From Astronomy to Astrophysics - How do we explore regions of space that we can not currently reach?

Frédéric GALLIANO

Département d'Astrophysique (DAp), Irfu, CEA Paris-Saclay, France

April 11, 2024

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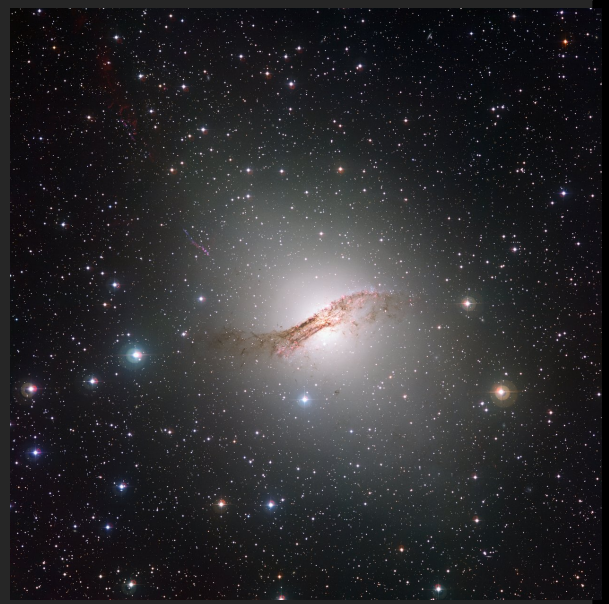

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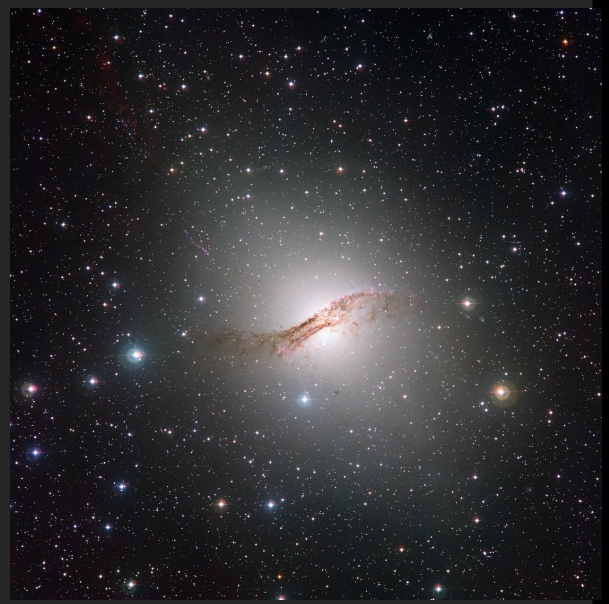

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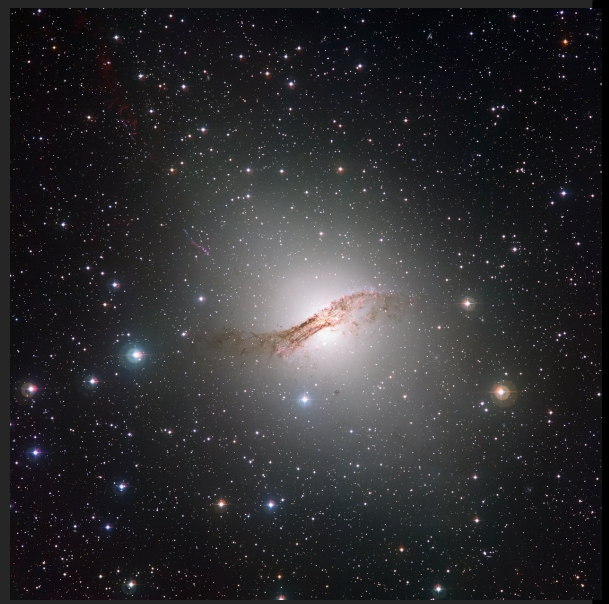

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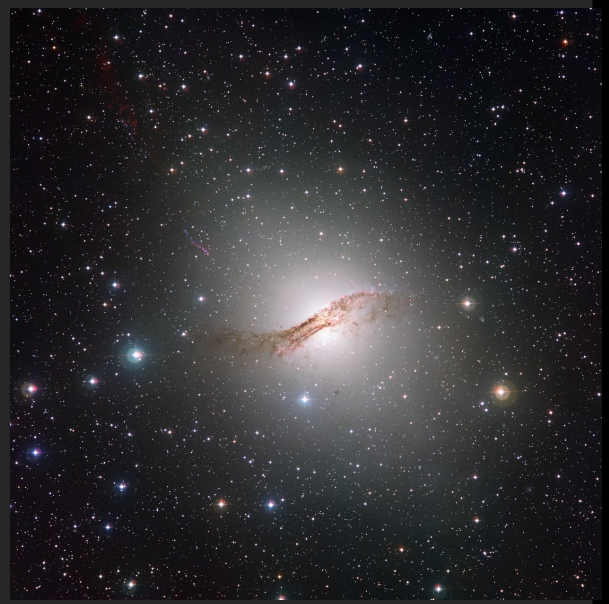

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1 INTRODUCTION

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   - The first observations of the sky
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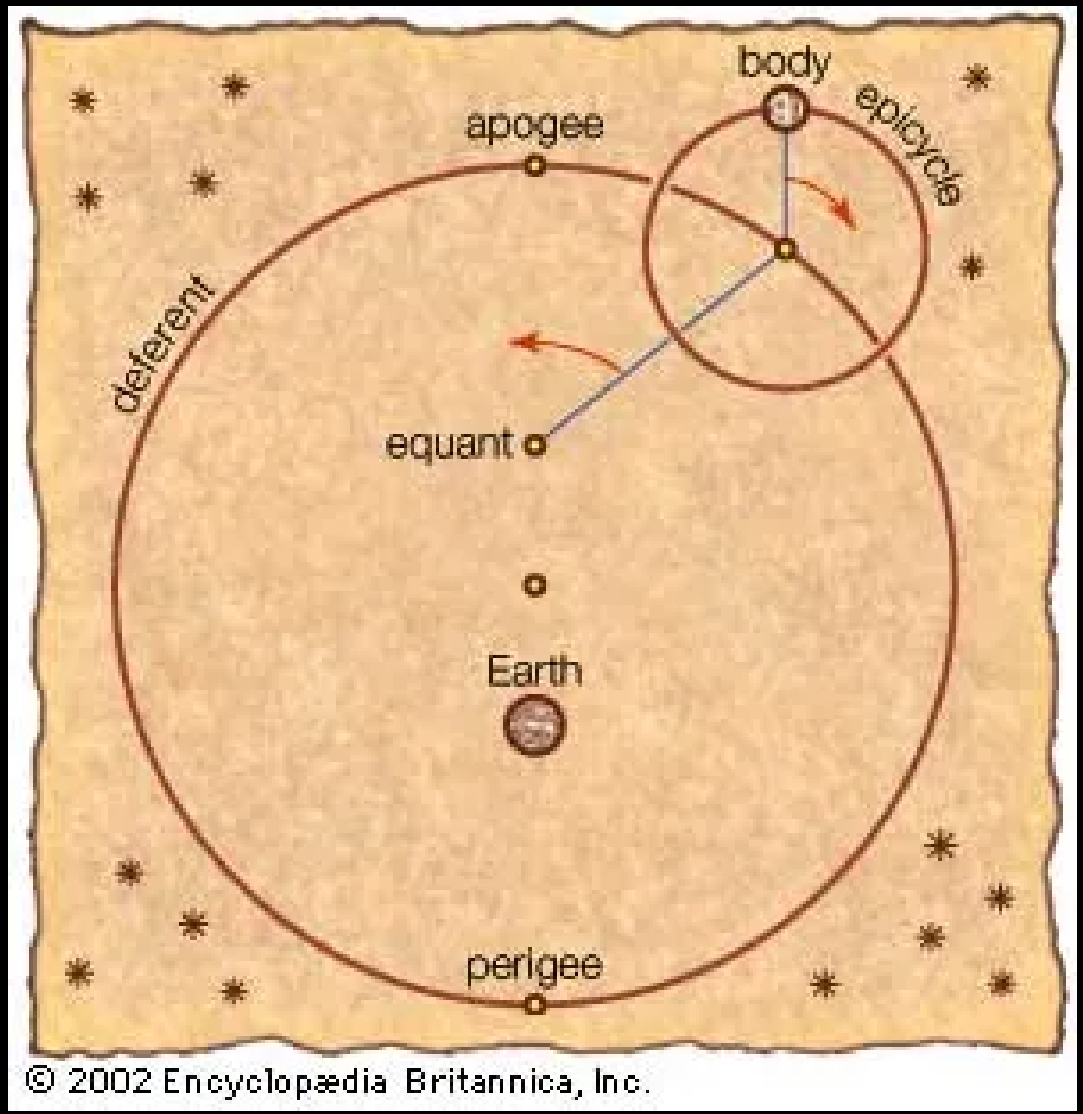

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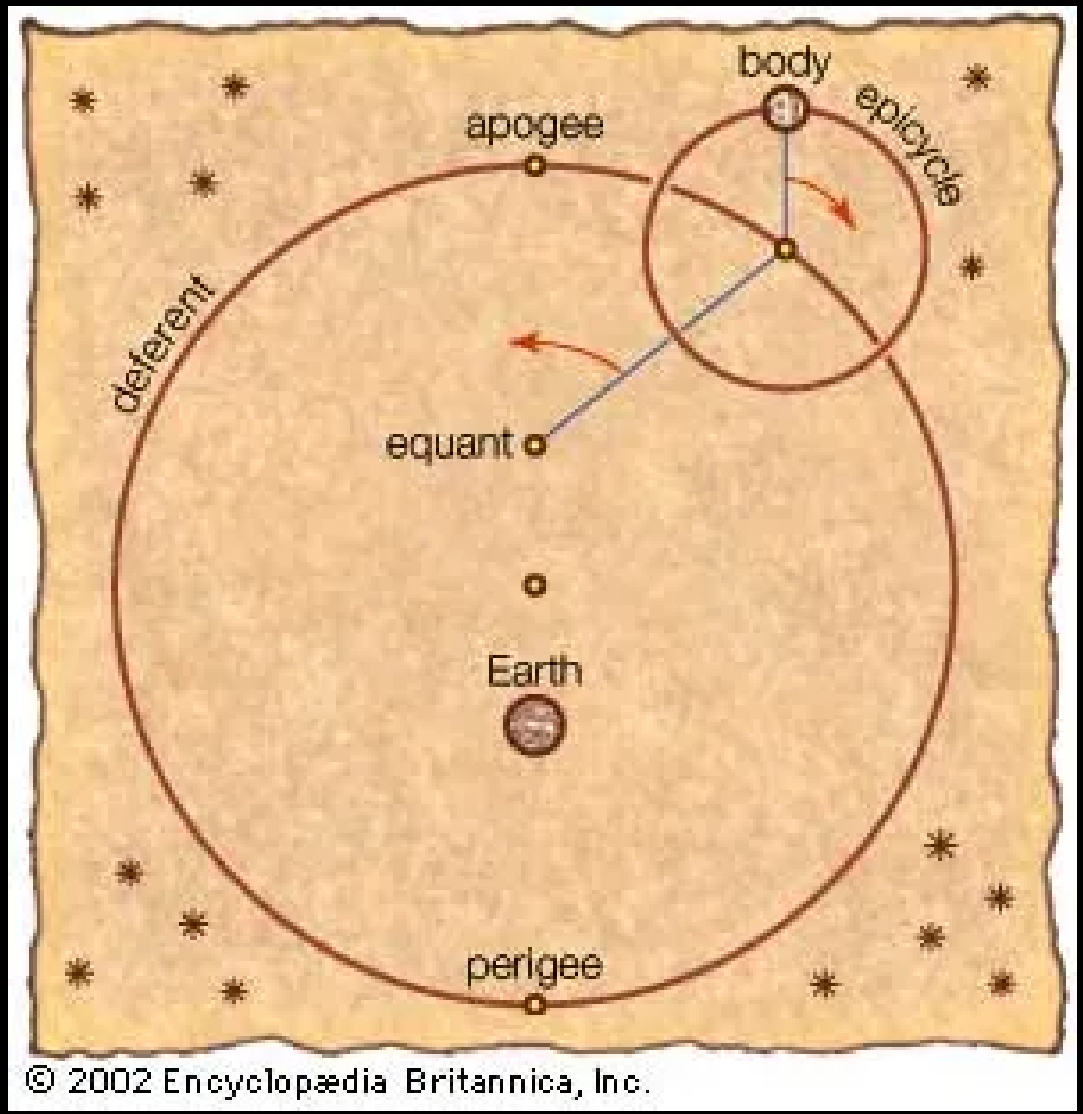

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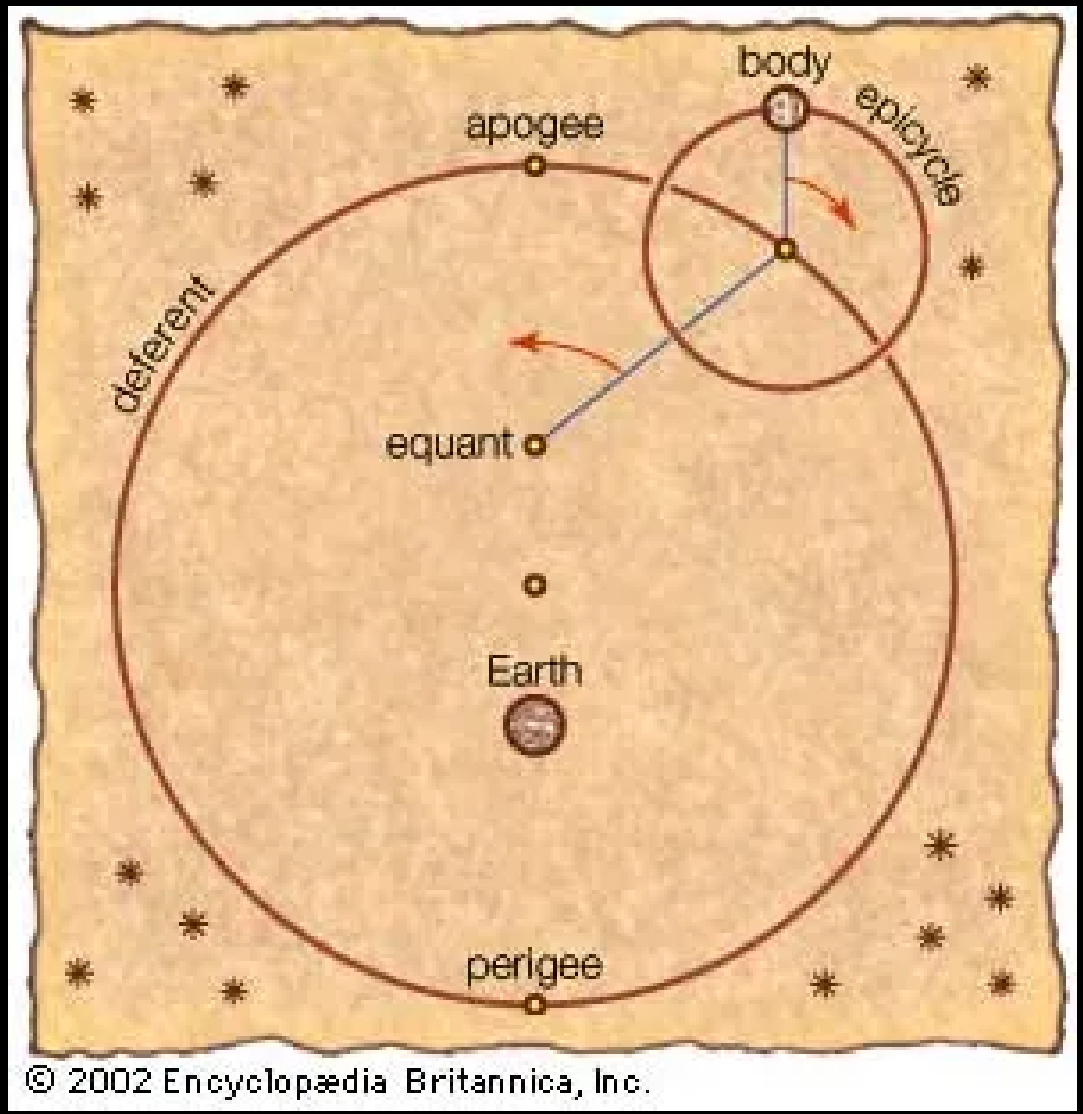

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From the end of Antiquity to Middle Age $\rightarrow$ prevalence of Ptolemaic system:

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- Quite accurate but wrong.

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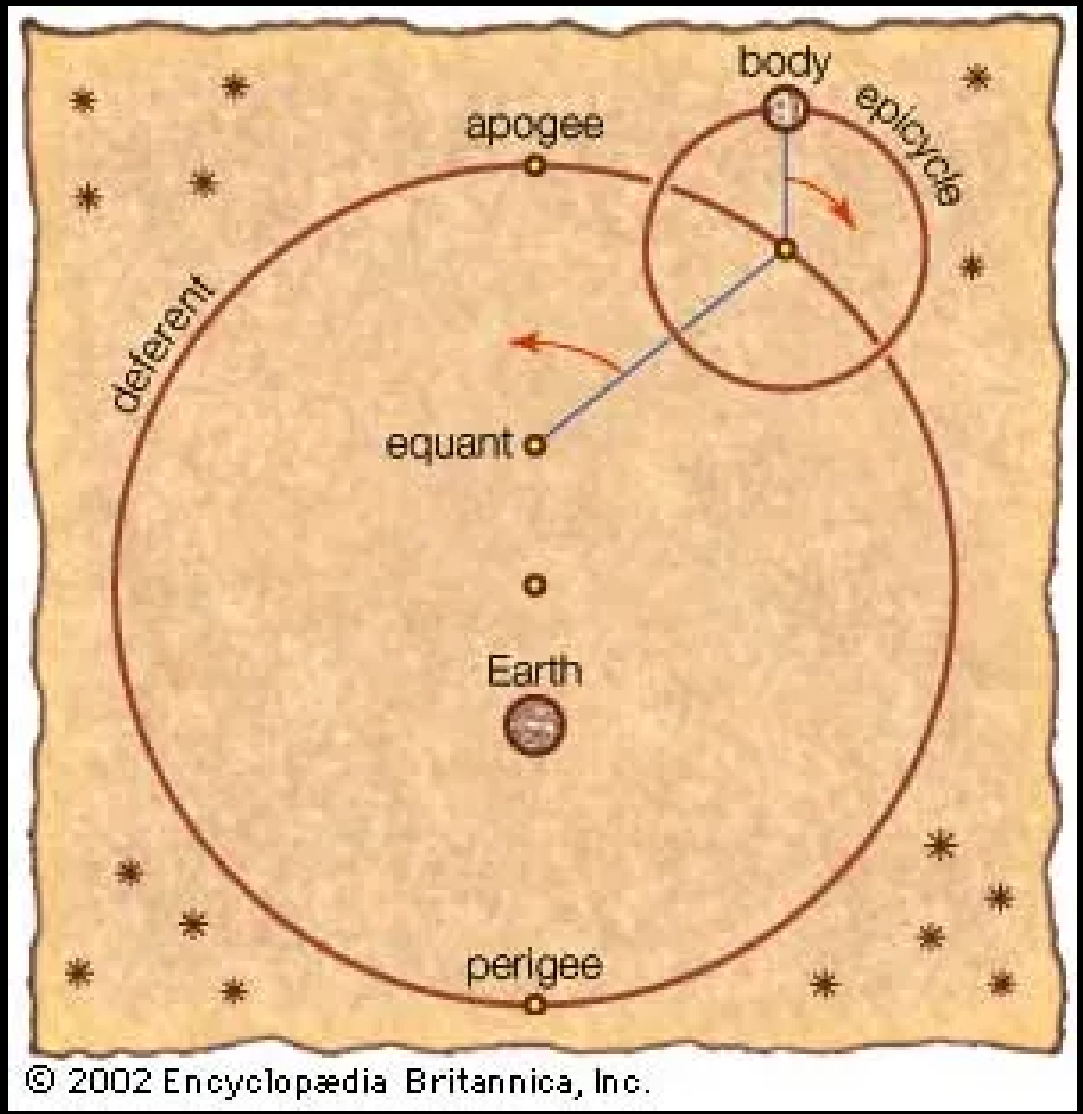

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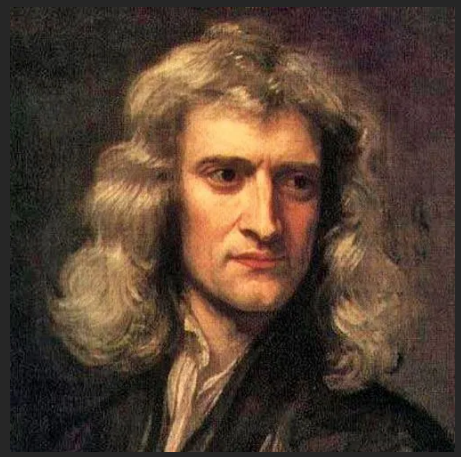

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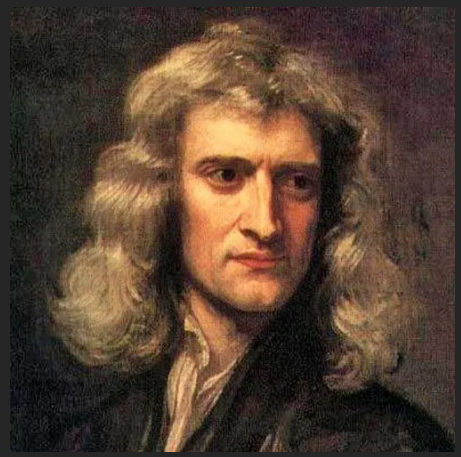

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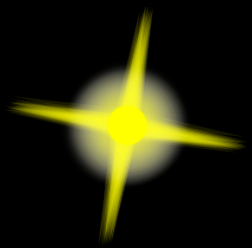
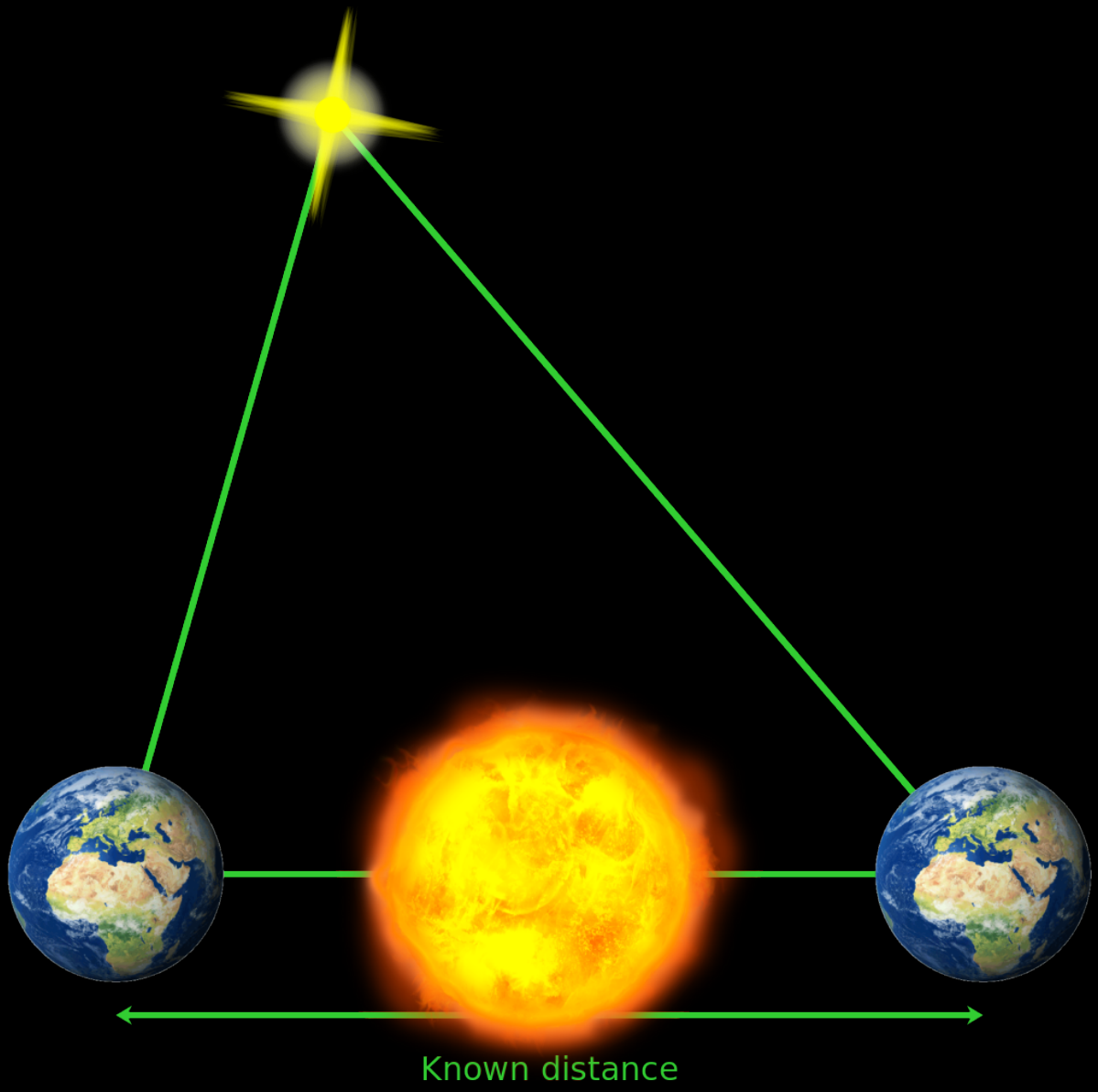
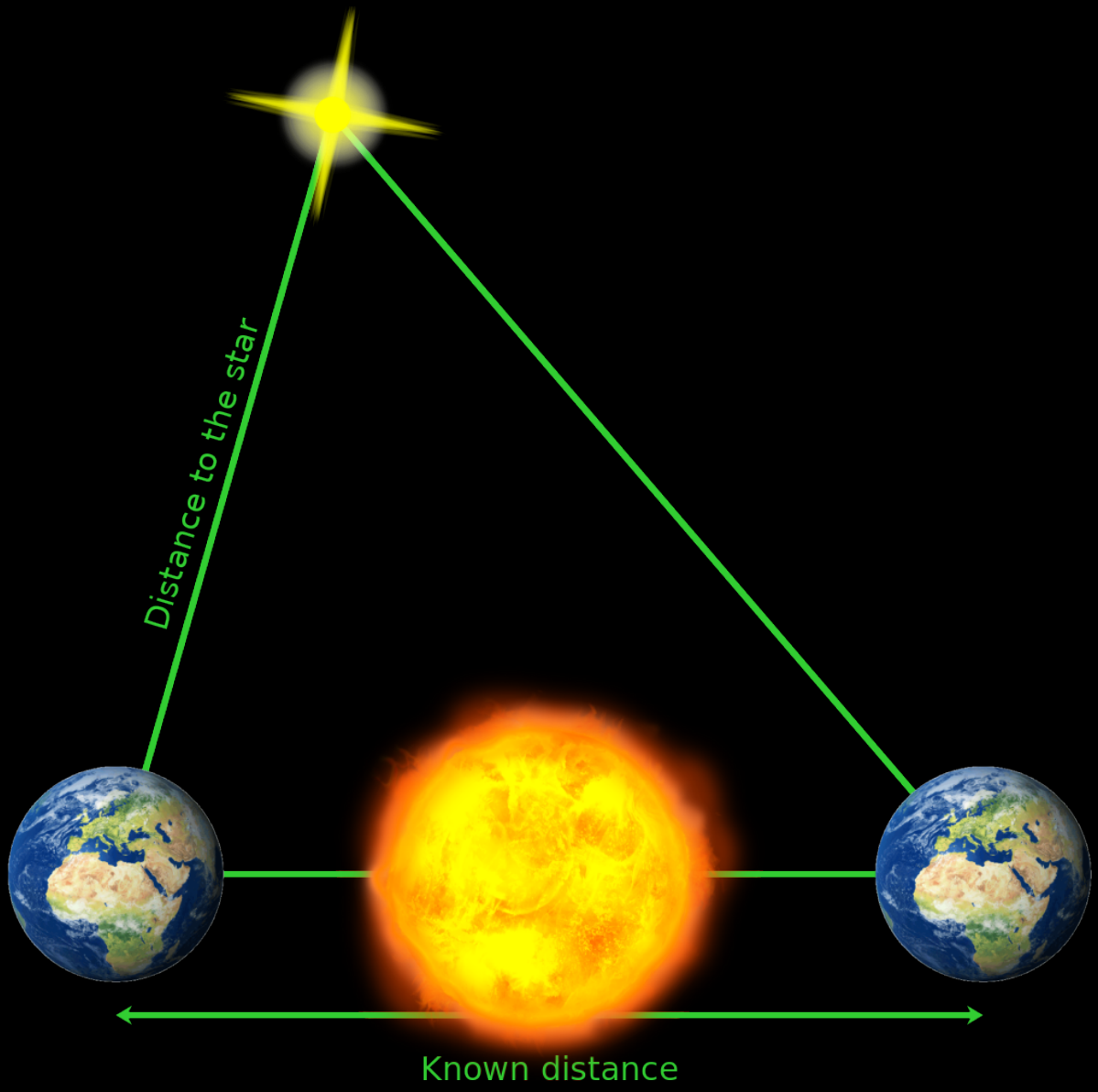
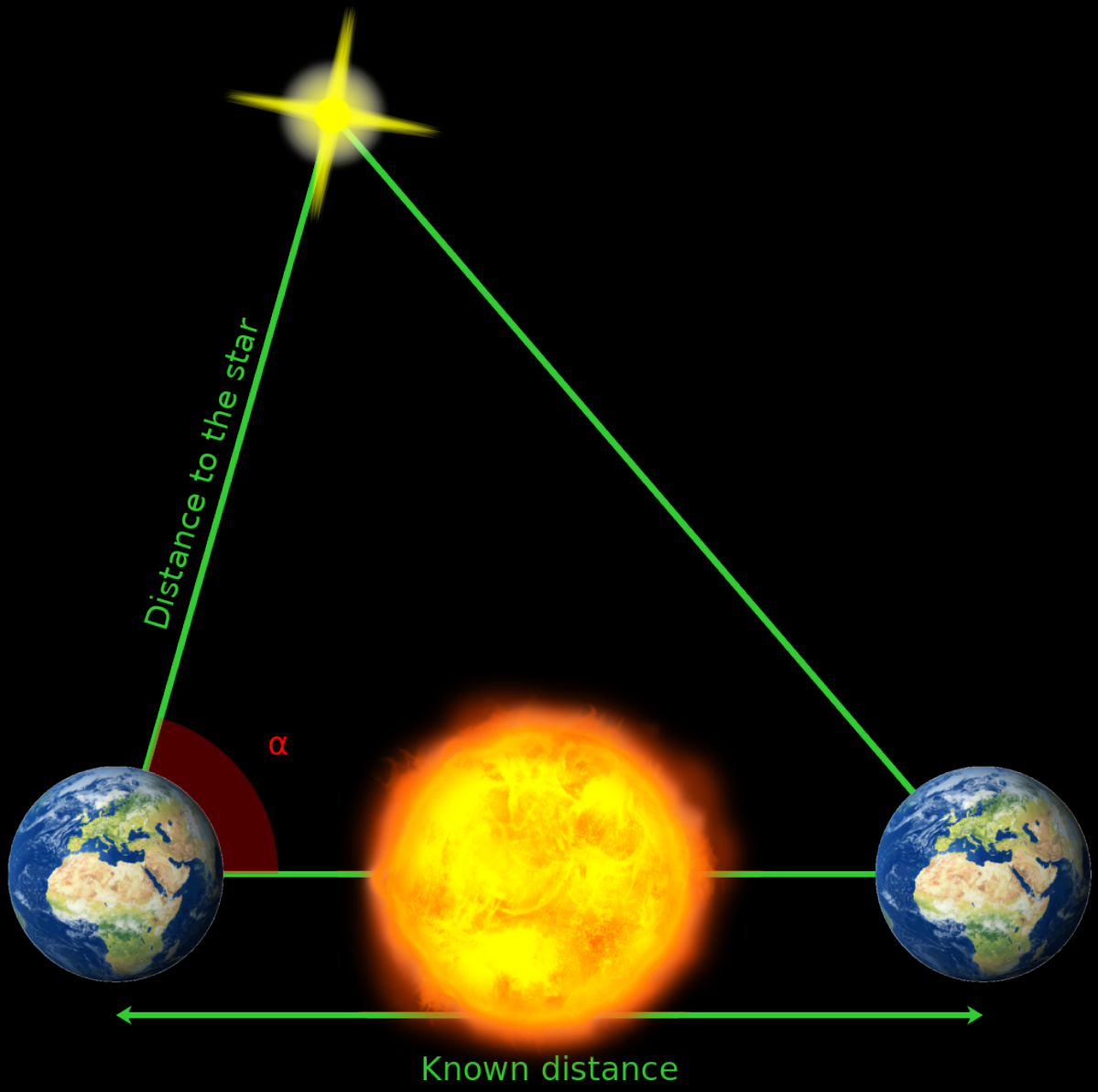



Known distance


Distance to the star
Known distance


Distance to the star
α
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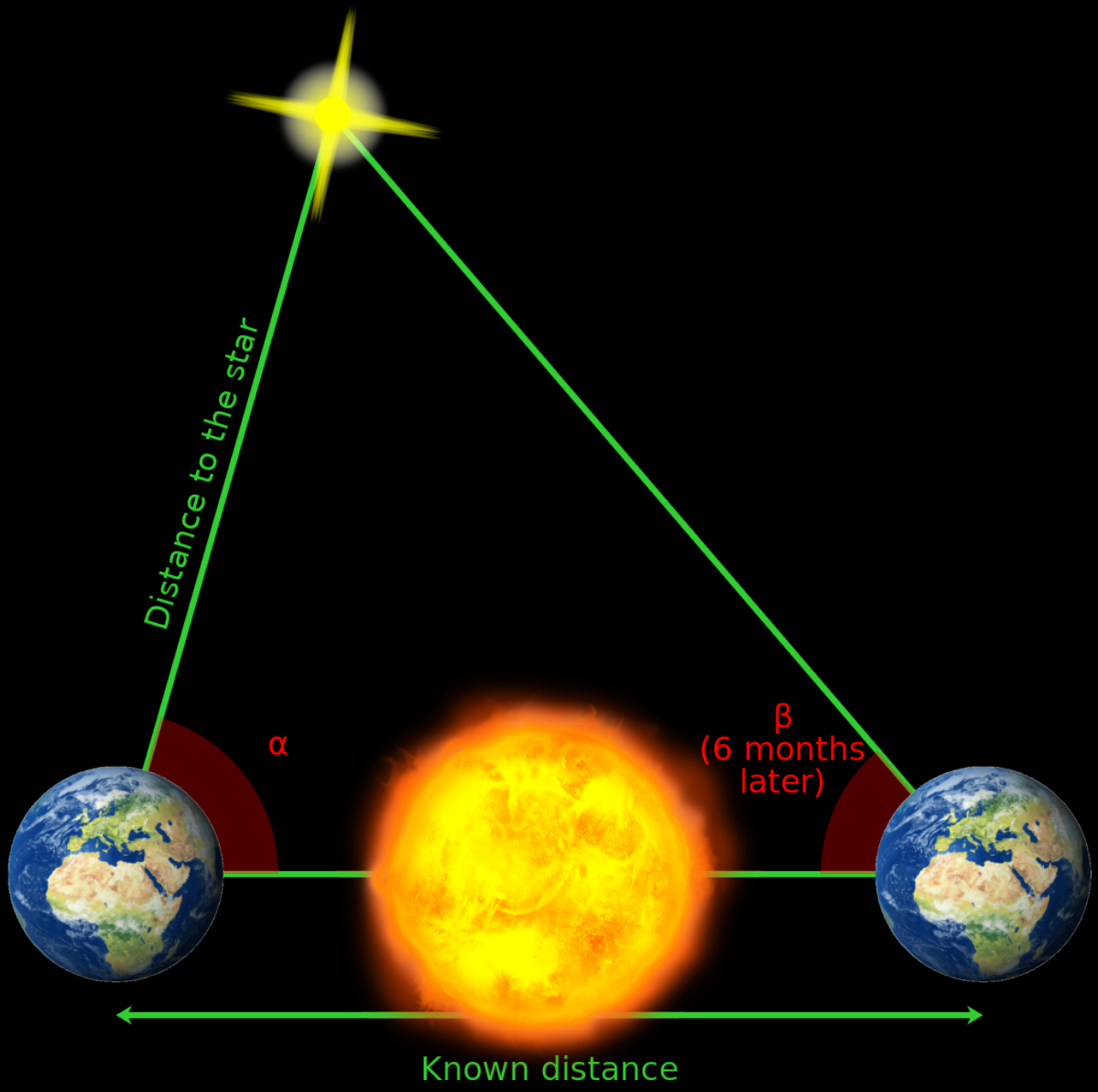
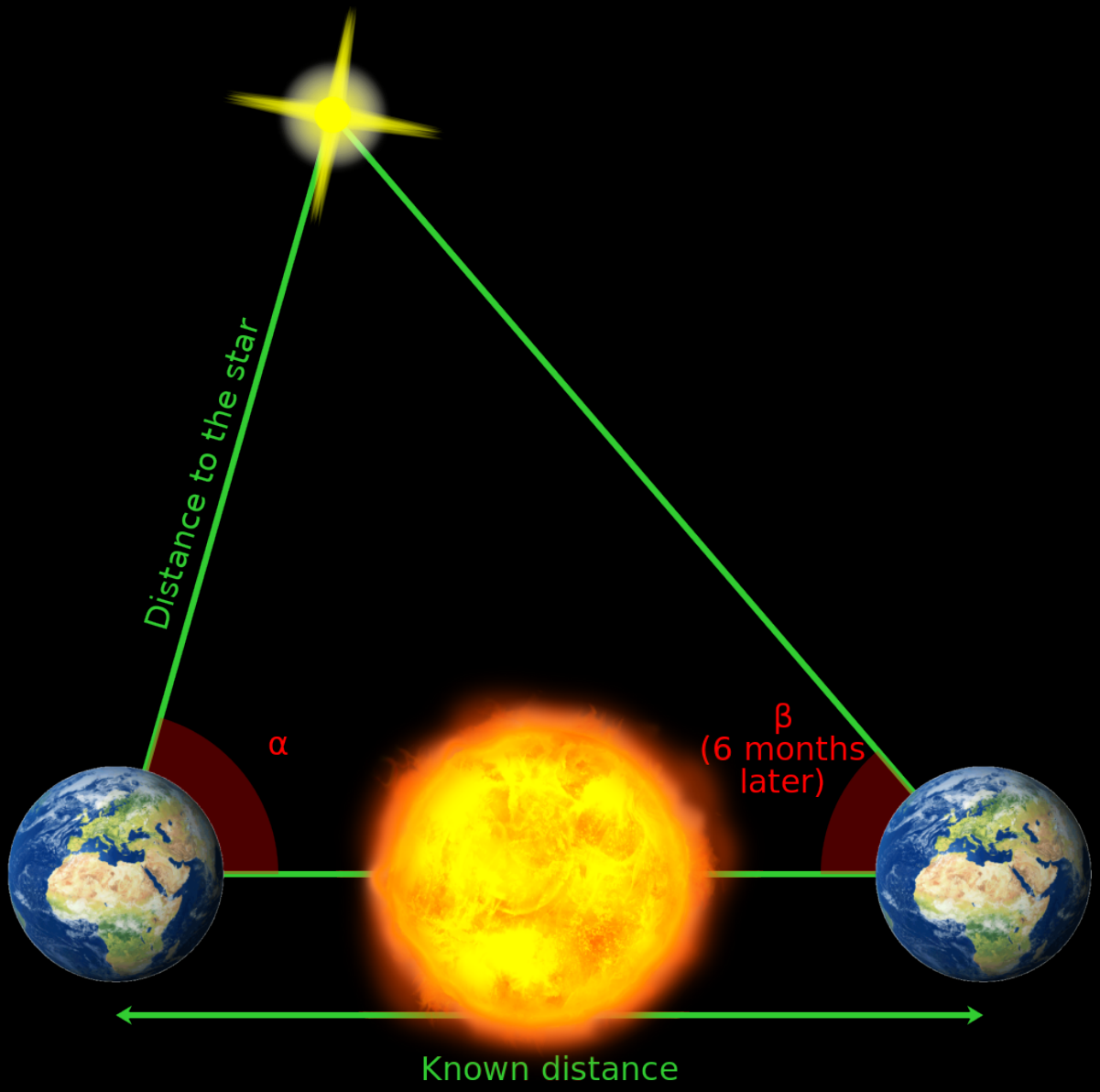
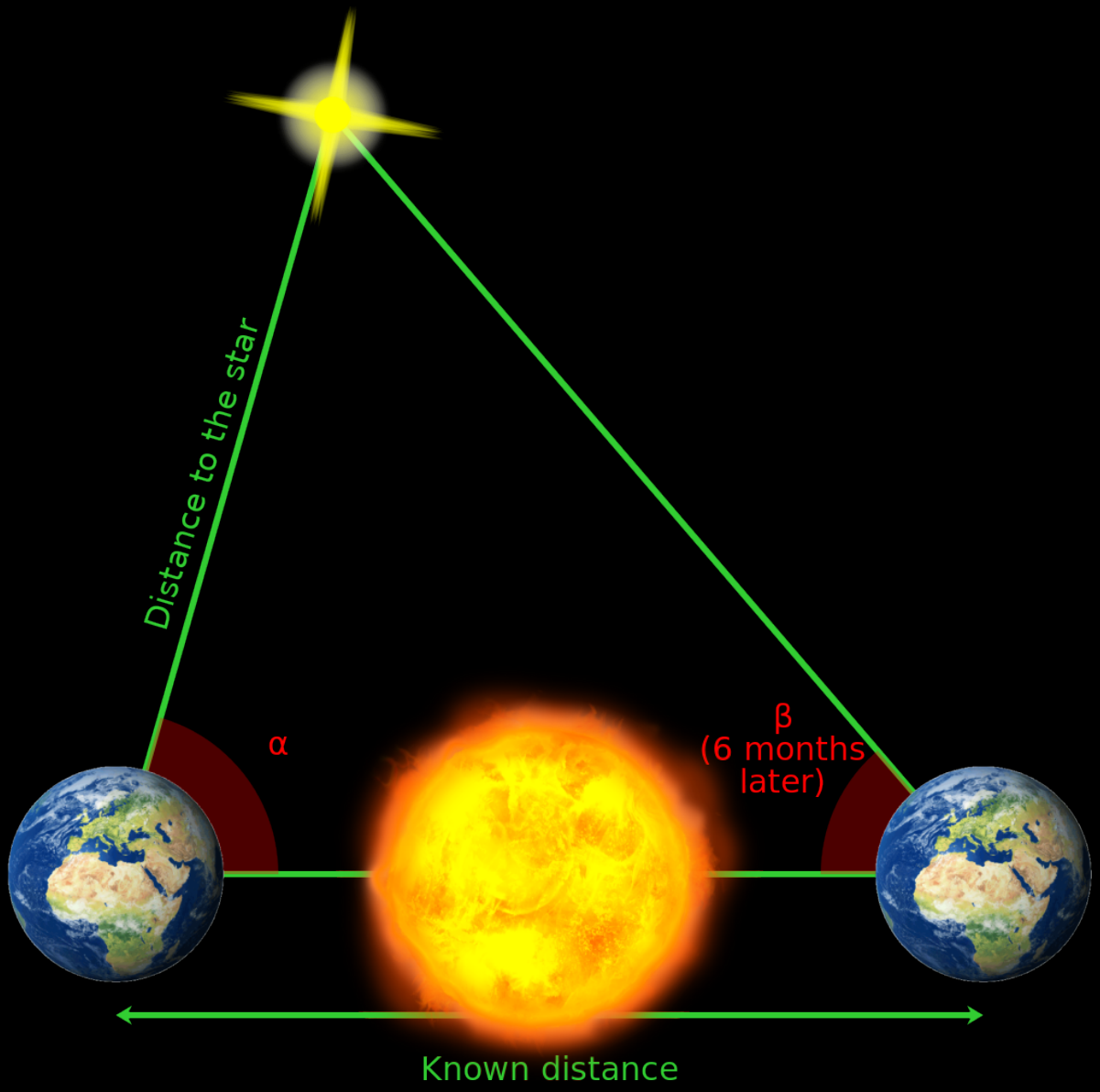

Distance to the star
α
β
(6 months
later)
Known distance



Measuring Parallaxes



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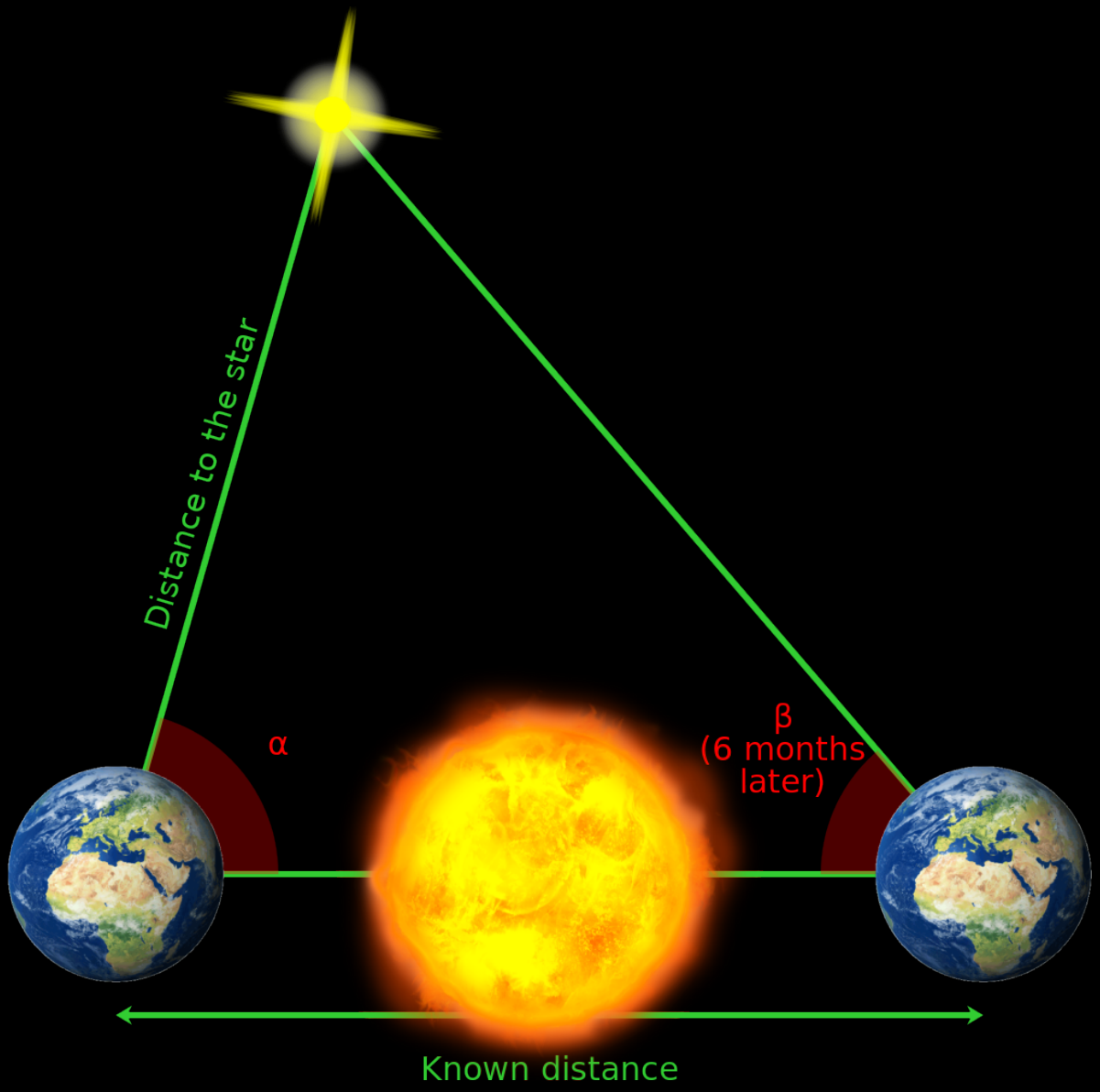

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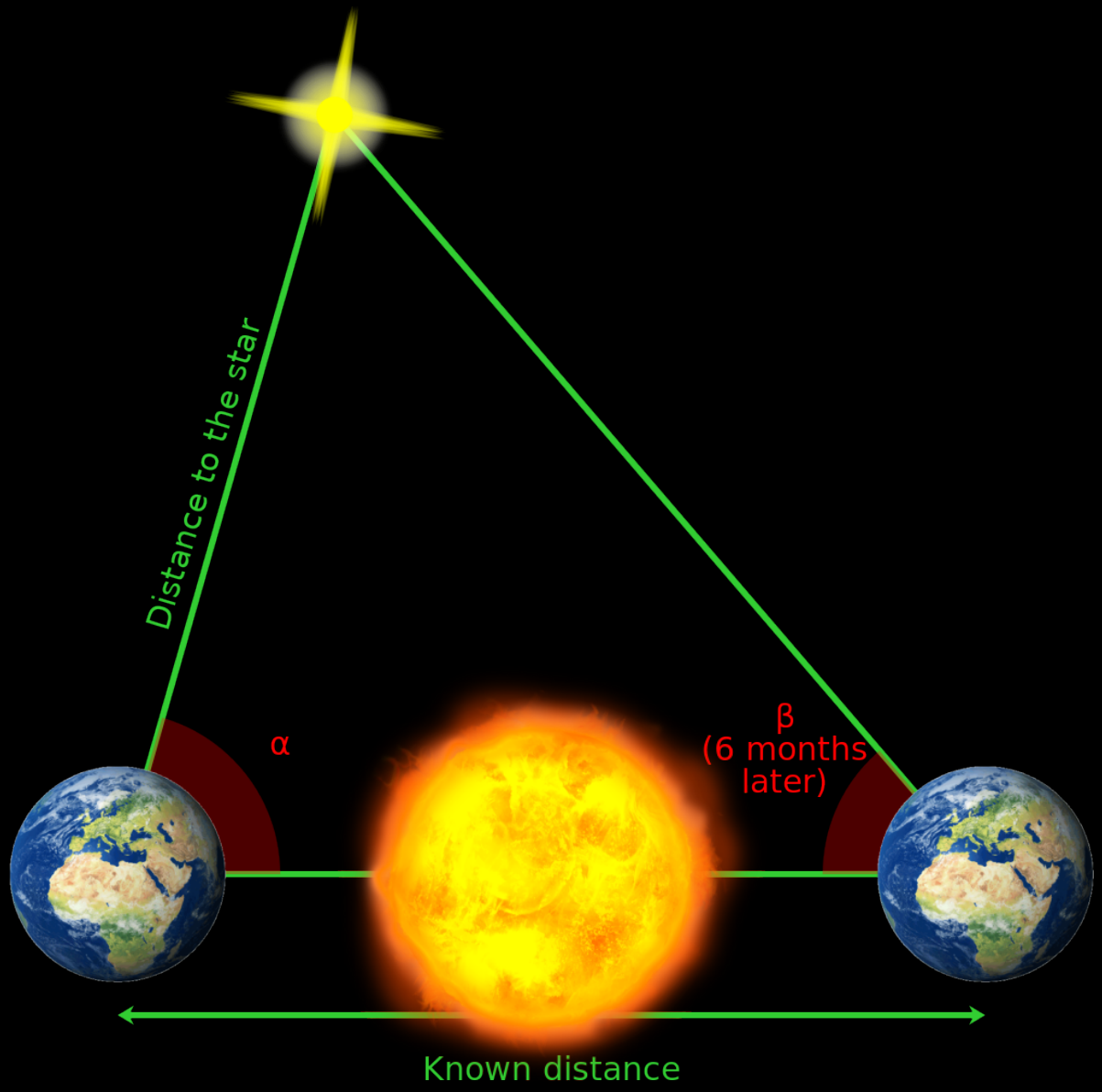

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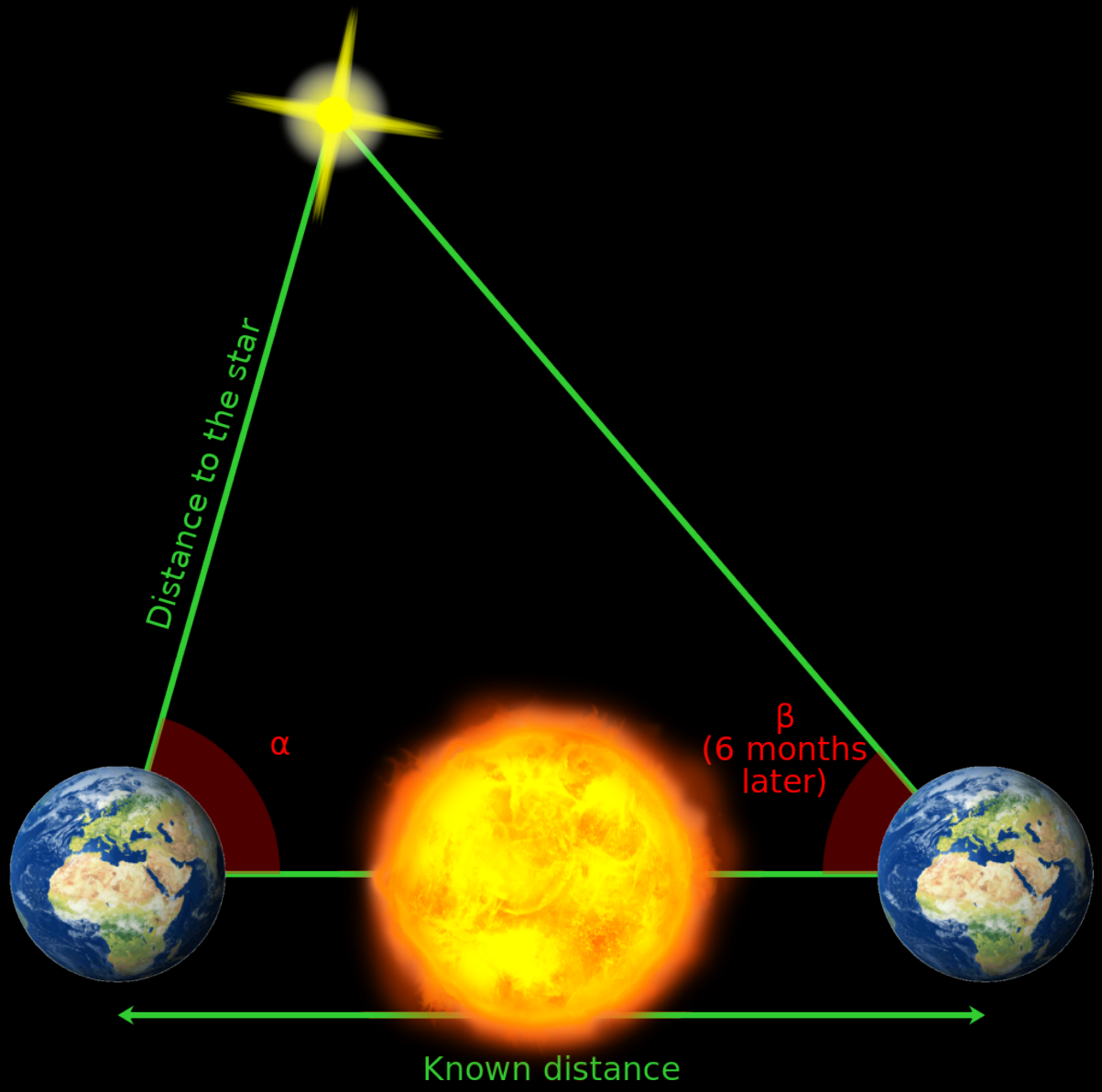

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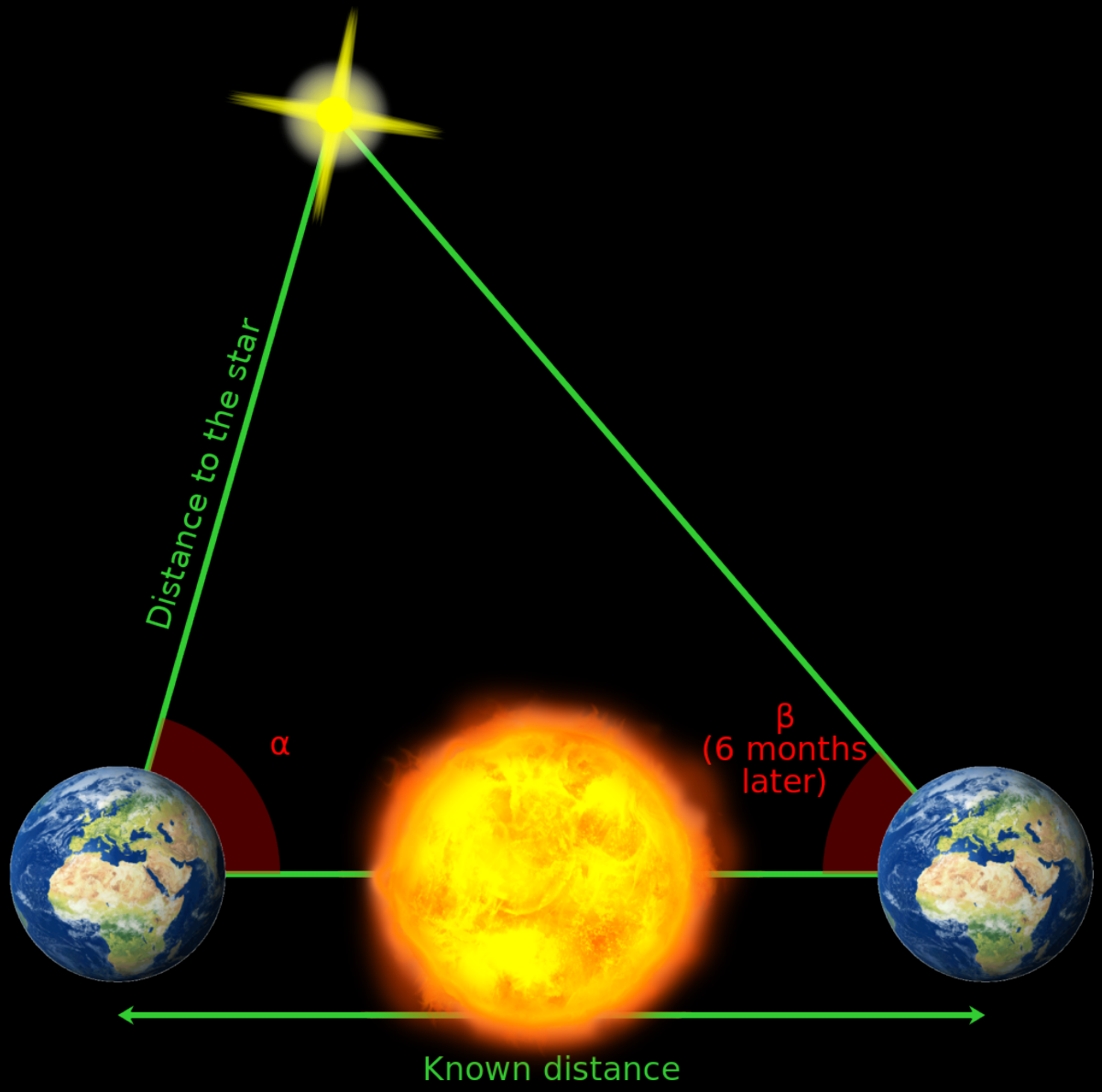

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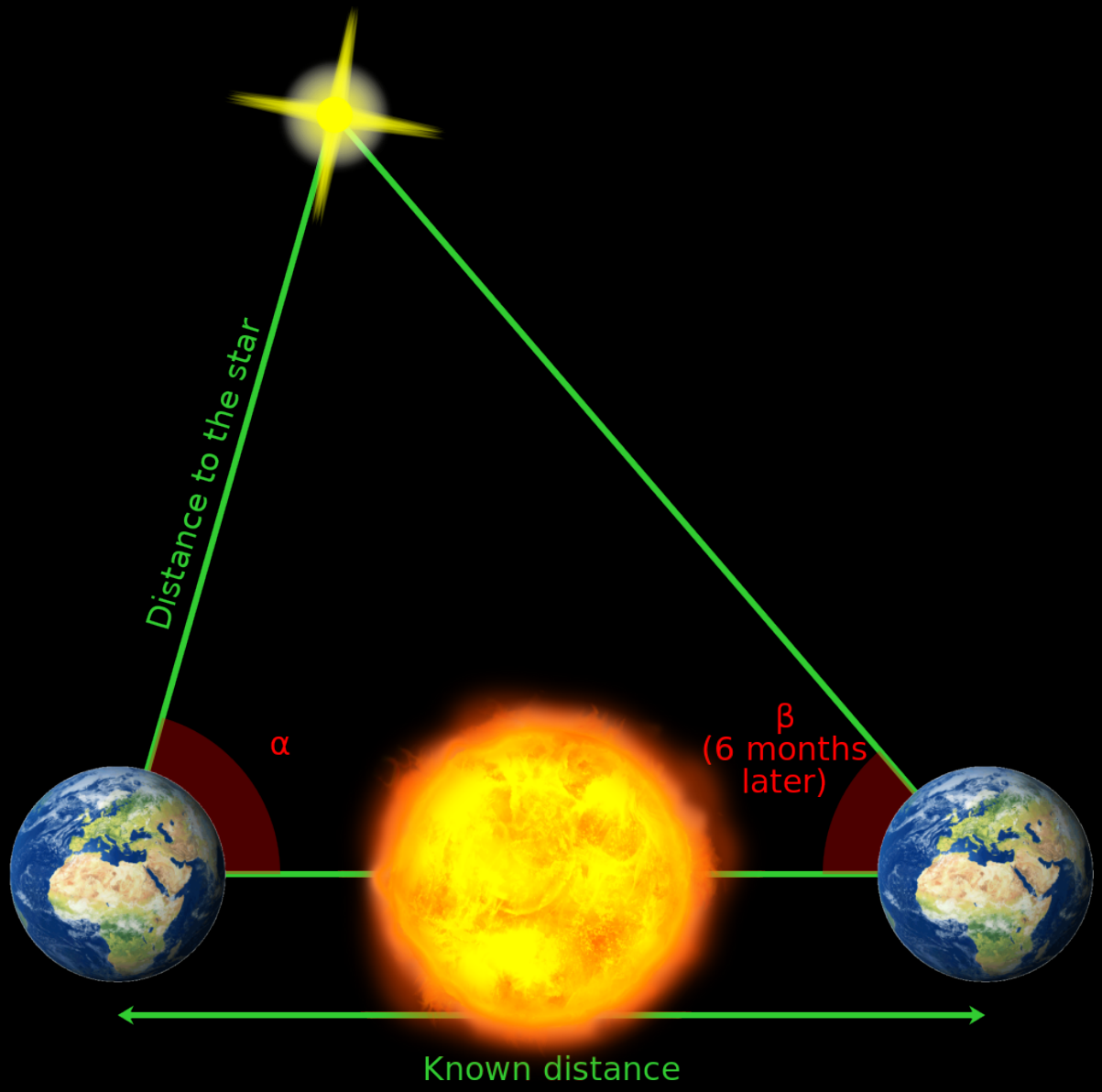

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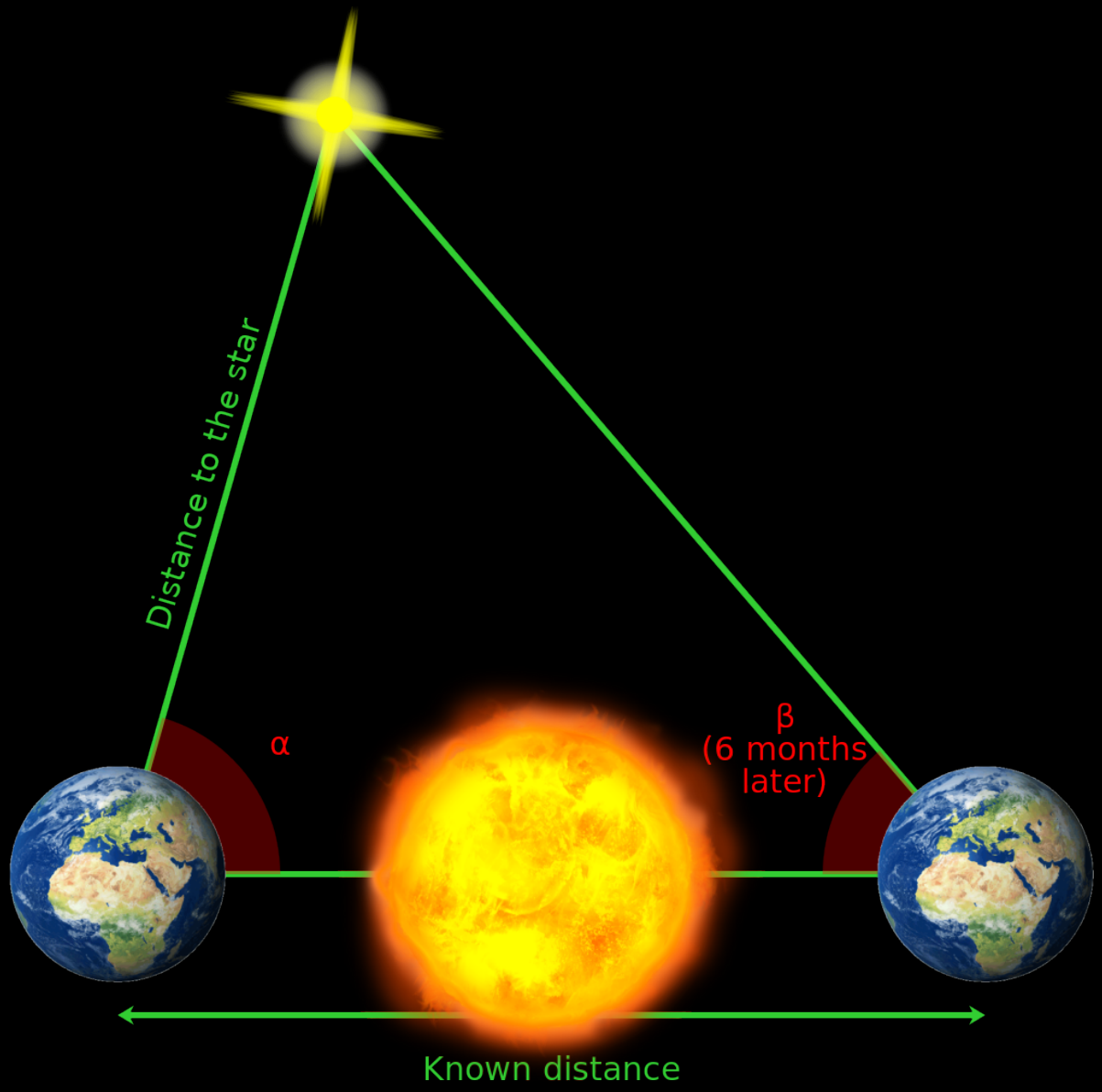

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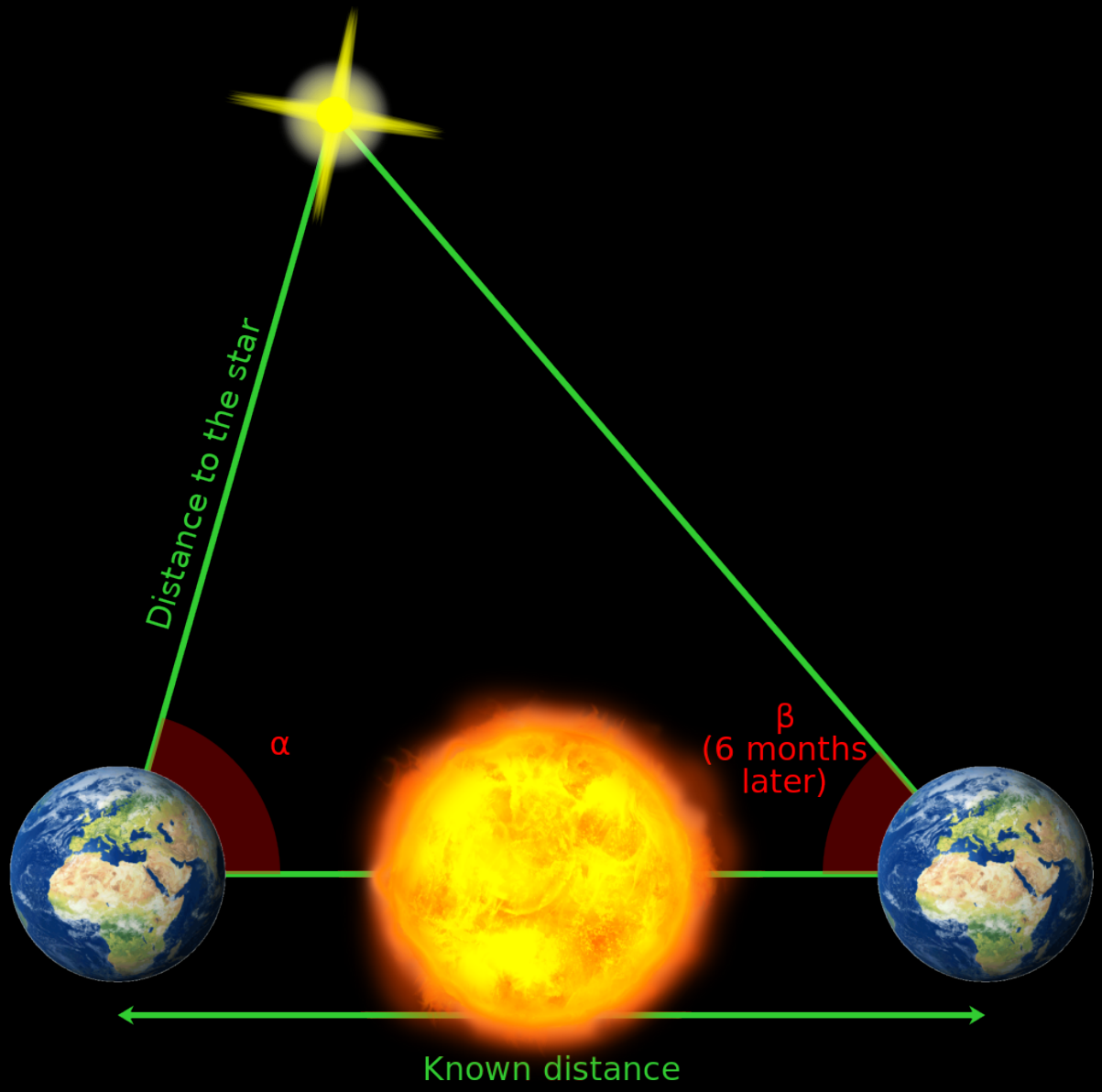

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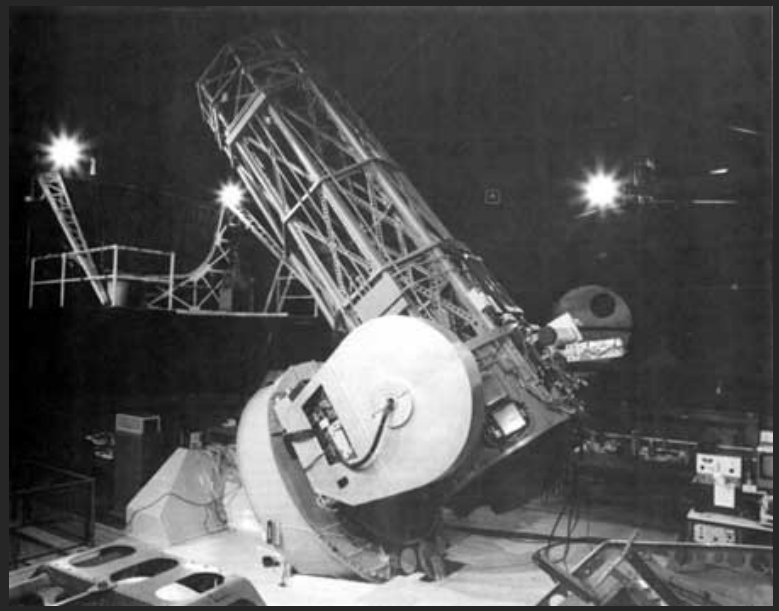

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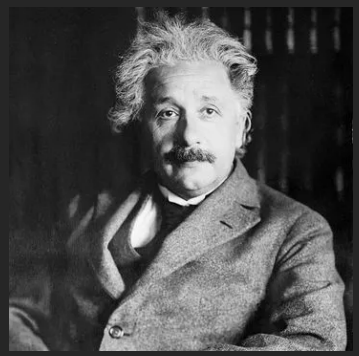

Albert EINSTEIN
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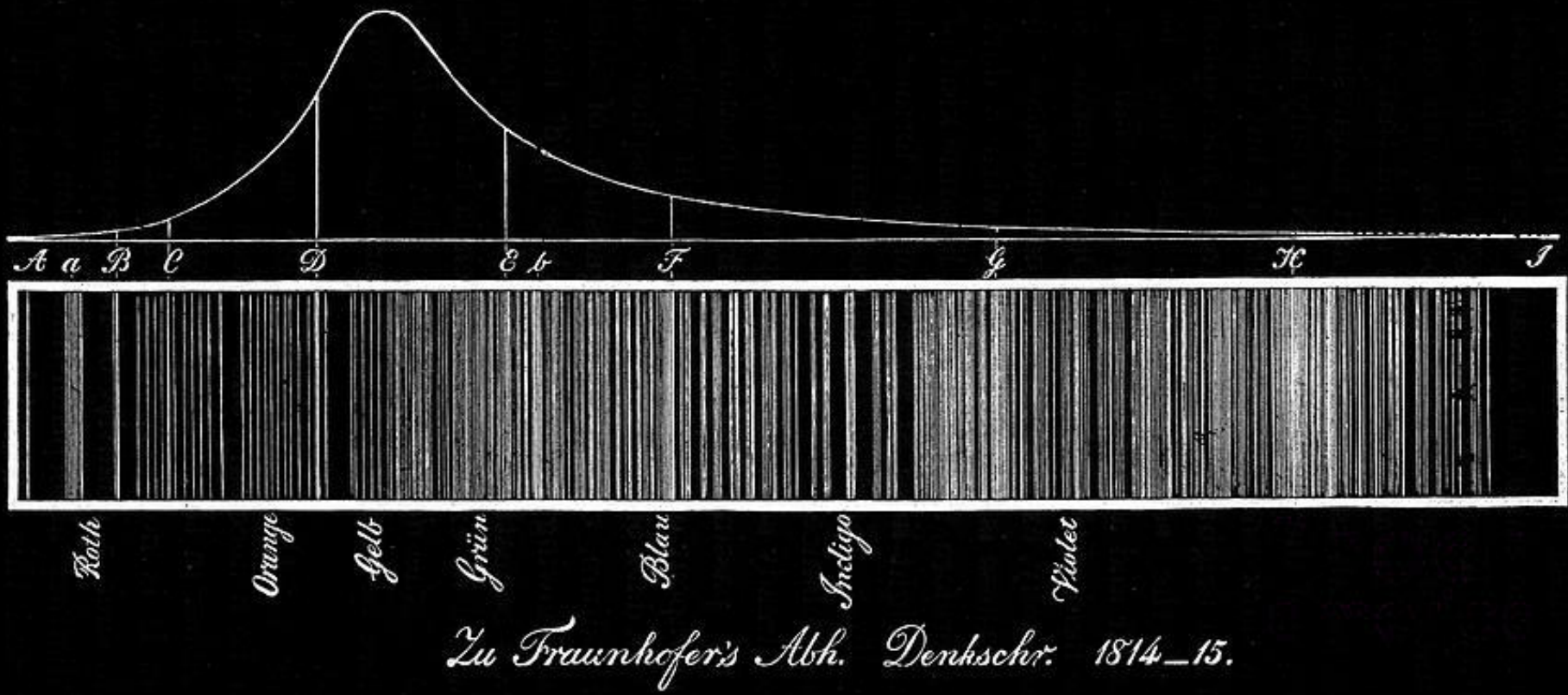

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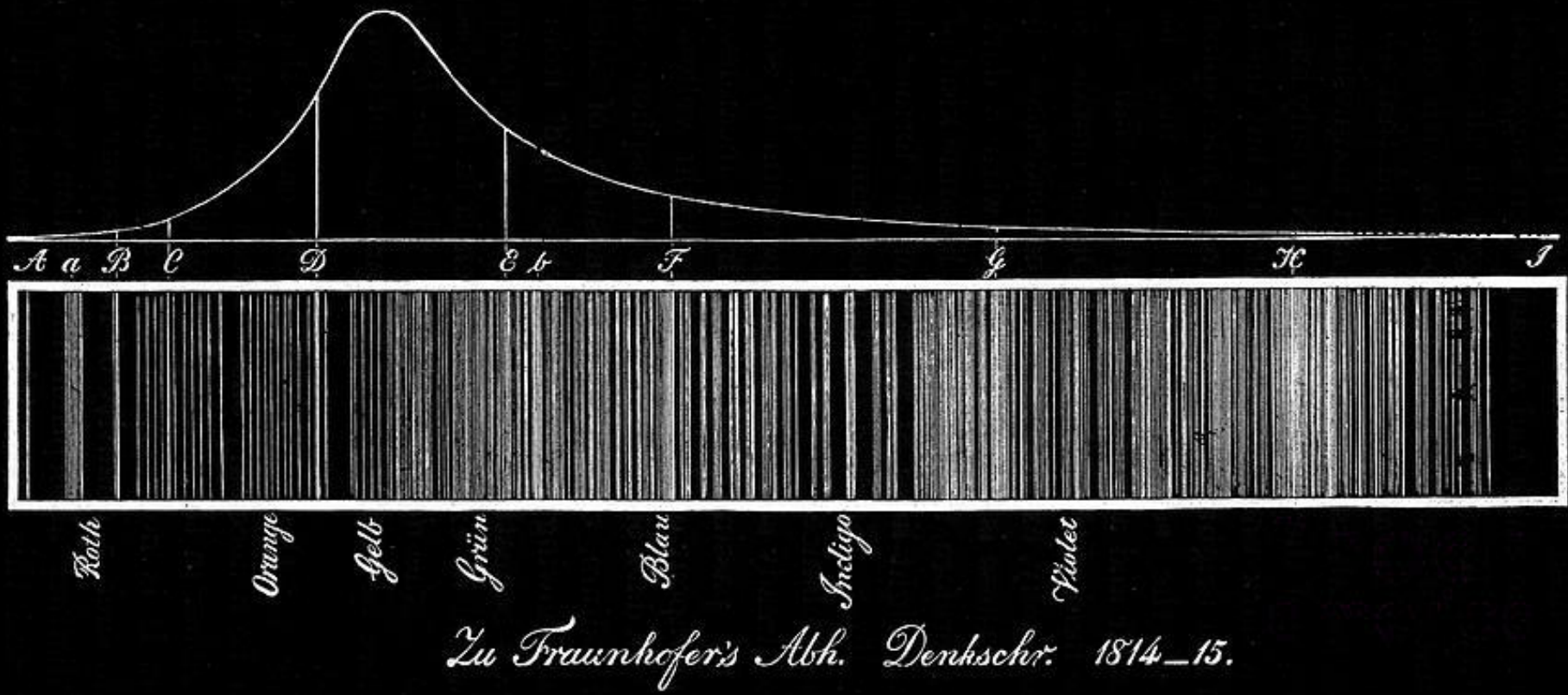

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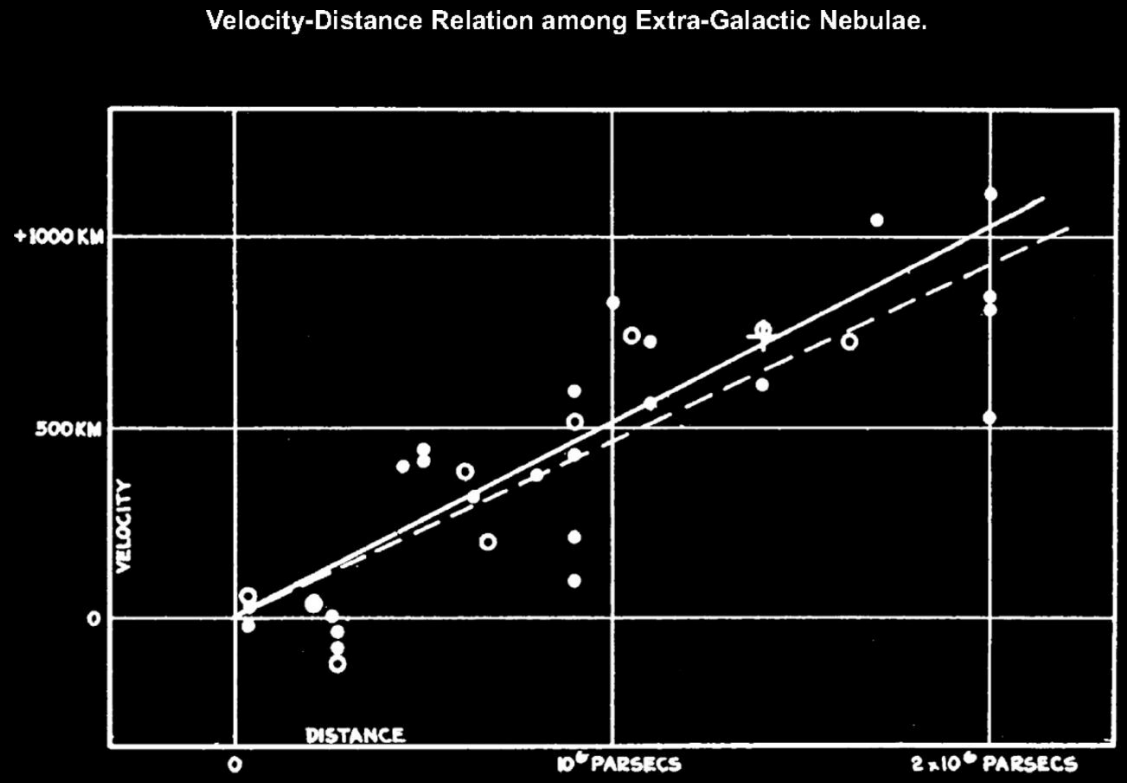

(Hubble, 1929; based on uncredited data by Vesto SLIPHER)

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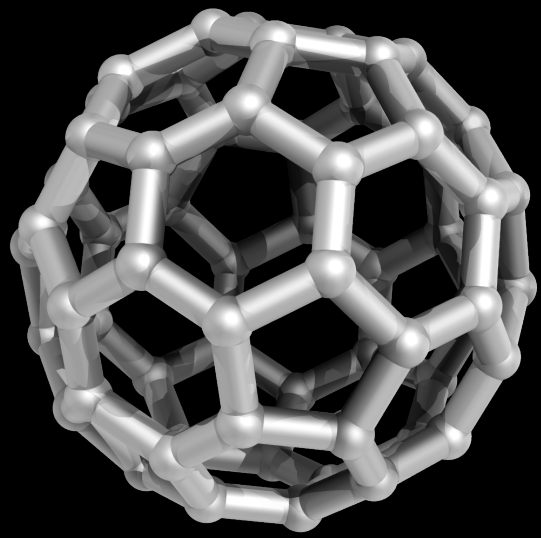

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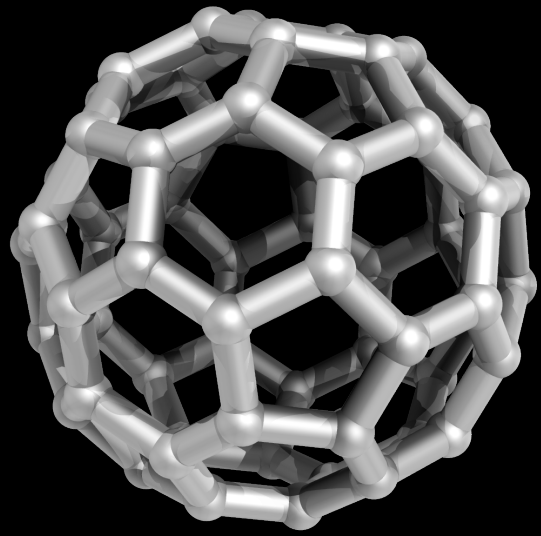

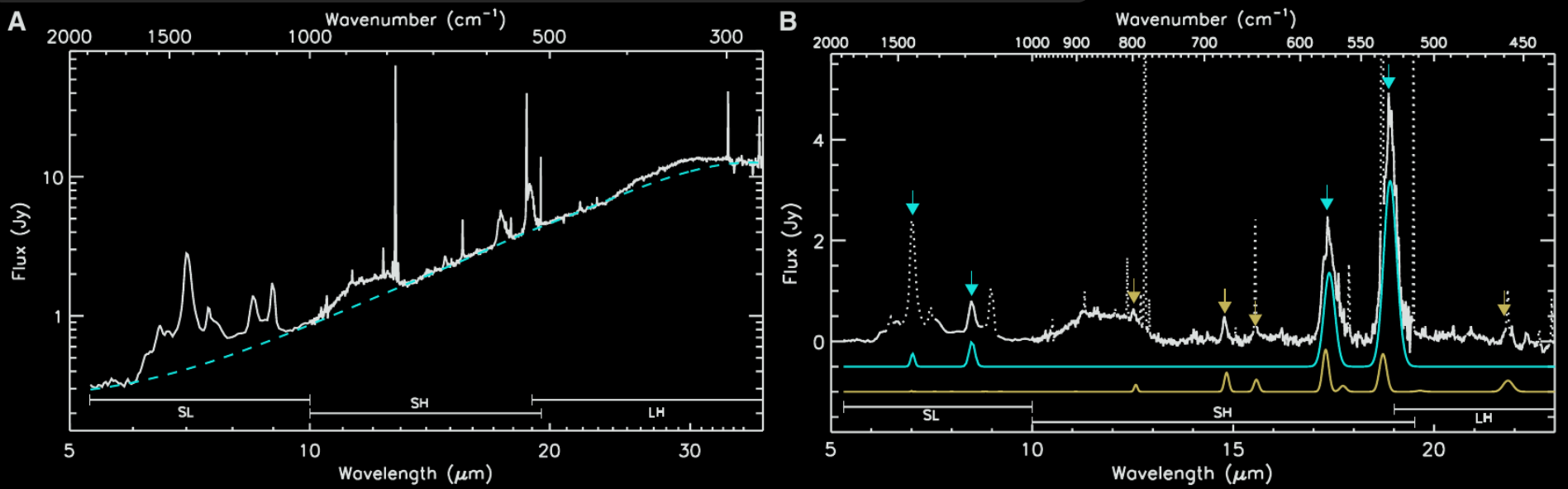

(Cami *et al.*, 2010; using the *Spitzer* space telescope)

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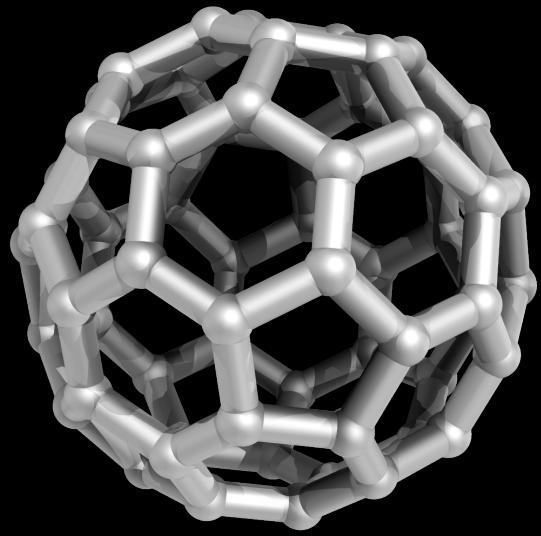

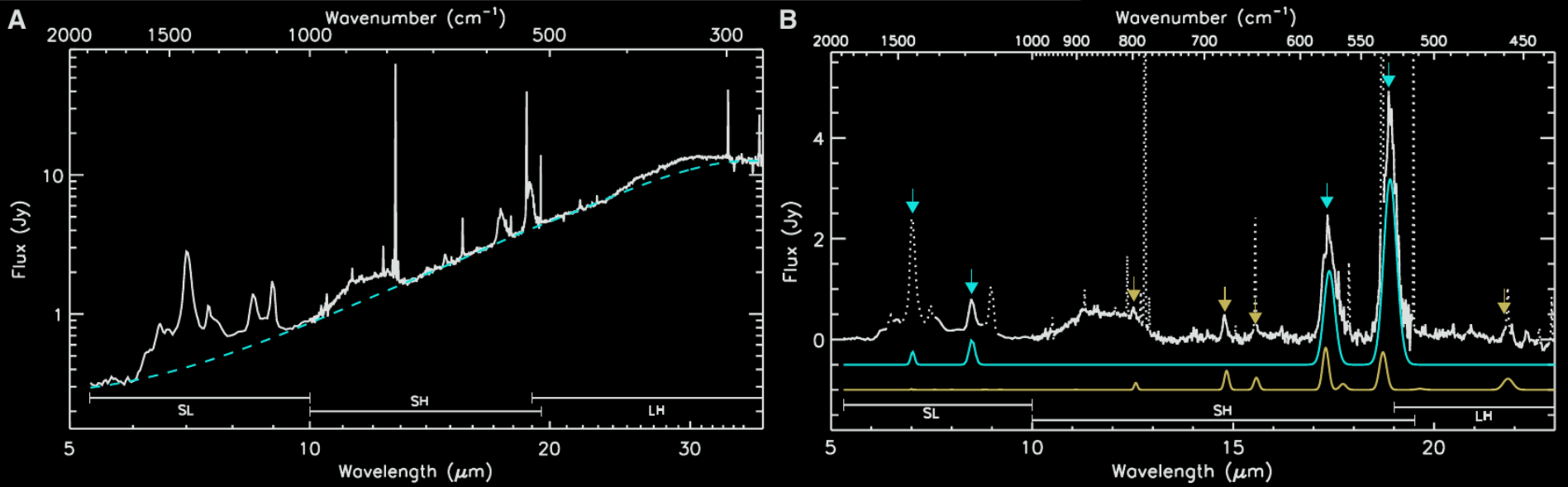

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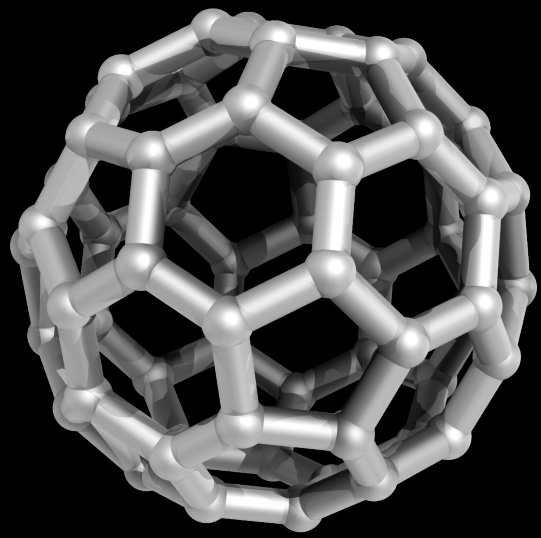
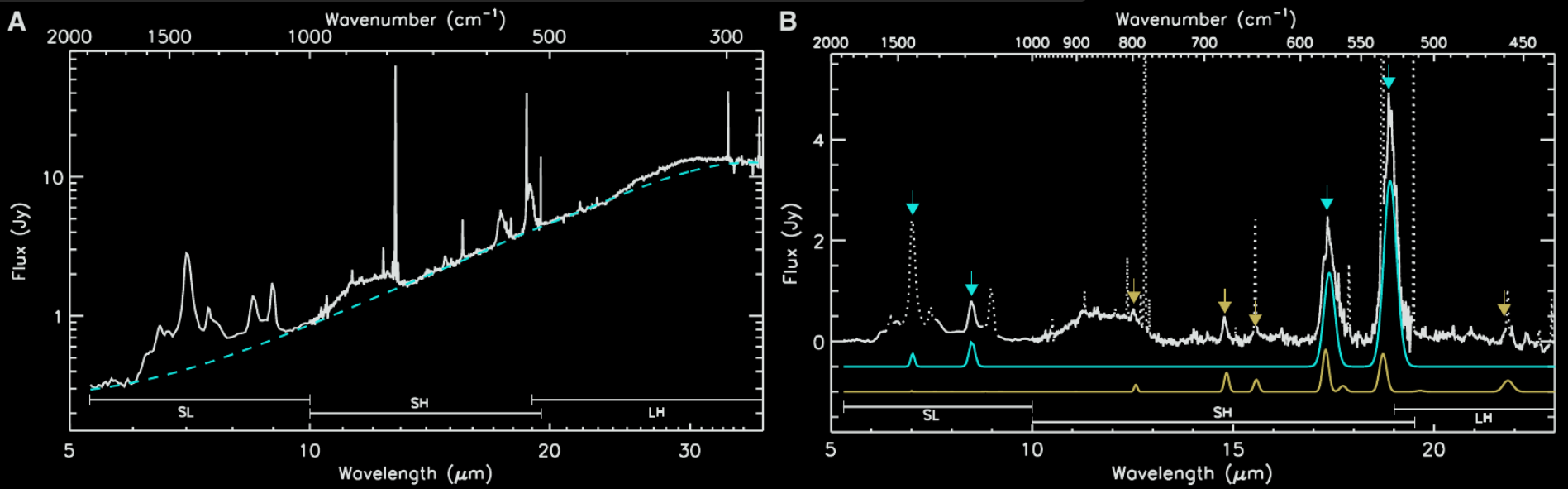
- Confirming the universality of the laws of physics.





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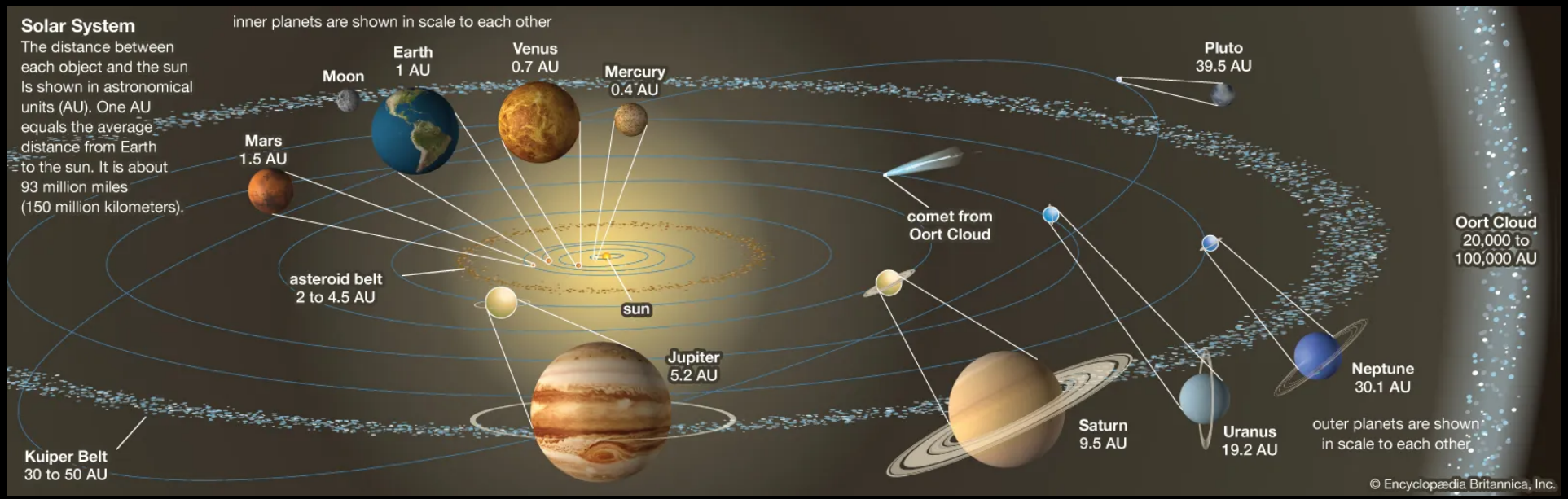
(Launch of the JWST, december 2021; source ESA)


Solar System
The distance between each object and the sun Is shown in astronomical units (AU). One AU equals the average distance from Earth to the sun. It is about 93 million miles (150 million kilometers).
inner planets are shown in scale to each other
Moon
Earth 1 AU
Venus 0.7 AU
Mercury 0.4 AU
Mars 1.5 AU
asteroid belt 2 to 4.5 AU
sun
Jupiter 5.2 AU
Kuiper Belt 30 to 50 AU
Pluto 39.5 AU
comet from Oort Cloud
Oort Cloud 20,000 to 100,000 AU
Neptune 30.1 AU
Saturn 9.5 AU
Uranus 19.2 AU
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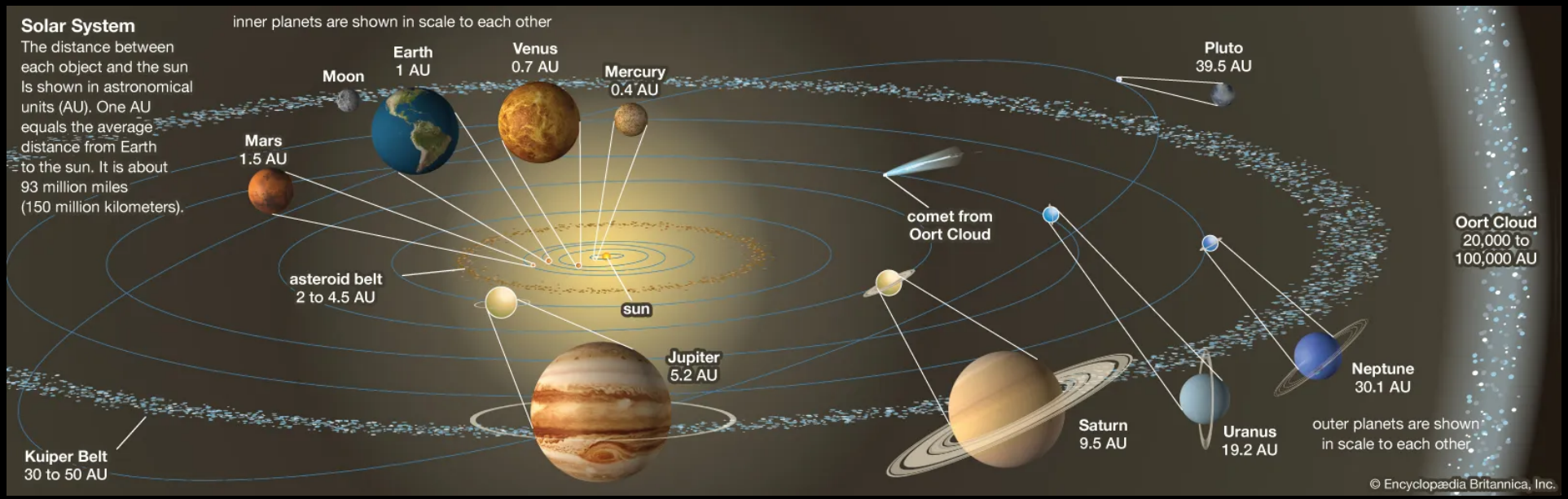
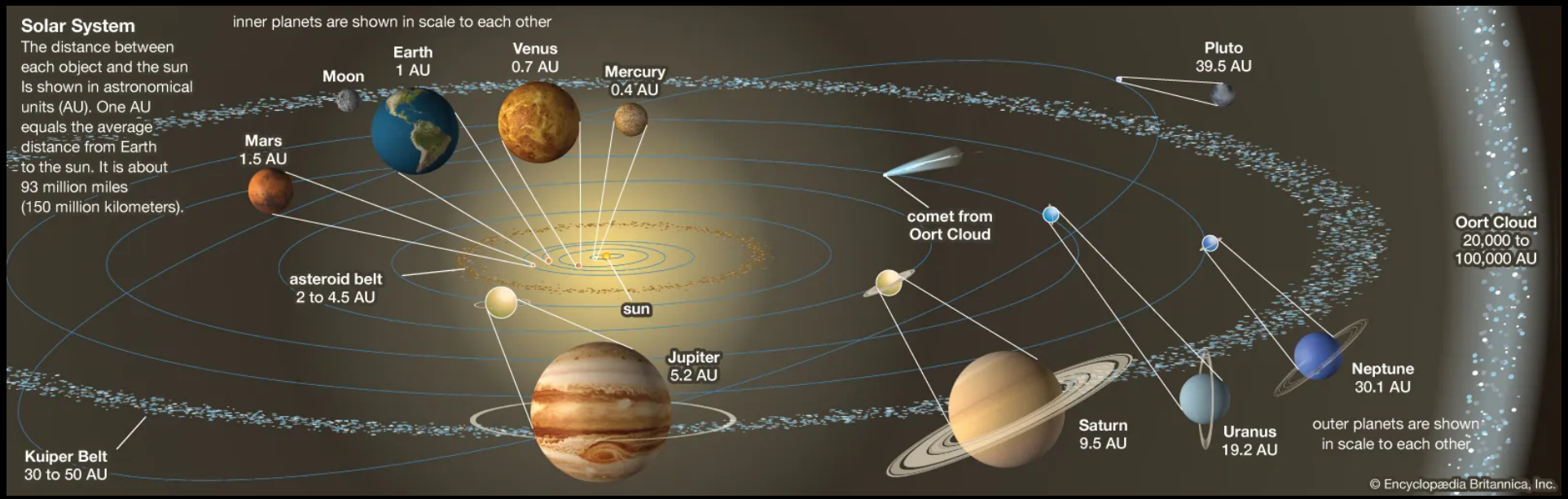
© Encyclopædia Britannica, Inc.



Kuiper Belt:

Ring constituted of small bodies beyond the planets.



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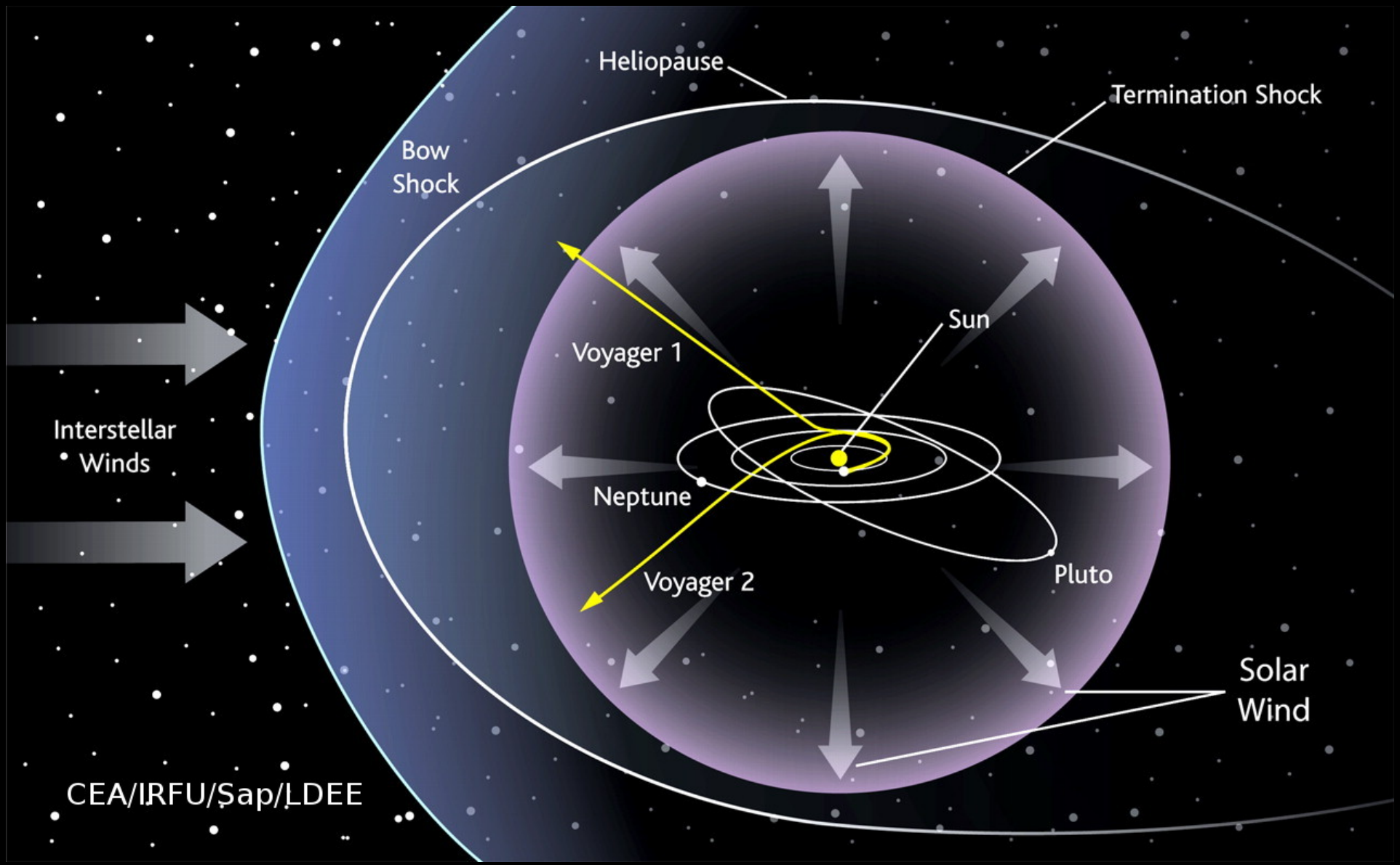
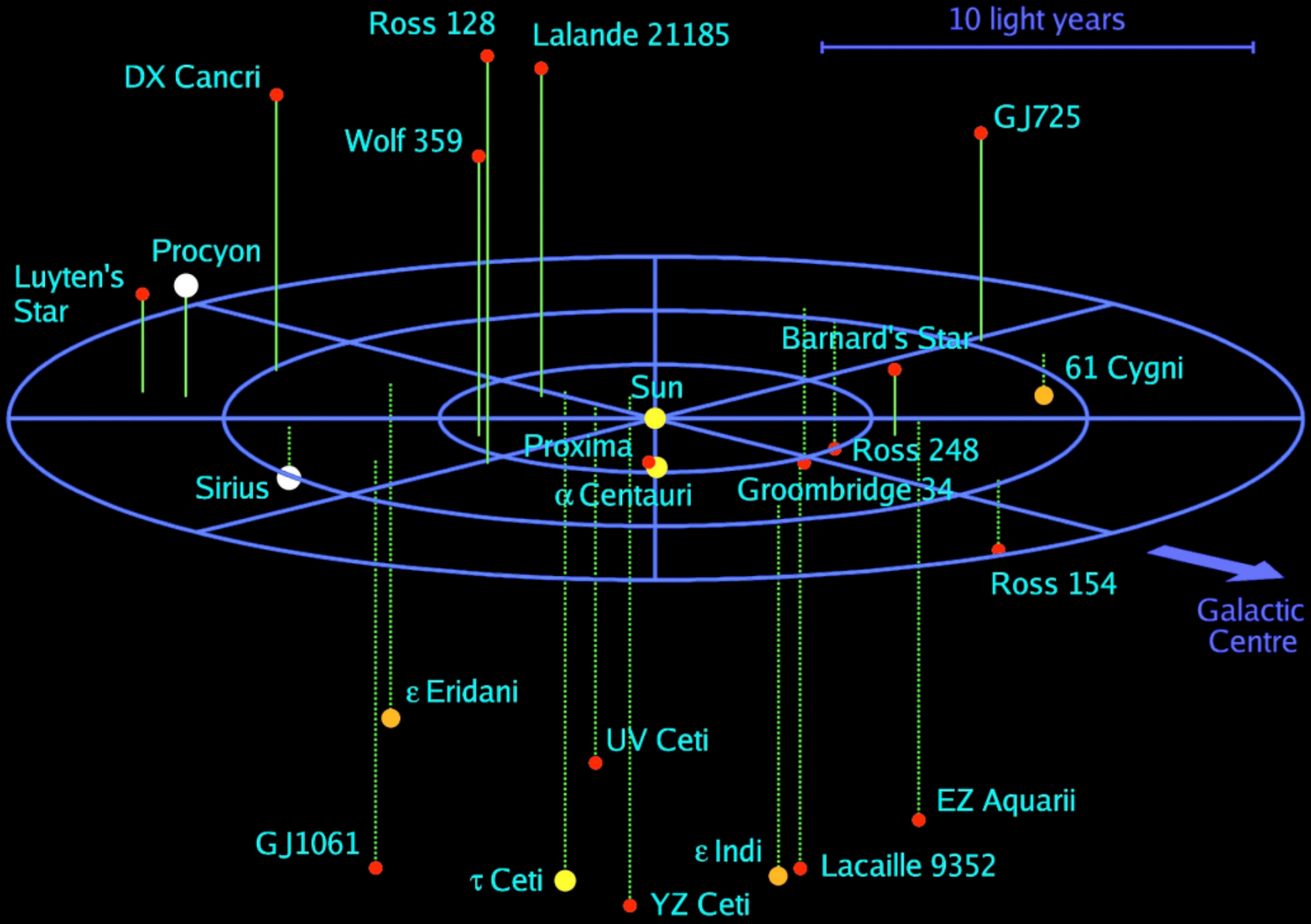
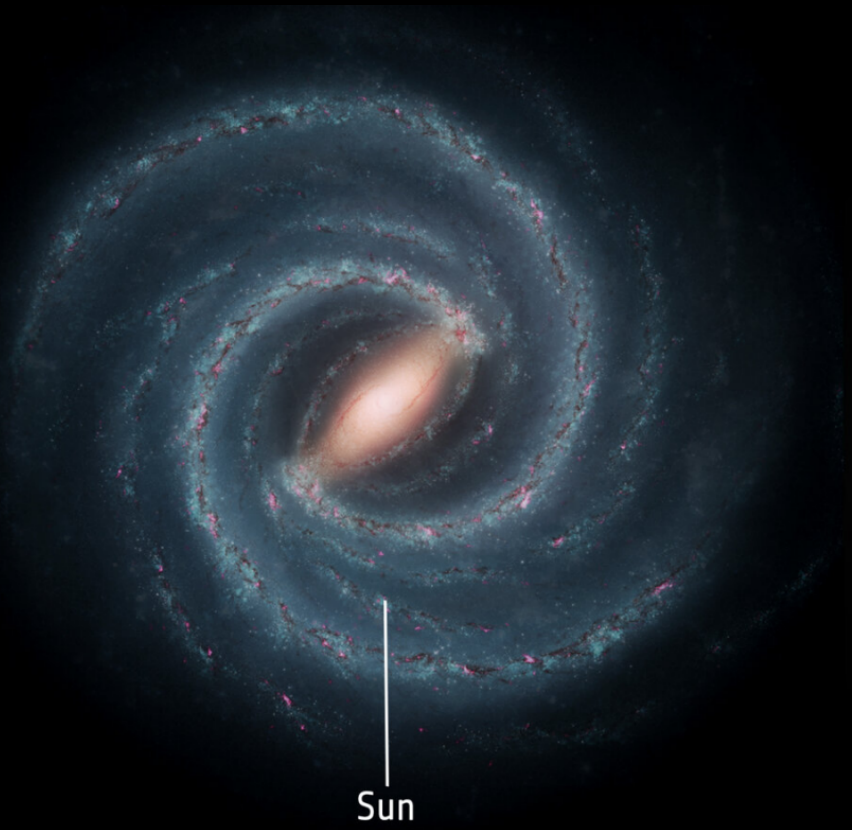
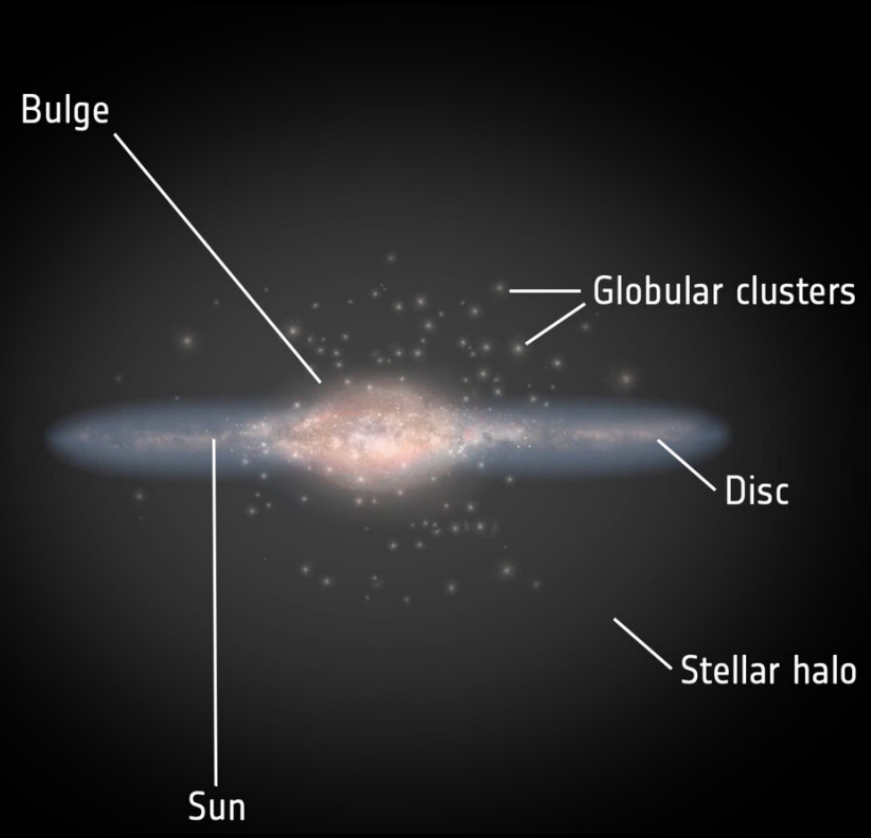
Oort Cloud:

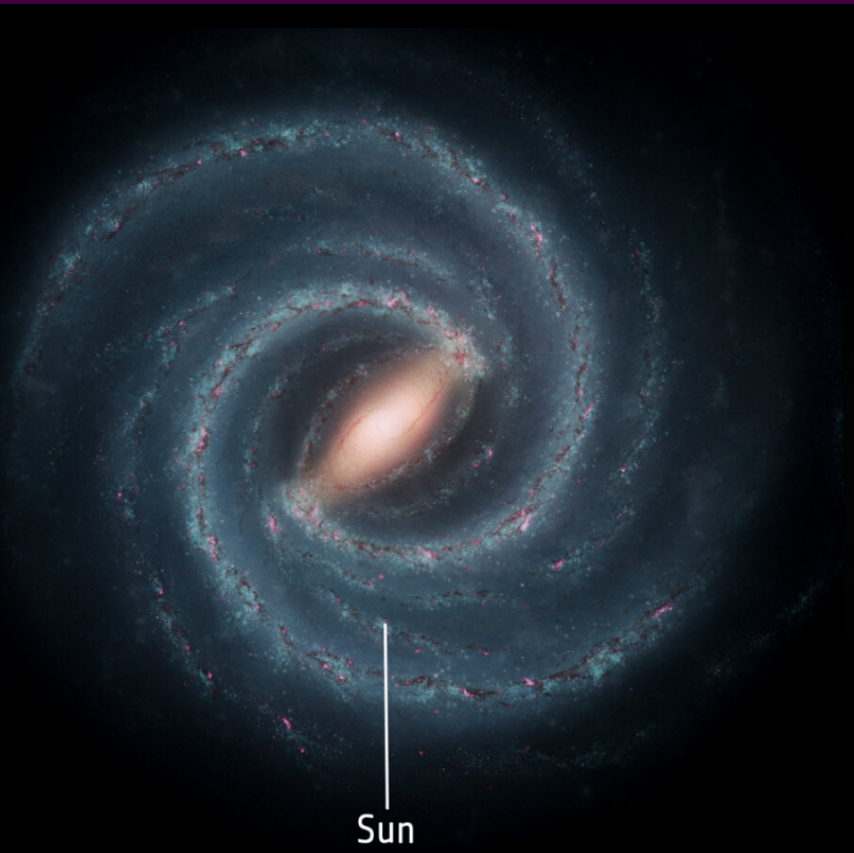
Sphere constituted of comets (icy) at the extreme edge of the Solar system.

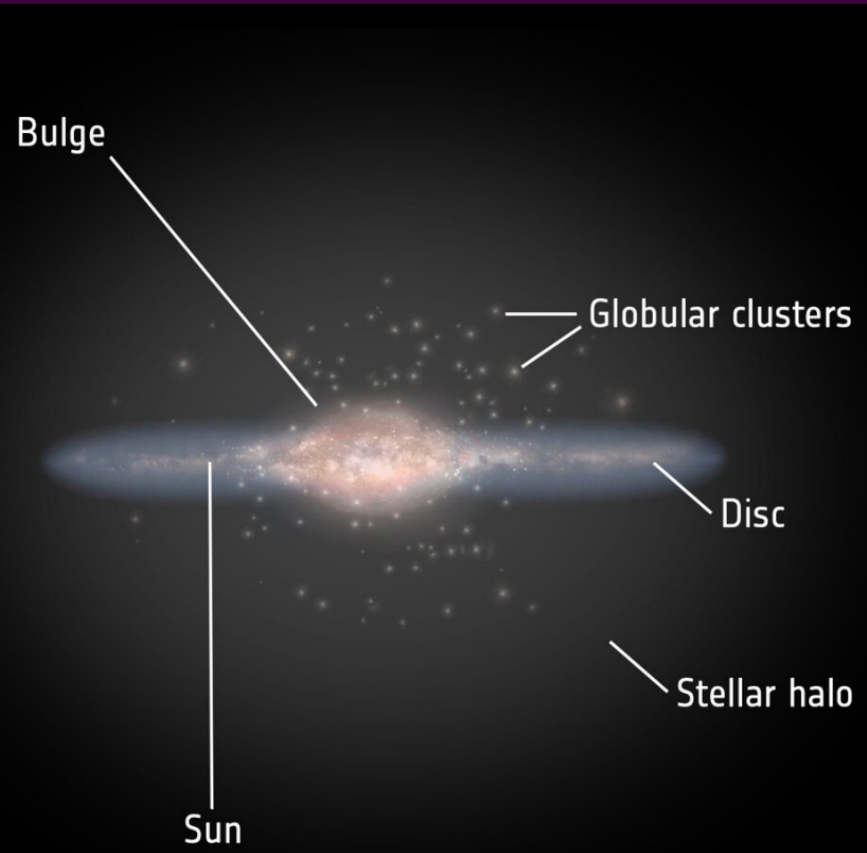

Heliopause
Termination Shock
Bow
Shock
Sun
Voyager 1
Interstellar
Winds
Neptune
Pluto
Voyager 2
Solar
Wind
CEA/IRFU/Sap/LDEE


10 light years
Ross 128
Lalande 21185
DX Cancri
Wolf 359
GJ725
Procyon
Luyten's Star
Barnard's Star
61 Cygni
Sun
Proxima
Ross 248
Sirius
α Centauri
Groombridge 34
Ross 154
Galactic Centre
ε Eridani
UV Ceti
EZ Aquarii
GJ1061
ε Indi
Lacaille 9352
τ Ceti
YZ Ceti


Sun


Bulge
Globular clusters
Disc
Stellar halo
Sun





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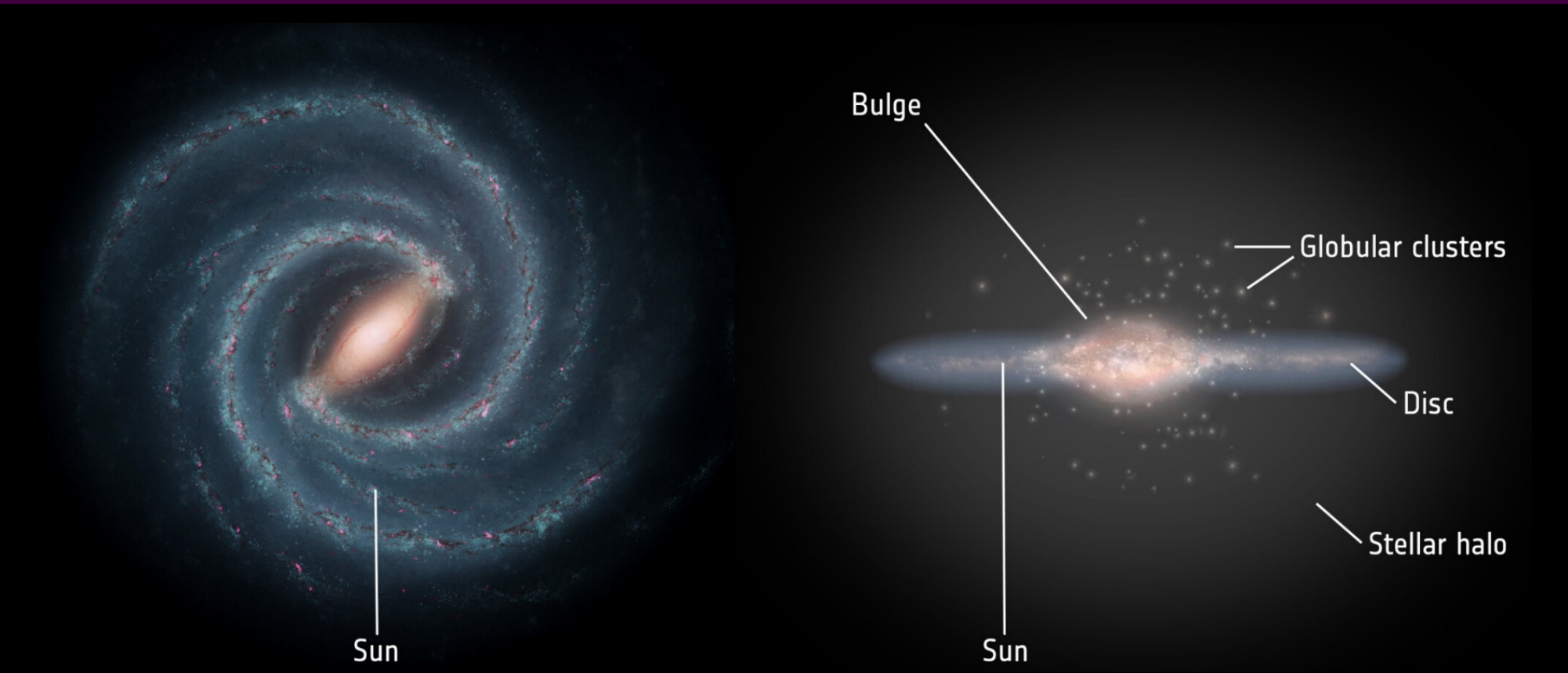

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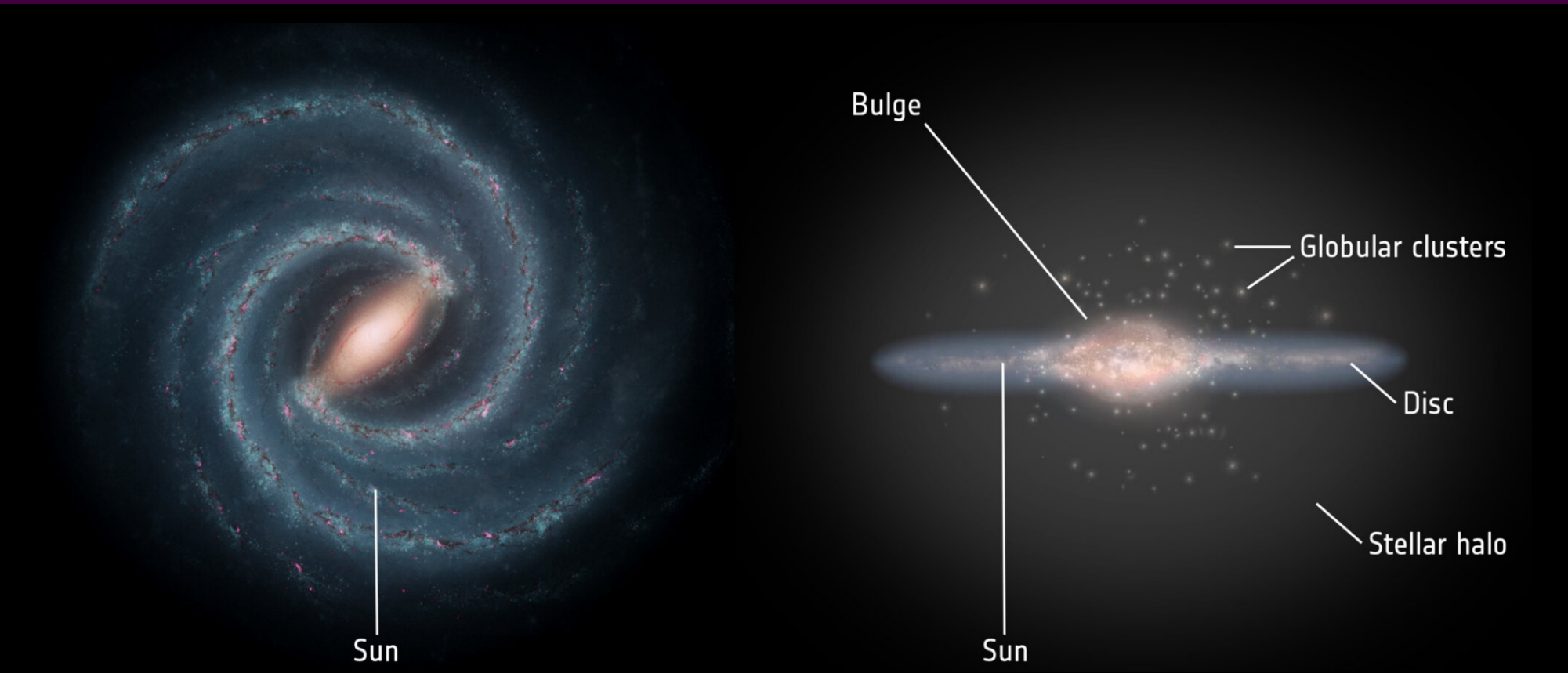

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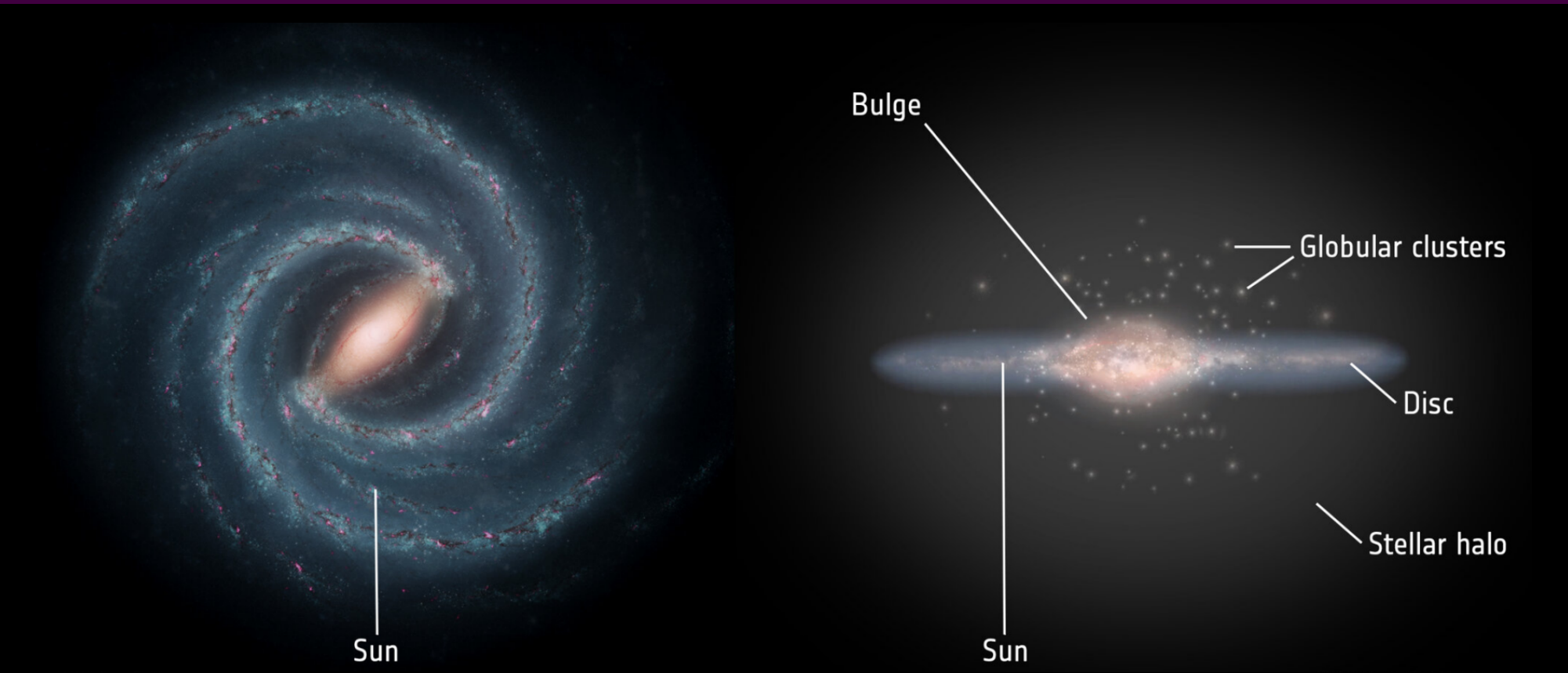

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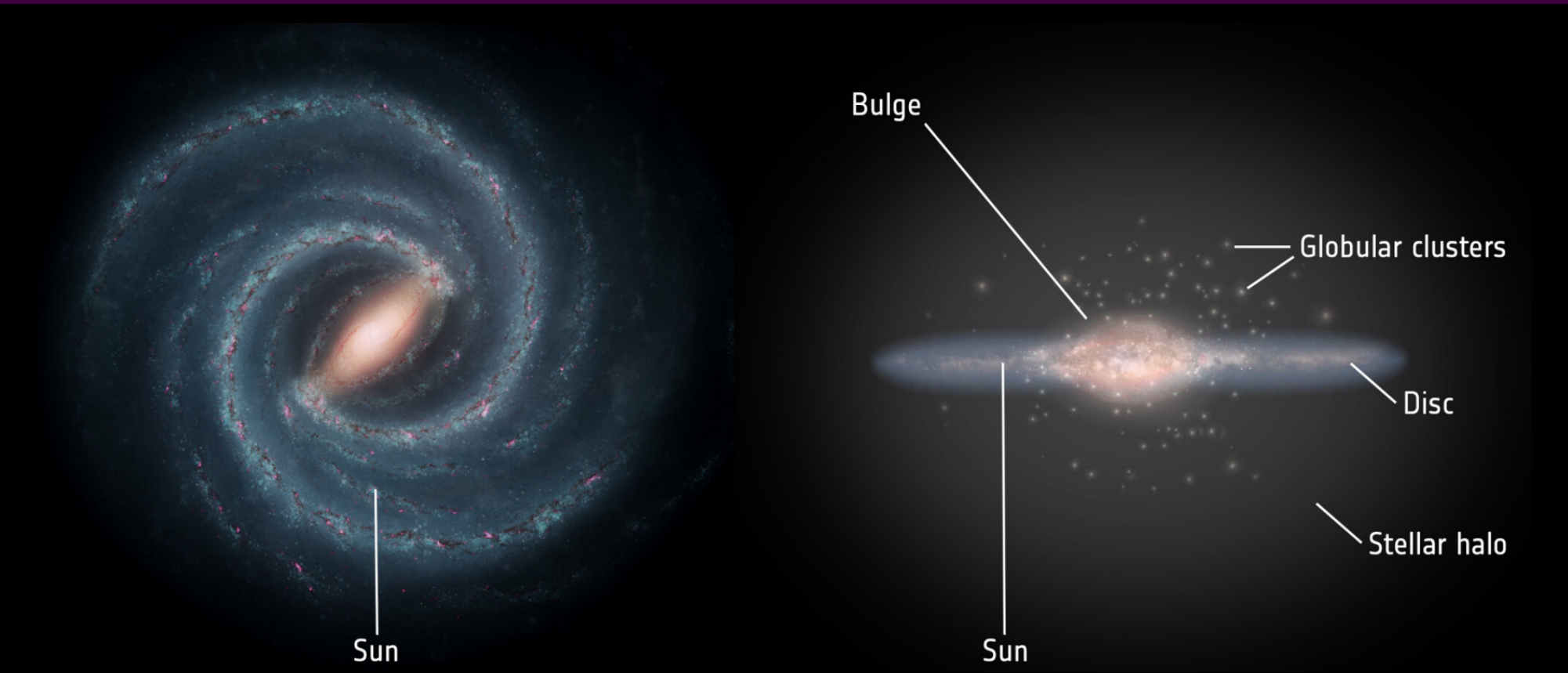

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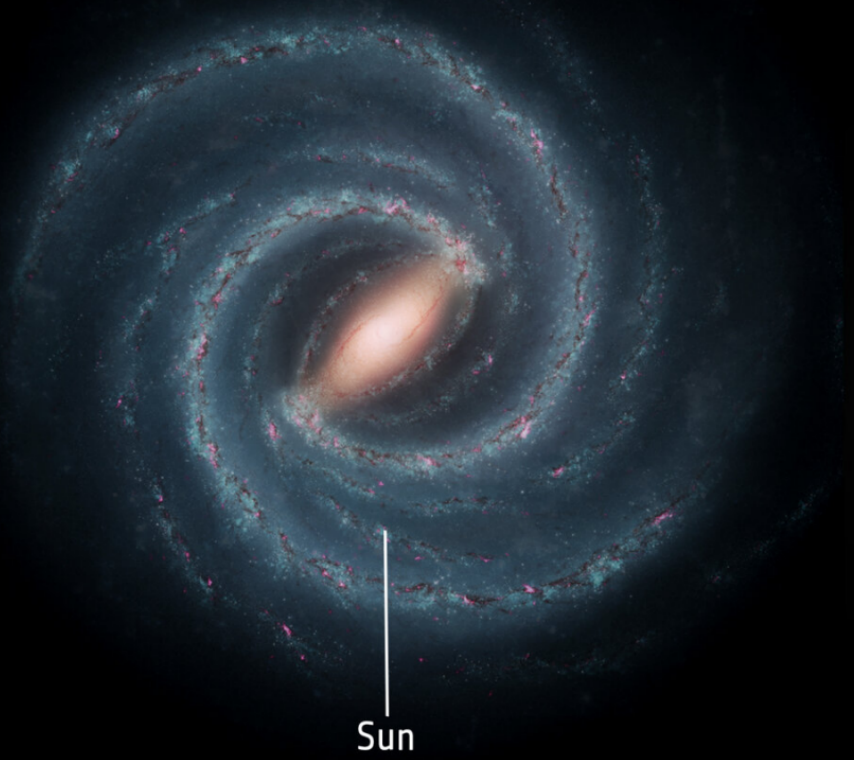

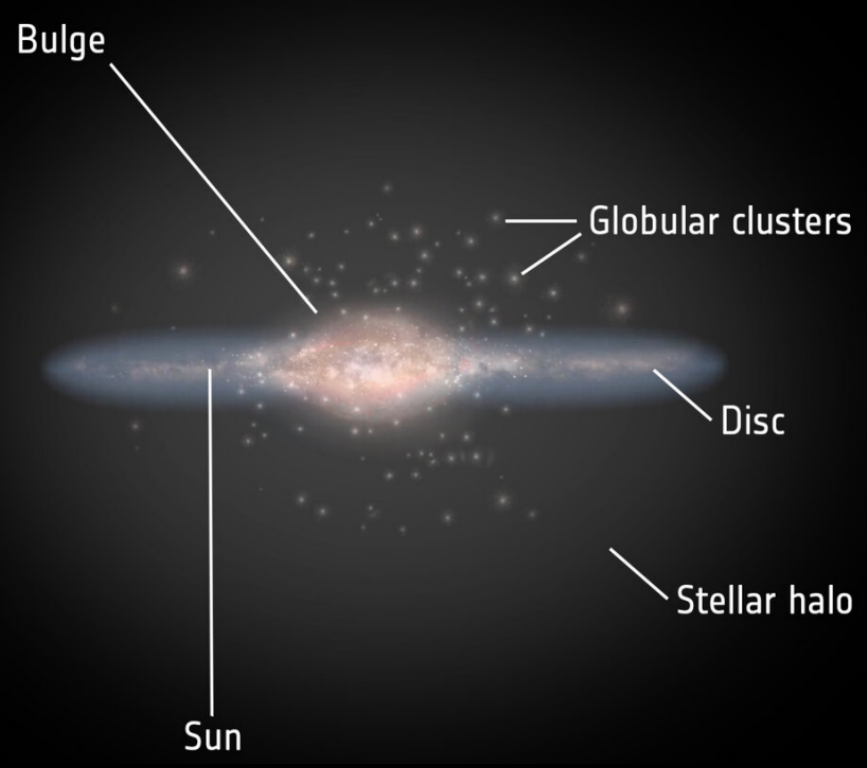

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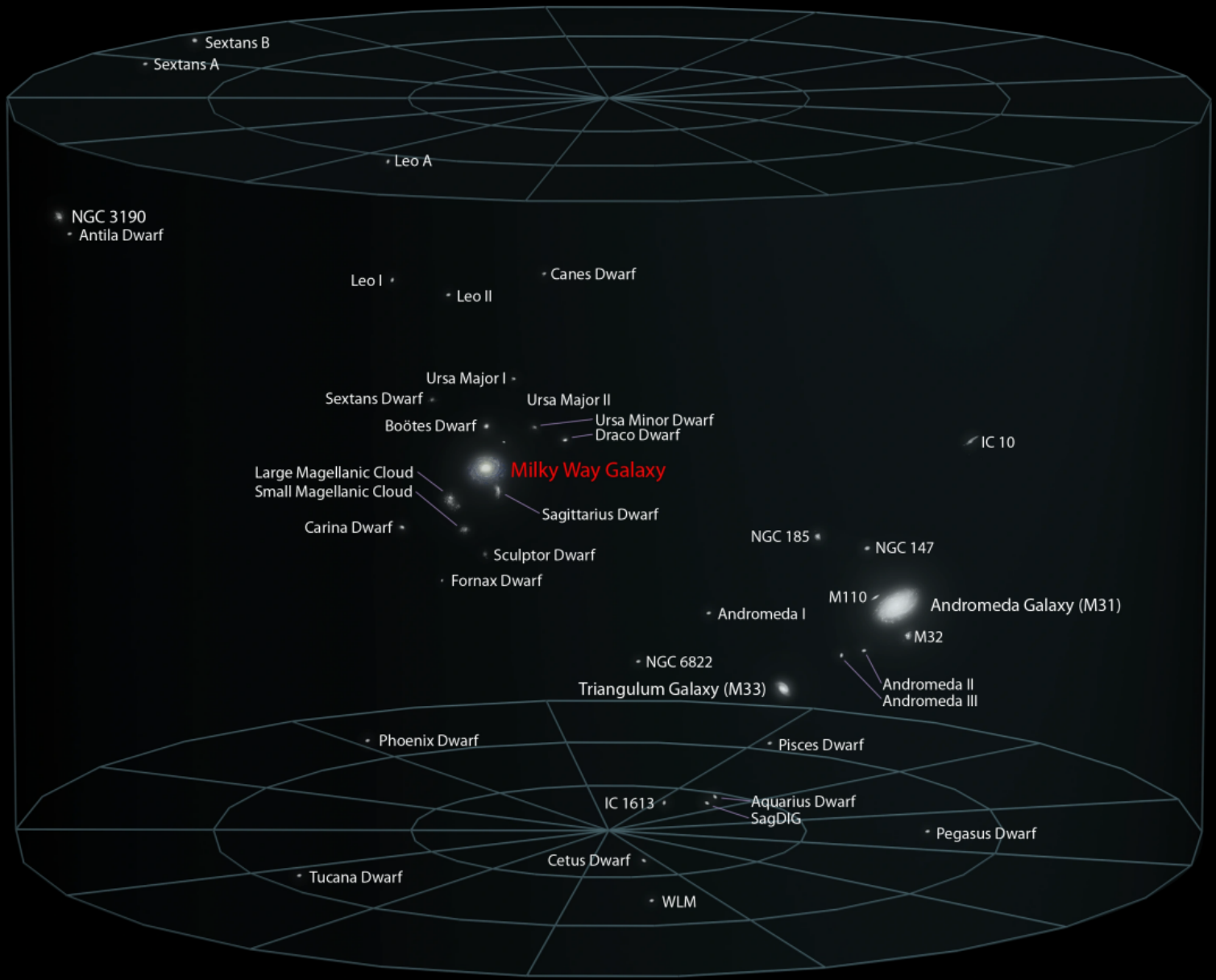
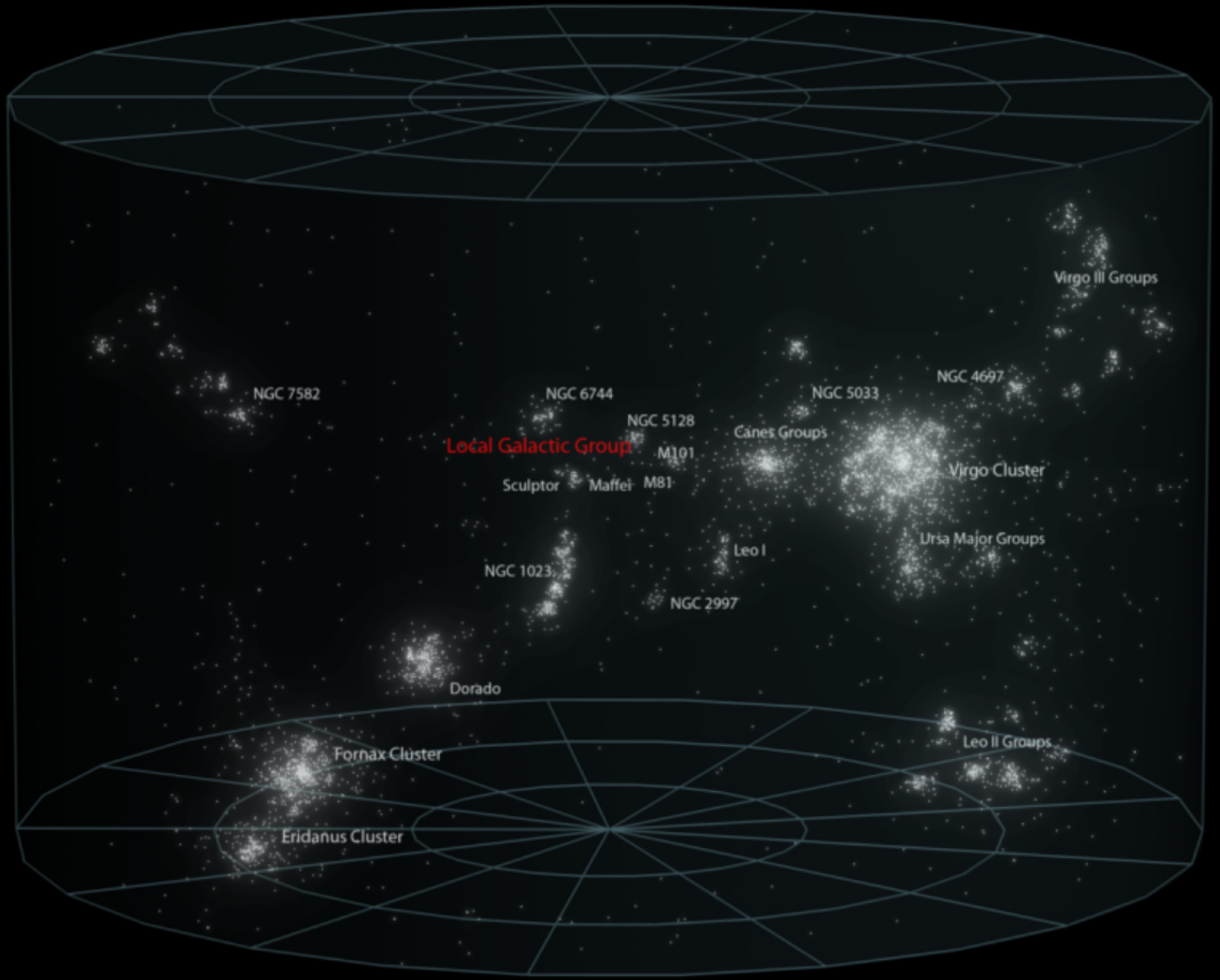
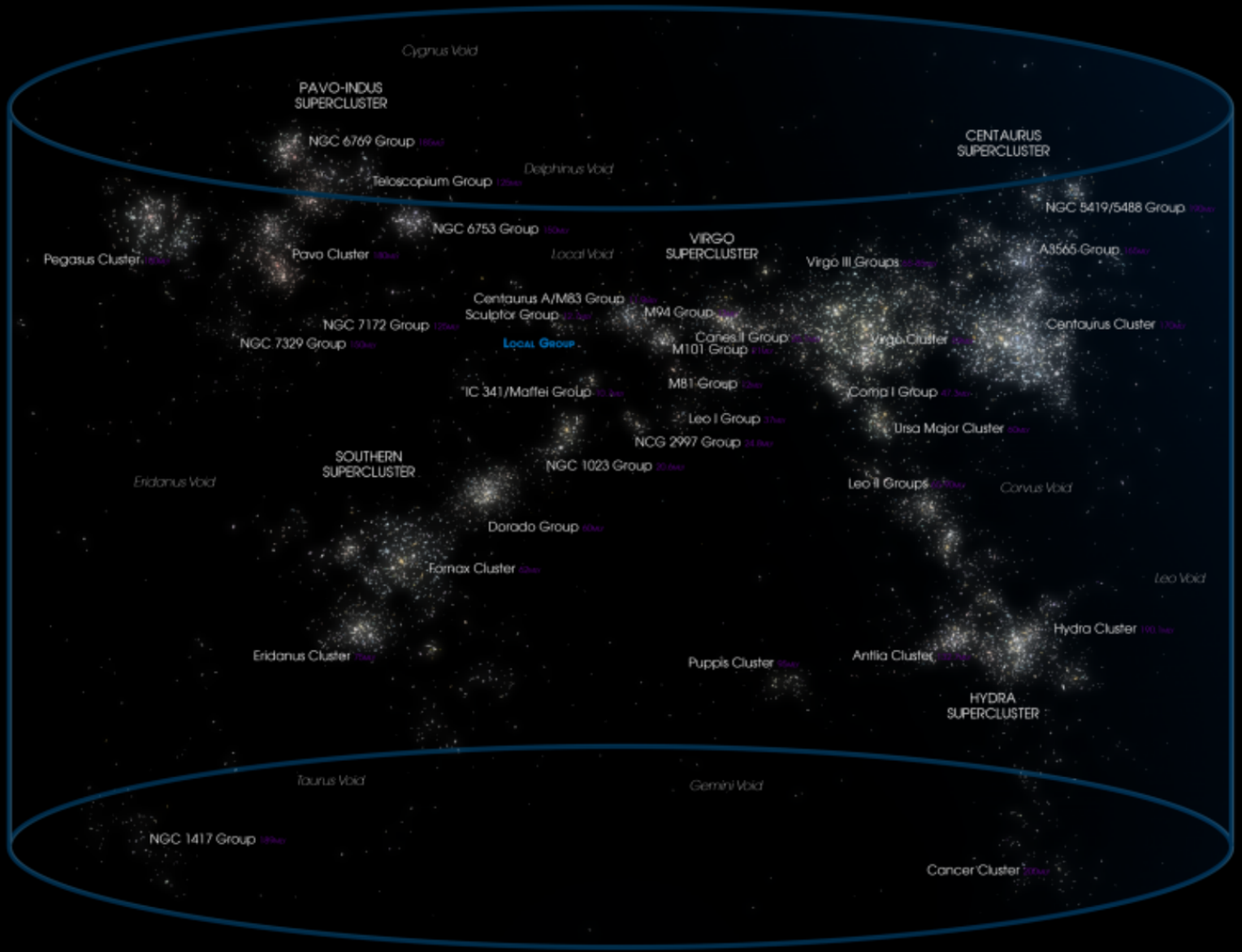
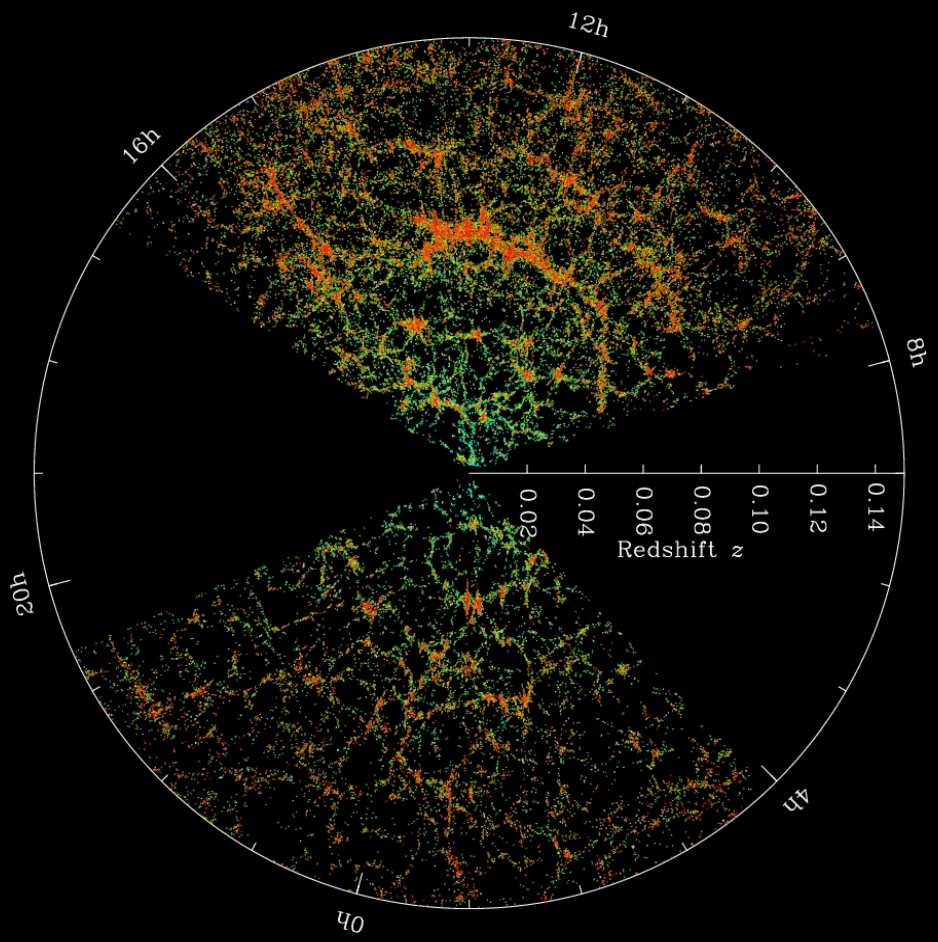
Halo *vs.* disk $\Rightarrow$ formation history of galaxies (Eggen, Lynden-Bell & Sandage, 1962).


Sextans B
Sextans A
Leo A
NGC 3190
Antila Dwarf
Leo I
Leo II
Canes Dwarf
Ursa Major I
Sextans Dwarf
Ursa Major II
Boötes Dwarf
Ursa Minor Dwarf
Draco Dwarf
IC 10
Large Magellanic Cloud
Small Magellanic Cloud
Milky Way Galaxy
Sagittarius Dwarf
Carina Dwarf
NGC 185
NGC 147
Sculptor Dwarf
Fornax Dwarf
M110
Andromeda Galaxy (M31)
Andromeda I
M32
NGC 6822
Triangulum Galaxy (M33)
Andromeda II
Andromeda III
Phoenix Dwarf
Pisces Dwarf
IC 1613
Aquarius Dwarf
SagDIG
Pegasus Dwarf
Cetus Dwarf
Tucana Dwarf
WLM

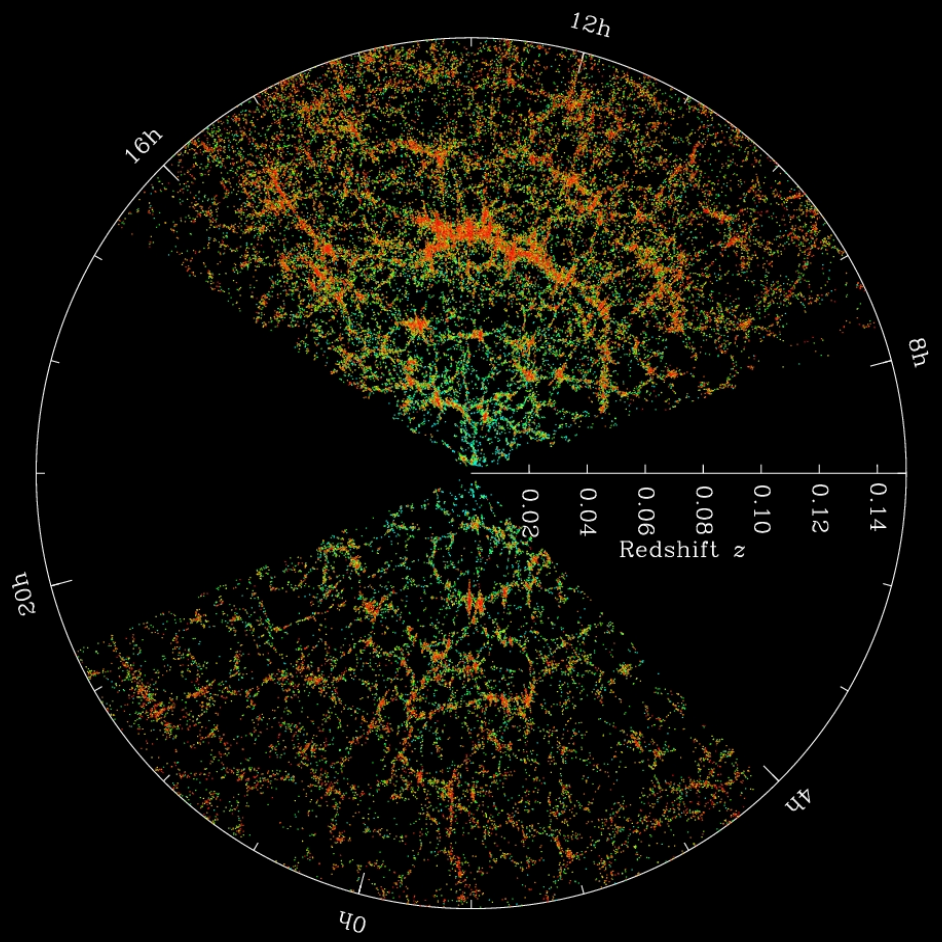

Virgo III Groups
NGC 7582
NGC 6744
NGC 5033
NGC 4697
NGC 5128
Canes Groups
Local Galactic Group
M101
Virgo Cluster
Sculptor
Maffei
M81
Ursa Major Groups
Leo I
NGC 1023
NGC 2997
Dorado
Leo II Groups
Fornax Cluster
Eridanus Cluster


Cygnus Void
PAVO-INDUS SUPERCLUSTER
NGC 6769 Group
Delphinus Void
Telescopium Group
CENTAURUS SUPERCLUSTER
NGC 5419/5488 Group
NGC 6753 Group
VIRGO SUPERCLUSTER
Pegasus Cluster
Pavo Cluster
Local Void
Virgo III Groups
A3565 Group
Centaurus A/M83 Group
Sculptor Group
M94 Group
NGC 7172 Group
NGC 7329 Group
Local Group
Canes II Group
M101 Group
Virgo Cluster
Centaurus Cluster
IC 341/Maffei Group
M81 Group
Coma I Group
Leo I Group
Ursa Major Cluster
NCG 2997 Group
SOUTHERN SUPERCLUSTER
NGC 1023 Group
Eridanus Void
Leo II Groups
Corvus Void
Dorado Group
Fornax Cluster
Leo Void
Hydra Cluster
Eridanus Cluster
Puppis Cluster
Antlia Cluster
HYDRA SUPERCLUSTER
Taurus Void
Gemini Void
NGC 1417 Group
Cancer Cluster



$\simeq$ 600 Mpc (Sloan Digital Sky Survey) $\uparrow$

Box of $\simeq$ 600 Mpc (CRK-HACC simulation) $\rightarrow$



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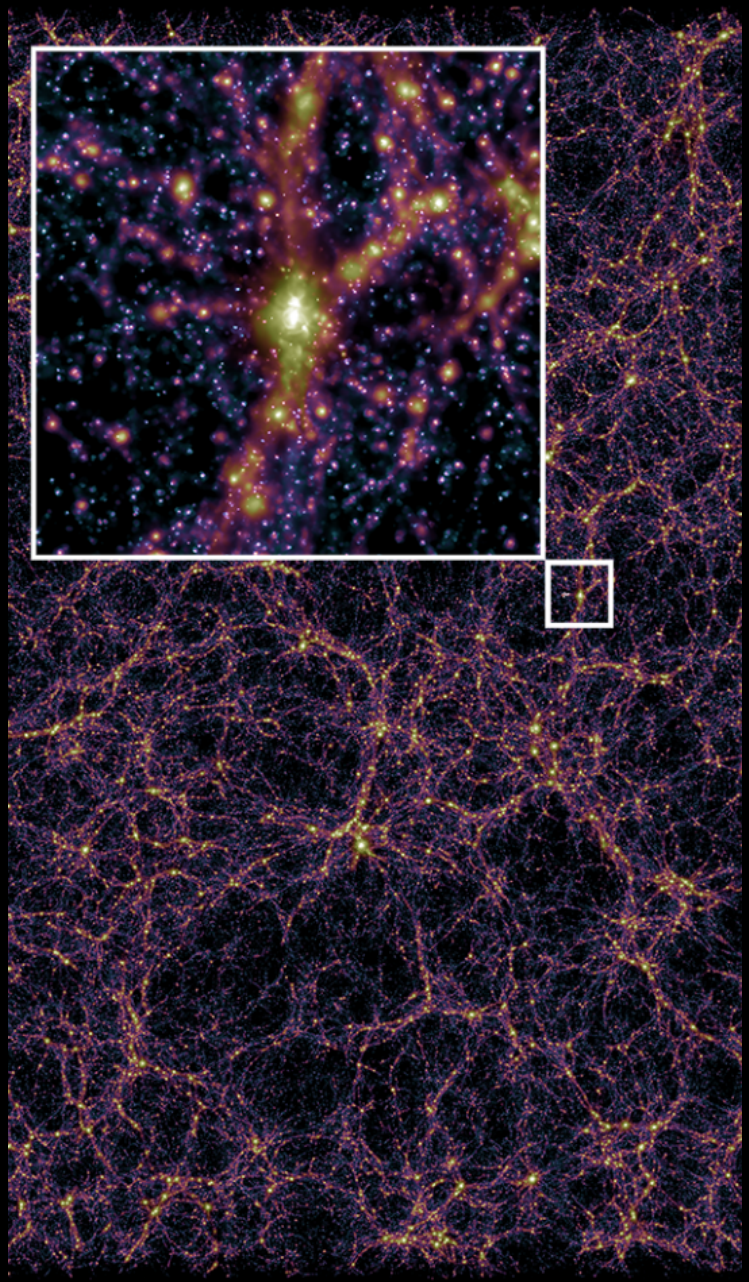

TOC of the Talk

1. INTRODUCTION
2. AN HISTORICAL PERSPECTIVE
   - The first observations of the sky
   - Astronomy: celestial mechanics
   - Astrophysics: the advent of spectroscopy
   - The Universe as we know it today: from the Solar system to the Big Bang
3. METHODOLOGIES FOR THE EXPLORATION OF DISTANT SPACE
   - *In situ* exploration
   - The current astrophysical vectors of information
   - The electromagnetic spectrum & the different astrophysical processes it probes
   - The complexity of astrophysical measures
4. AN OVERVIEW OF CONTEMPORARY OPEN QUESTIONS & HOT TOPICS
   - How does the Solar system work? How dit it form?
   - What is the origin of stars & planet, and how do they evolve?
   - How do galaxies form, and how does the Universe evolve?
   - Do we understand extreme conditions in the Universe?
5. SUMMARY & CONCLUSION

Voyager 1 & 2

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Voyager 1 & 2

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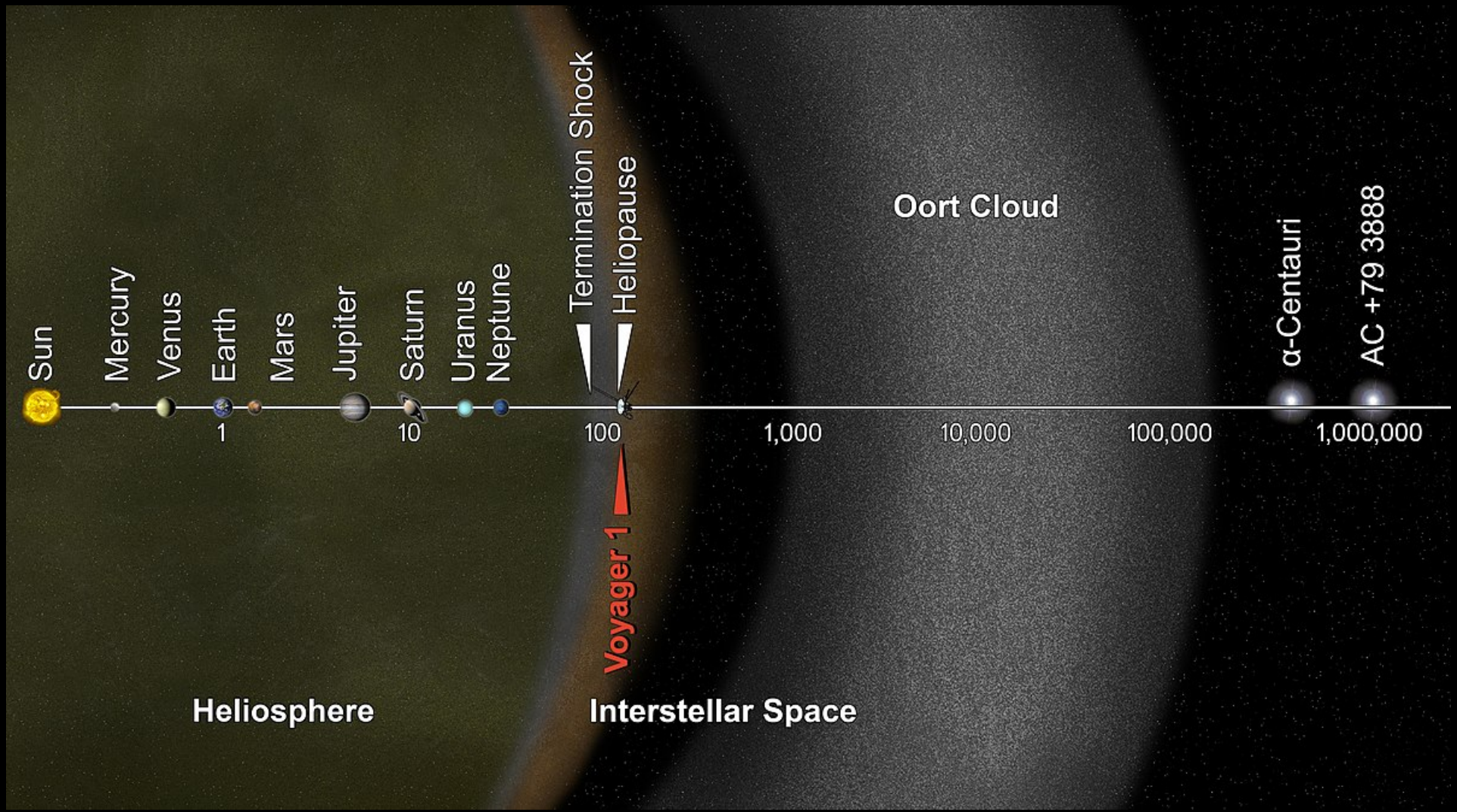

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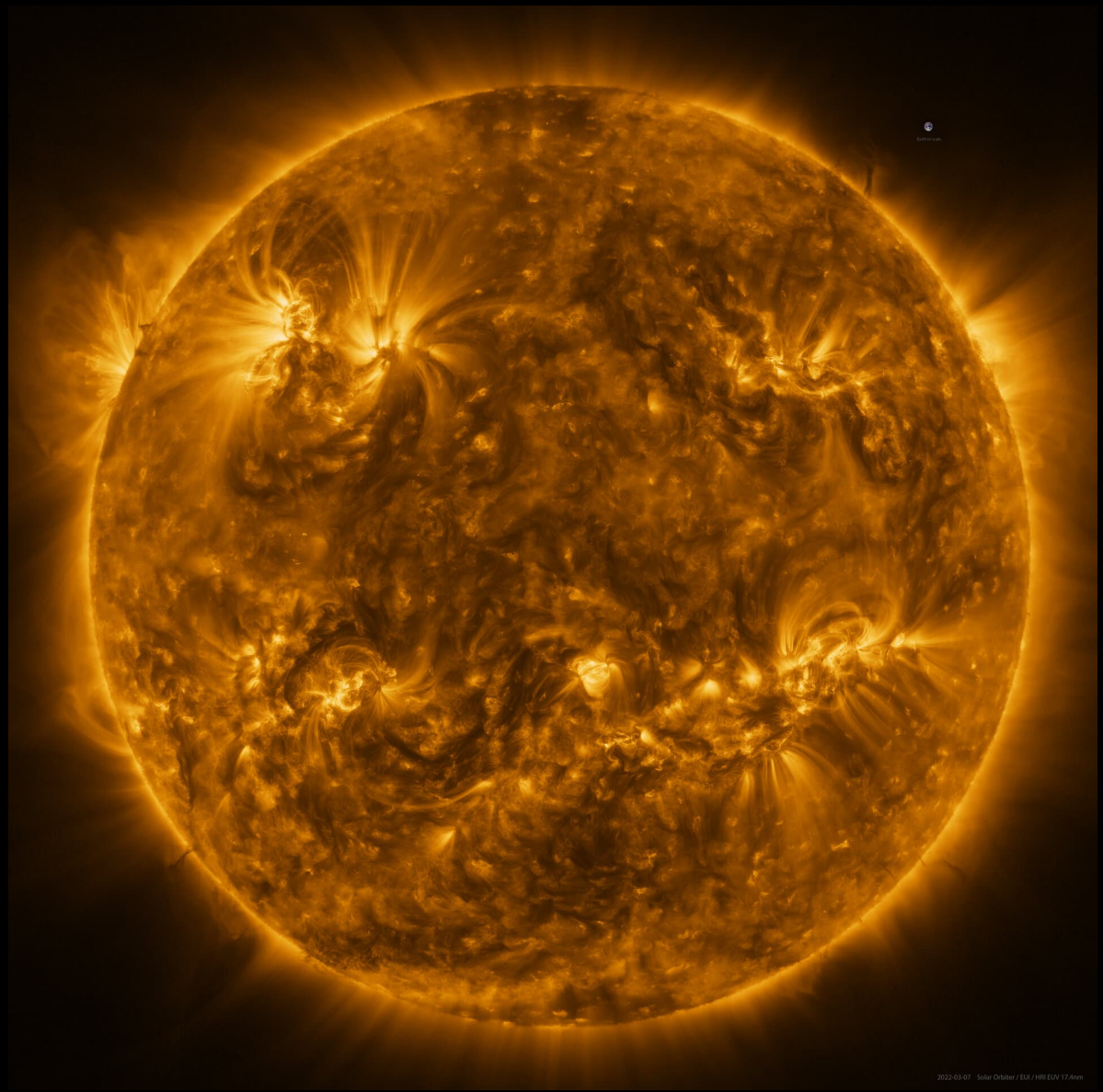

(Solar Orbiter; 2021)

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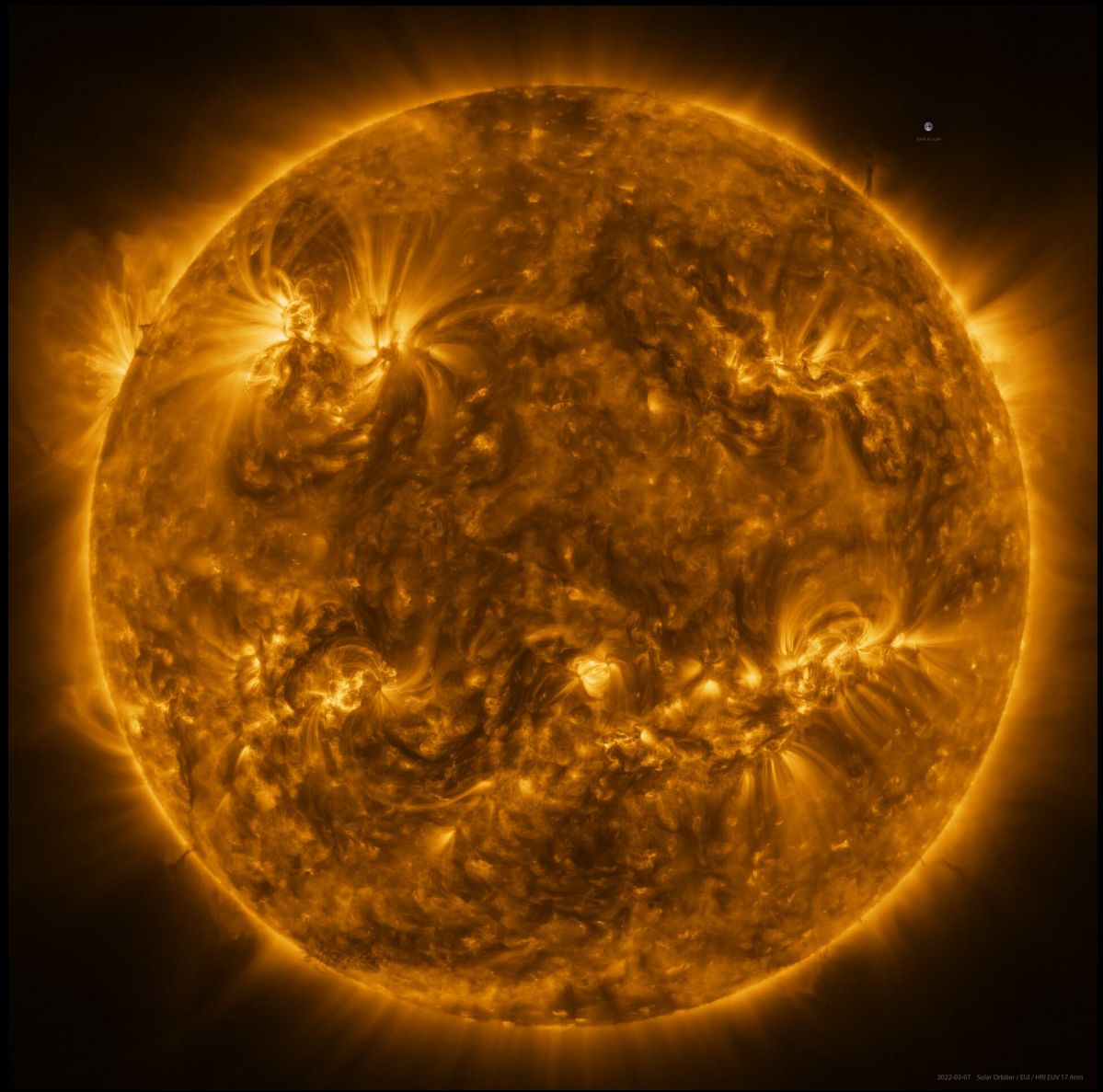

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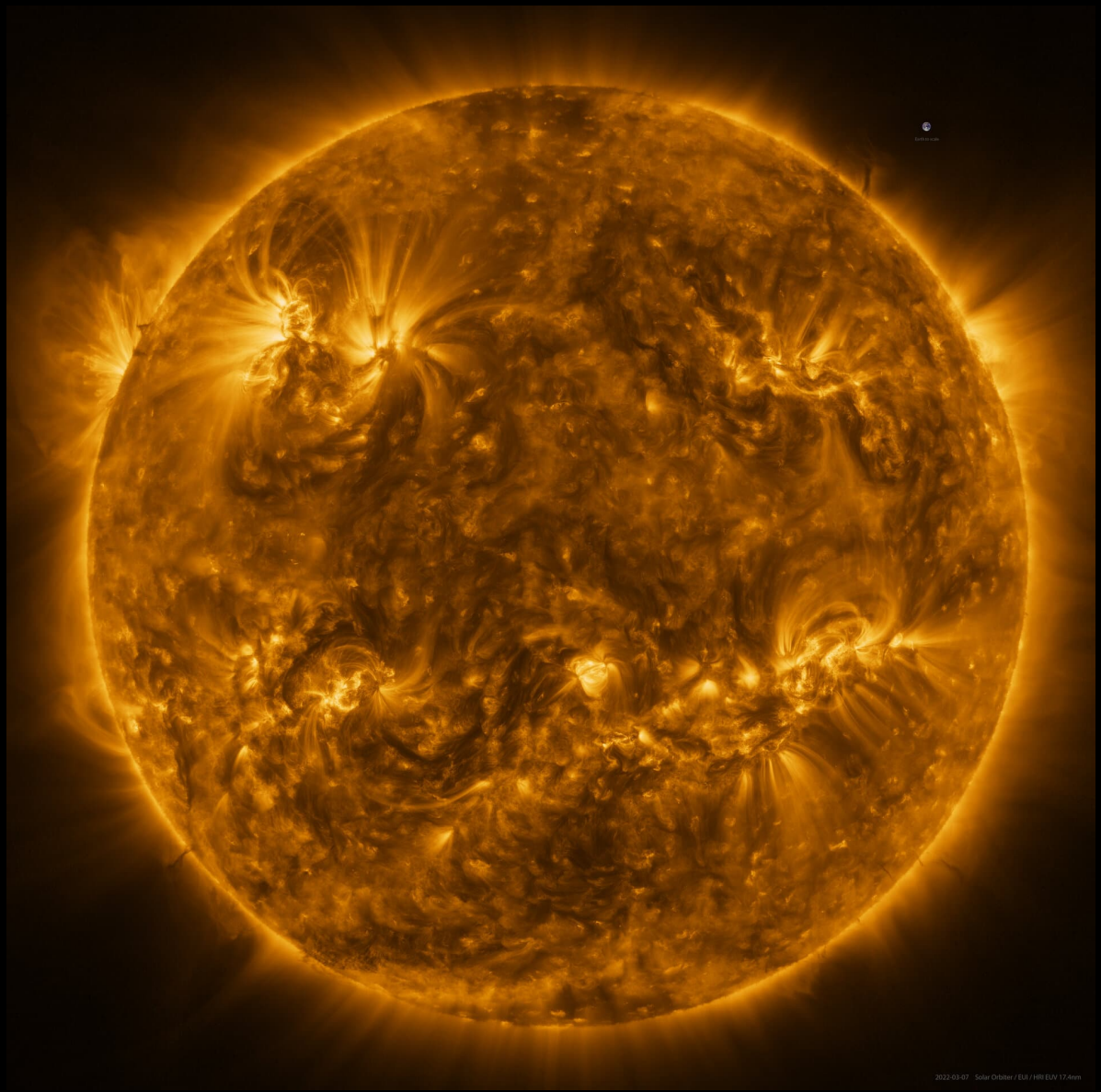

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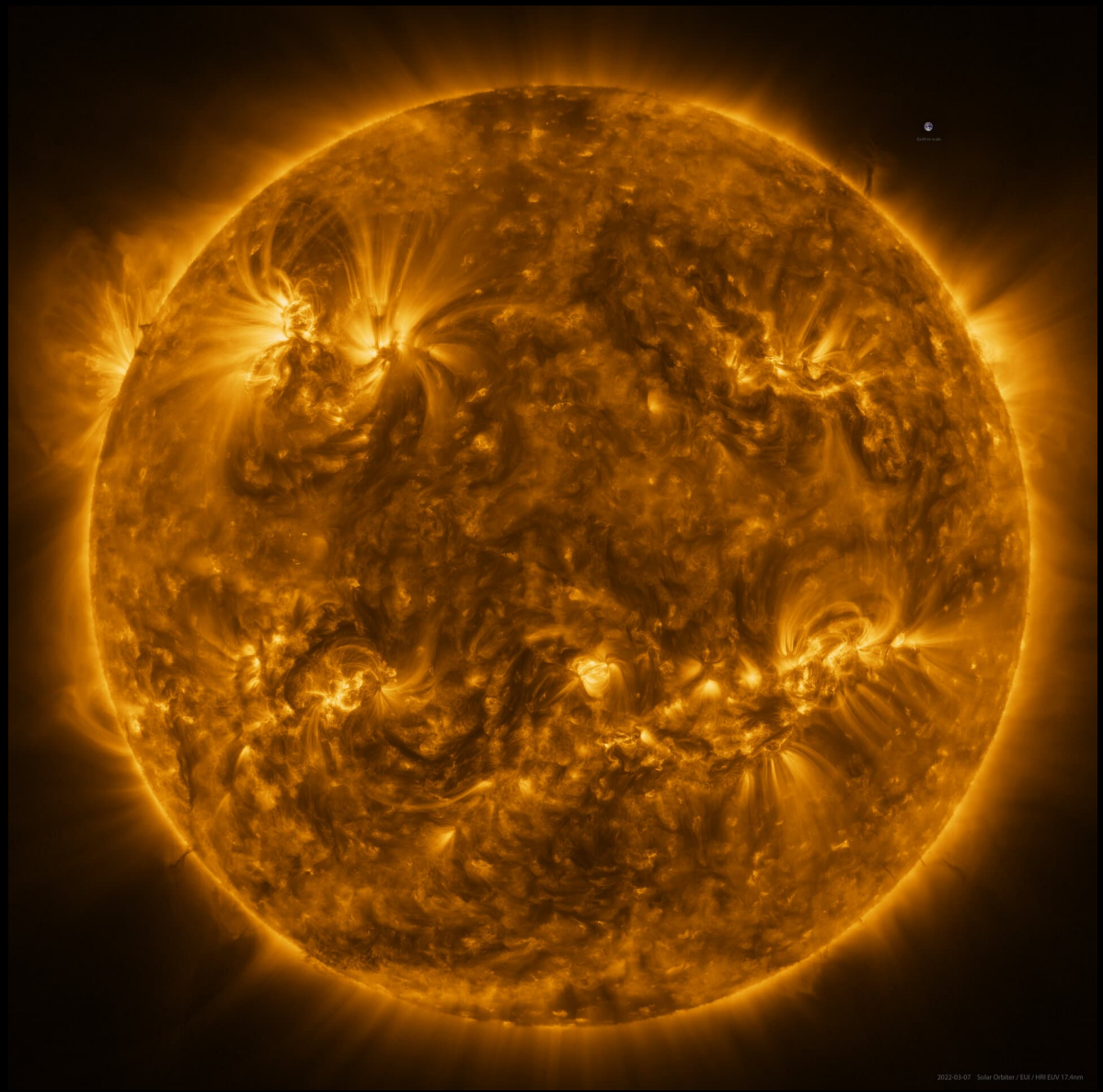

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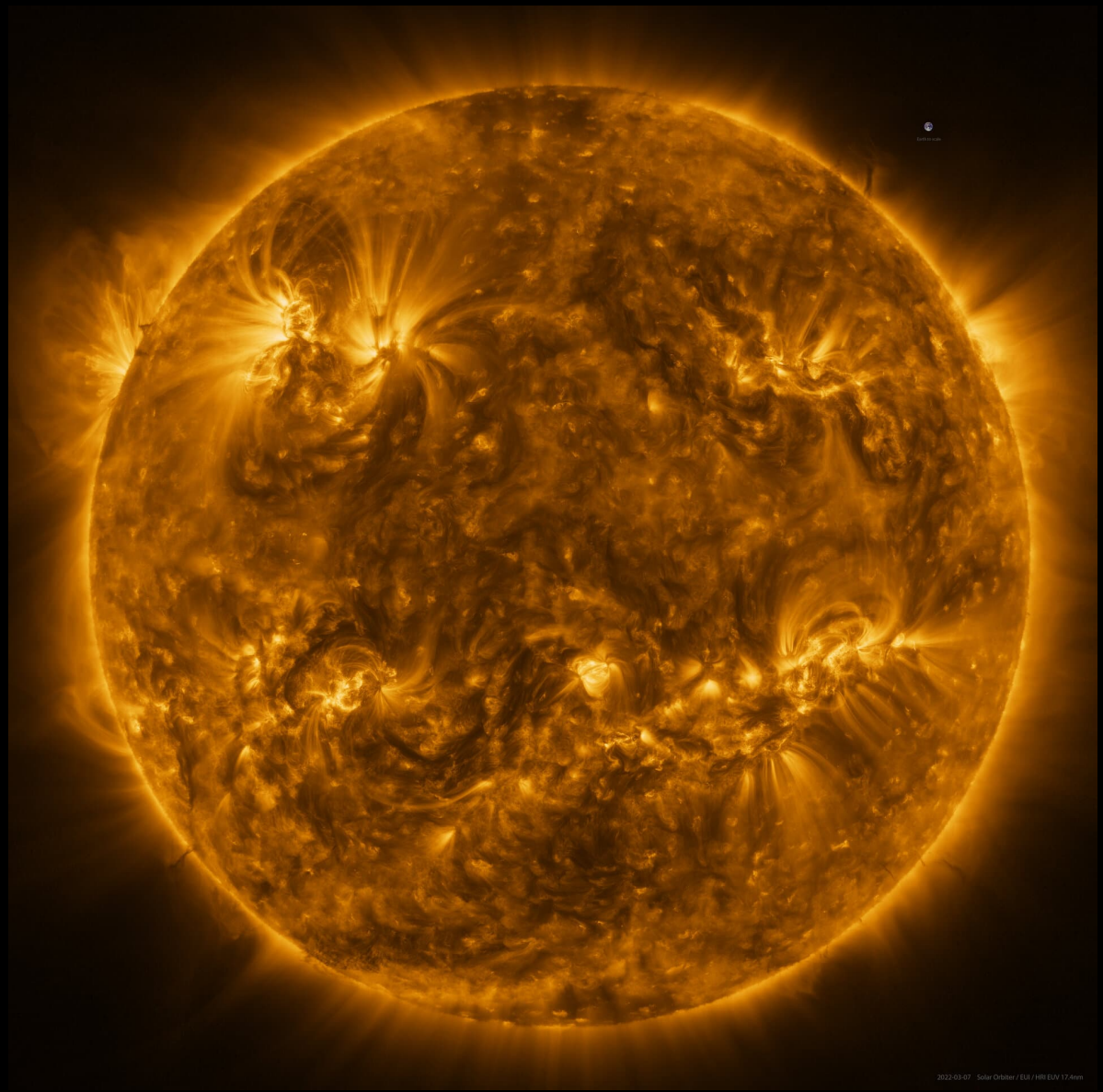
⇒ Since 1960 → 22 probes.



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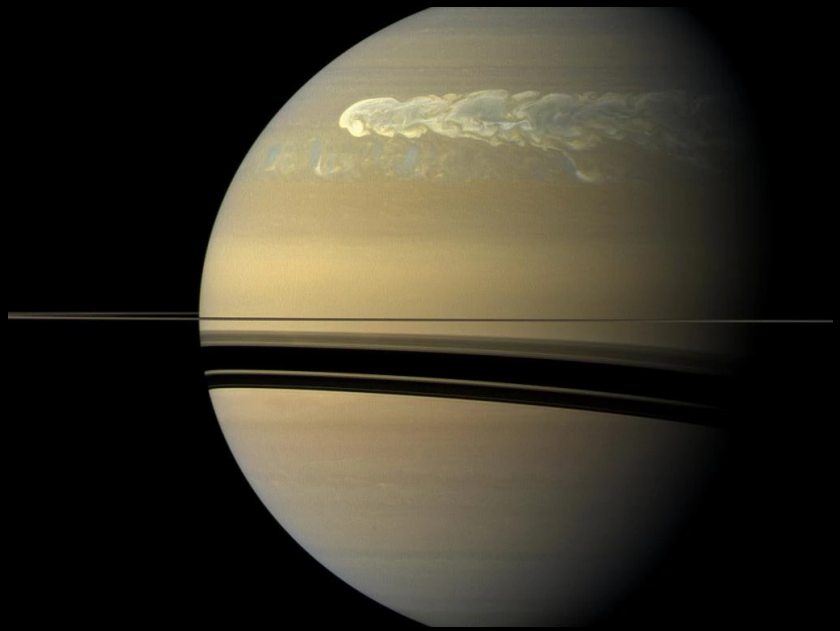

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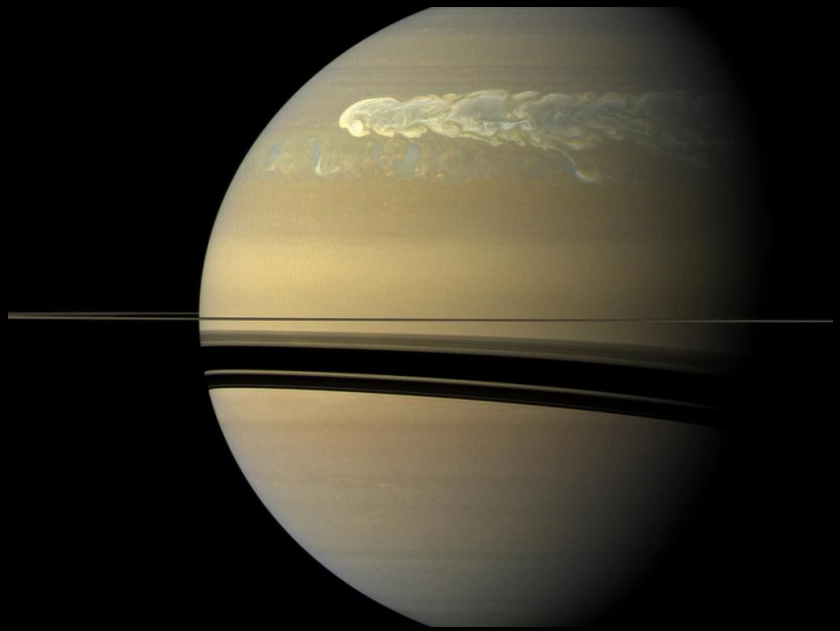

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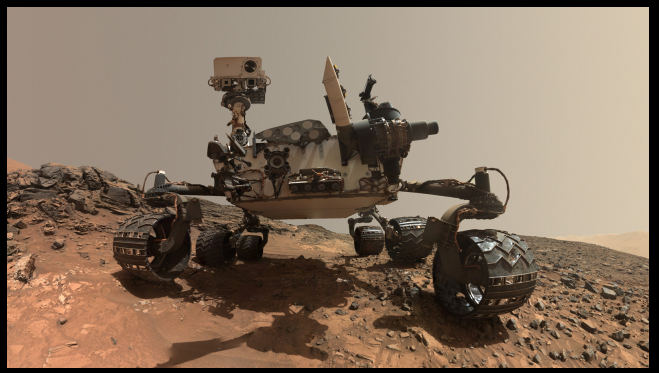

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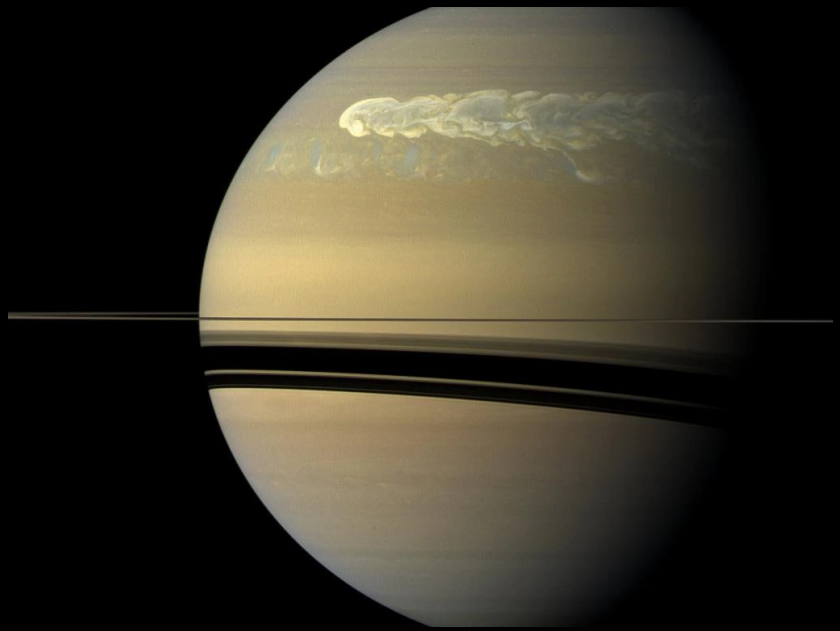

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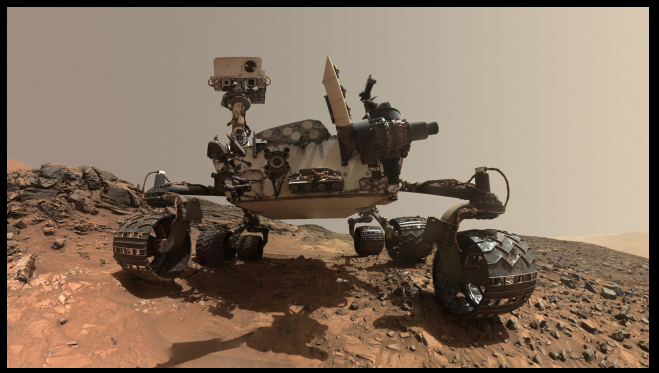

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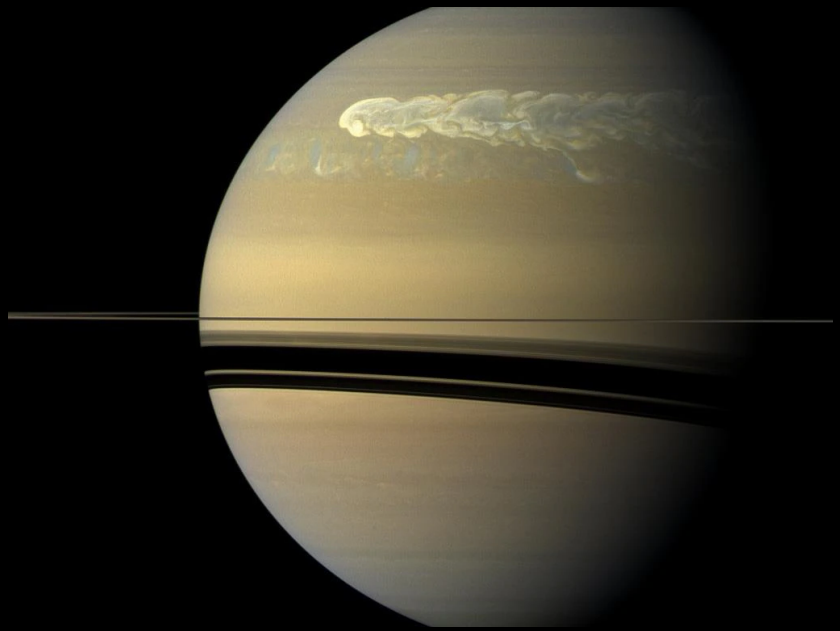

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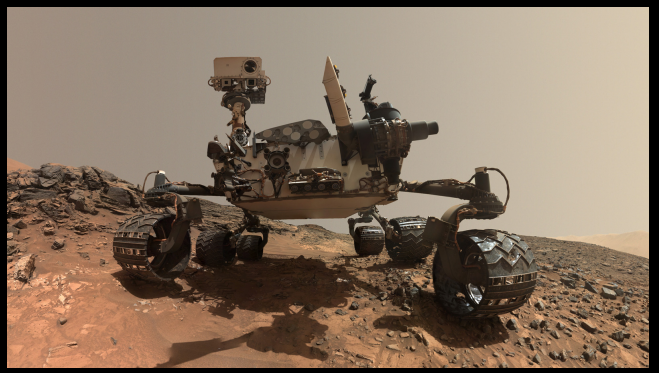

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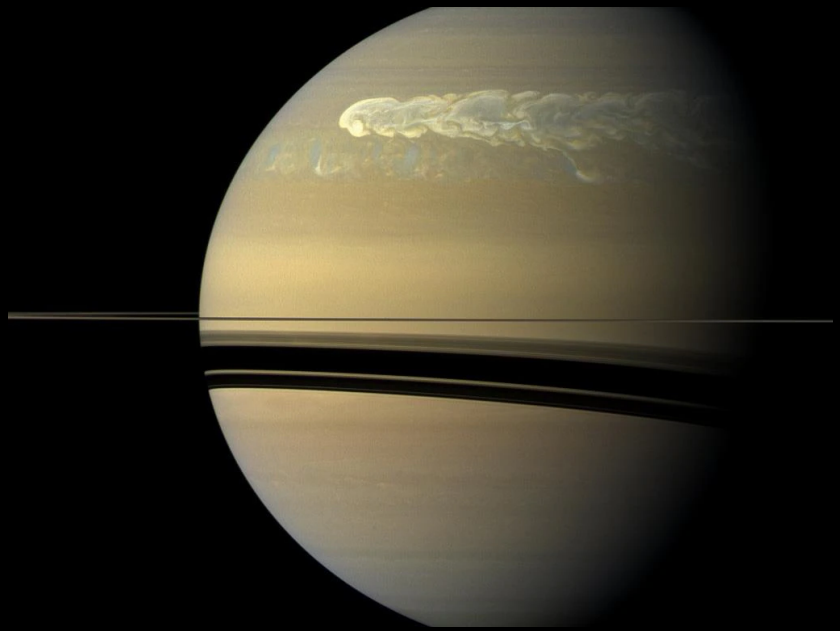

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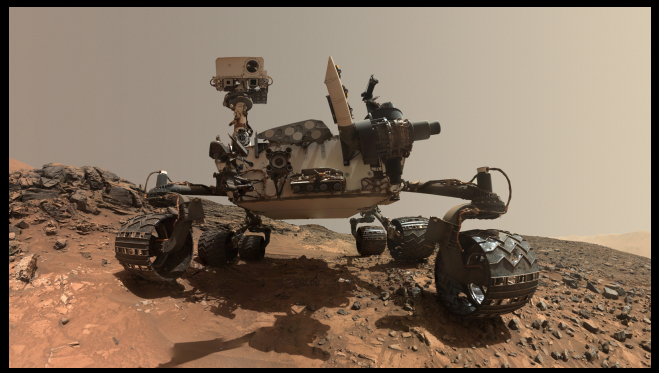

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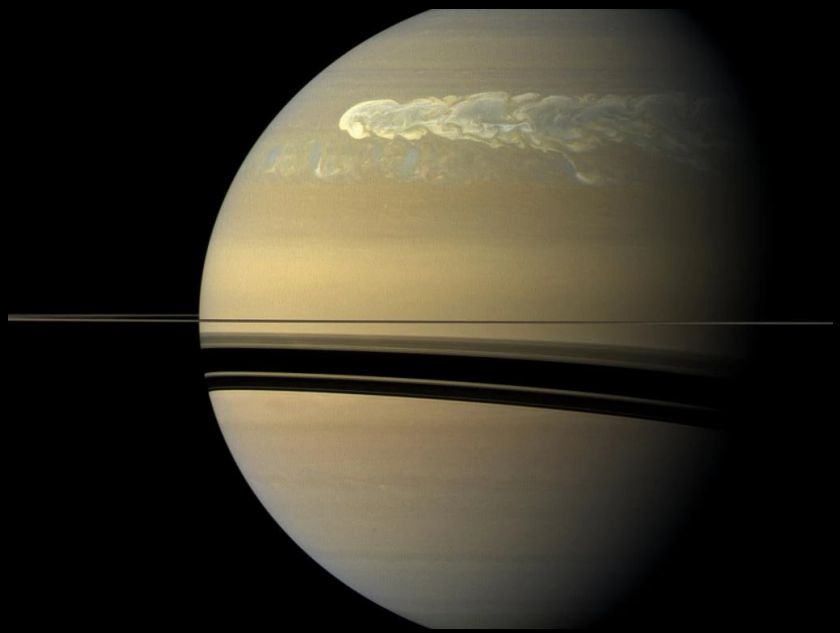

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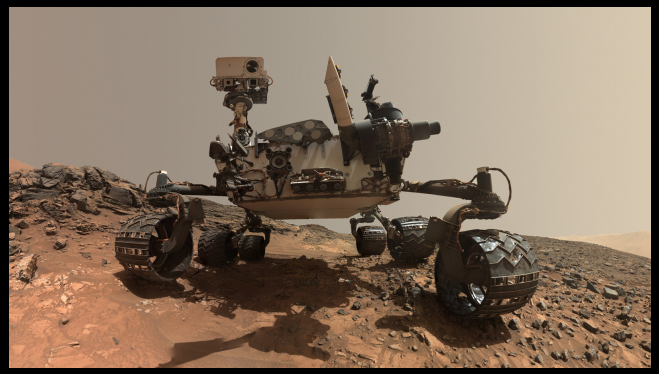

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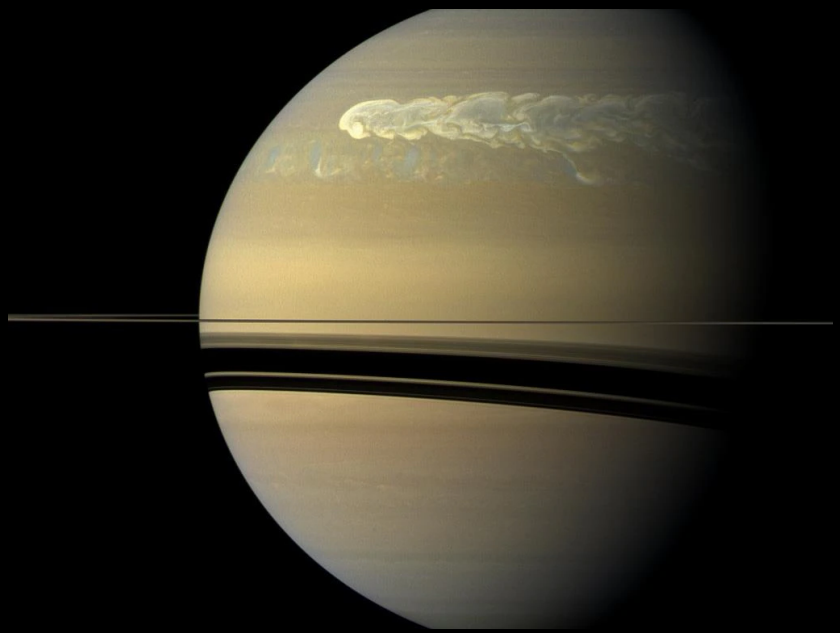

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Flybys & Landings (Successes/Attempts):

Mercury: 5/5 since 1974.
Venus: 34/81 since 1961.
Moon: 101/160 since 1959.
Mars: 43/69 since 1960.
Jupiter: 12/12 since 1973.
Saturn: 4/4 since 1979.
Titan: 1/1 since 2005.
Uranus: 1/1 since 1986.
Neptune 1/1 since 1989.
Pluto: 1/1 since 2015.

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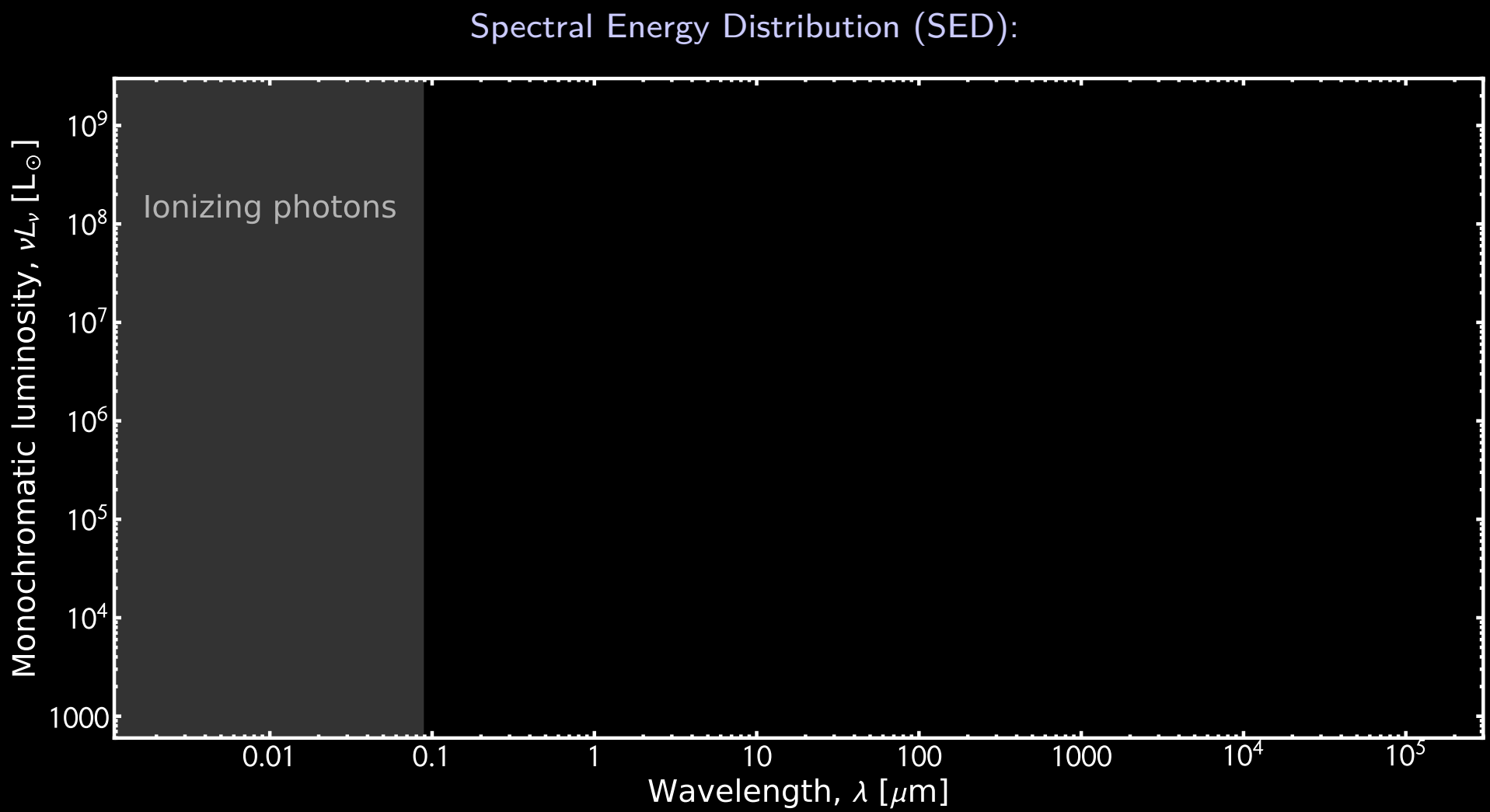
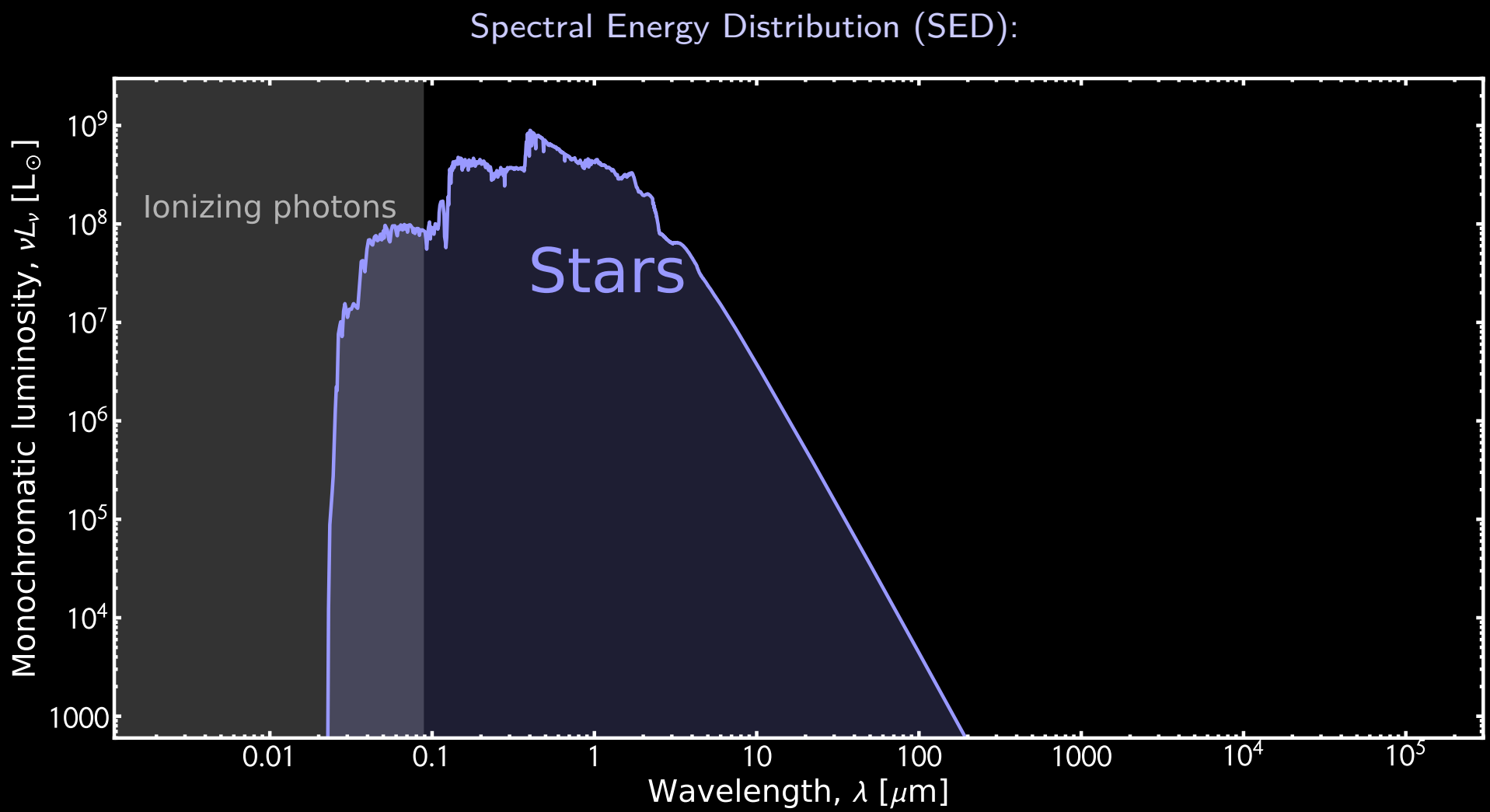
Gravitational waves: space-time perturbations originating in cataclysmic events, detected since 2015.


Spectral Energy Distribution (SED):
Ionizing photons
Monochromatic luminosity, νL_ν [$L_\odot$]
10^9
10^8
10^7
10^6
10^5
10^4
1000
0.01
0.1
1
10
100
1000
10^4
10^5
Wavelength, λ [μm]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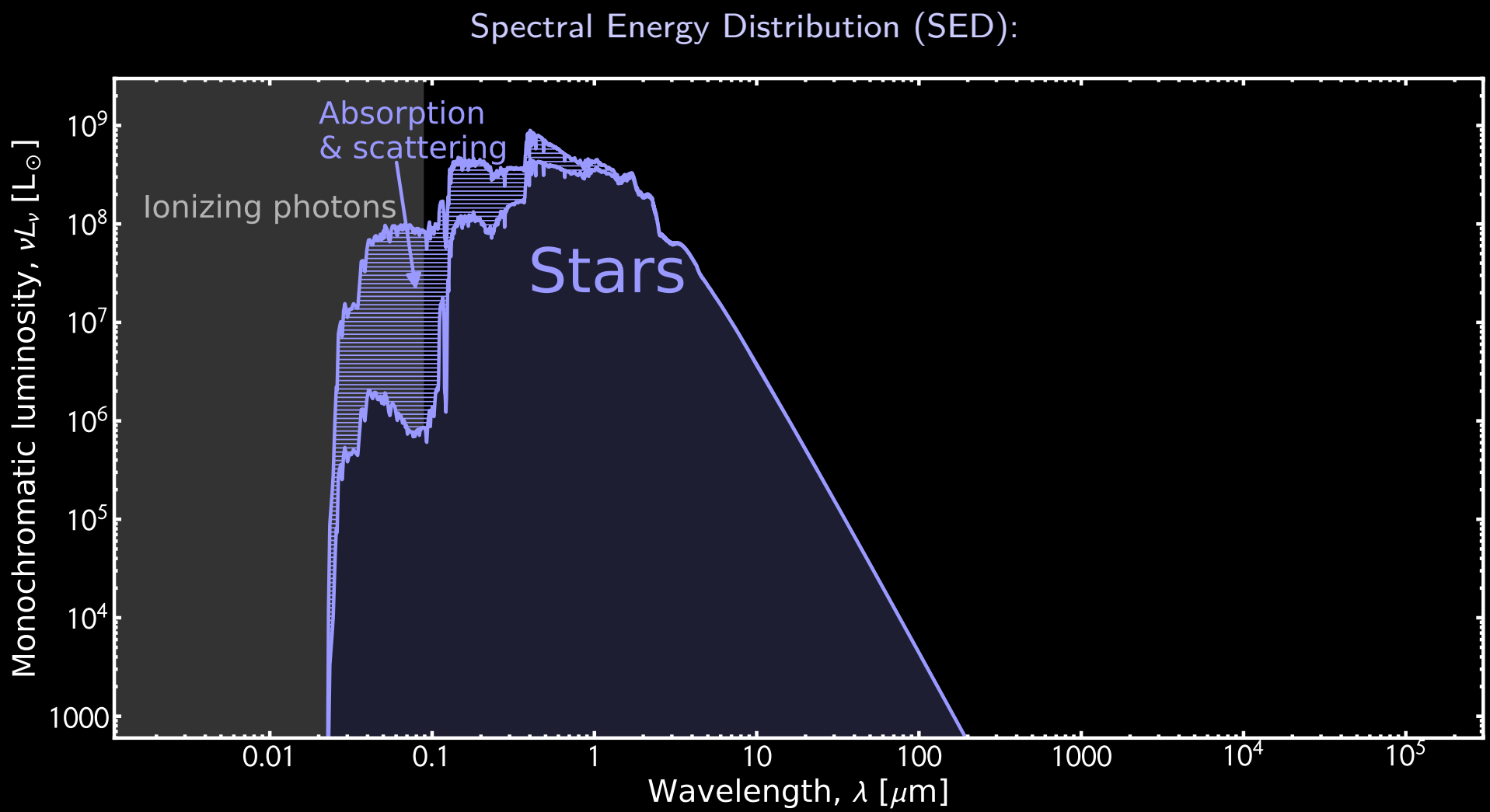
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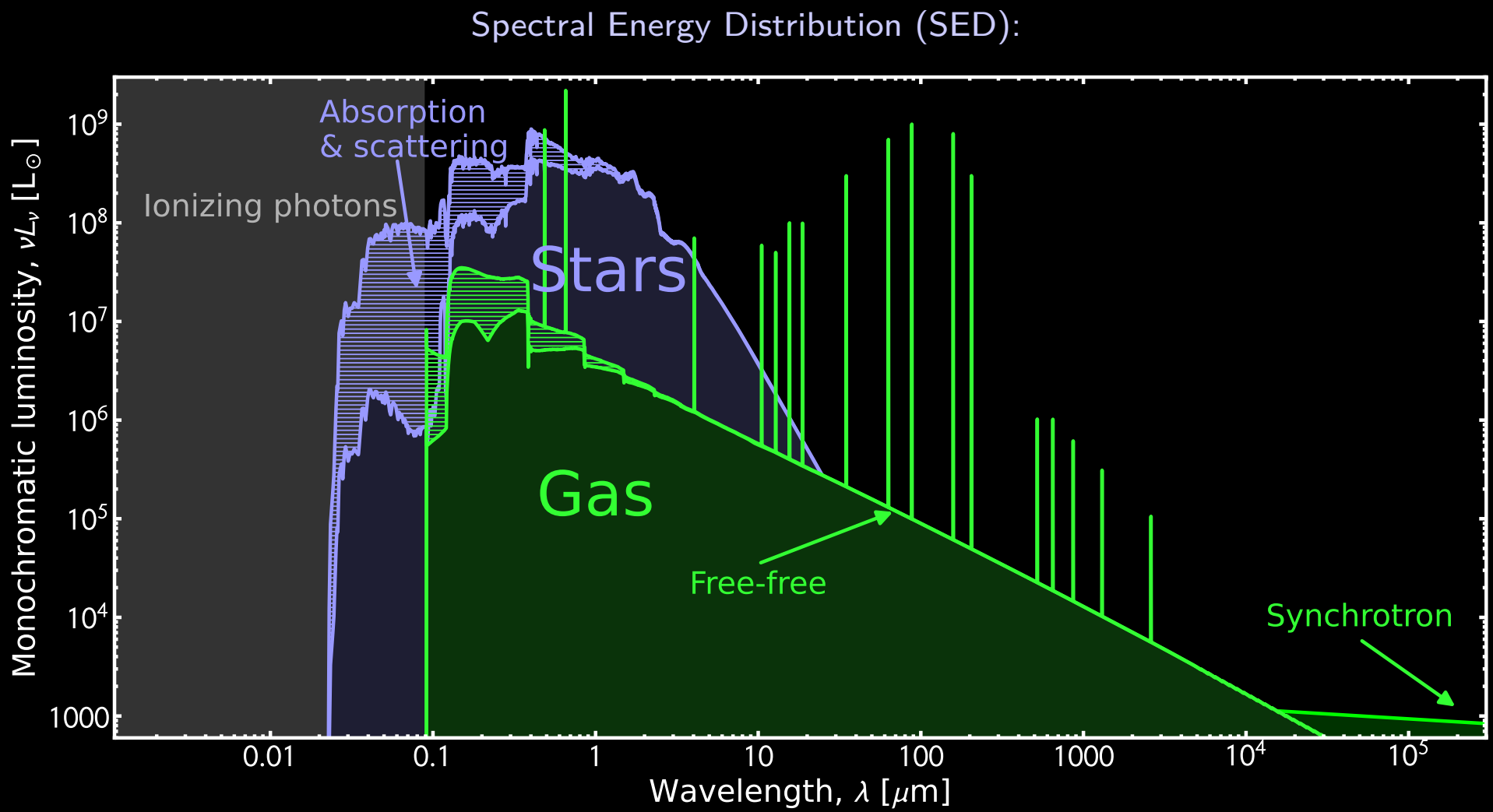
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Stars
Gas
Free-free
Synchrotron
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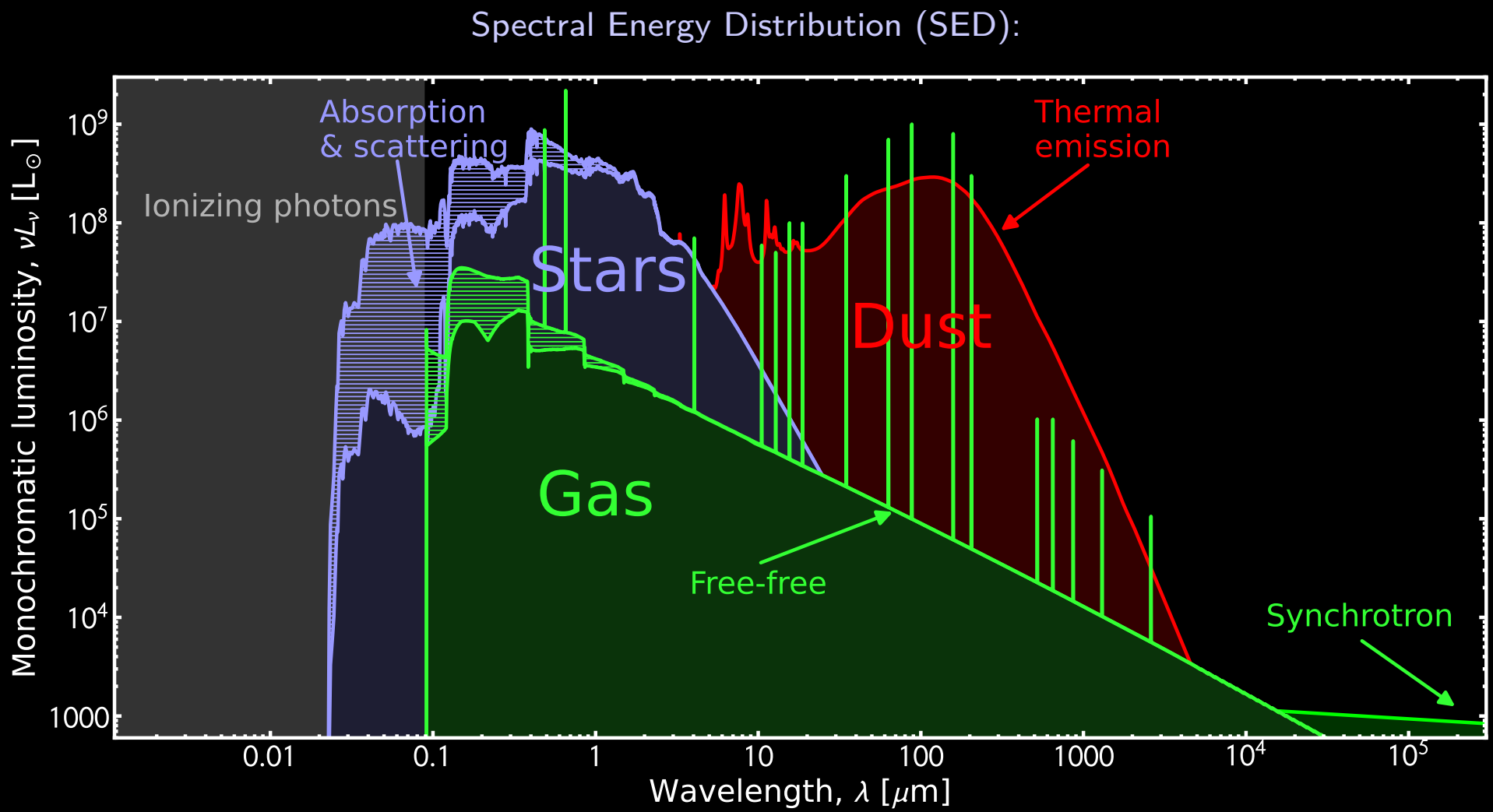
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Absorption
& scattering
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Stars
Thermal
emission
Dust
Gas
Free-free
Synchrotron
Monochromatic luminosity, νL_ν [$L_\odot$]
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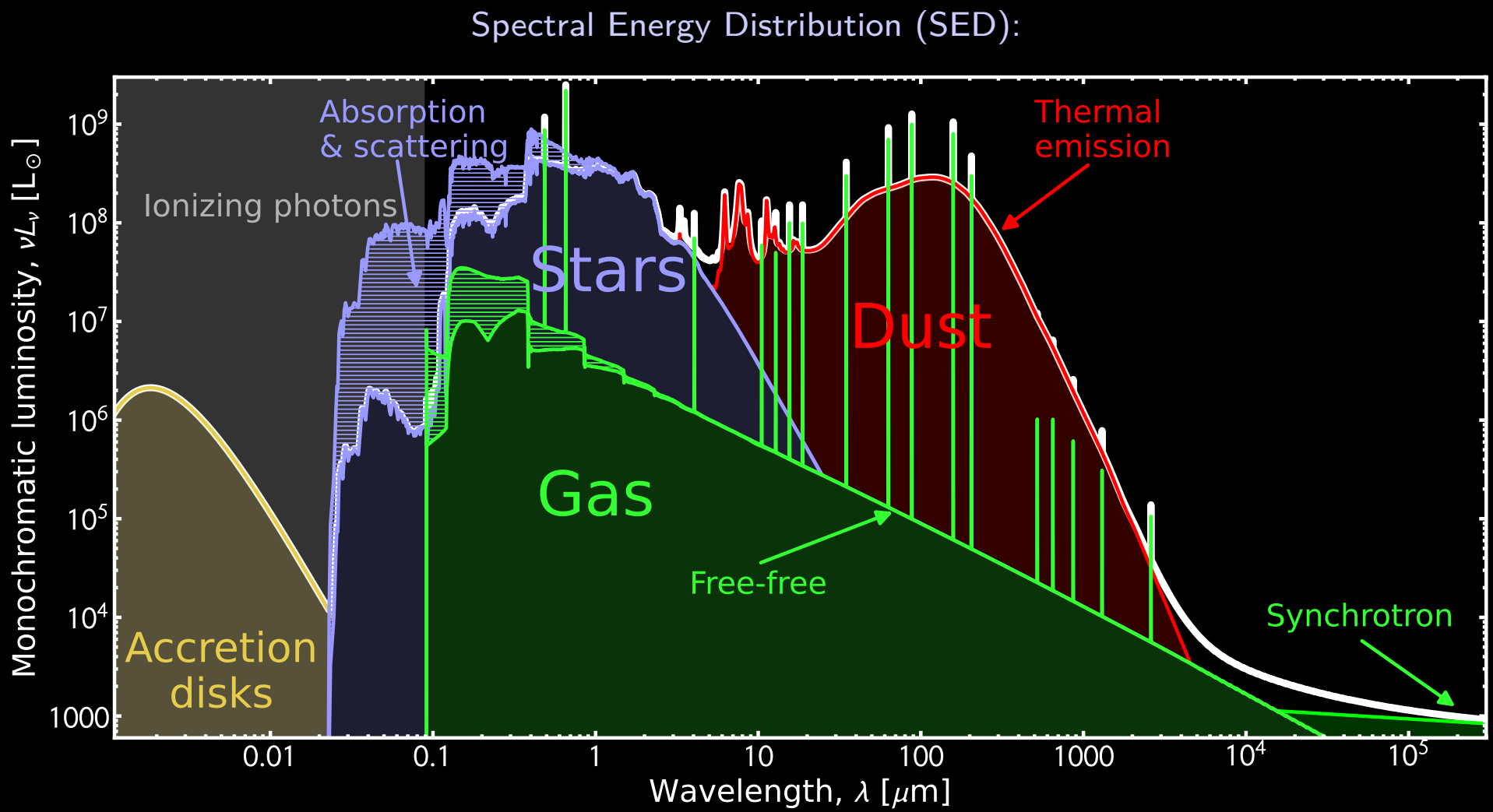
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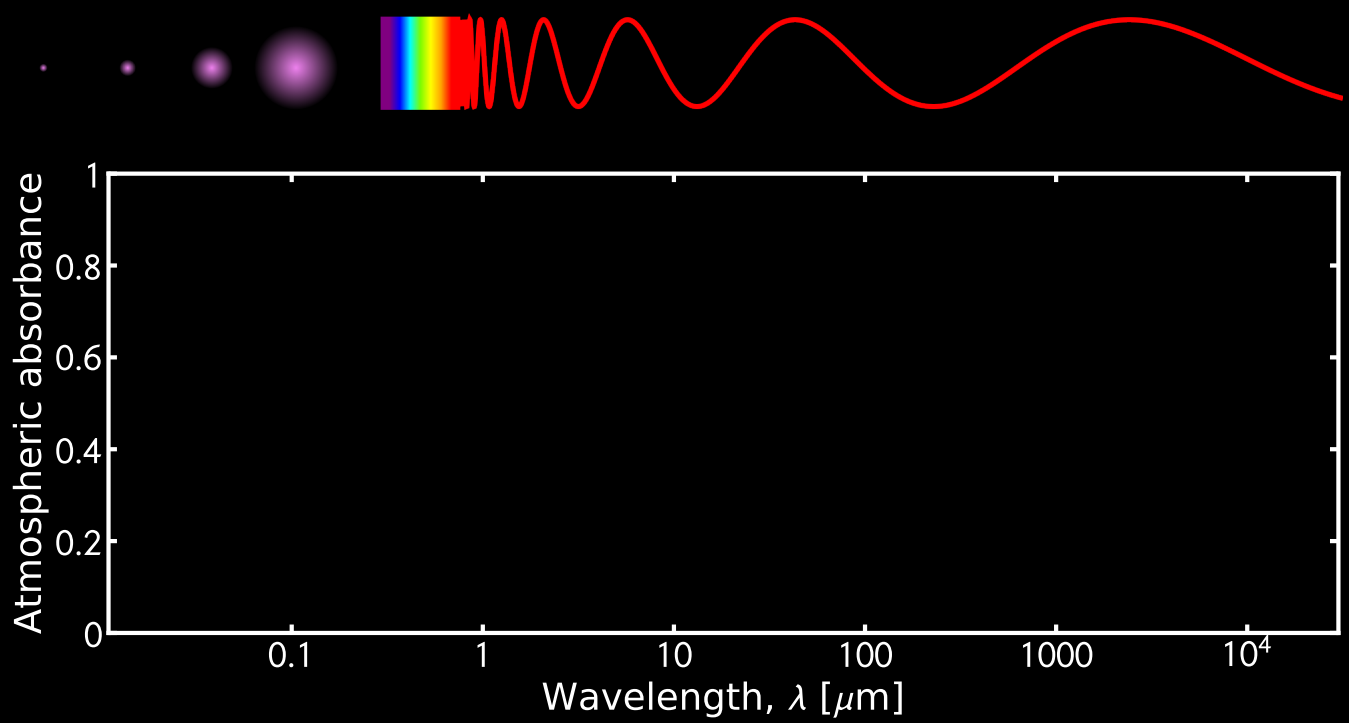
Atmospheric absorbance
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100
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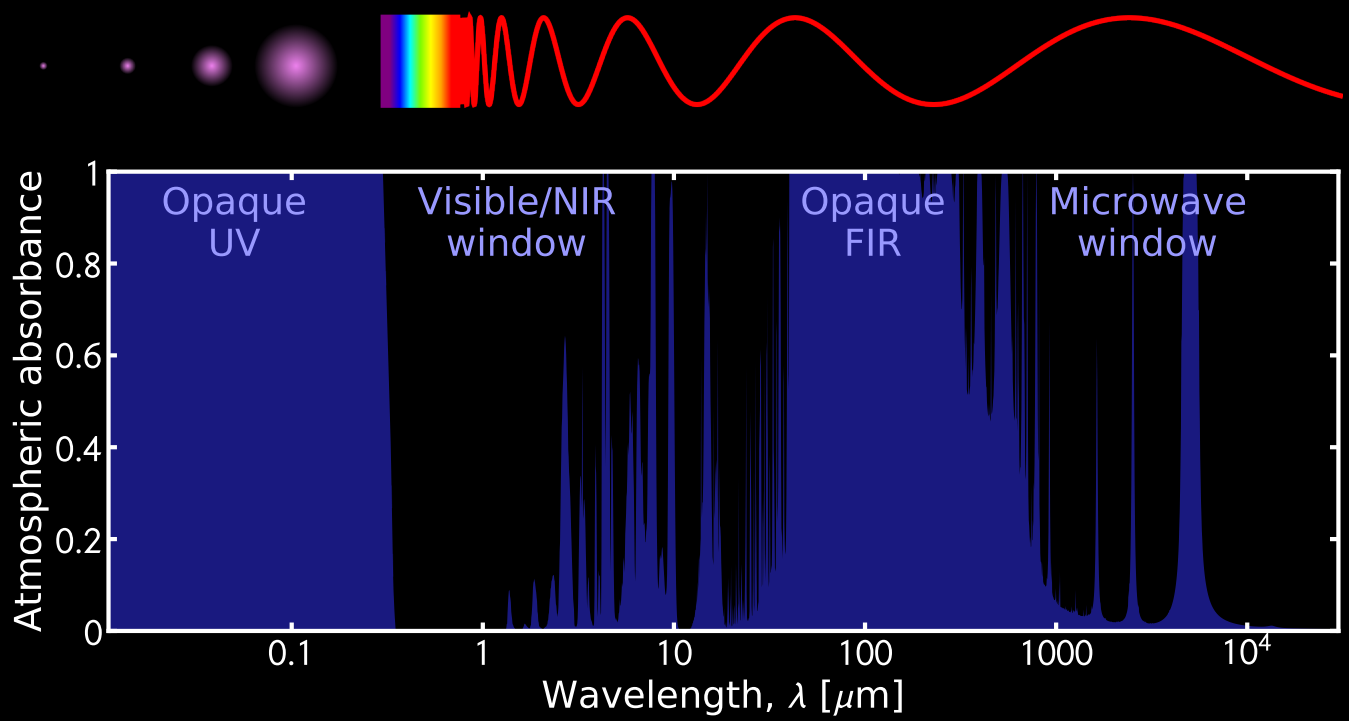
Wavelength, λ [μm]


Opaque
UV
Visible/NIR
window
Opaque
FIR
Microwave
window
Atmospheric absorbance
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0.2
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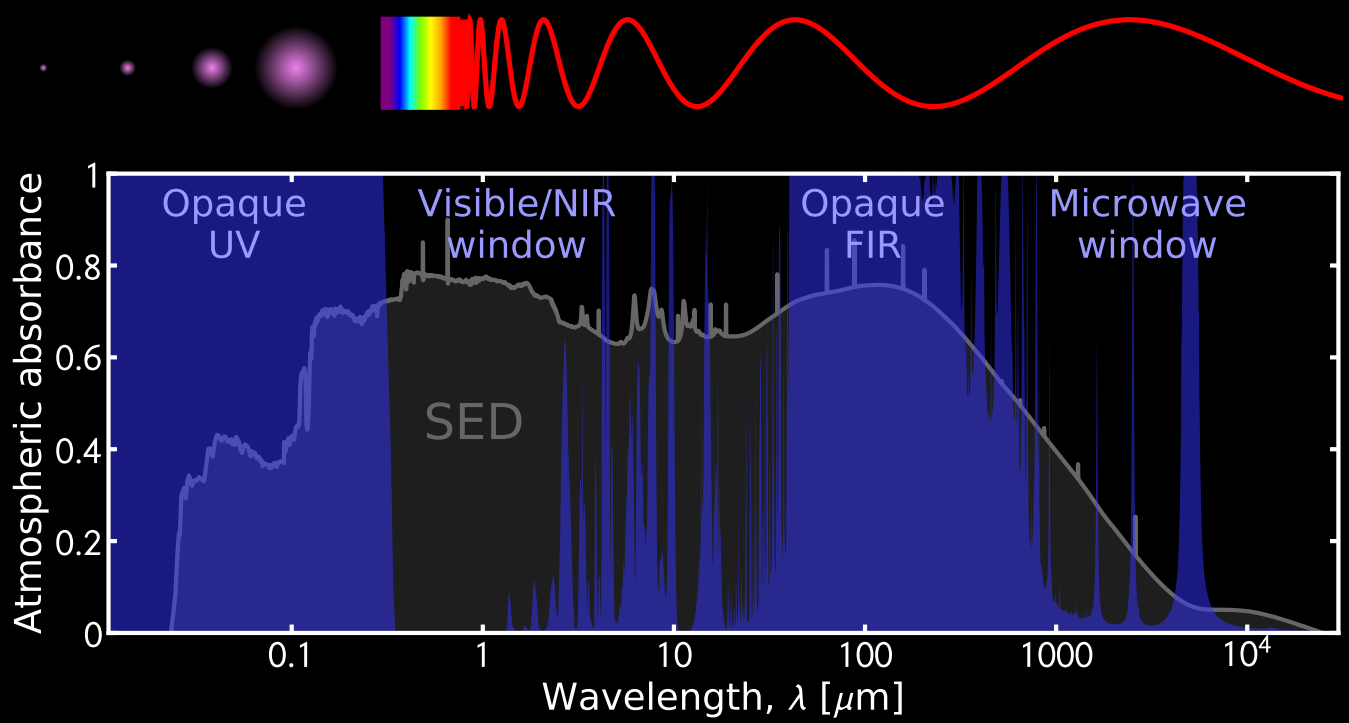
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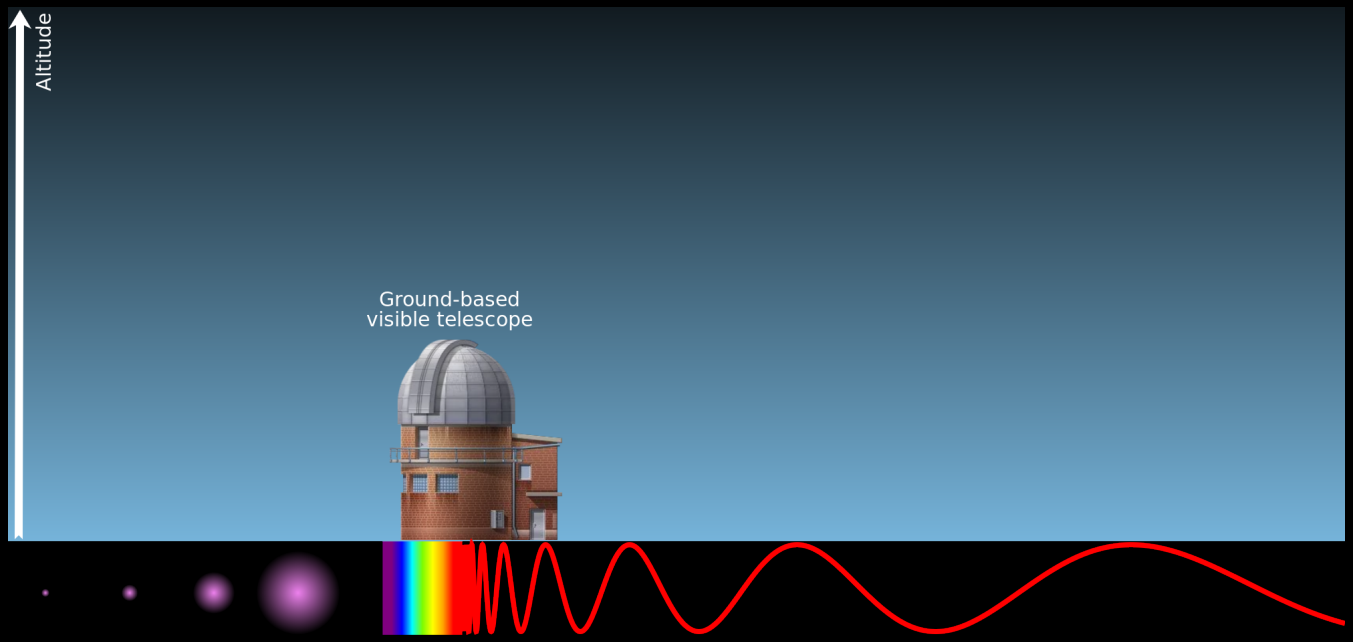
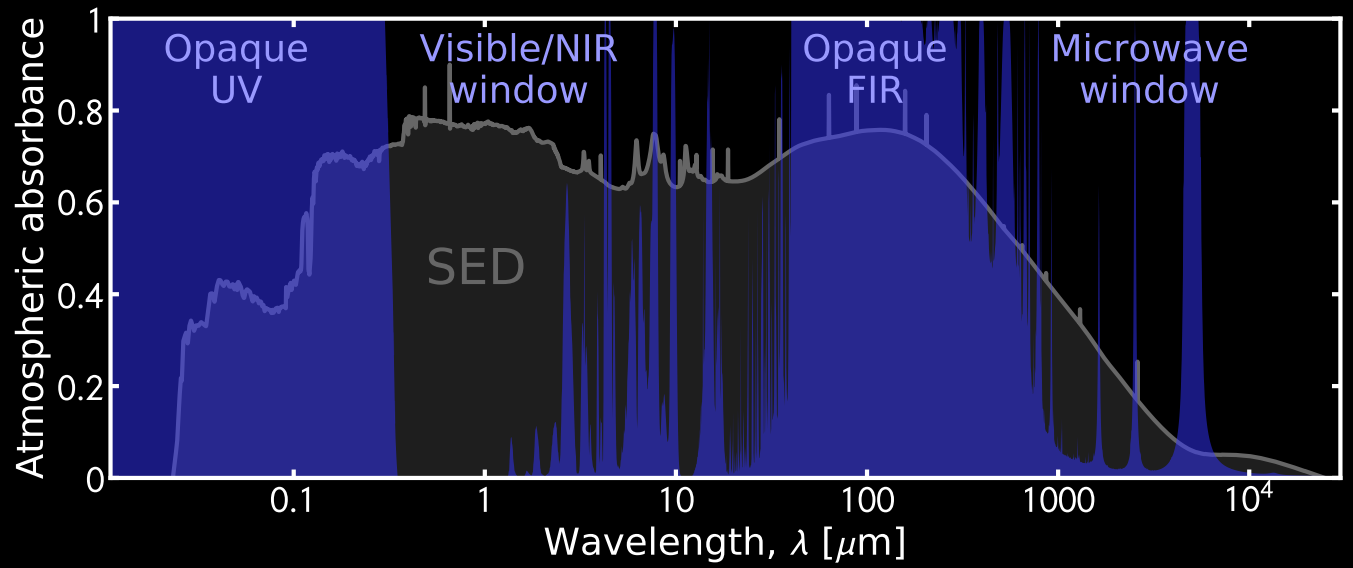

Altitude
Ground-based
visible telescope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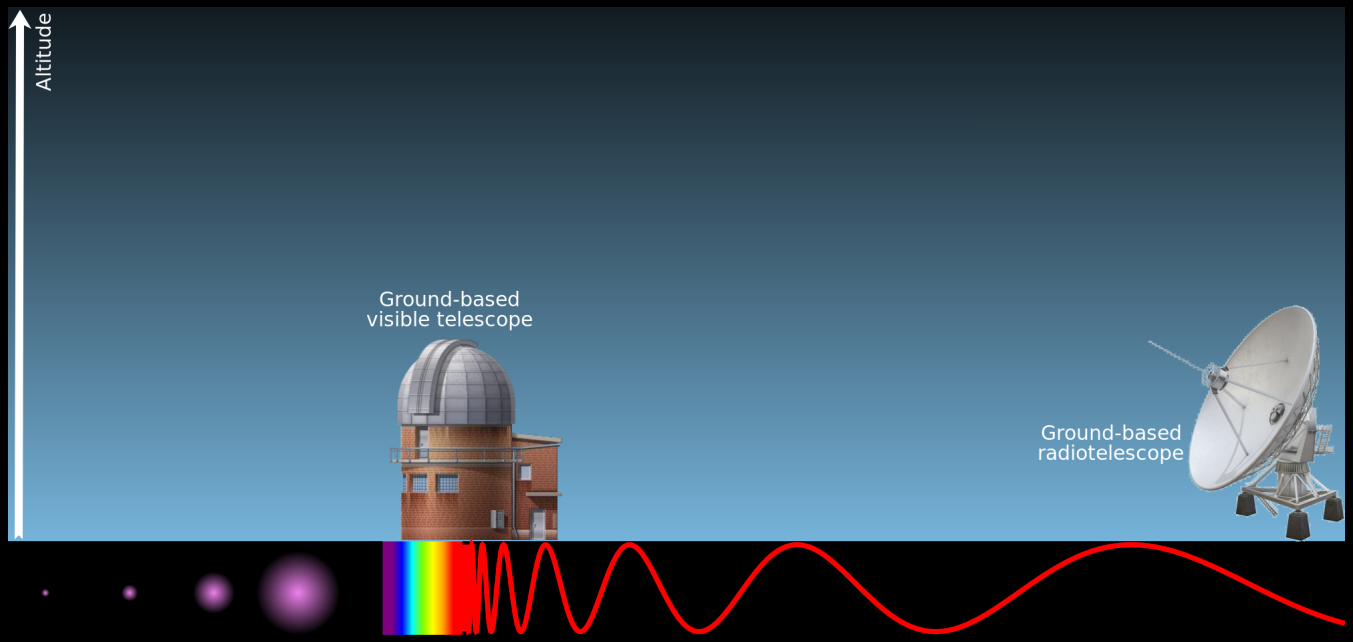
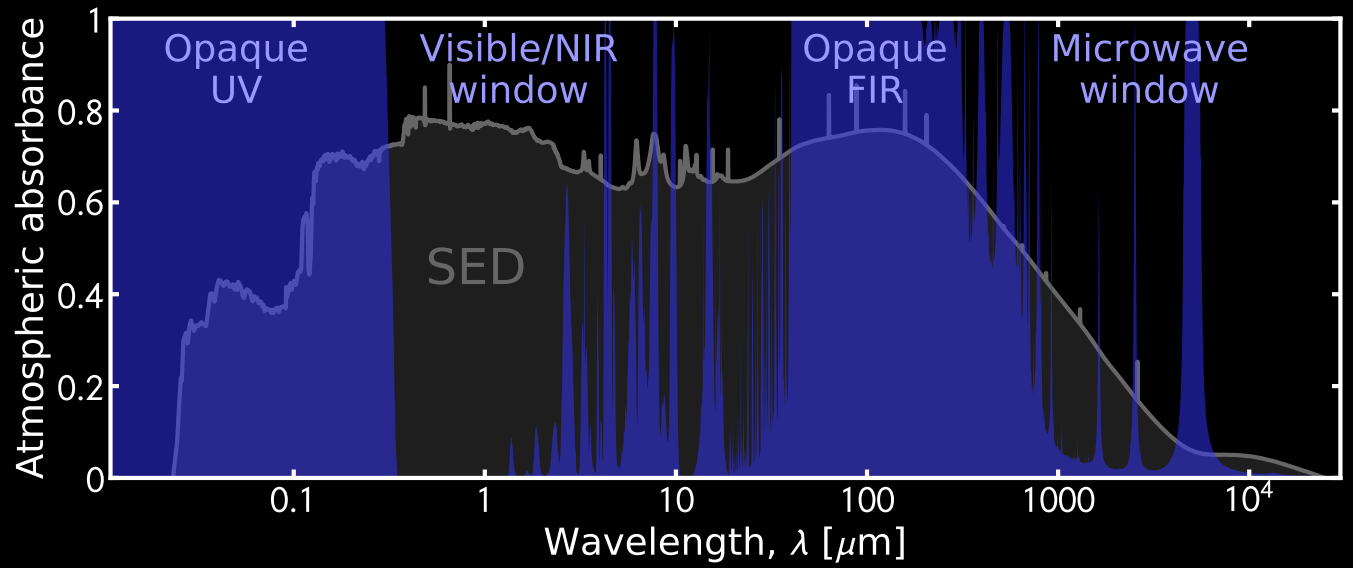

Altitude
Ground-based
visible telescope
Ground-based
radiotelescope


Opaque
UV
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window
Opaque
FIR
Microwave
window
SED
Atmospheric absorbance
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0.1
1
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100
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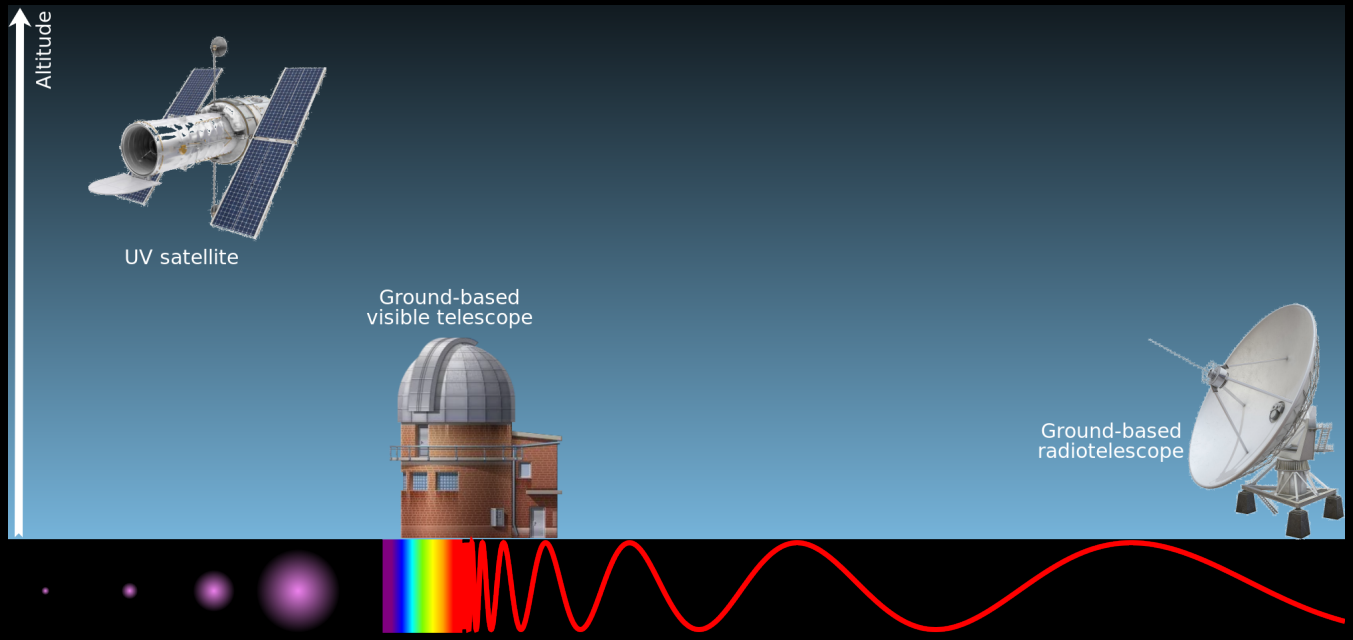
10^4
Wavelength, λ [μm]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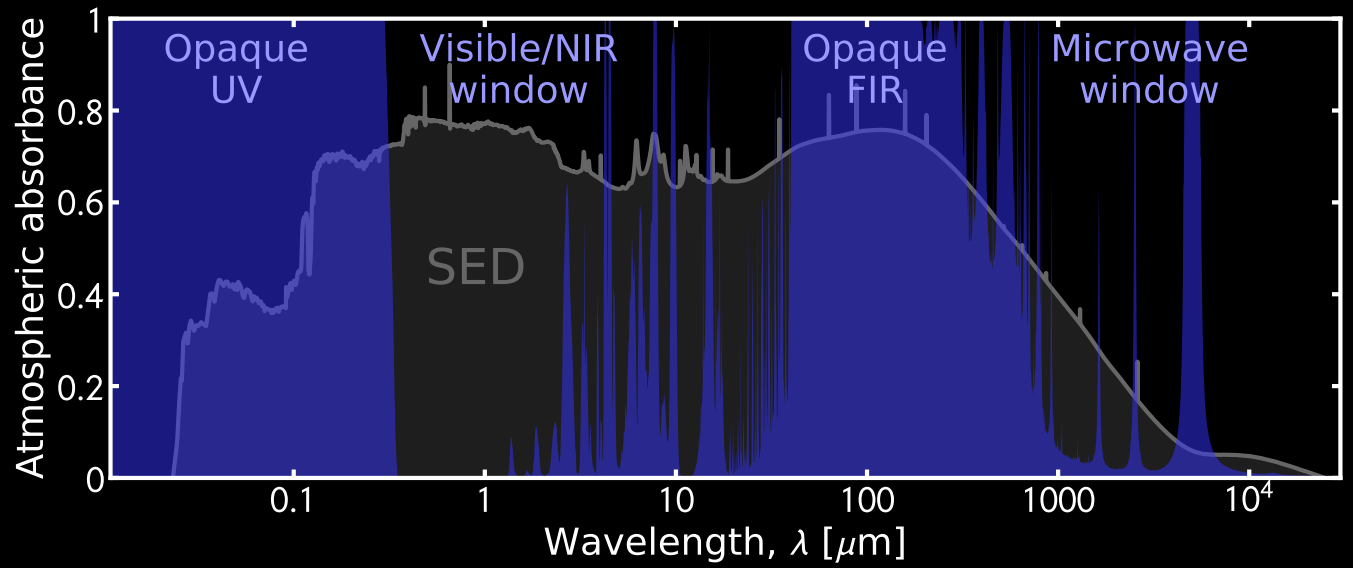
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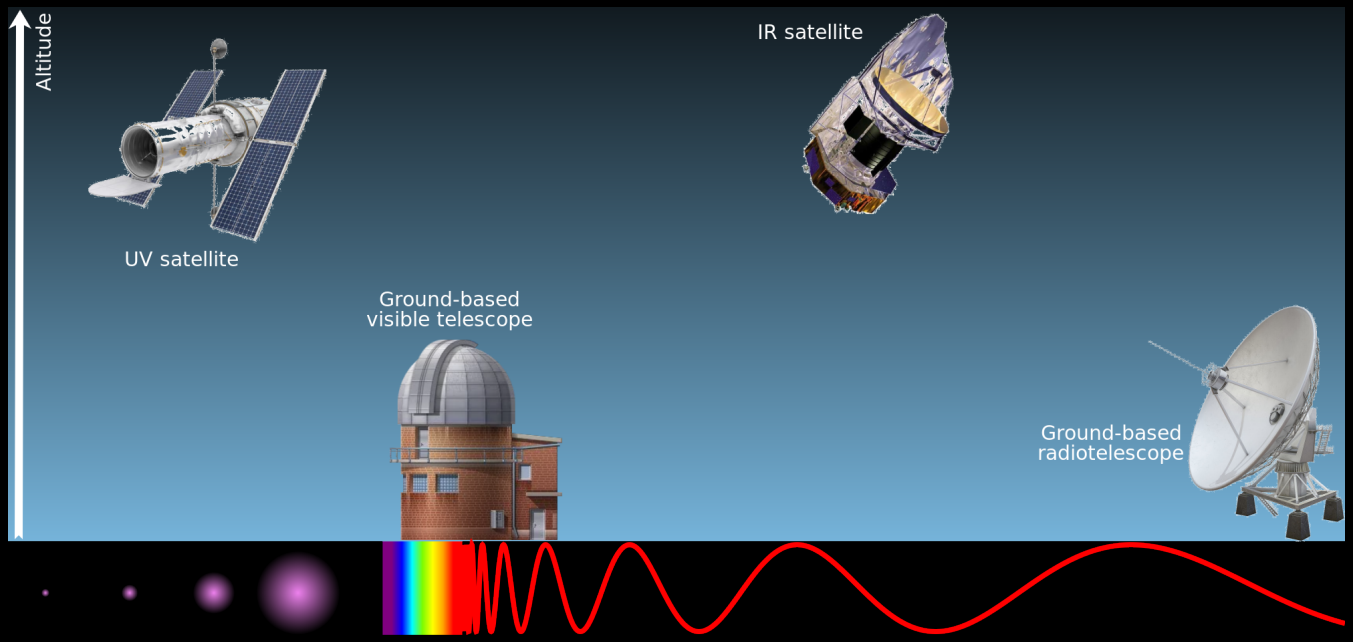
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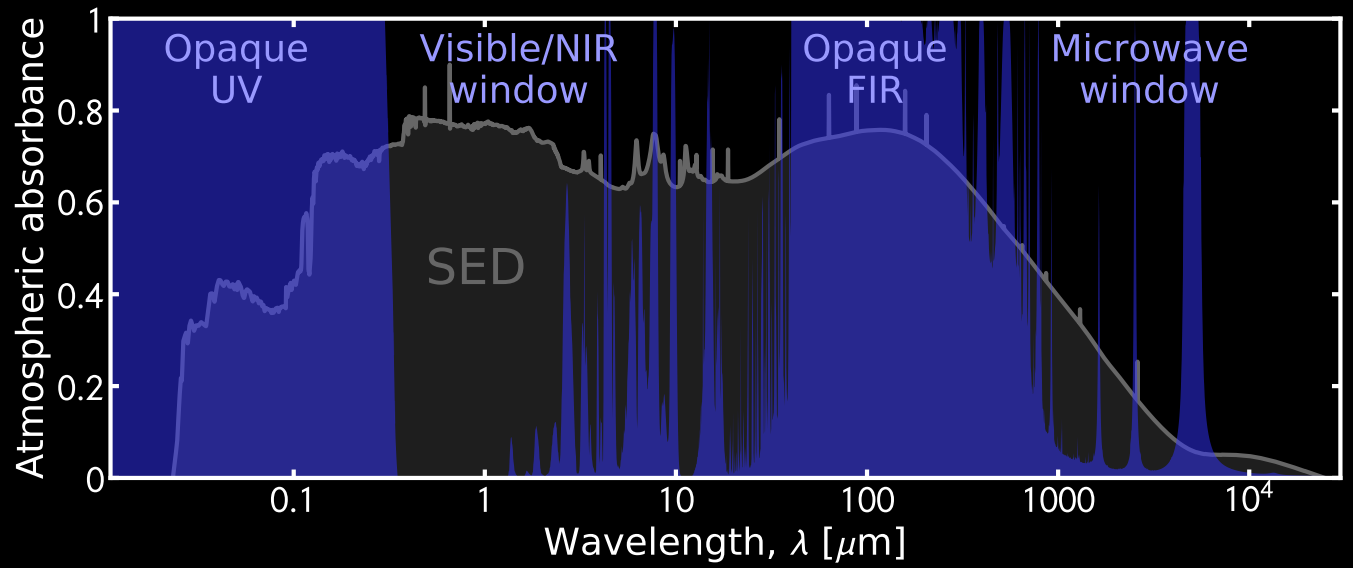
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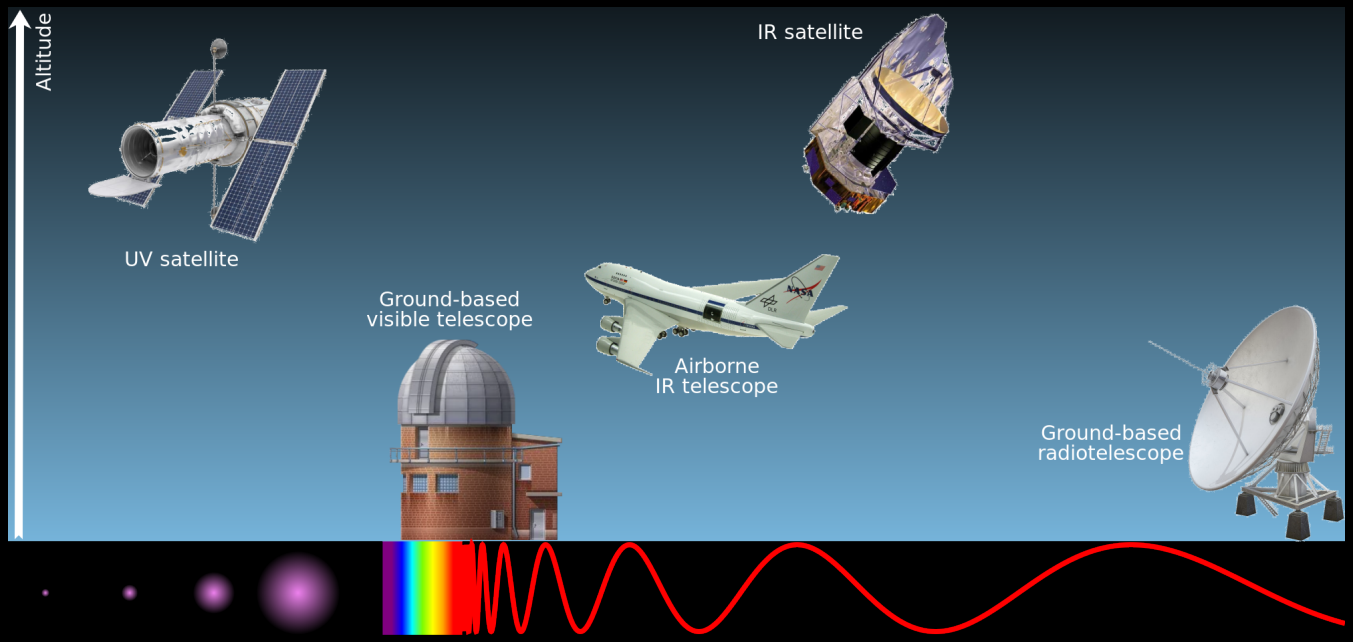
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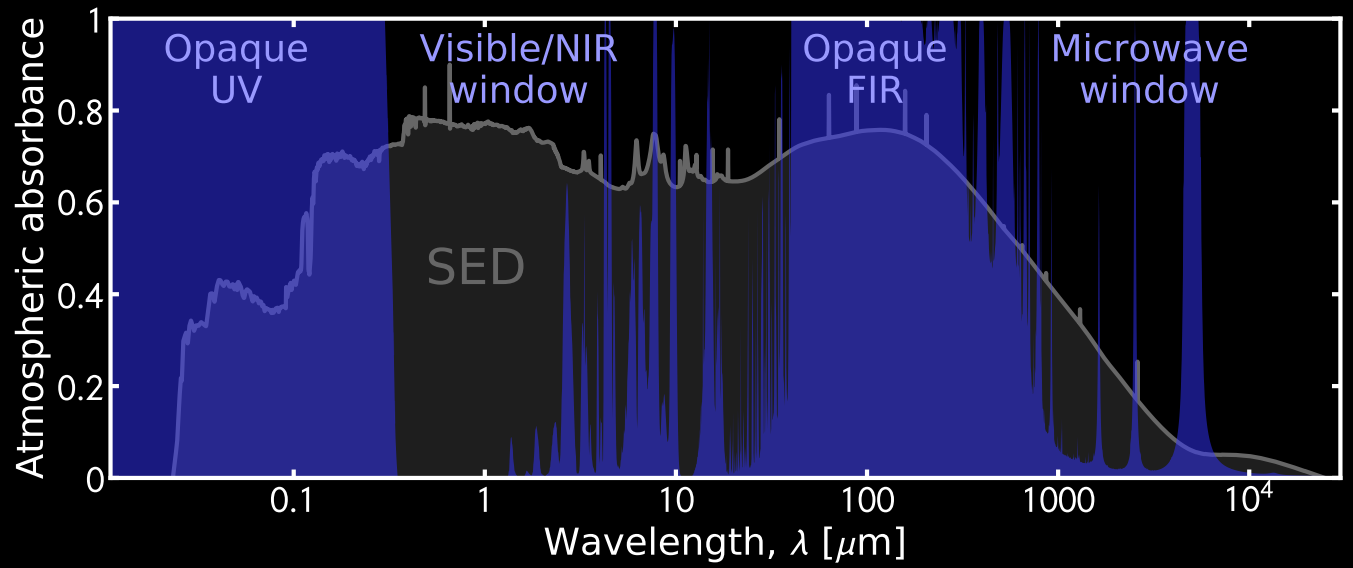
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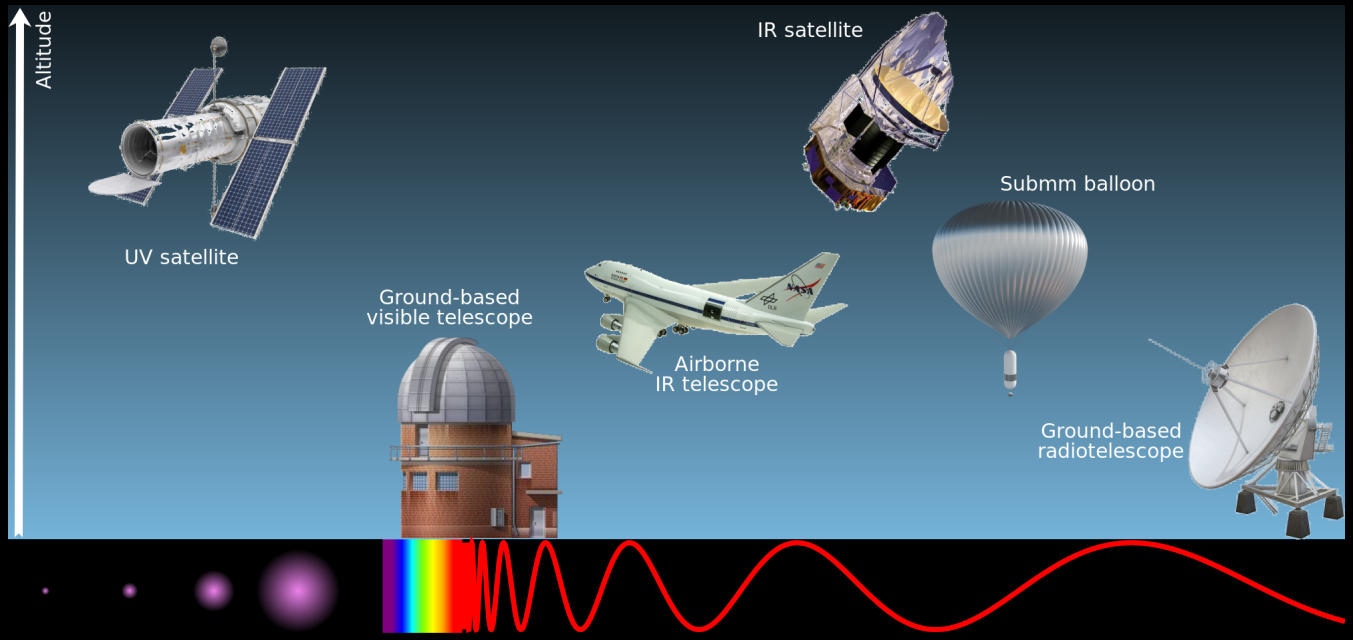
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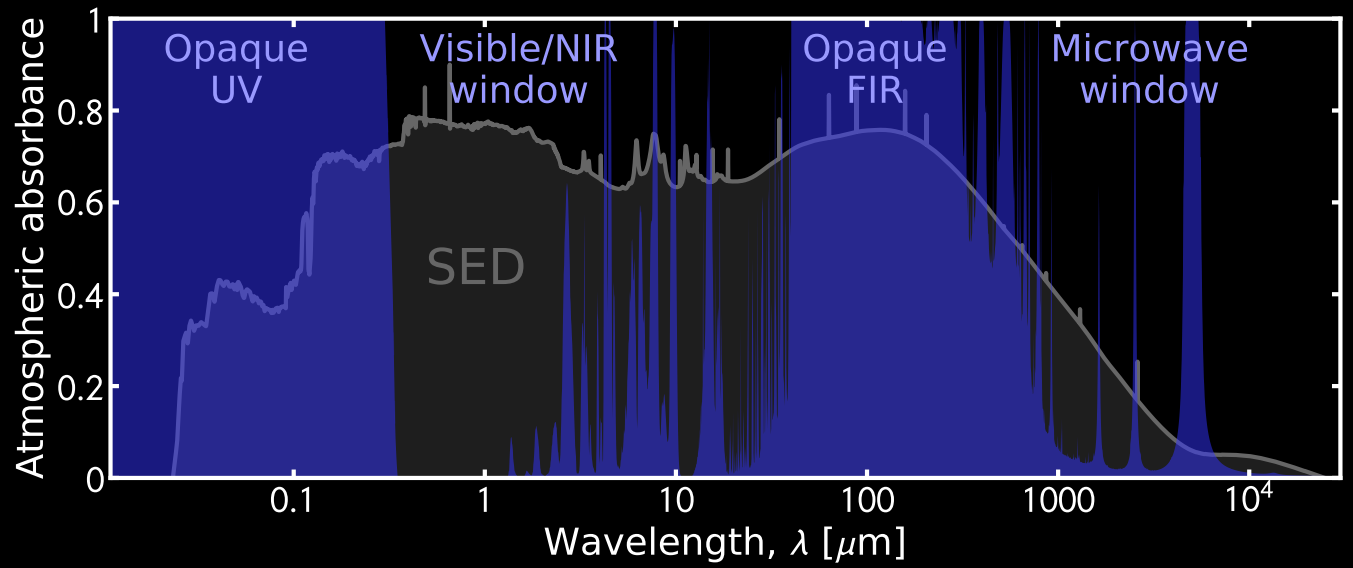
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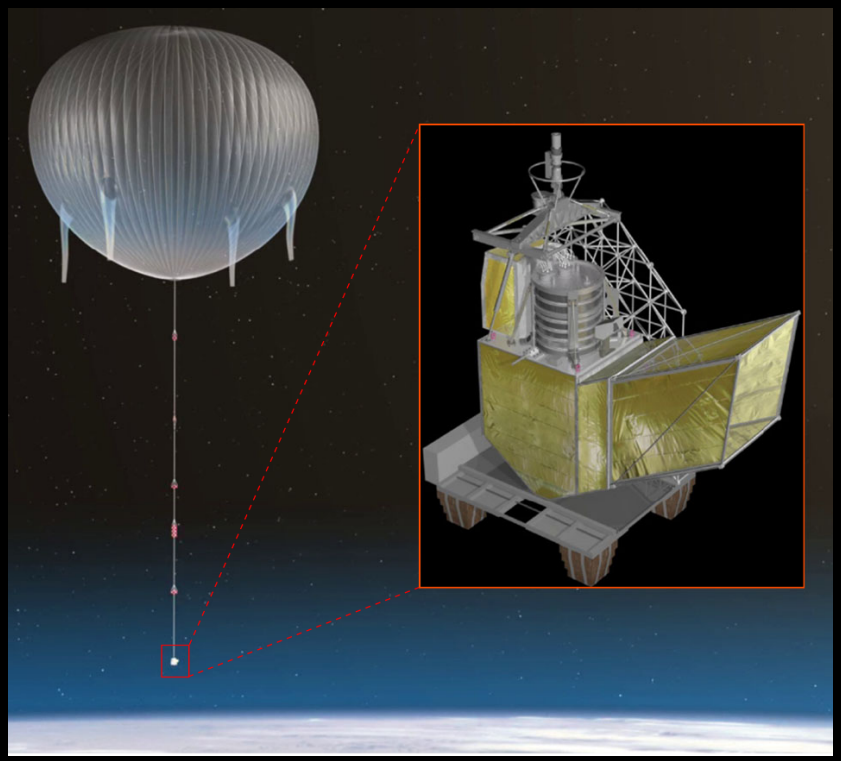

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Rockets can carry on instruments in a single sub-orbital flights (since 1967).

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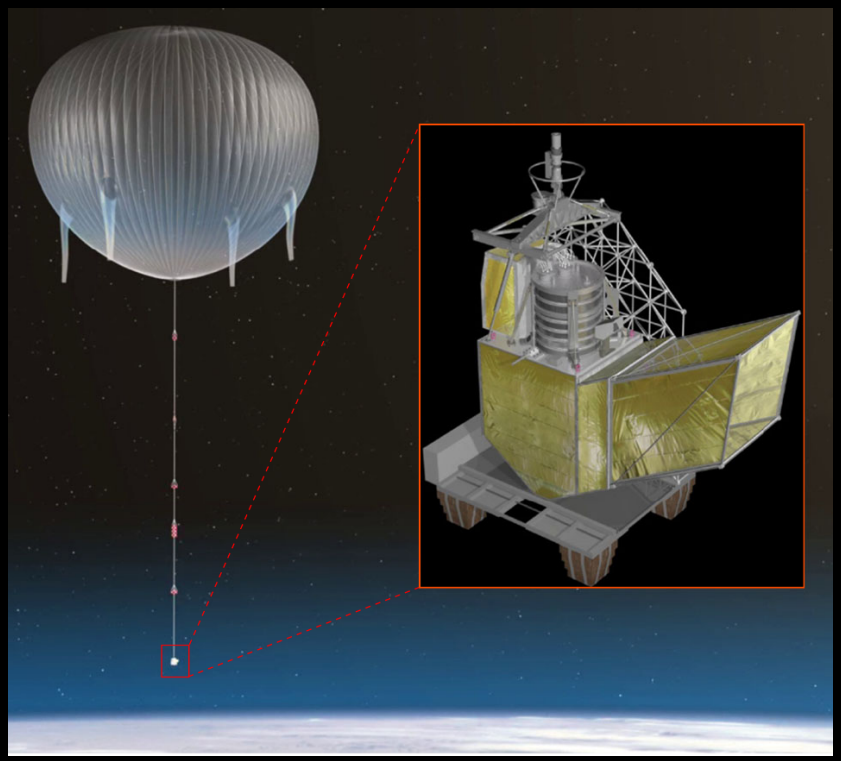

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(Pierre Auger Observatory; 2005-)

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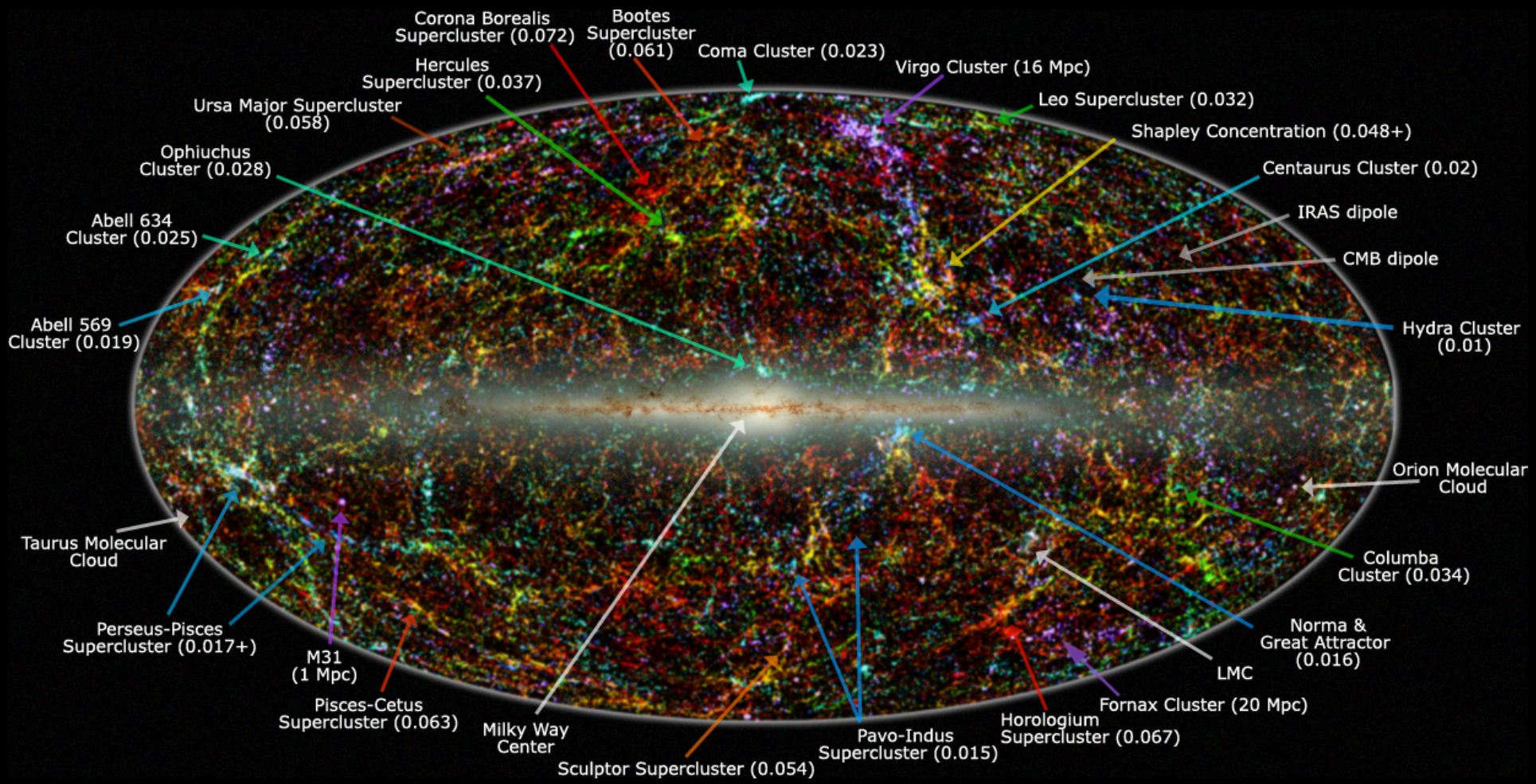
$\Rightarrow$ all these tracers are intercalibrated.

All sky Uranography:



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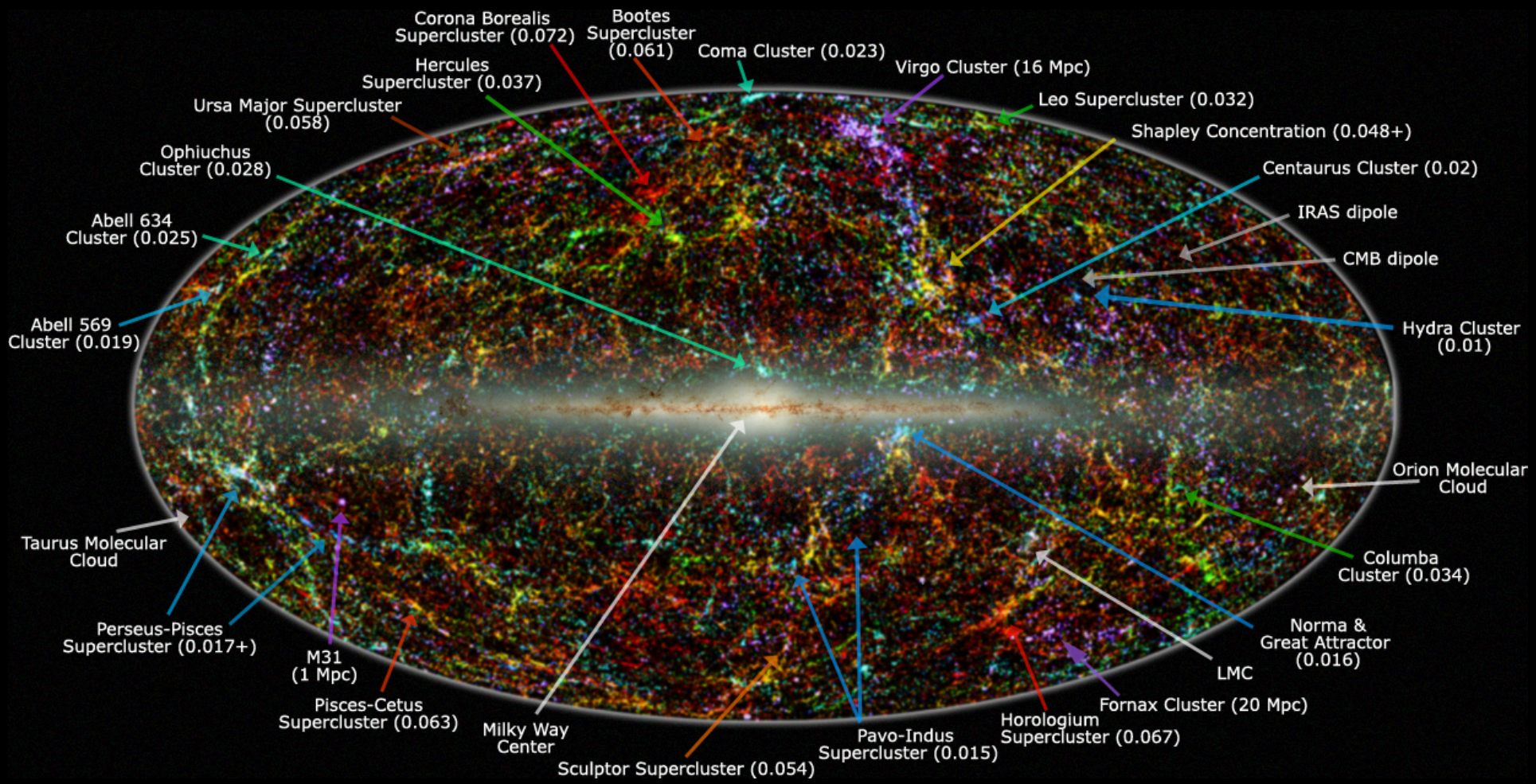

$\Rightarrow$ needs complex decomposition methods.

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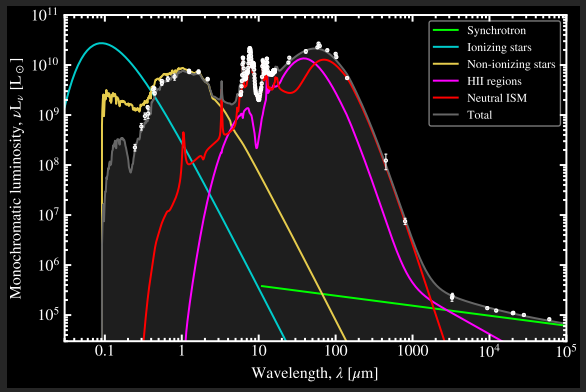

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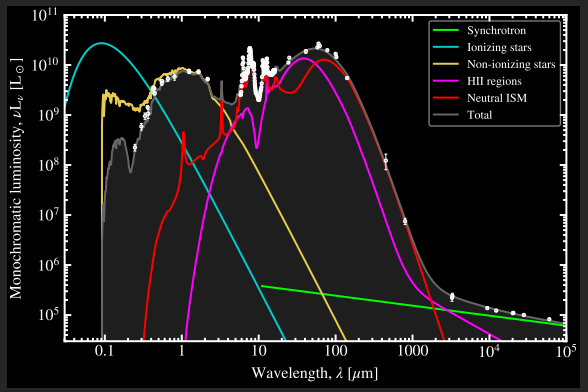

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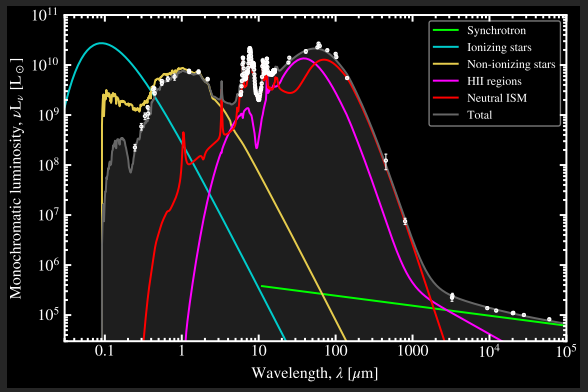

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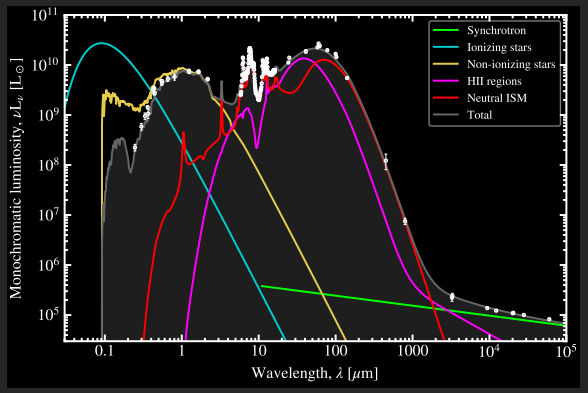

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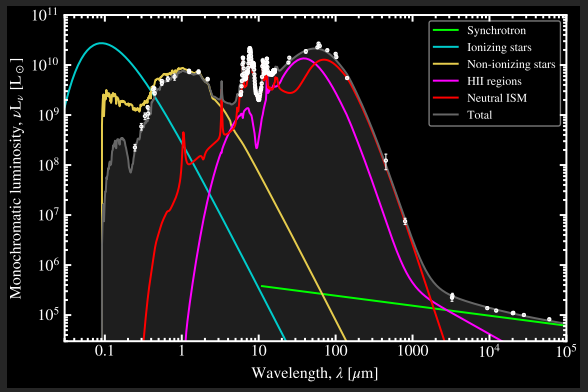

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$\simeq$ 80 new publications per week day.

TOC of the Talk

1. INTRODUCTION
2. AN HISTORICAL PERSPECTIVE
   - The first observations of the sky
   - Astronomy: celestial mechanics
   - Astrophysics: the advent of spectroscopy
   - The Universe as we know it today: from the Solar system to the Big Bang
3. METHODOLOGIES FOR THE EXPLORATION OF DISTANT SPACE
   - *In situ* exploration
   - The current astrophysical vectors of information
   - The electromagnetic spectrum & the different astrophysical processes it probes
   - The complexity of astrophysical measures
4. AN OVERVIEW OF CONTEMPORARY OPEN QUESTIONS & HOT TOPICS
   - How does the Solar system work? How dit it form?
   - What is the origin of stars & planet, and how do they evolve?
   - How do galaxies form, and how does the Universe evolve?
   - Do we understand extreme conditions in the Universe?
5. SUMMARY & CONCLUSION

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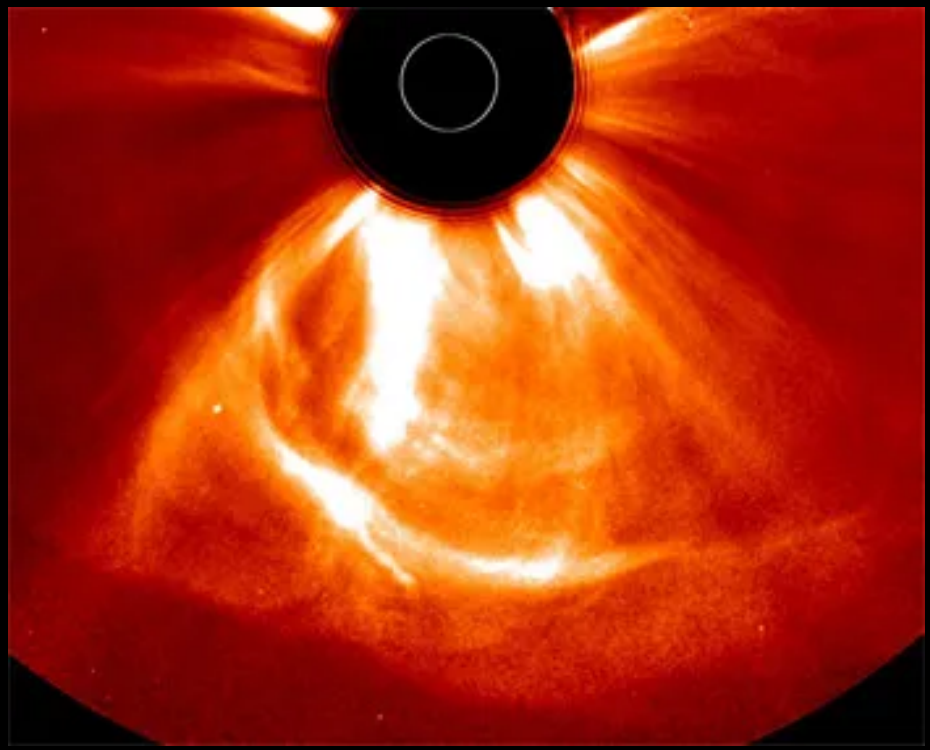

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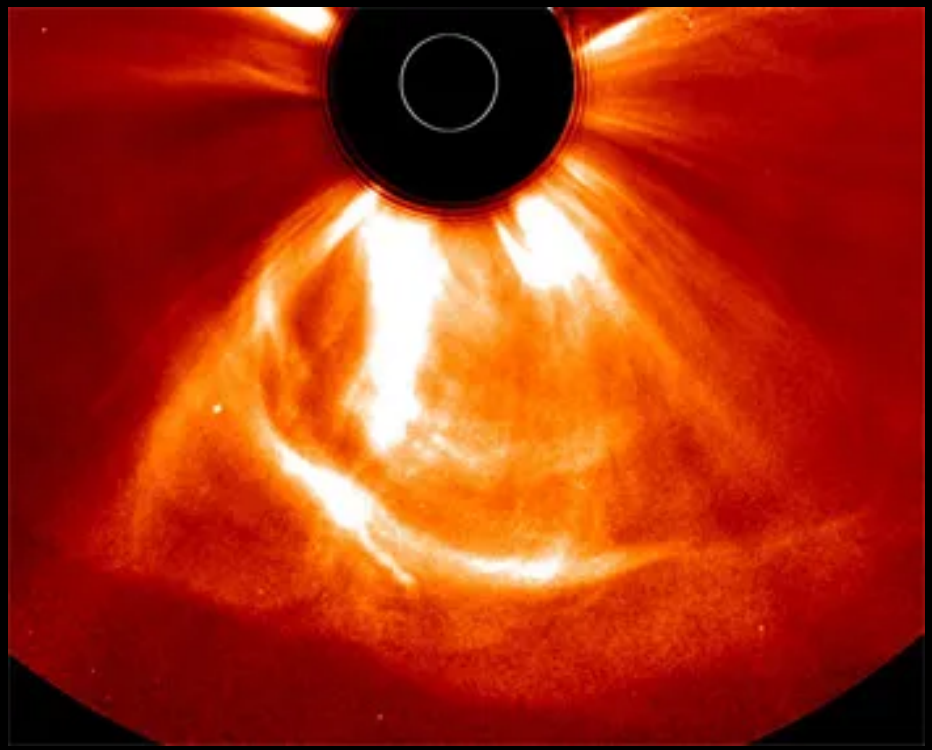

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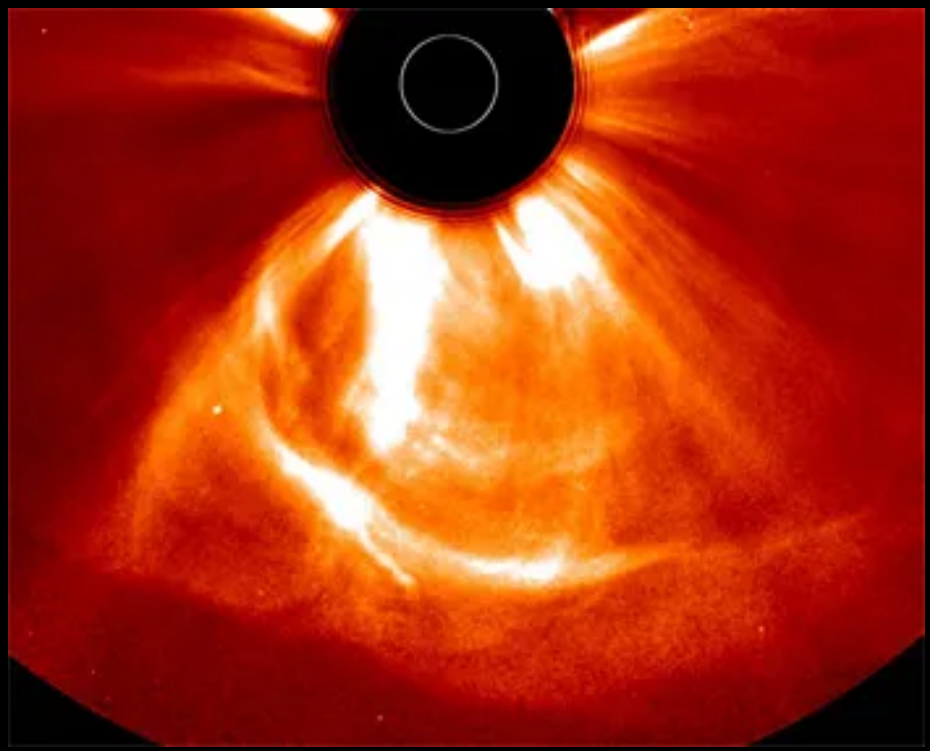

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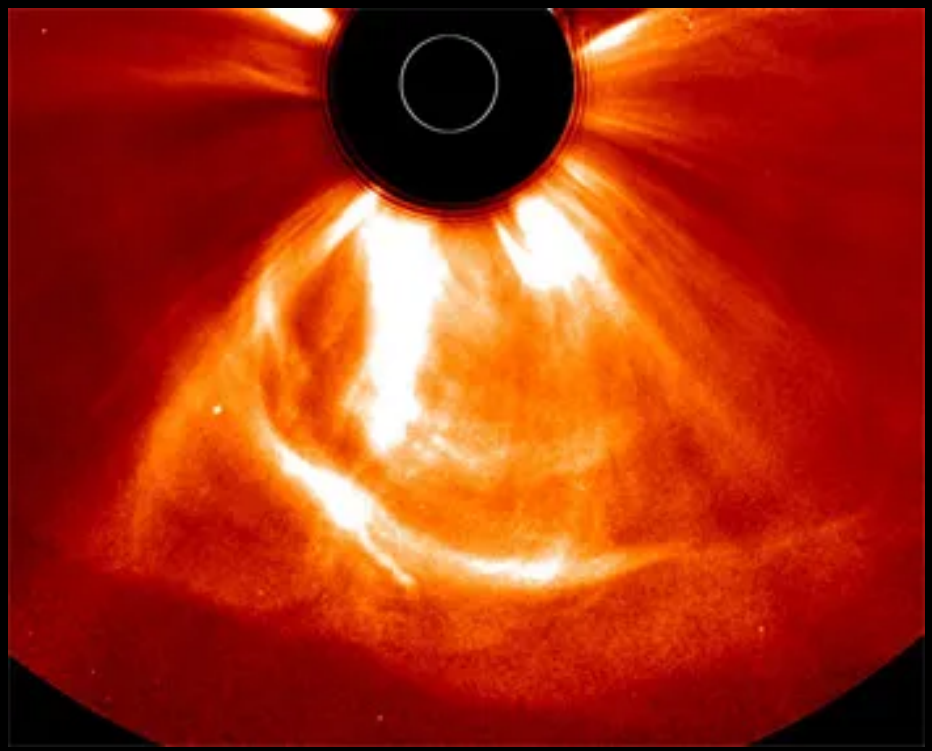

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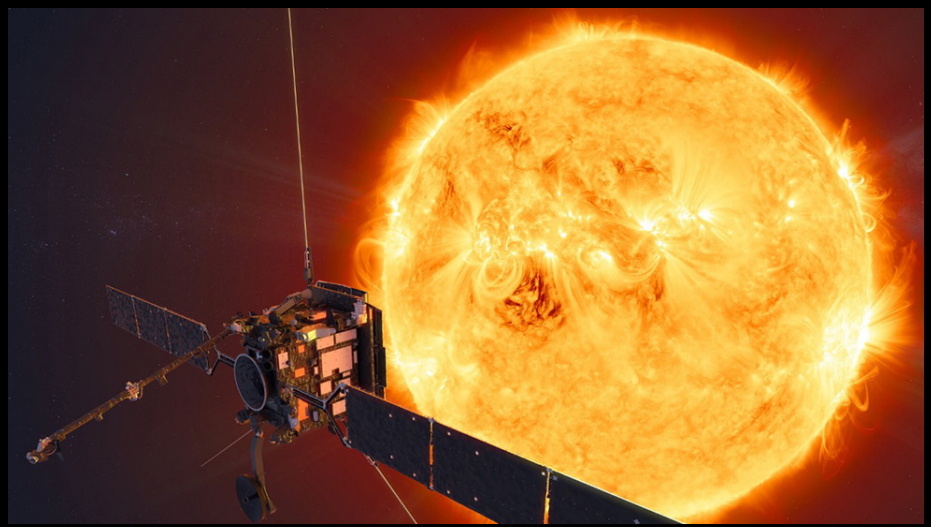
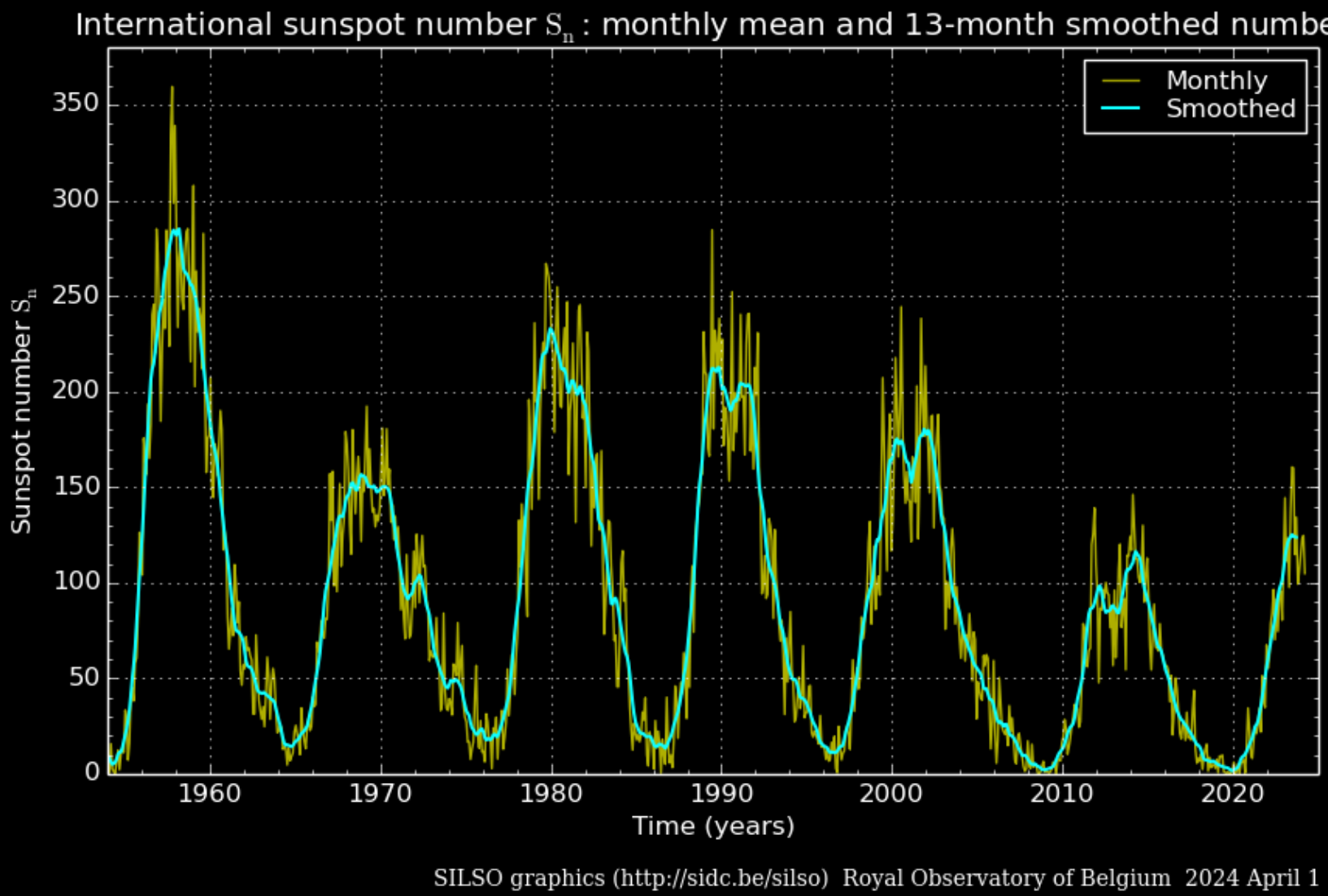


(Solar Orbiter, 2021-)

The 11 year Solar Cycle:



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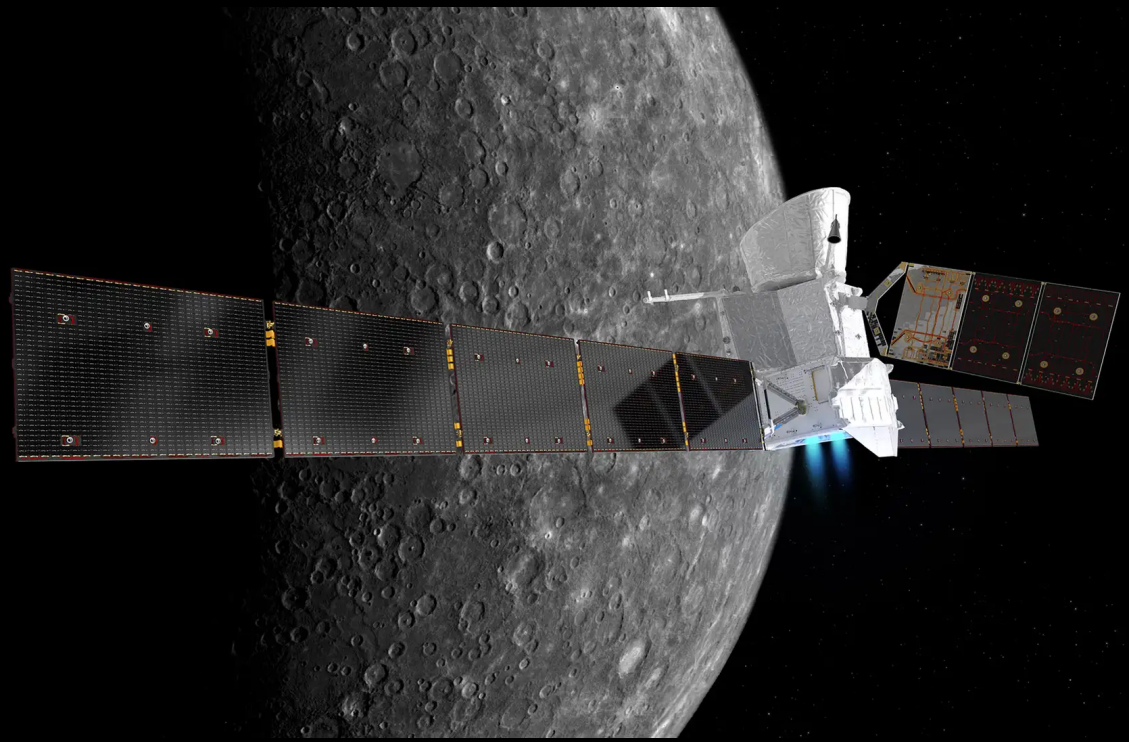

Mercury flybys
(BepiColombo, 2018-)

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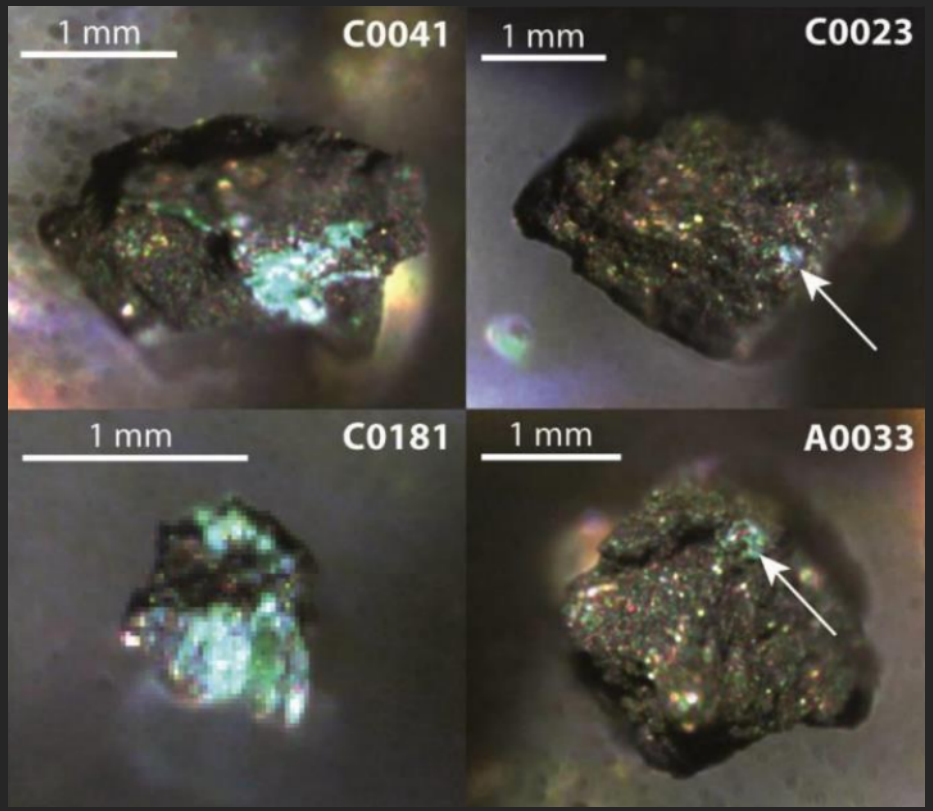

Laboratory study of returned samples from Ryugu (Loizeau *et al.*, 2023)

Habitability of “Ocean Worlds”

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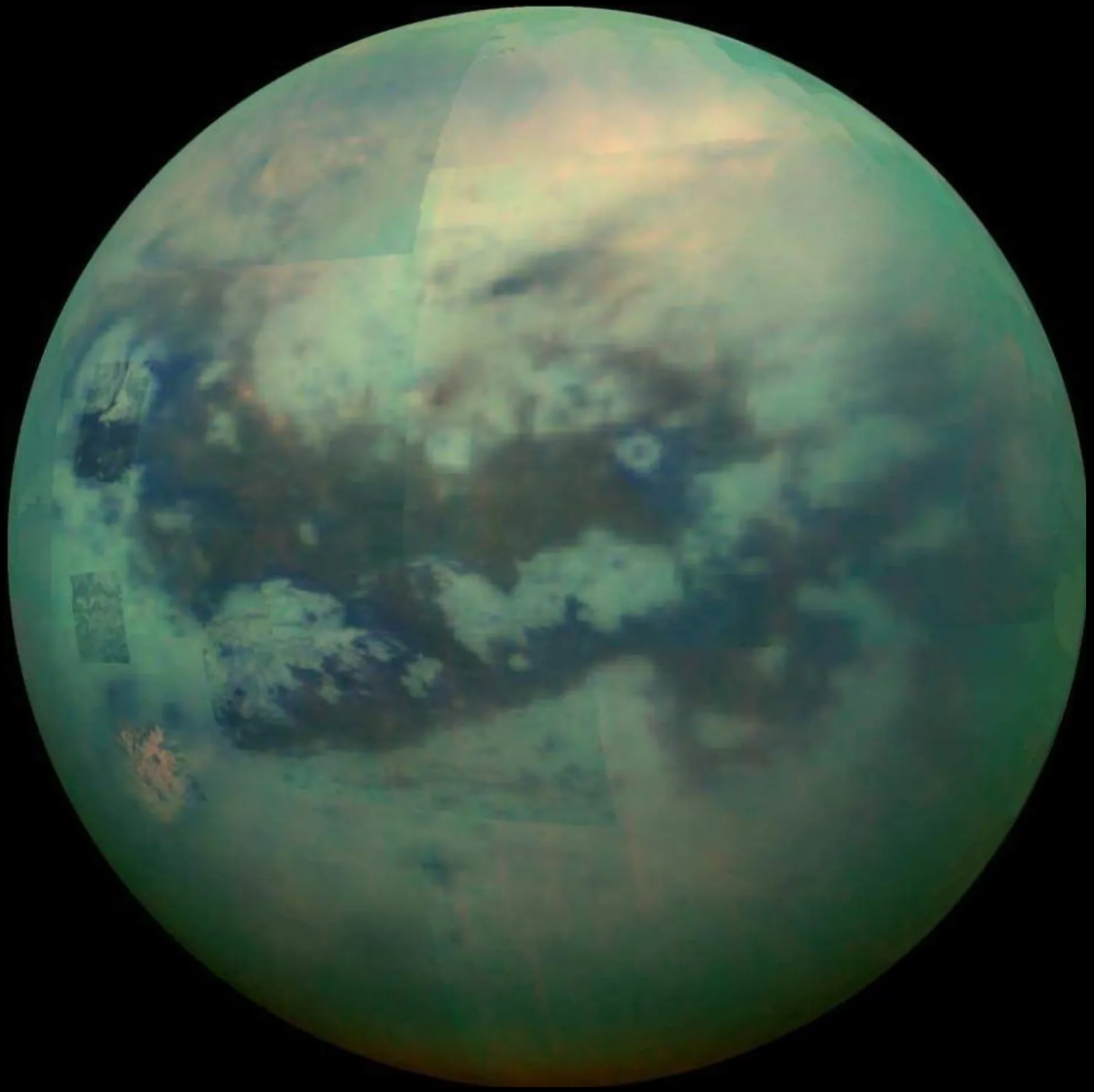
Satellites of Saturn: Titan.



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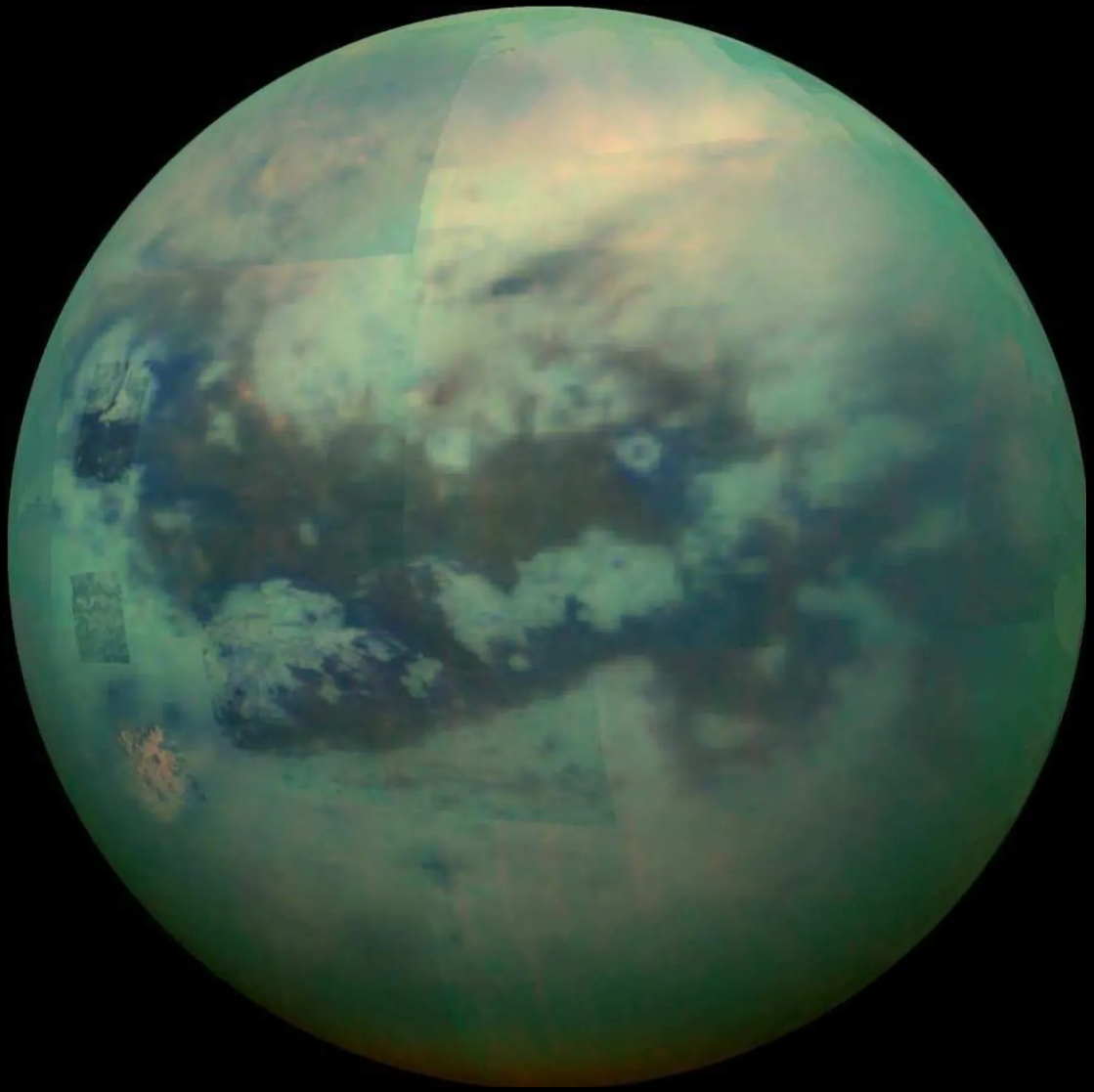

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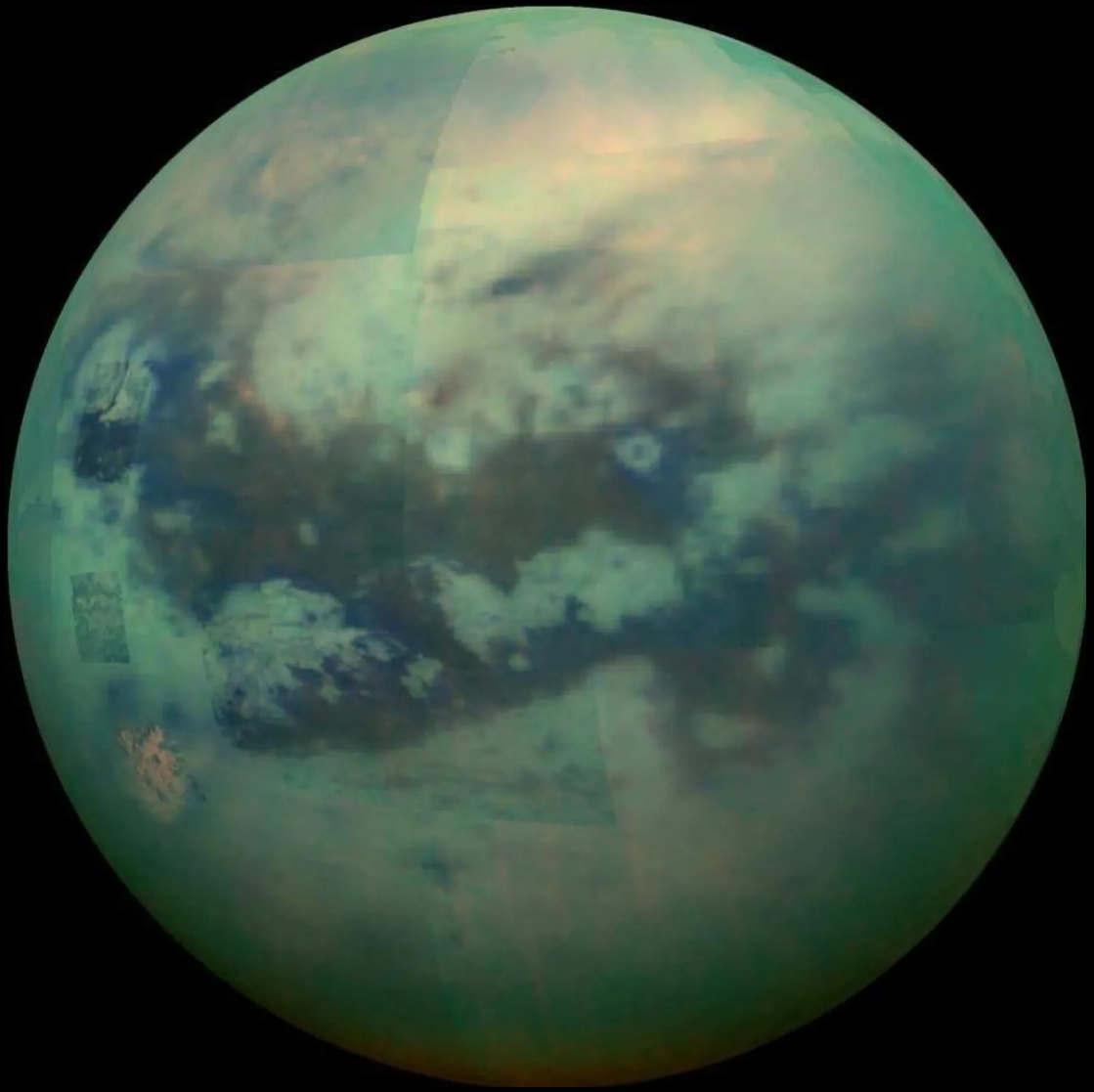

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Goals: finding organic molecules, presence of liquid water + understanding the chemical evolution of these environments.

JUICE, launched in 2023

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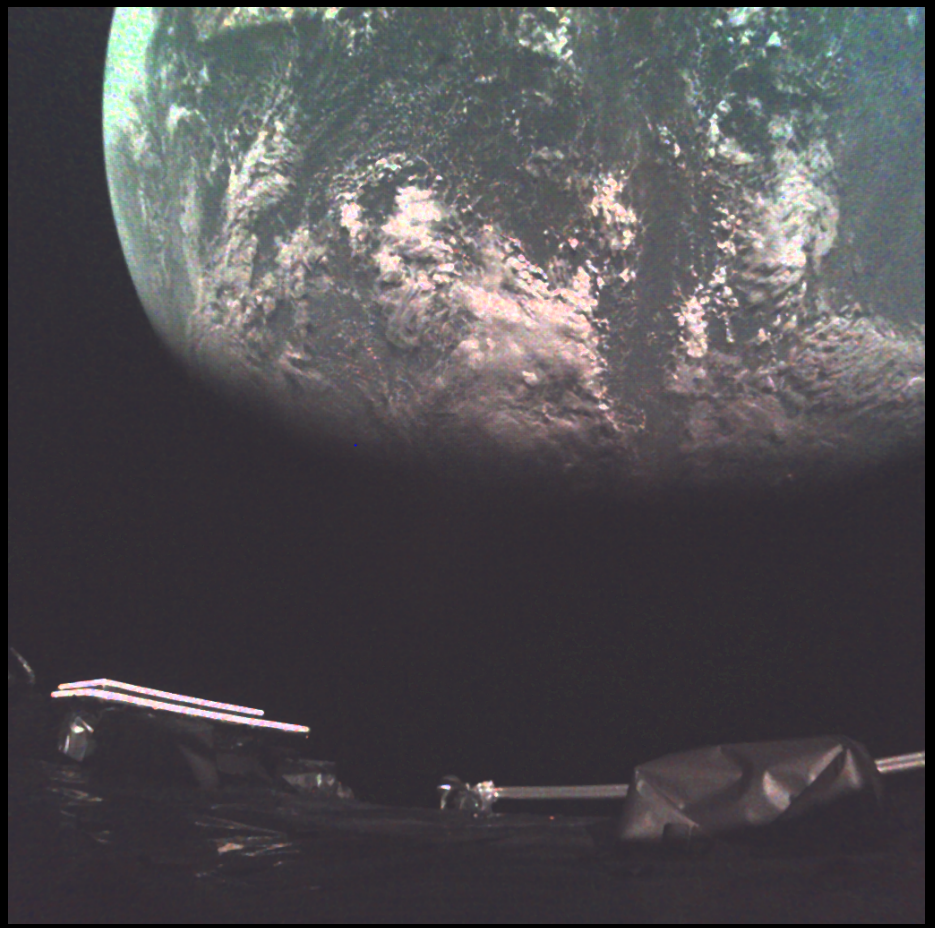
(The Earth seen from JUICE, 2023)



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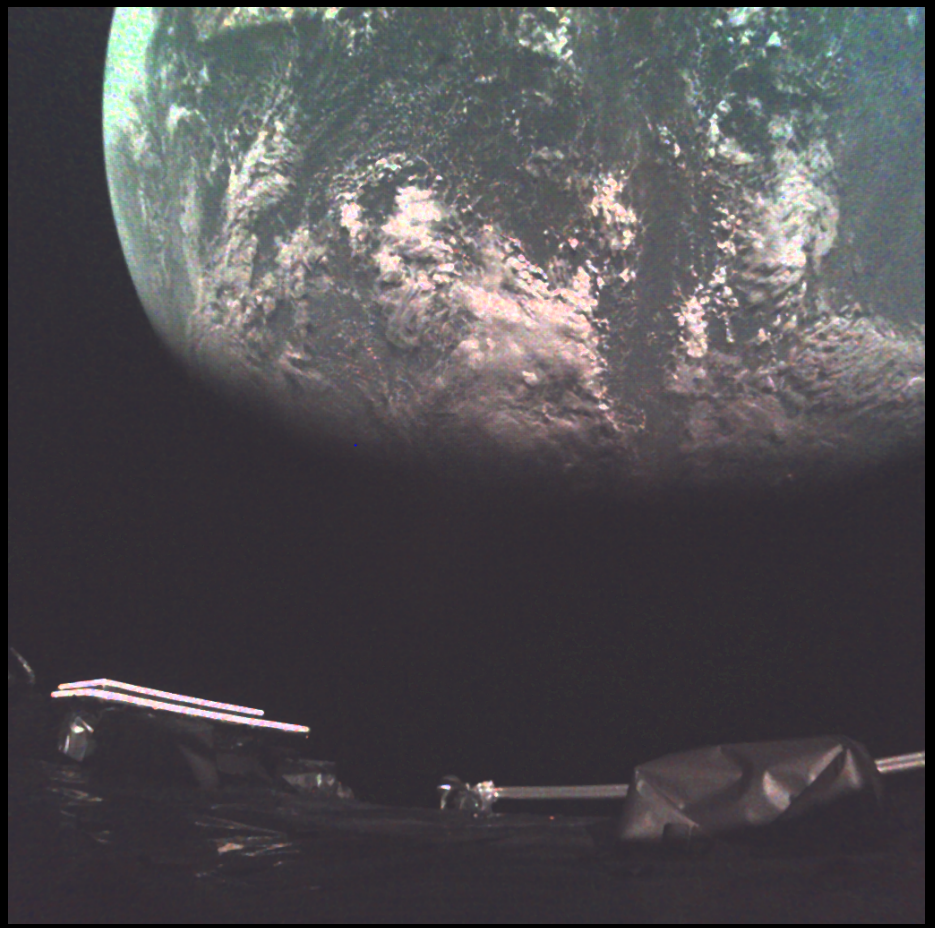

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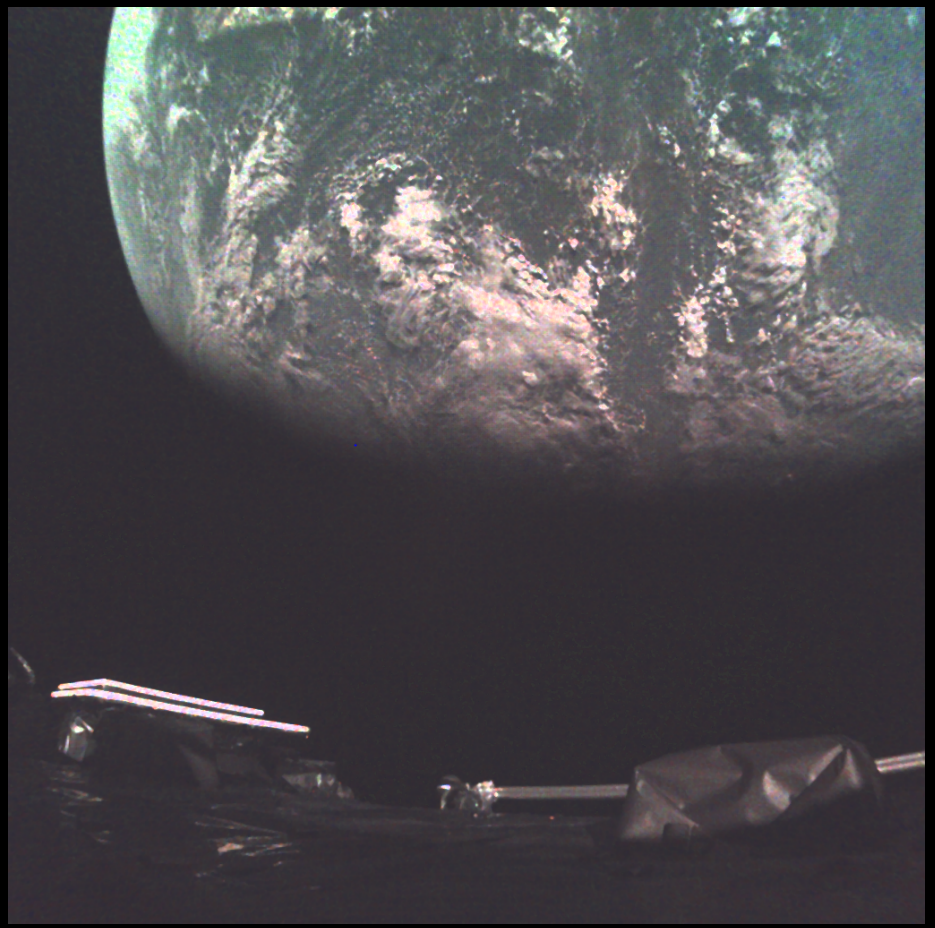

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- Look for potential habitability.

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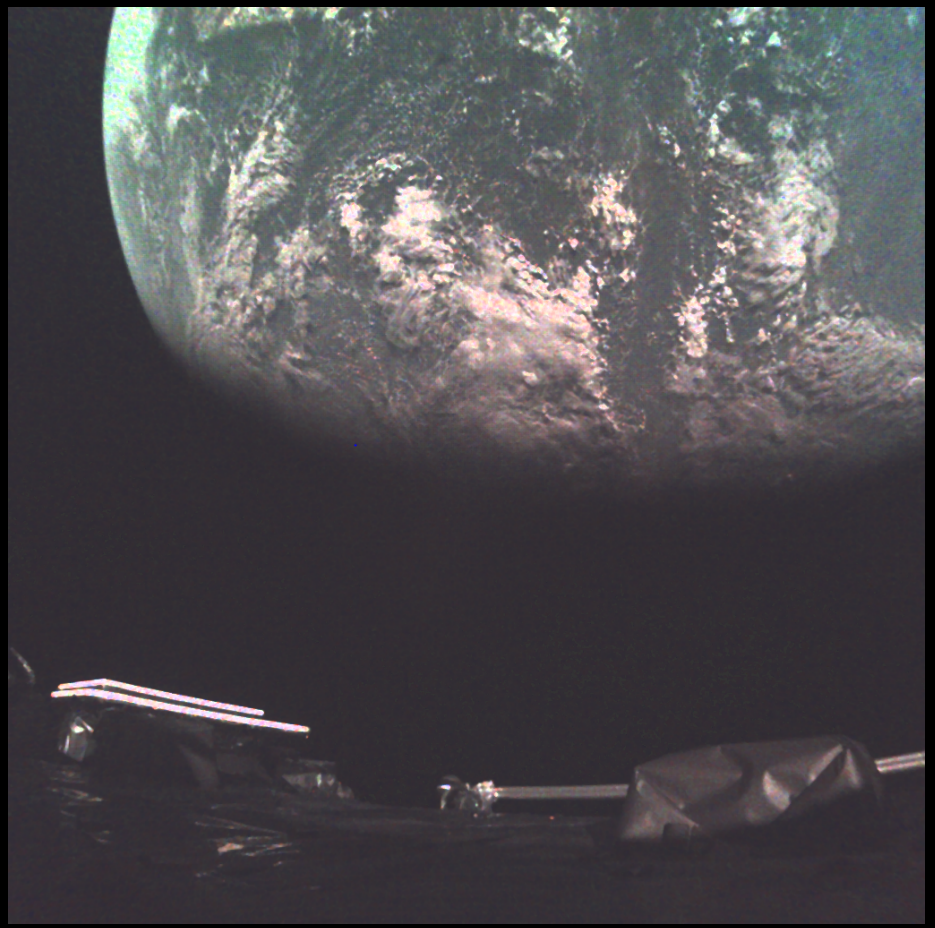
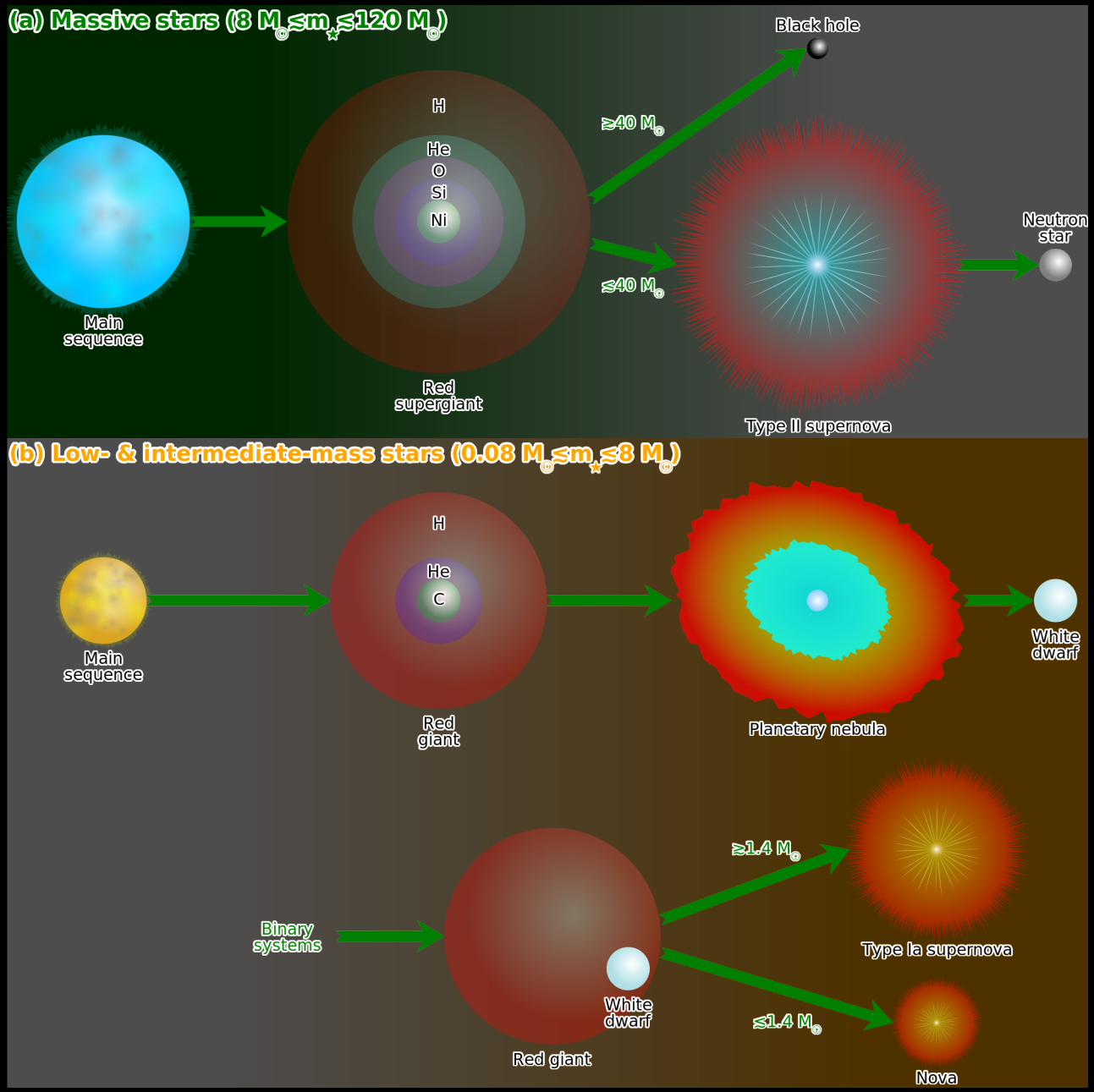
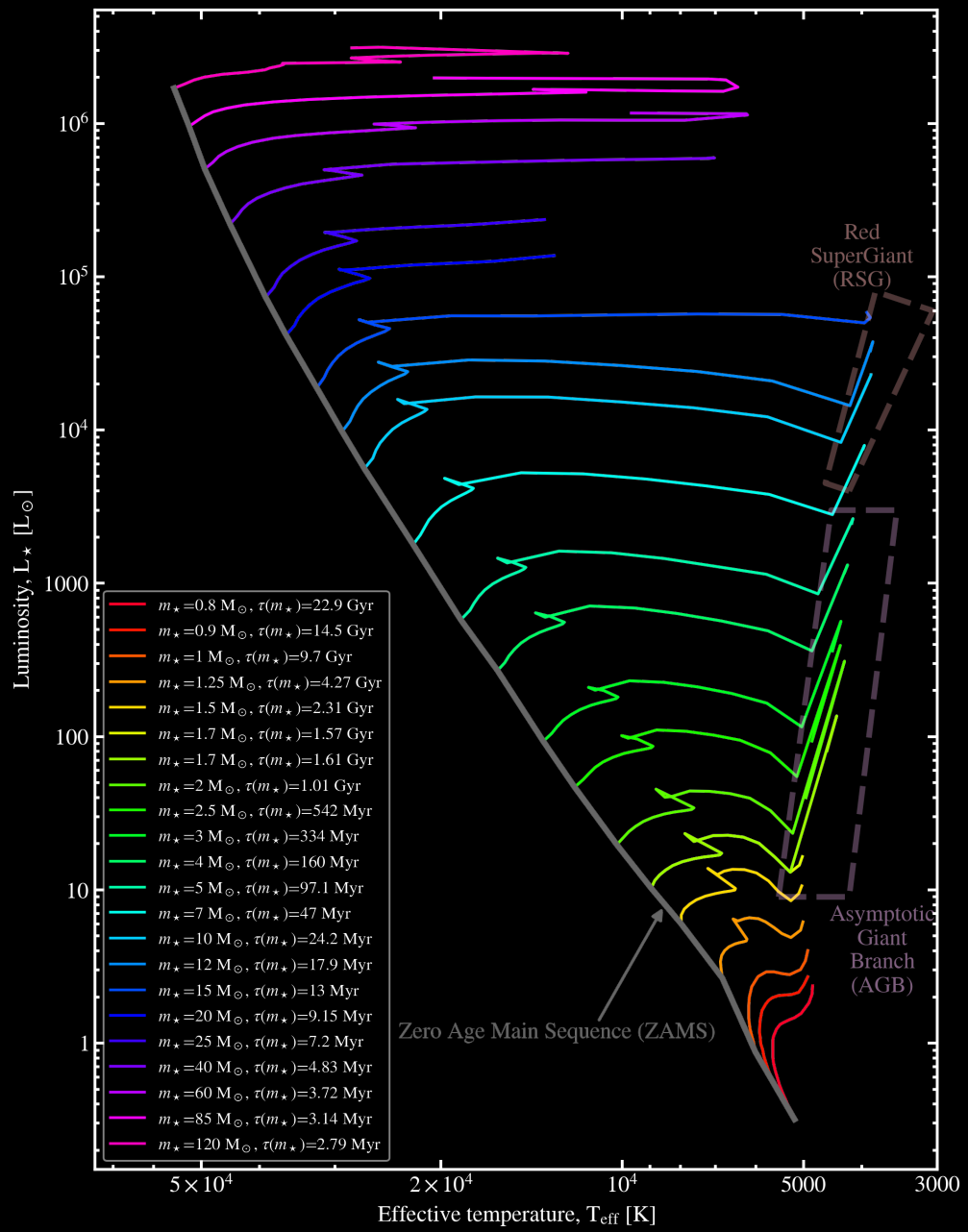



(a) Massive stars (8 M⊙≤m⋆≤120 M⊙)
Black hole
H
He
O
Si
Ni
≥40 M⊙
≤40 M⊙
Neutron star
Main sequence
Red supergiant
Type II supernova
(b) Low- & intermediate-mass stars (0.08 M⊙≤m⋆≤8 M⊙)
H
He
C
Main sequence
Red giant
Planetary nebula
White dwarf
≥1.4 M⊙
Binary systems
White dwarf
Type Ia supernova
≤1.4 M⊙
Red giant
Nova


Luminosity, L⋆ [L⊙]
Effective temperature, Teff [K]
Red SuperGiant (RSG)
Asymptotic Giant Branch (AGB)
Zero Age Main Sequence (ZAMS)
m⋆=0.8 M⊙, τ(m⋆)=22.9 Gyr
m⋆=0.9 M⊙, τ(m⋆)=14.5 Gyr
m⋆=1 M⊙, τ(m⋆)=9.7 Gyr
m⋆=1.25 M⊙, τ(m⋆)=4.27 Gyr
m⋆=1.5 M⊙, τ(m⋆)=2.31 Gyr
m⋆=1.7 M⊙, τ(m⋆)=1.57 Gyr
m⋆=1.7 M⊙, τ(m⋆)=1.61 Gyr
m⋆=2 M⊙, τ(m⋆)=1.01 Gyr
m⋆=2.5 M⊙, τ(m⋆)=542 Myr
m⋆=3 M⊙, τ(m⋆)=334 Myr
m⋆=4 M⊙, τ(m⋆)=160 Myr
m⋆=5 M⊙, τ(m⋆)=97.1 Myr
m⋆=7 M⊙, τ(m⋆)=47 Myr
m⋆=10 M⊙, τ(m⋆)=24.2 Myr
m⋆=12 M⊙, τ(m⋆)=17.9 Myr
m⋆=15 M⊙, τ(m⋆)=13 Myr
m⋆=20 M⊙, τ(m⋆)=9.15 Myr
m⋆=25 M⊙, τ(m⋆)=7.2 Myr
m⋆=40 M⊙, τ(m⋆)=4.83 Myr
m⋆=60 M⊙, τ(m⋆)=3.72 Myr
m⋆=85 M⊙, τ(m⋆)=3.14 Myr
m⋆=120 M⊙, τ(m⋆)=2.79 Myr

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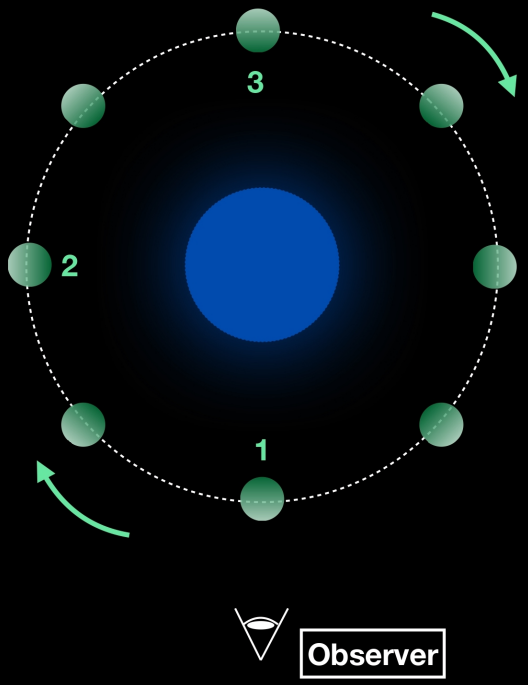

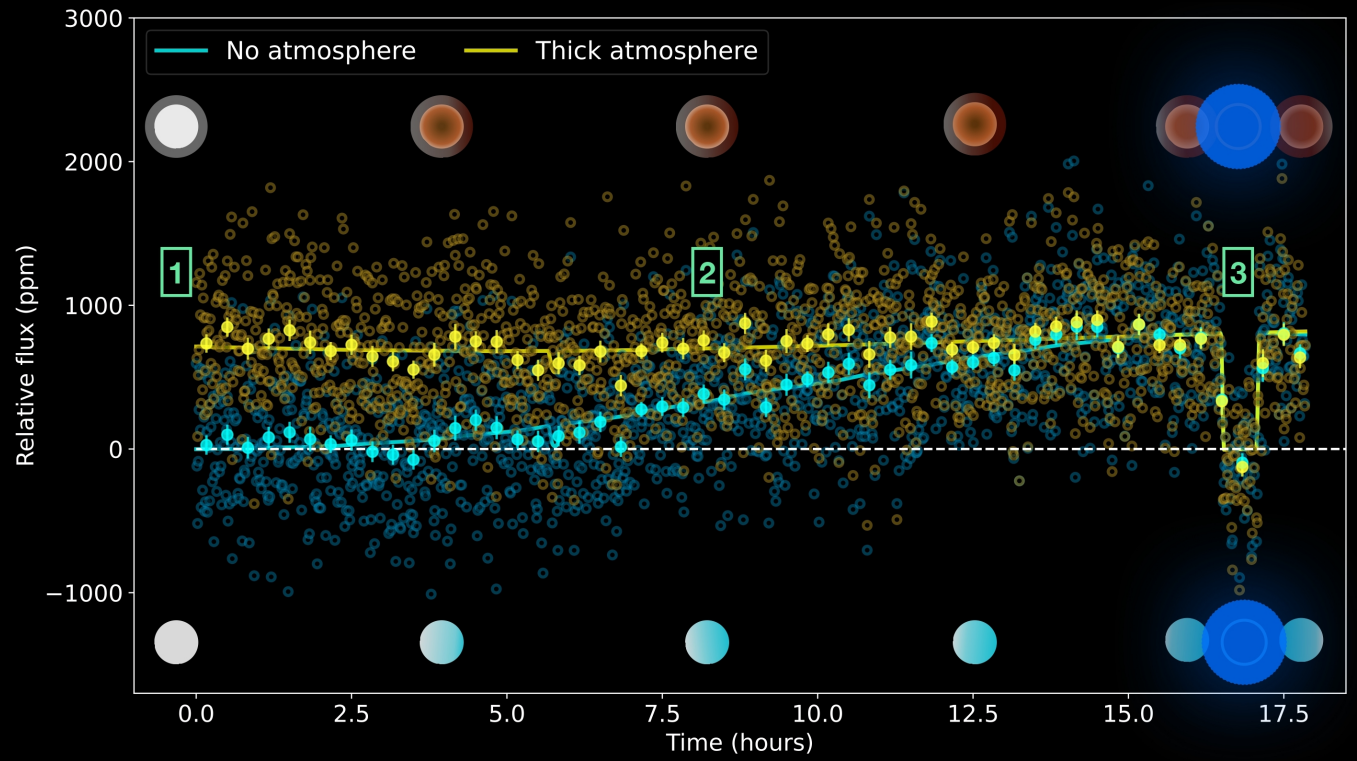

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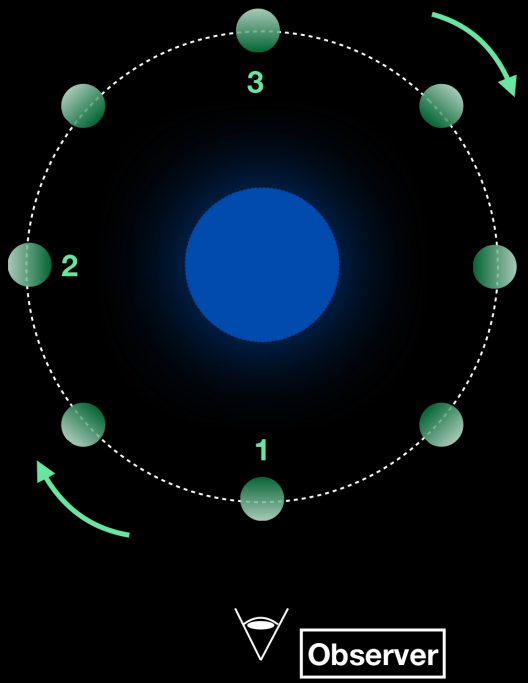

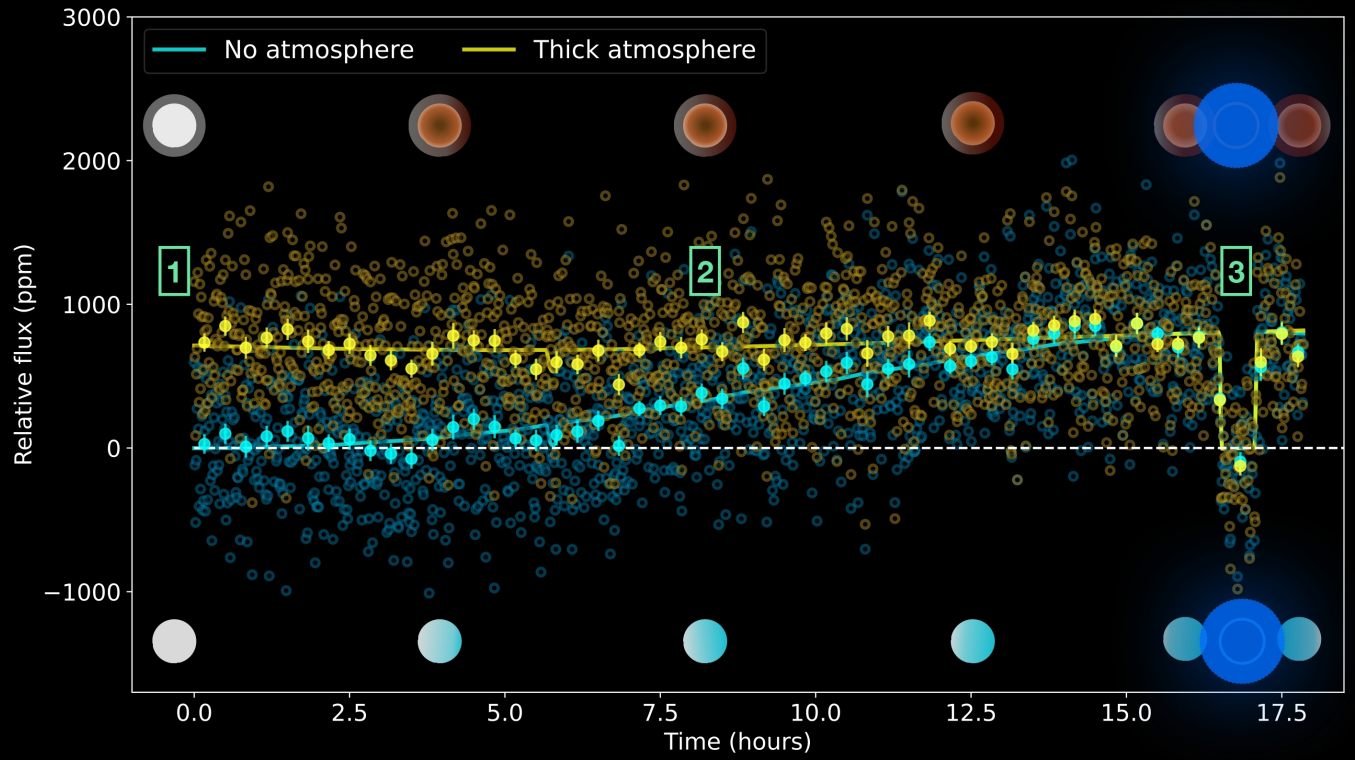

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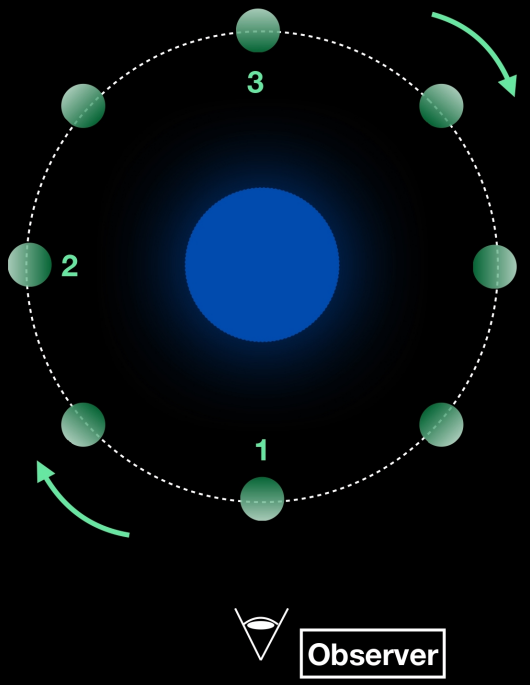
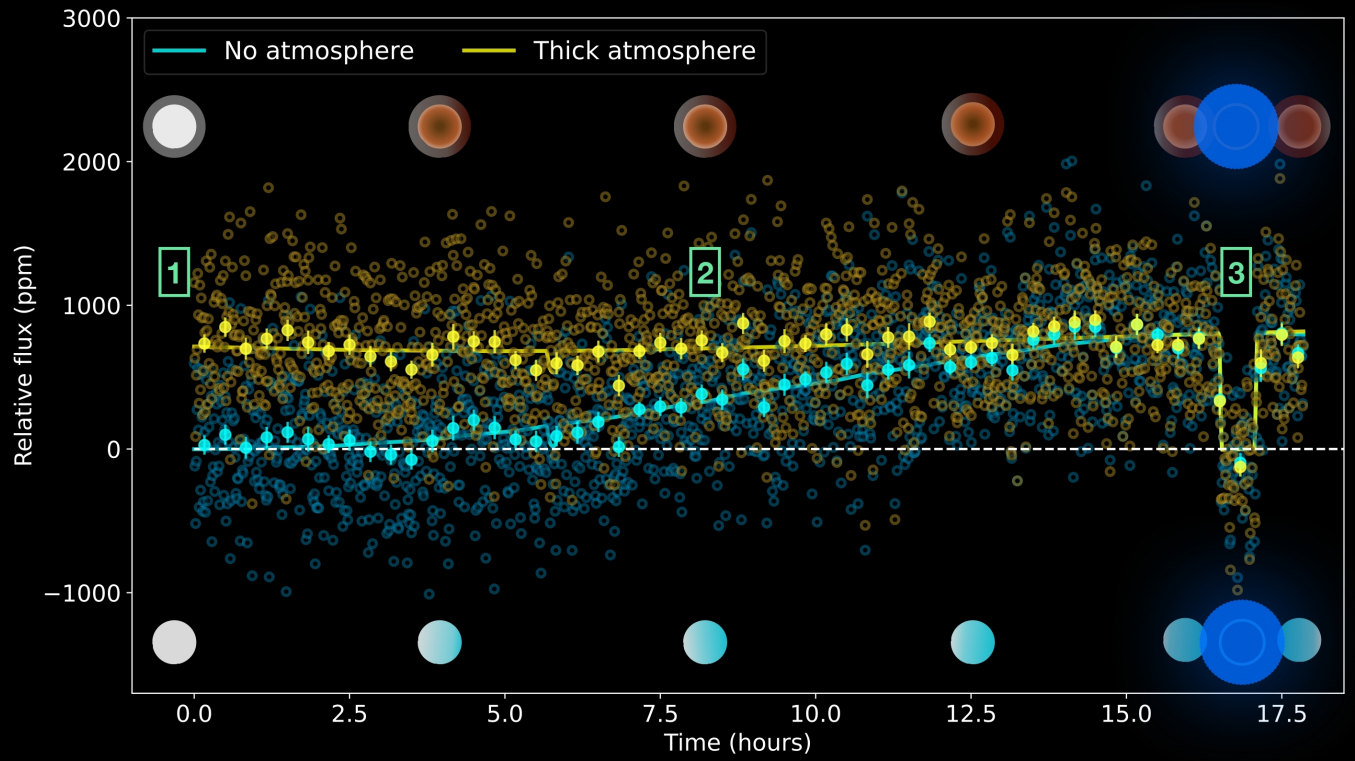
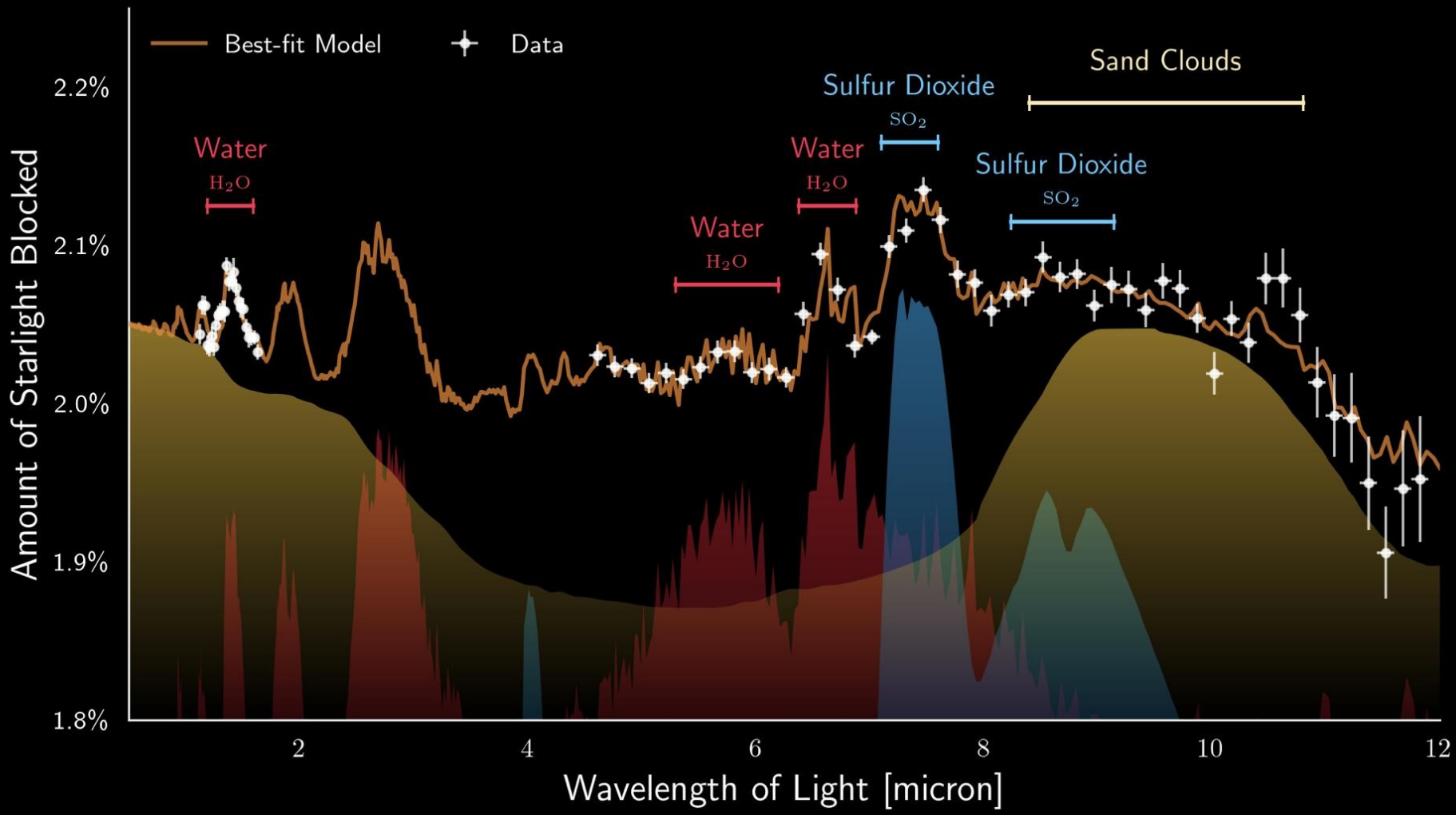
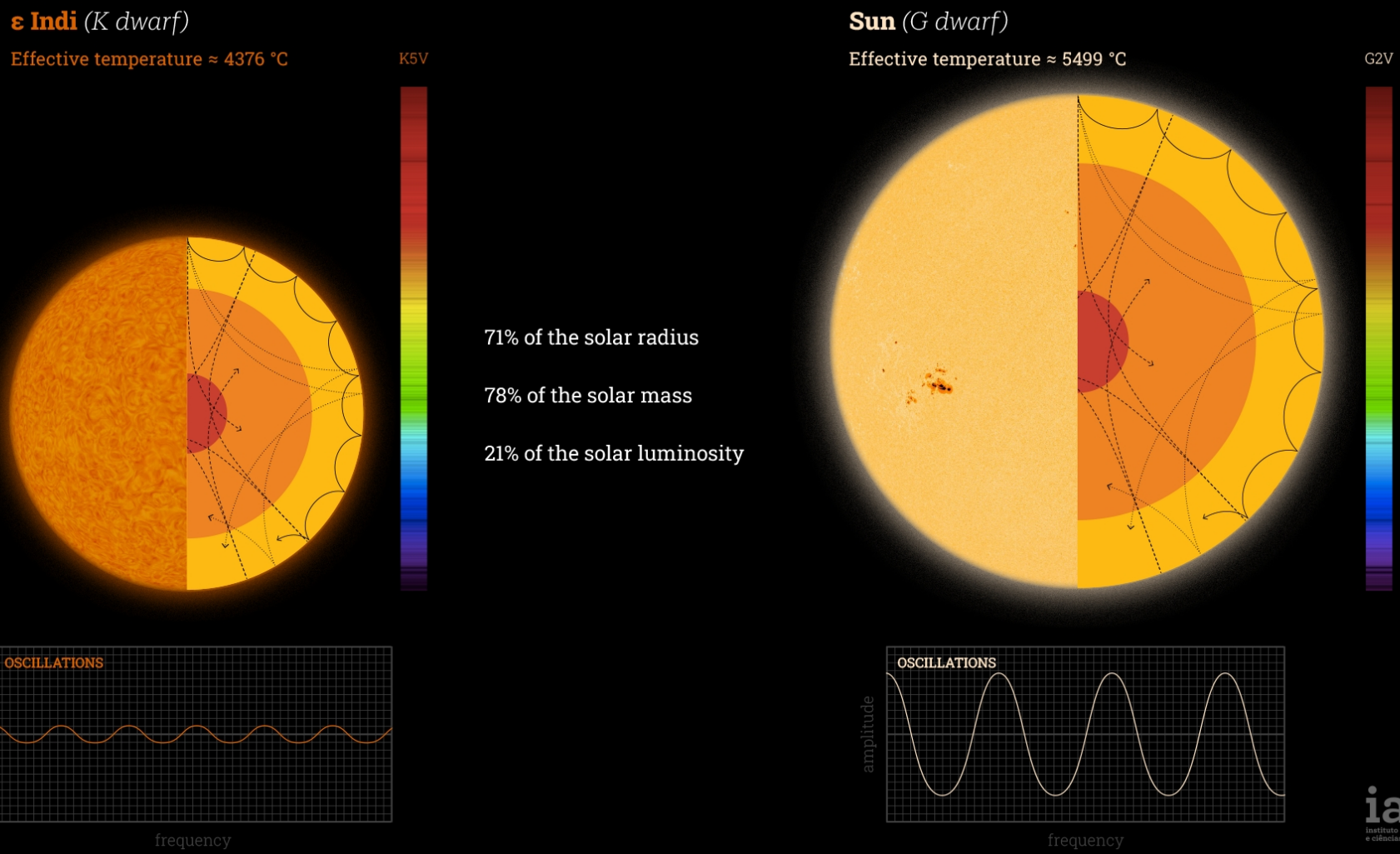
4. Direct imaging $\Rightarrow$ difficult (faint + high contrast).



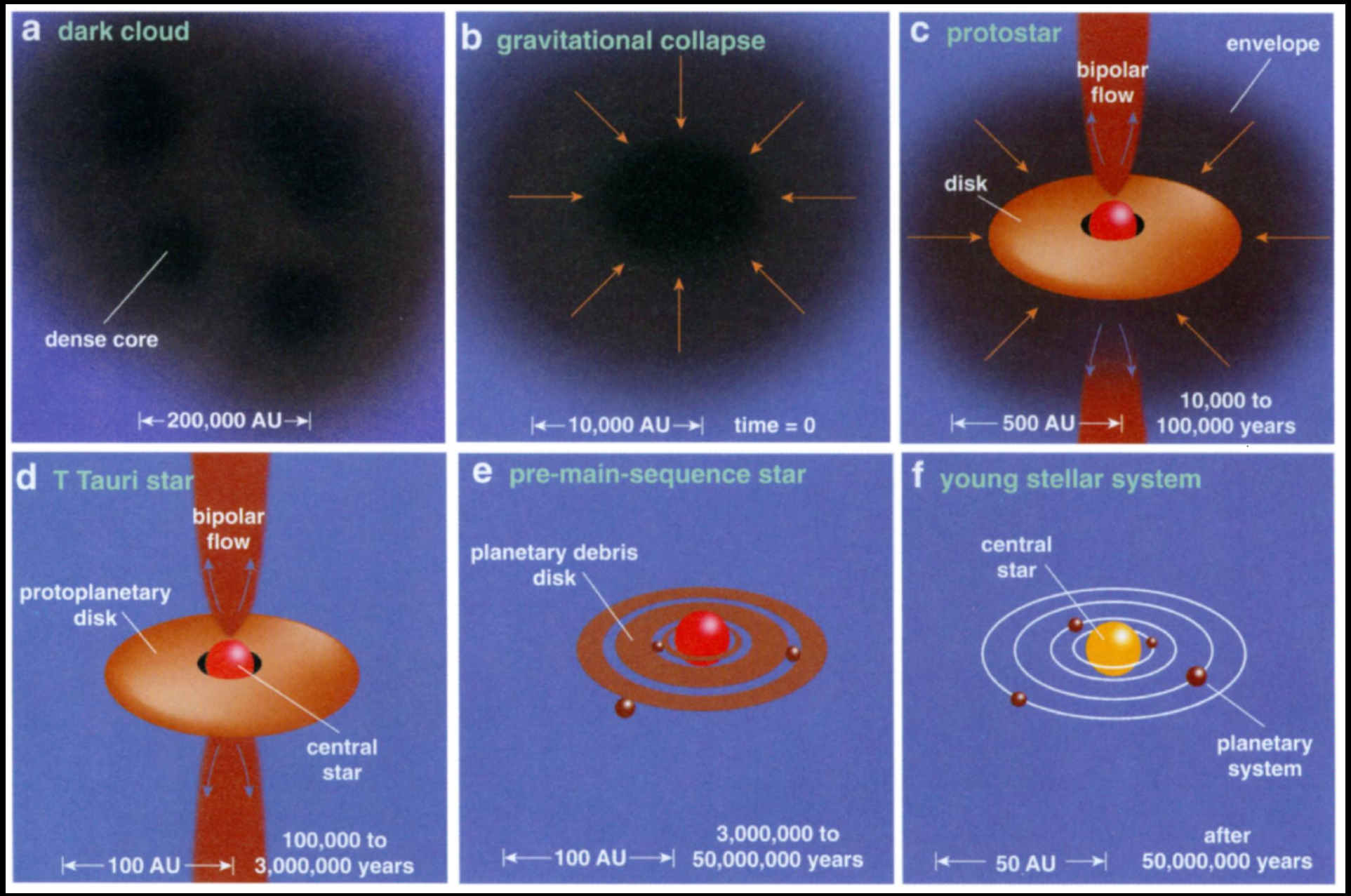


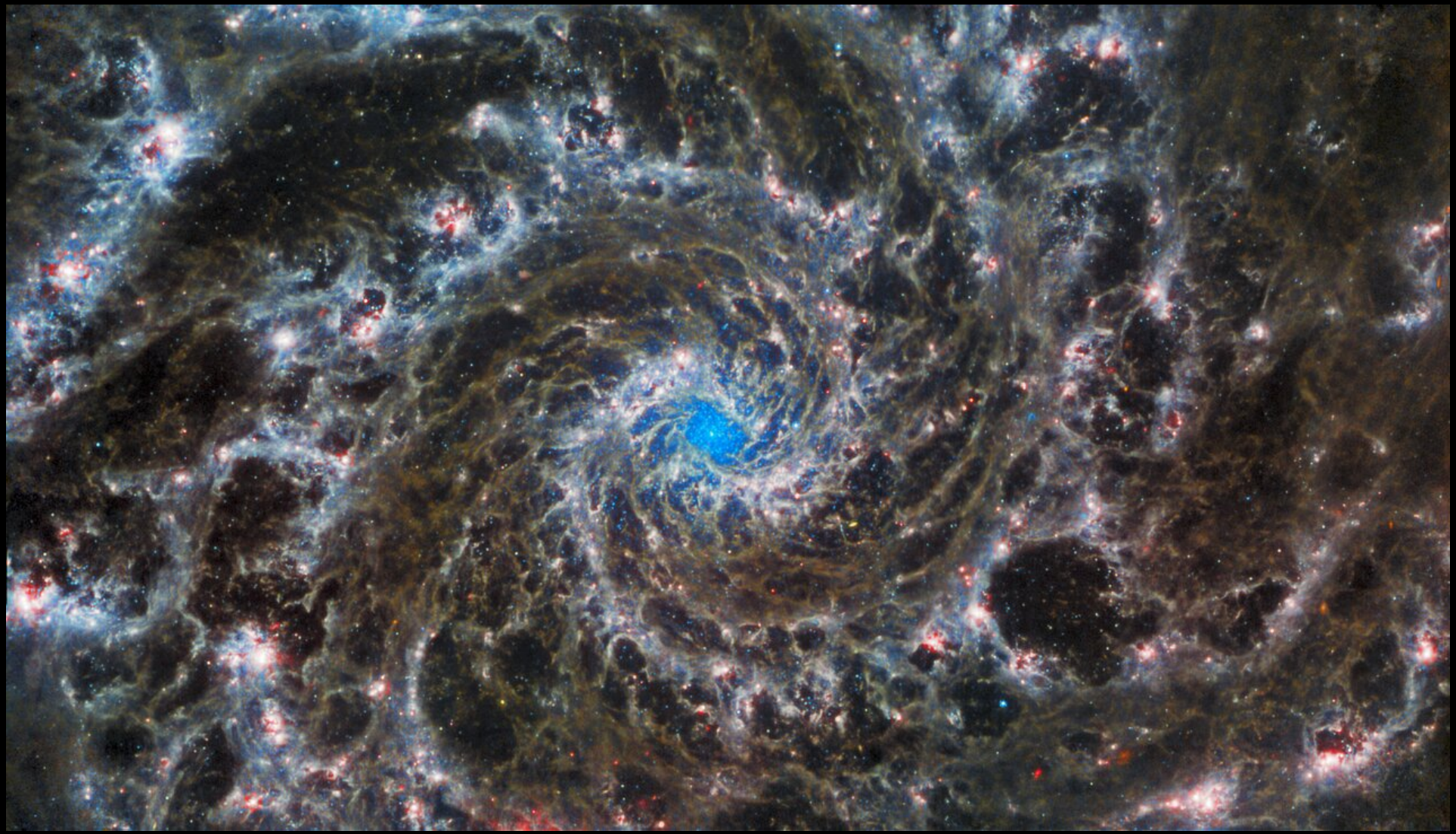


(WASP 107b, warm Neptune; JWST; Dyrek *et al.*, 2023)



(Smallest oscillations detected; Campante *et al.*, 2024)


a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years



(NGC 628; PHANGS JWST project)

(Carina nebula; JWST)

(L1527, protostar, JWST)

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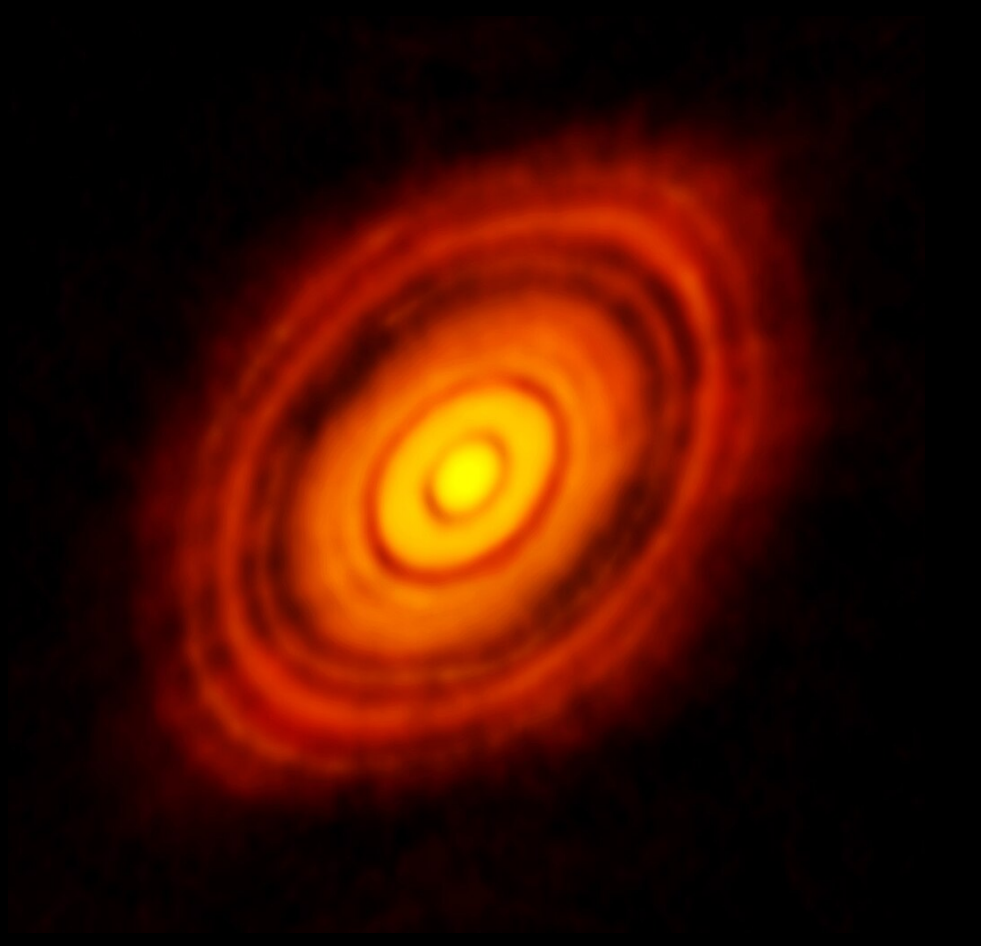
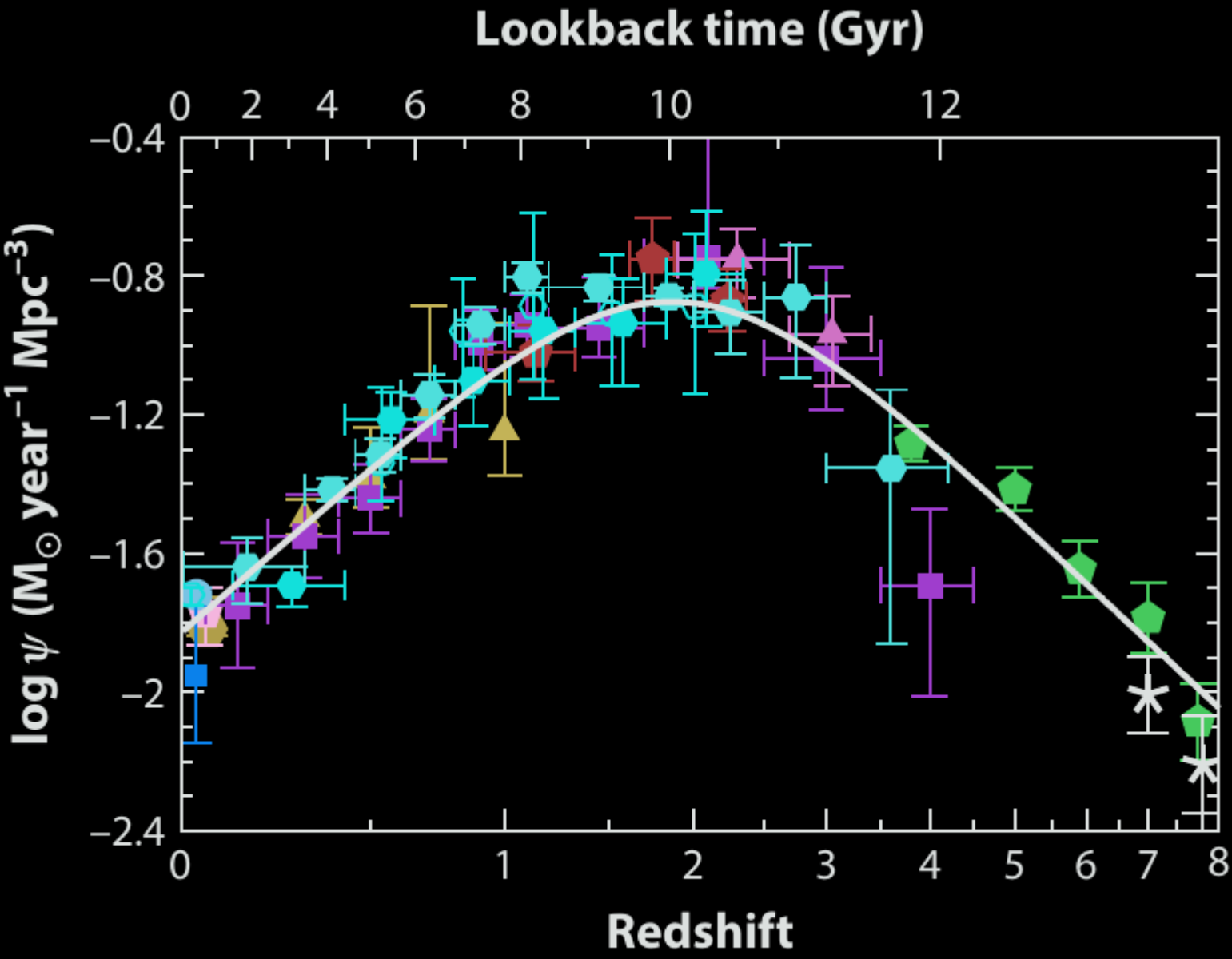


(HLτ, protoplanetary disk, ALMA)



(Madau & Dickinson, 2014)

The Most Distant Spectroscopically-Confirmed Galaxy To Date

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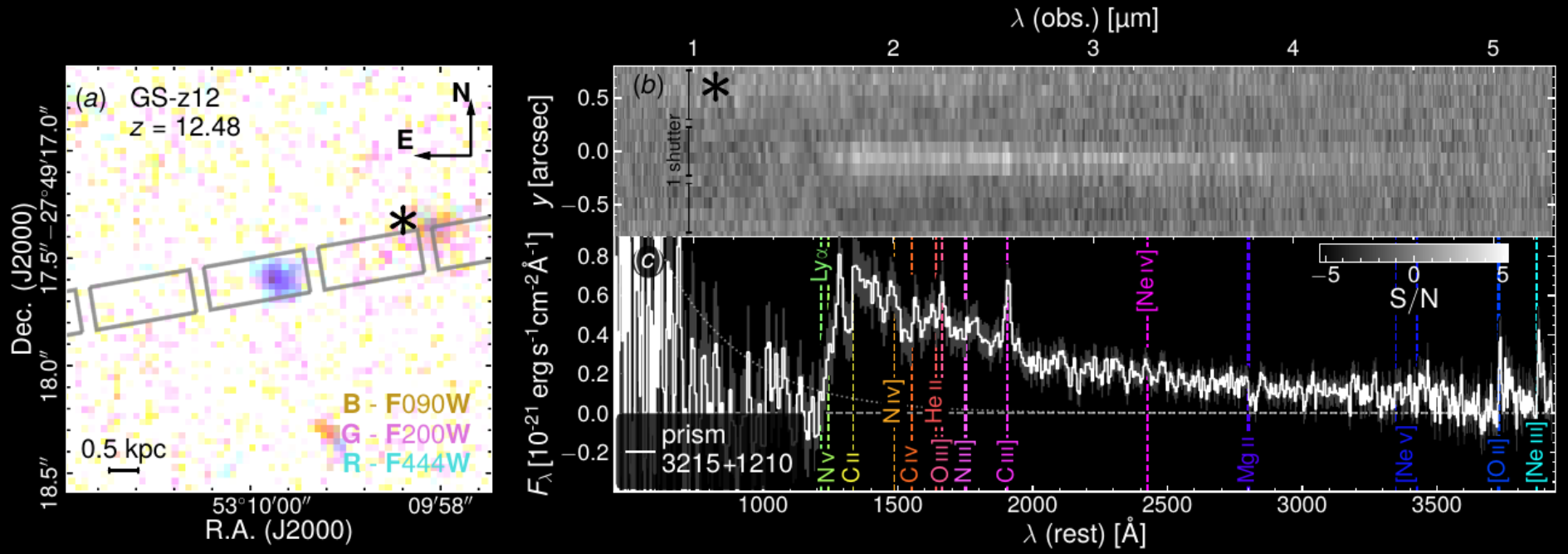

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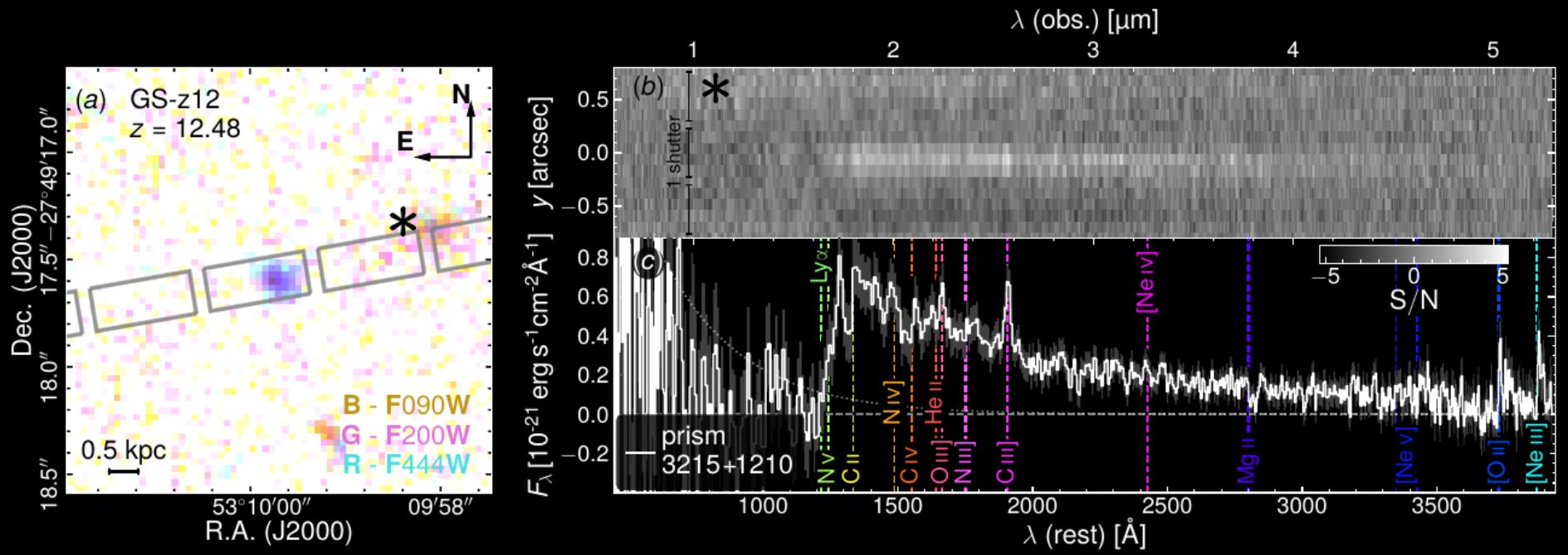
Photometric redshift, based on the shape of the SED → useful but potentially degenerate.



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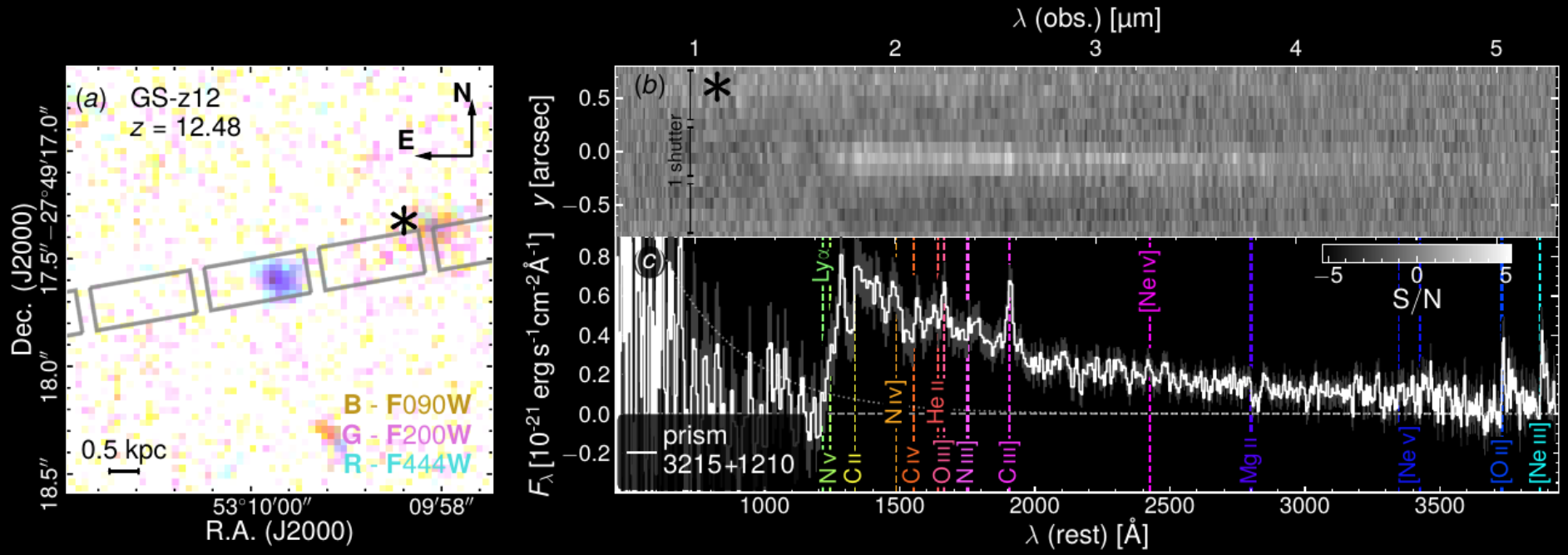

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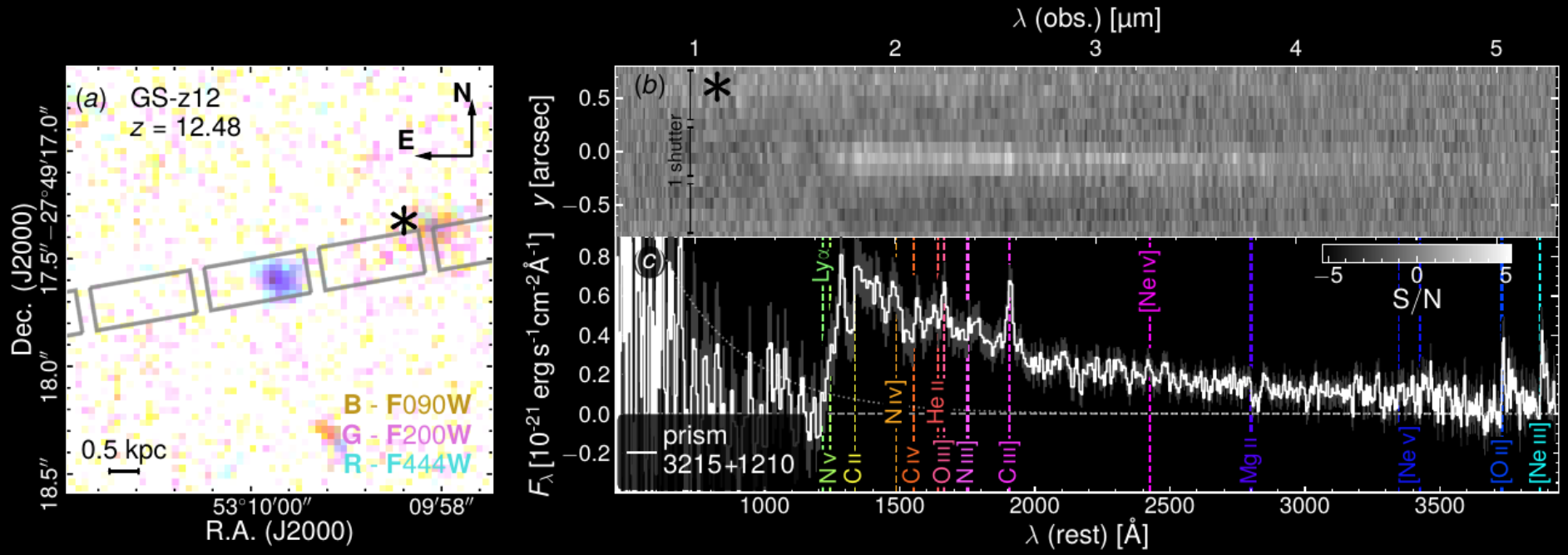
⇒ demonstrates that the laws of physics are identical ≃ 300 Myr after the Big Bang.



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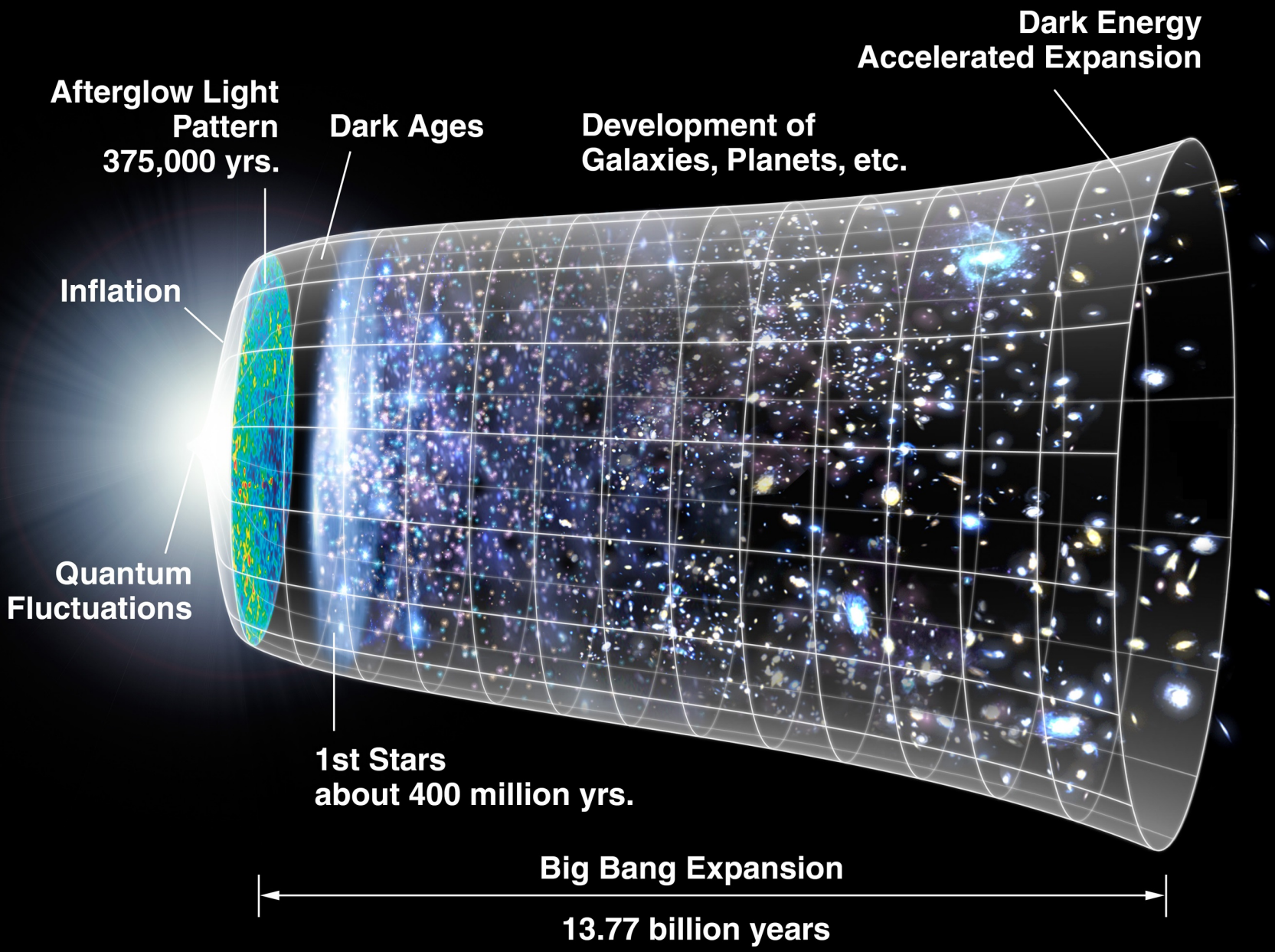
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

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- Corresponds to the *Cosmological constant* in Einstein's equation, Λ (if it is indeed constant).

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- Several alternative hypothesis: MOdified Newtonina Dynamics (MOND), primordial black holes, *etc.*

Dark Energy: large-scale energy.

- First inferred in 1980.
- Responsible for the acceleration of the expansion of the Universe.
- Equivalent to a negative pressure field.
- Corresponds to the *Cosmological constant* in Einstein's equation, Λ (if it is indeed constant).
- Represents $\simeq 68\,\%$ of the total energy of the present Universe.

Two Enigmatic Cosmological Quantities

Dark Matter: invisible, non-collisional, hypothetical matter (Weakly Interactive Massive Particles; WIMP).

- First inferred in 1930.
- Responsible for the flattening of the rotation curves of galaxies → dark matter halos.
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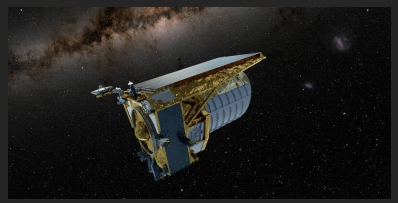
$\Rightarrow$ 2 very different quantities.

Euclid Satellite (2023-)



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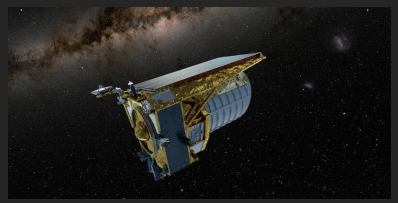

- Measuring the shape & redshift of millions of galaxies;

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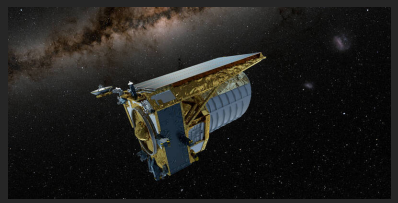

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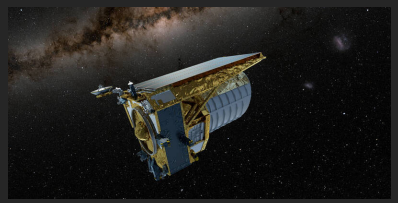
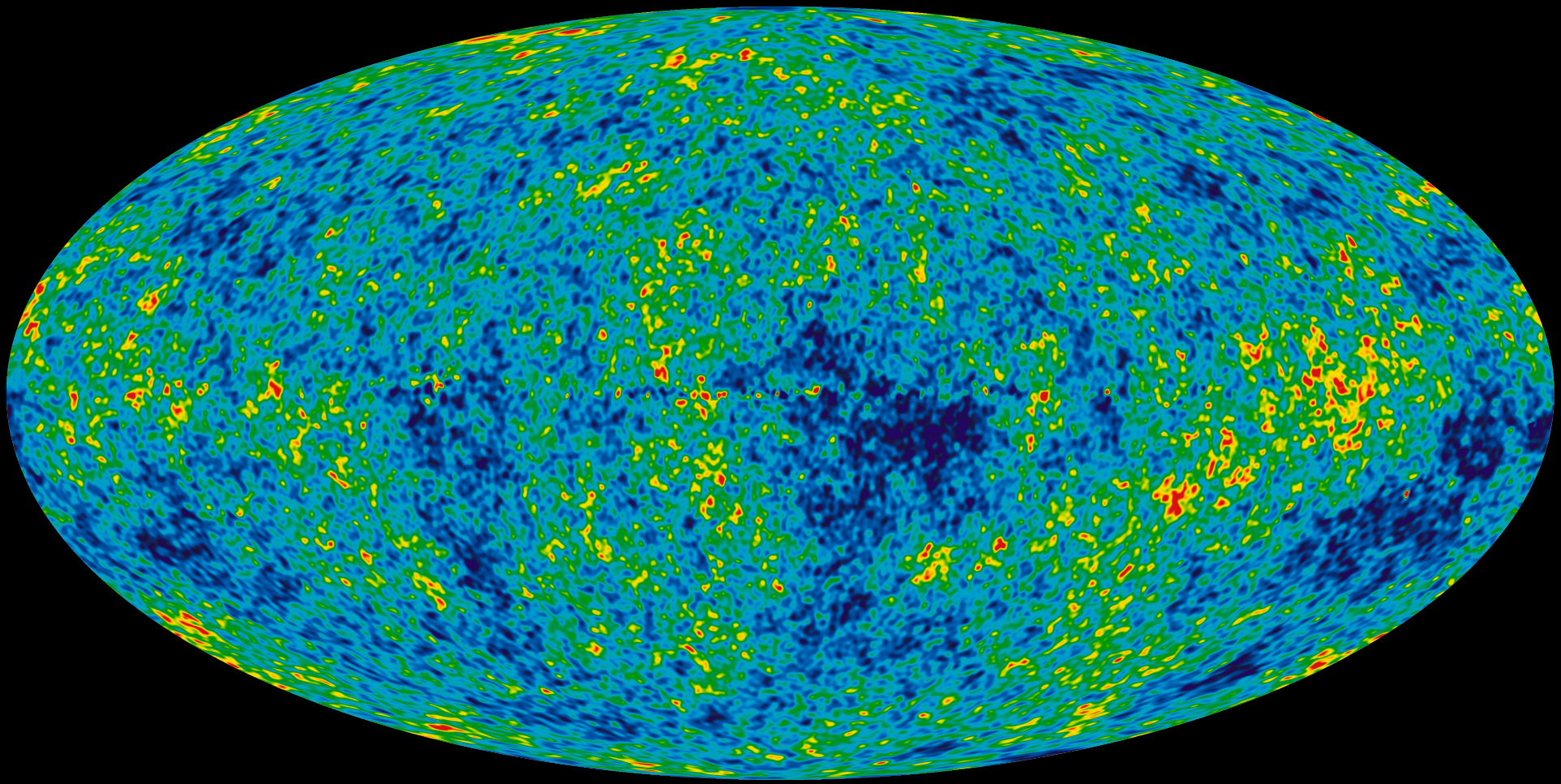


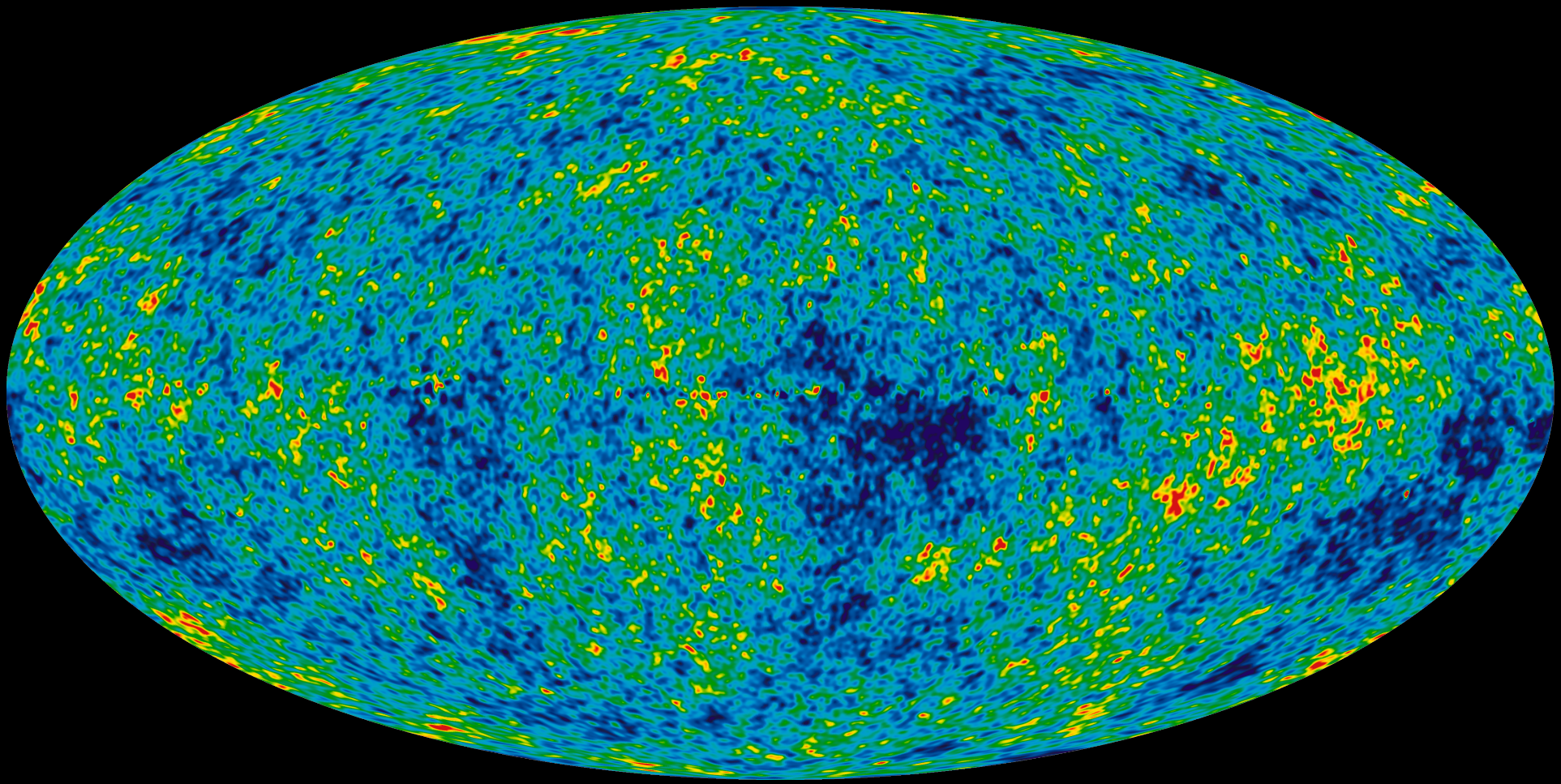
- Measuring the shape & redshift of millions of galaxies;

$\rightarrow$ probe cluster mass;

$\Rightarrow$ constrain cosmological parameters.



(Cosmological Microwave Background, CMB; WMAP, 2012)



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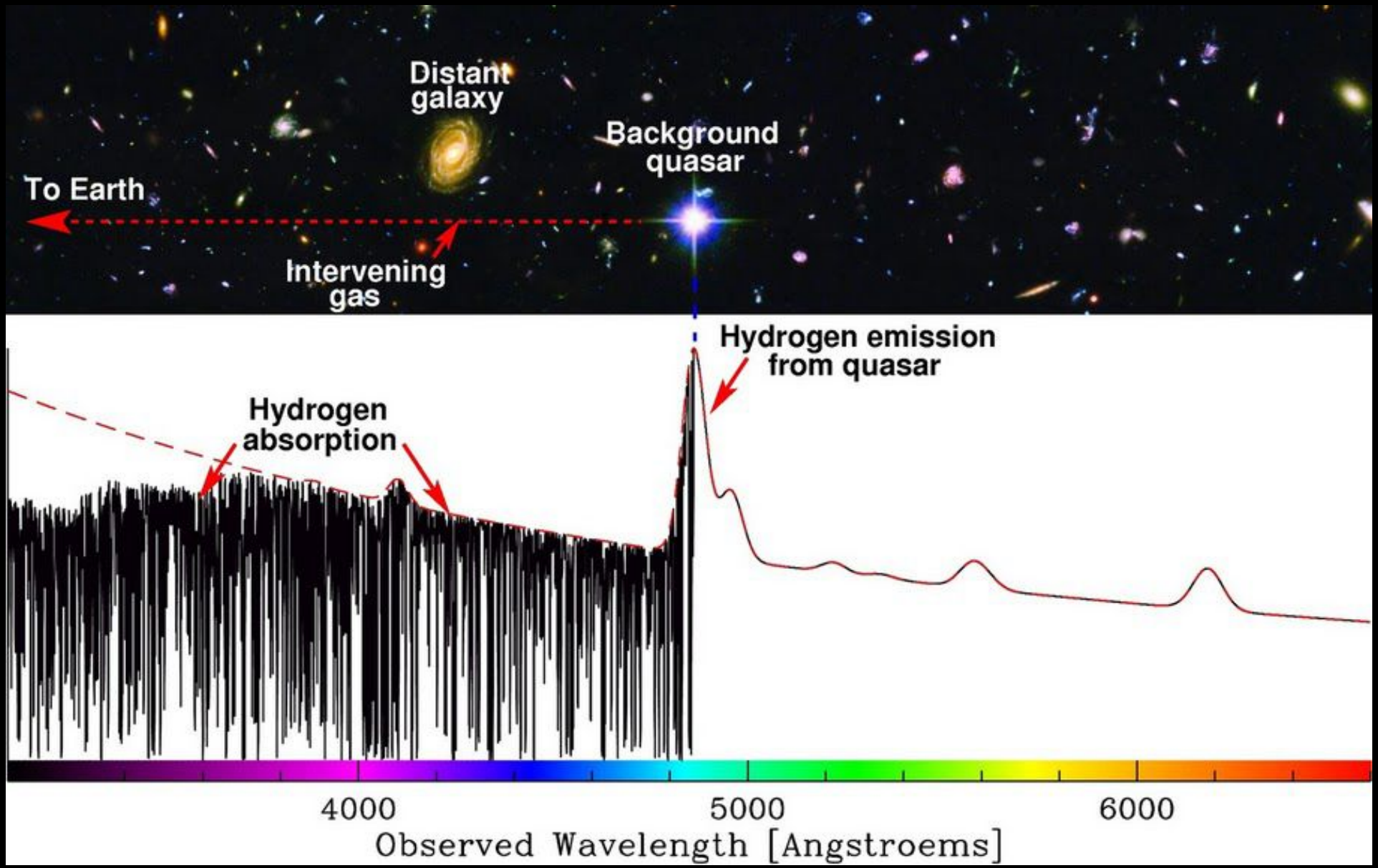
$\Rightarrow$ Baryonic Acoustic Oscillations $\rightarrow$ constrain dark energy.


Distant galaxy
Background quasar
To Earth
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
4000
5000
6000
Observed Wavelength [Angstroems]

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October 9, 2022: The *Gamma-Ray Burst of the Millenium* $\rightarrow$ duration of the γ flash $\simeq$ 600 s.

TOC of the Talk

1. **INTRODUCTION**
2. **AN HISTORICAL PERSPECTIVE**
   - The first observations of the sky
   - Astronomy: celestial mechanics
   - Astrophysics: the advent of spectroscopy
   - The Universe as we know it today: from the Solar system to the Big Bang
3. **METHODOLOGIES FOR THE EXPLORATION OF DISTANT SPACE**
   - *In situ* exploration
   - The current astrophysical vectors of information
   - The electromagnetic spectrum & the different astrophysical processes it probes
   - The complexity of astrophysical measures
4. **AN OVERVIEW OF CONTEMPORARY OPEN QUESTIONS & HOT TOPICS**
   - How does the Solar system work? How dit it form?
   - What is the origin of stars & planet, and how do they evolve?
   - How do galaxies form, and how does the Universe evolve?
   - Do we understand extreme conditions in the Universe?
5. **SUMMARY & CONCLUSION**

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