AY2024F

Junjie Mao

Radiative Processes in Astrophysics

Observation

Up to cosmic size scale

Goal

Theory

Down to atomic size scale

C/2012S1 (comet) | Jupiter (planet) | Sun (star) | Cas A (SNR) | M82 (galaxy) | Phoenix (gal. cluster) | Cosmic web filament

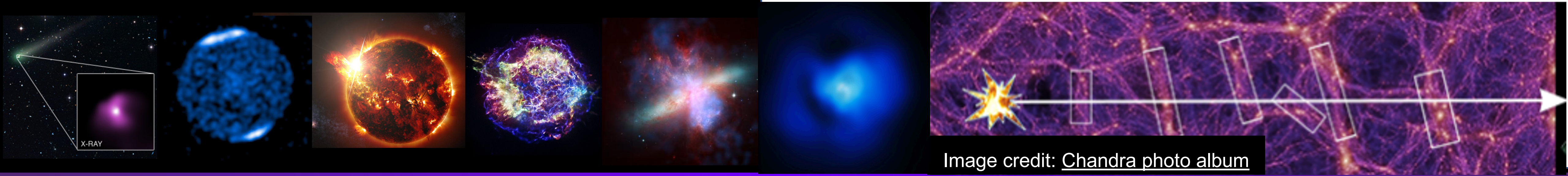


Image credit: Chandra photo album

Imaging of radiation

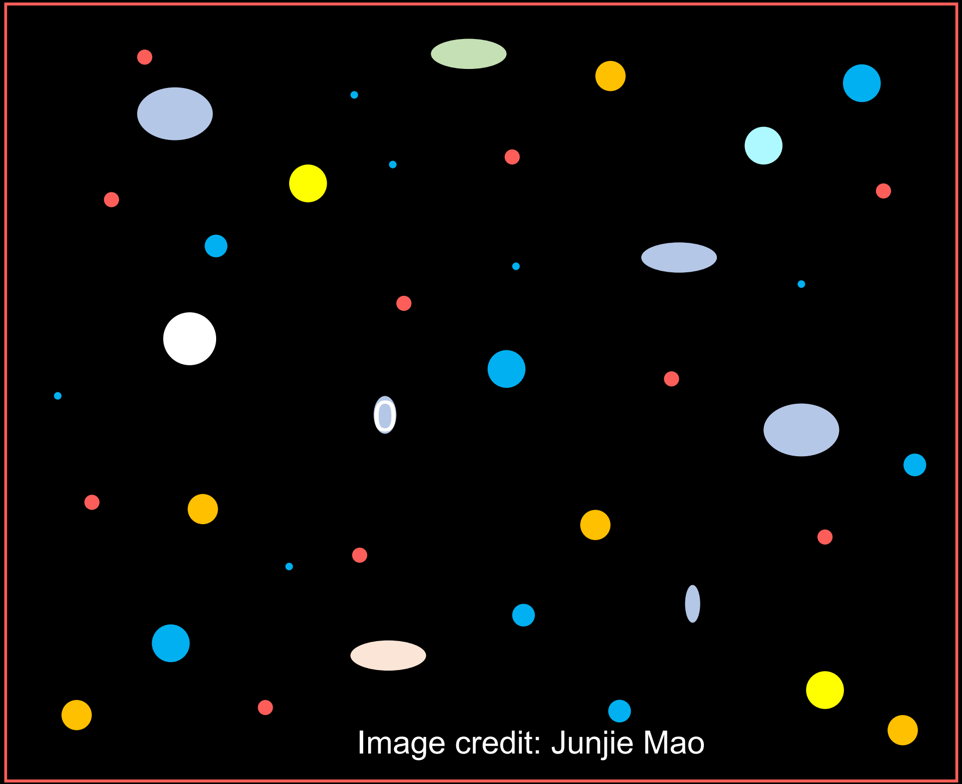


Image credit: Junjie Mao

2D spatial (x, y) distribution of events (e.g., photons)

Image credit: NASA, ESA, S. Beckwith (STScI) and the Hubble Ultra Deep Field Team

Timing of radiation

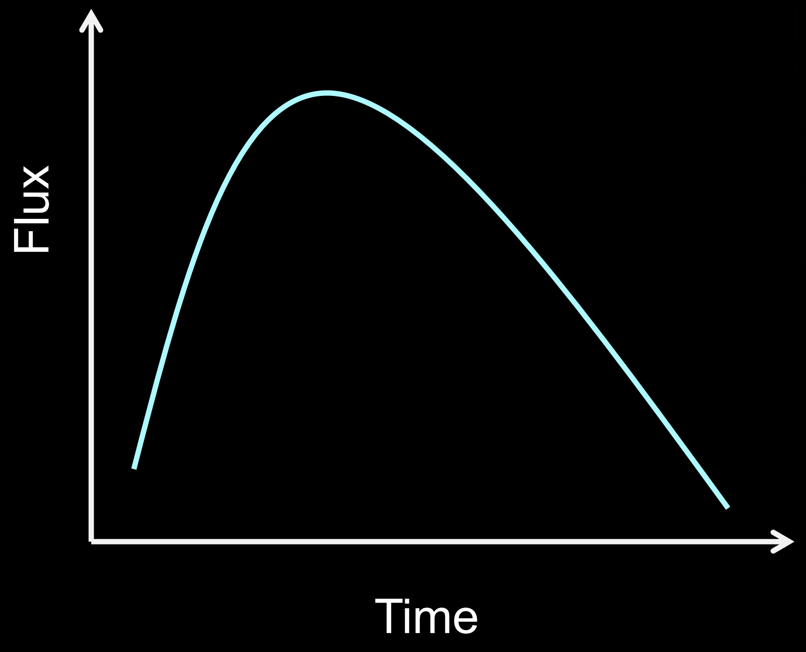
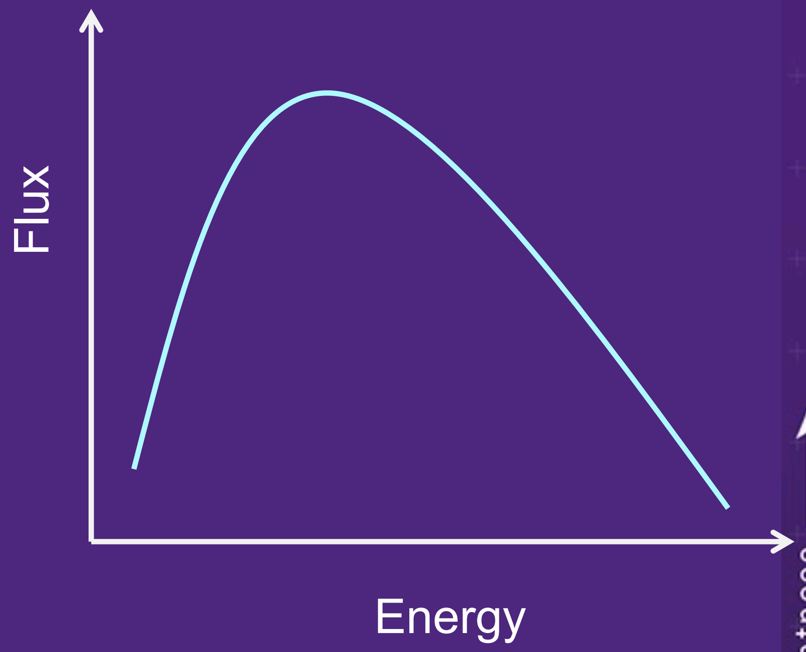


Image credit: APOD

Image: time (t) variation of events (e.g., photons)

Image credit: NASA, ESA, S. Beckwith (STScI) and the Hubble Ultra Deep Field Team

Spectrum of radiation



Spectrum: Energy (E) distribution of events (e.g., photons)

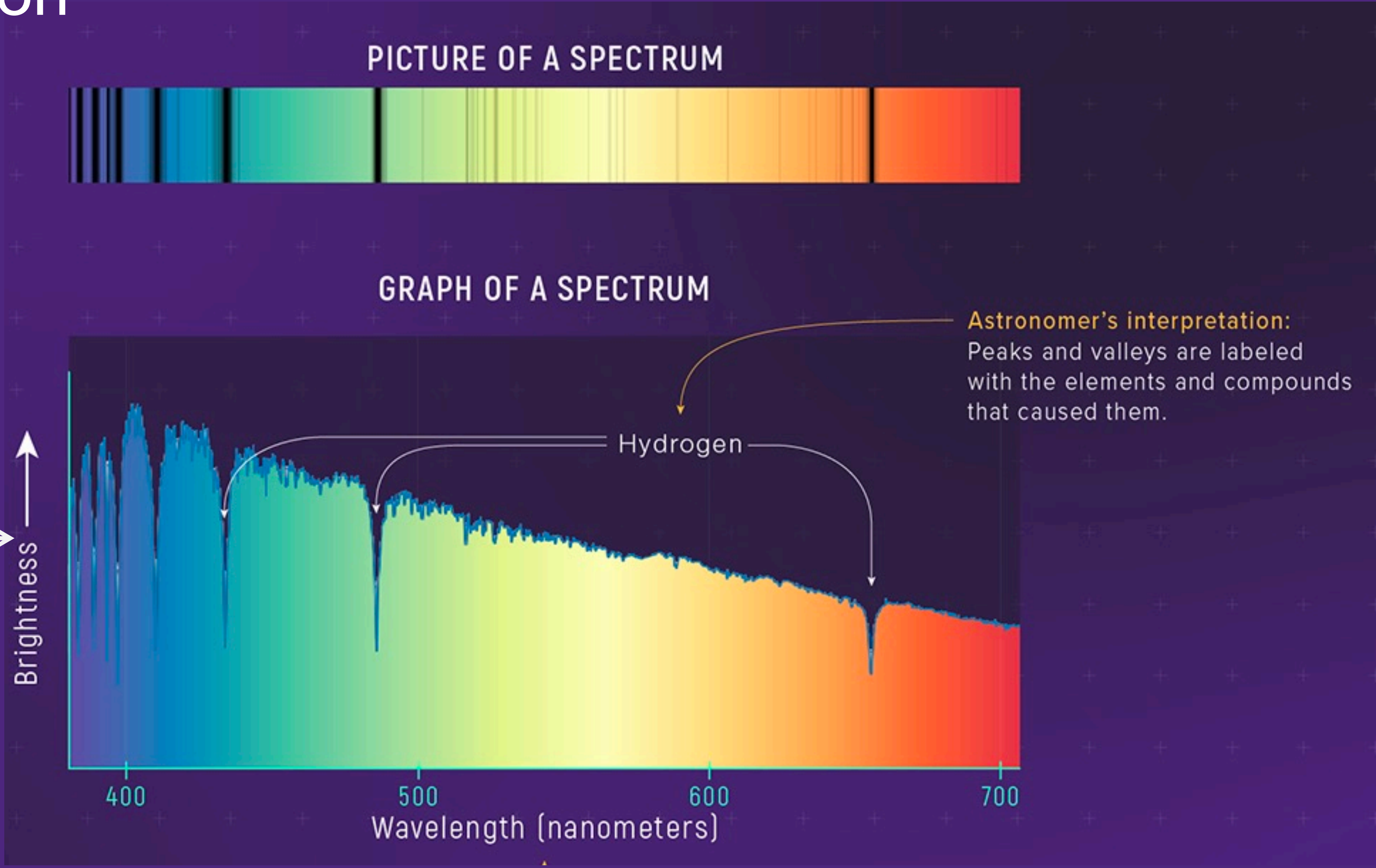
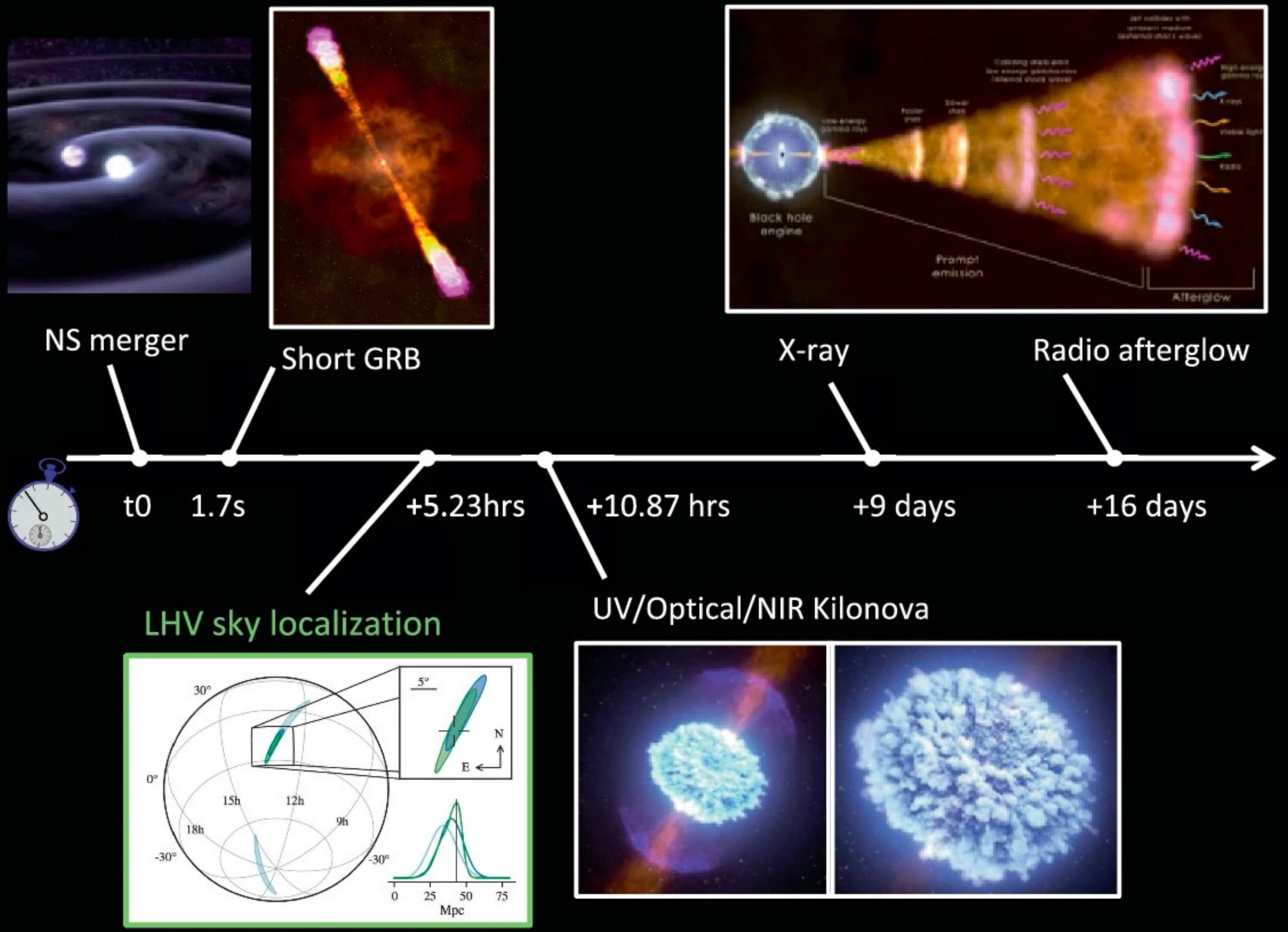


Image credit: NASA, ESA, Leah Hustak (STScI)

Chpt.1 Astrophysical messengers

1.1 Electromagnetic waves
1.2 Neutrinos
1.3 Cosmic rays
1.4 Gravitational waves

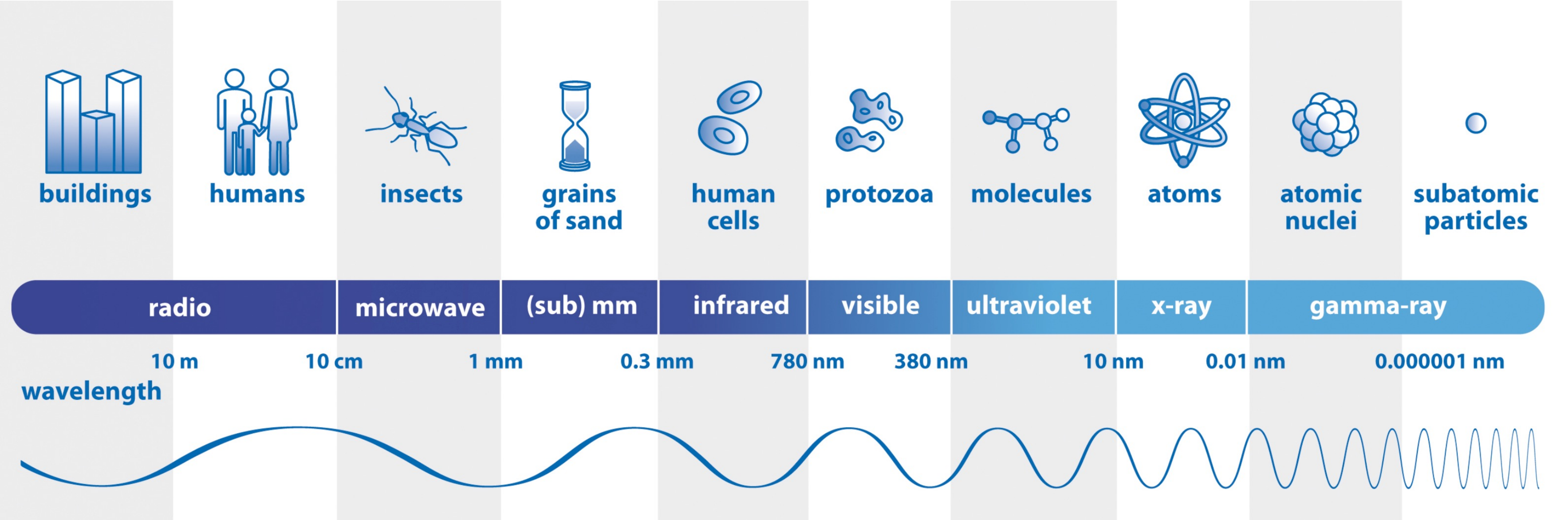


GW170817 (GW)
+GRB170817A (γ-ray)
+AT2017gfo (NIR to UV)
+ GRB afterglow (X-ray + radio)

Image credit: Branchesi (2023)

Electromagnetic waves

Image credit: ESA



speed of light

wavelength

frequency

$$c = \lambda\nu$$

Planck constant

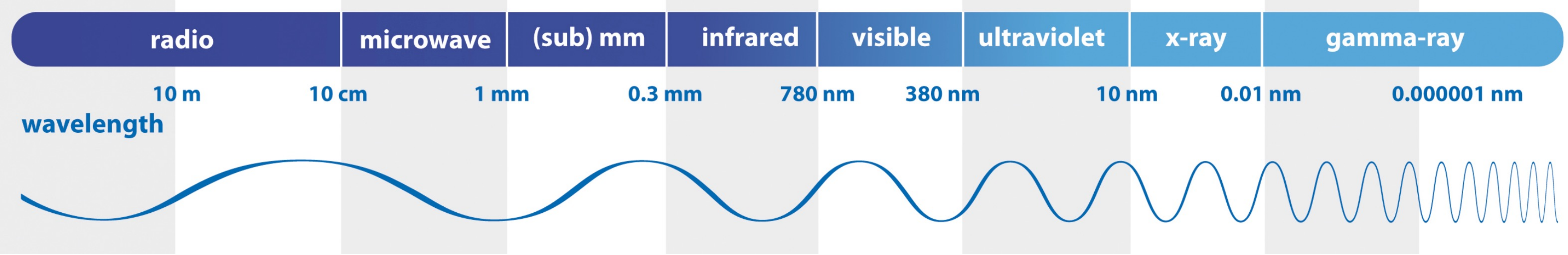
$$E = h\nu$$

$$T = E/k$$

Boltzmann constant

Electromagnetic waves

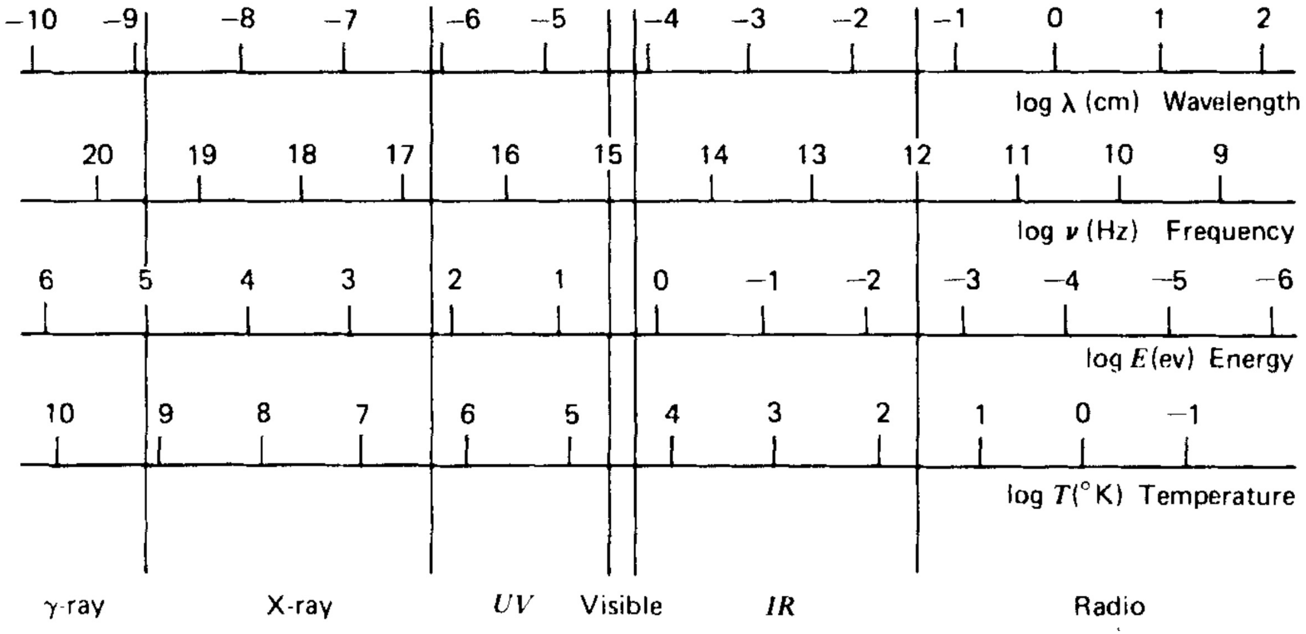
Image credit: ESA



$$c = \lambda \nu$$

$$E = h\nu$$

$$T = E/k$$



cm, μm (micron), nm, Å

MHz, GHz, THz

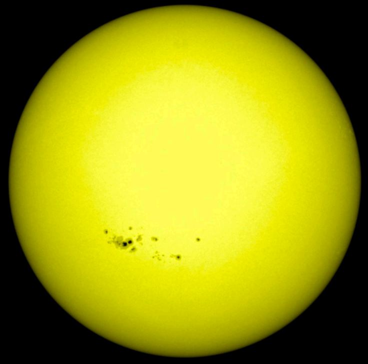
keV, MeV, GeV, PeV, TeV

K, (MK)

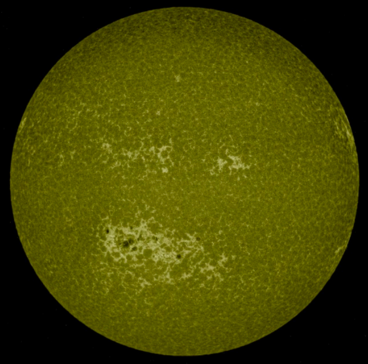
Rybicki & Lightman (1979; 2004)

Multiwavelength of the Sun

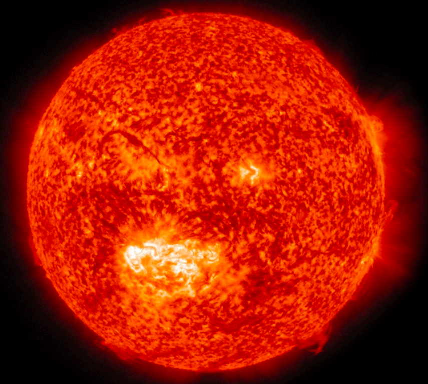
Image credit: NASA/SDO/GSFC



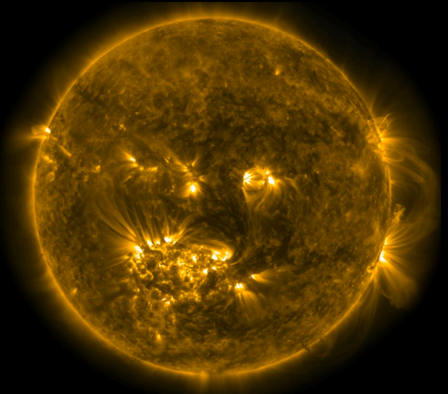
AIA 4500 Å
6000 Kelvin
Photosphere



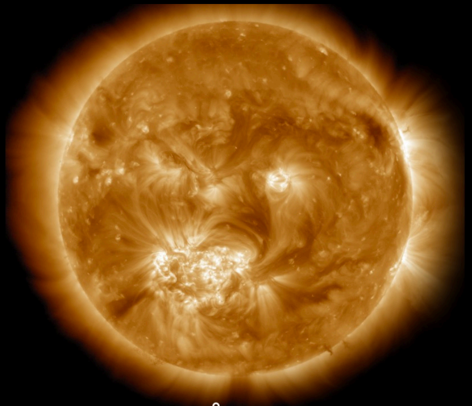
AIA 1600 Å
10,000 Kelvin
Upper photosphere/transition region



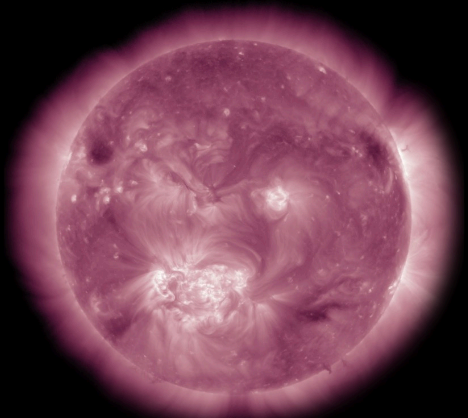
AIA 304 Å
50,000 Kelvin
Transition region/chromosphere



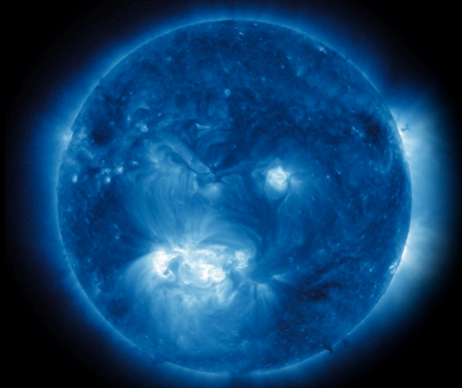
AIA 171 Å
600,000 Kelvin
Upper transition region/quiet corona



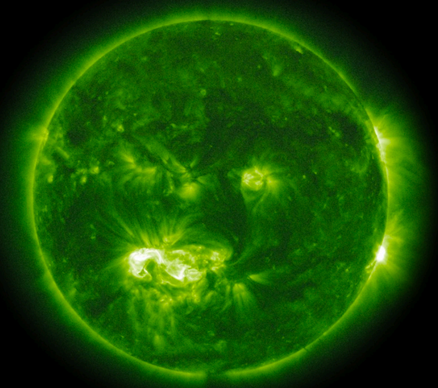
AIA 193 Å
1 million Kelvin
Corona/flare plasma



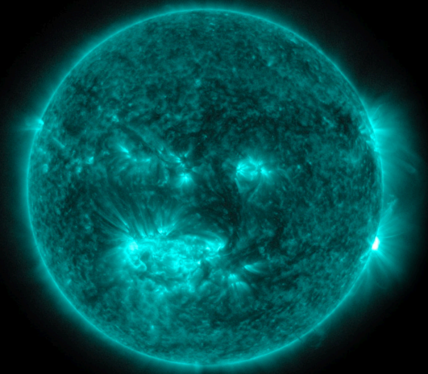
AIA 211 Å
2 million Kelvin
Active regions



AIA 335 Å
2.5 million Kelvin
Active regions



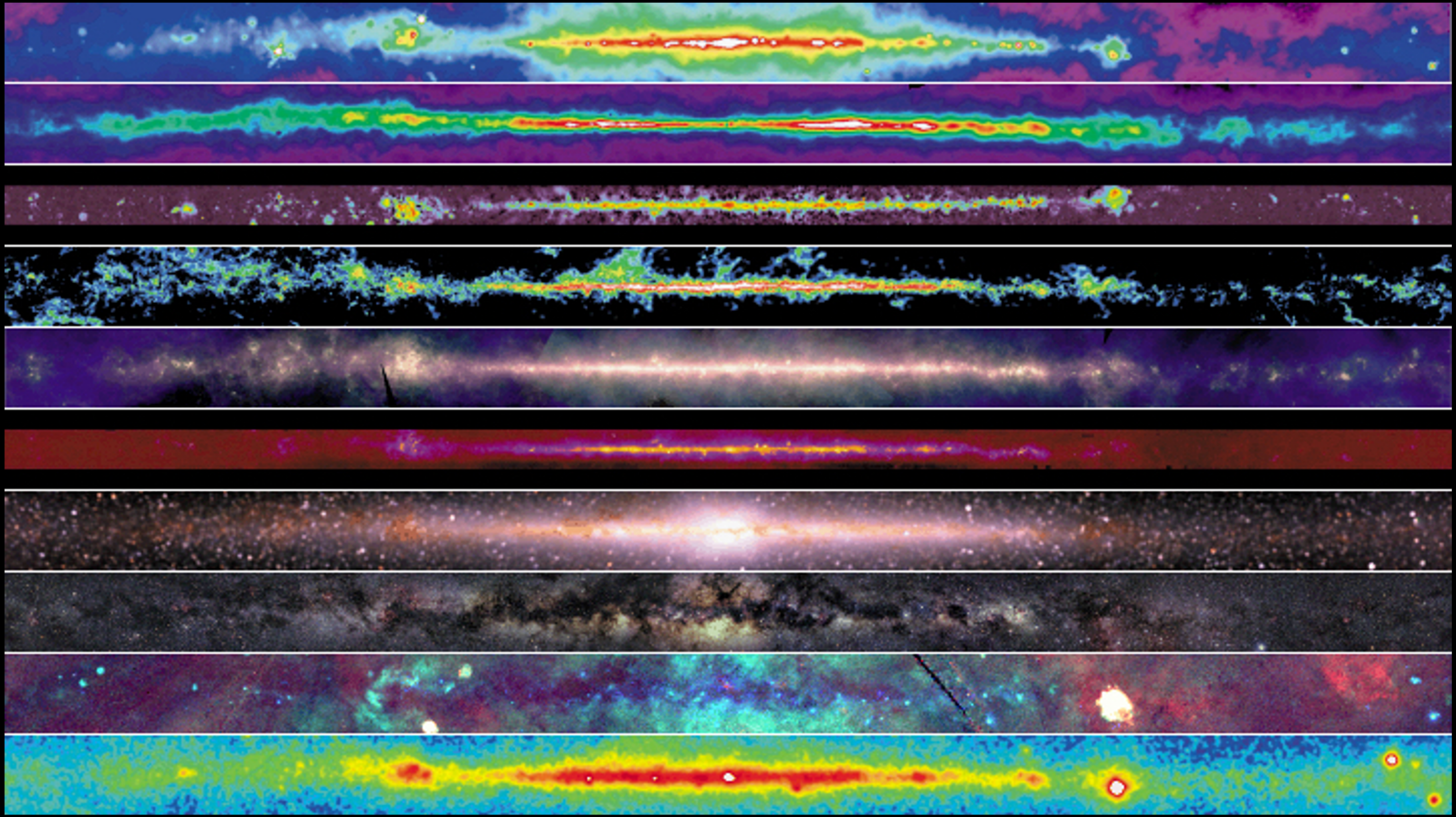
AIA 094 Å
6 million Kelvin
Flaring regions



AIA 131 Å
10 million Kelvin
Flaring regions

Multiwavelength of the Milky Way

<u>Image credit</u>: NASA/Goddard Space Flight Center



Radio (408 MHz)

Atomic hydrogen (1.4 GHz)

Radio (2.4 - 2.7 GHz)

Molecular hydrogen (115 GHz)

IR (12, 60, and 100 μm)

MIR (6.8 - 10.8 μm)

NIR (1.25, 2.2, and 3.5 μm)

Optical (4000 - 6000 Å)

X-ray (0.25 , 0.75, and 1.5 keV)

Gamma ray (>300 MeV)

Atmospheric window

Space missions (almost all UV, X-ray, and γ-ray missions)

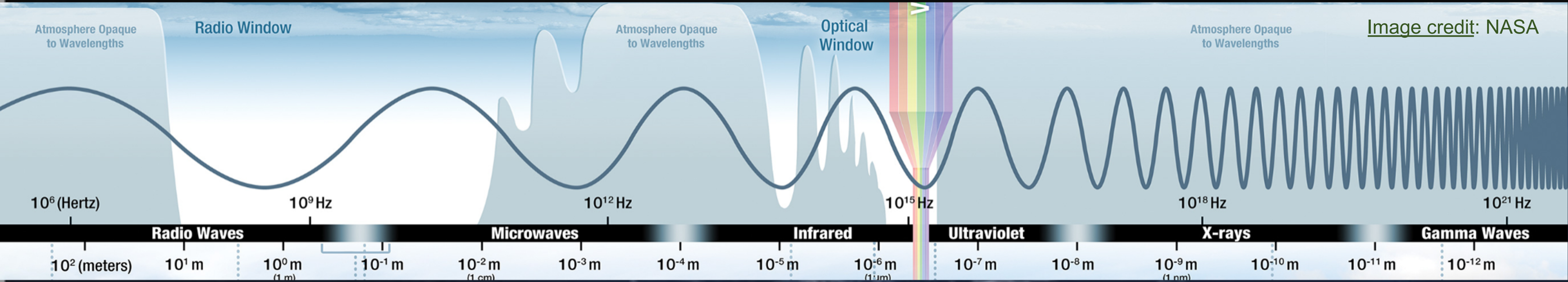
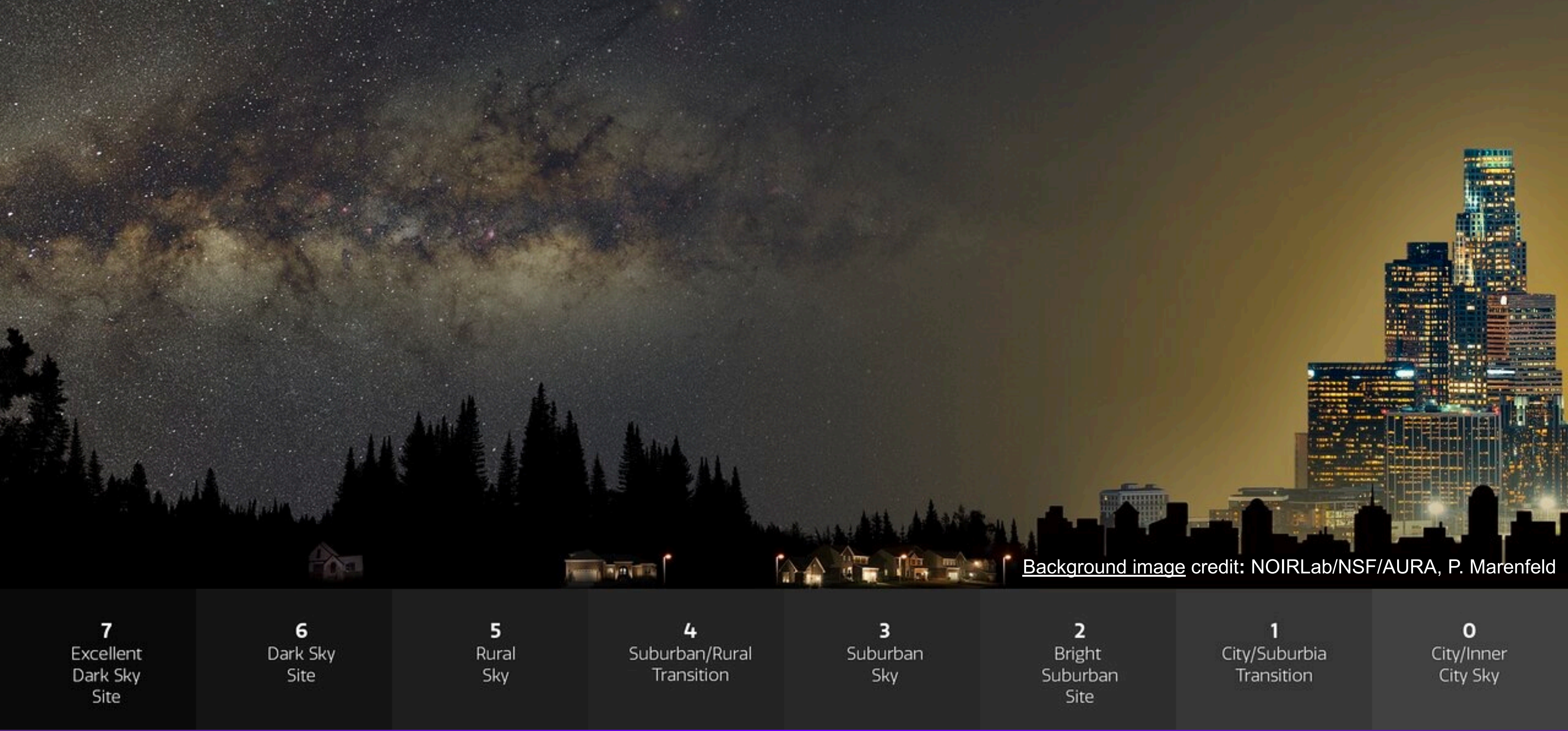


Image credit: NASA

Ground facilities (mainly radio, IR, and optical telescopes)

Background image credit: CMS

Not just atmospheric window



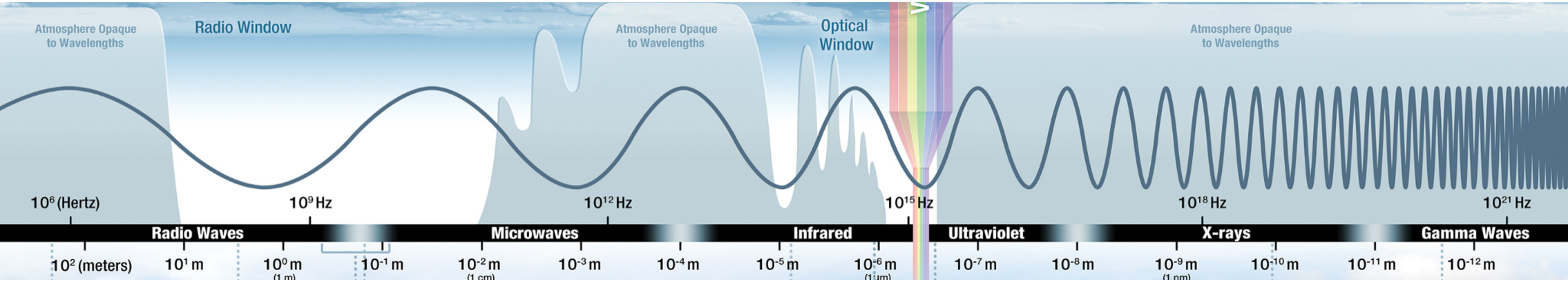
Background image credit: NOIRLab/NSF/AURA, P. Marenfeld

Not just atmospheric window

Background image credit: NOIRLab/NSF/AURA, P. Marenfeld

EM observing facilities

Image credit: NASA

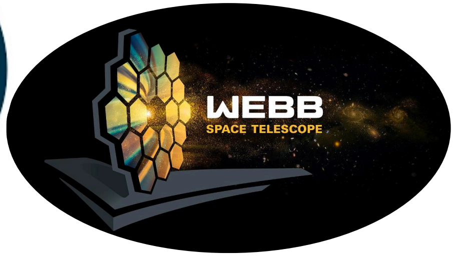


LOFAR (radio)
Image credit: ASTRON

Planck (microwave)
Image credit: ESA

HST (IR to UV)
Image credit: HST.org

Fermi (γ-ray)
Image credit: NASA



ALMA (microwave)
Image credit: ESO

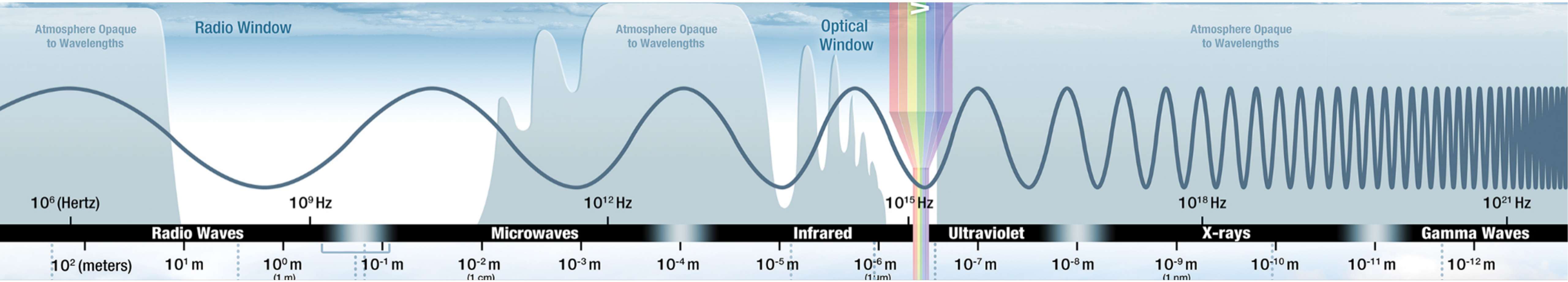
JWST (IR to optical)
Image credit: NASA

Gemini (IR to optical)
Image credit: NOIRLab

XRISM(X-ray)
Image credit: JAXA

EM observing facilities (cont.)

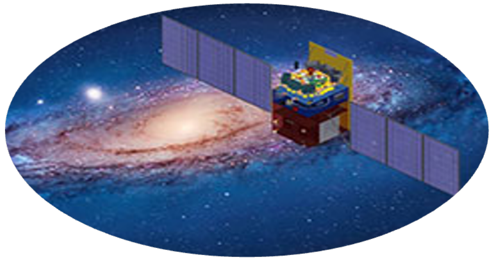
Image credit: NASA



ASO-S (UV to X-ray)
Image credit: PMO

FAST (radio)
Image credit: Nature

LAMOST (optical)
Image credit: NAOC



insight-HMXT
(X-ray to γ-ray)
Image credit: IHEP

Astrophysical messengers

Image credit: Madau & Dickinson (2014, ARAA)

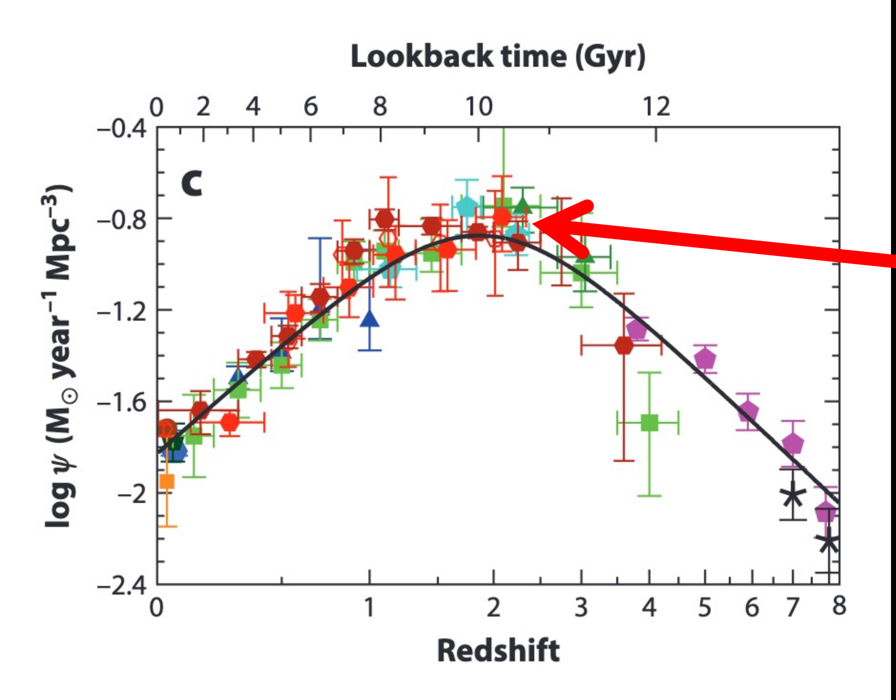
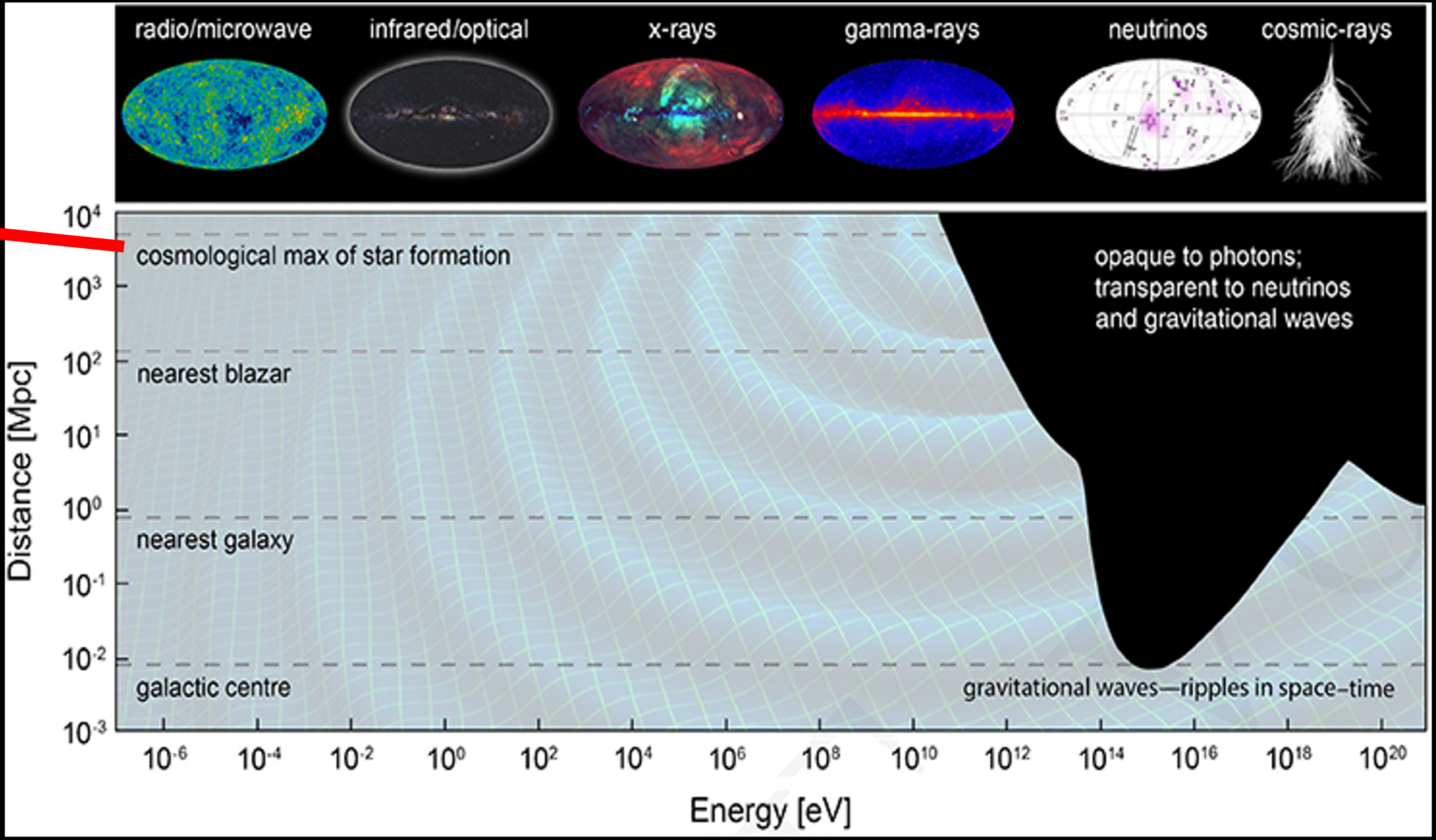


Image credit: Bartos & Kowalski, Multi-messenger Astronomy (book)

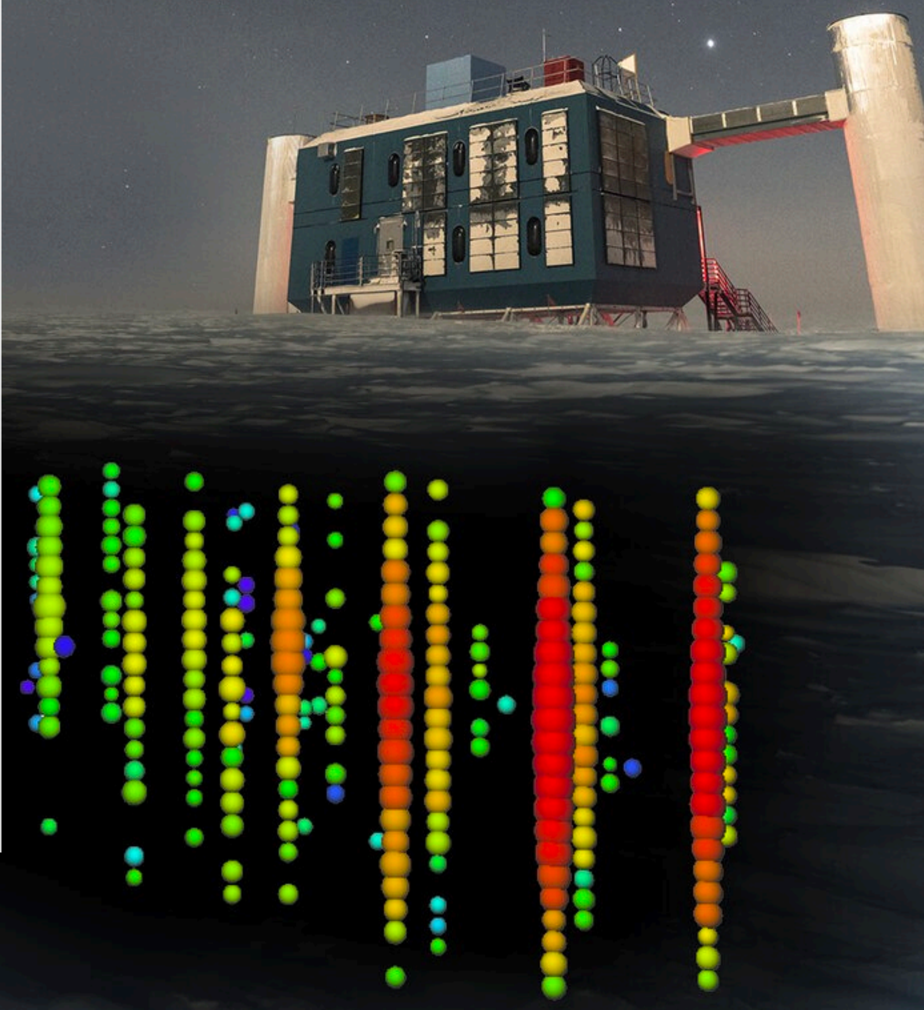


Electromagnetic waves
Neutrinos
Cosmic rays
Gravitational waves

Neutrinos

The neutrino was postulated by Wolfgang Pauli in the early 1930s but could only be detected for the first time in the 1950s

- Symbol is lowercase Greek letter: ν
  - Three flavors: electron ν_e, muon ν_μ, tau ν_τ
  - Oscillates between flavors
- Produced by nuclear processes
- Basic properties
  - Electrically neutral
  - Nearly massless
  - Travels close to the speed of light
- Interaction
  - Reacts to gravity and the weak nuclear force
  - Mostly passes through matter
  - Billions of neutrinos pass through our body every second



IceCube
(neutrinos)
Image credit: ESA

Neutrinos (IceCube)

High energy (~290 TeV) neutrino from IceCube-170922A was detected in association with a known gamma-ray blazar TXS 0506+056 ($z \sim 0.3365$). This is the third detections of individual astrophysical sources of neutrinos, after the Sun and SN1987A.

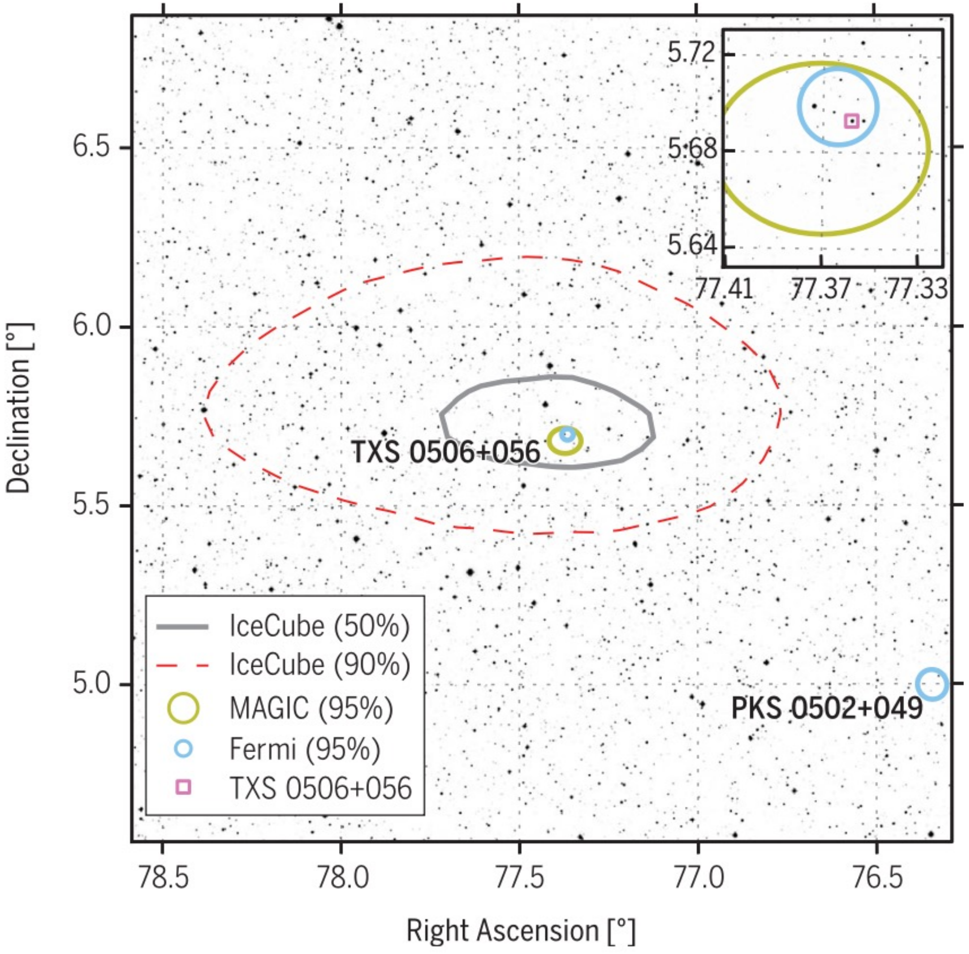
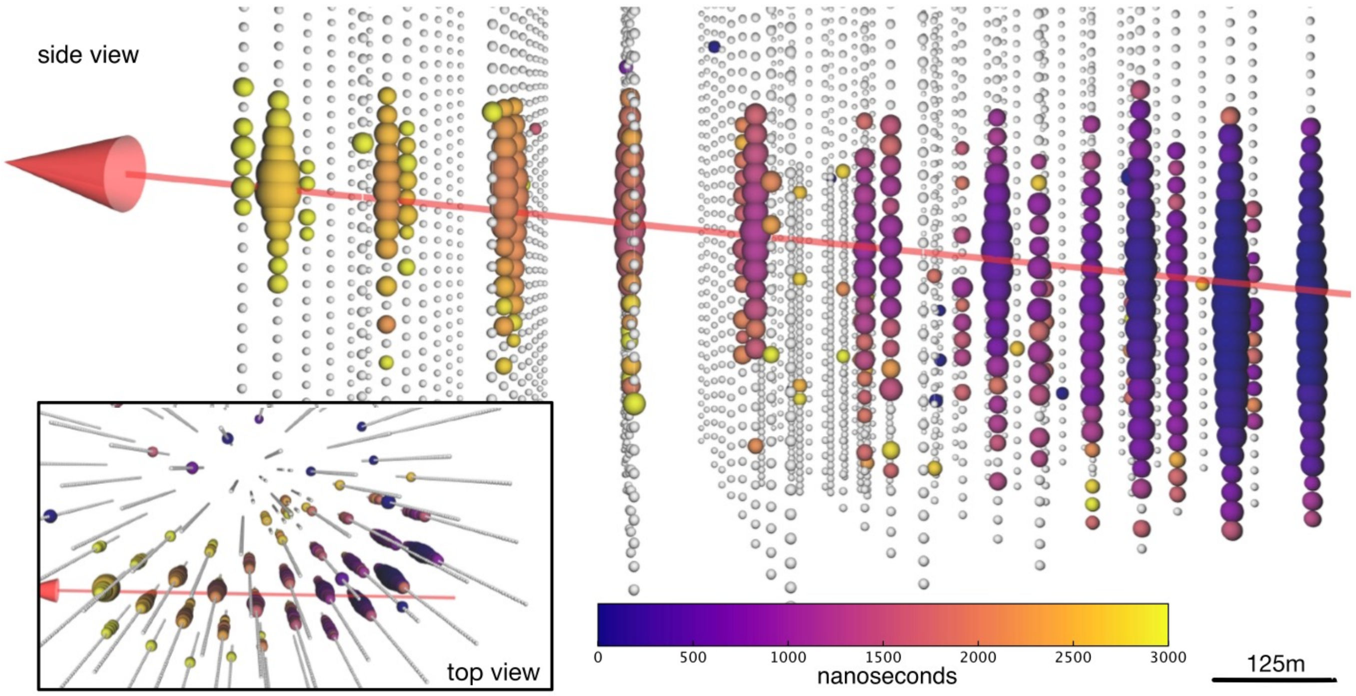


Image credit: IceCube collaboration (2023)

~5800 photoelectrons in ~3000 ns (from left to right)



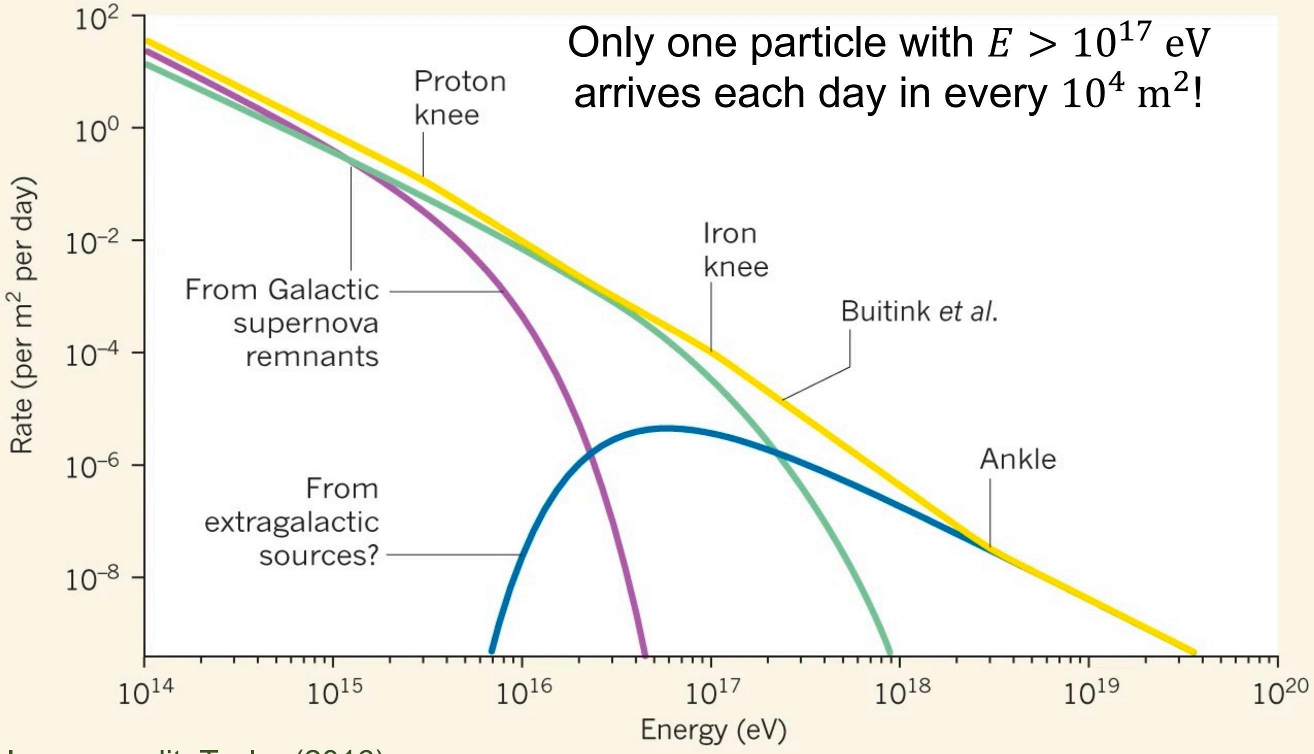
Cosmic rays

In 1912, Victor Hess discovered cosmic rays via a balloon flight
- Ionization radiation at 5300 m is 3 times that at the see level
- Penetrating radiation was entering the atmosphere from above.

- ❑ High-energy particles
  - ~89% protons (nuclei of hydrogen)
  - ~10% nuclei of helium
  - ~1% nuclei of heavier elements
- ❑ Origin
  - Mostly produced within the Milky Way (Galactic Cosmic Rays, GCRs)
  - The rest have extragalactic origins
- ❑ When passing through the Earth atmosphere, a shower of particles are produced
  - Mostly pion
    - Pion decay → muons (and more)
  - Muon
    - 207 times heavier than electrons
    - do not interact strongly with matter
    - Muon decay → 1 electron + 2 neutrinos

Image credit: A. Chantelauze, S. Staffi, L. Bret, Pierre Auger Collabration

Cosmic rays (LHAASO)

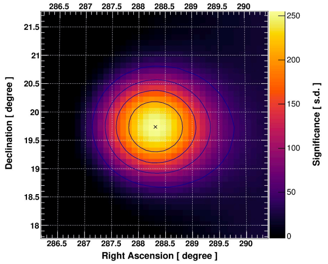


Only one particle with $E > 10^{17}$ eV arrives each day in every 10^4 m^2!

Image credit: Taylor (2016)

Large High Altitude Air Shower Observatory (LHAASO) (cosmic rays)

Image credit: Science



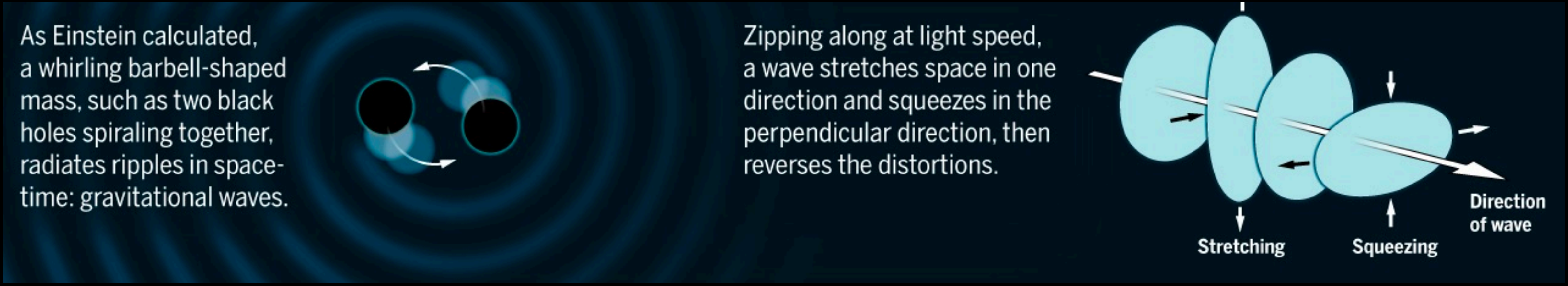
A TeV afterglow from GRB 221009A (LHAASO collaboration, 2023)

Clues about the origin of cosmic rays come from both their composition and their energy spectra.

Tera (trillion): $\mathrm{TeV} = 10^{12}$ eV
Peta (quadrillion): $\mathrm{PeV} = 10^{15}$ eV
Exa (quintillion): $\mathrm{EeV} = 10^{18}$ eV
Zetta (sextillion): $\mathrm{ZeV} = 10^{21}$ eV

Gravitational wave

Image credit: V. Altounian/Science



link: Astrobites

- Gravitational waves
  - "Ripples" in space-time caused
- Origin
  - Mostly produced by mergers of massive objects

Gravitational waves (LIGO)

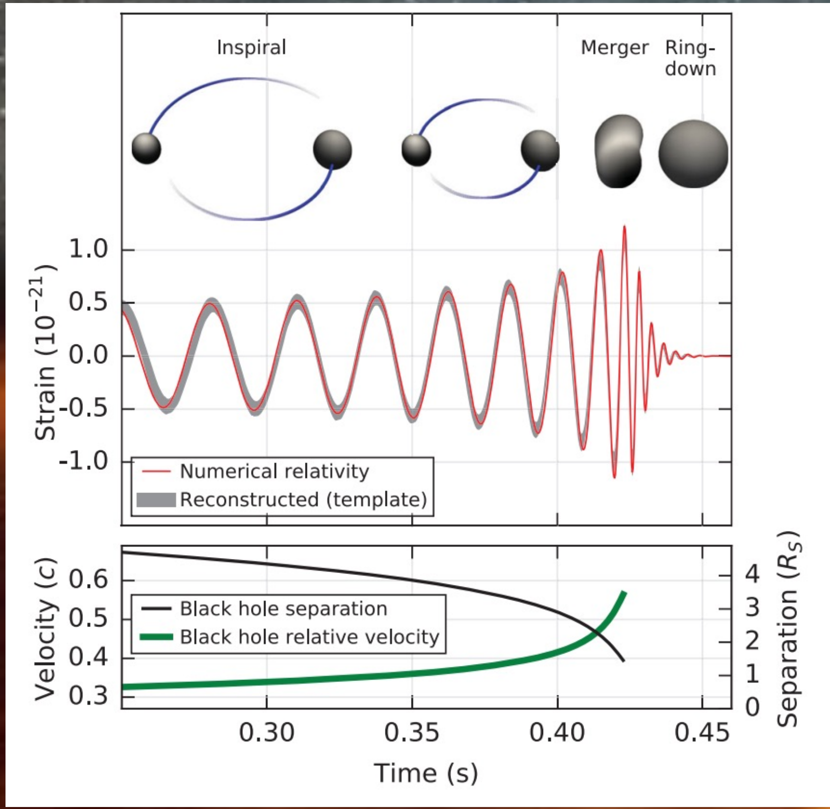


Image credit: Abbott et al. 2016

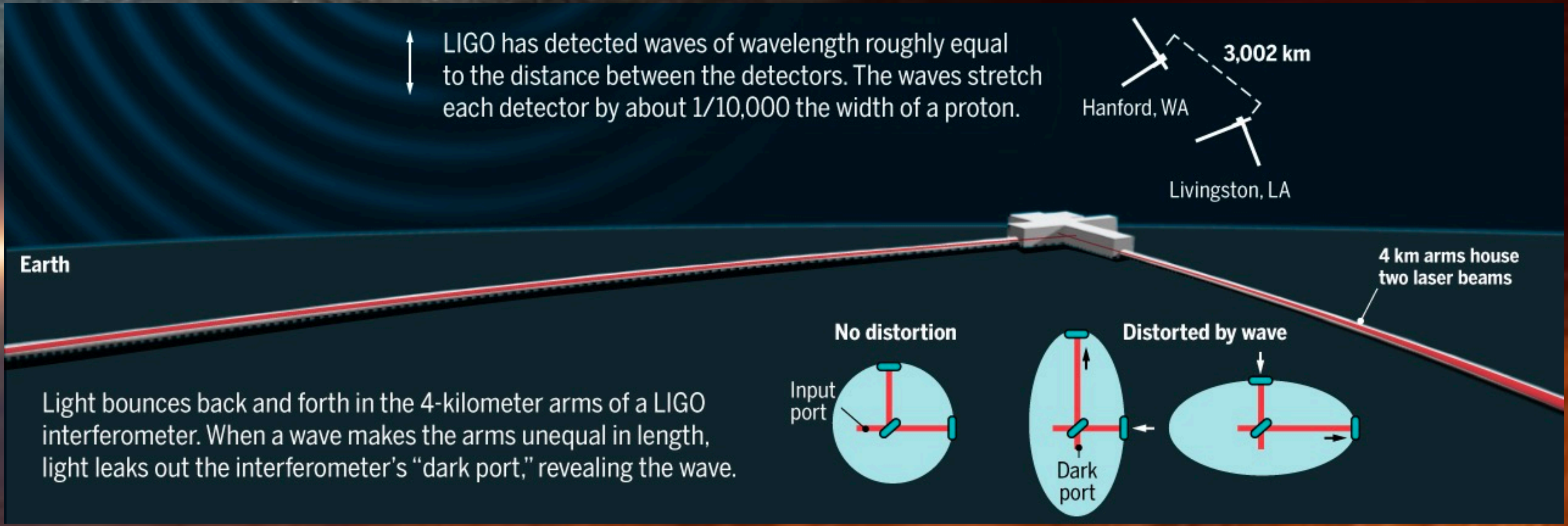
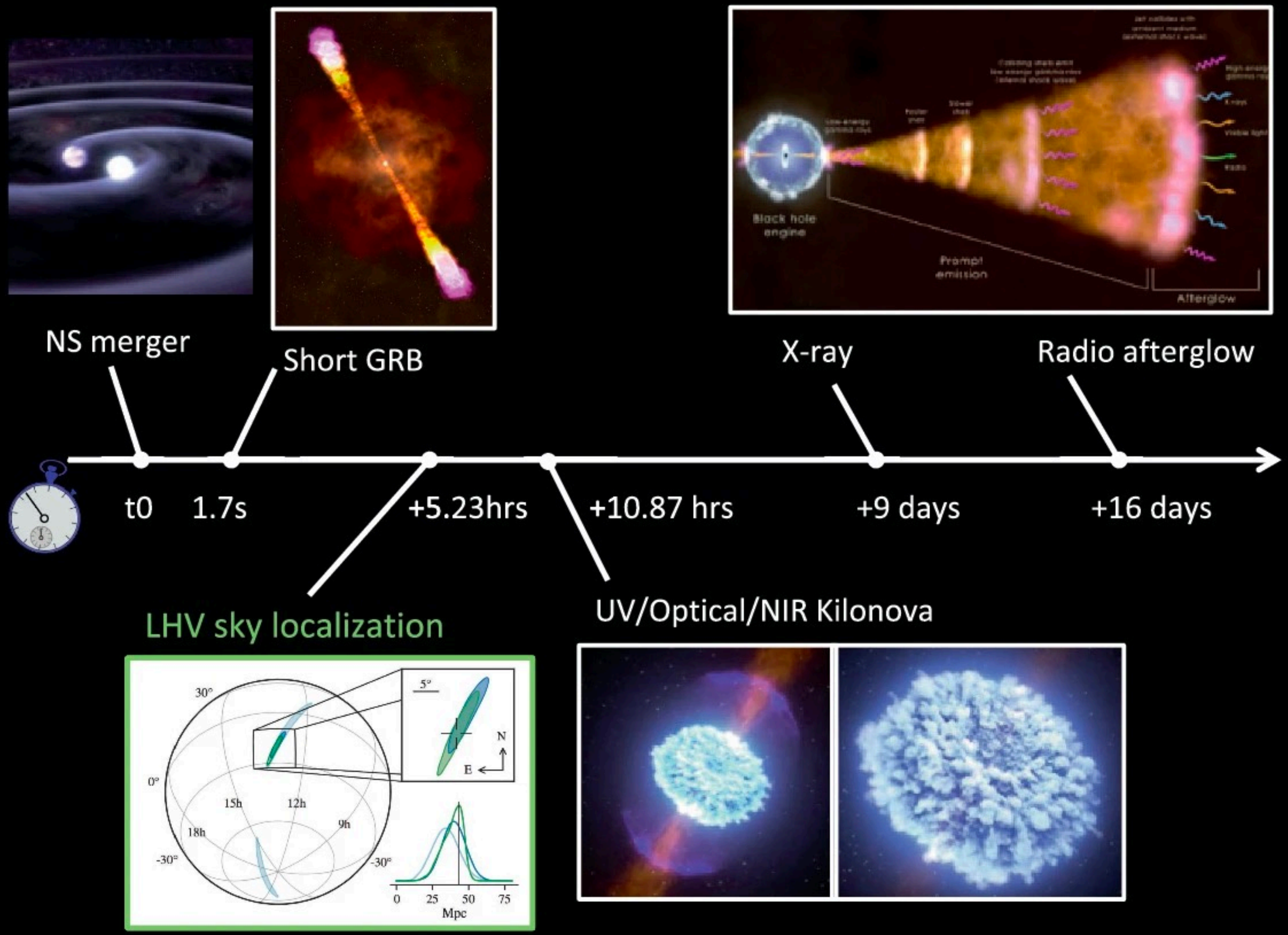


Image credit: V. Altounian/Science

Embrace the era of multi-messenger astronomy



GW170817 (GW)
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+ GRB afterglow (X-ray + radio)

Image credit: Branchesi (2023)