

Astronomy satellites

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Self-study material for “Covid Autumn 2020”

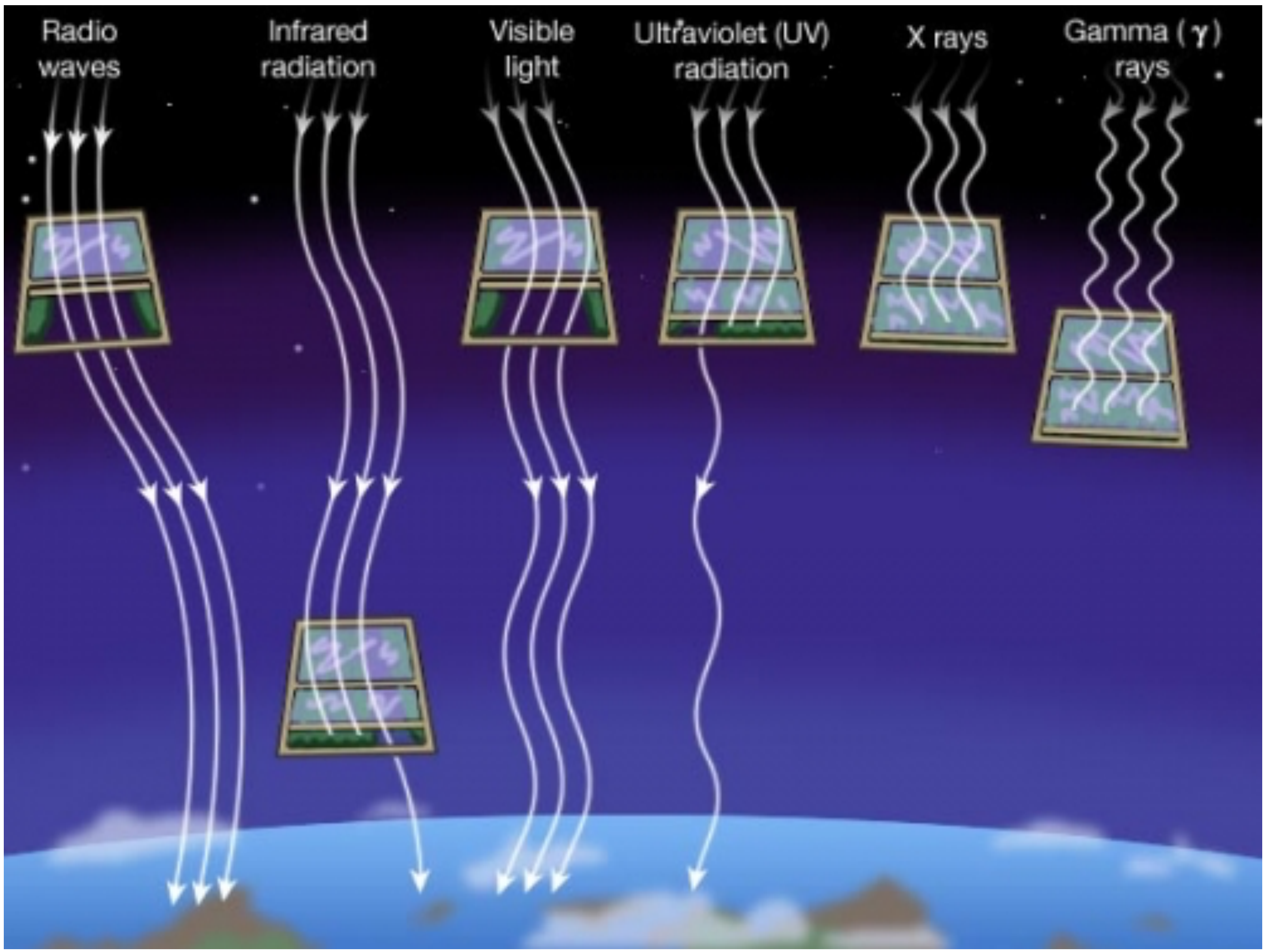
- This pdf is based on my original lecture slides of lecture “Astronomical space missions” for this course, complemented with explanatory text and additional new notes pages.
- Go through them in chronological order. With the very last slide you can check if you learned the main goals of this lecture. If not, go through them again!
- The aim is **not** to teach you a list of satellite names and launch years by heart, even though I give some such lists, but to give you an overview of the developments of satellites operating in various energy domains: what was possible at that time (in terms of instrument development), what were the scientific expectations, and what were the major breakthroughs and new findings.
- Through this material you should get an idea of what is (and especially, has been) possible, but also that satellite missions practically always are compromises -- but even so, they almost always produce unexpected new scientific breakthroughs.
- The focus of this lecture is in the past missions. Some coming lectures will address future missions.

Astronomy vs. space science

- Space science typically includes Earth-observing satellites and fundamental physics missions.
- Especially fundamental physics goals are often linked to astronomy.
- No clear division, but astronomy mission can be defined as "telescope in space looking somewhere else than towards the Earth".
  Also, planetary missions are often excluded (and in this lecture).
- European Space Agency ESA's own division:
  Astrophysics / Planetary / Solar-Terrestrial / Fundamental physics missions.
  Expert working groups in each category independently make recommendations on the choice of missions, mission extensions, etc. – Astronomy Working Group (AWG) for the astrophysics missions.

Electromagnetic spectrum

Wavelength gets shorter from radio towards gamma-rays, with higher energy.
The atmosphere does not let through all radiation from the space but blocks some of it totally, some partly.
The range of wavelengths that passes through the atmosphere is called a “window”.



Notes page: Electromagnetic spectrum

In astronomy, the optical wavelength range was historically important, because the human eye is sensitive to optical light and thus also the first instruments (optical telescopes) were developed basically just to “see” better. But also because the atmosphere does not block visible light it was possible to see light emitting objects in space from ground. So, actually optical astronomy was born because of these two fortunate coincidences!

Nowadays we know that also all the other wavelength ranges are important for astronomy, and practically all objects or at least subtypes of objects emit radiation at several wavelength domains or even across the whole electromagnetic spectrum. So, in order to understand the “big picture”, we need to study all objects using a wide variety of instruments, operating on many different wavelength ranges.

In addition to the visible light, the atmosphere lets through most of the radio emission in the wavelength range of some tens of metres to several millimetres (the ionosphere, in turn, prevents observations of radio waves longer than ≈ 30 m).

At shorter radio wavelengths, the millimetre and submillimetre domain, the atmosphere blocks some wavebands due to water vapour and oxygen, and the shorter radio wavelengths in general are more severely affected by water vapour: humidity and clouds. This is why many submillimetre telescopes are located on mountain tops (as, also, many optical telescopes, to increase the chances of clear skies and low water vapour content).

Most of the infrared spectrum is absorbed by atmospheric gasses and are best observed from space (with some infrared windows being observable from mountain top telescopes).

Ultraviolet light, X-rays and gamma-rays are blocked by the upper atmosphere and can not be observed from the Earth. This is naturally fortunate for all living organisms, because the high-energy radiation is harmful for them. This means, however, that in order to observe those wavelength domains, instruments need to be sent to the very highest atmospheric layers in balloons, sounding rockets, etc., or to be placed into space onboard satellites. The reason why X-ray astronomy and gamma-ray astronomy are still relatively new fields, at least compared to optical astronomy, is twofold: Even when X-rays were already known in physics and used in medicine, nobody realised that astronomical objects could actually emit X-rays. And when such hypotheses started to emerge, placing instruments above the atmosphere to observe them was elaborate, expensive, and time consuming.

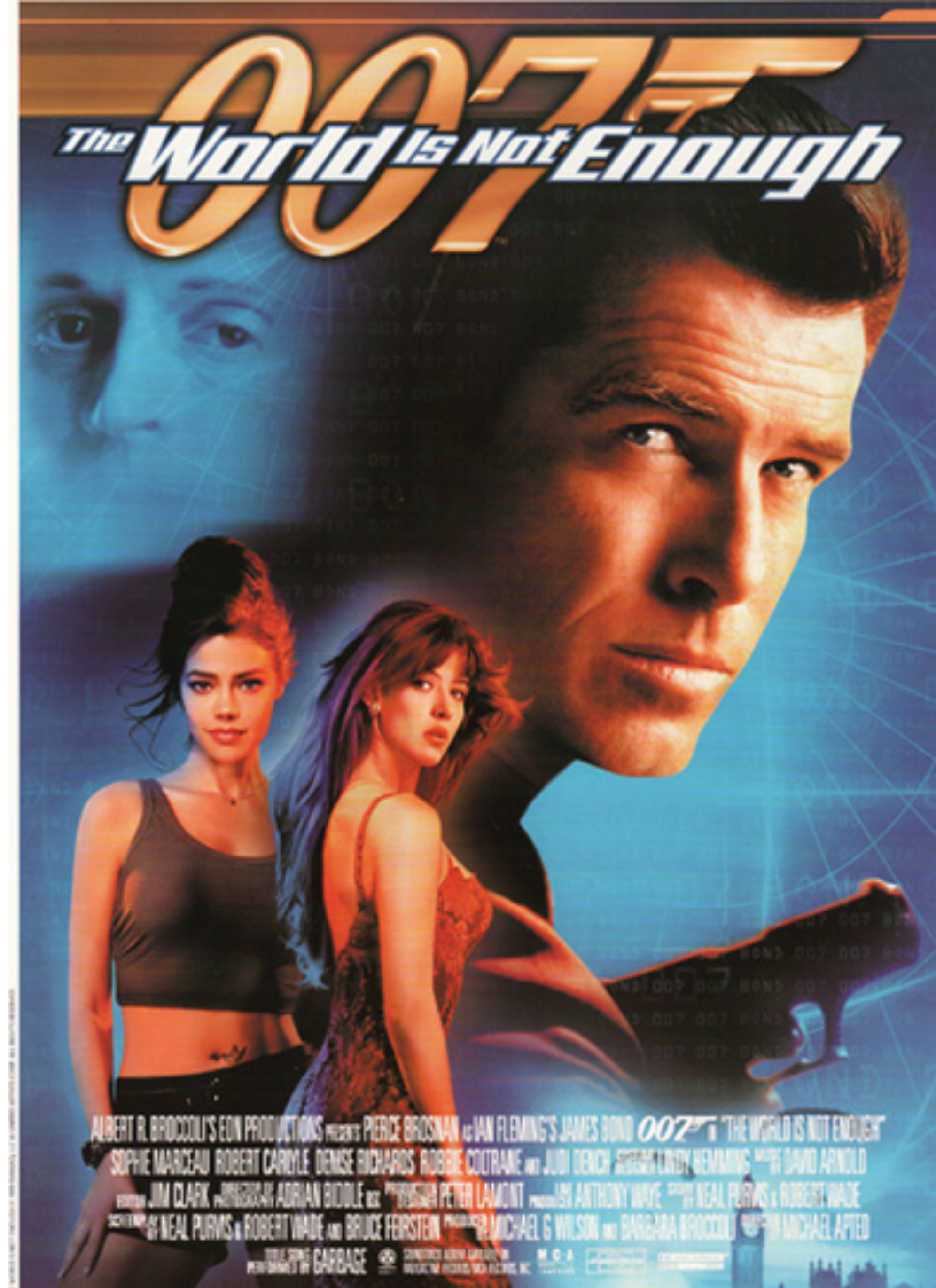
Nowadays astronomers are very agile in using data and instruments at any wavelength range to meet their science goals, even though the design and operation of instruments in the different energy domains varies so much that most astronomers can never be true experts of all wavelength regions. Typically we initiate wider collaborations to include experts of several energy domains to optimally combine forces in doing research, sometimes forming very large research collaborations.

- Gamma-ray*), X-ray, ultraviolet and parts of infrared and submillimetre to microwave wavelengths can only be observed from space (or sounding rockets or high-flying balloons).
  - Sounding rockets are low-cost, require only relatively short planning times, and can use also temporary launching sites. But their flight times are short, less than 30 minutes, often much less. They are most optimally used as test beds for equipment that will finally be onboard more expensive and more risky orbital spaceflight missions.

  *) Exception: Highest-energy gamma-rays (TeV energies) are observed from the Earth by the Cherenkov mechanism that makes a gamma-ray photon to undergo interactions that create energetic photons that can finally be observed as Cherenkov radiation that is detected as flashes of light by using large telescopes consisting of multiple mirror segments and detectors.

- Other wavelength domains are observable from Earth (ground, mountain top, in extreme cases balloons), but space environment is more stable. Sometimes already the choice of satellite orbit brings huge benefits to the desired observations (see slides about orbits towards the end of the lecture).

... That’s why for astronomers
”The World Is Not Enough”!

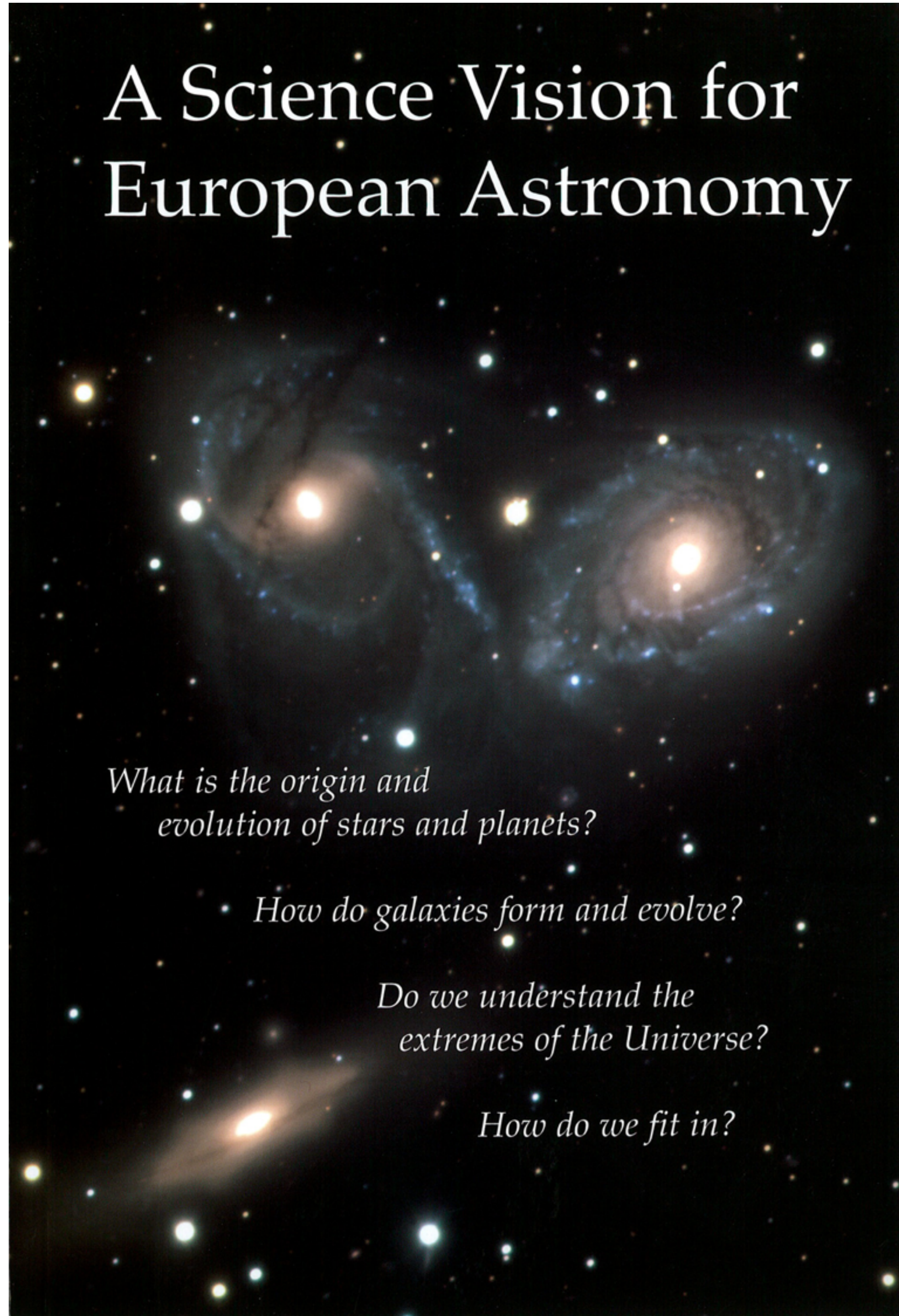


The World Is Not Enough

Space astronomer’s dilemma

- Discovery potential is huge,
  but we don’t often know exactly what to look for.
  - If we only ask for the type of observations that we know will give us results, we are building on existing results (incremental science). This is also useful and indeed also important, but the biggest breakthroughs and totally new findings can go undiscovered then.
  - It would be tempting to dream big and take risks.
- Building instruments is expensive and time-consuming, and their specifications/requirements need to be fixed years ahead of the operation.
  - Often lack of funding/time/manpower means relaxing the requirements during the process. Plans are made for technologies that are not fully developed, sometimes not even existing yet. Sometimes instruments or even missions are merged and compromises are made that way.
  - But also counterexamples exist: Planck satellites 70 GHz receiver (made in Finland!) outperformed specifications and exceeded all expectations!
- Convincing funding agencies to let us build instruments “as good as we possibly can” is difficult!

Thinking Big



… but resources are limited

When planning a space mission,
we are often required to keep the focus relatively narrow.
This means that we have to make choices and prioritise,
and the desired science goals do not always match the reality.

Two main types of missions

Observatory	**Survey**

Can use many different kinds of instruments.

Observatory: Individual scientists can apply for observing time for targeted sources.

Survey: Fixed observing strategy. Often a closed consortium.

Data released to public after proprietary period.

Survey: Sometimes (some) data released almost real-time, but may require strenuous processing.

Observatory: Example: large modern X-ray missions, Herschel

Survey: Example: Fermi, CMB and astrometry missions

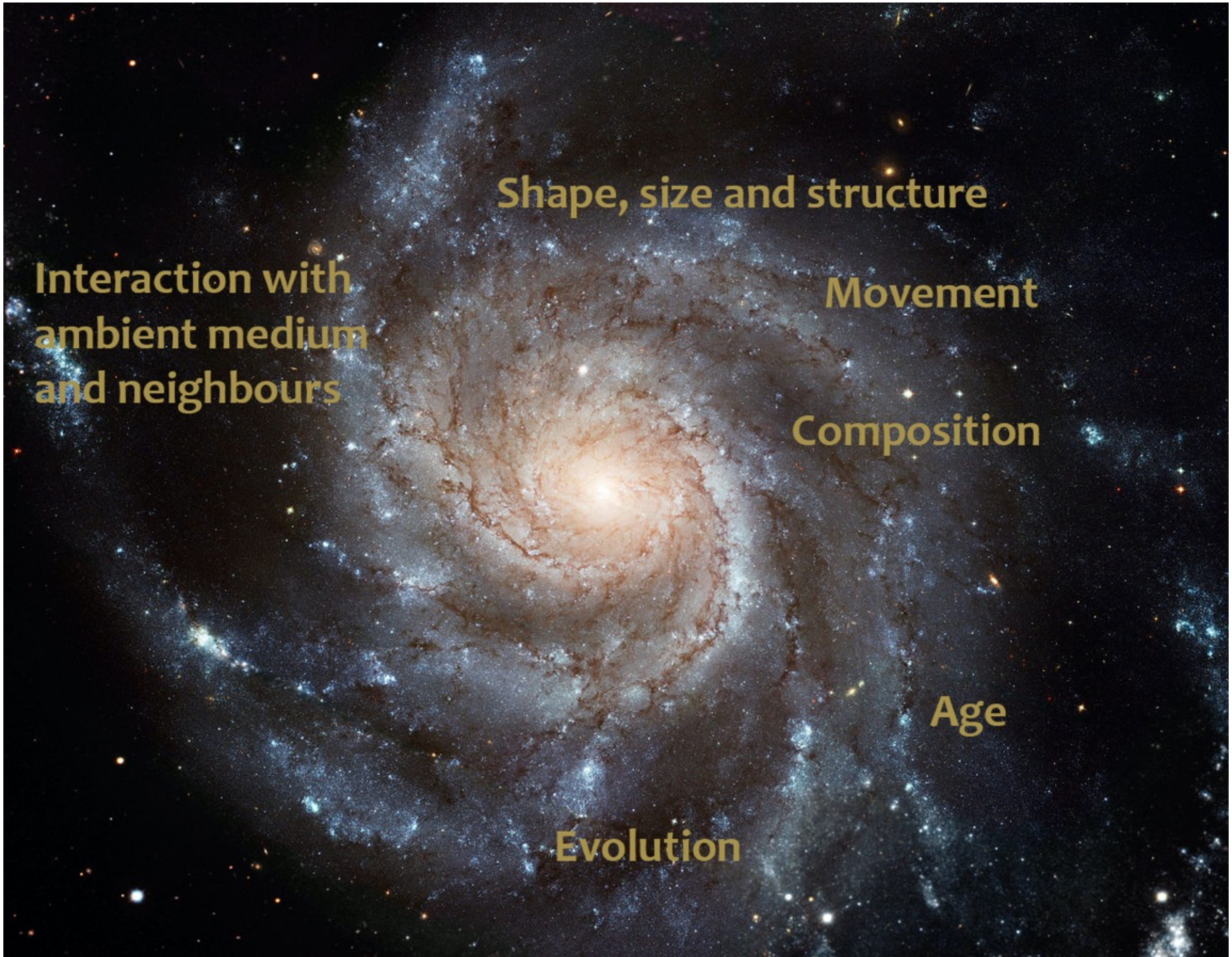
Also hybrids: surveys where observers can request for targeted project in addition to the pre-designed surveys

Detectors: general

- Goal: to determine the direction, time of arrival, energy, and intensity of the incoming photons.
- Imaging vs. spectroscopy vs. timing –
  different needs, different technologies.
- High-energy devices detect individual photons (that can accumulate over time), radio to optical devices collect the flux of the incoming photons.
  Also the wavelength sets limitations:
  at high energies no traditional mirrors or lenses can be used.
- Radio to optical: the direction can be defined fairly accurately, it is limited by the field of view or the beam size.
  At higher energies the position accuracy typically is/was much poorer. This is improving now!

Some examples of burning questions that astronomers wish to study by using satellite instruments

Galaxies


Shape, size and structure
Interaction with
ambient medium
and neighbours
Movement
Composition
Age
Evolution

Notes page: Galaxies

A galaxy is a gravitationally bound system of stars, interstellar gas, dust, and dark matter.

Galaxies are located in a huge range of distances (< 1 Mly to > 10 Gly), so it is easy to understand that our knowledge of the most distant galaxies is much sparser than of the nearby ones. Only the nearest galaxies can be studied in detail; there we can study the actual contents of the galaxies, their supernova remnants etc.

Local Group is the galaxy cluster where our own galaxy, Milky Way, belongs to, along with ca. 50 other galaxies. Even from these galaxies we get updated information with new observing methods and instruments. For example, it was just recently found that the mass of Andormeda Galaxy has probably been overestimated earlier, and this affects the simulations and predictions of the anticipated Milky Way - Andromeda collision (expected to happen in about 4 billion years, so no need to worry about it too much yet!)

From far-away galaxies typically only the brighest phenomena can be studied. With improving instrumentation the situation gradually improves, but there is still a lot to do.

In addition to the wide range of distances, also the sizes and morphologies of galaxies can be very different. They may contain just a few thousand stars, or as many as one hundred trillion (10^{14}) stars. The visual appearance can be of the one of the spiral types, elliptical types, or yet something else, “irregular”. Galaxies can also merge and interact, giving rise to lots of ineteresting phenomena.

Active Galaxies

Notes page: Active Galaxies

Active Galaxies are galaxies that show excess emission from very small volume in their nucleus, powered by supermassive black holes. When we address the central part only, we refer to them as Active Galactic Nuclei (AGNs). Quasars are a well known subtype of AGNs.

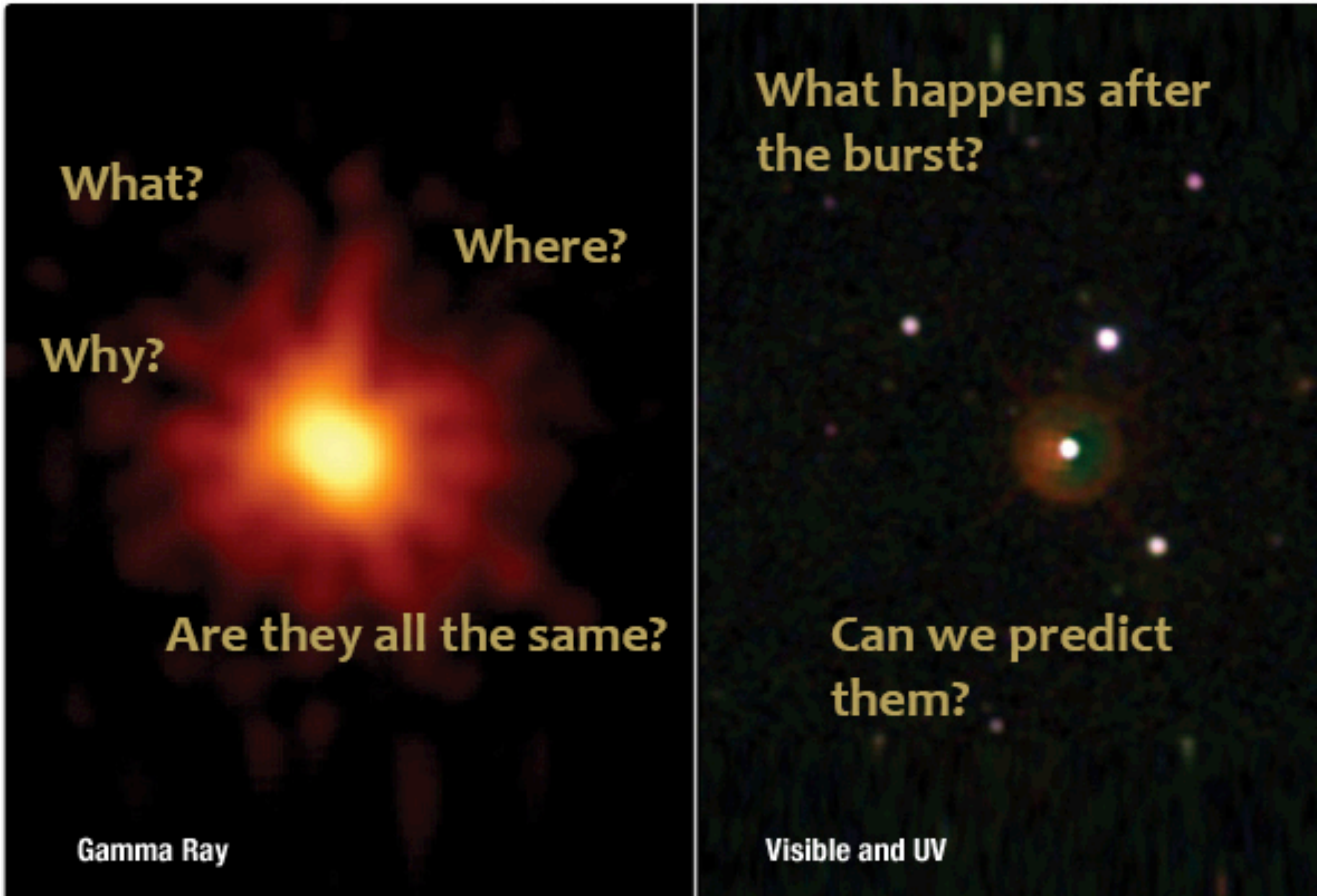
Some can, but not all do, radiate across the whole electromagnetic spectrum.

They can be variable in timescales of hours, days, months, years.

The exact location and mechanism of most of the emission is still not very well known.

Due to their distance and the compact volume of their central engine they appear point-like in single-instrument observations. The host galaxy and its surroundings can, however, be imaged, the spectra of the gas studied, etc.

Gamma-ray bursts (GRBs)



Notes page: Gamma-ray bursts (GRBs)

GRBs were first detected in 1967 by the Vela satellites, a series of satellites designed to detect covert nuclear weapons tests. Hundreds of theoretical models were proposed to explain these bursts in the years following their discovery, such as collisions between comets and neutron stars. Little information was available to verify these models until the 1997 detection of the first X-ray and optical afterglows and direct measurement of their redshifts using optical spectroscopy, and thus their distances and energy outputs. These discoveries, and subsequent studies of the galaxies and supernovae associated with the bursts, clarified the distance and luminosity of GRBs, definitively placing them in distant galaxies. Long GRBs were also connected with the explosion of massive stars.

The intense radiation of most observed GRBs is believed to be released during a supernova or hypernova as a rapidly rotating, high-mass star collapses to form a neutron star, quark star, or black hole. A subclass of GRBs (the "short" bursts) appear to originate from a different process: the merger of binary neutron stars.

The sources of most GRBs are billions of light years away from Earth, implying that the explosions are both extremely energetic and very rare. All observed GRBs have originated from outside the Milky Way galaxy.

Currently, orbiting satellites detect on average approximately one GRB per day.

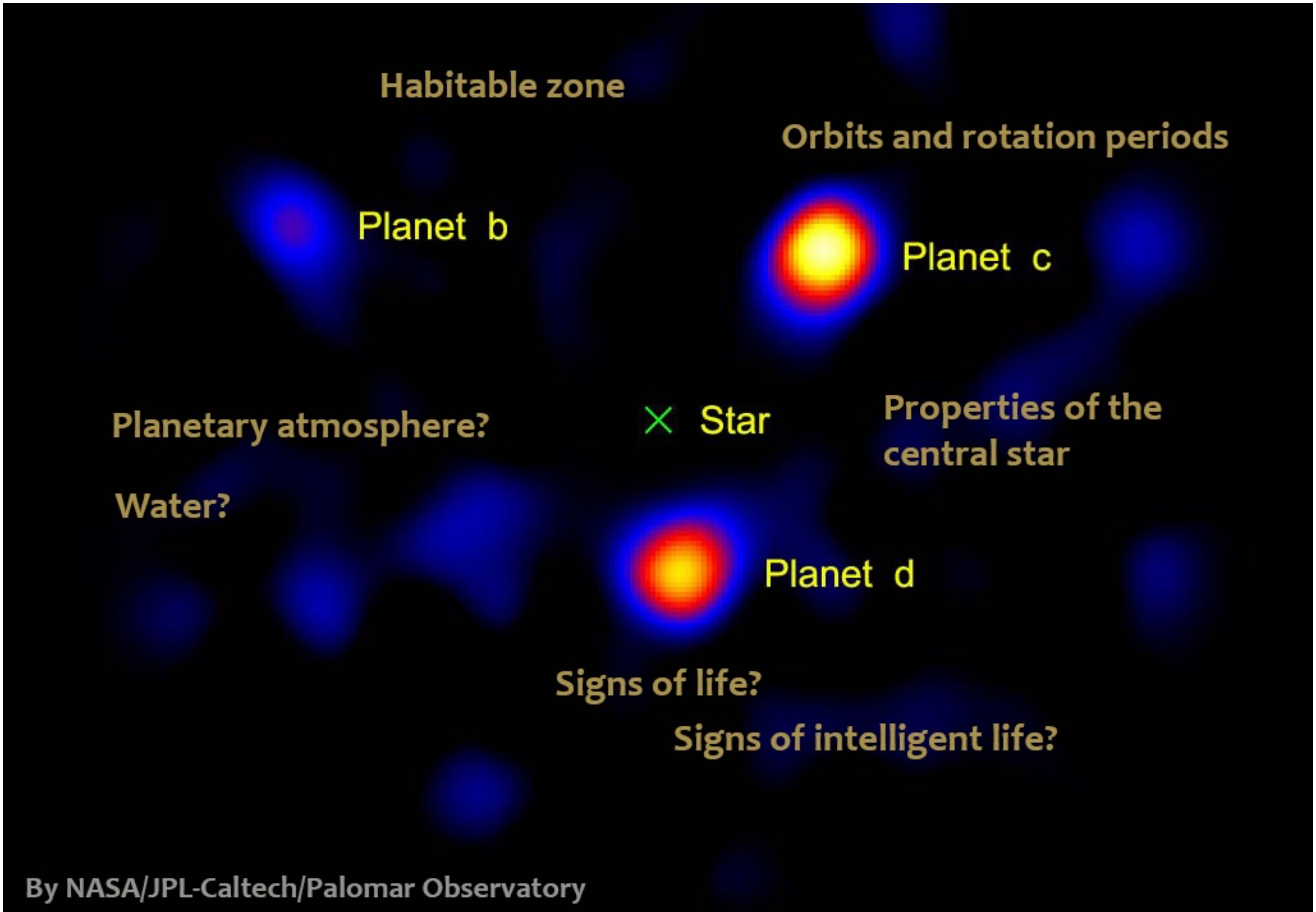
Compact stars

Notes page: Compact stars

X-ray binaries are star systems made up of two parts: a compact stellar remnant -- either a neutron star or a black hole; and a companion star -- a normal star like our Sun. As they orbit one another, the neutron star or black hole pulls in gas from the companion star. This heats the gas to millions of degrees, producing intense X-ray radiation and making these star systems some of the brightest X-ray sources in the sky.

A pulsar is formed when the core of a massive star is compressed during a supernova, which collapses into a neutron star. The neutron star retains most of its angular momentum, and since it has only a tiny fraction of its progenitor's radius, it is formed with very high rotation speed. A beam of radiation is emitted along the magnetic axis of the pulsar, which spins along with the rotation of the neutron star. The magnetic axis of the pulsar determines the direction of the electromagnetic beam, with the magnetic axis not necessarily being the same as its rotational axis. This misalignment causes the beam to be seen once for every rotation of the neutron star, which leads to the "pulsed" nature of its appearance, detected in the radio or X-ray domain.

Extrasolar planetary systems



Notes page: Exoplanets

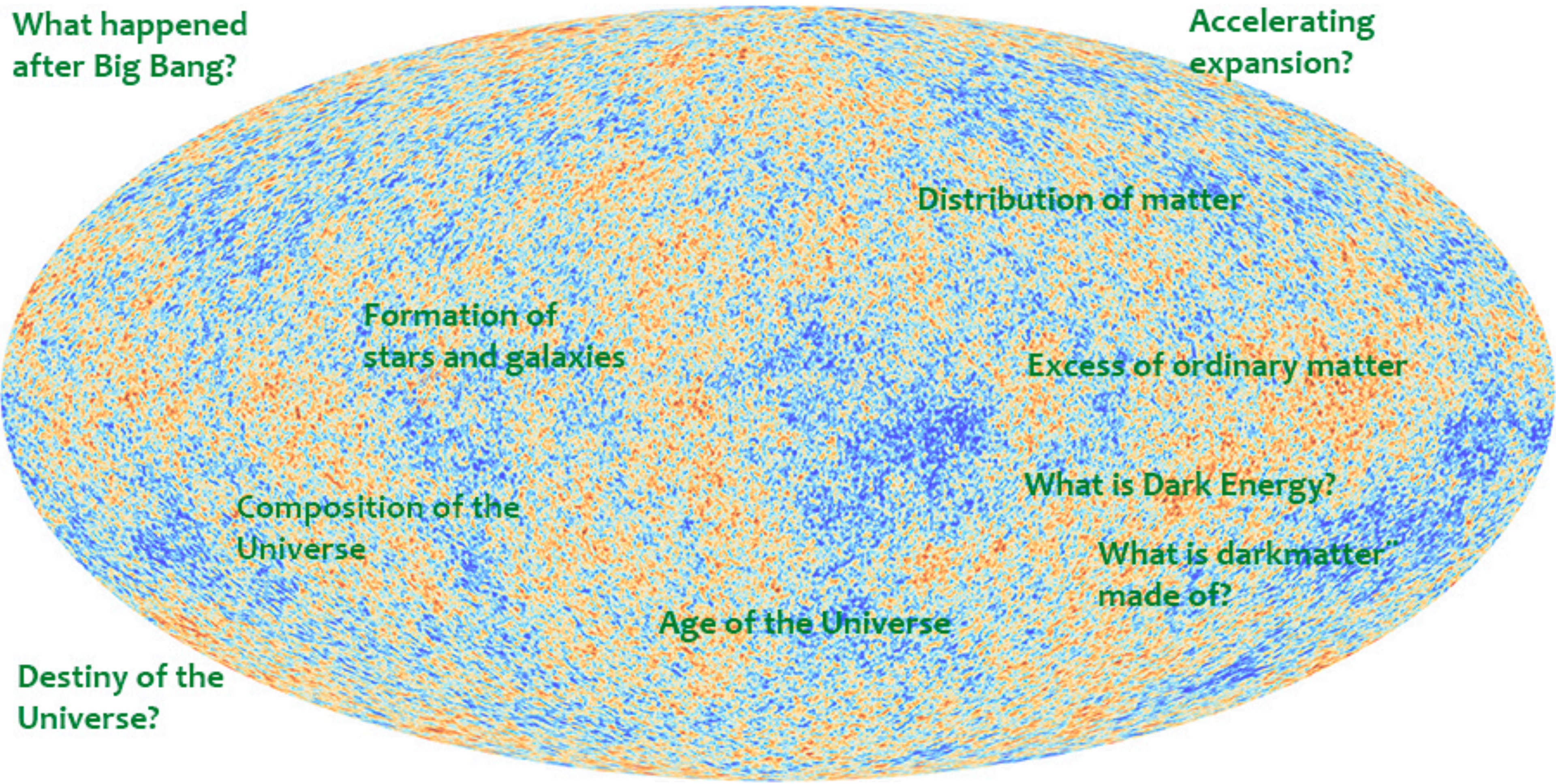
The first confirmed detection of planets outside our own Solar System (= “extrasolar planet” or “exoplanet”) came as late as in 1992, with the discovery of several terrestrial-mass planets orbiting the pulsar PSR B1257+12. The first confirmation of an exoplanet orbiting a main-sequence (“normal”) star was made in 1995, when a giant planet was found in a four-day orbit around the nearby star 51 Pegasi. Some exoplanets have been imaged directly by telescopes, but the vast majority have been detected through indirect methods such as the transit method and the radial-velocity method.
As of 1 October 2020, there are 4354 confirmed exoplanets in 3218 systems, with 712 systems having more than one planet.

The Kepler space telescope (was operational 2009-2018) found more than two thousand exoplanets. Kepler has also detected a few thousand candidate planets, of which a large fraction may be false positives; the confirmation of these results is still going on.

On the previous slide there are three known planets of the star HR8799, as imaged by the Hale Telescope. The light from the central star was blanked out by a vector vortex coronagraph. HR 8799 is a roughly 30 million-year-old main-sequence star located 129 light years (39 parsecs) away from Earth in the constellation of Pegasus. It has roughly 1.5 times the Sun's mass and 4.9 times its luminosity. It is part of a system that also contains a debris disk and at least four massive planets. These objects are near the upper mass limit for classification as planets; if they exceeded 13 Jupiter masses, they would be capable of deuterium fusion in their interiors and thus qualify as brown dwarfs.

Scientists are especially interested in the atmospheric composition of exoplanets, because the main driver is to search for Earth-like, habitable, or even life-carrying exoplanets. In general, the presence of oxygen in the atmosphere is considered to be an indication of life on an exoplanet, and the presence of liquid water on the surface is considered to be a requirement for life to be able to emerge.
Some milestones:
2001: sodium was detected in the atmosphere of HD 209458 b.
2008: water, carbon monoxide, carbon dioxide and methane were detected in the atmosphere of HD 189733 b.
2013: water was detected in the atmospheres of HD 209458 b, XO-1b, WASP-12b, WASP-17b, and WASP-19b.
2014: NASA reported that HAT-P-11b is the first Neptune-sized exoplanet known to have a relatively cloud-free atmosphere and, as well, the first time molecules of any kind have been found, specifically water vapor, on such a relatively small exoplanet.

Cosmic Microwave Background (CMB)



Notes page: CMB

The Cosmic Microwave Background (CMB) is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380000 years old. This is when photons started to travel freely through space rather than constantly being scattered by electrons and protons in plasma. The photons that existed at the time of this photon decoupling have been propagating ever since, though growing fainter and less energetic, since the expansion of space causes their wavelength to increase over time. Now they are observed in the microwave domain and the temperature of CMB is at ≈ 3 K.

The image on the previous page is a combination of numerous scans, unfolded to a galactic coordinate projection but with the plane of the Milky Way removed from the signal. The colours represent the tiny temperature fluctuations from the average signal and thus the deviation in matter densities. The tiny temperature fluctuations that correspond to regions of slightly different densities represent the seeds of all future structure: the stars and galaxies of today. If the image showed a totally even colour across the sky, everything would be at a constant temperature (a perfect black body spectrum), and no denser regions such as galaxies could exist.

Especially at high energies,
there was very little prior knowledge!

Evolution of high-energy missions in a nutshell ☺

- “Can we detect something?”
- “Wow, at least some objects XYZ can be detected at least sometimes. Can we learn more about them?”
- “There is a population of objects XYZ that can be detected. We want to monitor them for variability!”
- “We need better sensitivity”
- “We need better position accuracy”
- “We need a long lifetime”
- “We need better sky coverage”

- **Decades have passed, but there is still a lot to achieve!**

Gamma-rays

- **Note: a later lecture will focus on gamma-ray missions! This is just a general overview, along with other astronomy missions!**

- A very new field of astronomy compared to other wavelength ranges!
- 1950's: theoretical suggestions that some astronomical objects can produce gamma-ray emission.
- Cosmic ray interactions with interstellar gas, supernova explosions, and interactions of energetic electrons with magnetic field.
- First detectors were placed on balloons (above most of the atmosphere).

Gamma-rays

- $E > 100$ keV, $f > 10^{19}$ Hz, $\lambda < 10^{-11}$ m
  - Terrestrial vs. astronomical definitions somewhat different!
  - In astronomy the energy range matters, does not have to be from radioactive decay.
- Ionizing radiation (hazardous), but we are protected by atmosphere →
  γ-ray astronomy must be carried out from space.
- Energetic radiation from energetic or very hot objects.
  - Very few objects are so hot → mostly non-thermal radiation.

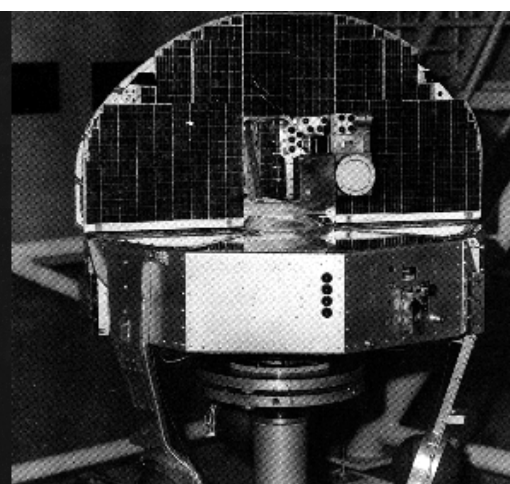
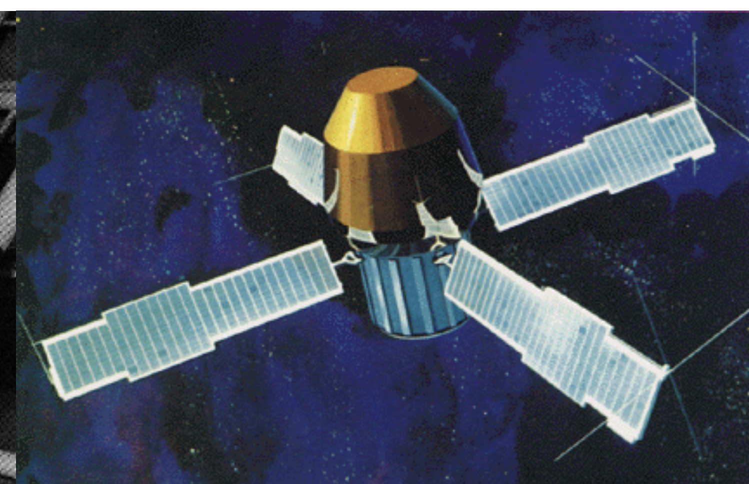
Gamma-ray detectors

- Due to the very short wavelength, mirrors or lenses can not be used for detectors.

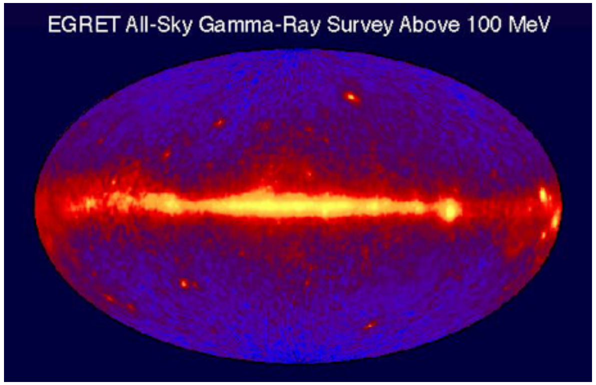
1. "Collect as many photons as possible from the direction of the target source."
   → scintillators, solid-state detectors (pretty much like in X-ray astronomy).
2. "Follow gamma-ray interaction within the detector"
   → Compton-scatter devices, pair devices

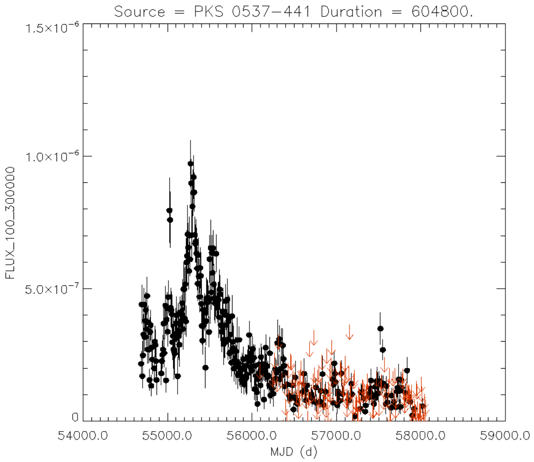
   The energy range and science goals
   determine the detector type.

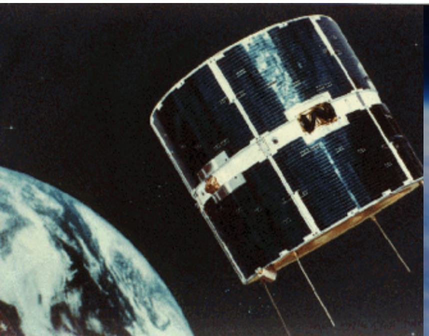
- The very first satellite capable of gamma-ray observations: Explorer 11 in 1961.
  - 31 gamma-ray events; no particular direction.
- 1967 Orbiting Solar Observatory (OSO) 3:
  cosmic gamma-ray (> 50 MeV) sky survey instrument
  - Cosmic gamma-rays from galactic and extragalactic sources
- 1972 Small Astronomy Satellite (SAS) 2:
  20-300 MeV gamma-ray observations
  - Geminga pulsar

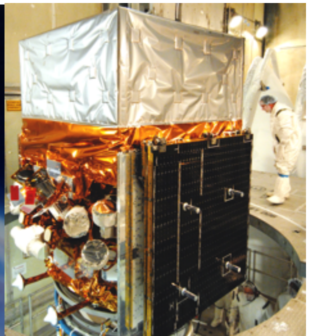




- COS-B 1975-1982: confirmed earlier discoveries and produced several new ones.
  2CG Catalogue of 25 sources, and a map of the Miky Way.
- Compton Gamma-Ray Observatory (CGRO) 1991-2000:
  The first all-sky survey above 100 MeV
  Position accuracy still poor
  - 271 sources, 170 unidentified
- Fermi gamma-ray space telescope
  2008-ongoing:
  good position accuracy, good sensitivity, continuous flux curves









X-rays

- **Note: A later lecture will focus on X-ray missions!**
  This is just a general overview.

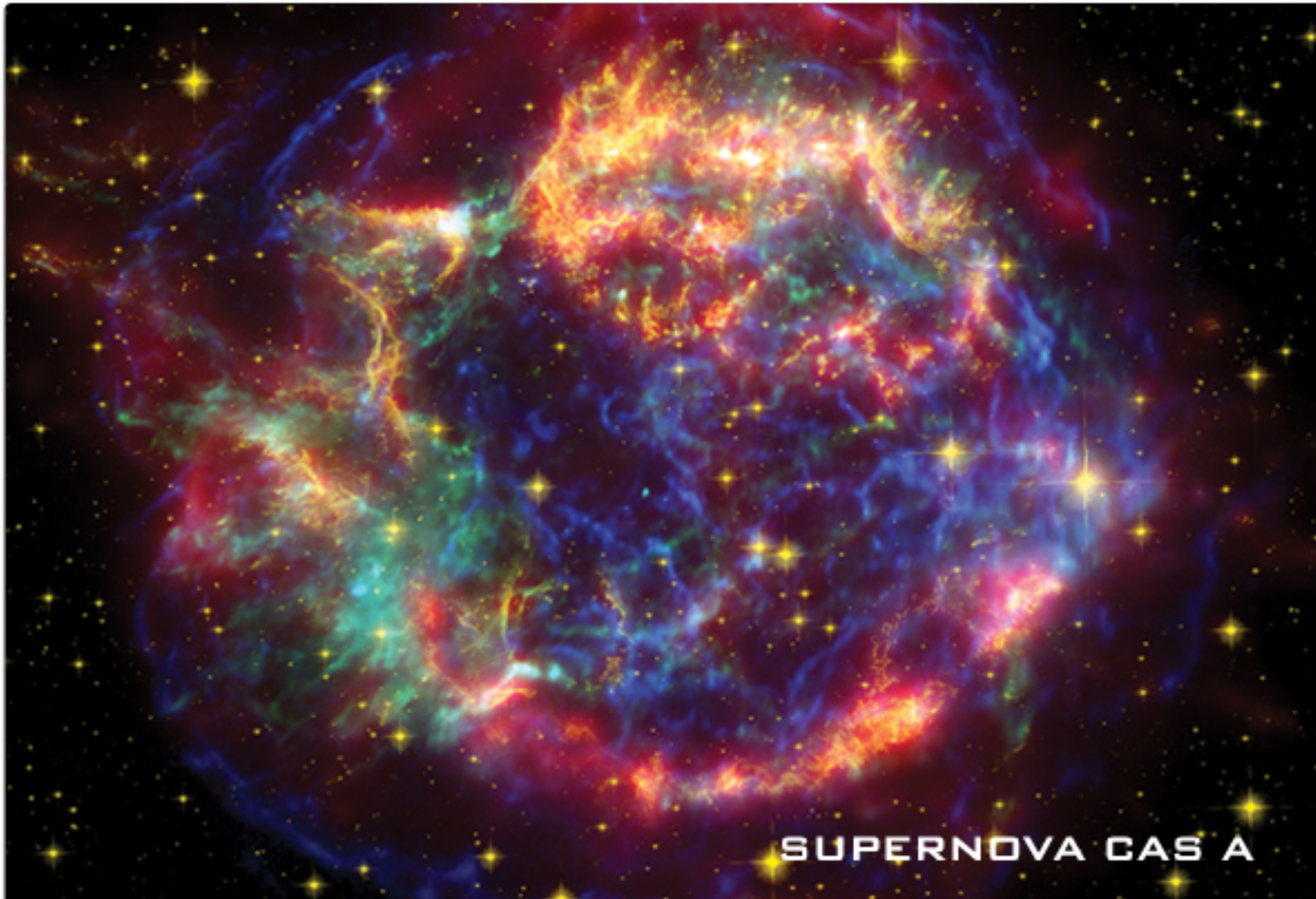
- Typically from objects that contain extremely hot gas (up to hundreds of millions degrees).
- X-rays from the Sun were known already in the 1940's (balloon experiments),
  X-ray binary (neutron star) ScoX-1 in 1962 (sounding rocket)

- X-ray telescopes: grazing-incidence optics (Wolter I design).
- Detectors are made of materials that X-rays interact with (e.g., gas that will "glow", or solid material that stops the high-energy photon).
  - Propotional counters, scintillators, calorimeters.

X-ray missions

- Early missions:
  - Uhuru (1970-1973):
    - The very first X-ray astronomy satellite.
    - Survey of the entire sky for X-ray sources.
- Well-known past missions:
  - Einstein Observatory (HEAO-2) (1978-2981)
  - The ROentgen SATellite, ROSAT (1990-1999).
  - The Advanced Satellite for Cosmology and Astrophysics, ASCA (=ASTRO-D) (1993-2001).
- Active missions:
  - The X-ray Multi-mirror Mission XMM, 1999→
  - Chandra X-ray satellite (formerly known as AXAF), 1999→
  - NuSTAR (Nuclear Spectroscopic Telescope Array), 2012→

IR (Spitzer) Optical (HST) X-Ray (Chandra)



→ For explanation, see next slide!

Notes page: multiwavelength image on previous page

This composite image emphasises the importance of combining data from many instruments/satellites. It is also important to understand how much work has been put into collecting the data and putting together such an image!

The supernova remnant Cassiopeia A (Cas A) was imaged by three of NASA's great observatories, and data from all three observatories were used to create this image. Infrared data from the Spitzer Space Telescope are colored red, optical data from the Hubble Space Telescope are yellow, and x-ray data from the Chandra X-ray Observatory are green and blue.

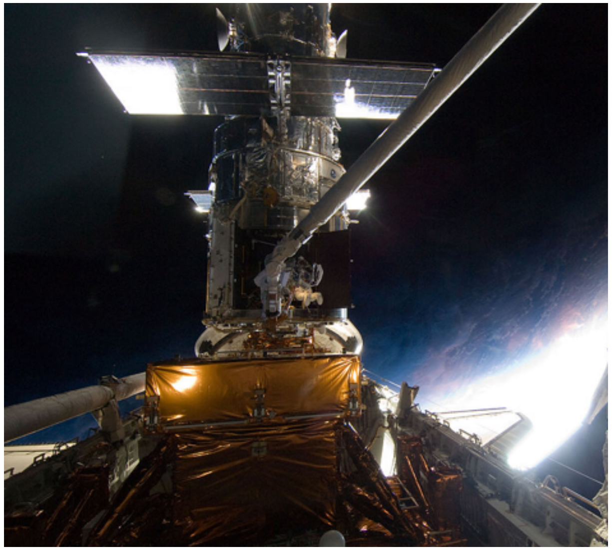
The X-ray data reveal hot gases at about ten million degrees Celsius that were created when ejected material from the supernova smashed into surrounding gas and dust at speeds of about ten million miles per hour. By comparing infrared and X-ray images, astronomers are learning more about how relatively cool dust grains can coexist within the super-hot, X-ray producing gas.

Ultraviolet

- UV is emitted by hotter objects than those emitting optical or NIR light → typically stars in their early or late stages of evolution.
- Also redshift effects: distant UV emission is detecetd in the optical; comparison studies of nearby UV objects can be made.
- Several missions since 1972.
  International Ultraviolet Explorer (IUE) 1978-1996 systematically surveyed the sky for eighteen years.
- UV detectors are sometimes combined with optical instruments, like in the Hubble Space Telescope.
- Extreme UV (< 100 nm) involves techniques resembling X-ray astronomy.
  Extreme Ultraviolet Explorer (EUVE) 1992-2001 operated at this band.

Optical

- No light pollution, no weather effects, overall stable conditions, no scintillation.
  - Superior angular resolution compared to same-size ground-based telescope.
  - But: much more expensive to build, very difficult to maintain.
- Major impact missions:
  - Hipparcos, 1989-1993. For precision astrometry.
  - Hubble Space Telescope, 1990→
    - Five servicing missions using the space shuttle!
  - Kepler, 2009-2018. To search for Earth-size exoplanets.
  - Gaia, 2013→ Aims to construct the largest and most precise 3D space catalog ever made






Notes page: Hubble Space Telescope (HST) highlights on previous slide

HST images have been widely published in the media throughout its operation, because in addition to the interesting findings, they simply are extremely beautiful! It is indeed much easier to explain to a layman with these pictures why your field of study is important (and should be supported!), than by showing, for example, gamma-ray flux curves ☺

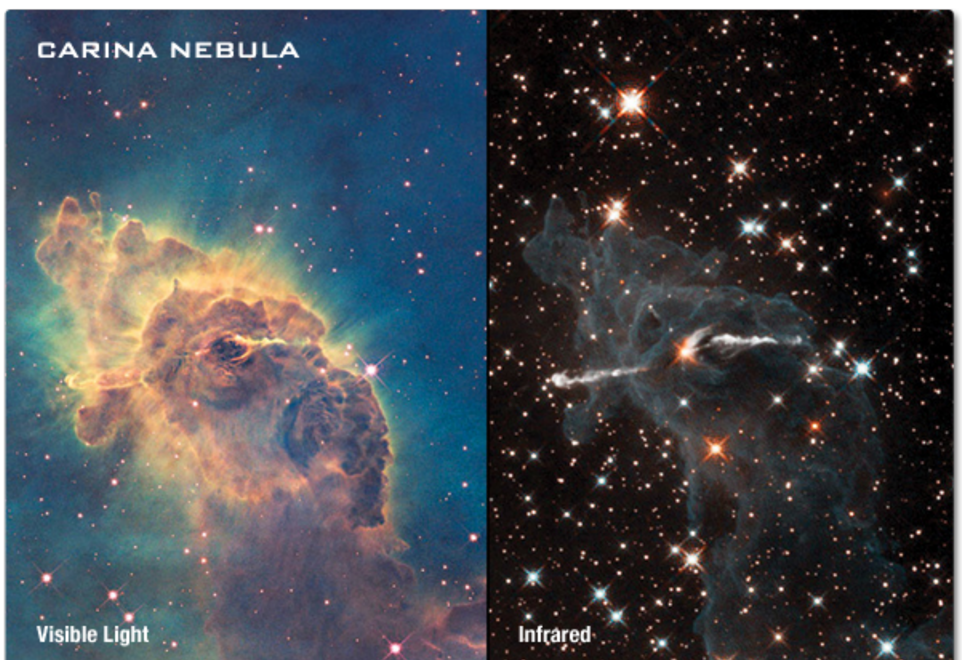
(From HST Press Releases)

1. Expanding halo of light around a distant star, named V838 Monocerotis (V838 Mon). This Hubble image was obtained with the Advanced Camera for Surveys on February 8, 2004. The illumination of interstellar dust comes from the red supergiant star at the middle of the image, which gave off a flashbulb-like pulse of light two years ago. V838 Mon is located about 20,000 light-years away from Earth in the direction of the constellation Monoceros, placing the star at the outer edge of our Milky Way galaxy.
2. Interacting galaxies called Arp 273. The larger of the spiral galaxies, known as UGC 1810, has a disk that is distorted into a rose-like shape by the gravitational tidal pull of the companion galaxy below it, known as UGC 1813. This image is a composite of Hubble Wide Field Camera 3 data taken on December 17, 2010, with three separate filters that allow a broad range of wavelengths covering the ultraviolet, blue, and red portions of the spectrum.
3. This reflecting cloud of dust and gas has two nearly symmetric lobes of matter that are being ejected from a central star. Each lobe of the nebula is nearly one light-year in length, making the total length of the nebula half as long as the distance from our Sun to our nearest neighbors- the Alpha Centauri stellar system, located roughly 4 light-years away. The Boomerang Nebula resides 5,000 light-years from Earth. Hubble's sharp view is able to resolve patterns and ripples in the nebula very close to the central star that are not visible from the ground.
4. Although NASA's Hubble Space Telescope has taken many breathtaking images of the universe, one snapshot stands out from the rest: the iconic view of the so-called "Pillars of Creation." The jaw-dropping photo, taken in 1995, revealed never-before-seen details of three giant columns of cold gas bathed in the scorching ultraviolet light from a cluster of young, massive stars in a small region of the Eagle Nebula, or M16.

   Though such butte-like features are common in star-forming regions, the M16 structures are by far the most photogenic and evocative. The Hubble image is so popular that it has appeared in movies and television shows, on tee-shirts and pillows, and even on a postage stamp. And in celebration of its 25th anniversary, Hubble revisited the famous pillars, providing astronomers with a sharper and wider view. Streamers of gas can be seen bleeding off pillars as the intense radiation heats and evaporates it into space. Stars are being born deep inside the pillars.

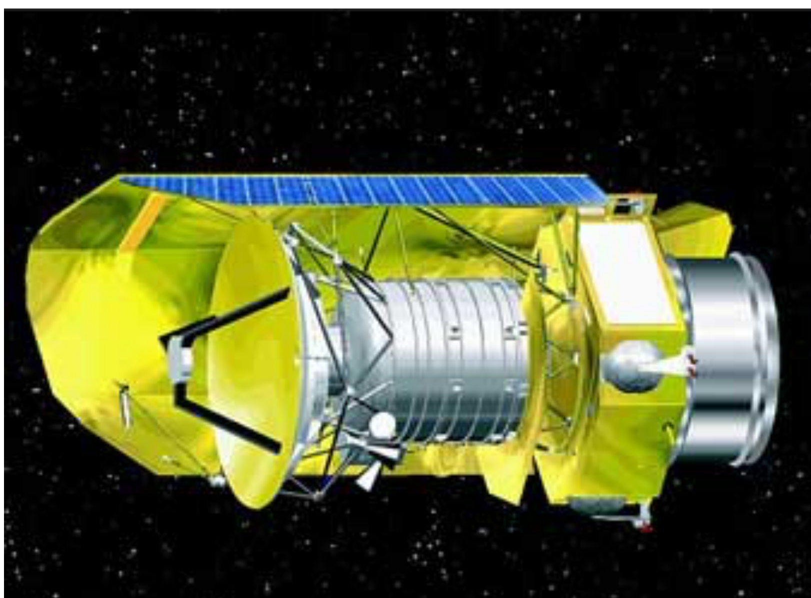
Infrared

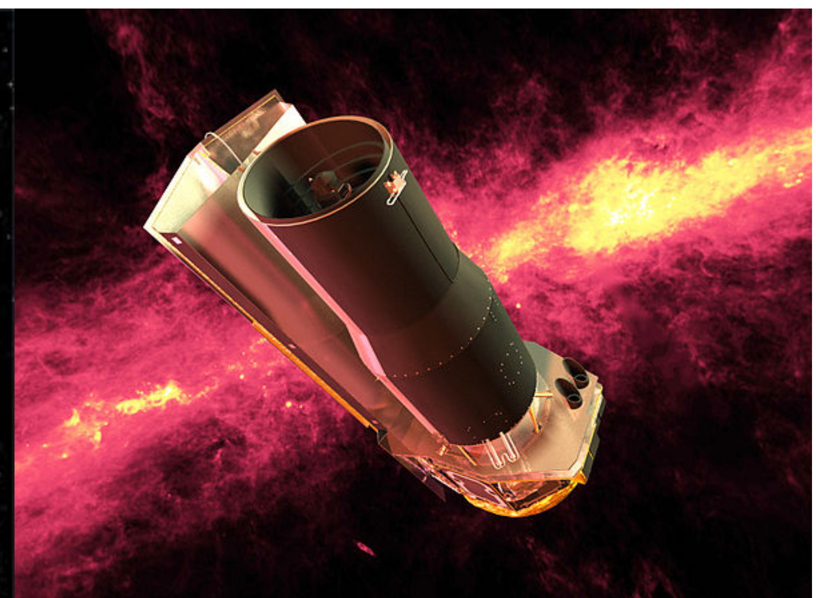
- Ideal for detecting objects that are too cool and faint to be detected at visible light,
  or to observe through dense regions of gas and dust which scatter visible light.



IR

- Near vs. far infrared (resemblance to optical vs. submm)
- Examples of recent and ongoing missions:
  - Herschel Space Observatory, FIR-to-submm, 2009-2013
  - Spitzer Space Telescope, 2003→ [Jan-2020]





Radio to submillimeter

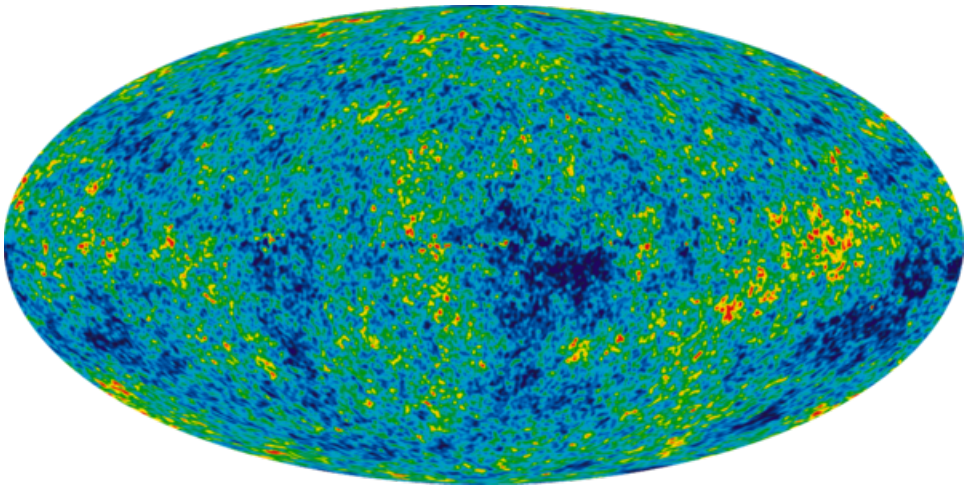
- Main reasons for doing radio astronomy from space:

  1) Sensitivity requirements & full sky coverage → Cosmic Microwave Background (CMB) missions.

  2) Increase of baselines (= growing the size of the "virtual telescope) for Very Long Baseline Interferometry (VLBI)

- But also
  - Observations of wavebands blocked by the atmosphere.
    - For example, the 52-68 GHz band is not observable from the ground due to atmospheric oxygen absorption. Some of the neighbouring frequency bands, however, can be observed from ground.
    - In the submm domain, the atmosphere is dominated by numerous water vapour absorption bands and it is only through "windows" between these bands that observations are possible.

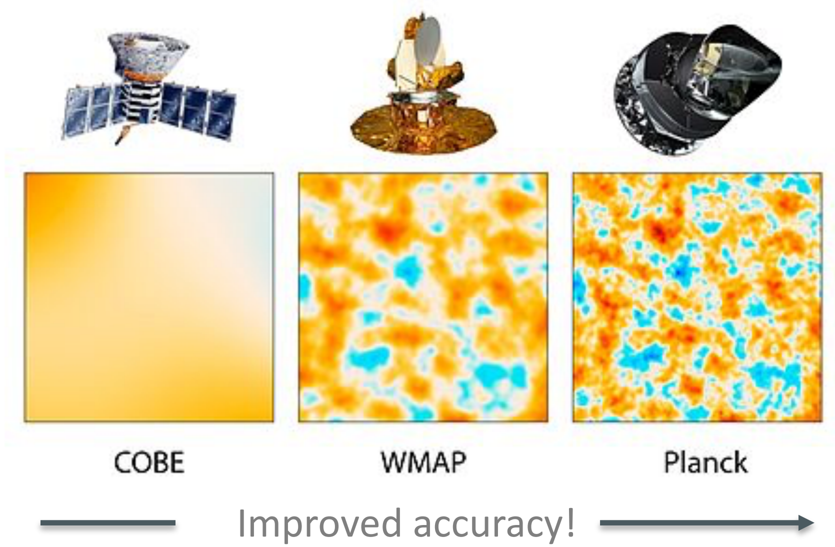
CMB Missions
(Cosmic Microwave Background



COBE 1989–1996

WMAP 2001–2010

Planck 2009–2013



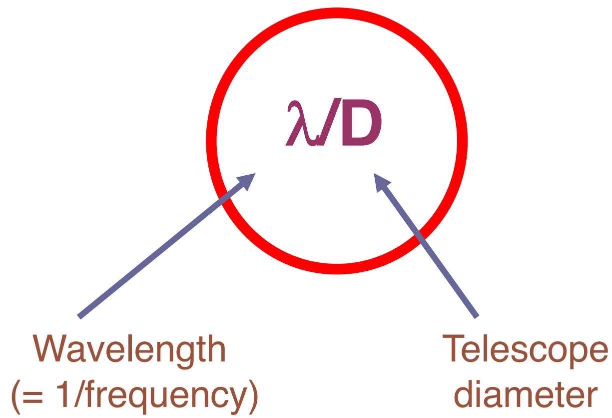
Note: More details of CMB studies will be covered in a later lecture!

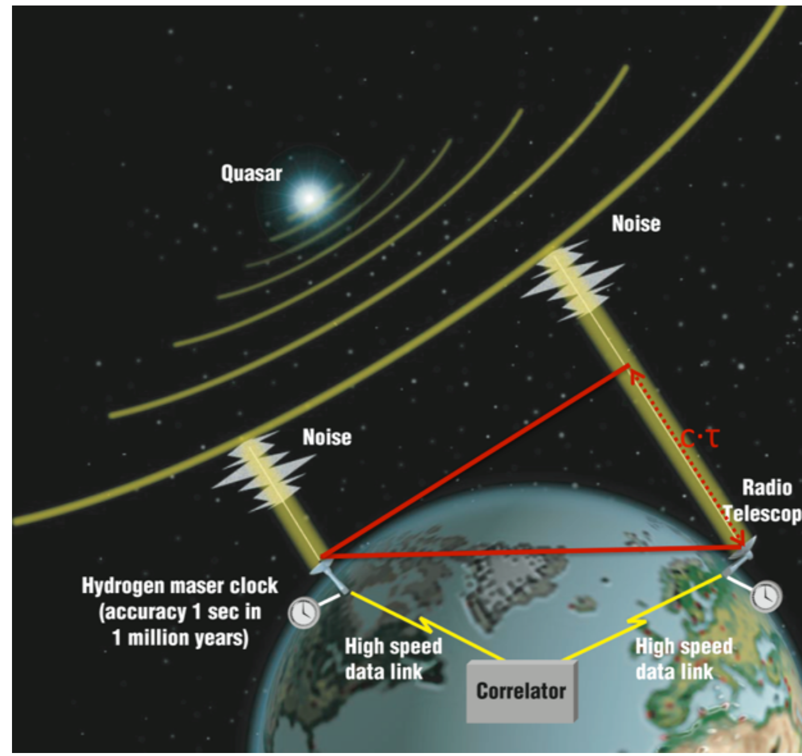
Very Long Baseline Interferometry (VLBI)

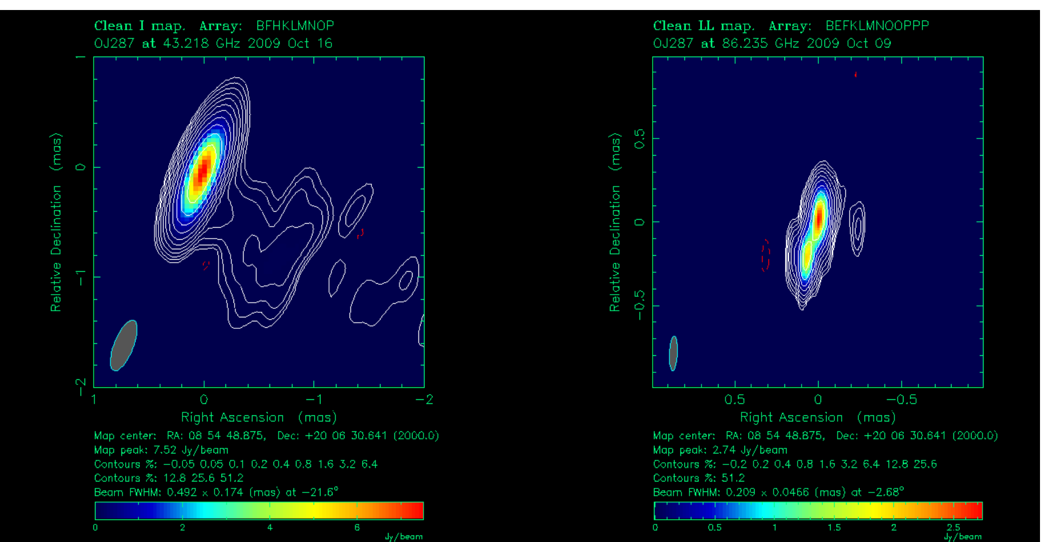
VLBI, the basics:

The angular resolution (“how small details we can see”) gets better with a bigger telescope. With VLBI we combine radio telescopes around the world to get an Earth-size “virtual telescope”. By putting one of the radio telescopes onboard a satellite, we can increase the size yet further.

The angular resolution also gets better with shorter wavelength.







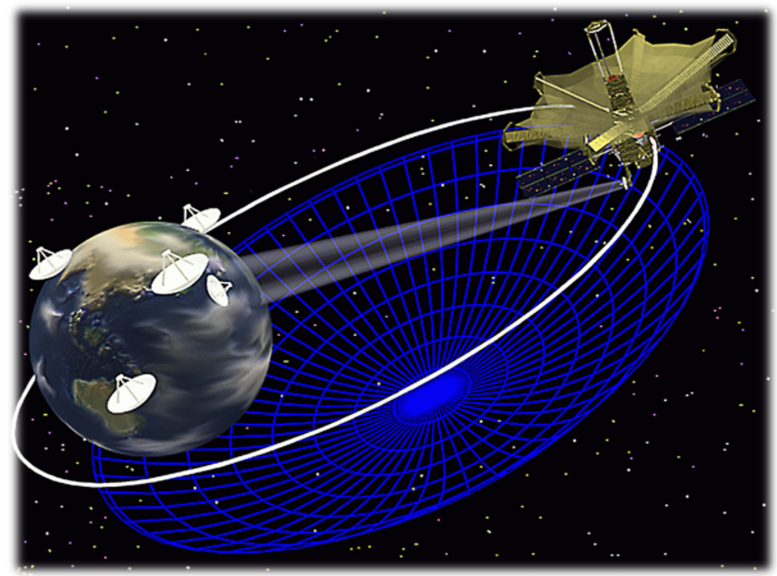
Space VLBI

HALCA (”Highly Advanced Laboratory for Communications and Astronomy”)
= VSOP (“VLBI Space Observatory Programme”), 1997–2005

A Japanese mission, 8-m radio dish on the satellite,
highly elliptical orbit with an apogee altitude of 21400 km, perigee altitude of 560 km.
1.6 GHz and 5 GHz observations; the 22 GHz receiver was unfortunately defunct from launch.

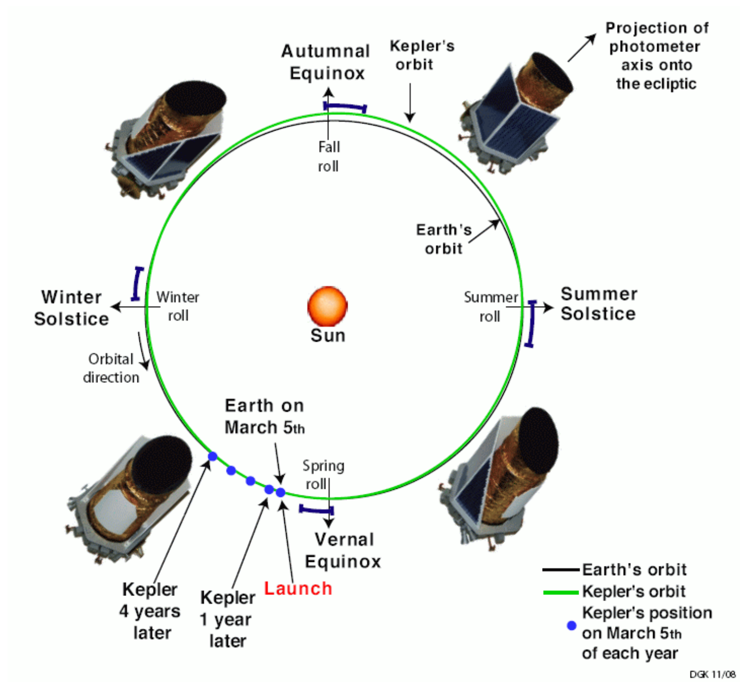
Spektr-R = RadioAstron, 2011-2019

A Russian mission. 10-m radio dish.
Initially orbit perigee of 10000 km and
an apogee of 390000 (yes!) km;
gradually transformed
to a slightly more stable orbit.
Observations at 0.32, 1.6, 5, and 22 GHz.



Orbits

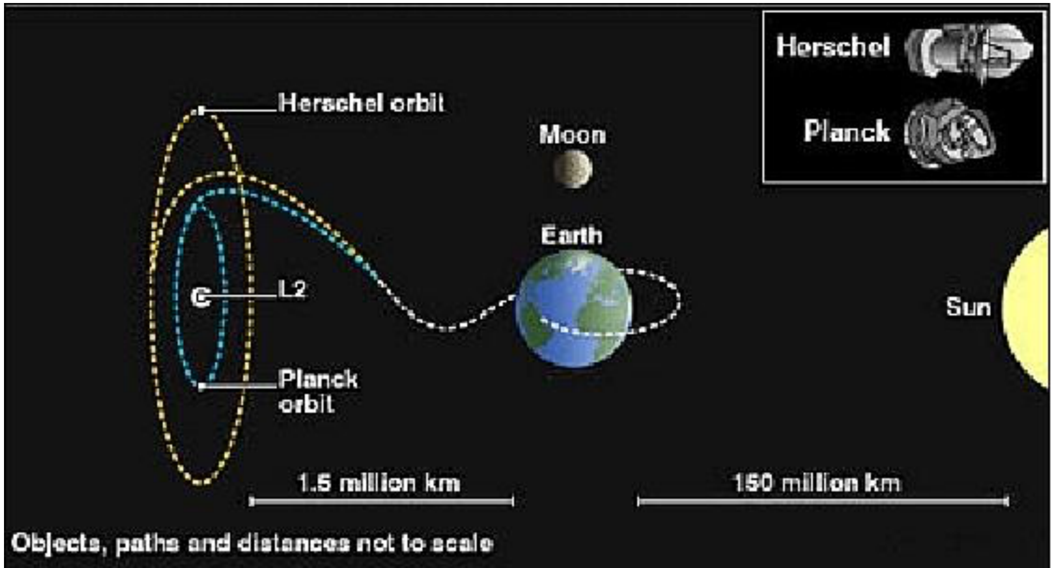
- Tradeoff among payload requirements, s/c technical constraints (communication etc.), and transfer-to-orbit cost.
- Earth Orbit: Majority of astro missions
  - Low-Earth Orbit, LEO, upto 2000 km.
    Easier to launch, easier to communicate with, servicing might be possible (STS; nowadays maybe robotic missions).
- Earth-trailing heliocentric orbit: Spitzer, Kepler
  - Avoids Earth occultations, stray light, gravitational perturbations, and torques inherent in an Earth orbit.
  - Less propellant to reach than L2
    → switching to smaller launcher was possible.



Kepler's solar array was rotated to face the Sun at the solstices and equinoxes, to optimize the amount of sunlight falling on the solar array and to keep the heat radiator pointing towards deep space.

Orbits

- Highly elliptical geocentric orbit:
  RadioAstron (11000 x 338000 km)
  - Optimized for certain baseline configurations for VLBI (arguable).
  - Large number of objects visible at any one point in the orbit.
- Lissajous orbits / L2: WMAP, Planck, Herschel, Gaia
  - Low temperatures can be reached and maintained.
  - Antennas pointing away from payload → minimal radio interference (RFI).
  - Orbits the Sun in exactly one year; stays in the same place relative to Earth.
  - L2 is only a semistable L point.
  - Halo orbit → s/c orbits around the L2; never in Earth's shadow. Manoeuvres needed also to keep axis direction.



Test questions. Can you answer these?

- Make a list of the radiation domains across the electromagnetic spectrum from radio to gamma-rays, and explain why satellite-based observations are needed or at least useful.
  Pay attention in particular to the wavelength ranges that can not at all be observed from the ground!
  Briefly describe the type of instruments that are used in each of the wavelength range.

- Familiarise yourself with the slides presented in the section "burning questions ..." (with examples from galaxies, AGNs, exoplanets, etc.). If you pick any one of the "burning questions", can you think of an instrument / wavelength region that would be especially useful for studying some of them? This is not an easy question! But the later slides that describe some of the past or ongoing missions should help there.

- Describe the pros and cons of the different satellite orbits when choosing an orbit for astronomical satellites.


Thank you
for your attention!