Concepts introduced in previous lectures:

Photon noise
Astronomical units: magnitude brightness scale, parsec
Lagrange invariant: large field = large optics
Airy pattern, Nyquist sampling
Atmosphere: emission, transmission, turbulence
Angular resolution and sensitivity in background-limited observations
Requirements for astronomical optical systems, measurements:

- collecting area (telescope diameter)
- angular resolution
- field of view
- spectroscopy, photometry
- astrometry

Space systems design, program management
Pupil plane, focal plane, plate scale (conversion between angle and distance)
Refracting vs. Reflecting telescopes
Challenges of large telescopes: holding the primary mirror
Telescope designs
Aberrations in telescopes: wavefront aberrations, distortions, chromatism

Astronomical Optics

3. Fundamentals of Telescope designs

3.3. Space vs. ground, cryogenic telescopes, design choices, challenges

Outline, Key concepts:

Space telescopes: how are they different from ground telescopes ?

Cryogenic telescopes

	Ground Observatories	Space Observatories
Wavelength coverage	400 nm to 50 μm with absorption windows	γ-ray to long-wave radio waves
Scattered light for coronagraphs	Atmosphere limited to $>10^{-8}$	Unknown, limited by technology; probably $<10^{-15}$ contrast
Angular resolution	2×10^{-4} arcsec (500-m @ 500 nm)	Unknown; may be $<10^{-7}$ arcsec (10-km baseline)
Thermal environment	~230 to 310 K	Extreme: ~20 K with sunshade
Gravity	1-g; The vector changes during the night.	0-g
Accessibility	Easy-to-fix hardware	Telescope inaccessible after launch
Operation cost	Keck ~24 M/year	~10 times as much

Space Telescopes

Advantages:
- no atmosphere: full access to spectra from radio to gamma ray
- no atmosphere: full angular resolution
- no atmosphere: no skyglow
- high stability measurements possible, well controlled environment (thermal management easier)
- possible to cool whole telescope
- no day/night cycle: can observe 24h / day

Disadvantages:
- can't fix what is broken (or very expensive to fix) → somewhat risky
- very expensive
- use of low-risk older components
- limited communication bandwidth (costly to transfer large data)
- communication is not continuous

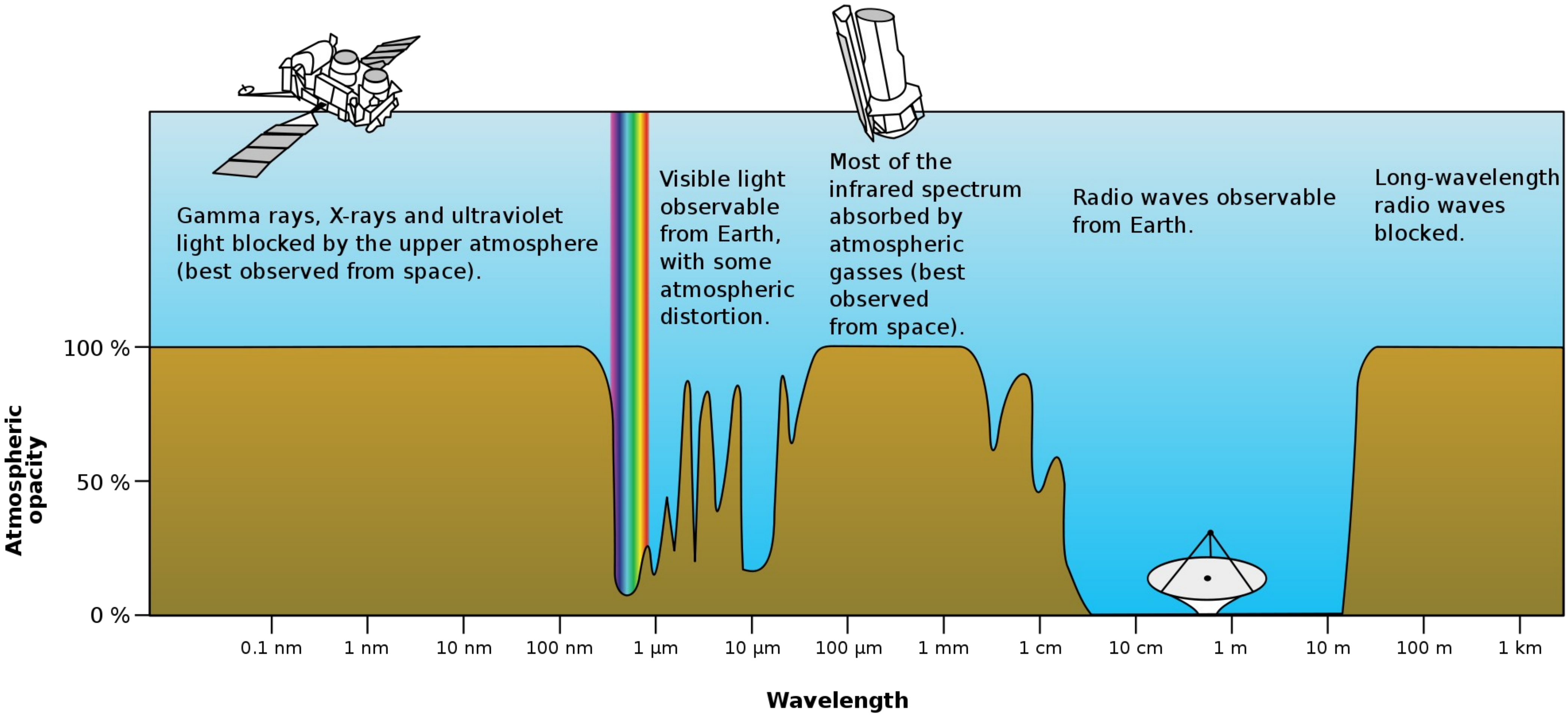
How do space telescopes differ from ground telescopes:

Low mass, but must be mechanically strong to resist launch
Low power consumption
Pointing using reaction wheels and thrusters

The first optical element in every ground-based telescope: Earth's atmosphere

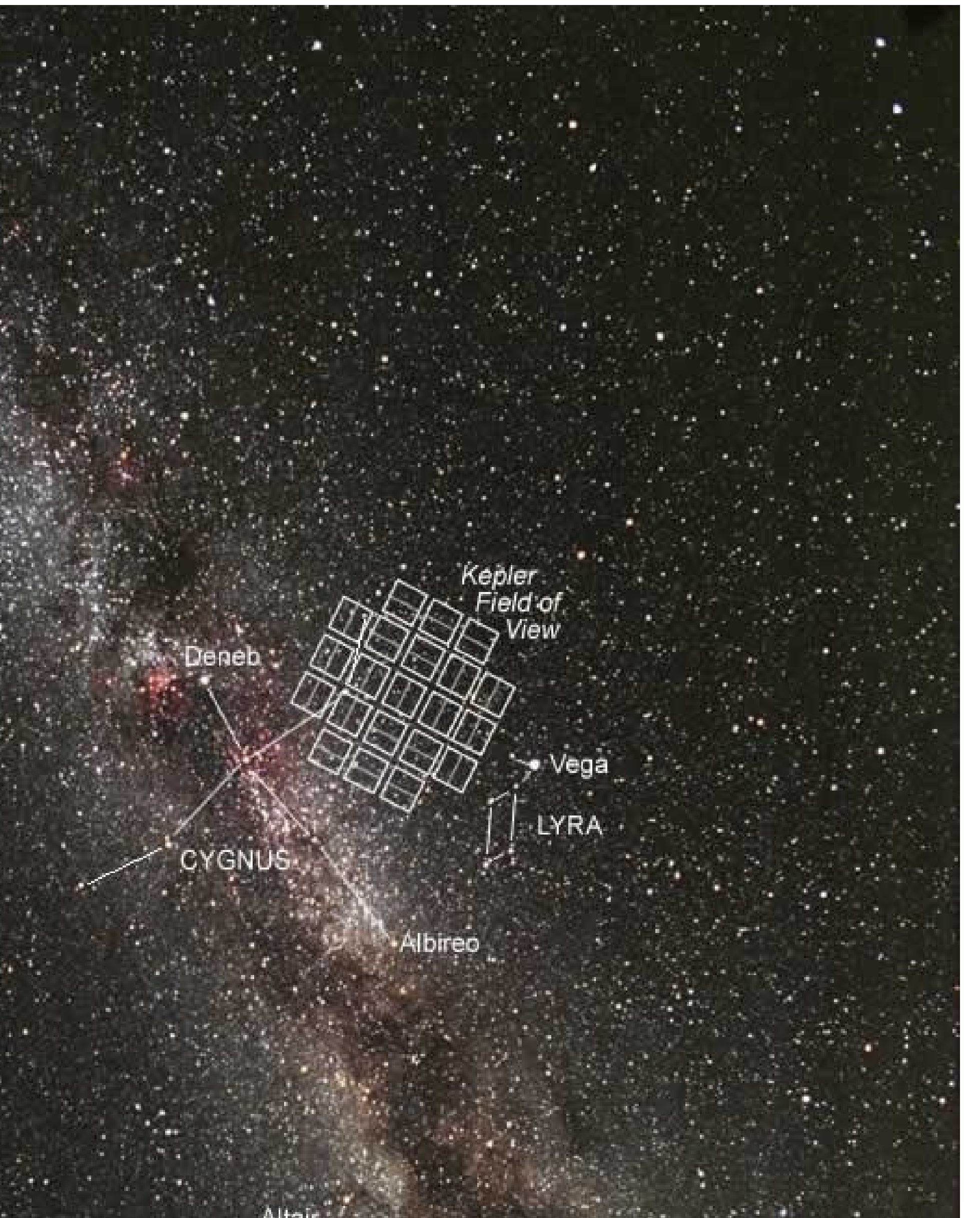
Transmission

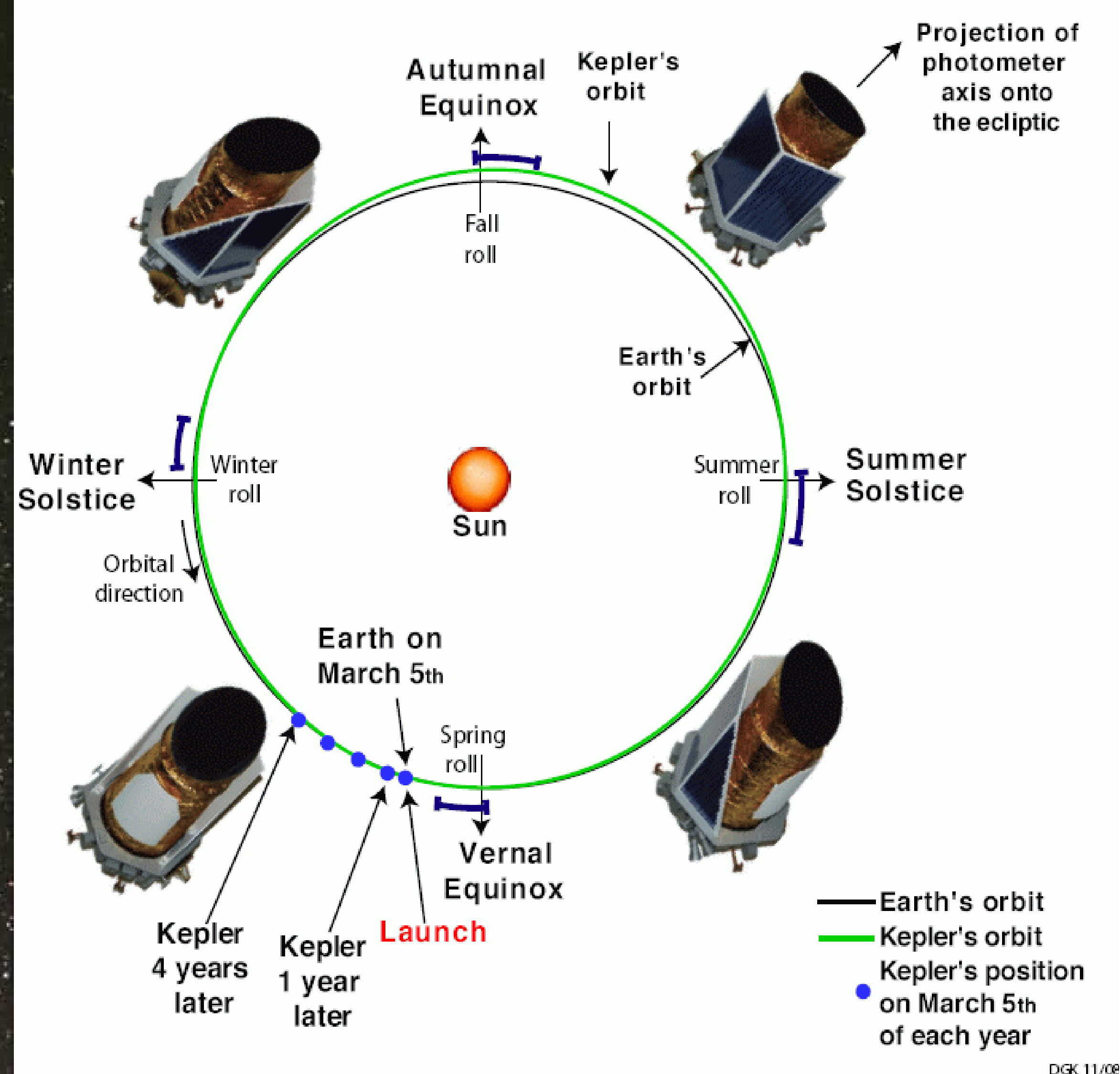
Atmosphere is fairly transparent in optical when not cloudy
nearIR: windows of transparency exist, main absorber is water vapor



Kepler Space Telescope: stability, and continuous viewing

Kepler stares at the same field for several years, and does precision photometry of a large number of stars to detect planetary transits





Cryogenic telescope systems for IR observations

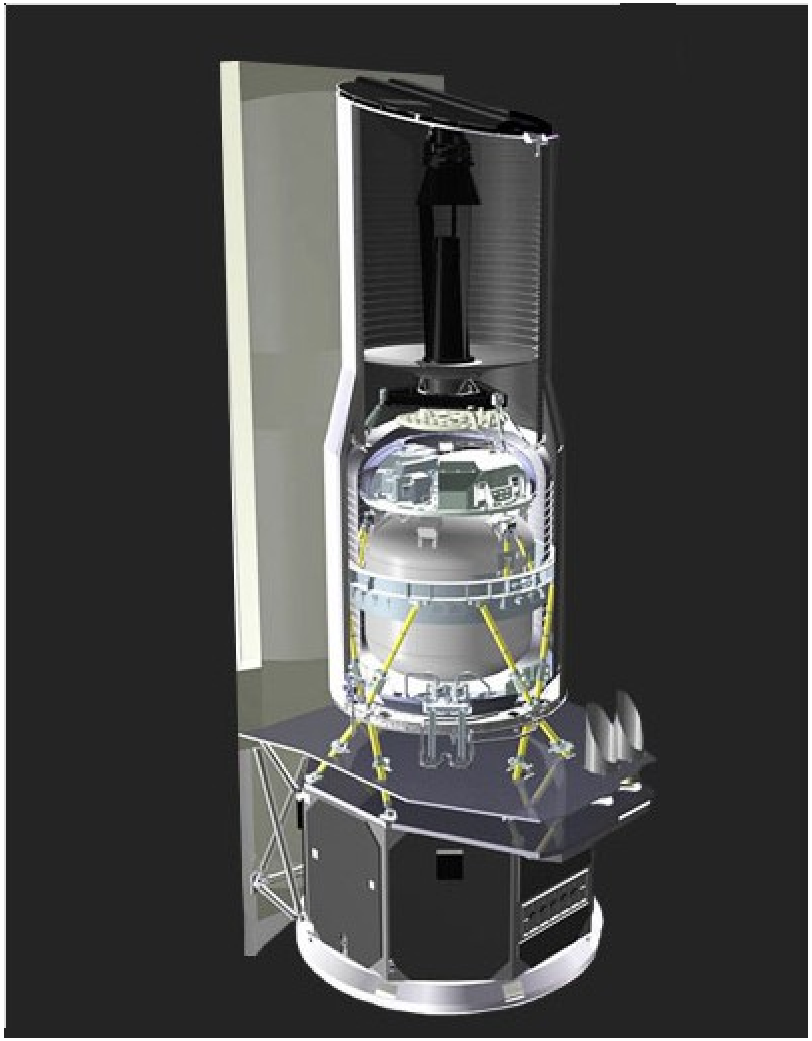
Blackbody radiation follows Planck's law:

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$

Total emission goes as emissivity x T^4

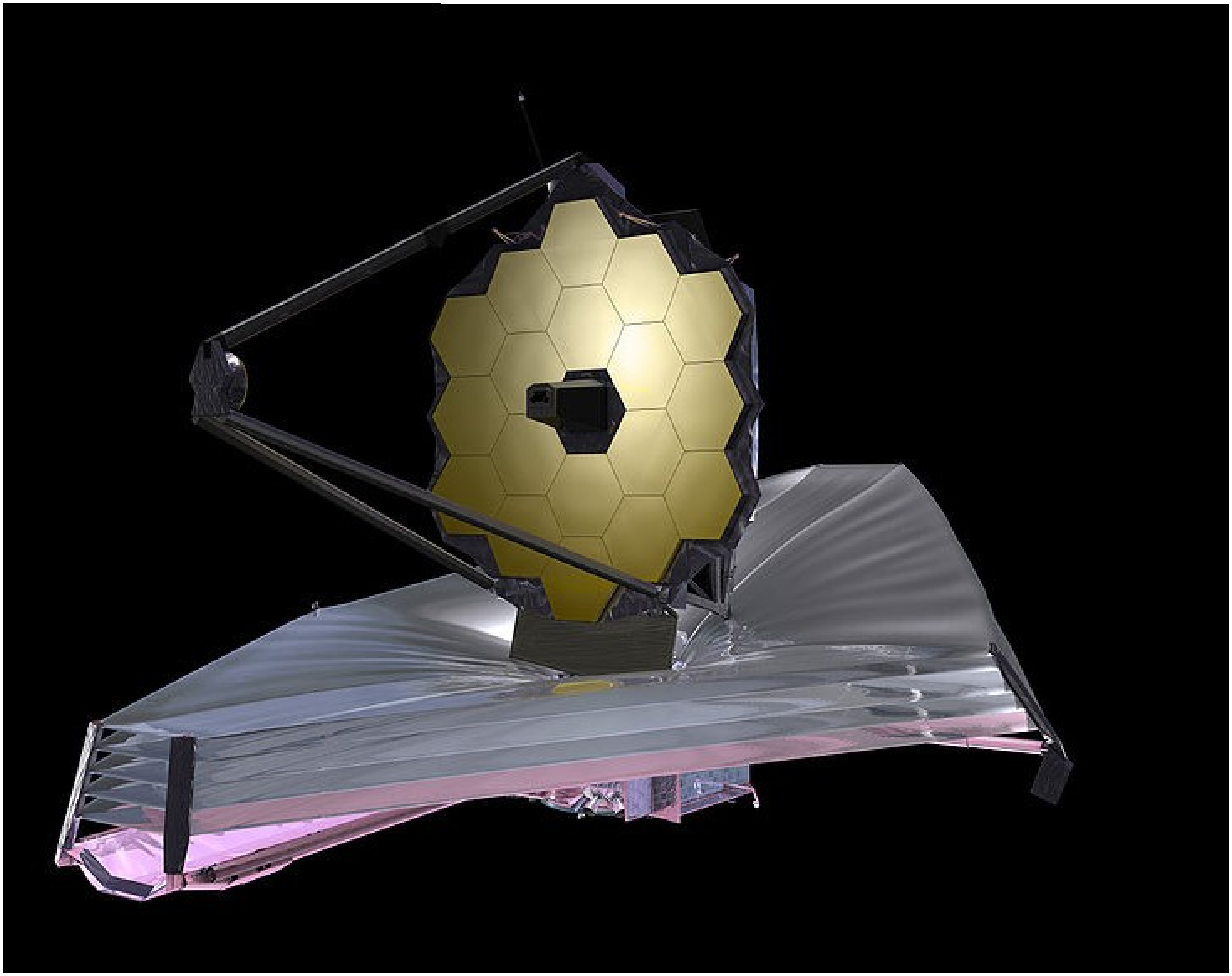
Full cryogenic telescopes only possible in space

Cold telescope + no IR-emitting atmosphere make space ideal environment for IR astronomy



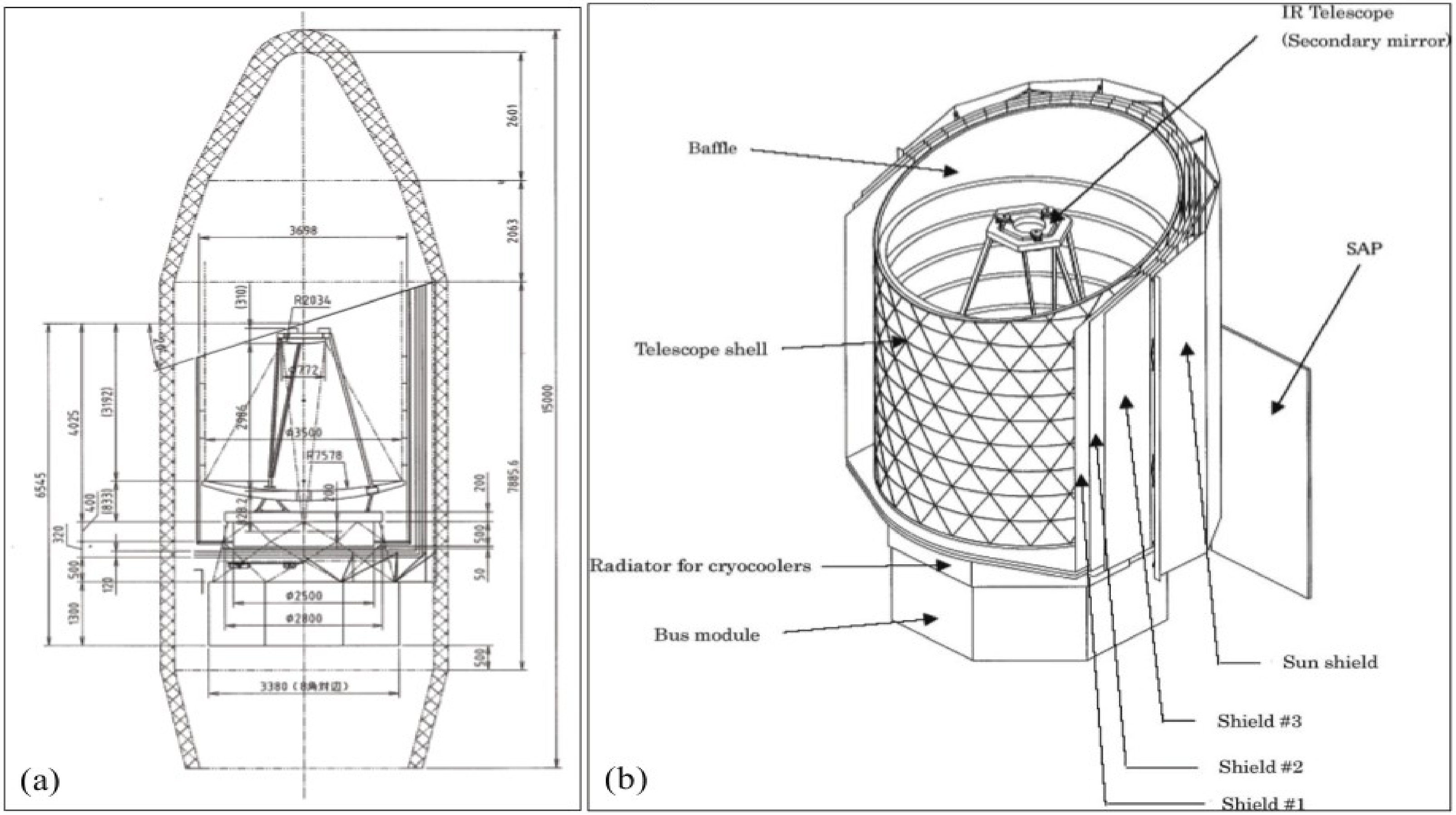
Spitzer Telescope: the liquid helium tank is visible in the center of this figure. It holds 360 liters of liquid Helium to cool the telescope to 35K for ~5 yrs

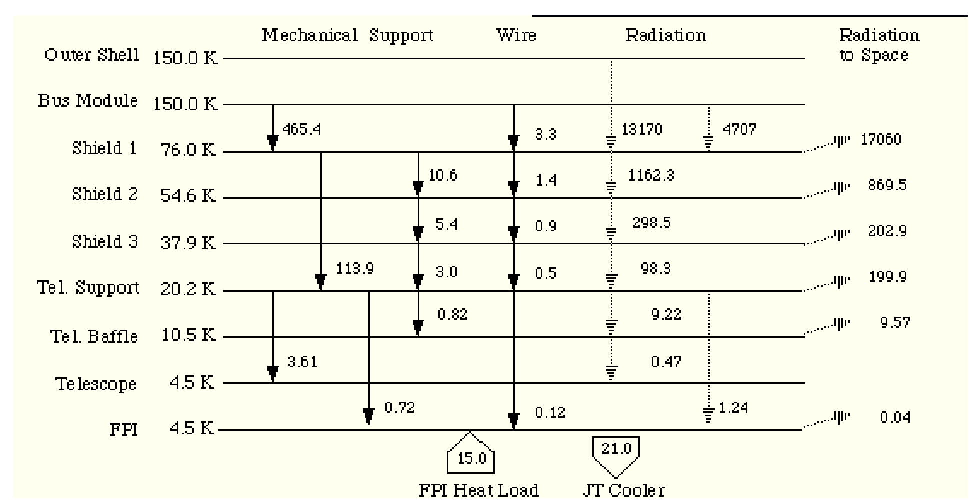
Passive Cooling can get to ~40K



JWST's sunshield keeps radiation due to Sun, Earth and Moon from heating the telescope → telescope should cool to ~40K passively

Active cooling of telescope to ~5K possible with liquid He





Source: SPICA mission (Japan)
3m IR telescope

Cryogenic telescope systems for IR observations

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Total emission goes as emissivity x T^4

To optimize sensitivity:
- reduce T
- reduce emissivity (gold coating is good for IR telescopes)

Note: Cryogenic telescopes do not use glass for their mirrors
JWST, Spitzer: Beryllium (Be)
Herschel : Silicon Carbide (SiC)

Gold-coated segment of JWST (6.5m diameter, to be launched in a few yrs)

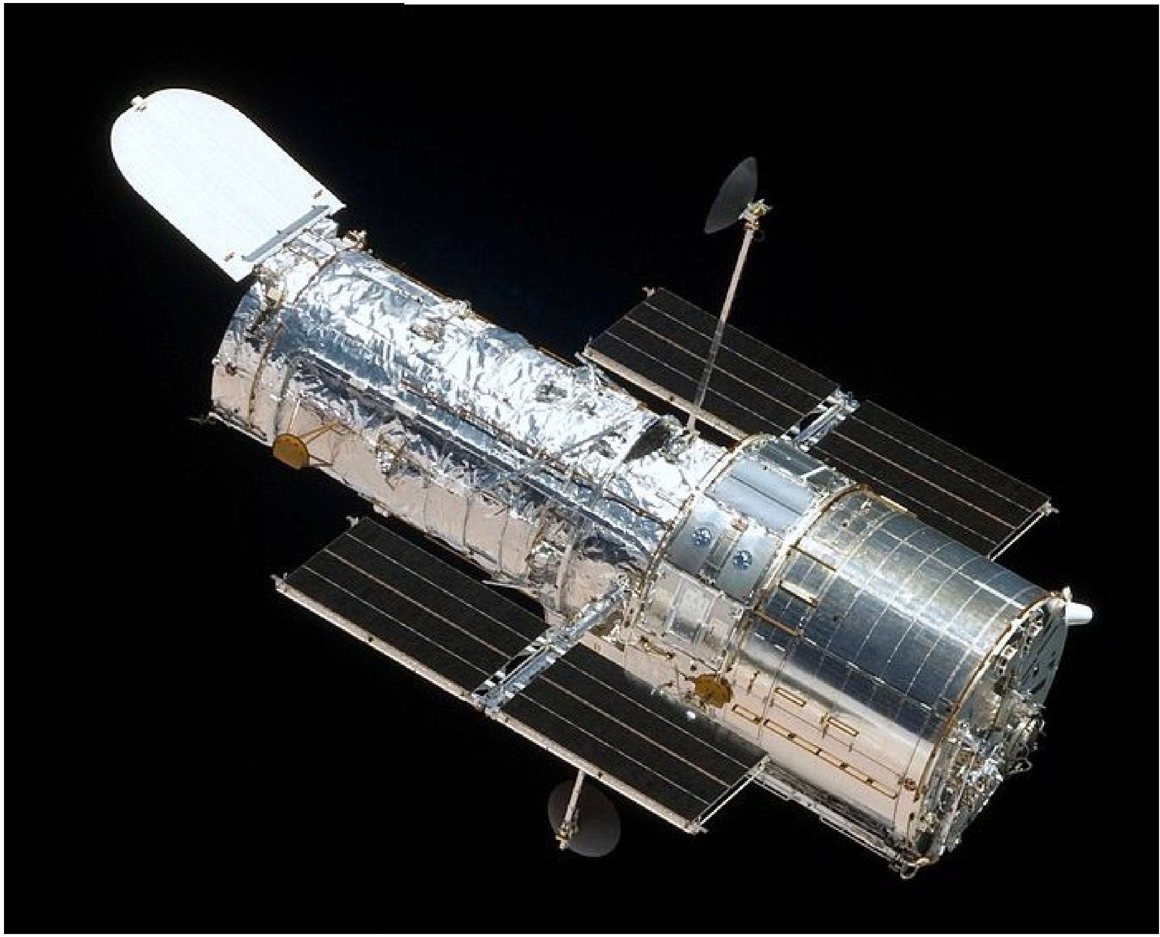
Orbits for space telescopes

Low Earth Orbit (<2000 km from surface)

Easy access

Frequent day/night cycles
→ difficult to keep telescope very stable
→ solar panels not always illuminated

Not stable over long timescales: altitude loss due to upper atmosphere



The Hubble Space Telescope (HST) is in LEO, h=559 km

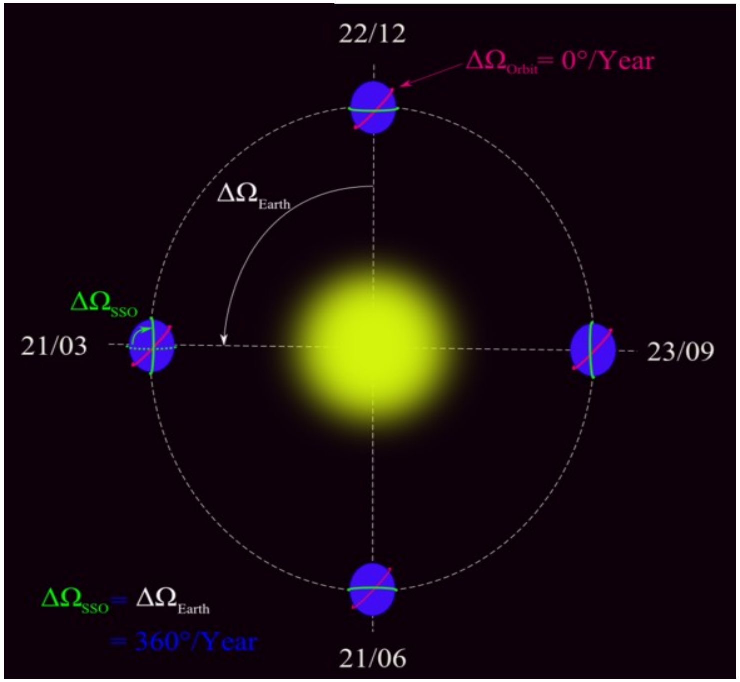
Orbits for space telescopes

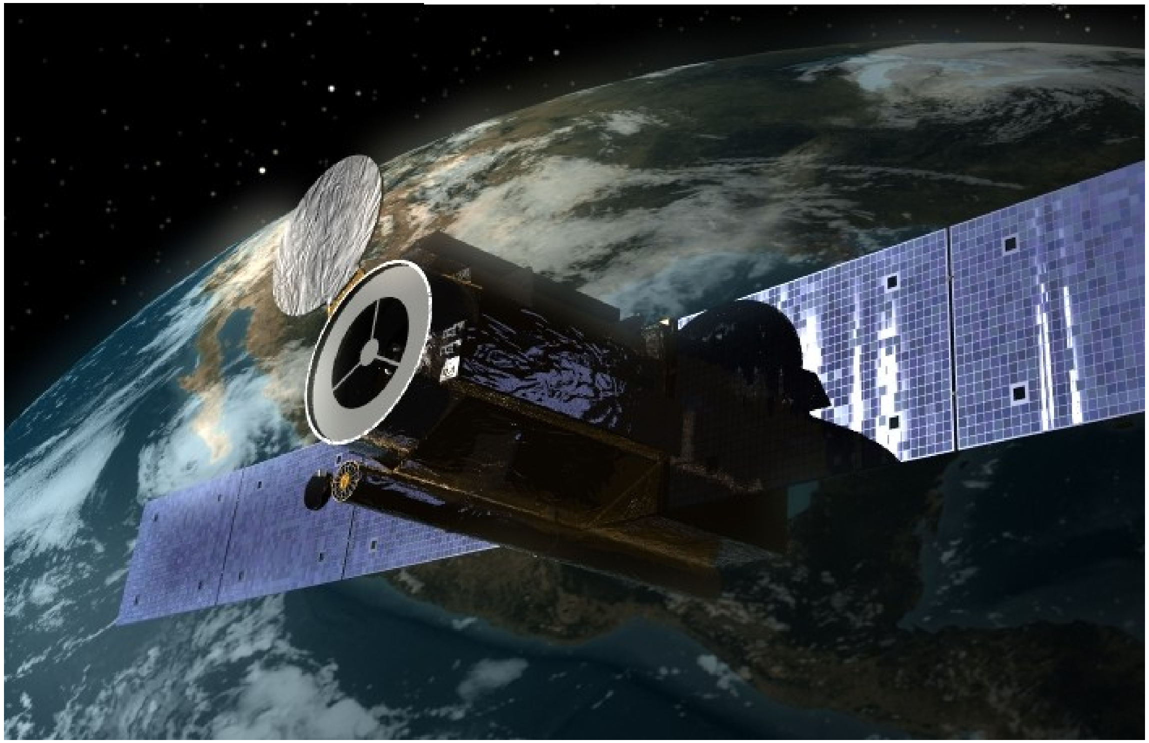
Sun-synchronous orbit (600-800 km, always sunlit)
Solar observation telescopes (Hinode, Yohkoh, TRACE)

Precession due to Earth's oblateness is adjusted to match orbital period of Earth around the Sun

Requires more energy

No occultations

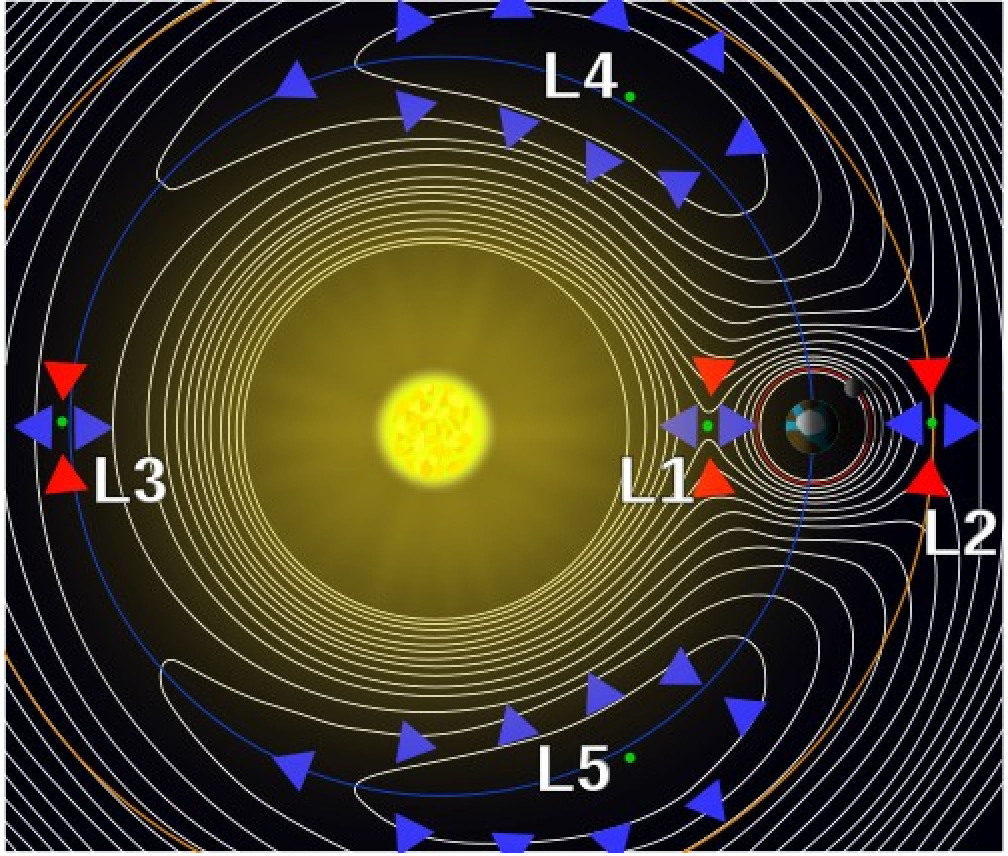




Hinode (optical / UV / Xray solar observatory)

Orbits for space telescopes

Lagrange points (Sun-Earth)

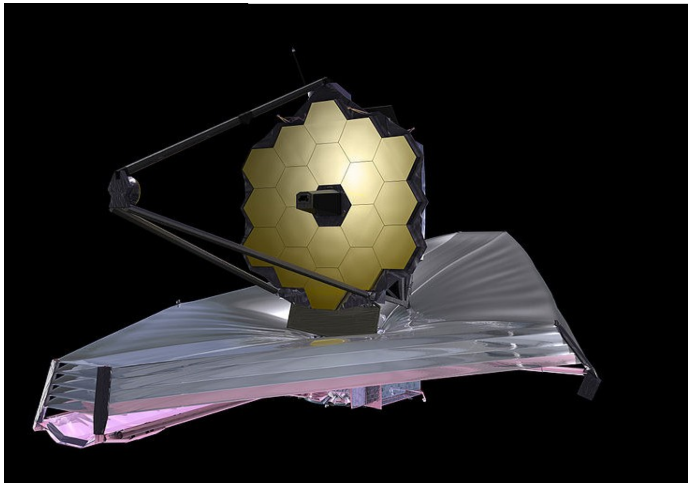


points where combined gravitational force of Earh and Sun allows co-rotation with Earth around Sun.

Stable environment (no eclipses, far from Earth and Moon)

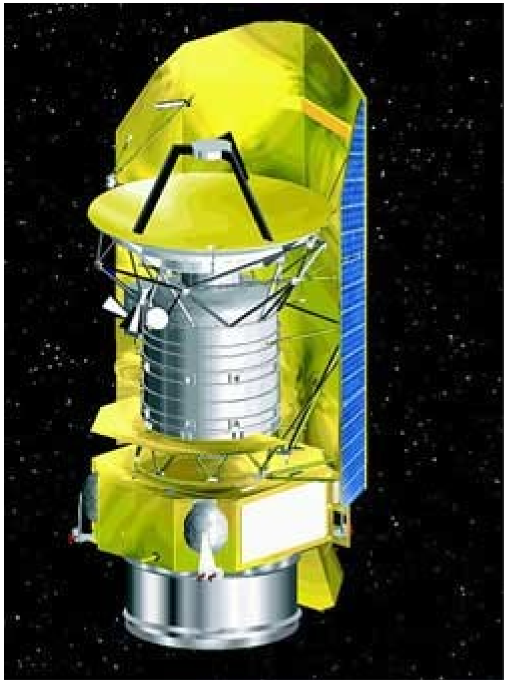
Difficult access

Requires station-keeping (not stable)



JWST
halo orbit around L2

Herschel
3.5m IR/submm telescope in halo orbit around L2



Orbits for space telescopes

Heliocentric: Earth trailing

Orbit close to Earth's orbit
Spacecraft slowly drifts away from Earth (~0.1 AU per year)

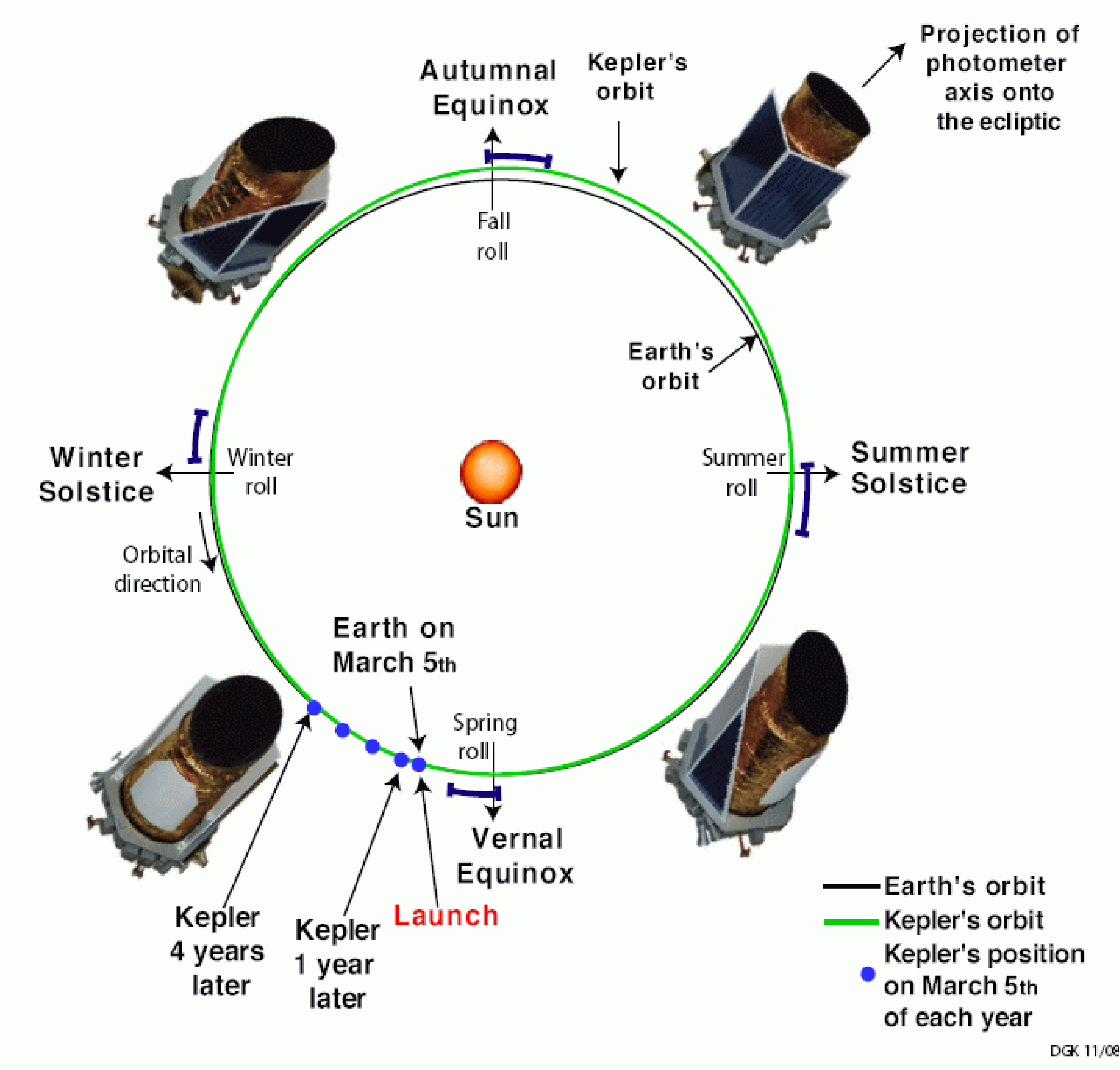
Stable environment (no eclipses, far from Earth and Moon)

No access

Reduced communication after a few years

No station-keeping

Kepler's orbit



Pointing space telescopes

Reaction wheels allow fine pointing and steering of the spacecraft without fuel (requires electric power provided by solar panels)

Change in speed or reaction wheel = smaller change in rotation speed for whole spacecraft

Control momentum gyroscope (CMG) = reaction wheel where the axis of rotation can be changed (as opposed to wheel rotation speed)

Reaction wheels and CMGs rely on conservation of angular momentum

Reaction wheels rotation speed can buildup with time, and needs to be offloaded using:

- **magnetic torquer** (use Earth's magnetic field): only works if close to Earth
- **thruster**: requires fuel
- Solar wind

Pointing to few milli-arcsecond is achieved in space : Hubble Space Telescope pointing is better than 10 milli-arcsecond