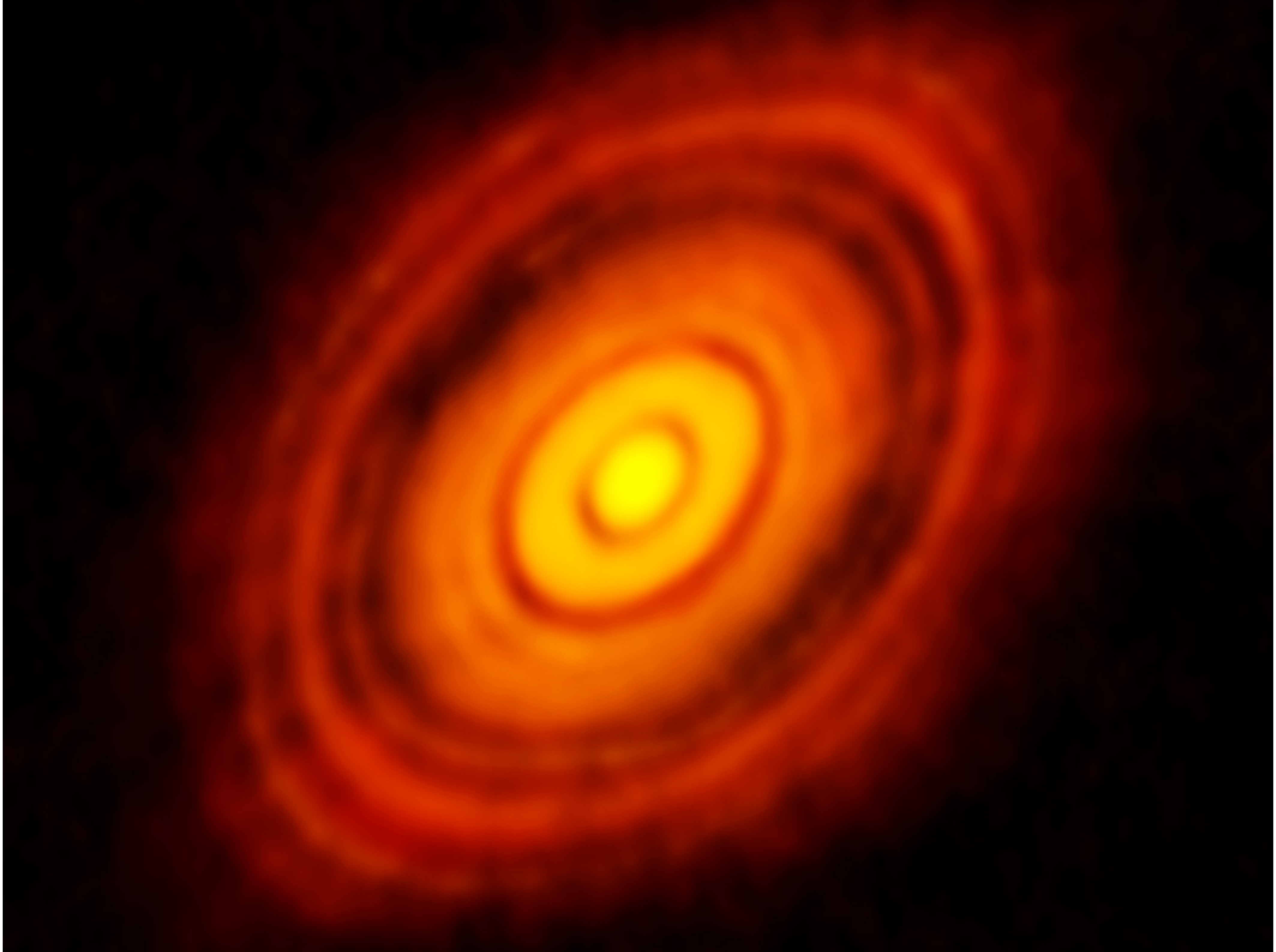
Essentials of
Radio and (Sub-)Millimeter Astronomy

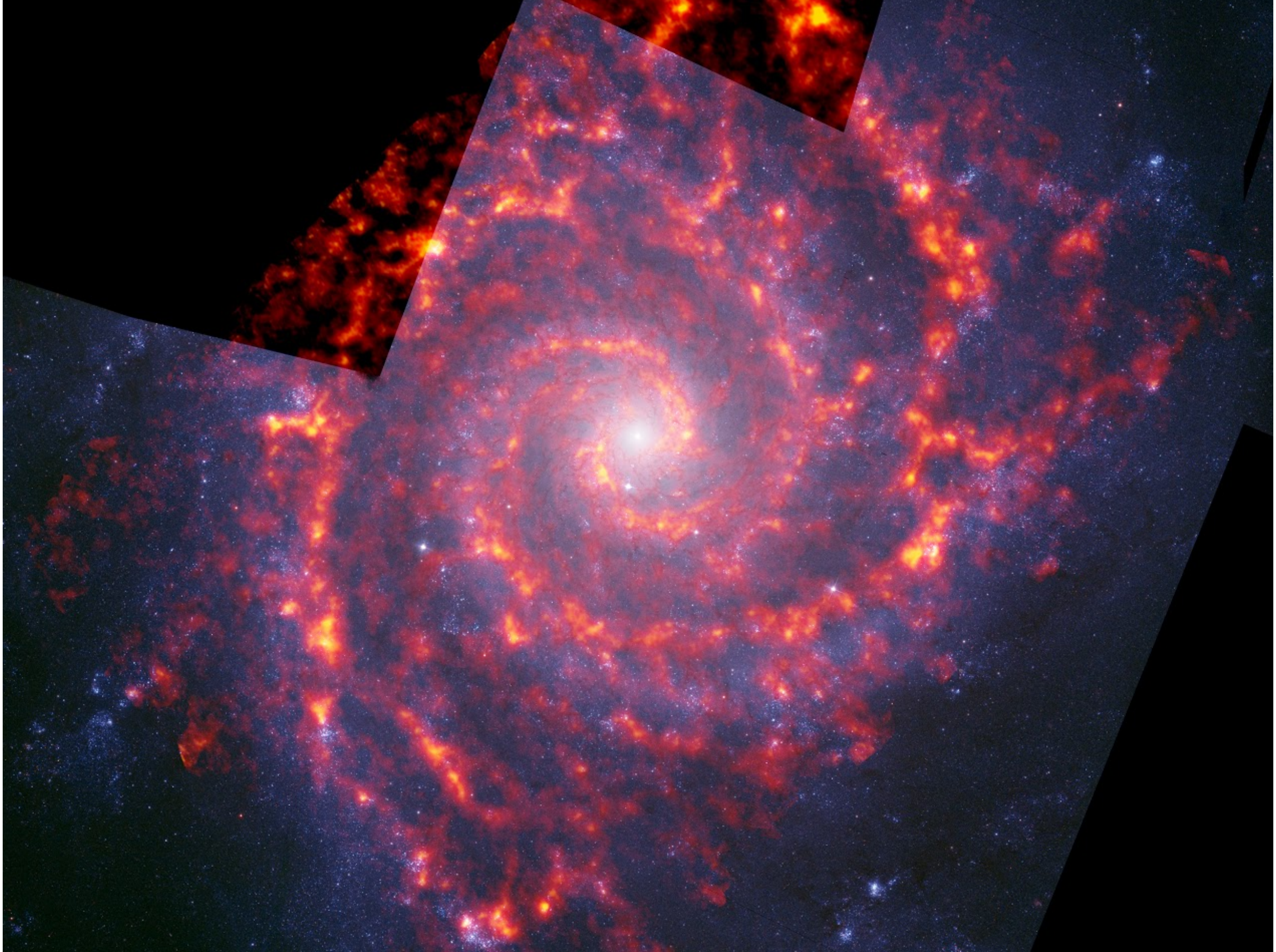
Fabian Walter (MPIA)

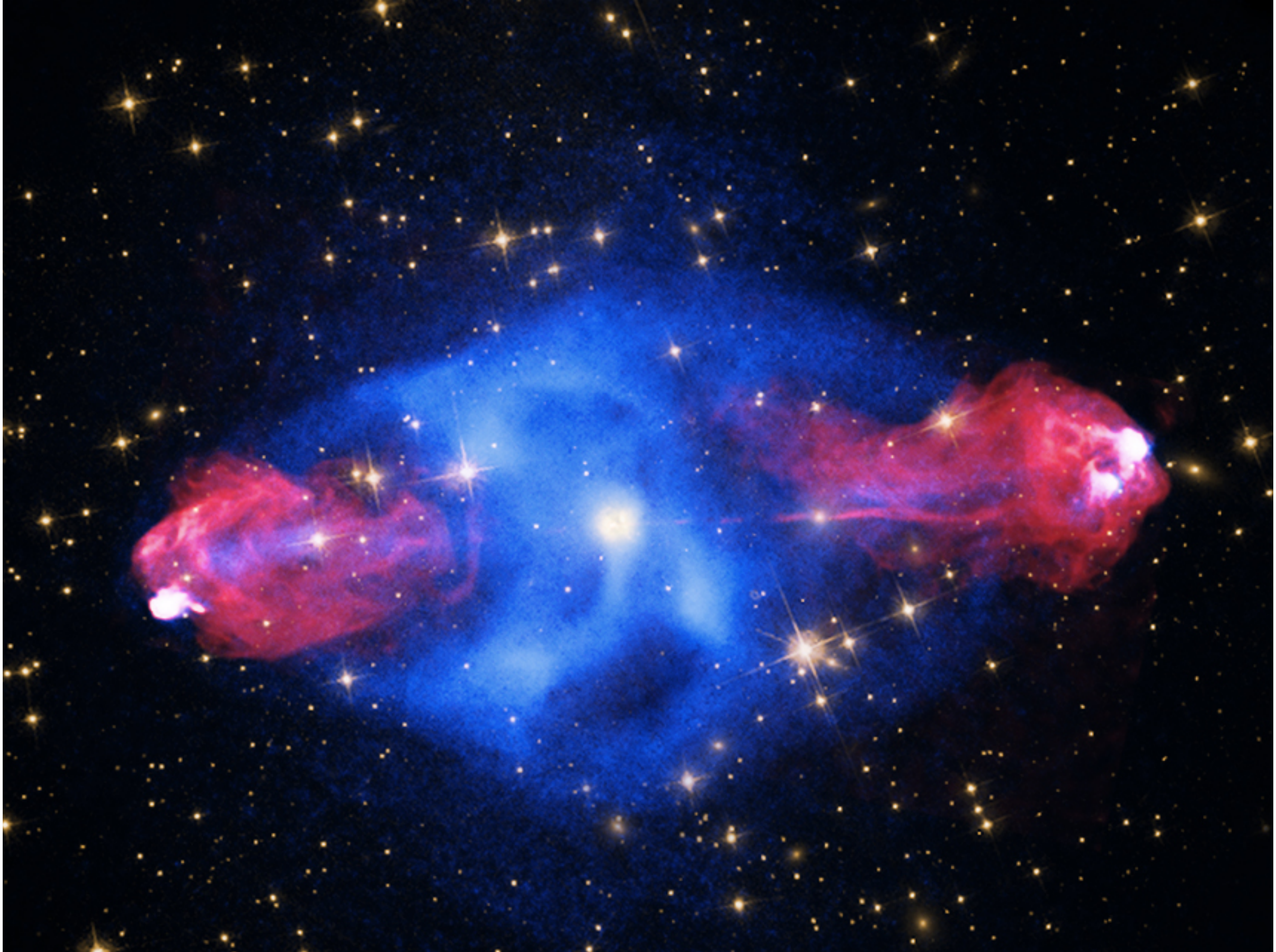
Tentative Schedule:

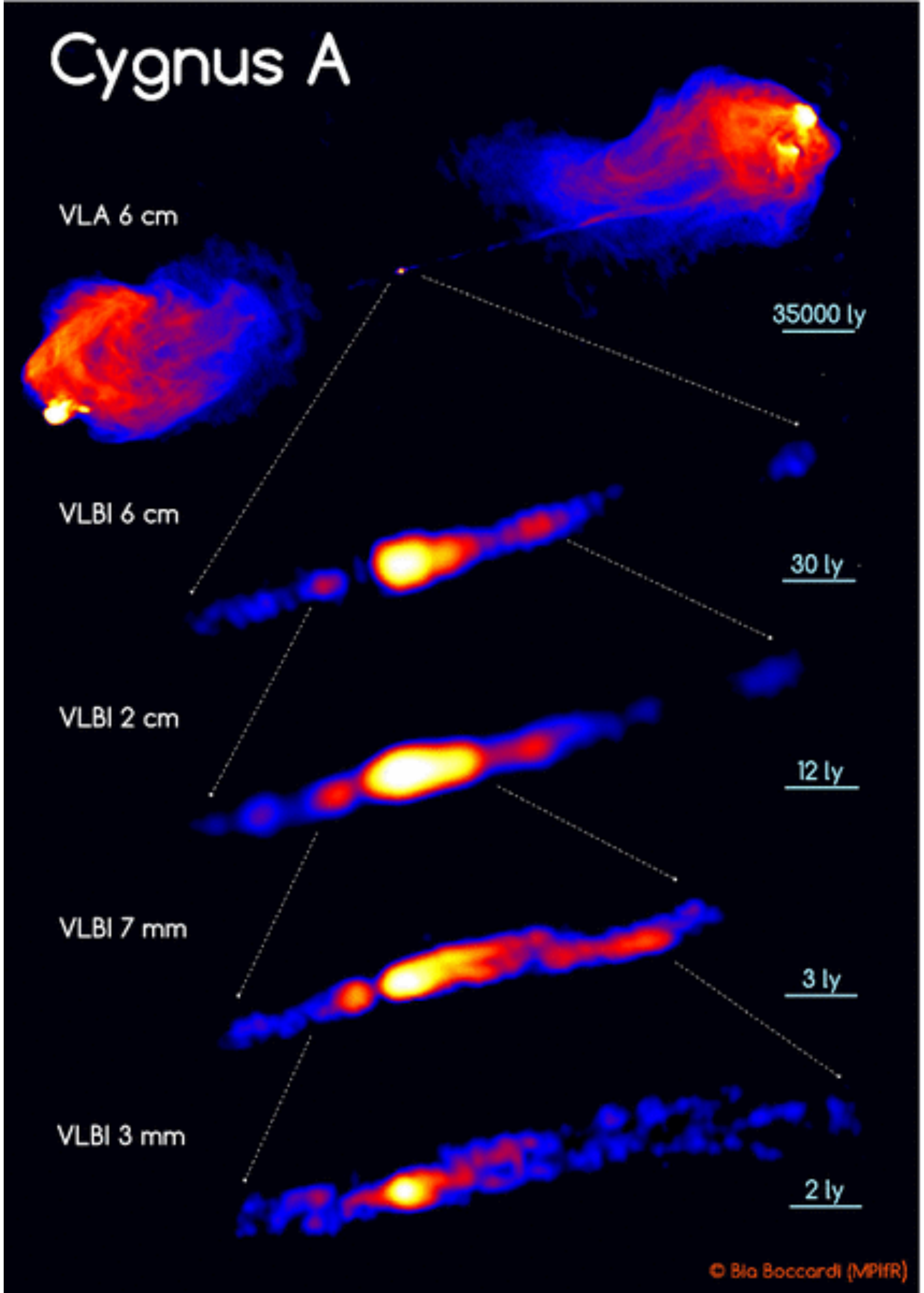
All times are Fridays, 9:15-10:45am

[1] April 22: Introduction and overview: Why radio and millimeter astronomy?
[2] April 29: Radiation Fundamentals, Emission mechanisms
[3] May 6: Atomic and Molecular Lines
[4] May 13: Radiometers / Receivers I
[5] May 20: Radiometers / Receivers II
[6] May 27: Interferometry - Basics
[7] June 3: Interferometry - Imaging I
[8] June 10: Interferometry - Imaging II
[9] June 17: Interferometry - Calibration
[10] June 24: The next generation of Interferometers
[11] July 1: Applications I: Protoplanetary Disks and the Event Horizon Telescope
[12] July 8: Applications II: Nearby and Distant Galaxies with ALMA
[13] July 15: Applications III: The Epoch of Reionization
[14] July 22: Q/A
[15] July 25-29: Examination week



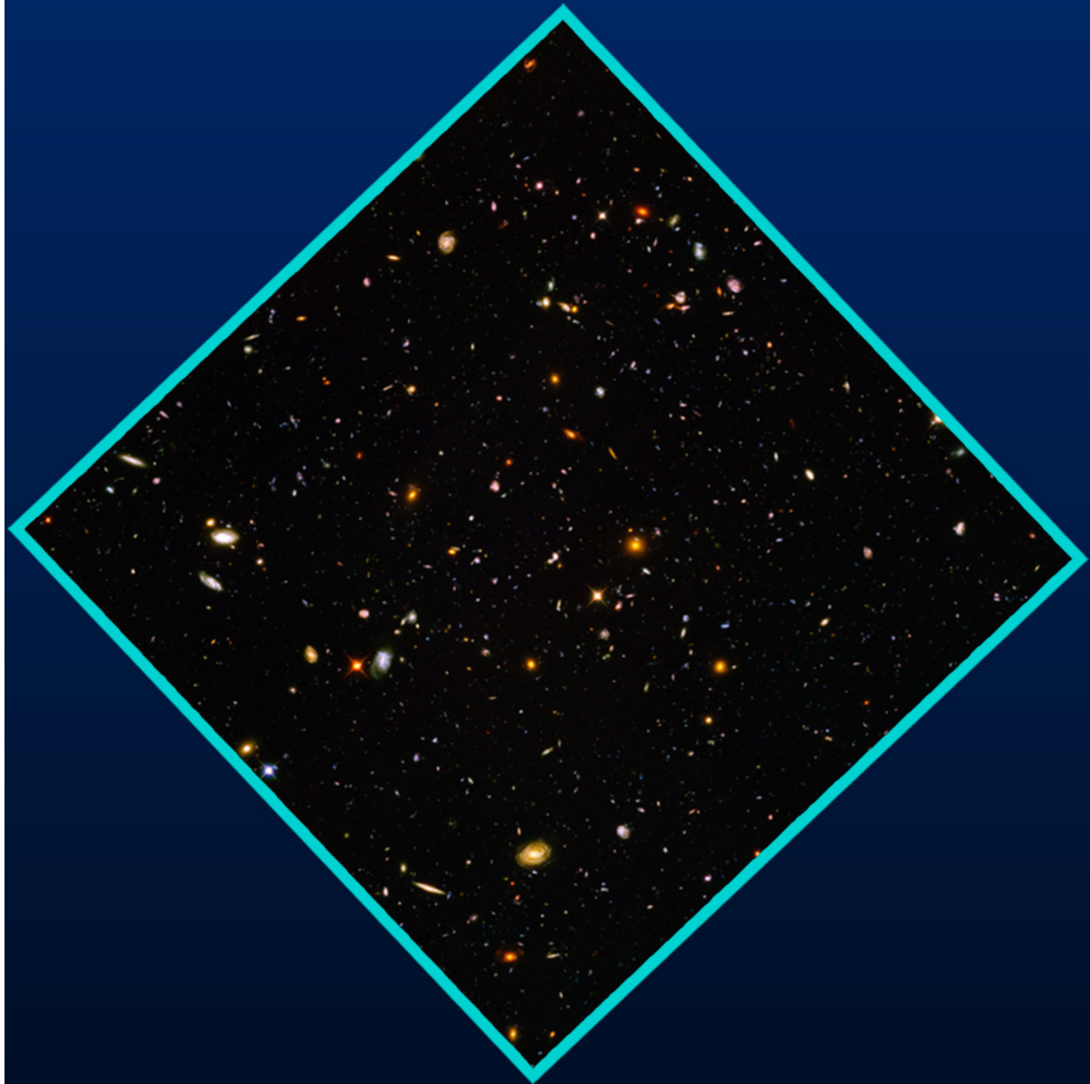





Cygnus A
VLA 6 cm
35000 ly
VLBI 6 cm
30 ly
VLBI 2 cm
12 ly
VLBI 7 mm
3 ly
VLBI 3 mm
2 ly
© Bia Boccardi (MPIfR)

ALMA view of the UDF

HST stellar emission



ALMA dust emission

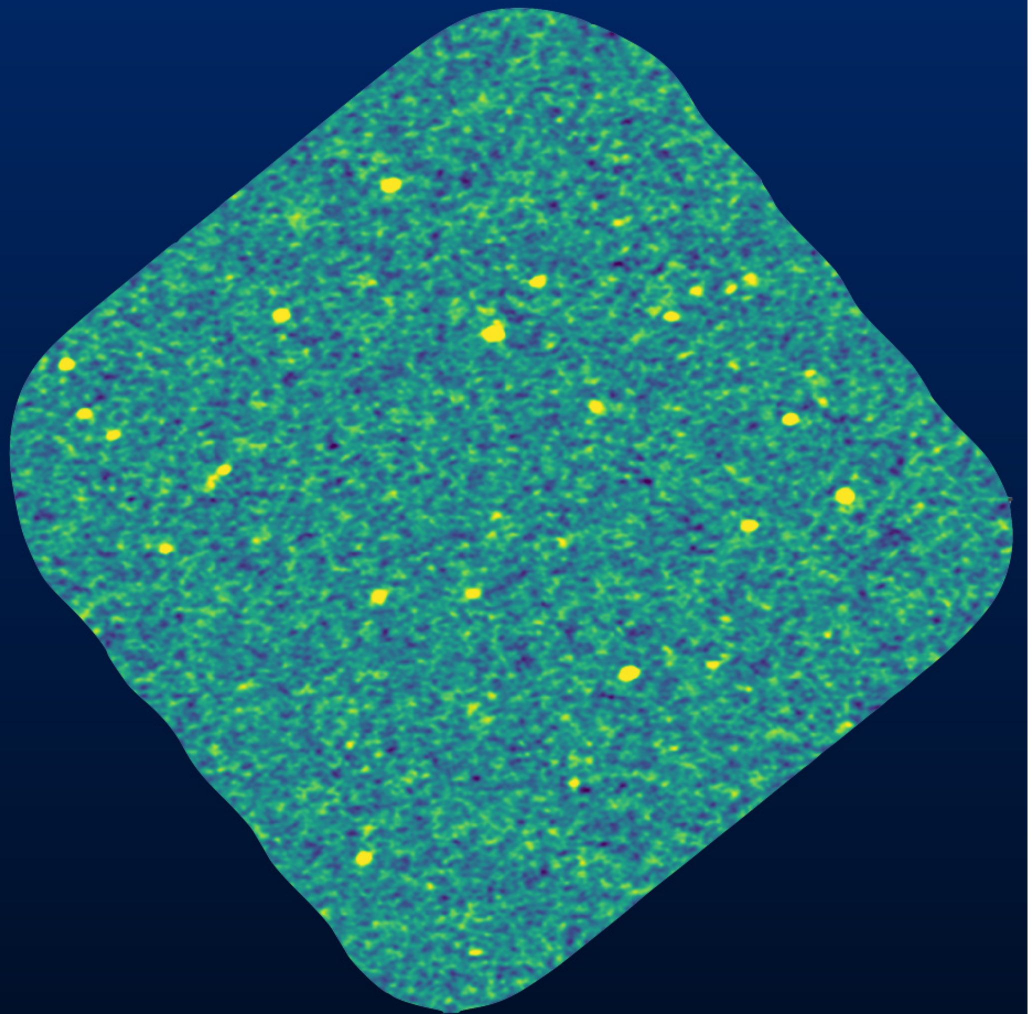


Image credits: *STScI, Decarli et al. 2019, Aravena el al. 2019, 2020*

ERA: Essential Radio Astronomy

https://science.nrao.edu/opportunities/courses/era/

ERA Navigation

Essential Radio Astronomy

by Jim Condon — last modified Mar 14, 2016

Essential Radio Astronomy (ERA) grew from lecture notes for the one-semester radio astronomy course taken by all astronomy graduate students at the University of Virginia. To attract advanced undergraduates with backgrounds in astronomy, physics, engineering, or astrochemistry to radio astronomy, we limited the prerequisites to basic physics courses covering classical mechanics, macroscopic thermodynamics, electromagnetism, and elementary quantum mechanics. Prior courses covering electromagnetism with vector calculus, electrical engineering, special relativity, statistical thermodynamics, advanced quantum mechanics, Fourier transforms, or astrophysics were *not* required. Nearly everything in *ERA* has been derived from first principles in order to fill the gaps in students' backgrounds and make *ERA* a useful reference for practicing radio astronomers.

Classical radio astronomy textbooks such as *Radio Astronomy* by J. D. Kraus emphasized radio engineering and were written for two-semester courses that prepared students for careers in radio astronomy. In this era of multiwavelength astronomy, most graduate students can afford to spend only one semester studying radio astronomy, during which only the most essential concepts can be presented. Our goal is to give them the background needed to read and understand the radio astronomy literature, to recognize when radio observations might help solve an astrophysical problem, and to design, propose, and analyze radio observations. The *ERA* textbook complements the longer and more technical *Tools of Radio Astronomy* textbook that "describes the tools radio astronomers need to pursue their goals" in greater detail. *ERA* was also shaped by our belief that radio astrophysics owes more to thermodynamics than to electromagnetism, so Kirchhoff's law appears more frequently than Maxwell's equations.

Originally, our brief lecture notes were printed and handed out to students in the traditional classroom environment: a chalk-dusted professor covered blackboards with equations which students faithfully copied into their notebooks for later study. To avoid this unnecessary work and free the students to concentrate on the ideas being presented, we expanded the abbreviated notes into complete texts with figures and full mathematical derivations, then converted them from TeX to html so they could be posted to the web and projected onto a screen in any classroom. Now the professor faces "heads up" students who can watch, listen, and ask questions without worrying about failing to write down a crucial step in some long derivation.

A broader goal of the National Radio Astronomy Observatory[1] is fostering the community of researchers using radio astronomy by attracting and training the most talented university students *anywhere in the world*. NRAO directors Paul Vanden Bout, Fred Lo, and Tony Beasley have generously supported our efforts to upgrade and expand all of the course materials (lectures, problem sets, exams) that are now available on this website. (The original but now obsolete web version can still be found here.)

We hope that the combination of this book and its associated website will facilitate teaching radio astronomy at the university level, especially at the many colleges and universities lacking "black belt" radio astronomers. The website can display large galleries of color images, link to interactive demonstrations and relevant articles on the web, present problem sets and solutions, and be updated frequently to present new findings or report errata from the book. We thank Princeton University Press for agreeing to a nonexclusive copyright that allows the book and website to coexist.

NRAO, Charlottesville   James J. Condon jcondon@nrao.edu
2016 March 12   Scott M. Ransom sransom@nrao.edu

1. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.↩

Lecture 1

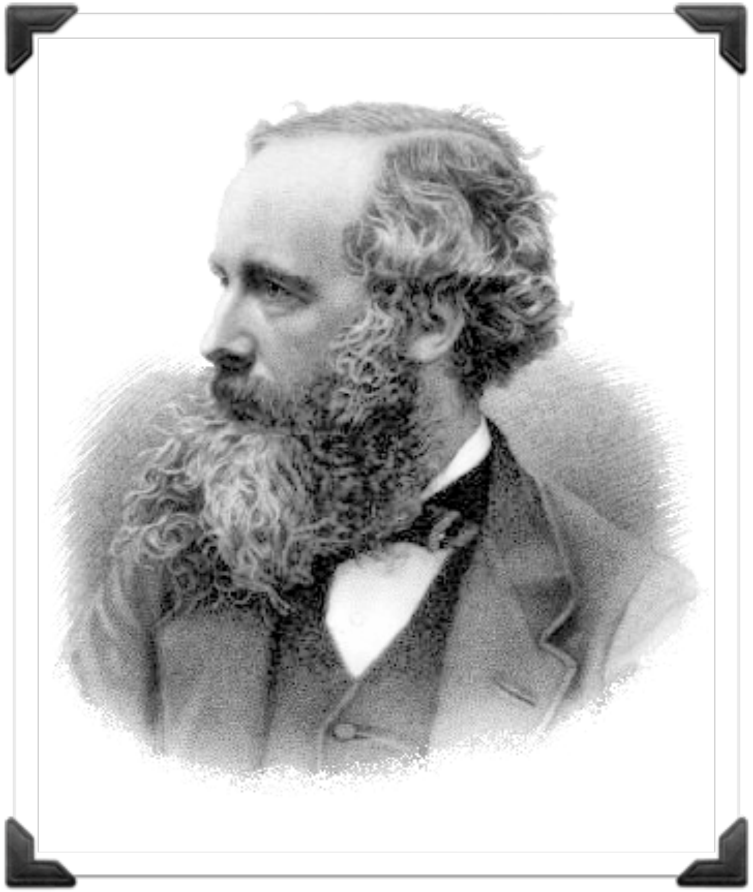
Radio / Millimeter Astronomy in a multiwavelength context

An optical telescope is visual and interesting. A radio telescope is an electronic instrument and you can't really see a lot of what makes it work. When it's done all you get is a computer printout.

Comments from an anonymous NSF referee.

From book “Open Skies” by Kellerman et al.

Maxwell 1862: physical description of light through electromagnetic waves

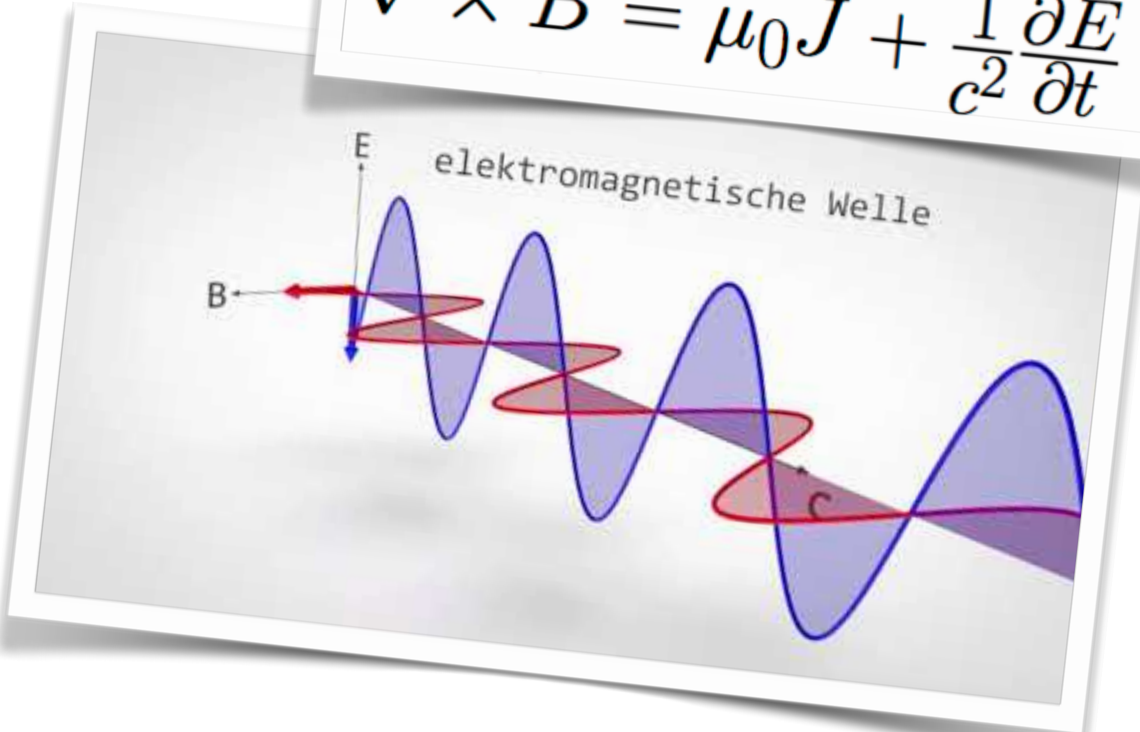


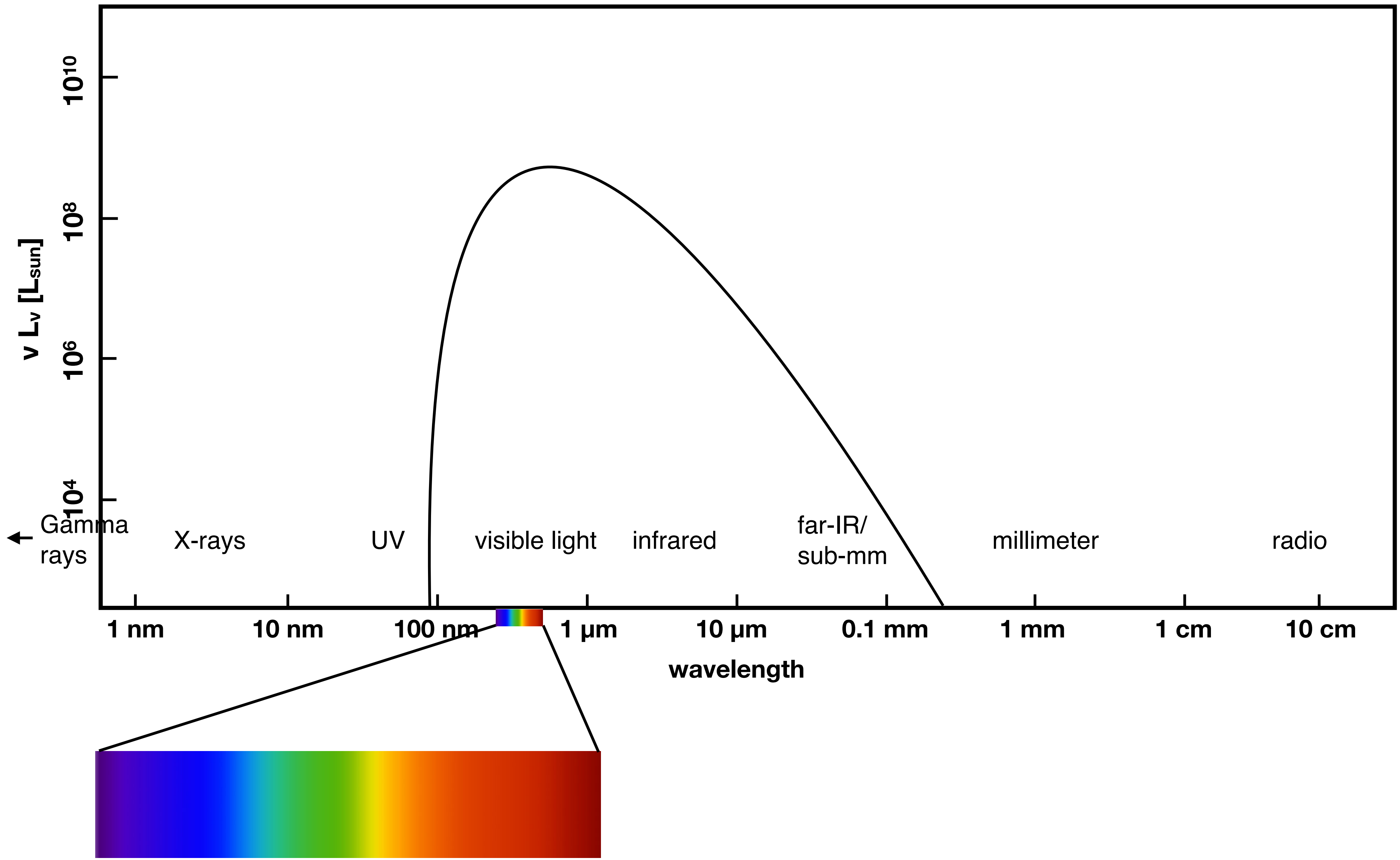
$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

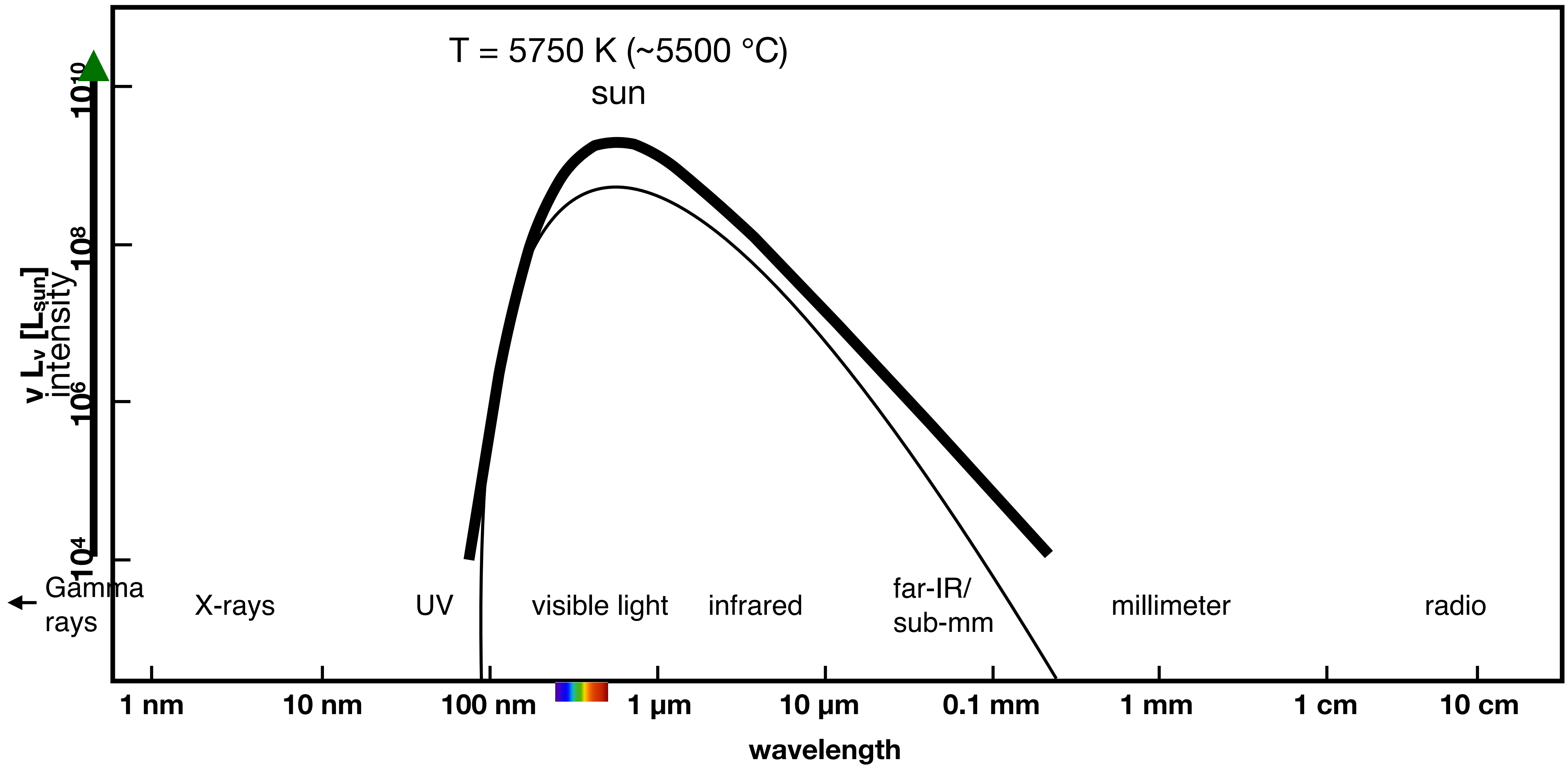




ν Lν [Lsun]
10^10
10^8
10^6
10^4
Gamma rays
X-rays
UV
visible light
infrared
far-IR/ sub-mm
millimeter
radio
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
wavelength

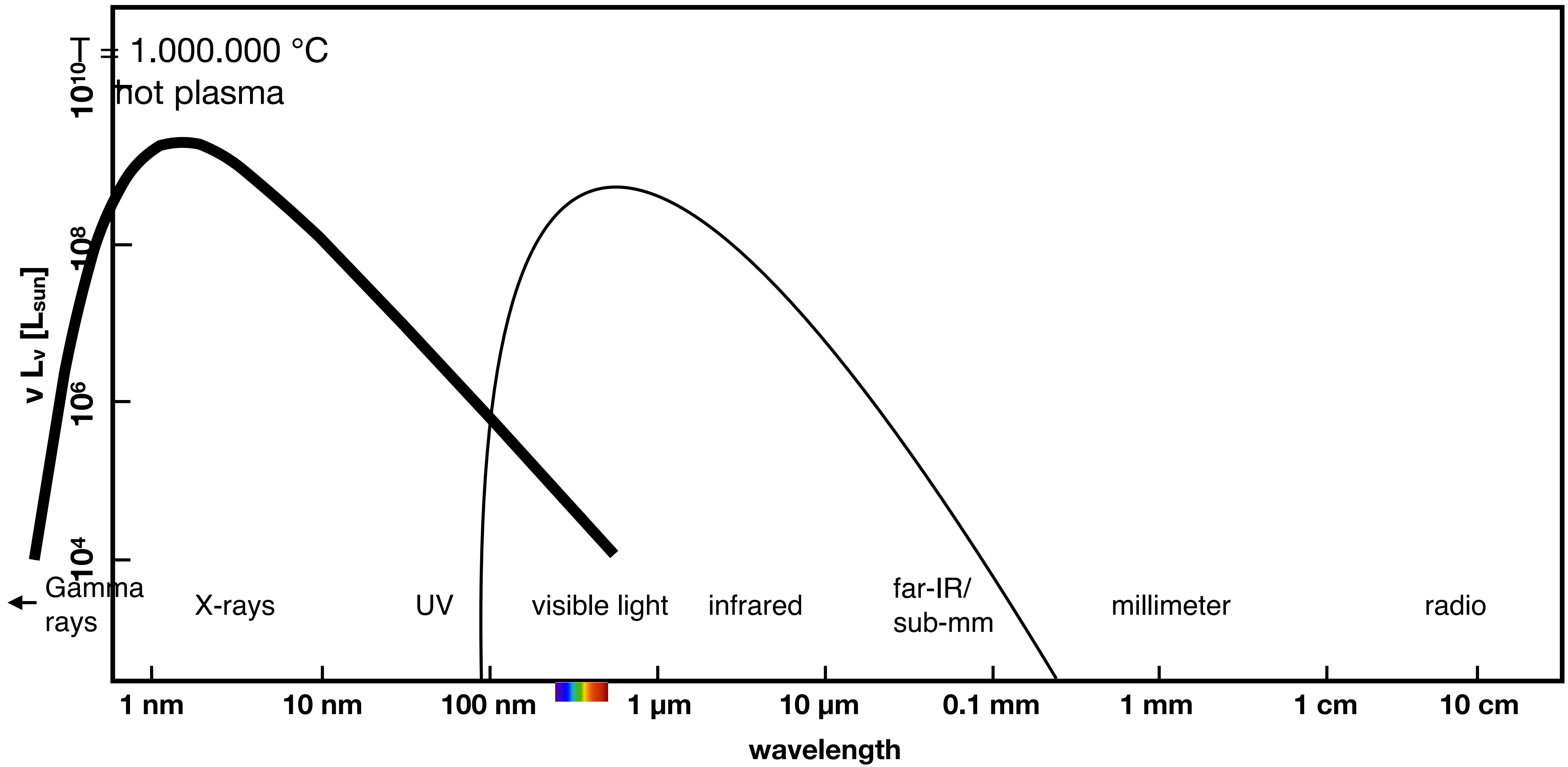
blackbody radiation

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$



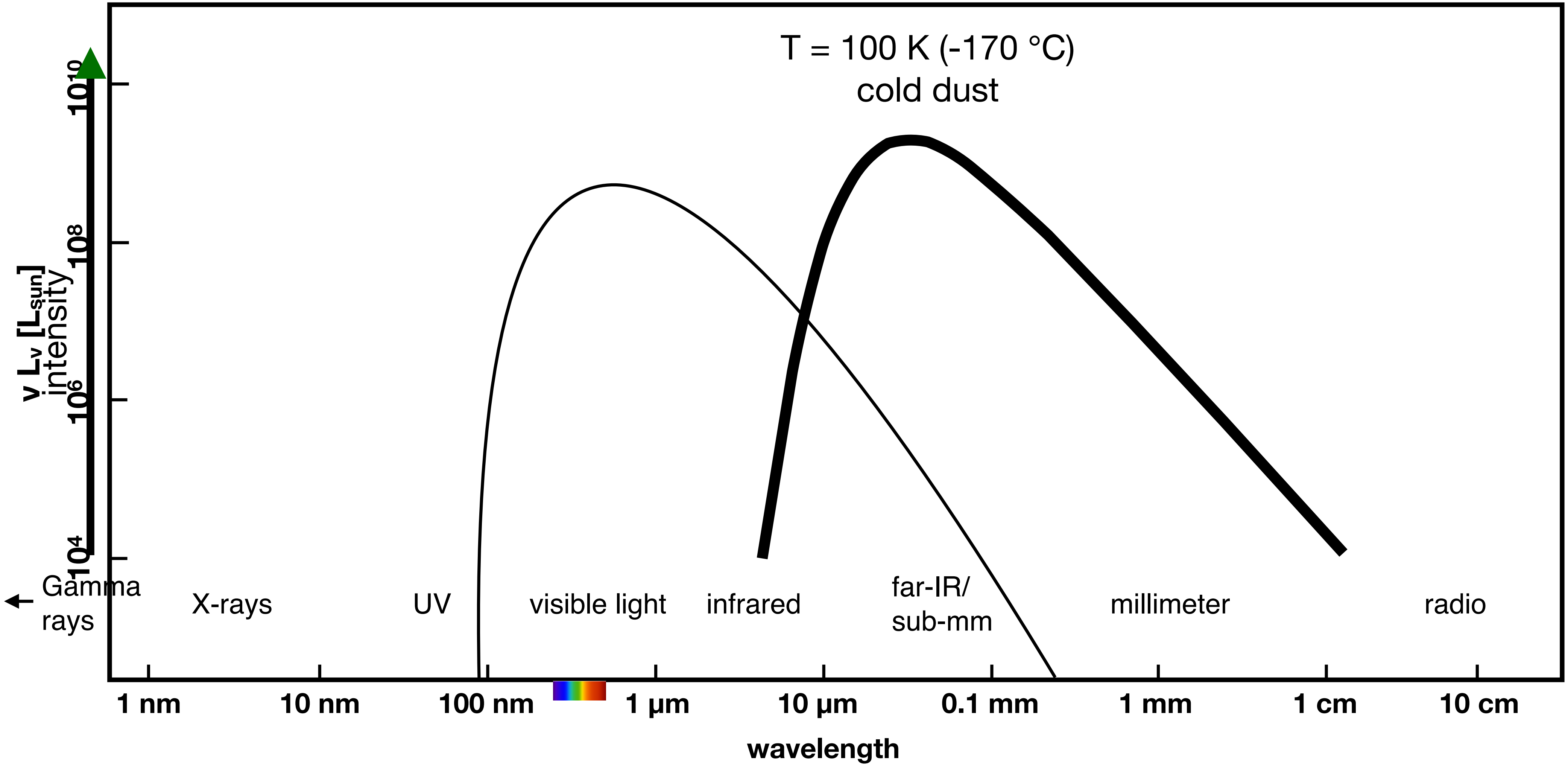
blackbody radiation

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$



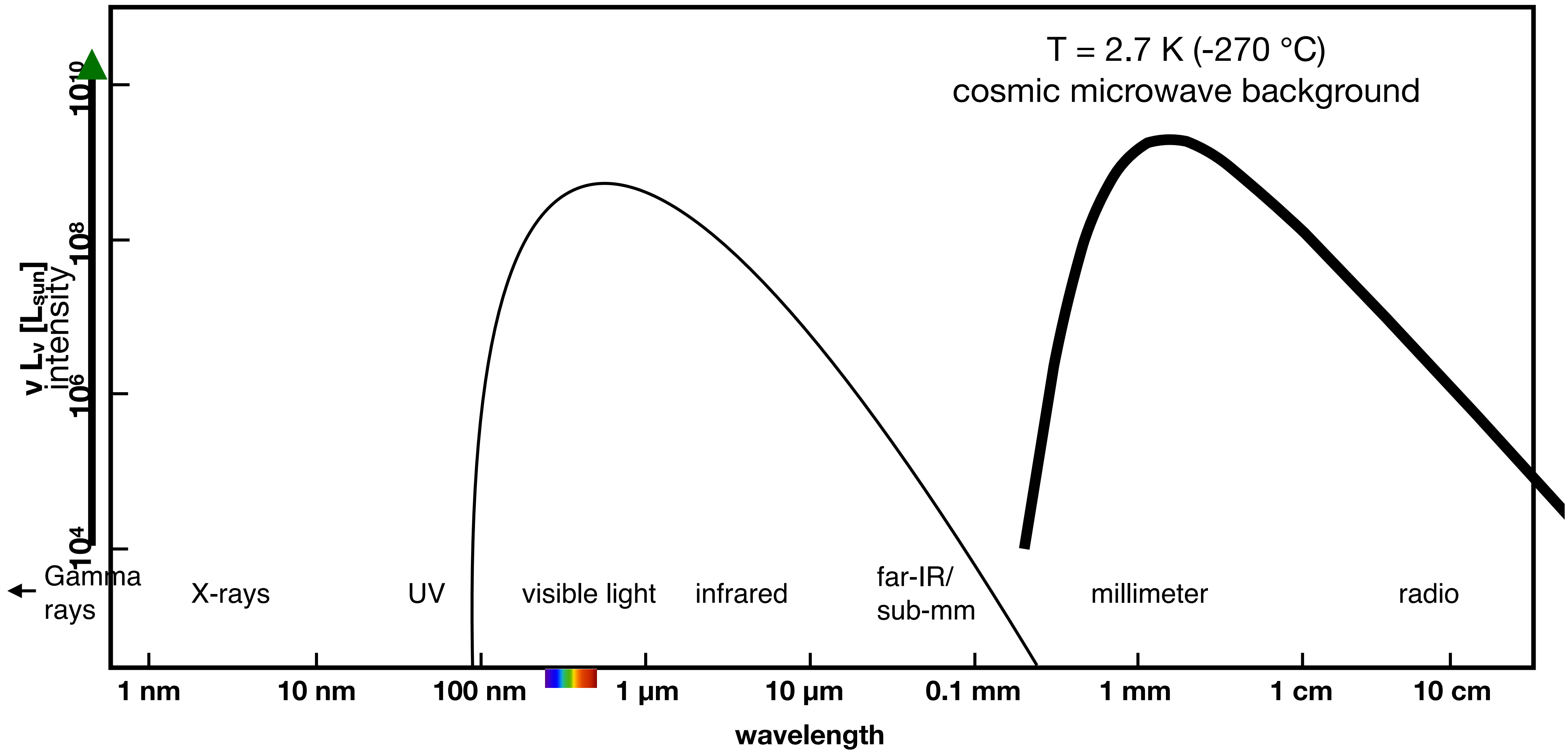
blackbody radiation

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

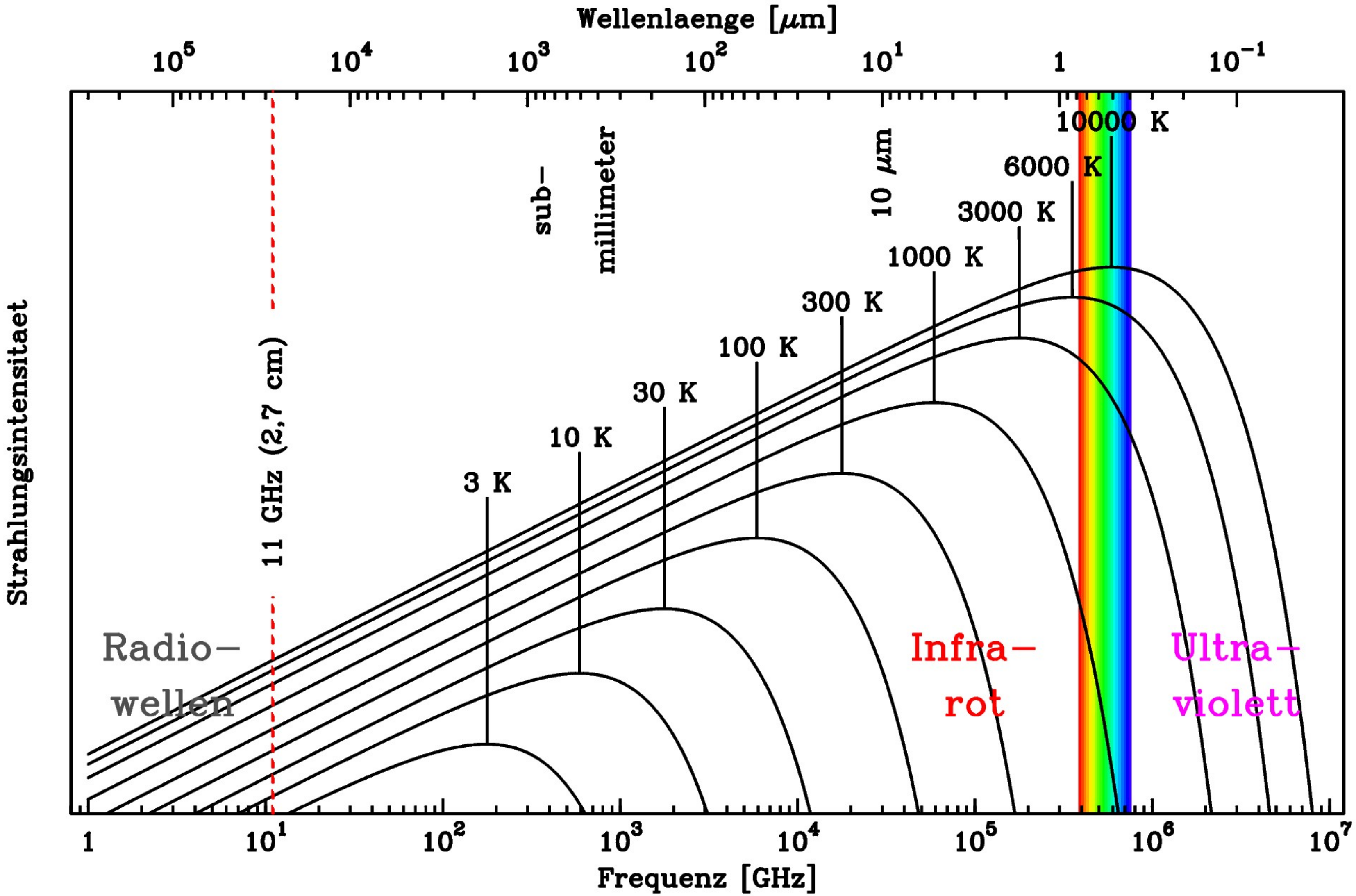


blackbody radiation

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

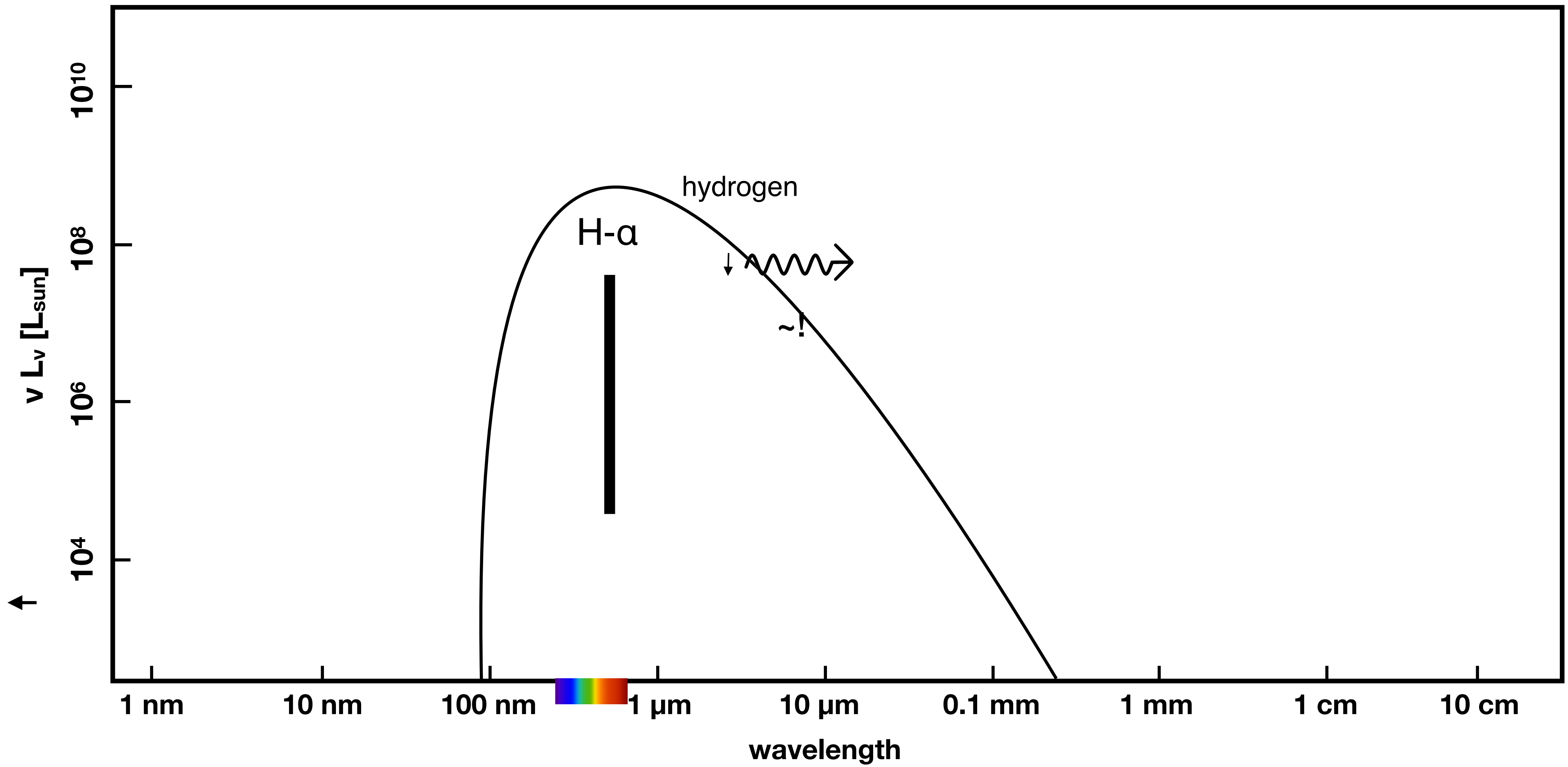


$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$



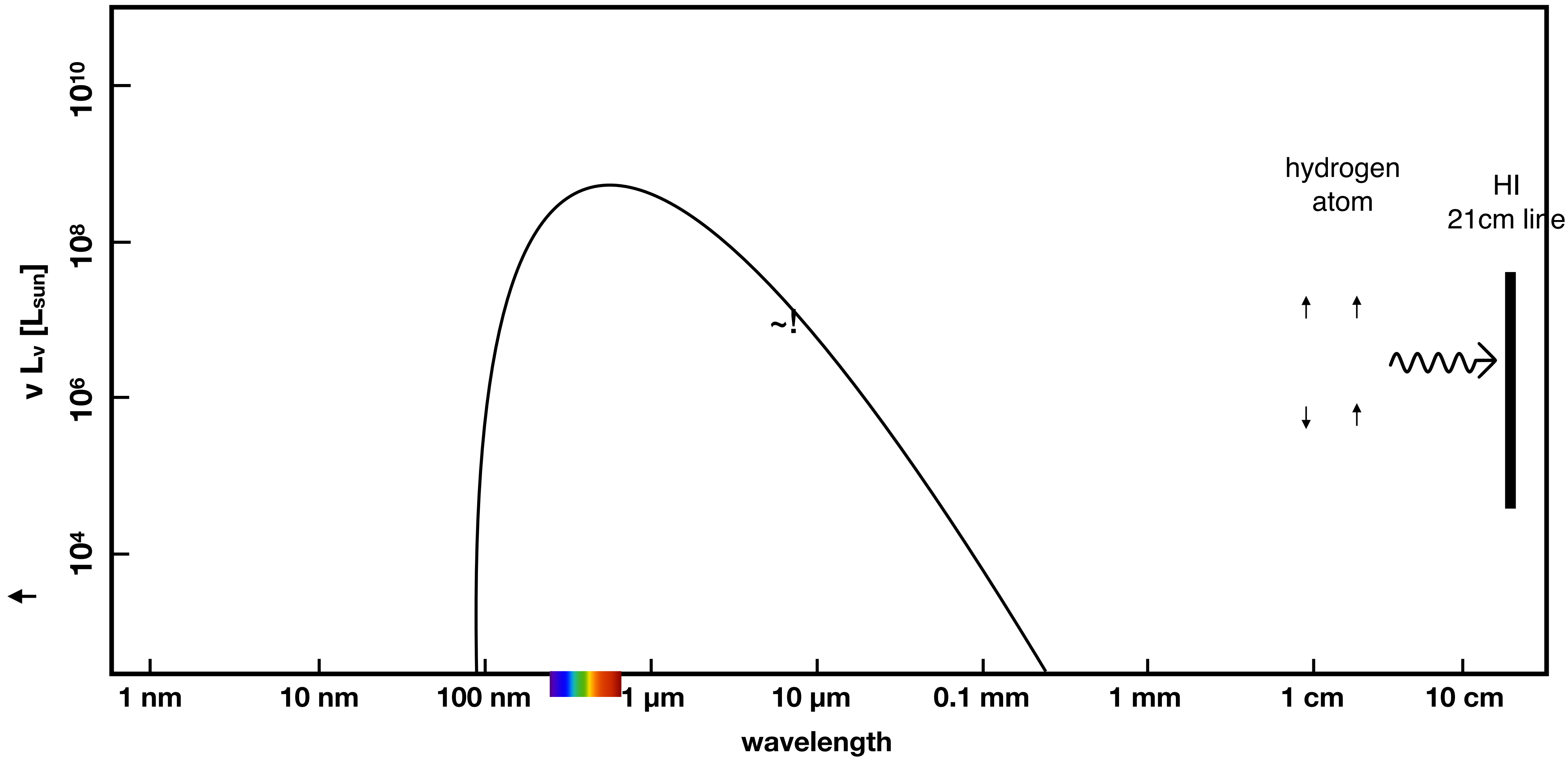
Line emission

e.g., spontaneous emission, rotation and vibration of molecules



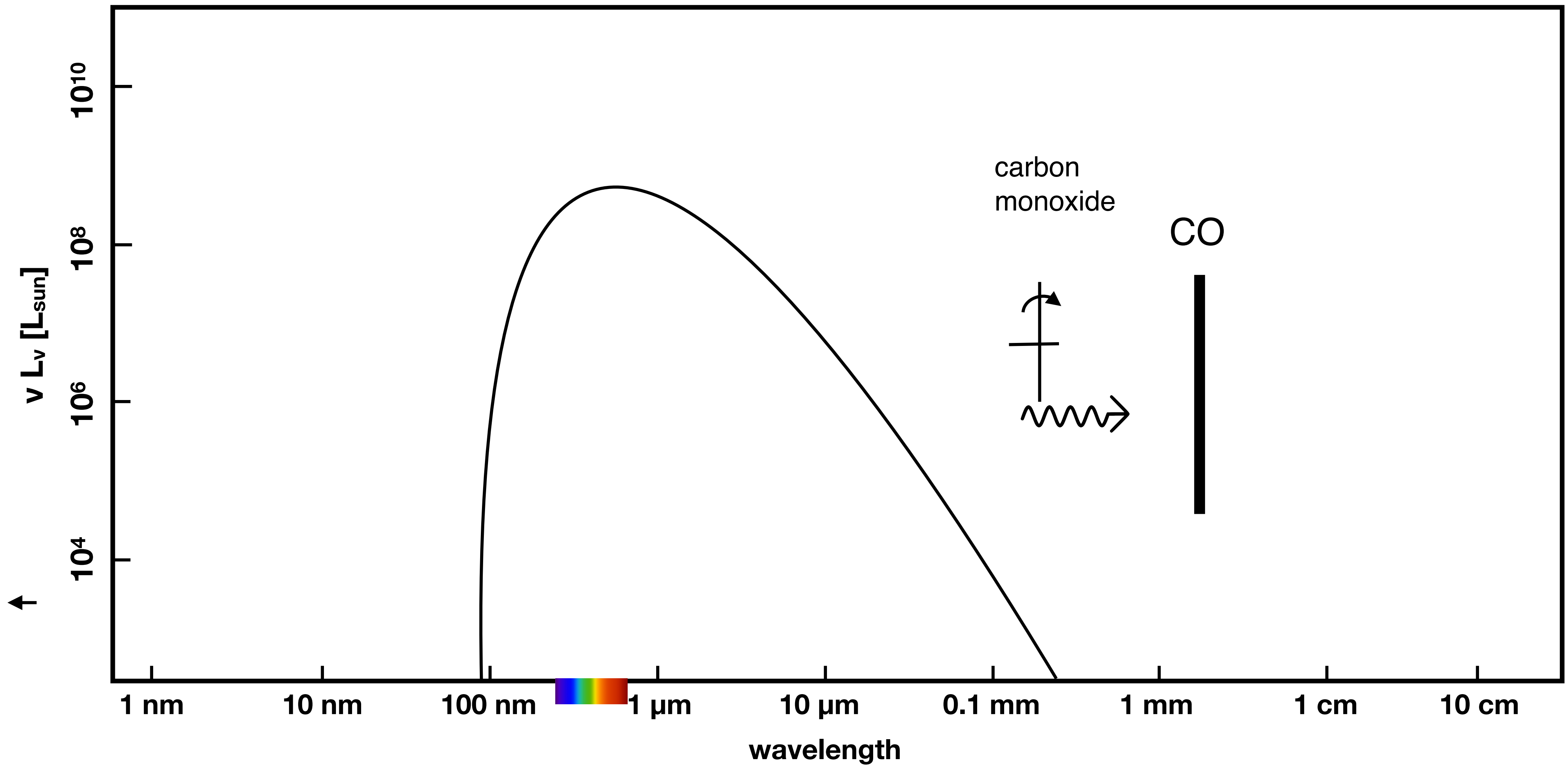
Line emission

e.g., spontaneous emission, rotation and vibration of molecules



Line emission

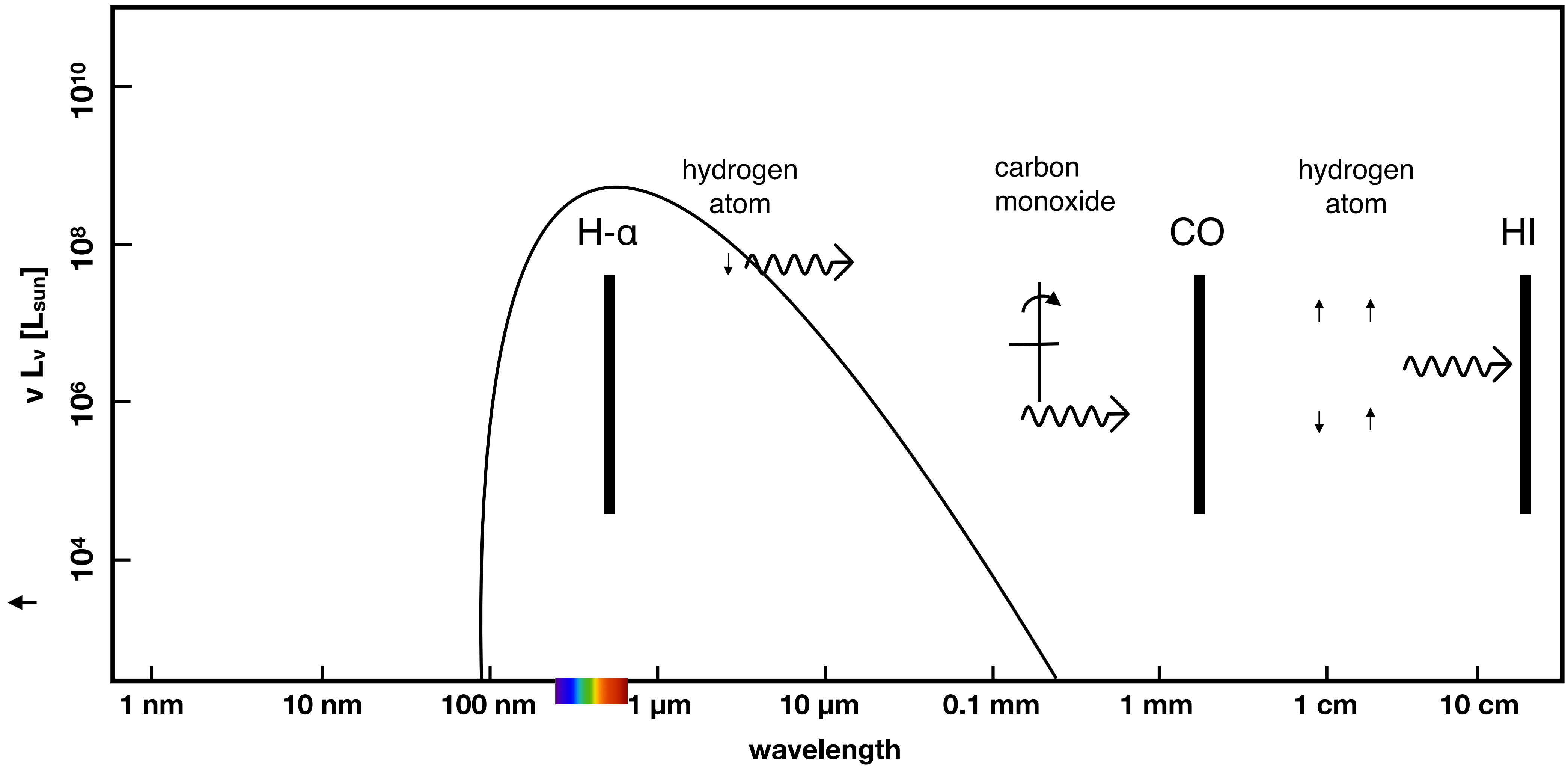
e.g., spontaneous emission, rotation and vibration of molecules



Line emission

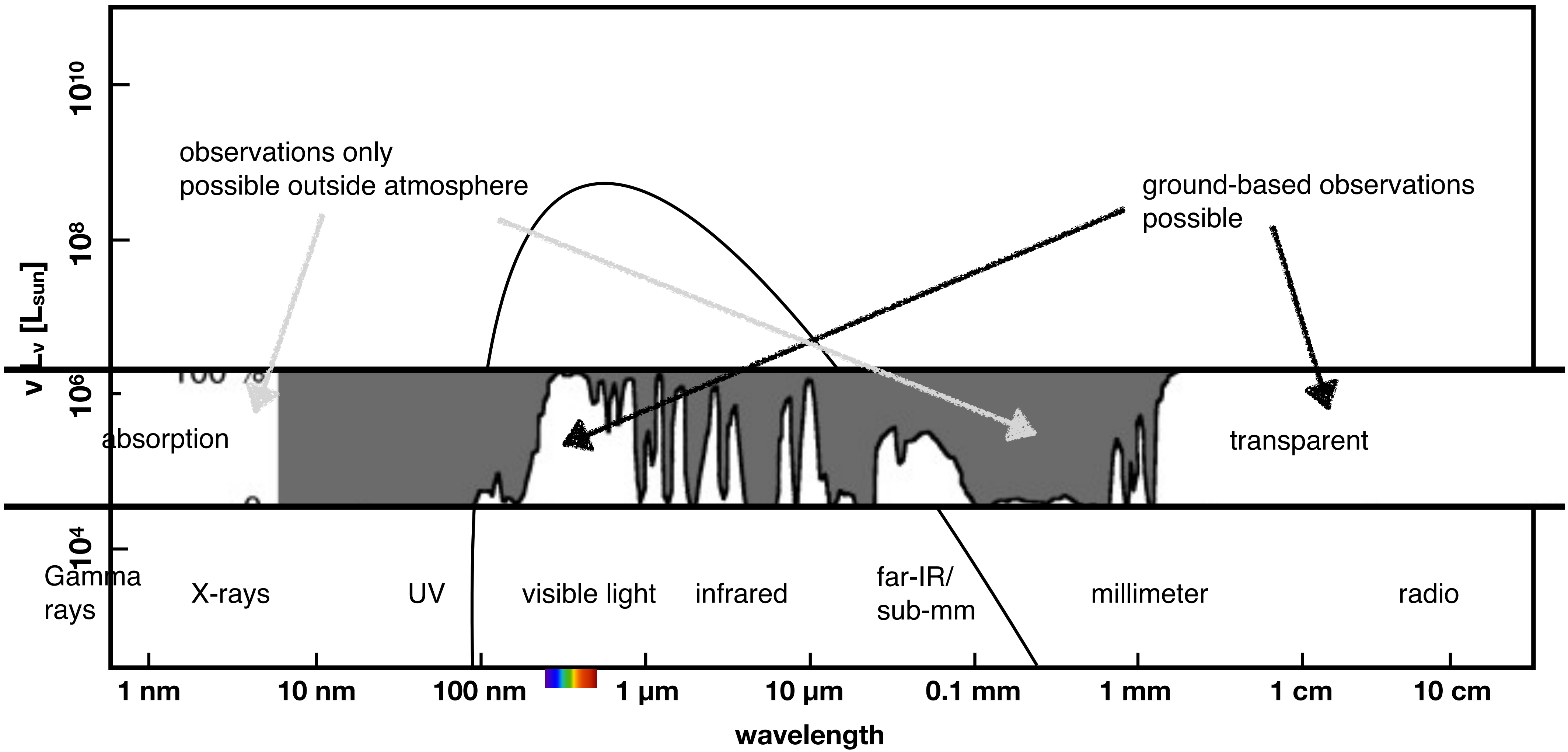
e.g., spontaneous emission, rotation and vibration of molecules

…10s of thousands of lines…



earth’s atmosphere: 78% nitrogen, 21% oxygen

CO_2, O_2, and H_2O are much less abundant, yet they absorb radiation



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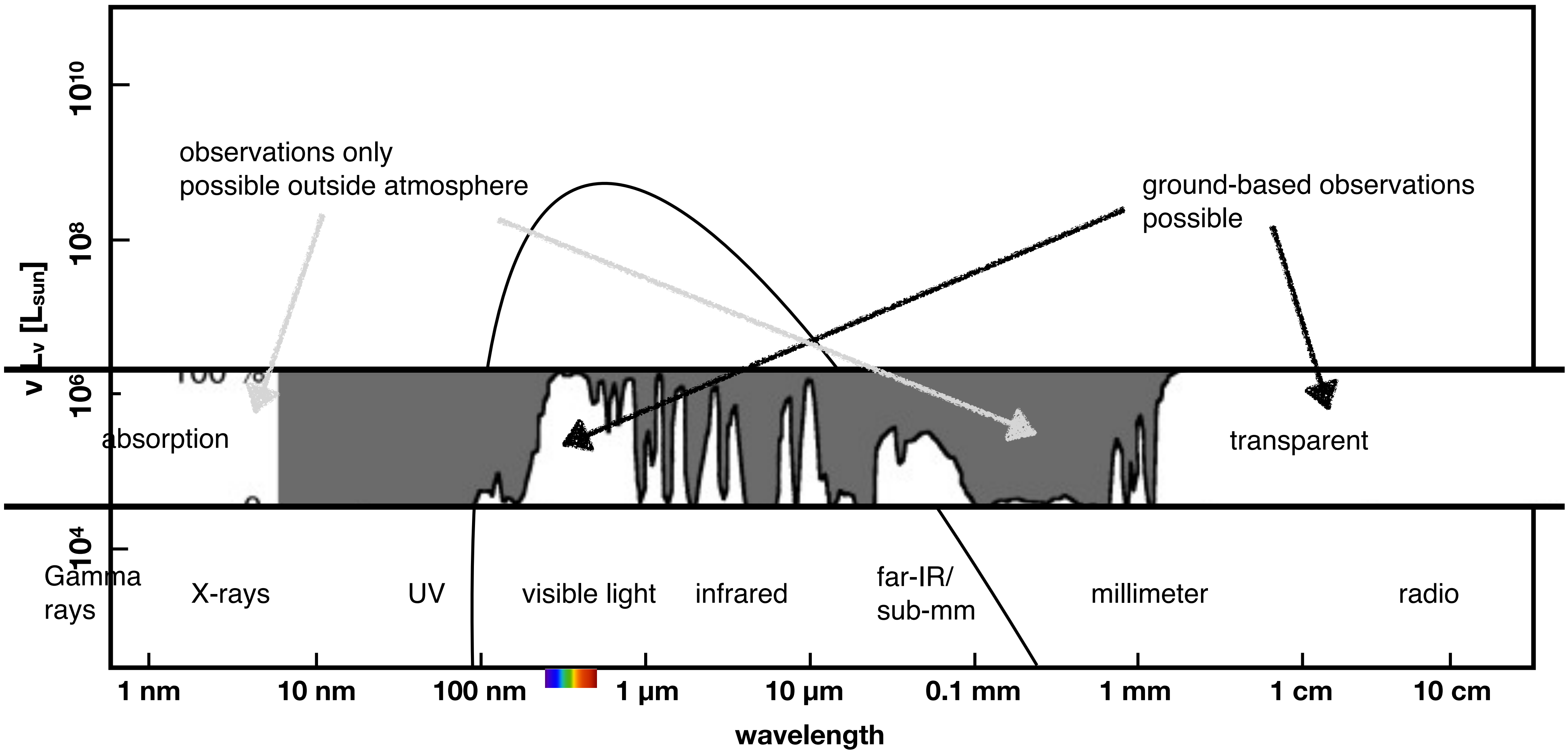


note: Rayleigh Jeans scattering ~frequency^4 — essentially no scattering in radio

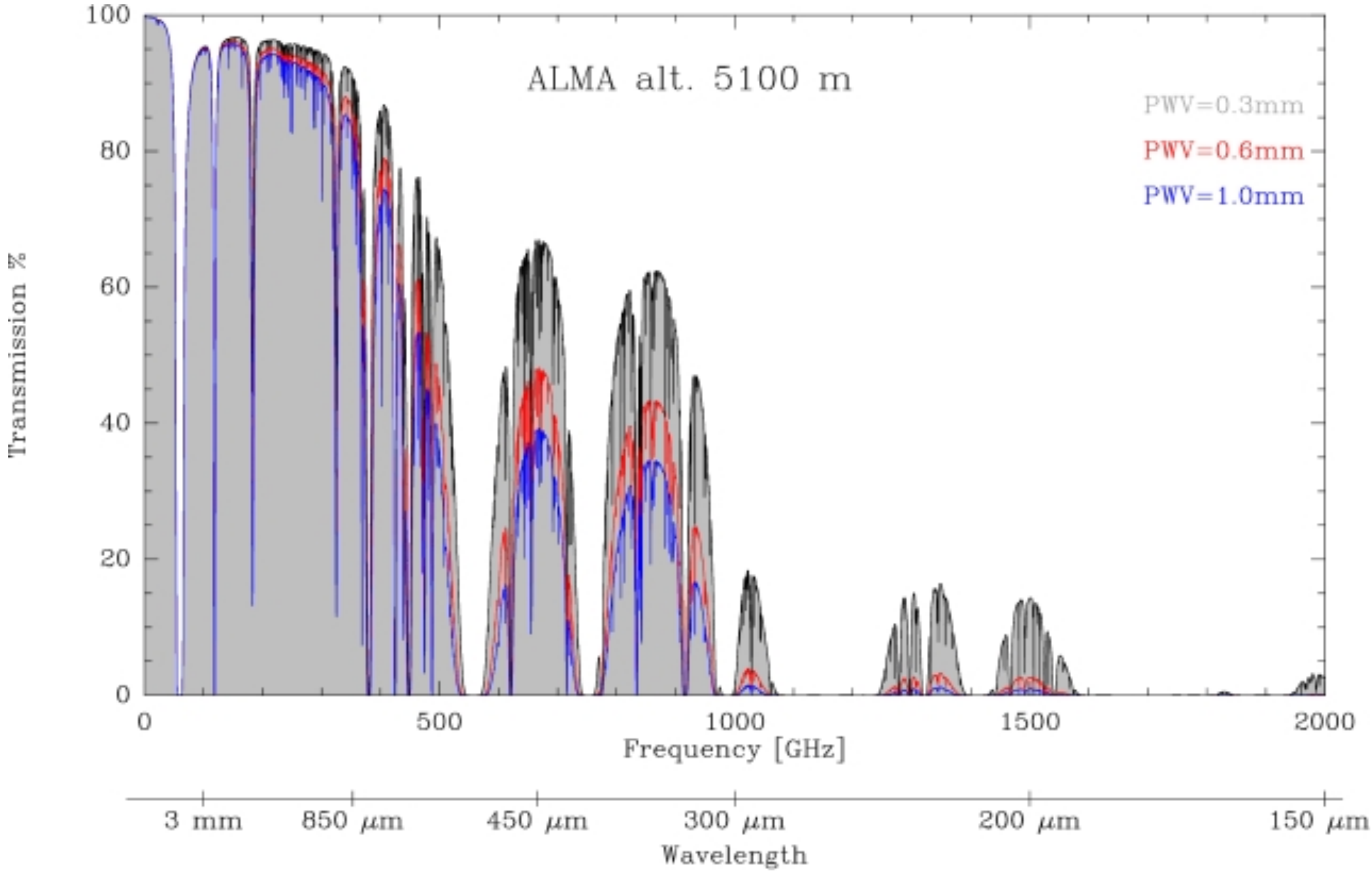
sun does not strongly emit in radio (at least to first order) - sky is radio-dark

Classical radio range: centimeter and meter waves,
MHz and GHz frequencies (< 30 GHz),
ionosphere reflects signals below 10 MHz

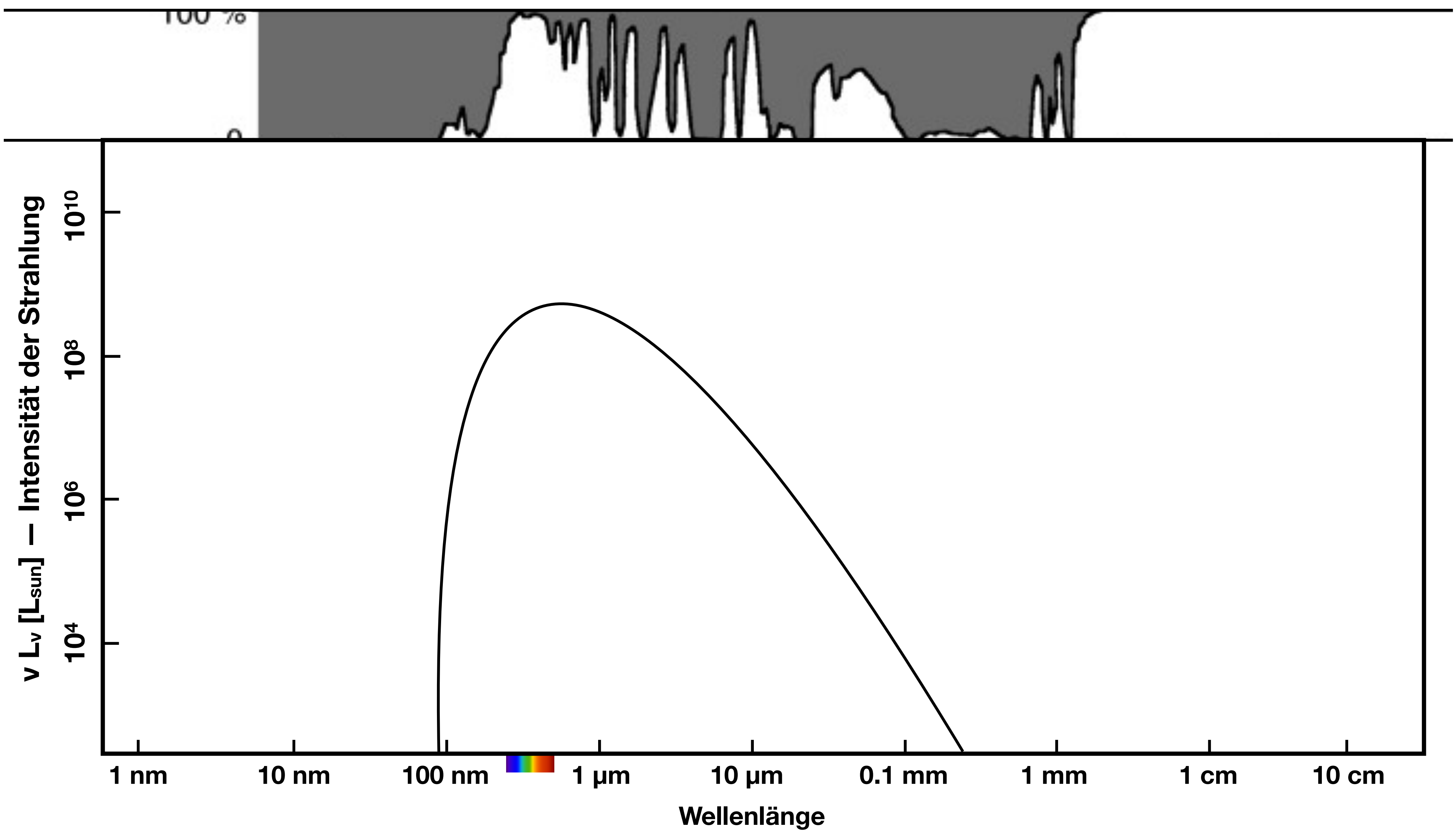
Millimeter range: mm waves, i.e. 10 … 1 mm (30 - 300 GHz),
atmospheric windows at 7, 3 and 1.3 mm

Sub-millimeter range: ~ 300 – 1000 μm (1000 … 300 GHz),
atmospheric windows at 350, 450 and 850 μm

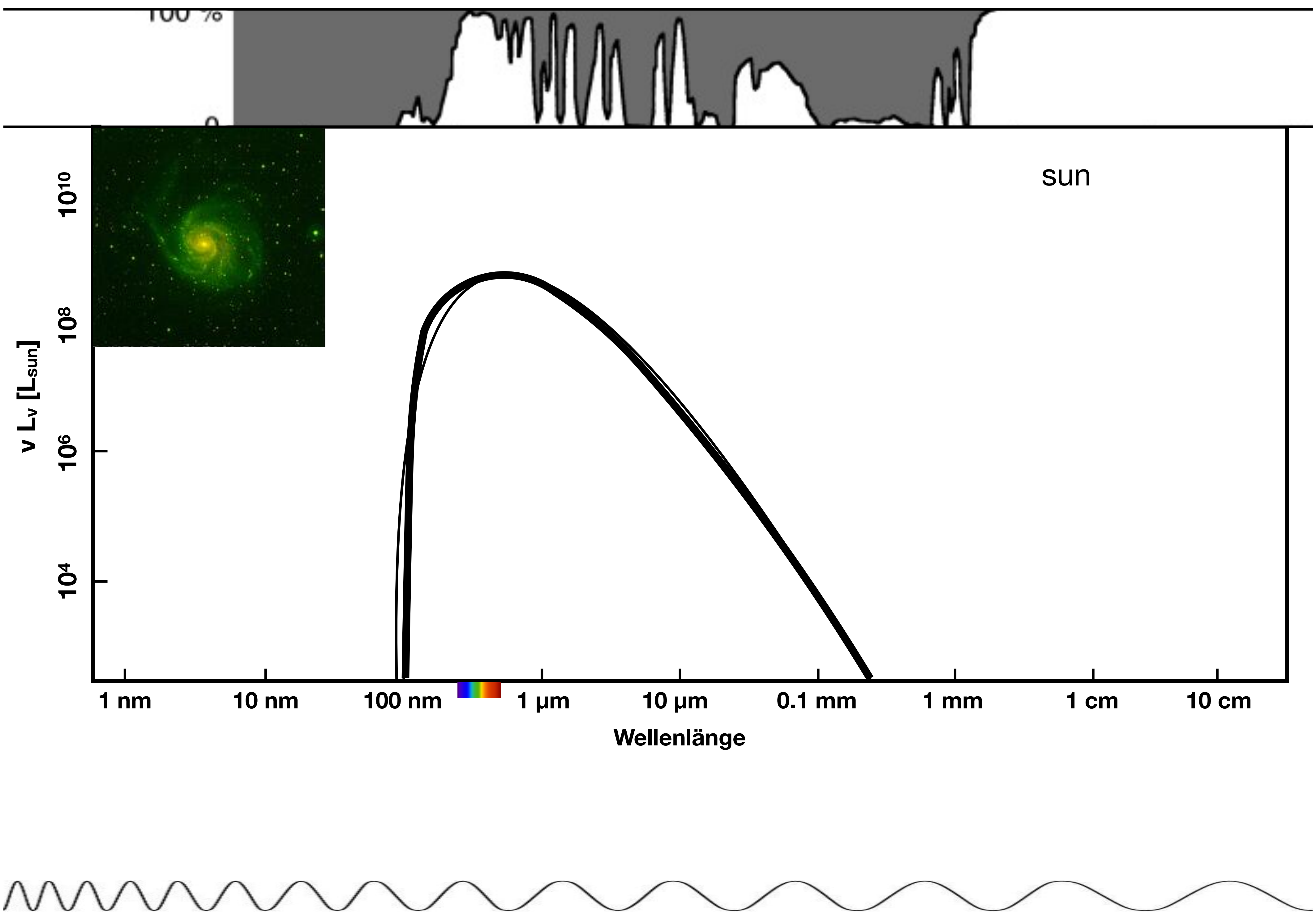
Atmospheric windows



SOFIA (stratosphere observatory) — up to 5 THz



100 %
0
ν Lν [Lsun] — Intensität der Strahlung
10¹⁰
10⁸
10⁶
10⁴
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge



100 %
0
sun
νL_ν [L_{sun}]
10^{10}
10^8
10^6
10^4
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge

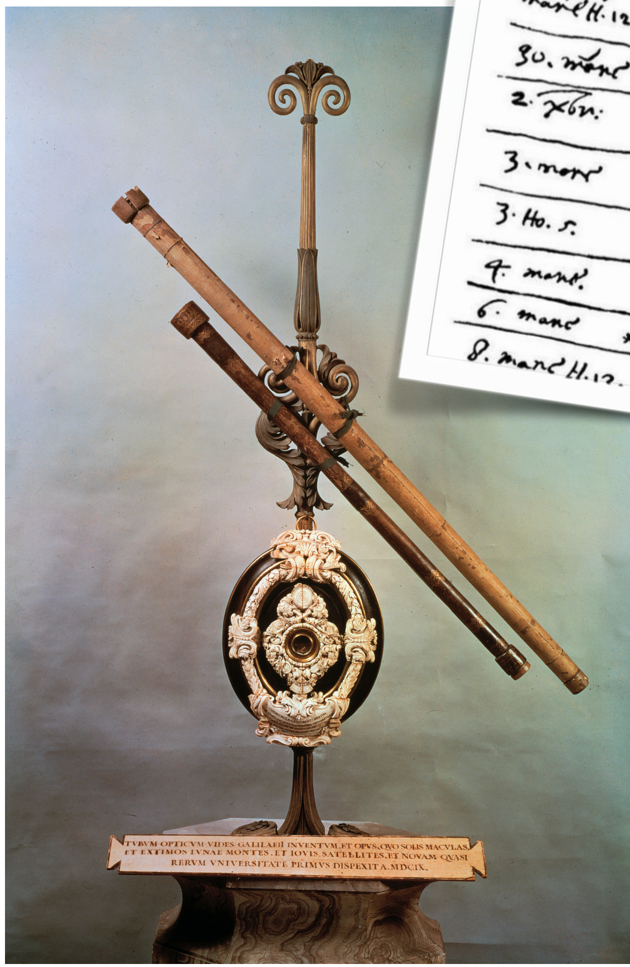
visible light

first drawings ~20.000 years ago (Lascaux cave)

visible light

first drawings ~20.000 years ago (Lascaux cave)

Galileo Galilei (January 1610) observations of Jupiter's moons

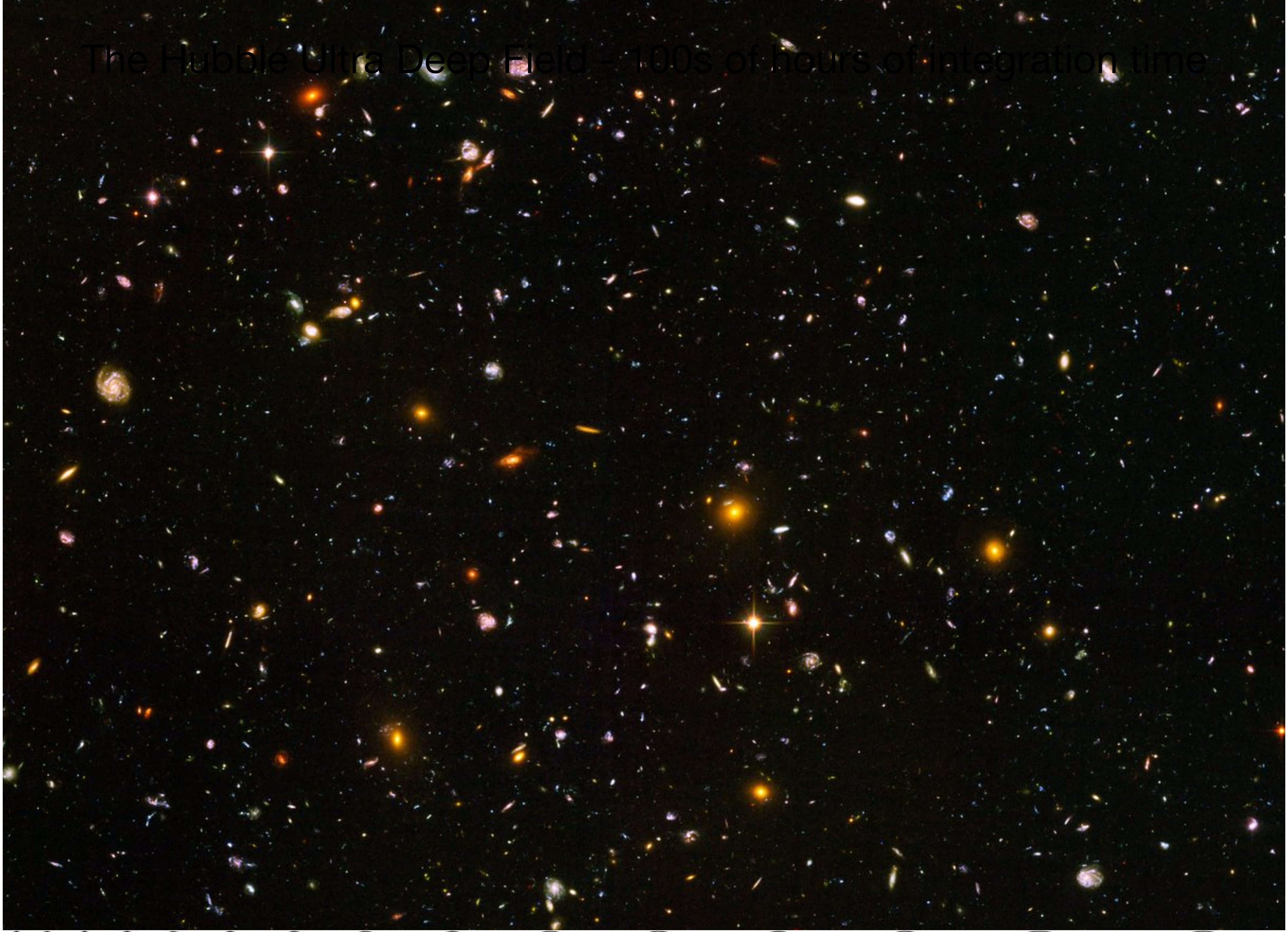


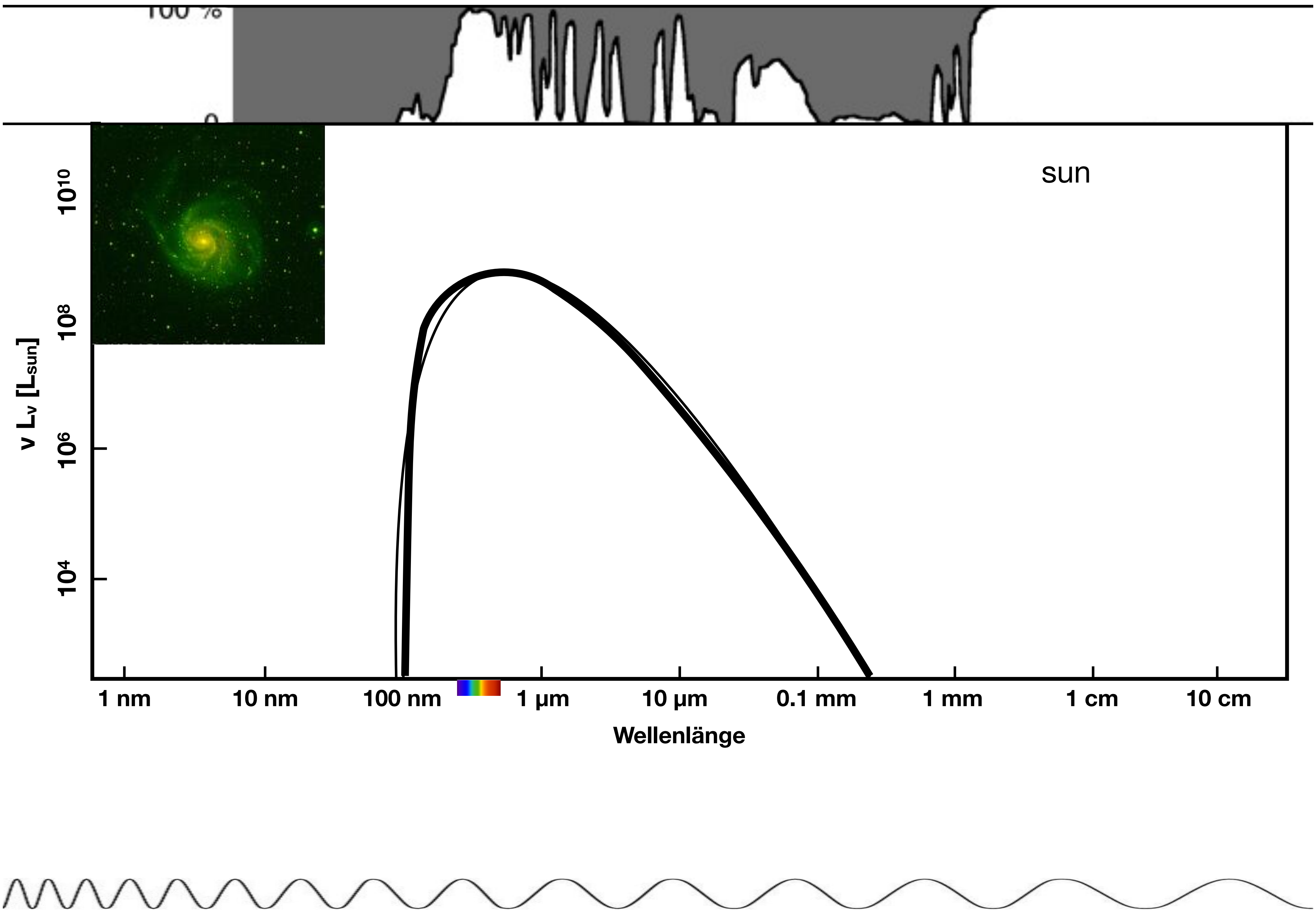
visible light

Very Large Telescope
European Southern Observatory

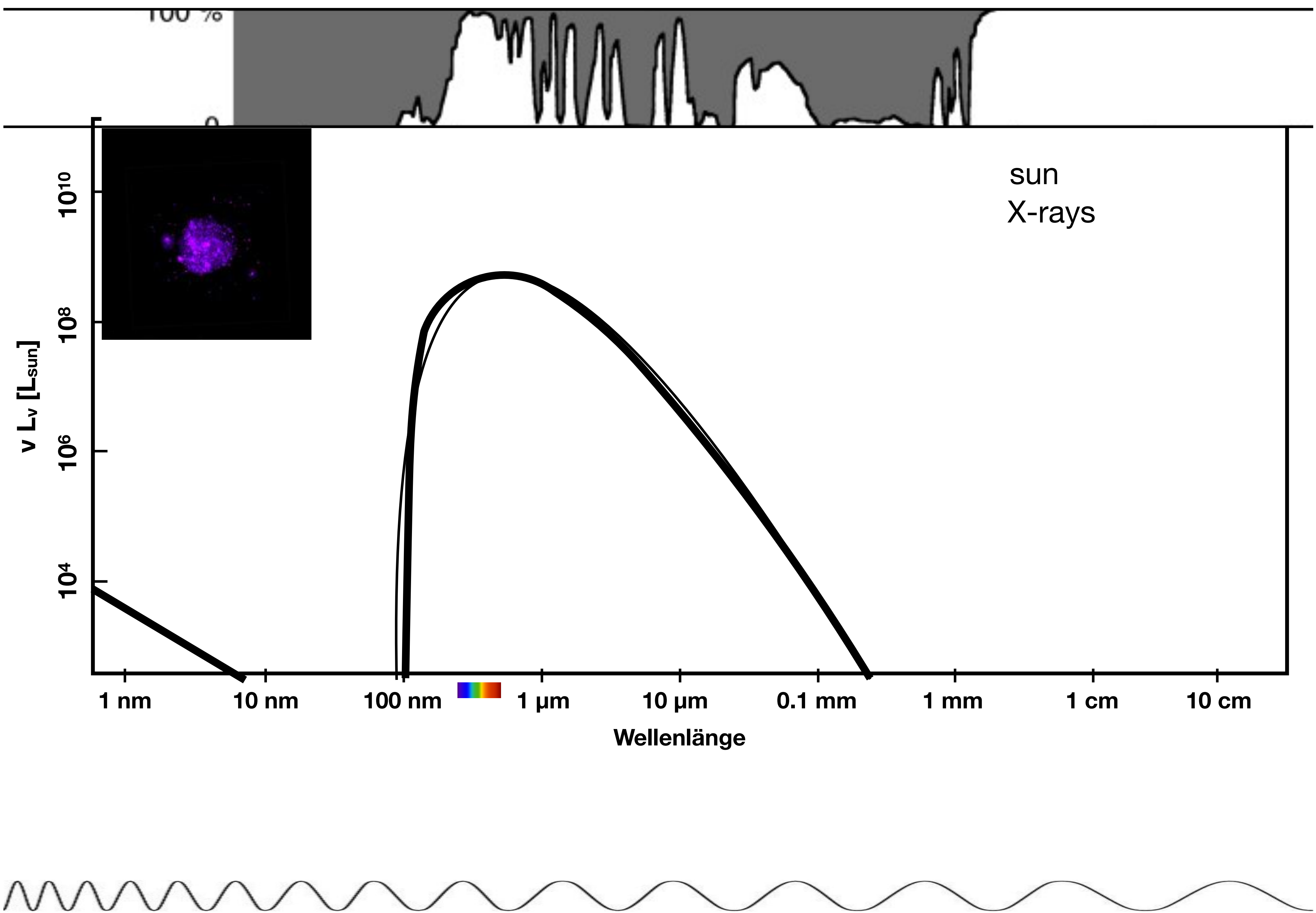
Hubble Space Telescope

The Hubble Ultra Deep Field - 100s of hours of integration time





100 %
0
sun
ν Lν [Lsun]
10¹⁰
10⁸
10⁶
10⁴
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge



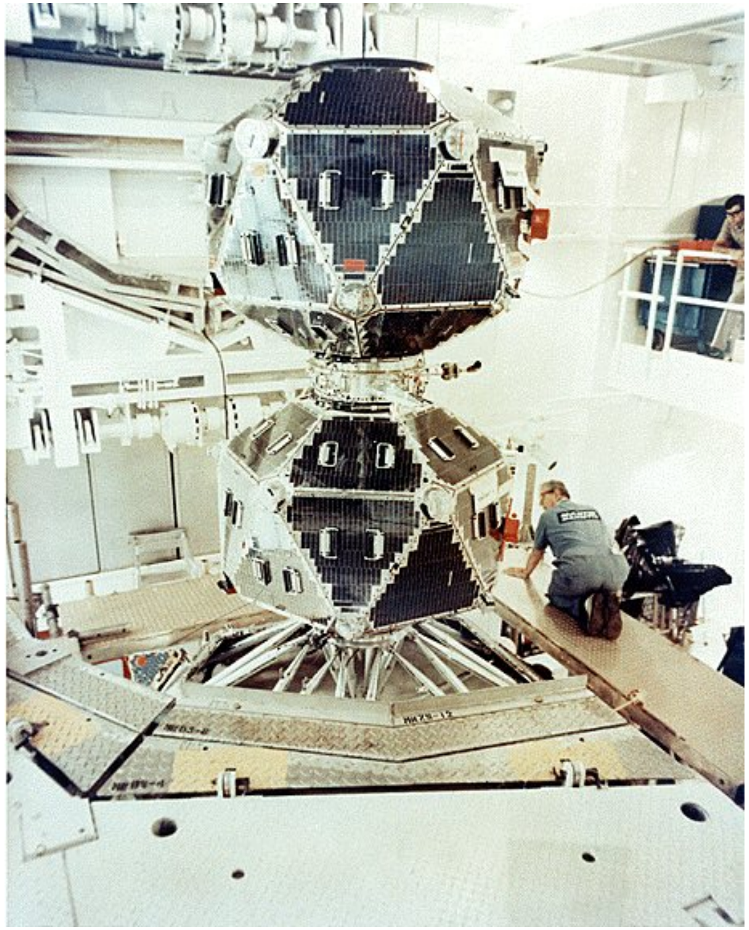
100 %
0
sun
X-rays
ν Lν [Lsun]
10¹⁰
10⁸
10⁶
10⁴
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge

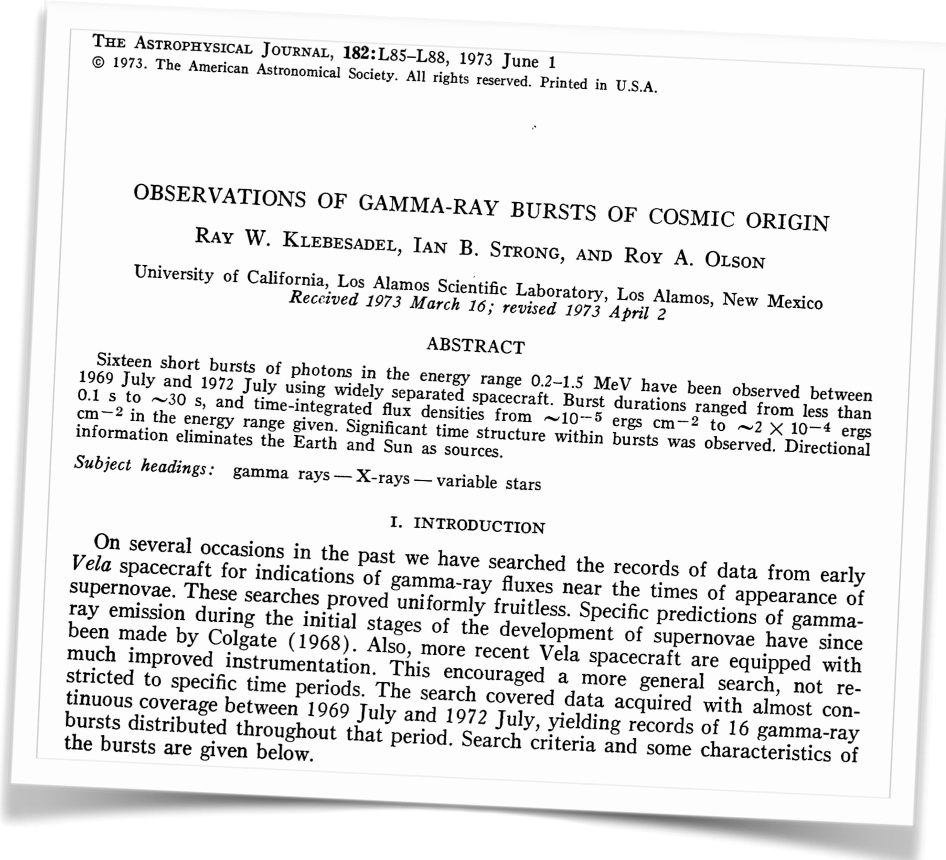
Gamma rays

First satellites in the 60s to observe the sun

Vela Satellit: built to detect nuclear explosions by USSR (note: gamma rays for backside of moon)

First astrophysical detect towards the end of the 60s.





THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

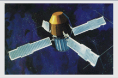
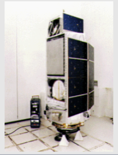
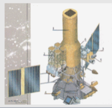
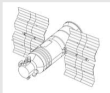
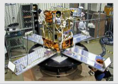
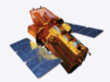
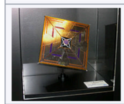
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from ~10^{-5} ergs cm^{-2} to ~2×10^{-4} ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

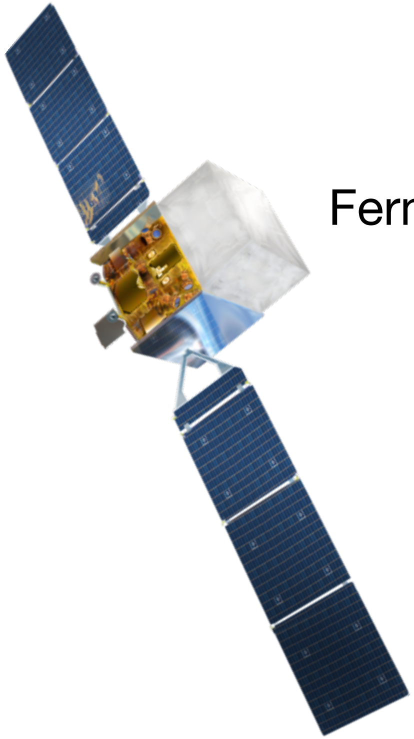
I. INTRODUCTION

On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-ray emission during the initial stages of the development of supernovae have since been made by Colgate (1968). Also, more recent Vela spacecraft are equipped with much improved instrumentation. This encouraged a more general search, not restricted to specific time periods. The search covered data acquired with almost continuous coverage between 1969 July and 1972 July, yielding records of 16 gamma-ray bursts distributed throughout that period. Search criteria and some characteristics of the bursts are given below.

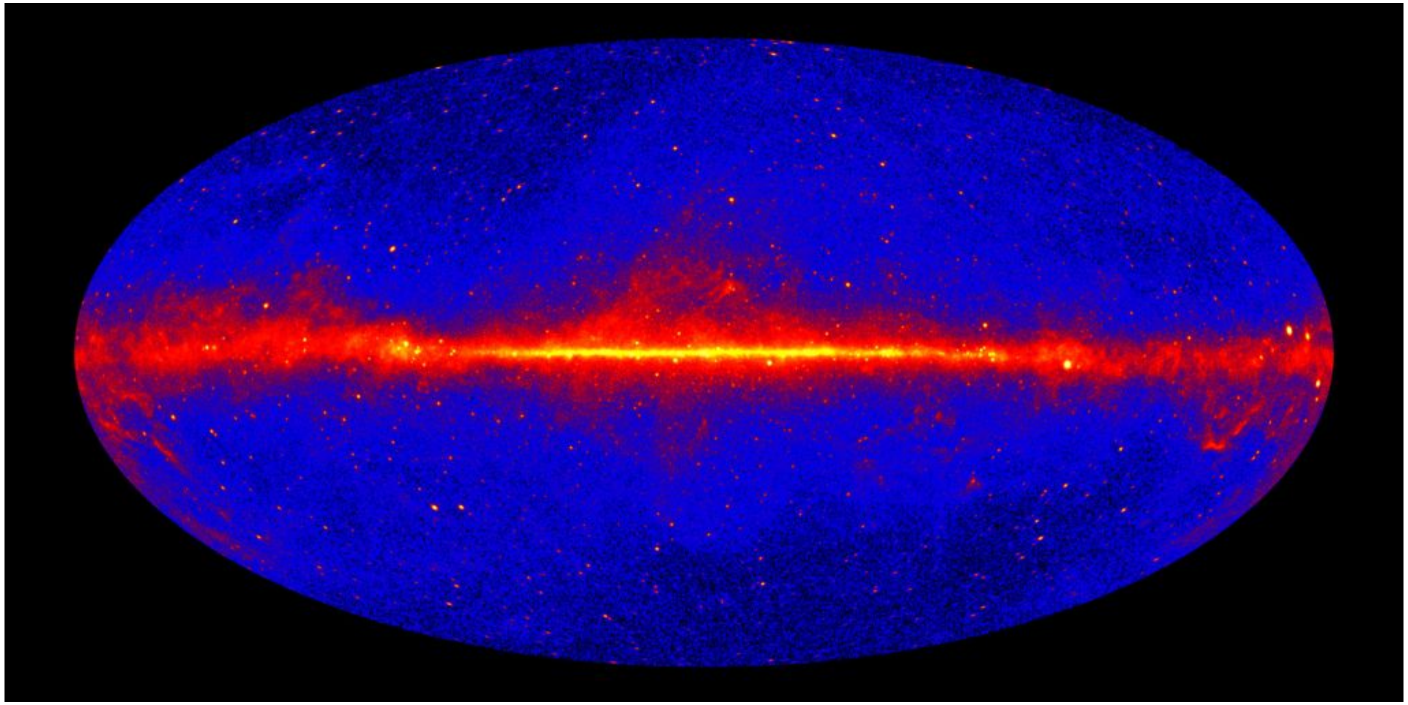
Gamma ray satellites

Photo	Name	Space Agency	Launch Date	Terminated	Location	Ref(s)
	Proton-1	USSR	16 Jul 1965	11 Oct 1965	Earth orbit (183-589 km)	[2]
	Proton-2	USSR	2 Nov 1965	6 Feb 1966	Earth orbit (191-637 km)	[2]
	Proton-4	USSR	16 Nov 1968	24 Jul 1969	Earth orbit (248-477 km)	[3]
	Second Small Astronomy Satellite (SAS 2)	NASA	15 Nov 1972	8 Jun 1973	Earth orbit (443–632 km)	[4][5]
	Cos-B	ESA	9 Aug 1975	25 Apr 1982	Earth orbit (339.6–99,876 km)	[6][7][8]
	3rd High Energy Astronomy Observatory (HEAO 3)	NASA	20 Sep 1979	29 May 1981	Earth orbit (486.4–504.9 km)	[9][10][11]
	Granat	CNRS & IKI	1 Dec 1989	25 May 1999	Earth orbit (2,000–200,000 km)	[12][13][14]
	Gamma	USSR, CNES, RSA	1 Jul 1990	1992	Earth orbit (375 km)	[15]
	Compton Gamma Ray Observatory (CGRO)	NASA	5 Apr 1991	4 Jun 2000	Earth orbit (362–457 km)	[16][17][18]
	Low Energy Gamma Ray Imager (LEGRI)	INTA	19 May 1997	Feb 2002	Earth orbit (600 km)	[19][20]
	High Energy Transient Explorer 2 (HETE 2)	NASA	9 Oct 2000	Mar 2008	Earth orbit (590–650 km)	[21][22][23]
	International Gamma Ray Astrophysics Laboratory (INTEGRAL)	ESA	17 Oct 2002	—	Earth orbit (639–153,000 km)	[24][25]
	Swift Gamma Ray Burst Explorer	NASA	20 Nov 2004	—	Earth orbit (585–604 km)	[26][27]
	Astrorivelatore Gamma ad Immagini LEggero (AGILE)	ISA	23 Apr 2007	—	Earth orbit (524–553 km)	[28][29]
	Fermi Gamma-ray Space Telescope	NASA	11 Jun 2008	—	Earth orbit (555 km)	[30]
	Gamma-Ray Burst Polarimeter (GAP)	JAXA	21 May 2010	—	Heliocentric orbit	[31]

Gamma rays

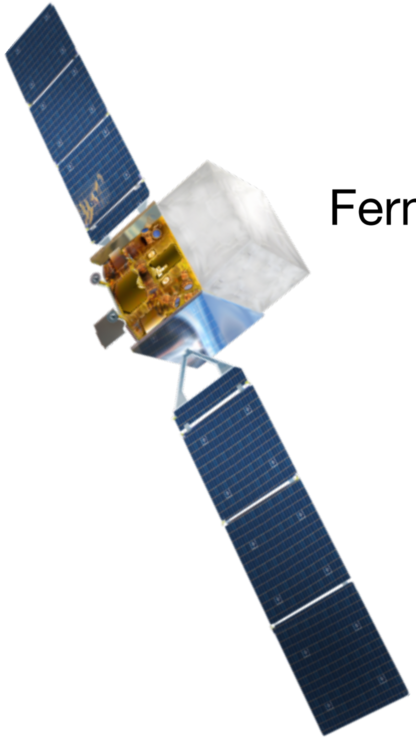


Fermi

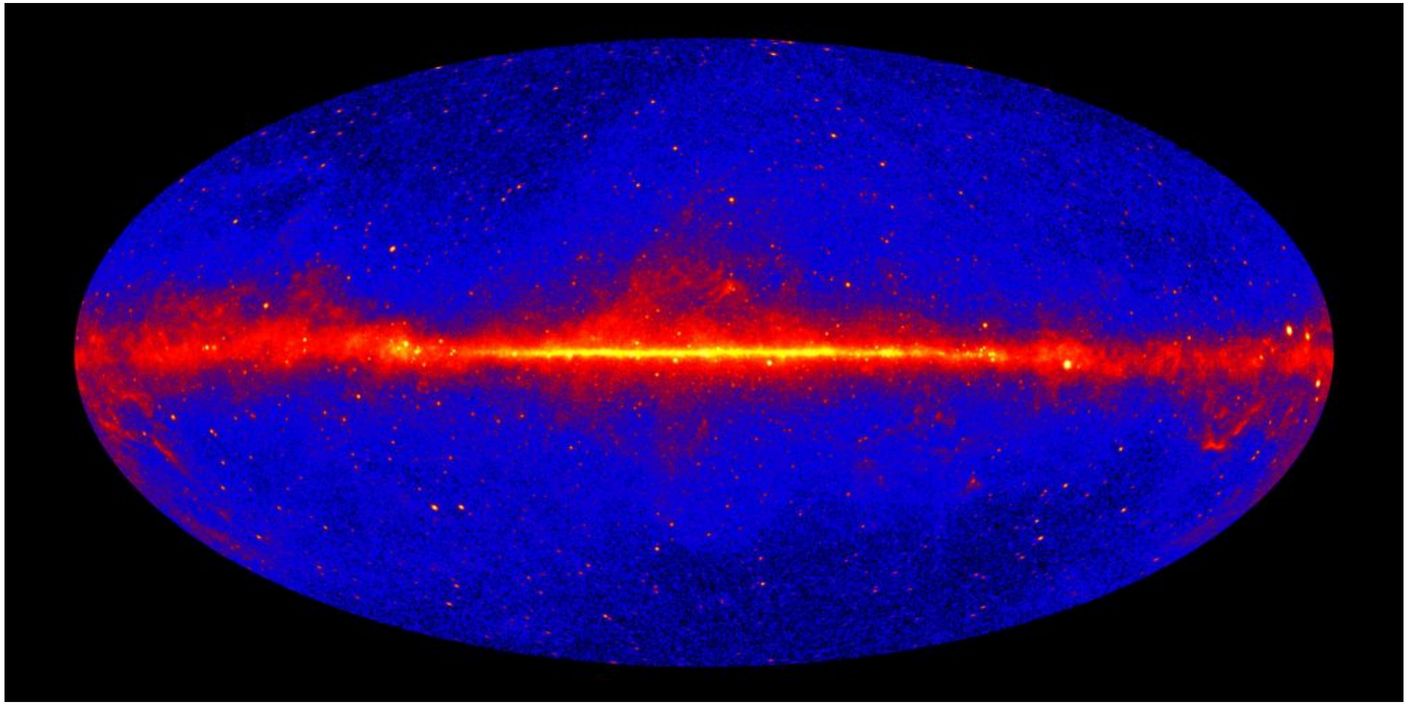


gamma ray sky, Fermi satellite

Gamma rays



Fermi

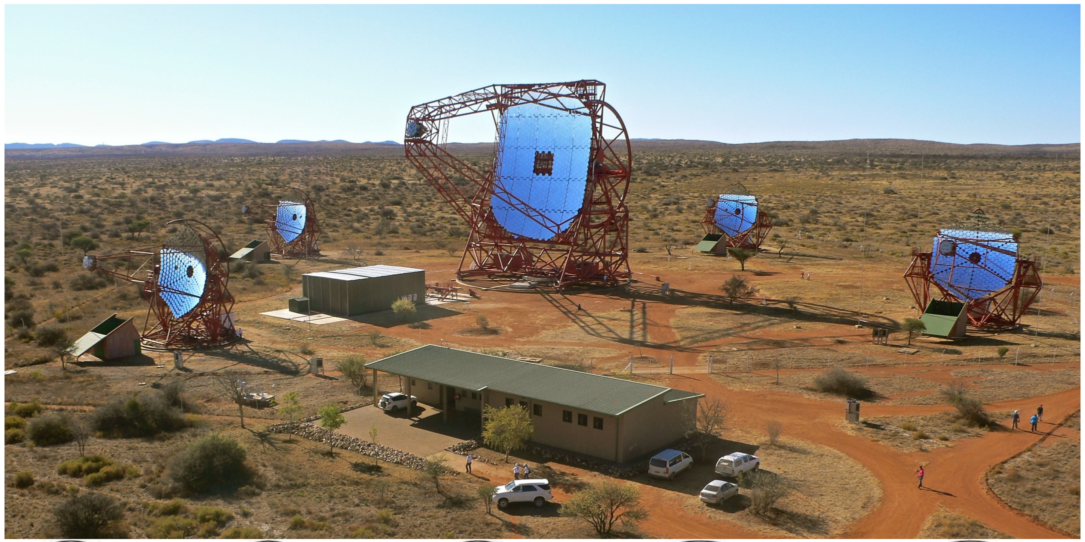


gamma ray sky, Fermi satellite

High Energy Stereoscopic System:

smart method to detect gamma rays
with ground-based telescopes
(Cherenkov radiation)

(MPK Heidelberg)



X-rays

First extraterrestrial X-ray / UV detection: 1949

First X-ray 1895

PHYSICAL REVIEW VOLUME 83, NUMBER 5 SEPTEMBER 1, 1951

Photon Counter Measurements of Solar X-Rays and Extreme Ultraviolet Light

H. Friedman, S. W. Lichtman, and E. T. Byram
U. S. Naval Research Laboratory, Washington, D. C.

(Received May 10, 1951)

Data telemetered continuously from photon counters in a V-2 rocket, which rose to 150 km at 10:00 A.M. on September 29, 1949, showed solar 8A x-rays above 87 km, and ultraviolet light around 1200A and 1500A above 70 km and 95 km, respectively. The results indicated that solar soft x-rays are important in *E*-layer ionization, that Lyman α-radiation of hydrogen penetrates well below *E*-layer, and that molecular oxygen is rapidly changed to atomic above 100 km.

A V-2 ROCKET, fired in September 1949, carried a set of photon counter tubes which were sensitive to light in the soft x-ray and extreme ultraviolet regions of the spectrum. Each tube responded to a relatively narrow portion of the spectrum in one of four bands covering 0–10A, 1100–1350A, 1425–1650A, and 1725–2100A. The experiment provided an uninterrupted telemetered recording of solar radiation intensities within these wavelength bands throughout the flight of the rocket. Intense solar x-ray emission was detected at altitudes above 87 kilometers. In the atmospheric window near λ 1200A, the photon counters responded strongly above a level of about 70 kilometers. Most of the solar radiation near the peak of the Schumann-Runge absorption band of molecular oxygen, was absorbed between the levels of approximately 95 and 115 km. Only one tube was flown which was sensitive to the longer wavelengths between the oxygen and ozone bands ($\sim$2000A). Its counting rate rose sharply when the rocket reached an altitude of 7 kilometers, but the tube was too sensitive to provide any useful data above 20 kilometers. These measurements support the ideas: that *E*-layer ionization is directly related to soft x-ray emission from the corona; that Lyman α-radiation penetrates the atmosphere well below *E*-layer; and that the transition from molecular to atomic oxygen takes place at altitudes near 100 km.

FLIGHT DETAILS

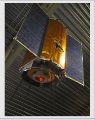
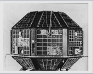
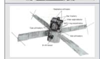
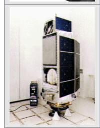
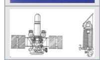
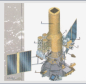
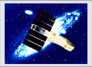
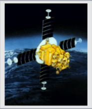
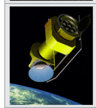
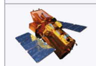
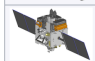
The rocket (V-2, No. 49) was fired at 10:00 A.M., M.S.T. on September 29, 1949 at the White Sands Proving Ground, New Mexico. The altitude of the sun was 43 degrees. No unusual solar activity was noted at the time of the flight. The telemetering record was continuous over the entire flight period of 336 seconds, during which time the rocket soared to a height of 150 km. Fuel cutoff was made at 64 seconds after take-off. For the first 60 seconds the rocket was in stable flight, after which time it developed a slow, steady roll of approximately 12 seconds average period. The roll persisted until the warhead was blown off at 336 seconds.

EXPERIMENTAL DETAILS

An assortment of 6 photon counter tubes was contained in two pressurized boxes, each unit comprising in effect a photon counter spectroscope. The boxes were located on opposite sides of the warhead, with exposed window areas parallel to the surface of the warhead. In addition to the counter tubes, each box also contained one control tube, sensitive only to cosmic rays, and one photocell for determining the roll orientation of the rocket with respect to the sun.

Each tube consisted of a chrome-iron cathode cylinder, $\frac{3}{4}$ inch in diameter and 2 inches long, and an anode wire, 0.025 inch in diameter. The cathode also served as the envelope of the tube. Glass caps, which supported the anode wire, were sealed to the steel cylinder at each end. A circular aperture $\frac{3}{16}$ in. in diameter was provided in a flat recess, milled midway along the length of the cathode. This aperture was covered by

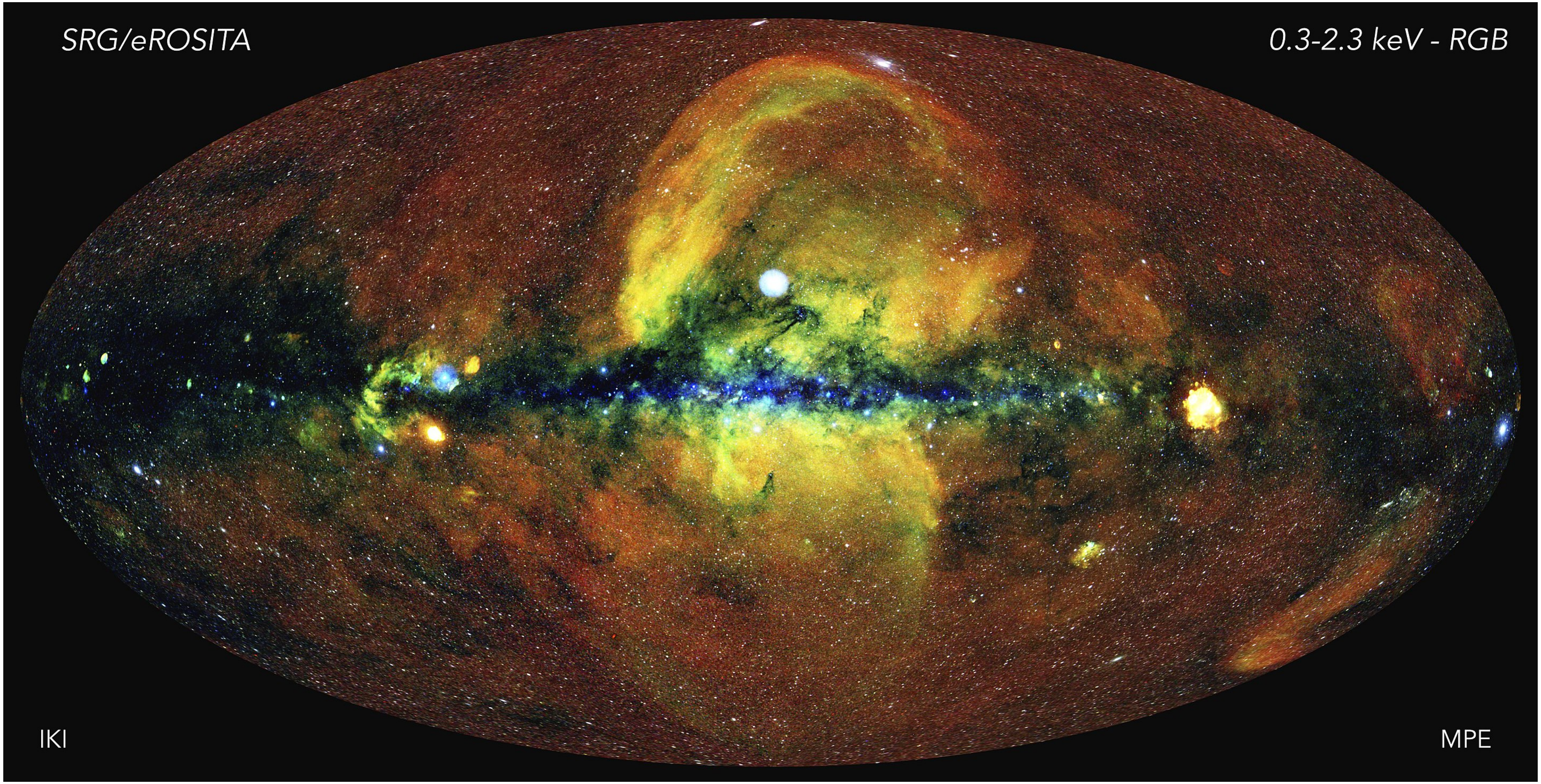
X-ray satellites

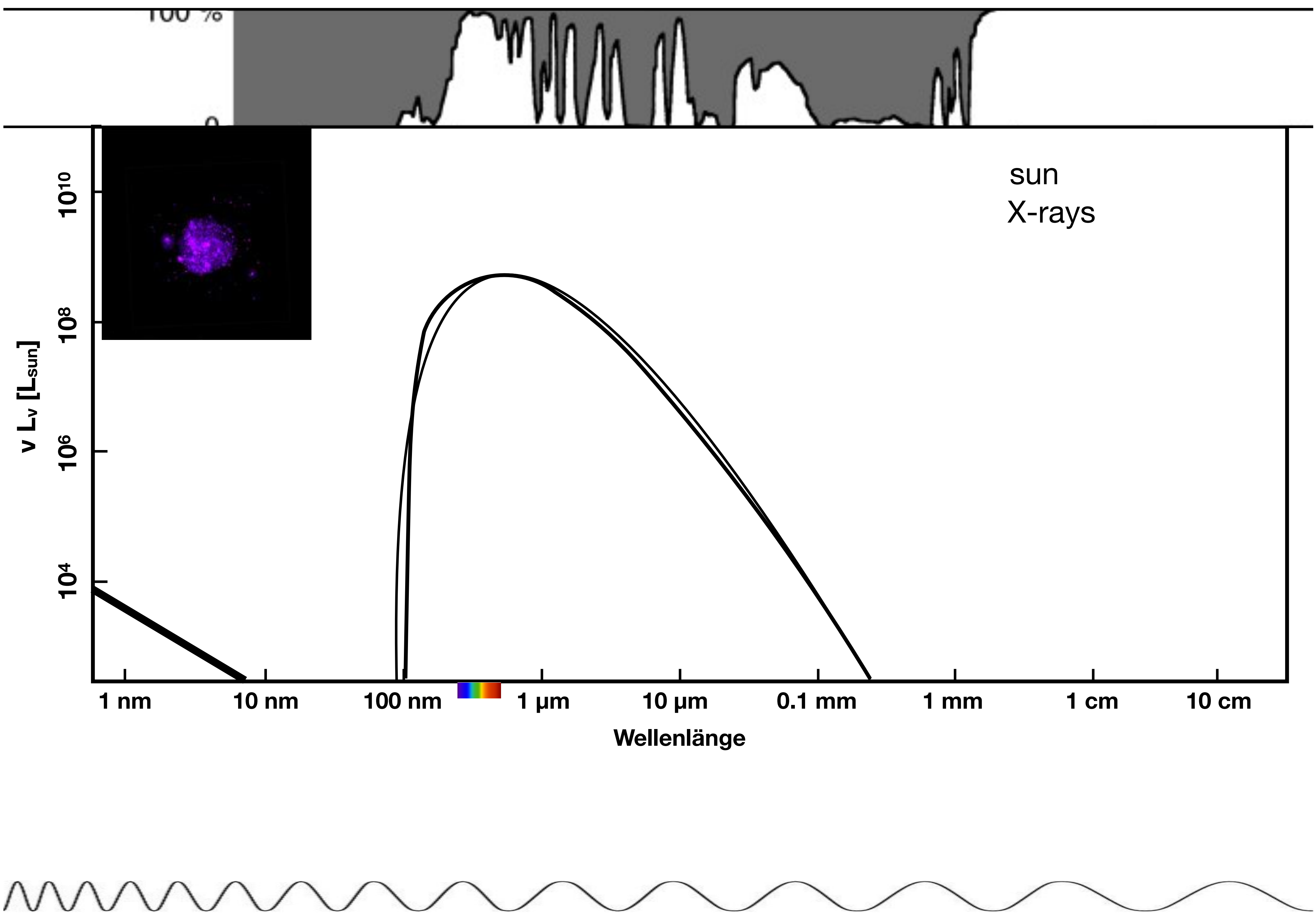
Photo	Name	Space Agency	Launch Date	Terminated	Location	Ref(s)
	Uhuru	NASA	12 Dec 1970	Mar 1973	Earth orbit (531–572 km)	[32][33][34]
	Astronomical Netherlands Satellite (ANS)	SRON	30 Aug 1974	Jun 1976	Earth orbit (266–1176 km)	[35][36]
	Ariel V	SRC & NASA	15 Oct 1974	14 Mar 1980	Earth orbit (520 km)	[37][38]
	Aryabhata	ISRO	19 Apr 1975	23 Apr 1975	Earth orbit (563–619 km)	[39]
	Third Small Astronomy Satellite (SAS-C)	NASA	7 May 1975	Apr 1979	Earth orbit (509–516 km)	[40][41][42]
	Cos-B	ESA	9 Aug 1975	25 Apr 1982	Earth orbit (339.6–99,876 km)	[6][7][8]
	Cosmic Radiation Satellite (CORSA)	ISAS	6 Feb 1976	6 Feb 1976	Failed launch	[43][44]
	1st High Energy Astronomy Observatory (HEAO 1)	NASA	12 Aug 1977	9 Jan 1979	Earth orbit (445 km)	[45][46][47]
	Einstein Observatory (HEAO 2)	NASA	13 Nov 1978	26 Apr 1981	Earth orbit (465–476 km)	[48][49]
	Hakucho (CORSA-b)	ISAS	21 Feb 1979	16 Apr 1985	Earth orbit (421–433 km)	[50][51][52]
	3rd High Energy Astronomy Observatory (HEAO 3)	NASA	20 Sep 1979	29 May 1981	Earth orbit (486.4–504.9 km)	[9][10][11]
	Tenma (Astro-B)	ISAS	20 Feb 1983	19 Jan 1989	Earth orbit (489–503 km)	[53][54][55]
	Astron	IKI	23 Mar 1983	Jun 1989	Earth orbit (2,000–200,000 km)	[56][57][58]
	EXOSAT	ESA	26 May 1983	8 Apr 1986	Earth orbit (347–191,709 km)	[59][60][61]
	Ginga (Astro-C)	ISAS	5 Feb 1987	1 Nov 1991	Earth orbit (517–708 km)	[62][63][64]
	Granat	CNRS & IKI	1 Dec 1989	25 May 1999	Earth orbit (2,000–200,000 km)	[12][13][14]
	ROSAT	NASA & DLR	1 Jun 1990	12 Feb 1999	Re-entry 23 October 2011.[65] Formerly Earth orbit (580 km)	[66][67][68]
	Broad Band X-ray Telescope / Astro 1	NASA	2 Dec 1990	11 Dec 1990	Earth orbit (500 km)	[69][70]
	Advanced Satellite for Cosmology and Astrophysics (ASCA, Astro-D)	ISAS & NASA	20 Feb 1993	2 Mar 2001	Earth orbit (523.6–615.3 km)	[71][72]
	Array of Low Energy X-ray Imaging Sensors (Alexis)	LANL	25 Apr 1993	2005	Earth orbit (749–844 km)	[73][74][75]
	Rossi X-ray Timing Explorer (RXTE)	NASA	30 Dec 1995	3 Jan 2012	Earth orbit (409 km)	[76][77][78]
	BeppoSAX	ASI	30 Apr 1996	30 Apr 2002	Earth orbit (575–594 km)	[79][80][81]
	A Broadband Imaging X-ray All-sky Survey (ABRIXAS)	DLR	28 Apr 1999	1 Jul 1999	Earth orbit (549–598 km)	[82][83][84]
	Chandra X-ray Observatory	NASA	23 Jul 1999	—	Earth orbit (9,942–140,000 km)	[85][86]
	XMM-Newton	ESA	10 Dec 1999	—	Earth orbit (7,365–114,000 km)	[87][88]
	High Energy Transient Explorer 2 (HETE 2)	NASA	9 Oct 2000	Mar 2008	Earth orbit (590–650 km)	[21][22][89]
	International Gamma Ray Astrophysics Laboratory (INTEGRAL)	ESA	17 Oct 2002	—	Earth orbit (639–153,000 km)	[24][25]
	Swift Gamma Ray Burst Explorer	NASA	20 Nov 2004	—	Earth orbit (585–604 km)	[26][27]
	Suzaku (Astro-E2)	JAXA & NASA	10 Jul 2005	2 Sep 2015	Earth orbit (550 km)	[90][91]
	AGILE	ISA	23 Apr 2007	—	Earth orbit (524–553 km)	[28][29]
	Nuclear Spectroscopic Telescope Array (NuSTAR)	NASA	13 Jun 2012	—	Earth orbit (603.5 km)	[92][93]
	Astrosat	ISRO	28 Sep 2015	—	Earth orbit (600–650 km)	[94][95][96]
	Hitomi (Astro-H)	JAXA	17 Feb 2016	28 Apr 2016	Earth orbit (575 km)	[97][98][99]
	Mikhailo Lomonosov	Moscow State University	28 Apr 2016	30 Jun 2018	Earth orbit (478–493 km)	[100][101]
	Hard X-ray Modulation Telescope (HXMT)	CNSA & CAS	14 Jun 2017	—	Low Earth orbit (545–554.1 km)	[102]
	Spektr-RG	RSRI & MPE	Jul 13, 2019	—	Sun-Earth L_2	[103]

X-ray satellites

German-Russing Spektr-RG space telescope:

2019: entire sky observed with eROSITA (MPE):





100 %
0
sun
X-rays
ν Lν [Lsun]
10¹⁰
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10⁶
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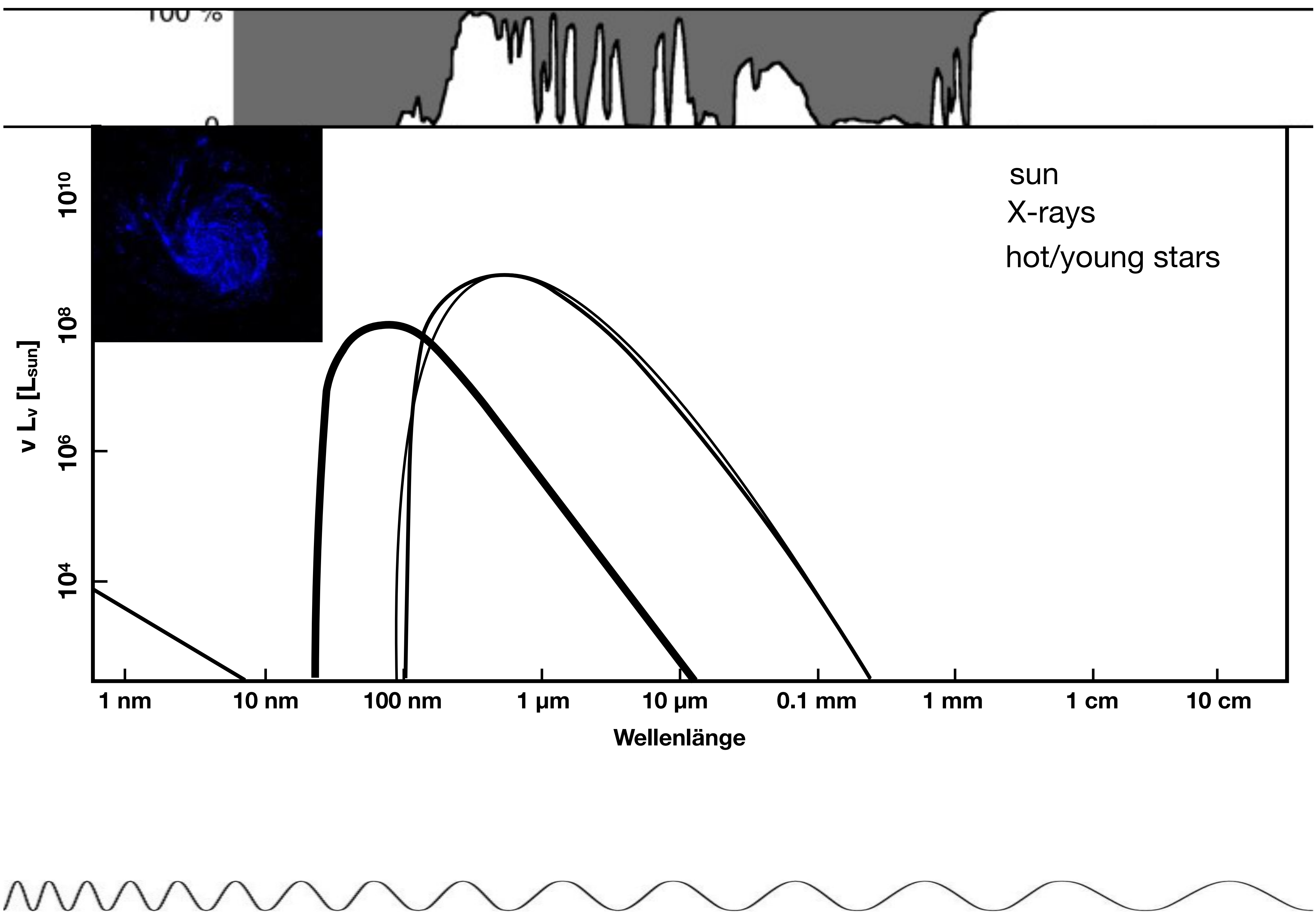
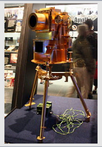
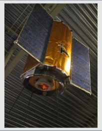
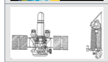
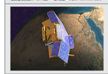
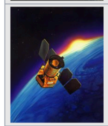
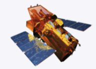
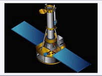
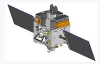
10 cm
Wellenlänge

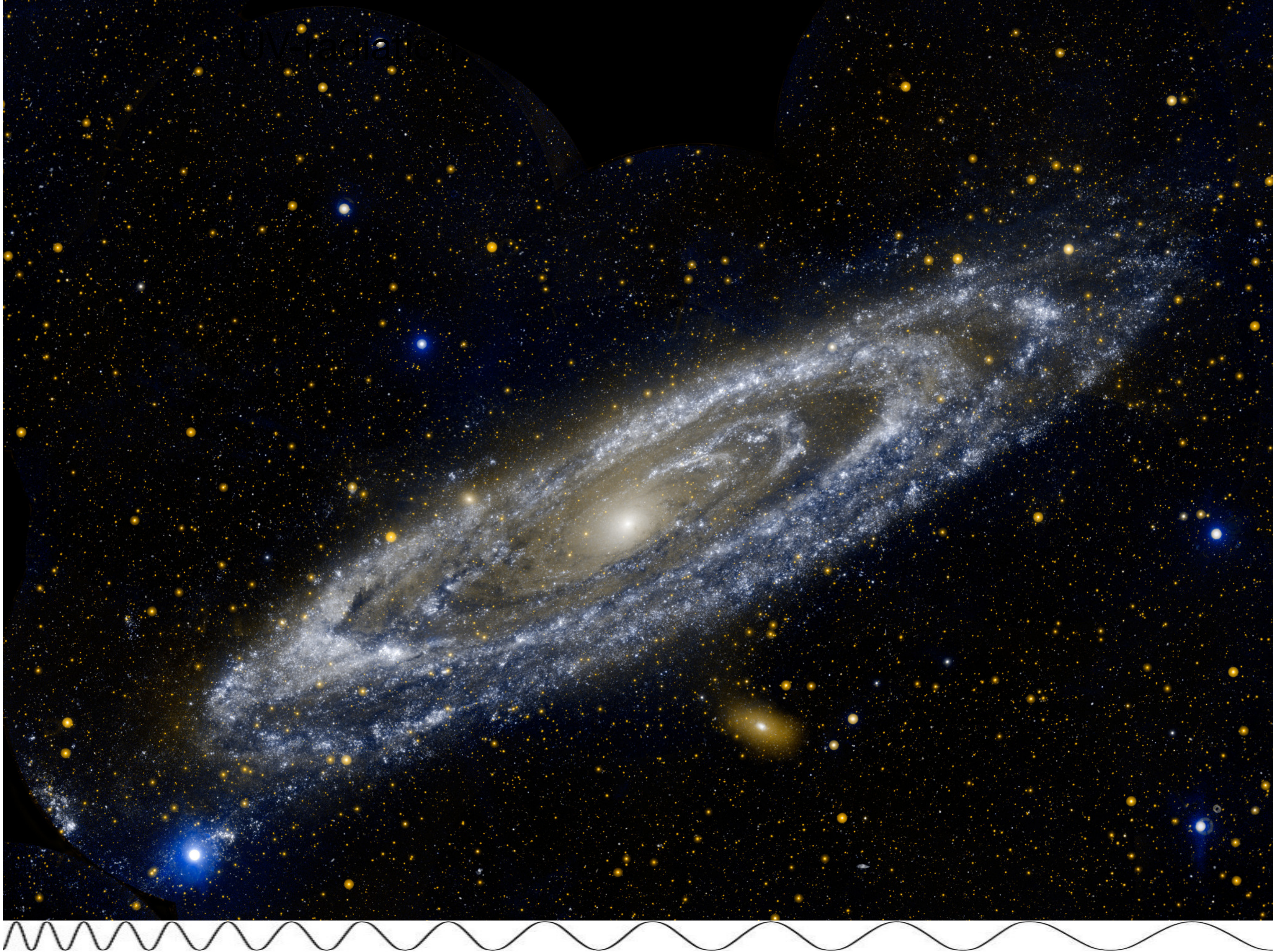


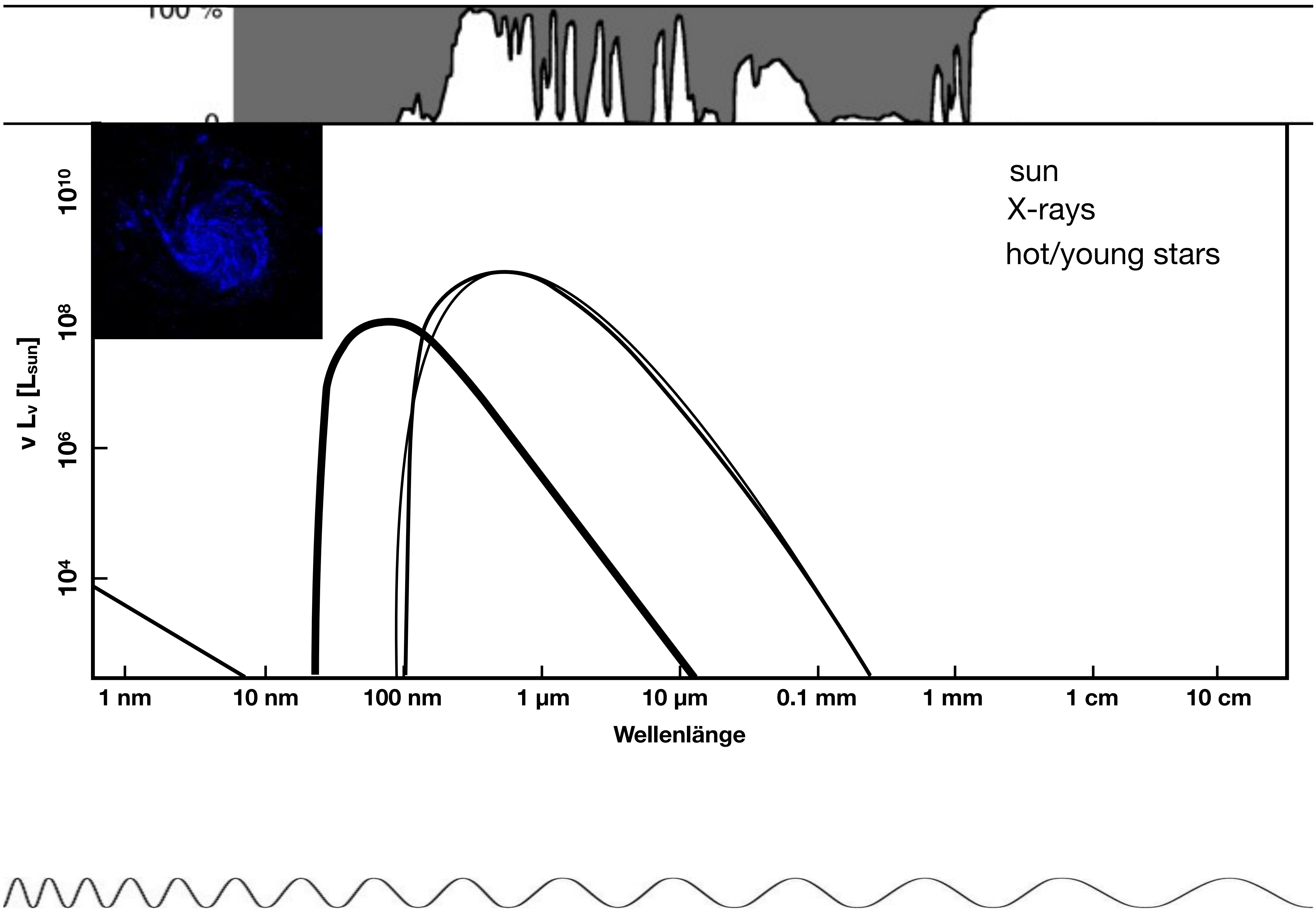
sun
X-rays
hot/young stars
ν Lν [Lsun]
10^10
10^8
10^6
10^4
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge

UV radiation: satellites

Photo	Name	Space Agency	Launch Date	Terminated	Observing Location	Ref(s)
	OAO-2 (Stargazer)	NASA	7 Dec 1968	Jan 1973	Earth orbit (749–758 km)	[106][107]
	Orion 1 and Orion 2 Space Observatories	USSR	19 Apr 1971 (Orion 1); (Orion 2) 18 Dec 1973	1971; 1973	Earth orbit (Orion 1: 200–222 km; Orion 2: 188–247 km)	[108][109]
	Far Ultraviolet Camera/Spectrograph (UVC)	NASA	16 Apr 1972	23 Apr 1972	Descartes Highlands on lunar surface	[110]
	OAO-3 *Copernicus*	NASA	21 Aug 1972	Feb 1981	Earth orbit (713–724 km)	[106]
	Astronomical Netherlands Satellite (ANS)	SRON	30 Aug 1974	Jun 1976	Earth orbit (266–1176 km)	[35][36]
	International Ultraviolet Explorer (IUE)	ESA & NASA & SERC	26 Jan 1978	30 Sep 1996	Earth orbit (32,050–52,254 km)	[111][112]
	Astron	IKI	23 Mar 1983	Jun 1989	Earth orbit (2,000–200,000 km)	[56][57][58]
	Hubble Space Telescope	NASA & ESA	24 Apr 1990	–	Earth orbit (586.47–610.44 km)	[113]
	Broad Band X-ray Telescope / Astro 1	NASA	2 Dec 1990	11 Dec 1990	Earth orbit (500 km)	[69][70]
	Extreme Ultraviolet Explorer (EUVE)	NASA	7 Jun 1992	31 Jan 2001	Earth orbit (515–527 km)	[114][115]
	Astro 2	NASA	2 Mar 1993	18 Mar 1993	Earth orbit (349–363 km)	[116][117]
	Far Ultraviolet Spectroscopic Explorer (FUSE)	NASA & CNES & CSA	24 Jun 1999	12 Jul 2007	Earth orbit (752–767 km)	[118][119]
	Cosmic Hot Interstellar Spectrometer (CHIPS)	NASA	13 Jan 2003	11 Apr 2008	Earth orbit (578–594 km)	[120][121]
	Galaxy Evolution Explorer (GALEX)	NASA	28 Apr 2003	28 Jun 2013	Earth orbit (691–697 km)	[122][123][124]
	Korea Advanced Institute of Science and Technology Satellite 4 (Kaistsat 4)	KARI	27 Sep 2003	2007 ?	Earth orbit (675–695 km)	[125][126]
	Swift Gamma Ray Burst Explorer (Swift)	NASA	20 Nov 2004	–	Earth orbit (585–604 km)	[26][27]
	Interface Region Imaging Spectrograph (IRIS)	NASA	27 Jun 2013	–	Earth orbit	[127][128]
	Hisaki (SPRINT-A)	JAXA	14 Sep 2013	–	–	[129]
	Venus Spectral Rocket Experiment	NASA	26 Nov 2013	reusable	suborbital to 300 km	[130]
	Lunar-based ultraviolet telescope (LUT)	CNSA	1 Dec 2013	–	Lunar surface	[131]
	Astrosat	ISRO	28 Sep 2015	–	Earth orbit (600–650 km)	[95][94][96]

no all-sky survey to date


UV-radiation


sun
X-rays
hot/young stars
ν Lν [Lsun]
10^10
10^8
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1 nm
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1 µm
10 µm
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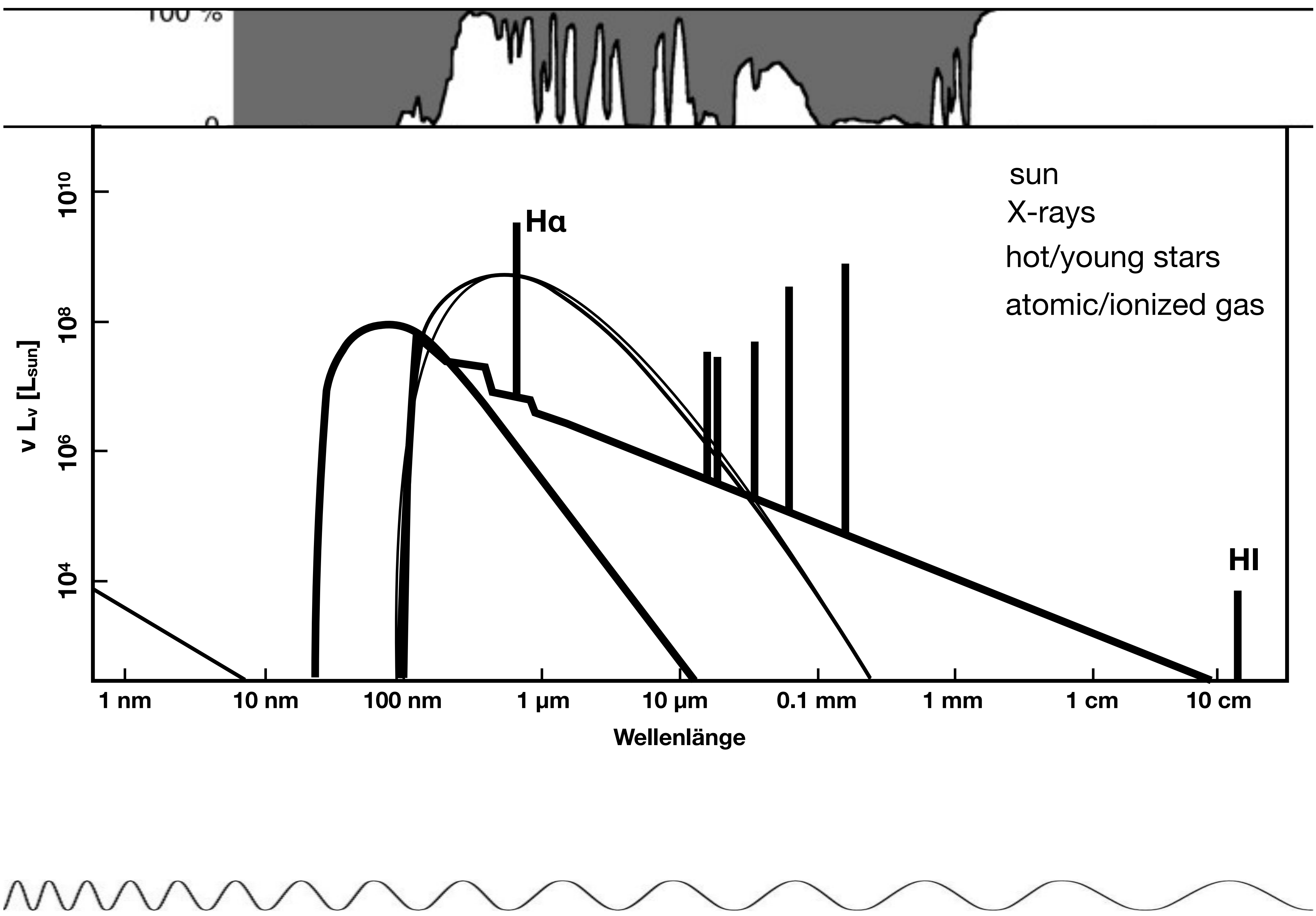
10 cm
Wellenlänge



100 %
0
sun
X-rays
hot/young stars
atomic/ionized gas
Hα
HI
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10^8
10^6
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ν Lν [Lsun]
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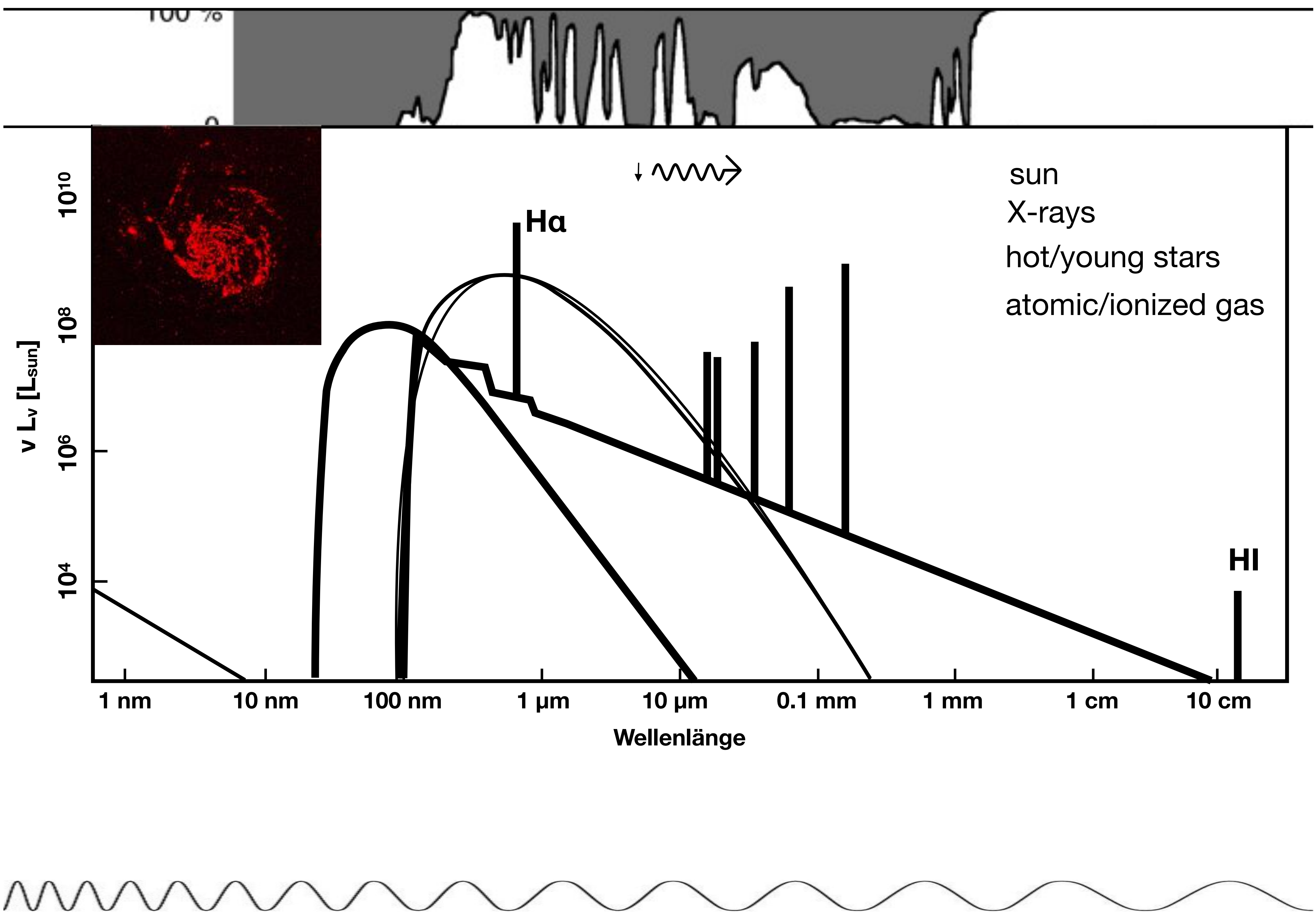
Wellenlänge


100 %
0
sun
X-rays
hot/young stars
atomic/ionized gas
Hα
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10^6
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ν Lν [Lsun]
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1 µm
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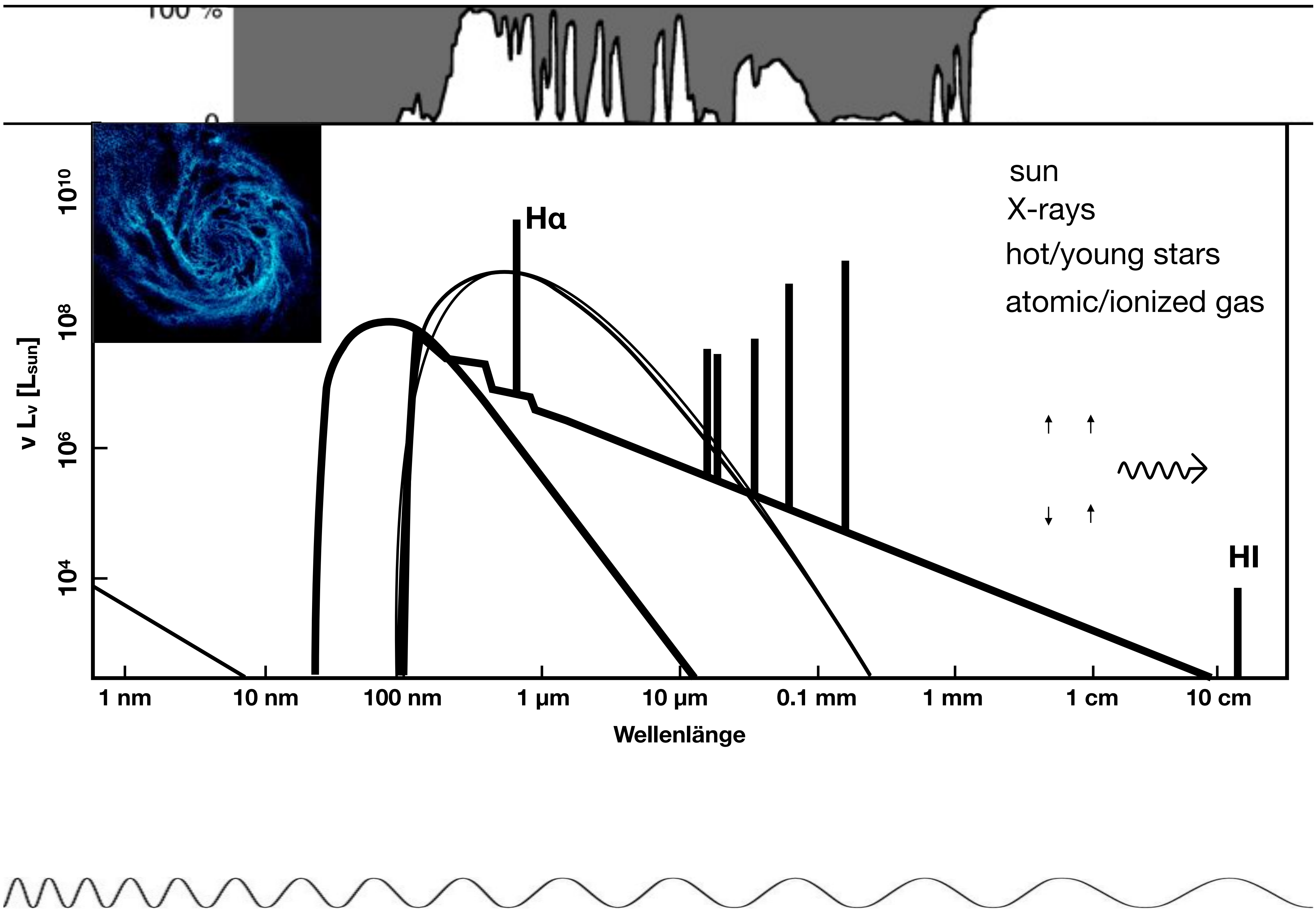
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge


100 %
0
sun
X-rays
hot/young stars
atomic/ionized gas
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ν Lν [Lsun]
10^10
10^8
10^6
10^4
1 nm
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100 nm
1 µm
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0.1 mm
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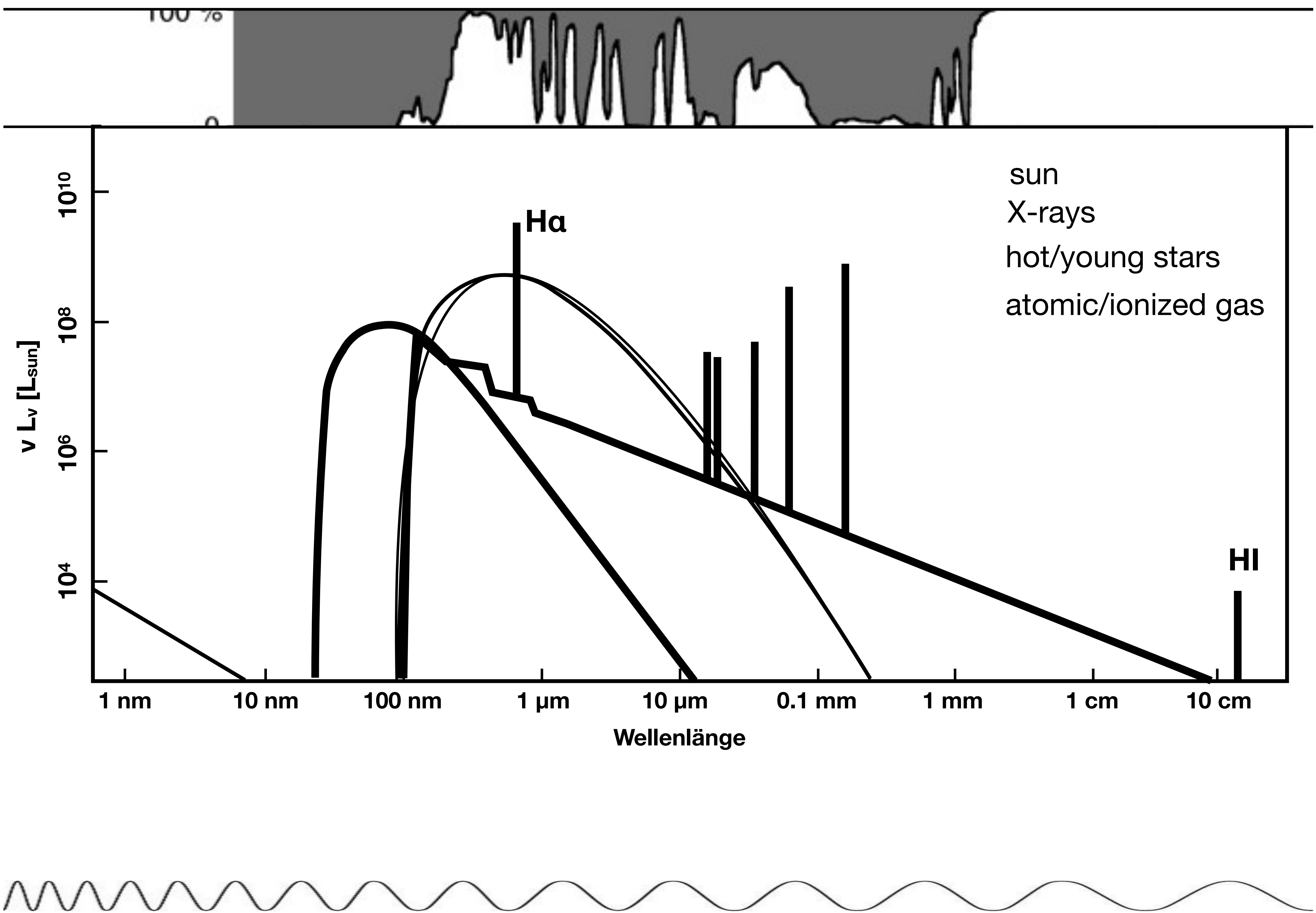
Wellenlänge


100 %
0
sun
X-rays
hot/young stars
atomic/ionized gas
Hα
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ν Lν [Lsun]
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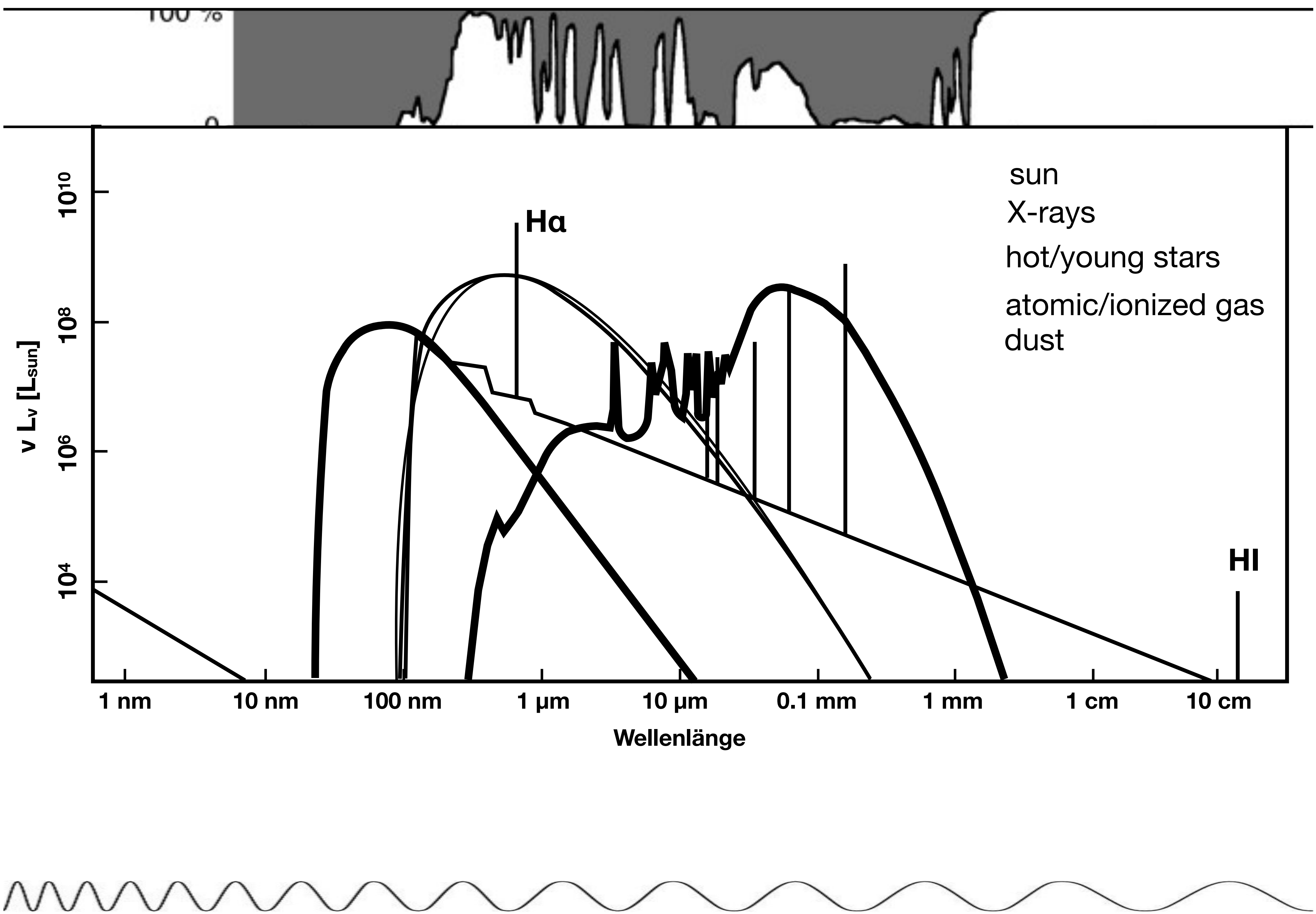
Wellenlänge


100 %
0
sun
X-rays
hot/young stars
atomic/ionized gas
dust
Hα
HI
ν Lν [Lsun]
10¹⁰
10⁸
10⁶
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1 nm
10 nm
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1 µm
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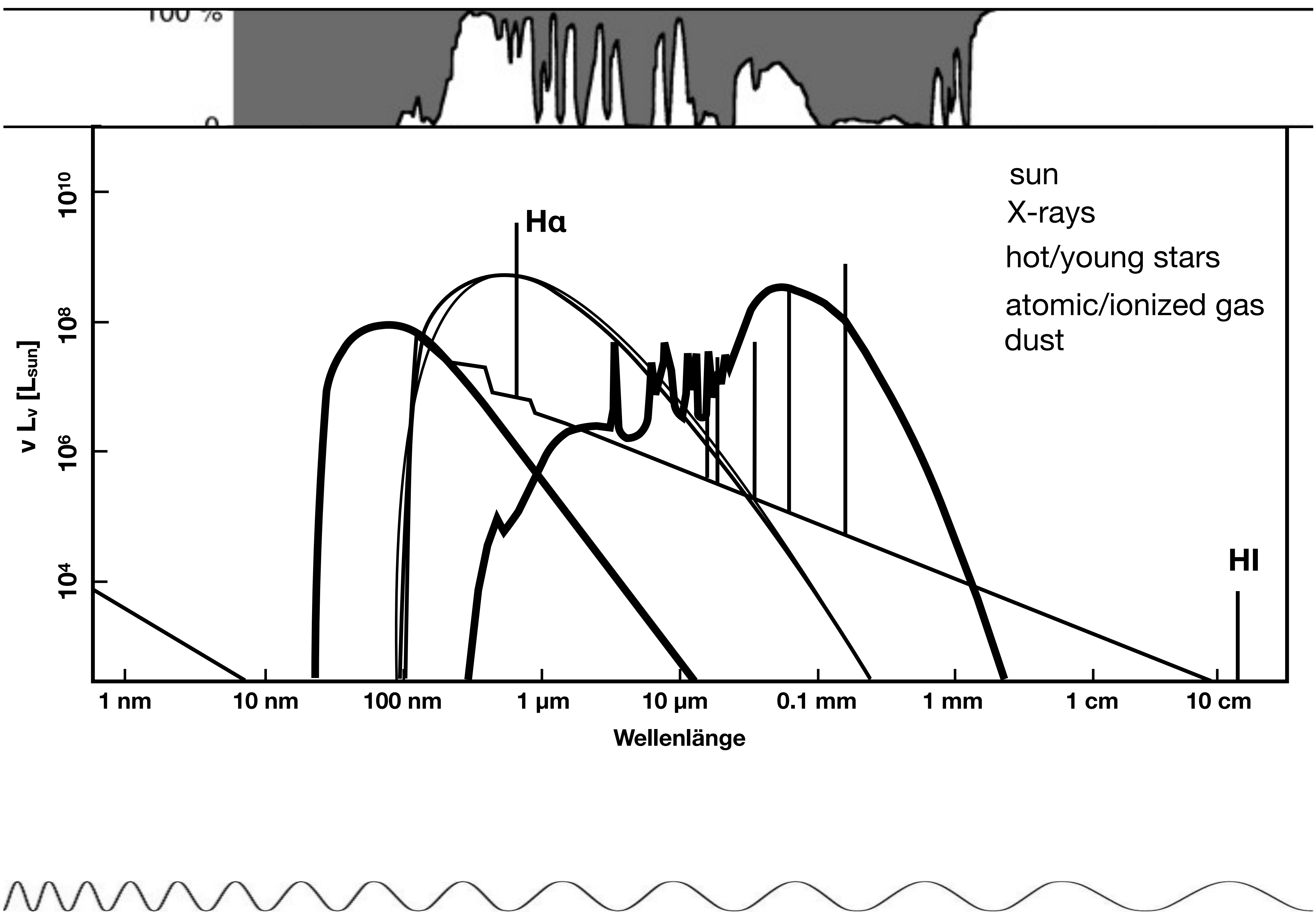
Wellenlänge



100 %
0
sun
X-rays
hot/young stars
atomic/ionized gas
dust
Hα
HI
νL_ν [L_{sun}]
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10^6
10^4
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
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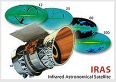
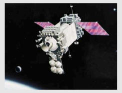
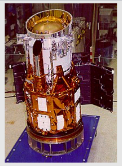
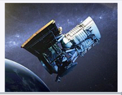
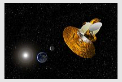
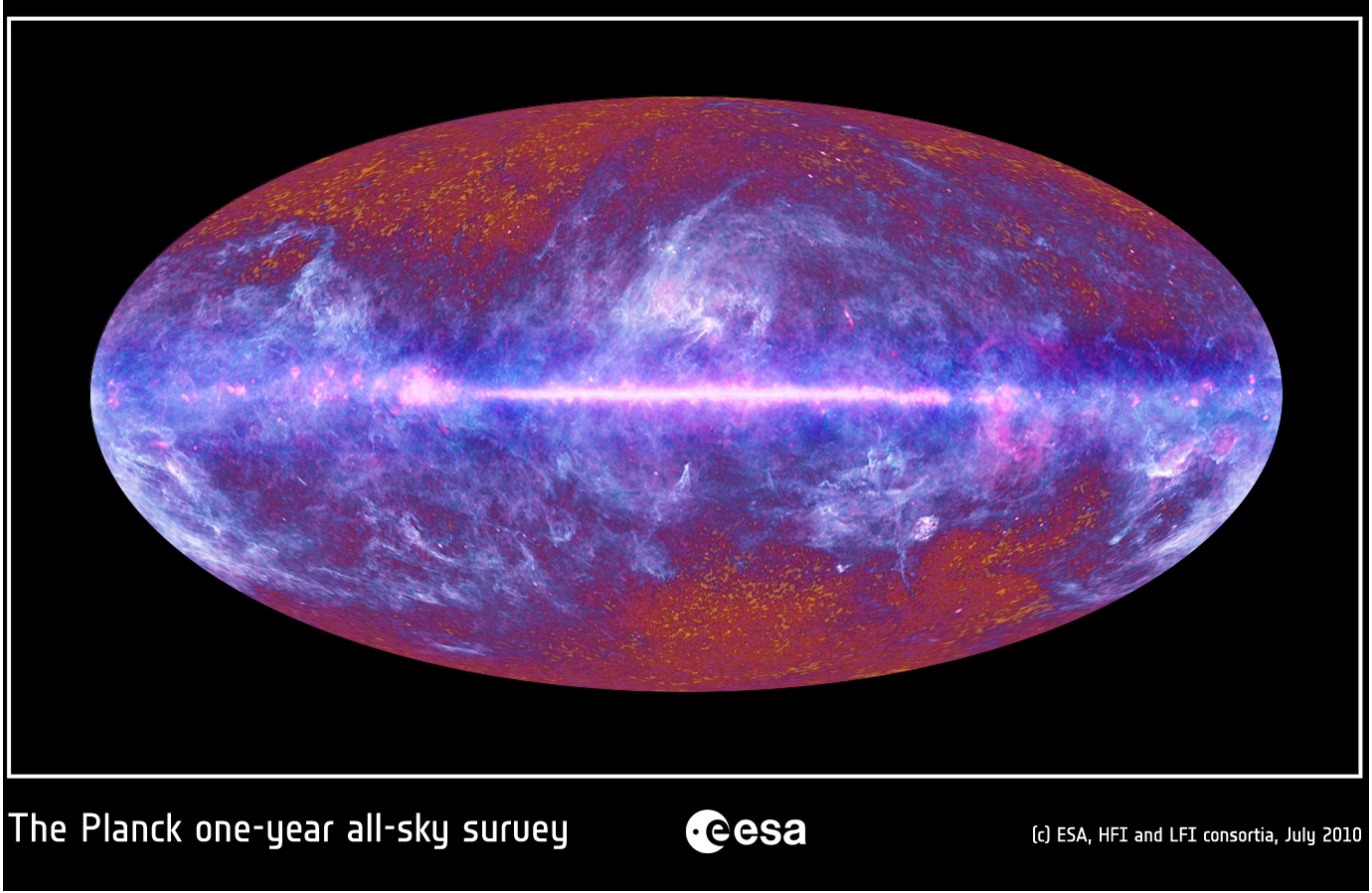
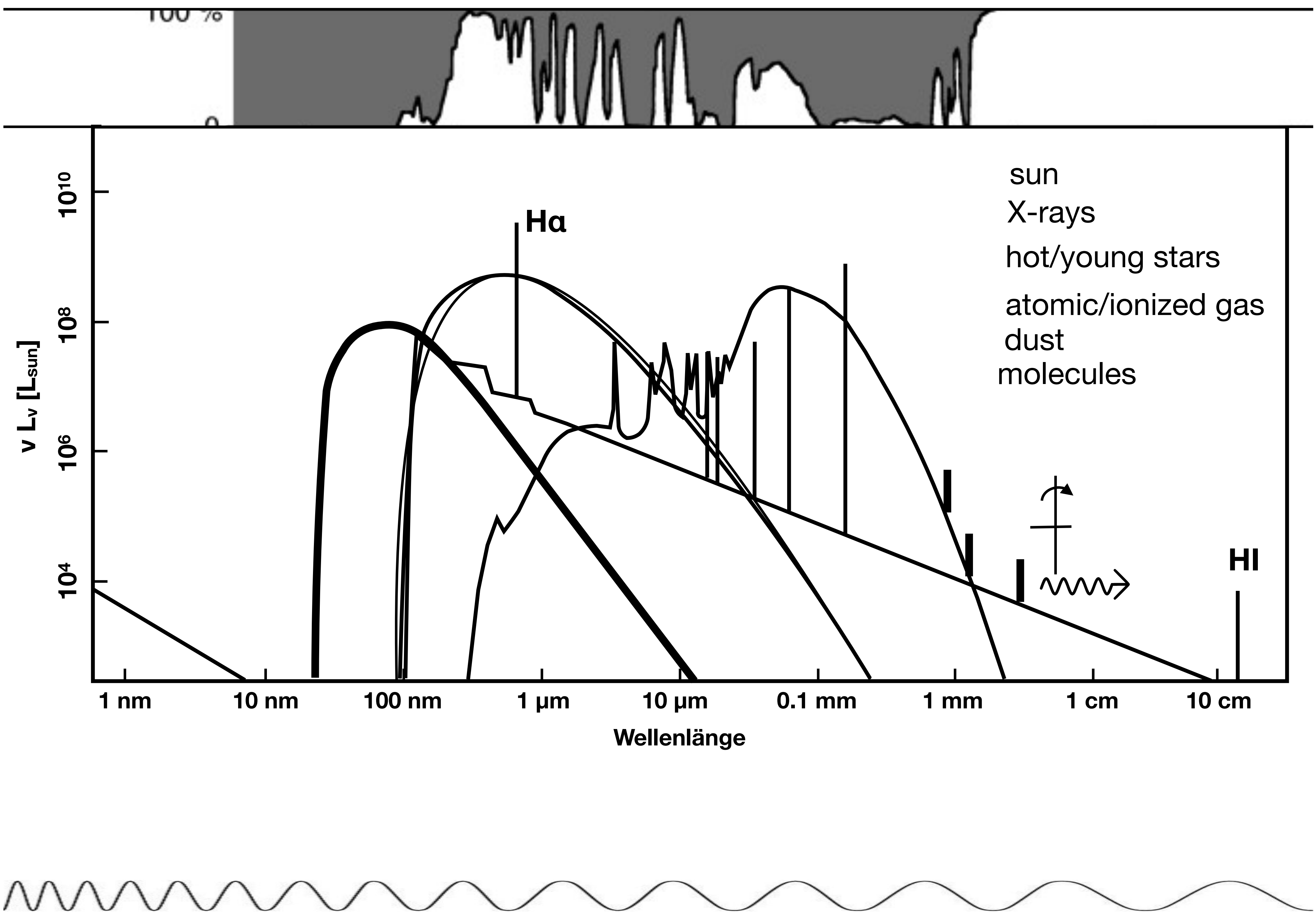
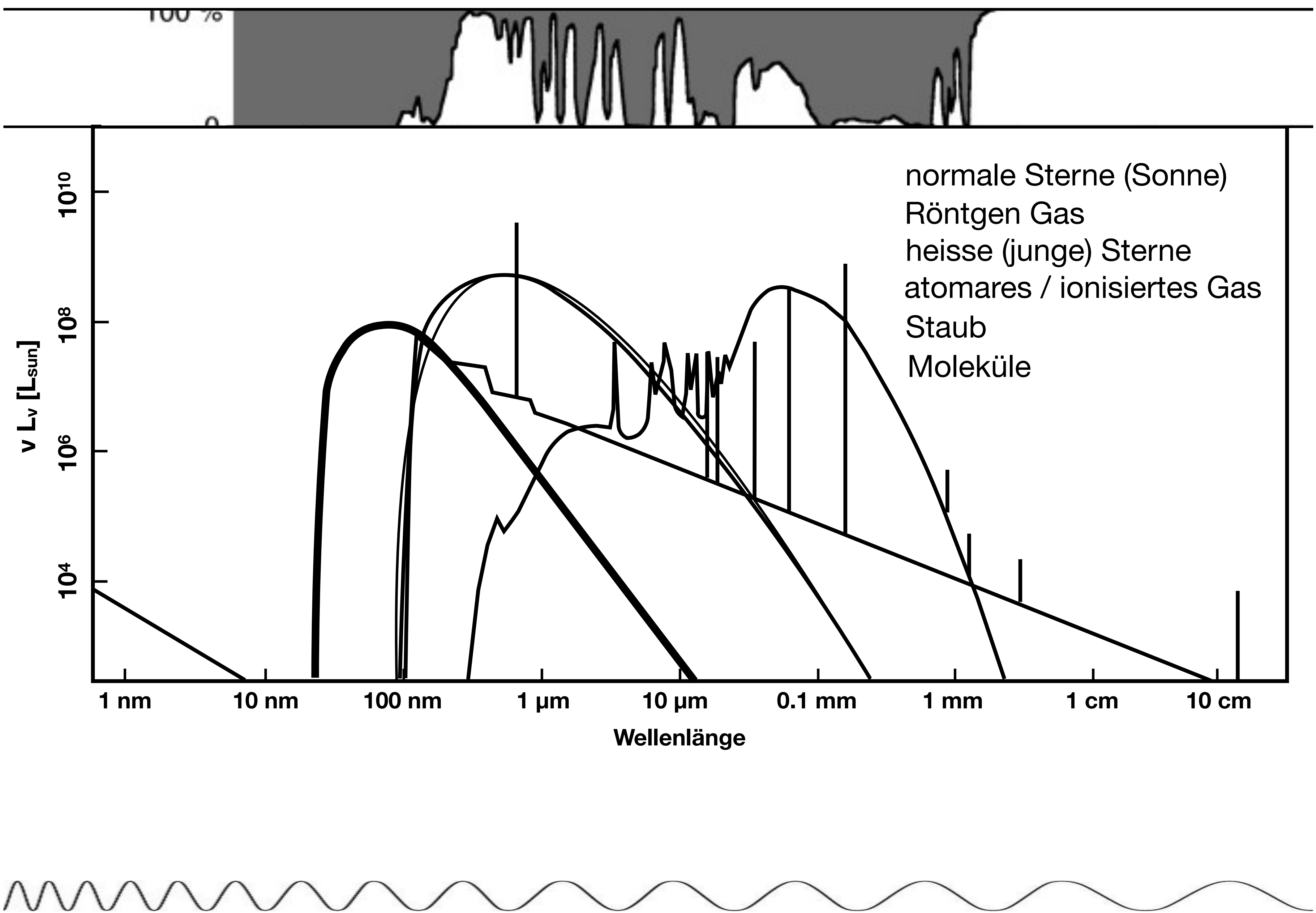
1 cm
10 cm
Wellenlänge

infrared radiation: satellites

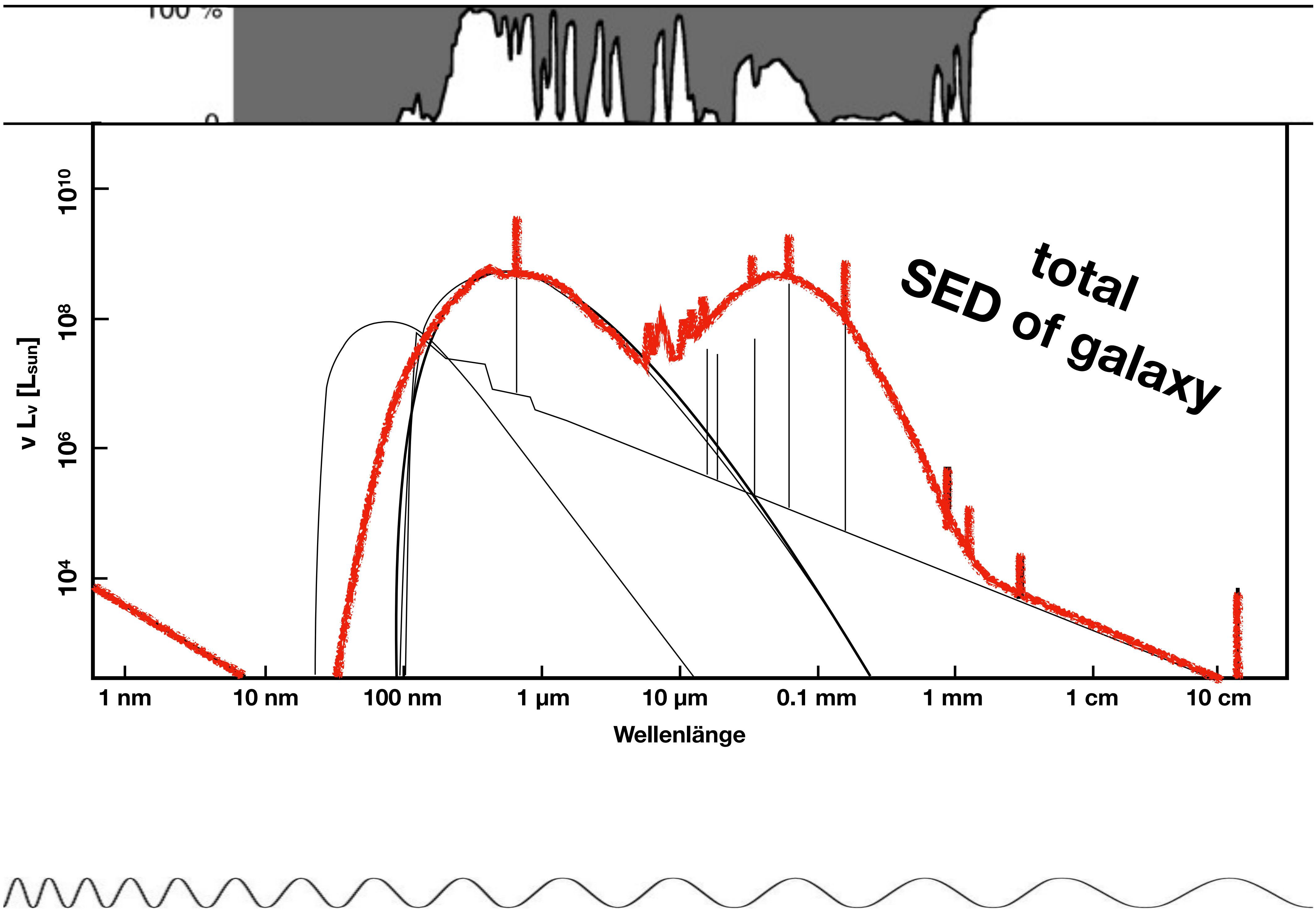
Photo	Name	Space Agency	Launch Date	Terminated	Location	Ref(s)
	IRAS	NASA	25 Jan 1983	21 Nov 1983	Earth orbit (889–903 km)	[151][152]
	Infrared Telescope in Space	ISAS & NASDA	18 Mar 1995	25 Apr 1995	Earth orbit (486 km)	[153][154]
	Infrared Space Observatory (ISO)	ESA	17 Nov 1995	16 May 1998	Earth orbit (1000–70500 km)	[155][156][157]
	Midcourse Space Experiment (MSX)	USN	24 Apr 1996	26 Feb 1997	Earth orbit (900 km)	[158]
	Submillimeter Wave Astronomy Satellite (SWAS)	NASA	6 Dec 1998	Last used in 2005	Earth orbit (638–651 km)	[159][160]
	Wide Field Infrared Explorer (WIRE)	NASA	5 Mar 1999	no observations	Re-entered May 10, 2011[161]	[162]
	Spitzer Space Telescope	NASA	25 Aug 2003	30 Jan 2020[163]	Solar orbit (0.98–1.02 AU)	[164][165]
	Akari (Astro-F)	JAXA	21 Feb 2006	24 Nov 2011[166]	Earth orbit (586.47–610.44 km)	[167][168]
	Herschel Space Observatory	ESA & NASA	14 May 2009 [169]	29 Apr 2013[170]	Sun-Earth L_2 Lagrange point	[171][172][173]
	Wide-field Infrared Survey Explorer (WISE)	NASA	14 Dec 2009	(hibernation Feb 2011 – Aug 2013)	Earth orbit (500 km)	[174][175][176]
	Cosmic Background Explorer (COBE)	NASA	18 Nov 1989	23 Dec 1993	Earth orbit (900 km)	[178][179]
	Odin	Swedish Space Corporation	20 Feb 2001	—	Earth orbit (622 km)	[180][181]
	WMAP	NASA	30 Jun 2001	Oct 2010	Sun-Earth L_2 Lagrange point	[182]
	Planck	ESA	14 May 2009	Oct 2013	Sun-Earth L_2 Lagrange point(mission) Heliocentric (Derelict)	[172][183][184]


The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010

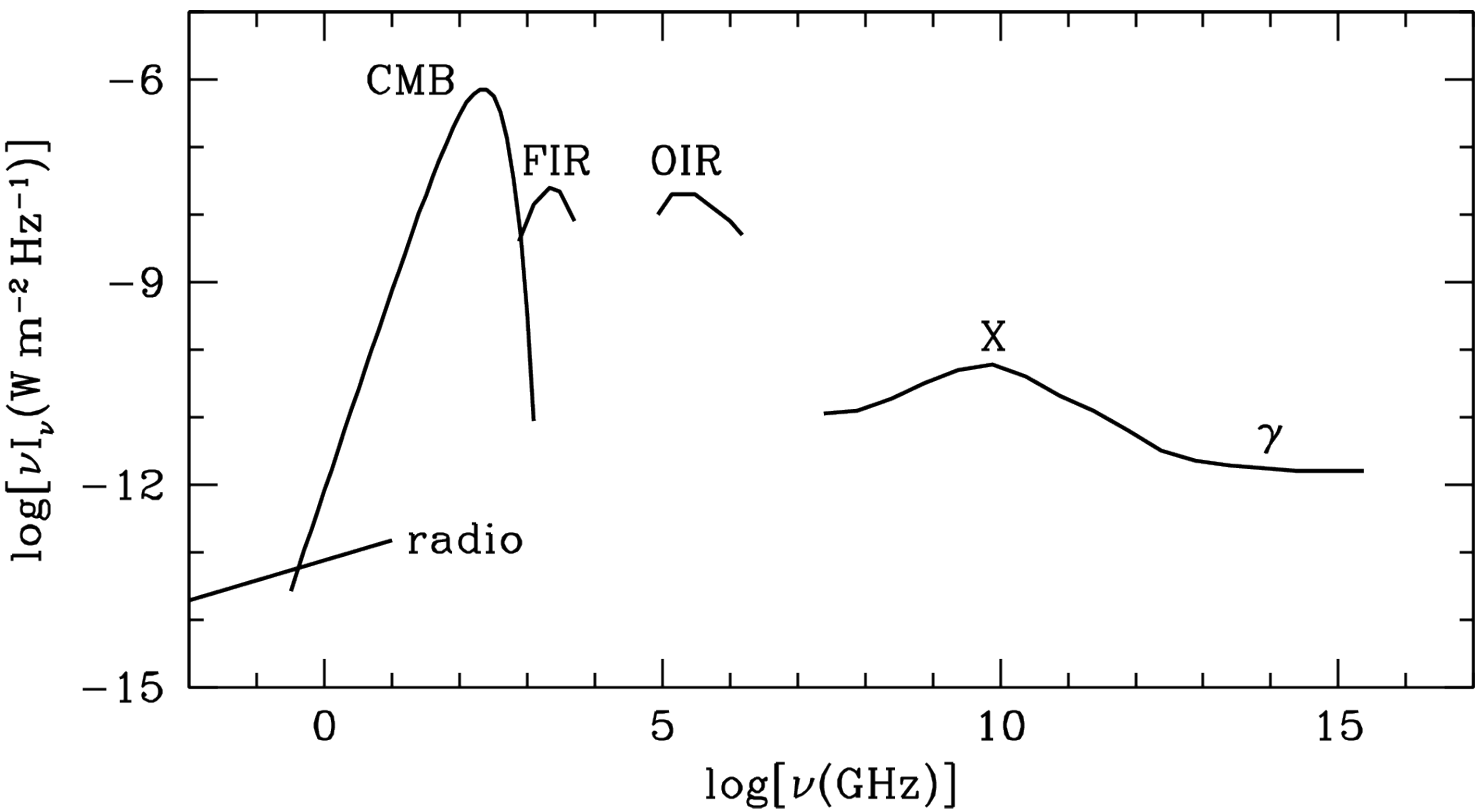

100 %
0
Hα
sun
X-rays
hot/young stars
atomic/ionized gas
dust
molecules
HI
10^{10}
10^8
10^6
10^4
ν Lν [Lsun]
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge



normale Sterne (Sonne)
Röntgen Gas
heisse (junge) Sterne
atomares / ionisiertes Gas
Staub
Moleküle
ν L_ν [L_sun]
10^10
10^8
10^6
10^4
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge


100 %
0
10^{10}
10^{8}
10^{6}
10^{4}
ν Lν [Lsun]
1 nm
10 nm
100 nm
1 µm
10 µm
0.1 mm
1 mm
1 cm
10 cm
Wellenlänge
total
SED of galaxy

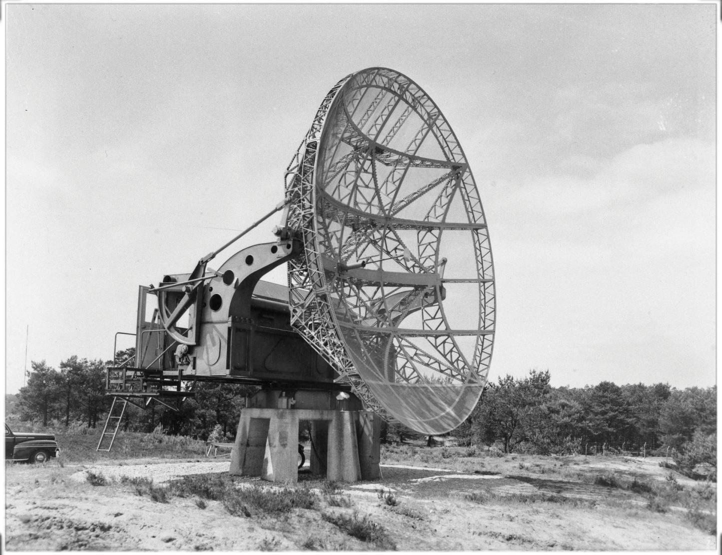
The electromagnetic spectrum of the **universe**



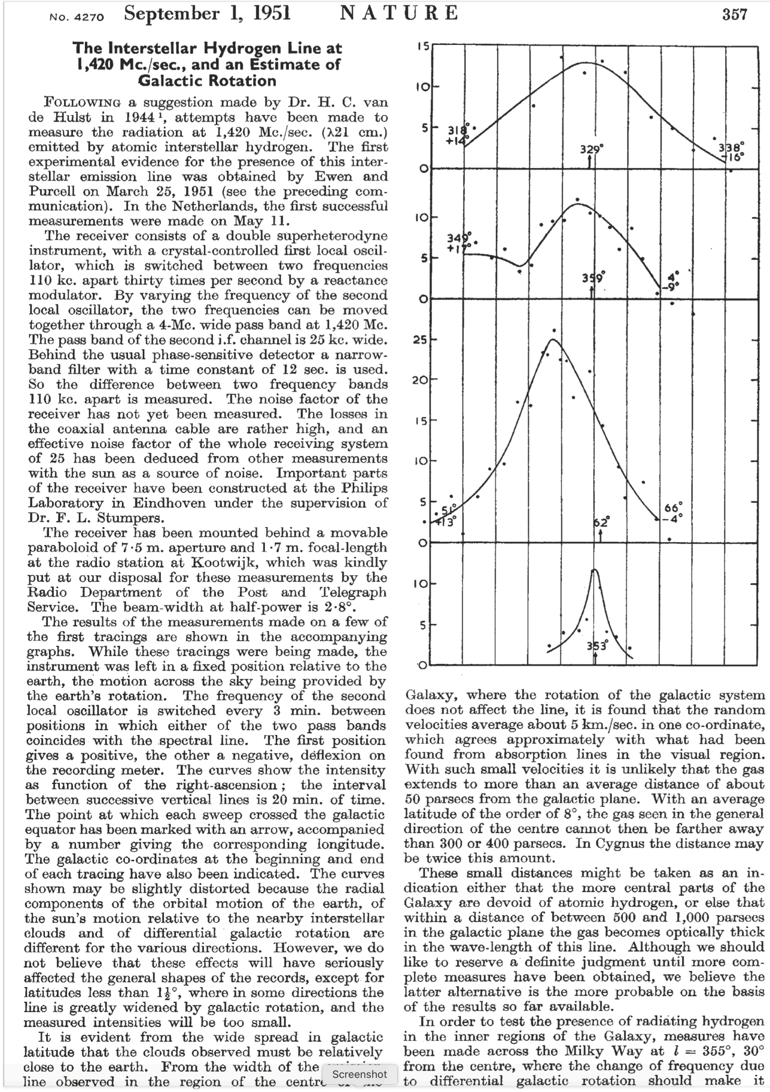
it’s all in the CMB!
highest peaks correspond to the most energetically important spectral ranges
—> radio not energetically relevant

radio waves

1951: detection of atomic hydrogen (21cm)



codename ‘Würzburg’ - 4000 radar antennas in WWII



The Interstellar Hydrogen Line at 1,420 Mc./sec., and an Estimate of Galactic Rotation

Following a suggestion made by Dr. H. C. van de Hulst in 1944[1], attempts have been made to measure the radiation at 1,420 Mc./sec. (λ21 cm.) emitted by atomic interstellar hydrogen. The first experimental evidence for the presence of this interstellar emission line was obtained by Ewen and Purcell on March 25, 1951 (see the preceding communication). In the Netherlands, the first successful measurements were made on May 11.

The receiver consists of a double superheterodyne instrument, with a crystal-controlled first local oscillator, which is switched between two frequencies 110 kc. apart thirty times per second by a reactance modulator. By varying the frequency of the second local oscillator, the two frequencies can be moved together through a 4-Mc. wide pass band at 1,420 Mc. The pass band of the second i.f. channel is 25 kc. wide. Behind the usual phase-sensitive detector a narrow-band filter with a time constant of 12 sec. is used. So the difference between two frequency bands 110 kc. apart is measured. The noise factor of the receiver has not yet been measured. The losses in the coaxial antenna cable are rather high, and an effective noise factor of the whole receiving system of 25 has been deduced from other measurements with the sun as a source of noise. Important parts of the receiver have been constructed at the Philips Laboratory in Eindhoven under the supervision of Dr. F. L. Stumpers.

The receiver has been mounted behind a movable paraboloid of 7·5 m. aperture and 1·7 m. focal-length at the radio station at Kootwijk, which was kindly put at our disposal for these measurements by the Radio Department of the Post and Telegraph Service. The beam-width at half-power is 2·8°.

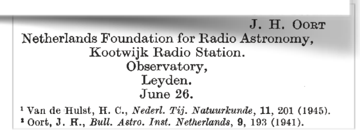
The results of the measurements made on a few of the first tracings are shown in the accompanying graphs. While these tracings were being made, the instrument was left in a fixed position relative to the earth, the motion across the sky being provided by the earth's rotation. The frequency of the second local oscillator is switched every 3 min. between positions in which either of the two pass bands coincides with the spectral line. The first position gives a positive, the other a negative, deflexion on the recording meter. The curves show the intensity as function of the right-ascension; the interval between successive vertical lines is 20 min. of time. The point at which each sweep crossed the galactic equator has been marked with an arrow, accompanied by a number giving the corresponding longitude. The galactic co-ordinates at the beginning and end of each tracing have also been indicated. The curves shown may be slightly distorted because the radial components of the orbital motion of the earth, of the sun's motion relative to the nearby interstellar clouds and of differential galactic rotation are different for the various directions. However, we do not believe that these effects will have seriously affected the general shapes of the records, except for latitudes less than 1½°, where in some directions the line is greatly widened by galactic rotation, and the measured intensities will be too small.

It is evident from the wide spread in galactic latitude that the clouds observed must be relatively close to the earth. From the width of the [Screenshot] line observed in the region of the centre [Screenshot]

Galaxy, where the rotation of the galactic system does not affect the line, it is found that the random velocities average about 5 km./sec. in one co-ordinate, which agrees approximately with what had been found from absorption lines in the visual region. With such small velocities it is unlikely that the gas extends to more than an average distance of about 50 parsecs from the galactic plane. With an average latitude of the order of 8°, the gas seen in the general direction of the centre cannot then be farther away than 300 or 400 parsecs. In Cygnus the distance may be twice this amount.

These small distances might be taken as an indication either that the more central parts of the Galaxy are devoid of atomic hydrogen, or else that within a distance of between 500 and 1,000 parsecs in the galactic plane the gas becomes optically thick in the wave-length of this line. Although we should like to reserve a definite judgment until more complete measures have been obtained, we believe the latter alternative is the more probable on the basis of the results so far available.

In order to test the presence of radiating hydrogen in the inner regions of the Galaxy, measures have been made across the Milky Way at $l = 355°$, 30° from the centre, where the change of frequency due to differential galactic rotation should make it

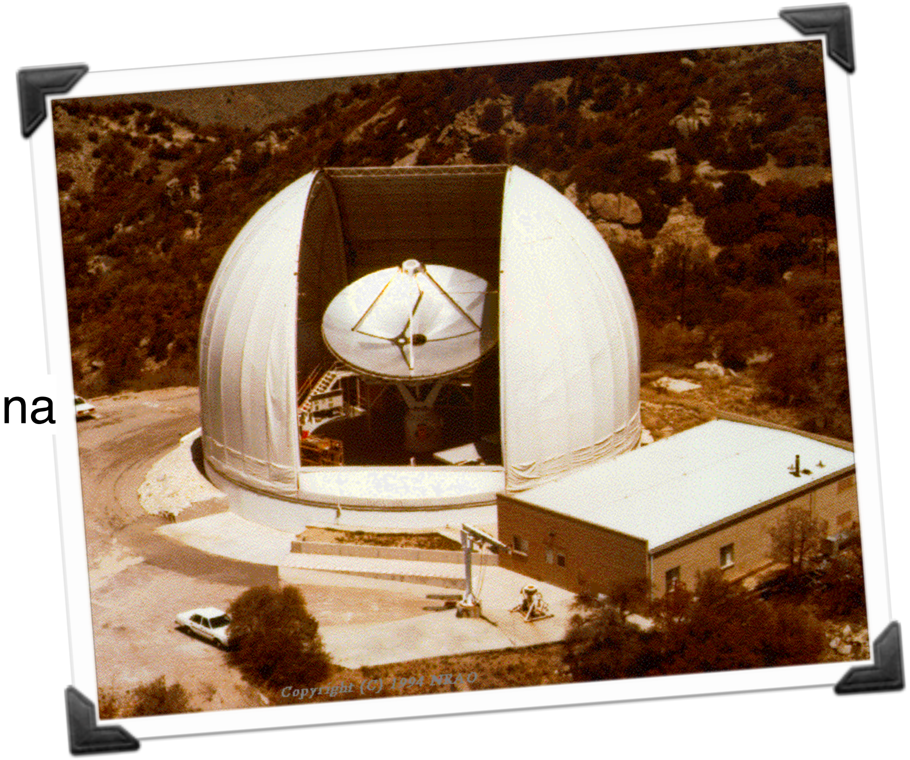


J. H. Oort
Netherlands Foundation for Radio Astronomy,
Kootwijk Radio Station.
Observatory,
Leyden.
June 26.

[1] Van de Hulst, H. C., *Nederl. Tij. Natuurkunde*, 11, 201 (1945).
[2] Oort, J. H., *Bull. Astro. Inst. Netherlands*, 9, 193 (1941).

millimeter detection

NRAO
12m antenna



1970: first detection of CO

THE ASTROPHYSICAL JOURNAL, 161:L43–L44, July 1970

CARBON MONOXIDE IN THE ORION NEBULA

R. W. WILSON, K. B. JEFFERTS, AND A. A. PENZIAS
Bell Telephone Laboratories, Inc., Holmdel, New Jersey, and
Crawford Hill Laboratory, Murray Hill, New Jersey
Received 1970 June 5

ABSTRACT

We have found intense 2.6-mm line radiation from nine galactic sources which we attribute to carbon monoxide.

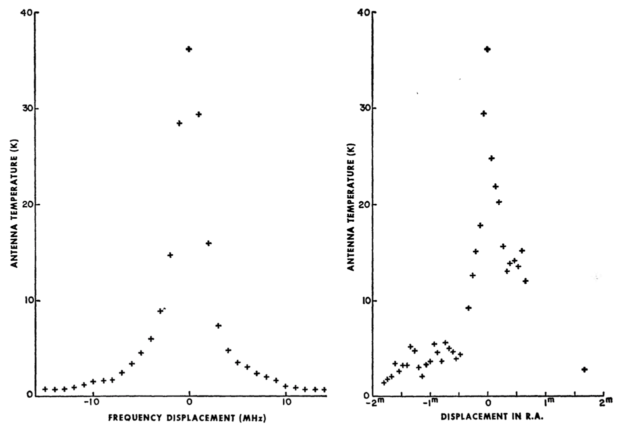


FIG. 1 FIG. 2

FIG. 1.—Spectrum of CO radiation in the Orion Nebula made with the NRAO forty-channel line receiver. The center frequency is 115, 267.2 MHz.

FIG. 2.—Distribution in right ascension of the peak antenna temperature of CO radiation at a declination of −5°24′21″.

Caltech OVRO
interferometer

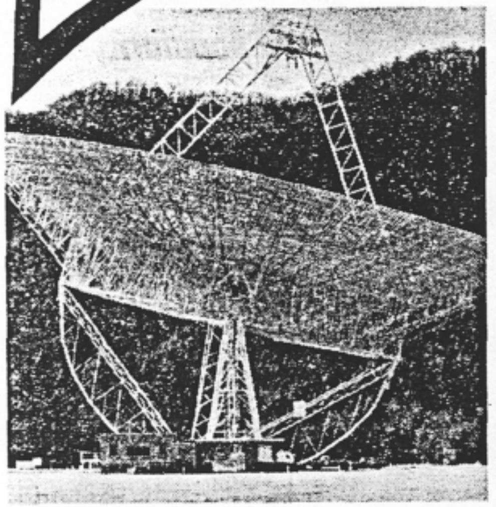
NEWS
January 31, 1989 30587 70¢

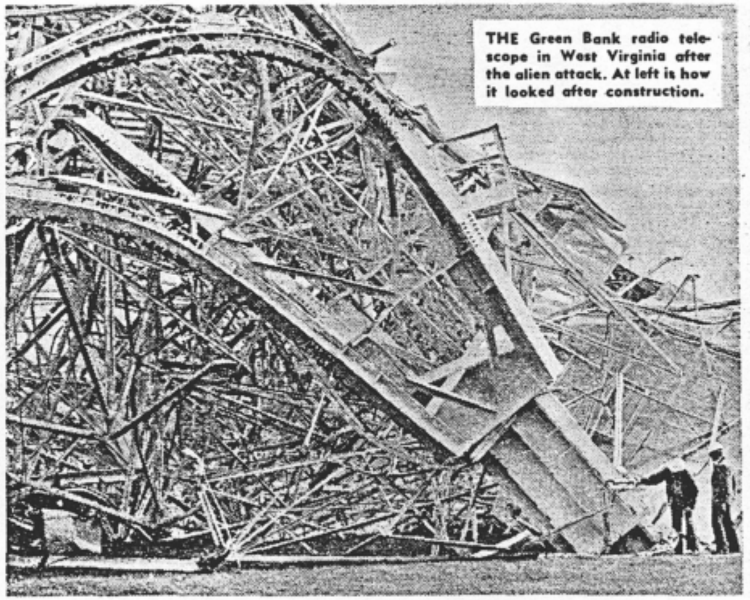
BRIDE IN CHAINS!
Hubby and landlady made her a slave, say police

America's most powerful radio telescope IS . . .

ZAPPED!

. . . by hostile space aliens!





THE Green Bank radio telescope in West Virginia after the alien attack. At left is how it looked after construction.

BEFORE ▲ AFTER ▶

Space aliens zapped the enormous radio telescope at Green Bank, W. Va., with a powerful laser to keep scientists from monitoring their activities in the northern hemisphere!

That's the claim of Swiss astronomer Peter Voisard,

shockwaves throughout the *world's scientific* community. But the handful of men who can talk about the Green Bank disaster with authority refused to describe the incident as *anything more* than "a mys-

zapped by extraterrestrials who wanted to mask their activity from mankind, Dr. Voisard said.

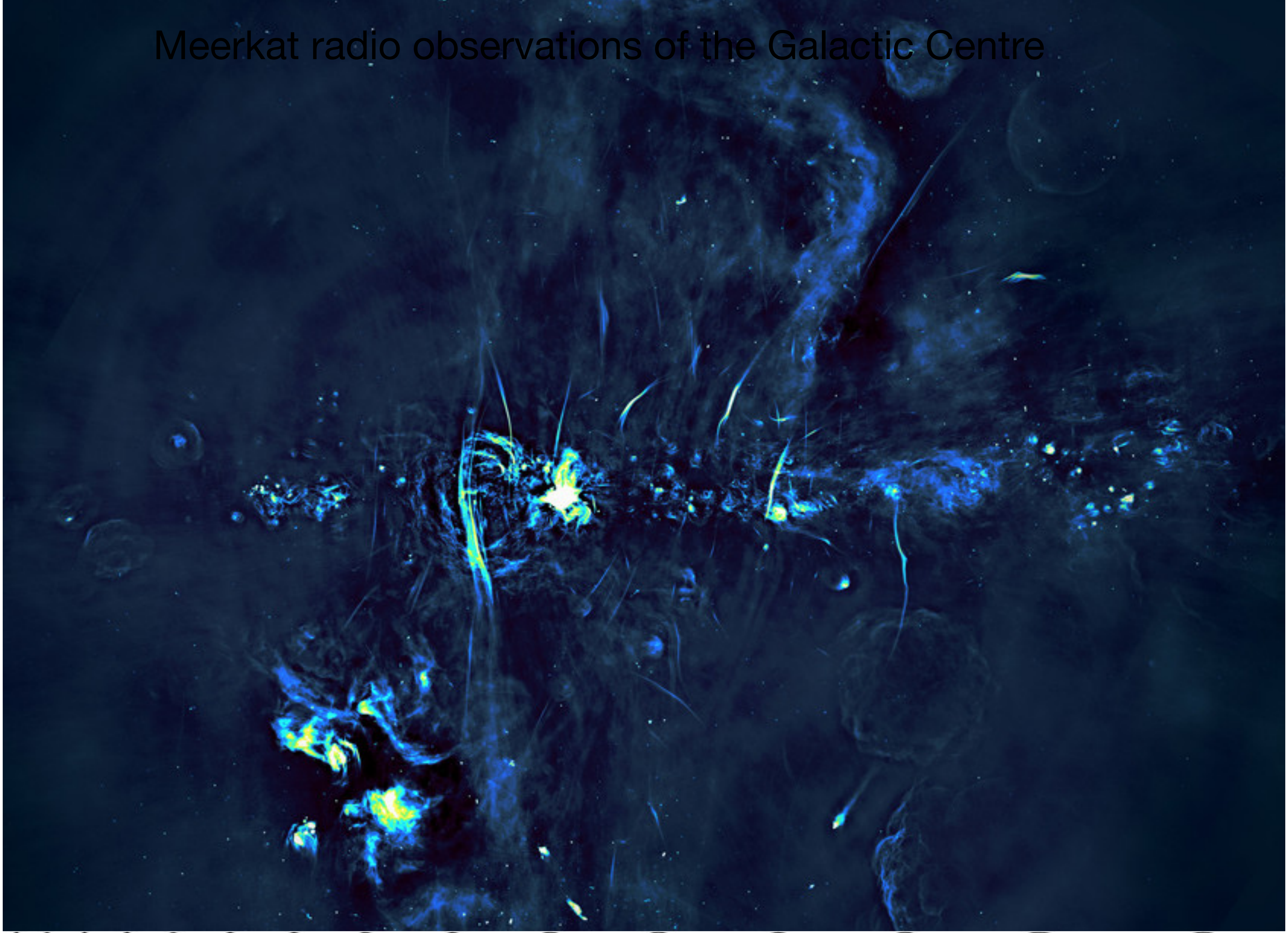
"Any other explanation defies logic," he continued. "The telescope had been in opera-

prove extraterrestrials toppled the telescope at Green Bank," he said. "But let's wait until all the evidence is in.

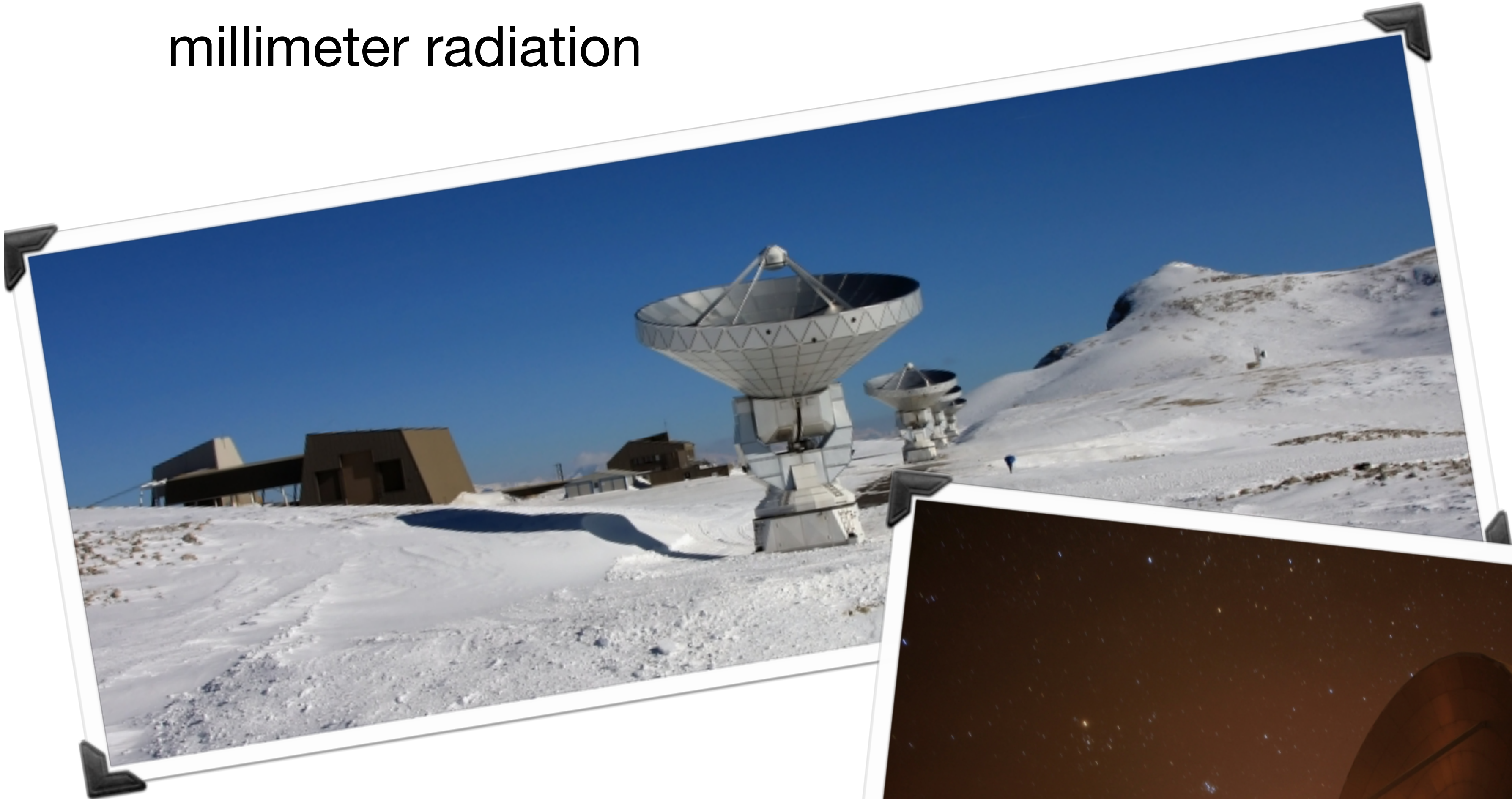
"Then we can take whatever steps are necessary to prevent things like this from

Meerkat interferometer

Meerkat radio observations of the Galactic Centre



millimeter radiation

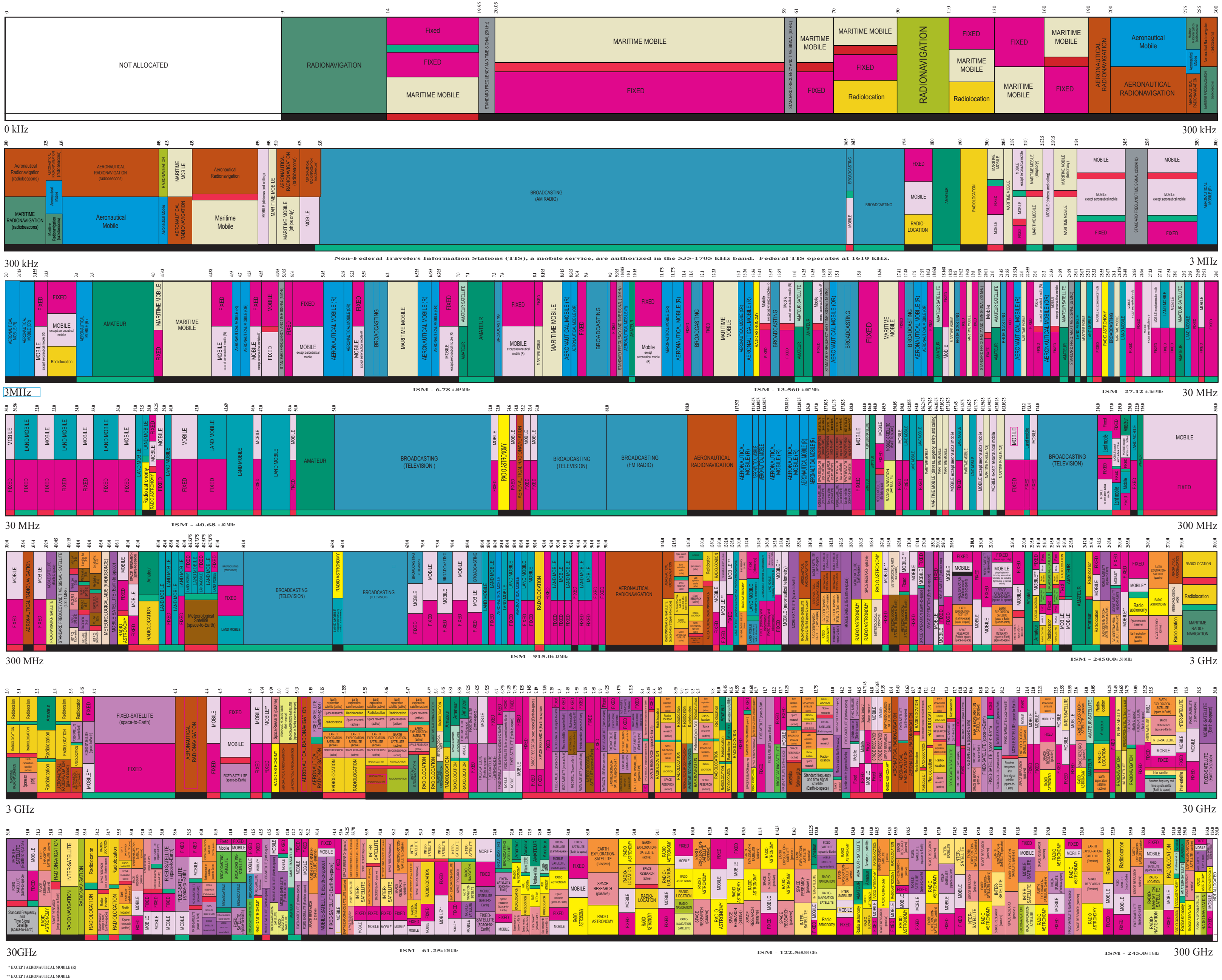


IRAM NOEMA interferometer
Plateau de Bure (French Alpes)

(Sub-)Millimeter — ALMA

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM



RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016

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PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

608.0 614.0 698.0 763.0 775.0 793.0 805.0 806.0 809.0 849.0 851.0 854.0 894.0 896.0 901.0 902.0 928.0 929.0 930.0 931.0 932.0 935.0 940.0 941.0 944.0 960.0 1164.0 1215.0 1240.0 1300.0 1350.0 1390.0 1392.0 1395.0 1400.0 1427.0 1429.5 1430.0 1432.0 1435.0 1525.0 1559.0 1610.0 1610.6 1613.8 1626.5 1660.0 1660.5 1668.4 1670.0 1675.0
ISM - 915.0± .13 MHz
5.25 5.255 5.35 5.46 5.47 5.57 5.6 5.65 5.83 5.85 5.925 6.425 6.525 6.7 6.875 7.025 7.075 7.125 7.145 7.19 7.235 7.25 7.3 7.45 7.55 7.75 7.85 7.9 8.025 8.175 8.215 8.4 8.45 8.5 8.55 8.65 9.0 9.2 9.3 9.5 9.8 10.0 10.45 10.5 10.55 10.6 10.68 10.7 11.7 12.2 12.7 13.25 13.4 13.75 14.0 14.2 14.4 14.5 14.7145 14.8 15.1365 15.35 15.4
50.4 51.4 52.6 54.25 55.78 56.9 57.0 58.2 59.0 59.3 64.0 65.0 66.0 71.0 74.0 76.0 77.0 77.5 78.0 81.0 84.0 86.0 92.0 94.0 94.1 95.0 100.0 102.0 105.0 109.5 111.8 114.25 116.0 122.25 123.0 130.0 134.0 136.0 141.0 148.5 151.5


STARLINK