Astronomical space observatories

From X rays to millimeter waves

Olivier Absil

F.R.S.-FNRS Senior Research Associate

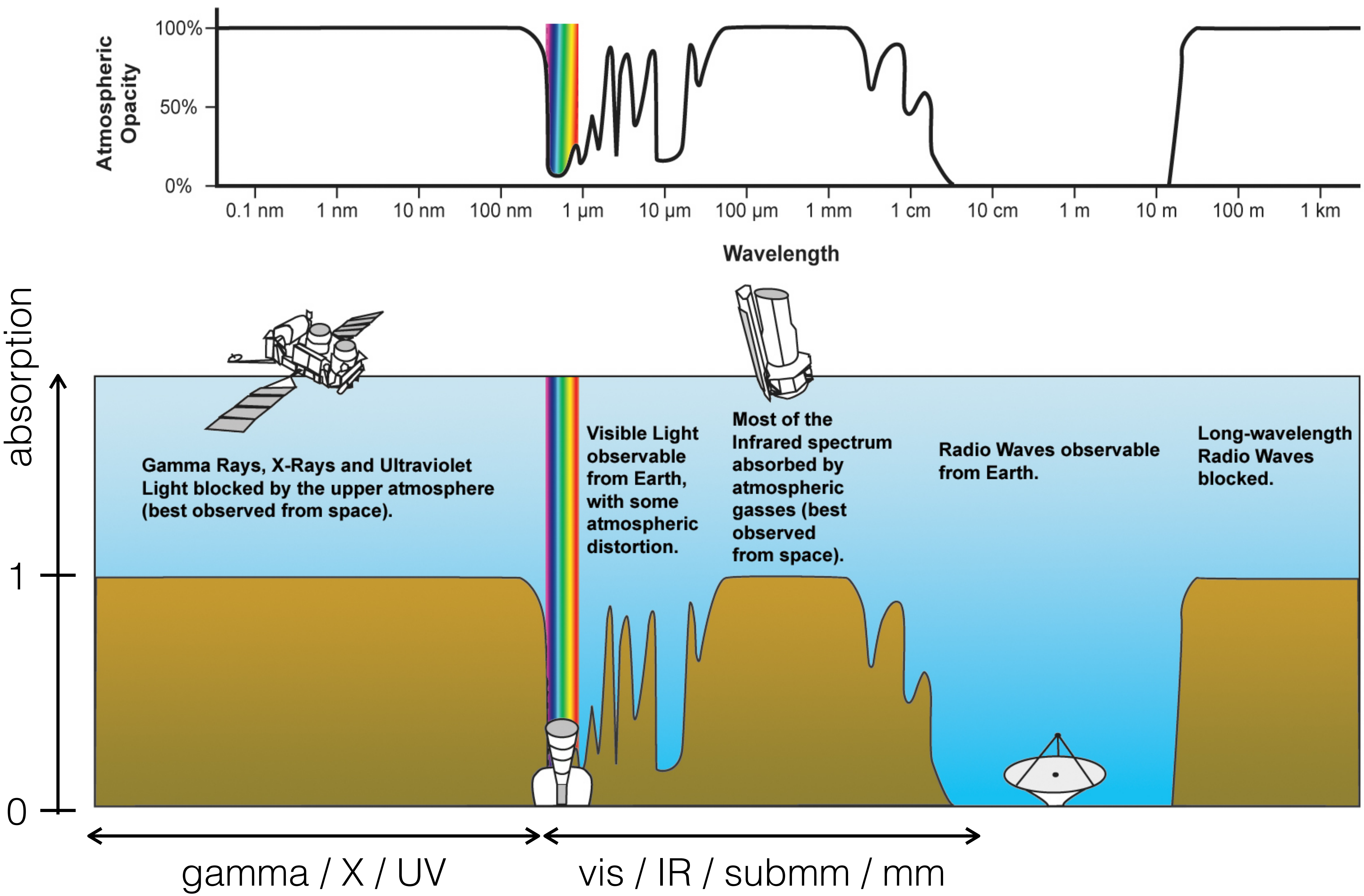
Space sciences, Technologies, and Astrophysics Research (STAR) Institute

olivier.absil@uliege.be

Why observing from space?

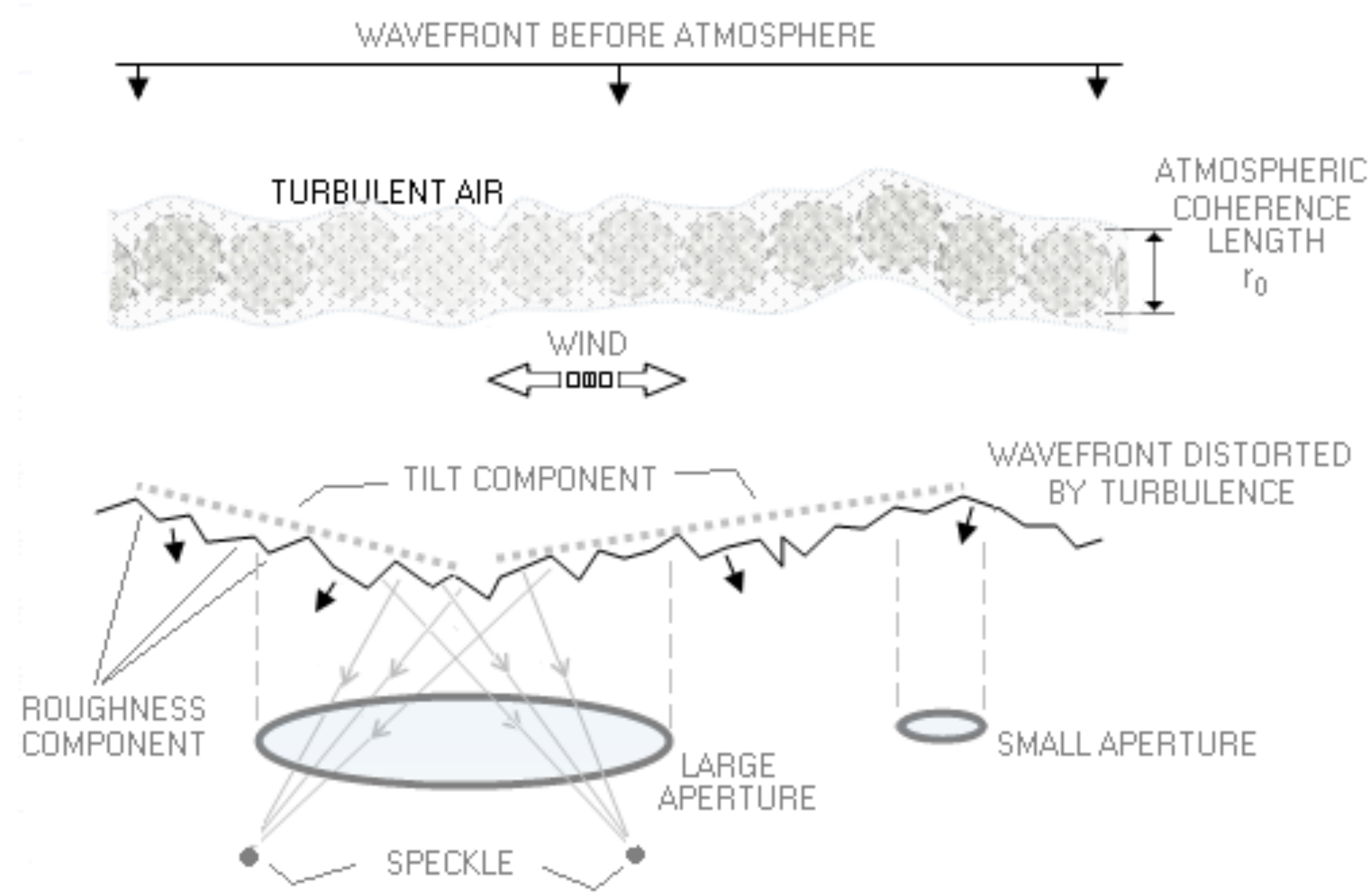
From X rays to millimeter waves

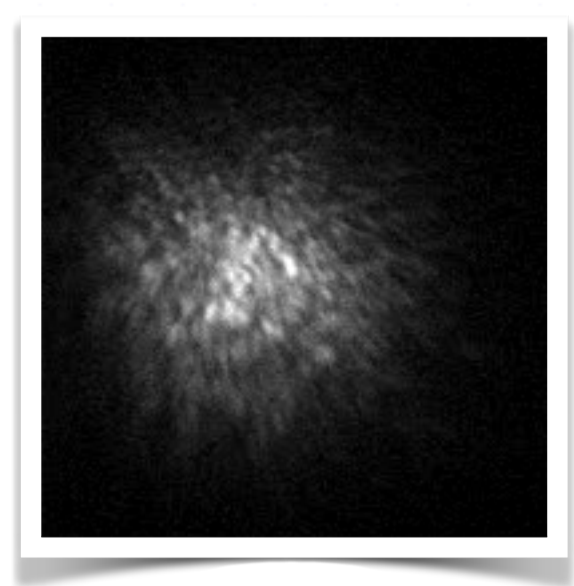
Atmospheric transmission

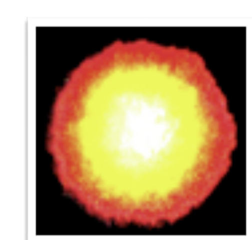


Atmospheric turbulence

- ✦ Corrugated wave front
- ✦ Image: spot size λ/r_0
  - r_0 = coherence length of turbulence (~10 cm)
  - resolving power limited to that of a 10-cm telescope





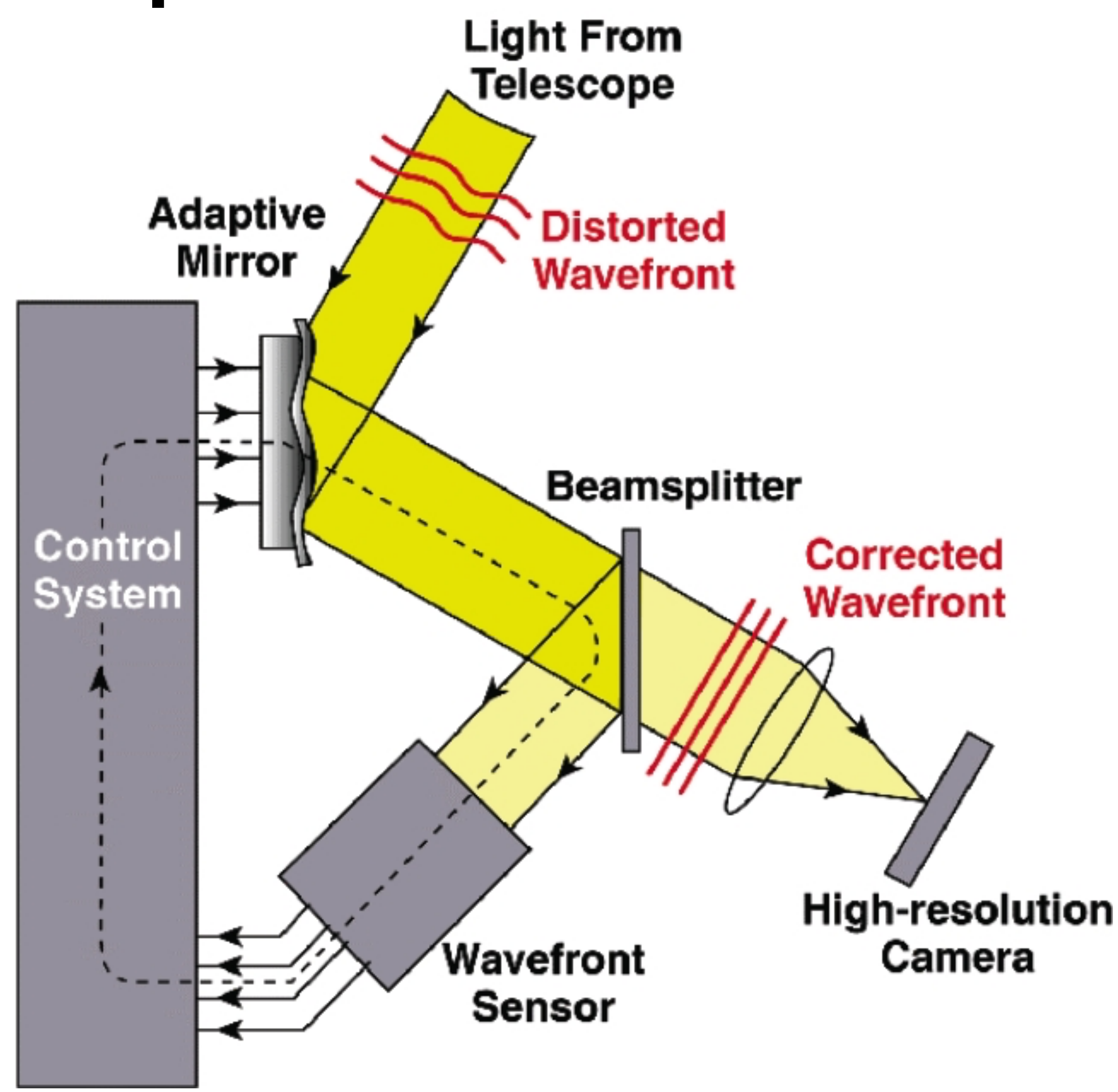


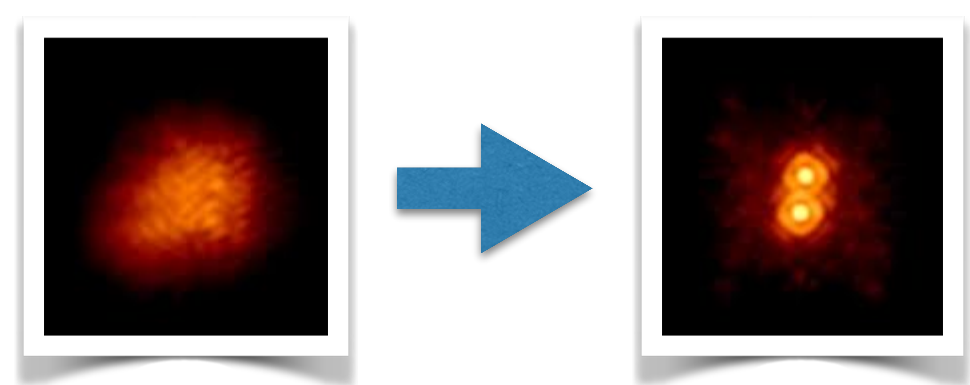
long exposure image

theoretical telescope PSF

Adaptive optics

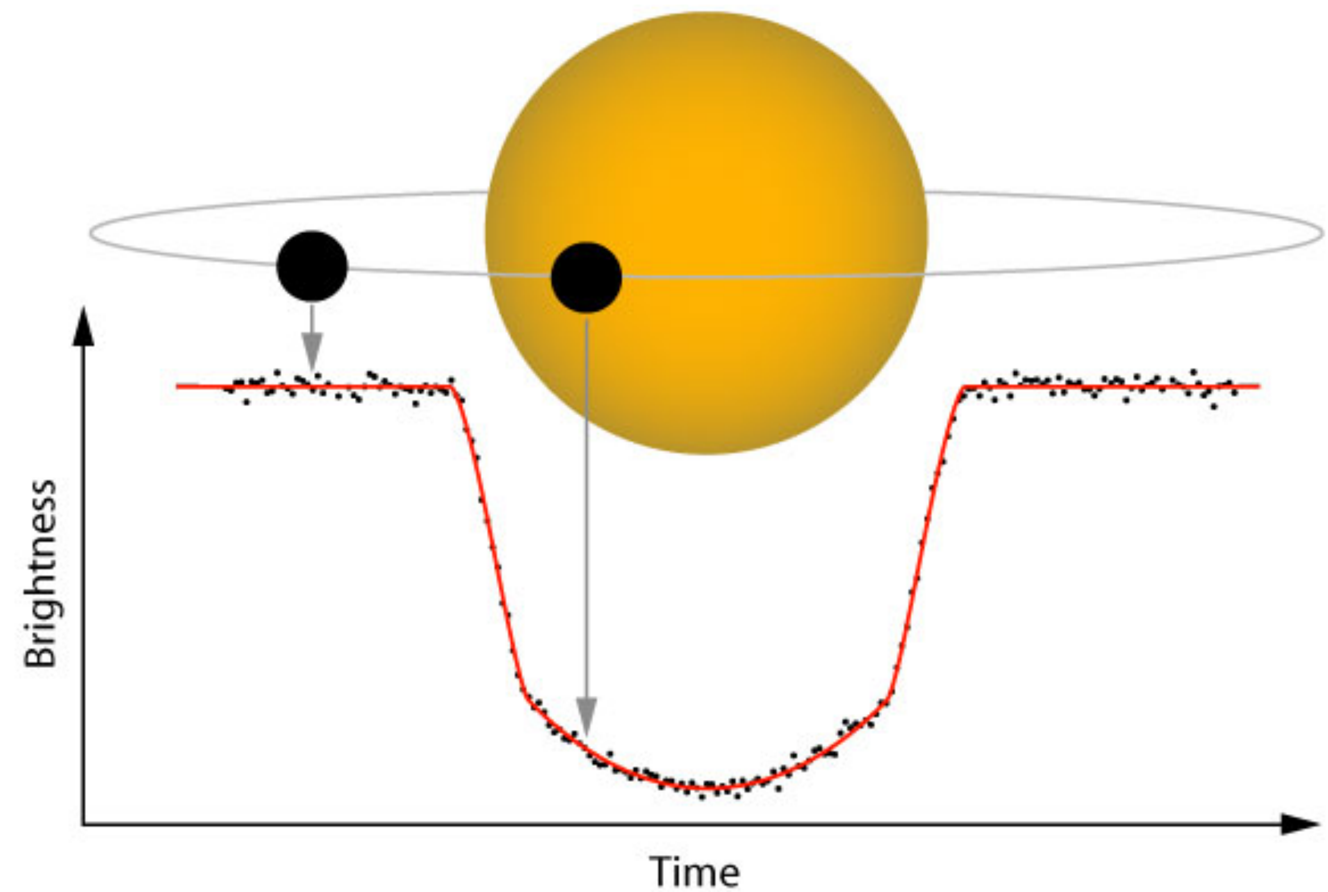
- Real-time wave front correction
  - wave front sensor
  - high-frequency deformable mirror (> 100 Hz)
- Correction is never complete
- Best solution: go to space!





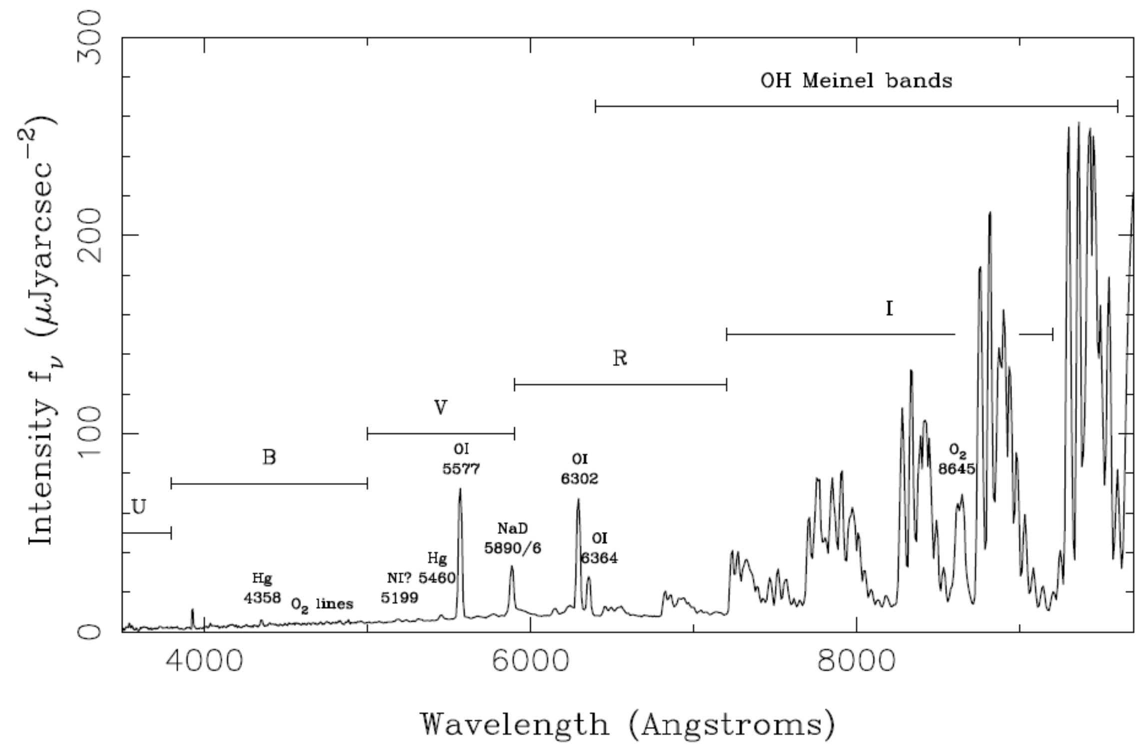
Stability / accuracy

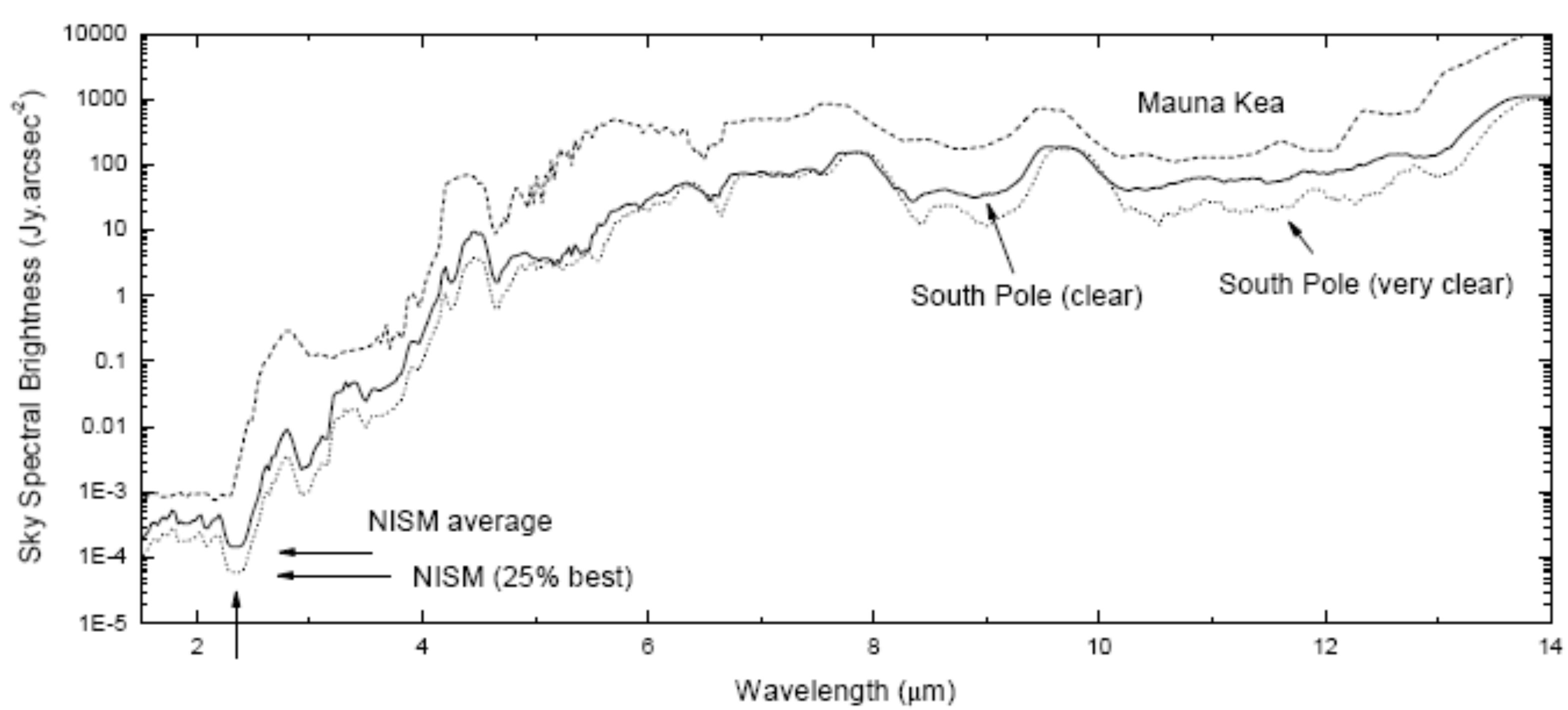
- Ground: scintillation, refraction, variability of the atmospheric transmission, etc.
- Space: enables high precision photometry



Sky emission / thermal background

- Visible range: airglow
- Infrared range: blackbody emission at 280 K (emissivity = 1 – transmission)



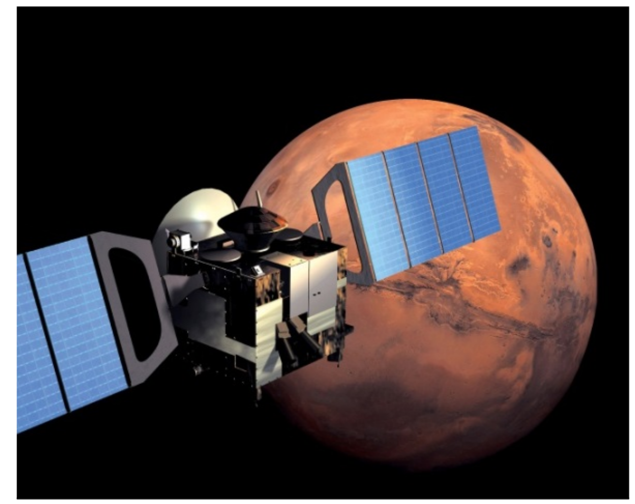


Summary: why space observatories?

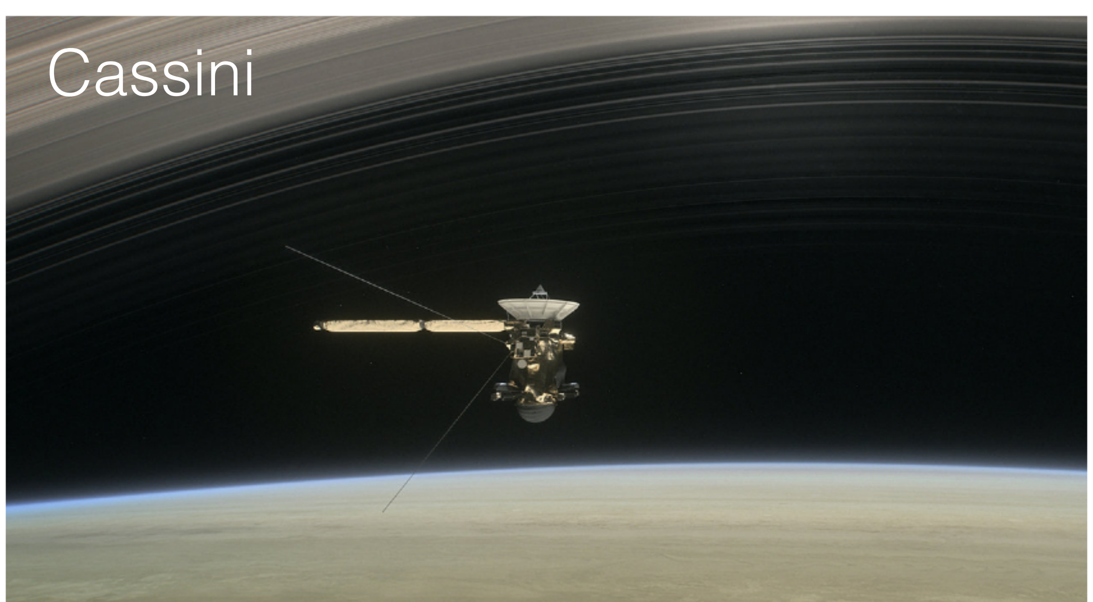
- ✦ Access to full spectrum —> new phenomena
- ✦ Sensitivity —> see fainter, farther, younger
- ✦ Resolving power —> more details
- ✦ Stability (thermal, mechanical) —> more accuracy
- ✦ And more:
    - cooling of the optics
    - no night/day cycle —> long observations

But also: in-situ exploration

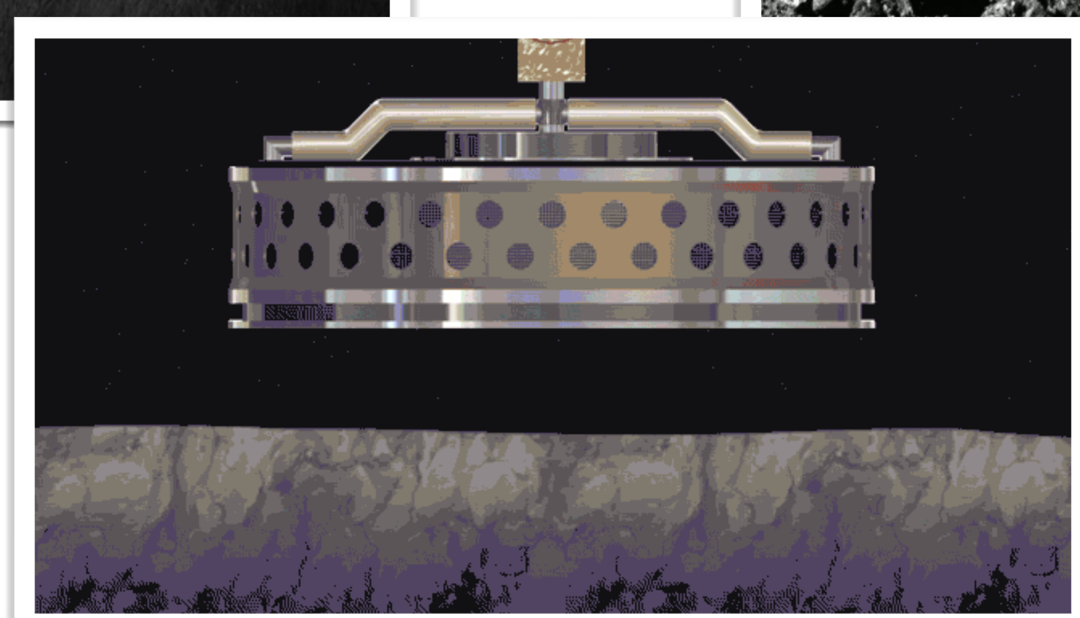
- ✦ Space rendez-vous
- ✦ Planetary orbiters
    - detailed cartography (3D)
    - magnetic field, …
- ✦ In-situ measurements (lander)



Mars Express, Curiosity, Perseverance, etc

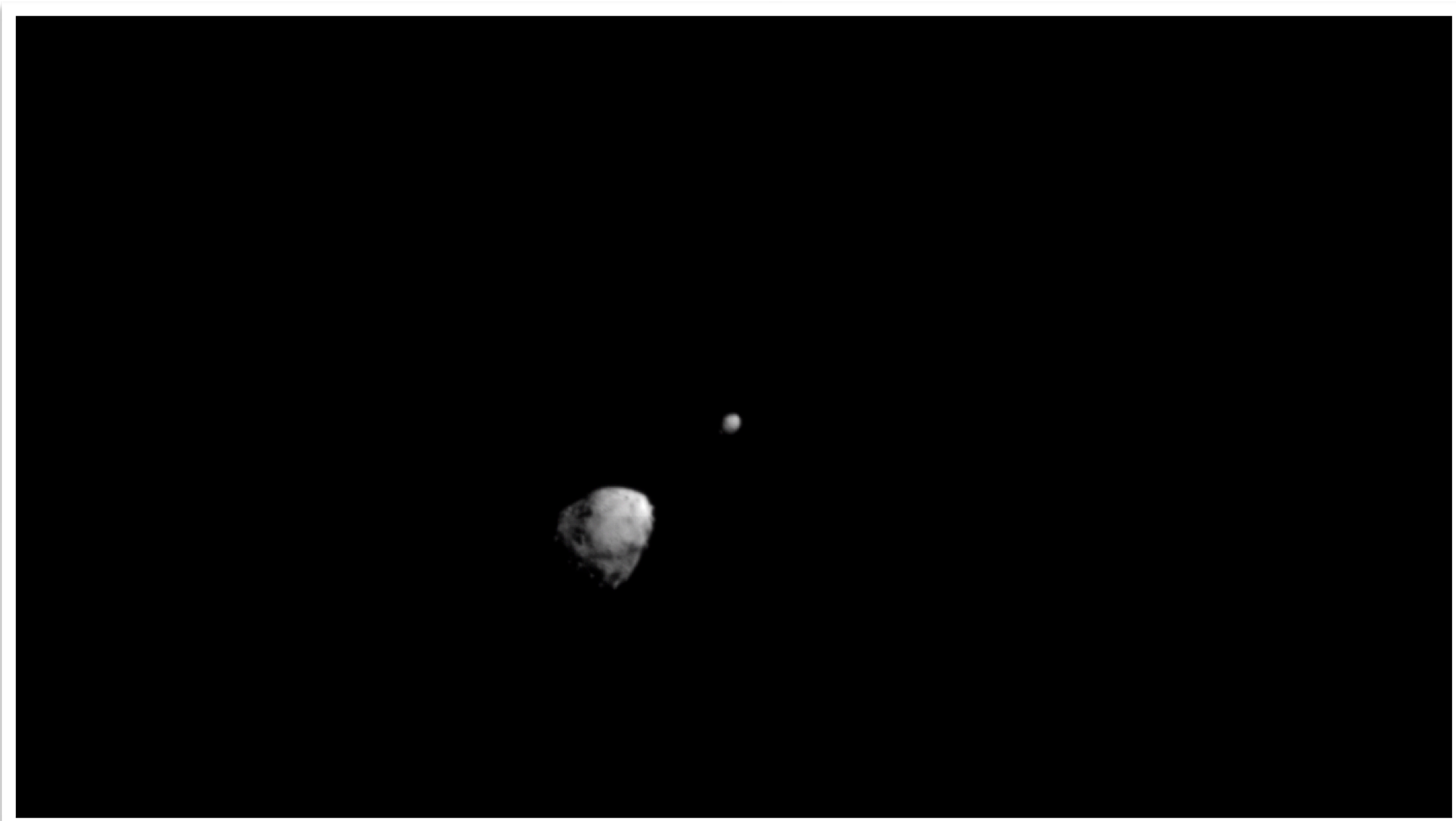


Collecting asteroid samples



120g collected during touch-and-go (Oct 20), back to Earth last year, now ready for analysis

Preventing Armageddon…
(and learning more about asteroids)



DART mission hitting asteroid moonlet Dimorphos on Sep 26, 2022

Outline of the lecture

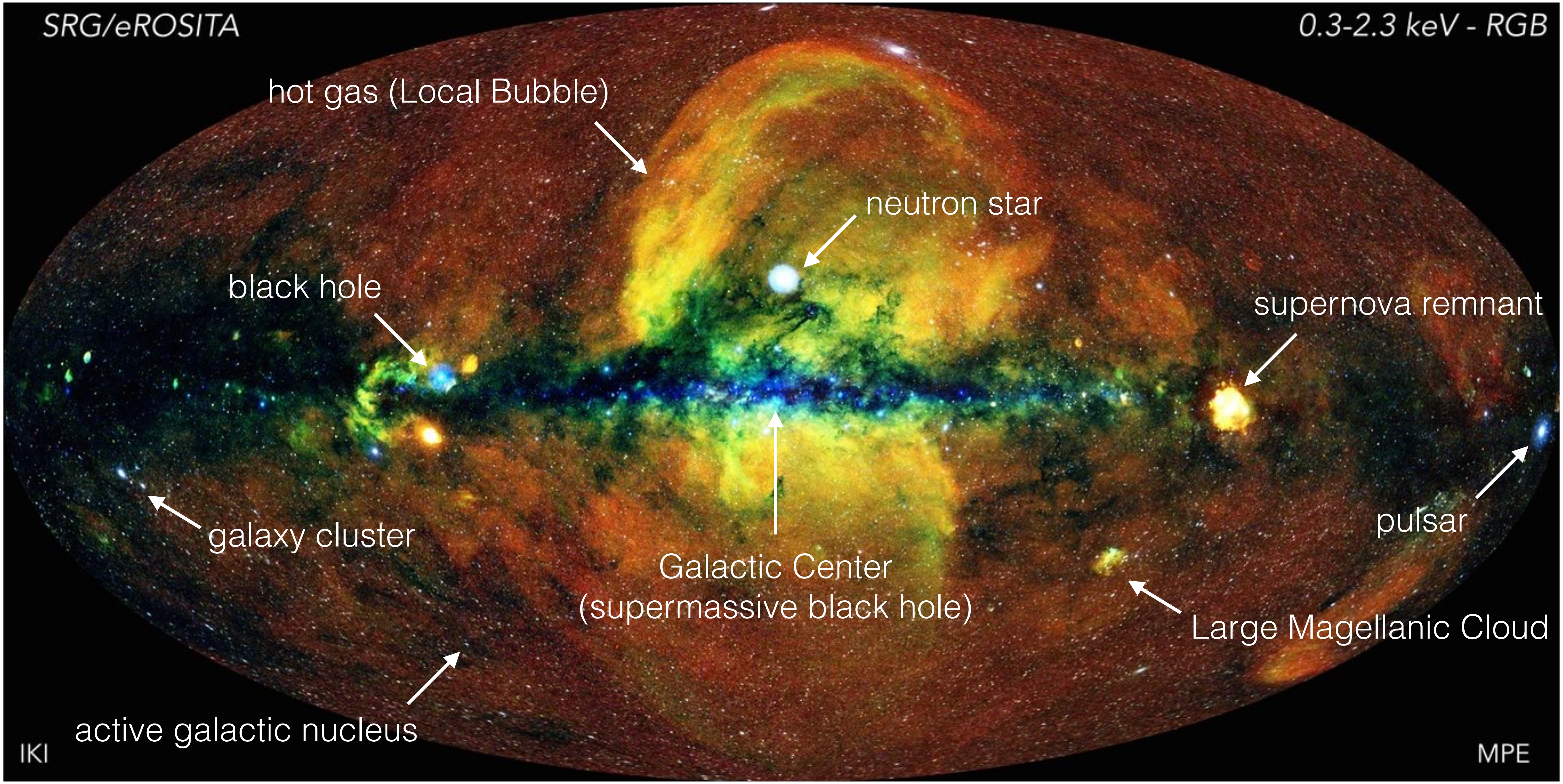
Lecture focused on **remote** observations:

1. X rays (0.1 nm —> 10 nm)
2. Visible / near infrared (300 nm —> 3 µm)
3. Mid-infrared (3 µm —> 30 µm)
4. Far-IR / submm / millimetric (30 µm —> 3 mm)

✦ Cosmic Vision: ESA’s scientific program

Structure of each section

- Main interests of the wavelength range
- Example(s) of space mission(s)
- Technical challenges
- Some scientific results
- Future missions

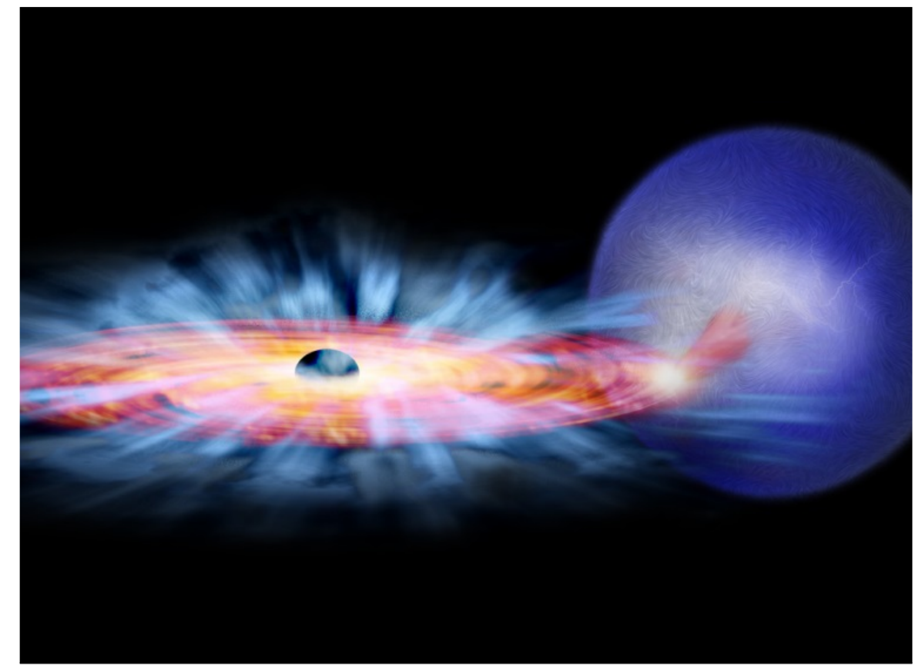


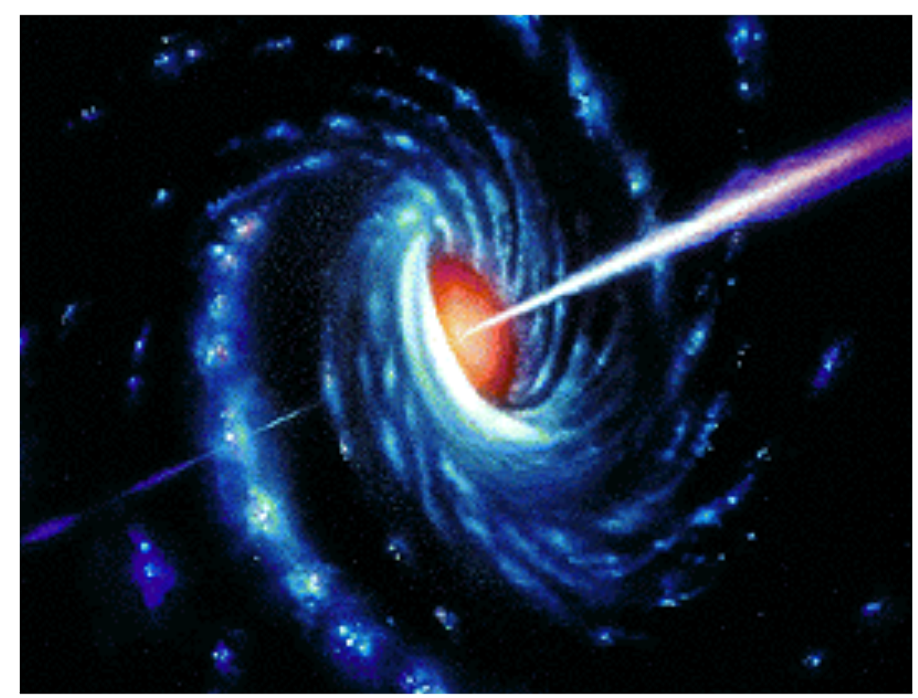
X-rays

From λ = 0.1 nm to λ = 10 nm

Astrophysical interests

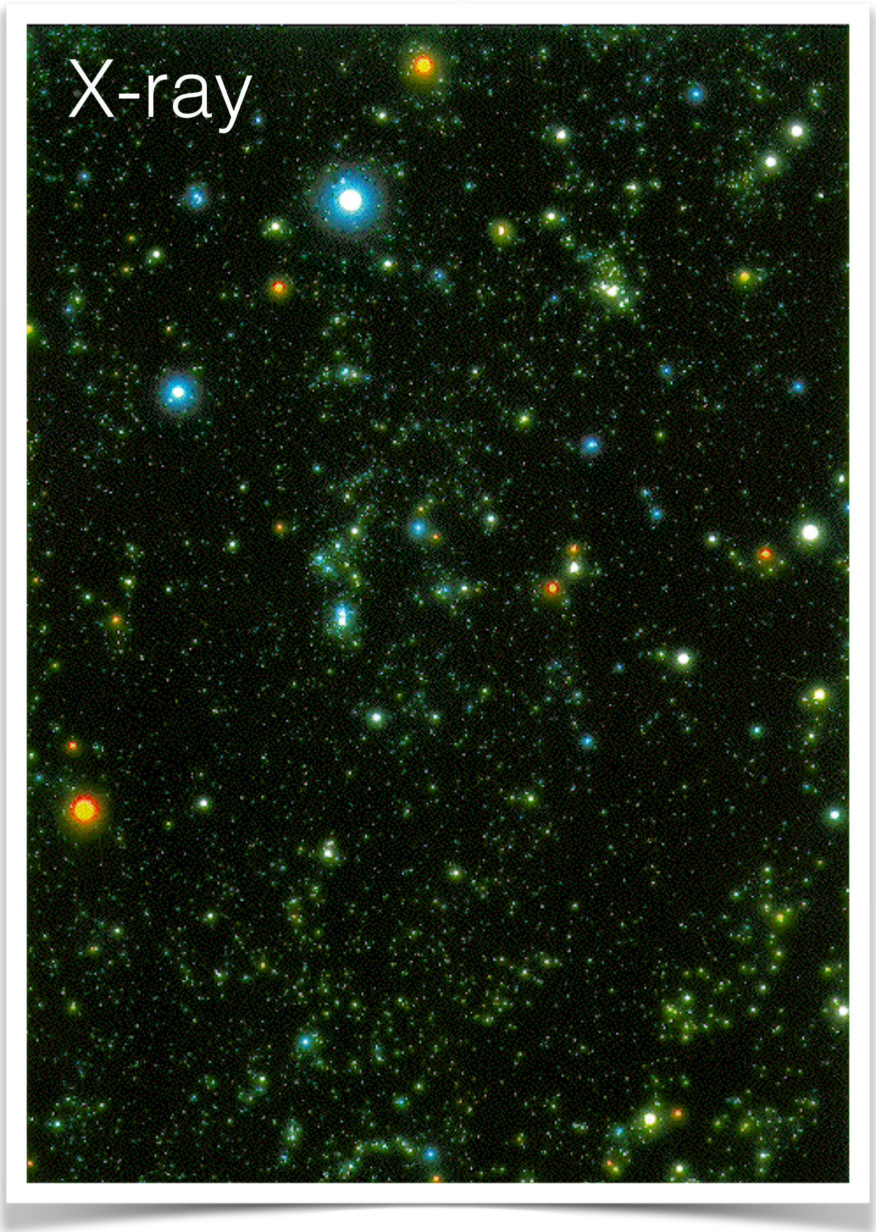
- Origin: hot gas, relativistic particles
  - stellar physics
  - X-ray binary = donor + accretor (neutron star, black hole)
  - quasars / active galactic nuclei
  - dark matter
- Violent phenomena





Astrophysical interests

- Another view on the Universe



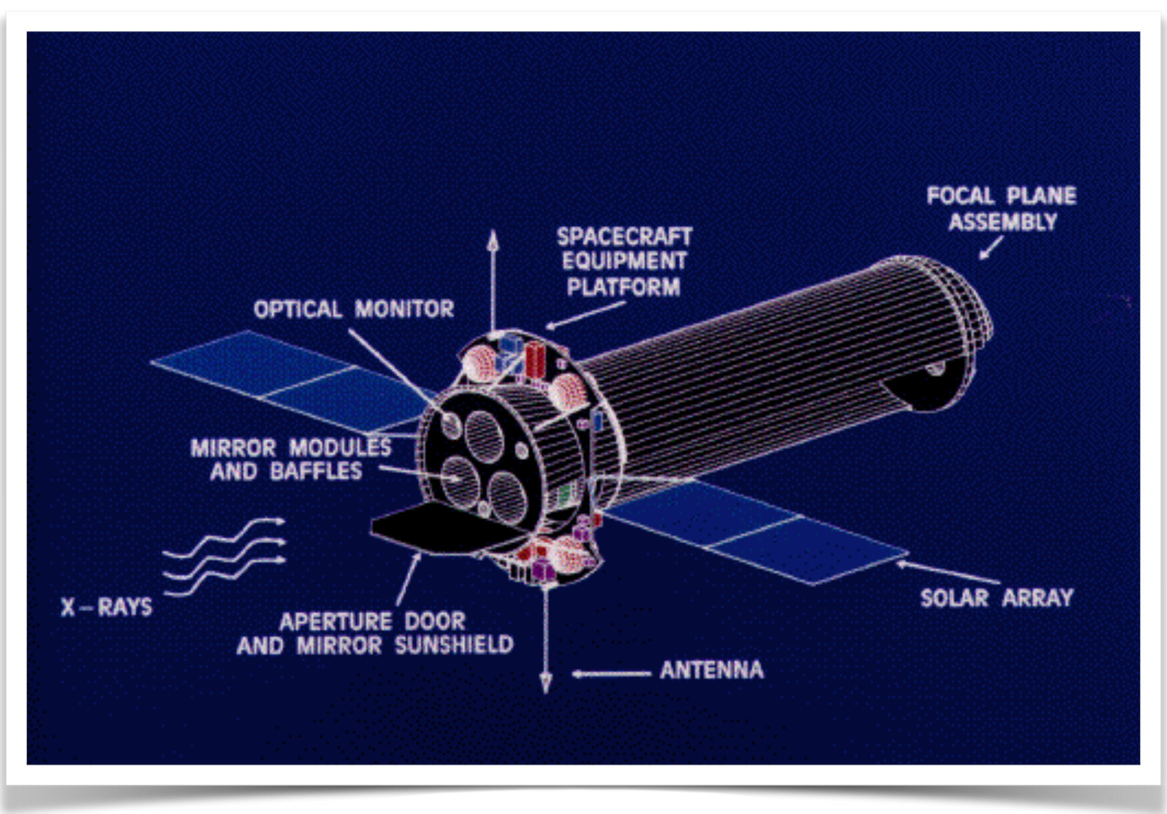
Two major missions (both still operating)

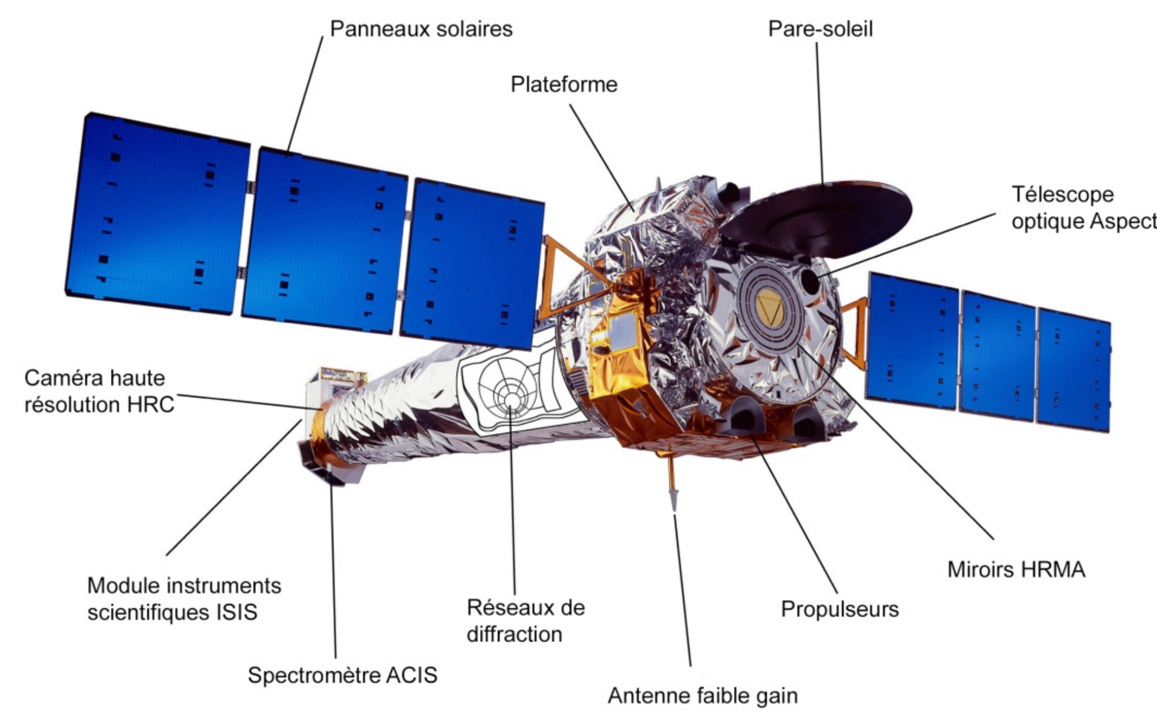
✦ XMM-Newton (1999)

- length: 10 m
- weight: 3.8 tons
- launch: Ariane 4

✦ Chandra (1999)

- length: 12 m
- weight: 1.5 tons
- launch: space shuttle

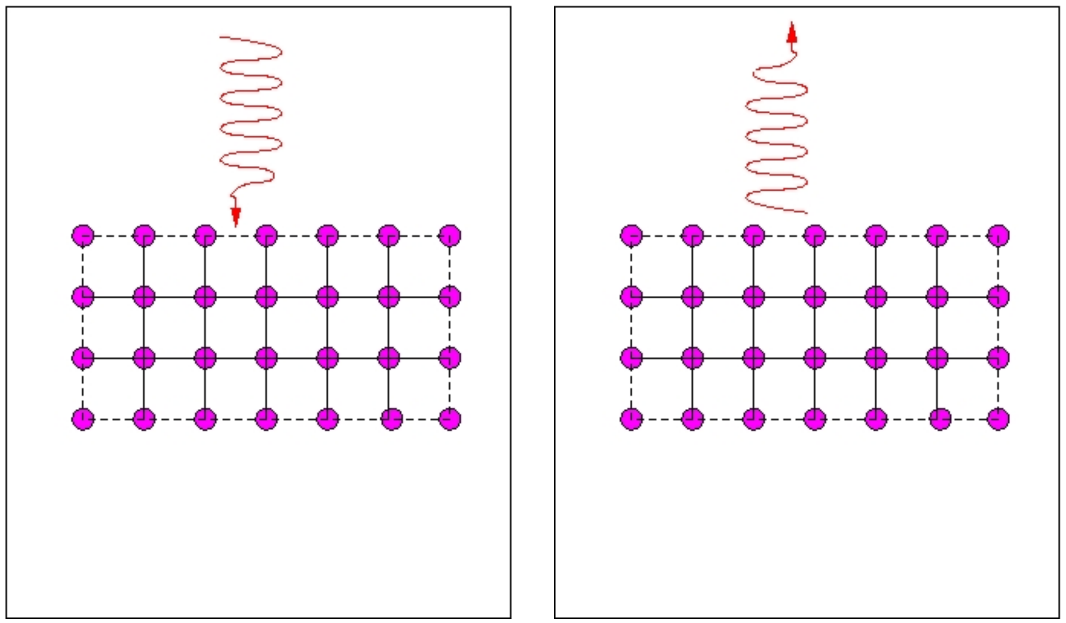




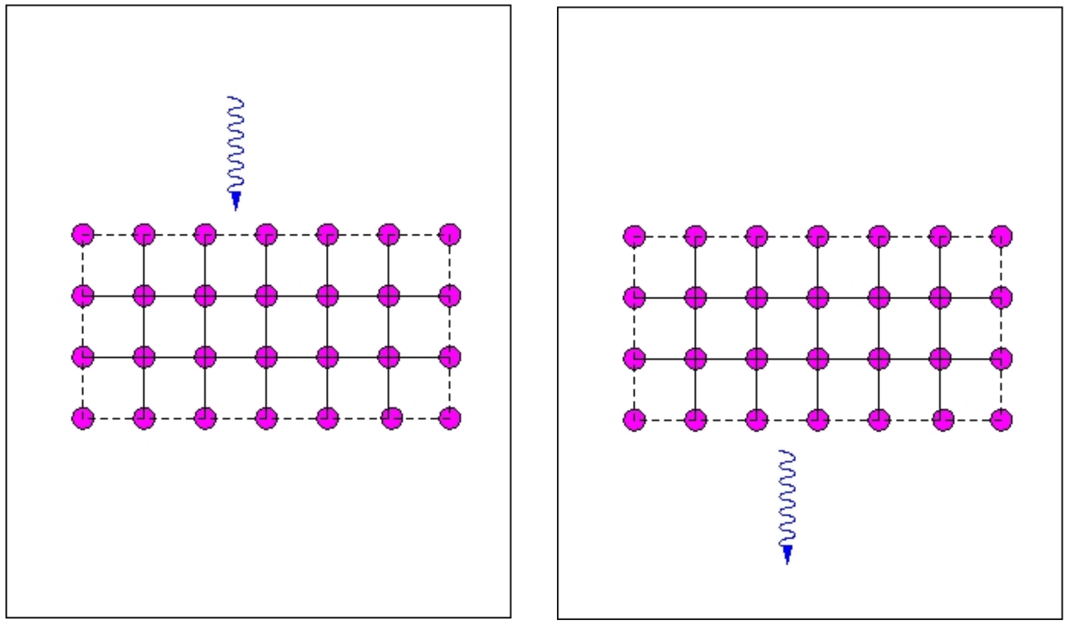
Focusing X rays

- A long story!
- X-rays —> high penetrating power
  - cannot be reflected off in normal incidence

Visible light

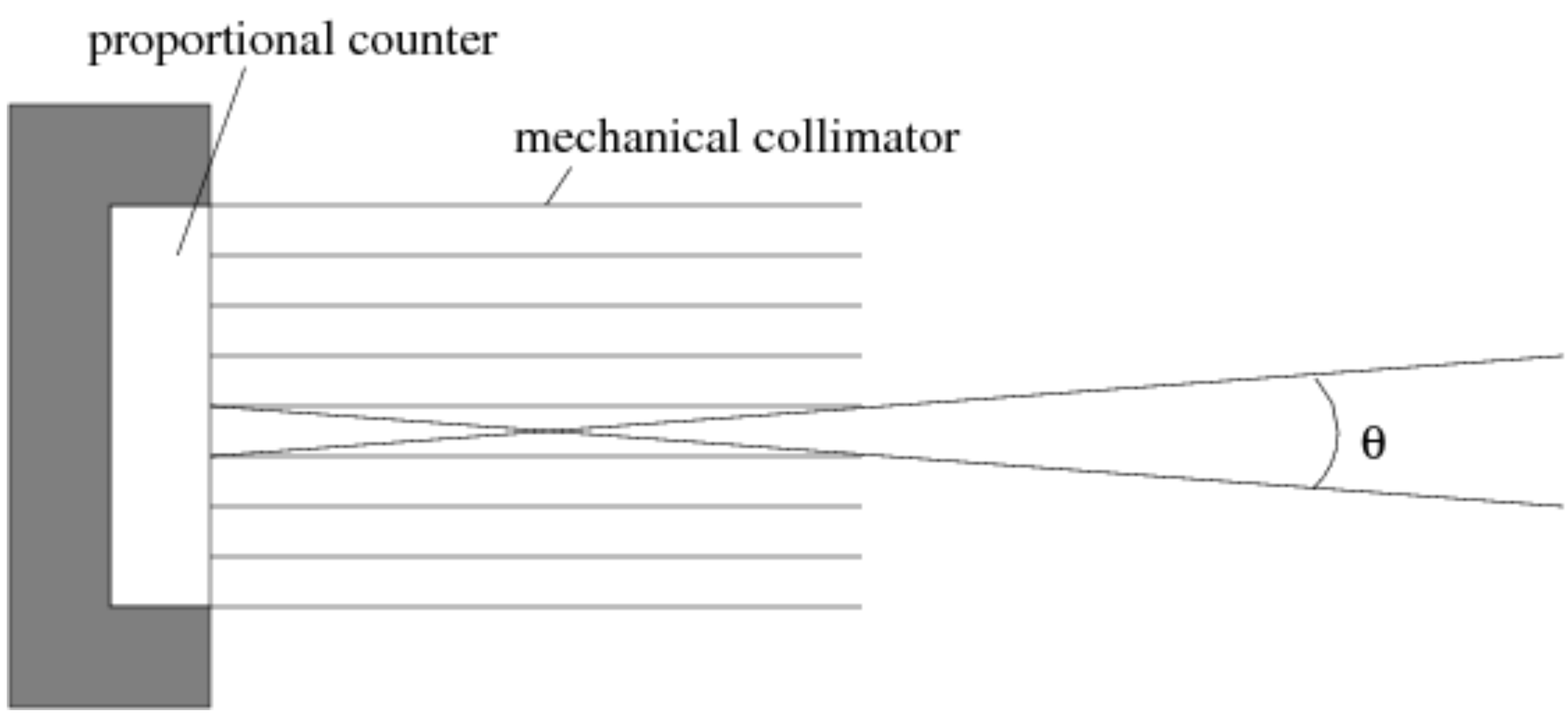


X rays



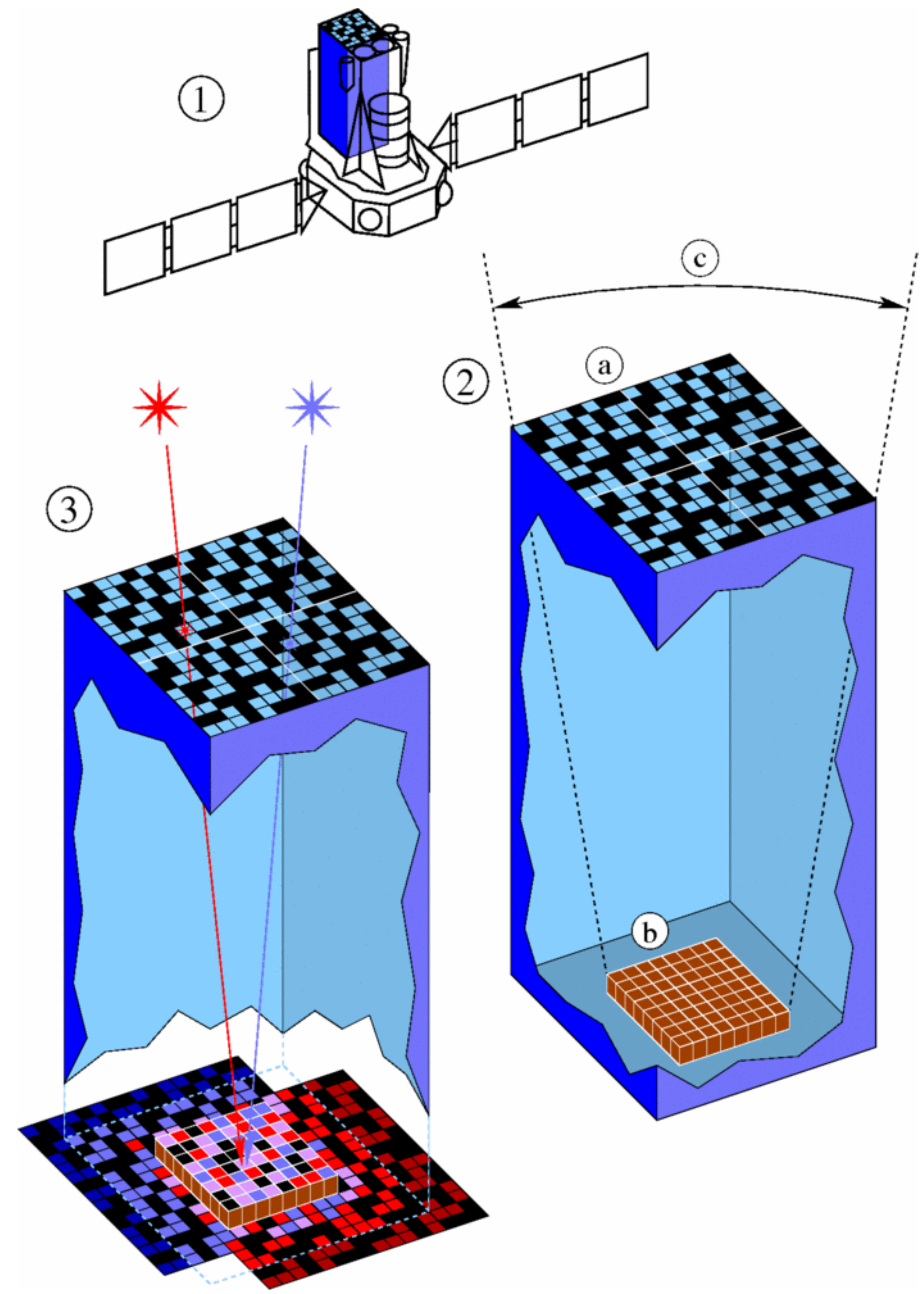
Focusing X rays

- First solution: mechanical collimator
  - set of hollow tubes in front of the detector to restrict the direction of light rays
- Does not give a true image (need to scan)



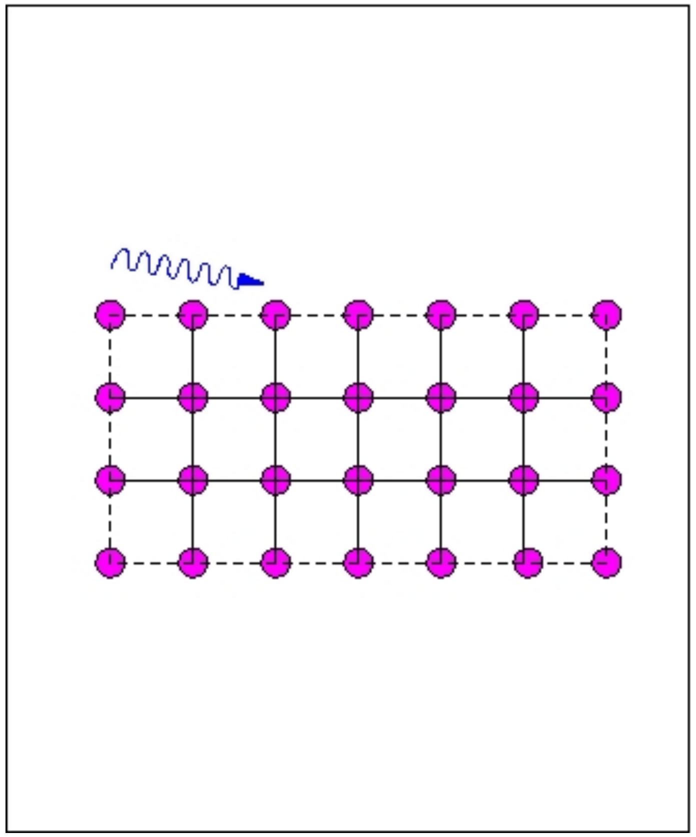
Focusing X rays

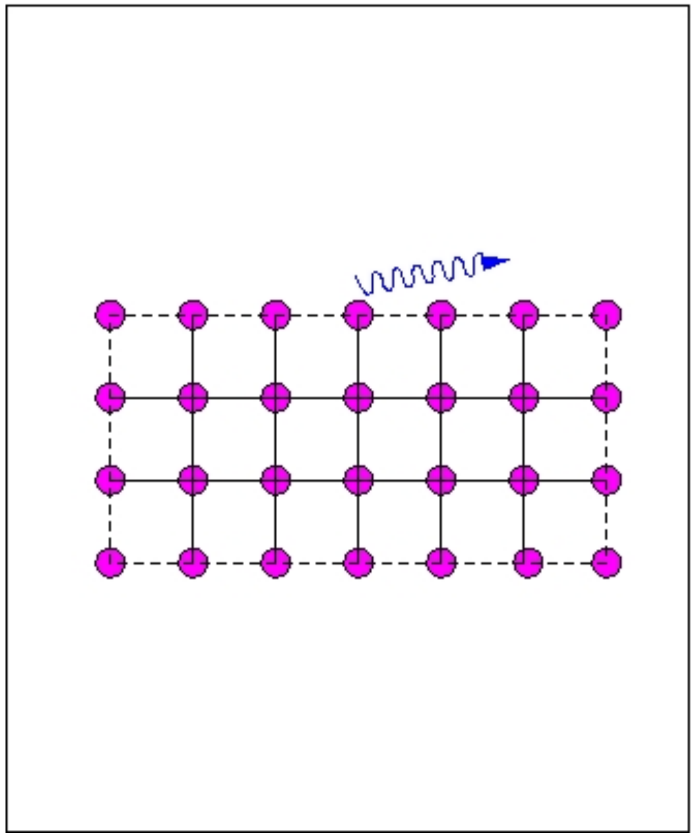
- ✦ Second solution: coded aperture
  - partial masking of telescope aperture
  - measure the superposition of mask shadow projected onto the detector
- ✦ Drawbacks
  - low resolving power
  - limited sensitivity (light spread on many pixels)
- ✦ Still used in ɣ-ray astronomy

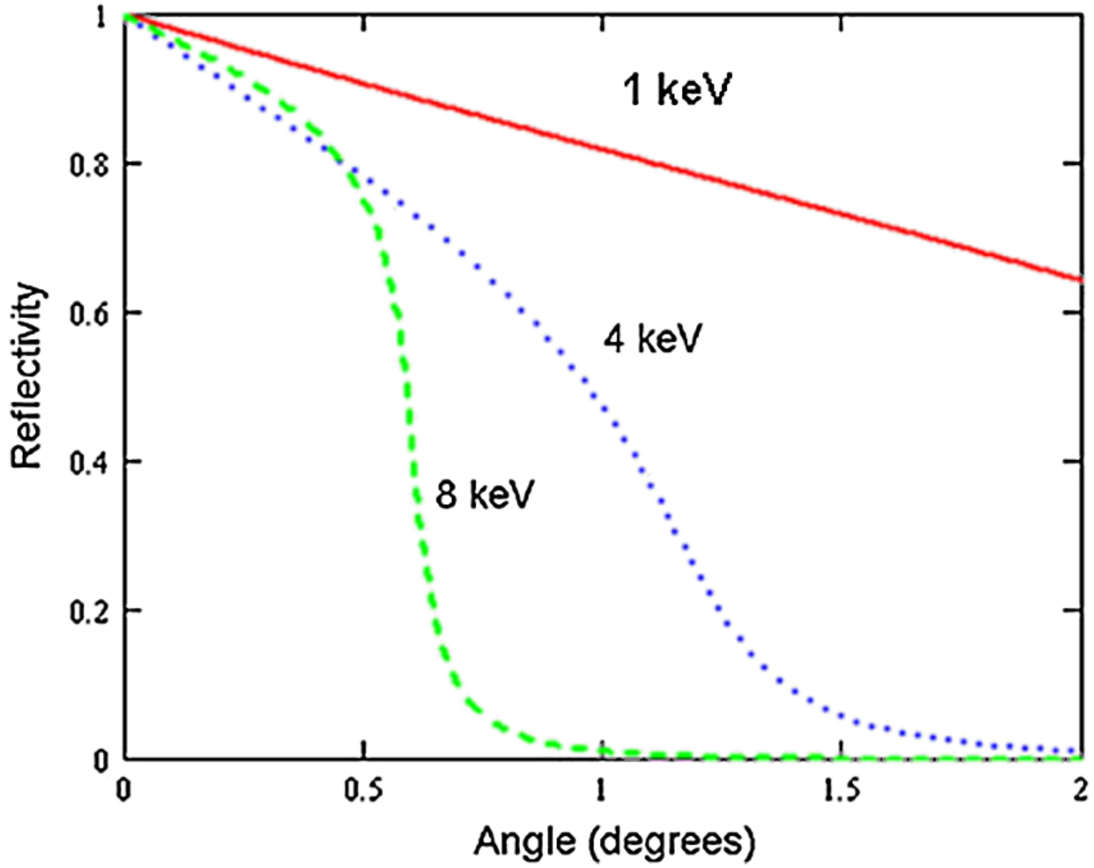


Focusing X rays

✦ Third solution: grazing incidence

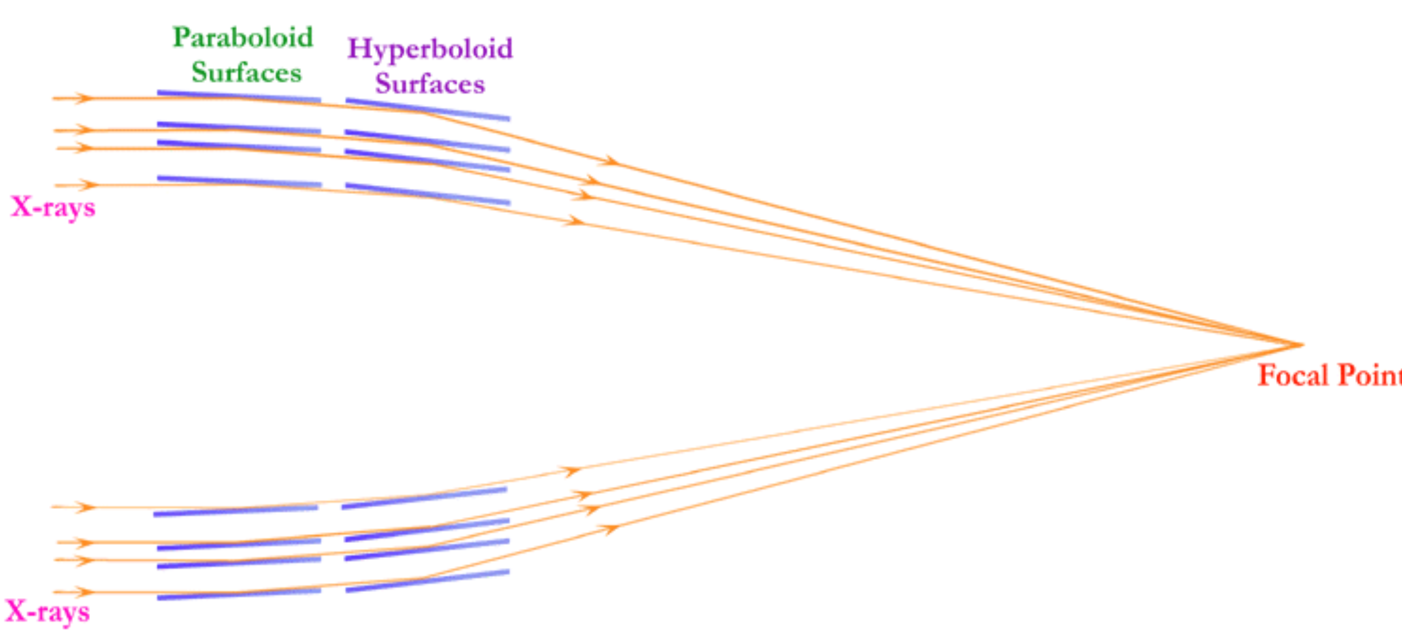


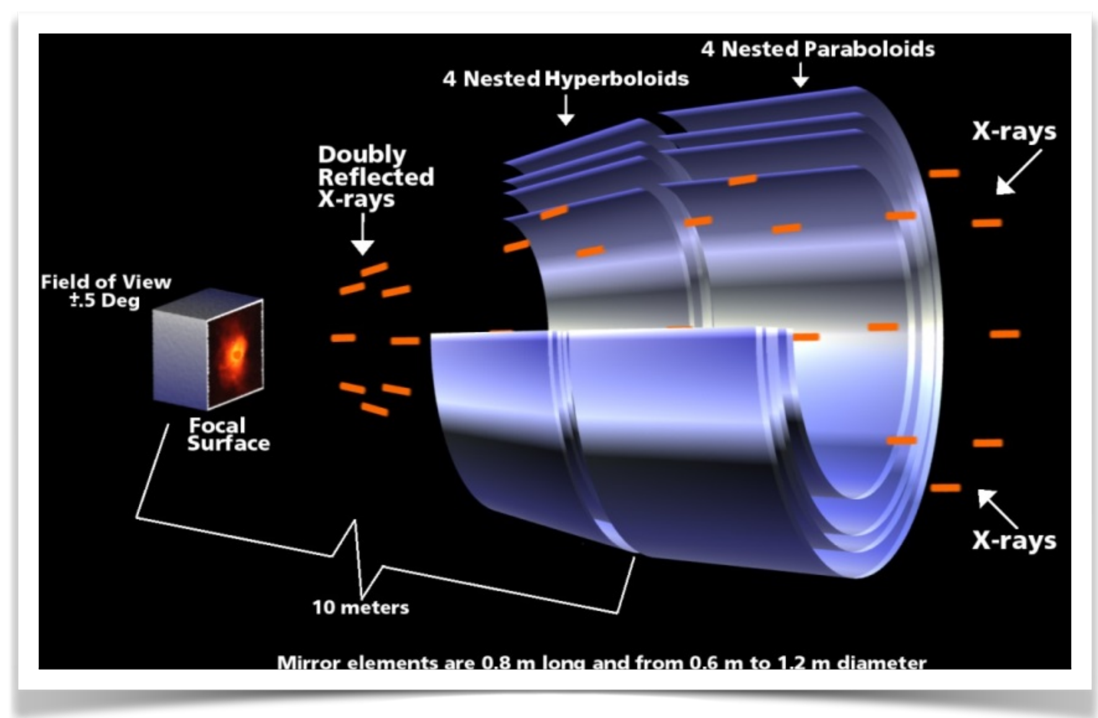




Focusing X rays

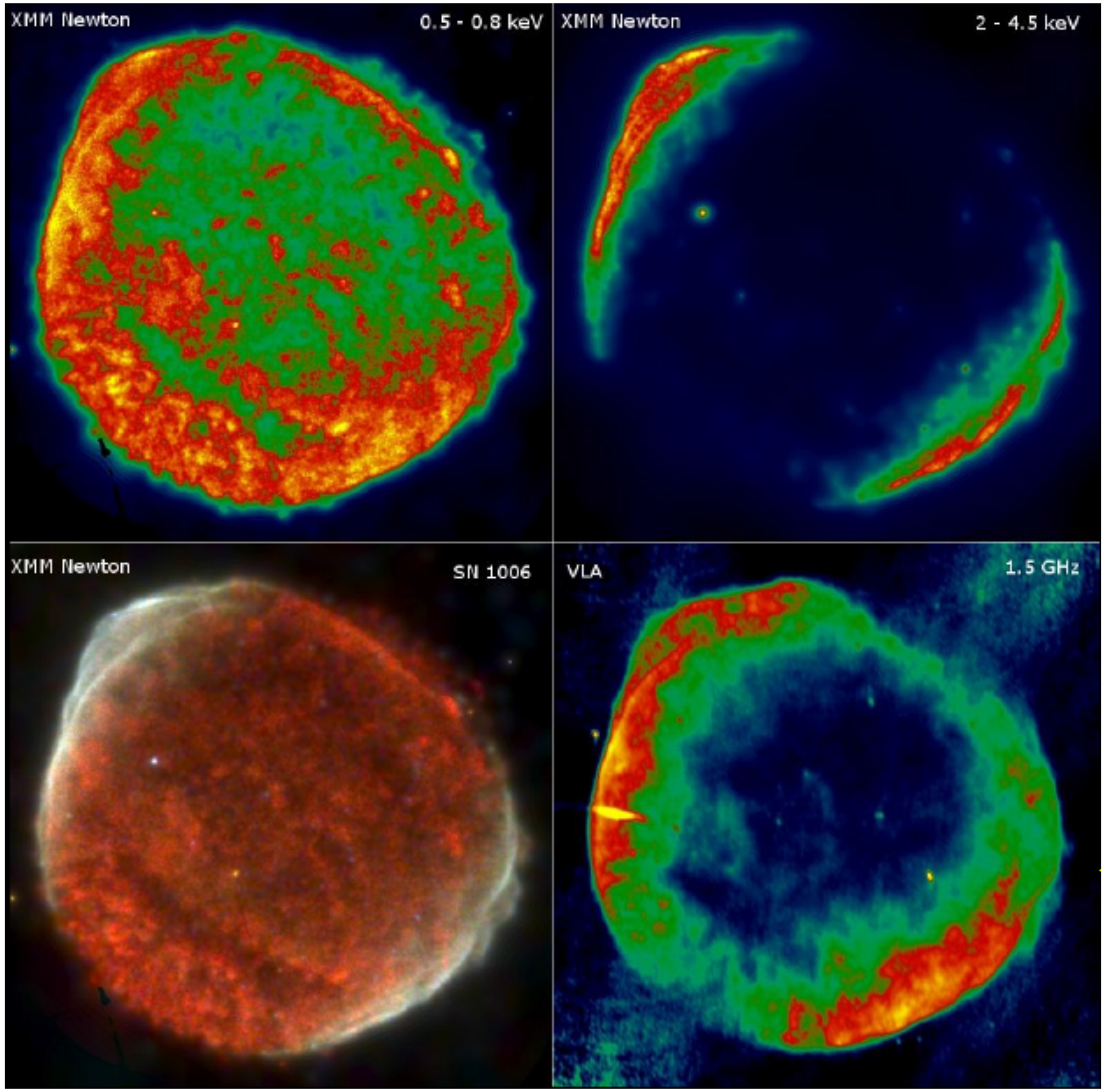
- Implementation of grazing incidence
  - true telescope, with very long focal length
  - Wolter-type design: combines two reflections (paraboloid and hyperboloid)
  - increase collecting area —> nested mirrors





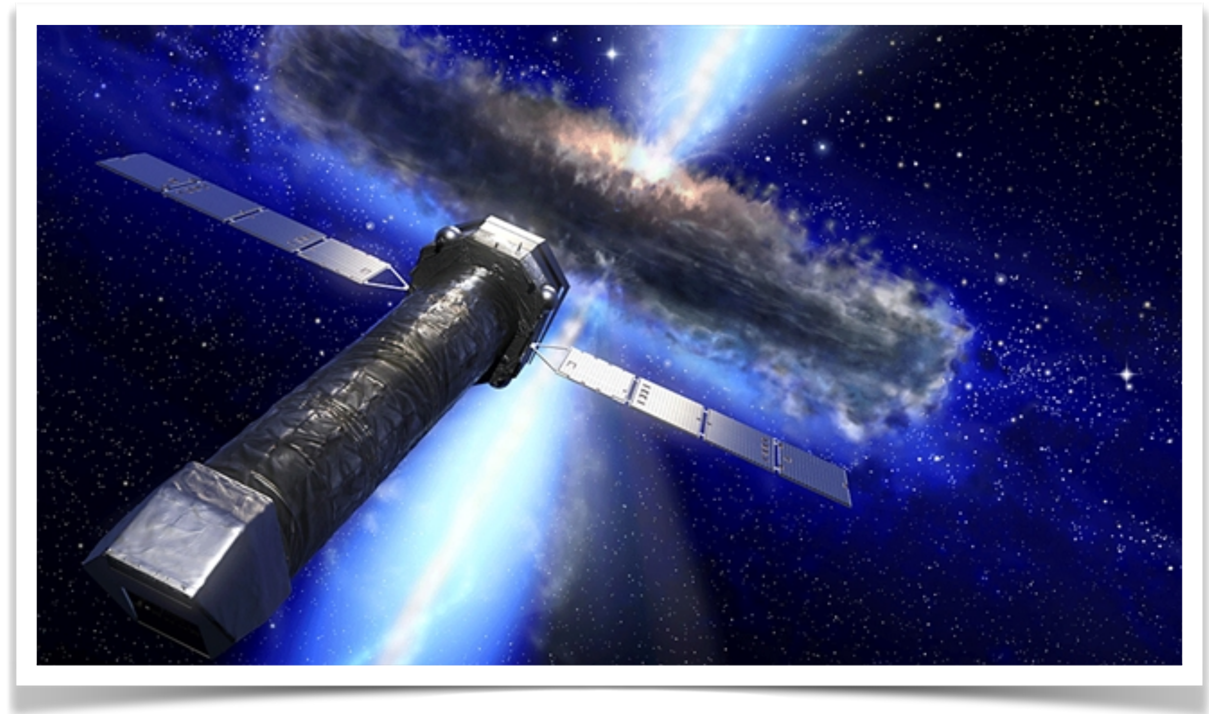
Major results

- Accretion/ejection phenomena
- Discovery of ultra-hot plasma (> 10^6 K)
- Supernovae: explosions and remnants
- Pulsars, magnetars, X-ray binaries, black holes, etc
- Highest energy: ɣ-ray bursts

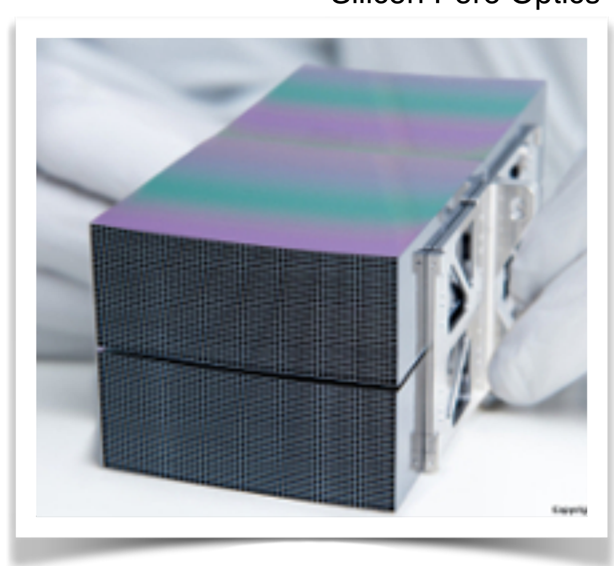


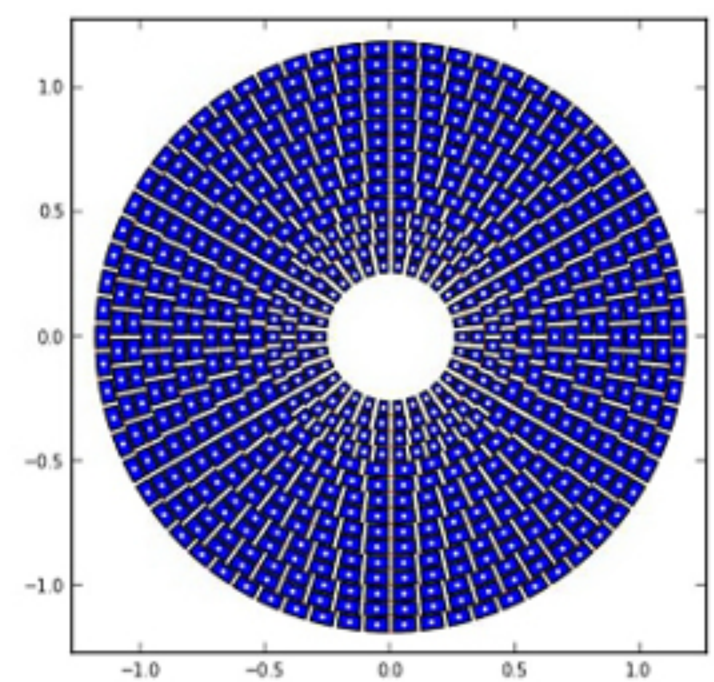
Future missions

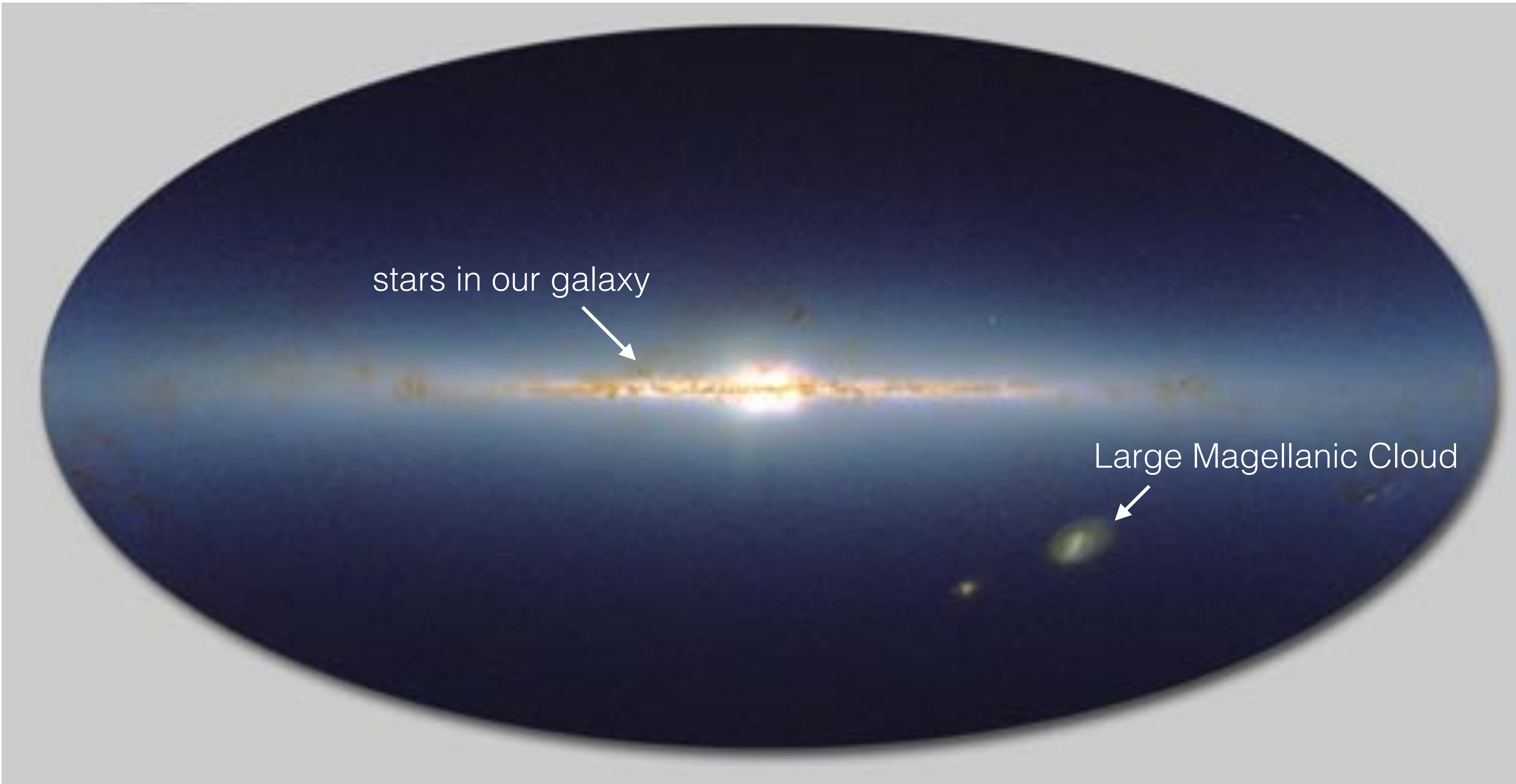
- Goal: increase collecting area
- ATHENA project (2035)
  - effective collecting area of 1.4 m^2 (3x more than XMM)
  - angular resolution: 5 arcsec
  - focal length: 11 m
  - mass < 6.5 tons
  - new lightweight technology
- To go beyond: deployable structures, formation flying



Silicon Pore Optics





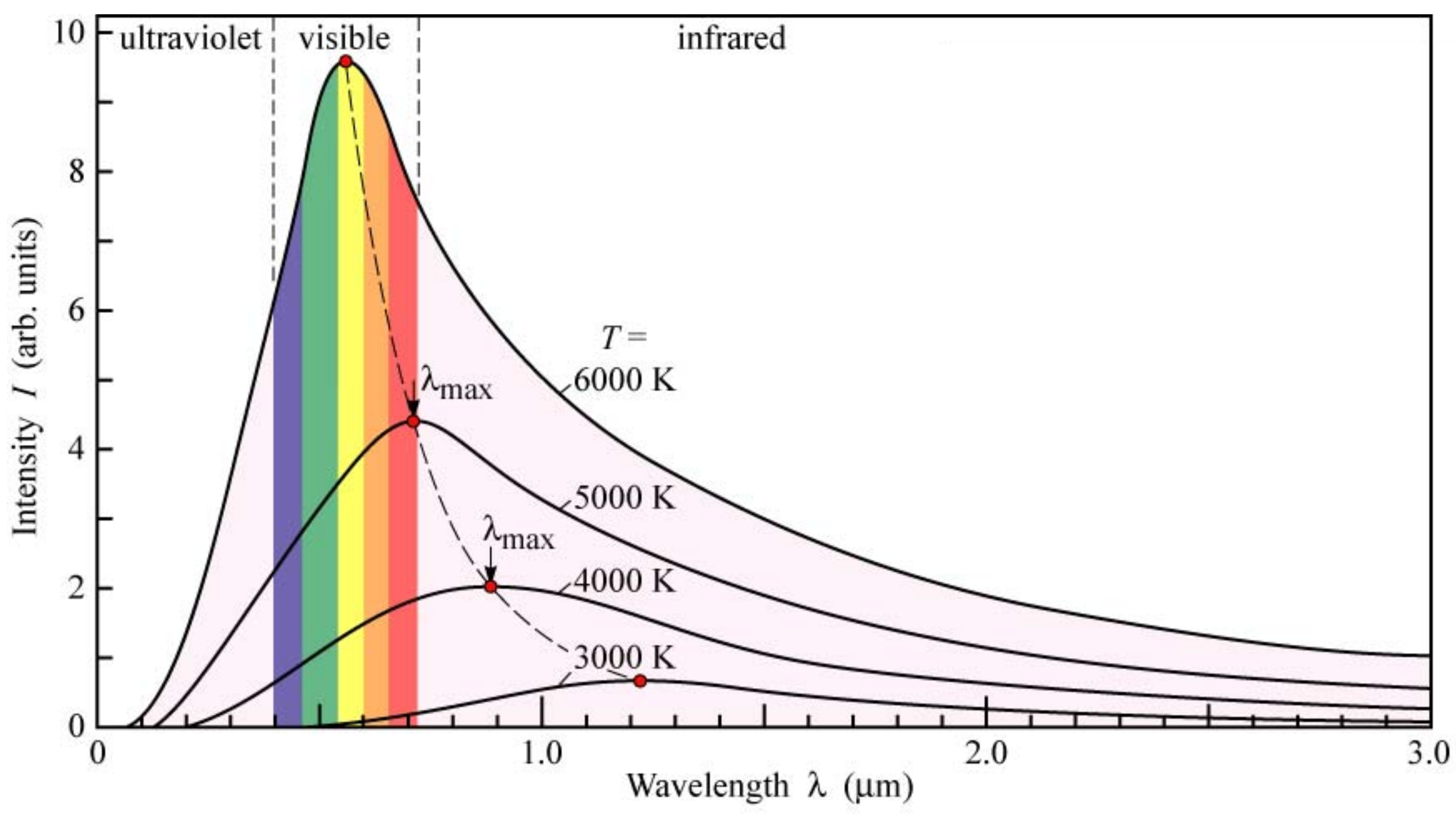


Visible / near-infrared

From λ = 300 nm to λ = 3 μm

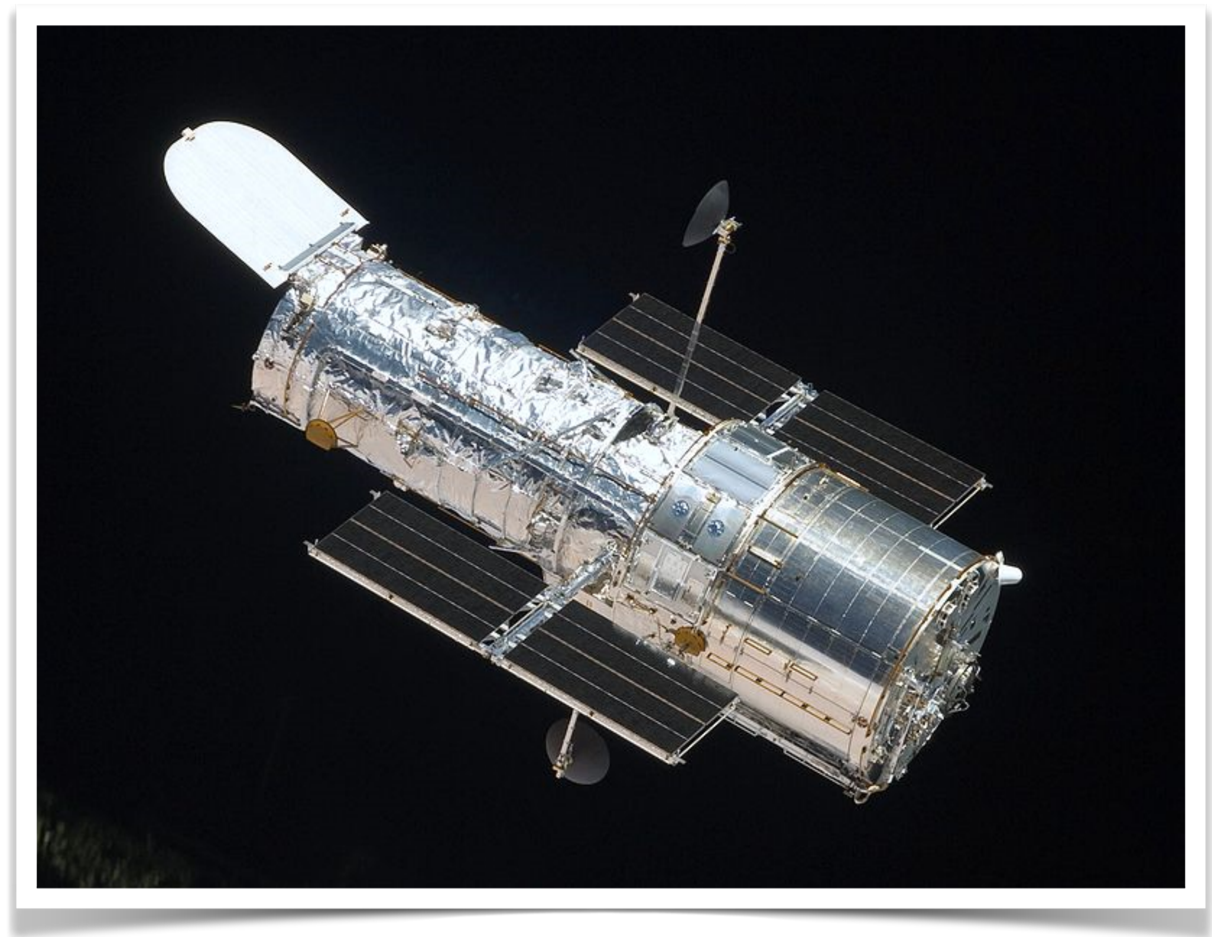
Astrophysical interests

- From Wien's law: λ_{max} (μm) = 2898 / T (K)
  - thermal emission at 3,000 - 10,000 K
  - realm of stars / galaxies



Hubble Space Telescope

- ✦ Idea born: 40's
- ✦ Project started: 60's
- ✦ Design / construction: 70's-80's
- ✦ Launch: 1990 (7 yr late)
  - space shuttle (Discovery)
  - low Earth orbit (560 km)
- ✦ Mission extended till 2026. Lifetime limited by failing gyroscopes and orbital decay (+ instruments aging).

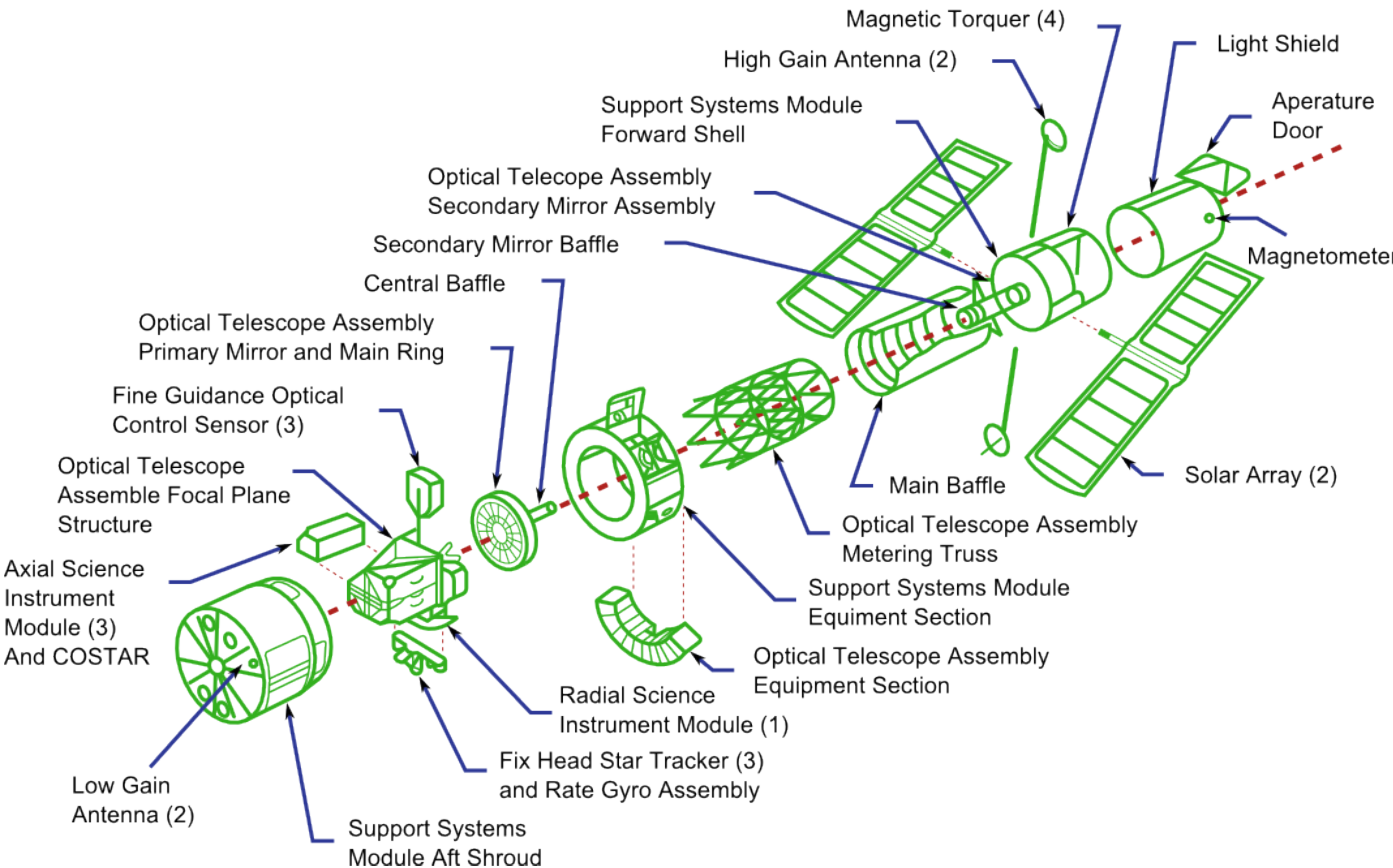


Length: 13 m
Weight: 11 tons

Hubble Space Telescope

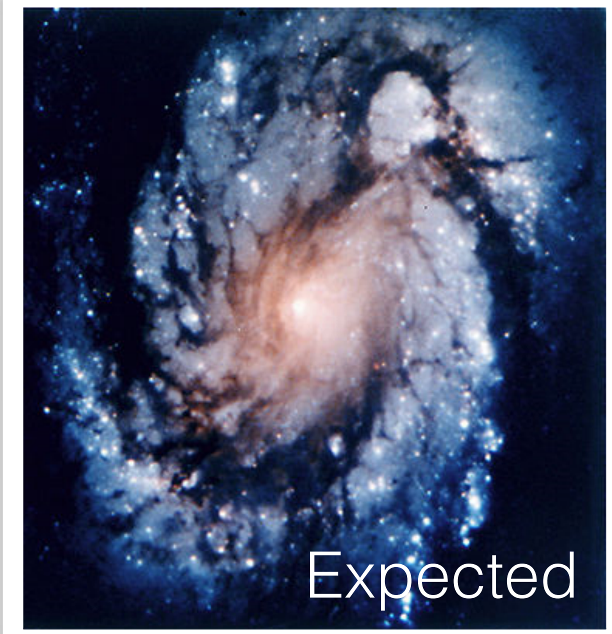
- Telescope diameter: 2.4 m
- Wavelength range: 115 nm to 2.4 μm
- Angular resolution 0.05 arcsec (visible light)
  - 20 x better than ground-based telescope w/o adaptive optics (but now the trend is reversing with the advent of extreme AO)
- Sensitivity ~50x better than ground-based 10 m-class telescopes (still true)
- Instruments: 3 imaging cameras + 2 spectrographs + guiding sensor
- The only serviceable space telescope
  - space rendez-vous with the shuttle
  - was initially supposed to be brought back on ground every 5 years!

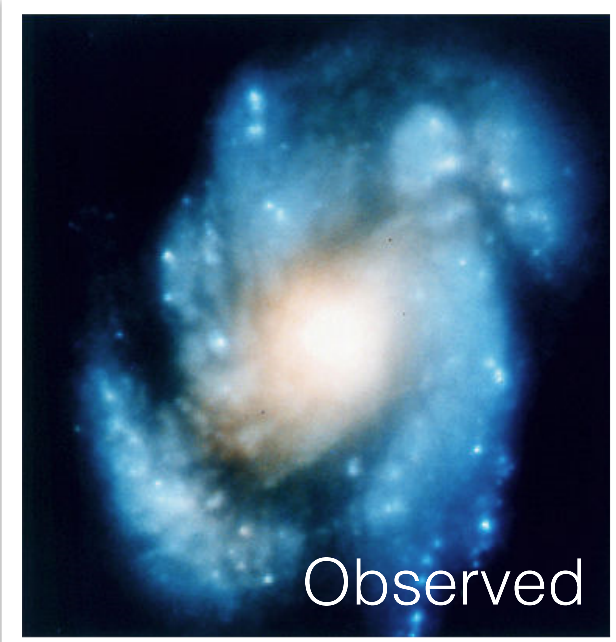
Complexity of the HST



HST's technical challenges

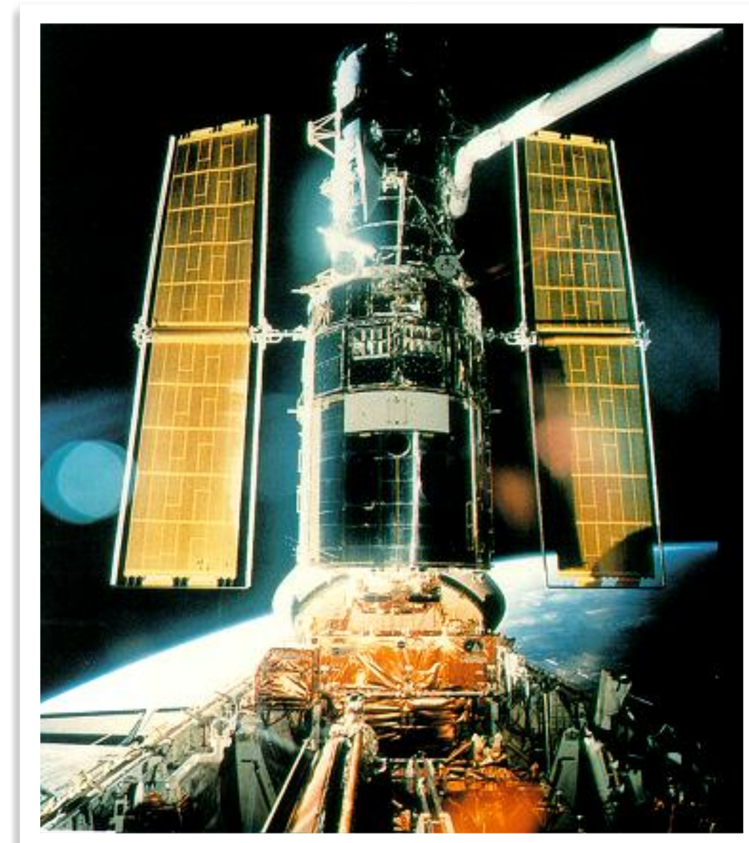
- ✦ Primary mirror: lightweight monolithic reflector
  - thickness: 2 cm (reduce weight)
  - honeycomb structure (resistant to launch)
- ✦ Diffraction-limited —> defects < $\lambda/10$
  - ultraviolet observations: λ = 100 nm
  - new computer-assisted polishing method
- ✦ Final mirror: 2 μm surface error on the sides
  - due to misaligned lens in test equipment for primary mirror (tested separately from full telescope)
  - spherical aberration is a catastrophe: resolution ~ 1 arcsec!

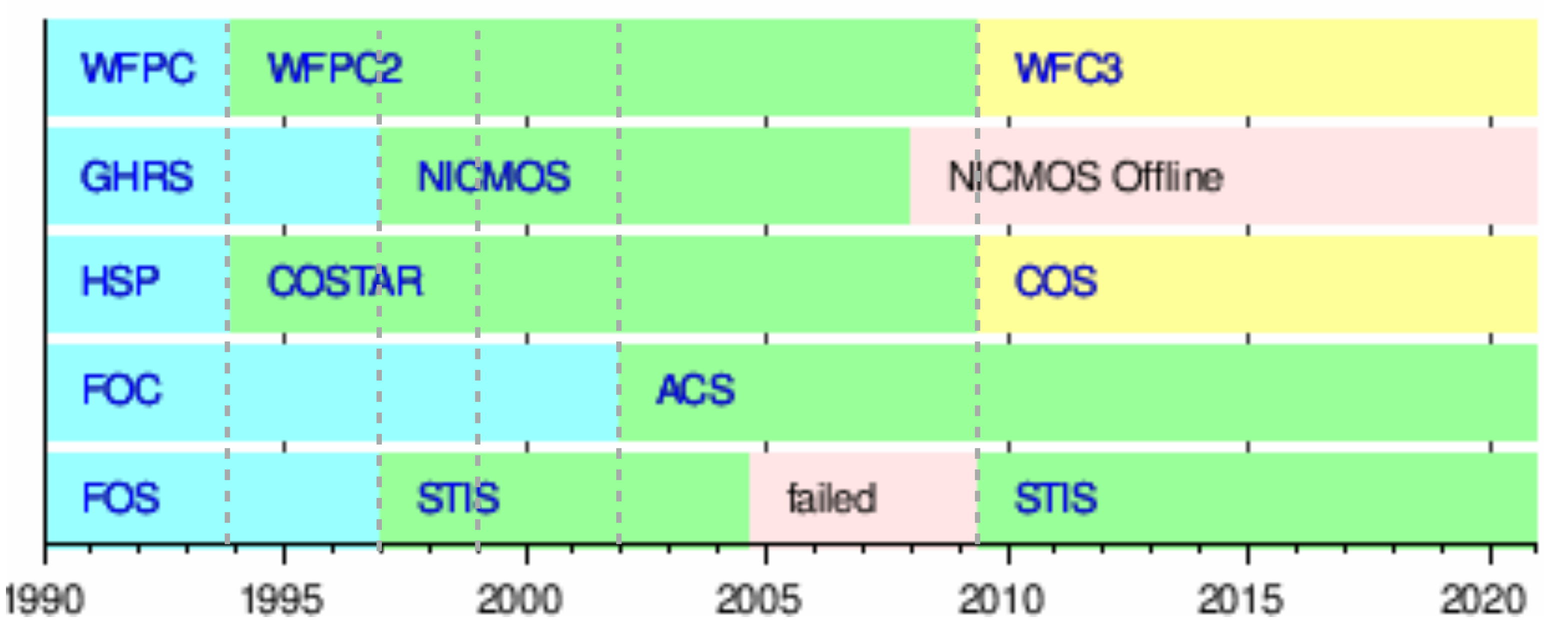




Servicing missions

- ✦ Mirror impossible to replace
  - new instruments —> integrated optical corrector
  - old instruments —> correcting package
- ✦ Missions in 1993, 1997, 1999, 2002, 2009
  - replacement of instruments, gyroscopes, solar panels, batteries, etc.
  - various repairs + orbital correction





Wide field camera

Near-IR camera and spectrograph

UV spectrograph

UV / visible / near-IR camera

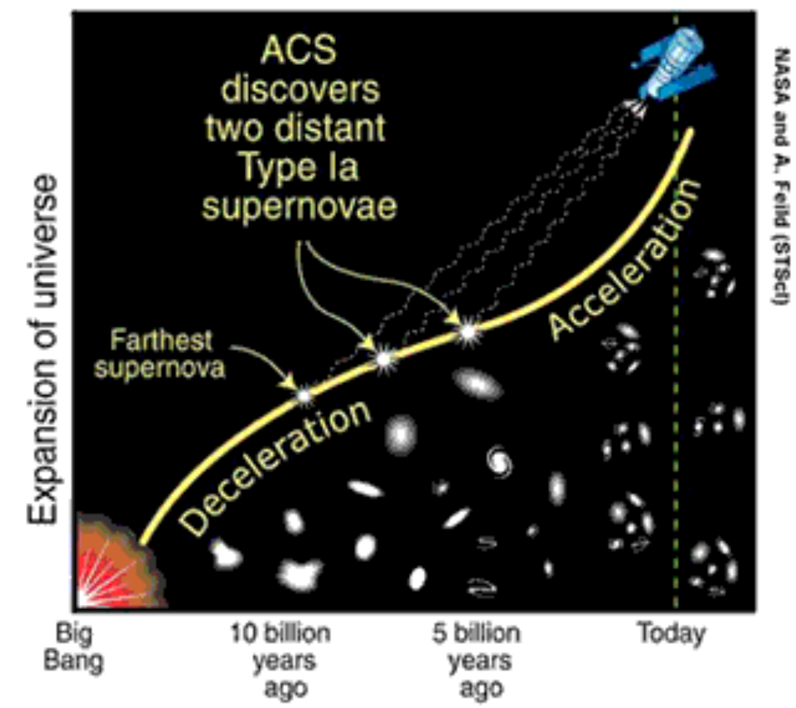
UV / visible / near-IR spectrograph

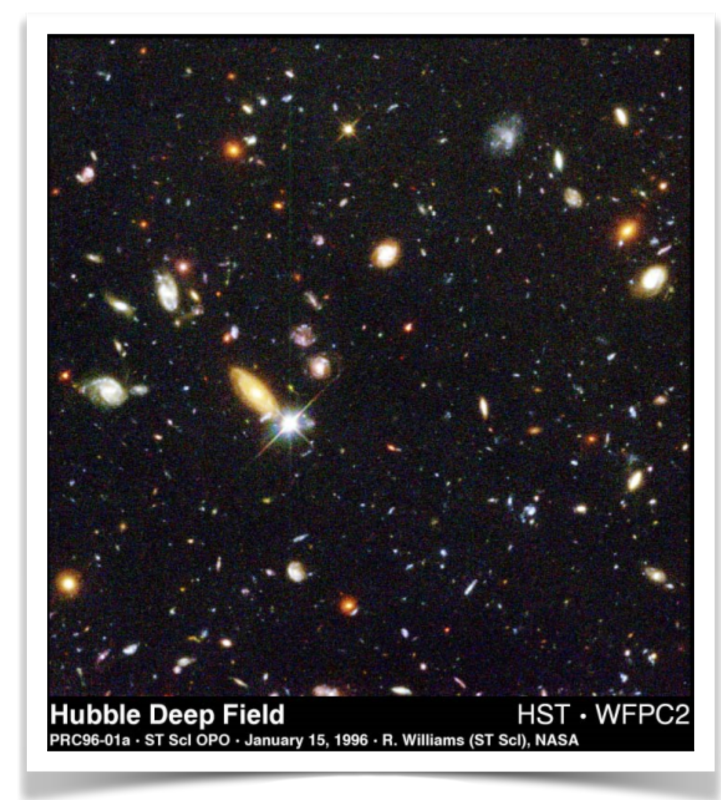
Other challenges

- ✦ Thermal / mechanical stability
  - 96 min day / night cycle
  - observations possible even during thermal shock thanks to multilayer insolation, carbon fiber structure, etc
- ✦ Future maintenance (without the shuttle)
  - no more servicing missions … unless private partner?
  - de-orbitation: initially foreseen with space shuttle, then external propulsion module considered. Finally capture system installed to enable de-orbit by crewed or robotic mission.
- ✦ Budget
  - 400 M$ —> 2.5 G$ (launch) —> ~9 G$ (2010)

Extragalactic discoveries

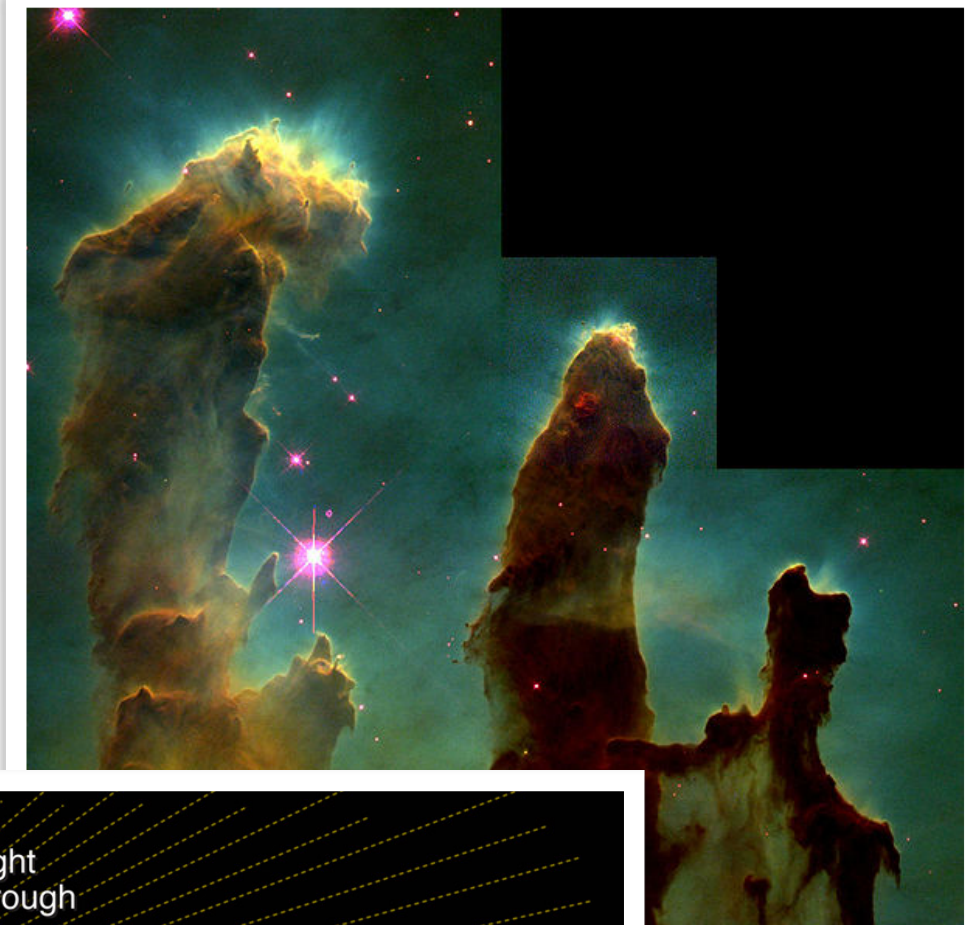
- ✦ Estimation of the Hubble constant (H_0)
  - Hubble-Lemaître law: $v = H_0 D$
  - HST —> measures D with Cepheids
- ✦ Expansion of the Universe
  - remote supernovae —> accelerating expansion!
  - requires dark energy
- ✦ Black holes at the center of galaxies
- ✦ Hubble Deep Field (10-day exposure): « primordial » galaxies

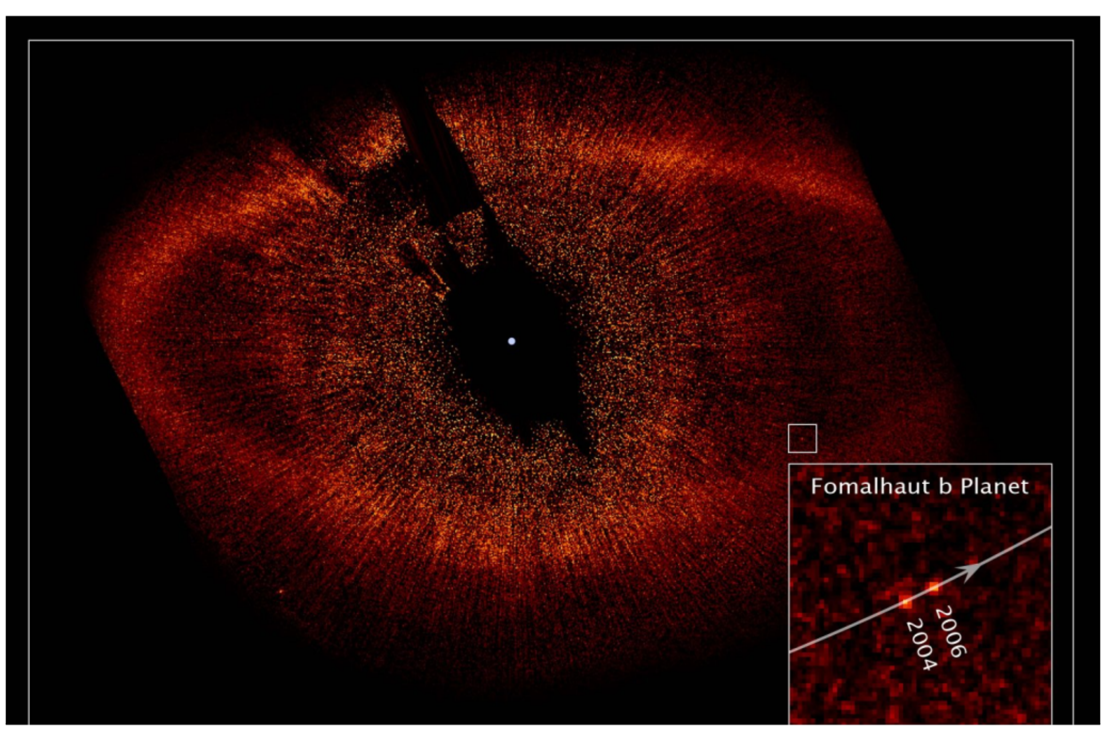


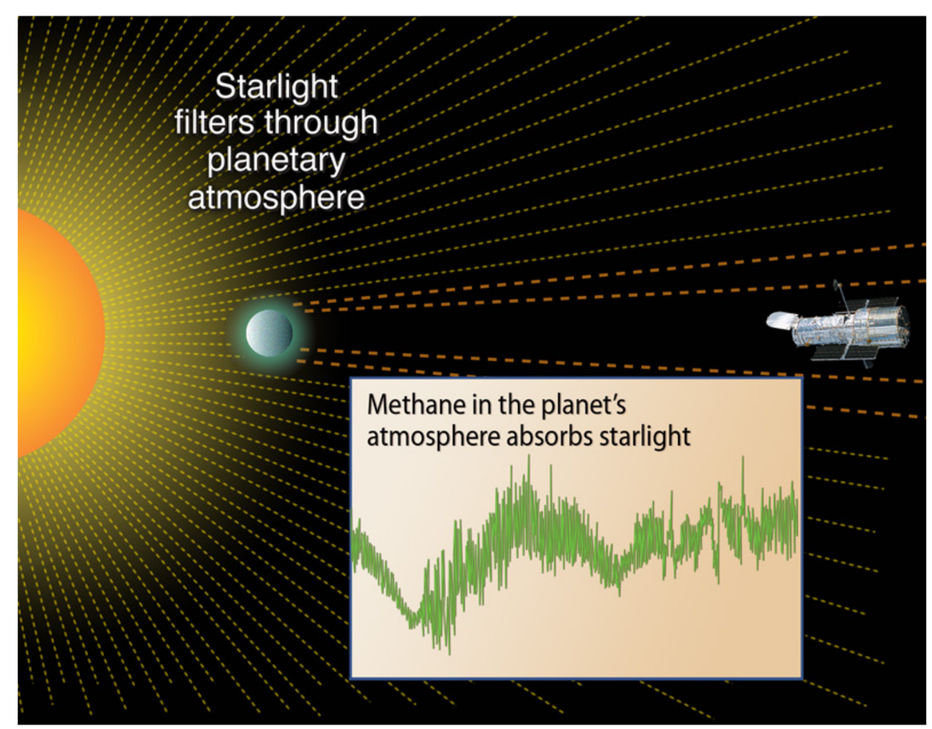


Galactic discoveries

- ✦ Star / planet formation
- ✦ Extrasolar planets
  - confirmation of planetary nature (transit)
  - first images of planetary systems
  - first exoplanet spectrum —> composition

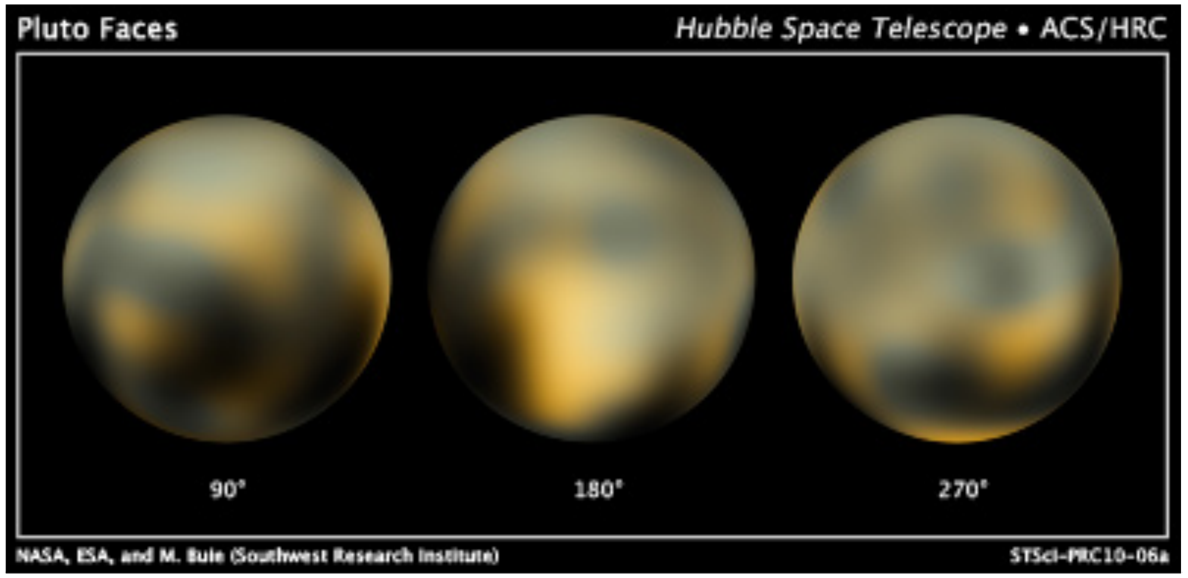


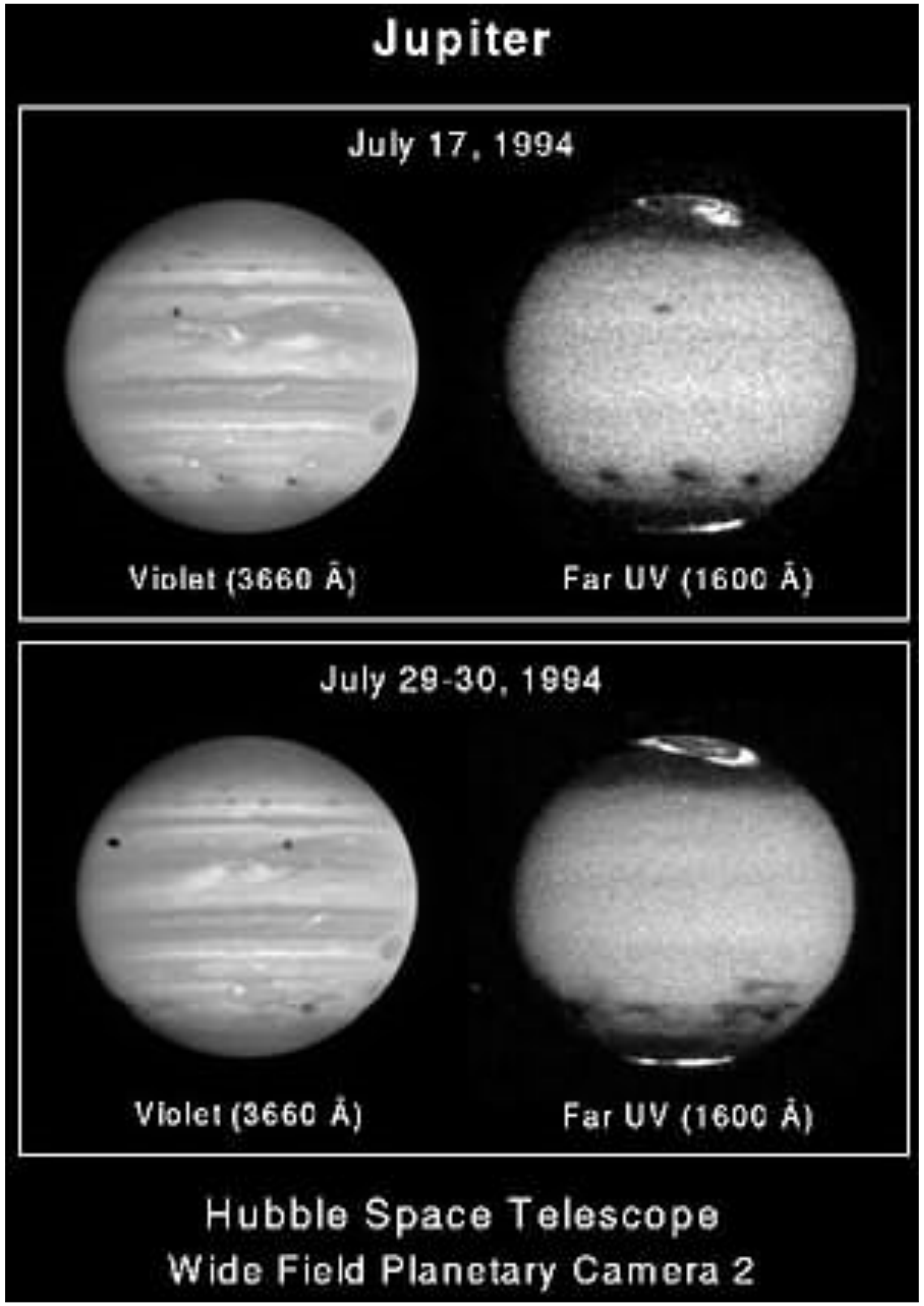




Solar system

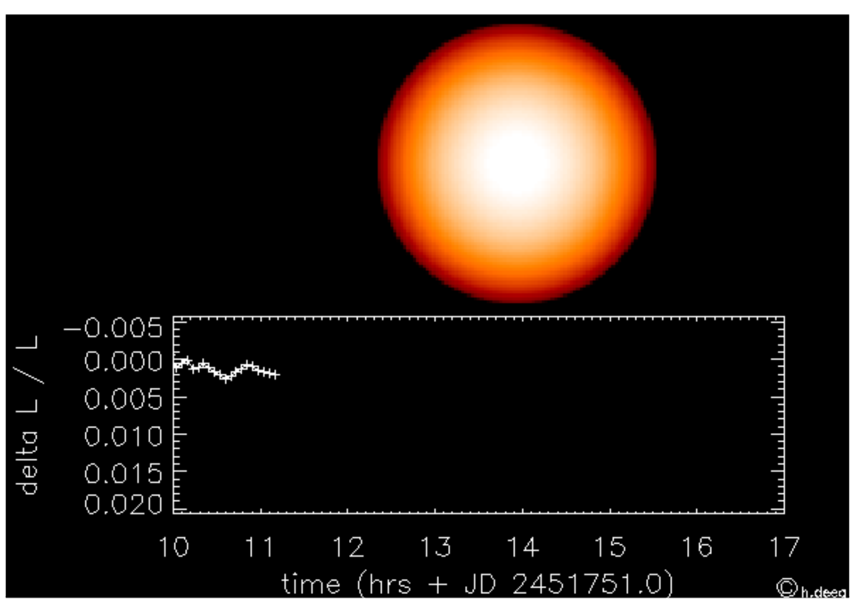
- ✦ Giant planets: aurorae, impacts, atmospheric dynamics, etc.
- ✦ Dwarf planets: Pluto's surface, small bodies in Solar System, etc.

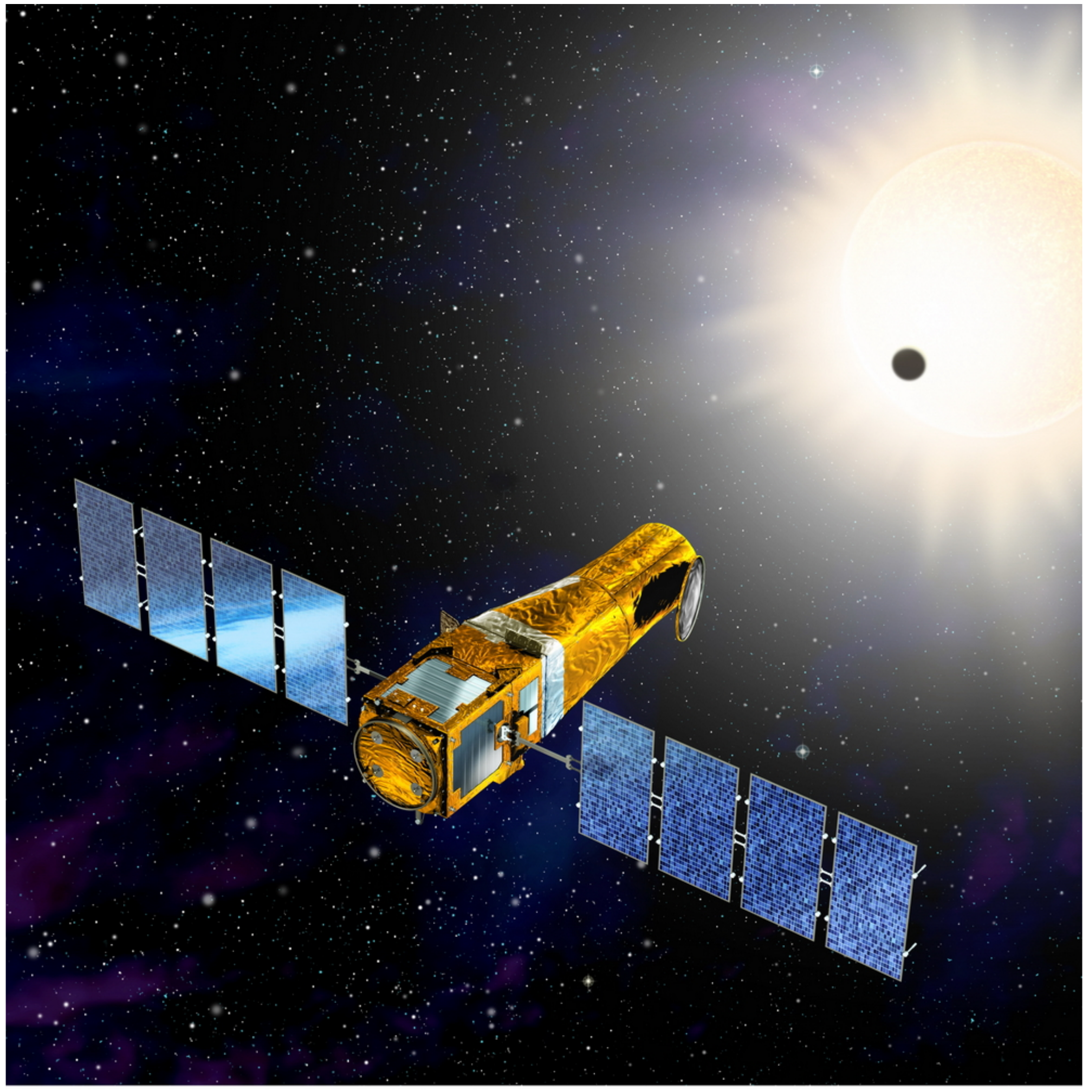




Other examples: CoRoT / Kepler / TESS

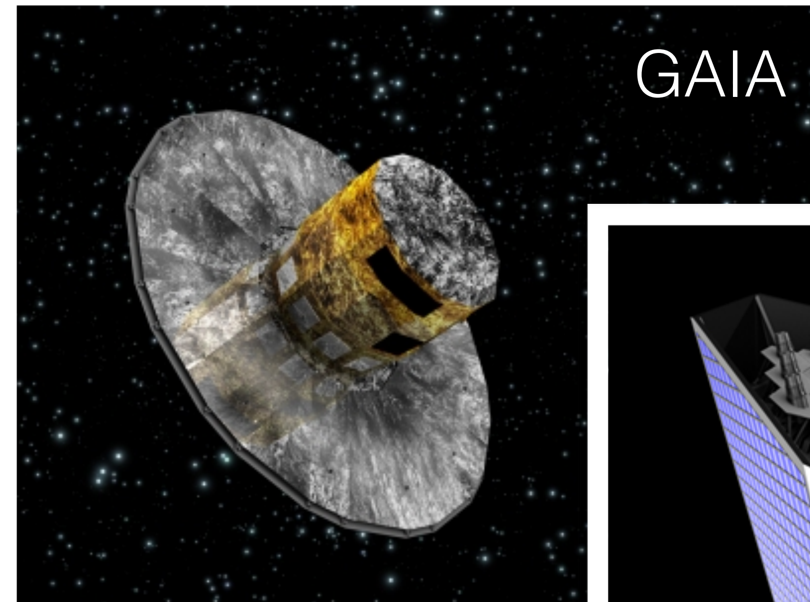
- ✦ Small telescopes providing high-precision photometry
    - down to 10 - 100 ppm
- ✦ Exoplanet detection by transits
    - first rocky planets
    - several potentially habitable planets
- ✦ Asterosismology

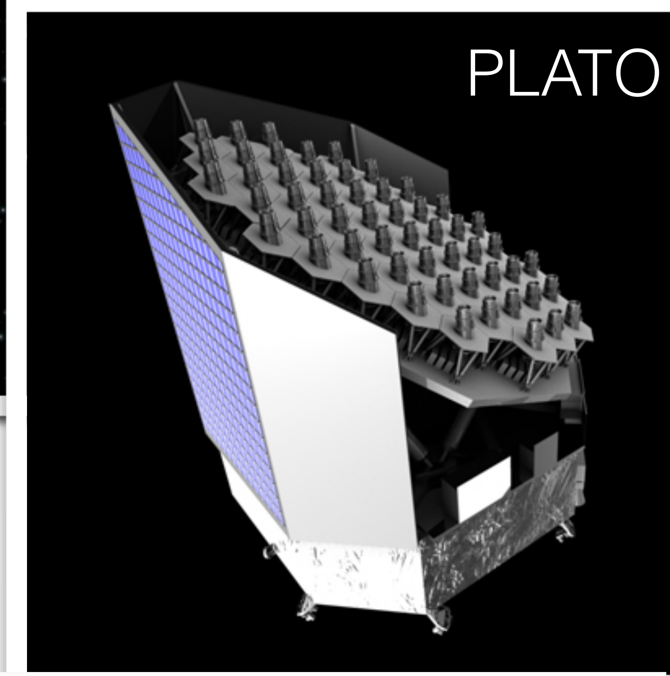


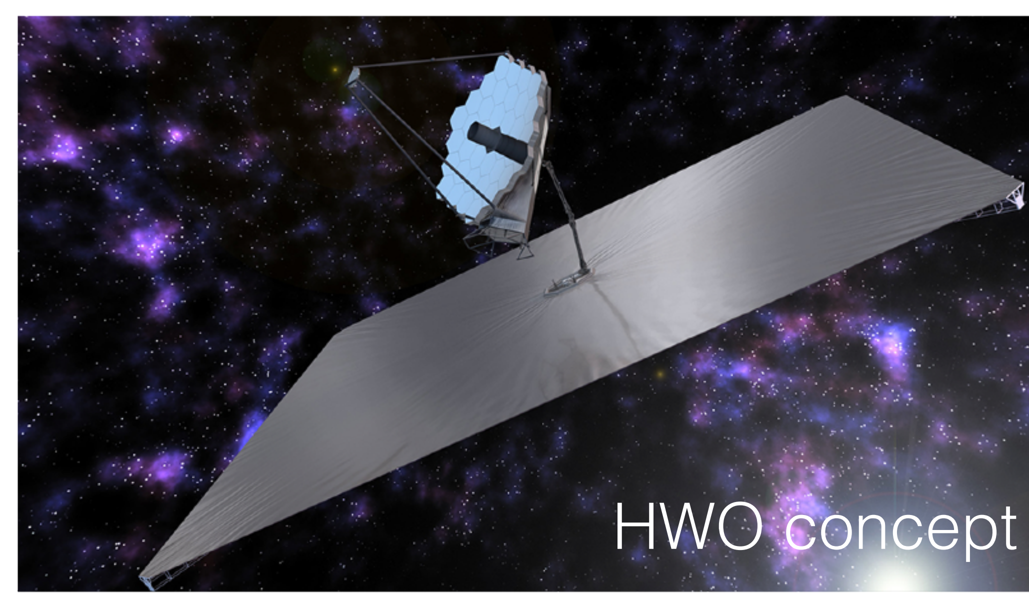


Latest & future missions

- ✦ GAIA (ESA, 2013)
  - 3D map of our Galaxy
  - 1,000,000 stars (position, velocity)
  - 106 CCDs —> 1 billion pixels
  - hyper-stable SiC structure
- ✦ ESA Cosmic Vision
  - Solar Orbiter (launched 2020)
  - EUCLID (launched 2023): dark energy / dark matter
  - PLATO (2026) and ARIEL (2029): extrasolar planets
- ✦ NASA's future large optical telescopes
  - Roman Space Telescope (2.4 m, 2027)
  - Habitable Worlds Observatory (~6 m, 2040s)

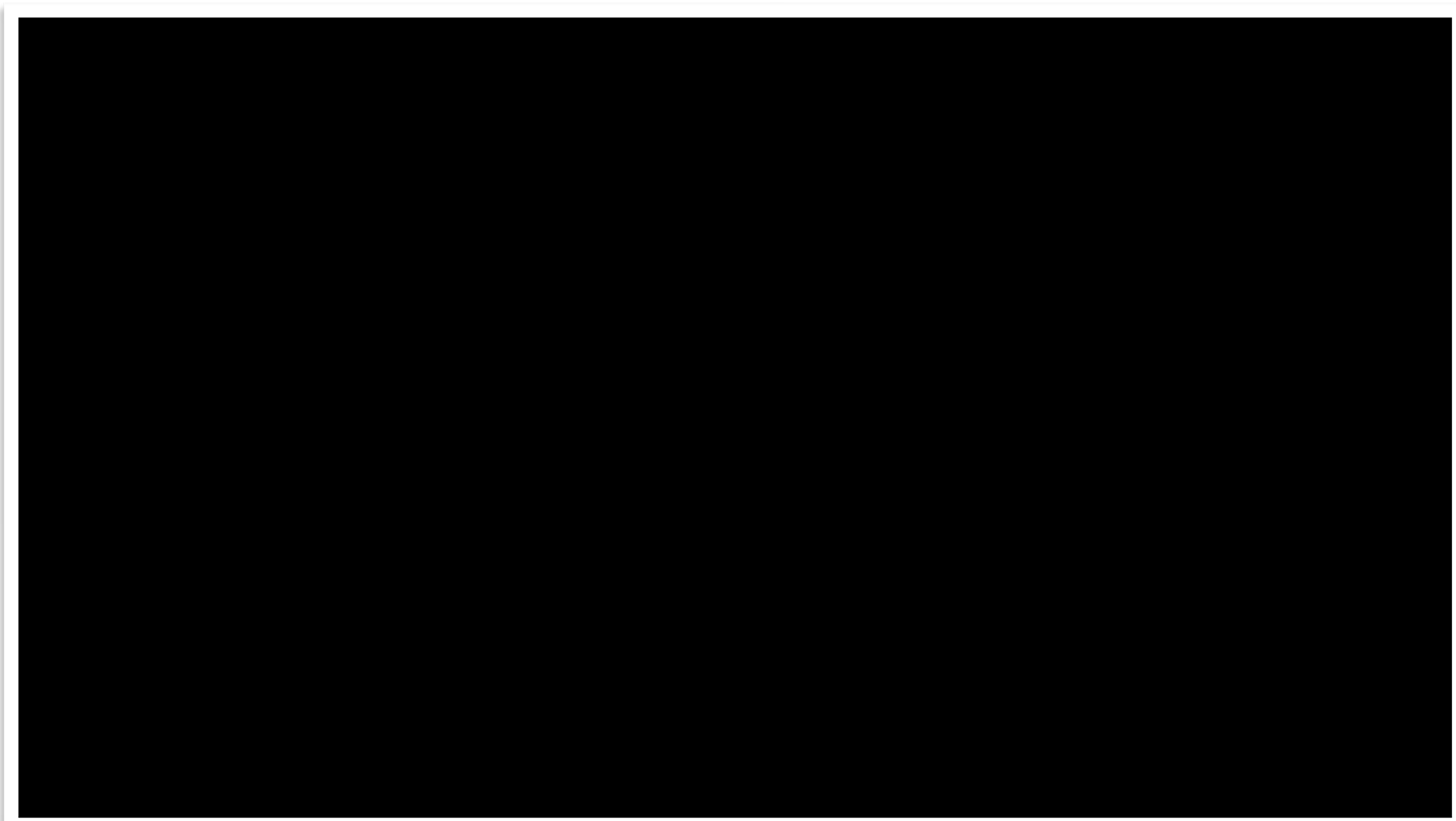




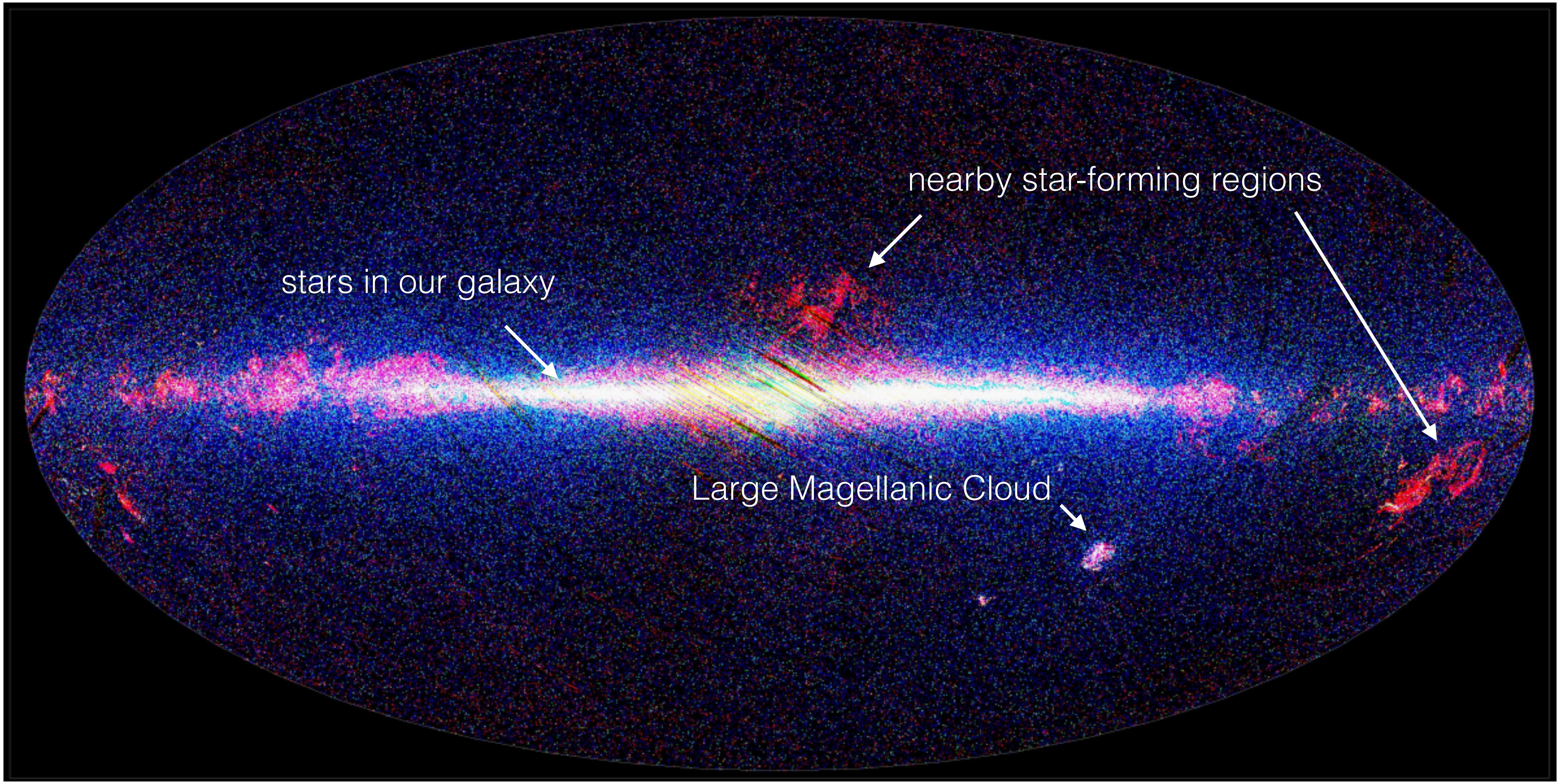


EUCLID first images

(released just one year ago)



EUCLID will observe billions of remote galaxies to understand dark matter / dark energy

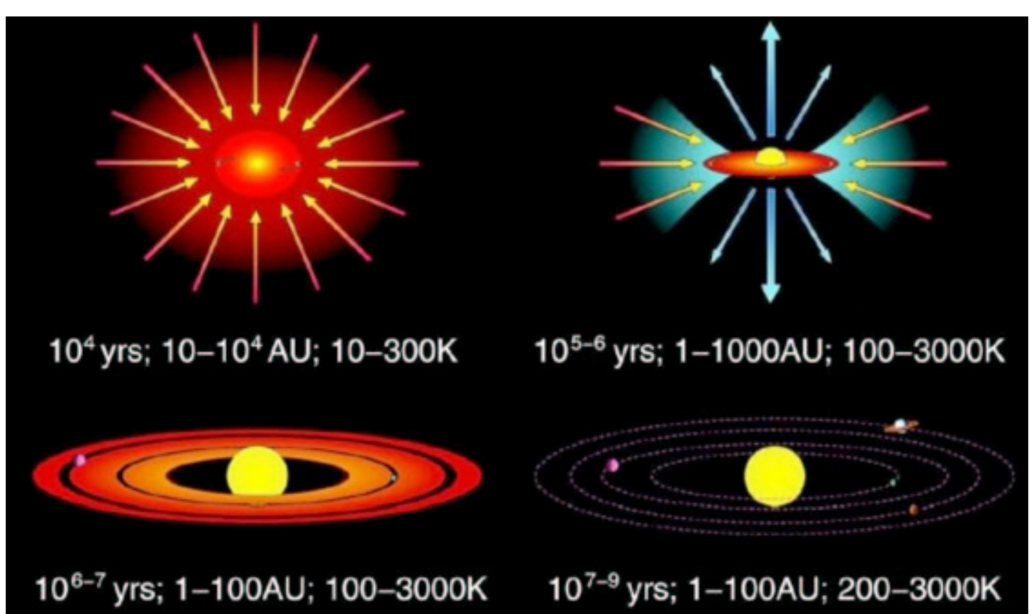


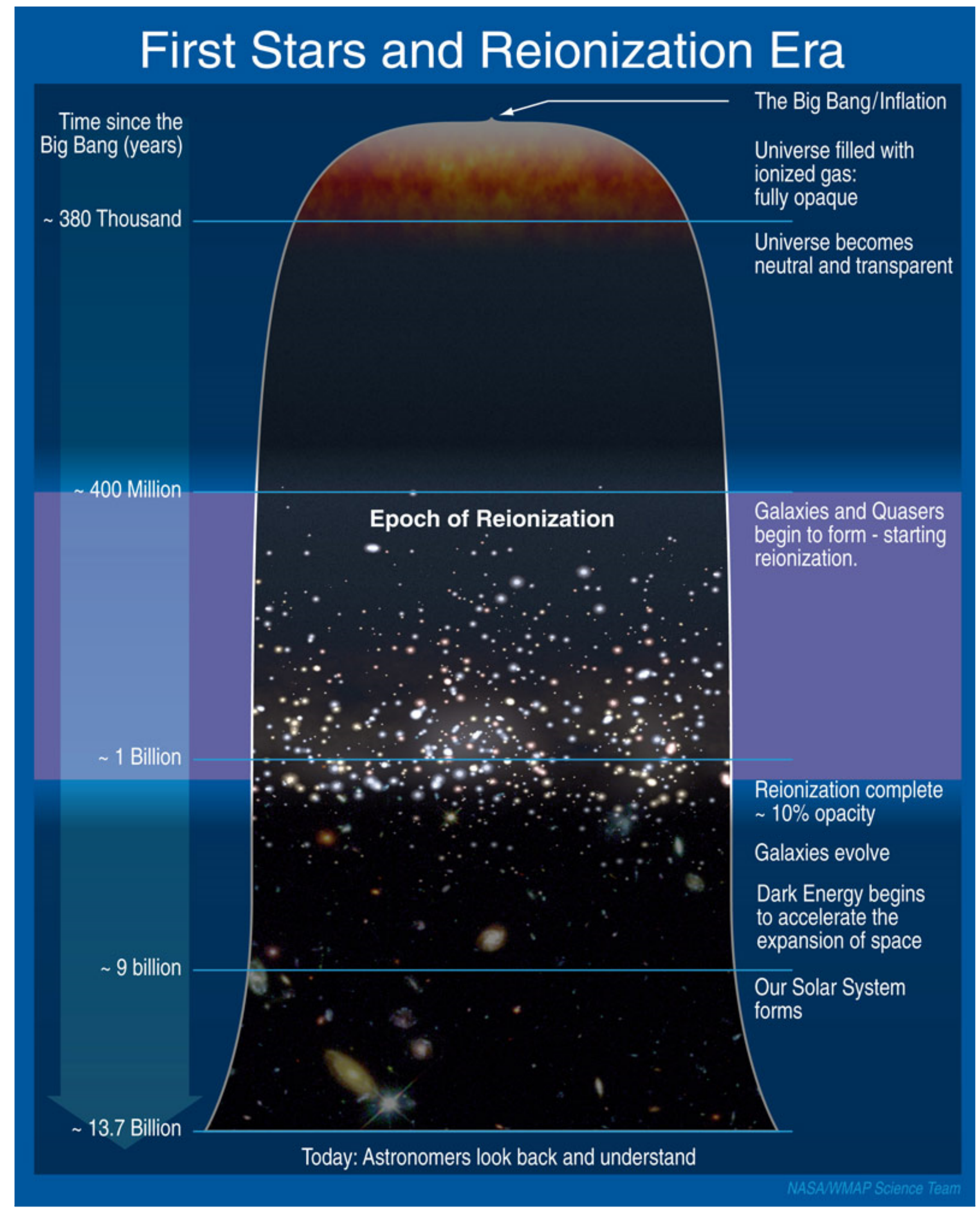
Mid-infrared

From $\lambda = 3\ \mu m$ to $\lambda = 30\ \mu m$

Astrophysical interests

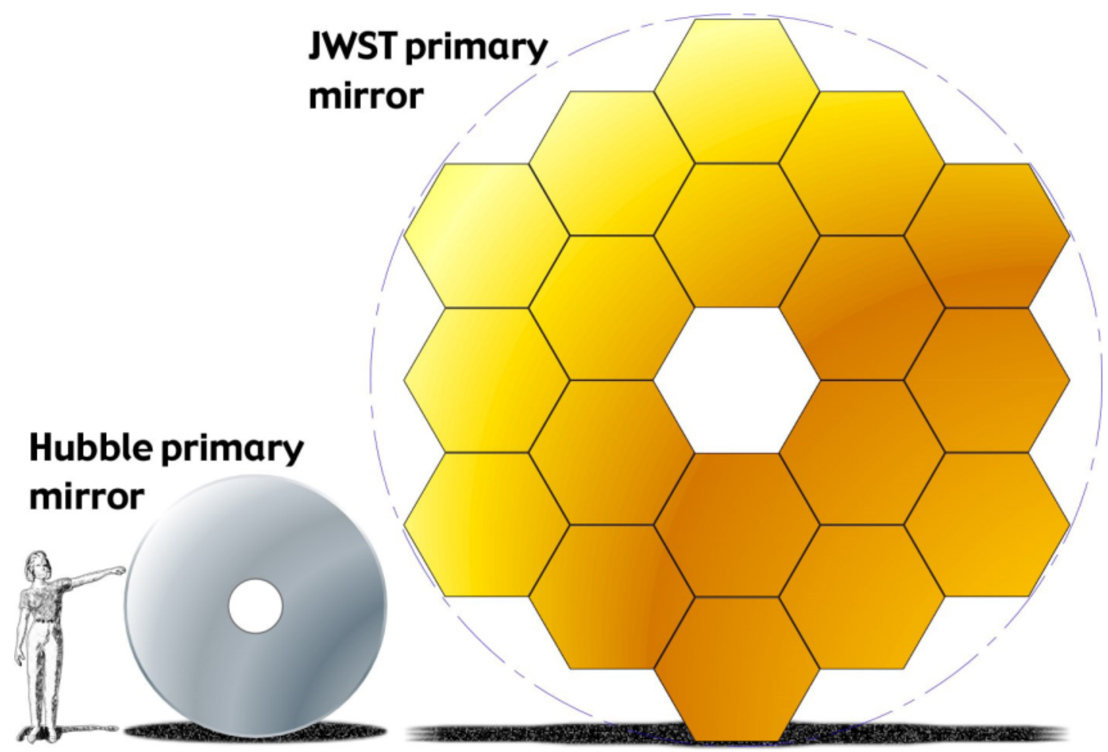
- ✦ Primordial universe
  - high redshift: visible shifted to mid-IR
  - first stars & galactic assembly
- ✦ Thermal emission @ 100 - 1,000 K
  - star / planet formation & exoplanets
  - mid-IR can see through dust!





James Webb Space Telescope

- Biggest space telescope
  - telescope diameter: 6.5 m
  - wavelength range: 0.6 - 29 μm
  - diffraction-limited beyond 2 μm
- NASA project with ESA and CSA contribution
- Launched from Kourou with Ariane 5 on Dec 25, 2021



A long testing campaign

Testing / shipping highlights

Aug 2019 @ Northrop Grumman
(JWST fully assembled)

Oct 2020 @ Northrop Grumman (final acoustic tests completed)

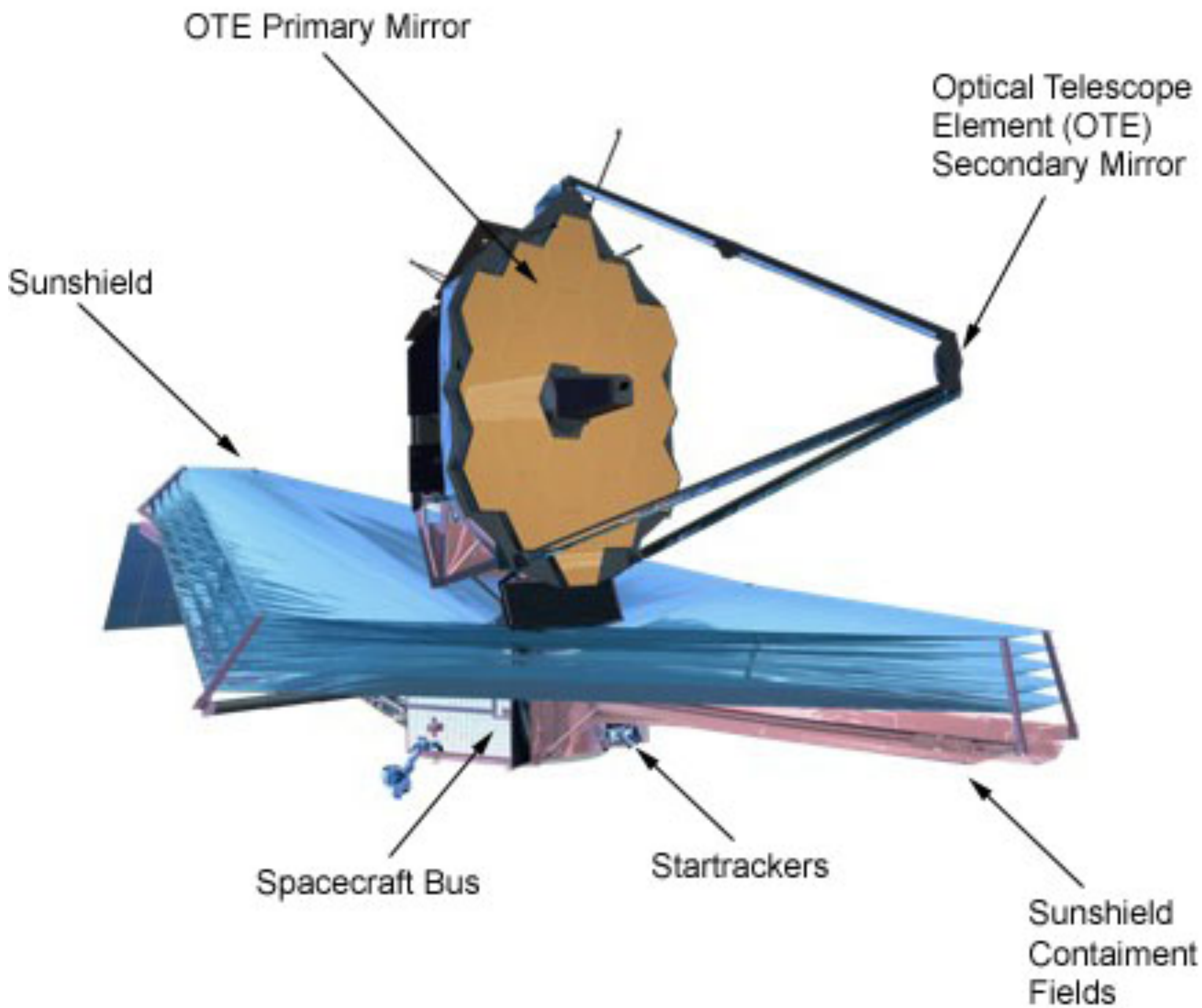
Oct 2021: arrival at Kourou

The JWST budget

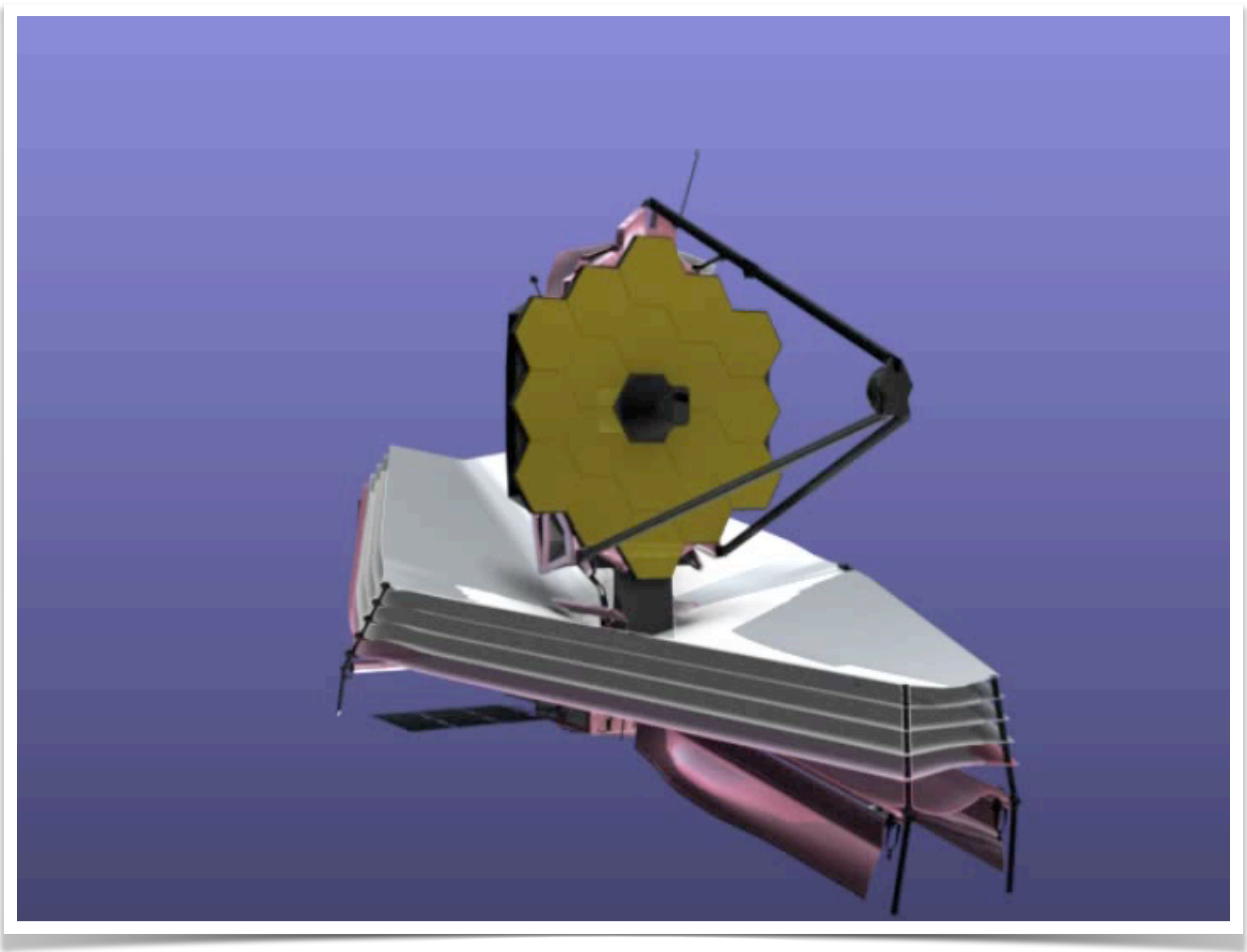
Year	Launch date	Budget	
1997	2007	0.5 B$	
1998	2007	1 B$	
1999	2007/2008	1 B$	
2000	2009	1.8 B$	
2002	2010	2.5 B$	
2003	2011	2.5 B$	
2005	2013	3 B$	
2006	2014	4.5 B$	
2008	2014	5.1 B$	
2010	2015/2016	6.5 B$	
2011	2018	8.7 B$	almost cancelled! / congress-approved cost cap
2018	2020	9.7 B$	updated cost cap
2020	2021	≥ 10 B$ (incl. operations)	

JWST size = tennis court!

JWST design

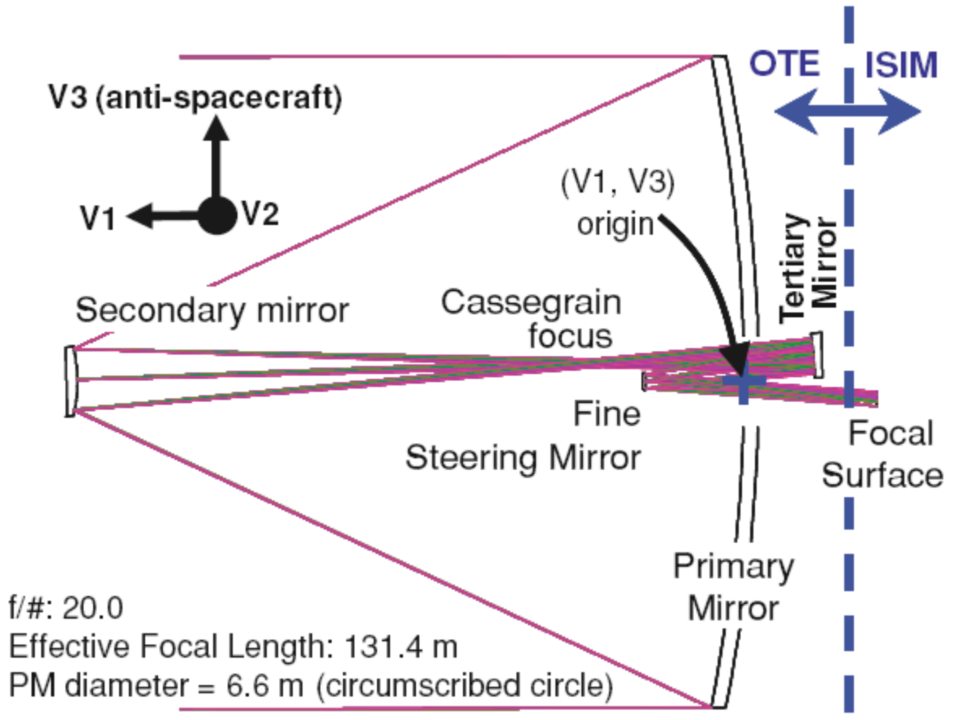

OTE Primary Mirror
Optical Telescope
Element (OTE)
Secondary Mirror
Sunshield
Spacecraft Bus
Startrackers
Sunshield
Containment
Fields

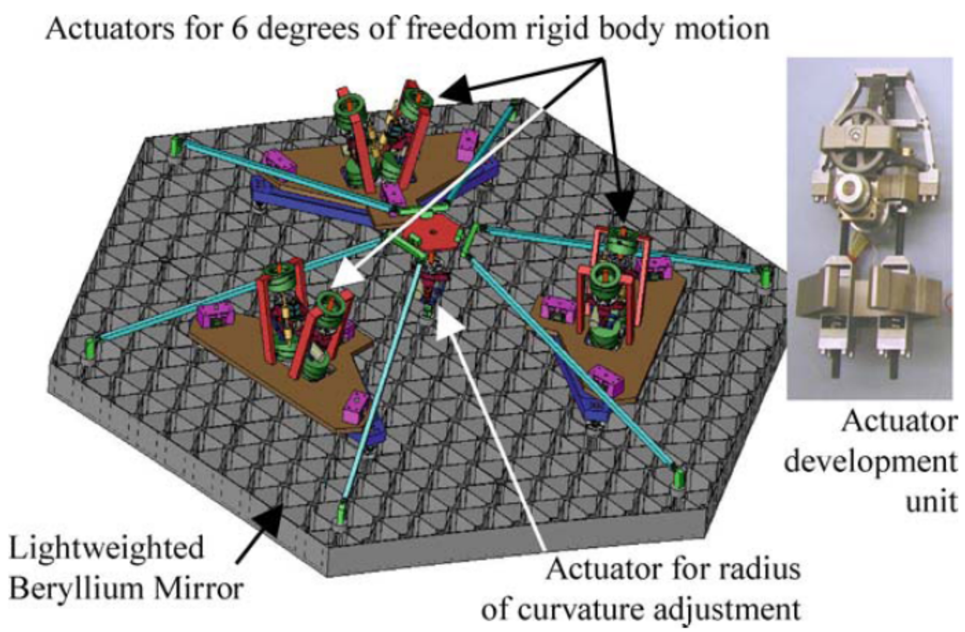
Deployable telescope



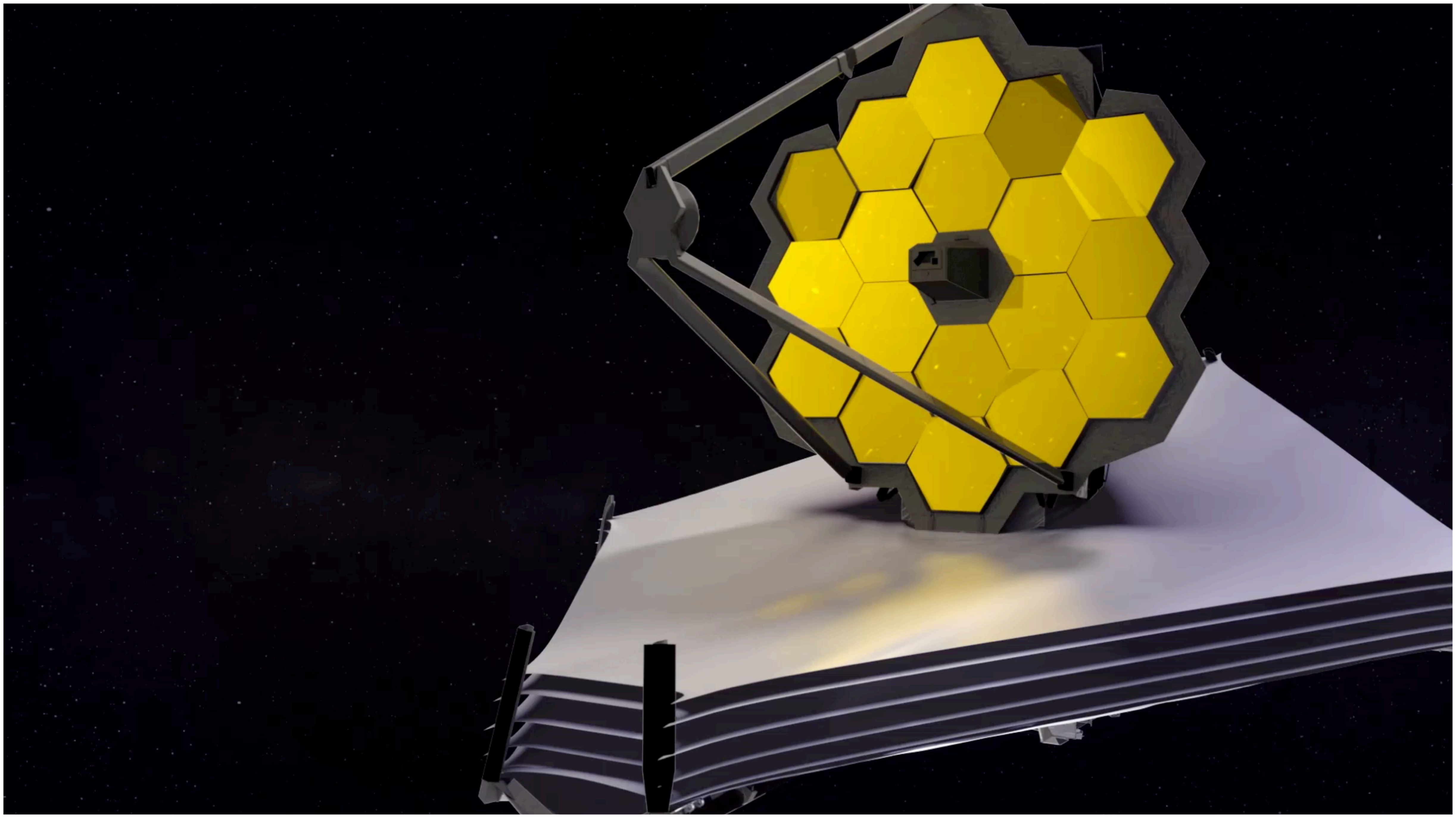
Lightweight segmented mirror

- ✦ Beryllium mirror, 10x lighter than HST by unit surface
  - high strength / weight ratio
  - high stiffness, low deformation
  - honeycomb design
  - gold coating
- ✦ Segment alignment control
  - several levels of sensing and correction
  - final alignment accuracy < 100 nm
  - re-aligned every 2 weeks



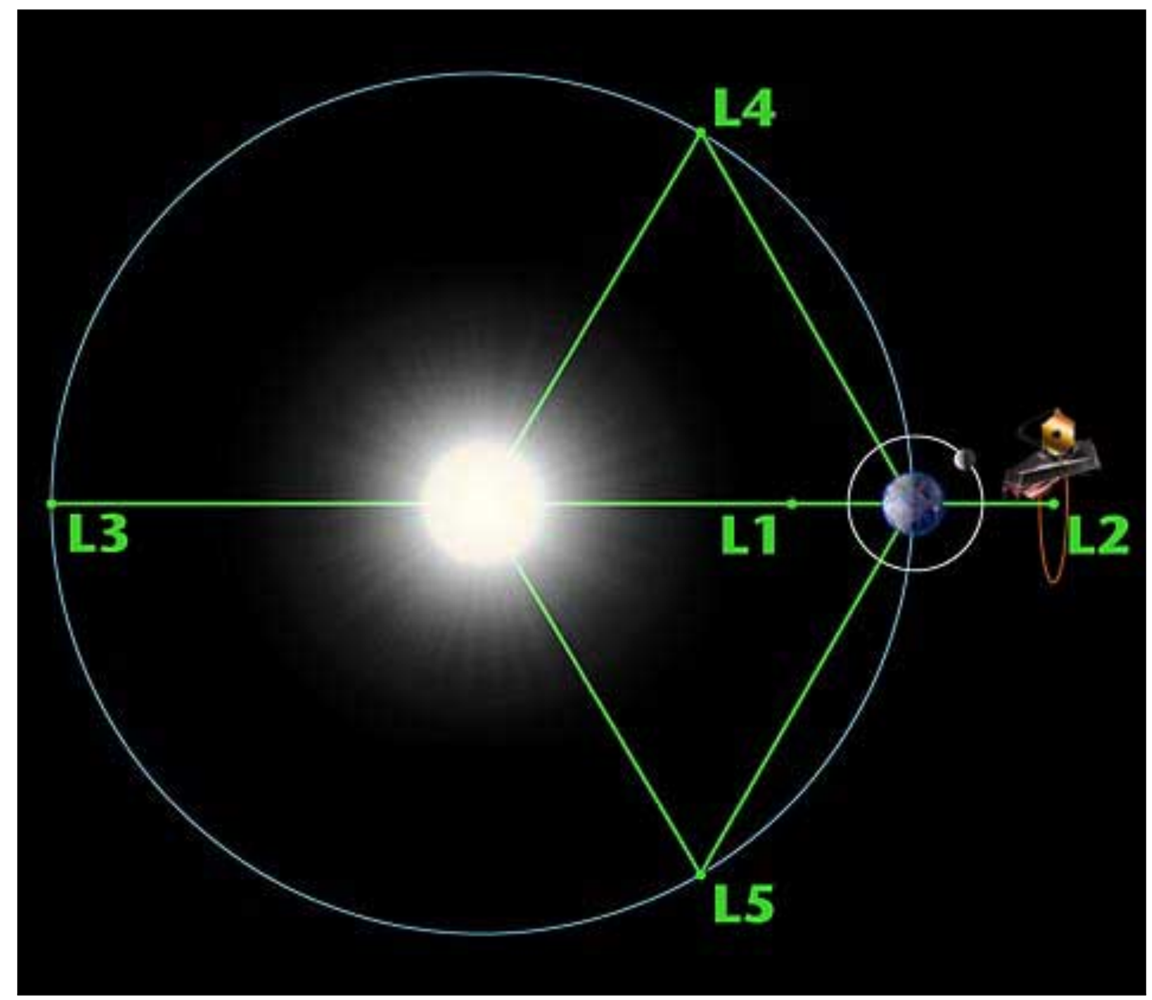


Telescope initial phasing



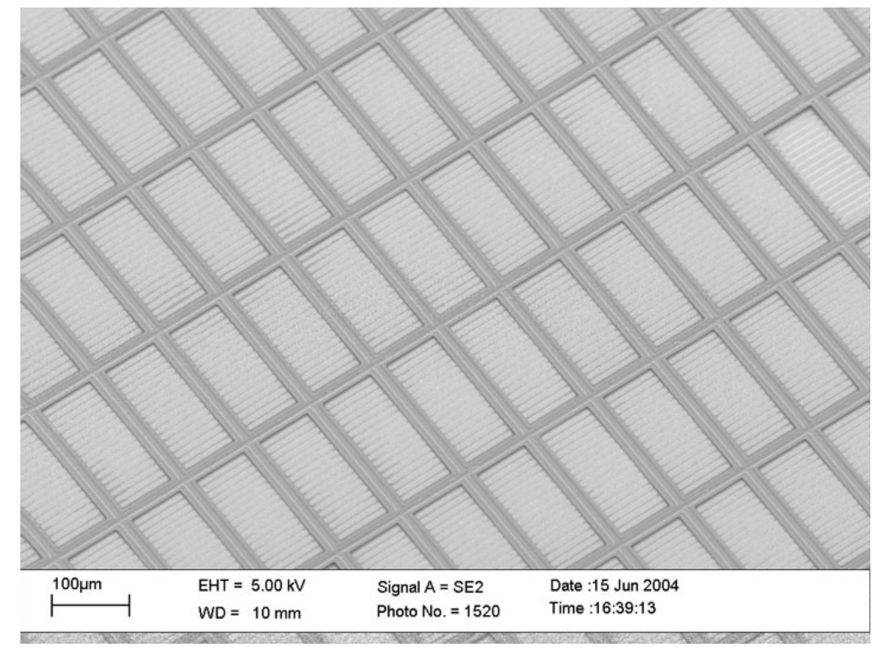
Cooling

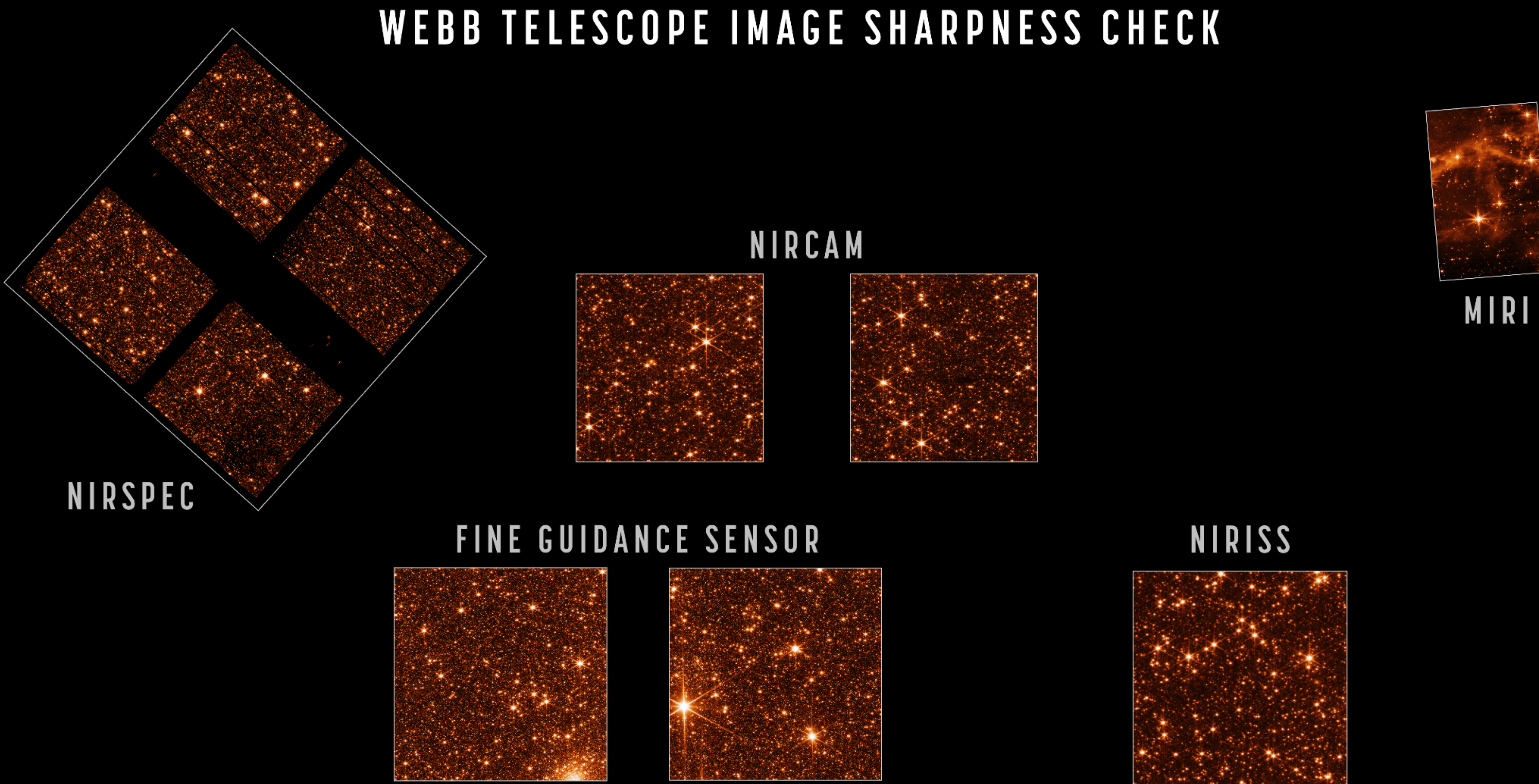
- ✦ Lagrange L2 point
- ✦ Mirror: passive cooling to 50 K
- ✦ Innovative sun shield
  - 5 coated polymer-film layers
  - reflects light without heating
  - thickness ~ 30 µm
  - resistant to micro-meteorites
- ✦ Instruments: cryogeny



Instruments

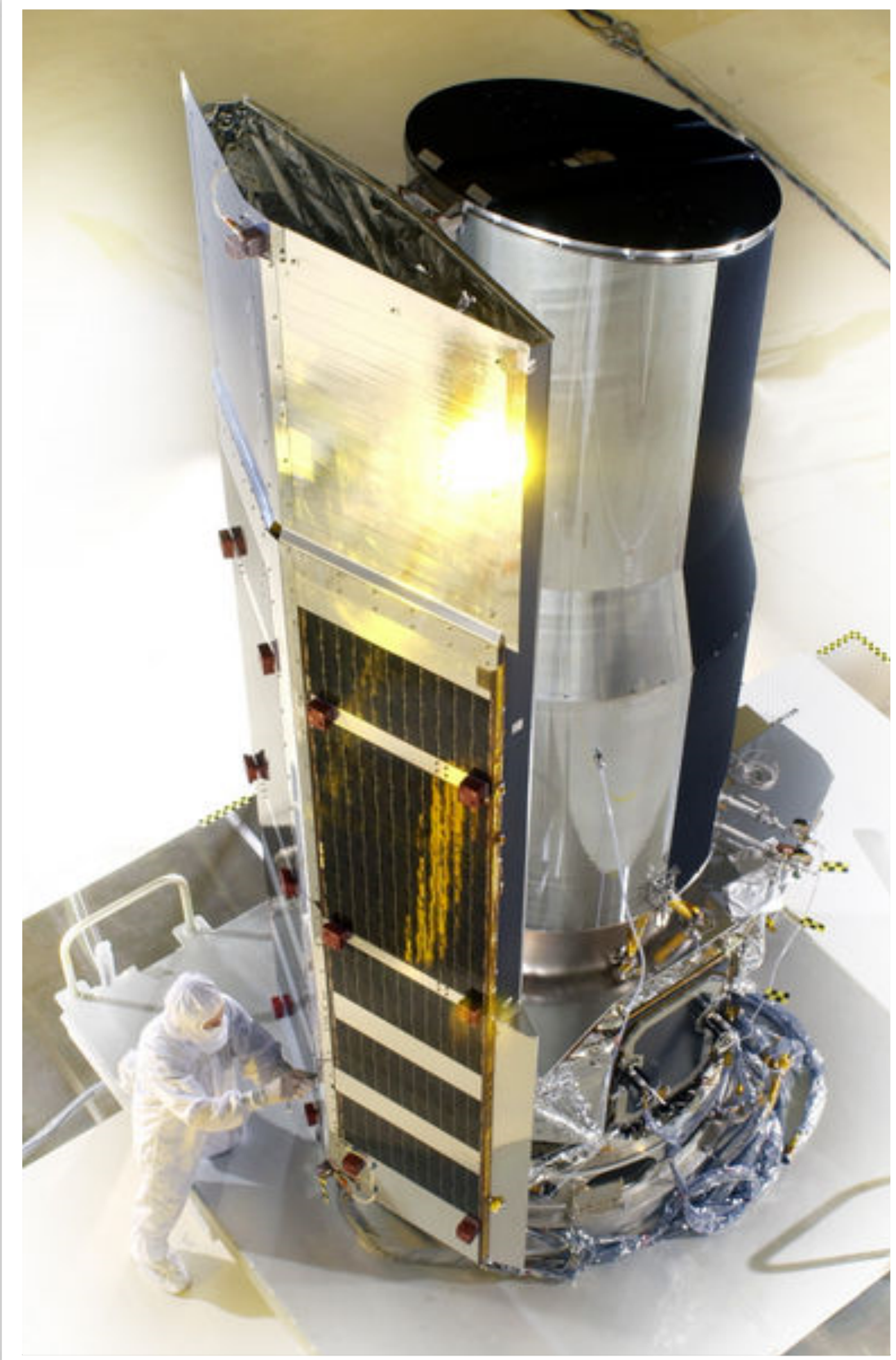
- ✦ NIRCam: imaging, 0.6 to 5 μm
- ✦ NIRSpec: spectroscopy, 0.6 to 5 μm
  - multi-object —> micro-shutter array (MEMS)
- ✦ NIRISS: wide-field imaging and spectroscopy, 0.6 - 5 μm
- ✦ MIRI: imaging and spectroscopy, 5 - 29 μm
  - non-local active cryogeny @ 6 K (Joule-Thomson cycle with helium)
  - new Si:As detectors




WEBB TELESCOPE IMAGE SHARPNESS CHECK
NIRSPEC
NIRCAM
MIRI
FINE GUIDANCE SENSOR
NIRISS

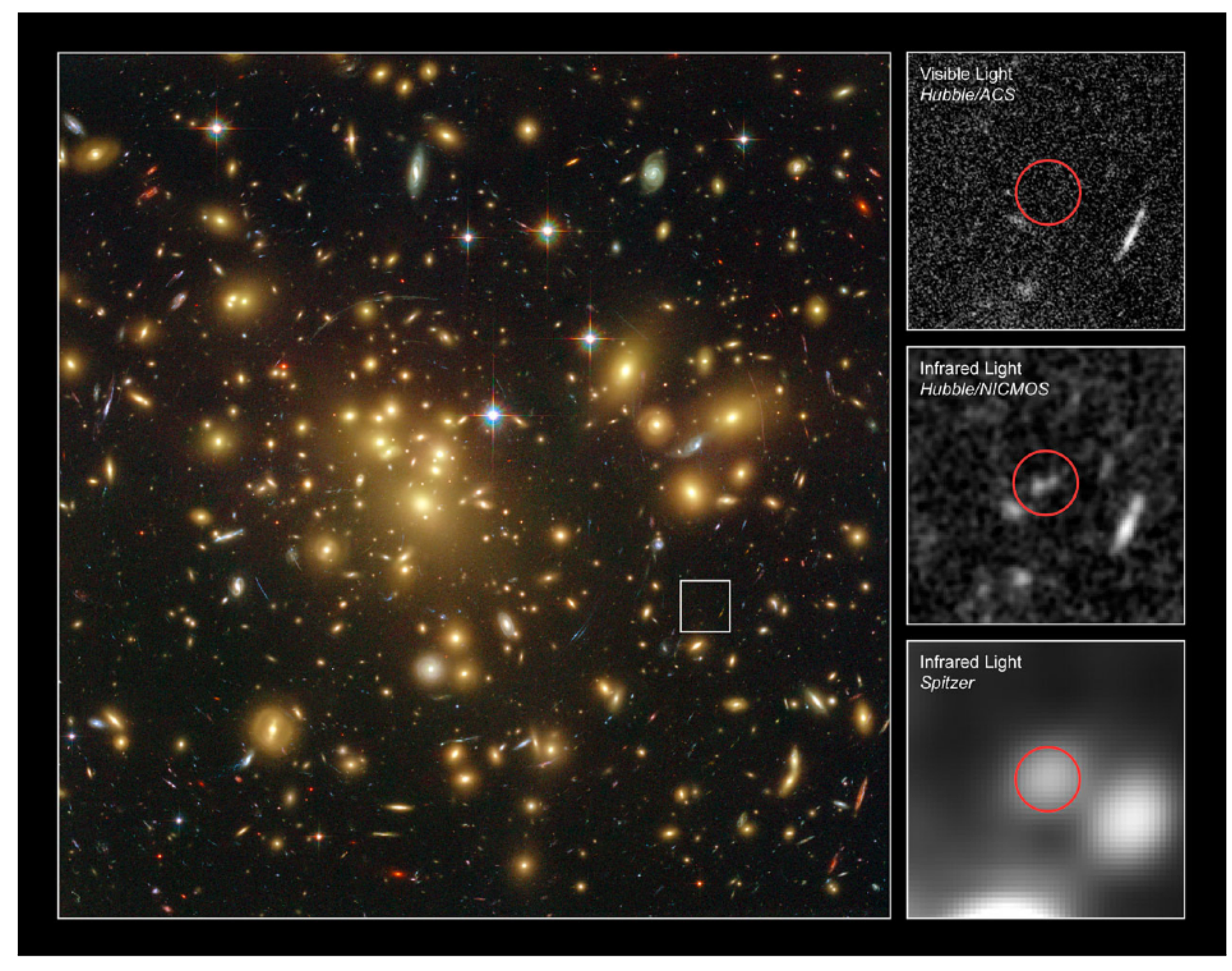
Other missions

- Spitzer Space Telescope (NASA, 2003)
  - 85 cm diameter
  - wavelengths from 3.6 to 160 μm
  - Earth-trailing orbit
  - cooling with 400 liter liquid helium tank (exhausted since 2009, but ‘warm’ operations only stopped in 2020)
- All-sky surveys
  - AKARI (JAXA, 2006)
  - WISE (NASA, 2009) — cooled to 17 K by solid hydrogen cryostat

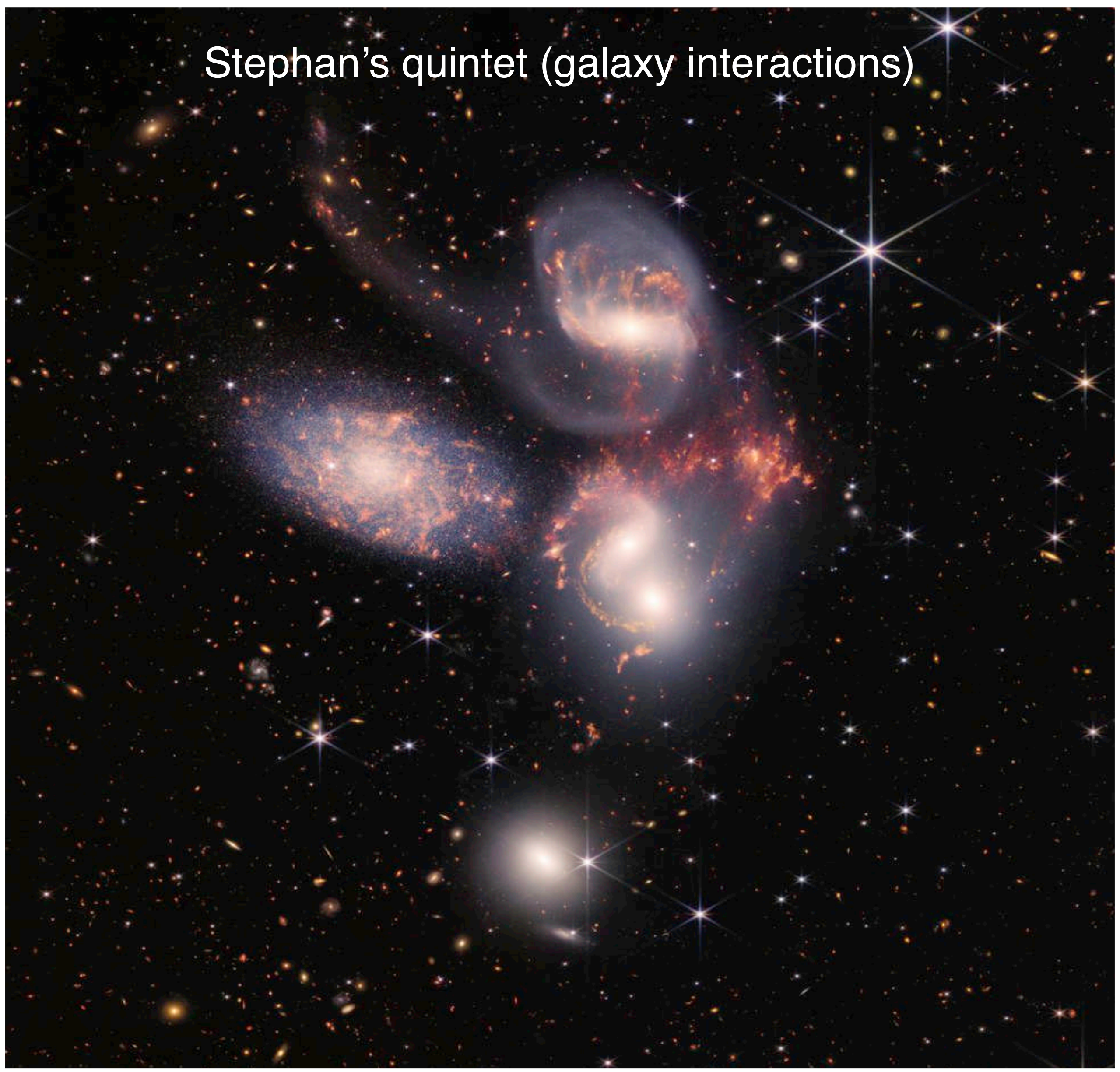


Galaxies

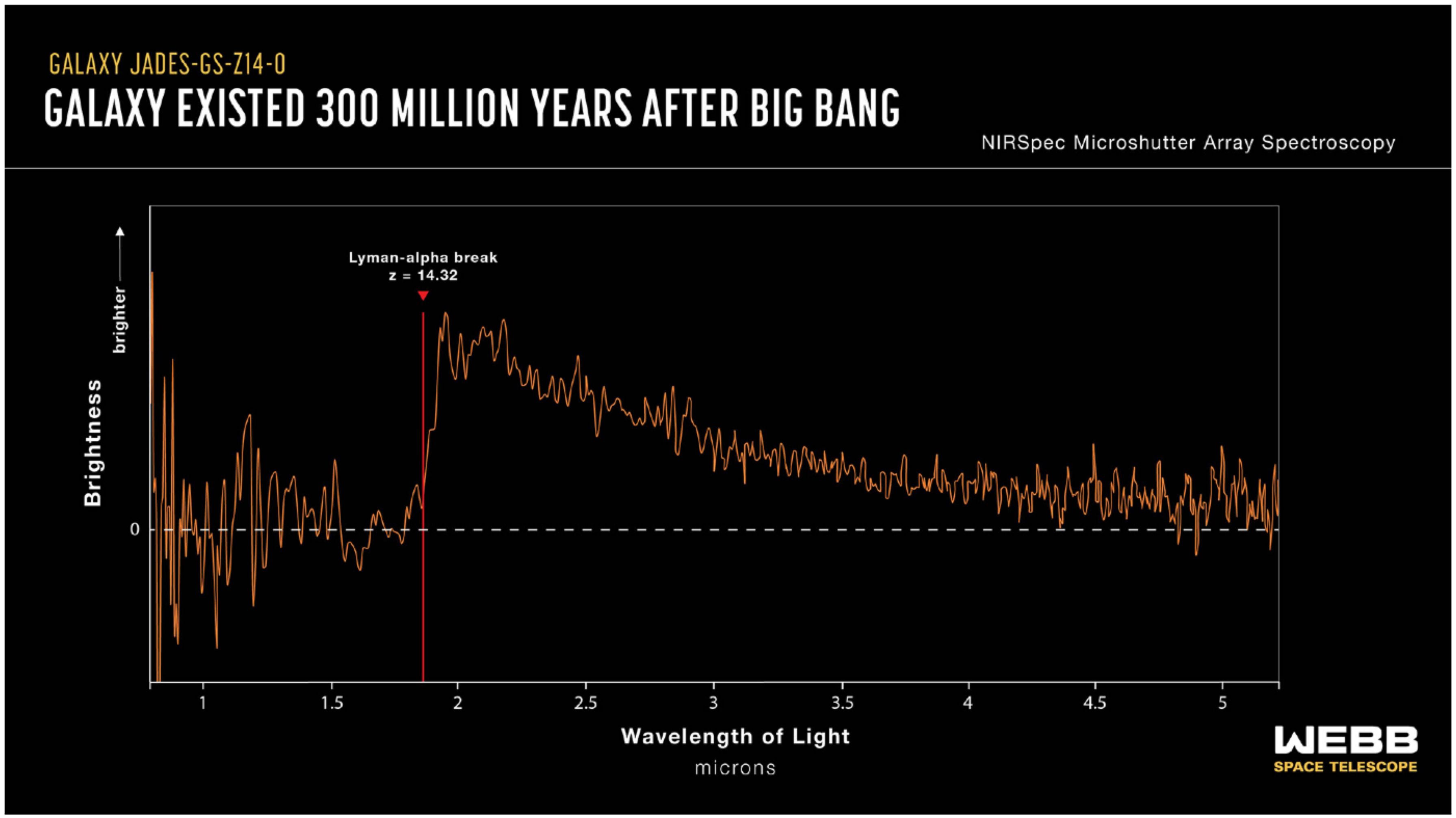
- First galaxies
- Galactic structure
  - star forming regions
  - cold dust and gas

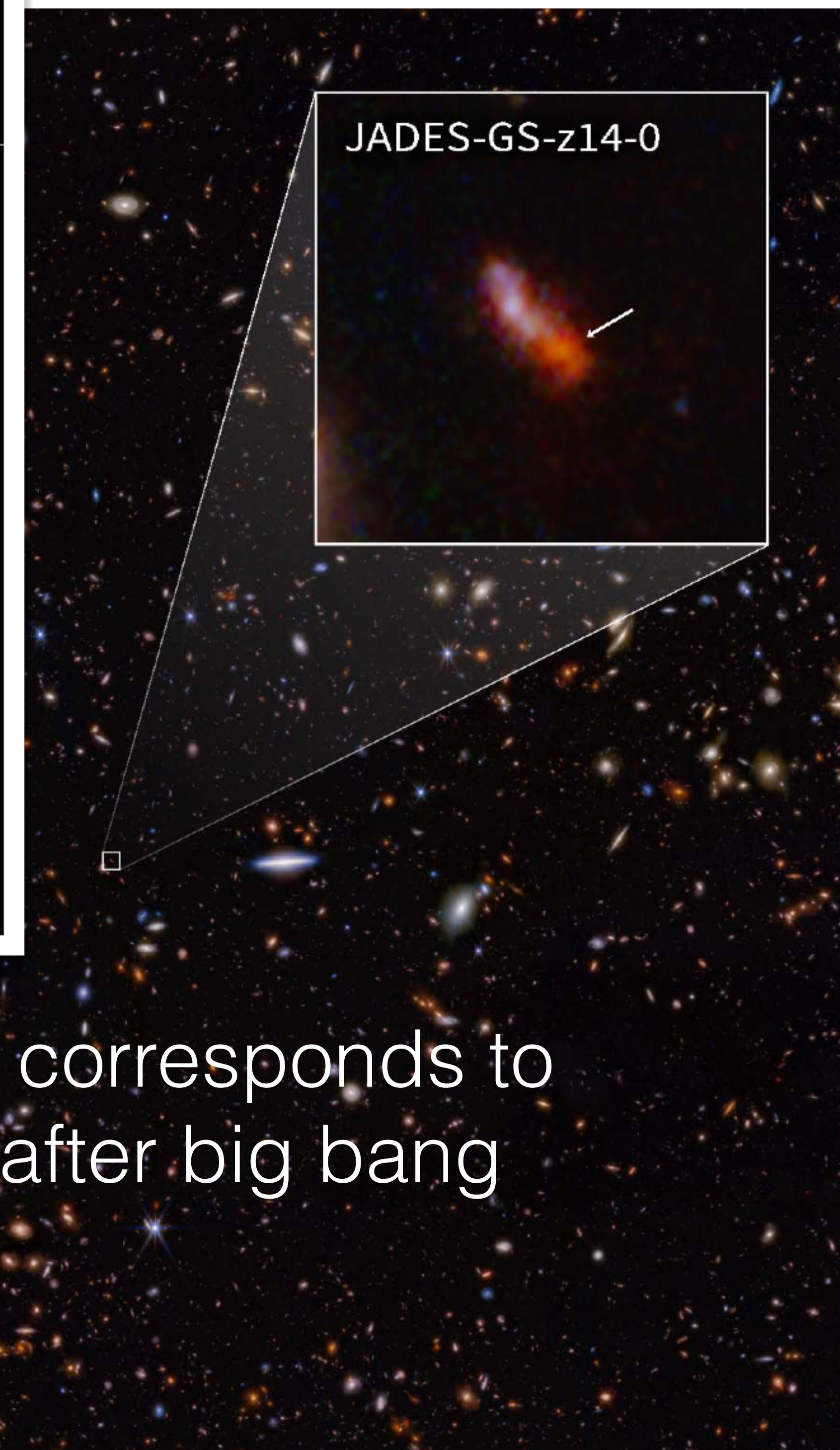


Early JWST highlights



Most distant galaxy (so far)

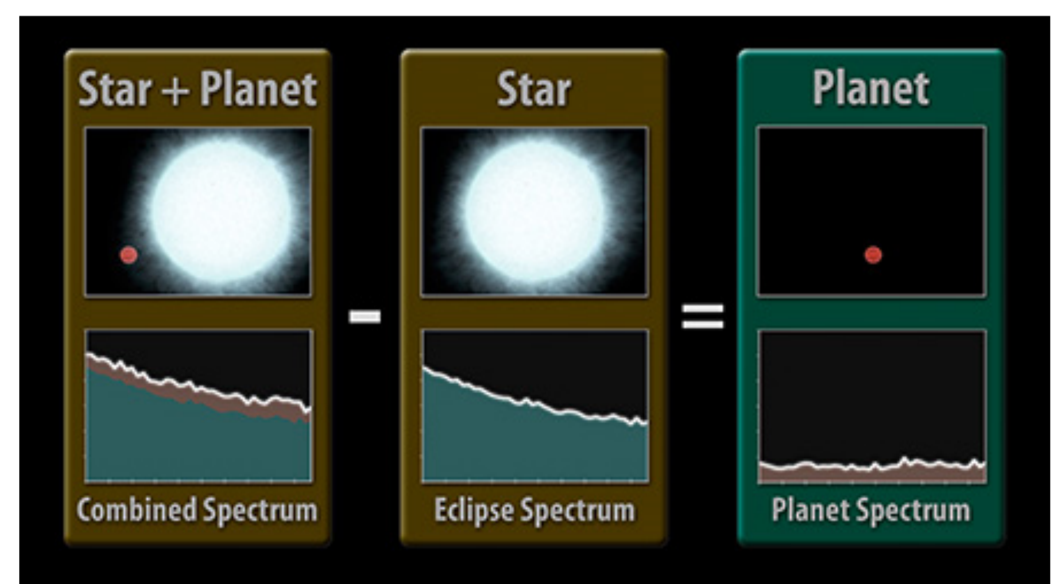




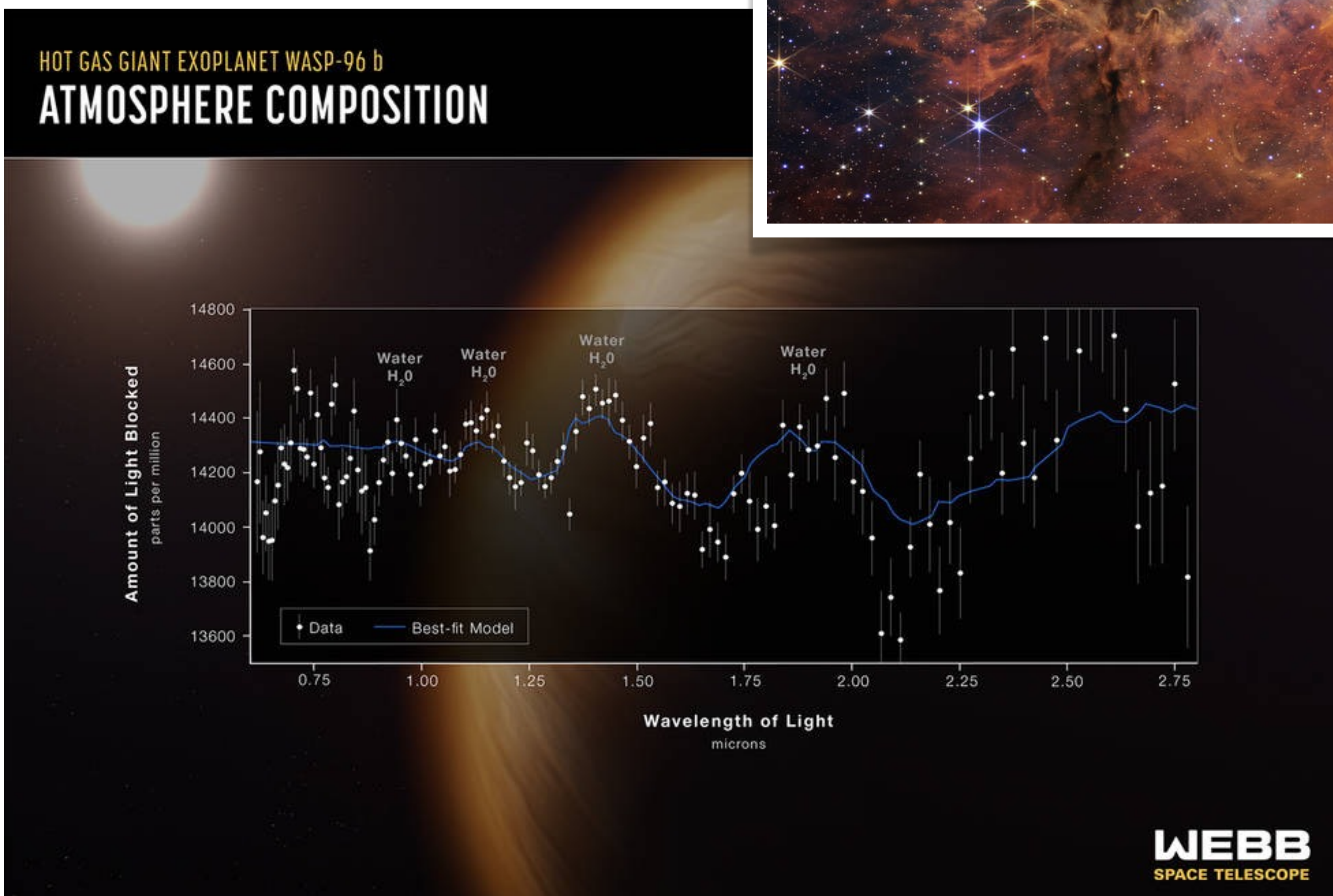
Redshift z = 14.3 — corresponds to 300 millions years after big bang

Stars and planets

- Observation of the youngest, forming stars
- Cold brown dwarfs
- Circumstellar disks (IRAS, 1984)
- First measurement of exoplanet temperature (Spitzer, 2006)

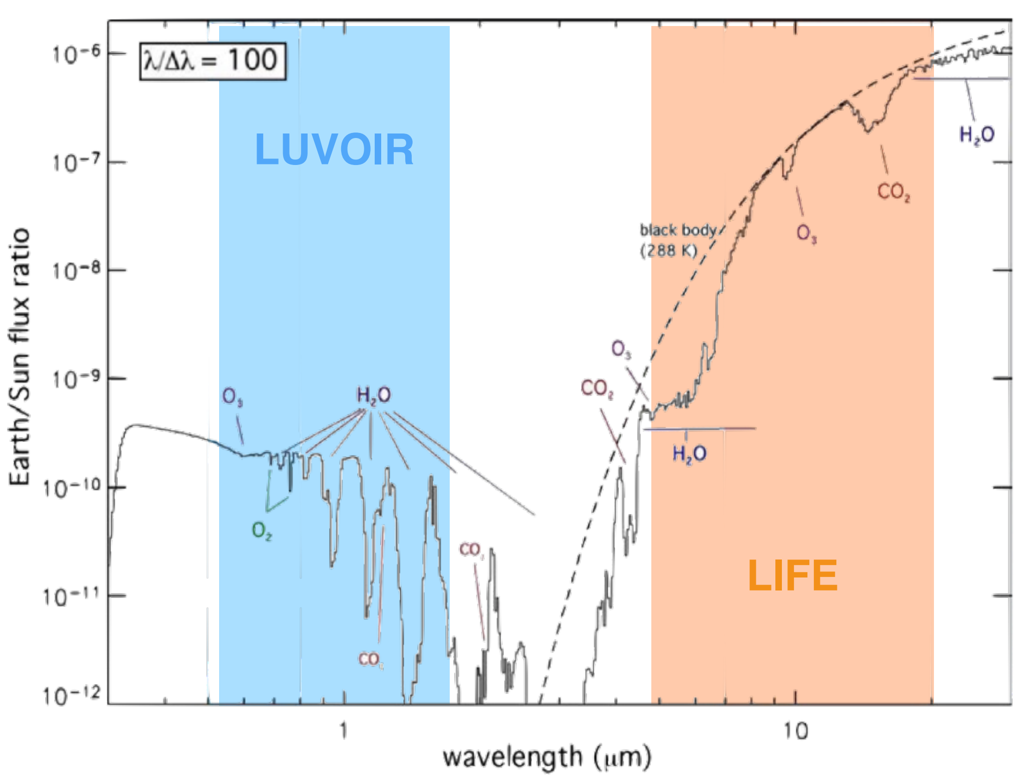


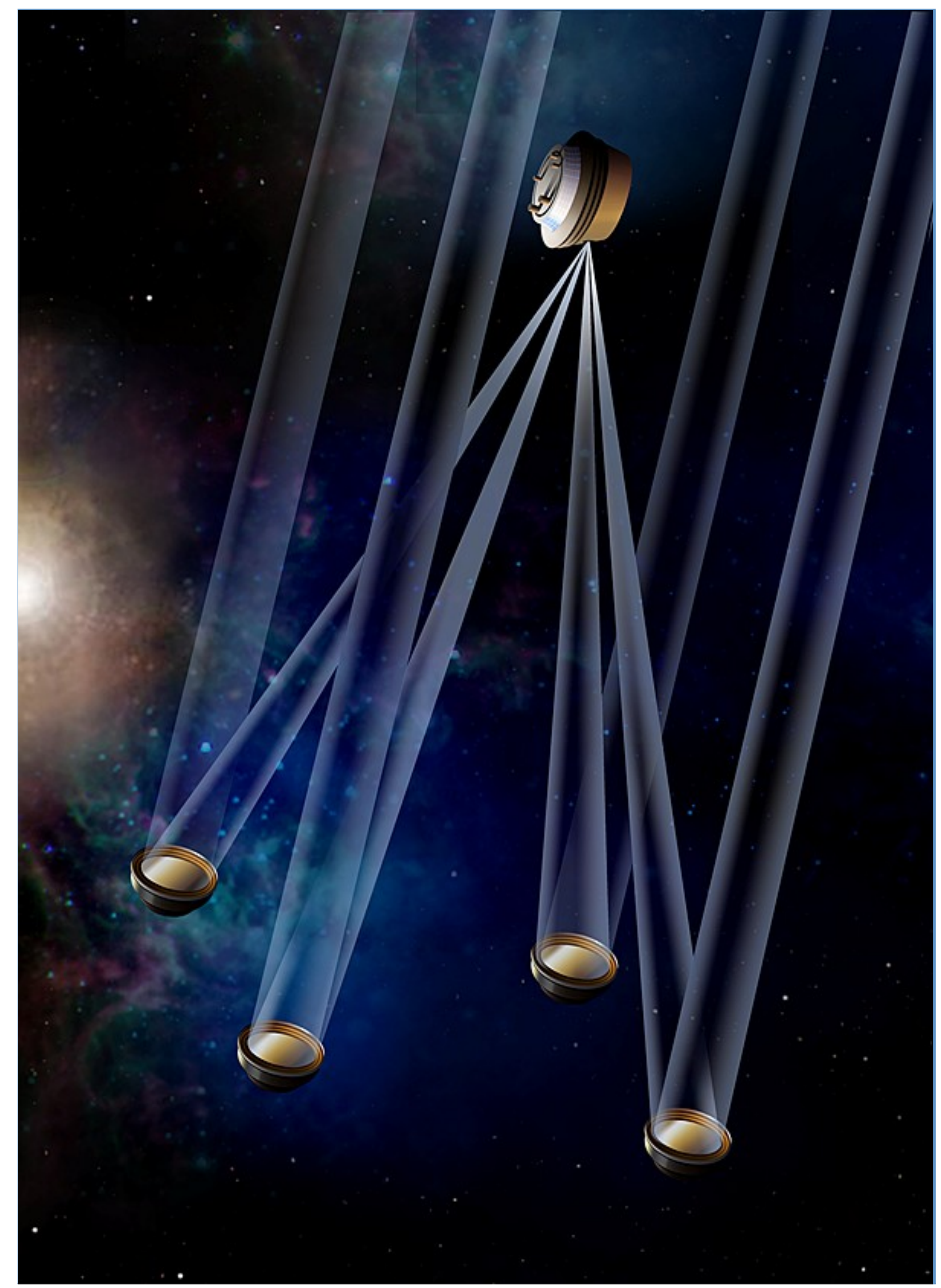
Early JWST highlights

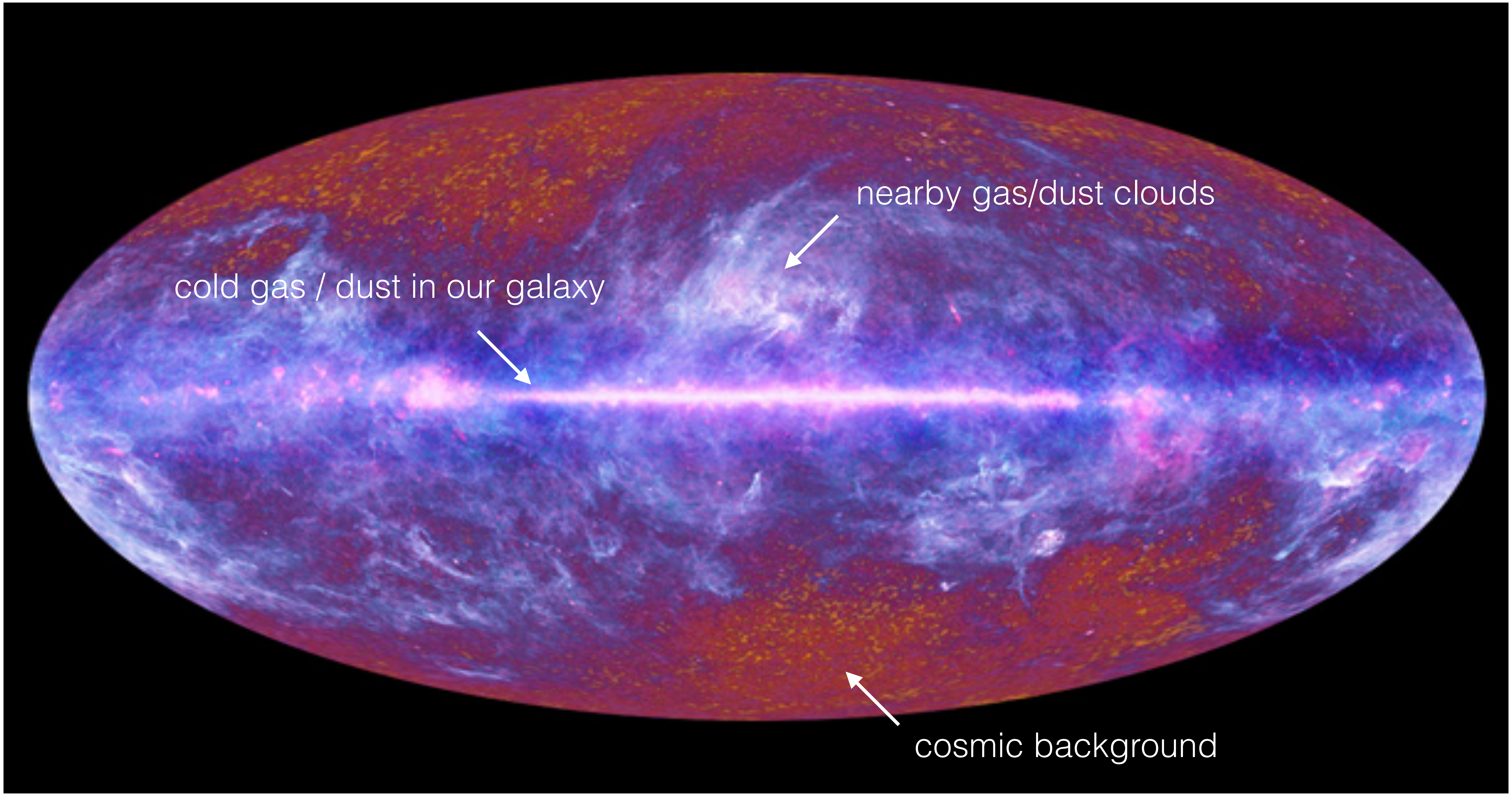


Future: interferometry

- ✦ Formation flying
  - no size limit
  - angular resolution: λ / Baseline
- ✦ Direct imaging of Earth-like planets
  - possible discovery of life!





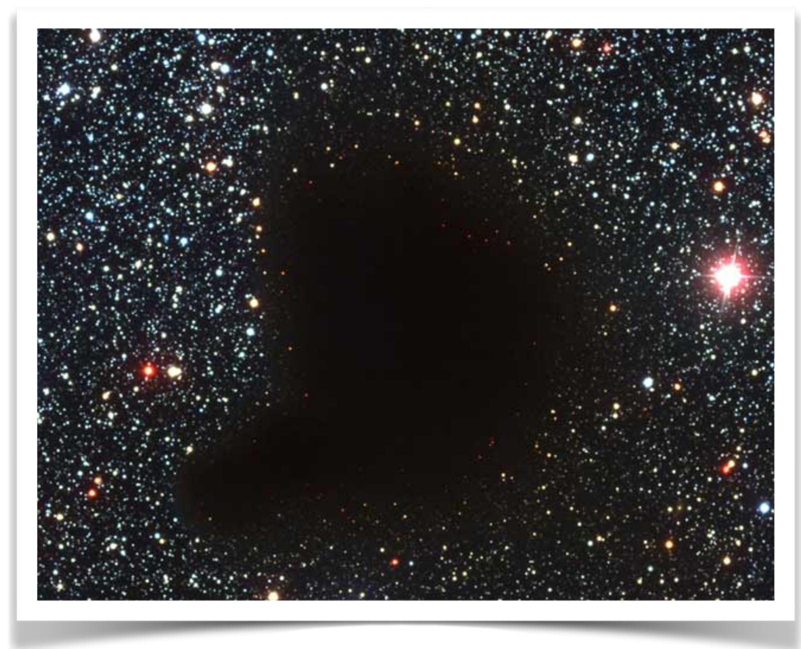


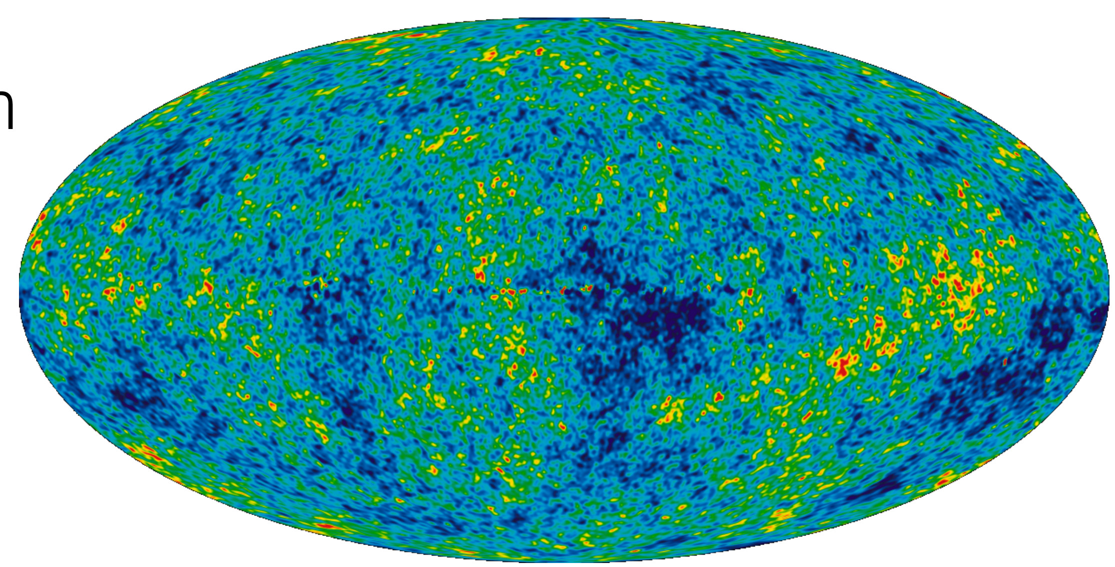
Far-IR / submm / mm

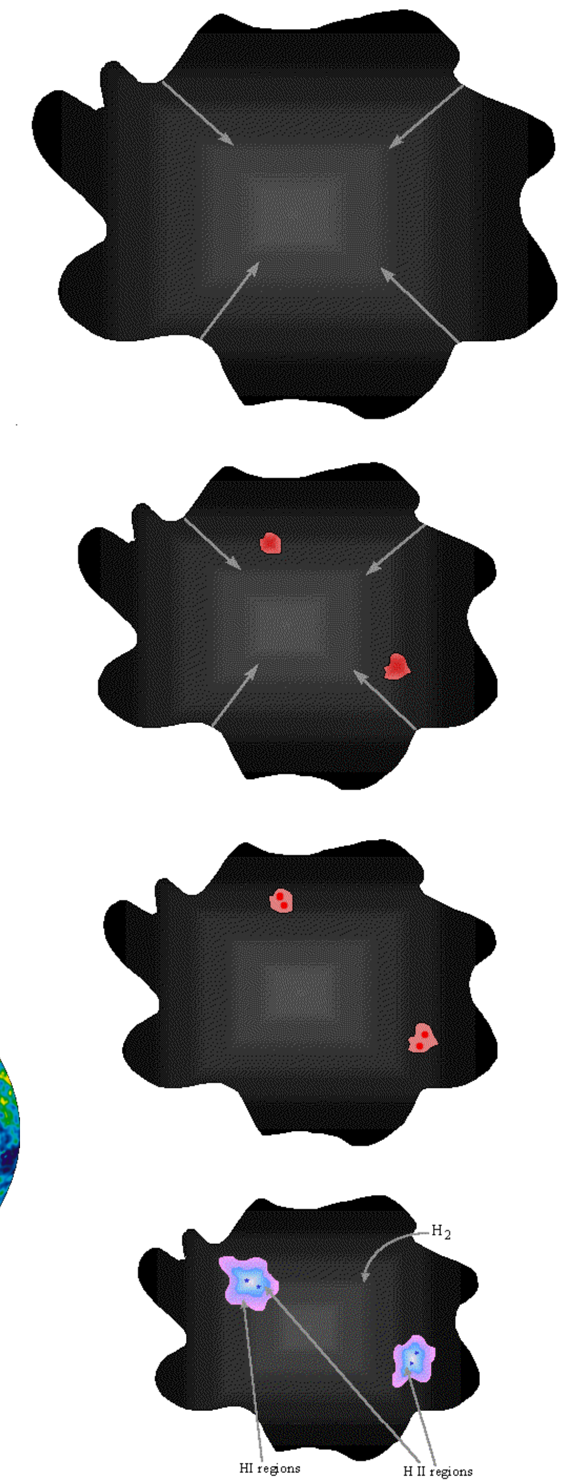
From λ = 30 μm to λ = 3 mm

Astrophysical interests

- ✦ Cold thermal phenomena (< 100 K)
    - molecular clouds
    - outer solar system
- ✦ Cosmic microwave background at ~3 K
    - thermal radiation from early Universe (recombination), predicted by Big Bang theory

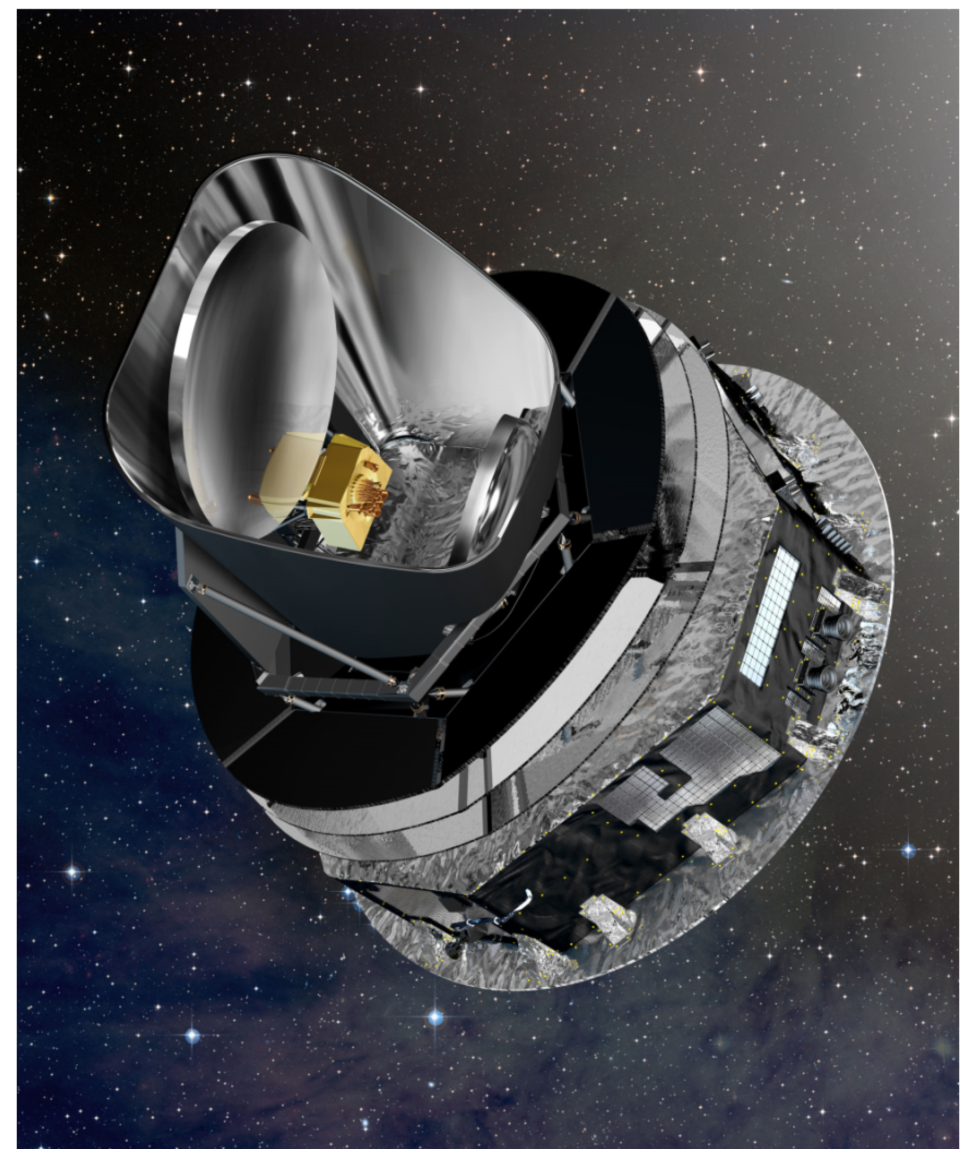






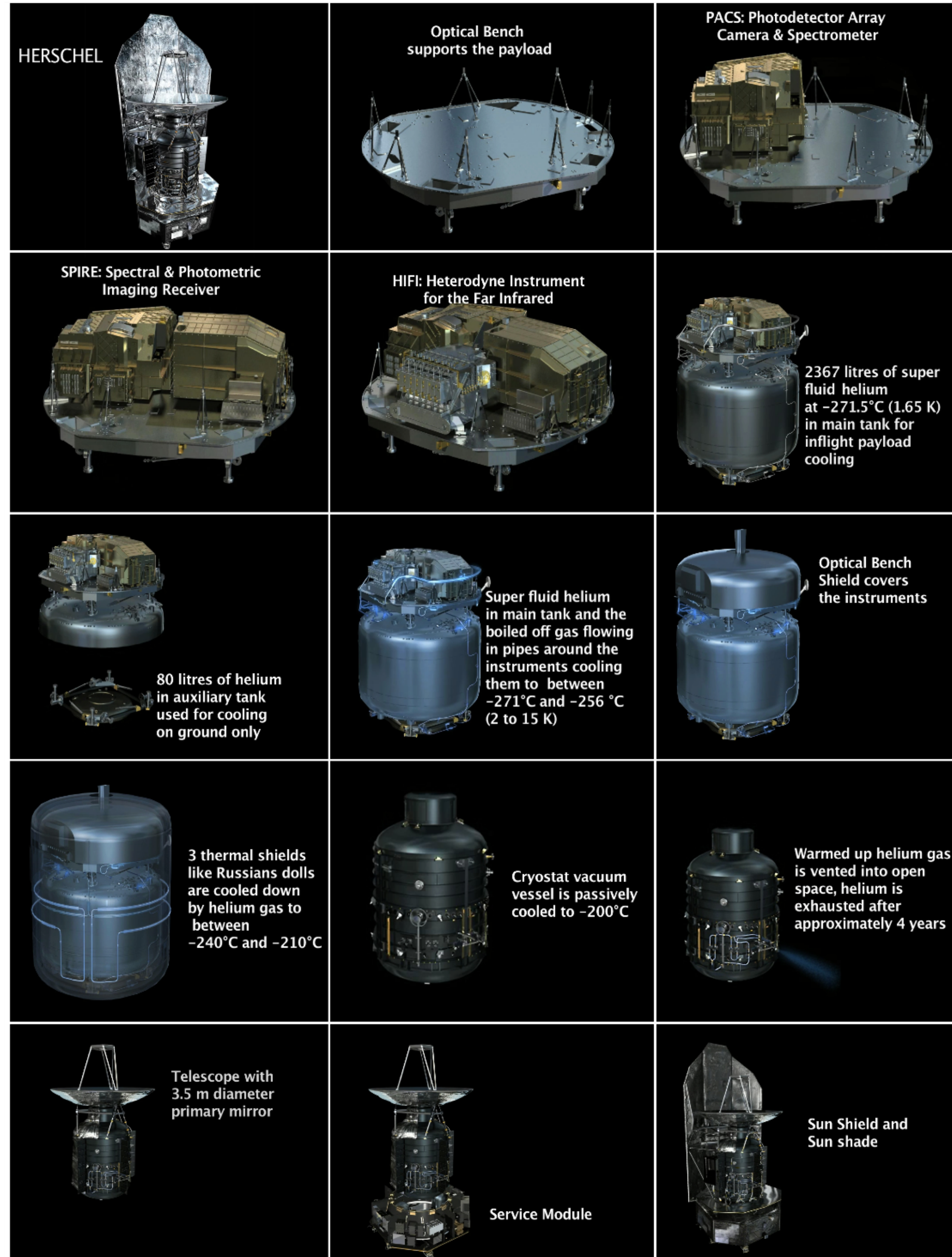
Examples:
Herschel & Planck

- ESA missions, launched together by Ariane V (May 2009)



Herschel

- Diameter: 3.5 m (SiC)
- Wavelengths: 55 to 672 µm
- Size: 7.5 x 4 x 4 m
- Weight: 3.4 tons
- Orbit: Lagrange L2
- Duration: 3.5 years
- Cooling: a few Kelvins



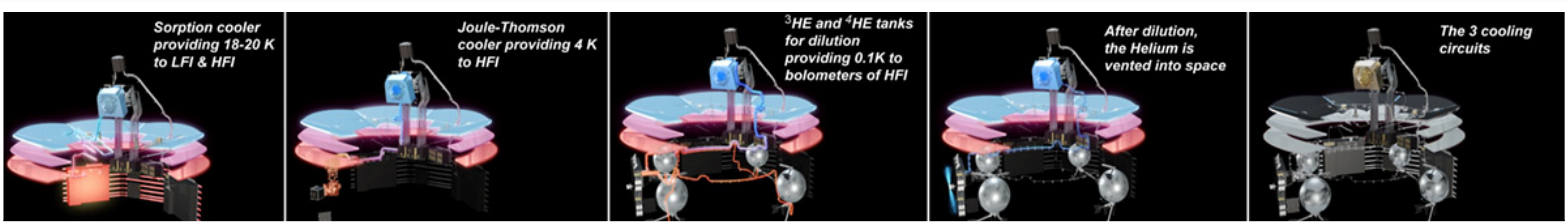
Planck

- Diameter: 1.5 m
- Range: 0.3 to 10 mm
- Size: 4.2 m (cube)
- Weight: 1.9 tons
- Duration: 2 years (2 full sky surveys)

Cooling

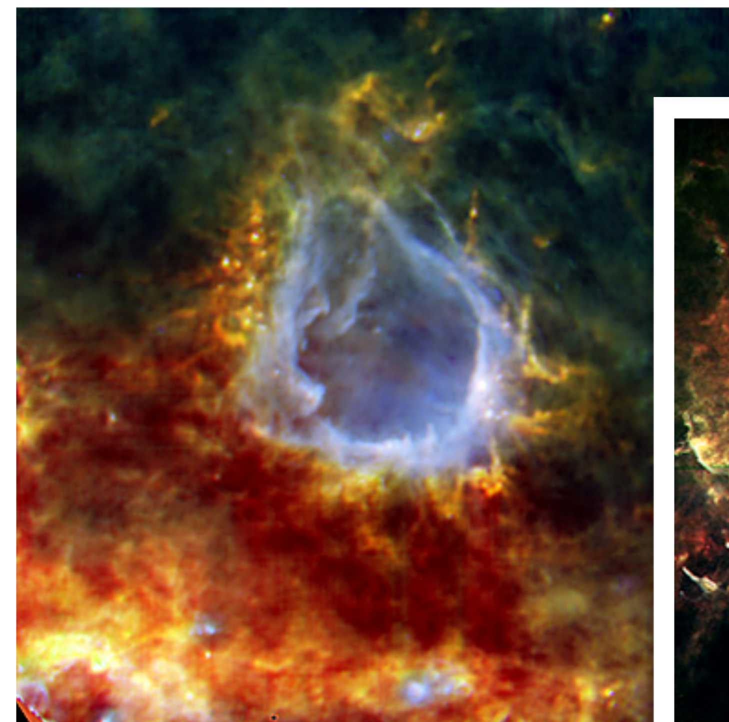
Tests @ CSL

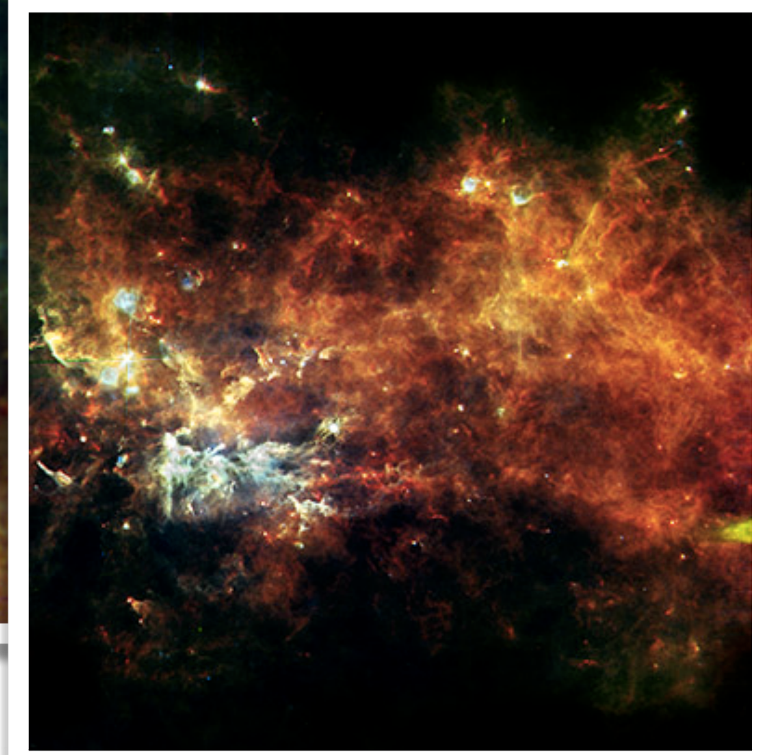
- ✦ Telescope: 15 - 20 K
- ✦ Focal plane: 5 - 6 K
- ✦ Bolometers: 0.1 - 0.3 K
- ✦ Several cooling agents
    - sun shield / baffle
    - hydrogen sorption cooler
    - Helium Joule-Thomson cooler (frictionless pump)
    - $^3He/^4He$ dilution cooler
- ✦ Extreme stability (~0.01 K level)

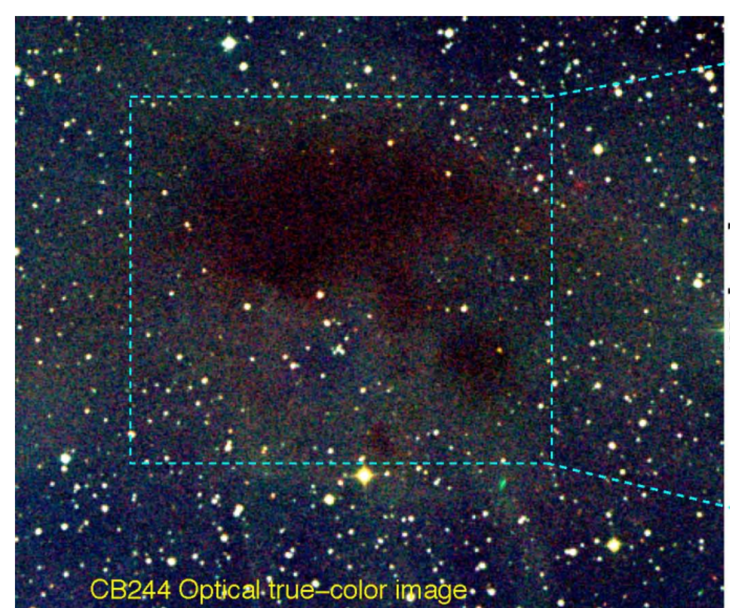


Herschel results

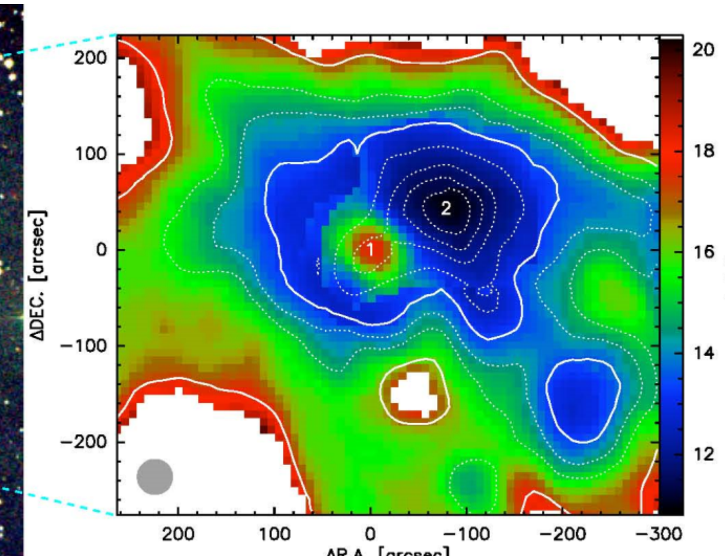
- Assembly of the first galaxies (starburst galaxies)
- Star formation
    - massive stellar embryos found in filaments across our galaxy
- Mass loss of evolved (dying) stars
- Molecular chemistry
    - in cold molecular clouds (H_2O, O_2, complex organics)
    - planetary surfaces and atmospheres
    - composition of comets (e.g., deuterium content)







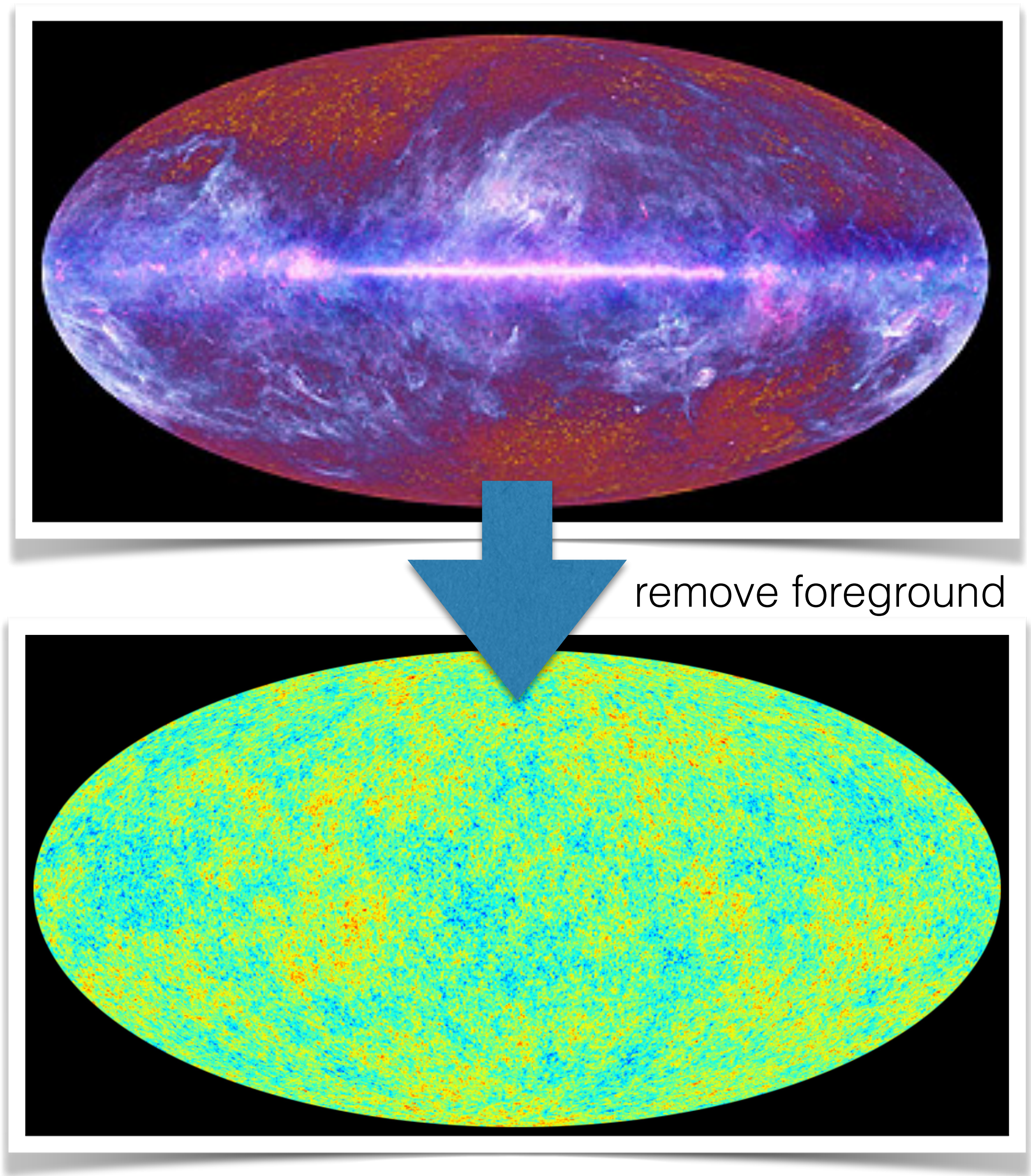
CB244 Optical true-color image



CB244 Dust temperature (color) and column density (white contours)

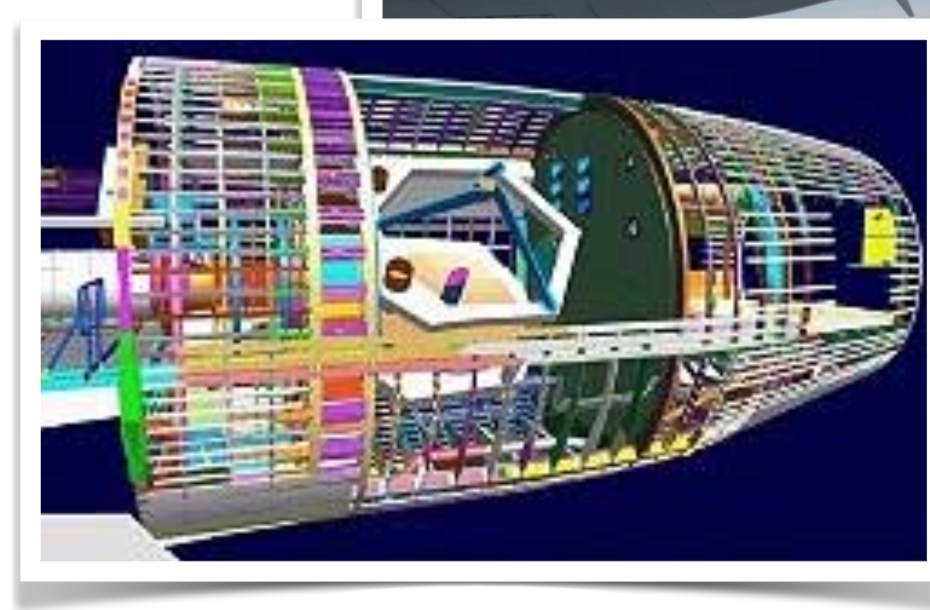
Planck results

- ✦ CMB at 2.7 K
  - anisotropies measured at the $\Delta T/T = 10^{-6}$ level
  - unprecedented angular resolution (5 arcmin)
- ✦ Large scale properties of the Universe
  - 26% content of dark matter (5% ordinary matter)
  - clumps and the origin of large scale structures
- ✦ Validation of inflation models



Other example: SOFIA

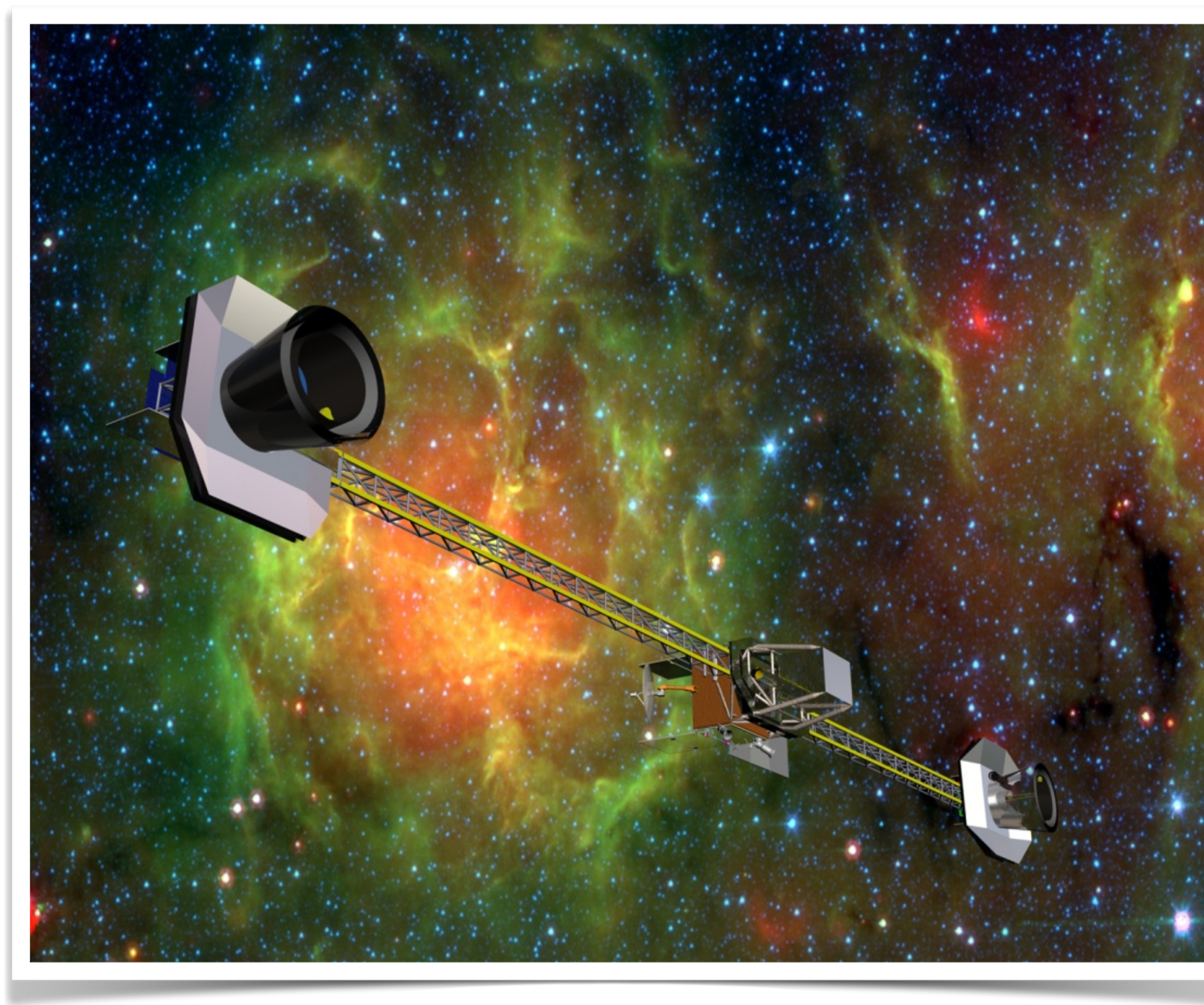
- ✦ 2.5 m telescope
- ✦ Altitude > 13 km
- ✦ Range: 300 nm - 1.6 mm
  - mostly 5 - 300 μm
- ✦ Modified Boeing 747-SP
  - reinforced structure for 20-ton telescope
  - big hole in fuselage, avoiding turbulence!



SOFIA open-door flight test

Future: interferometry

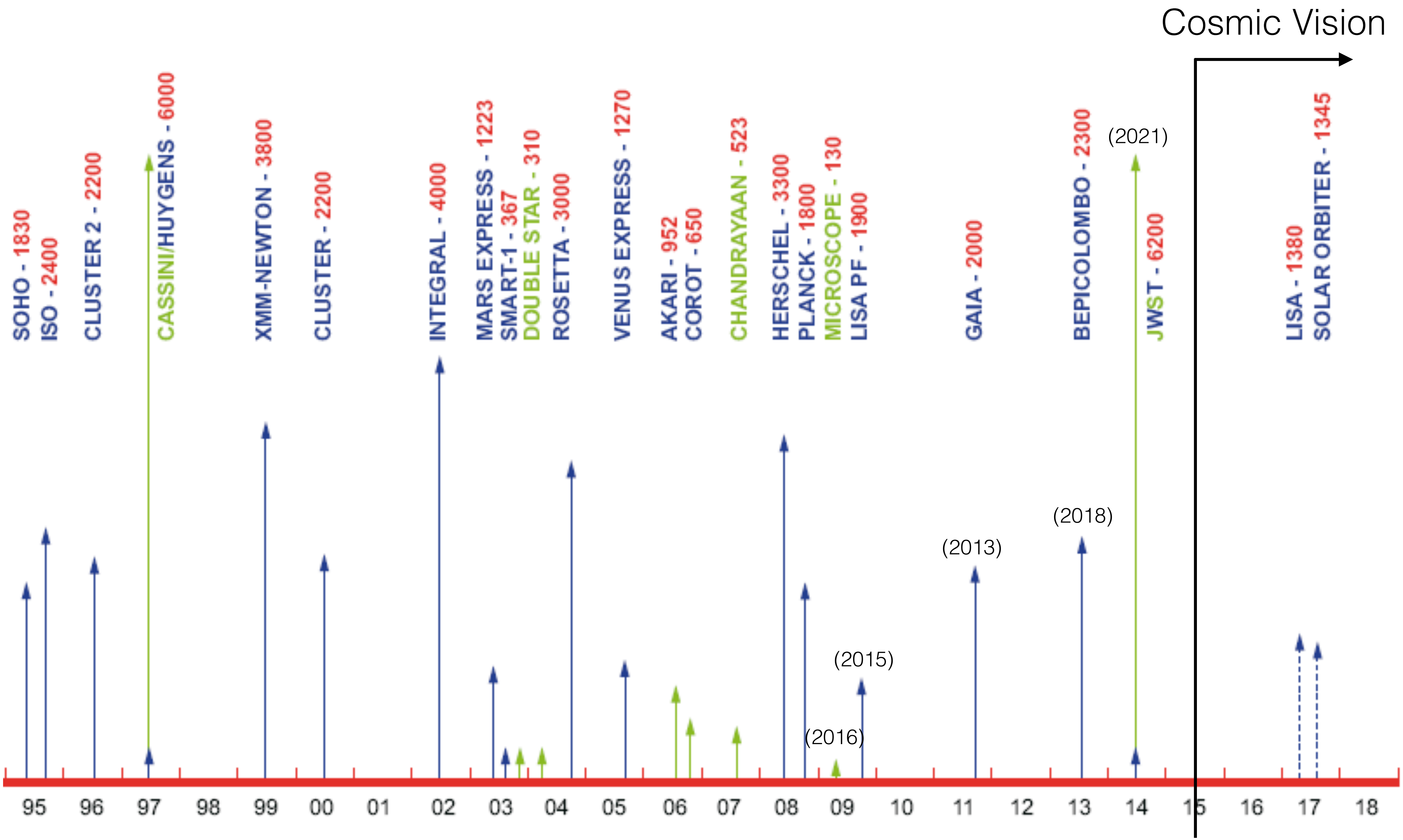
- Illustrated here: SPIRIT concept (formation flying also considered)
- Baselines: 7 - 35 m (deployable)
- 1-m class telescopes
- Range: 25 - 400 μm
- Cooling
  - optics at 4 K
  - bolometers at 50 mK
- Aperture synthesis
  - array: sliding & rotation



Cosmic Vision 2015-2025

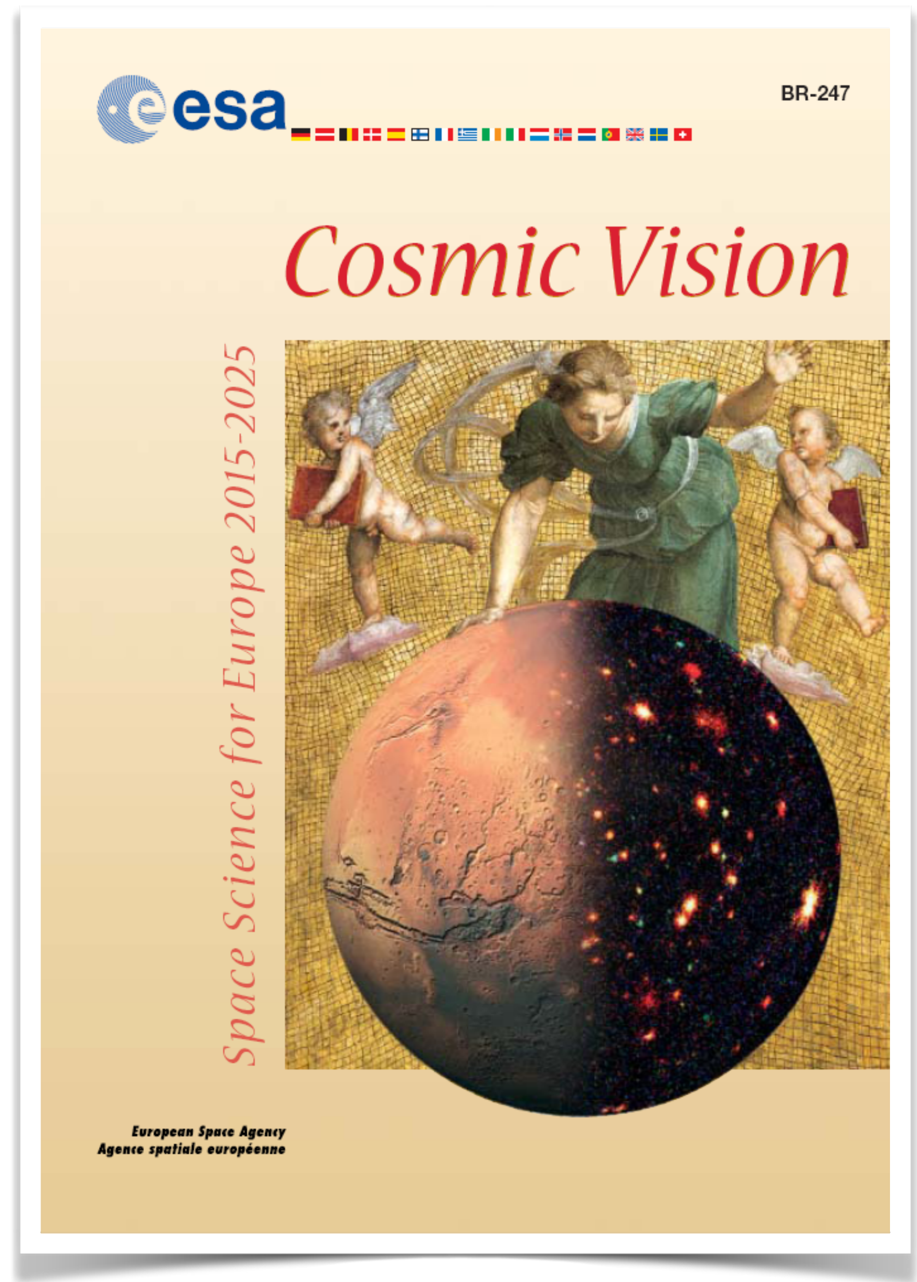
The ESA scientific program

Horizon 2000+ program



Cosmic Vision

- ✦ Four themes
  - What are the conditions for planet formation and the emergence of life?
  - How does the Solar System work?
  - What are the fundamental physical laws of the Universe?
  - How did the Universe originate and what is it made of?
- ✦ Several mission opportunities



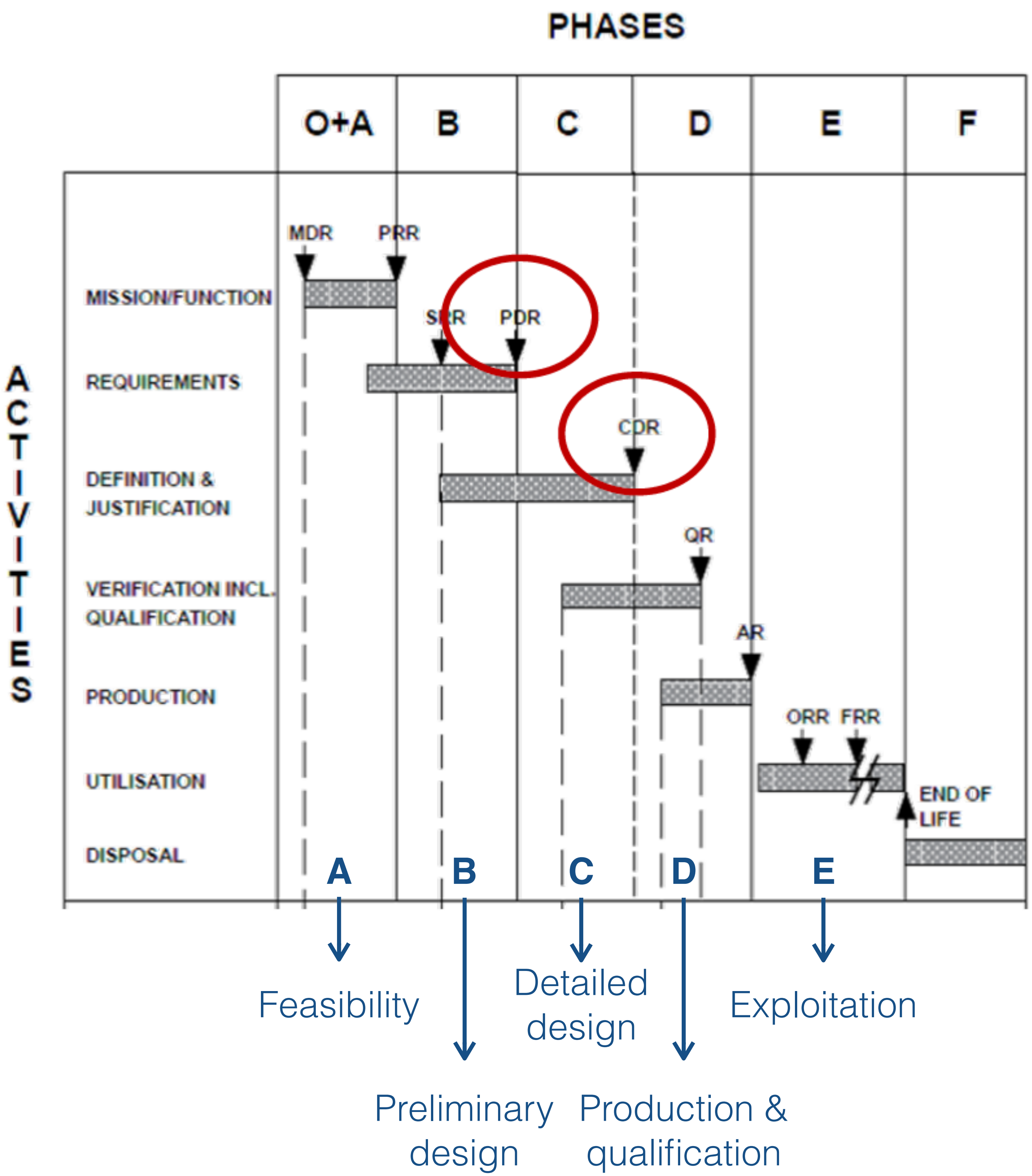
Mission opportunities

- ✦ At first, two classes of missions
  - Large missions (~900 M€, ESA contribution)
  - Medium missions (~500 M€, mostly stand-alone)
- ✦ Several calls for mission concepts
  - 2007: one Large (L1, 2022) and two Medium (M1-M2, 2019-2020)
  - 2010: one Medium (M3, 2026)
  - 2013: two Large (L2-L3, 2028-2034)
  - 2015: one Medium (M4, 2028), one Small (S2, 2021)
  - 2016: one Medium (M5, 2032)
  - 2019: M6 mission plan cancelled due to budget
  - 2021: one Medium mission (M7, 2035)
- ✦ Two more mission categories added during Cosmic Vision program
  - Small missions (~50 M€, ESA contribution) — two funded
  - Fast missions for special, fast-track opportunities — two funded

Call for mission #1 (M1, M2, L1)

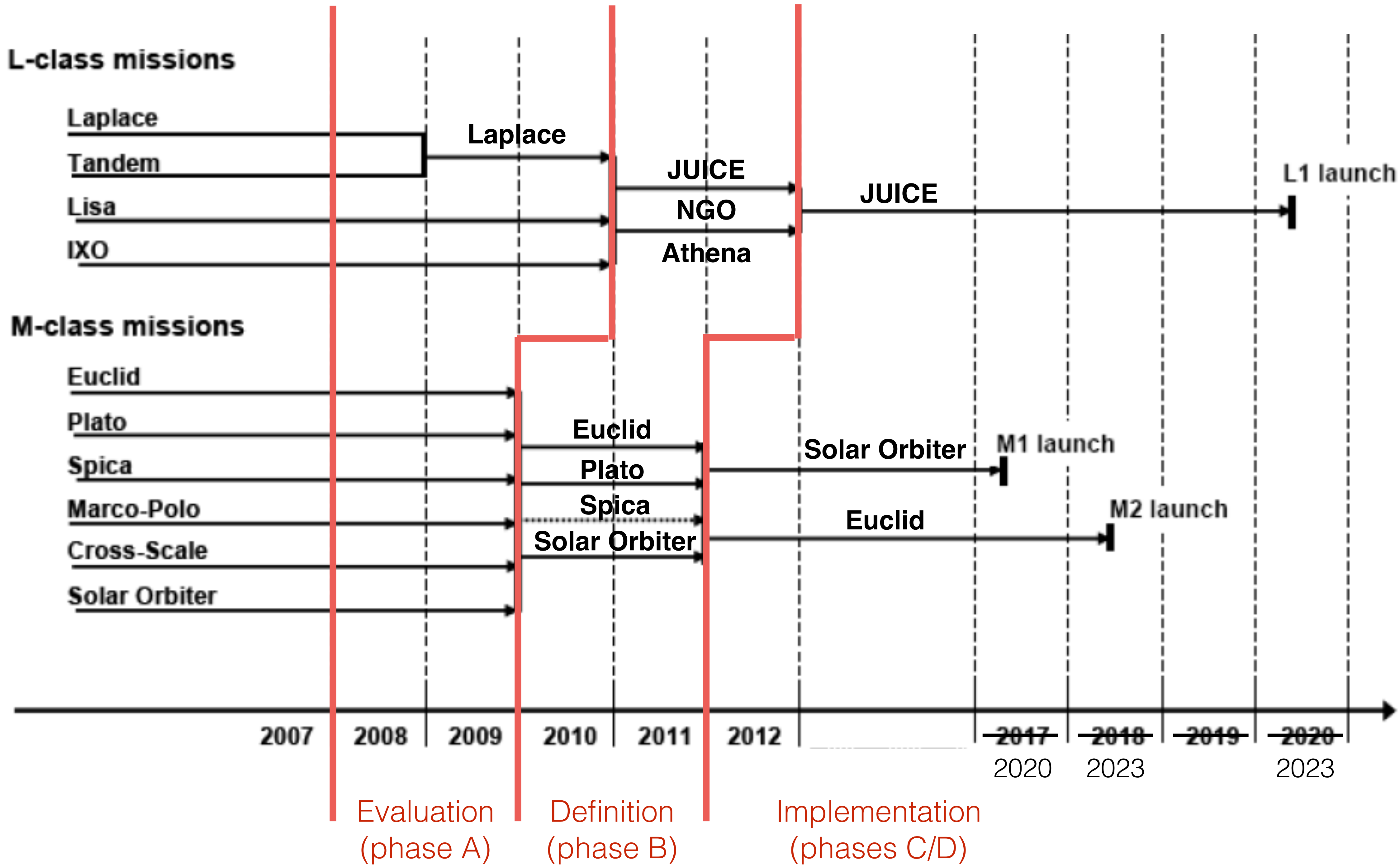
- 6 M-class missions pre-selected for study
  - Euclid (dark energy, lensing)
  - Plato (exoplanets)
  - Spica (IR observatory, JAXA collaboration)
  - Marco-Polo (asteroid sample return)
  - Cross-Scale (magnetosphere, shock waves)
  - Solar Orbiter (Sun at high resolution - Horizon 2000+)
- 4 L-class missions pre-selected for study (NASA collaboration?)
  - Laplace (Jupiter-Europe system)
  - TandEM (Saturn-Titan-Enceladus system)
  - IXO (X-ray observatory)
  - LISA (gravitational waves - Horizon 2000+)

Phases of a space project



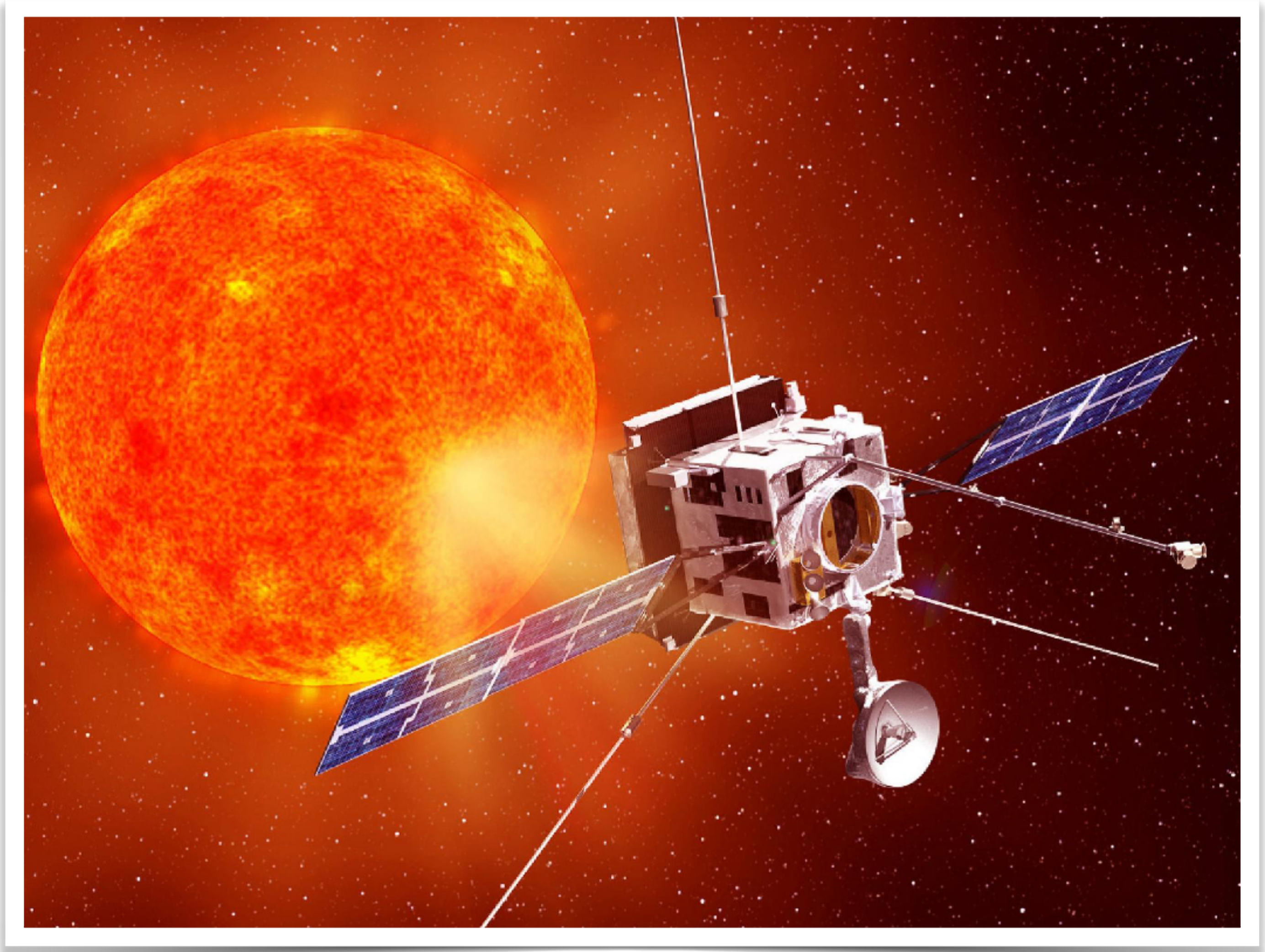
AR = Acceptance Review
CDR = Critical Design Review
FRR = Flight Readiness Review
MDR = Mission Definition Review
ORR = Operational Readiness Review
PDR = Preliminary Design Review
PRR = Preliminary Requirements Review
QR = Qualification Review
SRR = System Requirements Review

Selection process



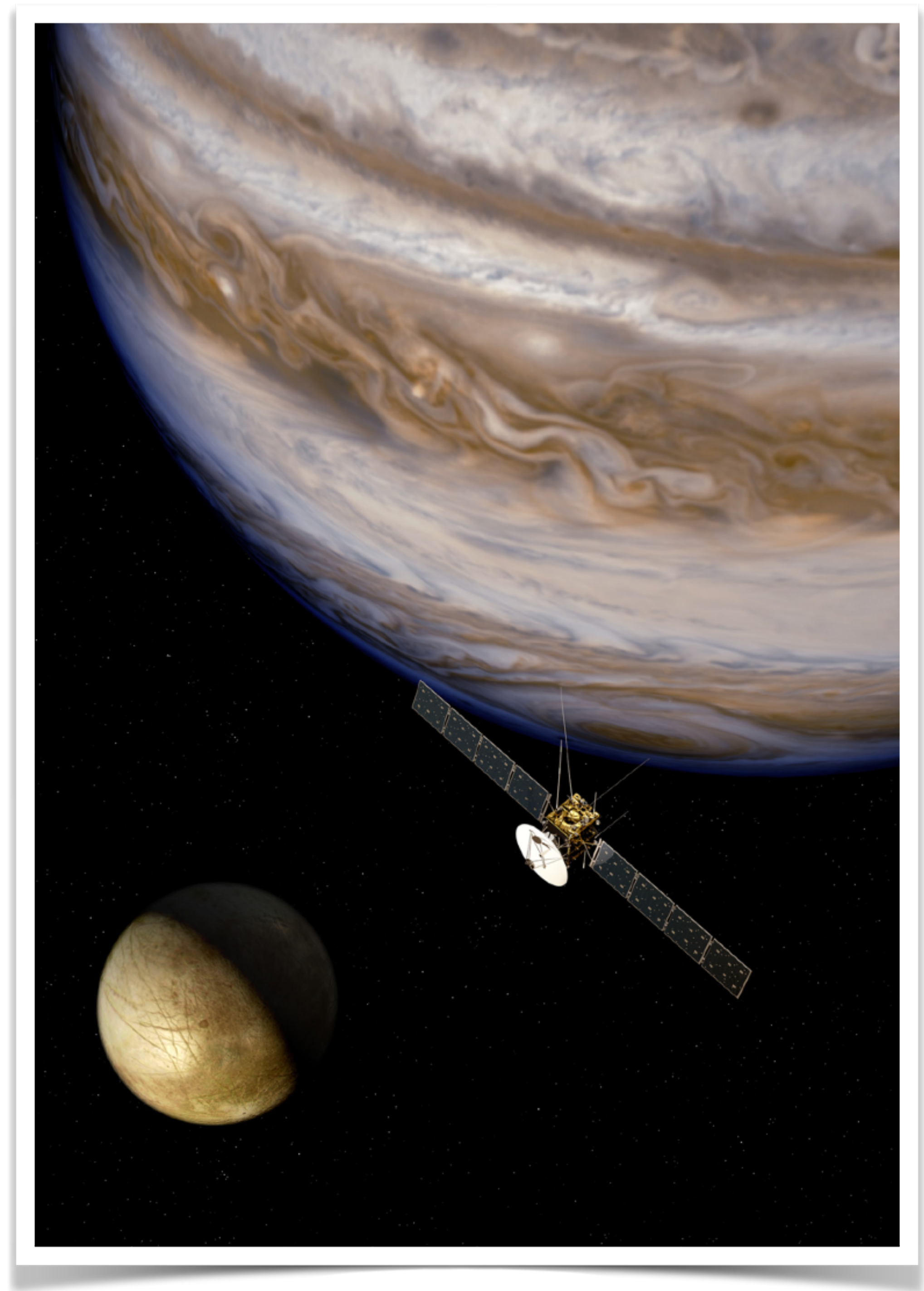
Solar Orbiter

- Orbit at 1/4th of Sun-Earth distance
- Heat shield to reduce temperature from 600°C outside to 60°C inside spacecraft
- One of the instruments (EUI) built by CSL



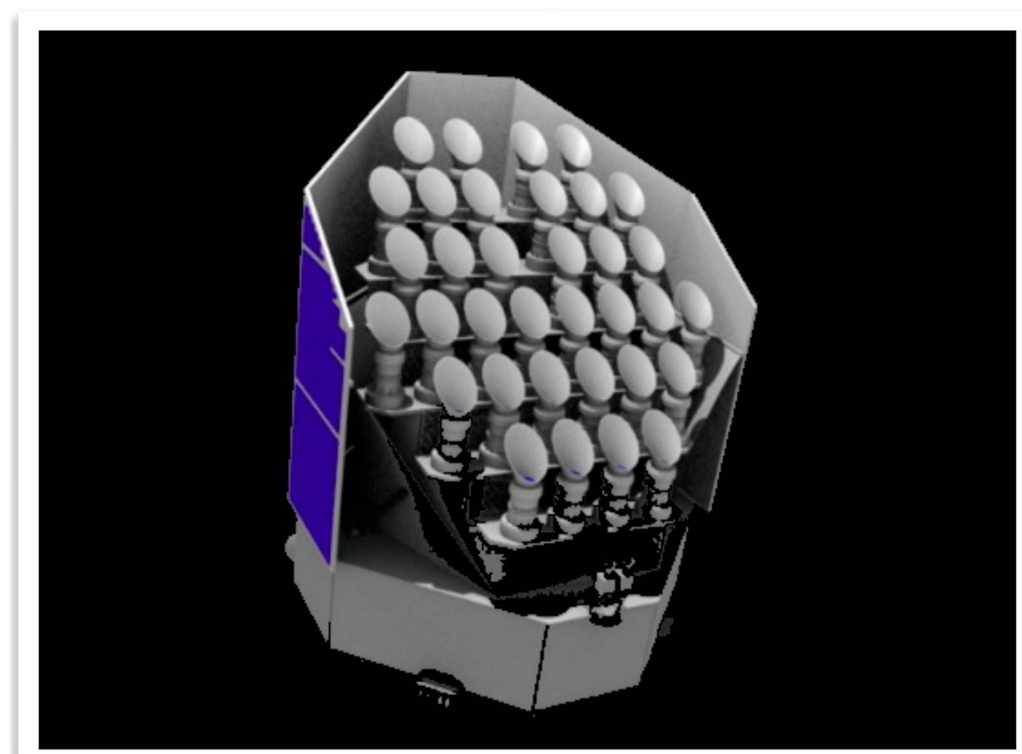
JUICE

- ✦ Mission to the Jupiter icy moons (Ganymede, Europa, Callisto)
- ✦ More challenges
  - power budget and solar panels (97 m^2!!!)
  - radiation tolerance (Jupiter magnetosphere)
  - mass budget (10 instruments)
  - orbital dynamics (flybys)
  - communications
  - planetary protection (sterilization)



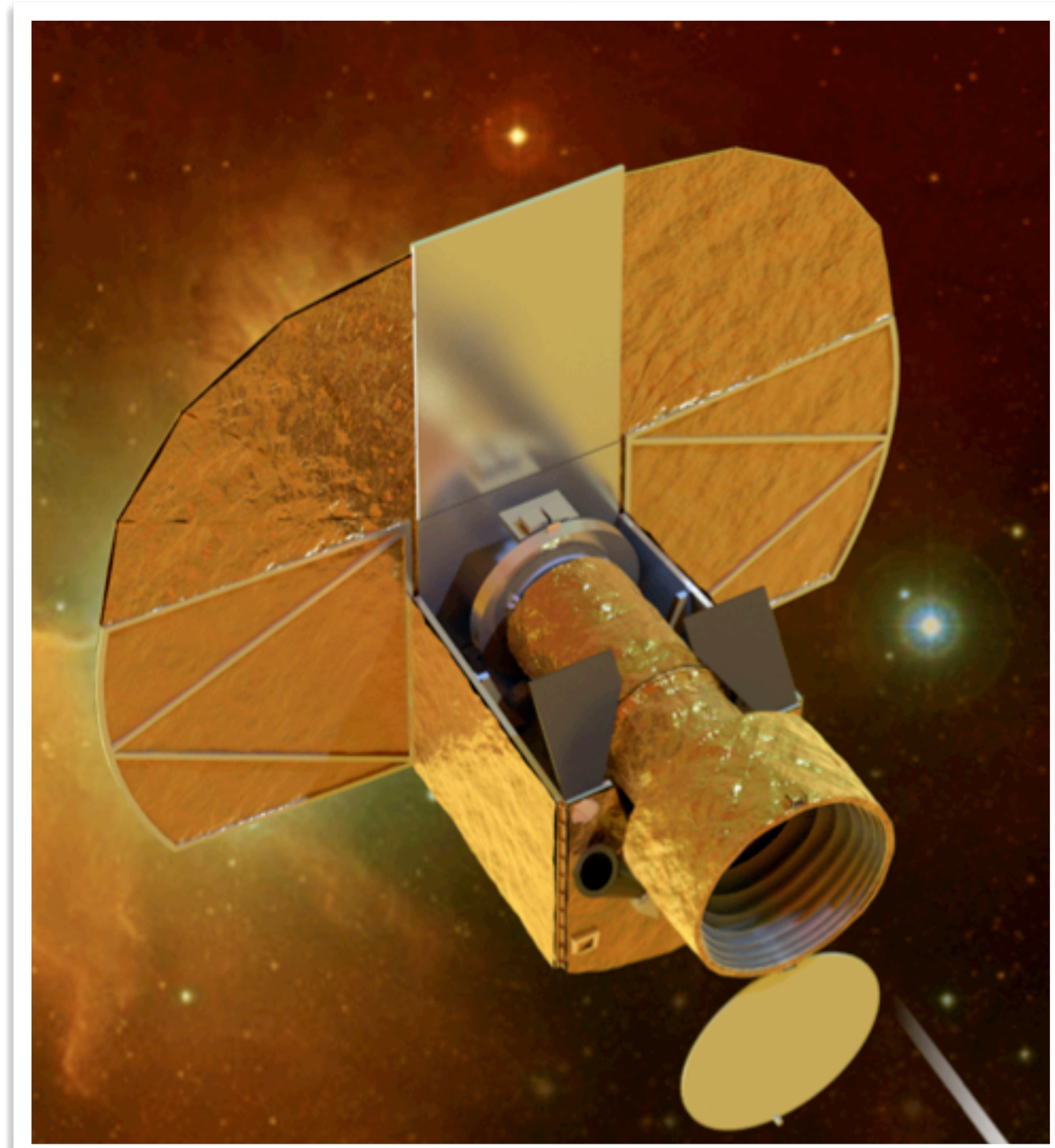
Call for mission #2 (M3)

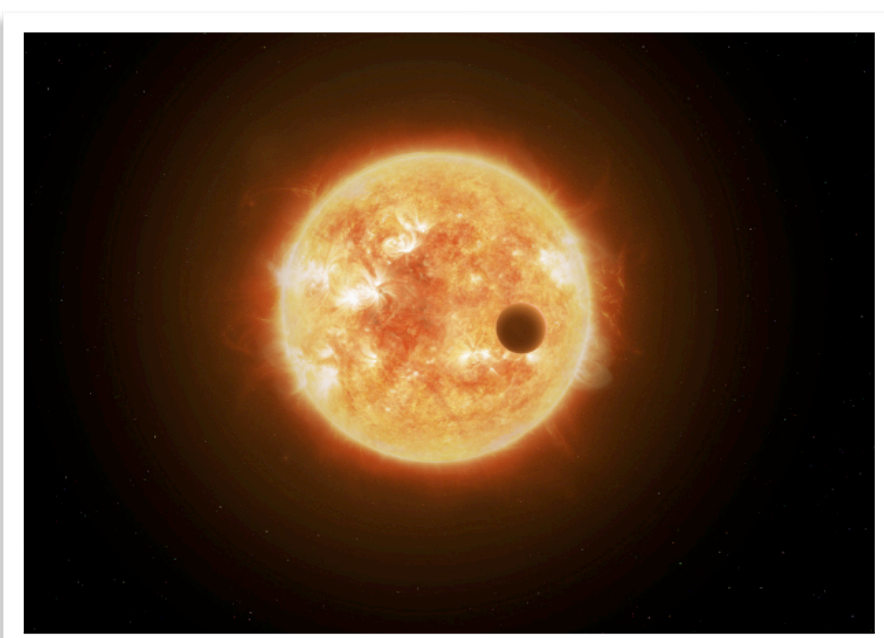
- Four (out of 47) M-class missions selected for assessment
  - EChO: Exoplanet Characterization Observatory
  - PLATO: PLAnetary Transits and Oscillations of stars
  - LOFT: Large Observatory For X-ray Timing
  - STE-QUEST: Space-Time Explorer and Quantum Equivalence Principle Space Test
- Down-selection (2014): PLATO
- Launch expected in 2026
  - 26 cameras currently being assembled and tested at CSL



Call for missions #3 (S1)

- Cost to ESA: 50 M€
- Max total cost: 150 M€
- 26 proposals submitted
- CHEOPS selected
- Launched in Dec 2019

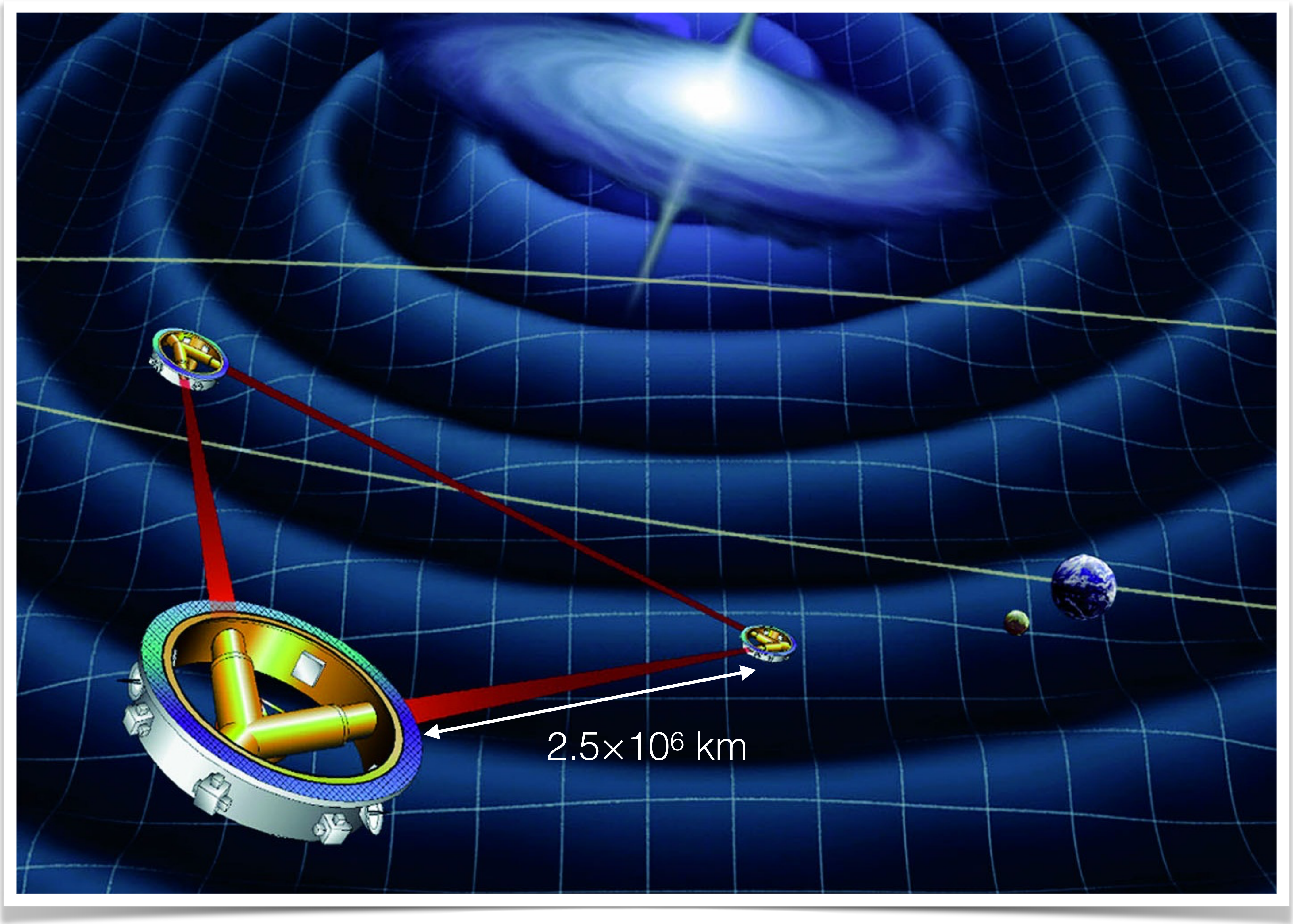




L2 & L3 missions

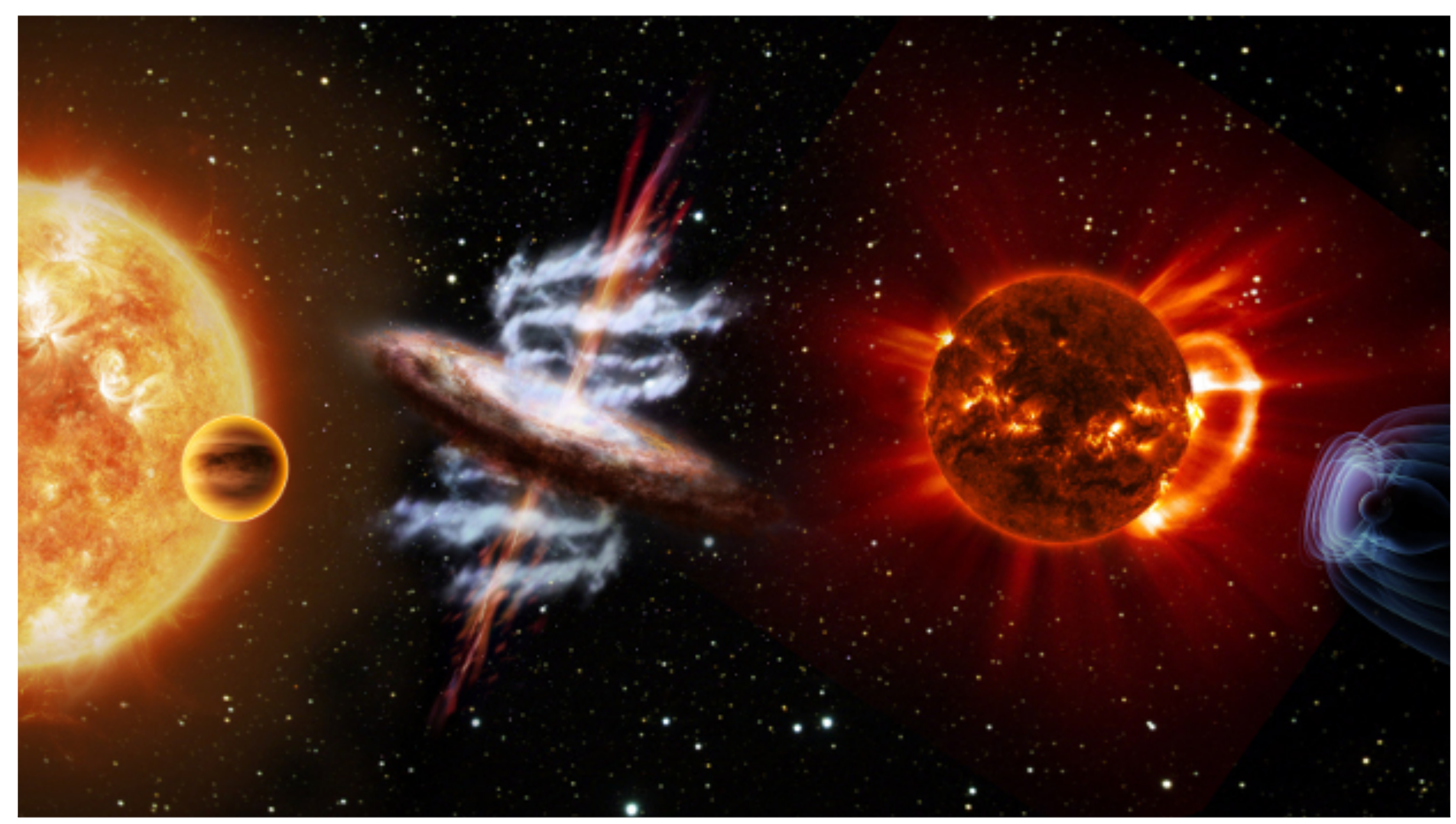
- Themes selected by ESA working groups in 2013
  - L2: the hot and energetic universe (~2035)
  - L3: the search for gravitational waves (~2035)
- L2 mission concept selected in 2014: ATHENA (Advanced Telescope for High Energy Astrophysics)
- L3 mission concept confirmed in 2017: LISA (Laser Interferometer Space Antenna)
  - does not rely on electromagnetic radiation any more!

LISA: gravitational waves



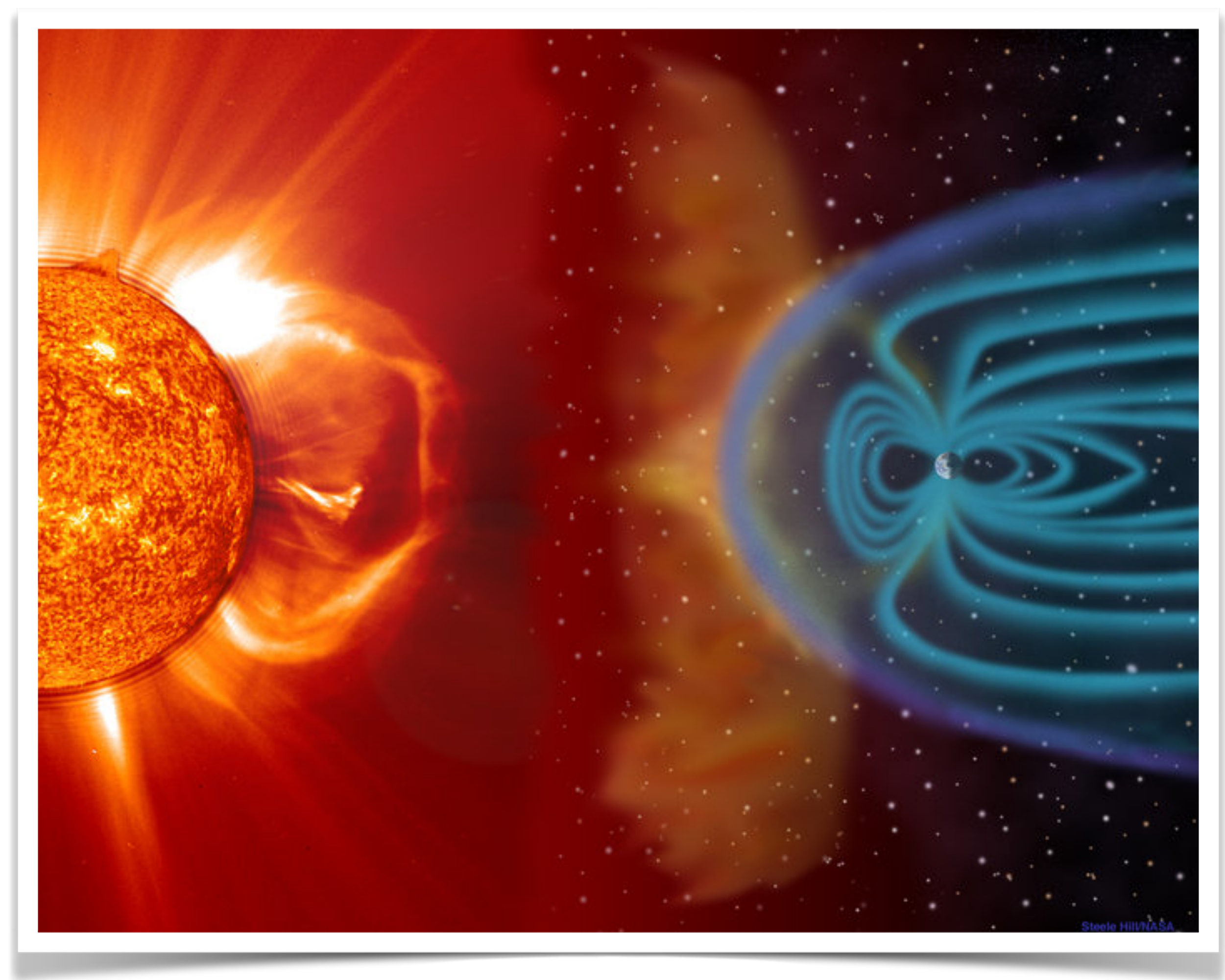
Call for Missions #4 (M4)

- Three (out of 27) candidates selected in June 2015
  - ARIEL: Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (≈EChO)
  - THOR: Turbulence Heating ObserveR
  - XIPE: X-ray Imaging Polarimetry Explorer
- ARIEL selected Nov 2017
- Planned launch: 2029



Call for Missions #5 (S2)

- Special call for missions in partnership with China
  - shared participation of both agencies
- 13 proposals received
- SMILE selected
  - interactions between the Earth magnetosphere and the supersonic solar wind
- Launch: 2025



Call for Missions #6 (M5)

- ✦ Call released in April 2016
- ✦ Selection of missions for study: May 2018
  - ~~SPICA: far-infrared telescope~~
  - THESEUS: ɣ-ray / X-ray telescope
  - EnVision: Venus orbiter
- ✦ Phase A studies completed in 2021 —> EnVision selected.
- ✦ Phase B1 (preliminary design) completed —> mission adopted. Phase B2 now started.
- ✦ Planned launch date: 2031

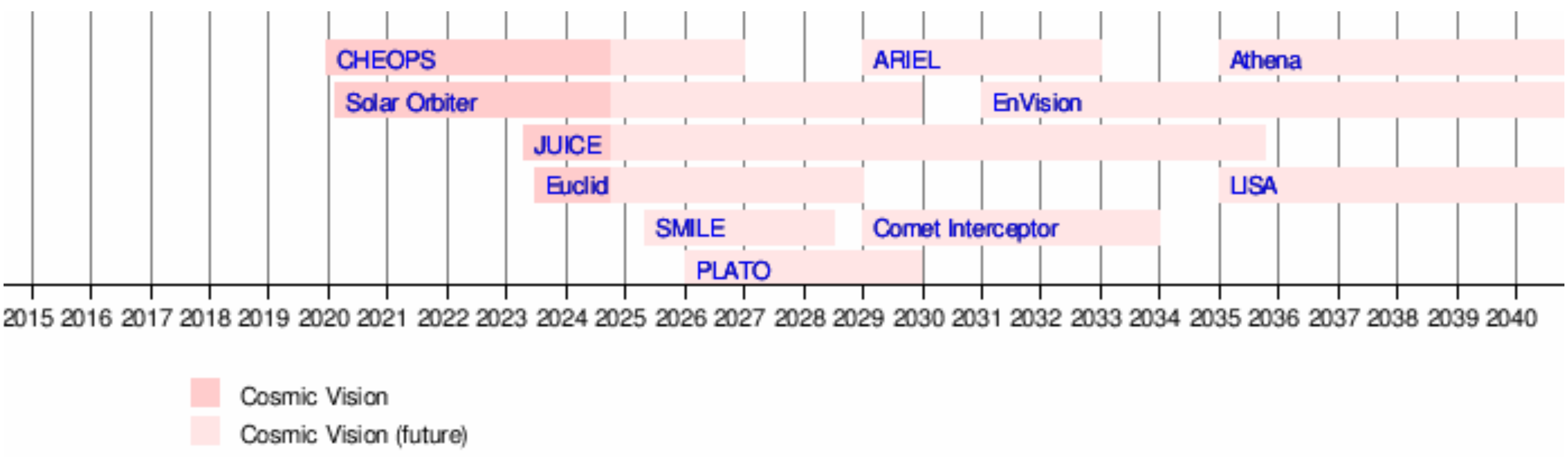
Last call: M7

- ✦ Call released in December 2021, after M6 was cancelled due to budget issues
- ✦ November 2022: five mission concepts pre-selected
- ✦ November 2023: three missions down-selected
  - M-MATISSE: habitability and evolution of Mars
  - Plasma Observatory: plasma environment around Earth
  - THESEUS: ɣ-ray / X-ray telescope focusing on transient events
- ✦ Phase A studies to be completed in 2026, when one mission will be selected
- ✦ Planned launch date: 2035

Cosmic Vision summary

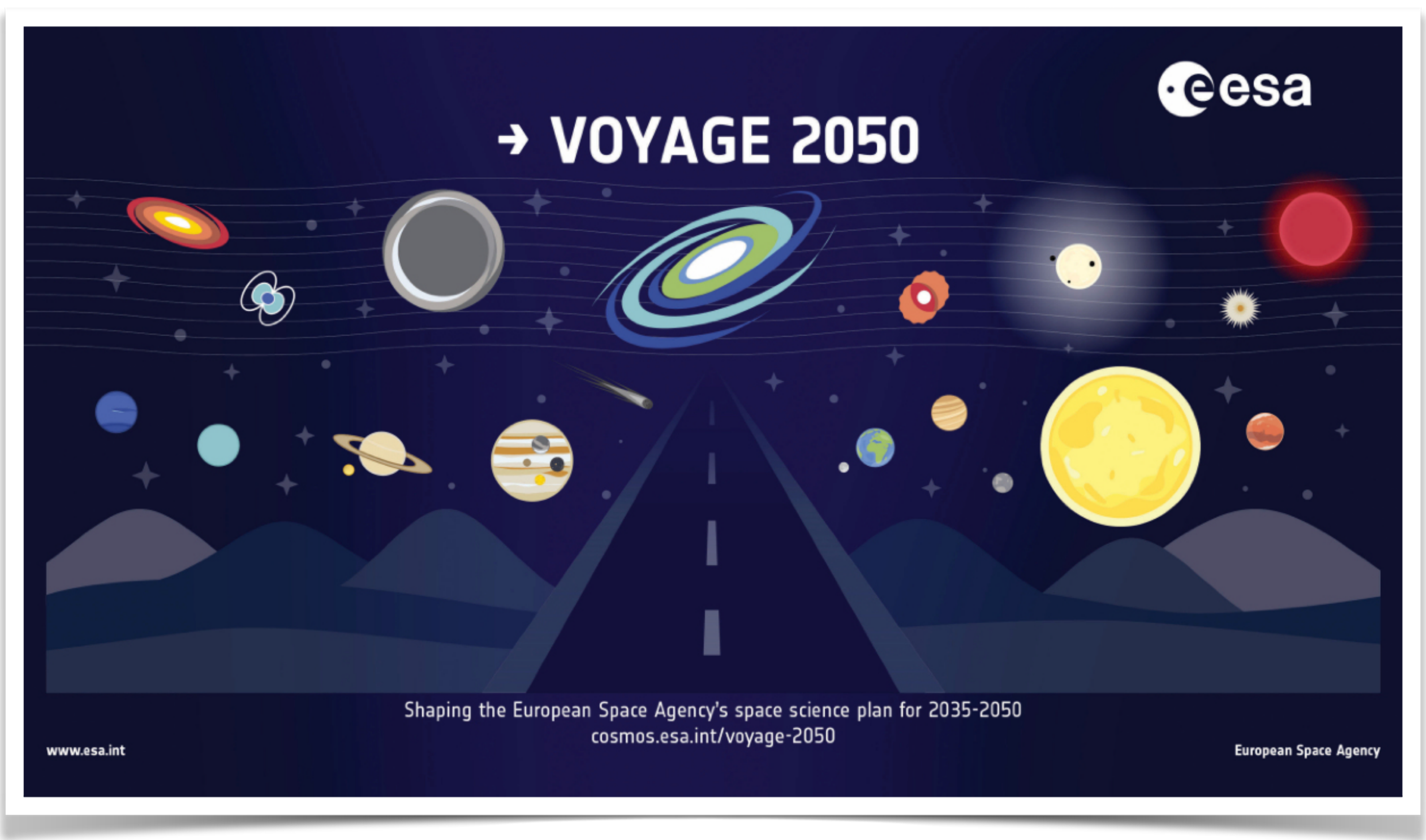
✦ Also two F-type missions

- Comet Interceptor: will target long-period comet or interstellar object (to be launched with ARIEL)
- ARRAKIHS: wide-field deep imaging to complement Euclid science (launch in the early 2030s)



Already preparing the next program: Voyage 2050

- Top priorities for large missions identified:
  - moons of the giant planets (habitability)
  - temperate exoplanets (rocky planets), or the Milky Way (Gaia-like)
  - new physical probes of the early Universe (gravitational waves)



Want to contribute?

Masters thesis at STAR Institute

ground- and space-based instrumentation (including CSL)

data analysis / scientific exploitation

—> contact me, or Michaël De Becker <michael.debecker@uliege.be>