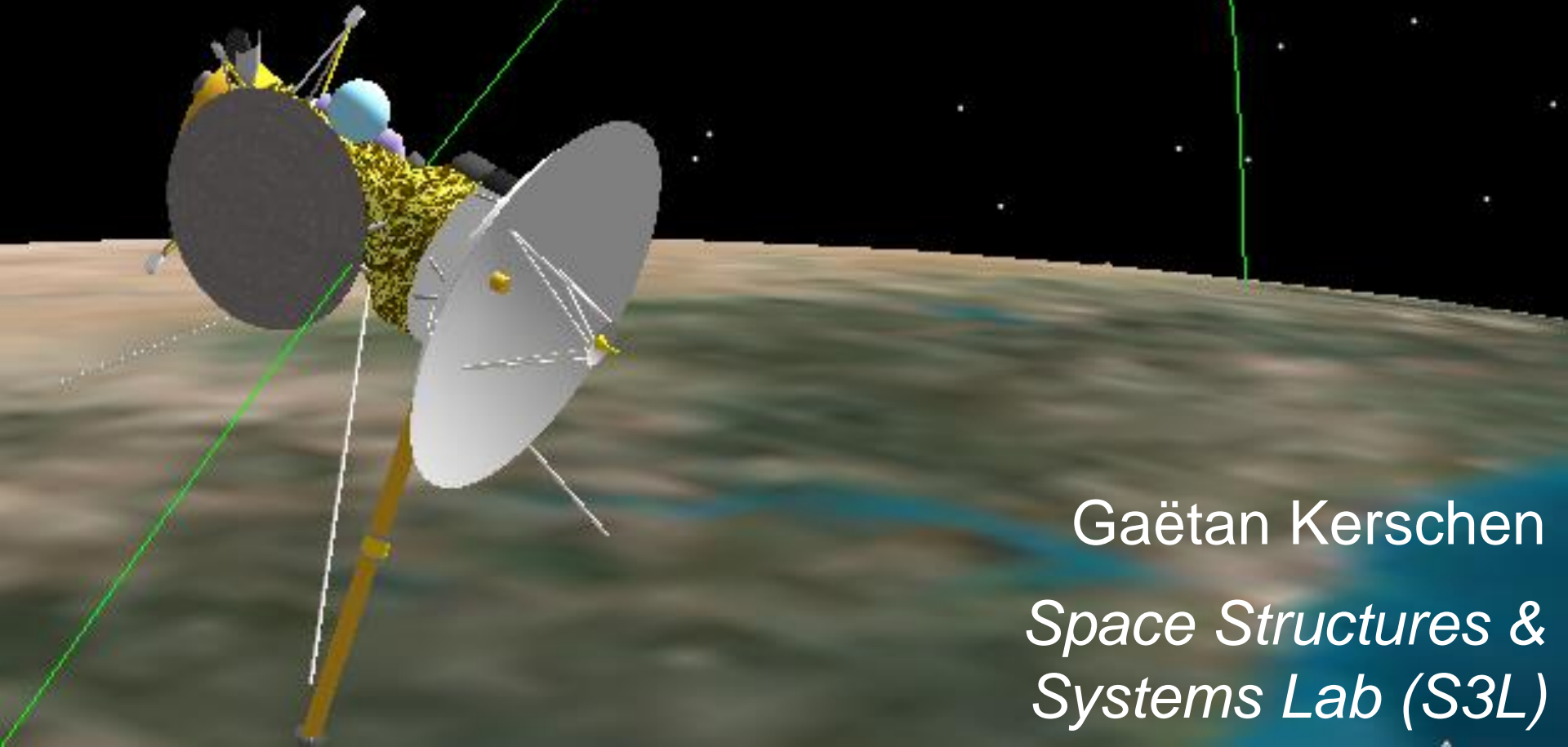


Cassini Classical Orbit Elements  
Time (UTCG): 15 Oct 1997 09:18:54.000  
Semi-major Axis (km): 6685.637000  
Eccentricity: 0.020566  
Inclination (deg): 30.000  
RAAN (deg): 150.546  
Arg of Perigee (deg): 230.000  
True Anomaly (deg): 136.530  
Mean Anomaly (deg): 134.891

# Aerodynamics (AERO0024)



Gaëtan Kerschen  
*Space Structures &  
Systems Lab (S3L)*

# Instructors — Gaëtan Kerschen

## Contact details

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Aerospace and Mechanical Engineering Department
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- [g.kerschen@uliege.be](mailto:g.kerschen@uliege.be), 04 3664852
- <http://www.s3l.be>

## Contact details

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Aerospace and Mechanical Engineering Department
- Room: +2/522 (B52 building)
- [n.leclere@uliege.be](mailto:n.leclere@uliege.be)



# Course Organization

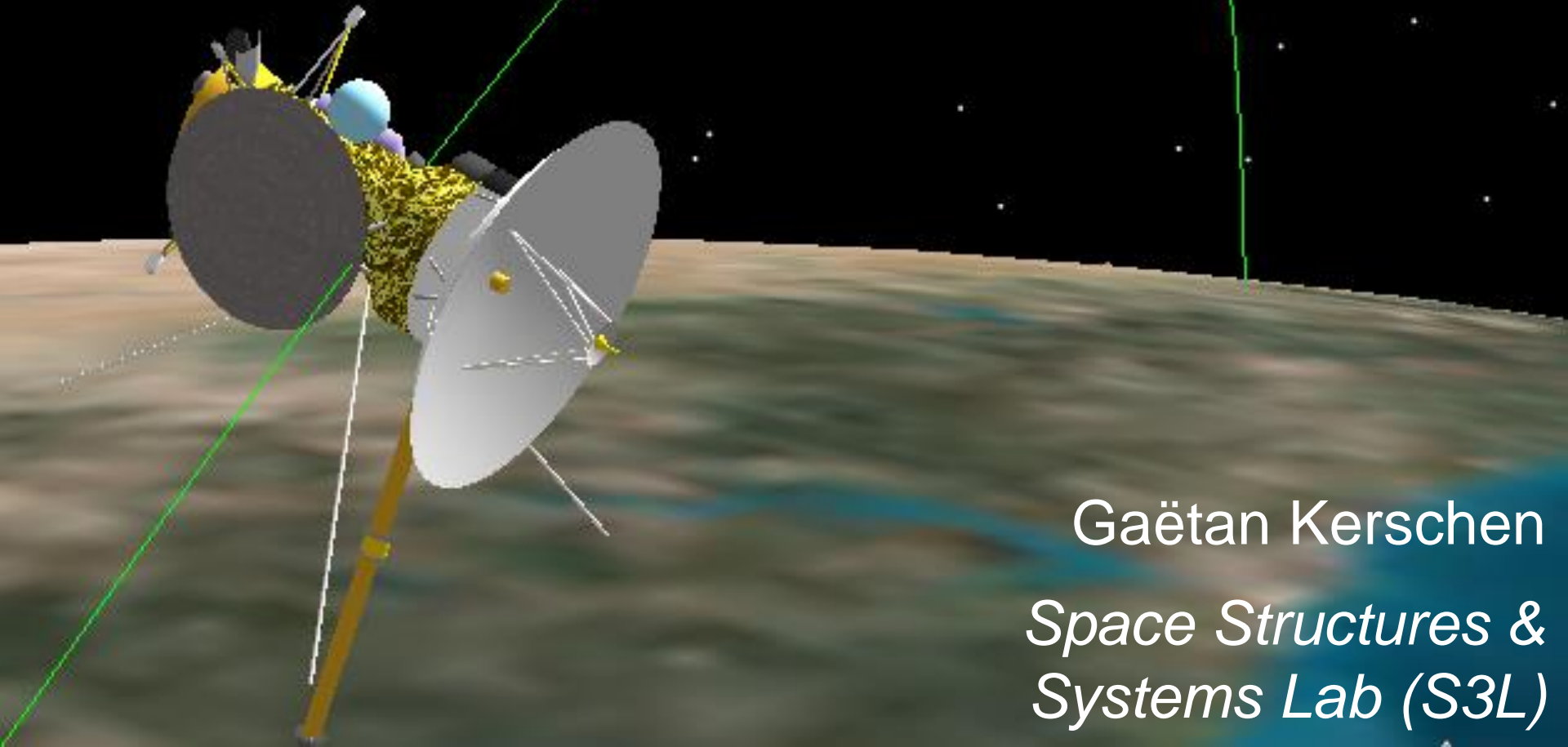
See web site.

Cassini Classical Orbit Elements  
Time (UTCG): 15 Oct 1997 09:18:54.000  
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# Aerodynamics

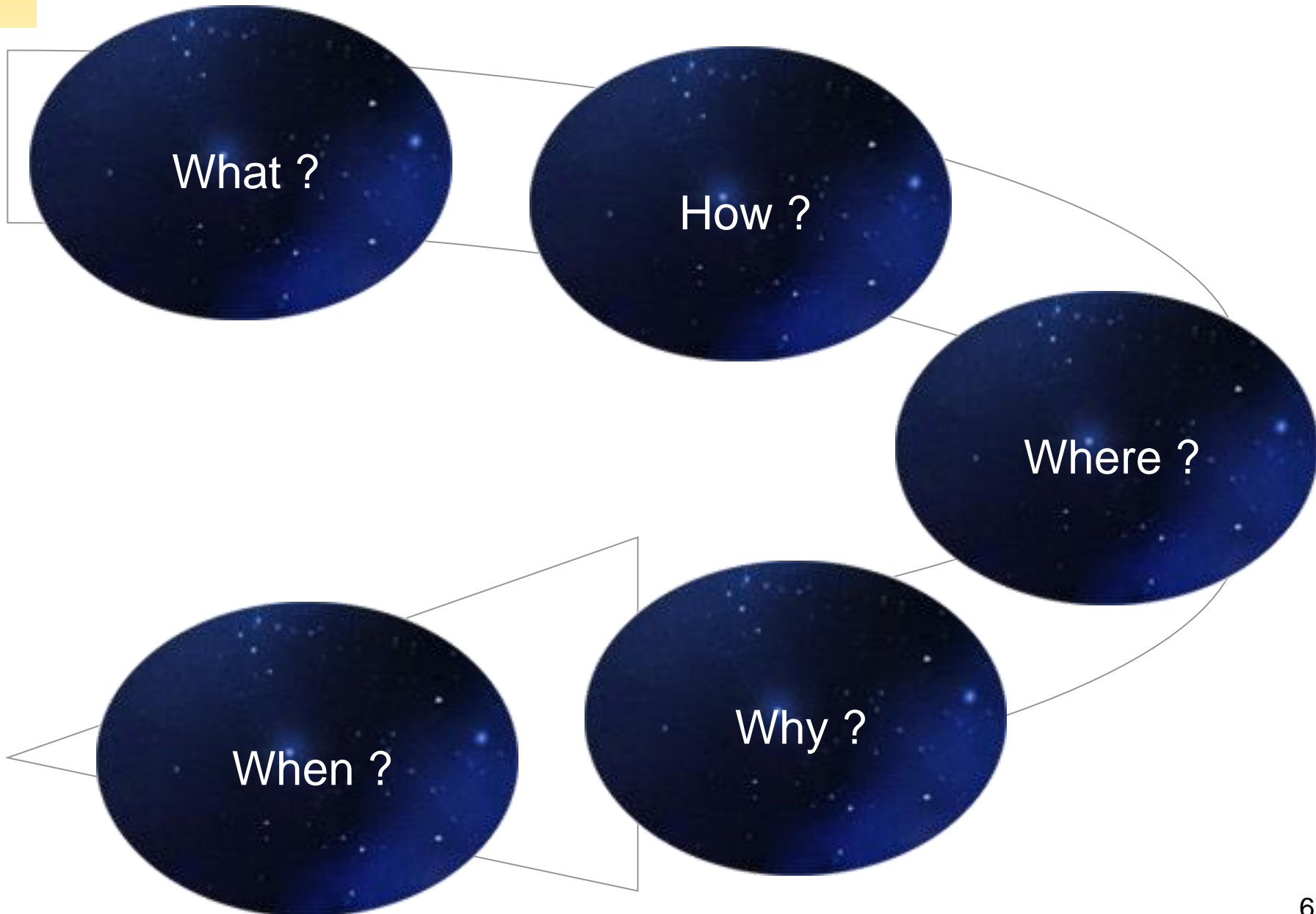
(AERO0024)

## 1. *Introductory Lecture*



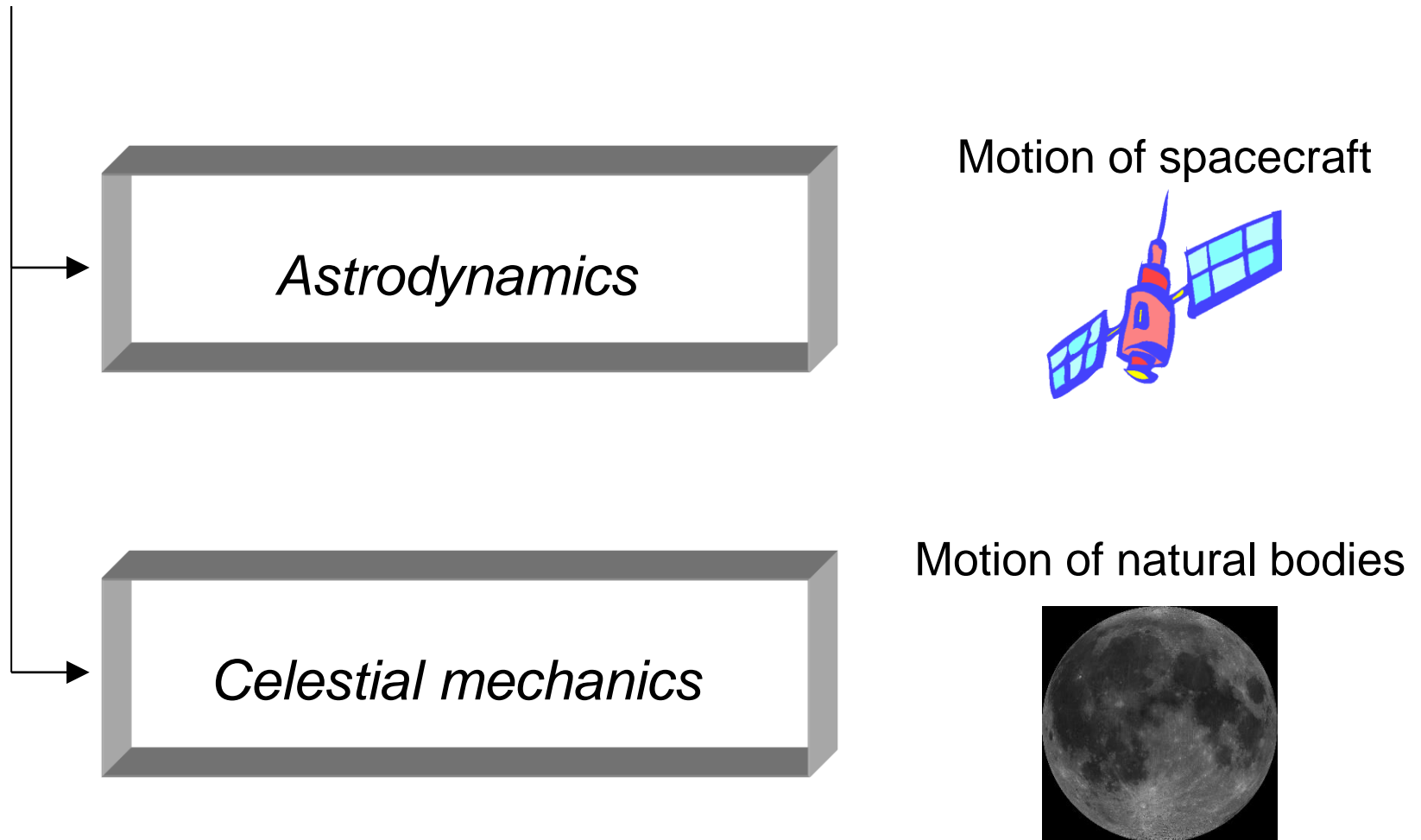
Gaëtan Kerschen  
*Space Structures &  
Systems Lab (S3L)*

# Introductory Lecture



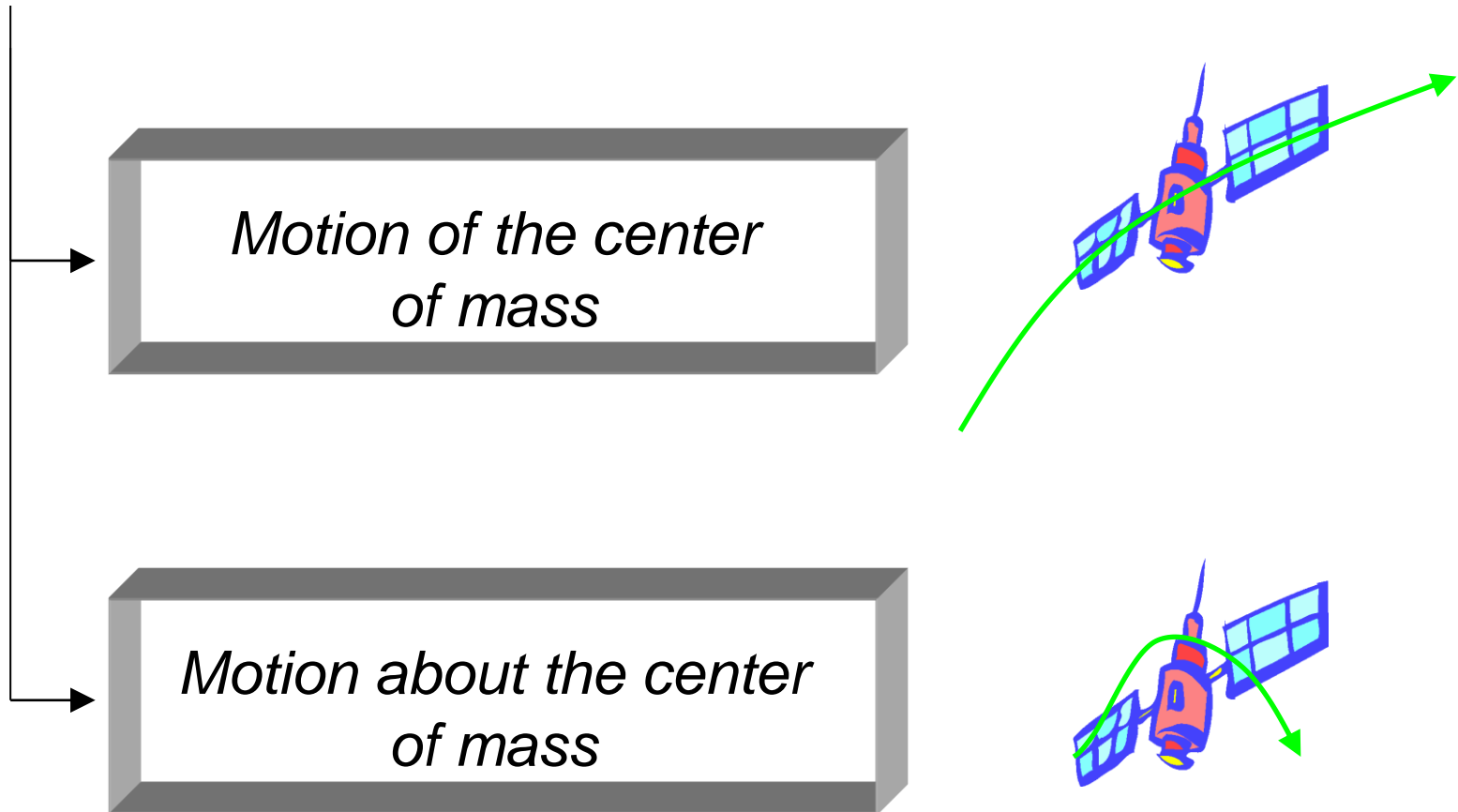
# Space Mechanics

*Space mechanics* is the science concerned with the description of the motion of bodies in space.

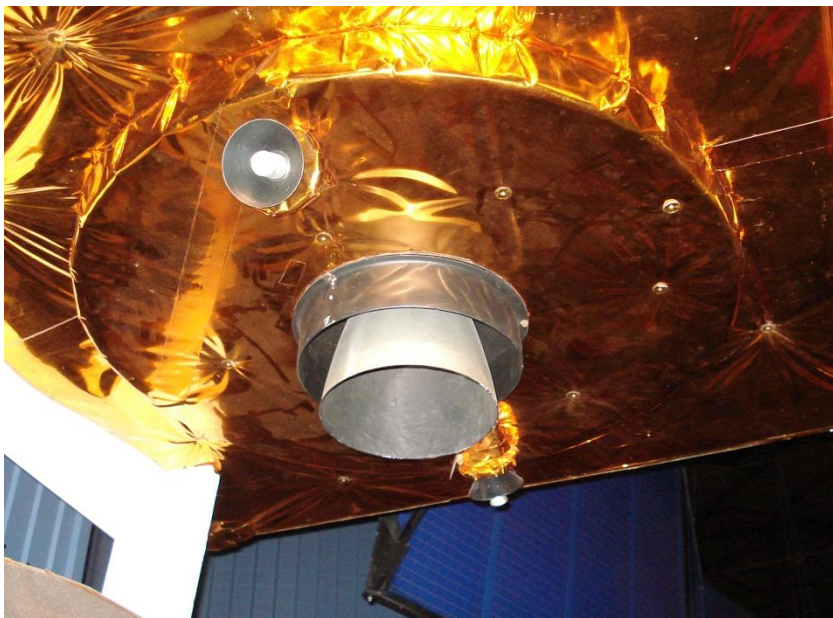


# Astrodynamics

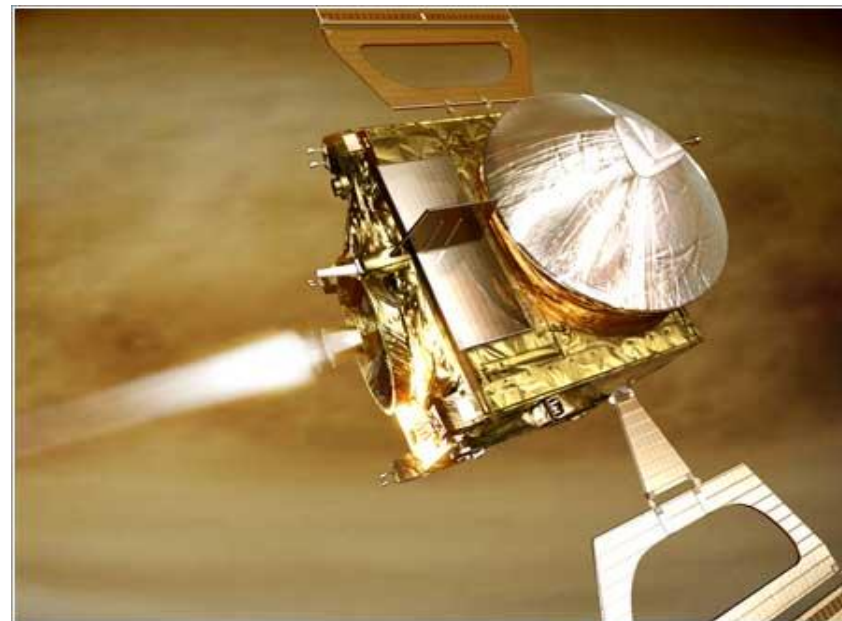
*Astrodynamics* is commonly divided into orbital motion and attitude motion.



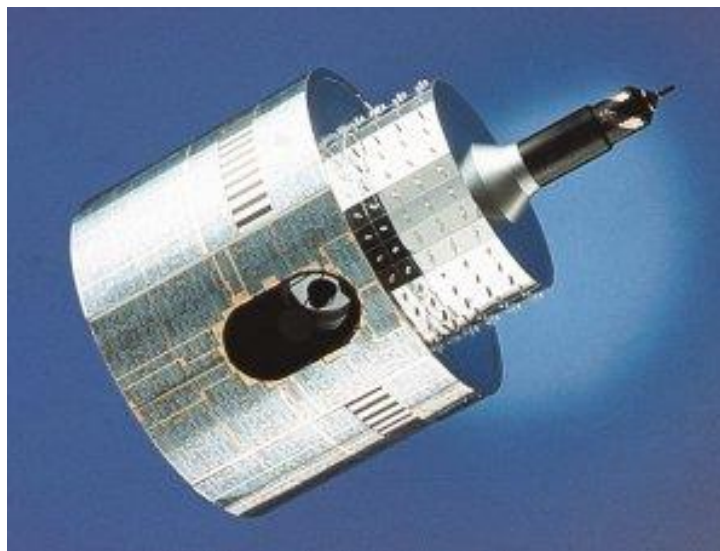




Apogee motor for orbit circularization (Eutelsat)



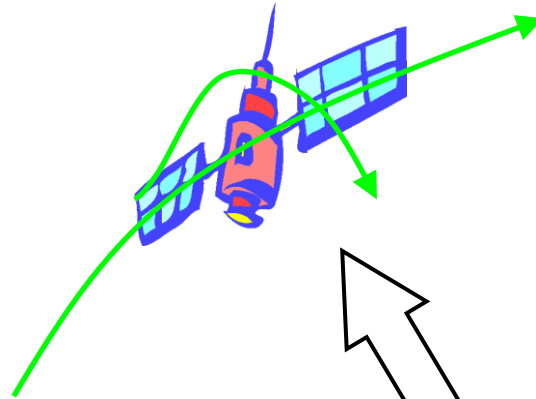
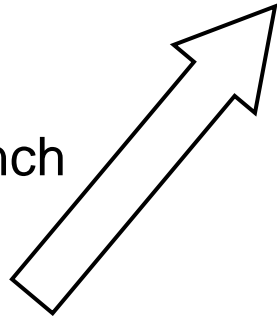
Braking maneuver (Venus Express)



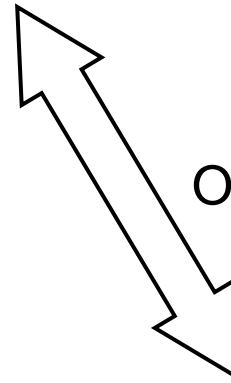
Meteosat: 6 thrusters for orbit maintenance

# The Whole Story...

Orbital launch



Orbit determination



**Launch vehicle**



**Ground station**

# Course Objective

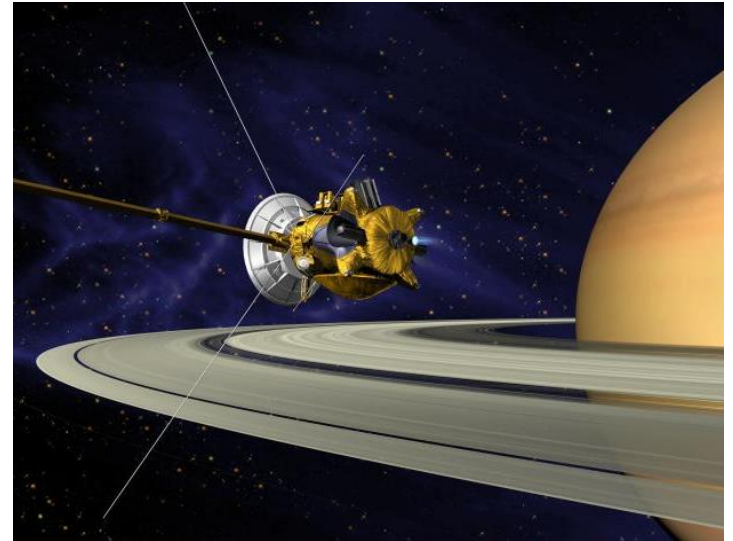
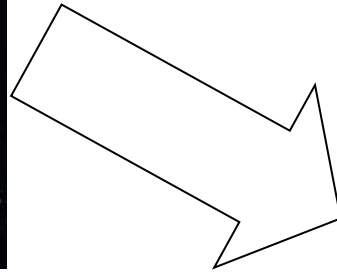
Develop a *fundamental* and *comprehensive* knowledge of *astrodynamics*:

- ⇒ Celestial mechanics will not be our primary focus.
- ⇒ Orbital motion will be covered in great detail, and attitude motion will not be touched upon.

# Course Objective



**COURSE  
OBJECTIVE**

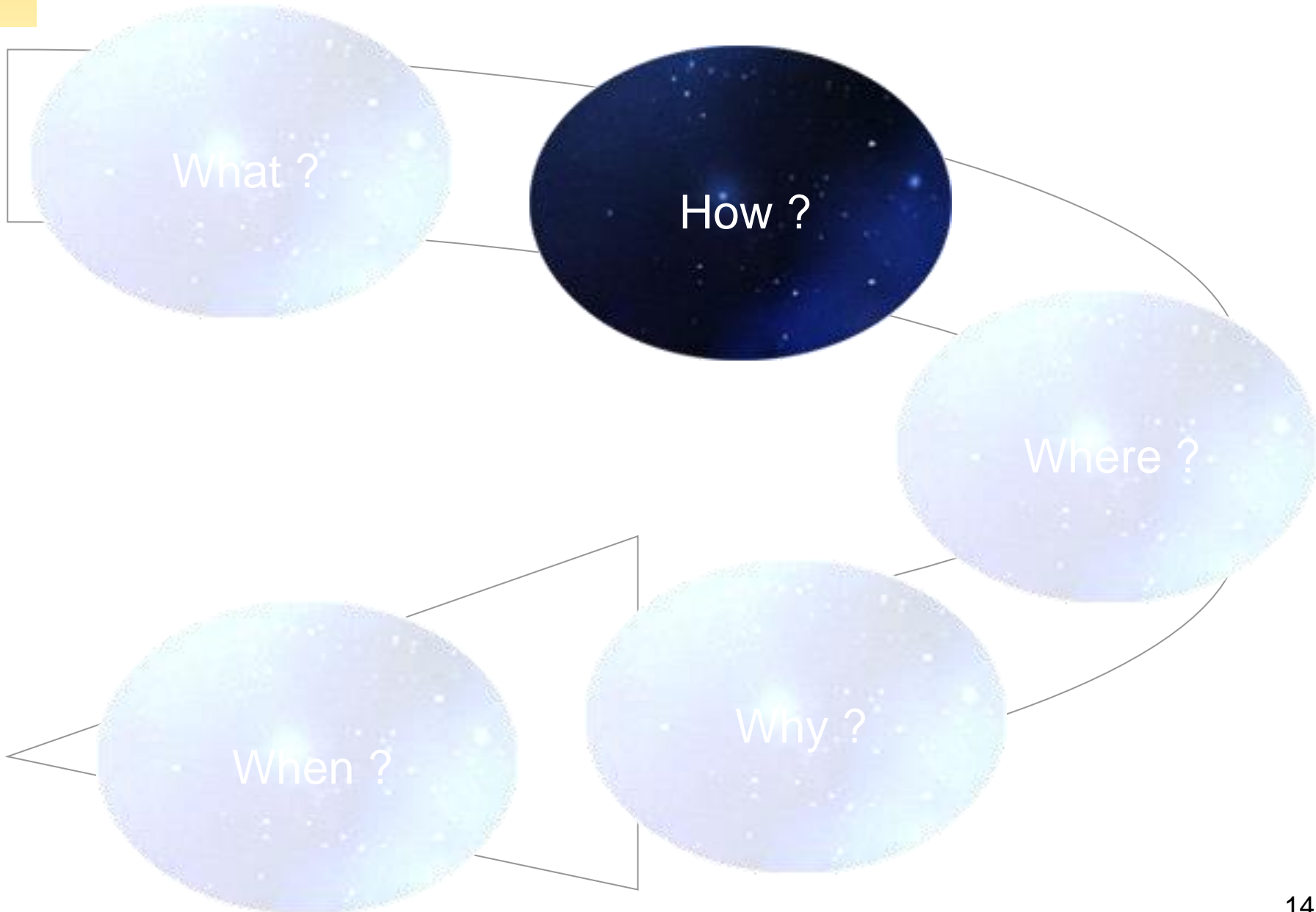


# Expected Learning Outcomes

Upon completion of this course, you will be able to:

1. Understand the key features of common satellite orbits
2. Develop a detailed knowledge of the two-body problem
3. Calculate orbital parameters of satellites
4. Estimate orbit perturbations and their effects
5. Design maneuvers to accomplish desired change of orbit
6. Design interplanetary trajectories
7. Solve basic and more advanced orbital mechanics problems using Matlab

# Introductory Lecture



Cassini Classical Orbit Elements  
Time (UTCG): 15 Oct 1997 09:18:54.000  
Semi-major Axis (km): 6685.637000  
Eccentricity: 0.020566  
Inclination (deg): 30.000  
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# Aerodynamics (AERO0024)

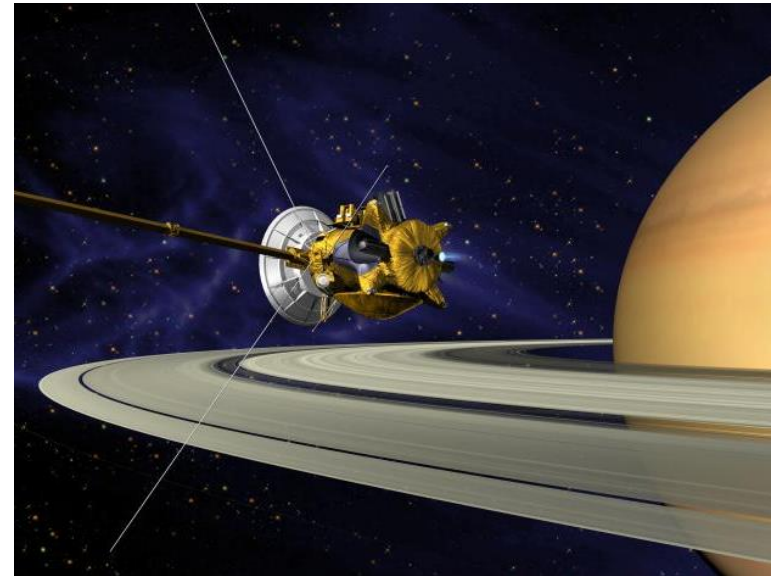
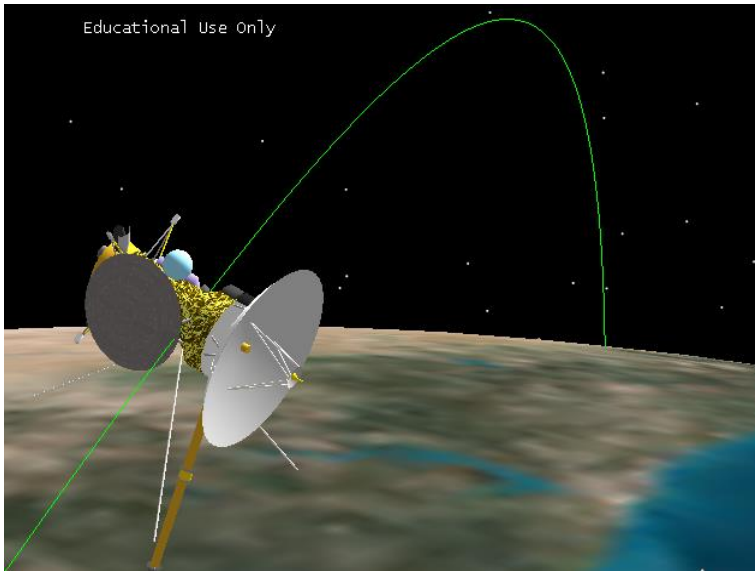
## 1. *Introductory Lecture*



Gaëtan Kerschen  
*Space Structures &  
Systems Lab (S3L)*

# Cassini-Huygens Mission

Mission to Saturn ... but.... the spacecraft is in earth parking orbit (170 x 445 km,  $i=30^\circ$ )

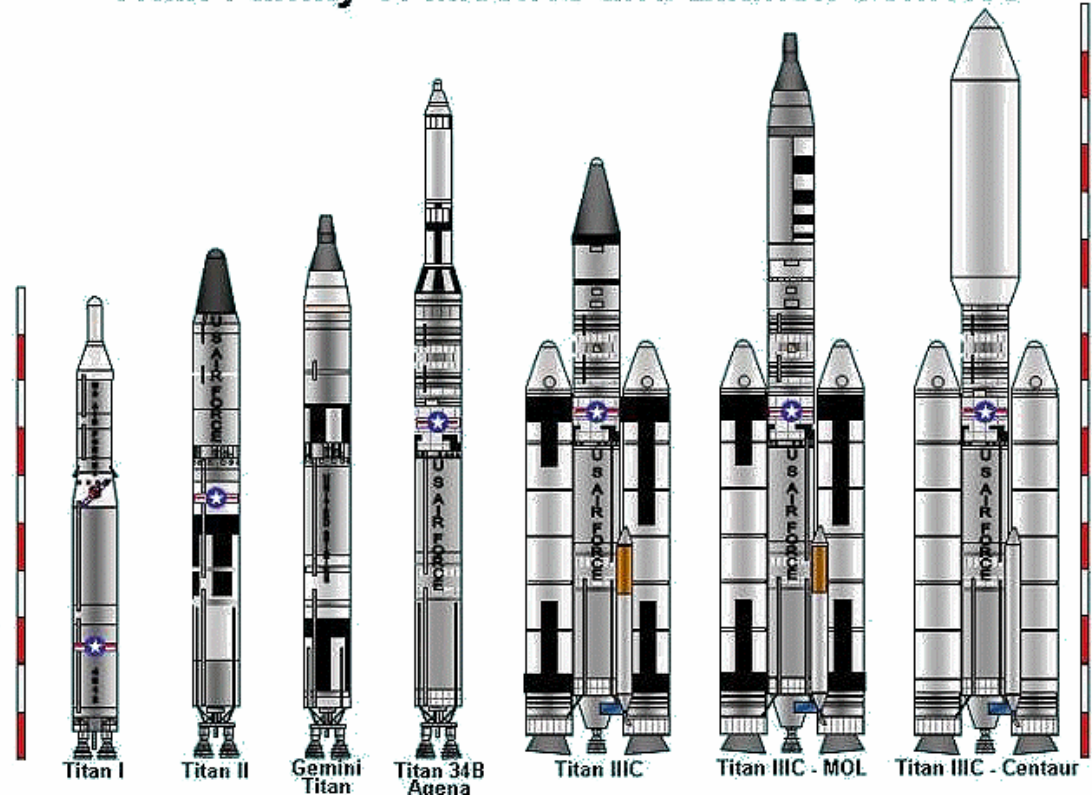




# Launch

- Oct. 15, 1997, 08:55 UTC: lift-off from Cape Canaveral (30-day launch window)
- T+2m11, 58.5 km: stage 1 ignition
- T+2m23, 68.3 km: solid rocket boosters separation
- T+3m27, 101.4 km: fairing jettisoning
- T+5m23, 167.3 km: stage 2 ignition & stage 1 separation
- T+9m13, 206.7 km: Centaur separation and first burn
- T+11m13, 170x445 km: end of first burn (parking orbit)
- T+28m13, 170x445 km: second burn
- T+36m13  $\Rightarrow$  VENUS: Cassini separation with C/CAM (hyperbolic trajectory,  $C_3=16.6\text{km}^2/\text{s}^2$ )

# Titan Family of Missiles and Launch Vehicles



# En Route for Venus



There is no launch vehicle powerful enough to send Cassini on a direct path to Saturn

# Mostly An Unpowered Flight But...

TCM/ OTM	Date	Event	Duration [s]	Delta v [m/s]		Propellant Remaining [kg]		
				Actual		Mono	Bi	Bi Used
(1)	(2)	(3)	(4)	Bi (5)	Mono (6)	Mono (11)	Bi (12)	Bi Used (13)
1	09.11.97	V1-Launch	34,13	2,70		131,86	3.000,00	5,05
2	25.02.98	V1			0,18		2.994,95	
3	Canceled	V1					2.994,95	
4	Canceled	V2-CA					2.994,95	
5	03.12.98	V2-DSM	5.275,23	450,00		129,61	2.994,95	780,08
6	04.02.99	V2	125,21	11,55		129,25	2.214,88	18,52
7	18.05.99	V2			0,23		2.196,36	
8	Canceled	V2					2.196,36	
9	06.07.99	Earth	466,91	43,49		128,37	2.196,36	69,04
10	19.07.99	Earth	54,63	5,13		128,30	2.127,32	8,08
11	02.08.99	Earth	383,78	36,29		128,21	2.119,24	56,75
12	11.08.99	Earth	128,46	12,25		128,16	2.062,49	19,00
13	31.08.99	Earth-CA	69,90	6,69		128,05	2.043,49	10,34
14	14.06.00	Flush	5,74	0,55		126,39	2.033,15	0,85
15	Canceled	Jupiter					2.032,30	
16	Canceled	Jupiter					2.032,30	
17	28.02.01	Flush	5,32	0,51		124,89	2.032,30	0,79
18	01.04.02	Flush	9,85	0,89		122,60	2.031,30	1,46
19	01.05.03	Flush	17,53	1,58		120,32	2.029,84	2,59
20	27.05.04	Phoebe	362,00	34,70		118,06	2.027,25	53,53
21	17.06.04	Phoebe-CA	38,38	3,68		117,94	1.973,72	5,68
22	Canceled	Pre SOI						
Cruise				609,99	0,40			1.031,74

# Two Venus Swingby

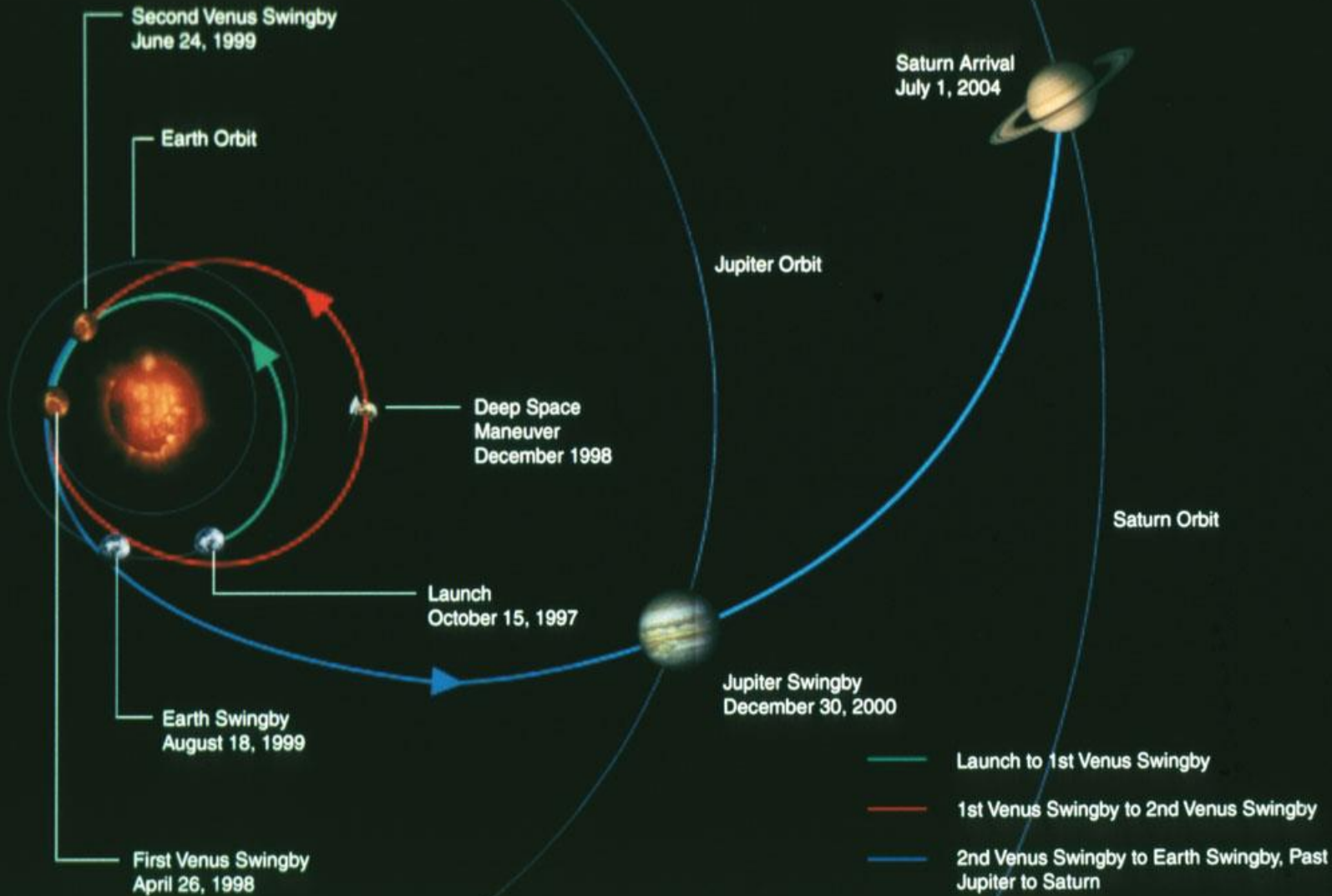
TCM-1 (*):	correct errors due to launch
TCM-2:	very small corrections before Venus encounter
TCM-3 and TCM-4:	cancelled (mission redesign !)
⇒ Venus swingby #1	minimum altitude of 284 km
TCM-5:	deep-space maneuver
TCM-6, TCM-7:	bias removal due to redesign
TCM-8:	cancelled
⇒ Venus swingby #2	

---

(\*) HGA pointed toward the sun (thermal shield)  
and use of the LGA for communications

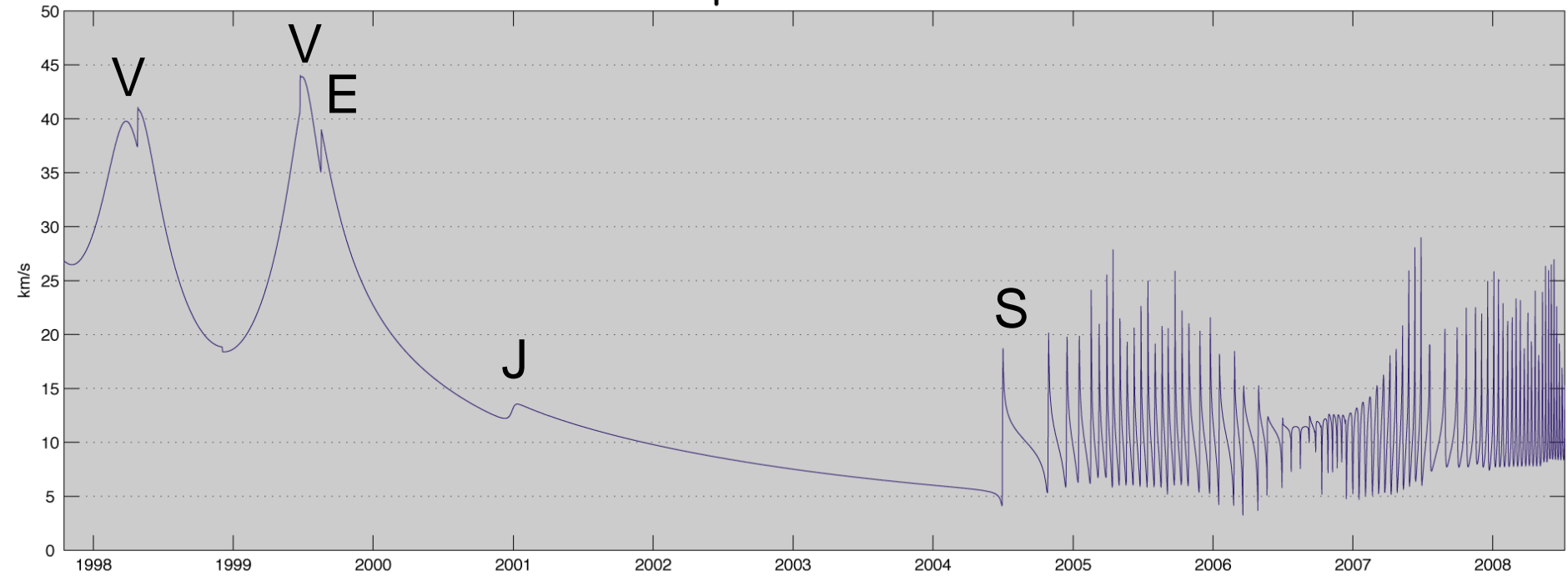
# Cassini Interplanetary Trajectory

V  
V  
E  
J  
G  
A

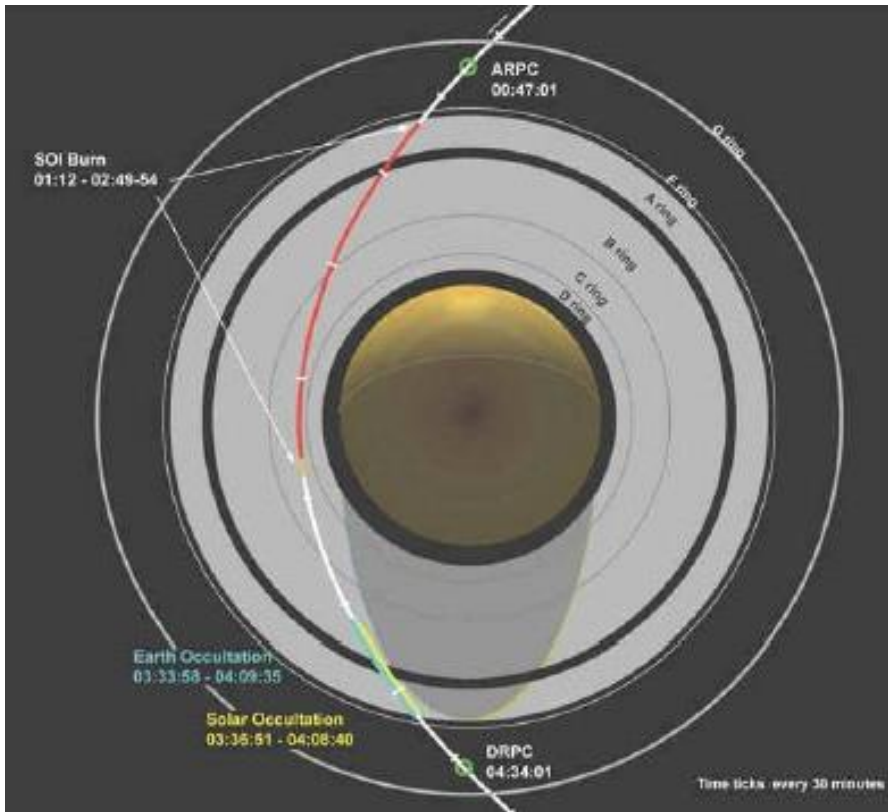


# Swingby Effects

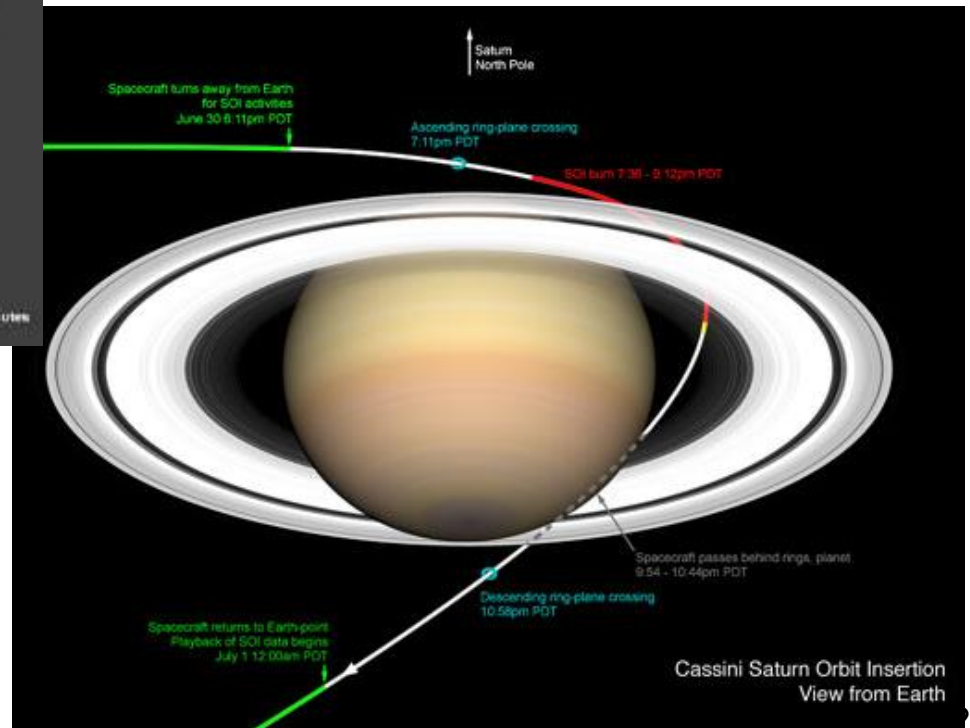
Cassini's speed related to the Sun



# Saturn Orbit Insertion (SOI)



$\Delta V=633 \text{ m/s} \Rightarrow$   
periapsis=1.3  $R_s$ ,  $i=16.8^\circ$ ,  $T=148\text{d}$   
(initial orbit)

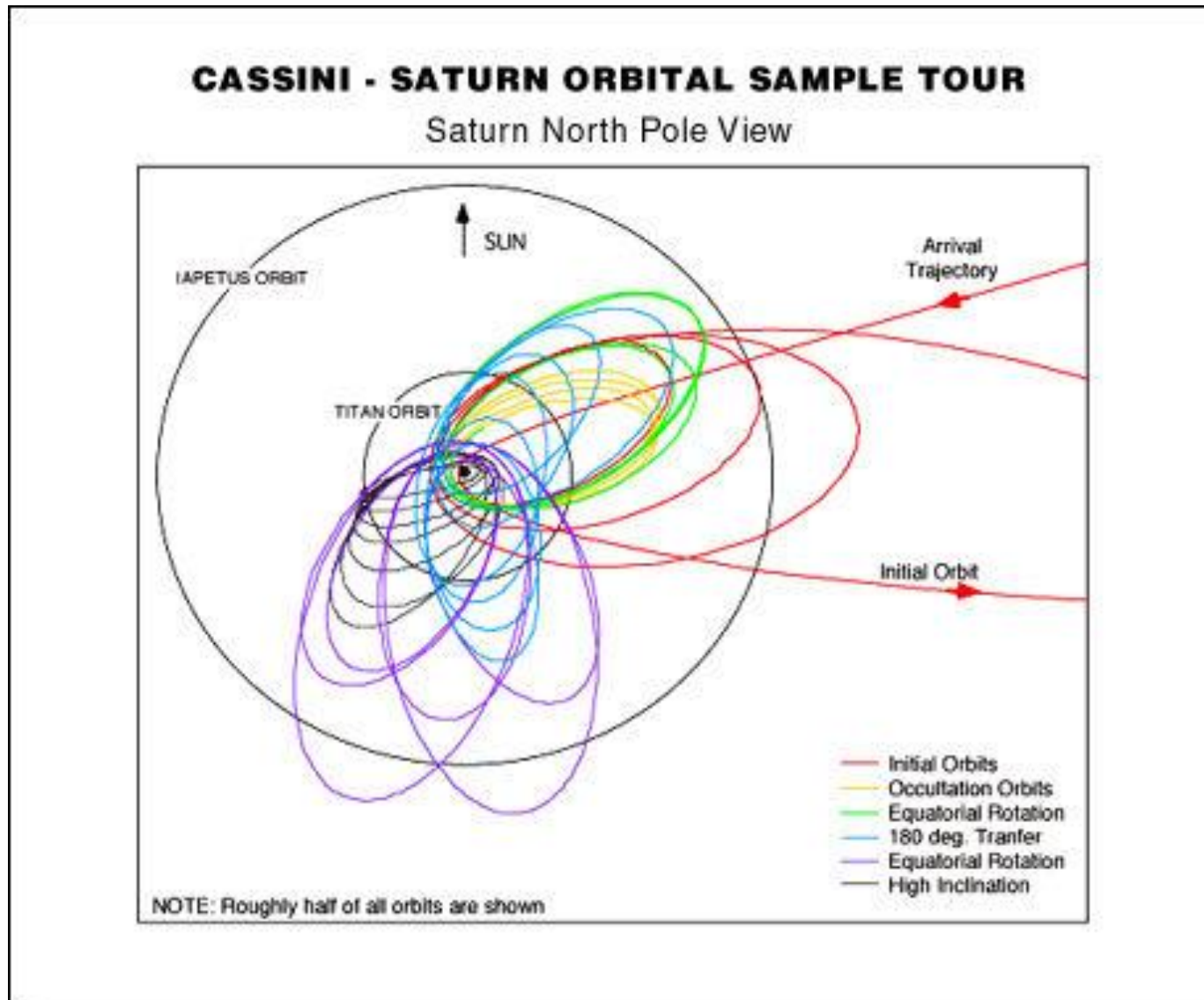




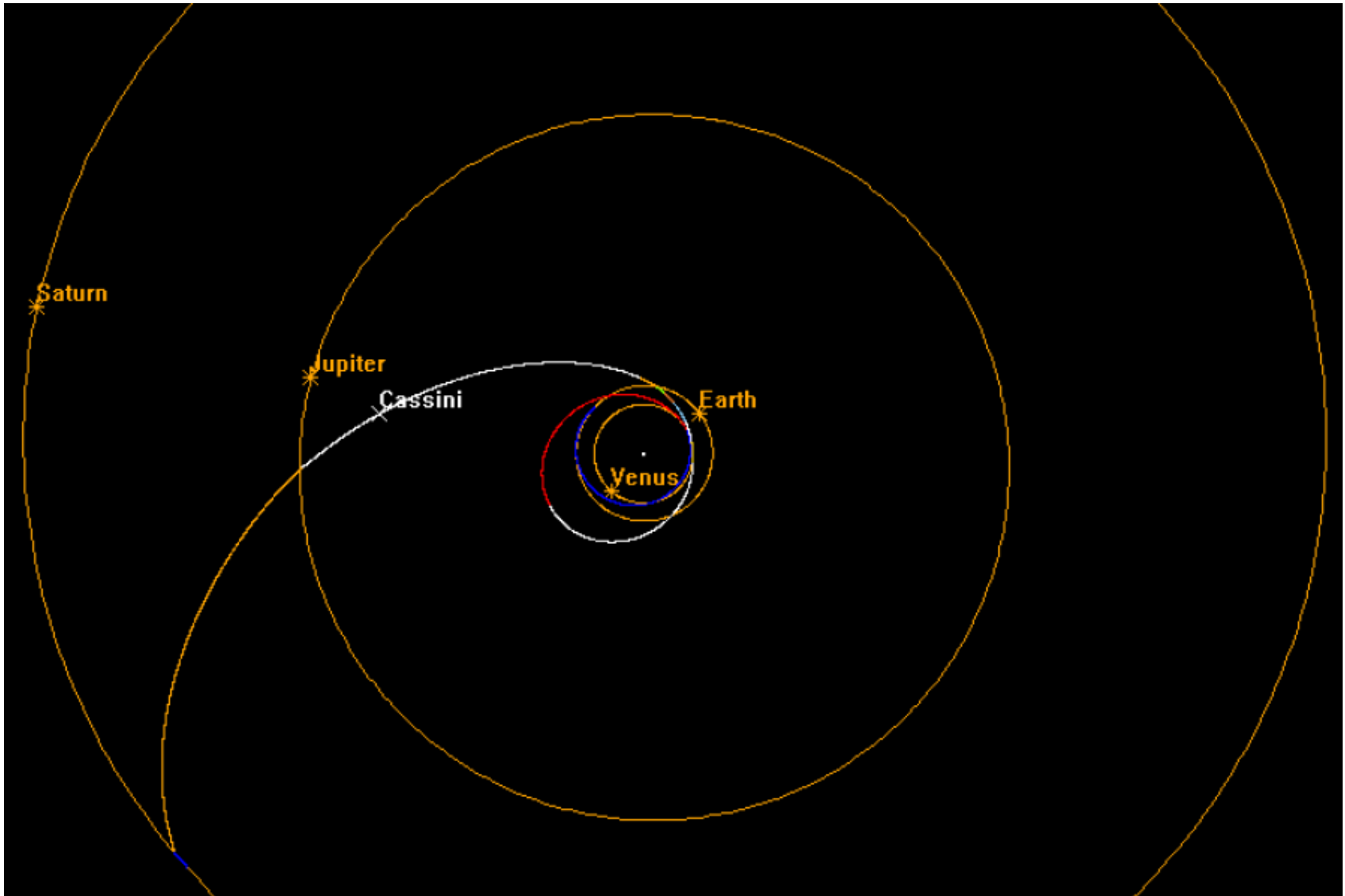
# Saturn Orbit Insertion

EDT	Cassini Saturn Orbit Insertion Timeline
08:51 PM	Switch to LGA antenna 1; telemetry off; carrier only
09:11 PM	Turn to protective attitude
10:11 PM	<b>Ascending ring plane crossing (D=98,500 miles)</b>
10:21 PM	Turn to burn attitude (10-minute turn; 6 spare minutes)
10:35 PM	Open latch valves for helium pressurization
10:36 PM	<b>SOI burn begins; dV=1,400 mph; dT=96.4 minutes</b>
10:59 PM	Cassini moves behind F ring as seen from Earth
11:06 PM	Cassini moves behind A ring; begin 25-minute comm loss
11:31 PM	6 minutes of comm through Cassini division
11:37 PM	Cassini moves behind B ring; possible 28-minute comm loss
11:54 PM	Minimal orbit achieved; not useable
12:03 AM	Saturn closest approach. D=12,400 miles from cloudtops
12:05 AM	Spacecraft moves behind C ring; comm resumes
12:12 AM	<b>Saturn orbit Insertion burn ends</b>
12:15 AM	Begin turn to Earth pointing; comm reconfig
12:18 AM	Spacecraft HGA pointed toward Earth
12:24 AM	Spacecraft moves behind D ring; communications still likely
12:30 AM	Switch to HGA comm
12:31 AM	Spacecraft turns off Earth point for science observations
12:39 AM	Jettison Ion and Neutral Mass Spectrometer cover
12:54 AM	Cassini moves behind C ring; no comm possible
12:57 AM	Spacecraft passes behind Saturn; remains in science attitude
01:32 AM	Turn to protective attitude for descending ring plane crossing
01:33 AM	Spacecraft emerges from behind Saturn; no comm
01:44 AM	Spacecraft emerges from behind A ring; no comm
01:58 AM	<b>Descending ring plane crossing (D=98,500)</b>
03:00 AM	Spacecraft turns to Earth; SOI data playback
03:12 AM	Main engine cover opened for post SOI maneuver
06:49 AM	Switch to reaction wheel attitude control
08:39 AM	First SOI images downlinked

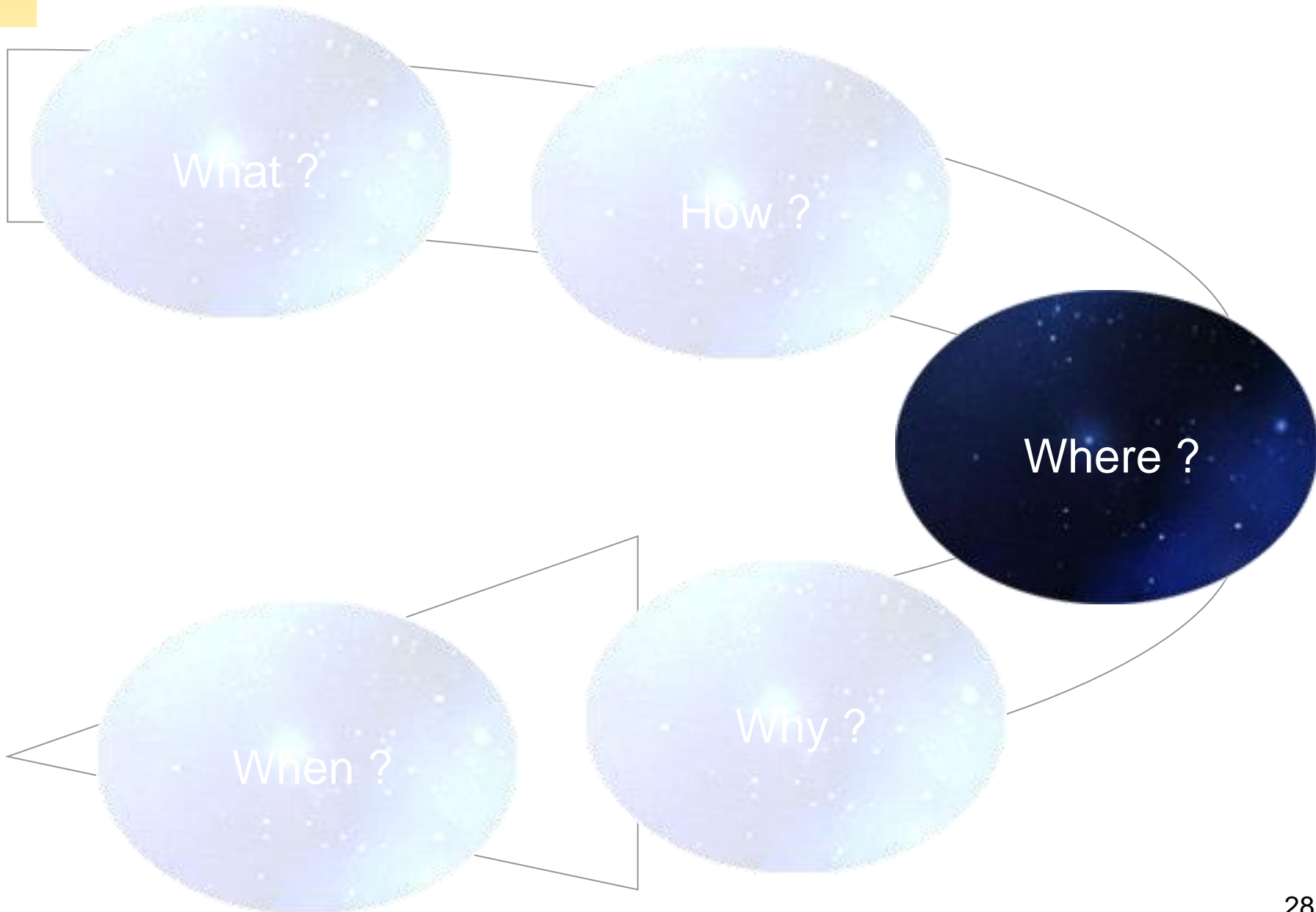
# Orbits Around Saturn: The “Petal Tour”



# Cassini-Huygens using STK



# Introductory Lecture



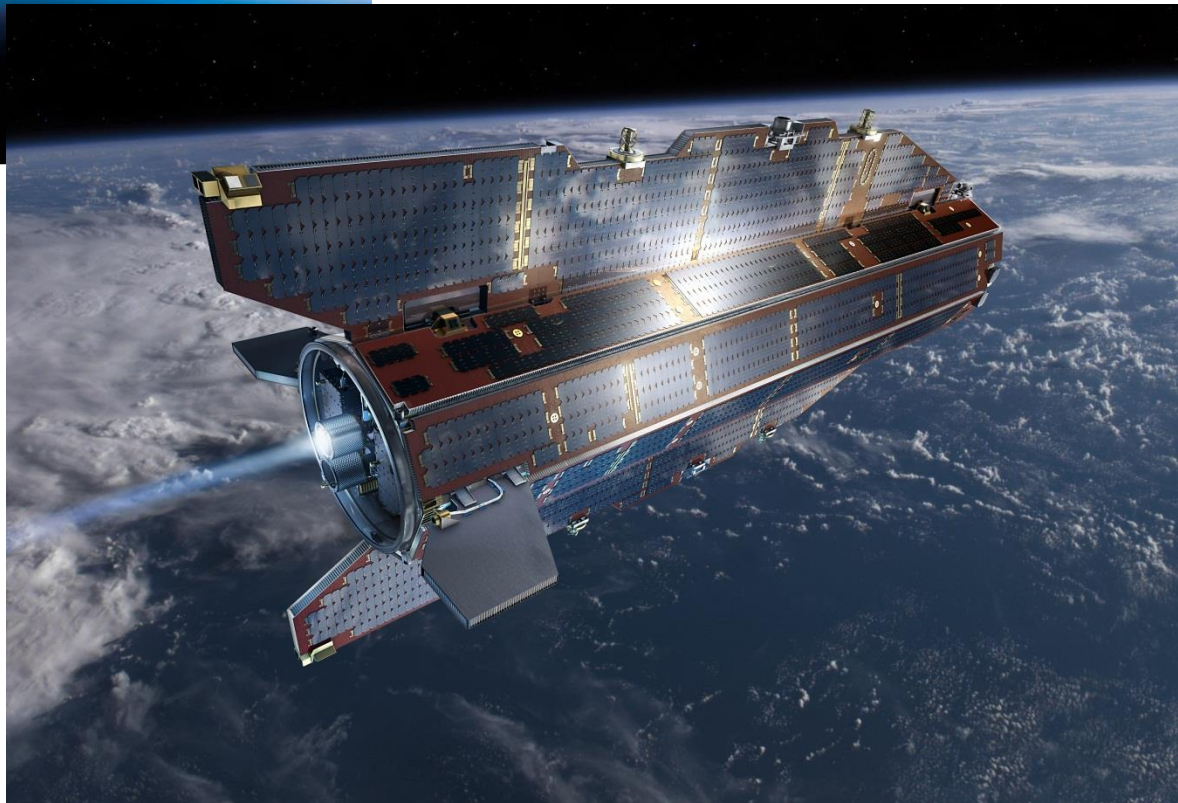
# GOCE (ESA)

*Payload:* gravity mission (gravity field and geoid). The gravitational signal is stronger closer to the earth. Orbit as low as possible, but keep non-gravitational accelerations to a minimum:

**250 kms, SSO ( $i=96.5^\circ$ )**

Very demanding *environment*: atmosphere

*Satellite:* propulsion system, 20 months mission



# GOES (NOAA)

*Payload:* earth monitoring with a continuous coverage

**35800 kms, GEO (60°W, 75°W, 105°W, 135°W,  $i=0^\circ$ )**

Demanding *orbit*: GTO, station-keeping and link budget

*Satellite:* propellant, apogee motor



Movie



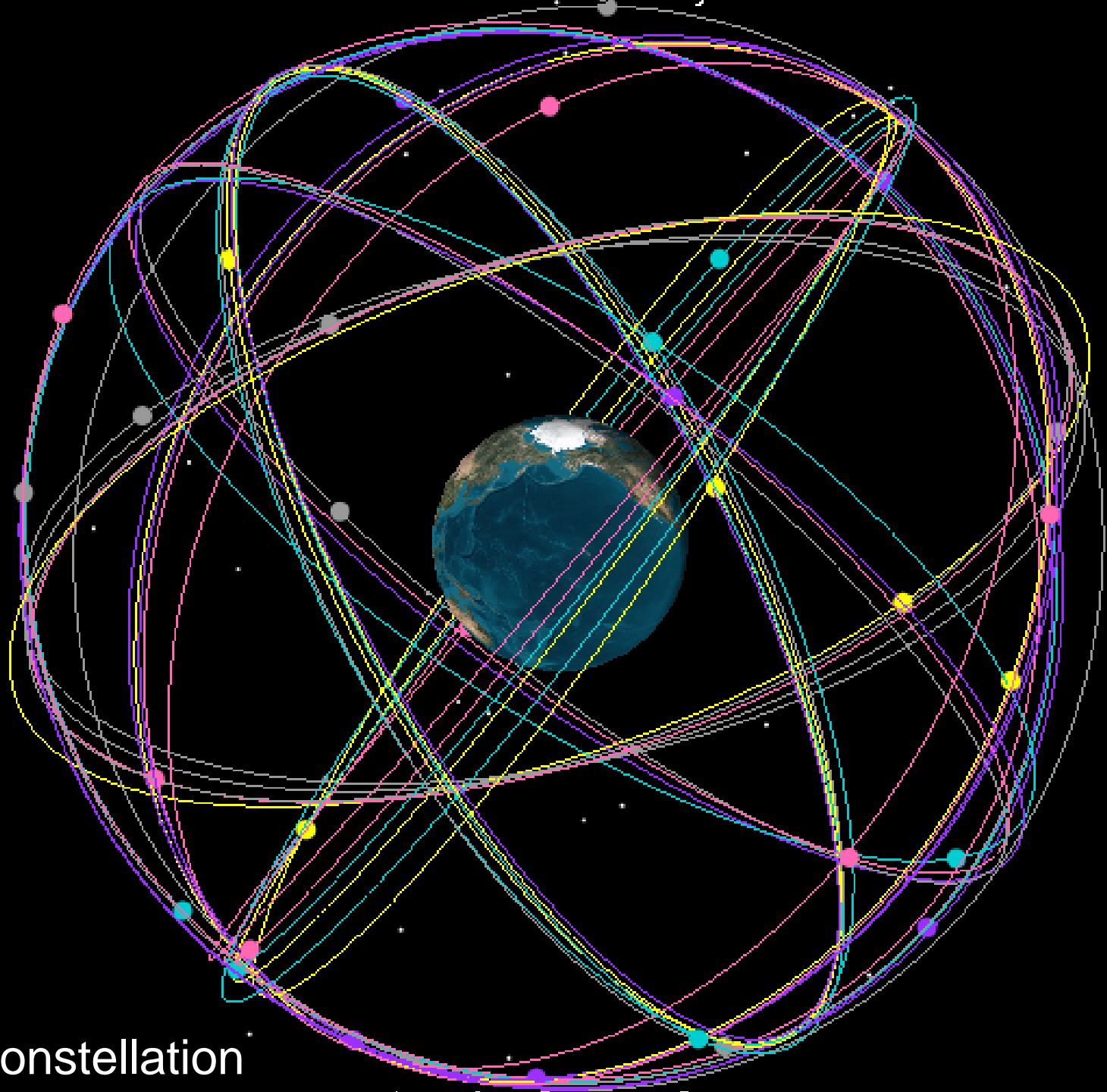
# GPS (USA)

*Payload:* navigation. At least 4 satellites visible, at all sites on the globe, and at all times:

**Constellation (24), 20200 kms, MEO ( $i=55^\circ$ )**

Demanding *environment*: radiation (outer belt)

*Satellite*: shielding



GPS constellation

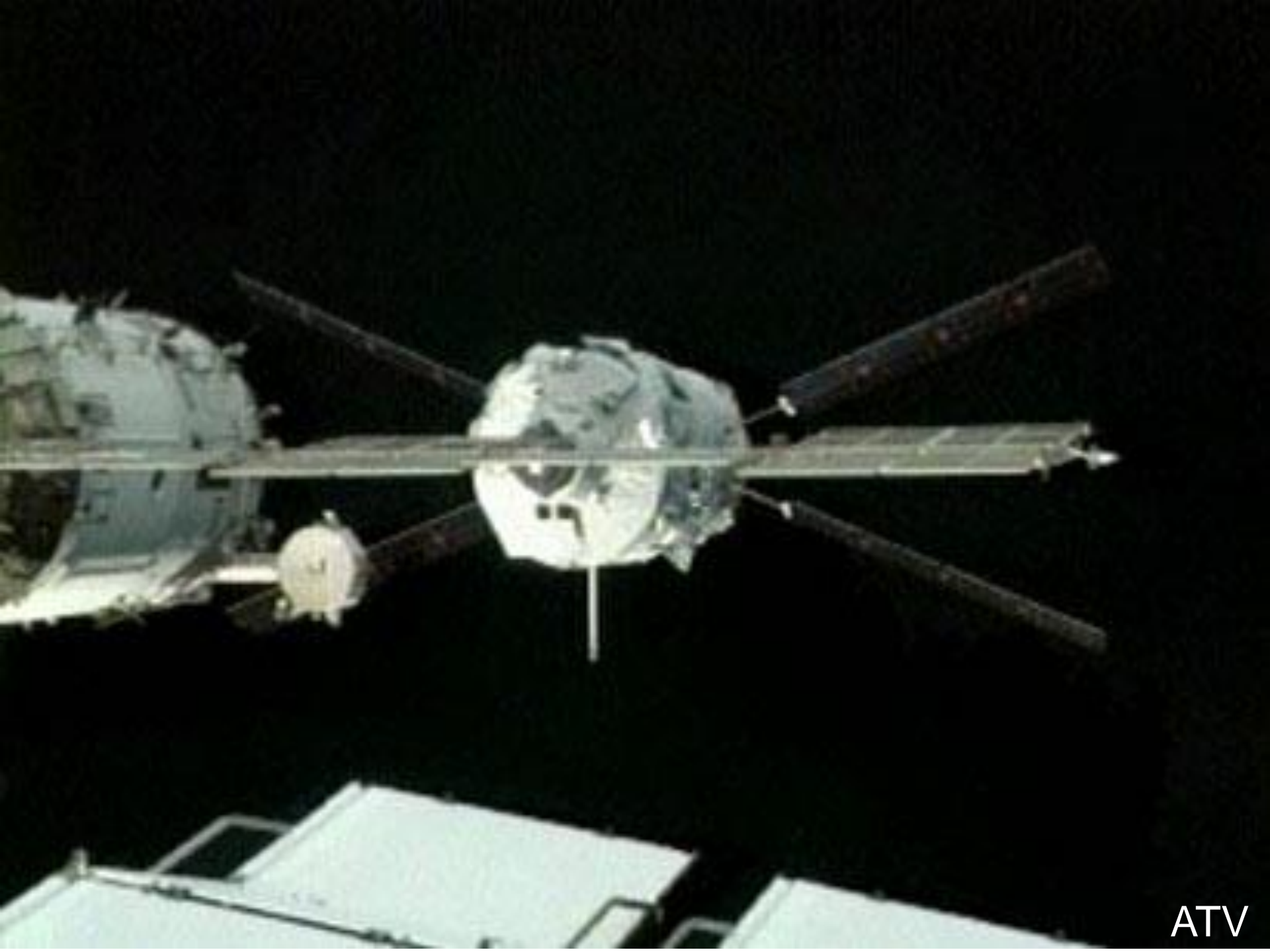
# International Space Station (International)

*Payload*: scientific experiments. Lifetime and access are key issues:

**350 kms, LEO ( $i=51^\circ$ )**

Demanding *environment*: atmosphere

*Satellite*: reboost necessary



ATV

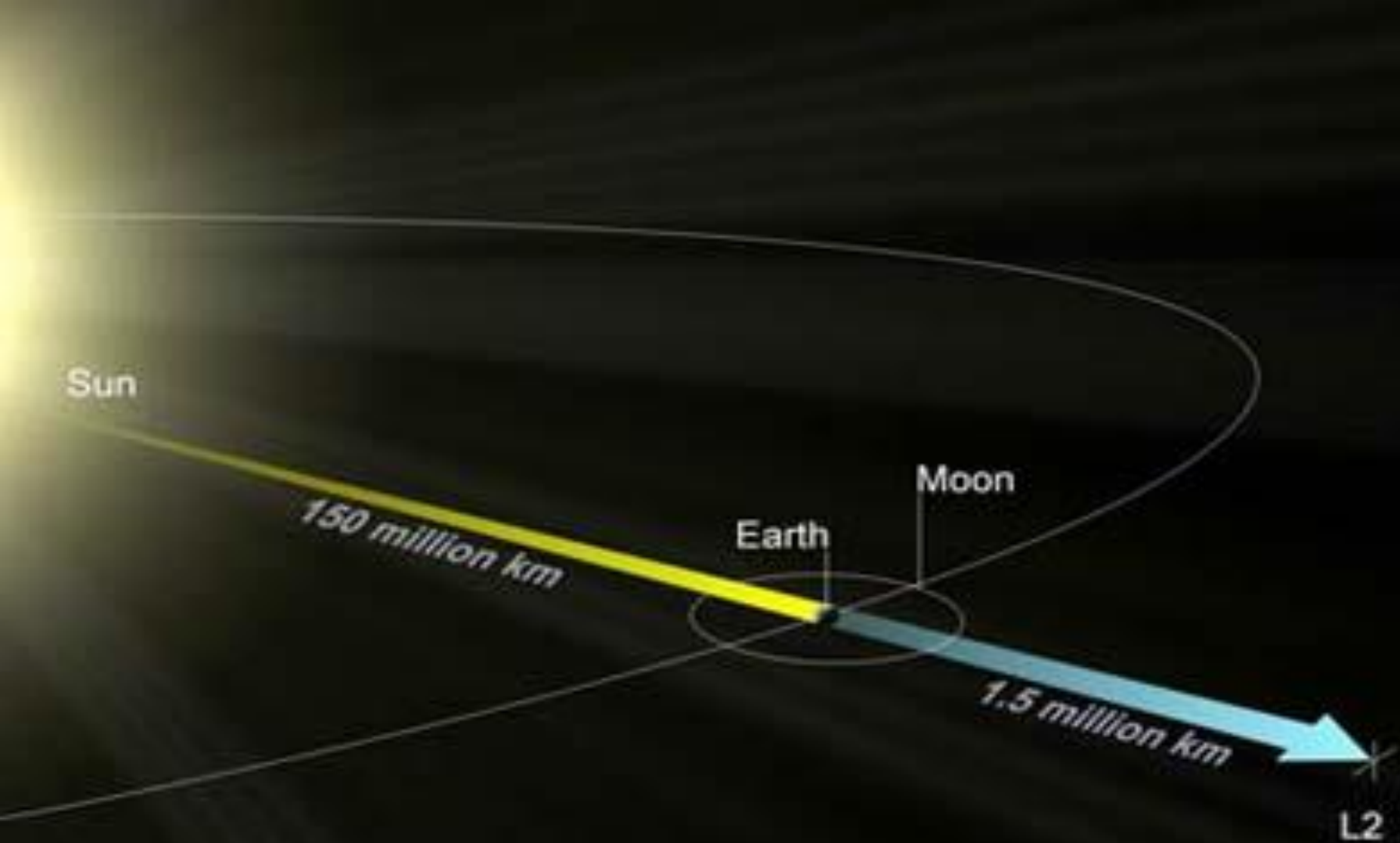
# J. Webb Space Telescope (ESA-NASA)

*Payload:* infrared telescope. Thermal stability is an issue:

**Sun-Earth  $L_2$  halo orbit (1.5 millions km)**

Benign and unchanging *environment* (small station-keeping maneuvers)

*Satellite:* propellant

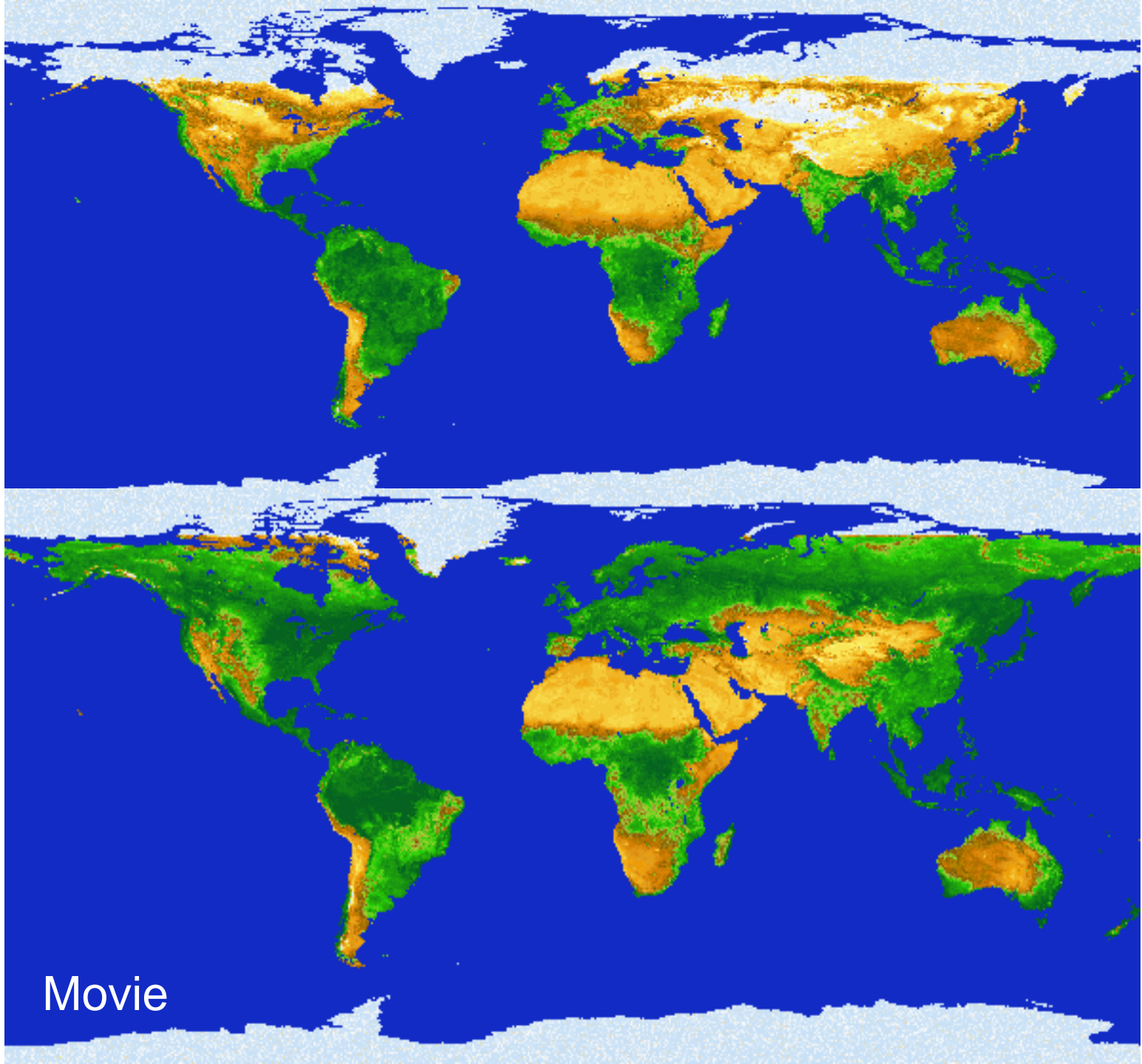


# SPOT-5 (CNES)

*Payload:* daily monitoring of terrestrial vegetation cover.  
Constant ground illumination and passes above the same points on the ground at regular intervals

**820 kms, phased-SSO ( $i=98.7^\circ$ )**

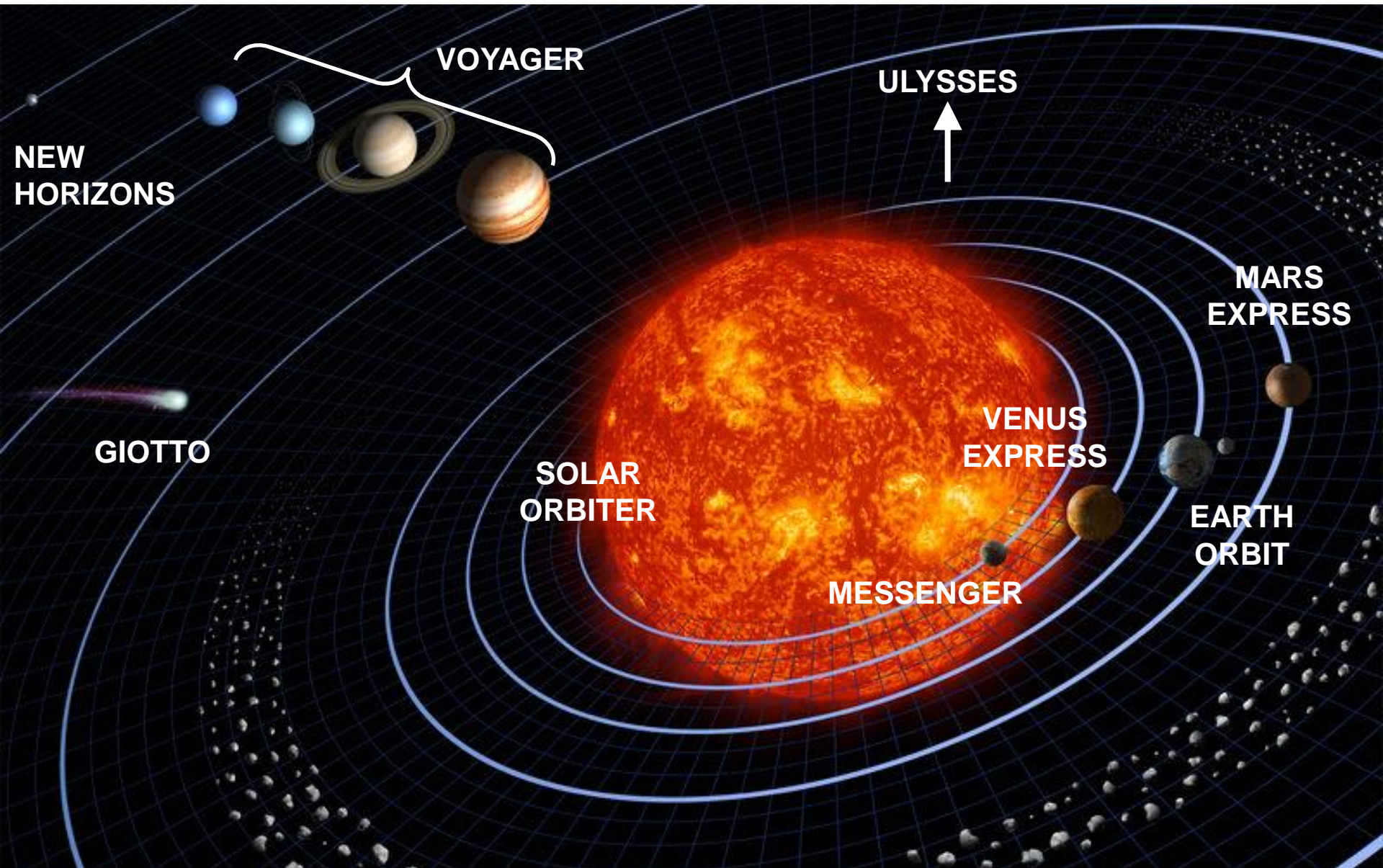
*Satellite:* nothing particular



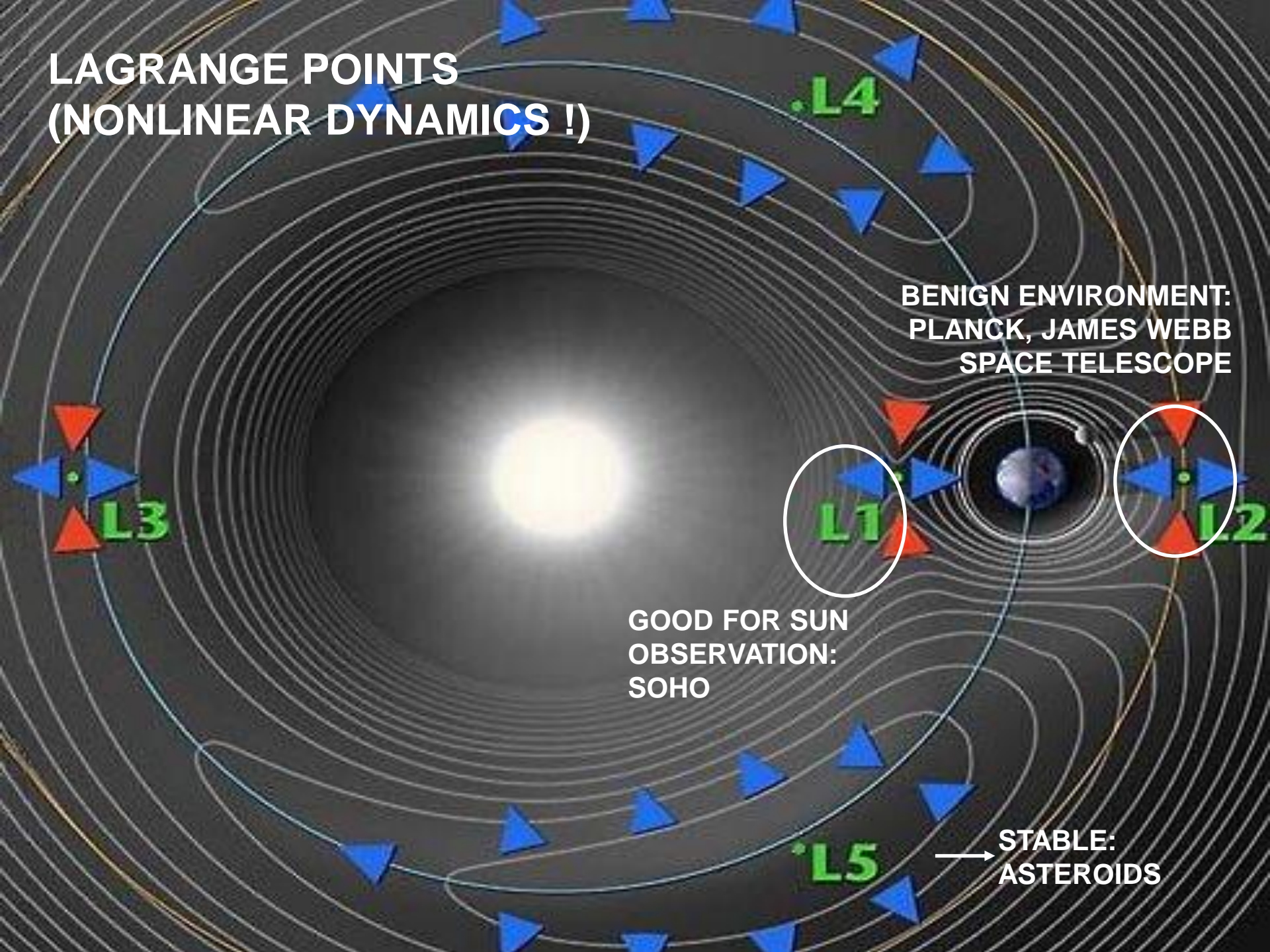
Movie



# Conclusion 1: Satellites Are Everywhere



# LAGRANGE POINTS (NONLINEAR DYNAMICS !)



**BENIGN ENVIRONMENT:  
PLANCK, JAMES WEBB  
SPACE TELESCOPE**

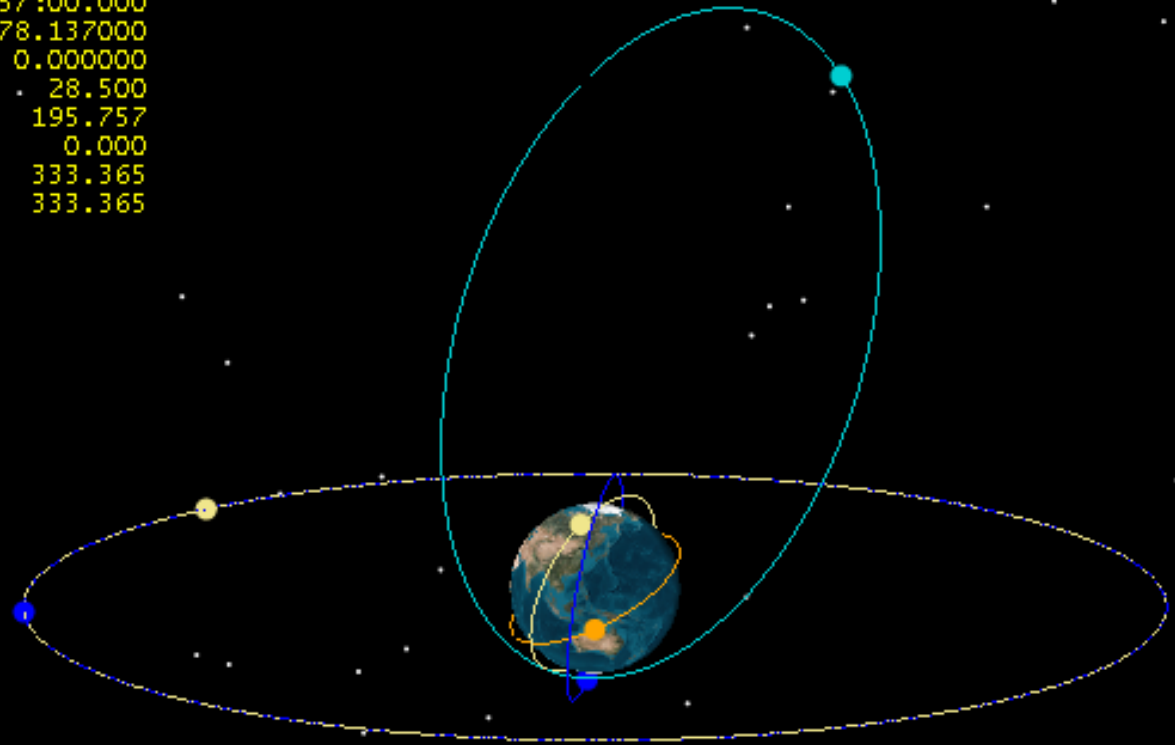
**GOOD FOR SUN  
OBSERVATION:  
SOHO**

**STABLE:  
ASTEROIDS**

# Conclusion 2: Orbits Are Varied

```
HST Classical Orbit Elements
Time (UTCG):      2 Sep 2008 03:57:00.000
Semi-major Axis (km): 6978.137000
Eccentricity:     0.000000
Inclination (deg): 28.500
RAAN (deg):       195.757
Arg of Perigee (deg): 0.000
True Anomaly (deg): 333.365
Mean Anomaly (deg): 333.365
```

Educational Use Only



METEOSAT 6-7, HST,



GEO

$i=0$



LEO

$i=28.5$

SPOT-5, MOLNIYA



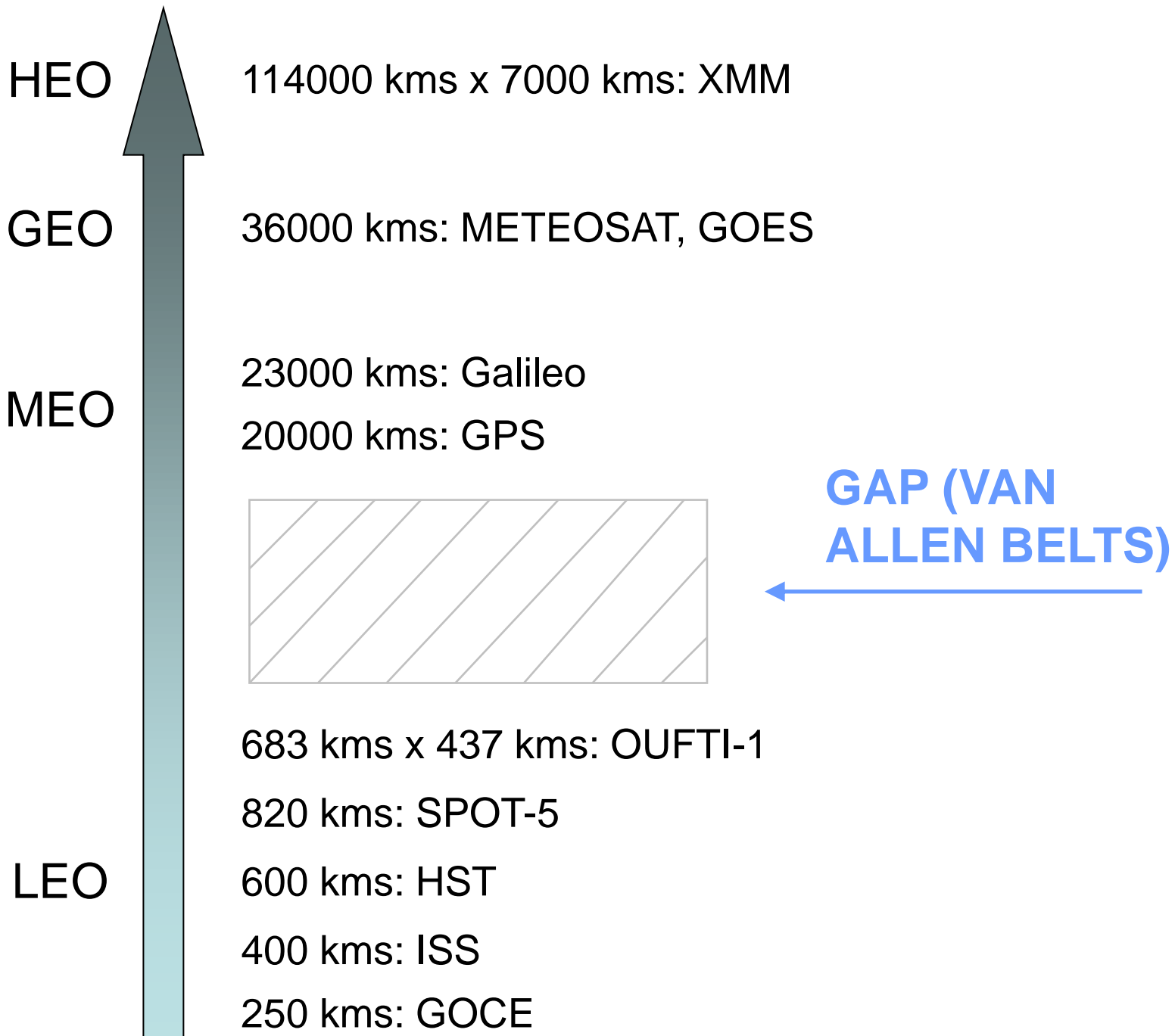
(LEO) SSO

$i=98.7$



Molniya

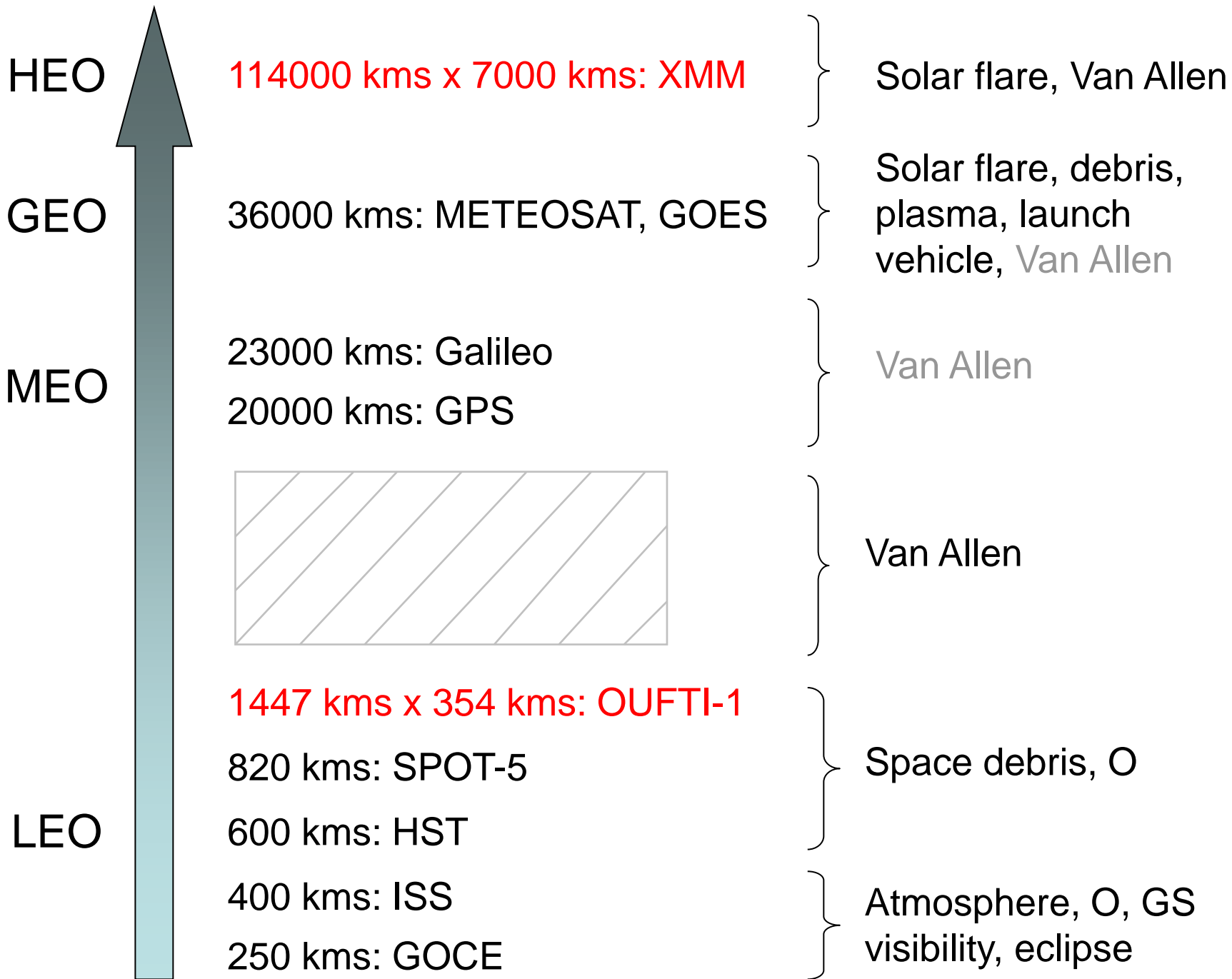
$i=63.4$



## Conclusion 3: Orbit Constraints

---

Magnetic field, temperatures, atmosphere, launch vehicle, ground station visibility, eclipse duration, ...



# Conclusion 4: Why ? $\Leftrightarrow$ Where ?

LEO (<2000kms)

High spatial resolution

Direct launch

Transmission time

SSO

Low temporal resolution

Limited duration of visibility

Atmospheric drag (<500km)

Satellite tracking

GEO (35800 kms)

High temporal resolution

Continuous, large coverage

Fixed ground antennas

Low spatial resolution

GTO

Signal round-trip  
transmission



+

-

# Conclusion 4: Why ? $\Leftrightarrow$ Where ?

Communications

GEO (low latitudes)  
Molniya (high latitudes)  
Polar LEO (constellation  
for global coverage)

Weather

GEO (METEOSAT) or  
polar LEO (METOP)

Earth resources

Polar LEO for global coverage

Navigation

Inclined MEO for global coverage

Astronomy

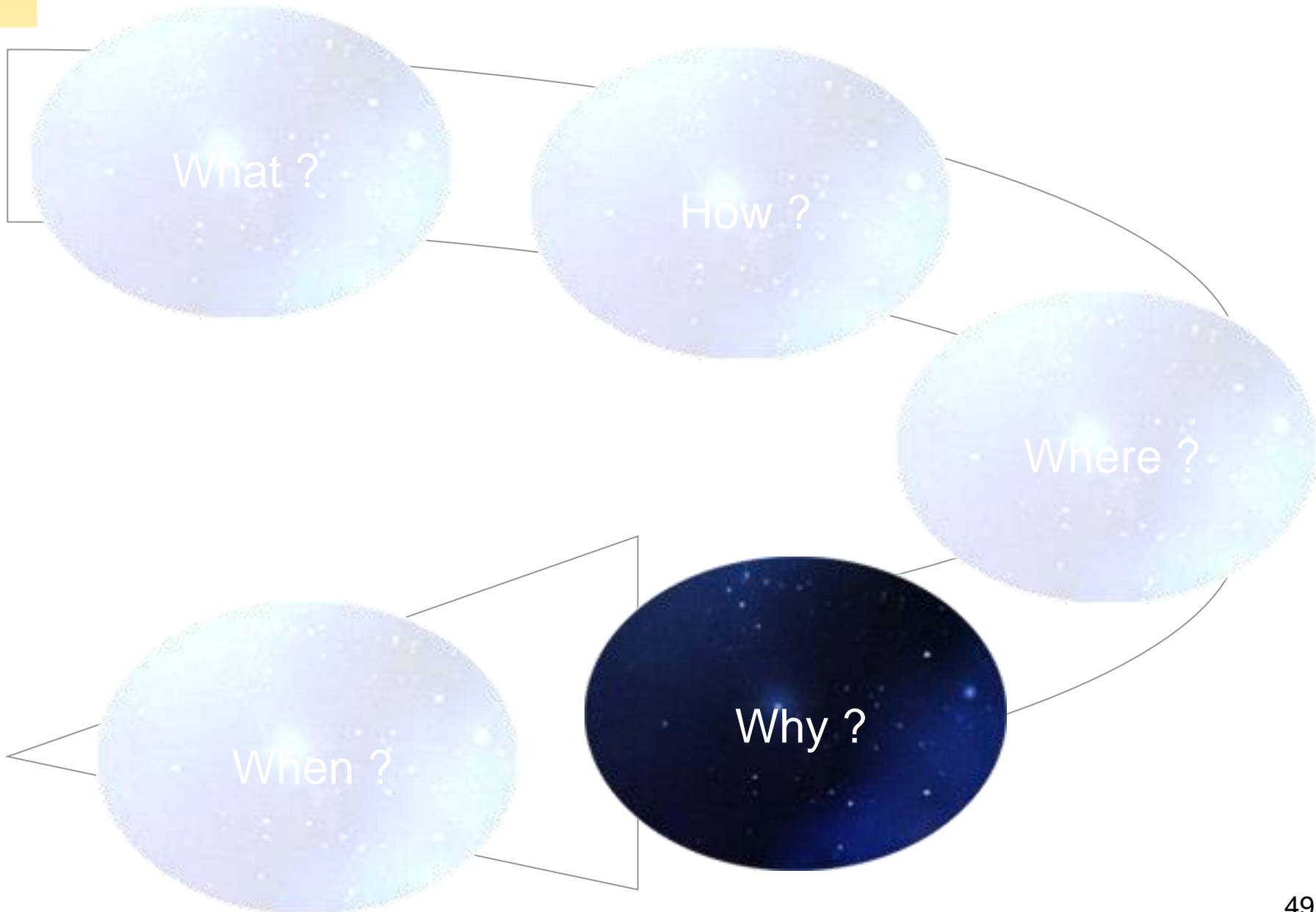
LEO, HEO, GEO, Lagrange points

Space station

LEO for easy access



# Introductory Lecture

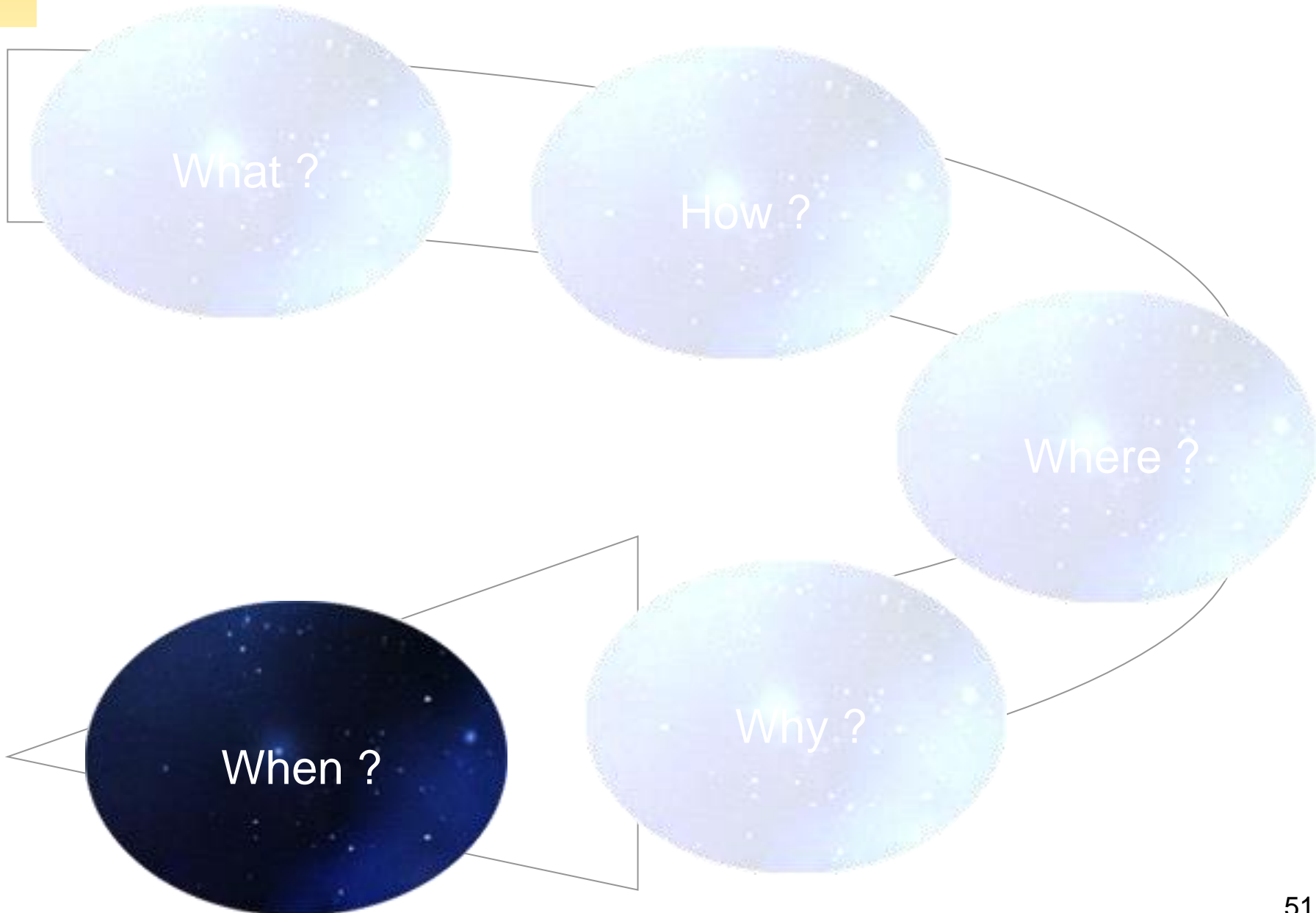




# Why ?

Already covered !

# Introductory Lecture



# The Company We Keep

Aristotle, Ptolemaeus

*Geocentric theory*

Copernicus, Brahe, Galileo, Kepler,  
Newton, Halley, Euler, Lambert, Gauss,  
Lagrange.

*The golden age*

Poincaré, Tsiolkovski, Goddard, Von  
Braun, Korolev and ... Coquilhat

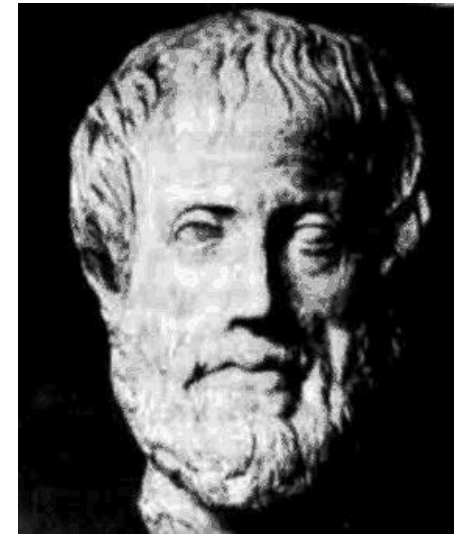
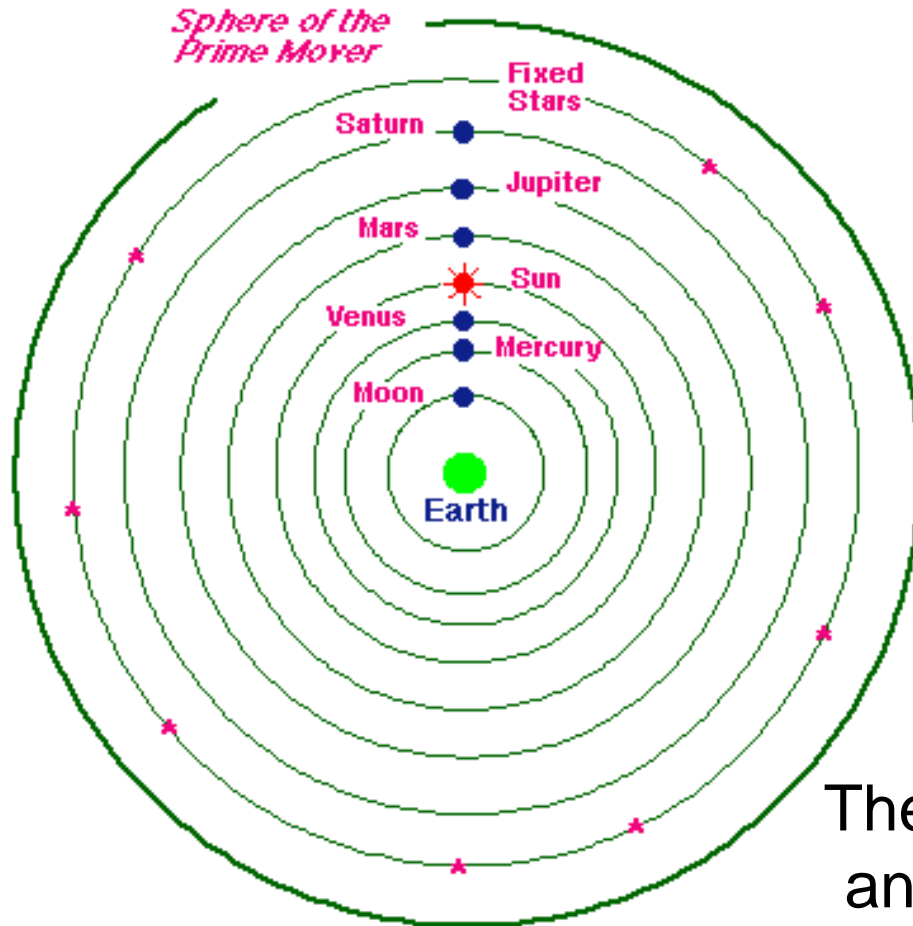
*The modern age*

Sputnik & co...

*The satellite era*

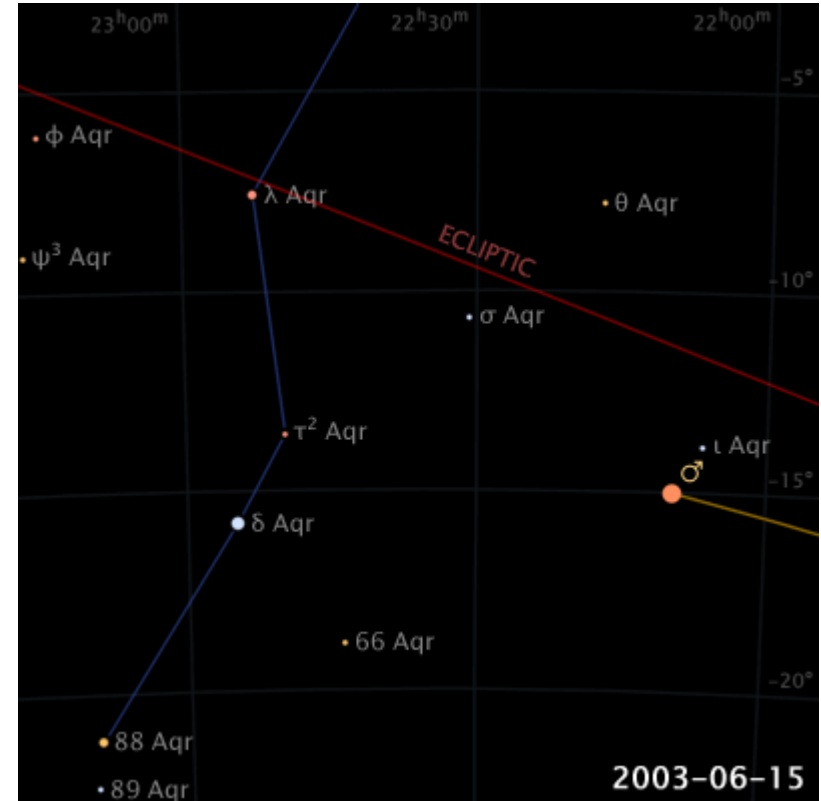
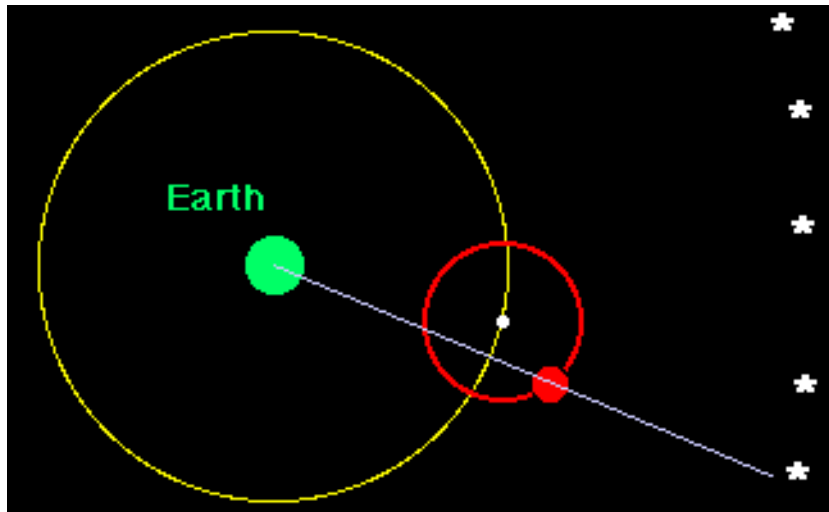
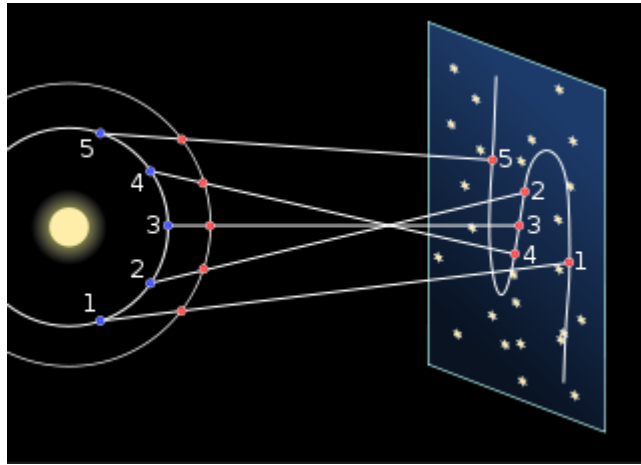
# Aristotle (300 BC)

Earth at the center of the universe & uniform circular motion.



The varying planetary brightness and retrograde motion could not be accommodated !

# Retrograde Motion



Apparent retrograde motion of Mars in 2003

# Ptolemaeus (100 AD)

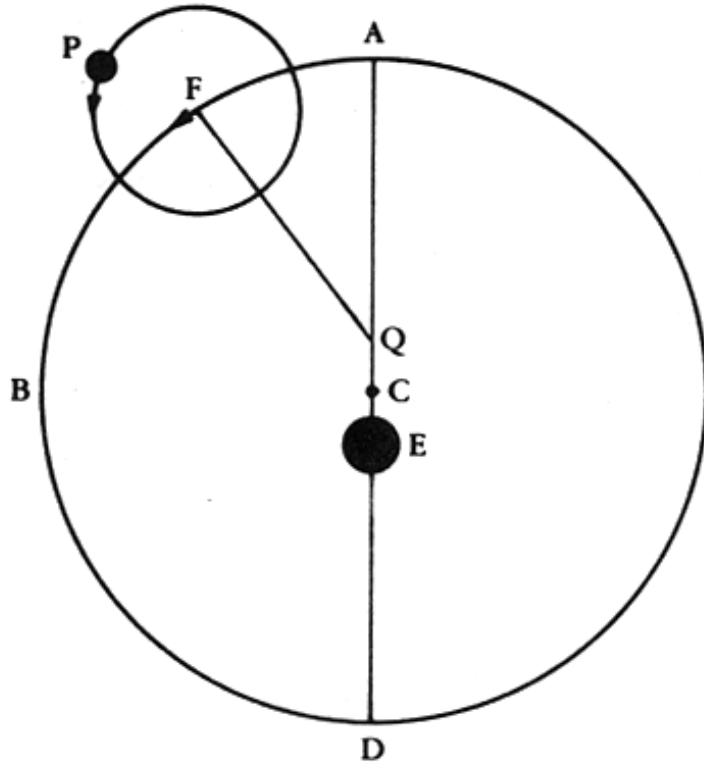
Mathematical constructions that accounted successfully for the motions of heavenly bodies within the standards of observational accuracy of his day.

Varying brightness and retrograde motion explained.

Accepted for over a millennium as the correct model.



# Ptolemaic System



E: Earth, P: Planet.

C: Geometric center of the eccentric circle (the Earth is not the center of the cosmos !)

Q: Equant point (imaginary point that "sees" the planet move at a uniform angular speed)

F: Center of the epicycle (to account for the observed retrograde motion of the planets)

Idea: break down the complex observed planetary motion into components with perfect circular motions. **The uniform circular motion is saved !**

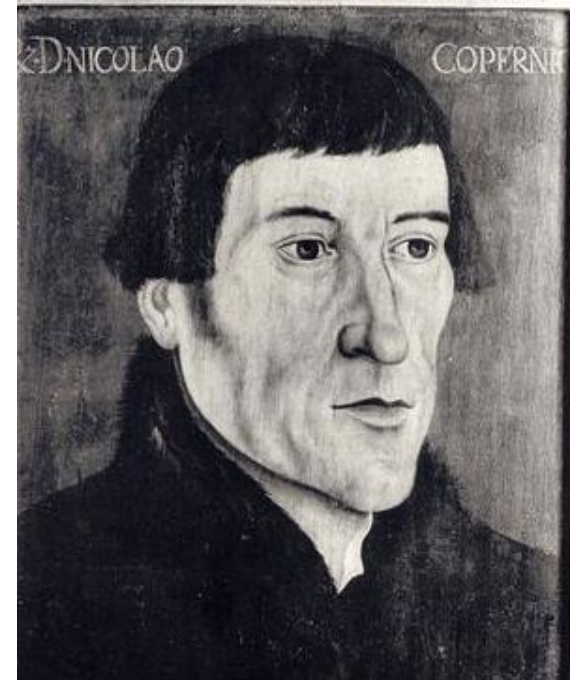


# Copernicus (1473-1543, Polish)

First astronomer to formulate a scientifically-based heliocentric cosmology (but other published heliocentric hypotheses centuries before him).

*Revolutionibus orbium coelestium*  
(*On the revolutions of the celestial spheres*) is regarded as the starting point of modern astronomy.

All planets on circular orbits around the Sun.



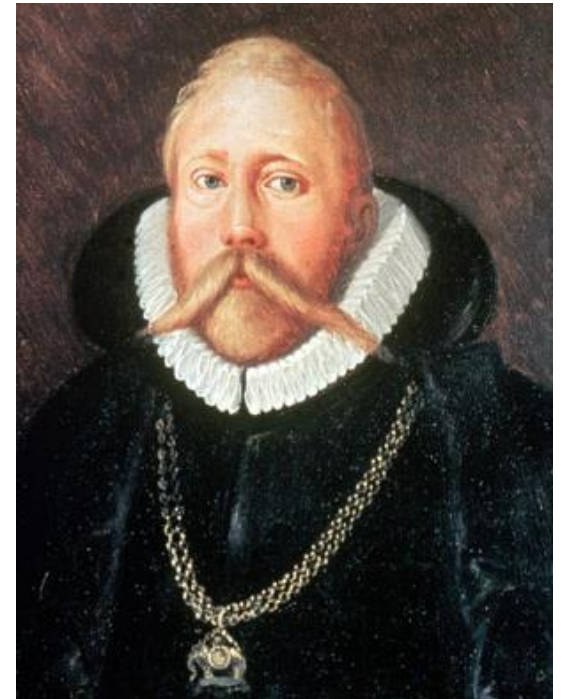
# Tycho Brahe (1546-1601, Danish)

Accurate and numerous observations of planetary and star positions in the pretelescope era.

No adequate mathematical tools to exploit these observations.

Earth's axial tilt:  $23^{\circ} 31.5'$   
(currently  $23^{\circ} 26'$ ).

He believed in geocentrism (the sun orbited the Earth while the other planets orbited the sun).



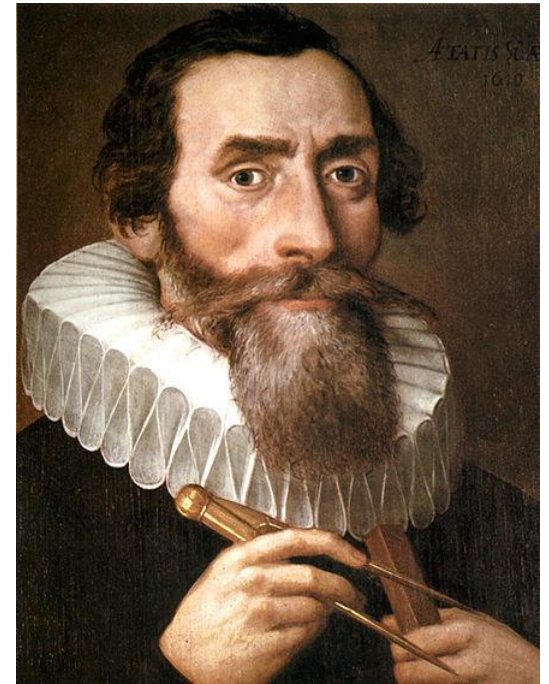
*An experimentalist*

# Johannes Kepler (1571-1630, German)

Met Tycho Brahe in 1600 and found a mathematical description for his observations. He realized that Brahe's data did not fit a Copernician view of the solar system.

Introduced the idea of elliptic orbits of the planet.

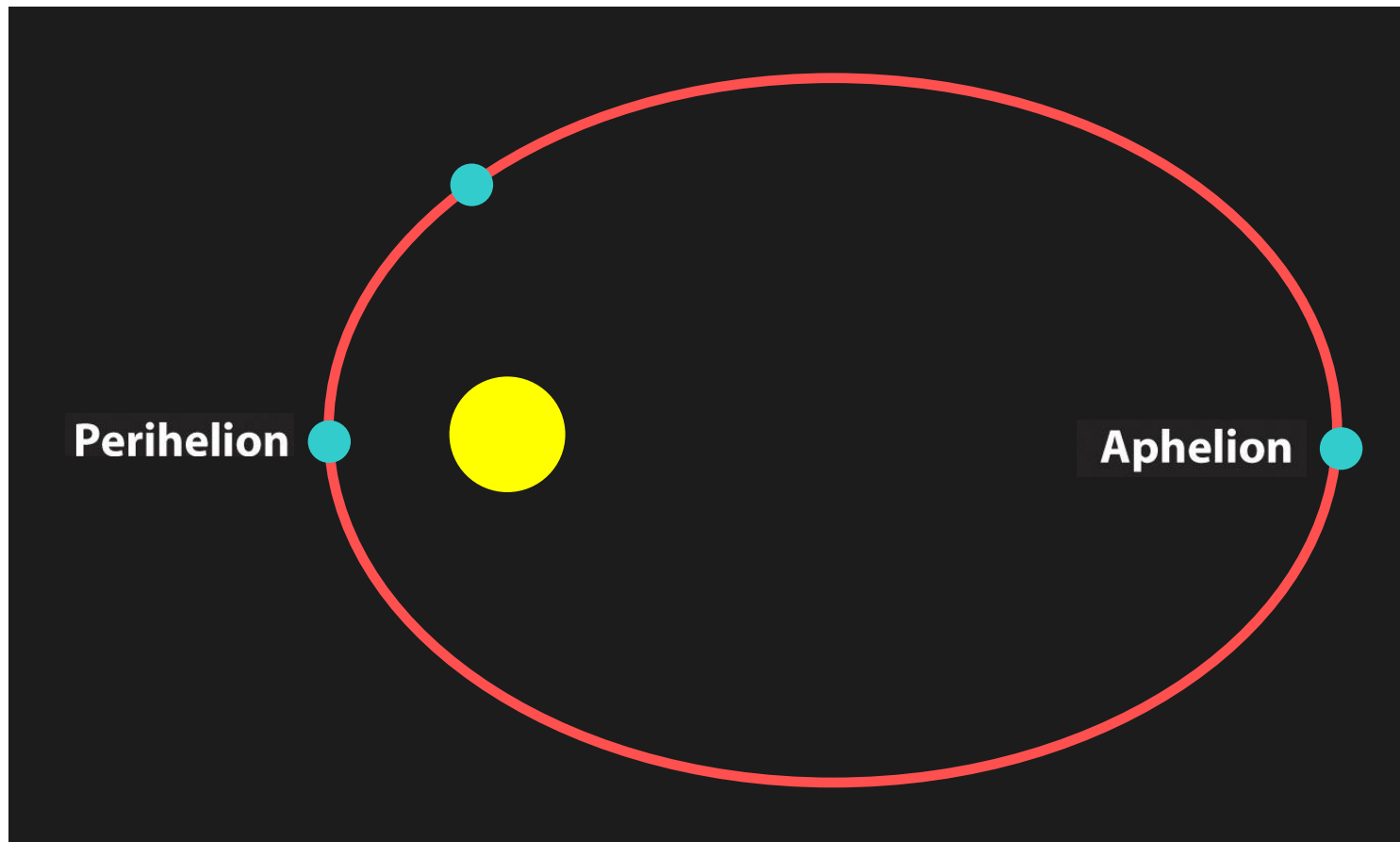
Kepler's primary obligation was to produce horoscopes for the emperor Rudolf II. He considered astrology as a source of income rather than science...



*A mathematician*

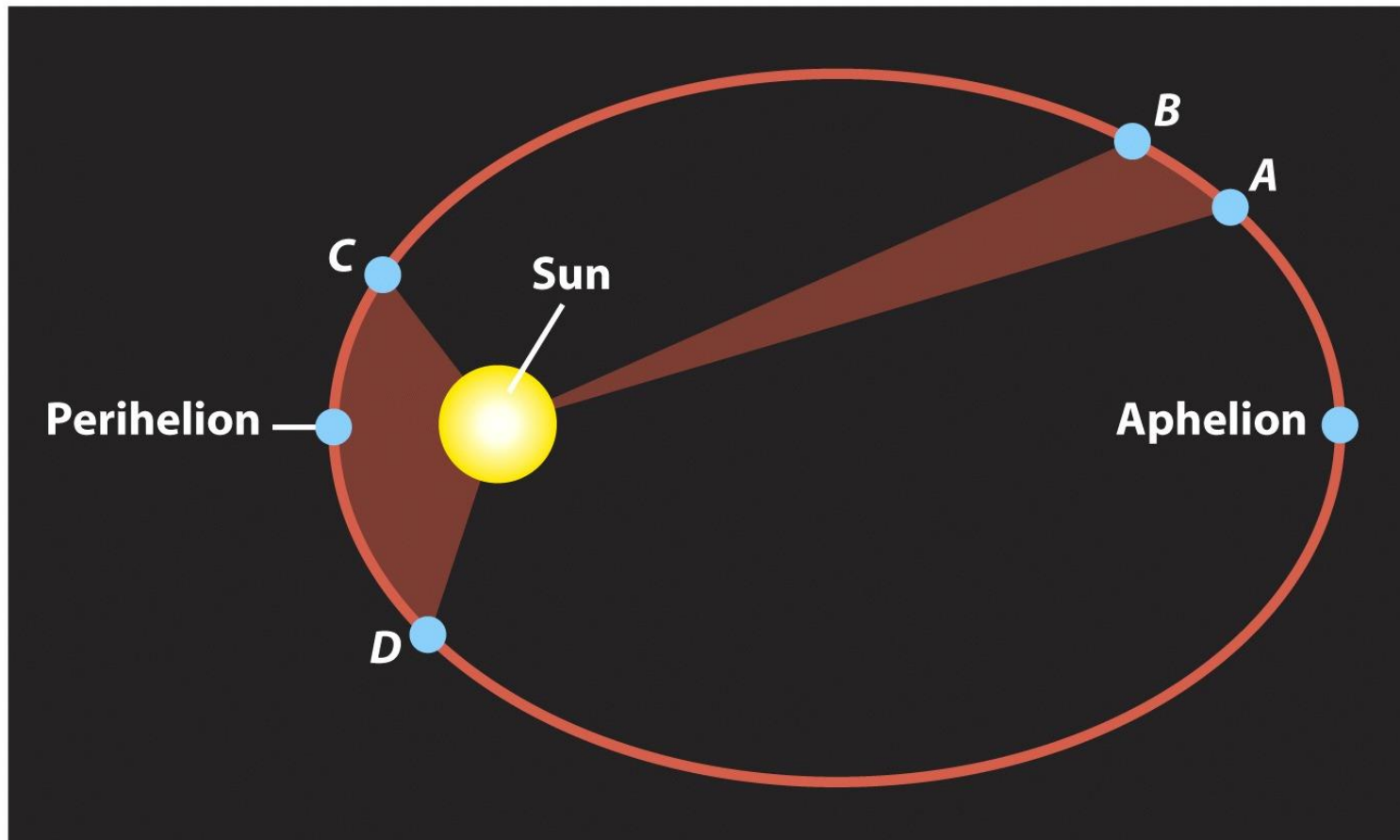
# First Kepler's Law (1609)

*The orbit of each planet is an ellipse with the sun at one focus.*



# Second Kepler's Law (1609)

*The line from the sun to a planet sweeps out equal areas inside the ellipse in equal lengths of time.*



# Third Kepler's Law (1619)

*The squares of the orbital periods of the planets are proportional to the cubes of their mean distances from the sun.*

$$\frac{T_1^2}{T_2^2} = \frac{a_1^3}{a_2^3}$$

*T, period*

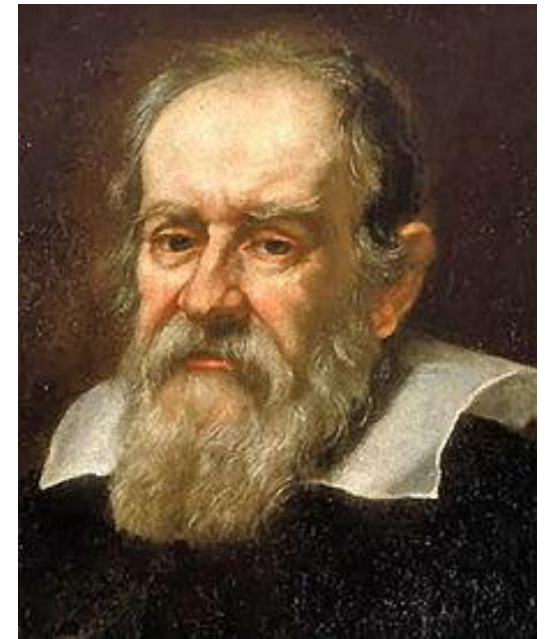
*A, semi-major axis*

# Galileo Galilei (1564-1642)

Did not invent the telescope but greatly improved the design the year following its invention (1609).

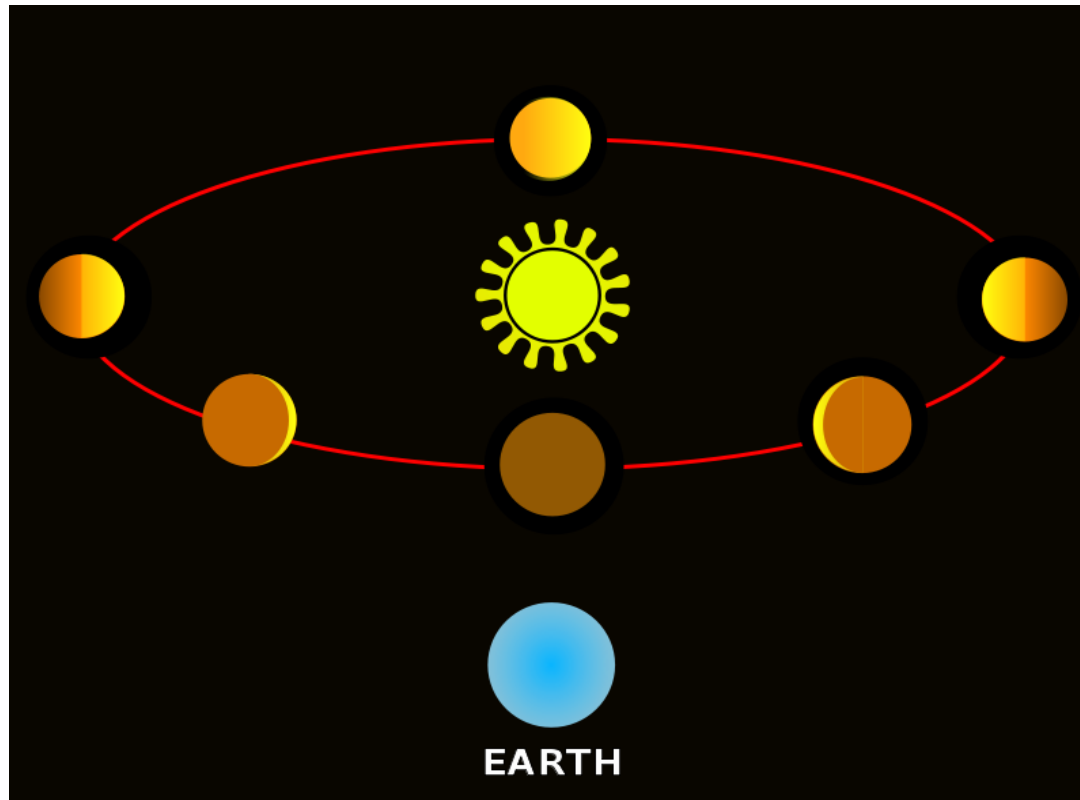
On 7 January 1610 he observed *three fixed stars, totally invisible by their smallness, all within a short distance of Jupiter.*

On 10 January, he noted that one of them had disappeared. Within a few days he concluded that they were orbiting Jupiter. He had discovered Io, Europa and Callisto. He discovered the fourth, Ganymede, on 13 January.



# Confirmation of Heliocentric System

He made the first conclusive observational proof that confirmed the hypothesis of heliocentric system.

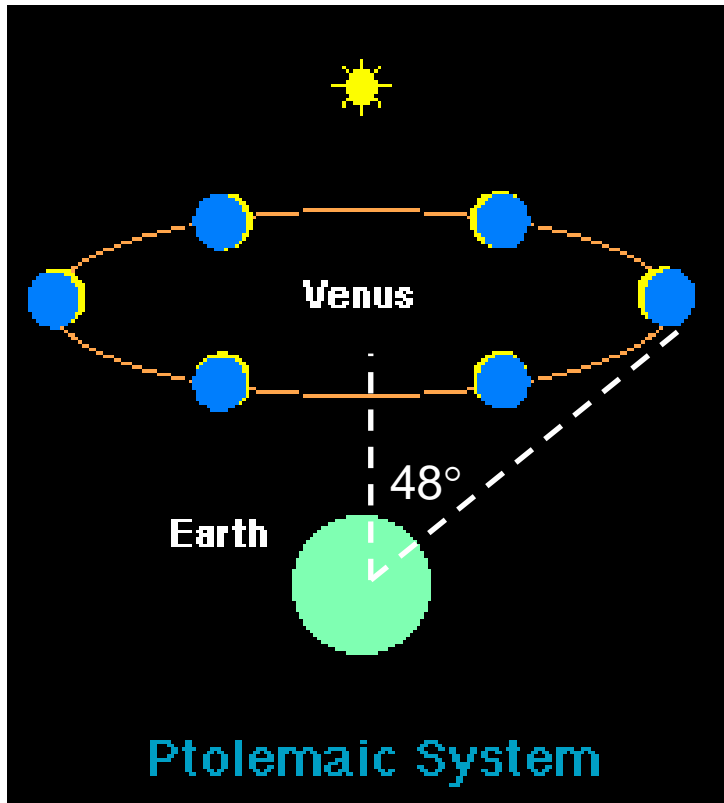


*The phases of Venus (1610)*

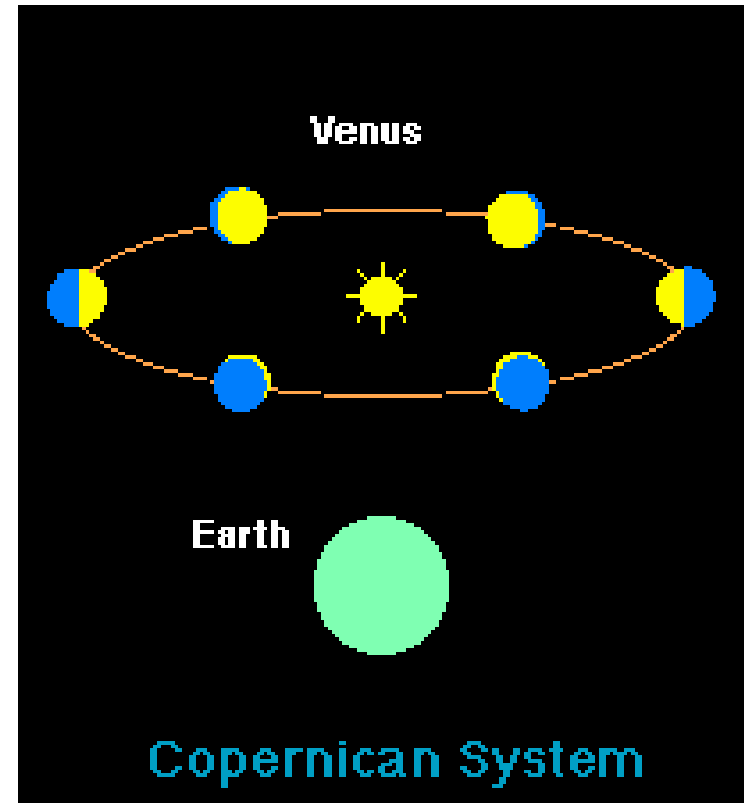


# Confirmation of Heliocentric System

Empirical fact: Venus never appeared more than  $48^\circ$  east or west of the sun.



Venus should always be in crescent phase as viewed from the Earth.



Venus should exhibit a complete set of phases over time as viewed from the Earth.

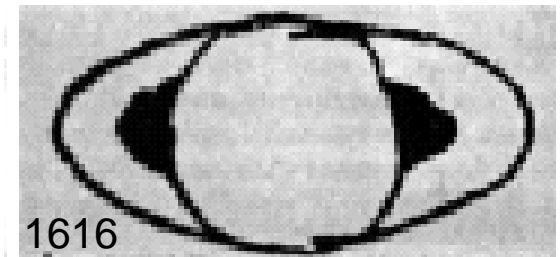
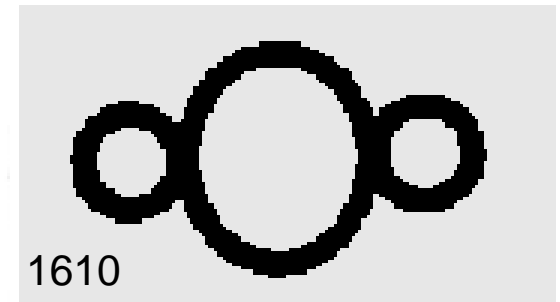
# Other Key Discoveries

The first to observe Saturn's rings (1610). In 1612, he noted that the rings had “disappeared” ! In 1616, they “reappeared”.

One of the first to observe sunspots in 1612 (the sun rotates !).

Discovered lunar mountains and craters and estimated of the mountains' heights.

Observed Neptune (1612) but did not realize it was a planet.



Galileo's sketches  
of Saturn

# Controversy

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Among other things, Galileo openly questioned the veracity of the Book of Joshua (10:13) wherein the sun and moon were said to have remained unmoved for three days to allow a victory to the Israelites.

He was found vehemently suspect of heresy (Roman Inquisition).

He was eventually forced to recant his heliocentrism and spent the last years of his life under house arrest.

# Kinematics vs. Dynamics of Motion

Kepler developed, using Tycho Brahe's observations, the first **kinematic** description of orbits.

But a **dynamic** description that involves the underlying influence (gravity) was missing.

# Isaac Newton (1642-1727, English)

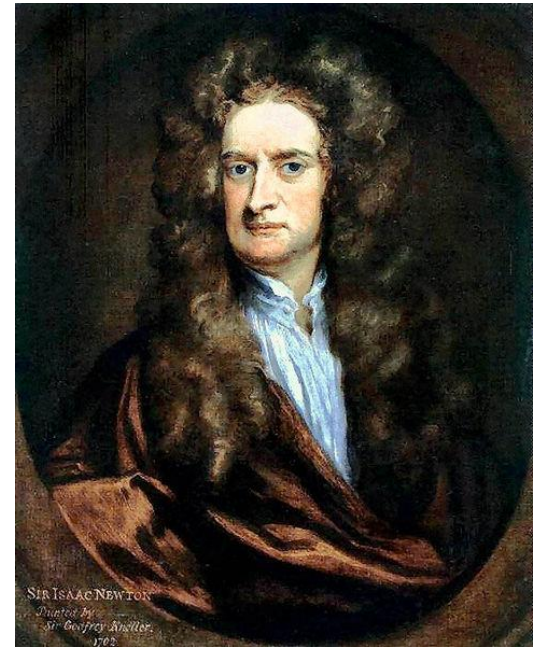
Introduced the three laws of motion.

Introduced the inverse square law of gravitational force.

$$\vec{F} = G \frac{Mm}{\|\vec{r}\|^3} \vec{r}$$

*Philosophiæ Naturalis Principia Mathematica* (1687) is considered to be the most influential book in the history of science.

Developed the first "practical" reflecting telescope.



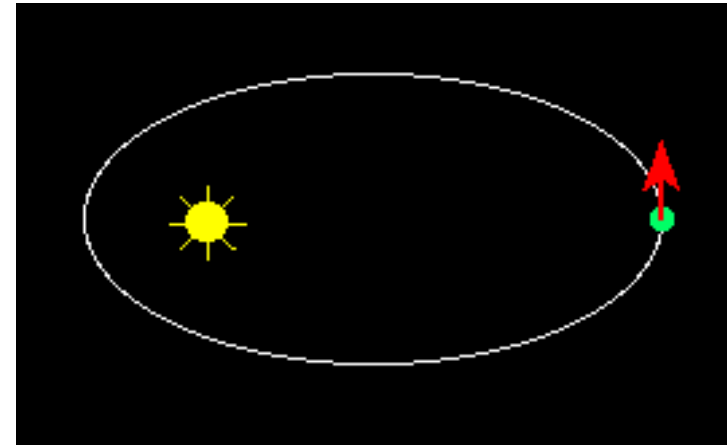
*A physicist/engineer*

# Kepler's Laws and Gravitation

Demonstrated the consistency between Kepler's laws and his theory of gravitation, removing the last doubts about heliocentrism.

Kepler's first and third laws are a natural consequence of the inverse-square gravitational force field of the sun.

Kepler's second law is a consequence of the conservation of angular momentum.

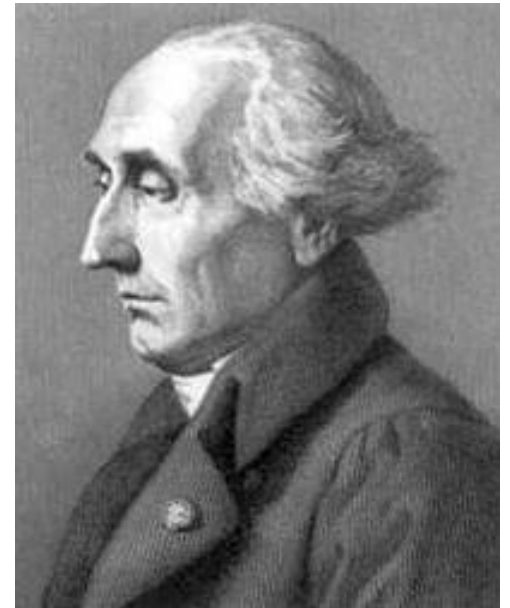


# Lagrange (1736-1813, Italian)

Worked on the restricted three-body problem and found in 1772 five fixed points where the third body experiences zero net force.

These points were named Lagrange points or libration points (concept of Halo orbits widely used: SOHO, JWST).

It took over a hundred years before his mathematical theory was observed with the discovery of the Trojan asteroids in the 1900s at the Lagrange points of the Sun–Jupiter system.



# 1500-1800: The Golden Age

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By 1800, the physics laws which govern astrodynamics were known. These same principles are used today for orbit prediction, orbit determination and mission design



# Poincaré (1854-1912, French)

Established the concept of non-integrable dynamical system.

In his research on the three-body problem, he became the first person to discover a chaotic deterministic system which laid the foundations of modern chaos theory.



# Tsiolkovsky (1857-1935, Russian)

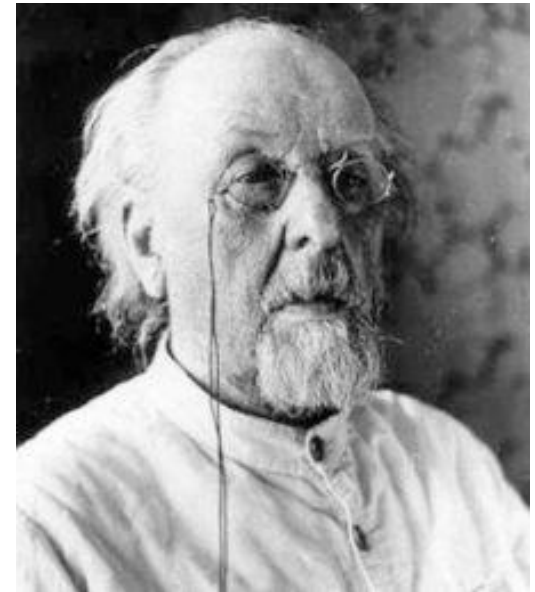
Published calculations in 1898 and 1903 that described in depth the use of rockets for launching orbital space ships. The first academic treatise on rocketry.

Never built any practical models.

$$\Delta v = v_e \ln \frac{m_0}{m_1}$$

$v_e$ , exhaust velocity  
 $m_0$  initial mass  
 $m_1$  final mass

*Rocket equation*



# But... Coquilhat (1811-1890, Belgian)

Established the rocket equation in 1873 !

*Trajectoires des fusées volantes dans le vide*, Mémoires de la Société Royale des Sciences de Liège.

Recent “discovery”.



TRAJECTOIRES  
DES  
FUSÉES VOLANTES DANS LE VIDE  
PAR  
M. COQUILHAT,

Général major ; officier de l'ordre de Léopold ;  
décoré de la Croix commémorative ; chevalier de l'ordre du Lion néerlandais,  
de l'Aigle rouge de 3<sup>me</sup> classe, de S'-Stanislas de 2<sup>me</sup> classe,  
de S'-Anne de 2<sup>me</sup> classe, du Méjidié ; commandeur de l'ordre de la Tour et l'Épée ;  
membre de la Société royale des sciences de Liège.

# Goddard (1882-1945, American)

Launched the world's first modern rocket in March 1926 (liquid-fueled).



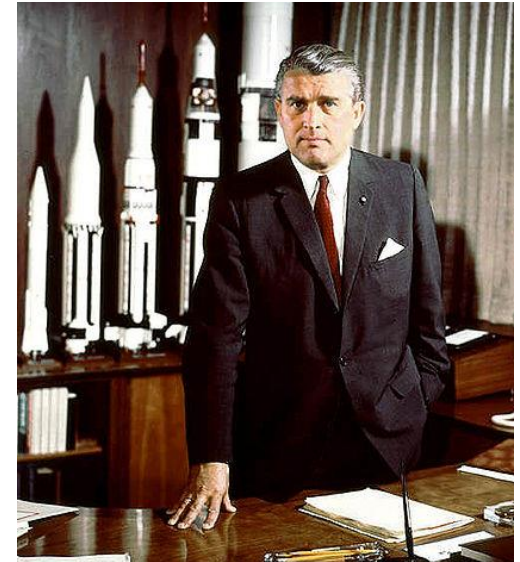
# Von Braun (1912-1977, German)

One of the most important rocket developers (1930s-1970s).

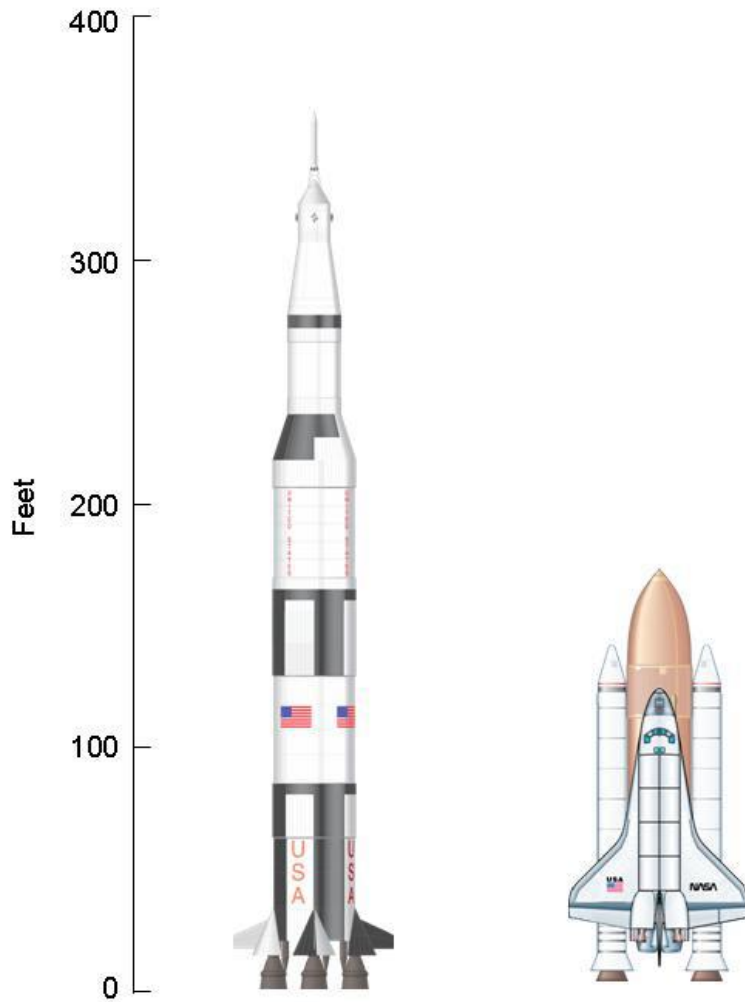
Leader of the “rocket team” which developed the V-2 ballistic missile for the Nazis during World War II.

After World War II, he worked with the USA. He built the Jupiter ballistic missile, used to launch Explorer I.

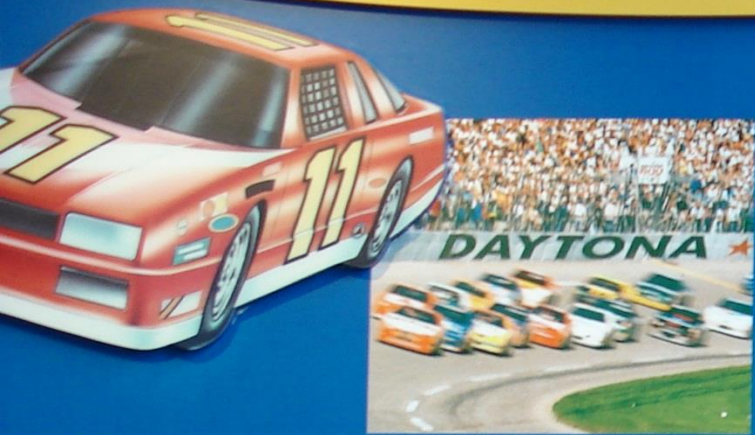
Chief architect of the Saturn V launch vehicle.



# Saturn V



# MORE POWERFUL THAN...



## **EIGHT THOUSAND DAYTONA 500 STARTING FIELDS**

The Saturn V's first stage alone generated approximately 160,000,000 horsepower. That makes it over eight thousand times more powerful than all of the race cars in this year's Daytona 500 combined.

## **ELECTRICITY TO NYC FOR 1-1/4 HOURS**

The Saturn V's first two stages together generated enough energy to have supplied electricity to New York City for over one hour and fifteen minutes.



## **OVER TWO HUNDRED F-18 JET FIGHTERS**

The five F-1 engines in the rocket's first stage together generated over 7.5 million pounds of thrust, a force larger than the thrust produced by two hundred thirteen F-18 jet fighters.

# Korolev (1907-1966, Russian)

Flew to Germany to recover the technology of the V-2 rocket and produced a working replica of the rocket, R-1.

Produced the first intercontinental ballistic missile, the R-7 Semiorokha which could carry the Soviet's nuclear bomber over a distance of 7000 km.

In modified form, the R-7 launched Sputnik in October 1957, the first artificial satellite, into orbit, and became the basis for the Soyuz space launcher.



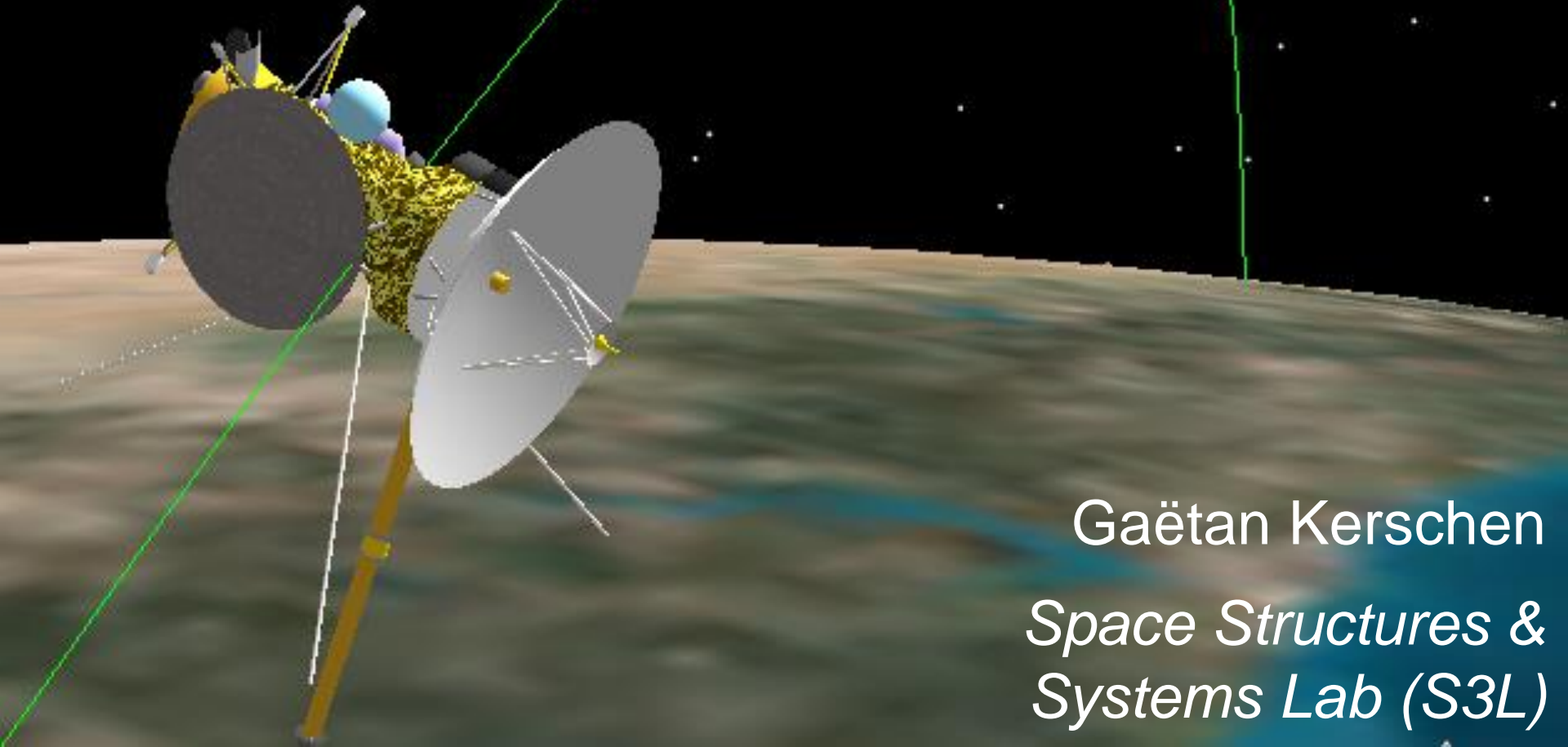


Cassini Classical Orbit Elements  
Time (UTCG): 15 Oct 1997 09:18:54.000  
Semi-major Axis (km): 6685.637000  
Eccentricity: 0.020566  
Inclination (deg): 30.000  
RAAN (deg): 150.546  
Arg of Perigee (deg): 230.000  
True Anomaly (deg): 136.530  
Mean Anomaly (deg): 134.891

# Aerodynamics

(AERO0024)

## 1. *Introductory Lecture*



Gaëtan Kerschen  
*Space Structures &  
Systems Lab (S3L)*