Introduction to Planetary Sciences

Textbook

Fundamental Planetary Science: Physics, Chemistry and Habitability

By Lissauer J.J., Pater I.d, Cambridge University Press (2019)

Instructor

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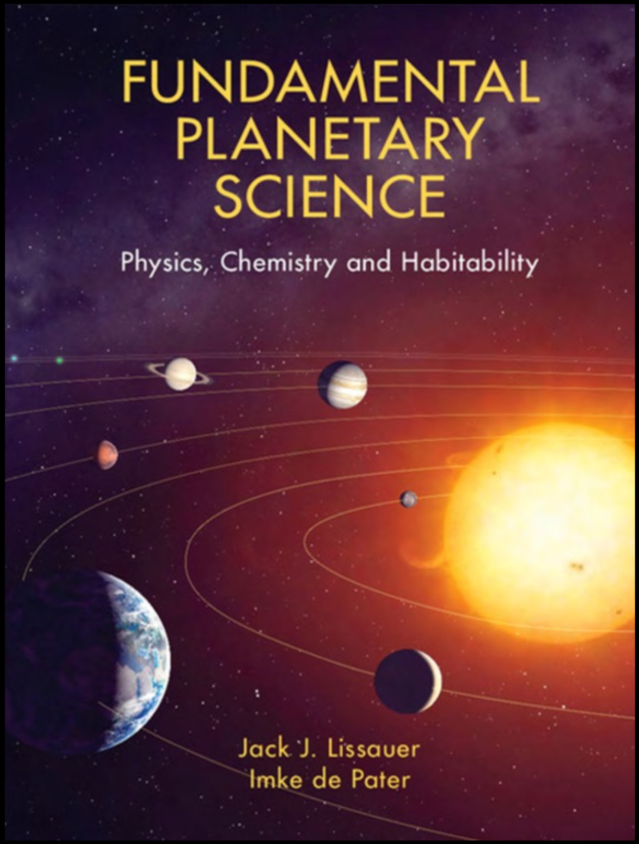
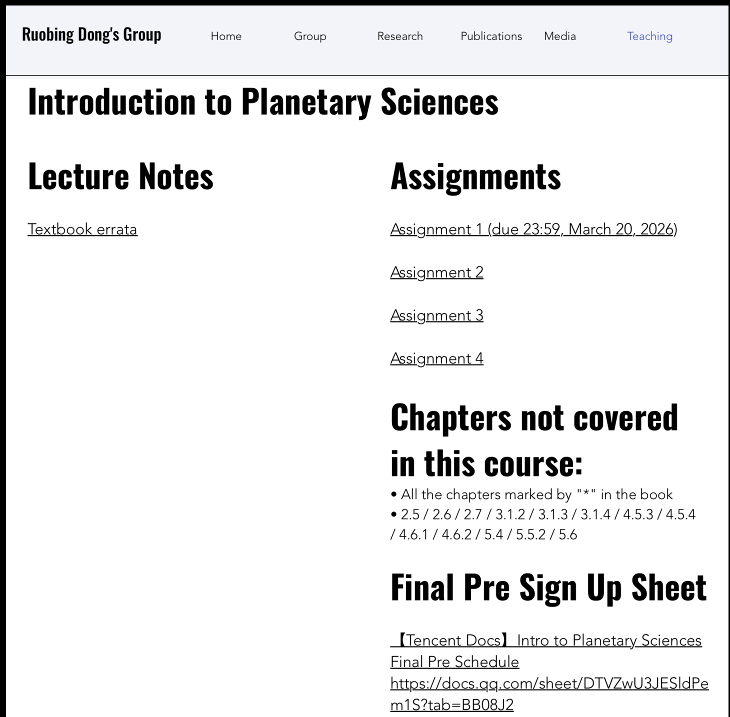
- Office: KIAA 313
- Office hours: by appointment



Introduction to Planetary Sciences

Course Website

https://www.ruobingdong.com/introductiontoplanetarysciences



Tentative schedule

Assignment

Presentation

Final

March

	M	T	W	T	F	S	S
9	23	24	25	26	27	28	1
10	2	3	4	5	6	7	8
11	9	10	11	12	13	14	15
12	16	17	18	19	20	21	22
13	23	24	25	26	27	28	29
14	30	31	1	2	3	4	5

April

	M	T	W	T	F	S	S
14	30	31	1	2	3	4	5
15	6	7	8	9	10	11	12
16	13	14	15	16	17	18	19
17	20	21	22	23	24	25	26
18	27	28	29	30	1	2	3
19	4	5	6	7	8	9	10

May

	M	T	W	T	F	S	S
18	27	28	29	30	1	2	3
19	4	5	6	7	8	9	10
20	11	12	13	14	15	16	17
21	18	19	20	21	22	23	24
22	25	26	27	28	29	30	31
23	1	2	3	4	5	6	7

June

	M	T	W	T	F	S	S
23	1	2	3	4	5	6	7
24	8	9	10	11	12	13	14
25	15	16	17	18	19	20	21
26	22	23	24	25	26	27	28
27	29	30	1	2	3	4	5
28	6	7	8	9	10	11	12

Evaluations

- Assignments – 10%
  - 4 assignments in total
  - Full credit as long as the assignment is submitted on time
- Final Presentation – 30%
  - Duration: 20 minutes
  - Topic selection deadline: end of April
  - Presentation dates: May 25 and June 1
- Final Exam – 60%
  - Problems will be drawn from the assignments

Assignment 1

Problem 1

Scale the entire solar system such that the diameter of the Earth is 1 cm.

1. Calculate the size of the Sun and the other planets.
2. Calculate the distances from the planets to the Sun.
3. How far is the nearest star to the Sun in this system?

Problem 2

Lagrangian points

a. L1, L2, and L3 are along the line joining two masses m_1 and m_2 in the circular restricted three body problem. Assuming R is the distance between the two main objects, and $m_2 << m_1$, find out the separation between L1 and m_2.
   Hint 1: start from the definition of L points.
   Hint 2: when $m_2 << m_1$, L1 and L2 are very close to m_2.
b. Find out the separation between L2 and m_2.
c. Evaluate L1 and L2 locations in the case of the Sun-Earth system. Express the results in units of both km and in Earth-Moon separation.
d. Is L3 closer or further away from the COM than m_2? Why?
e. L4 (and L5) forms an equilateral triangle with m_1 and m_2. Prove that it is a Lagrangian Point in the special case of $m_2 = m_1$.

Problem 3

What's the time interval between two consecutive tides induced by the moon?
   Hint 1: how many tides induced by the moon between two successive moonrises?
   Hint 2: You might want to think about time in sidereal time. If you are unfamiliar with the concept, Wikipedia and Figure 2.21 in the book might be helpful.

Problem 4

The sun is losing 6×10^{12} grams of mass every second at the moment via its solar wind and by converting mass into radiation. The Earth orbits the Sun. As the mass of the Sun decreases, the Earth is held a bit less strongly, and its orbit expands.

a. Derive Eqn. (2.65) in the textbook. You can assume circular orbits.
b. Evaluate the expansion rate in units of cm/yr.

Hint: the orbital angular momentum of the Earth is conserved in this process.

Final Presentation (30%)

- Topic: introduce a solar system probe
  - Pick one Solar System probe that was launched after 2000 and targeted a Solar System object (e.g., Curiosity on Mars).
  - The mission must be at least partially successful and have returned scientific results, i.e., please do not choose missions that failed at launch (e.g., exploded on the launch pad).
  - You may pick from this list:

  https://en.wikipedia.org/wiki/List_of_Solar_System_probes
- Sign-up: First come, first serve.
- Treat your presentation as a mini-lecture for the rest of the class

Ruobing Dong's Group

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Introduction to Planetary Sciences

Lecture Notes

Textbook errata

Assignments

Assignment 1 (due 23:59, March 20, 2026)

Assignment 2

Assignment 3

Assignment 4

Chapters not covered in this course:

- All the chapters marked by "*" in the book
- 2.5 / 2.6 / 2.7 / 3.1.2 / 3.1.3 / 3.1.4 / 4.5.3 / 4.5.4 / 4.6.1 / 4.6.2 / 5.4 / 5.5.2 / 5.6

Final Pre Sign Up Sheet

【Tencent Docs】Intro to Planetary Sciences Final Pre Schedule
https://docs.qq.com/sheet/DTVZwU3JESldPem1S?tab=BB08J2

Intro to Planetary Sciences Final Pre Schedule ☆ Recently saved 14:52

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	A	B	C	D	E	F
	Date	Name of the probe	Presenter	wiki link to the probe		
	May 25					
	May 25					
	May 25					
	May 25					
	May 25					
	May 25					
	June 1					
	June 1					
11	June 1					
12	June 1					
13	June 1					
14	June 1					

Introduction to Planetary Sciences

The scientific study of planets, moons, and planetary systems, both solar and extra-solar, and the processes that form them.

This course is physics heavy, and involves some amount of math

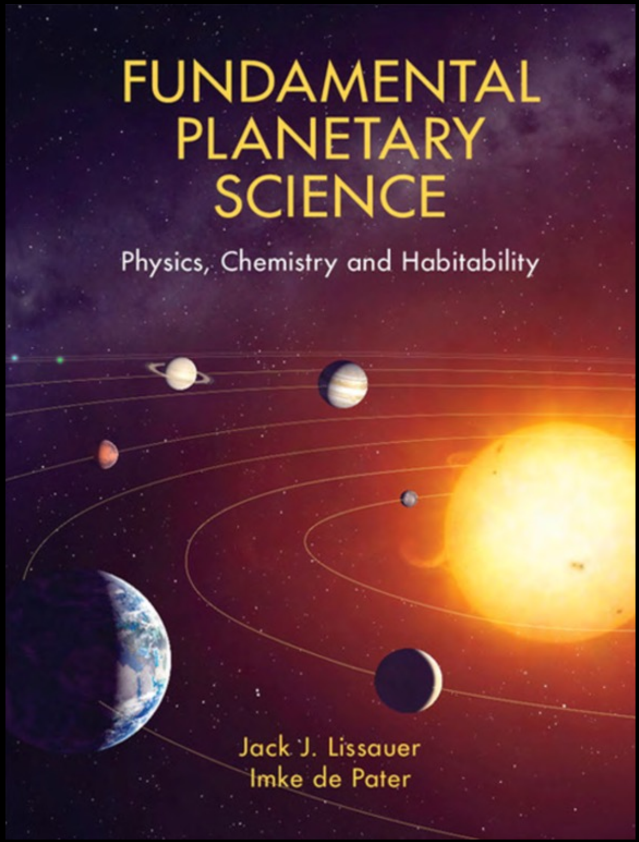
Questions?

Introduction to Planetary Sciences

Please read the textbook prior to each session

In the classroom we will:

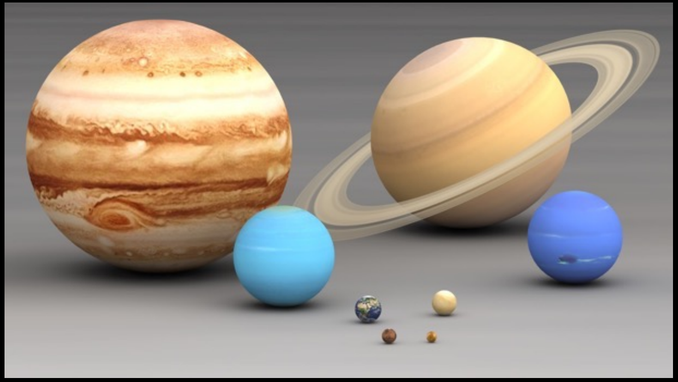
- *highlight the important points*
- *visualize things*
- *show derivations*
- *Q & A*



What is a planet?

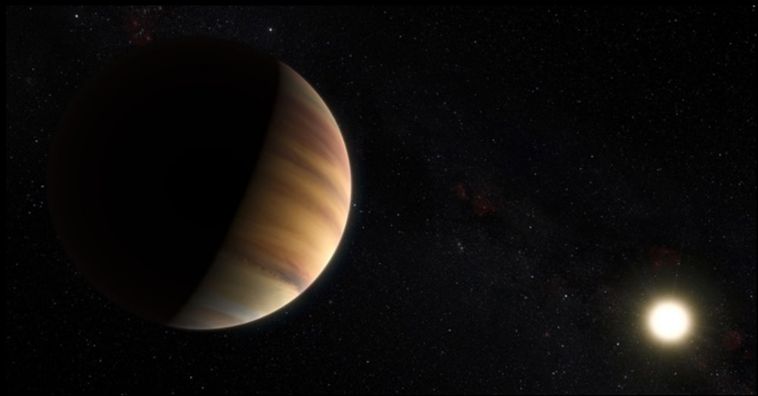
A planet is an object that

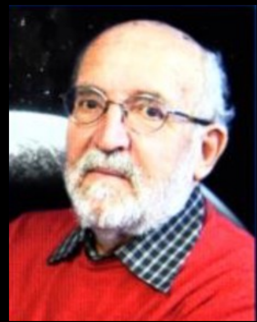
- is in orbit around the Sun
- has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape,
- has cleared the neighborhood around its orbit.



- Prehistory: Mercury, Venus, Mars, Jupiter, Saturn (Copernicus Heliocentrism 16^{th} century)
- 1781: Uranus
- 1846: Neptune

- 1995: 51 Peg b – the first exoplanet

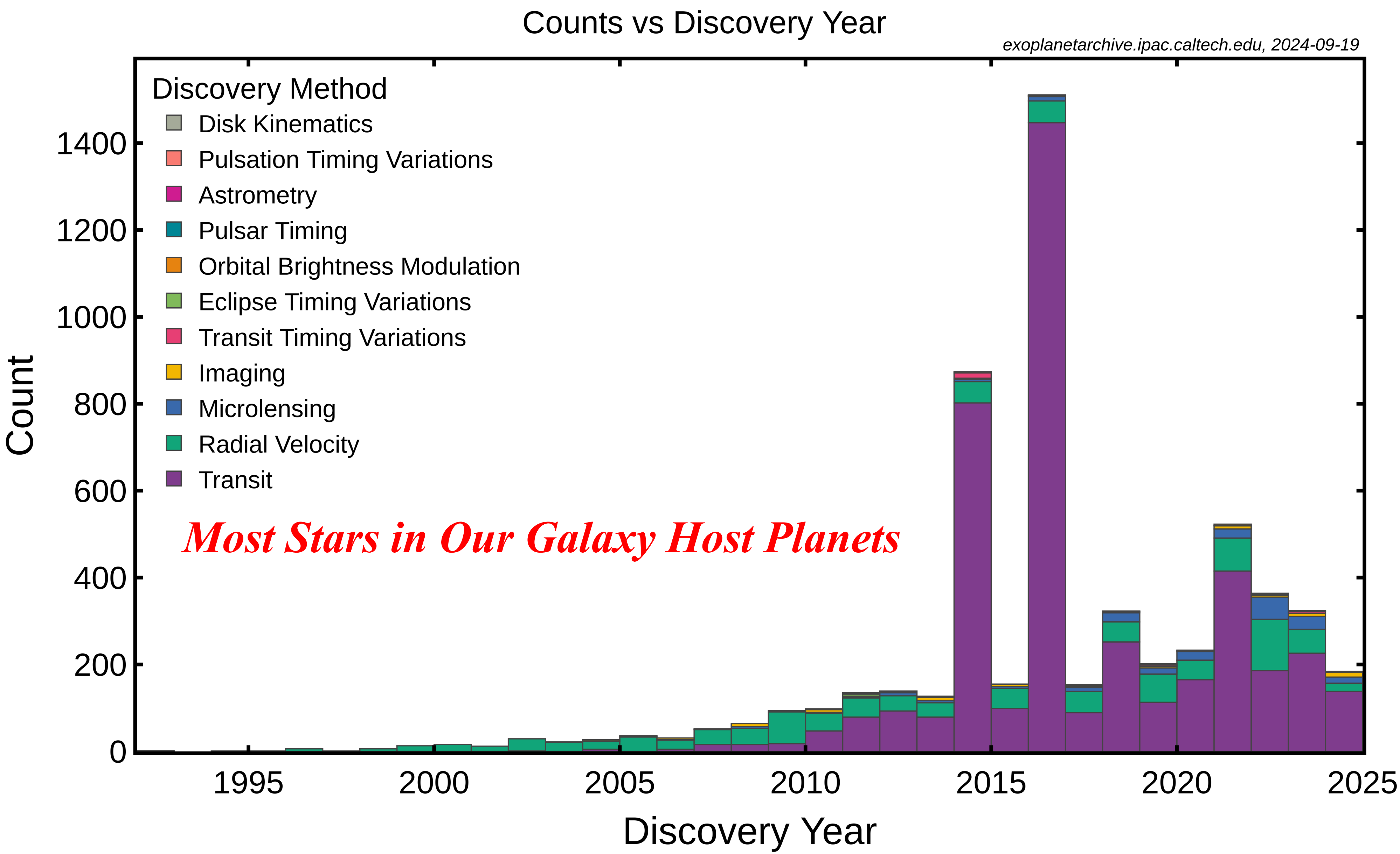


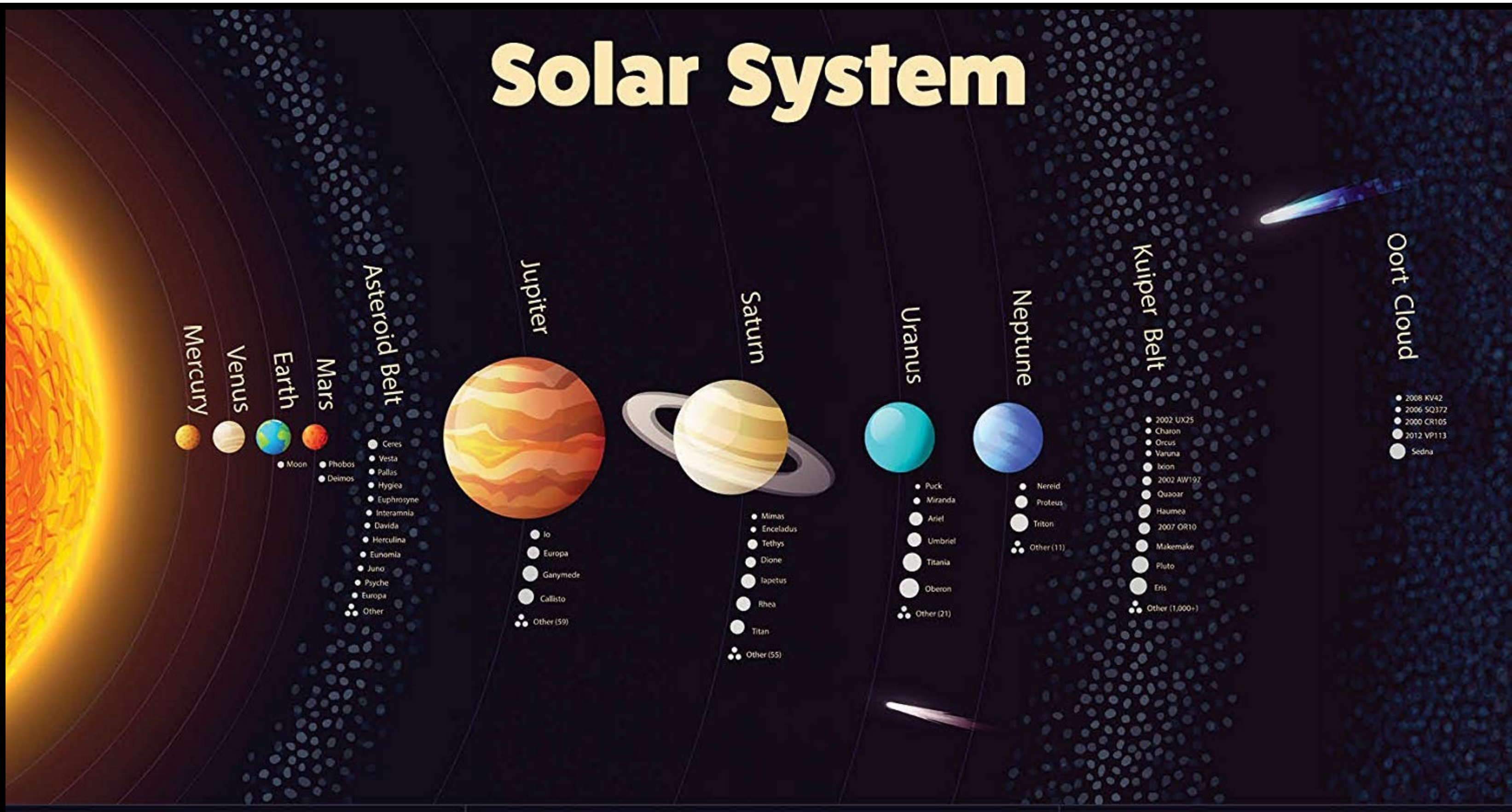


Michel Mayor

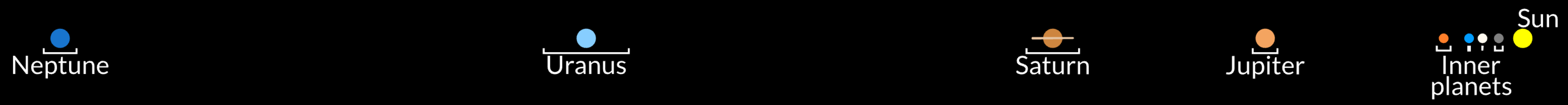
Didier Queloz

We will cover both solar system & extro-solar systems in this course

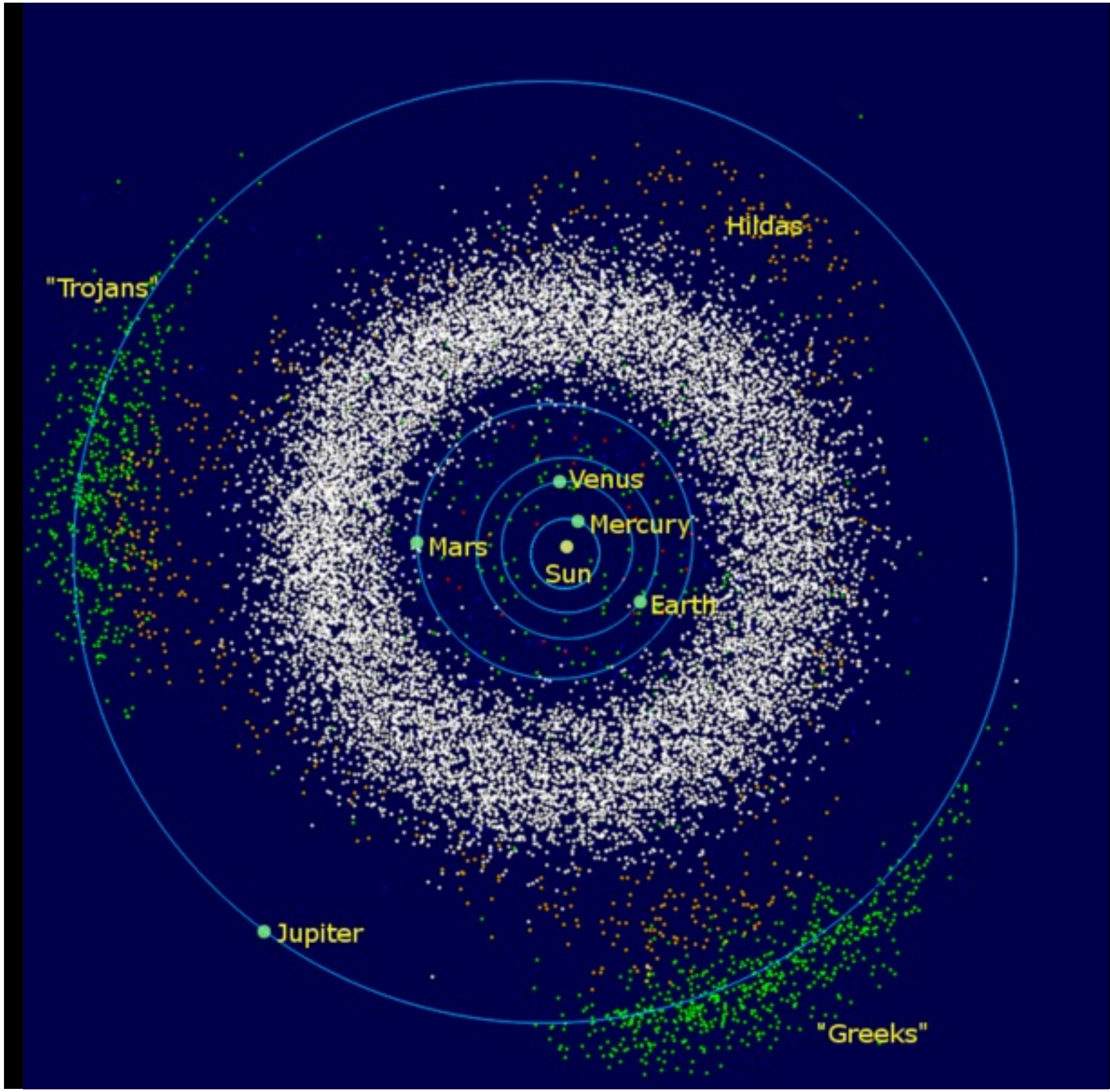

Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-09-19
Discovery Method
Disk Kinematics
Pulsation Timing Variations
Astrometry
Pulsar Timing
Orbital Brightness Modulation
Eclipse Timing Variations
Transit Timing Variations
Imaging
Microlensing
Radial Velocity
Transit
Most Stars in Our Galaxy Host Planets
Count
0
200
400
600
800
1000
1200
1400
1995
2000
2005
2010
2015
2020
2025
Discovery Year



- Planets
  - Terrestrial planets
  - Gas giants
  - Ice giants
- Moons and rings
- Minor objects
  - Asteroid belt
  - Kuiper belt
  - Oort cloud
  - Centaurs, comets, scattered disk objects, etc
- Dust (zodiacal light)

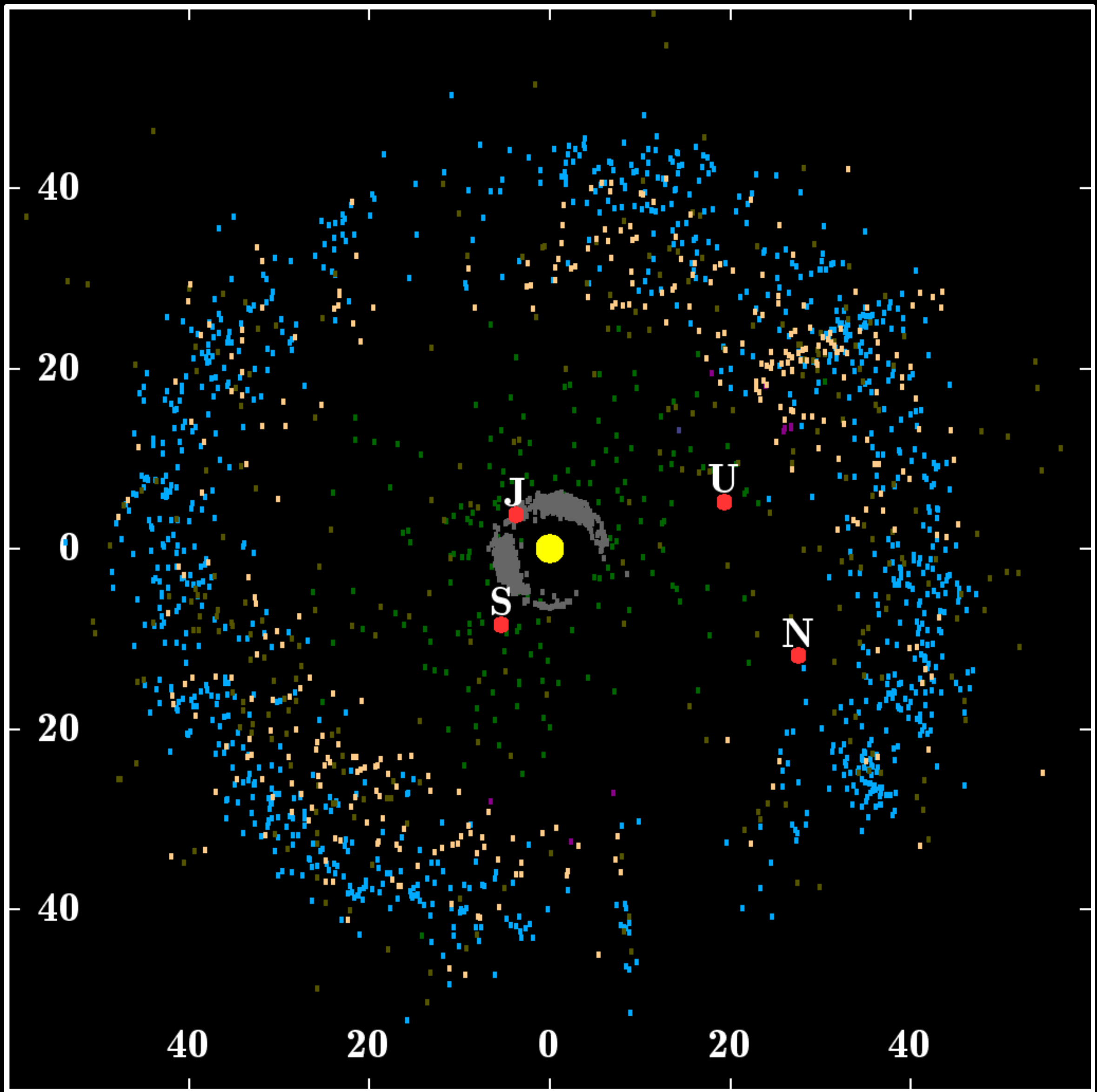


https://en.wikipedia.org/wiki/Solar_System



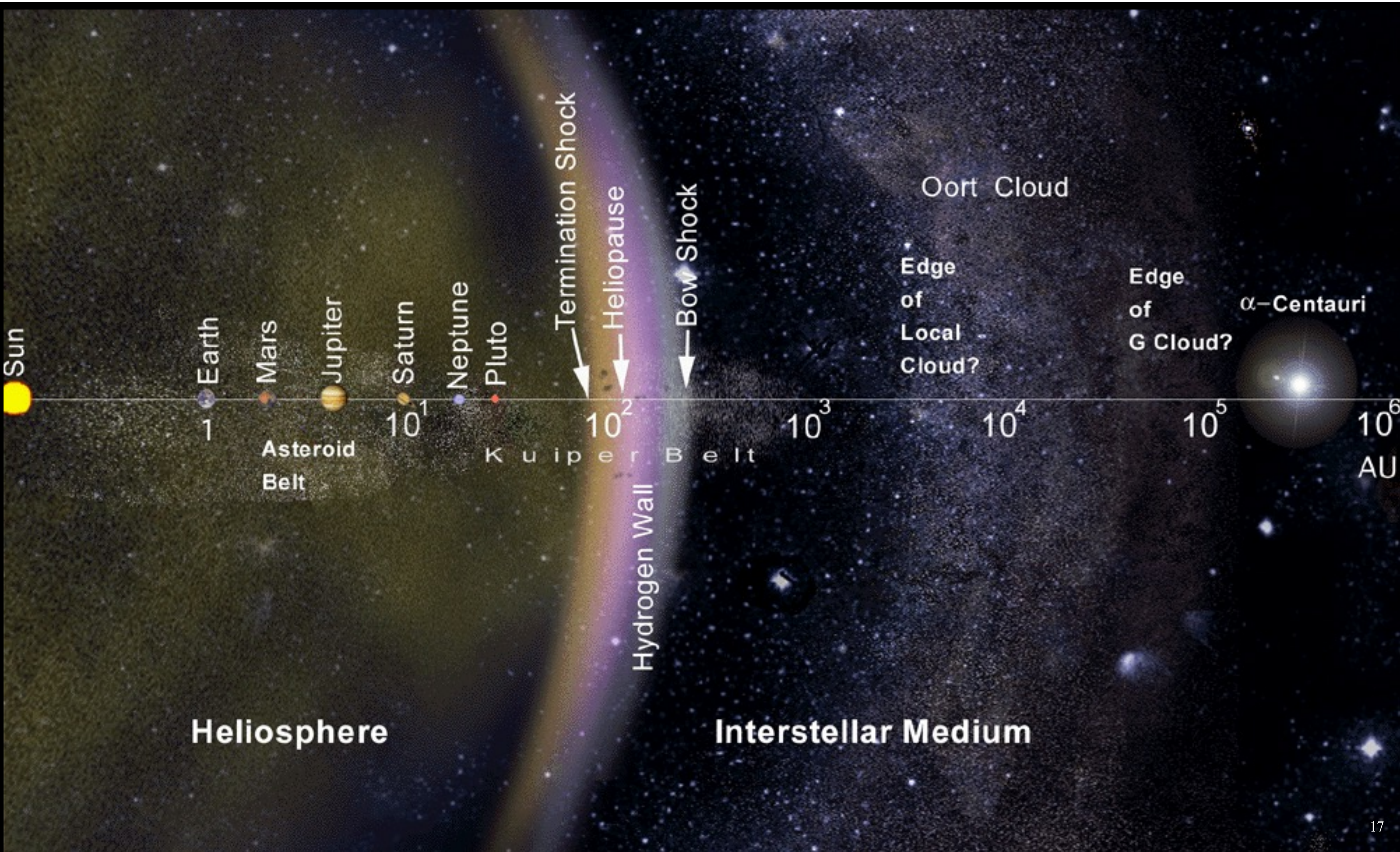
Inner Solar System

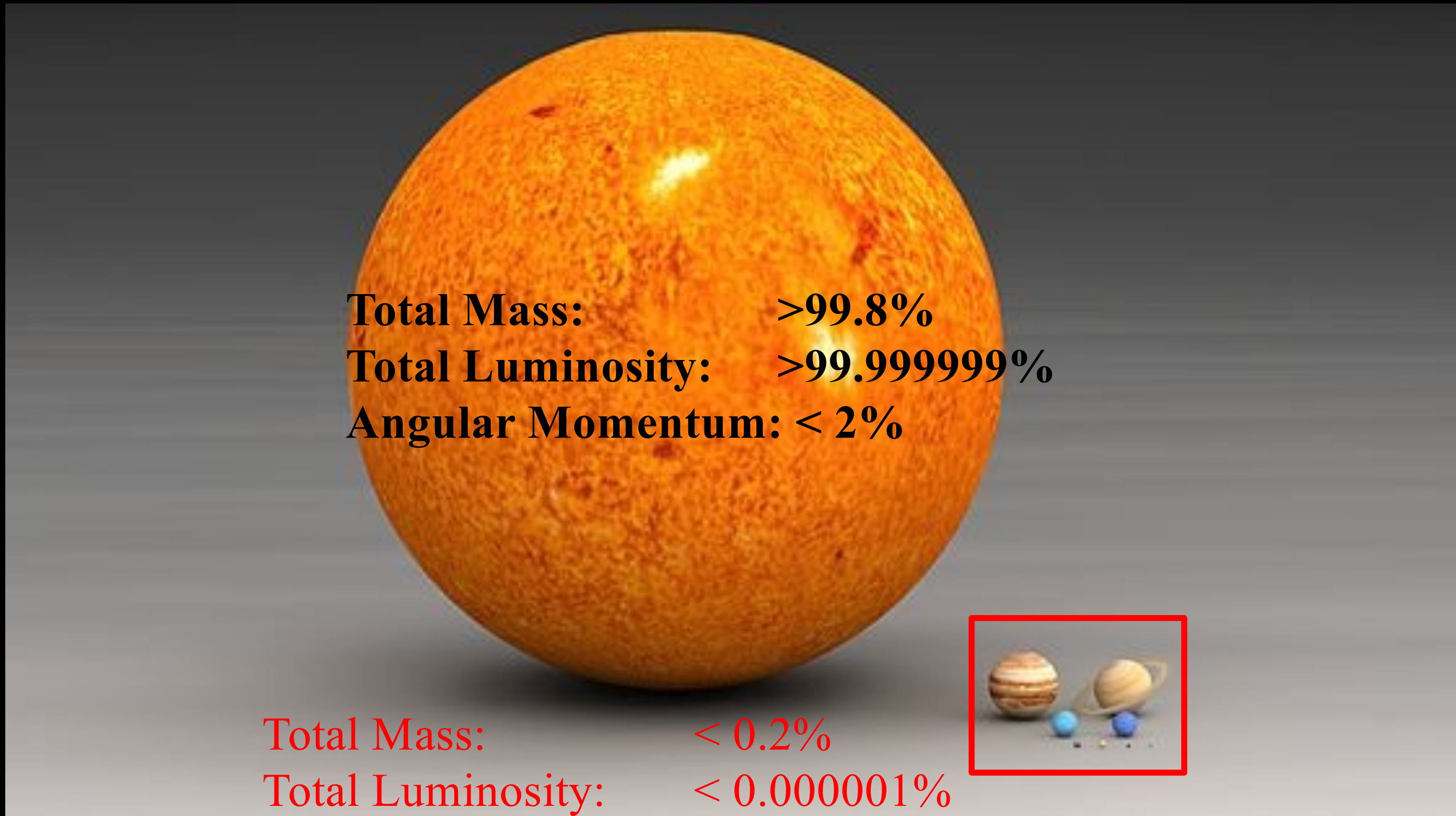
https://en.wikipedia.org/wiki/Asteroid_belt



Outer Solar System

https://en.wikipedia.org/wiki/Kuiper_belt

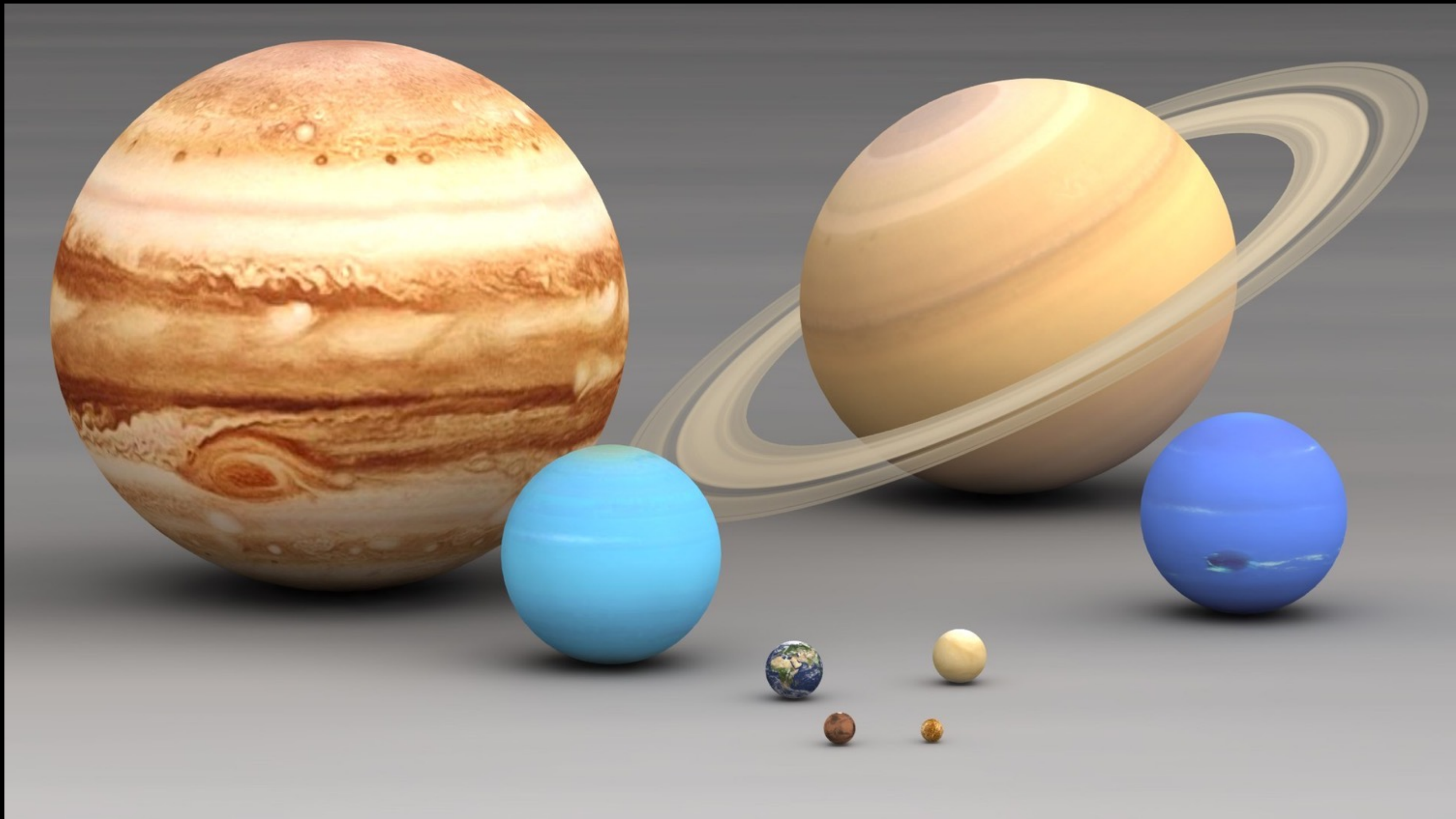

Sun
Earth
Mars
Jupiter
Saturn
Neptune
Pluto
Termination Shock
Heliopause
Bow Shock
Oort Cloud
Edge of Local Cloud?
Edge of G Cloud?
α−Centauri
1
10^1
10^2
10^3
10^4
10^5
10^6
AU
Asteroid Belt
Kuiper Belt
Hydrogen Wall
Heliosphere
Interstellar Medium



Total Mass: >99.8%
Total Luminosity: >99.999999%
Angular Momentum: < 2%

Total Mass: < 0.2%
Total Luminosity: < 0.000001%
Angular Momentum: > 98%

https://en.wikipedia.org/wiki/Solar_System



https://en.wikipedia.org/wiki/Solar_System

Planetary Properties

C.1.4.

(1) Orbit
(2) Mass, distribution of mass
(3) Size
(4) Rotation rate and direction
(5) Shape
(6) Temperature
(7) Magnetic field
(8) Surface composition
(9) Surface structure
(10) Atmospheric structure and composition

Dynamics (Chapter 2)

- Universal law of gravity

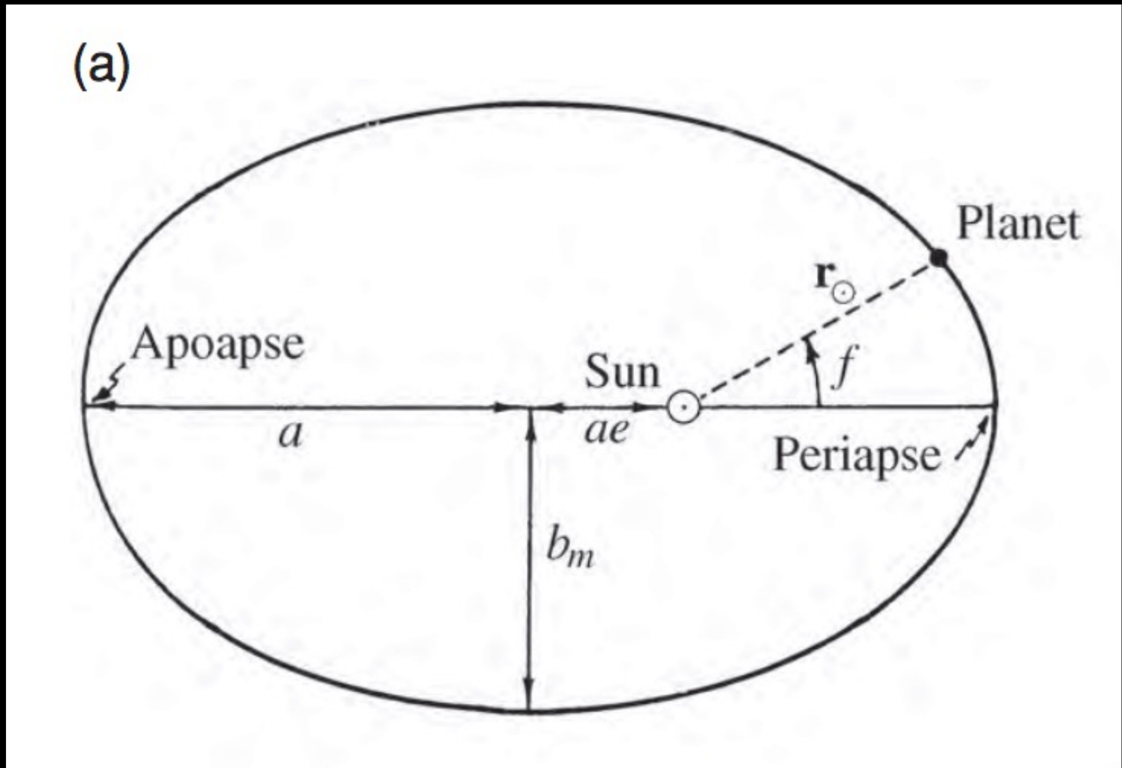
$$\mathbf{F}_{g12} = -\frac{G m_1 m_2}{r^2}\hat{\mathbf{r}},$$

$$\mathbf{r} \equiv \mathbf{r}_1 - \mathbf{r}_2$$

$$\hat{\mathbf{r}} \equiv \mathbf{r}/r$$

- Newton's laws
- Kepler's laws
  1. All planets move along elliptical paths with the Sun at one focus.
  2. A line connecting any given planet and the Sun sweeps out area at a constant rate.
  3. The square of a planet's orbital period about the Sun (in years) is equal to the cube of its semimajor axis (in AU).

An Elliptical Orbit

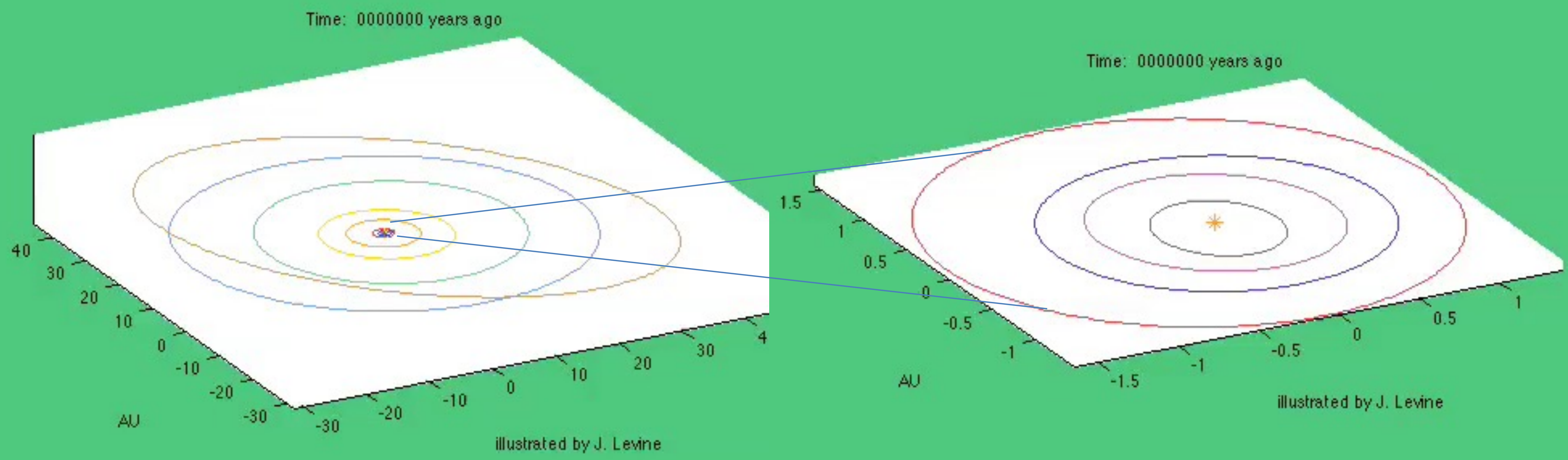


- Focus
- ***a***
- ***e***
- Periapse
- Apoapse

Orbital Motions in the Solar System

Outer Solar System

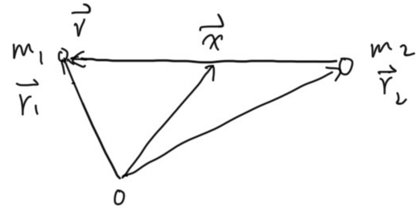
Inner Solar System



Two body problem

→

one body problem



$$\begin{cases} \vec{r} = \vec{r}_1 - \vec{r}_2 & \text{relative position} \\ \vec{x} = \dfrac{m_1\vec{r}_1 + m_2\vec{r}_2}{m_1+m_2} & \text{COM} \end{cases}$$

$$\begin{cases} m_1 \dfrac{d^2\vec{r}_1}{dt^2} = -\dfrac{G m_1 m_2}{|\vec{r}_1-\vec{r}_2|^3}(\vec{r}_1-\vec{r}_2) & (2\text{-}7) \\ m_2 \dfrac{d^2\vec{r}_2}{dt^2} = -\dfrac{G m_1 m_2}{|\vec{r}_2-\vec{r}_1|^3}(\vec{r}_2-\vec{r}_1) & (2\text{-}8) \end{cases}$$

(2.7)+(2.8) $\quad m_1\dfrac{d^2\vec{r}_1}{dt^2} + m_2\dfrac{d^2\vec{r}_2}{dt^2} = \vec{F}_{21} + \vec{F}_{12} = 0$

$$\| $$

$$(m_1+m_2)\frac{d}{dt^2}\left(\frac{m_1\vec{r}_1+m_2\vec{r}_2}{m_1+m_2}\right) = (m_1+m_2)\boxed{\frac{d^2\vec{x}}{dt^2}} = 0$$

COM no acceleration

$$\frac{d^2\vec{r}}{dt^2} = \frac{d^2}{dt^2}(\vec{r}_1-\vec{r}_2) = -\frac{G m_2}{|\vec{r}_1-\vec{r}_2|^3}(\vec{r}_1-\vec{r}_2) - \left(-\frac{G m_1}{|\vec{r}_2-\vec{r}_1|^3}(\vec{r}_2-\vec{r}_1)\right)$$

$$= -\frac{G m_2}{|\vec{r}_1-\vec{r}_2|^3}(\vec{r}_1-\vec{r}_2) - \frac{G m_1}{|\vec{r}_2-\vec{r}_1|^3}(\vec{r}_1-\vec{r}_2)$$

$$= -\underbrace{(m_1+m_2)}_{M}\frac{G(\vec{r}_1-\vec{r}_2)}{|\vec{r}_1-\vec{r}_2|^3} = -\frac{GM}{r^2}\hat{r}$$

An Elliptical Orbit

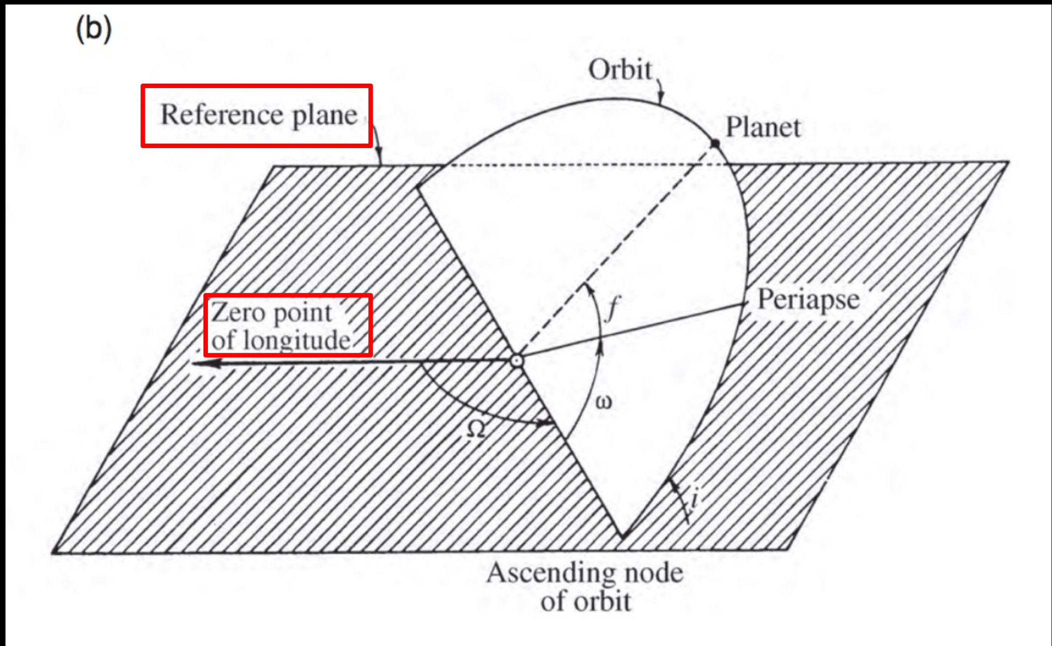
Two Body Problem

- The relative motion of the two bodies is completely equivalent to that of a massless particle orbiting a *fixed* central mass *M*.

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{GM}{r^2}\hat{\mathbf{r}},$$

Geometry of an Elliptical Orbit in 3D

Need one reference plane and a reference direction



- ***i*:** inclination

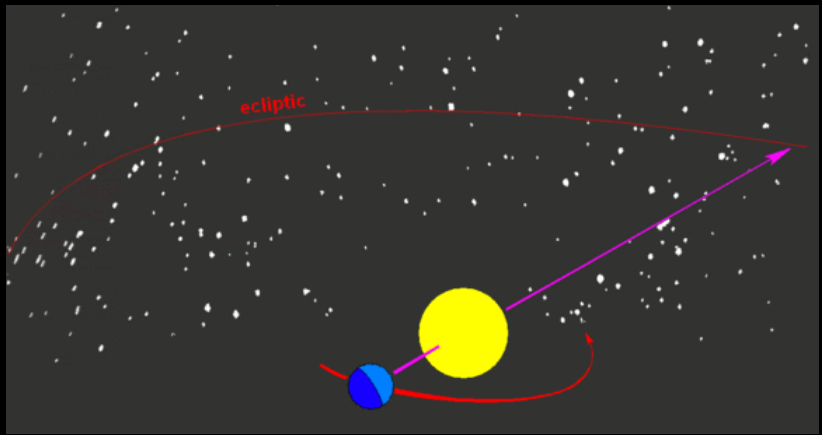
(0-90: prograde; 90-180: retrograde)

- Line of nodes (two of them)
- ***Ω*:** longitude of the ascending node
- ***ω*:** argument of periapse
- ***f*:** true anomaly

Geometry of an Elliptical Orbit in 3D

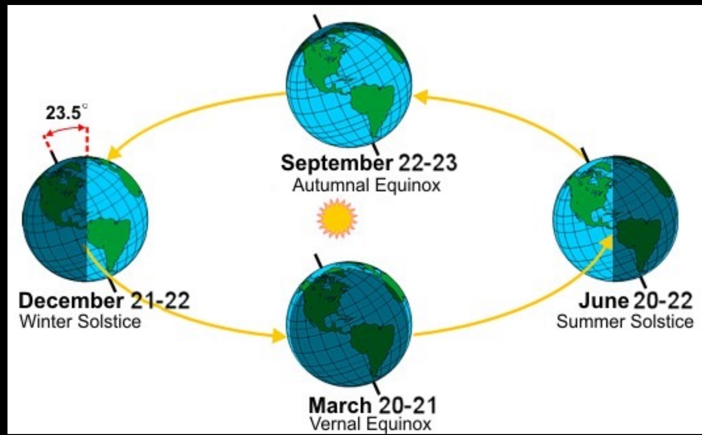
For heliocentric orbits, the convention is to use the ecliptic plane (the orbital plane of Earth around the Sun) as the reference plane, and the vernal equinox as the reference direction

Ecliptic



The Earth's orbital plane about the Sun

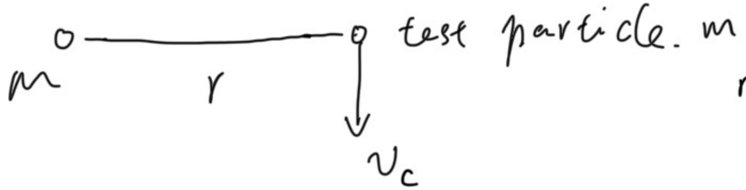
Equinox



The instant of time when the plane of Earth's equator passes through the center of the Sun.

Wiki

Circular orbits velocity v_c



$$m\frac{v_c^2}{r} = \frac{GMm}{r^2} \Rightarrow v_c = \sqrt{\frac{GM}{r}}$$

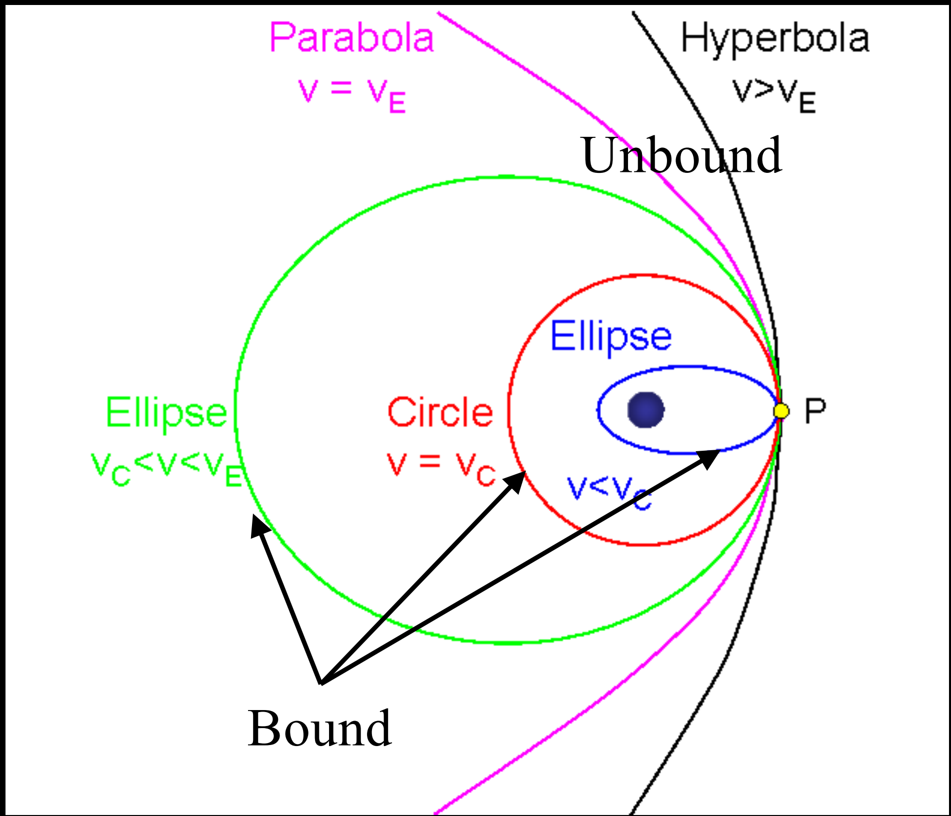
Total E of the particle $E_{tot} = -\frac{GMm}{r} + \frac{1}{2}mv^2$

If $E_{tot} < 0 \Rightarrow$ bound orbits

$\geq \Rightarrow$ unbound

$E_{tot} = 0 \Rightarrow v_e = \sqrt{\frac{2GM}{r}}$ escape velocity

Bound and Unbound Orbits



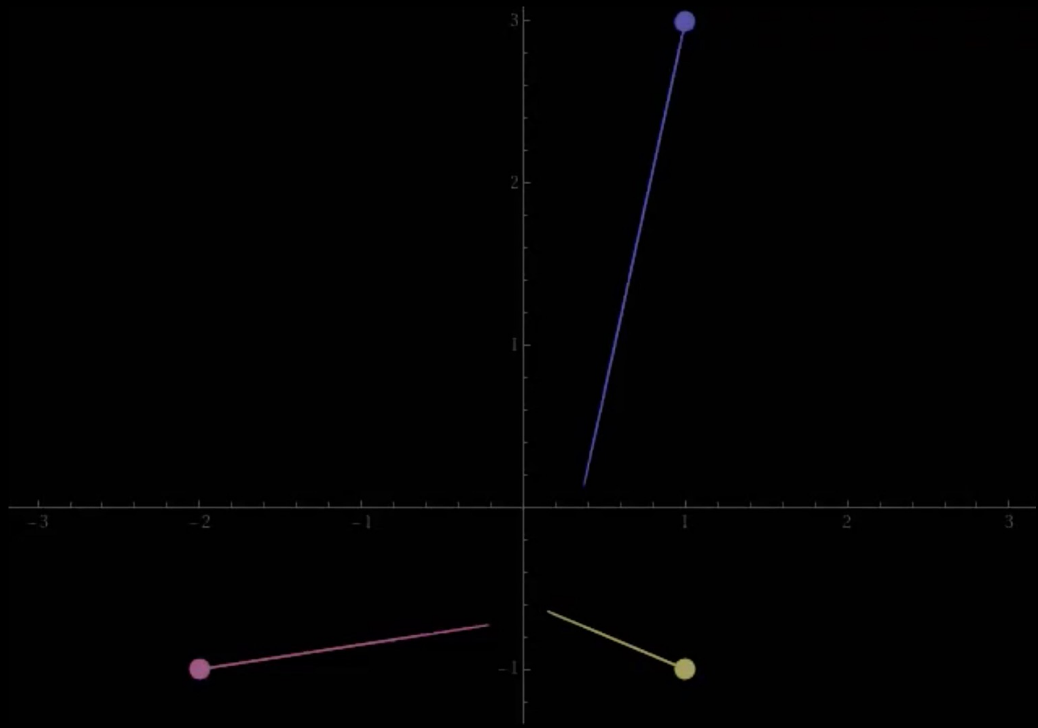
$$v_c = \sqrt{\frac{GM}{r}}.$$

$$v_e = \sqrt{\frac{2GM}{r}} = \sqrt{2}\, v_c.$$

Richard Pogge

The Three Body Problem (C.2.2)

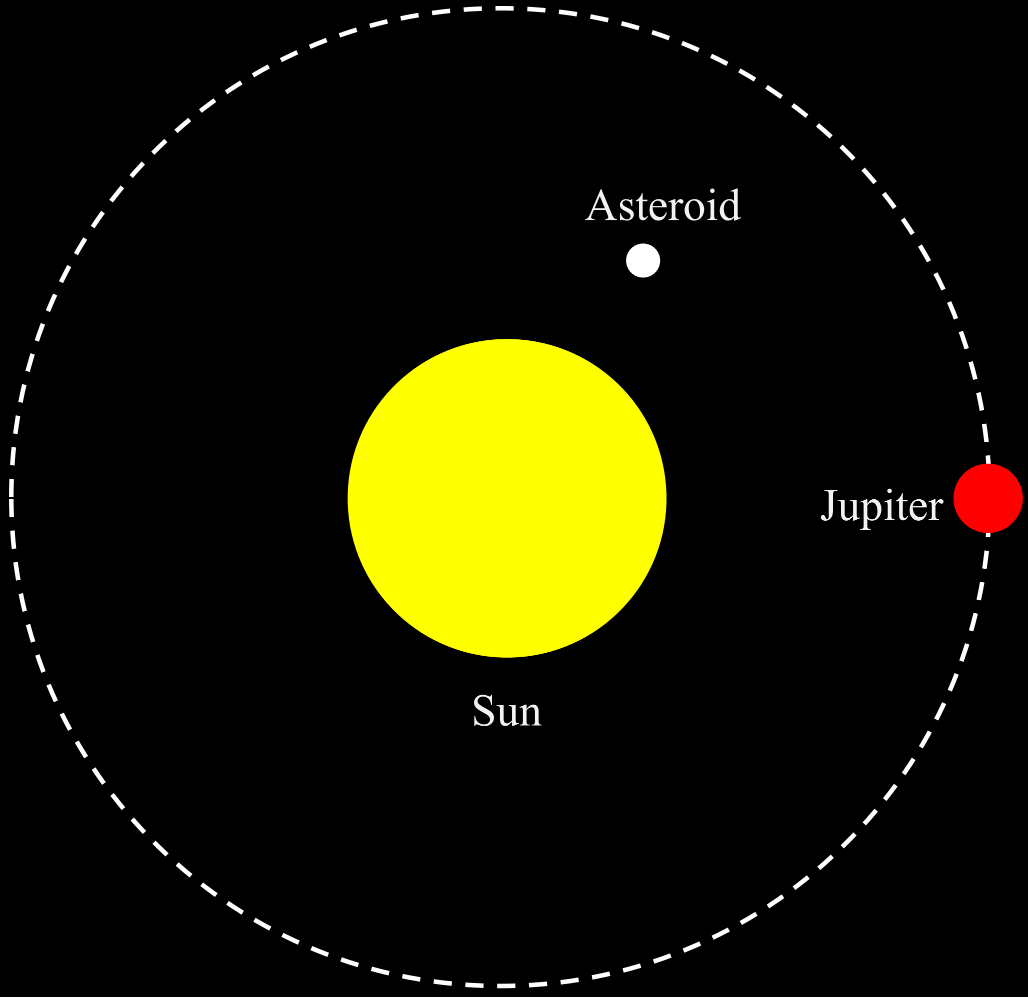
Orbits are chaotic in the most general case



Michael Dörr & Volker Dörr
https://www.youtube.com/watch?v=rr0JpgKPKgg

The Three Body Problem (C.2.2)

Orbits are chaotic in the most general case



Ways to simplify the problem

- Restricted three-body problem: one of the bodies is of negligible mass
  - The 1st and 2nd bodies are on a stable orbit not affected by the 3rd body.
- Circular restricted three-body problem: the relative motion of the two massive particles is a circle
- Planar circular restricted three-body problem: all three bodies travel within the same plane.

Circular Restricted Three-body Problem

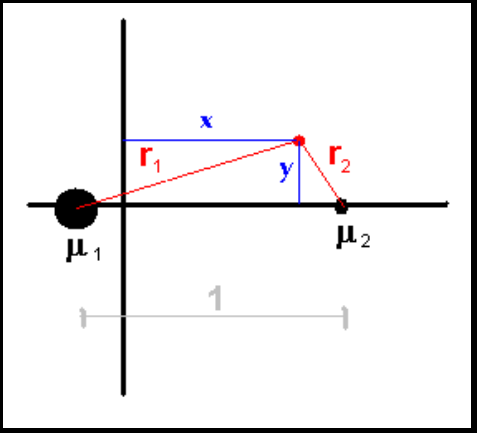
The relative motion of the two massive particles is a circle

- Constant of motion: a quantity that is conserved throughout the motion. Example: linear momentum of an isolated system
- Jacobi's Constant is a constant of motion in the circular restricted three-body problem (2.27)

$$C_J = 2U - v^2$$

$$U \equiv \frac{\Omega^2}{2}\left(x^2 + y^2\right) + \frac{Gm_1}{r_1} + \frac{Gm_2}{r_2}$$

- A given value specifies the magnitude of the test particle's velocity (in the rotating frame) as a function of position.
- Locations (x, y) with $v^2 < 0$ is not permitted.
- The zero-velocity surface bounds the trajectory of a particle with fixed C_J.



Non-inertial frame rotates at the same rate as the binary

$$C_J = \Omega^2(x^2+y^2) + \frac{2Gm_1}{r_1} + \frac{2Gm_2}{r_2} - v^2 = C_J$$

known

const

$$v^2 = 0 \longrightarrow 2U(x,y) = C_J \rightarrow \text{a curve } y(x)$$

zero velocity curve

Circular Restricted Three-body Problem

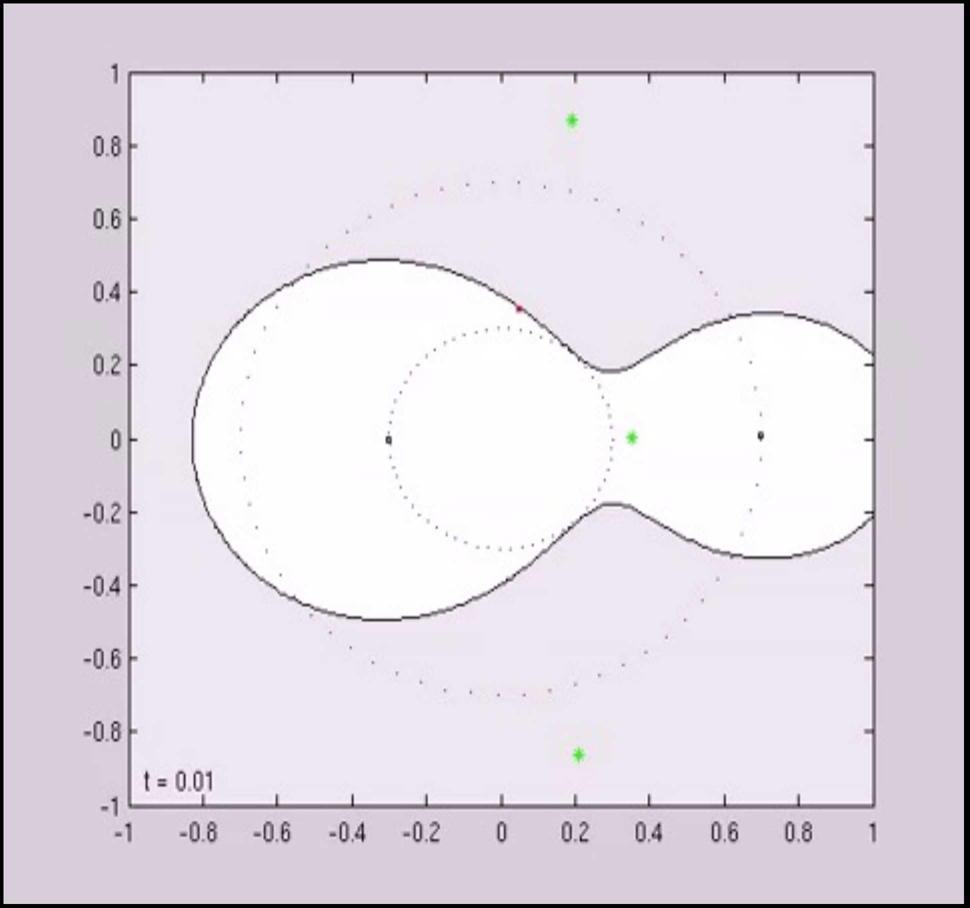
Zero-velocity Curve

Motion of a test particle

- Black dots: massive objects (mass ratio 7:3).
- Doted curves (circles): orbits of the two objects in inertial frame
- Solid curve: zero-velocity curve for a certain C_J
- White region: permitted
- Gray region: forbidden; the particle cannot enter these areas.

When the particle approaches the zero-velocity curve, its speed in the co-rotating frame approaches 0.

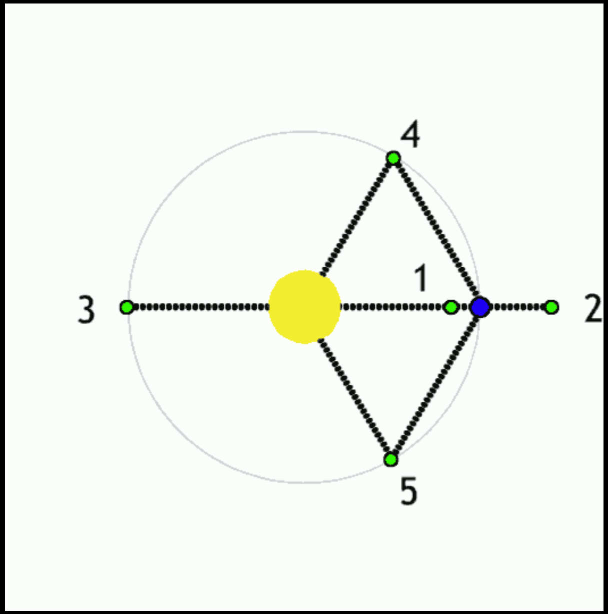
Justin Eldridge
https://www.youtube.com/watch?v=xDLiUe8XYL0



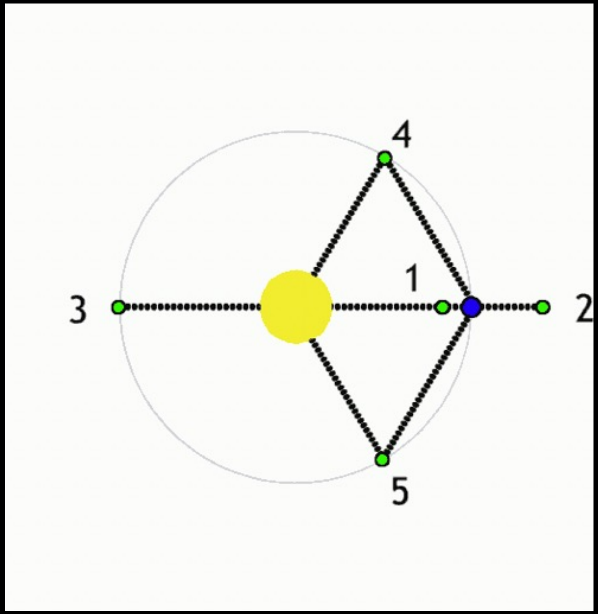
Five Lagrangian Points in Circular Restricted Three-body Problem

Definition: Points near two large bodies in orbit where a smaller object will maintain its position relative to the large orbiting bodies.

Inertial frame



Co-rotating frame

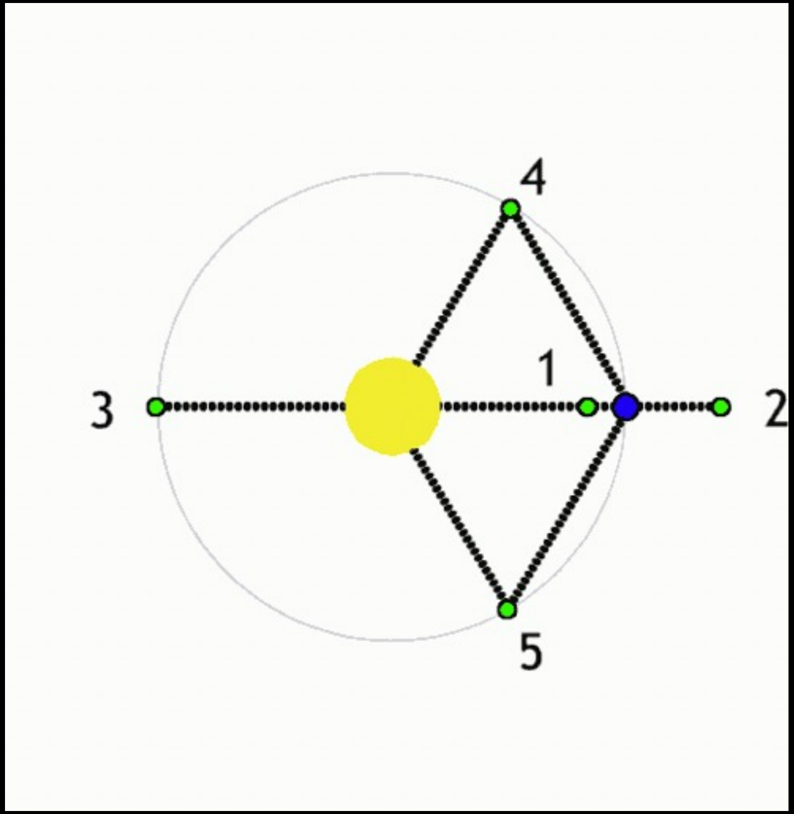


Wiki
https://en.wikipedia.org/wiki/Lagrangian_point

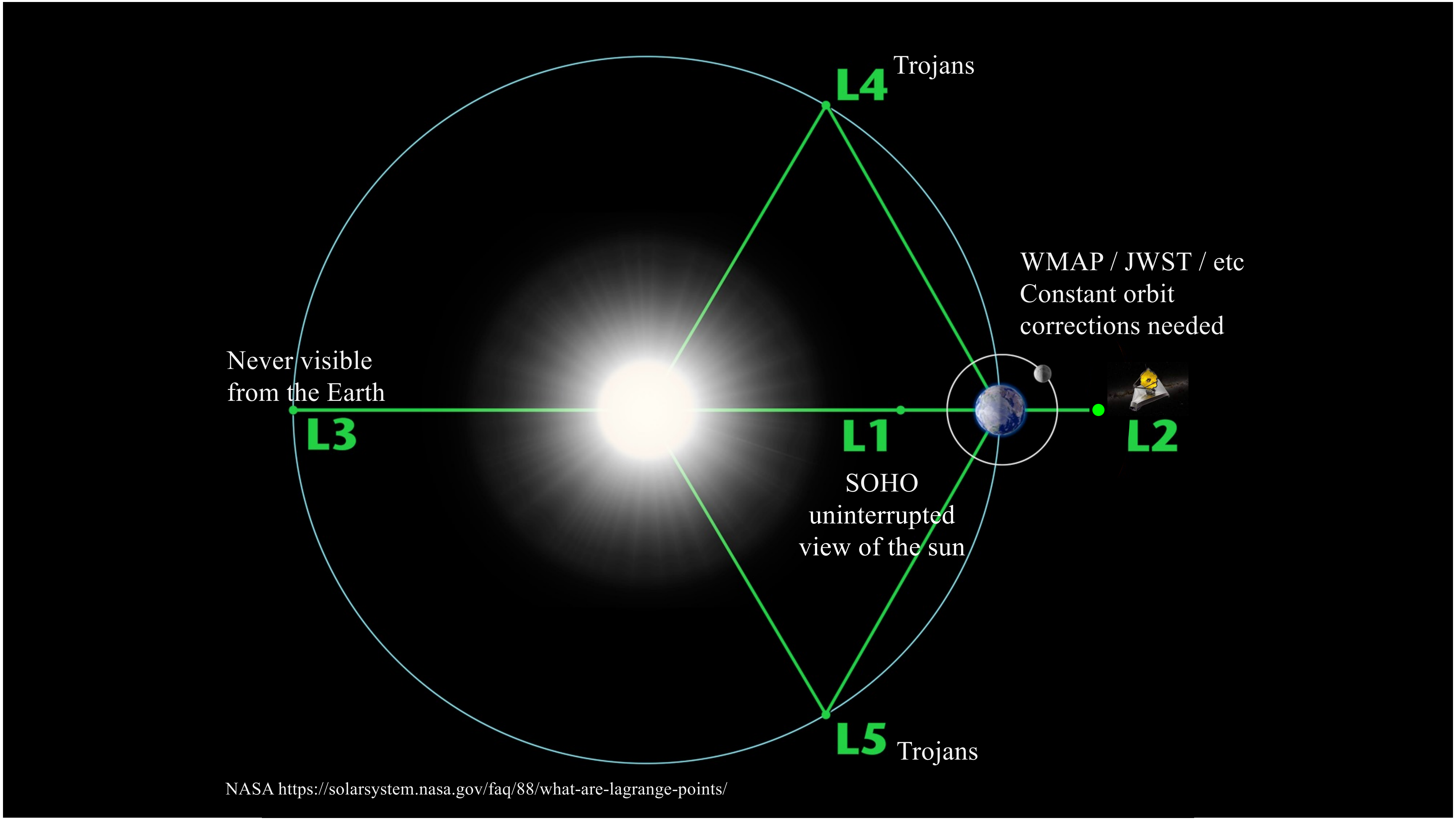
Five Lagrangian Points

- $L1$, $L2$, $L3$: along a line joining m_1 and m_2 (assignment)
- $L4$, $L5$: equilateral triangles with m_1 and m_2 (assignment)
- All five points are in the orbital plane of the two massive bodies.
- Stability:
  - L1 / L2 / L3: unstable
  - L4 / L5: stable for $m_1/m_2 > 25$
  - Motions around L4/L5: Libration – oscillate back and forth

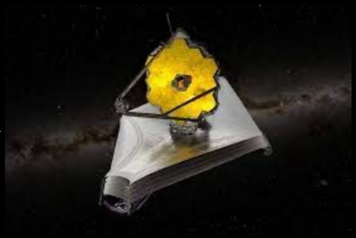
Co-rotating frame

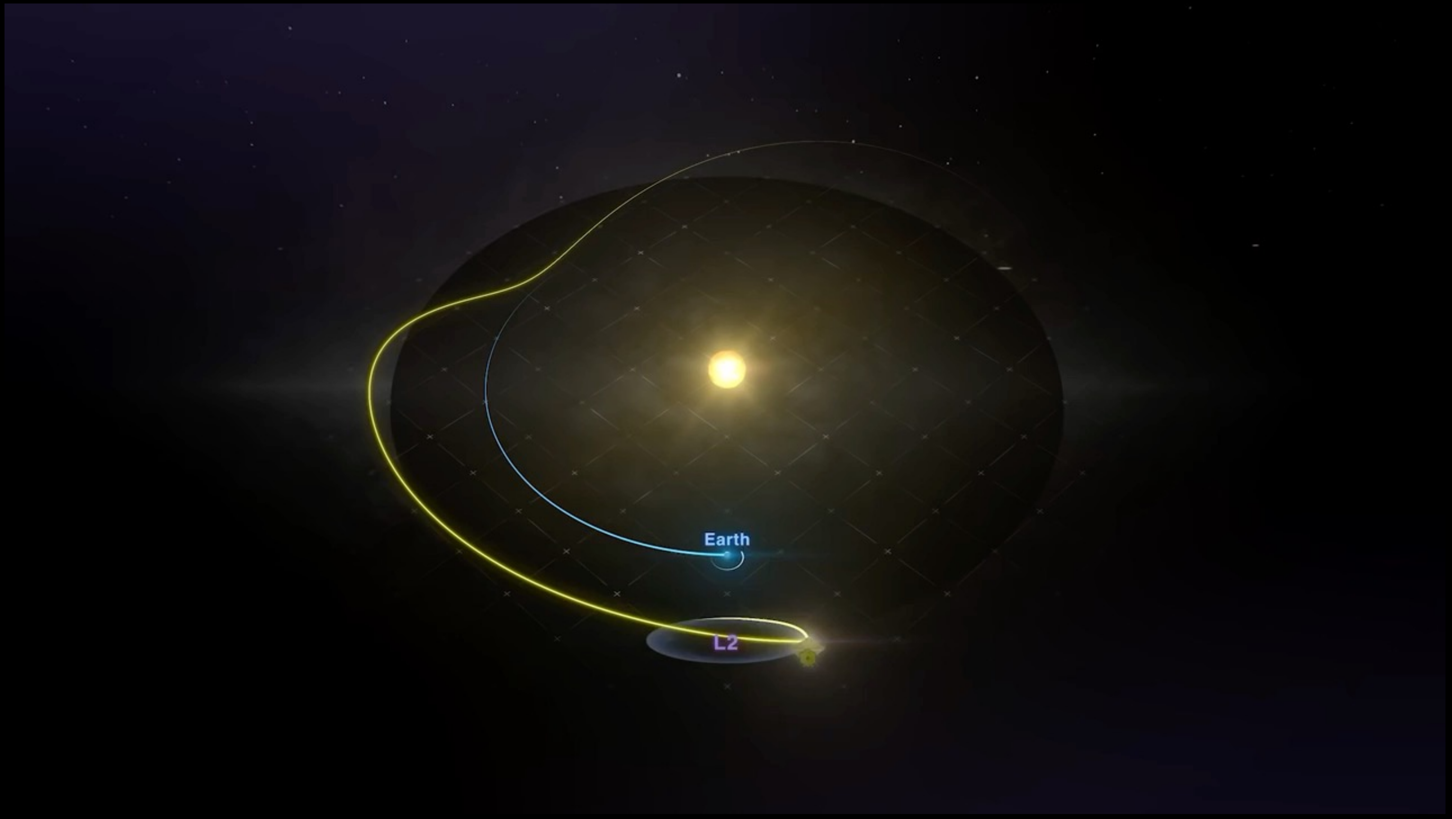


Wiki
https://en.wikipedia.org/wiki/Lagrangian_point


Trojans
L4
WMAP / JWST / etc
Constant orbit
corrections needed
Never visible
from the Earth
L3
L1
L2
SOHO
uninterrupted
view of the sun
L5
Trojans
NASA https://solarsystem.nasa.gov/faq/88/what-are-lagrange-points/

The James Webb Space Telescope is Located at L2

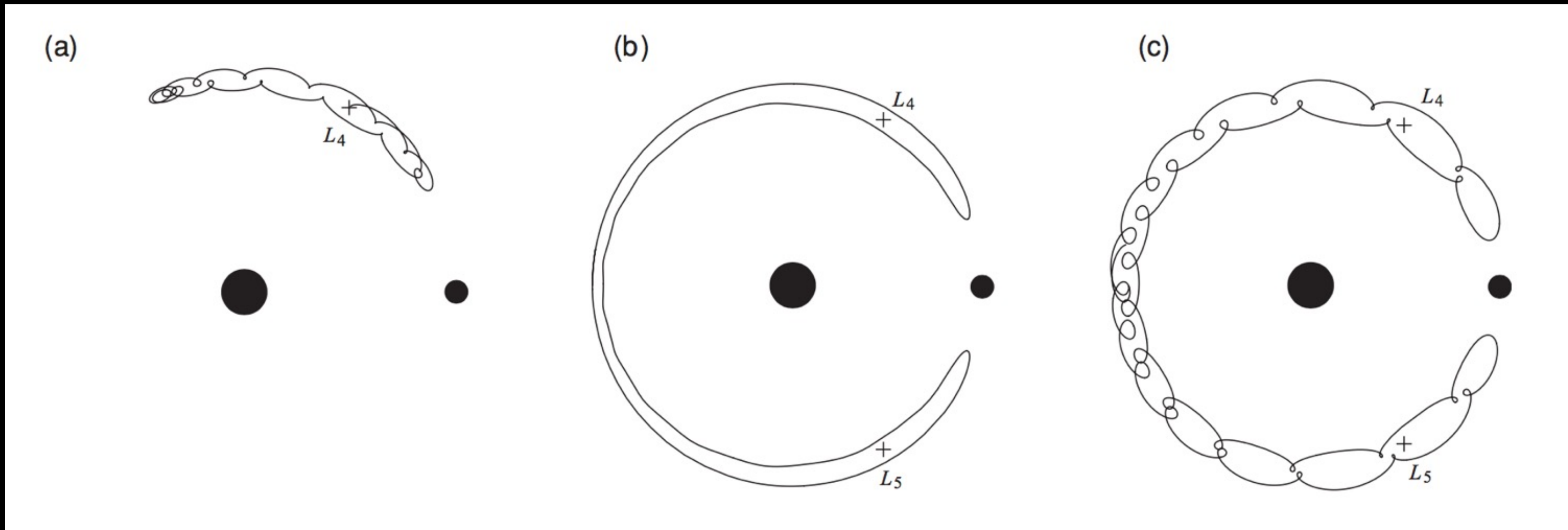




NASA

Orbits around L4 and L5 in the Rotating Frame

In a reference frame corotating with the planet



A tadpole orbit

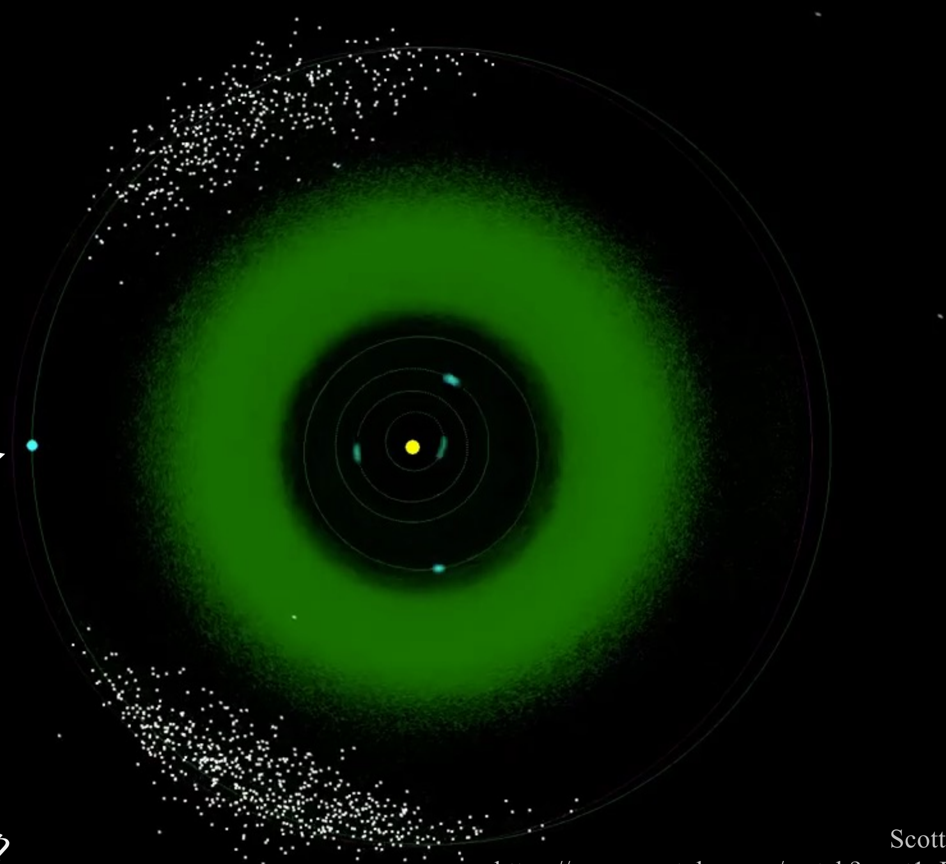
A horseshoe orbit

Another horseshoe orbit, with larger eccentricity

Jupiter Trojan: Objects on Tadpole Orbits around L4 & L5

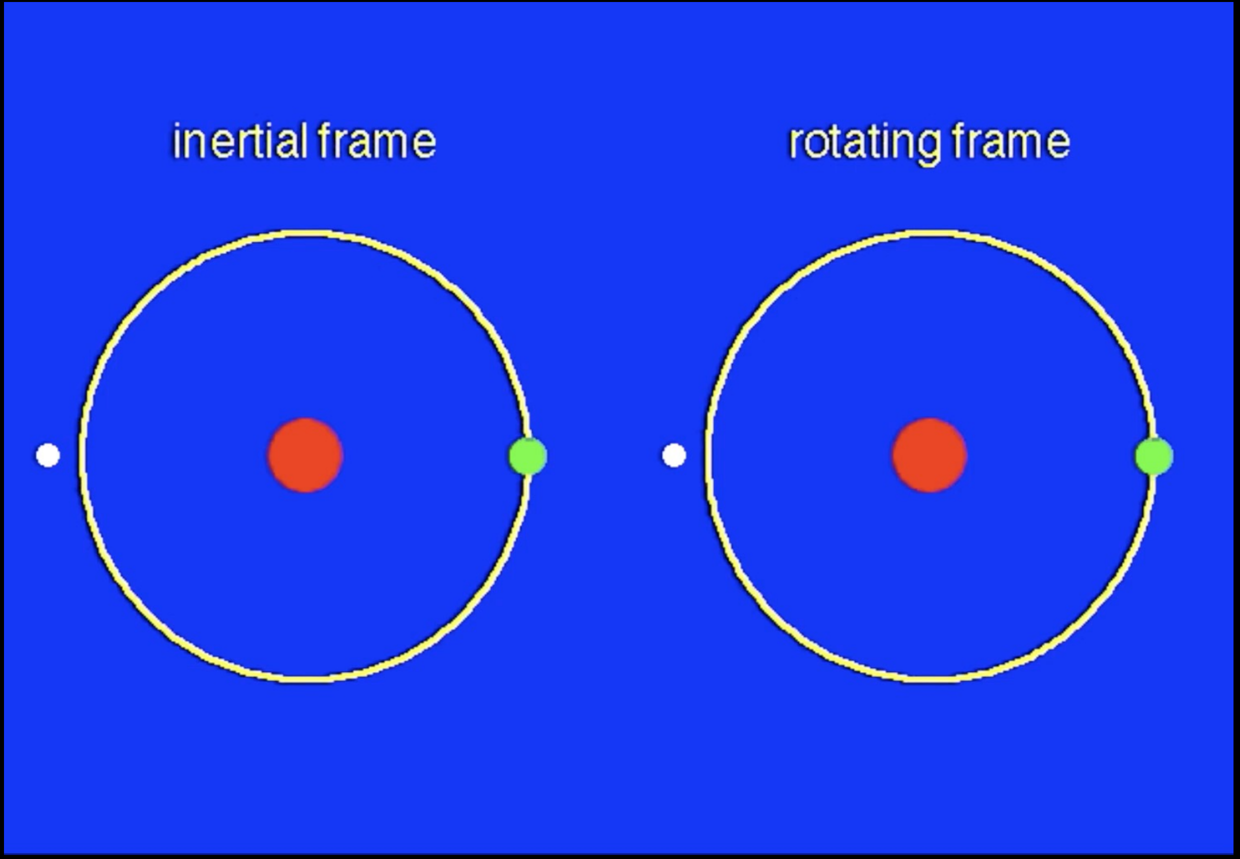
A frame corotating with Jupiter's mean motion

(but why Jupiter is still moving?)



Scott Manley
https://www.youtube.com/watch?v=yt1qPCiOq-8

Horseshoe orbit



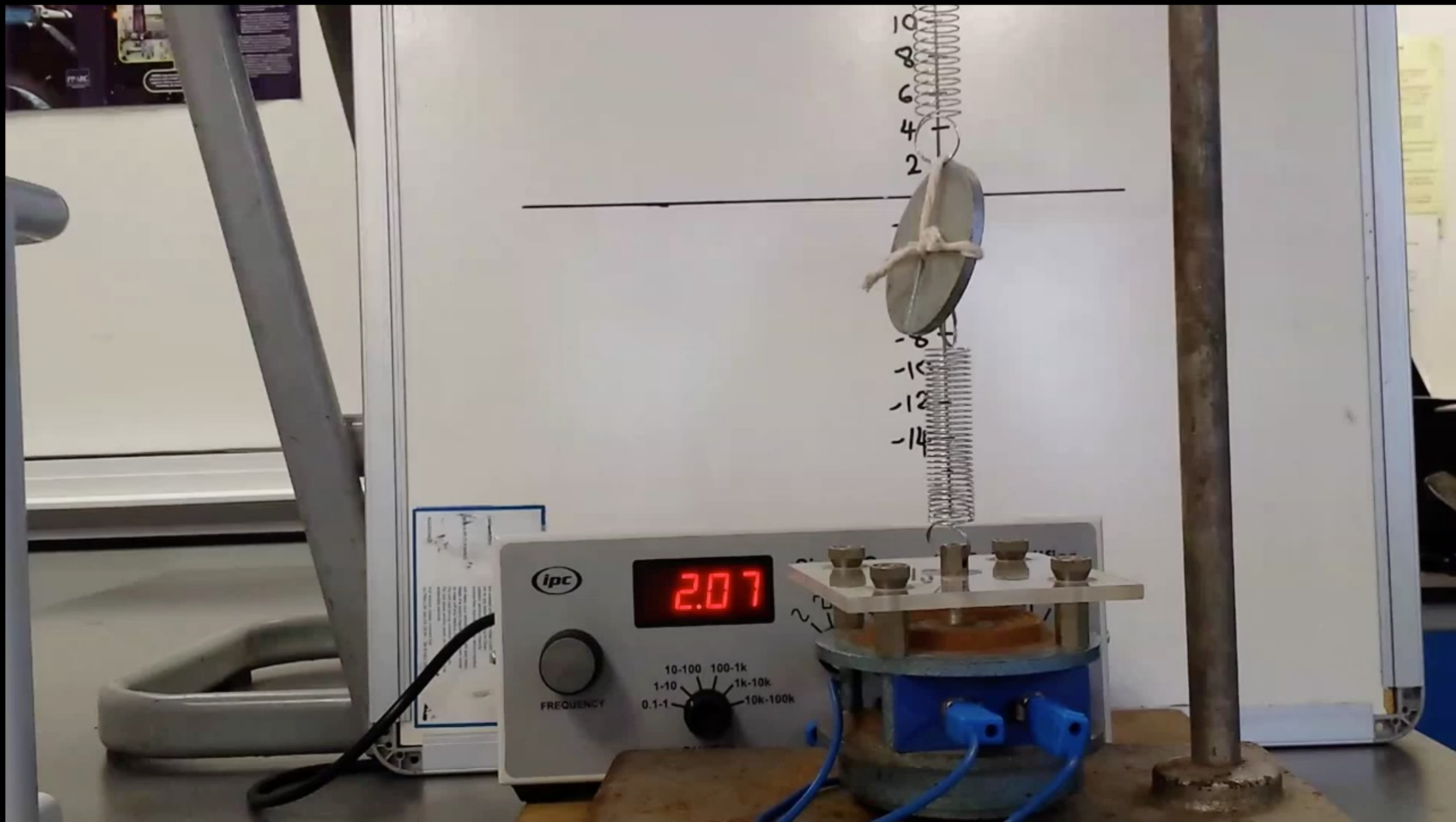
Jim Kaiser
https://www.youtube.com/watch?v=gsHBE3DWCP4

Questions?

Assignment 1: derive Lagrangian points

Resonance (C.2.3)

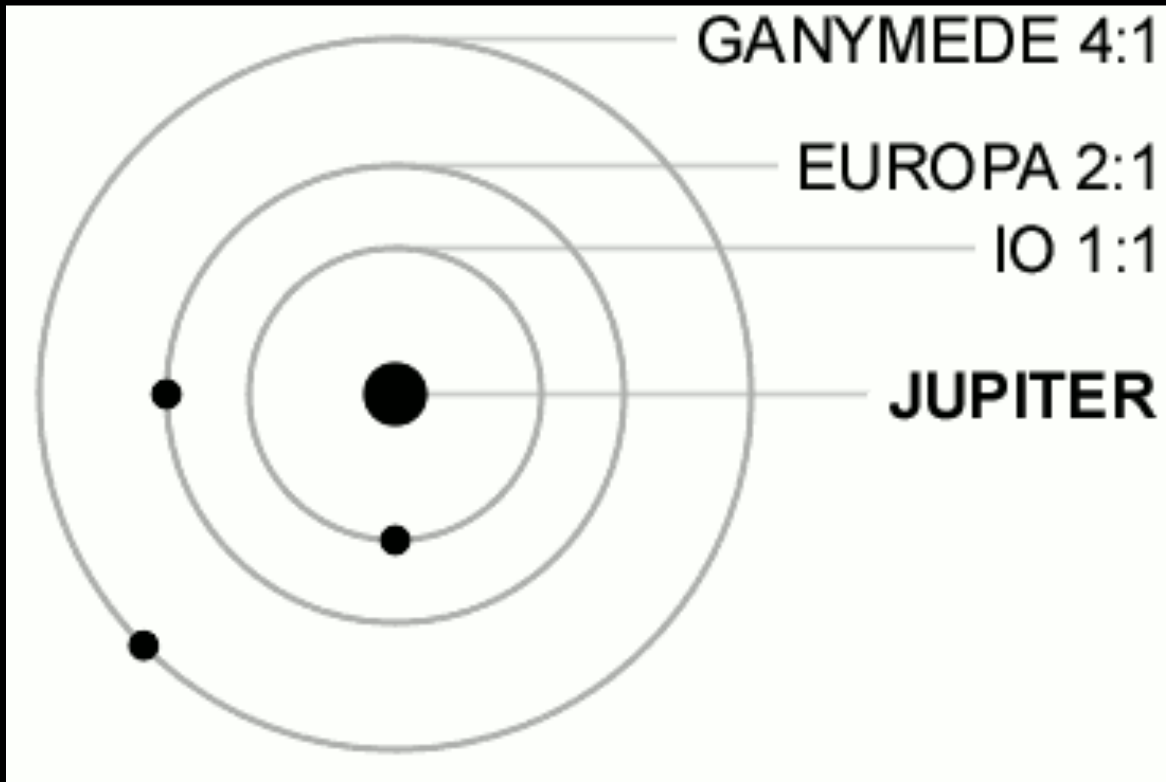
when the frequency of an applied periodic force is equal or close to a natural frequency of the system



Daniel Powell
https://www.youtube.com/watch?v=jewSVEBkI_s

Mean Motion Resonance

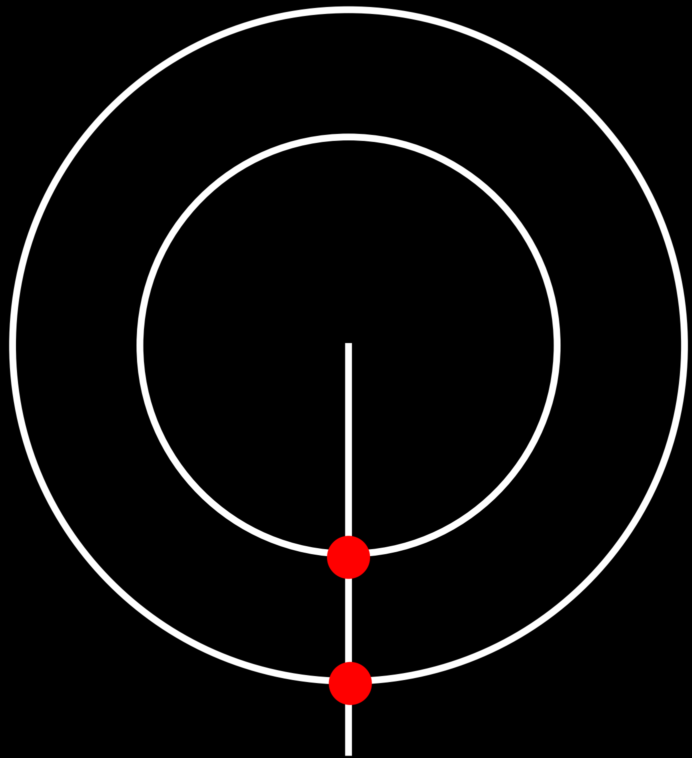
Orbital periods of two bodies are commensurate (e.g., have a ratio of the form N/(N+1), N/(N + 2), etc, where N is an integer).



https://en.wikipedia.org/wiki/Orbital_resonance

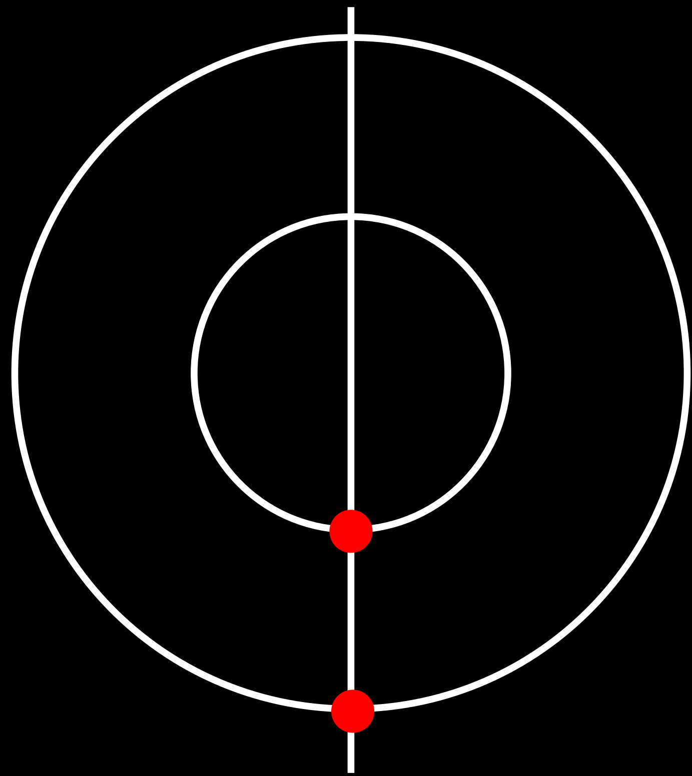
1st Order MMR

N / (N+1), e.g., 2 / 3



2nd Order MMR

N / (N+2), e.g., 1 / 3

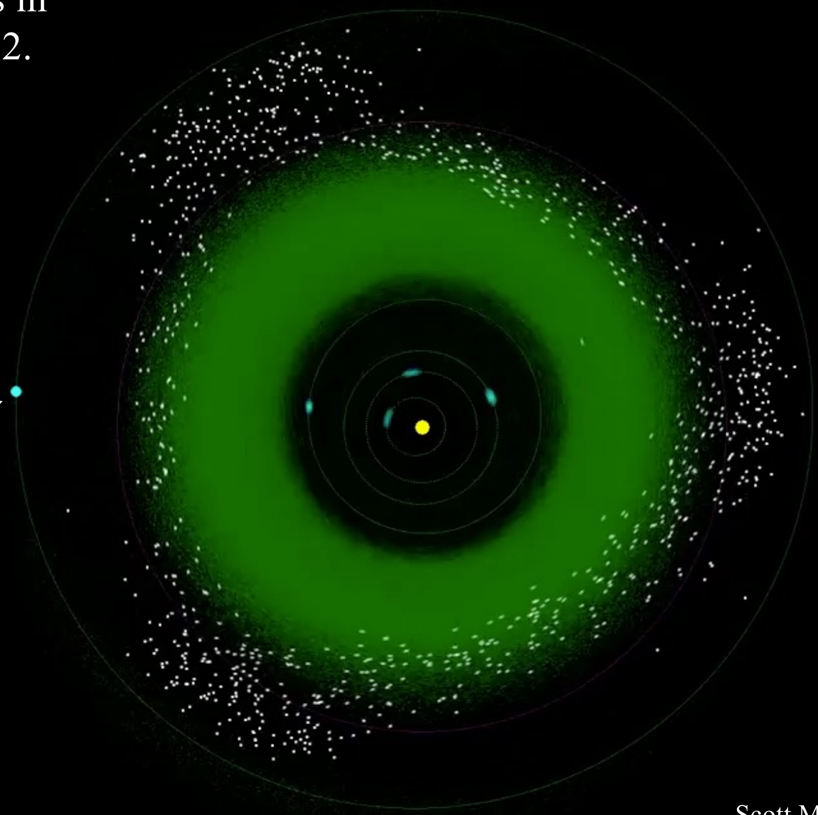


Conjunction: objects being at the same longitude in their orbits

Objects in 3:2 Resonance with Jupiter

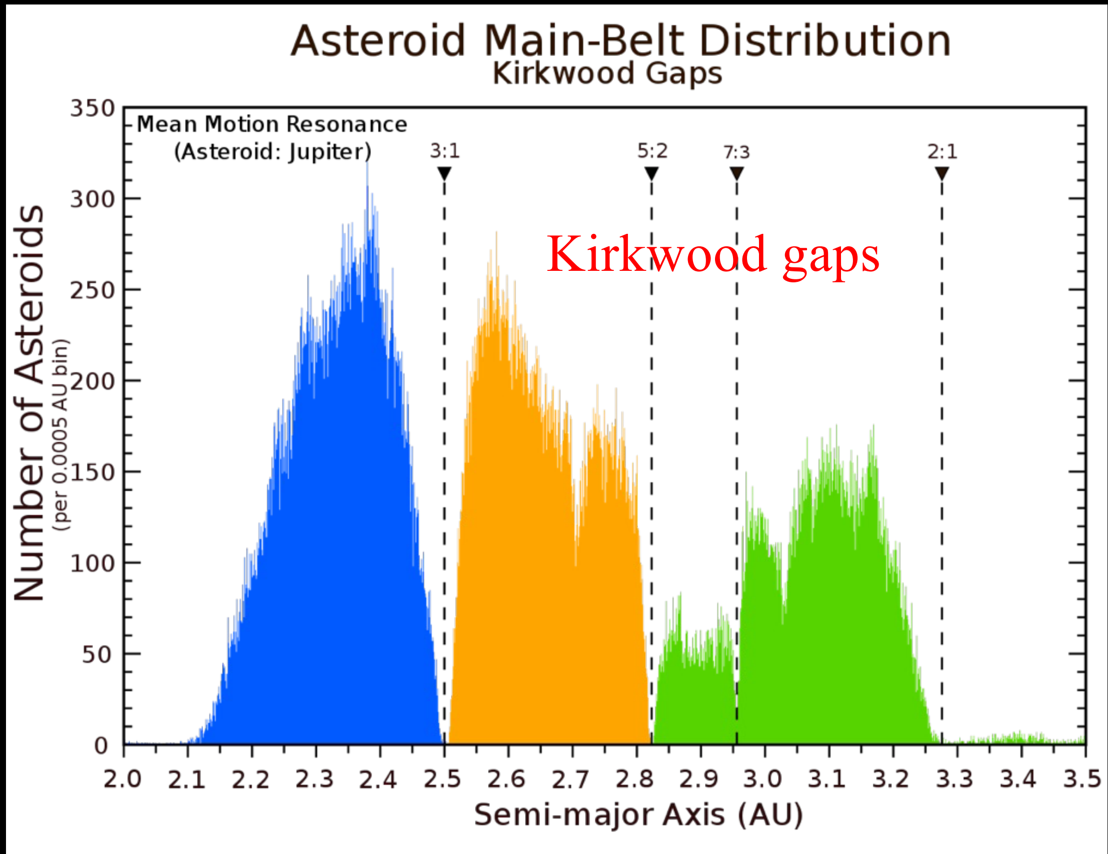
Objects in this group complete 3 orbits in the time that Jupiter takes to complete 2.

A frame corotating with Jupiter's mean motion



Scott Manley
https://www.youtube.com/watch?v=yt1qPCiOq-8

Unstable Mean Motion Resonances with Jupiter in the Asteroid Belt



Alan Chamberlain
https://en.wikipedia.org/wiki/Asteroid_belt