

Astronomical space observatories

From X rays to millimeter waves

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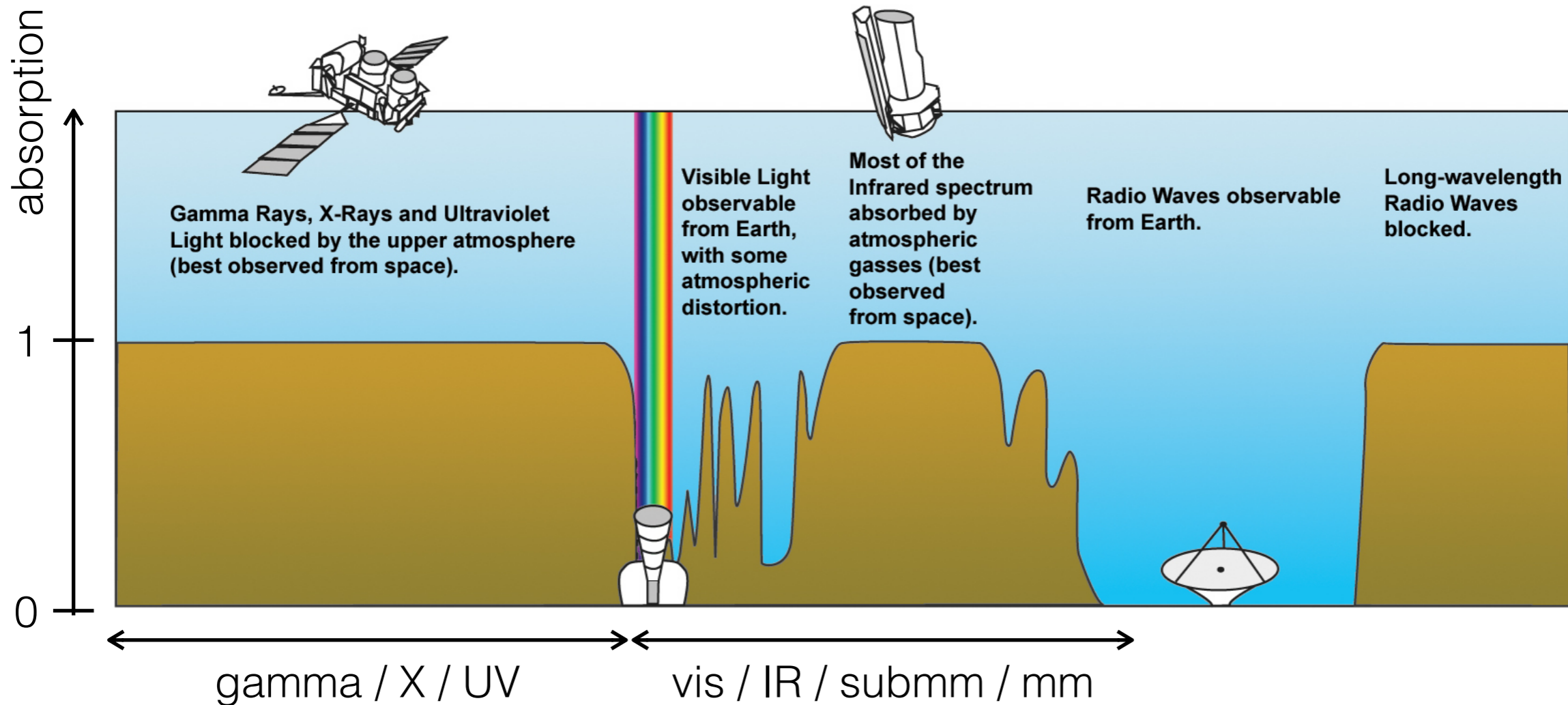
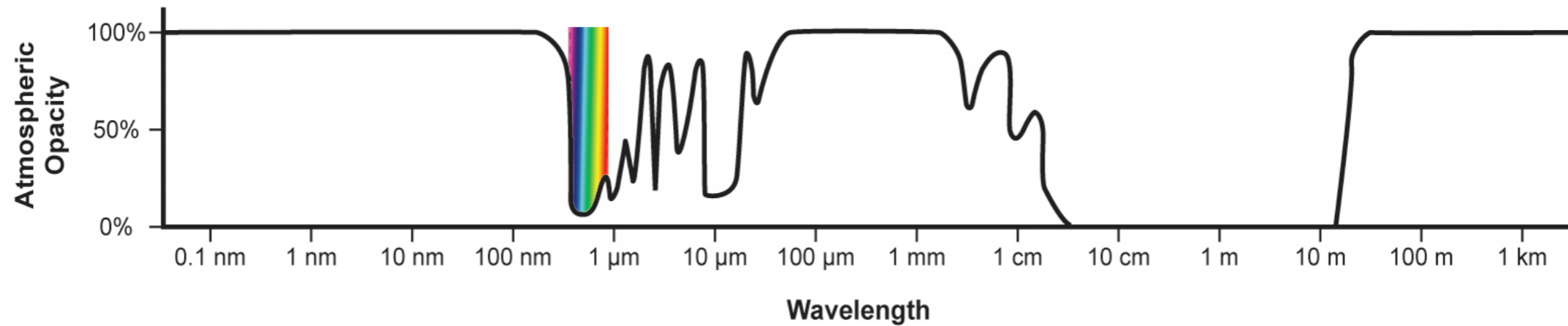
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Why observing from space?

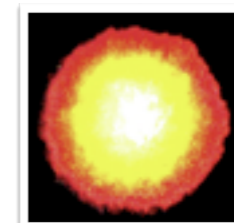
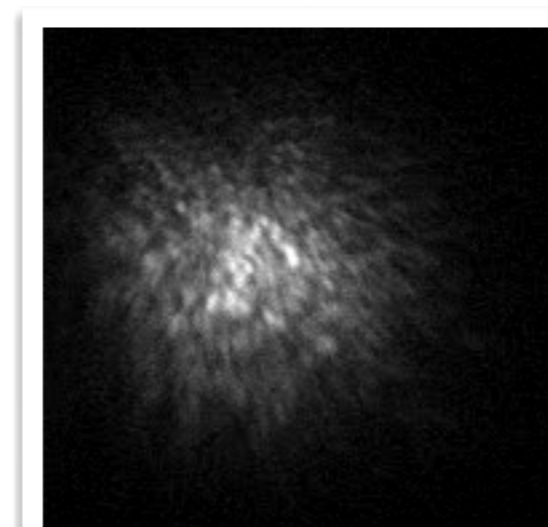
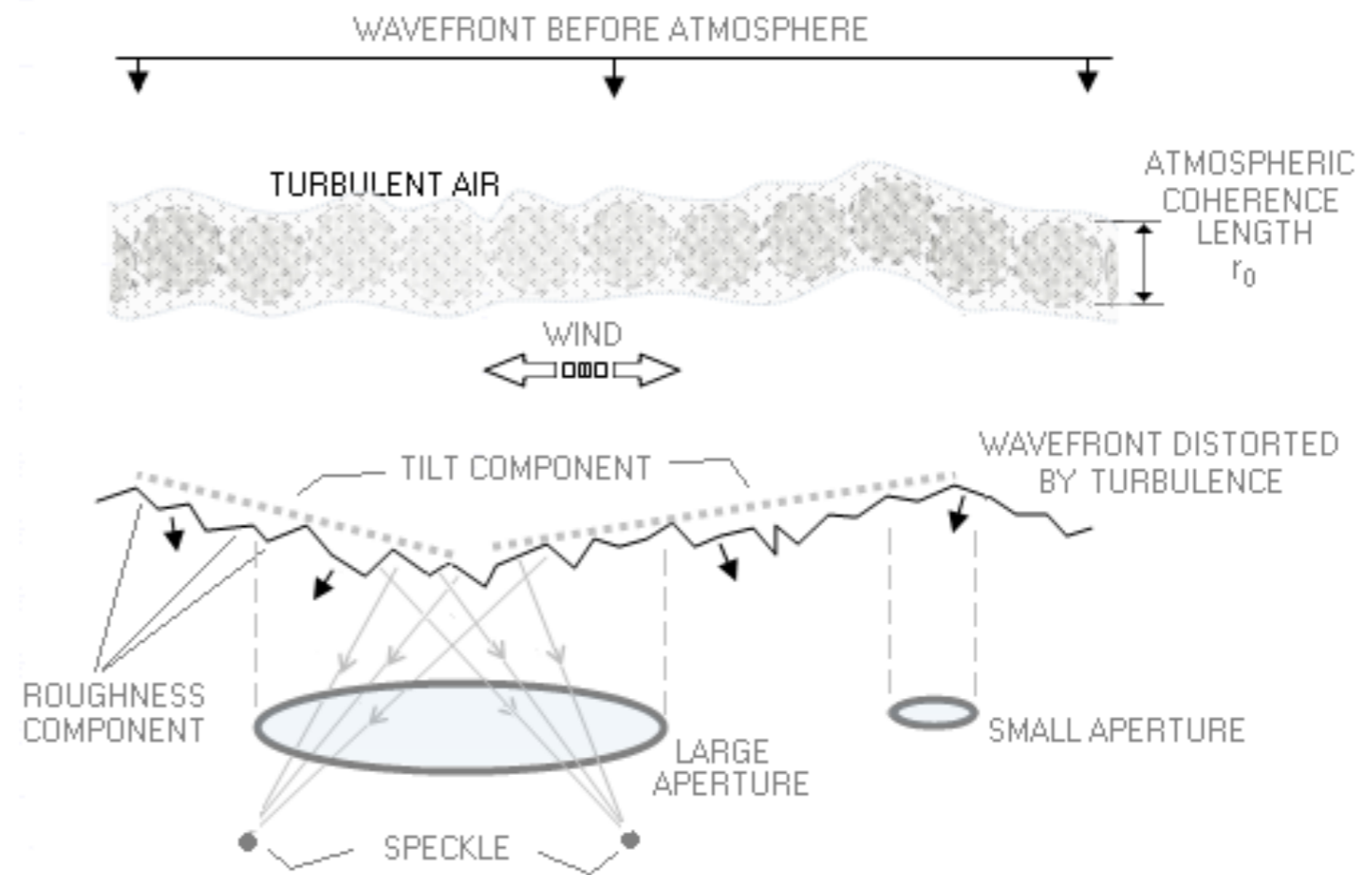
From X rays to millimeter waves

Atmospheric transmission

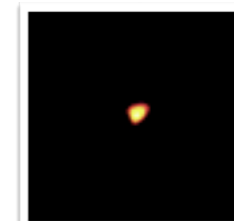


Atmospheric turbulence

- ◆ 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



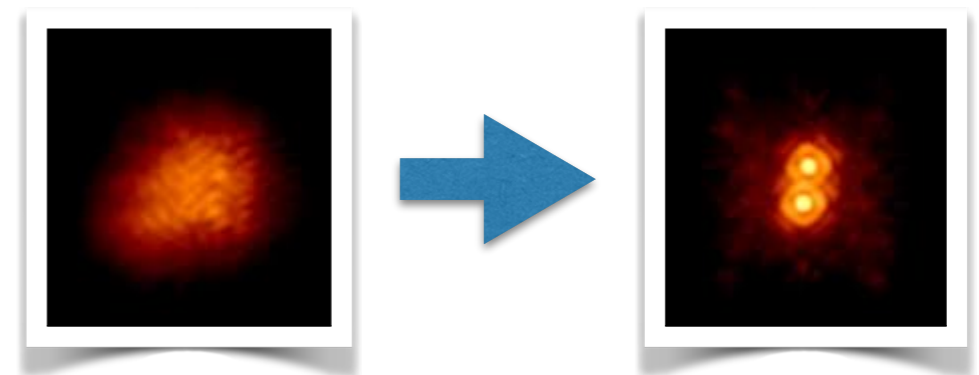
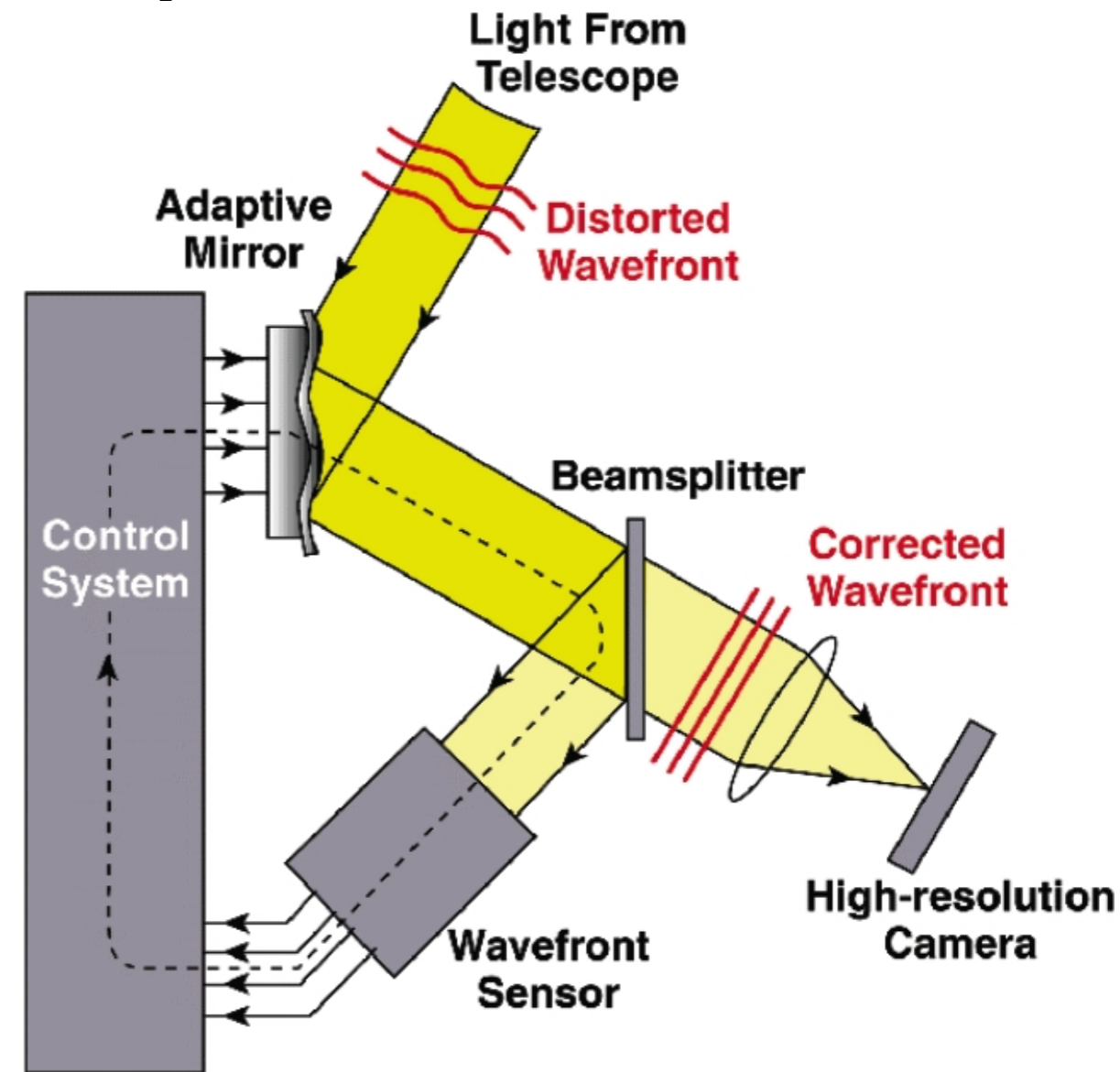
long exposure image



theoretical telescope PSF

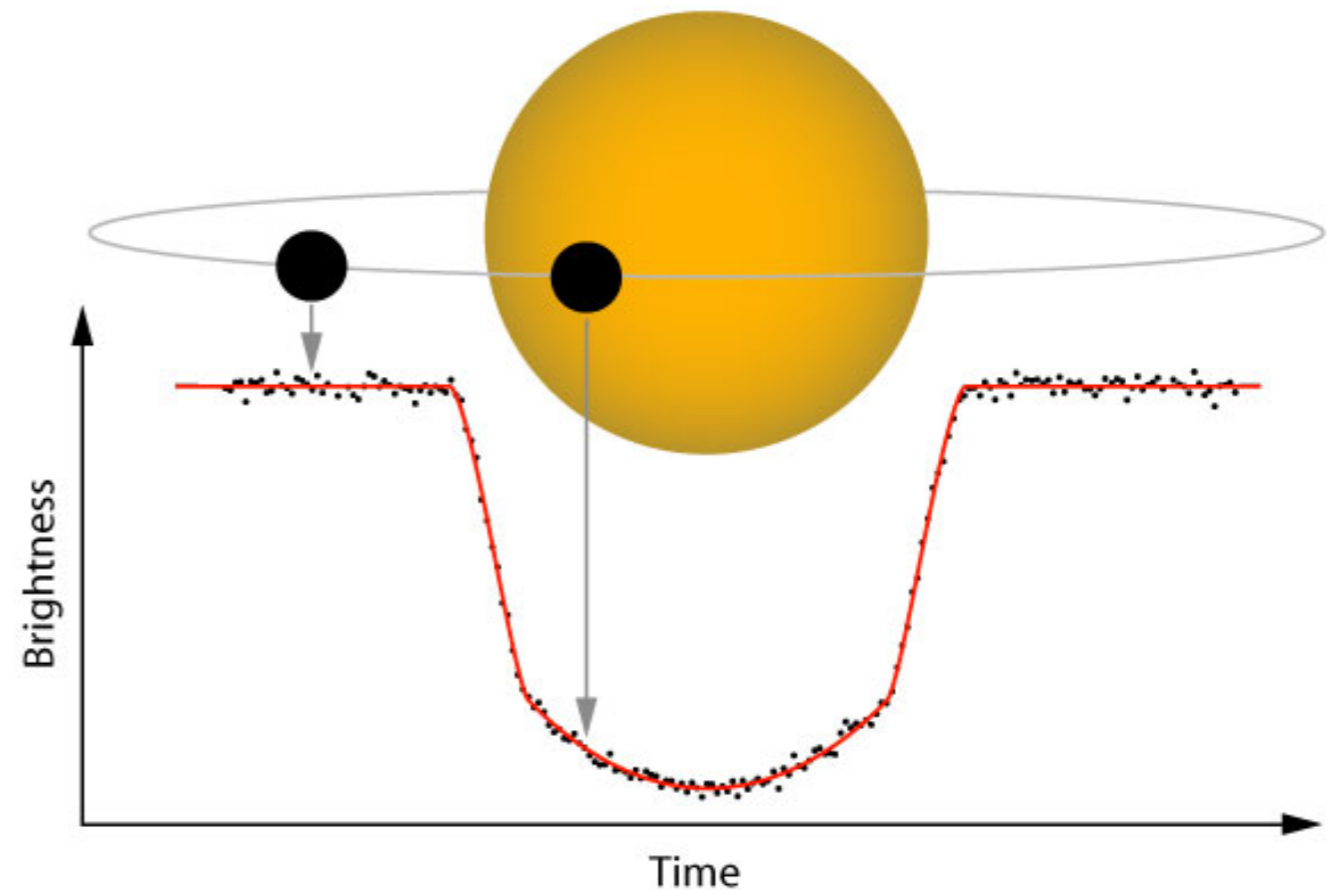
Adaptive optics

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



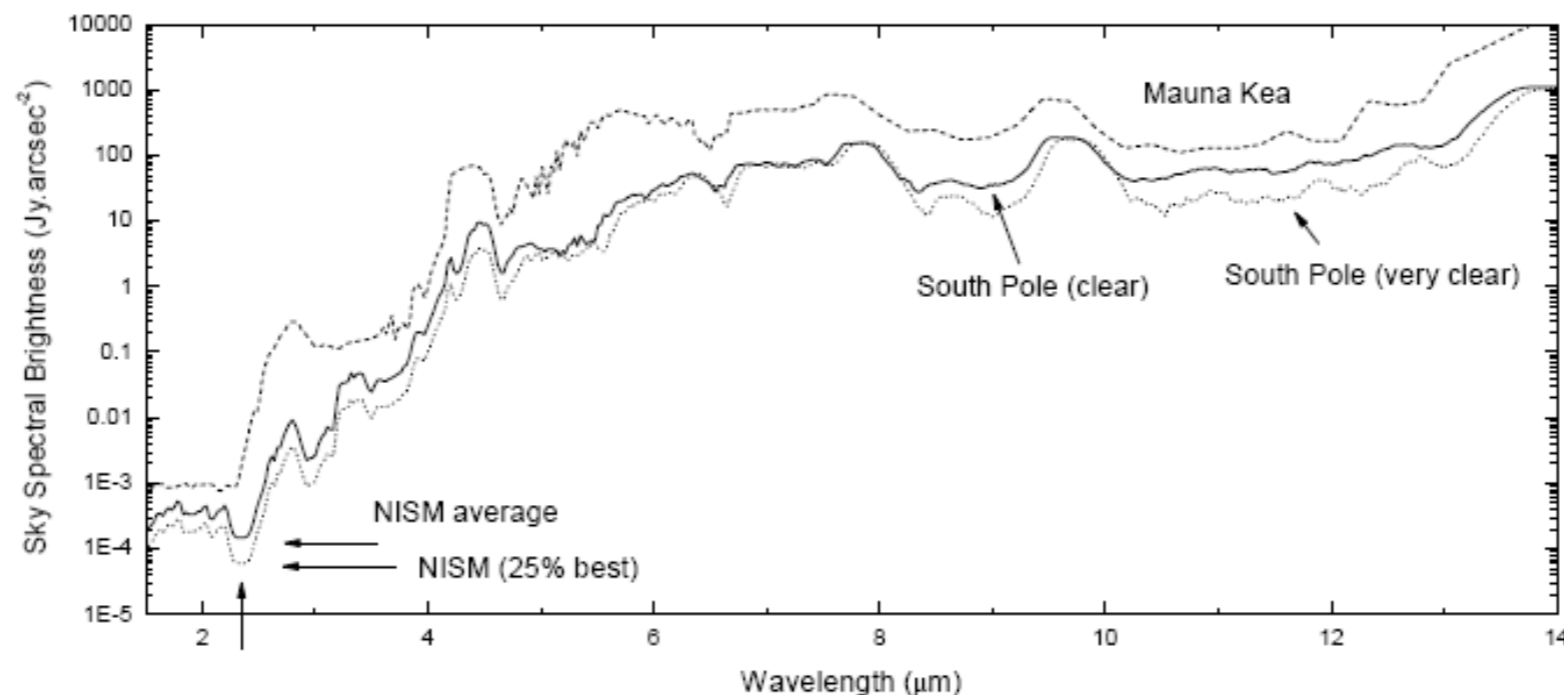
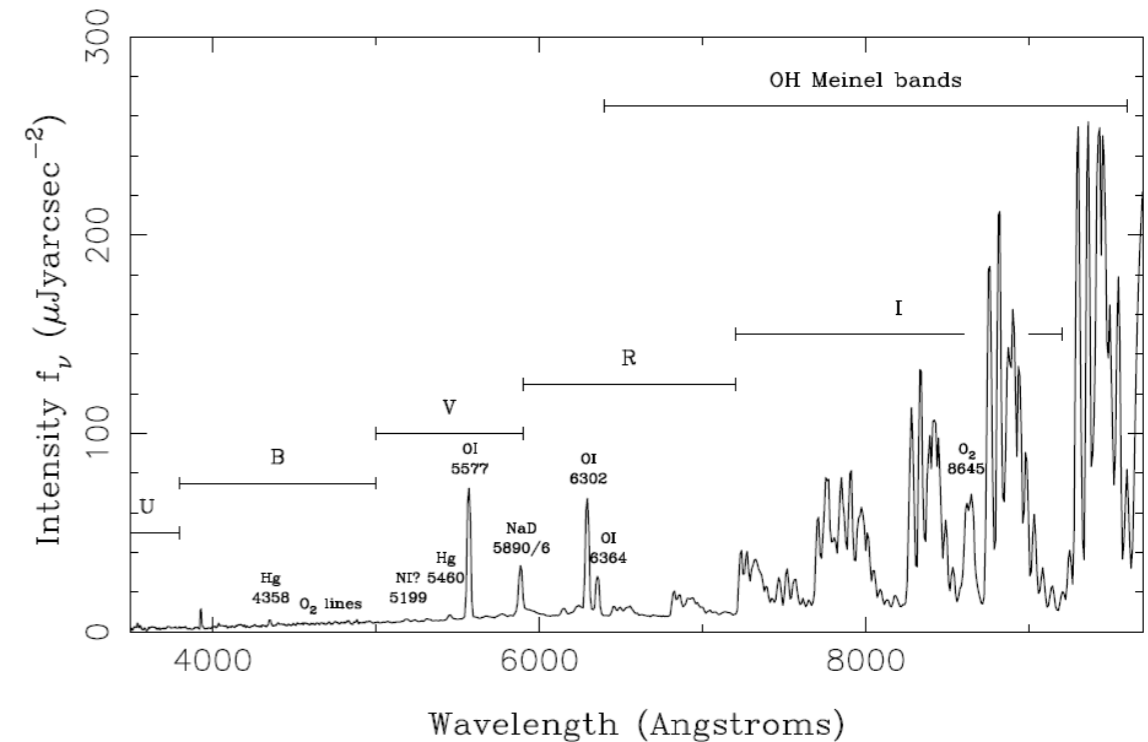
Stability / accuracy

- ◆ 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)

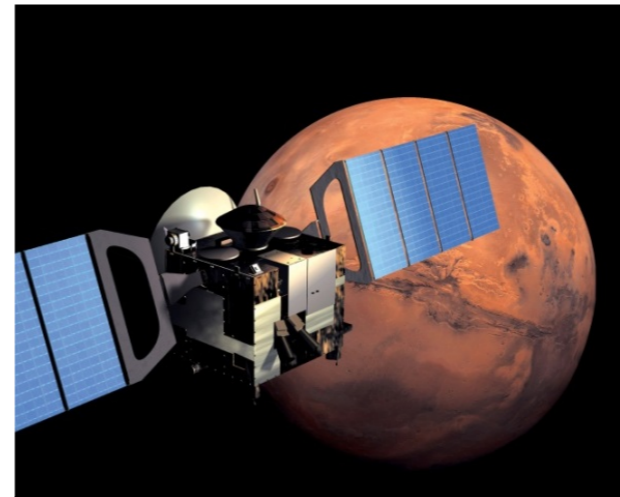


Summary: why space observatories?

- ◆ 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

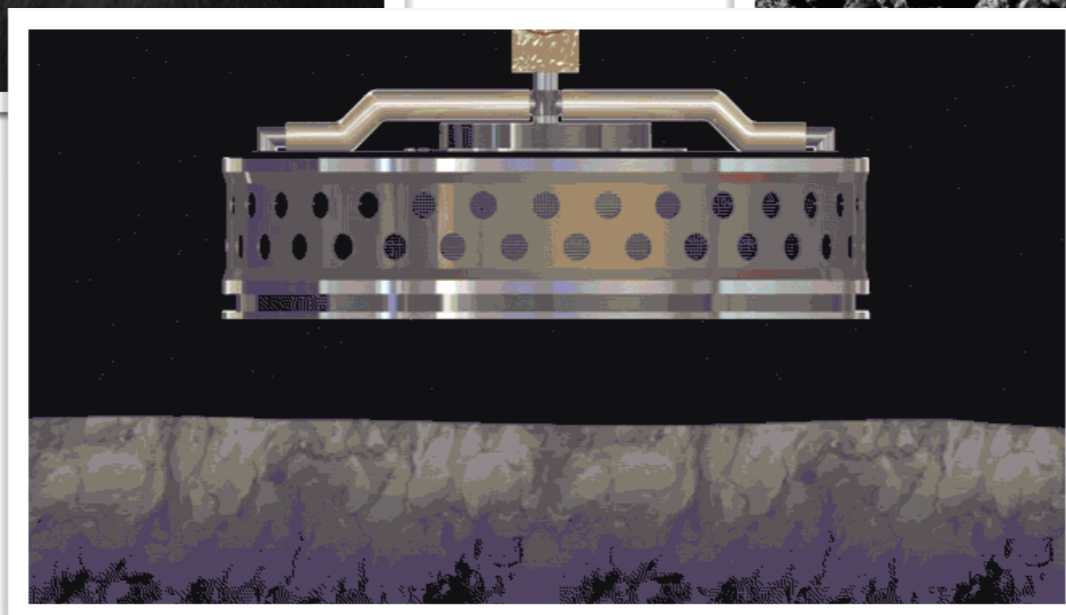


Cassini



Rosetta

Collecting asteroid samples



60g collected during touch-and-go (Oct'20), back to Earth 2 months ago

Preventing Armageddon... (and learning more about asteroids)



DART mission hitting asteroid moonlet Dimorphos on Sep 26, 2022

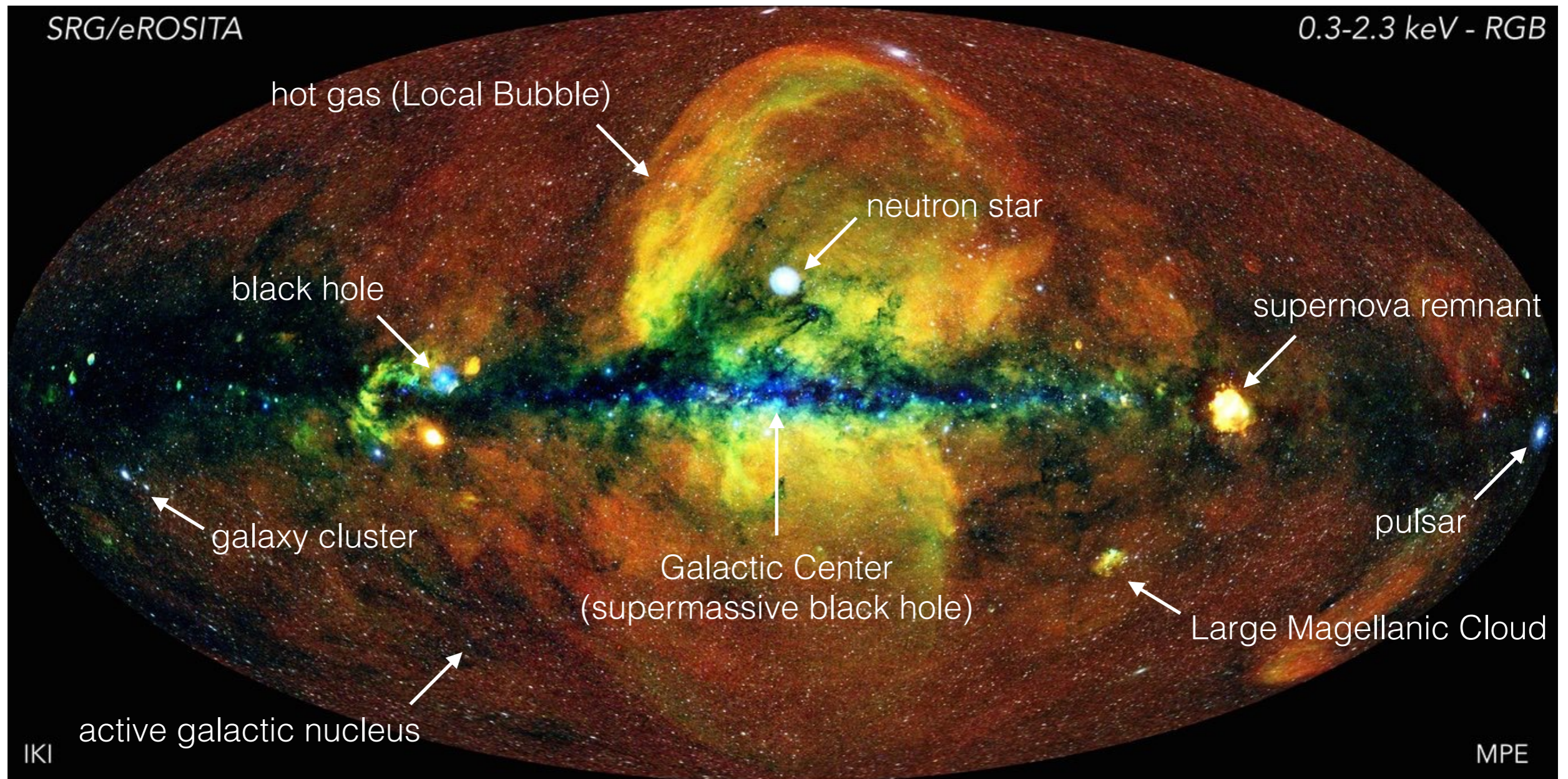
Outline of the lecture

Lecture focused on **remote** observations:

1. X rays (0.1 nm \rightarrow 10 nm)
 2. Visible / near infrared (300 nm \rightarrow 3 μ m)
 3. Mid-infrared (3 μ m \rightarrow 30 μ m)
 4. Far-IR / submm / millimetric (30 μ m \rightarrow 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

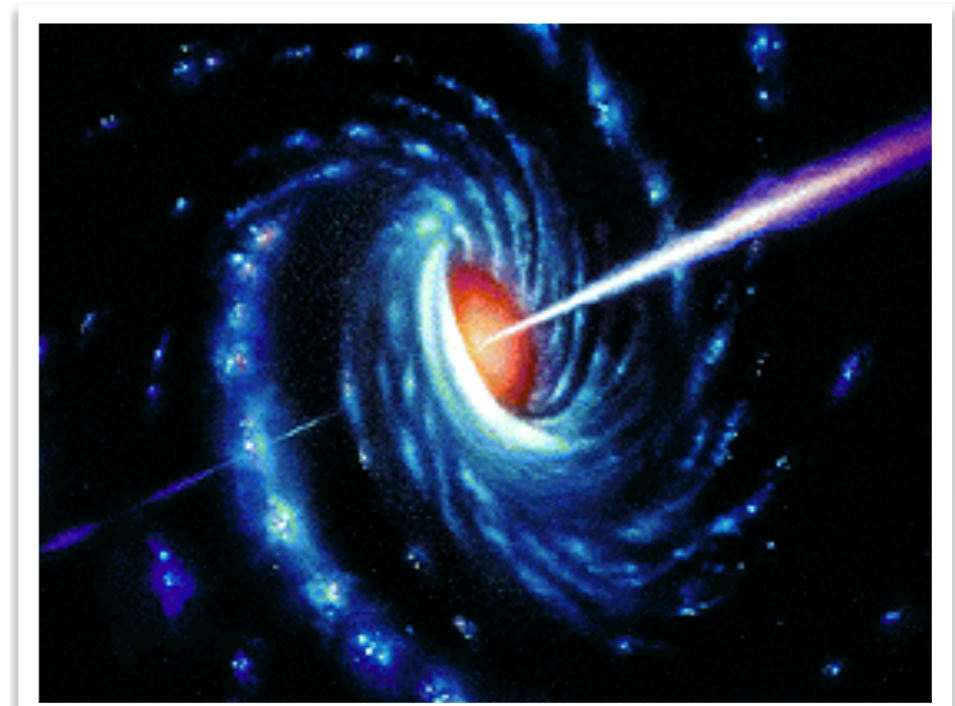
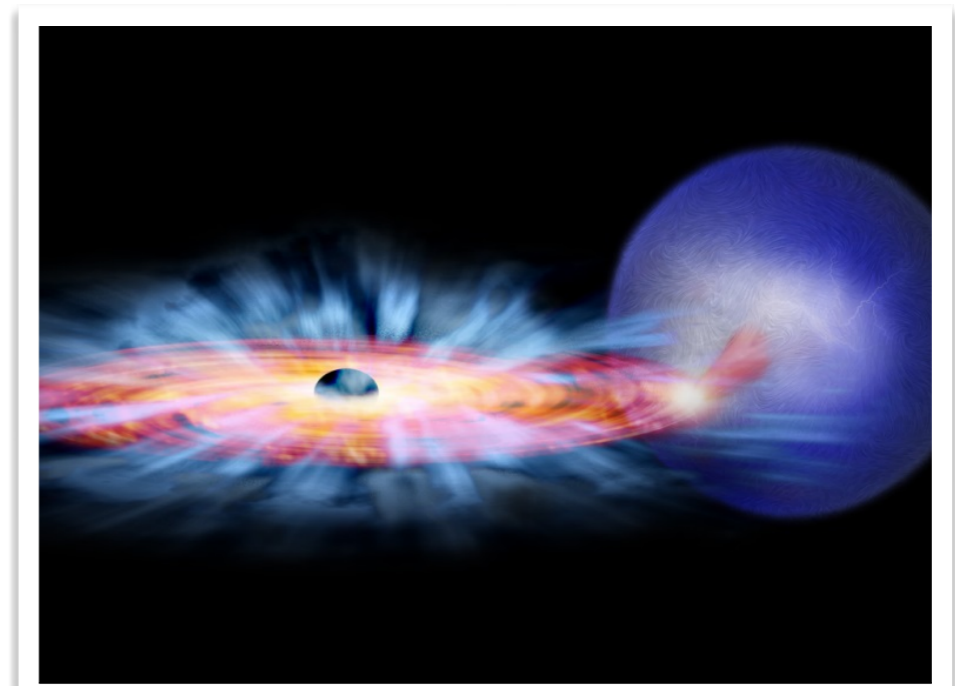


X-rays

From $\lambda = 0.1 \text{ nm}$ to $\lambda = 10 \text{ nm}$

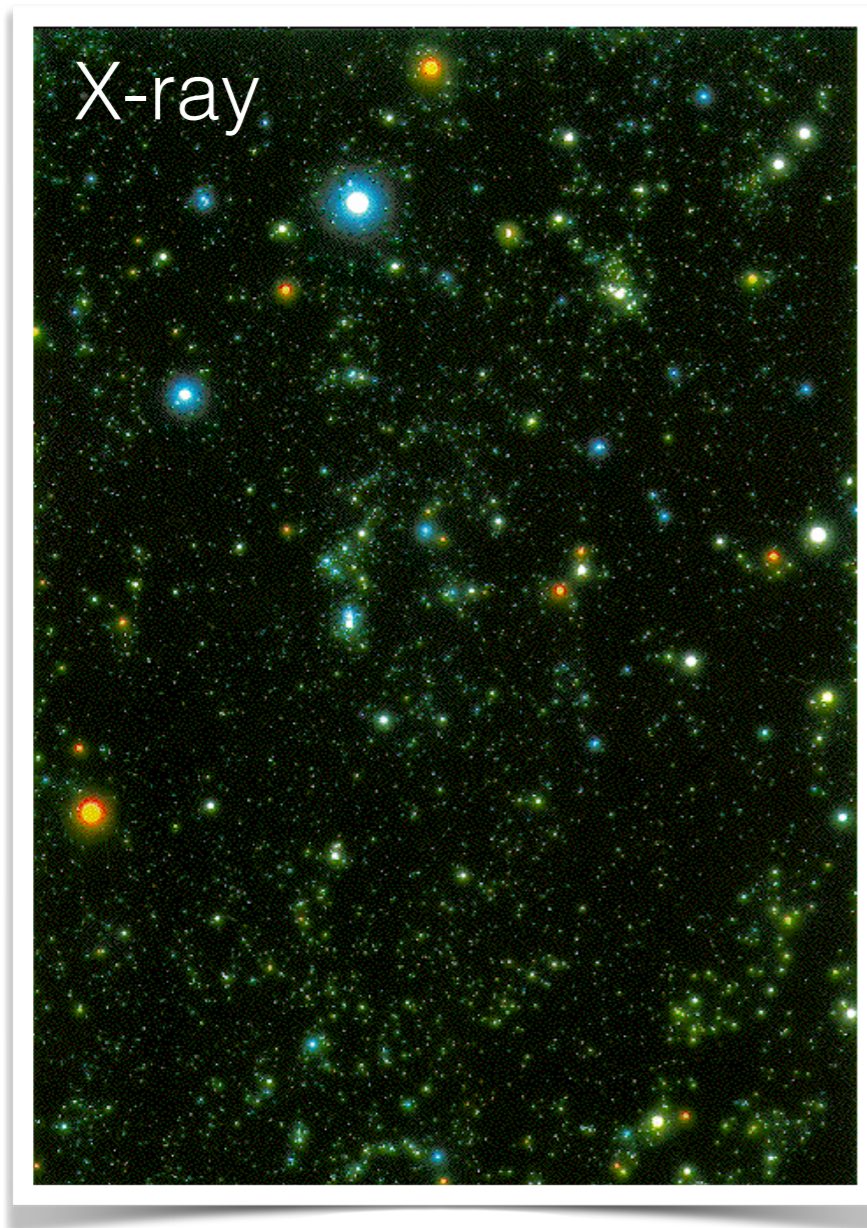
Astrophysical interests

- ◆ 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

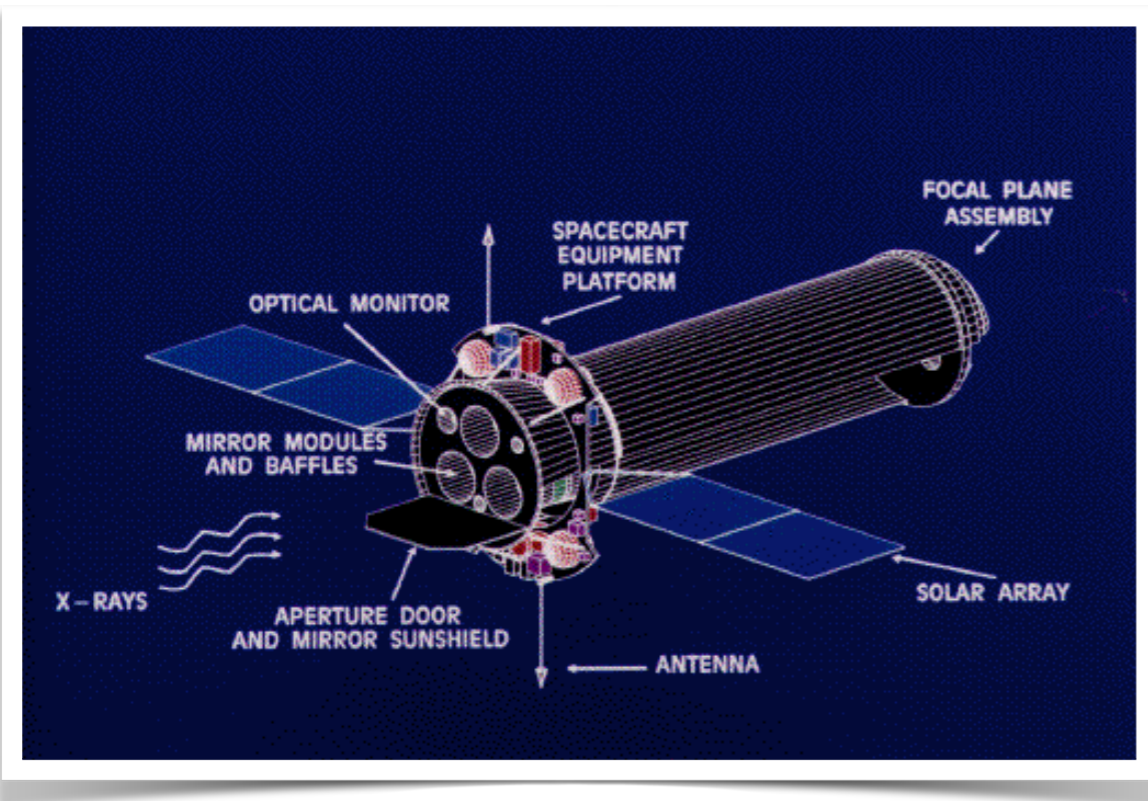
- ◆ Another view on the Universe



Two major missions (both still operating)

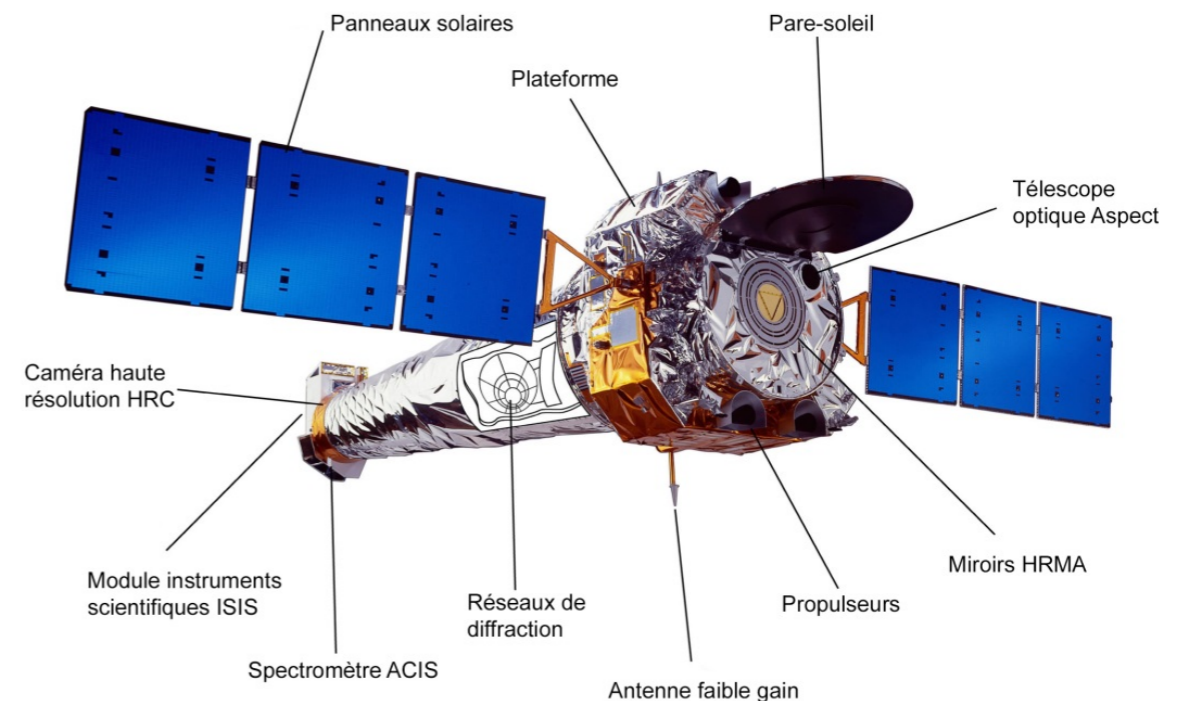
◆ XMM-Newton (1999)

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



◆ Chandra (1999)

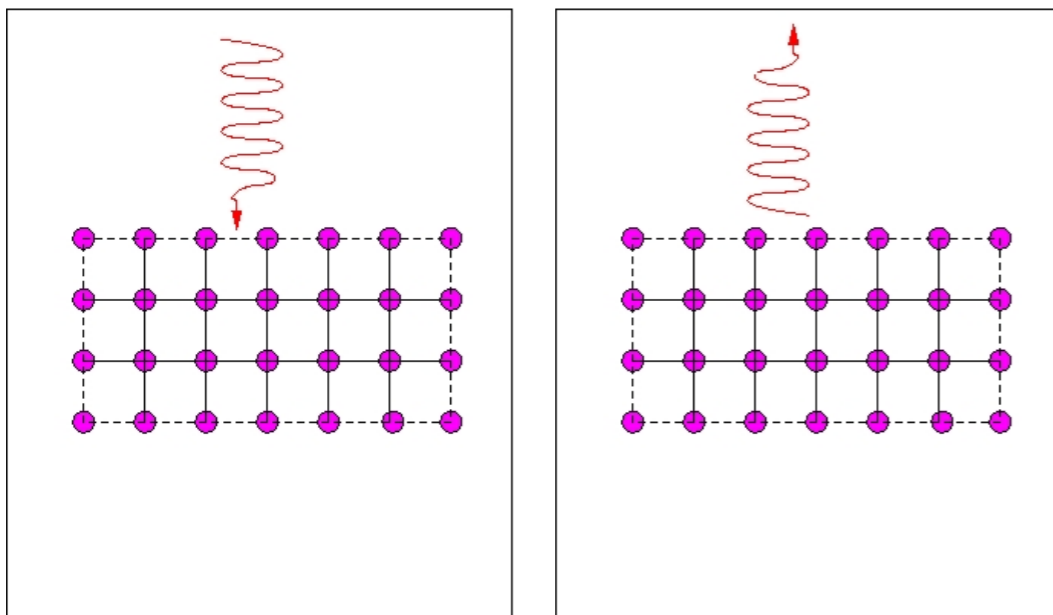
- length: 12 m
- weight: 1.5 tons
- launch: space shuttle



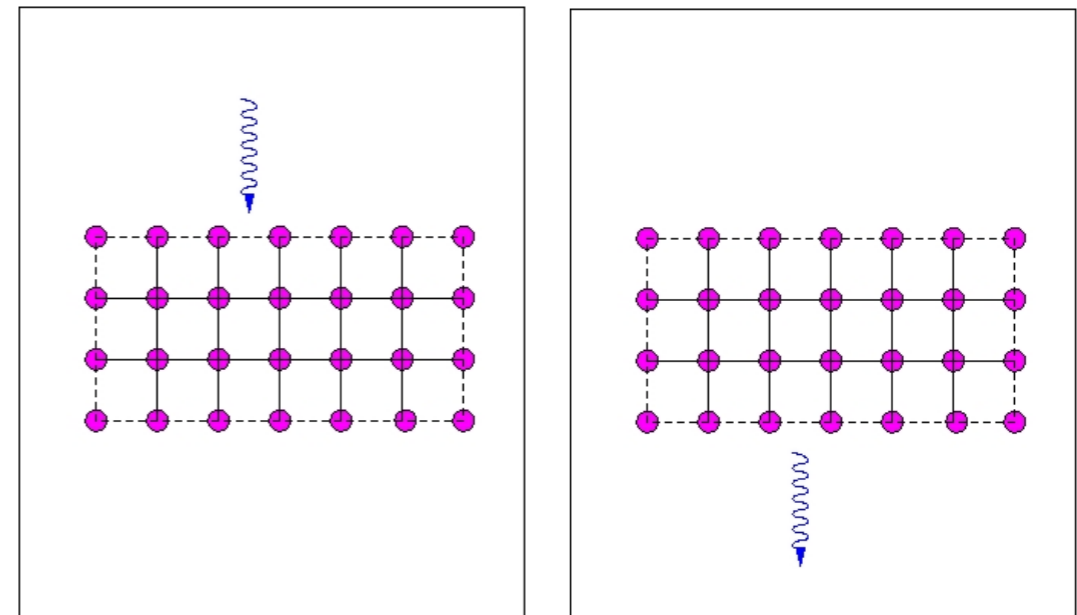
Focusing X rays

- ◆ A long story!
- ◆ X-rays \rightarrow high penetrating power
 - cannot be reflected off in normal incidence

Visible light

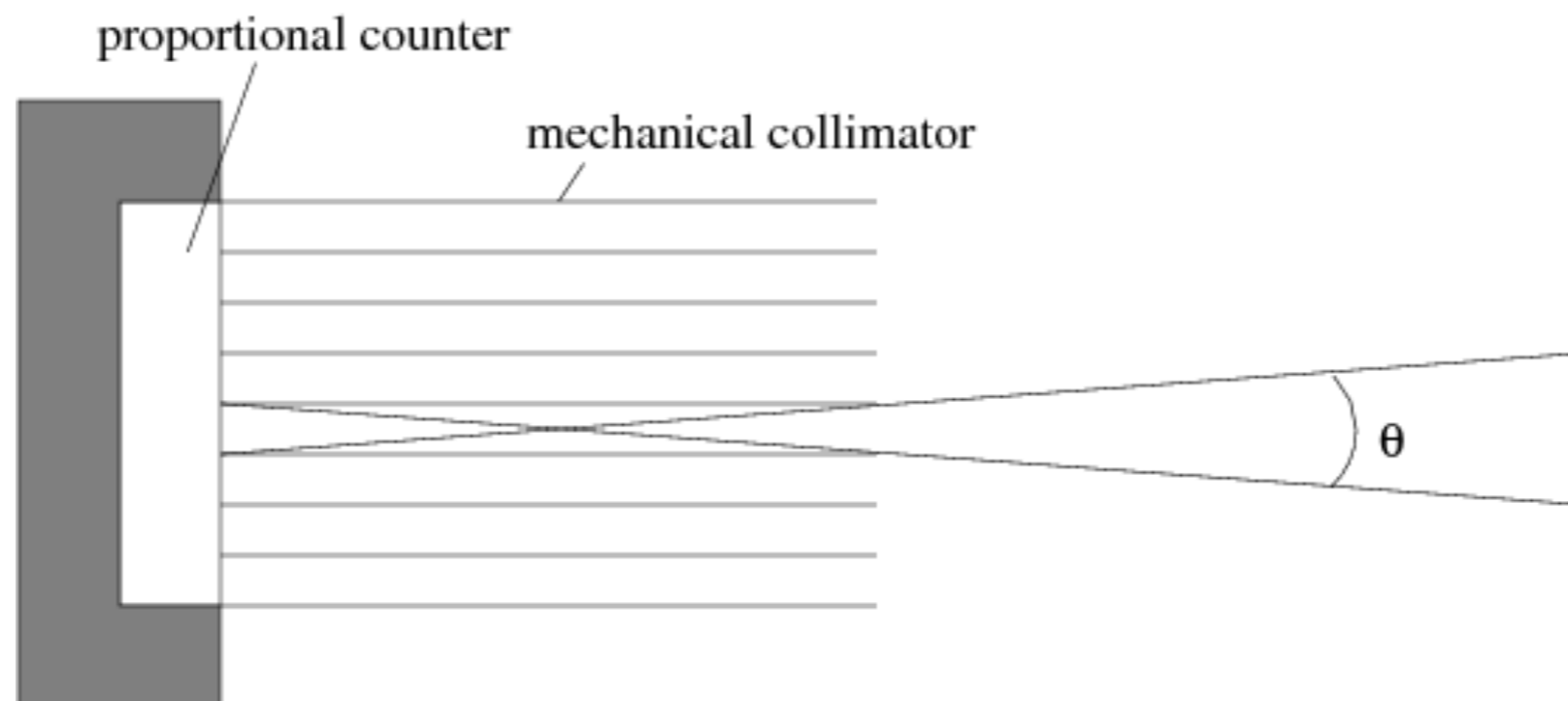


X rays



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

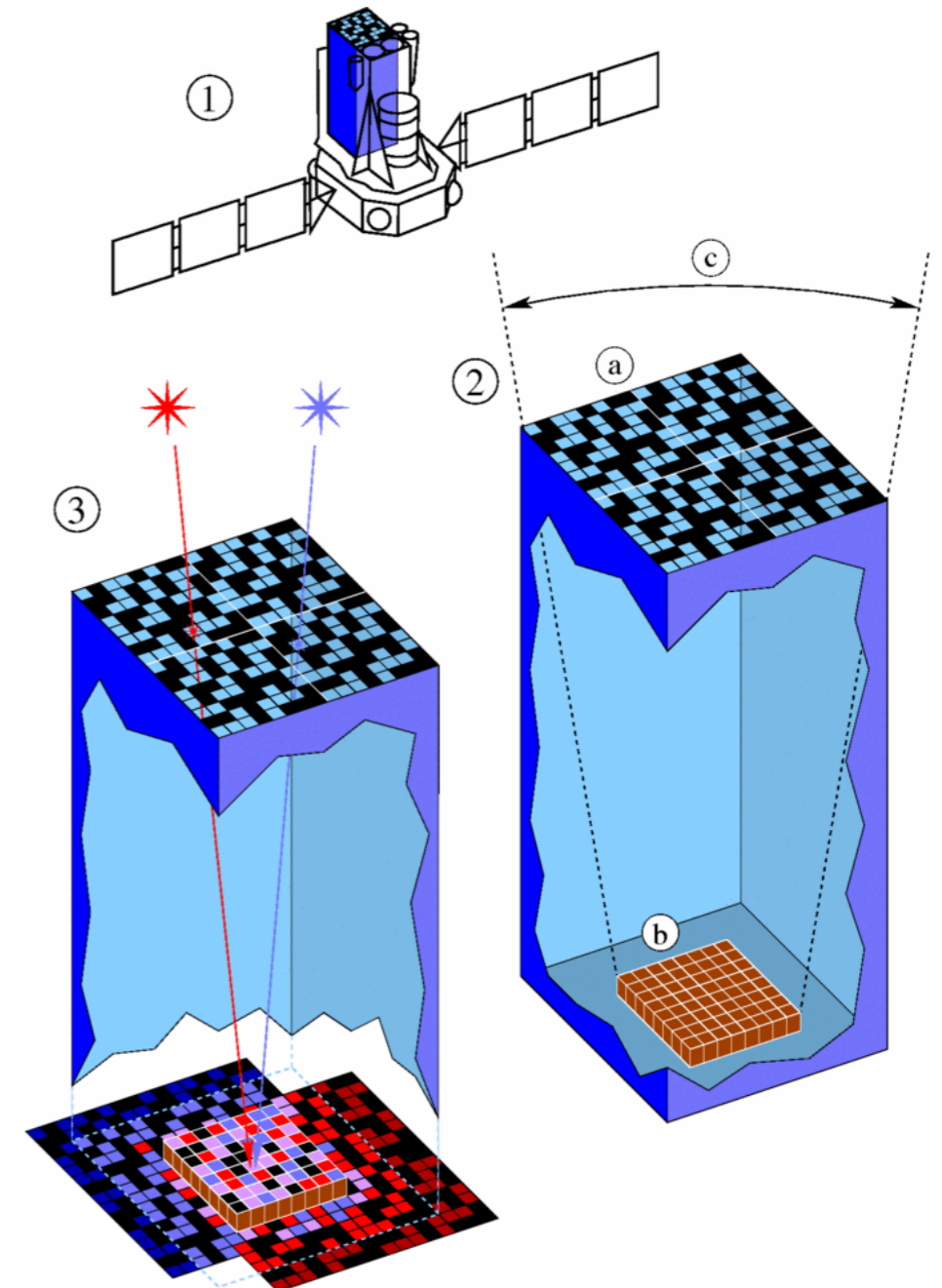
◆ Second solution: coded aperture

- partial masking of telescope aperture
- measure the superposition of mask shadow projected onto the detector

◆ Drawbacks

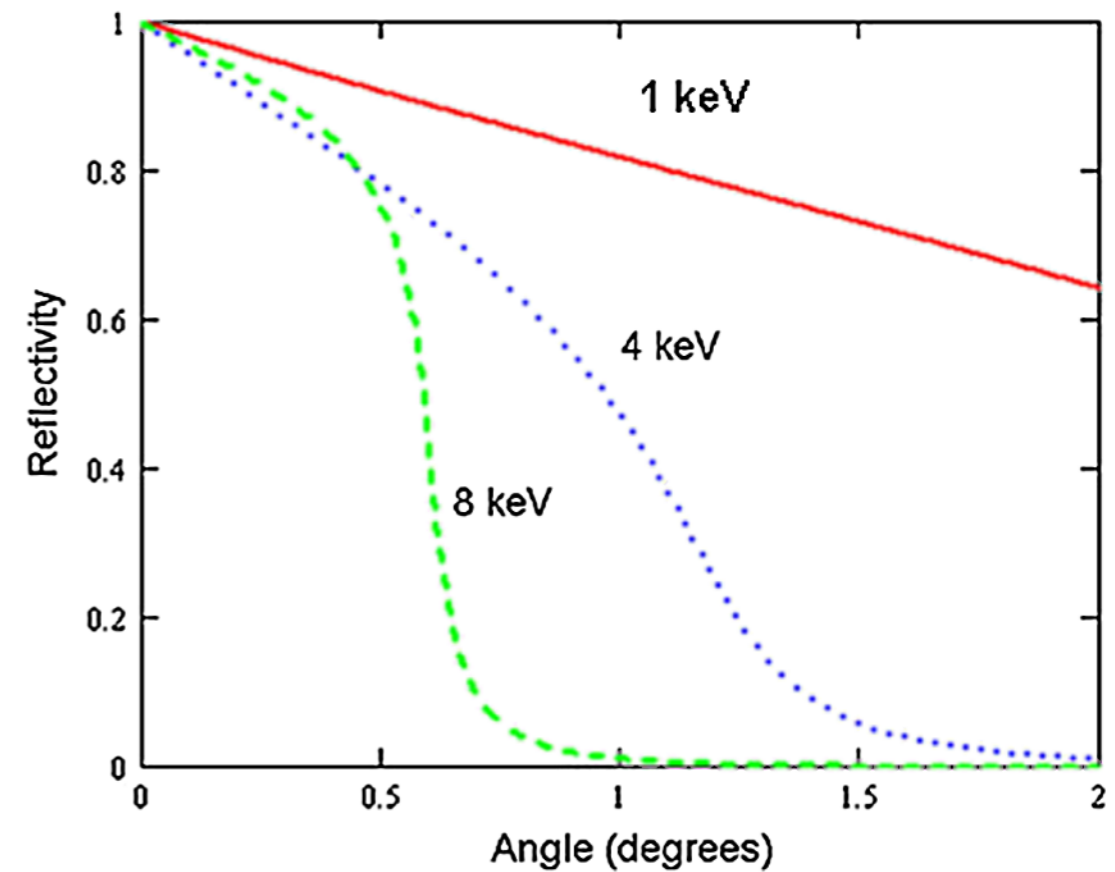
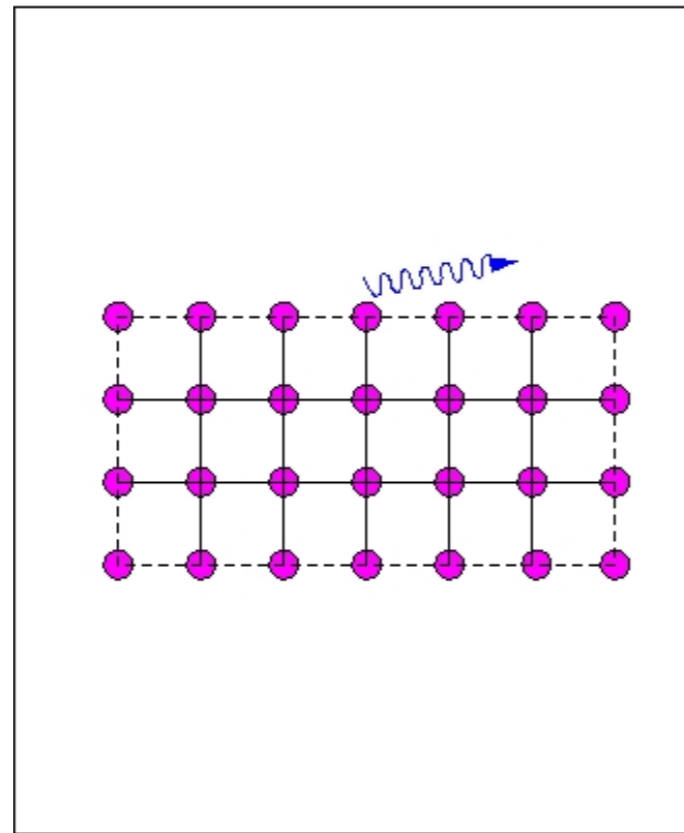
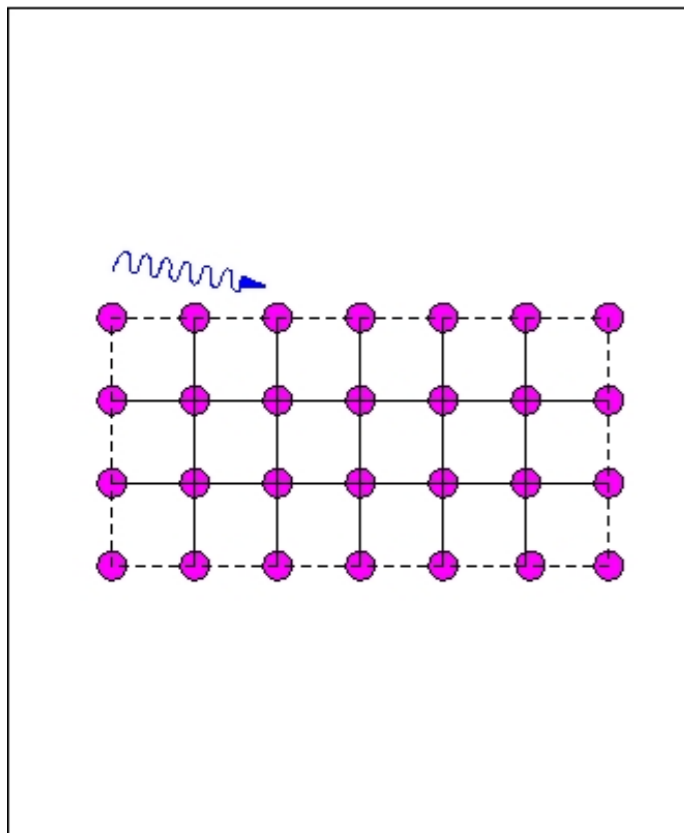
- low resolving power
- limited sensitivity (light spread on many pixels)

◆ Still used in γ -ray astronomy



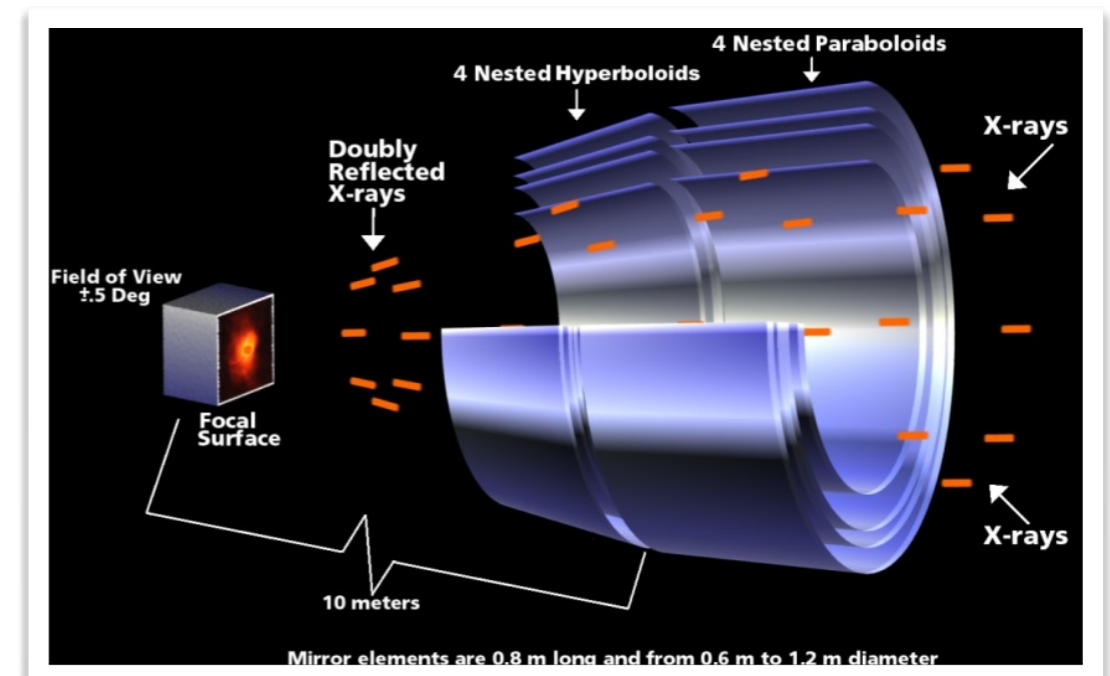
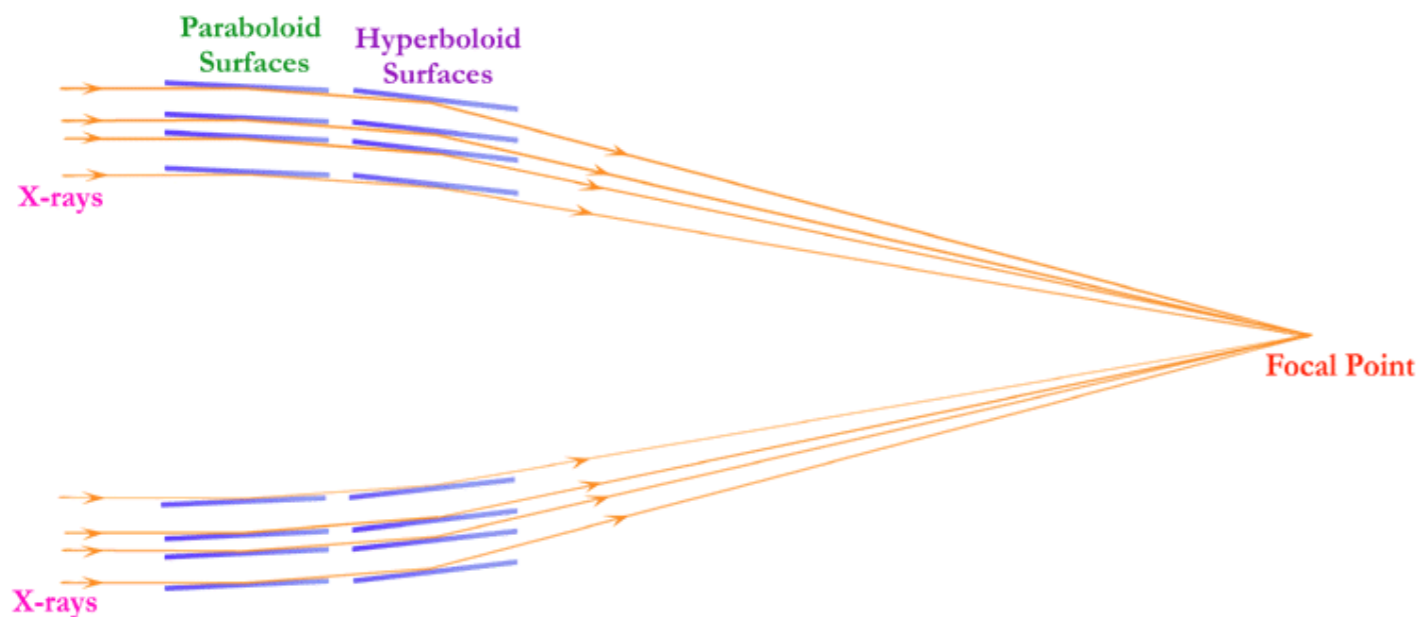
Focusing X rays

- ◆ Third solution: grazing incidence



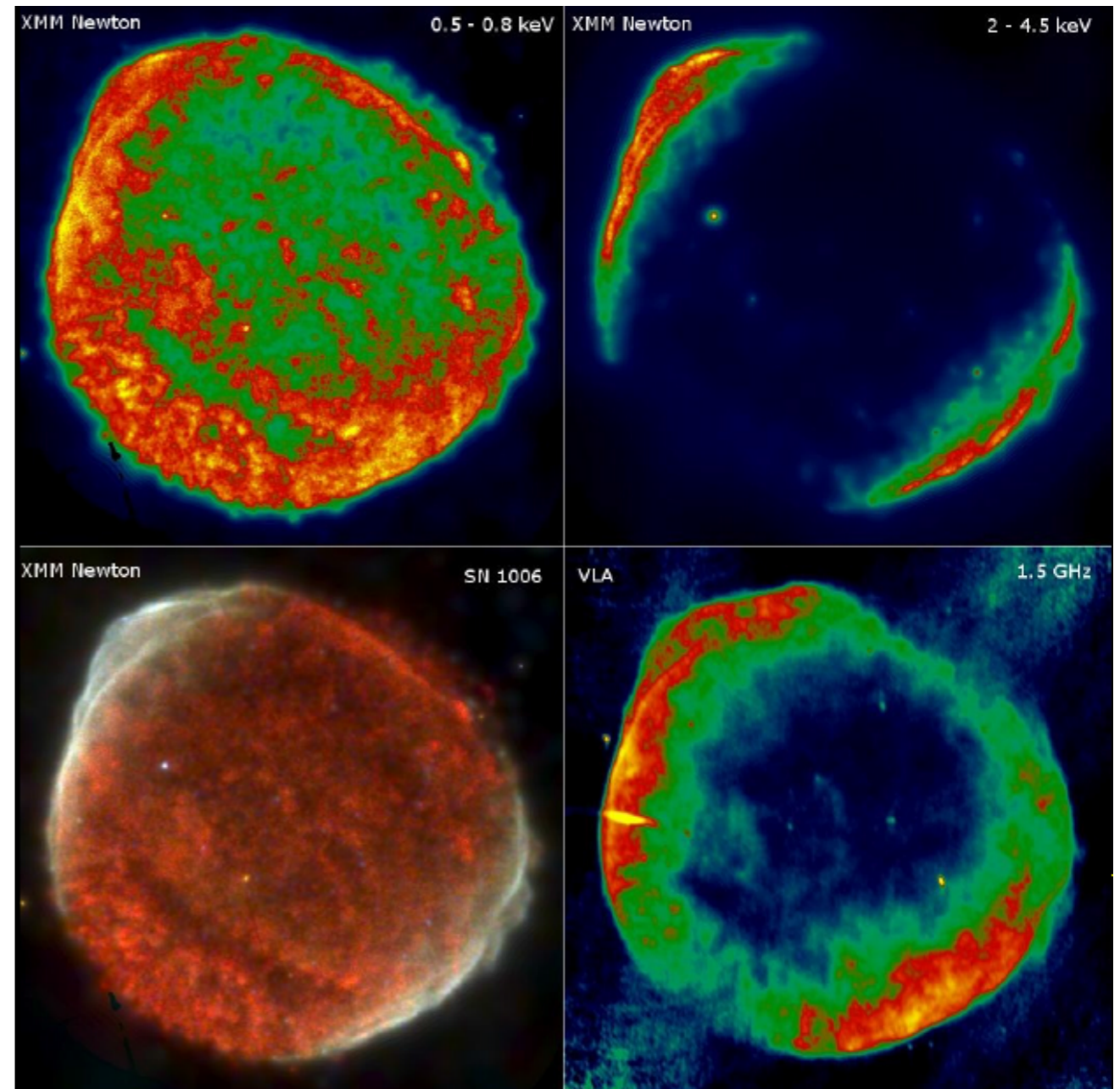
Focusing X rays

- ◆ 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



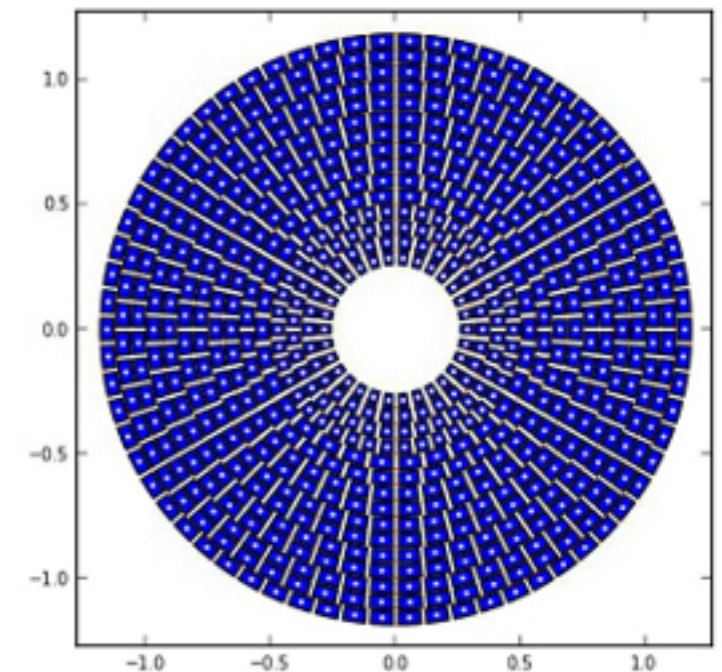
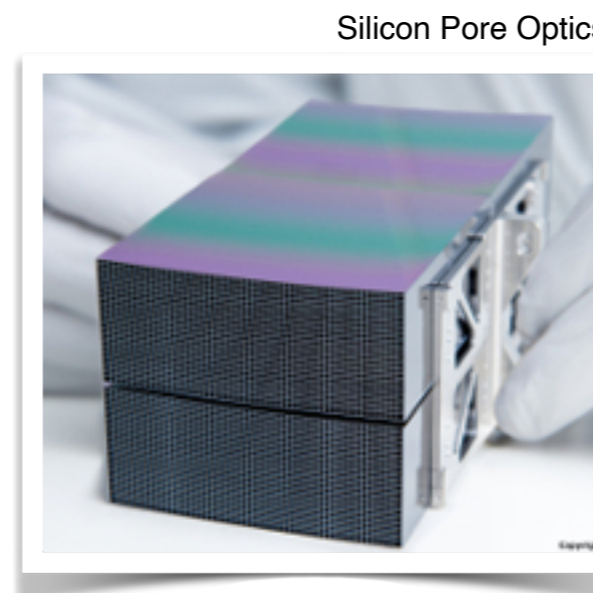
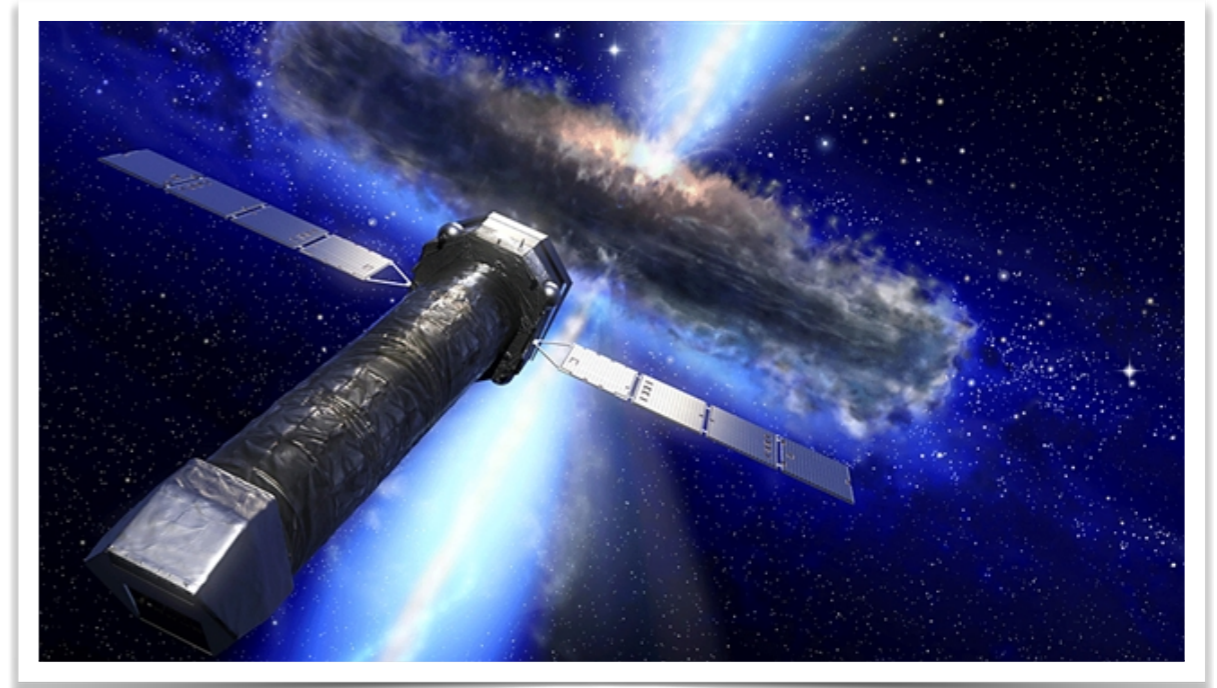
Major results

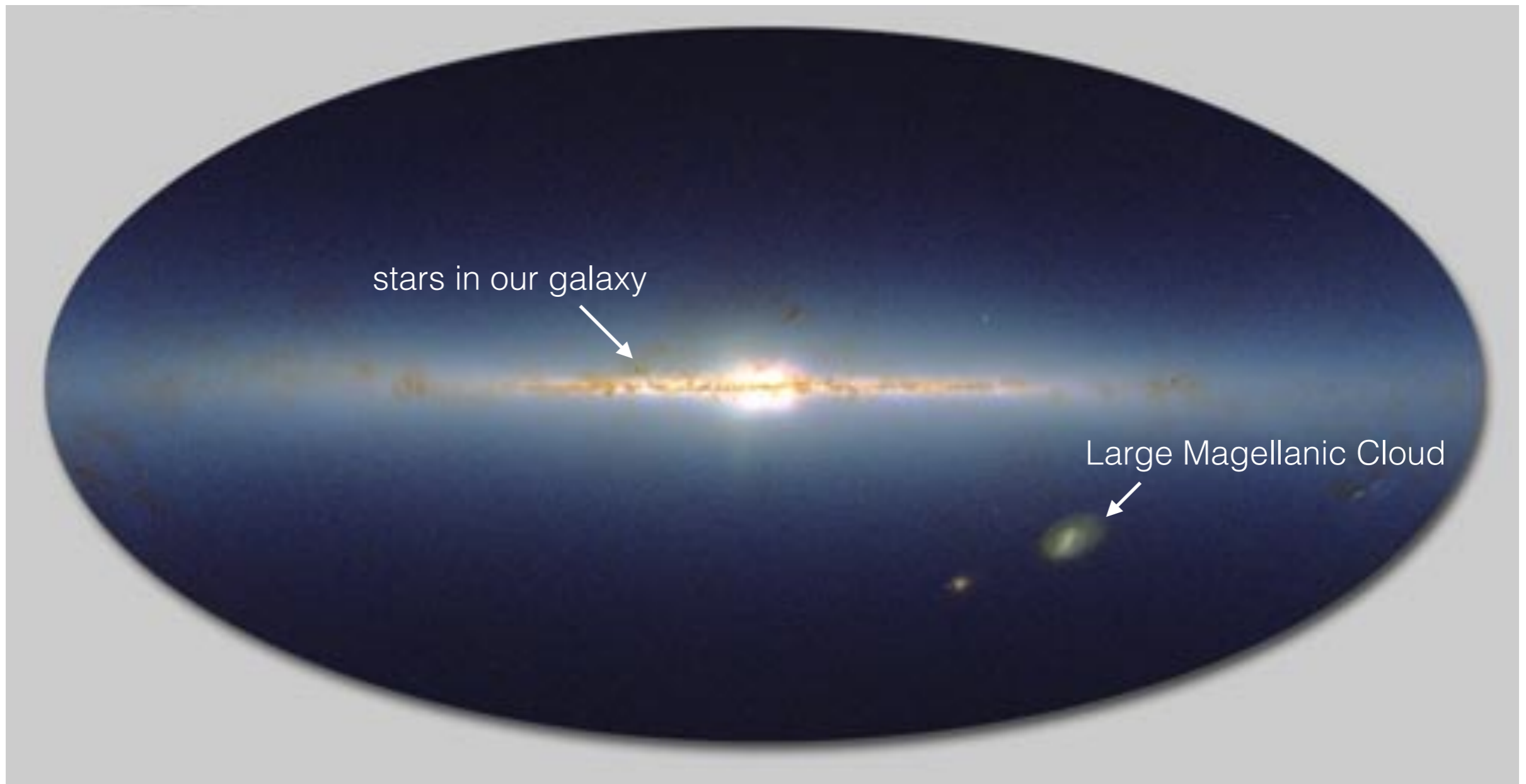
- ◆ Accretion/ejection phenomena
- ◆ Discovery of ultra-hot plasma ($> 10^6$ K)
- ◆ Supernovae: explosions and remnants
- ◆ Pulsars, magnetars, X-ray binaries, black holes, etc
- ◆ Highest energy: γ -ray bursts



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





stars in our galaxy

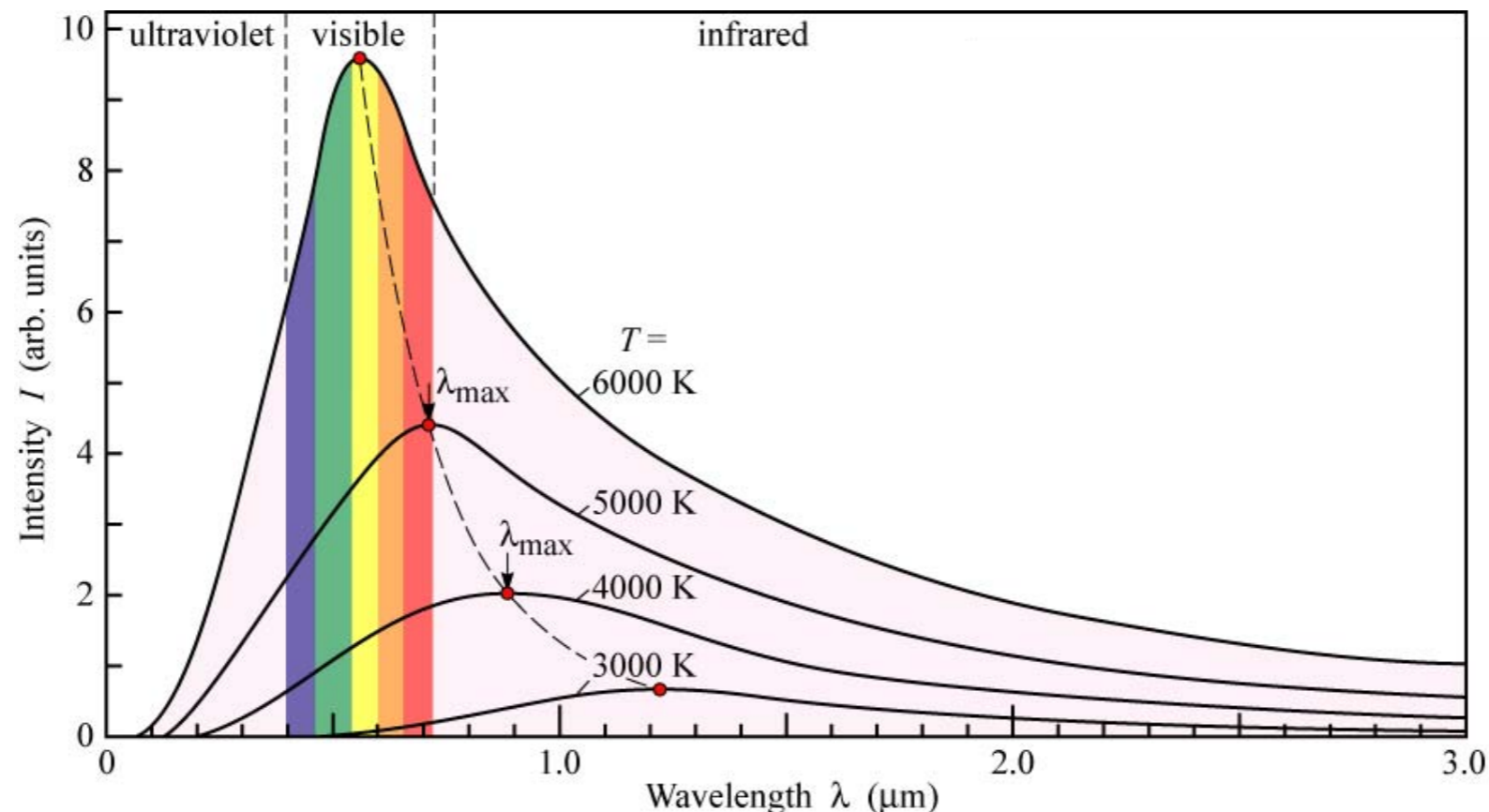
Large Magellanic Cloud

Visible / near-infrared

From $\lambda = 300 \text{ nm}$ to $\lambda = 3 \mu\text{m}$

Astrophysical interests

- ◆ From Wien's law: $\lambda_{\max} (\mu\text{m}) = 2898 / T (\text{K})$
 - 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).



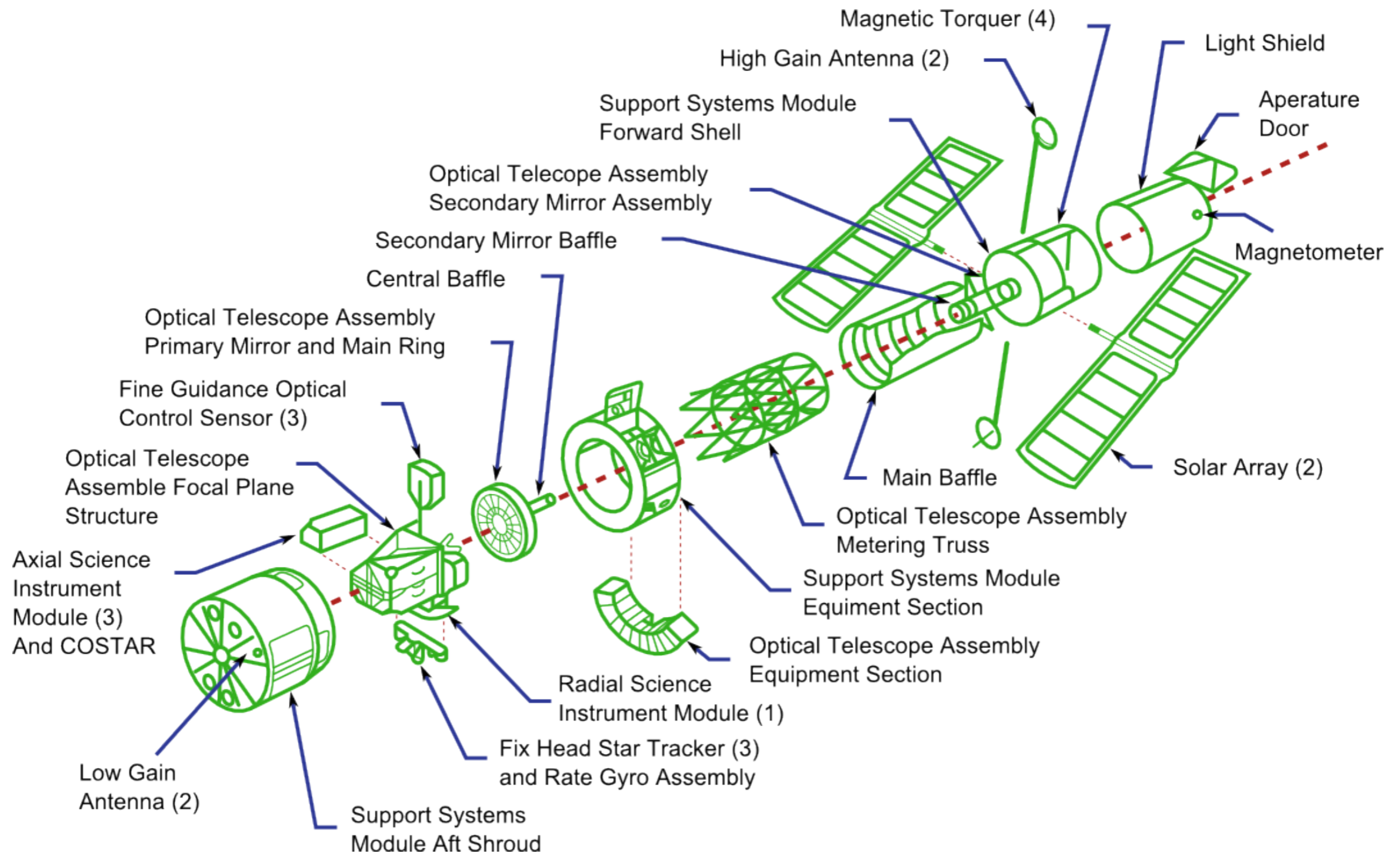
Length: 13 m
Weight: 11 tons



Hubble Space Telescope

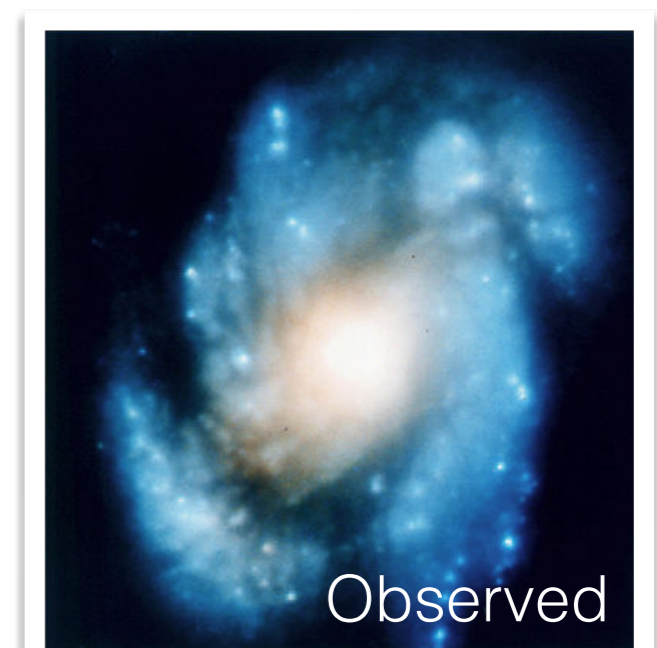
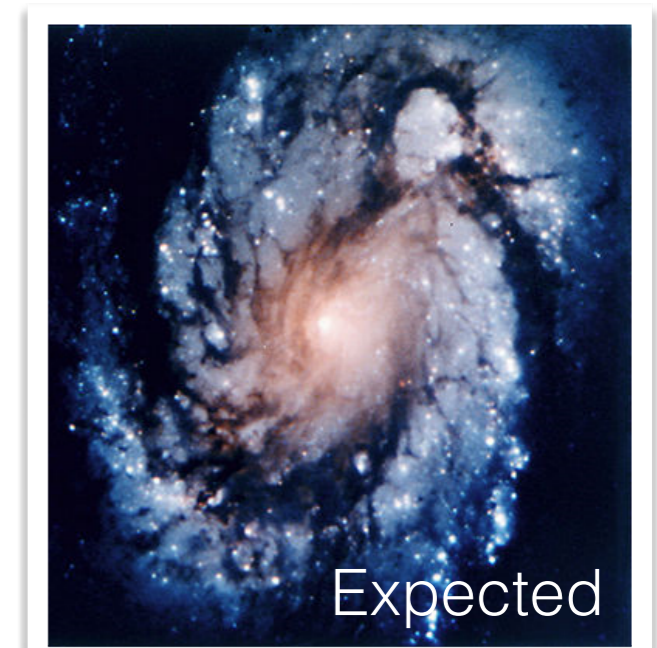
- ◆ Telescope diameter: 2.4 m
- ◆ Wavelength range: 115 nm to 2.4 μm
- ◆ Angular resolution 0.05 arcsec (visible light)
 - 20 x better than ground-based telescope w/o adaptive optics (but now the trend is reversing with the advent of extreme AO)
- ◆ Sensitivity ~50x better than ground-based 10 m-class 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



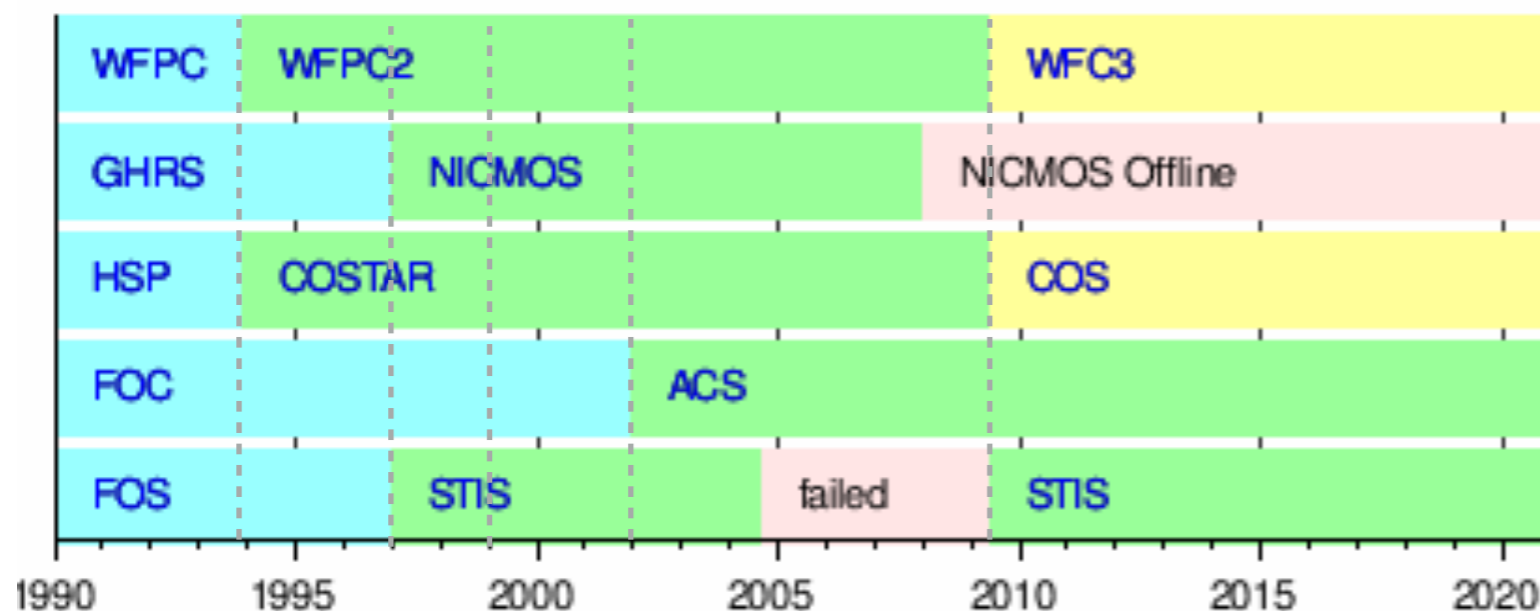
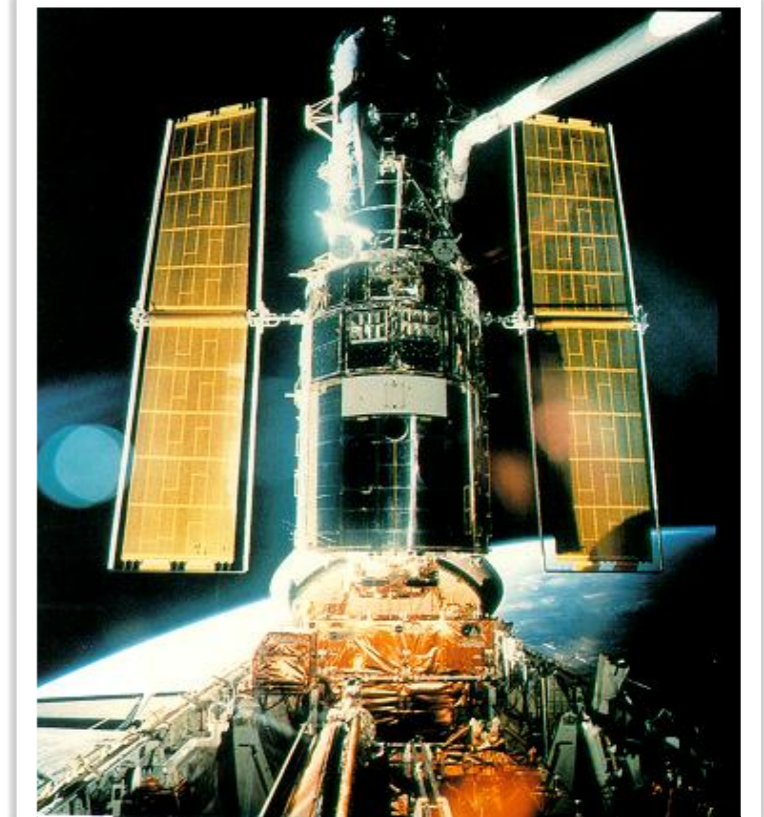
HST's technical challenges

- ◆ Primary mirror: lightweight monolithic reflector
 - thickness: 2 cm (reduce weight)
 - honeycomb structure (resistant to launch)
- ◆ Diffraction-limited \rightarrow defects $< \lambda/10$
 - ultraviolet observations: $\lambda = 100$ nm
 - new computer-assisted polishing method
- ◆ Final mirror: $2 \mu\text{m}$ 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

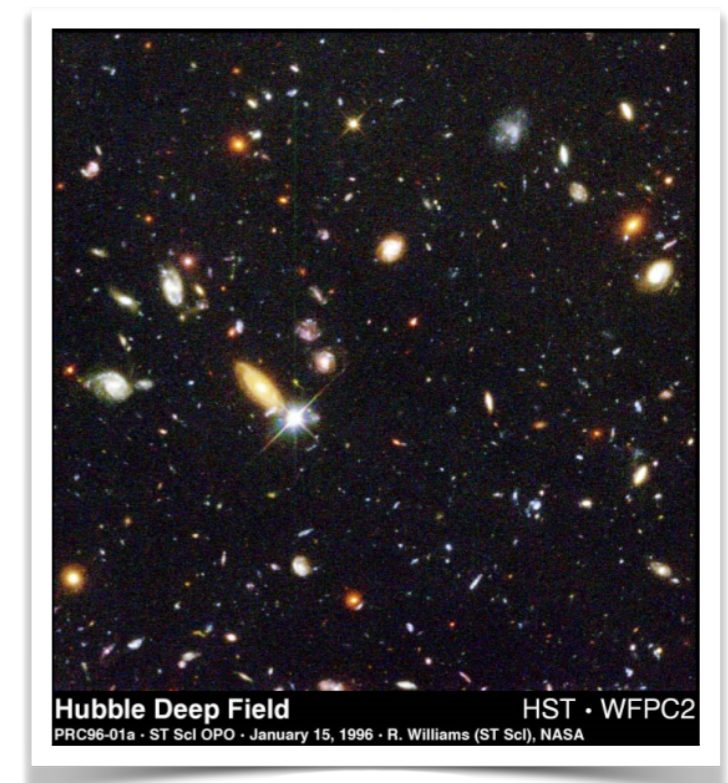
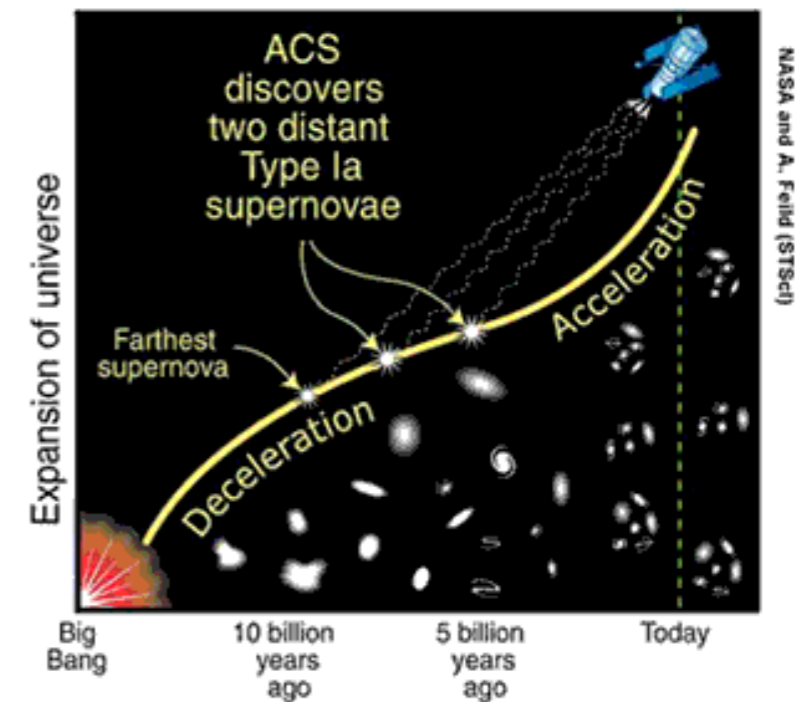
UV / visible / near-IR spectrograph

Other challenges

- ◆ Thermal / mechanical stability
 - 96 min day / night cycle
 - observations possible even during thermal shock thanks to multilayer insulation, 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)

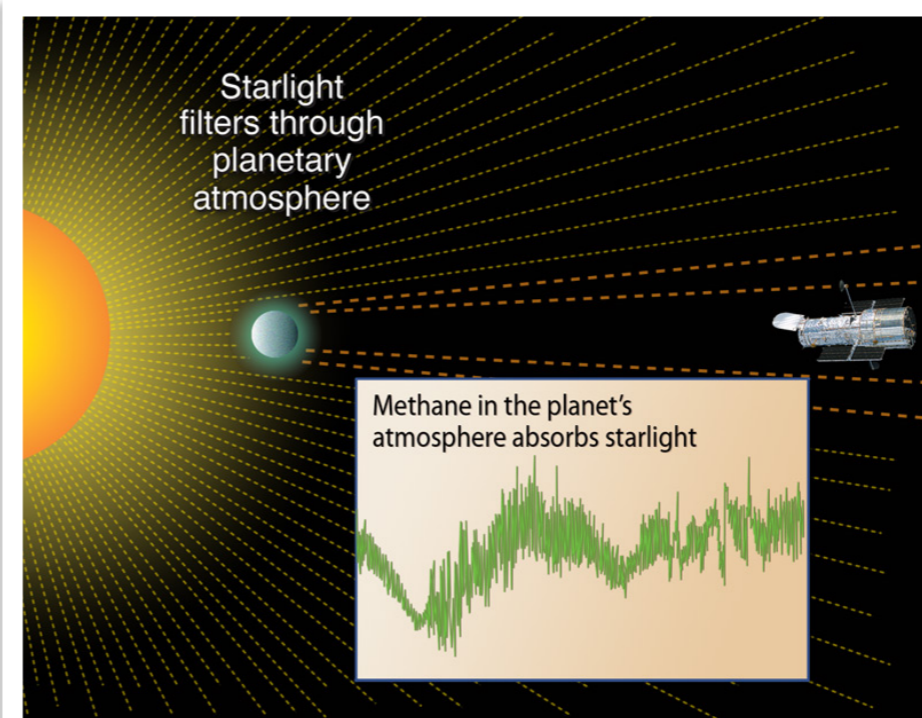
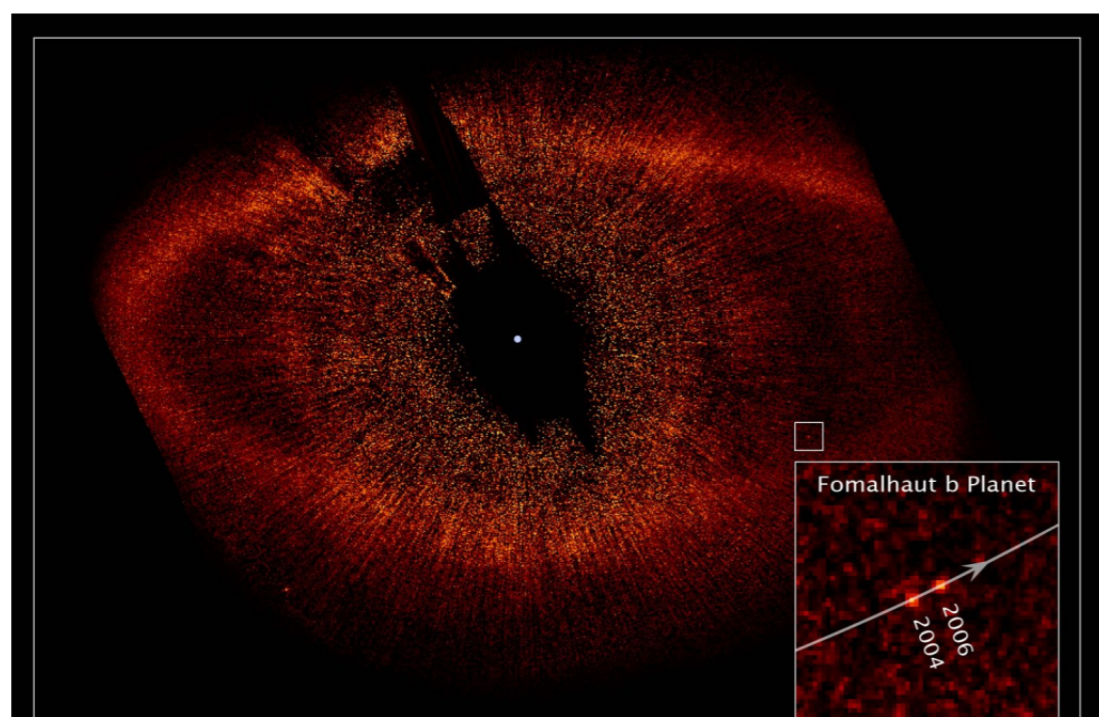
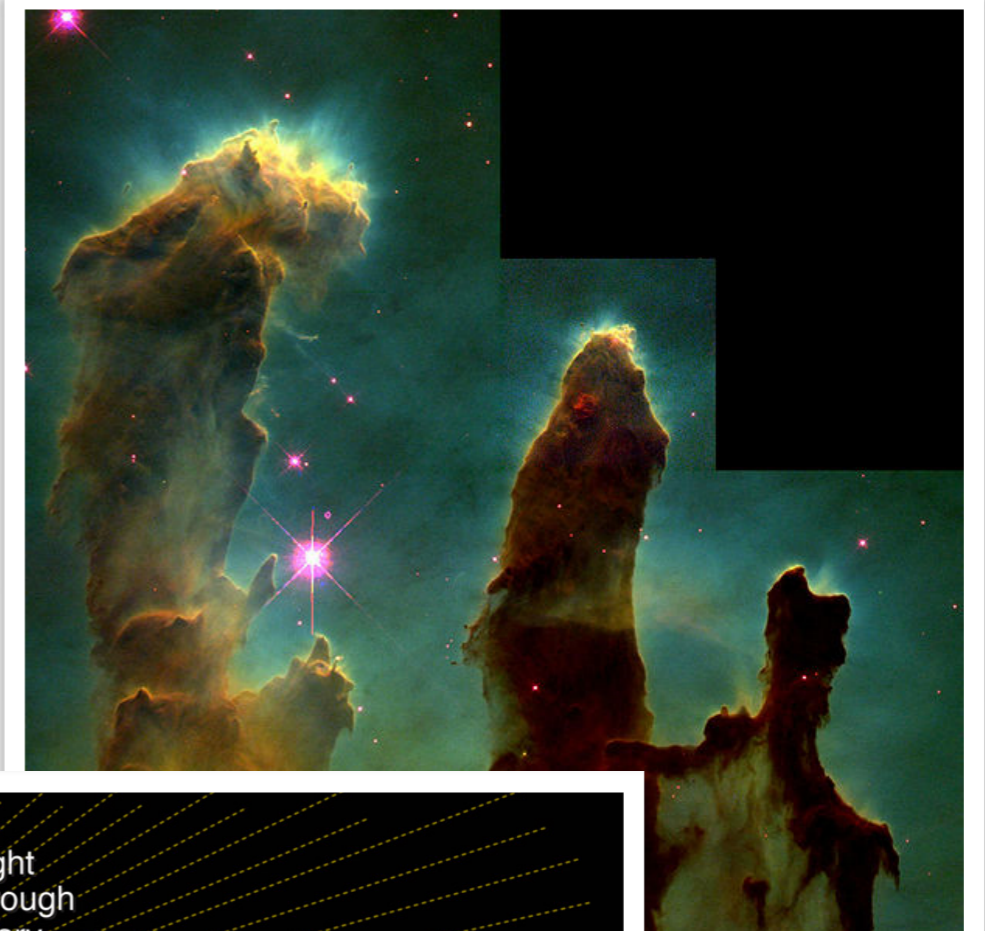
Extragalactic discoveries

- ◆ 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



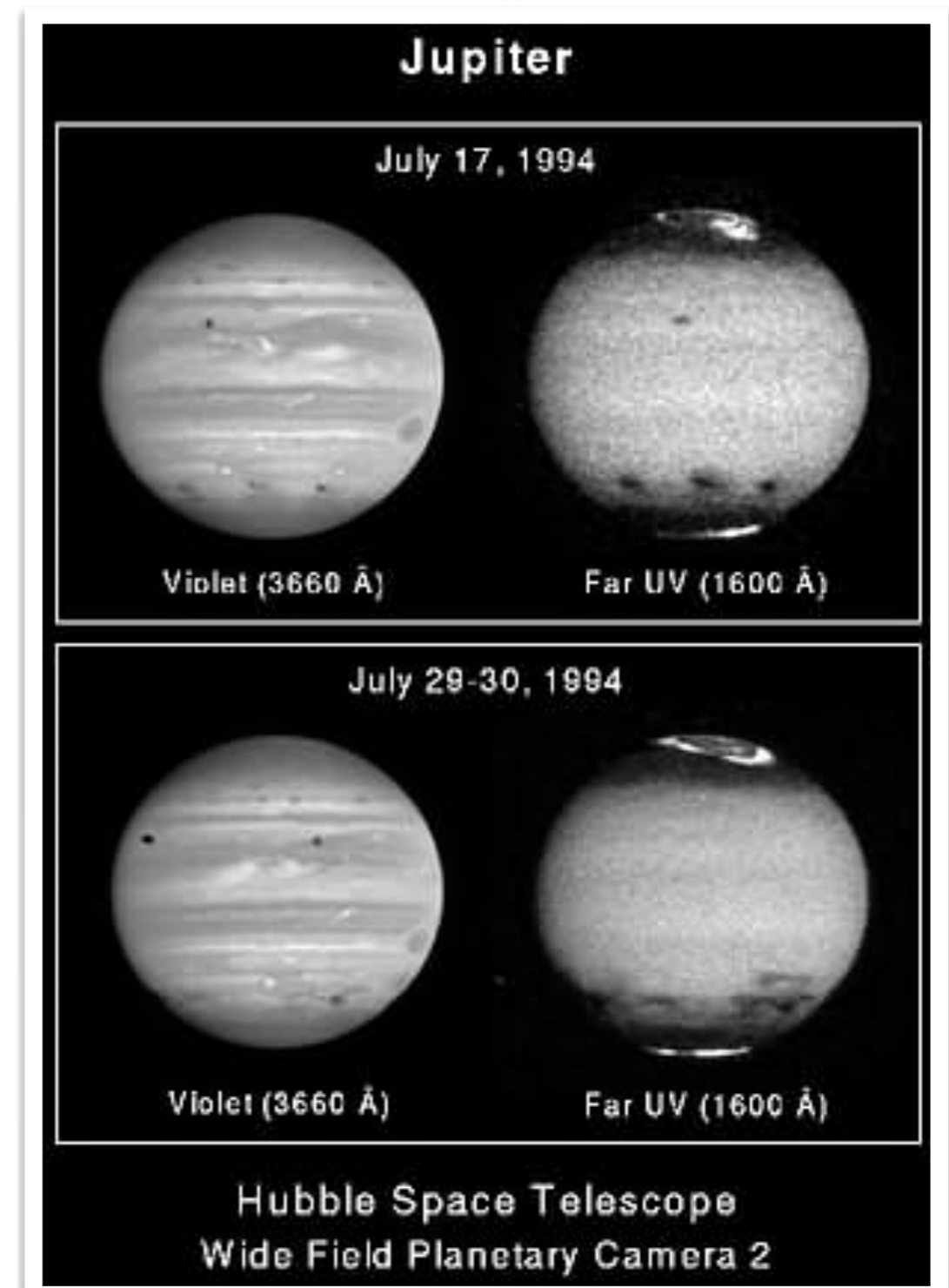
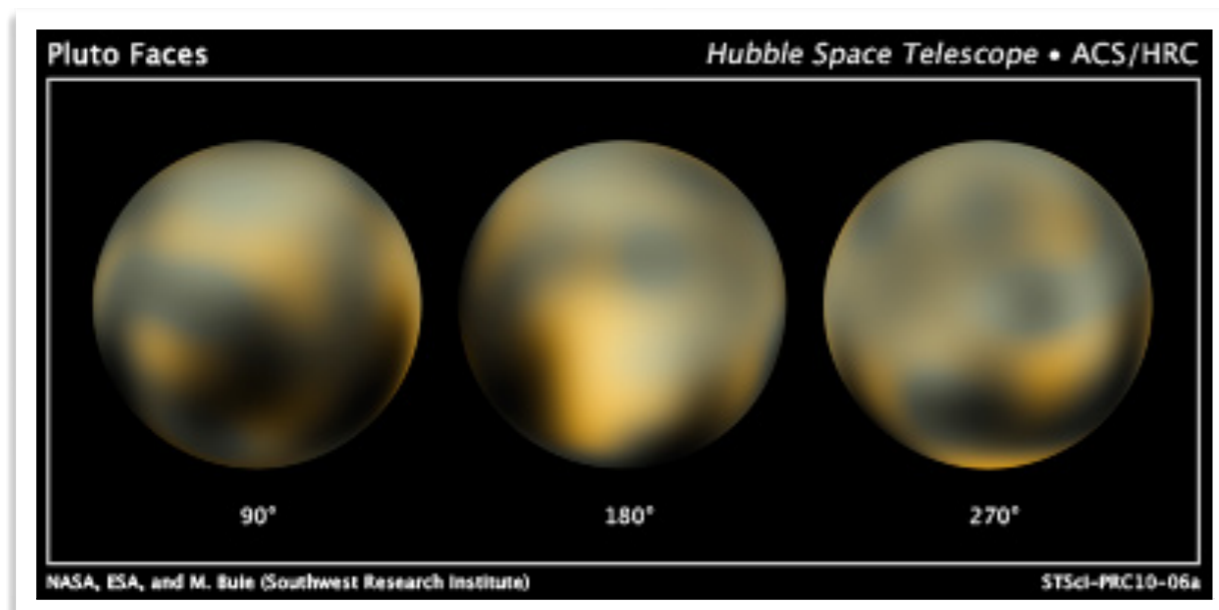
Galactic discoveries

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



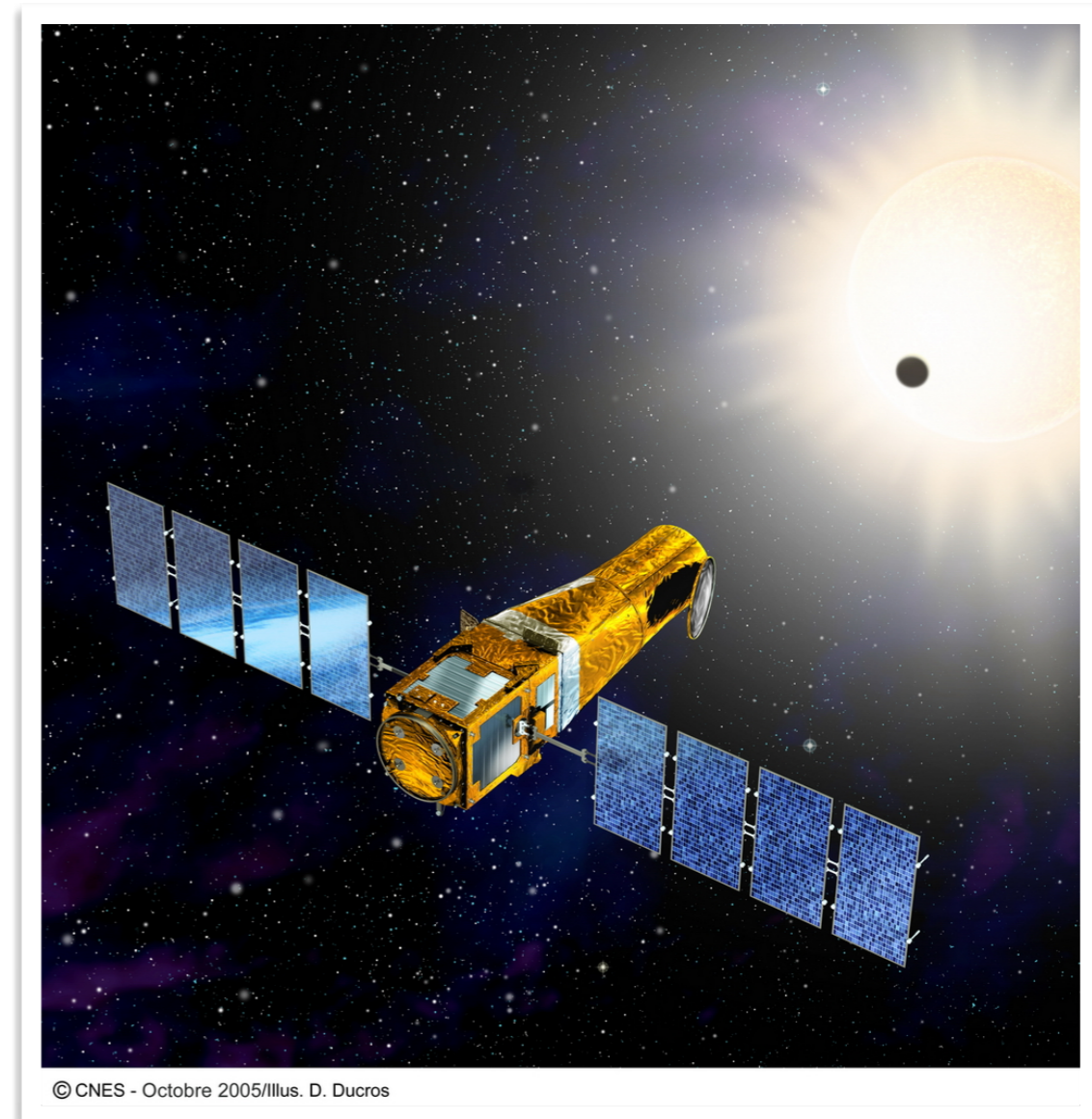
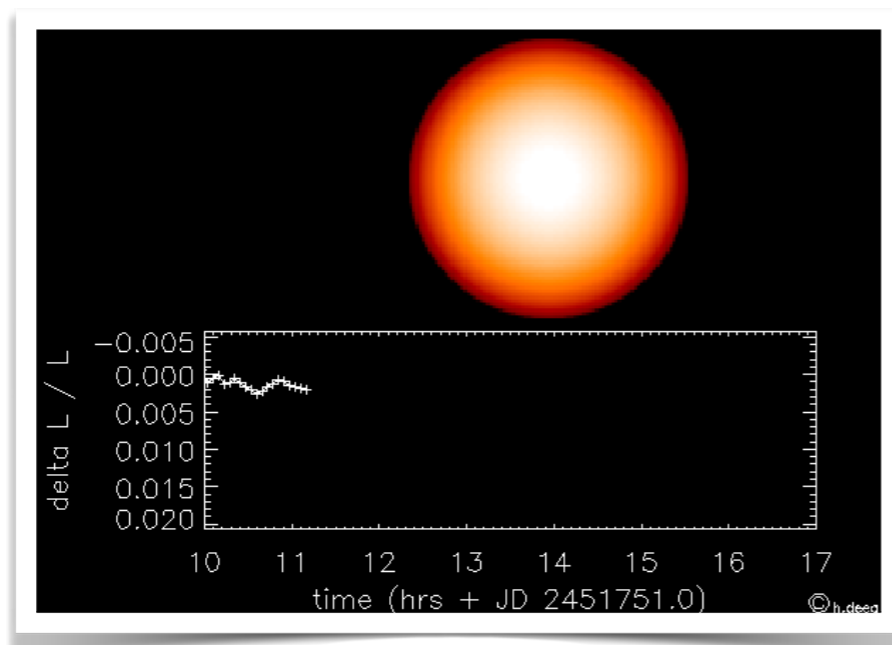
Solar system

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



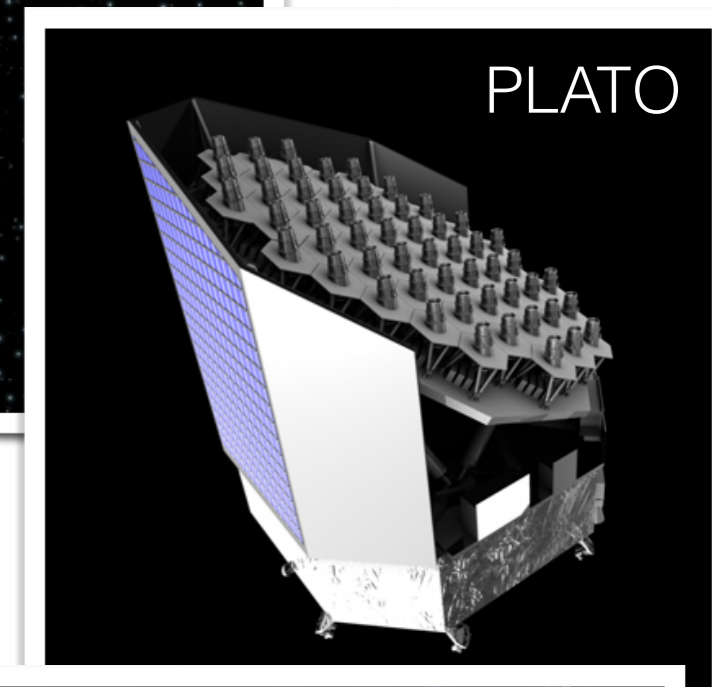
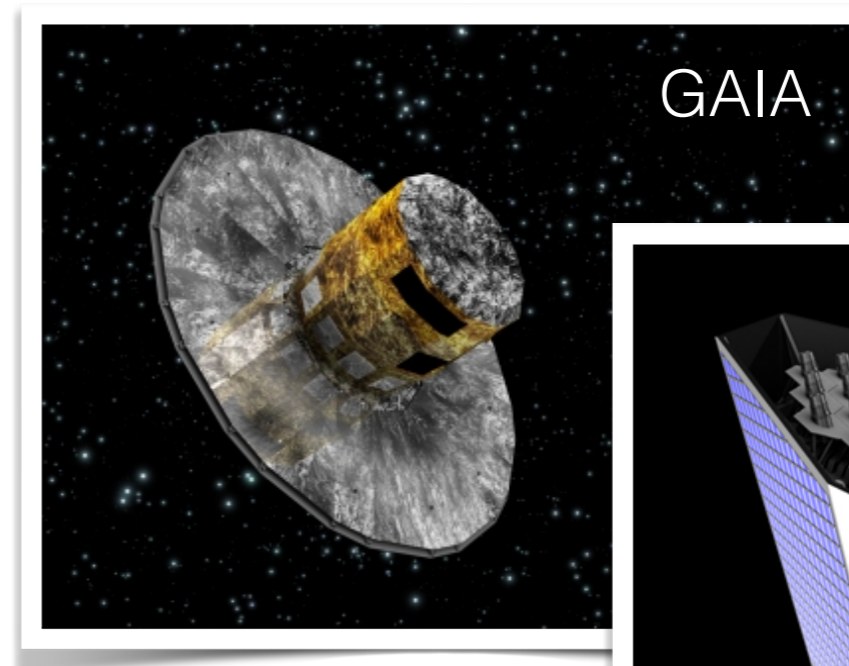
Other examples: CoRoT / Kepler / TESS

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

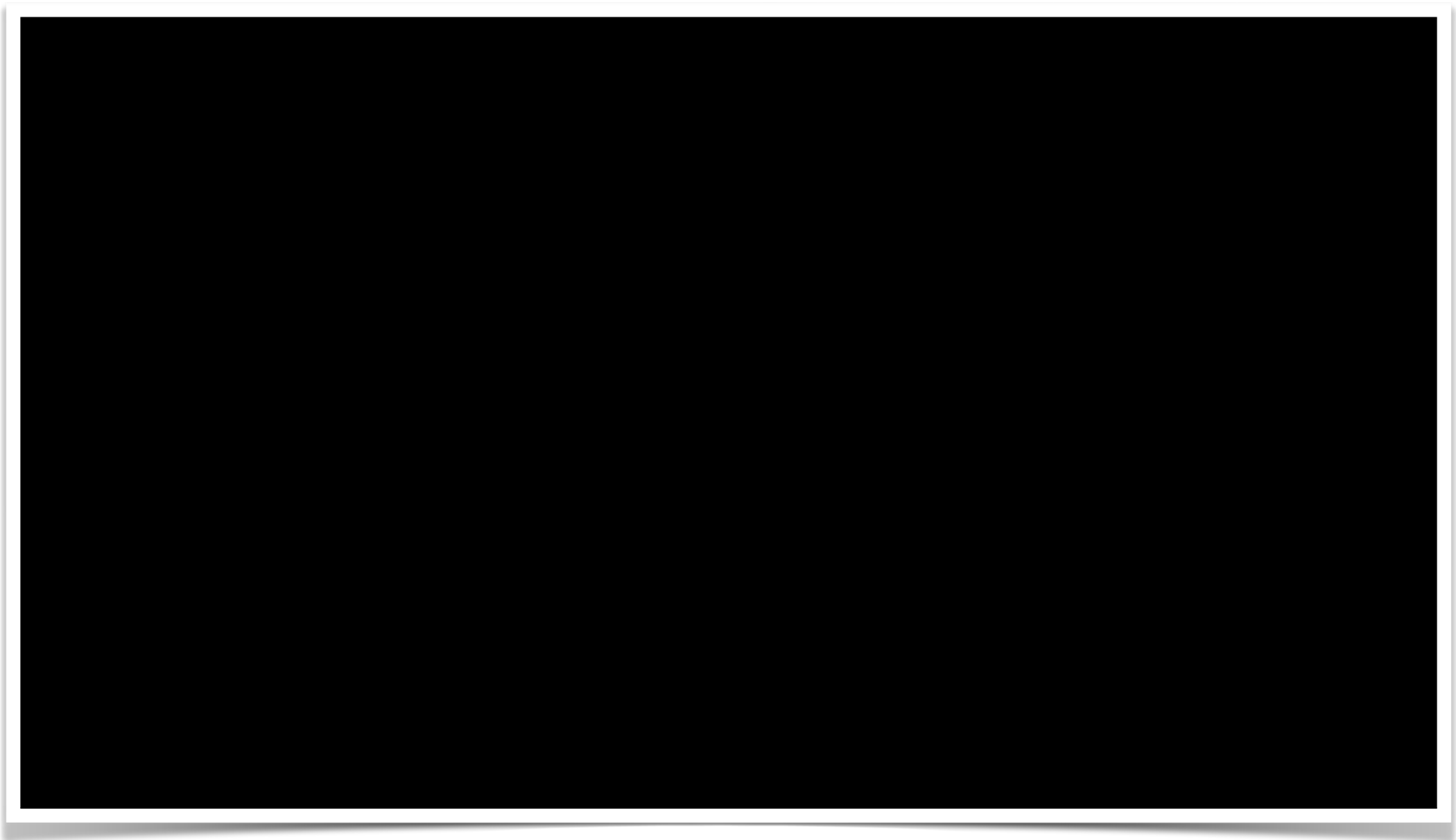


Latest & future missions

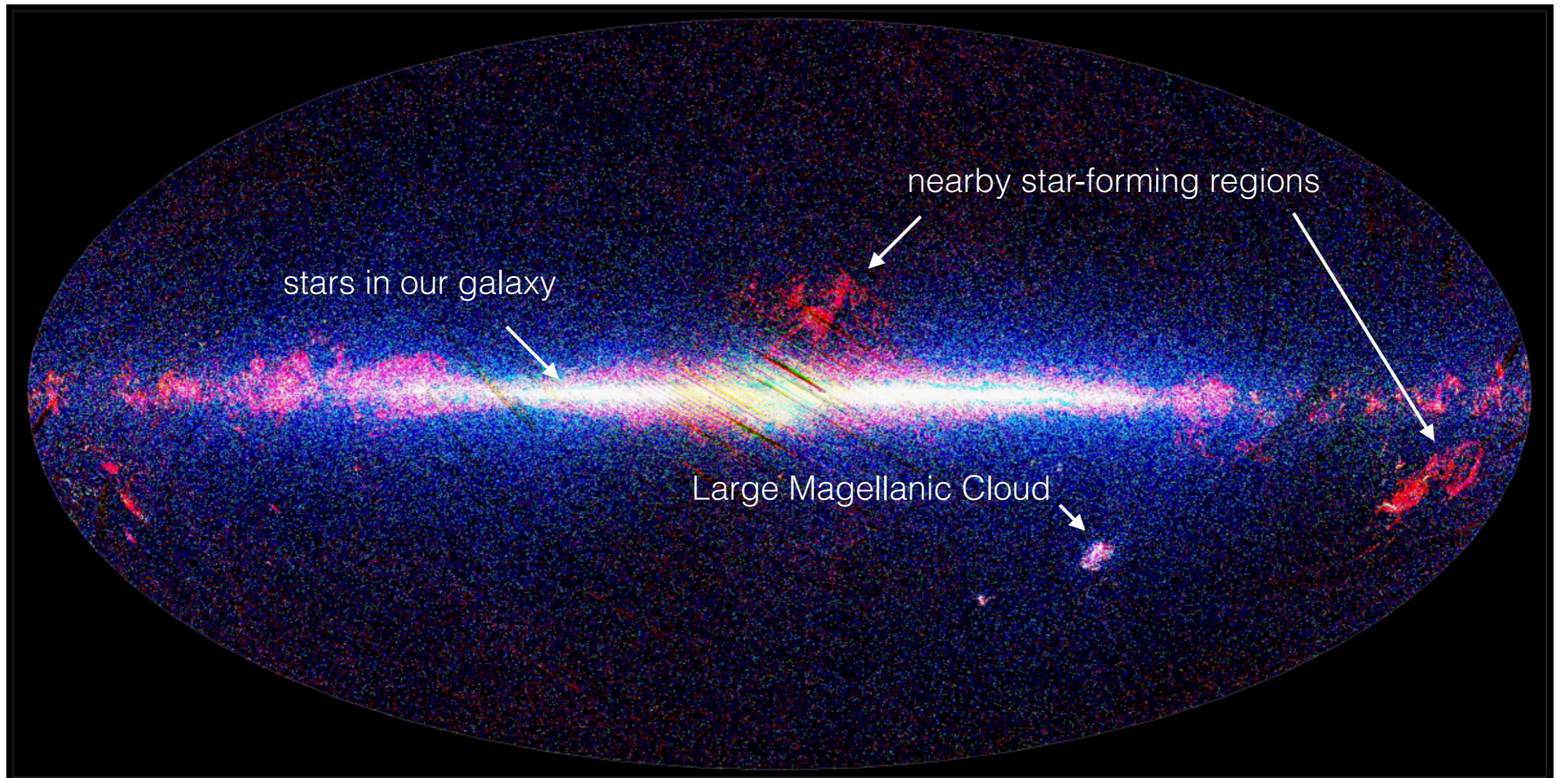
- ◆ GAIA (ESA, 2013)
 - 3D map of our Galaxy
 - 1,000,000 stars (position, velocity)
 - 106 CCDs → 1 billion pixels
 - hyper-stable SiC structure
- ◆ ESA Cosmic Vision
 - Solar Orbiter (2020, on its way)
 - EUCLID (2023): dark energy / dark matter
 - PLATO (2026) and ARIEL (2029): extrasolar planets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



EUCLID first images (released yesterday)



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

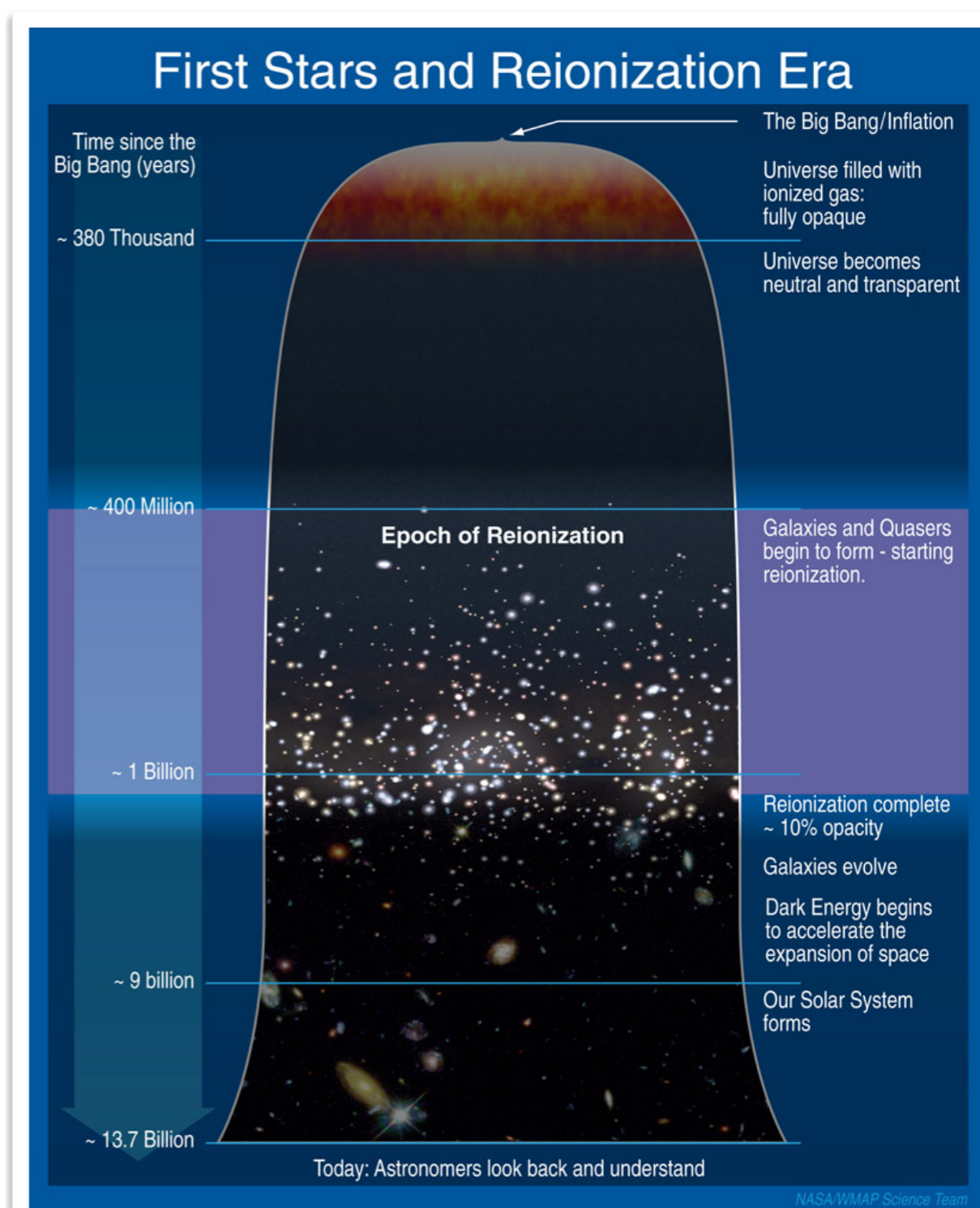
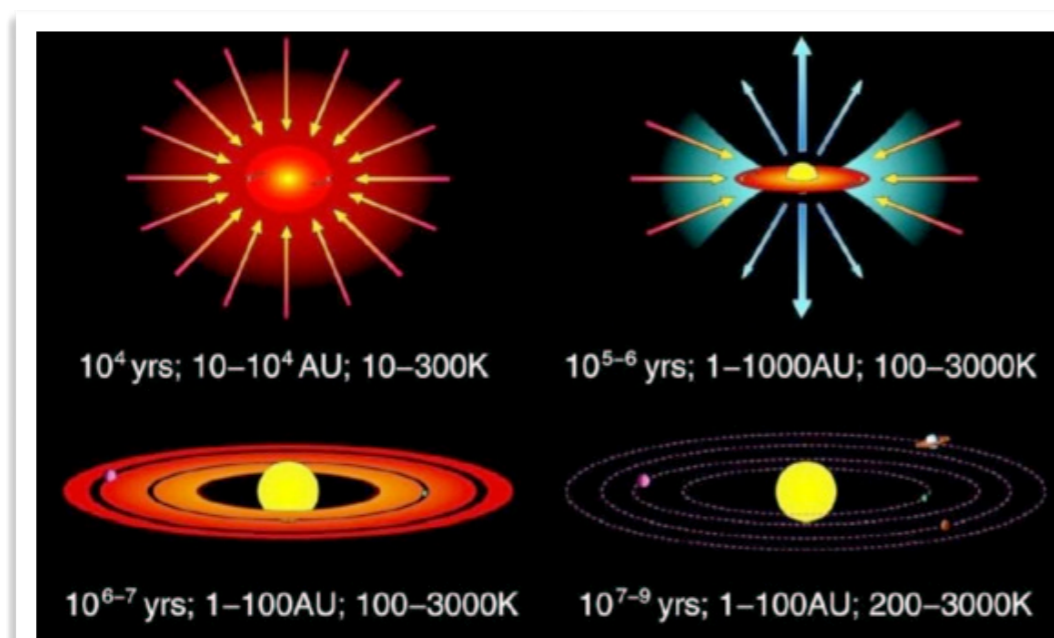


Mid-infrared

From $\lambda = 3 \mu\text{m}$ to $\lambda = 30 \mu\text{m}$

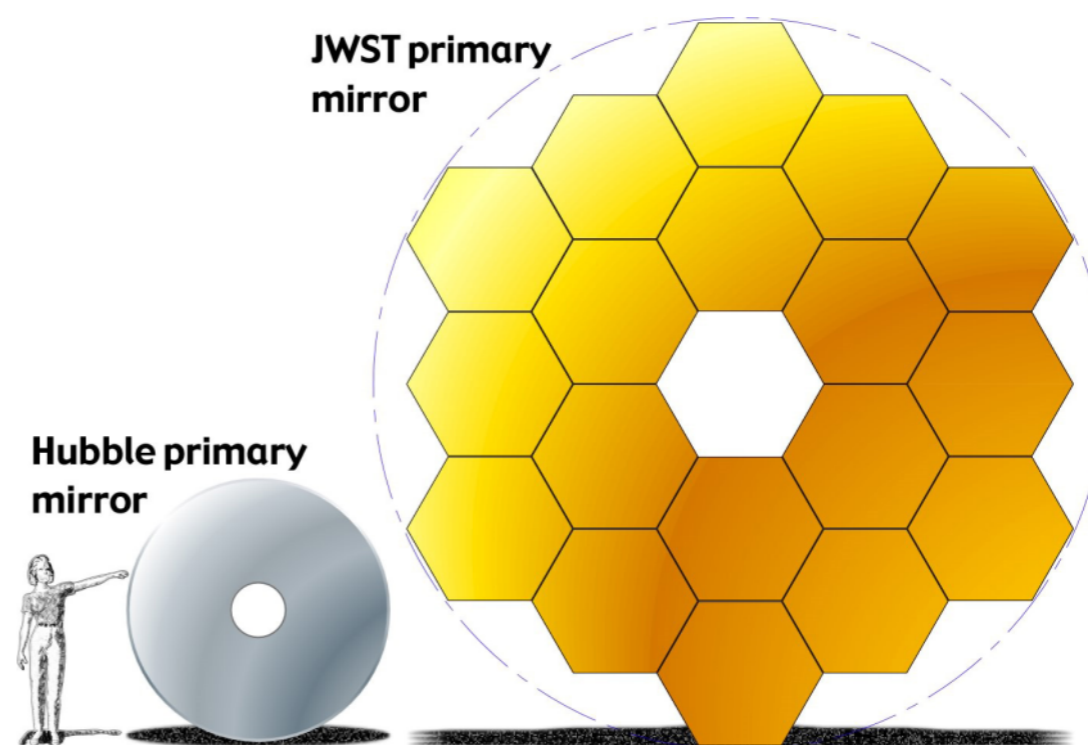
Astrophysical interests

- ◆ 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\$
2018	2020	9.7 B\$
2020	2021	≥ 10 B\$



almost cancelled!

congress-approved cost cap

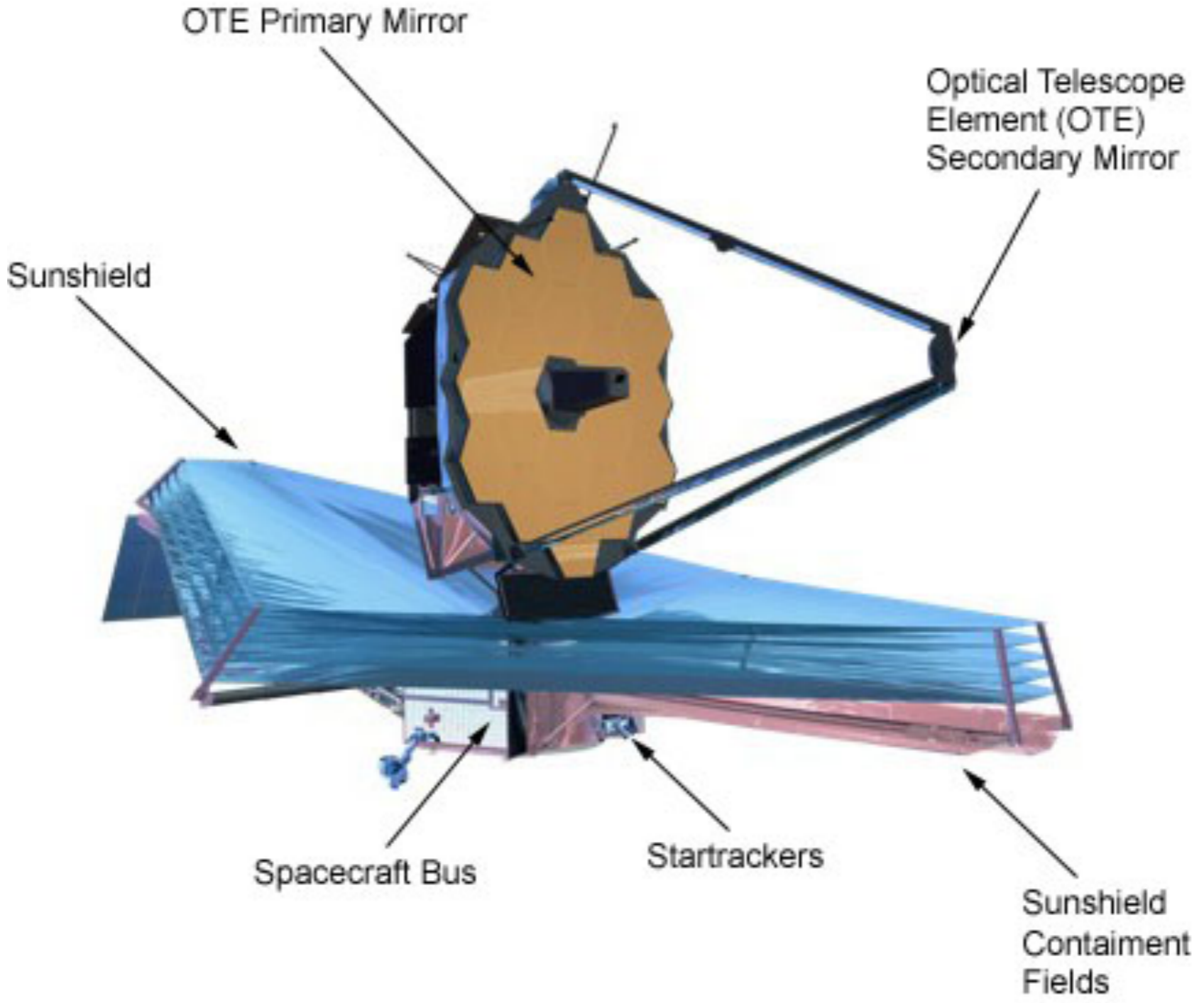
updated cost cap

(incl. operations)

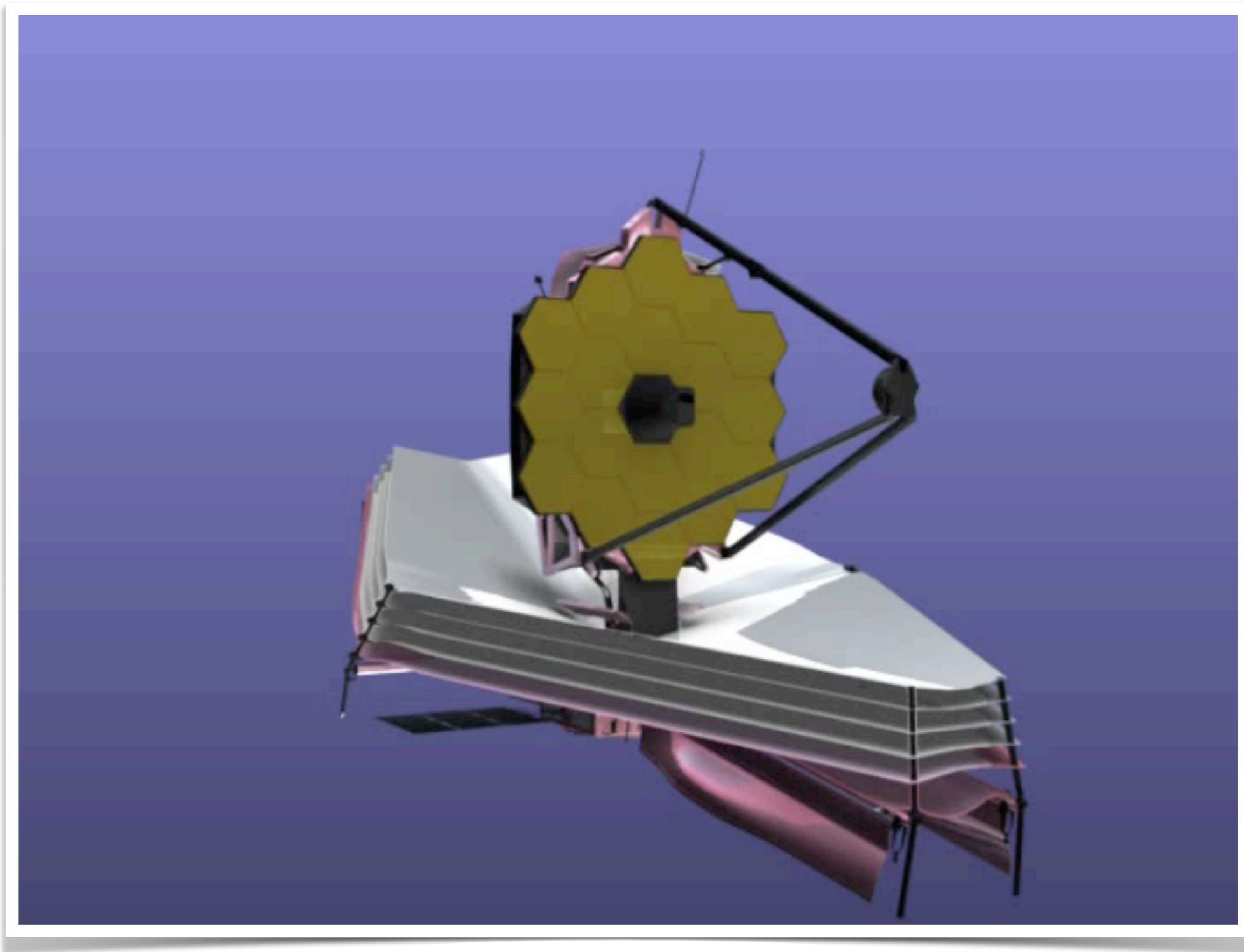
JWST size = tennis court!



JWST design



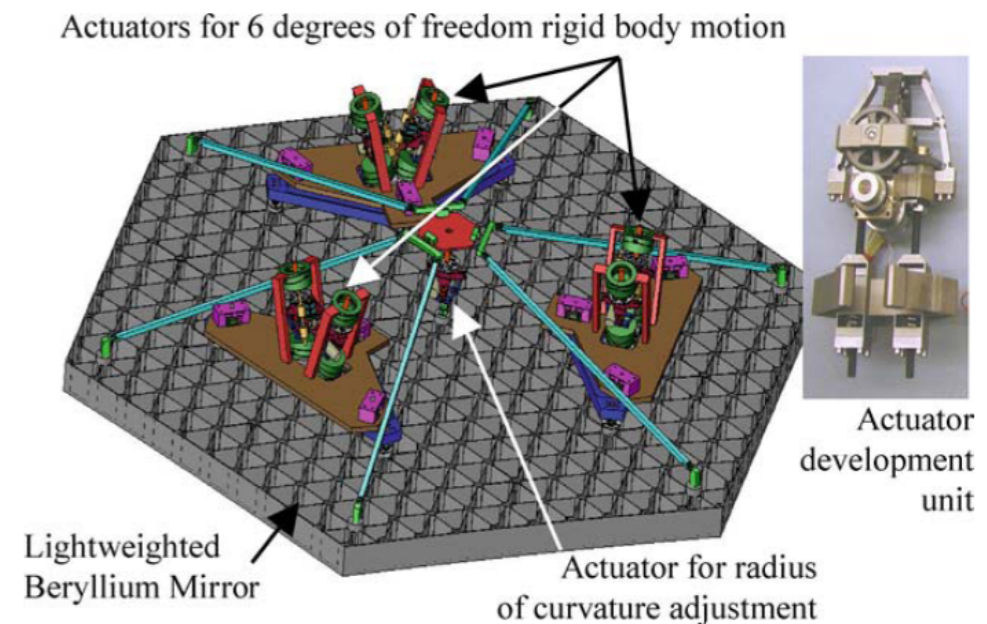
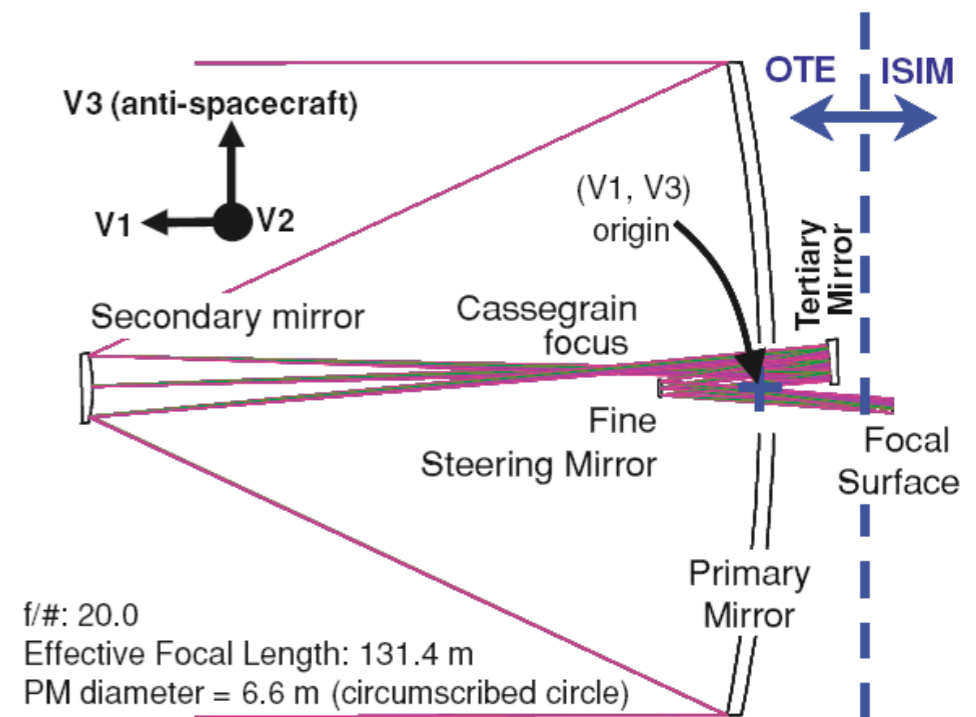
Deployable telescope



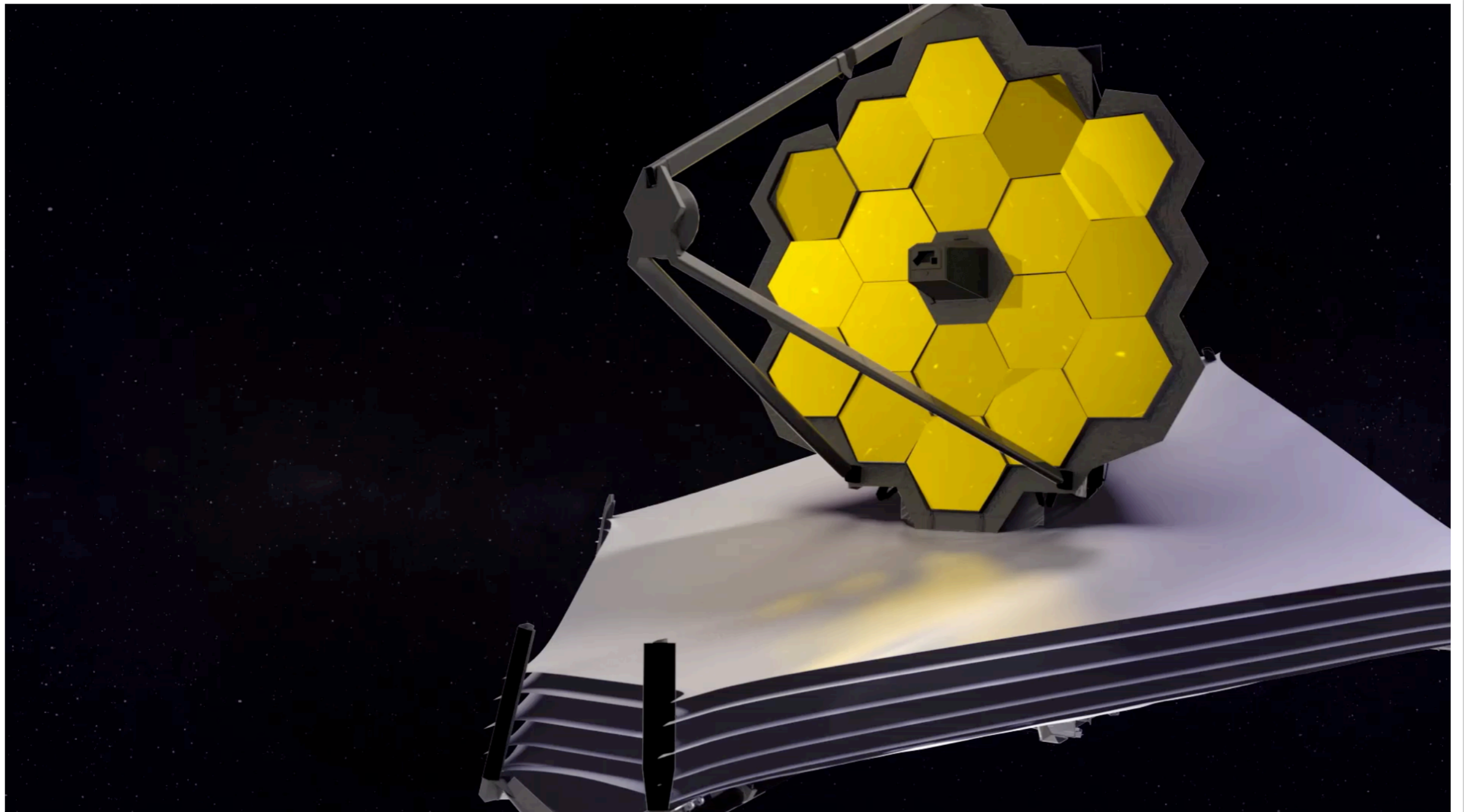
Lightweight segmented mirror

- ◆ 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

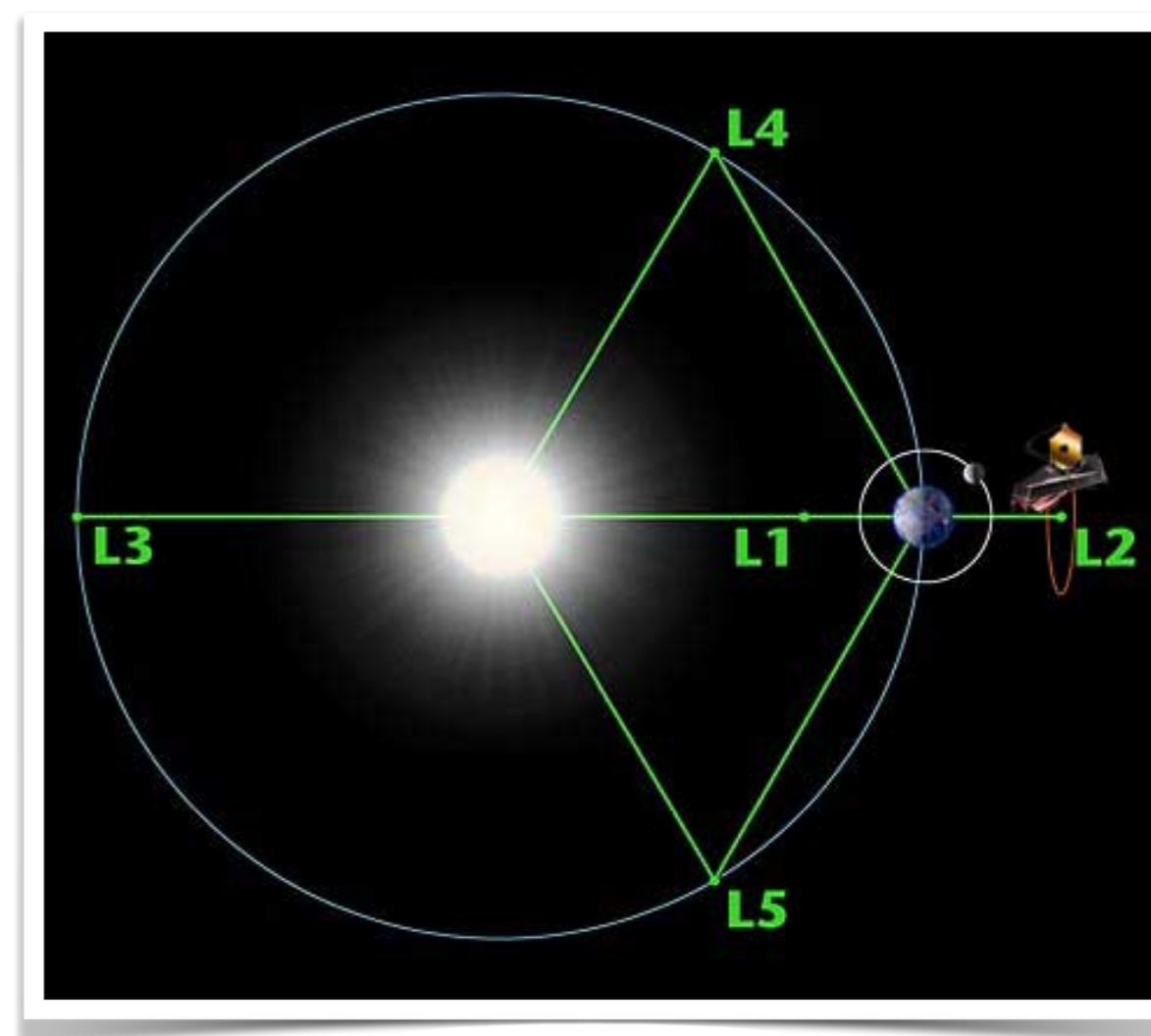


Telescope initial phasing



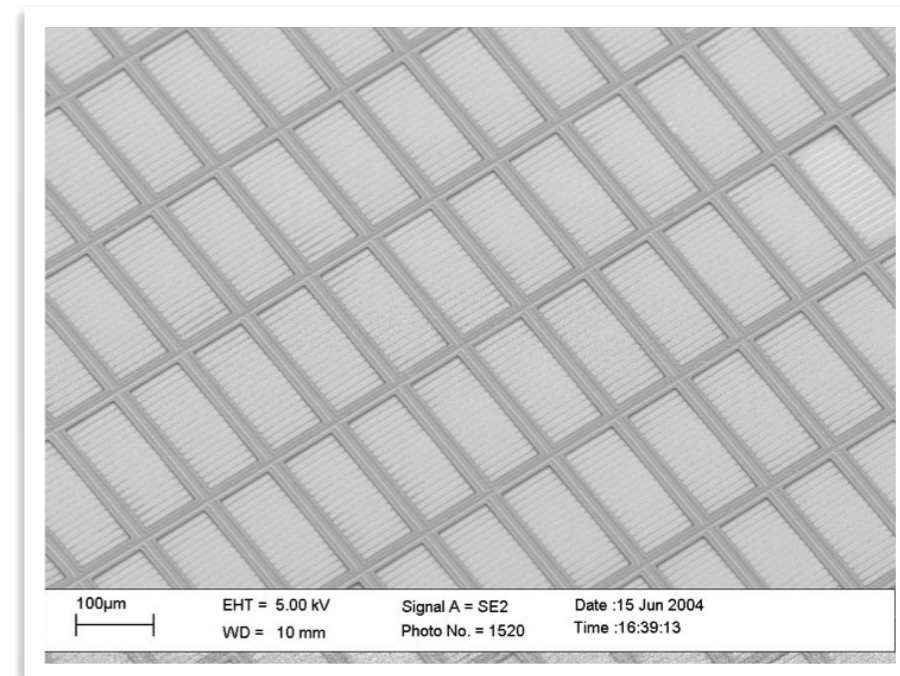
Cooling

- ◆ Lagrange L2 point
- ◆ Mirror: passive cooling to 50 K
- ◆ Innovative sun shield
 - 5 coated polymer-film layers
 - reflects light without heating
 - thickness $\sim 30 \mu\text{m}$
 - resistant to micro-meteorites
- ◆ Instruments: cryogeny

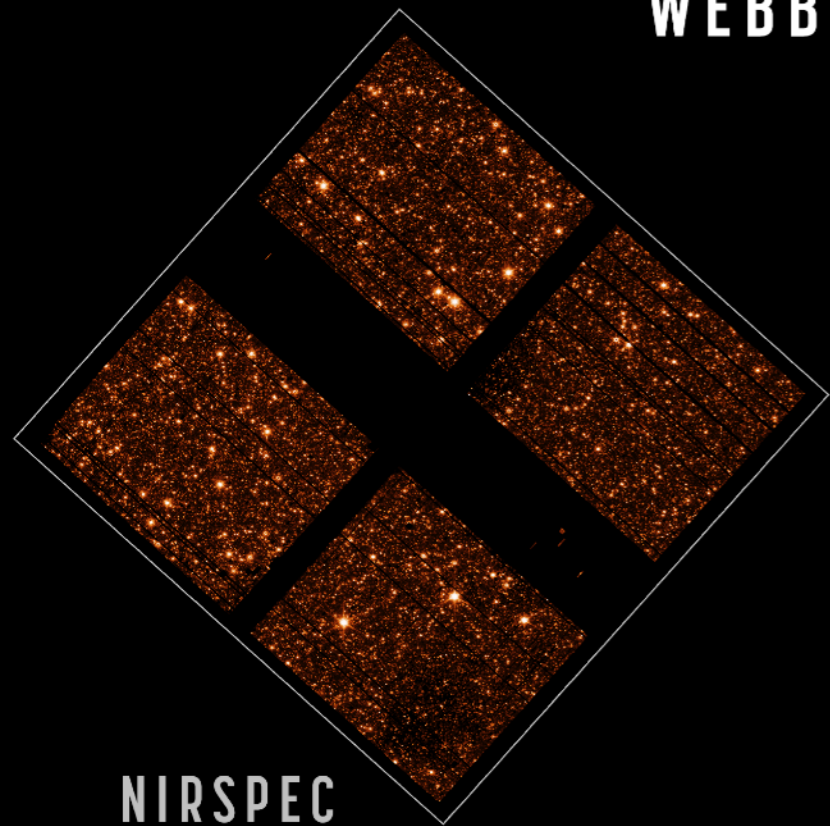


Instruments

- ◆ NIRCam: imaging, 0.6 to 5 μm
- ◆ NIRSpect: spectroscopy, 0.6 to 5 μm
 - multi-object \rightarrow 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

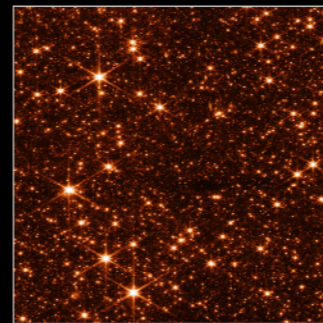
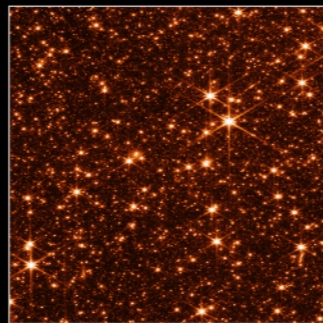


WEBB TELESCOPE IMAGE SHARPNESS CHECK

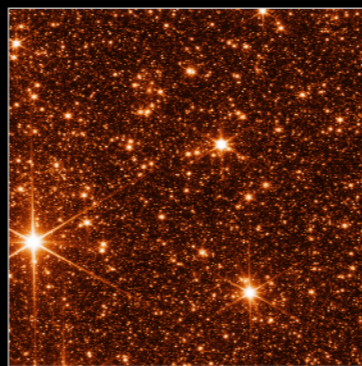
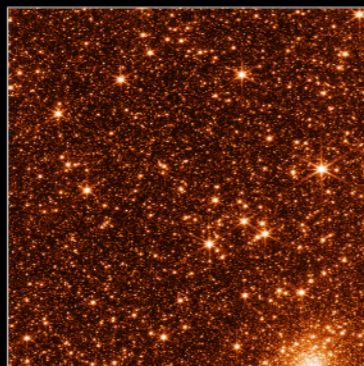


NIRSPEC

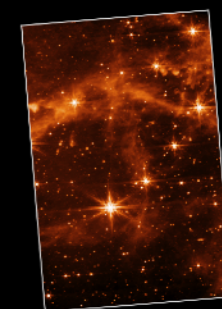
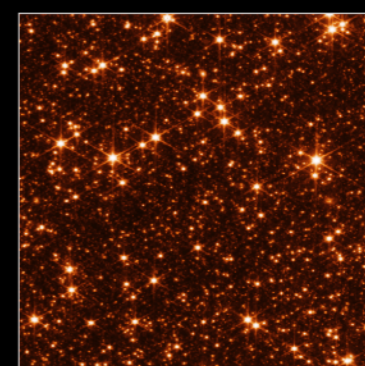
NIRCAM



FINE GUIDANCE SENSOR



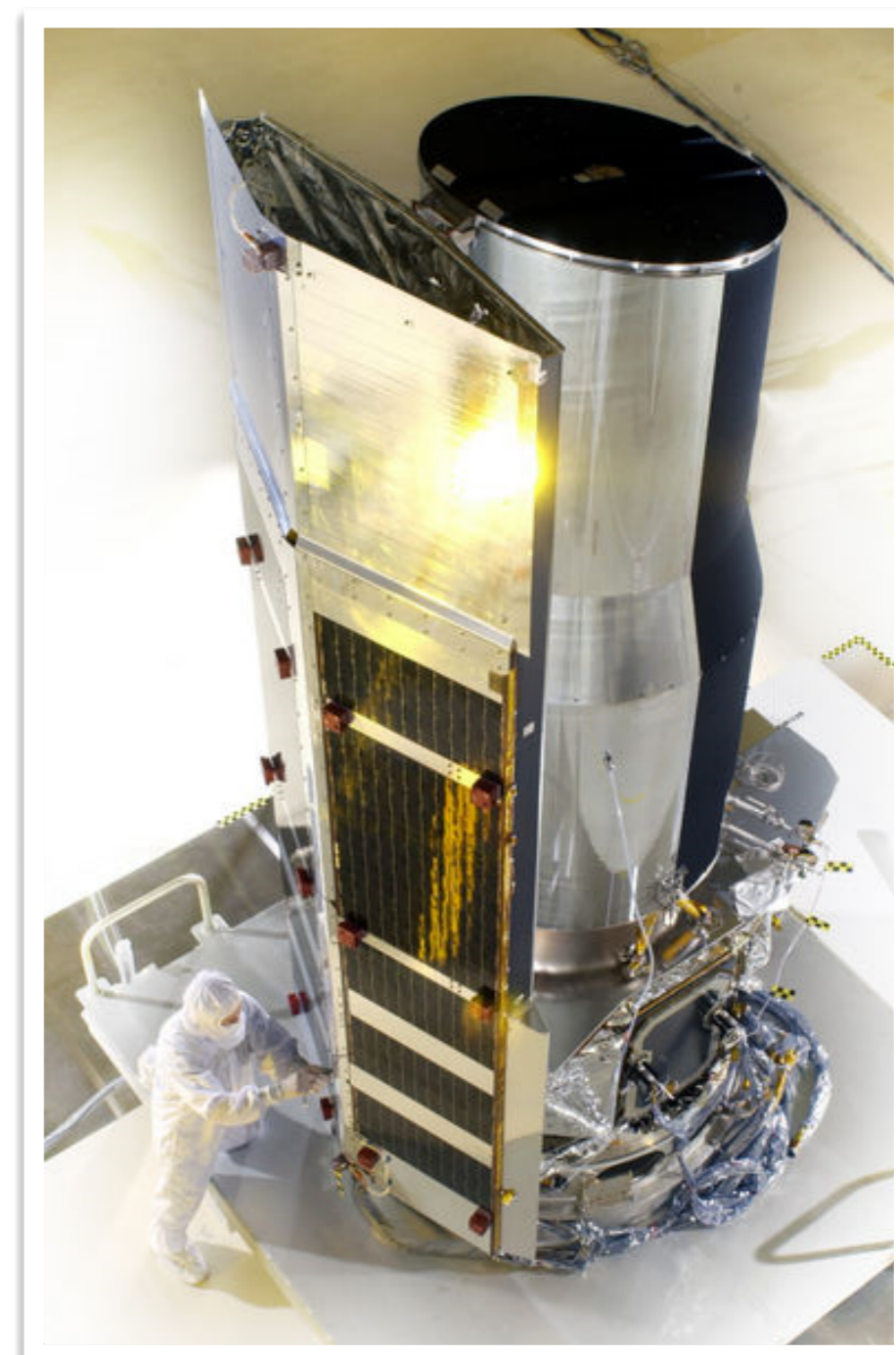
NIRISS



MIRI

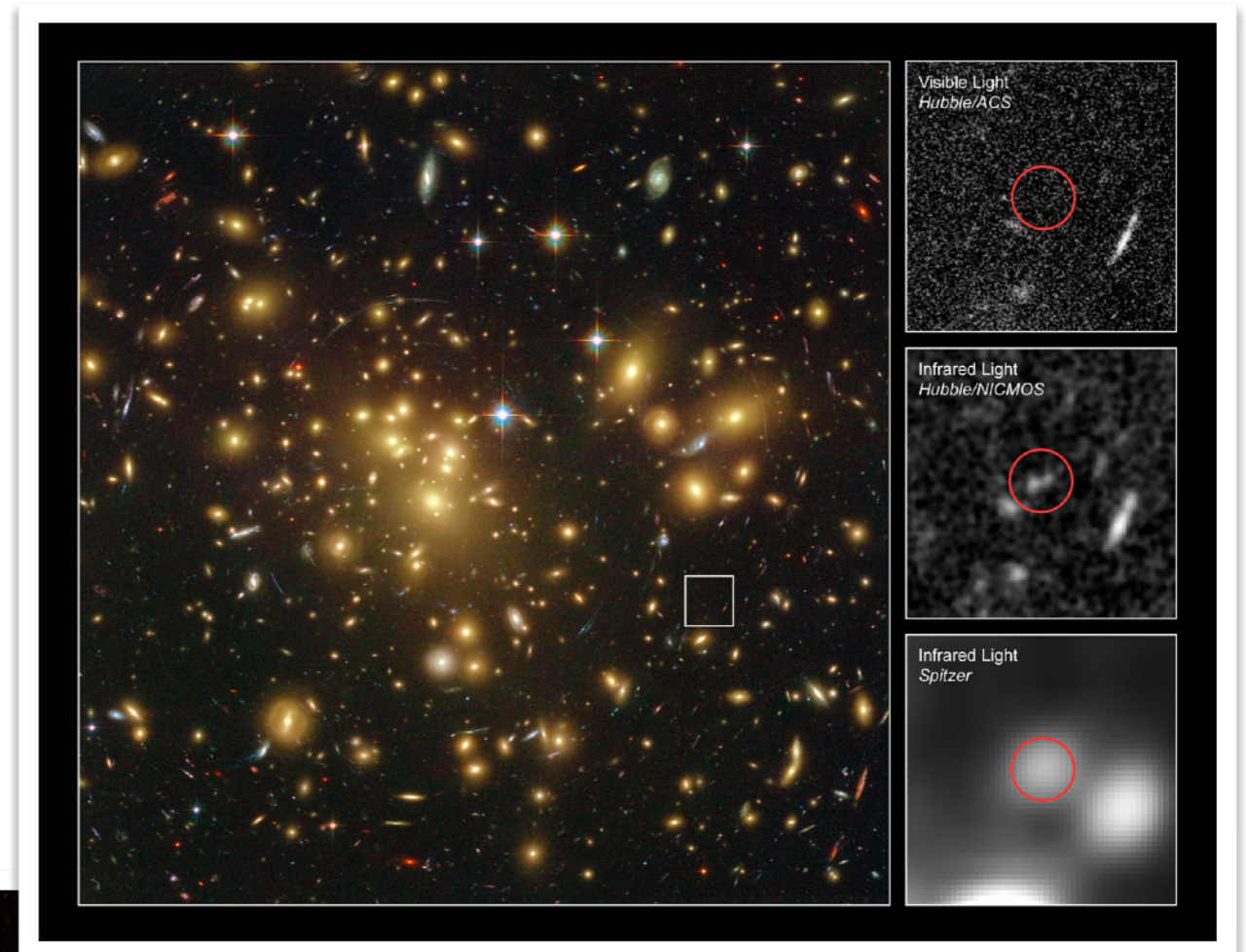
Other missions

- ◆ 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

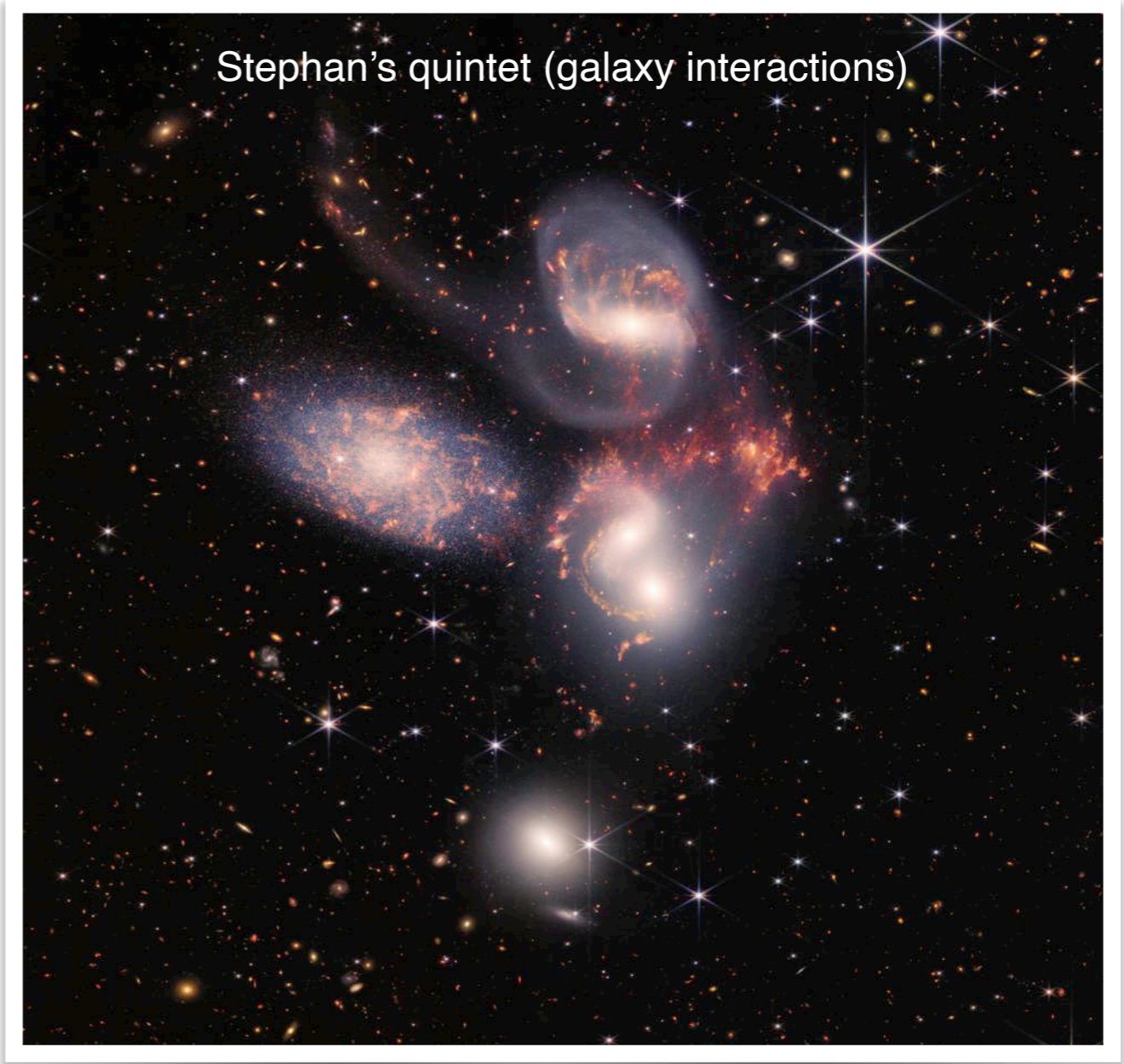


Galaxies

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

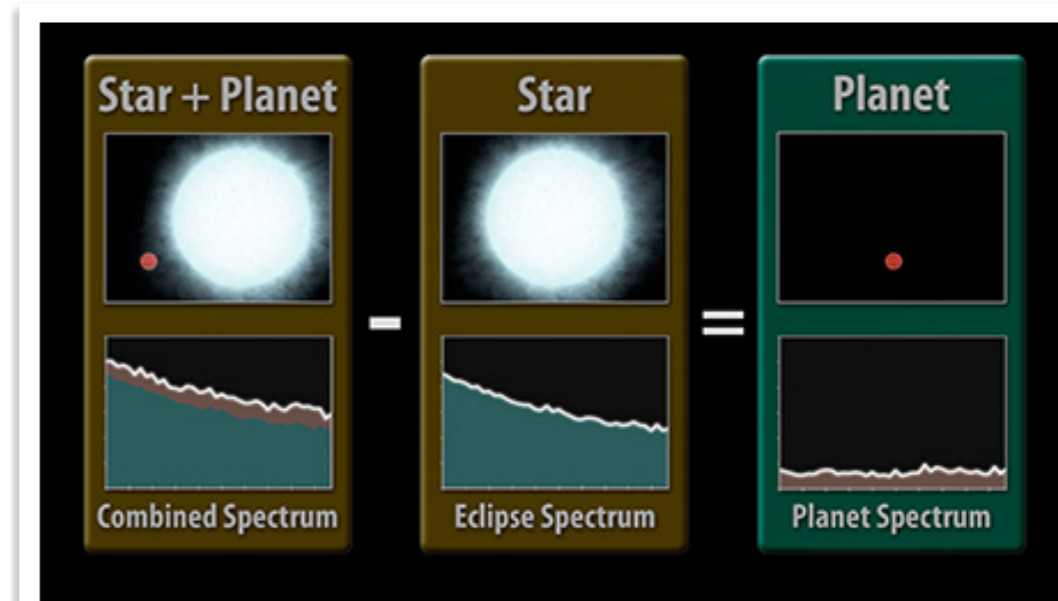


Early JWST highlights



Stars and planets

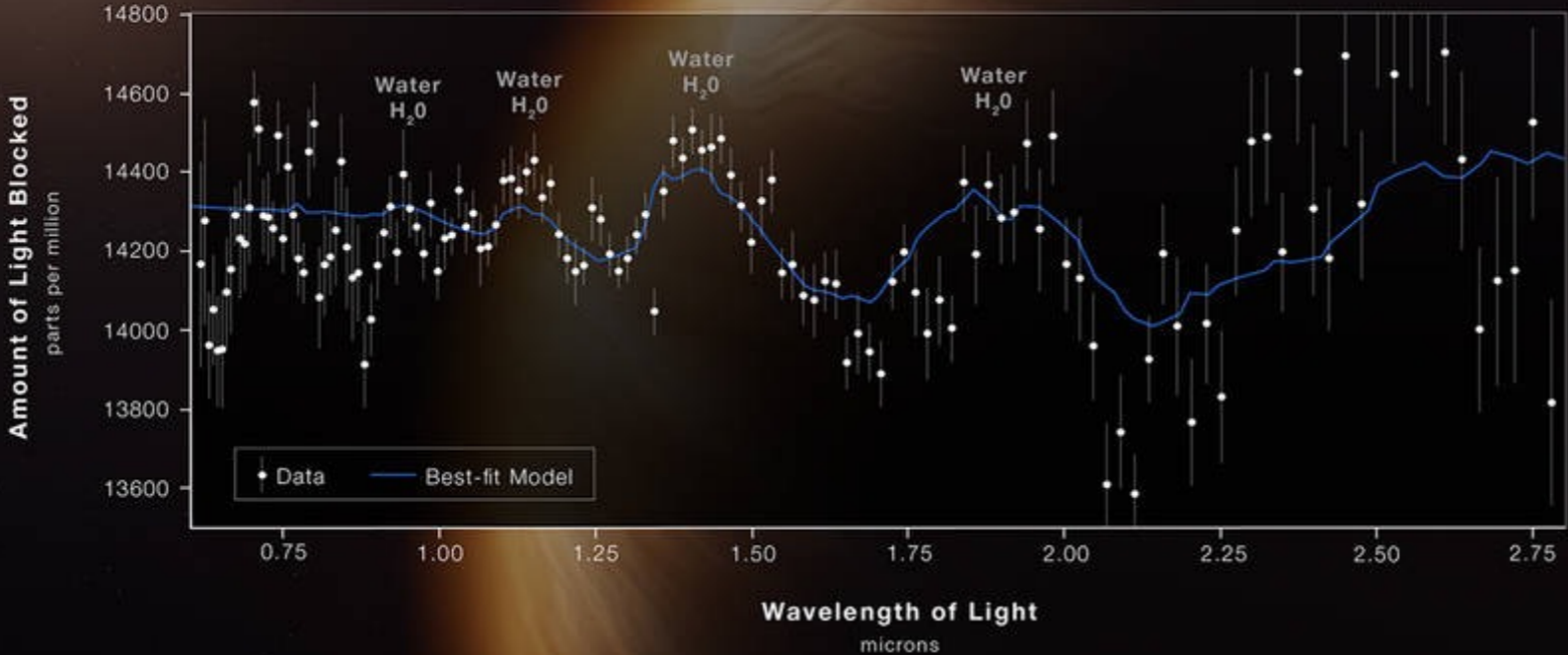
- ◆ Observation of the youngest, forming stars
- ◆ Cold brown dwarfs
- ◆ Circumstellar disks (IRAS, 1984)
- ◆ First measurement of exoplanet temperature (Spitzer, 2006)



Early JWST highlights

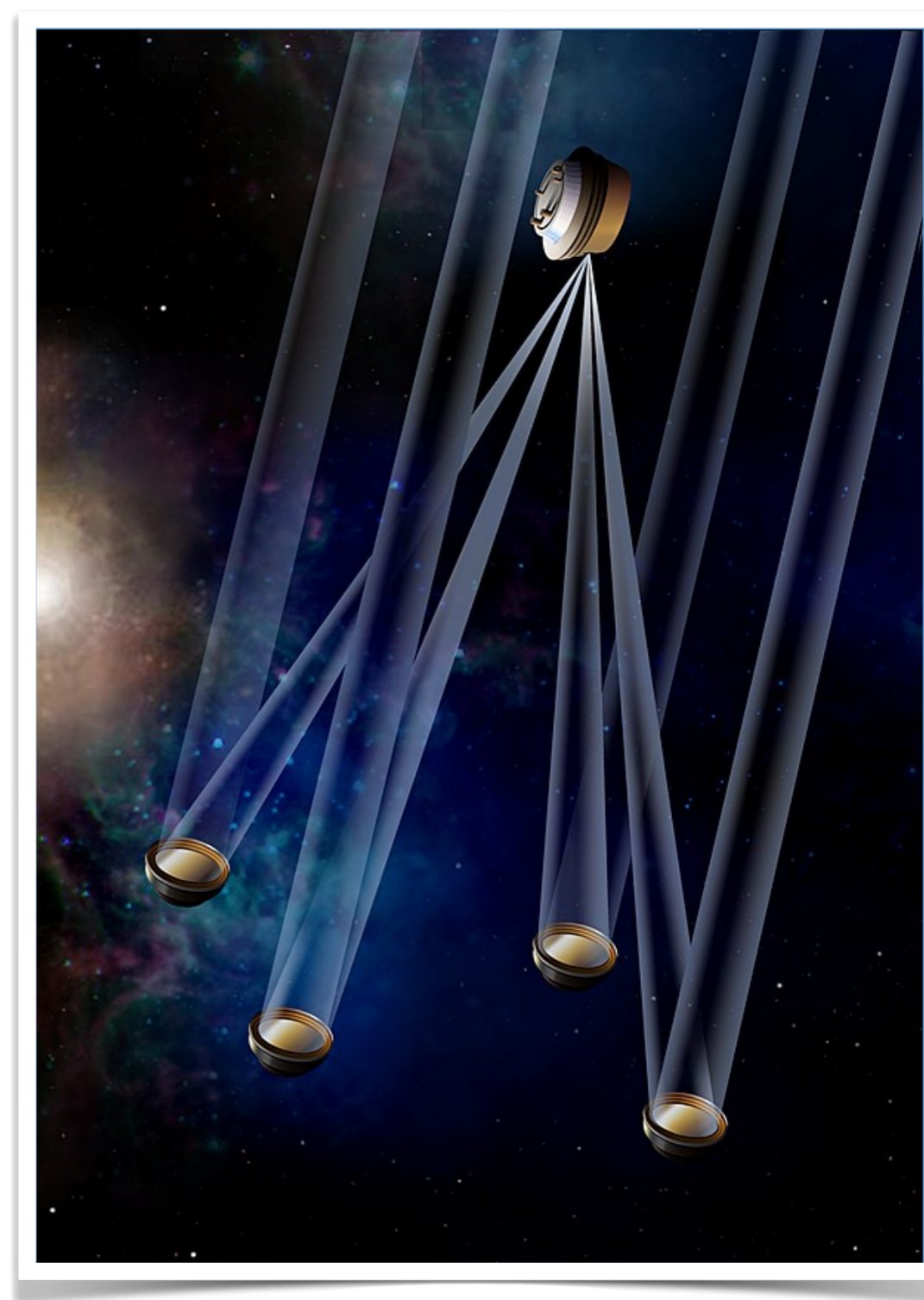
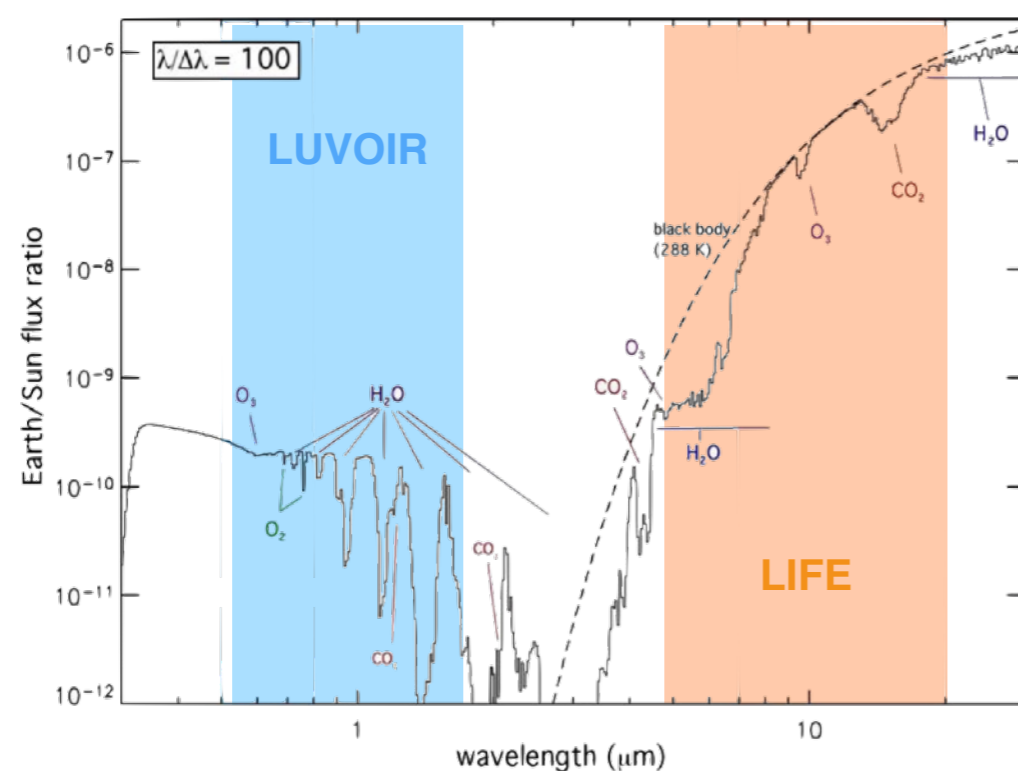


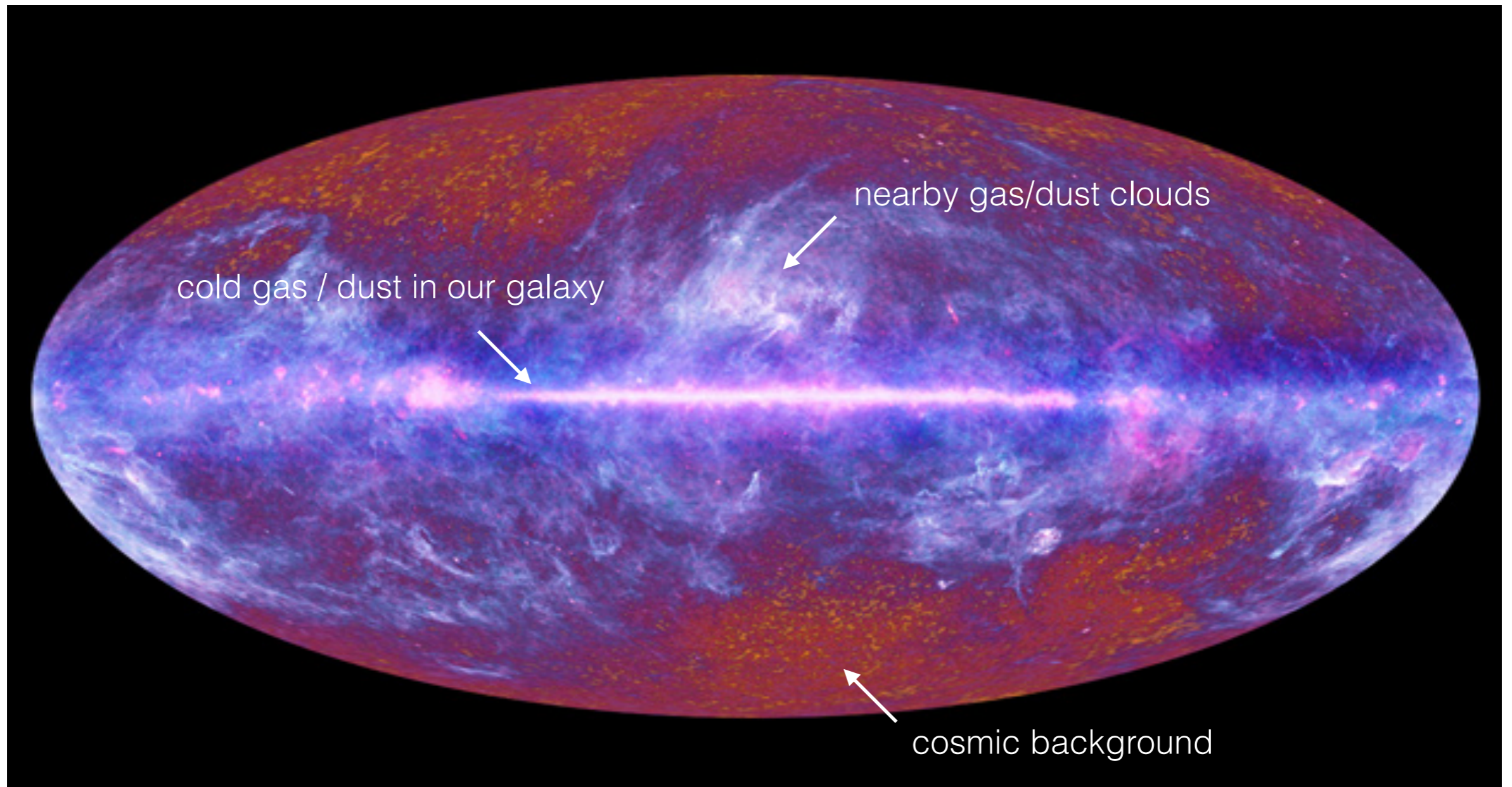
HOT GAS GIANT EXOPLANET WASP-96 b ATMOSPHERE COMPOSITION



Future: interferometry

- ◆ Formation flying
 - no size limit
 - angular resolution: $\lambda / \text{Baseline}$
- ◆ Direct imaging of Earth-like planets
 - possible discovery of life!





Far-IR / submm / mm

From $\lambda = 30 \mu\text{m}$ to $\lambda = 3 \text{ mm}$

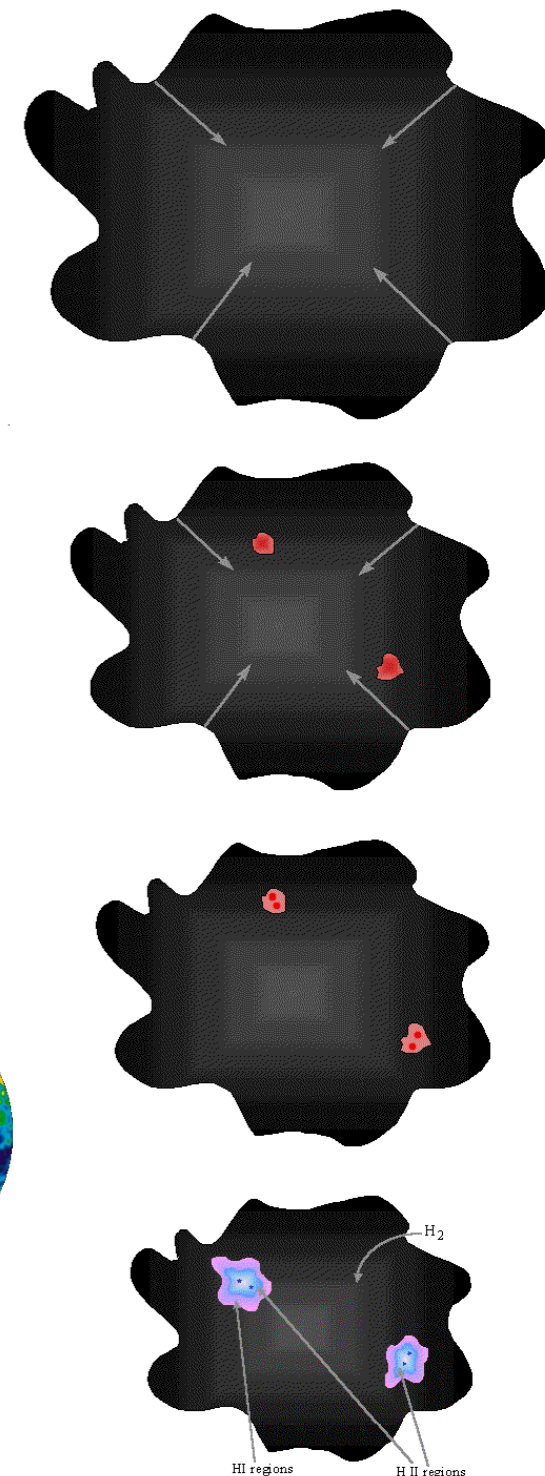
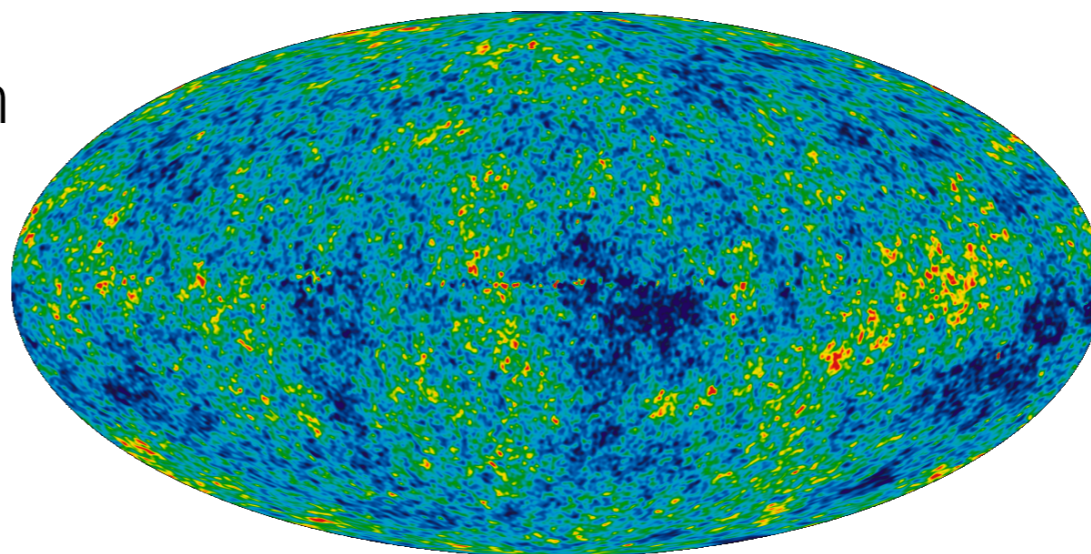
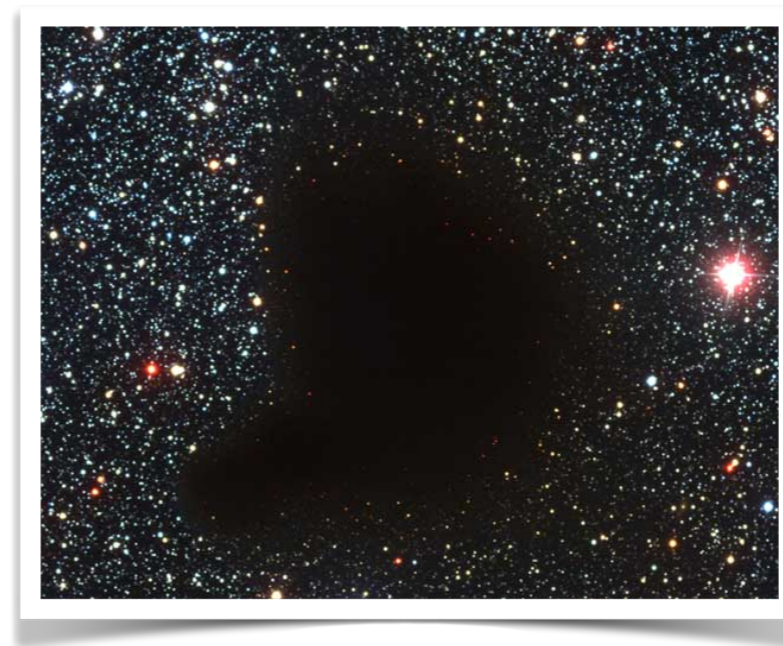
Astrophysical interests

◆ Cold thermal phenomena (< 100 K)

- molecular clouds
- outer solar system

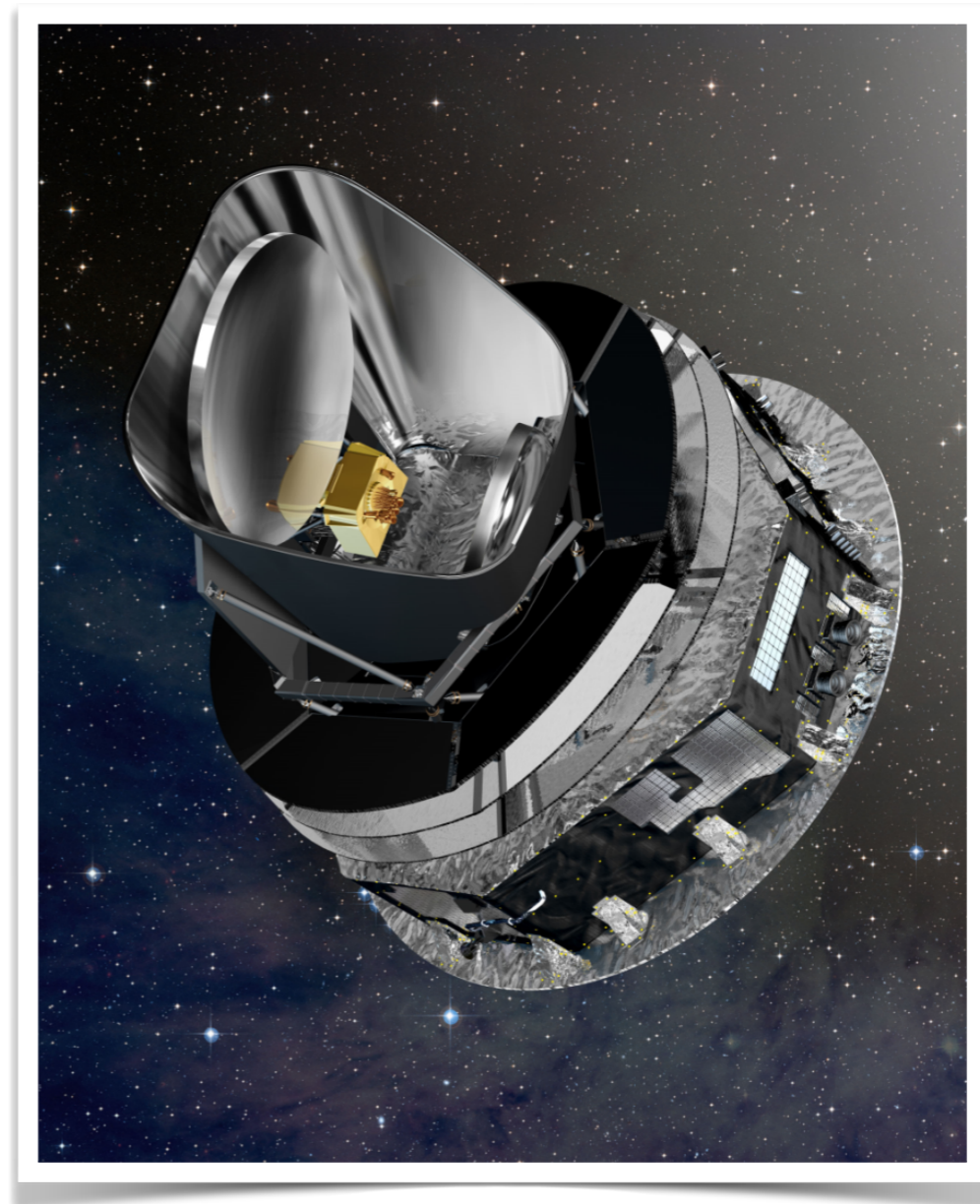
◆ Cosmic microwave background at ~ 3 K

- thermal radiation from early Universe (recombination), predicted by Big Bang theory



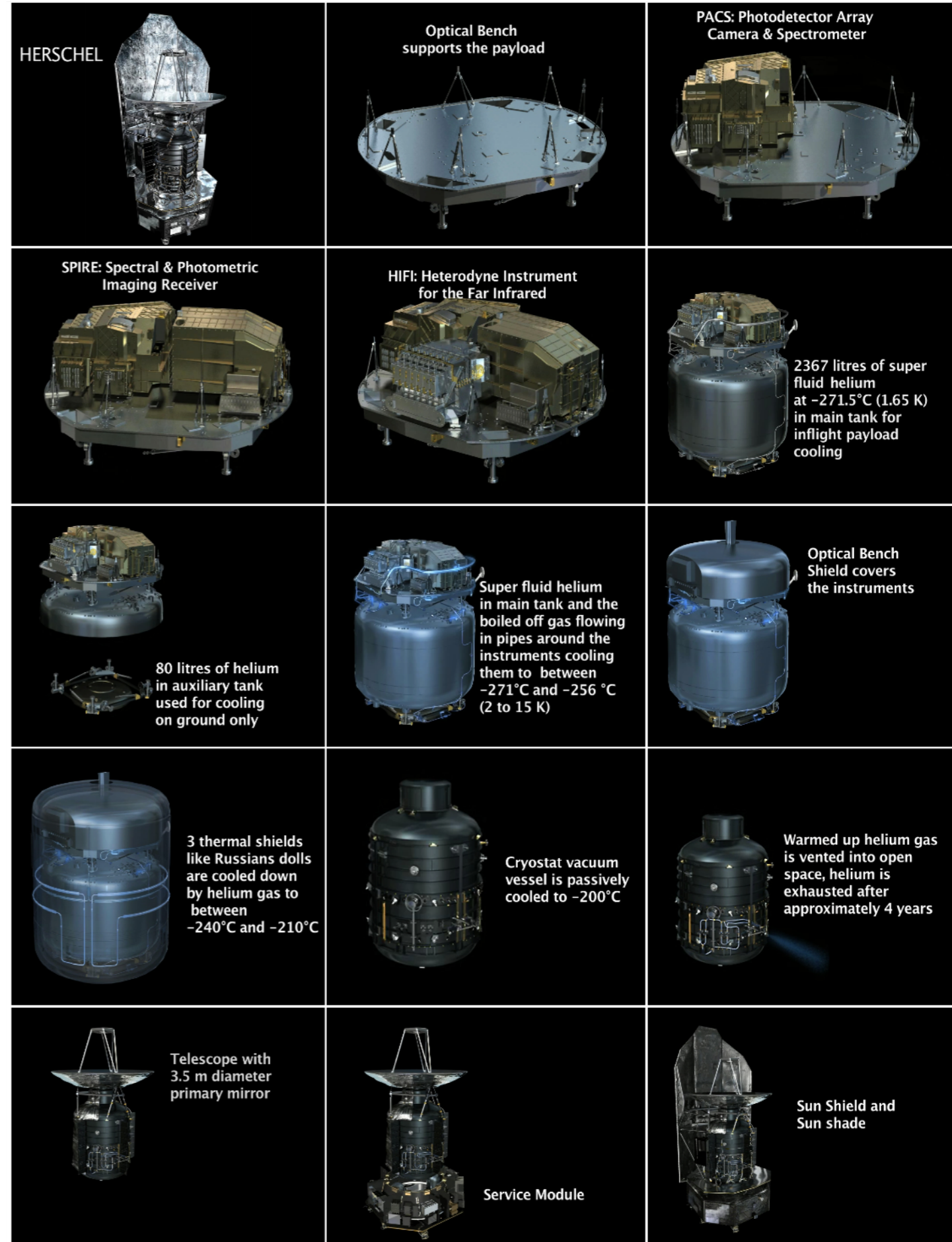
Examples: Herschel & Planck

- ◆ 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

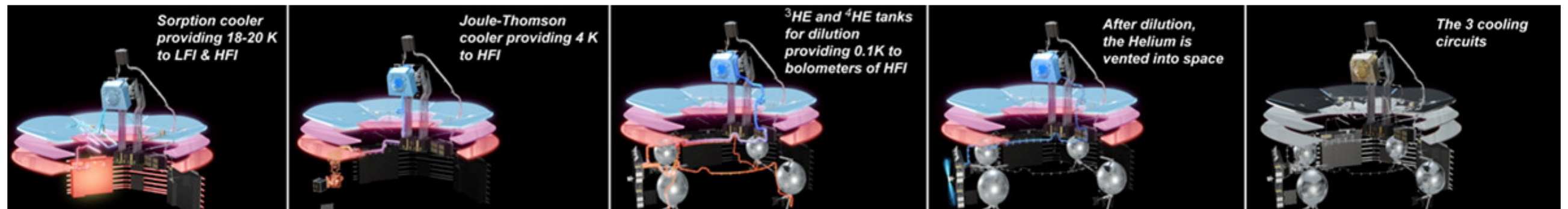
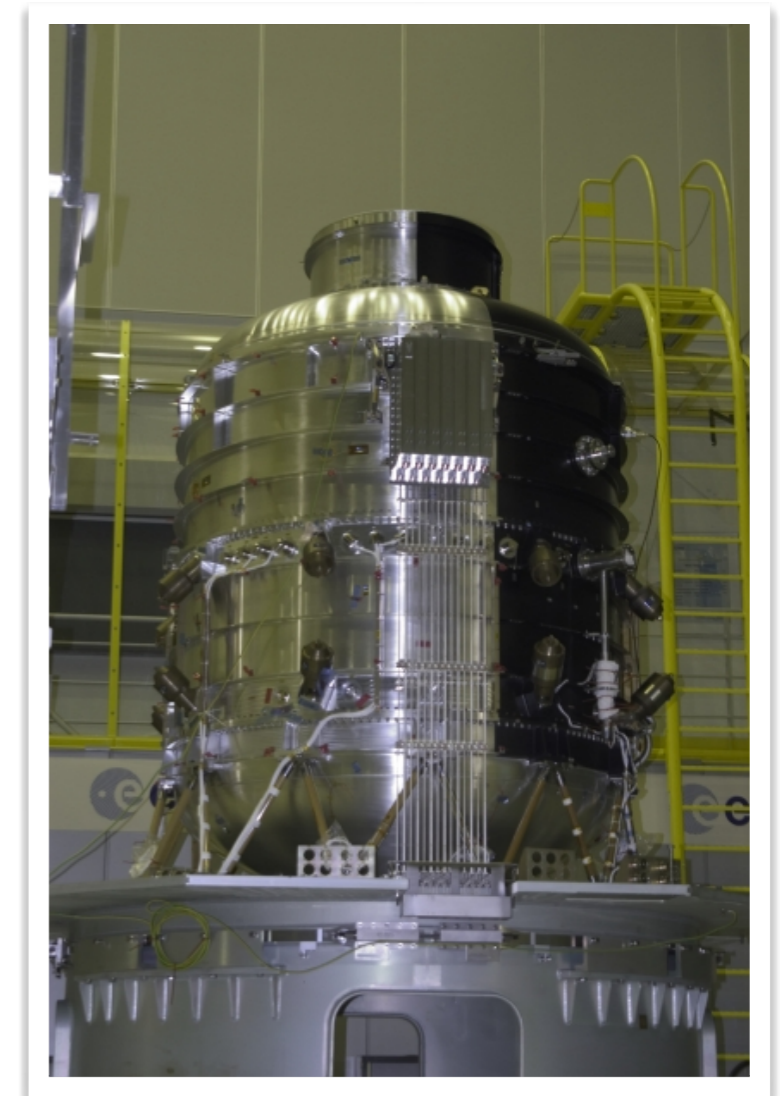
- ◆ Diameter: 1.5 m
- ◆ Range: 0.3 to 10 mm
- ◆ Size: 4.2 m (cube)
- ◆ Weight: 1.9 tons
- ◆ Duration: 2 years (2 full sky surveys)



Cooling

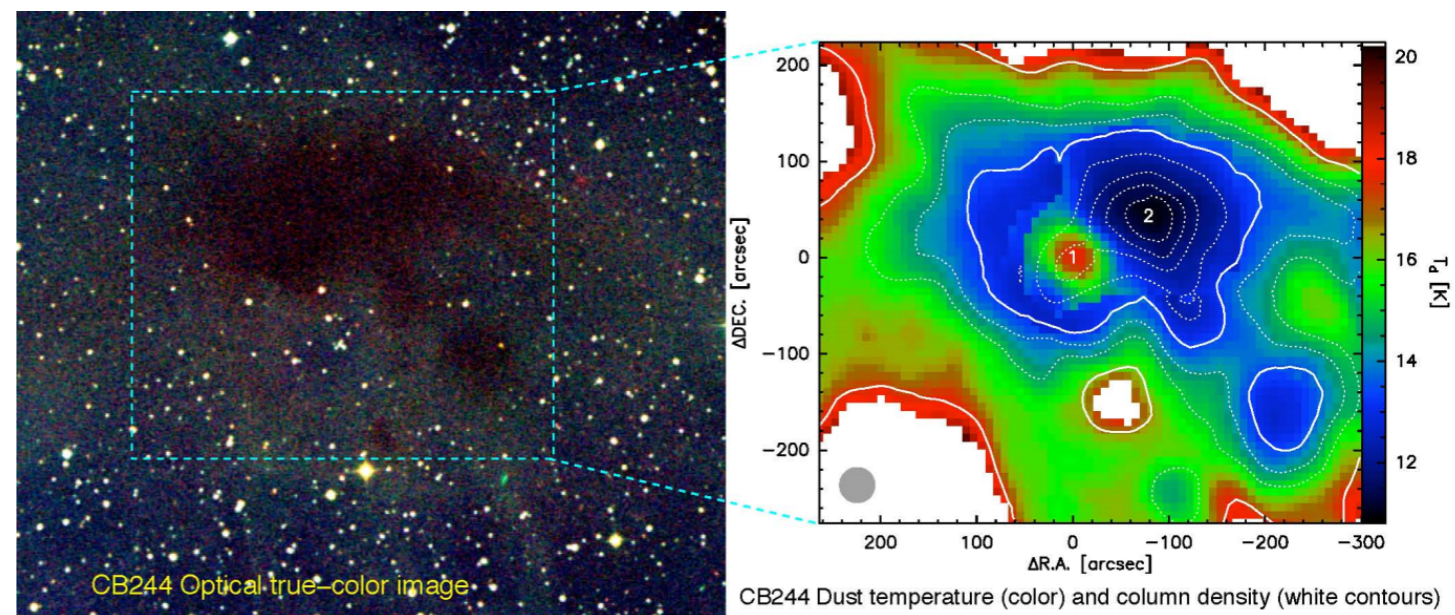
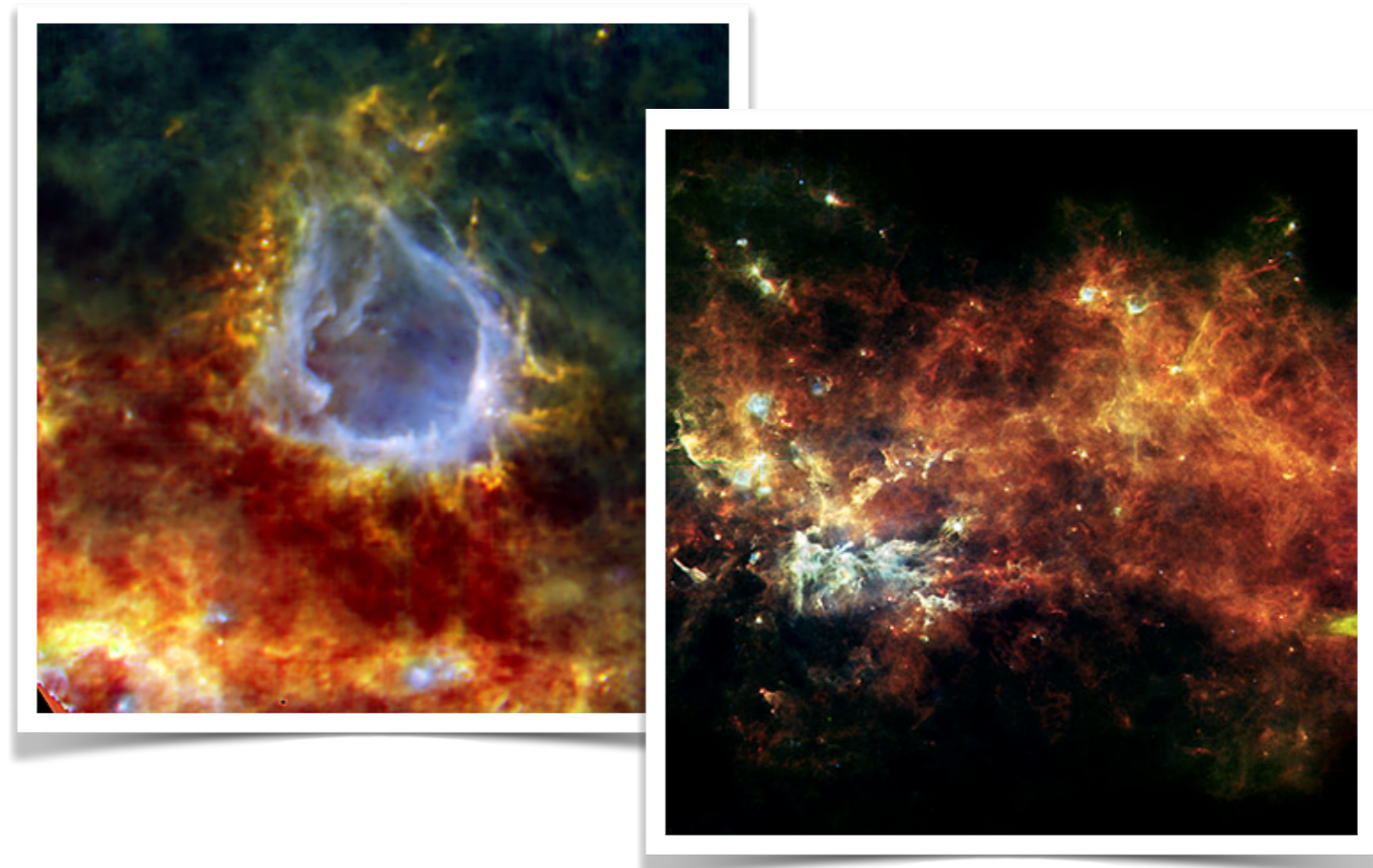
Tests @ CSL

- ◆ 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)
 - $^3\text{He}/^4\text{He}$ dilution cooler
- ◆ Extreme stability (~ 0.01 K level)



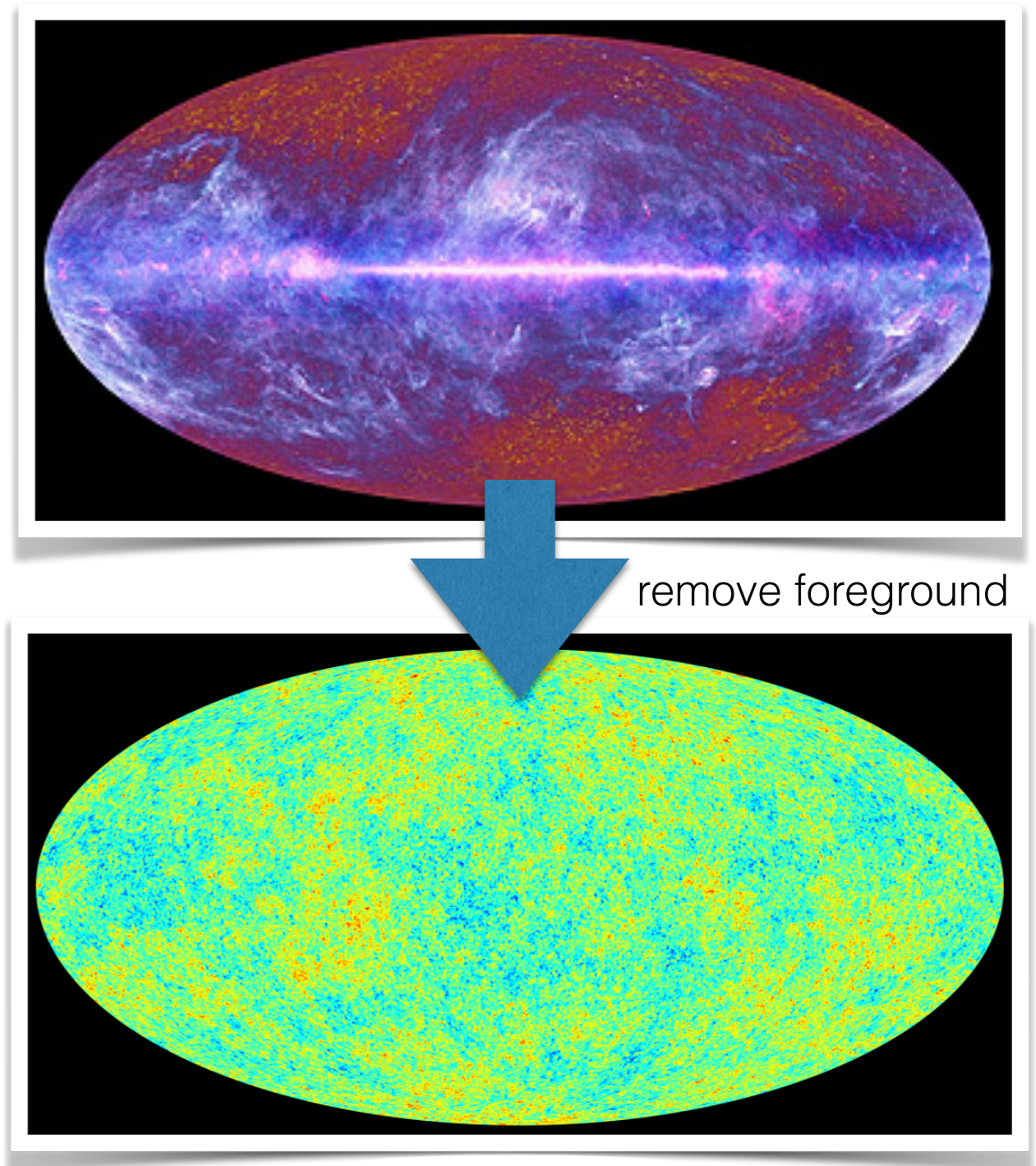
Herschel results

- ◆ 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 (H₂O, O₂, complex organics)
 - planetary surfaces and atmospheres
 - composition of comets (e.g., deuterium content)



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!



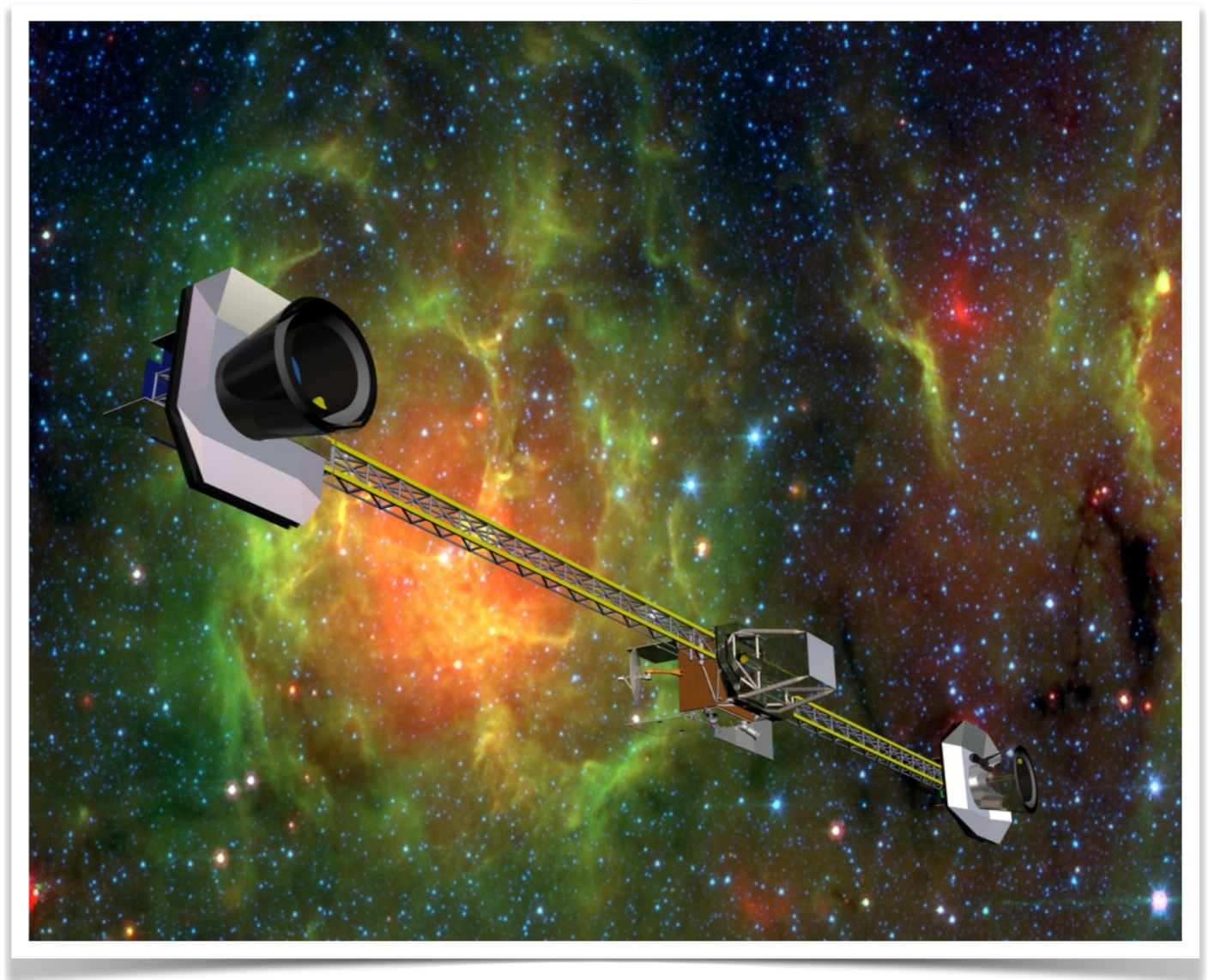
SOFIA open-door flight test

2010



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

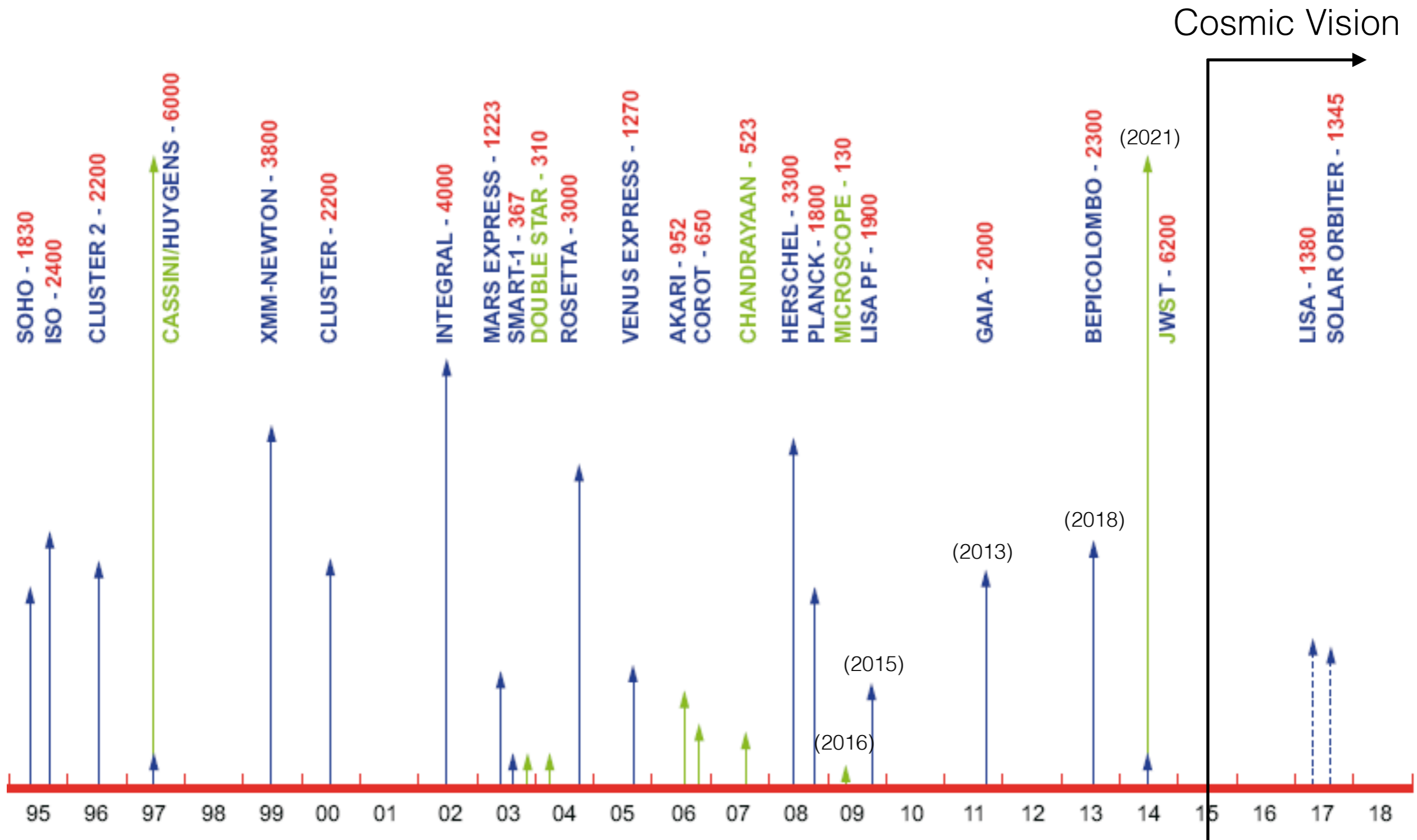




Cosmic Vision 2015-2025

The ESA scientific program

Horizon 2000+ program

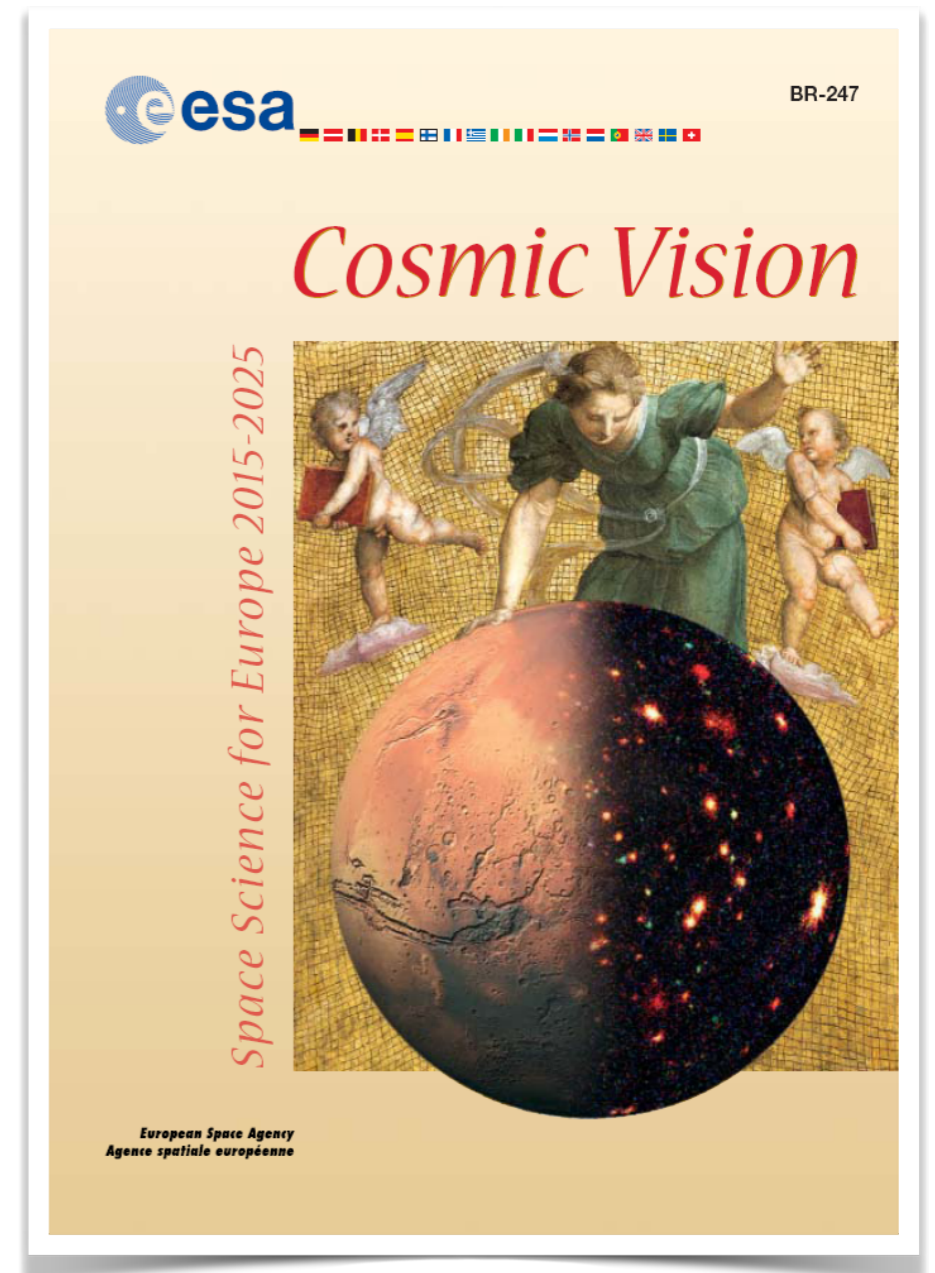


Cosmic Vision

◆ 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

- ◆ Three classes of missions
 - Large missions (~900 M€, ESA contribution)
 - Medium missions (~500 M€, mostly stand-alone)
 - Small missions (~50 M€, ESA contribution)

- ◆ Several calls for mission concepts
 - 2007: one Large (L1, 2022) and two Medium (M1-M2, 2019-2020)
 - 2010: one Medium (M3, 2026)
 - 2012: one Small (S1, 2018)
 - 2013: two Large (L2-L3, 2028-2034)
 - 2015: one Medium (M4, 2028), one Small (S2, 2021)
 - 2016: one Medium (M5, 2032)

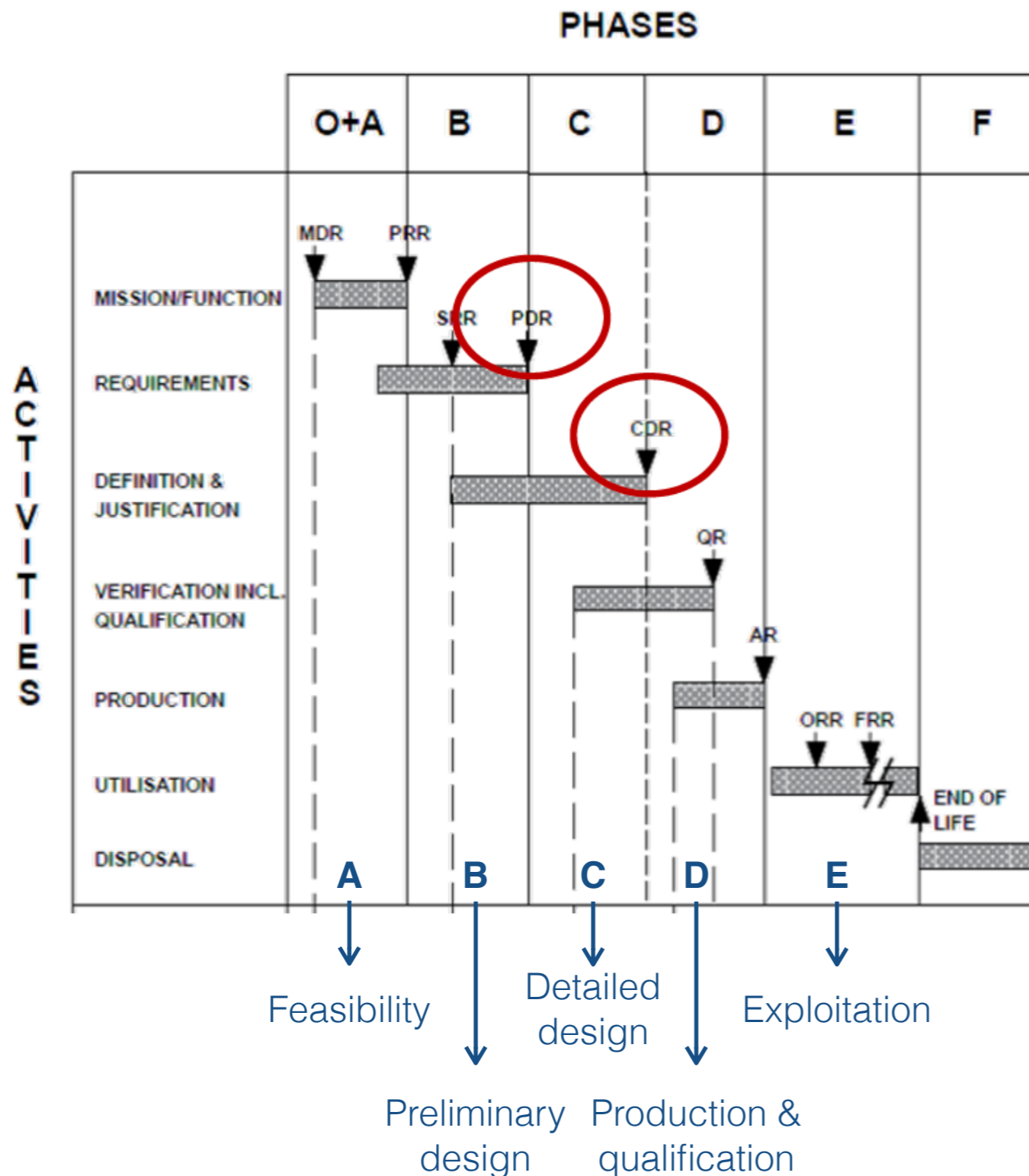
Call for mission #1

(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 \(Sun at high resolution - Horizon 2000+\)](#)

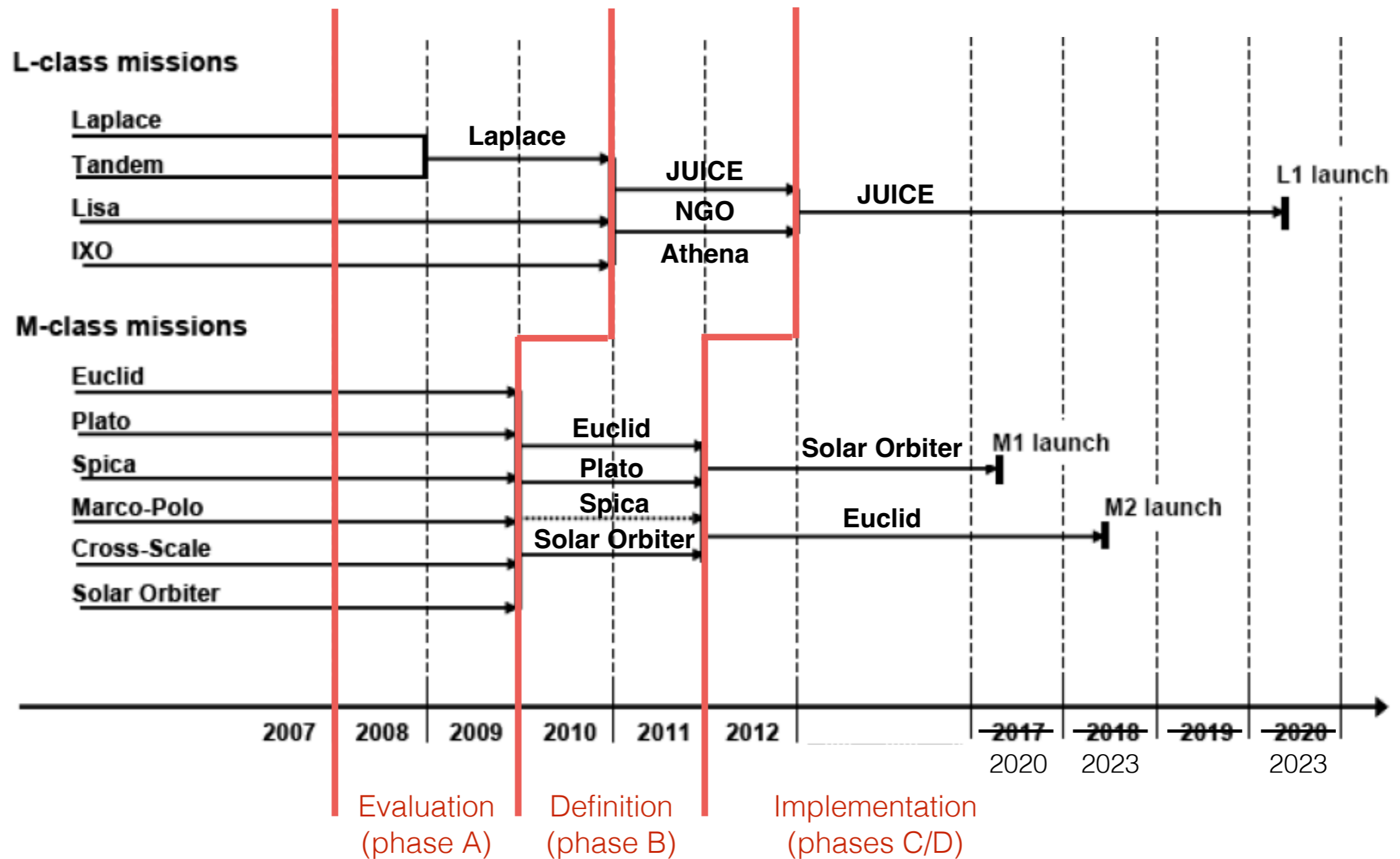
- ◆ 4 L-class missions pre-selected for study (NASA collaboration?)
 - Laplace (Jupiter-Europe system)
 - TandEM (Saturn-Titan-Enceladus system)
 - IXO (X-ray observatory)
 - [LISA \(gravitational waves - Horizon 2000+\)](#)

Phases of a space project



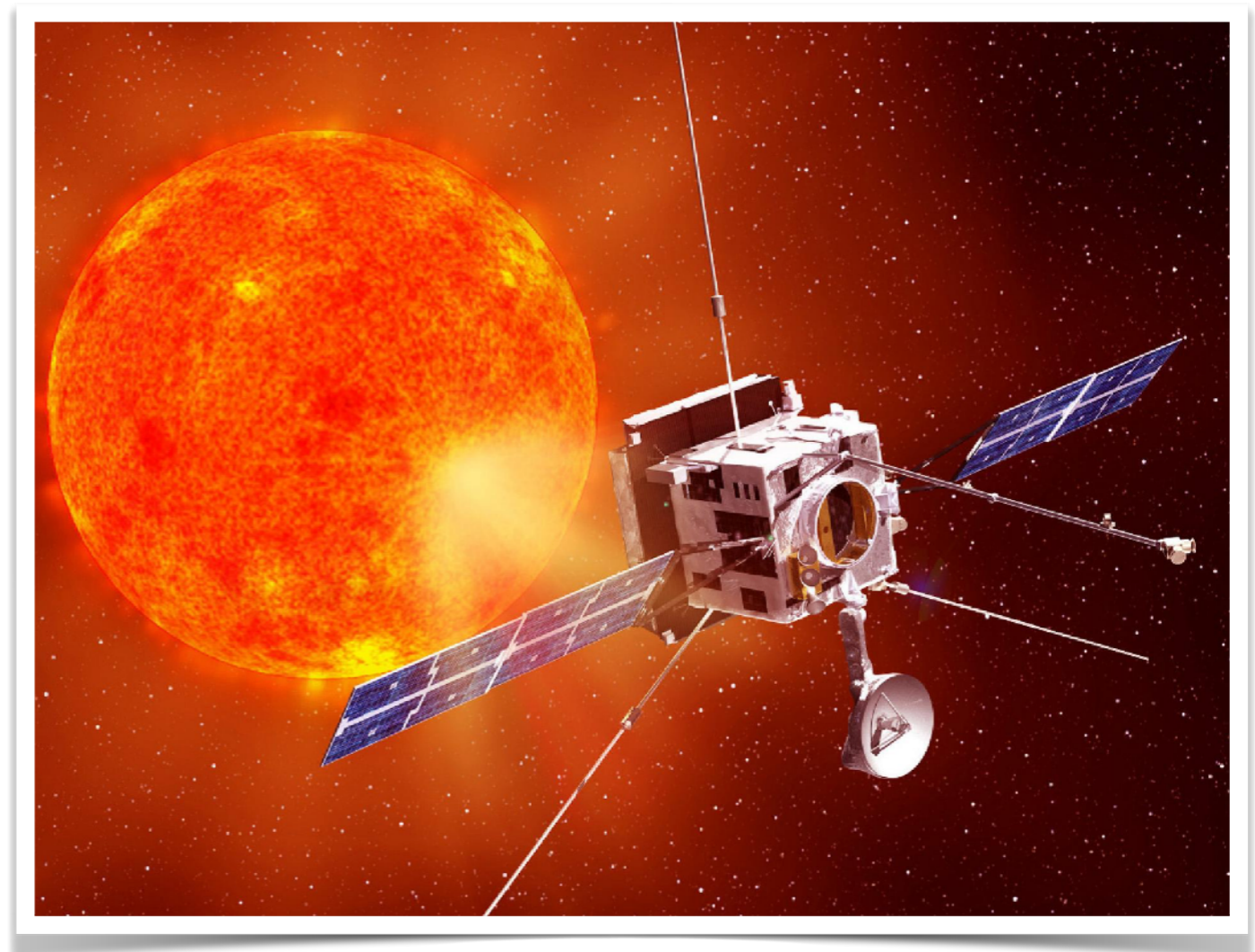
AR = Acceptance Review
 CDR = Critical Design Review
 FRR = Flight Readiness Review
 MDR = Mission Definition Review
 ORR = Operational Readiness Review
 PDR = Preliminary Design Review
 PRR = Preliminary Requirements Review
 QR = Qualification Review
 SRR = System Requirements Review

Selection process



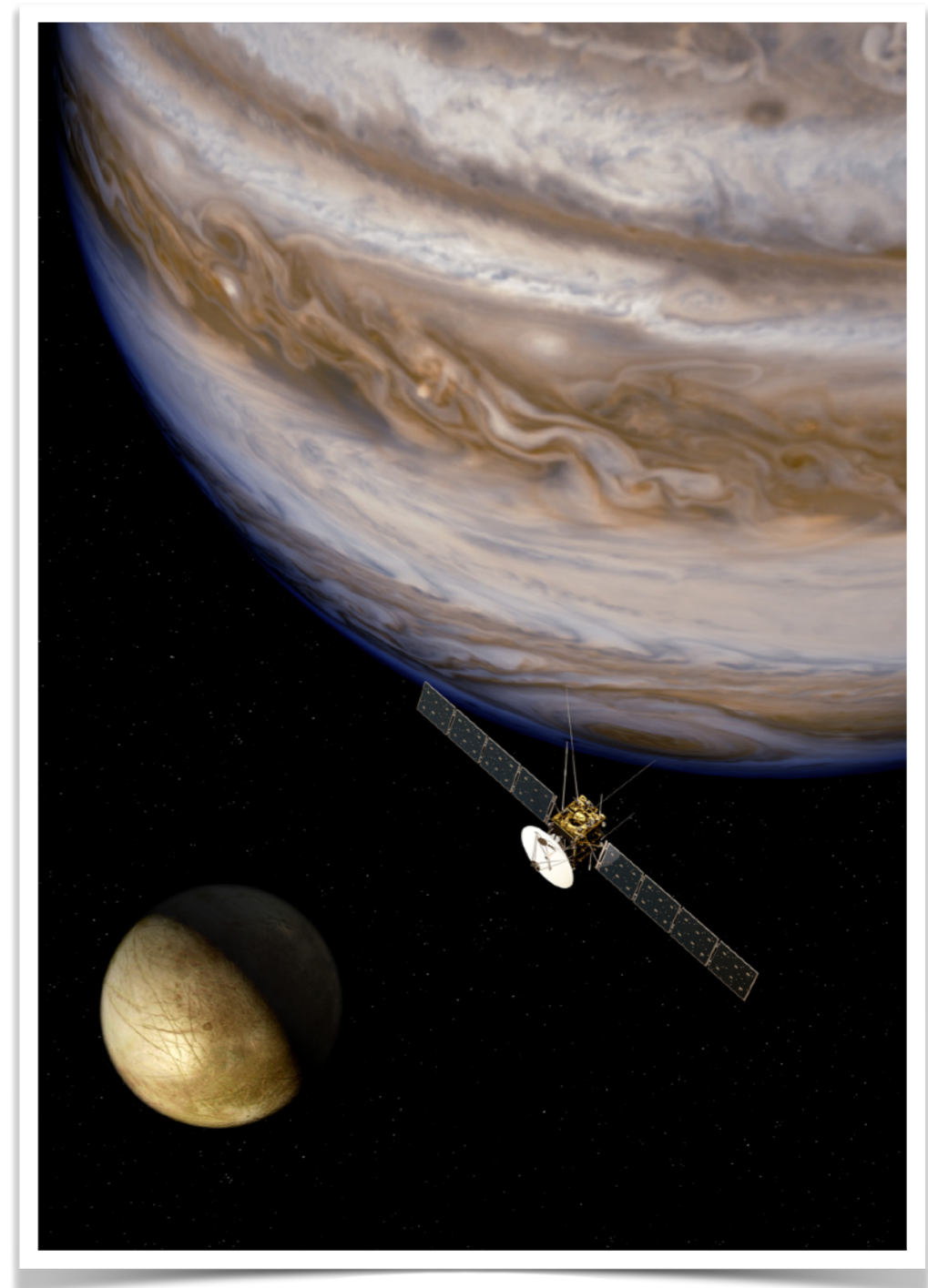
Solar Orbiter

- ◆ 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



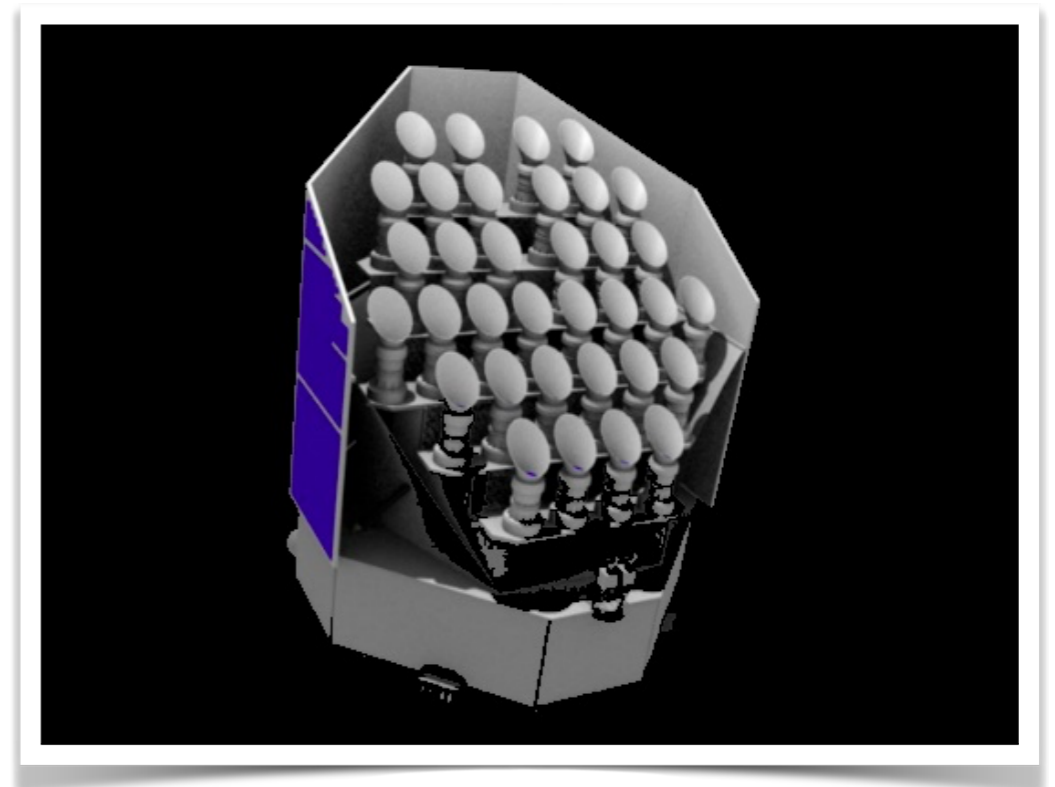
JUICE

- ◆ Mission to the Jupiter icy moons (Ganymede, Europa, Callisto)
- ◆ More challenges
 - power budget and solar panels (97 m²!!!)
 - radiation tolerance (Jupiter magnetosphere)
 - mass budget (10 instruments)
 - orbital dynamics (flybys)
 - communications
 - planetary protection (sterilization)



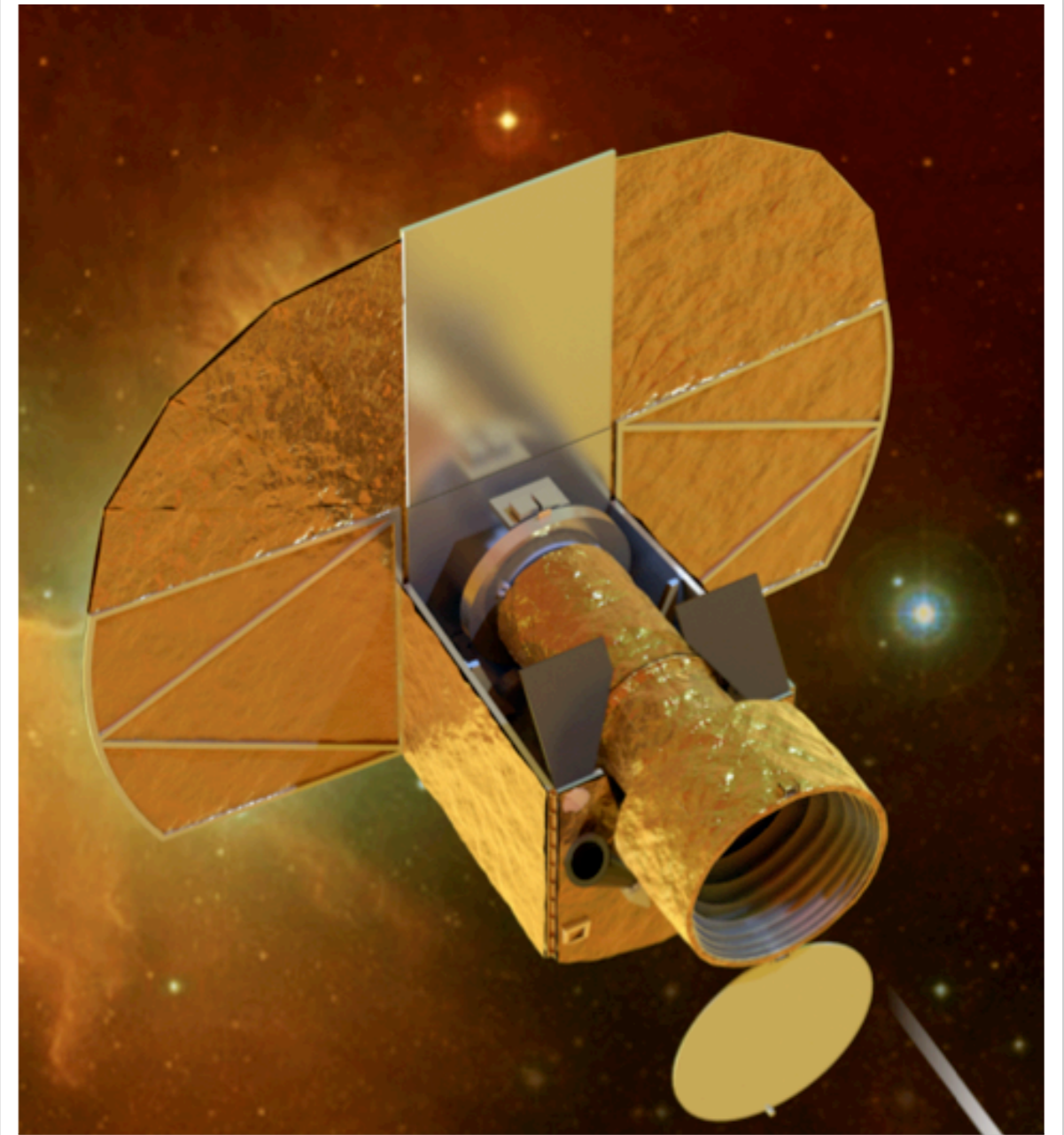
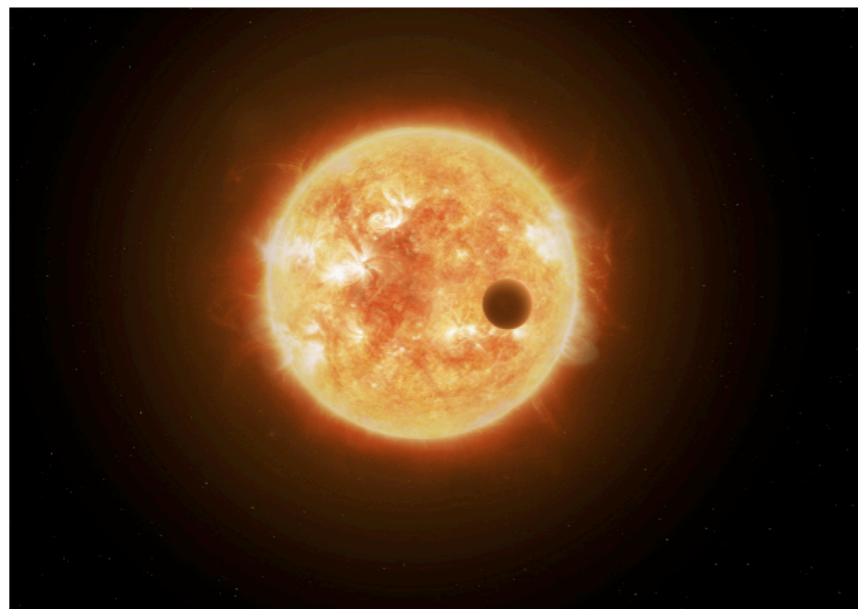
Call for mission #2 (M3)

- ◆ 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)

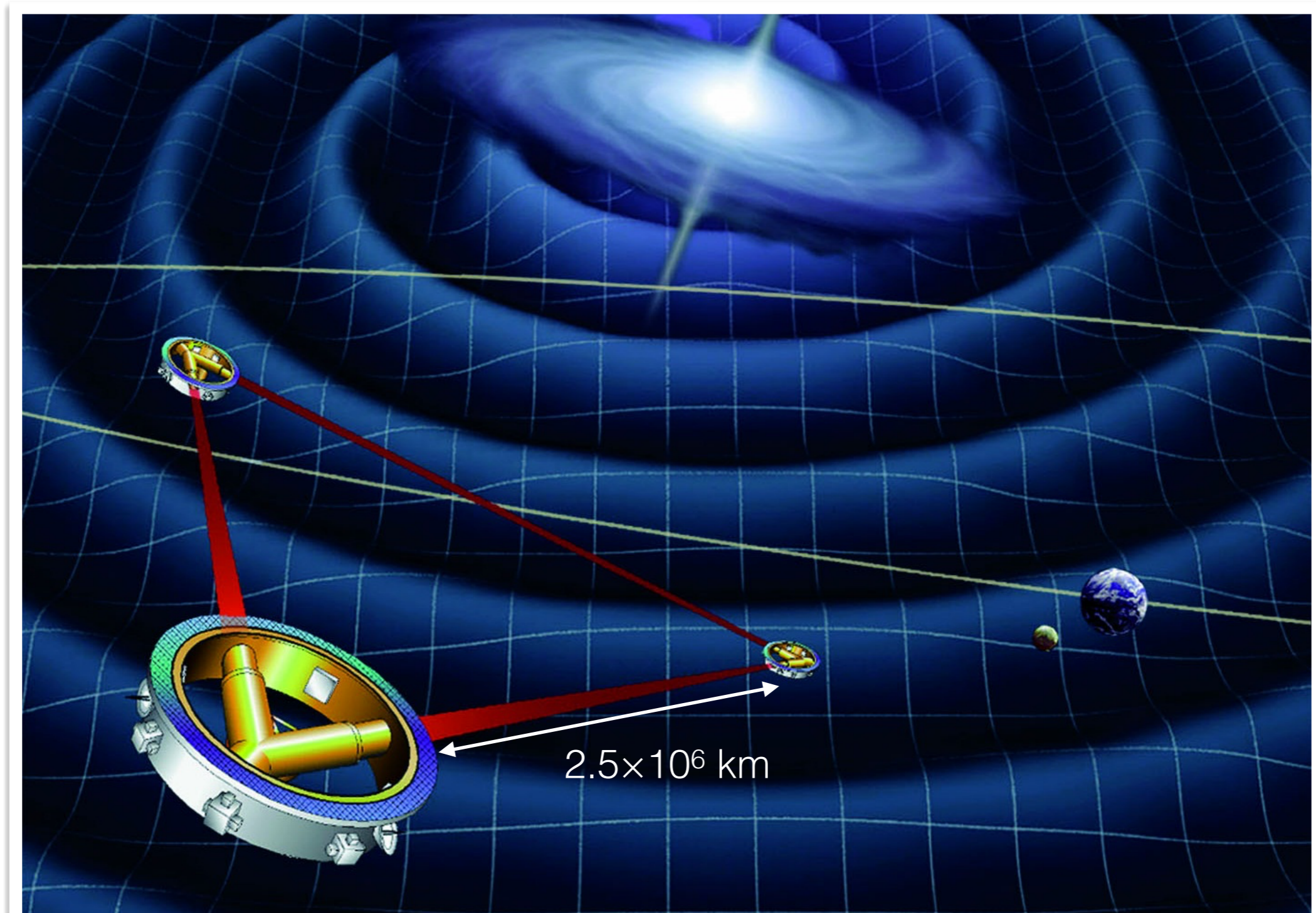
- ◆ Cost to ESA: 50 M€
- ◆ Max total cost: 150 M€
- ◆ 26 proposals submitted
- ◆ CHEOPS selected
- ◆ Launched in Dec 2019



L2 & L3 missions

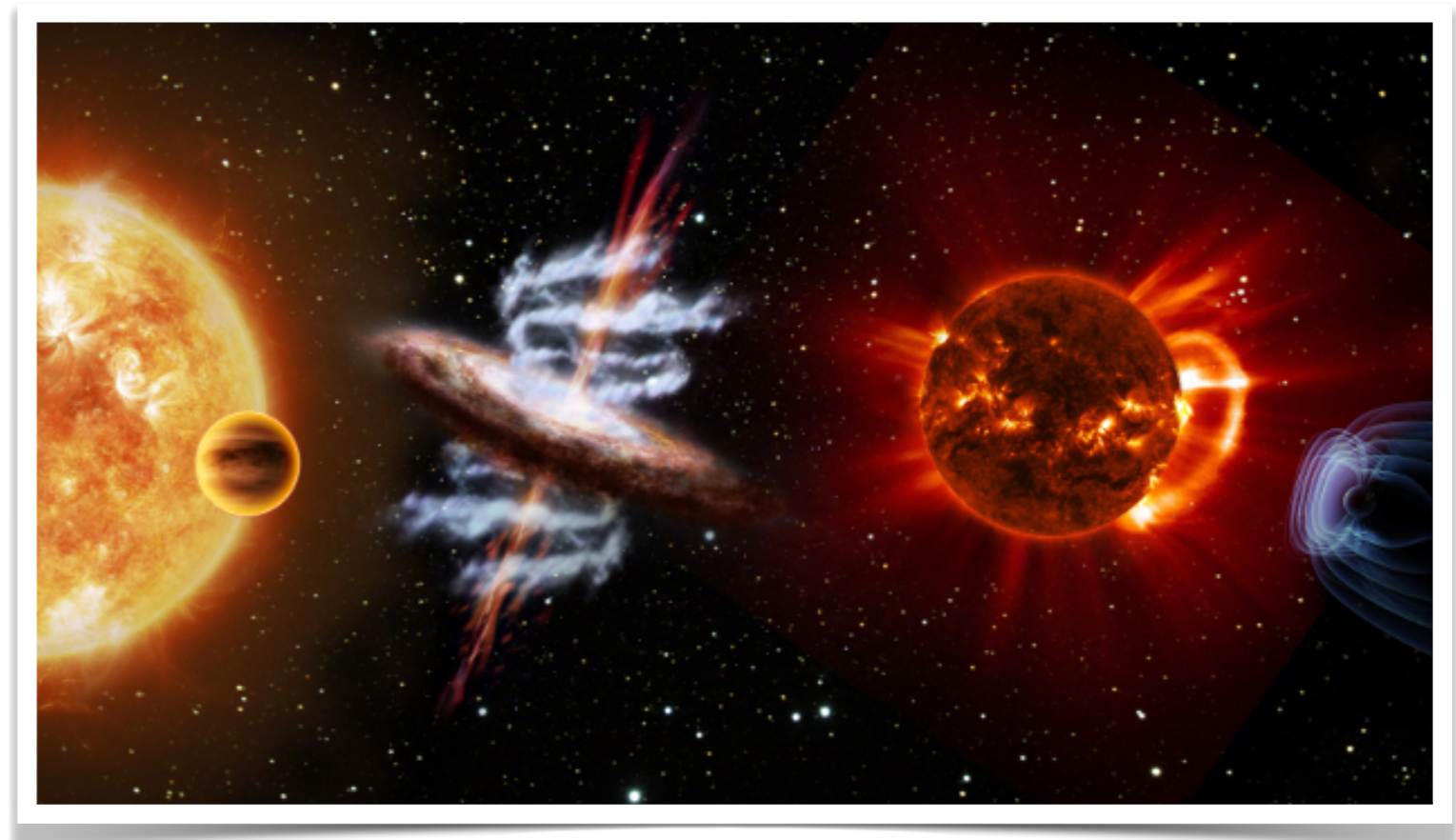
- ◆ Themes selected by ESA working groups in 2013
 - L2: the hot and energetic universe (2035)
 - L3: the search for gravitational waves (2037)
- ◆ L2 mission concept selected in 2014: ATHENA (Advanced Telescope for High Energy Astrophysics)
- ◆ L3 mission concept confirmed in 2017: LISA (Laser Interferometer Space Antenna)
 - does not rely on electromagnetic radiation any more!

LISA: gravitational waves



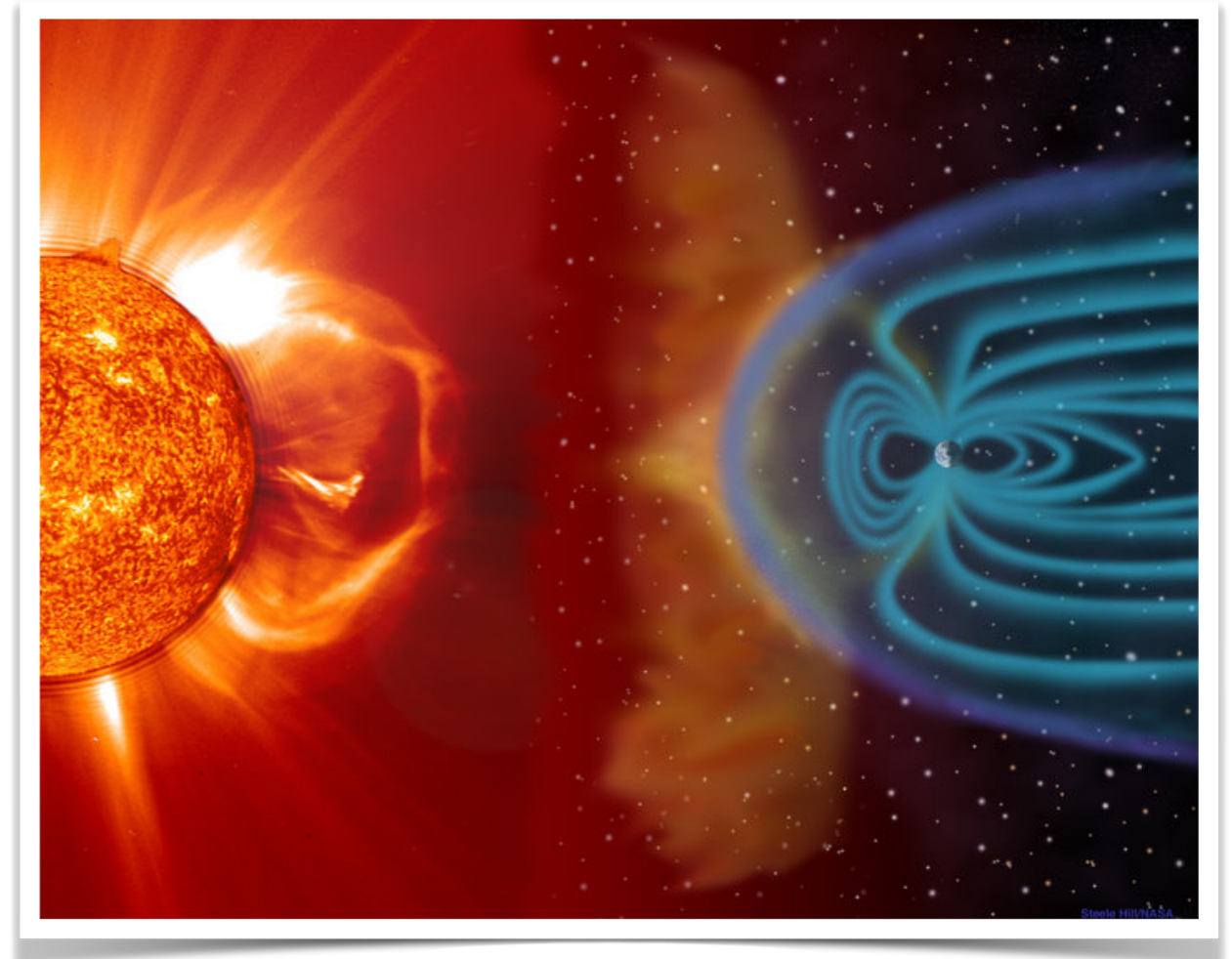
Call for Missions #4 (M4)

- ◆ Three (out of 27) candidates selected in June 2015
 - ARIEL: Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (\approx 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



Latest call: M5

- ◆ Call released in April 2016
- ◆ Selection of missions for study: May 2018
 - ~~SPIGA: far-infrared telescope~~
 - THESEUS: γ -ray / X-ray telescope
 - EnVision: Venus orbiter
- ◆ Phase A completed in 2021, leading to selection of EnVision. Now entering Phase B (preliminary design).
- ◆ Planned launch date: 2032

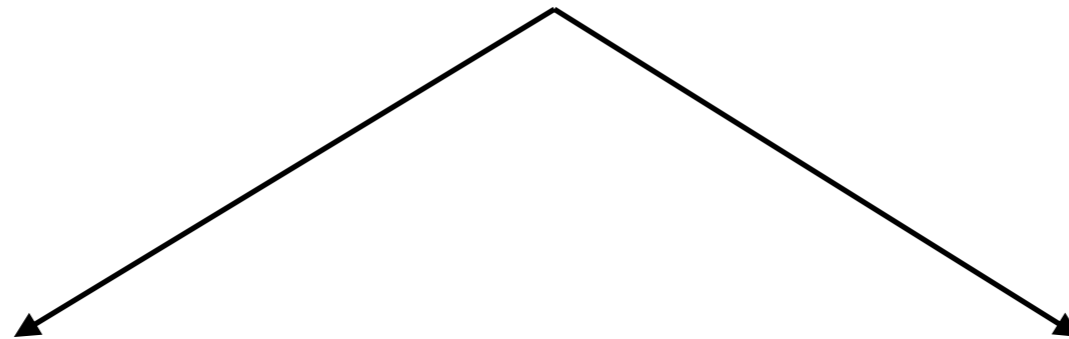
Next program: Voyage 2050

- ◆ Top priorities for large missions already identified:
 - moons of the giant planets (habitability)
 - from temperate exoplanets to the Milky Way (rocky planets)
 - 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: Michaël De Becker <michael.debecker@uliege.be>