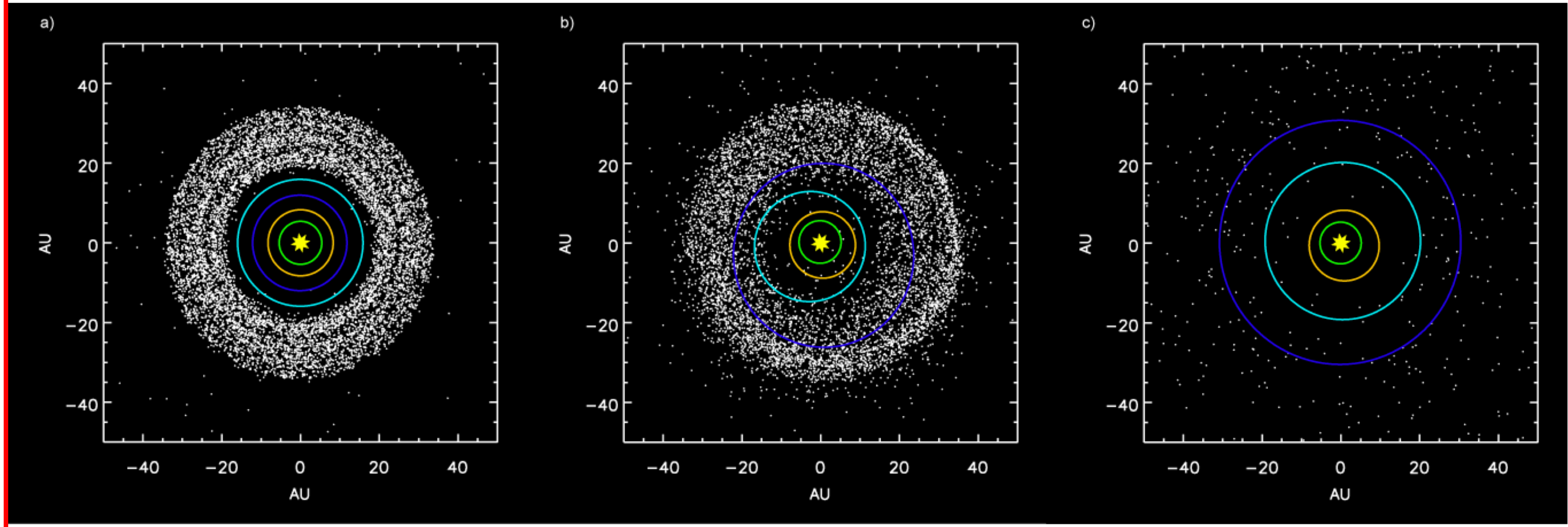
I. Migration by interaction with the gas disk: hot Jupiters



Chambers (2009)

Migrations

II. Migration by planet-planet or planet-planetesimals interactions

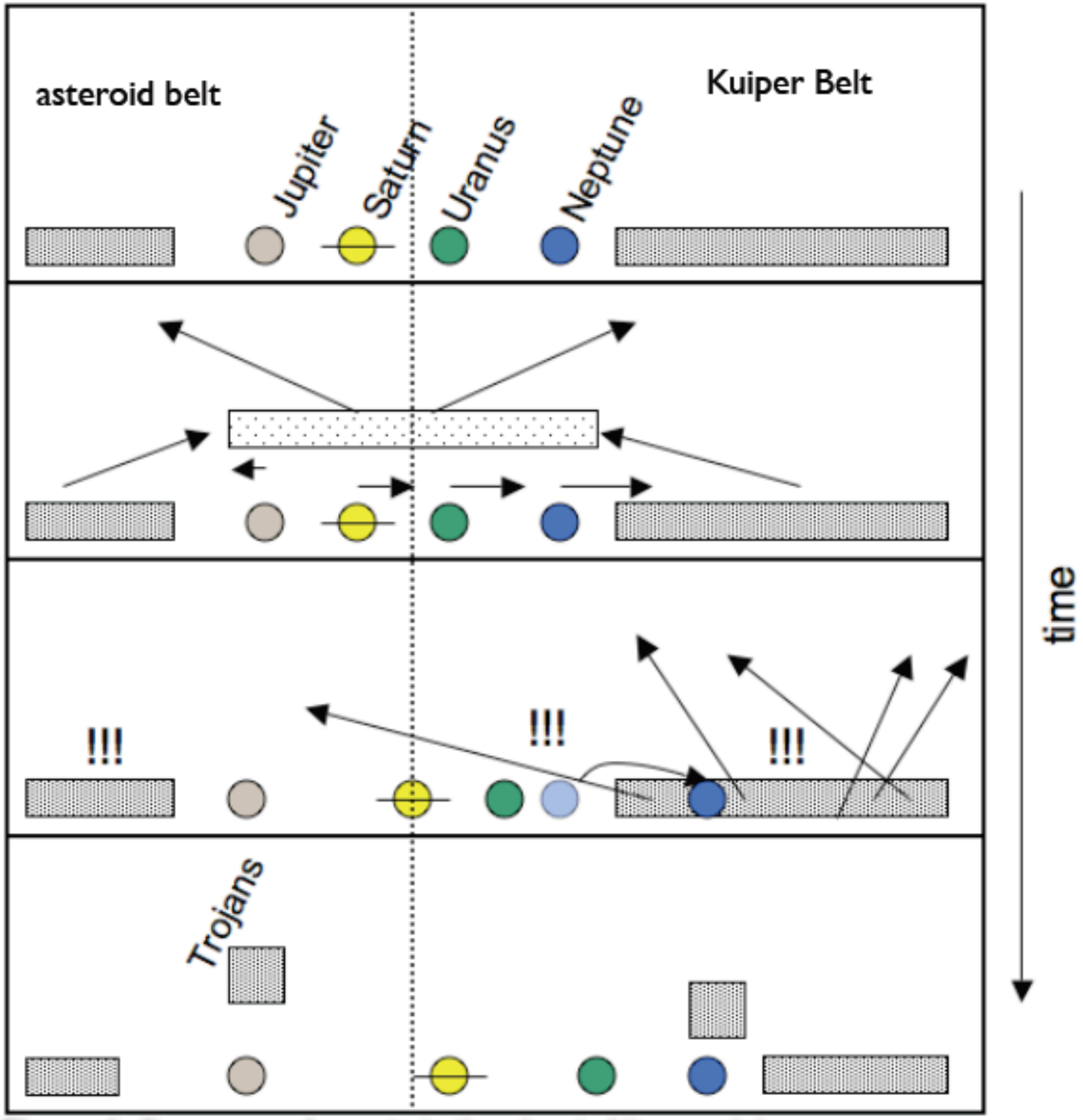


Nice model

Jupiter-Saturn-Neptune-Uranus orbit between 5.5 and 17 au. Beyond: planetesimals
~ 550-600 Myr: Jupiter and Saturn get into 1:2 resonance.
Neptune goes past Uranus and destabilizes the planetesimals disk.
Neptune-Uranus-Saturne capture the planetesimals and send them progressively inwards.
Jupiter, more massive, ejects them to very wide and eccentric orbits
By exchange of angular momentum, the orbits of Neptune and Uranus-Saturn lengthen, while the orbit of Jupiter is shortened.

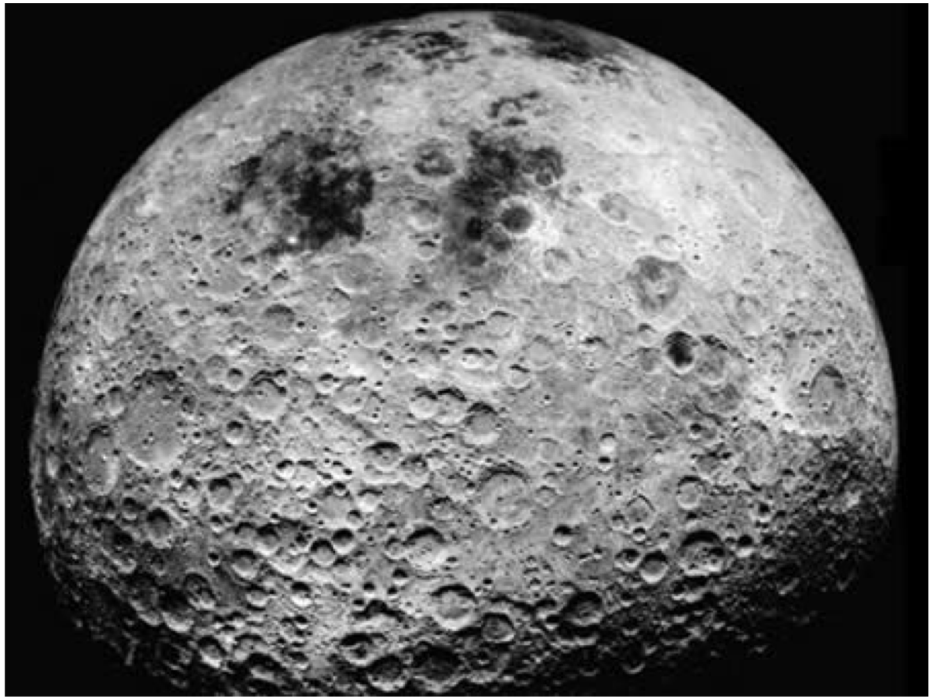
Migrations

II. Migration by planet-planet or planet-planetesimals interactions



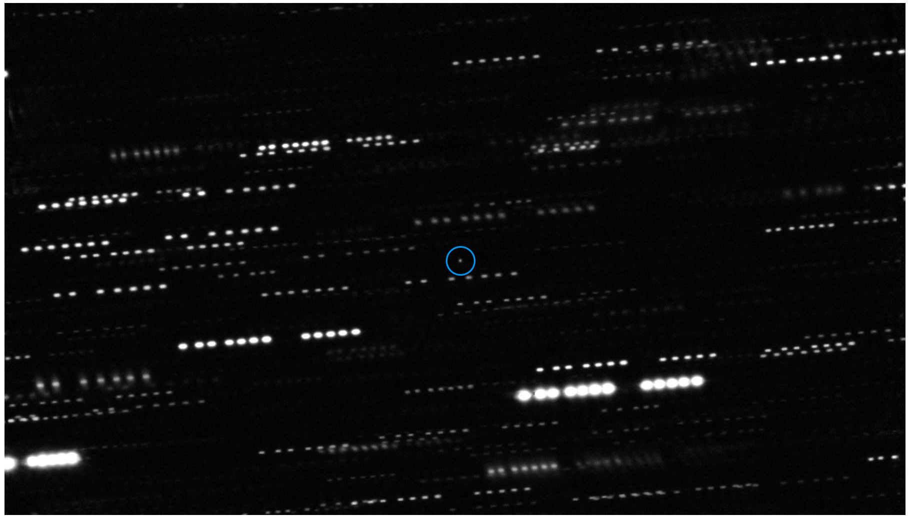
Migrations

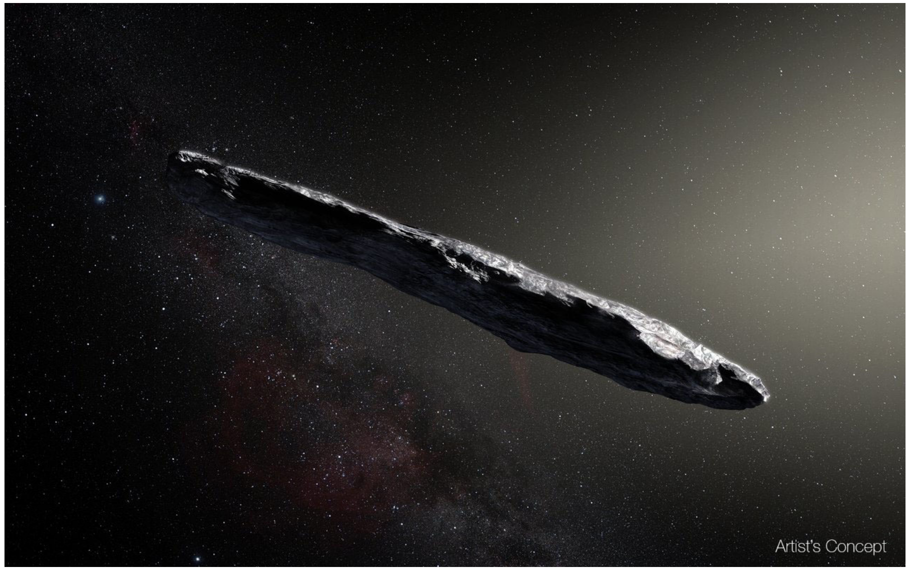
II. Migration by planet-planet or planet-planetesimals interactions



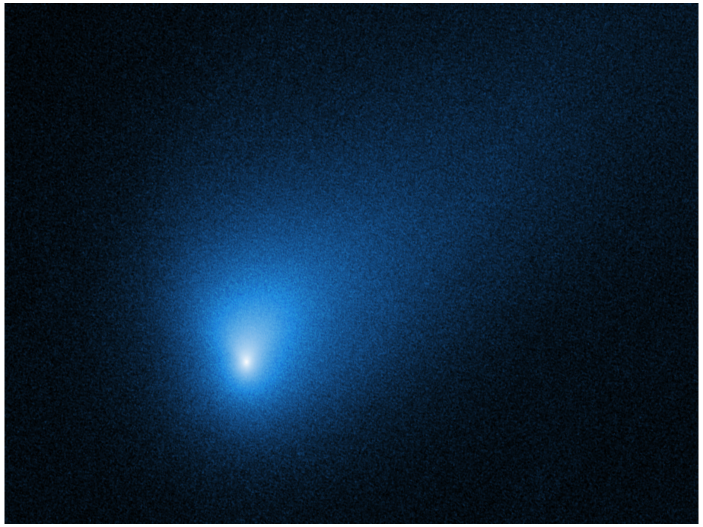
Ejection of planetesimals

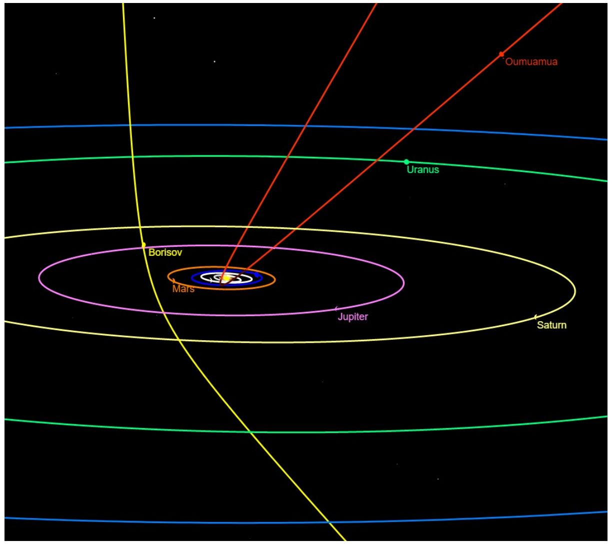
1I/ ‘Oumuamua





2I/Borisov

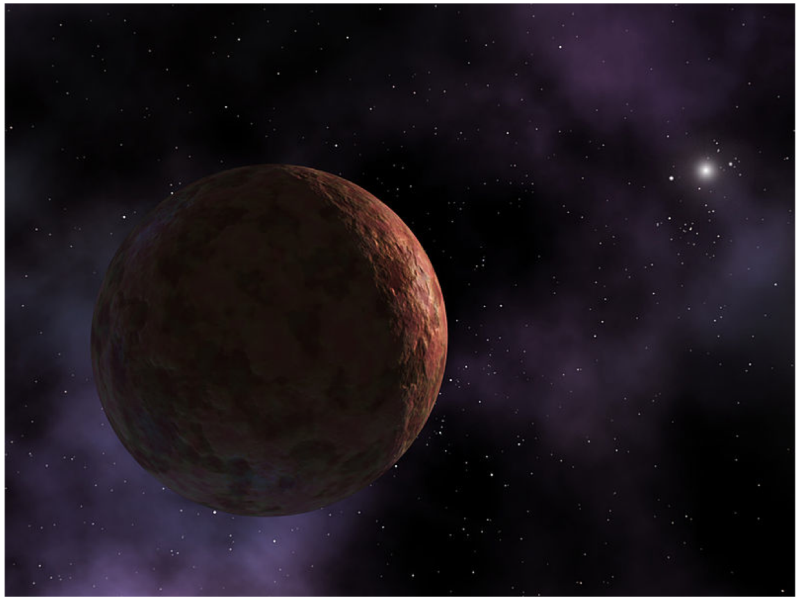


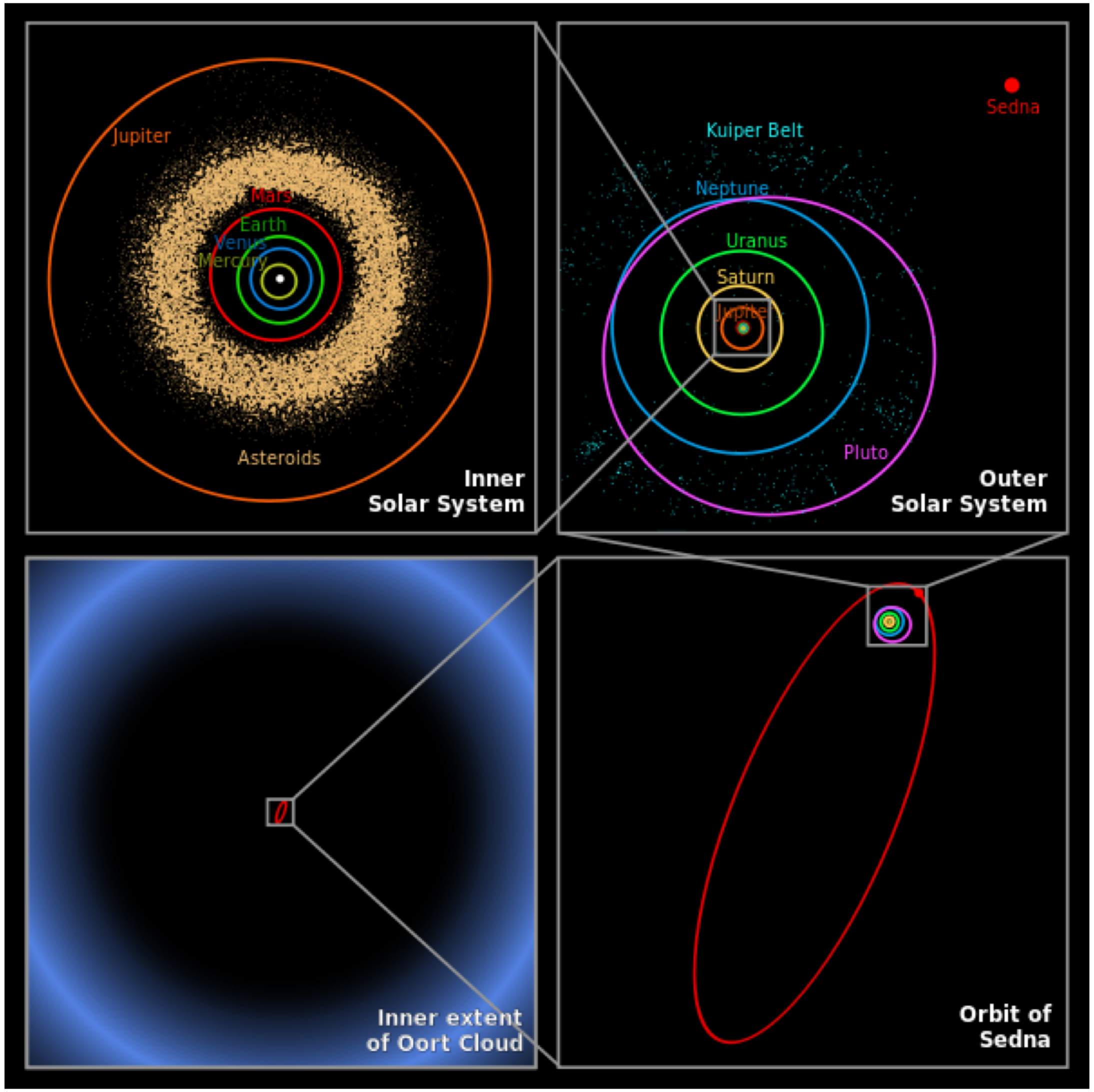


Credits: ESO / K. Meech NASA /ESA / D. Jewitt (UCLA)

The solar system is not isolated

The peculiar orbit of Sedna…





R=500km
a = 519 au, P=11,420 yr
Q = 937 au, **q=76 au**
e=0.85, i=12°

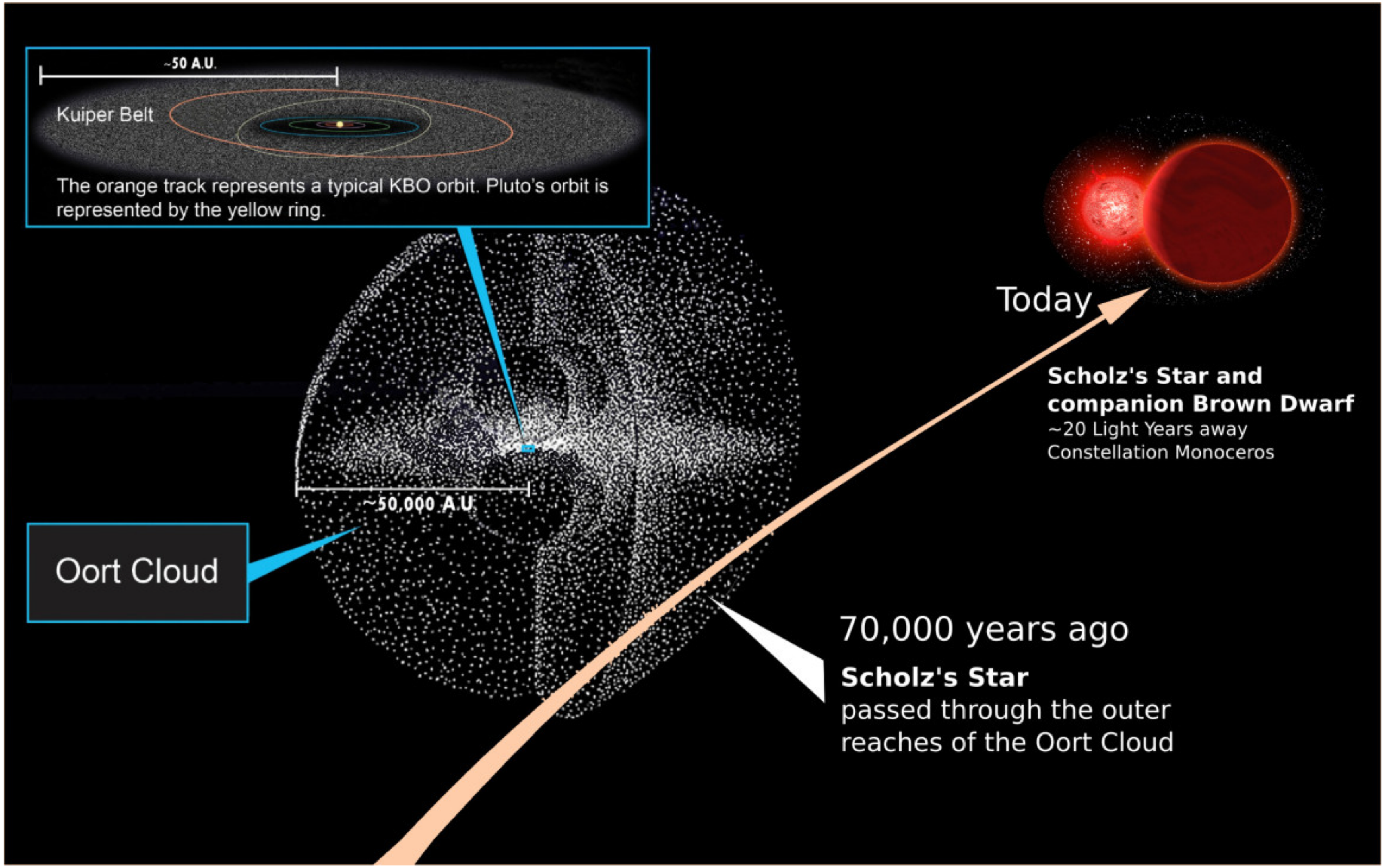
Trans-Neptunian pertubated by a stellar flyby? *(e.g. Brown et al. 2004)*

… or dwarf exoplanet captured by the Sun? *(e.g. Morbidelli & Levison 2004)*

… or TNOs perturbated by a ninth planet? *(e.g. Batygin & Brown 2016)*

The solar system is not isolated

Scholz's star (M9-type star + BD) passed at ~50,000 au ~70,000 years ago *(Mamajek et al. 2015)*



Conclusions

1. **Solar system** = 1 G-type star + 4 terrestrial planets + 2 gas giants + 2 ice giants, all planets orbiting +- in the same plane
   + small bodies and dwarf planets under the dynamical domination of giant planets

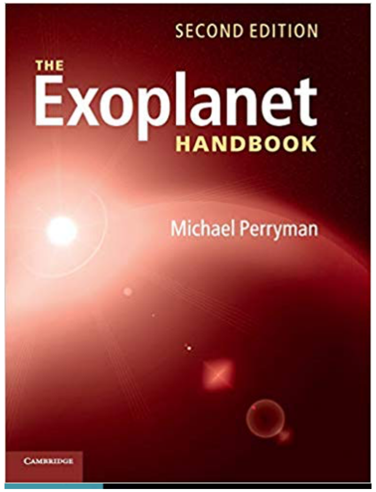
2. The modern version (core accretion – Grand Tack – Nice model) of the **nebular hypothesis** can reproduce the structure of the solar system :
   - Dust ➔ planetesimals ➔ planetary embryos ➔ planets
   - Gaz disk migration (inspired by exoplanets!)
   - Importance of the planet-planet and planet-planetesimals interactions

3. **Remaining mysteries**: formation of chondrules and of planetesimals

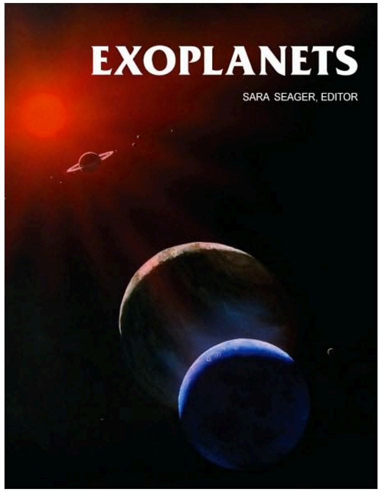
4. The planetary formation process is both highly dependent on initial conditions (mass, composition and angular momentum of the disc) and stochastic
   ➔ **we can expect a large diversity of planetary systems**

5. **Formation by gravitational instability**: possible in the colder areas of very massive disks?

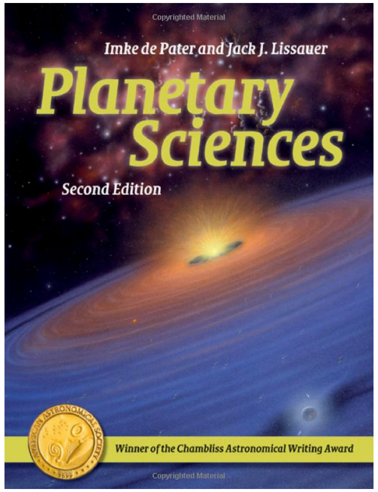
References



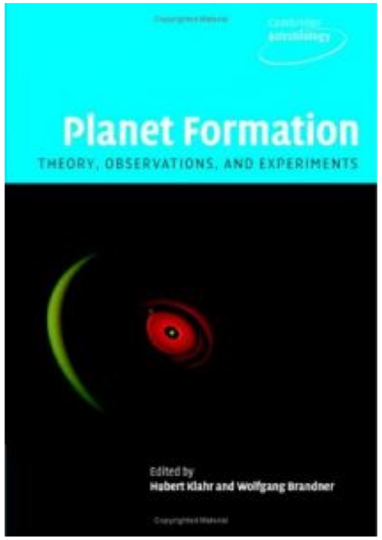
M. Perryman
Cambridge University Press
Chapters 1, 10, 12



S. Seager
University of Arizona Press
Chapters 1, 12, 13, 14, 15



I. de Pater & J. J. Lissauer
Cambridge University Press
Chapters 1 & 13



W. Brandner
Cambridge Astrobiology Series