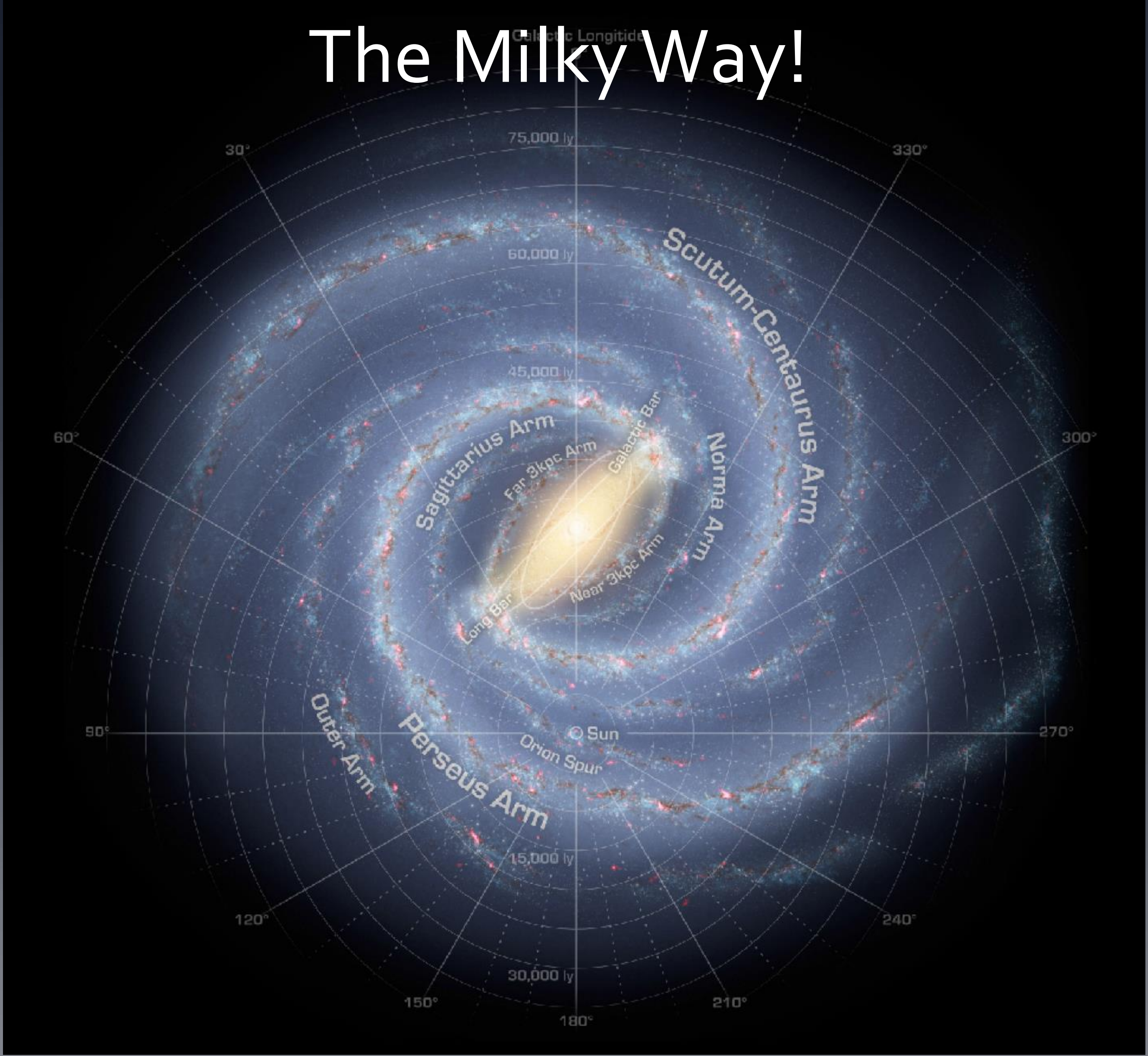
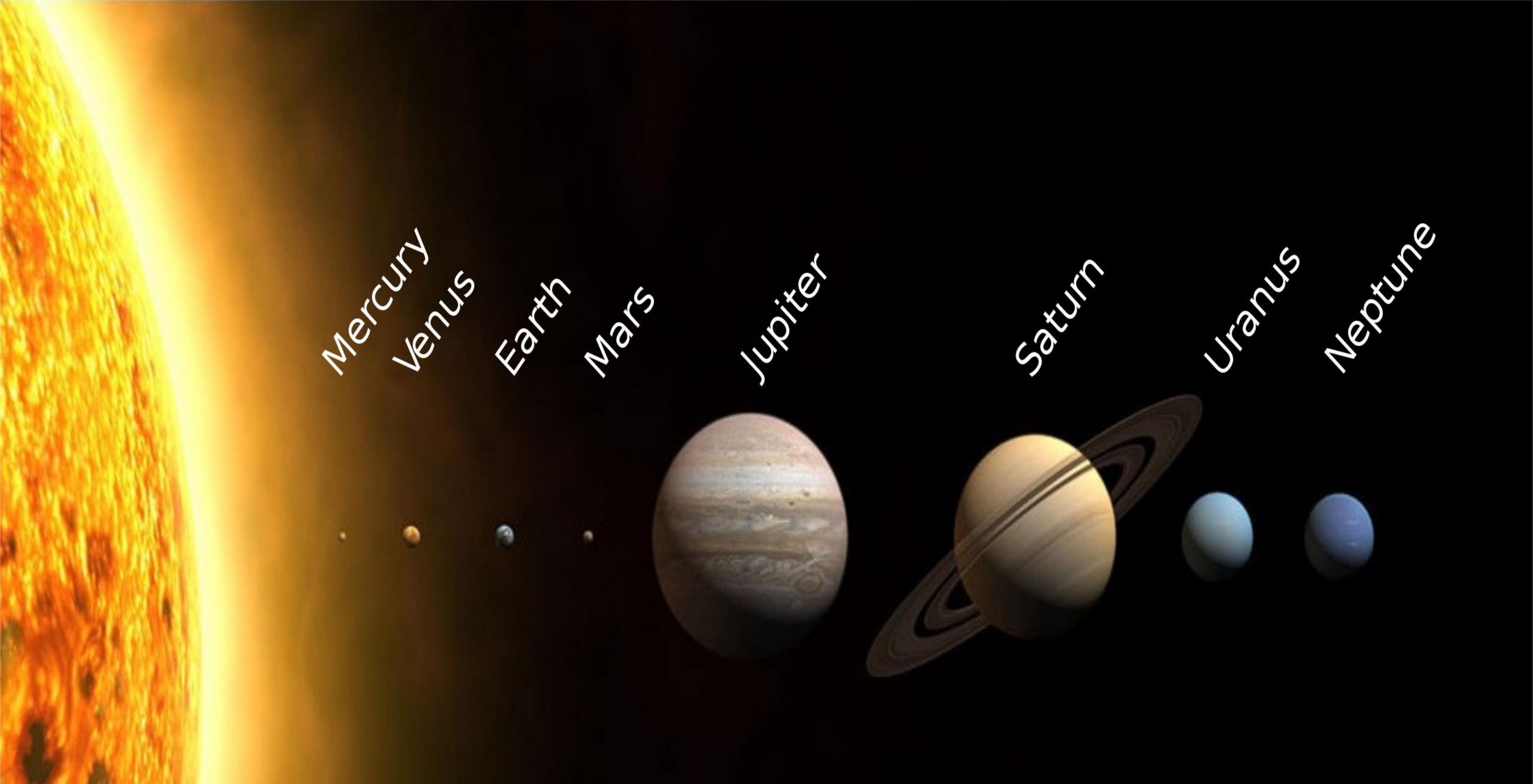
The Milky Way!



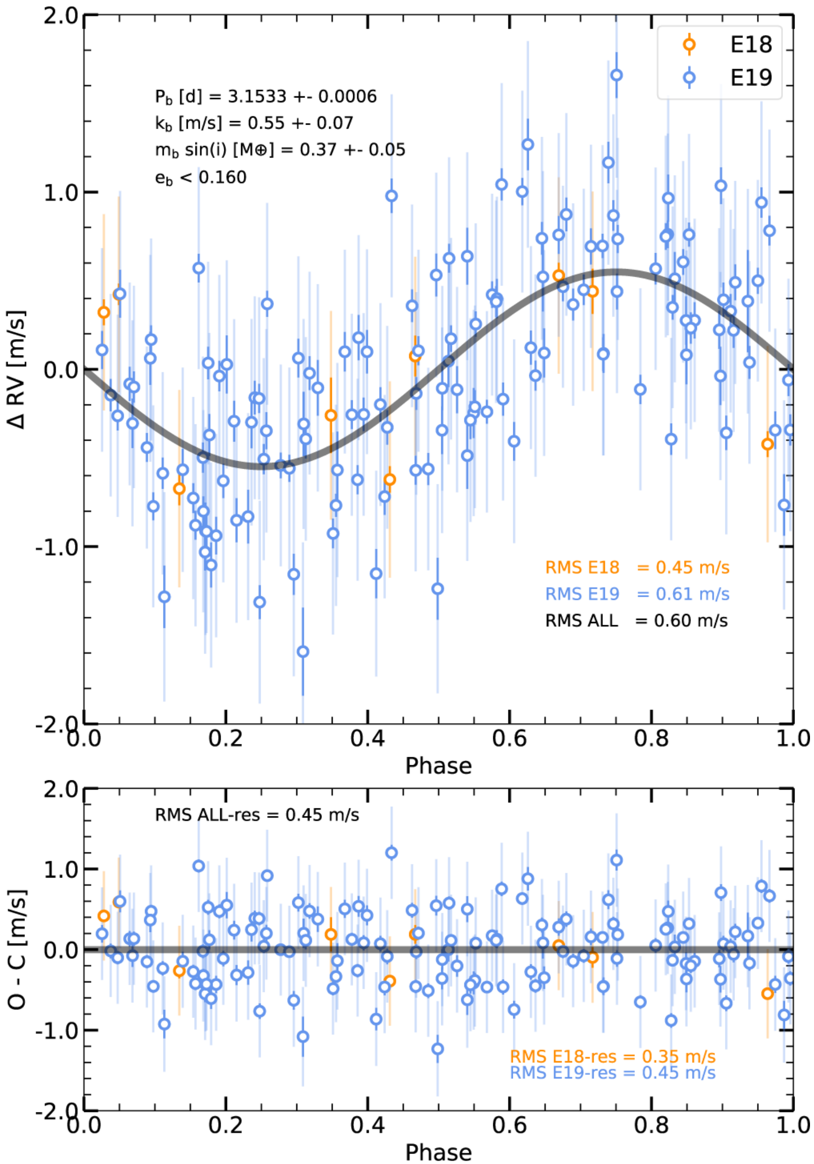
Homework

- Next assignment: oral report due before class on October 24
  - Select an astronomy-related topic and present a 5 minute talk
    - Feel free to select anything related to astronomy!
    - Some suggestions in the assignment
  - 7 slides maximum (1 title slide + up to 6 with content)
  - Record and upload!
    - One option: “share screen” option in tencent/zoom so that screen is recorded
    - Upload to the site circulated by wechat

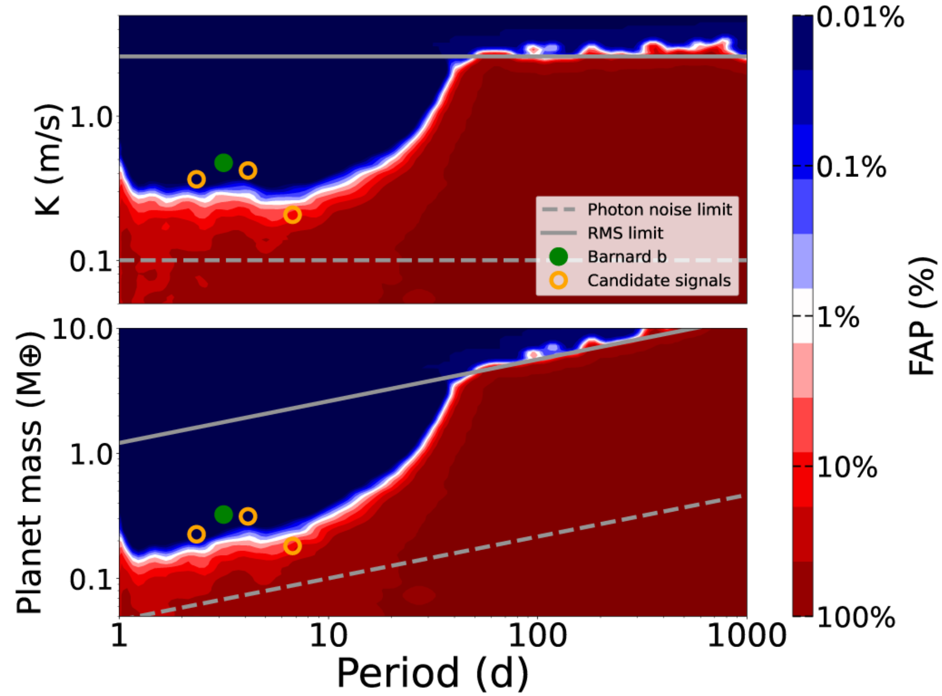


Last week: Exoplanets!

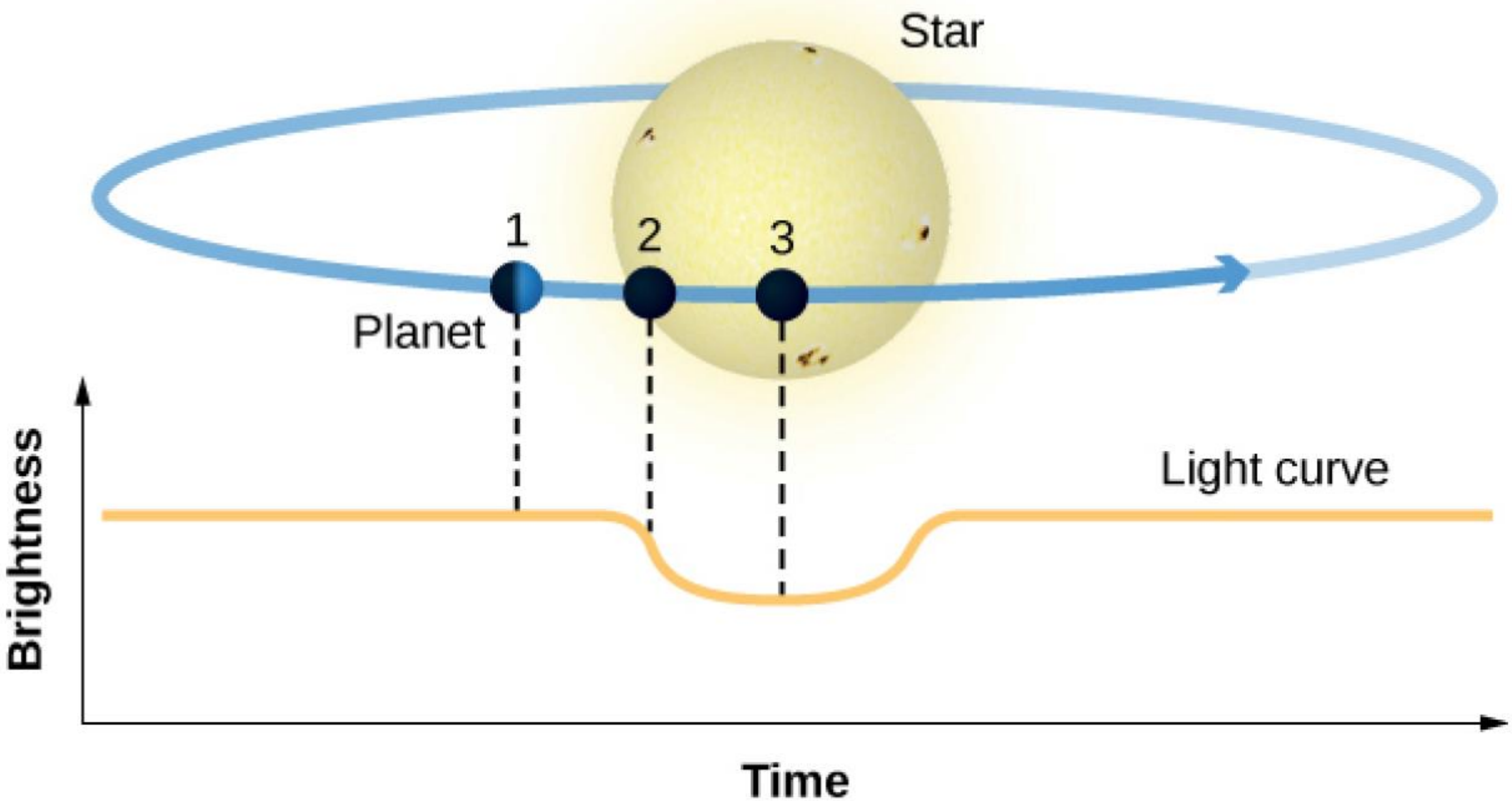
Barnard star planet:
-3-day period
-0.37 M_{earth}



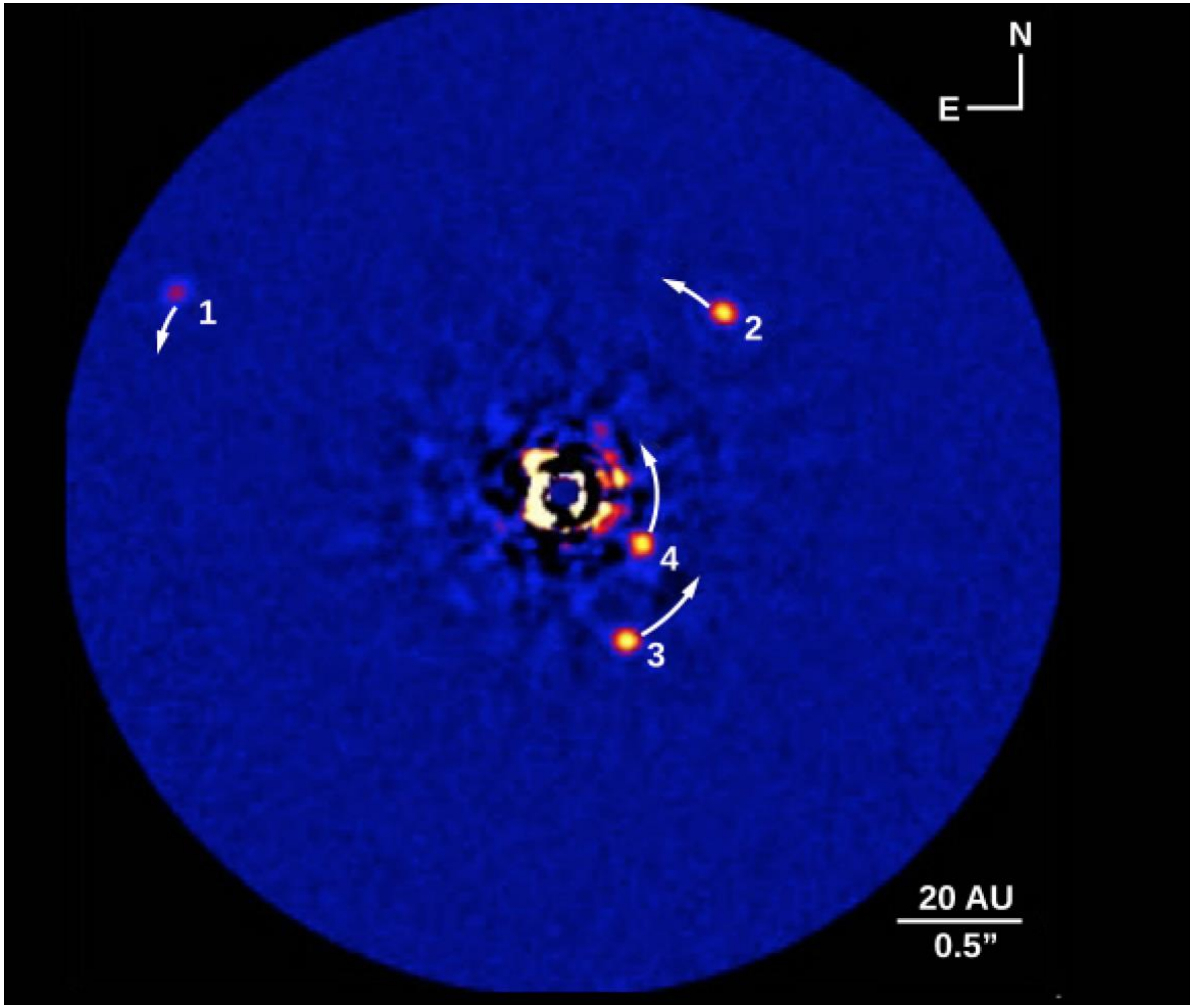
Radial velocity signal+residual



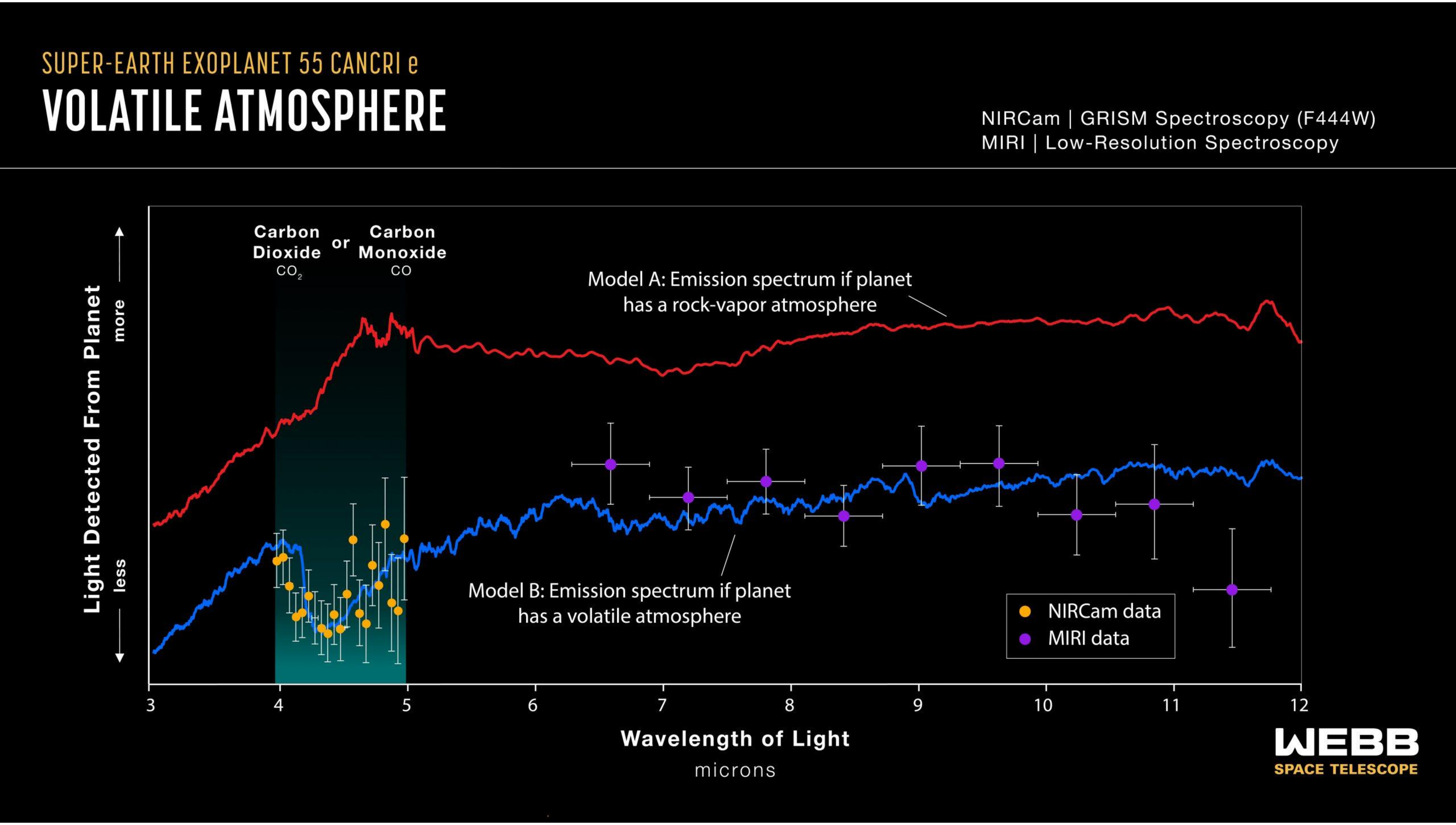
Bias: sensitivity to planet mass/radius

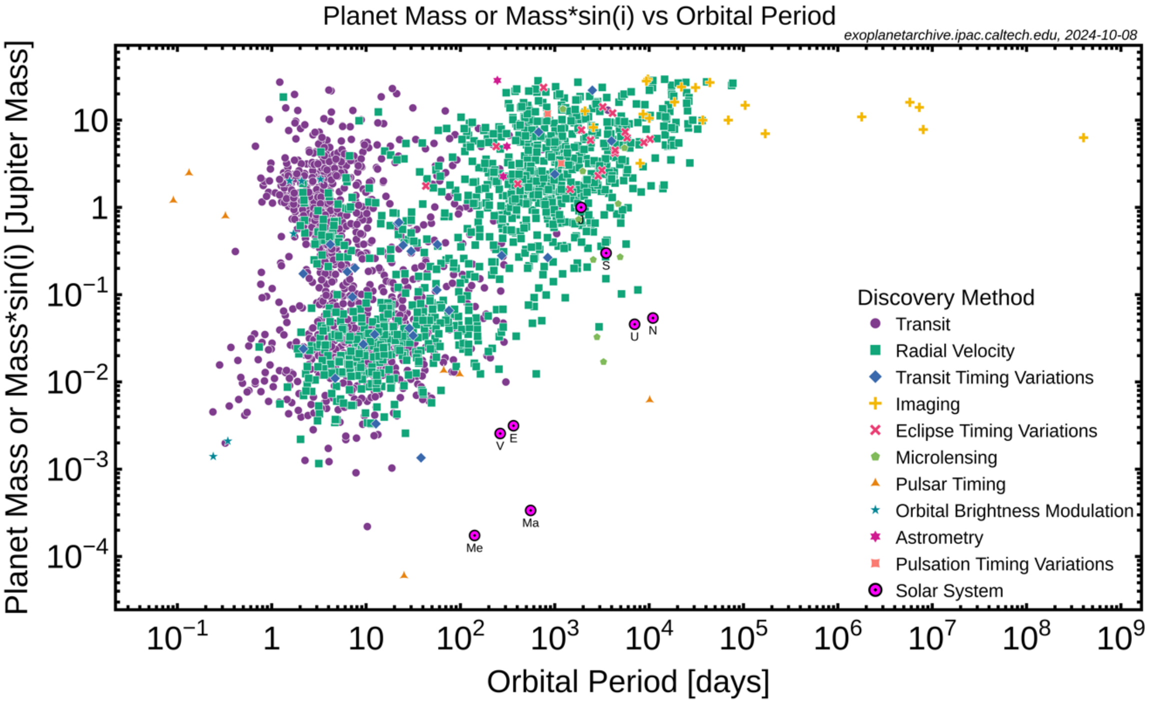

Star
1
2
3
Planet
Brightness
Light curve
Time

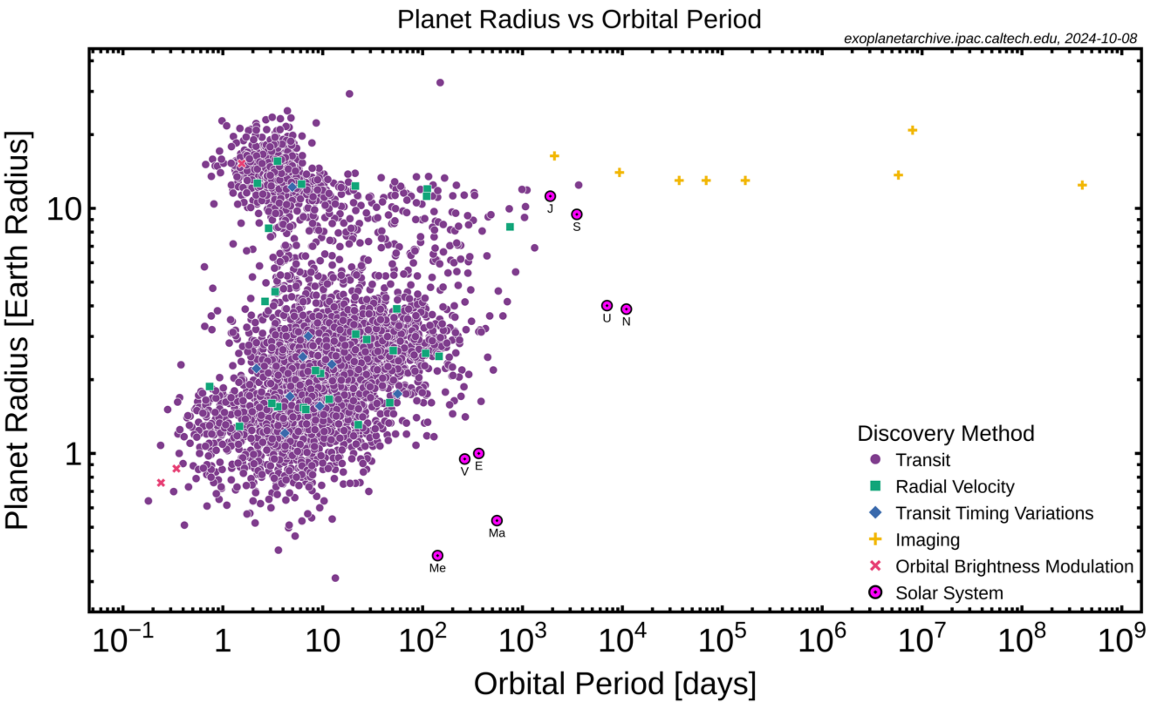
Direct Imaging: requires coronagraph to block out the star (similar to eclipse)



First atmosphere around a terrestrial exoplanet







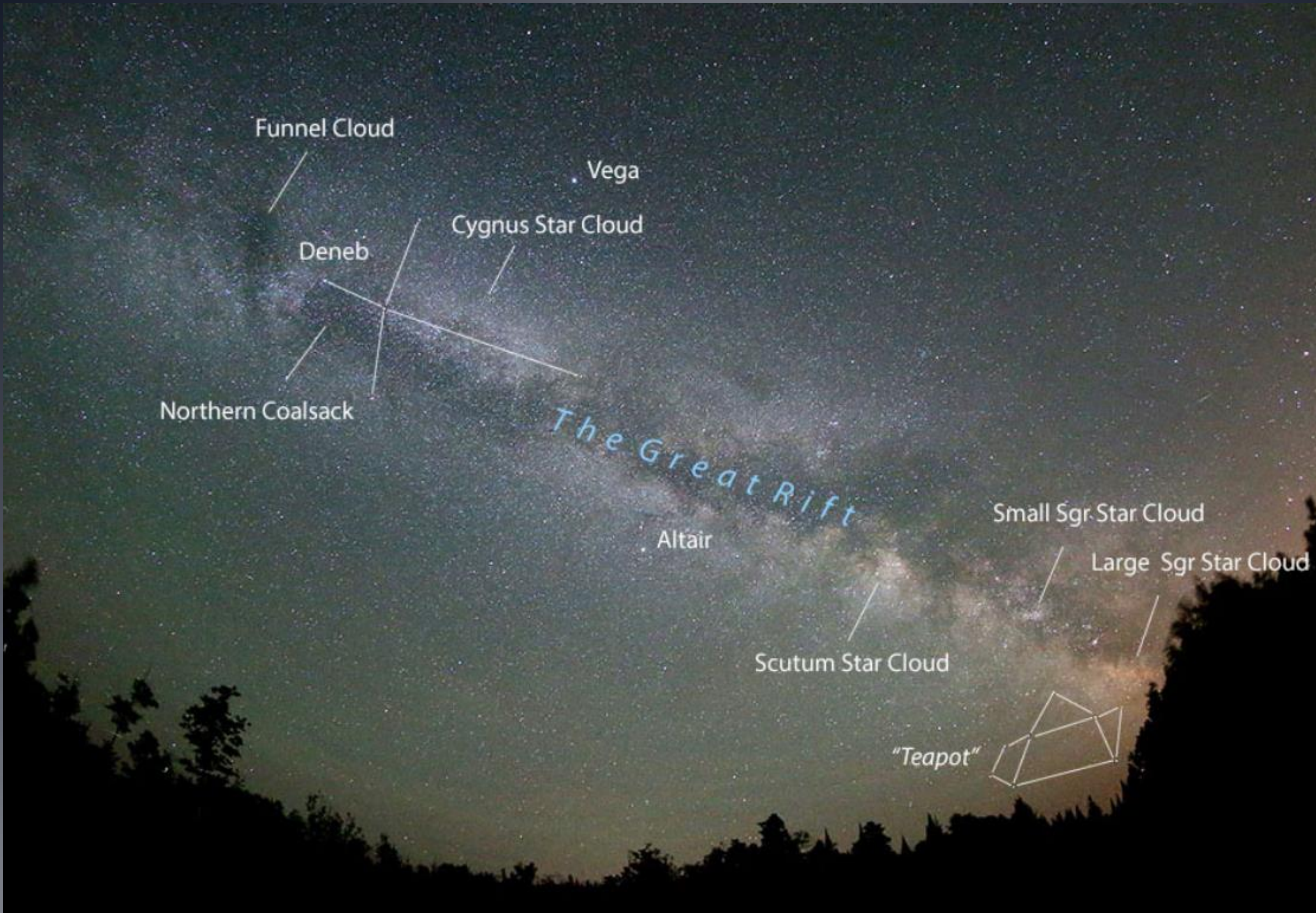
Planets are everywhere!

Each detection method is biased

The Milky Way!

Stars: The Building Blocks of the Universe

The Milky Way! It's full of stars!


Funnel Cloud
Vega
Cygnus Star Cloud
Deneb
Northern Coalsack
The Great Rift
Altair
Small Sgr Star Cloud
Large Sgr Star Cloud
Scutum Star Cloud
"Teapot"

Milky Way: keywords

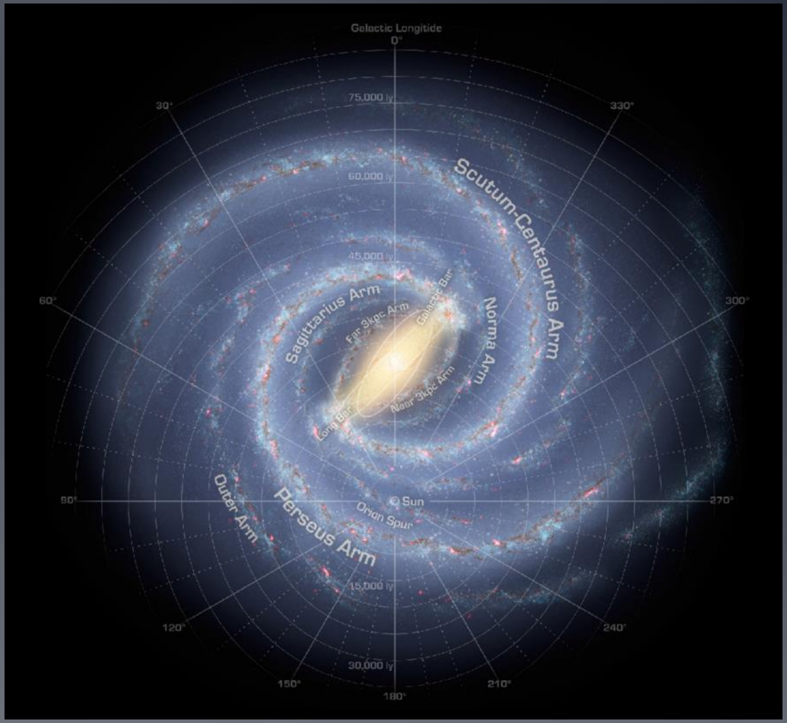
- Galaxy: gravitationally bound system of stars, gas, dust, and dark matter.
  - 1000-100,000 light years in radius
  - Many kinds of shapes and sizes

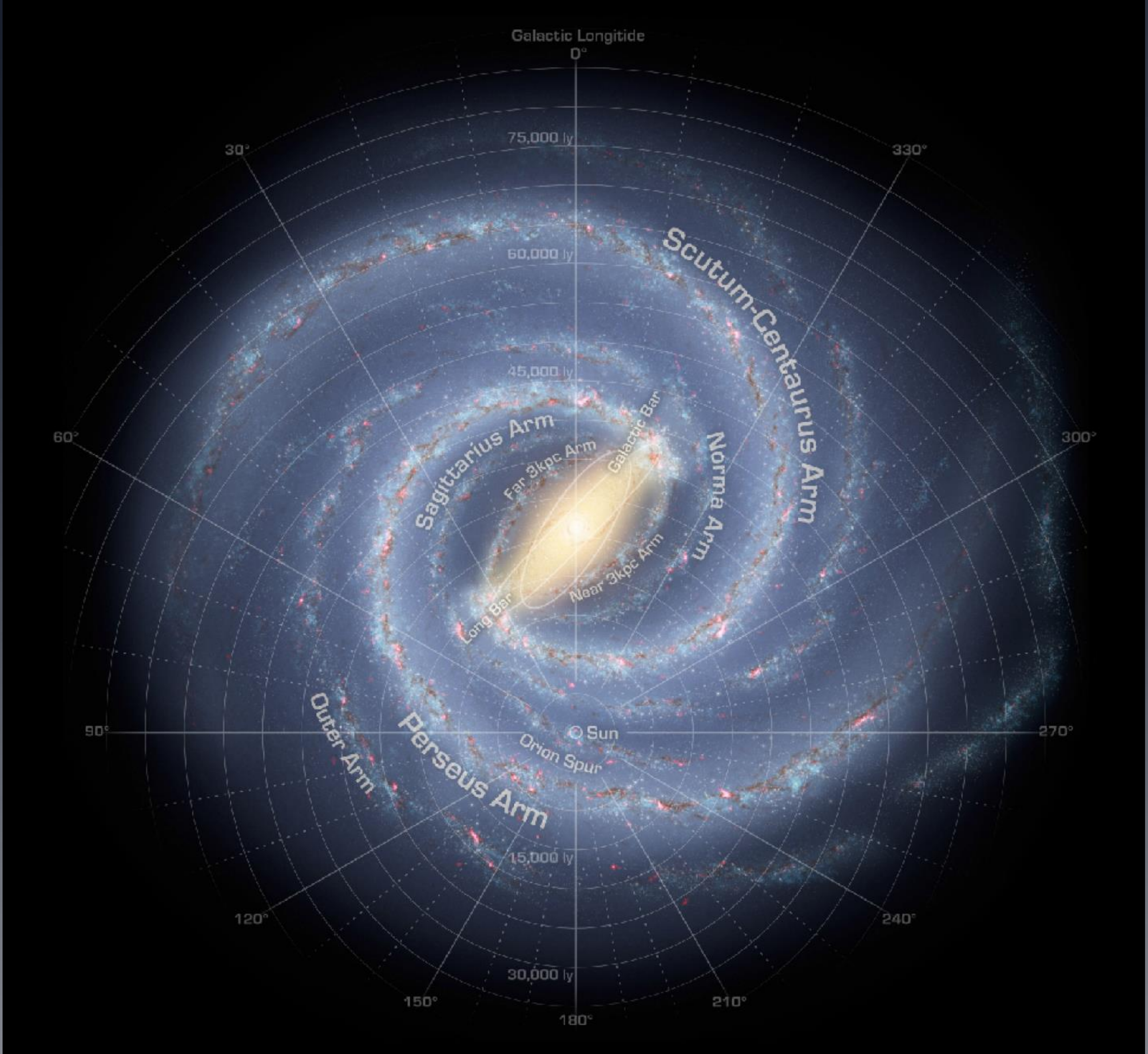
- Range: 10^8-10^{14} stars
  - Milky Way: 10^{11} stars (a large galaxy)

- Supermassive black hole
  - Milky Way: 4 10^6 Msun (small central black hole)

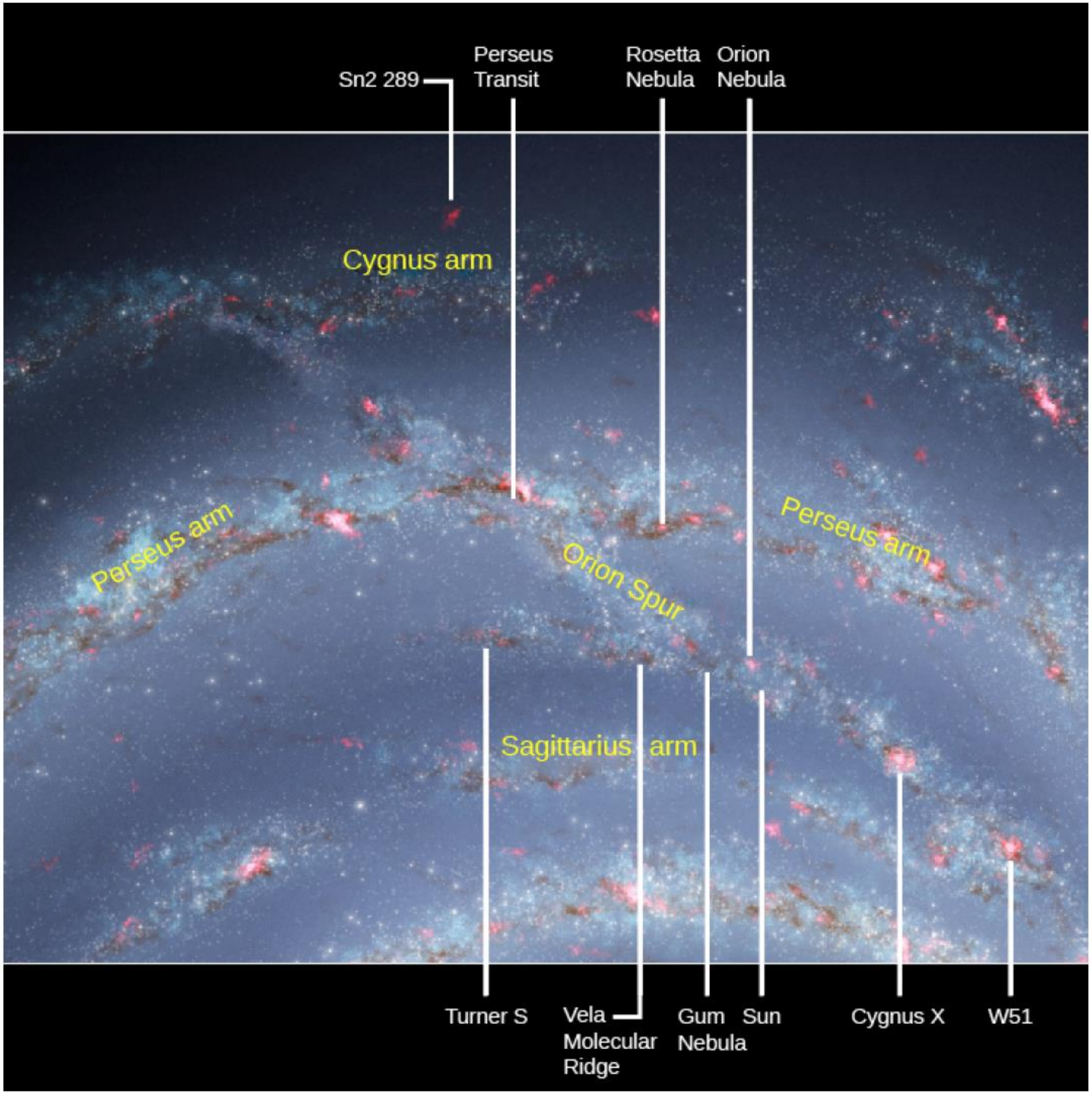
Milky Way: keywords

- Spiral arms: "shape" of young stars/dense gas in some galaxies
- Supermassive black hole: massive black hole at center of galaxy
- Dark Matter halo: spherical halo of dark matter around the galaxy
- Galactic rotation: rotation of stars/gas around galaxy
- Central bulge: bulge around nucleus of galaxy



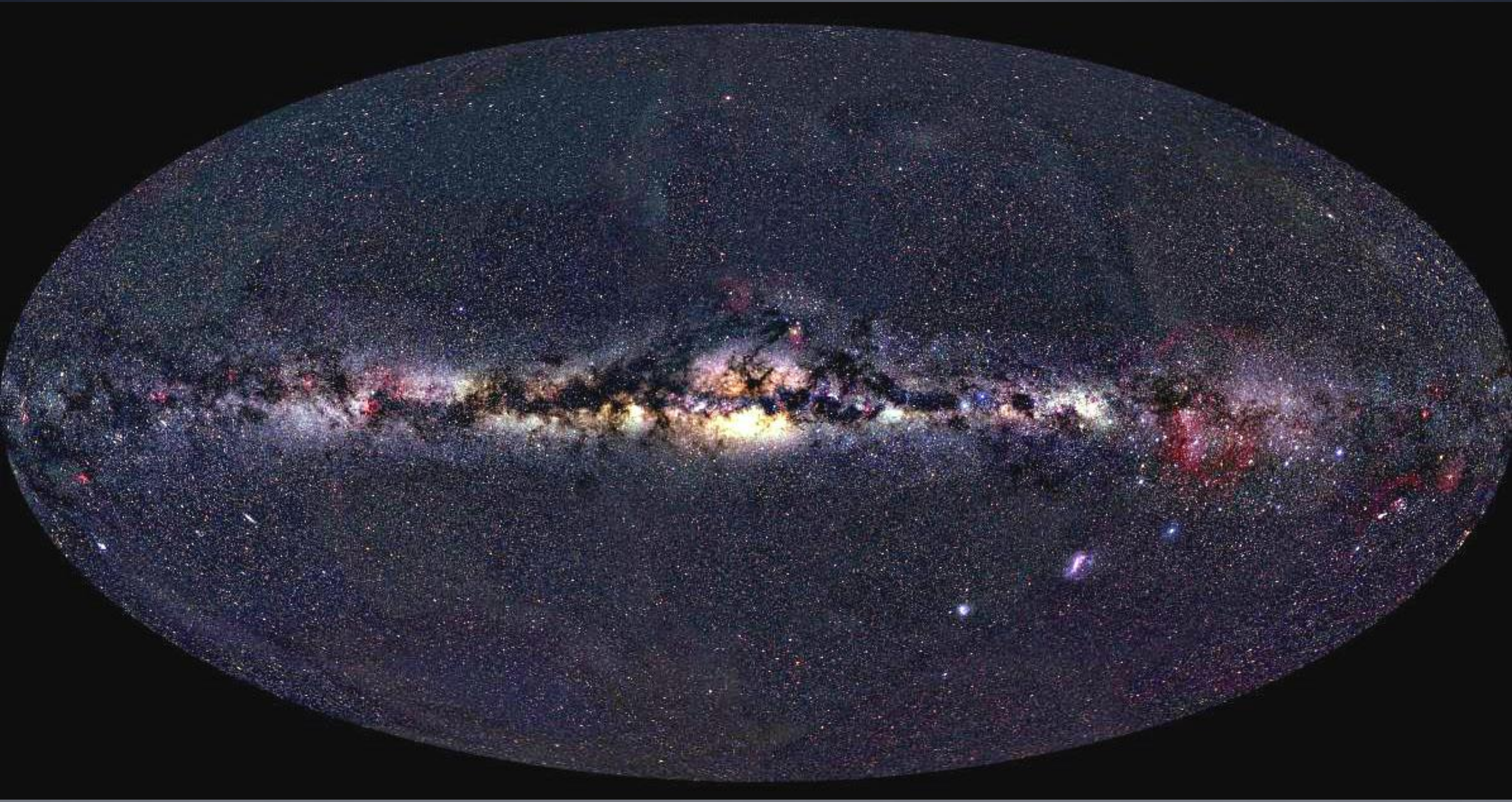


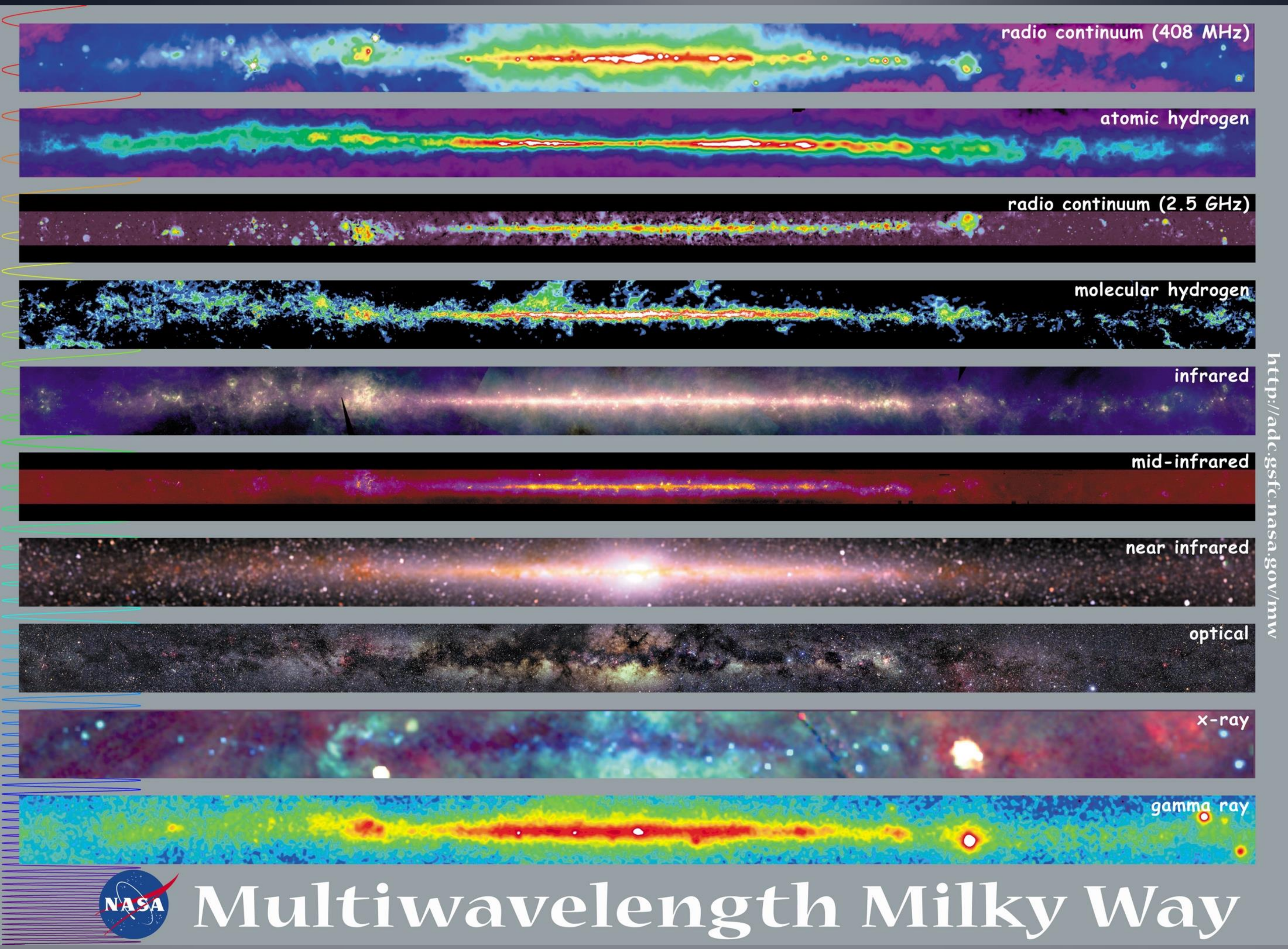
Galactic Longitide
0°
75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
Galactic Bar
Sagittarius Arm
Far 3kpc Arm
Norma Arm
60°
300°
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
90°
Sun
270°
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°
180°



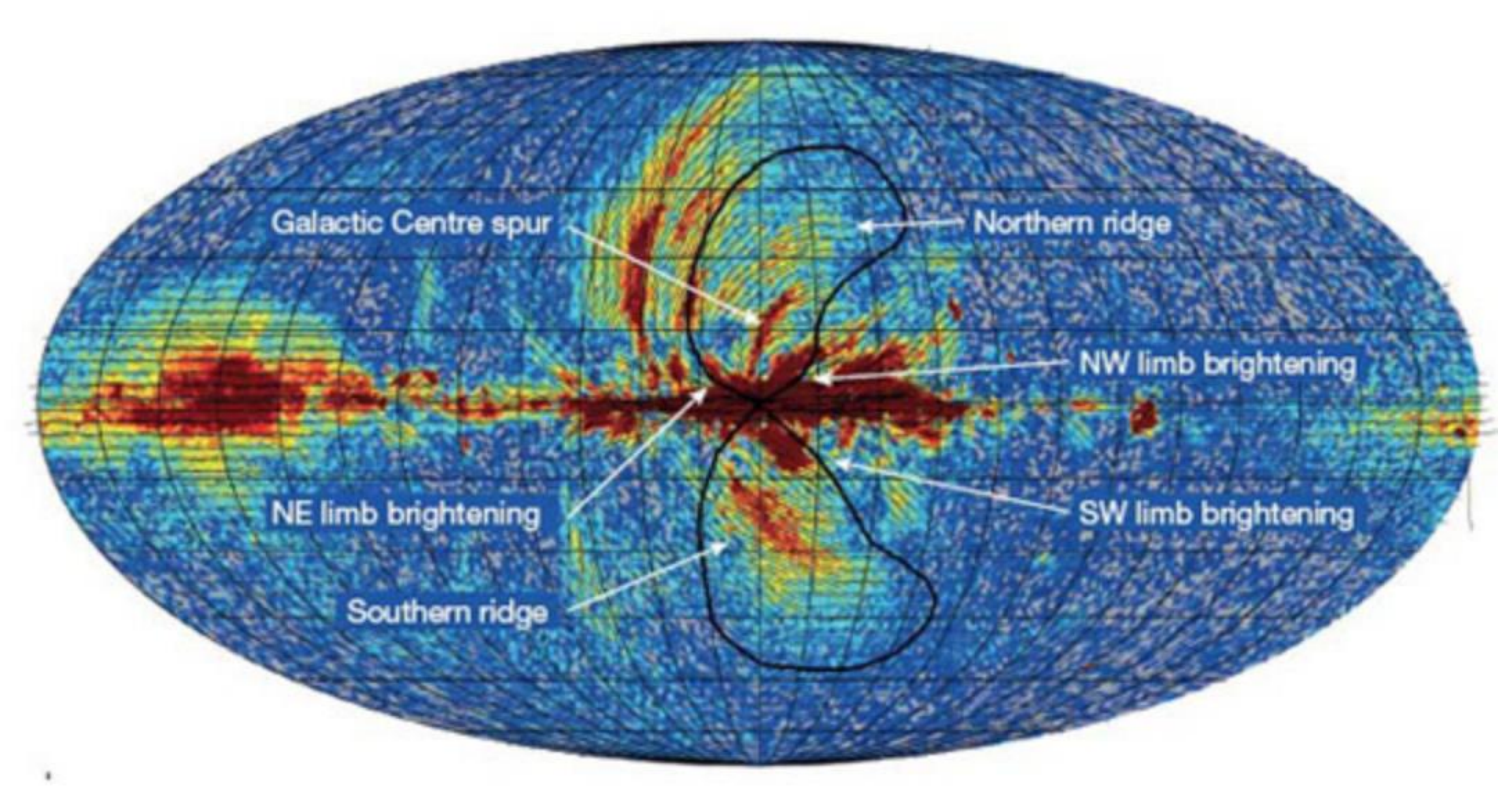
Sn2 289
Perseus Transit
Rosetta Nebula
Orion Nebula
Cygnus arm
Perseus arm
Orion Spur
Perseus arm
Sagittarius arm
Turner S
Vela Molecular Ridge
Gum Nebula
Sun
Cygnus X
W51

All-sky optical map

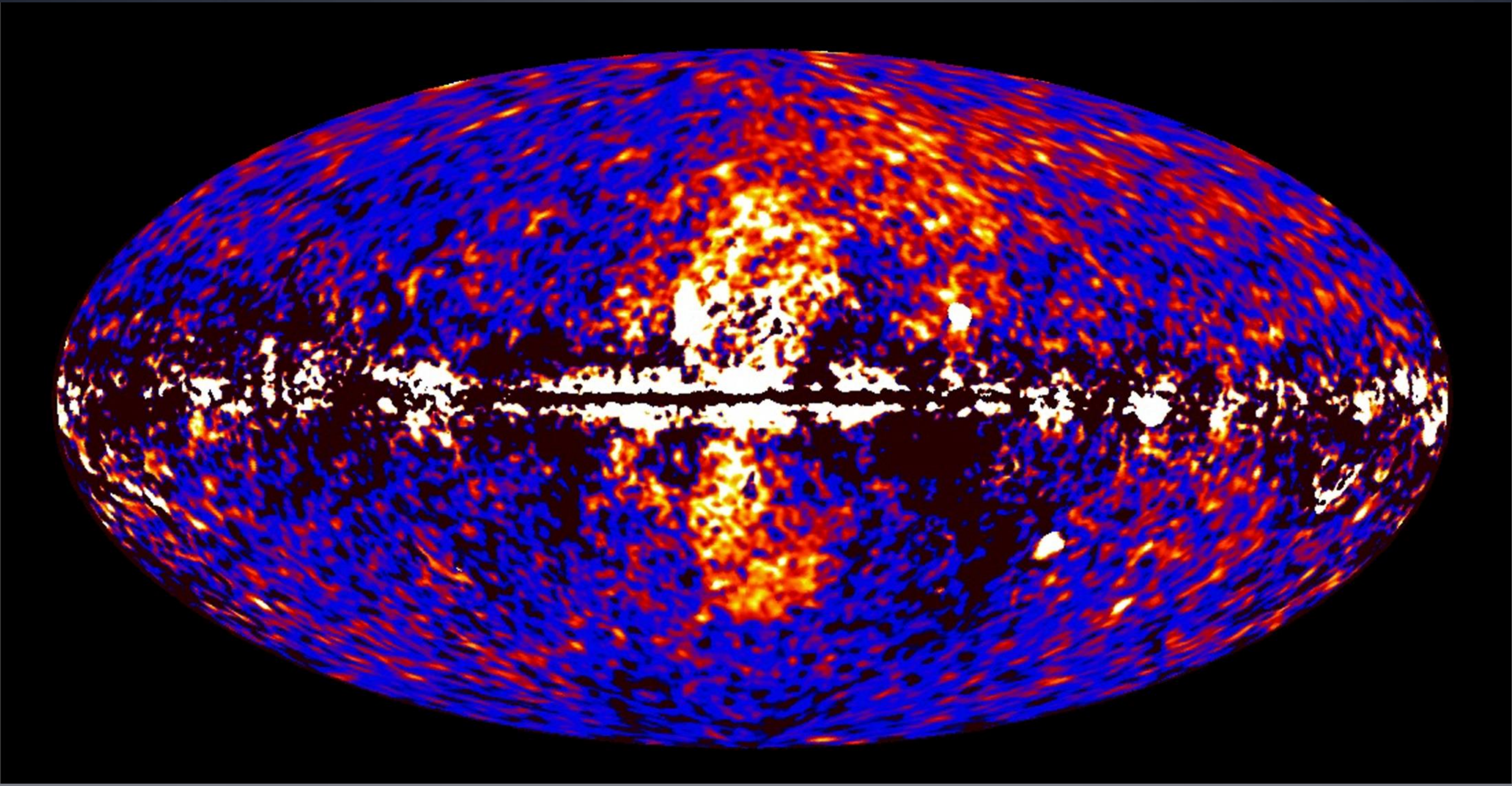


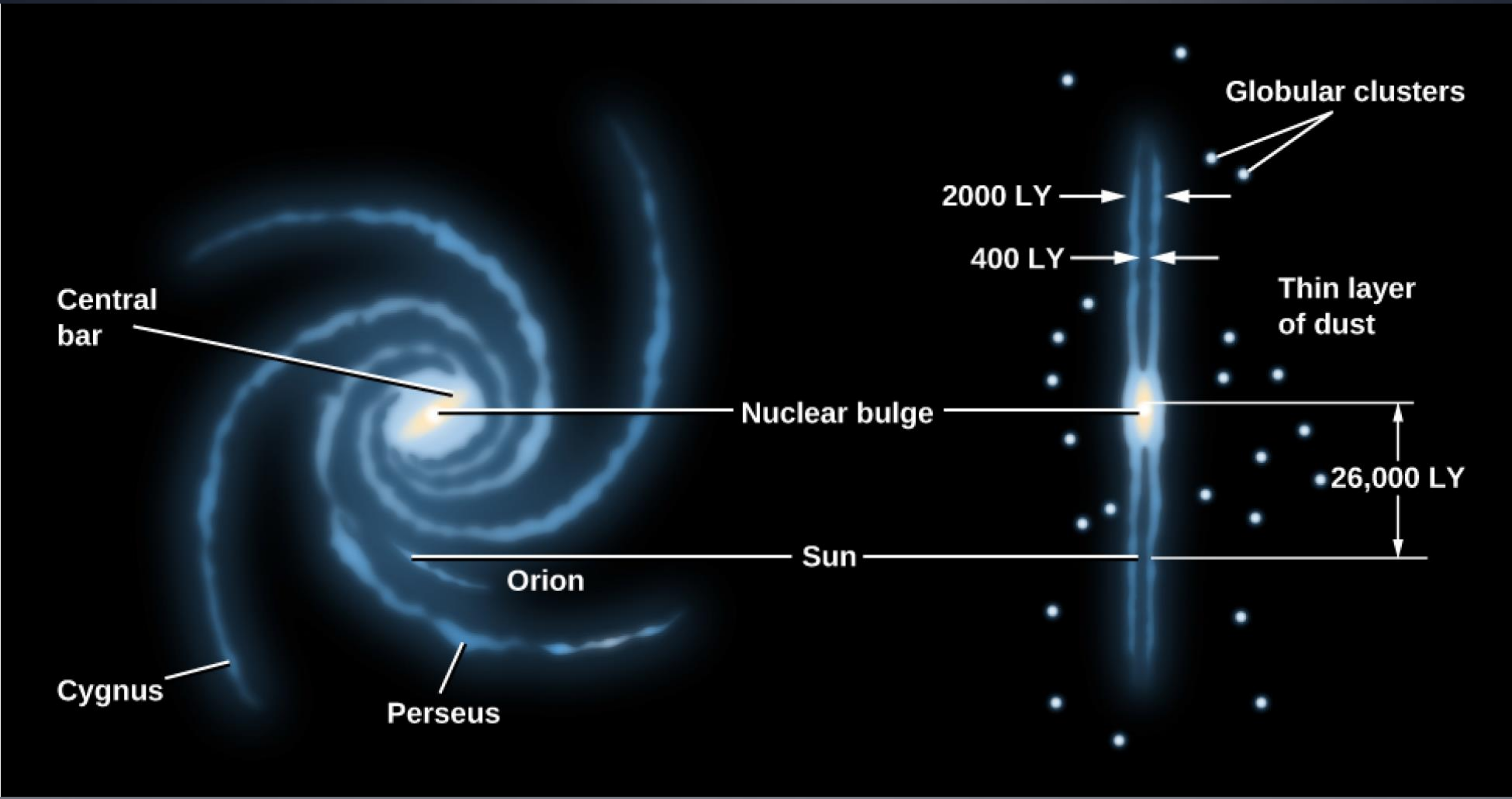

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

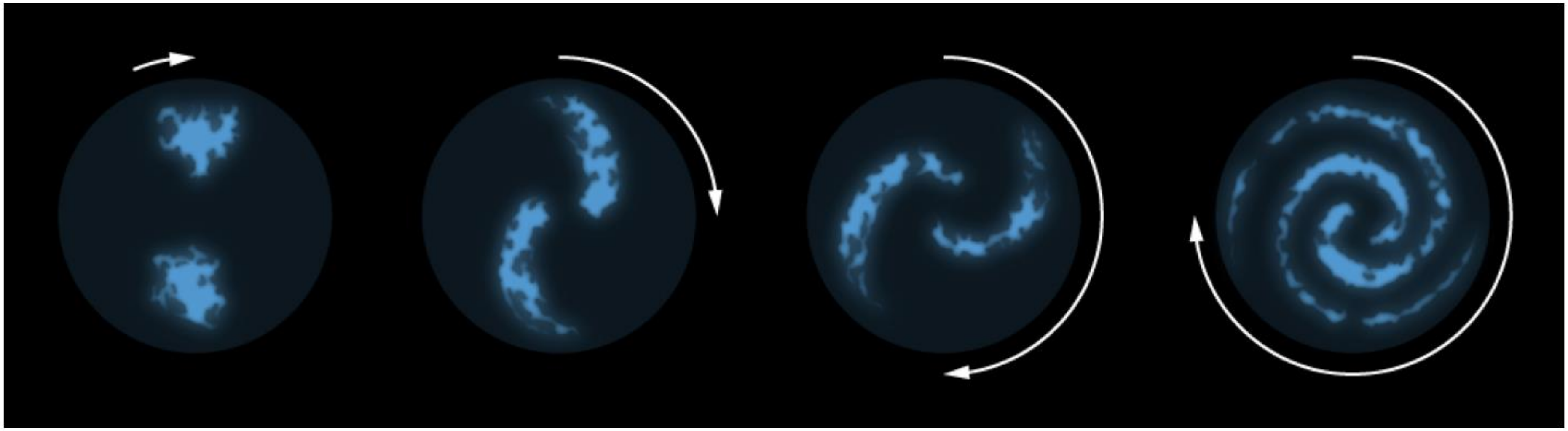
Milky Way/All Sky: radio emission

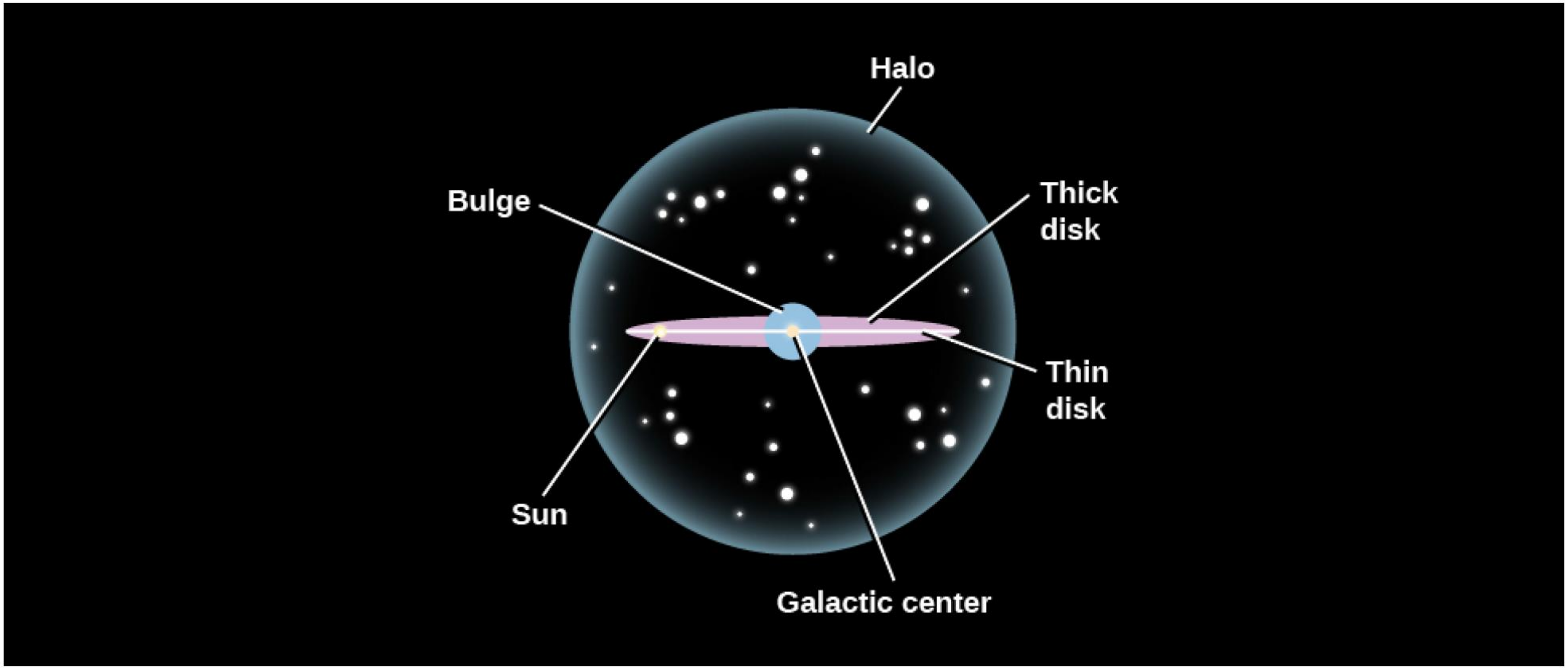


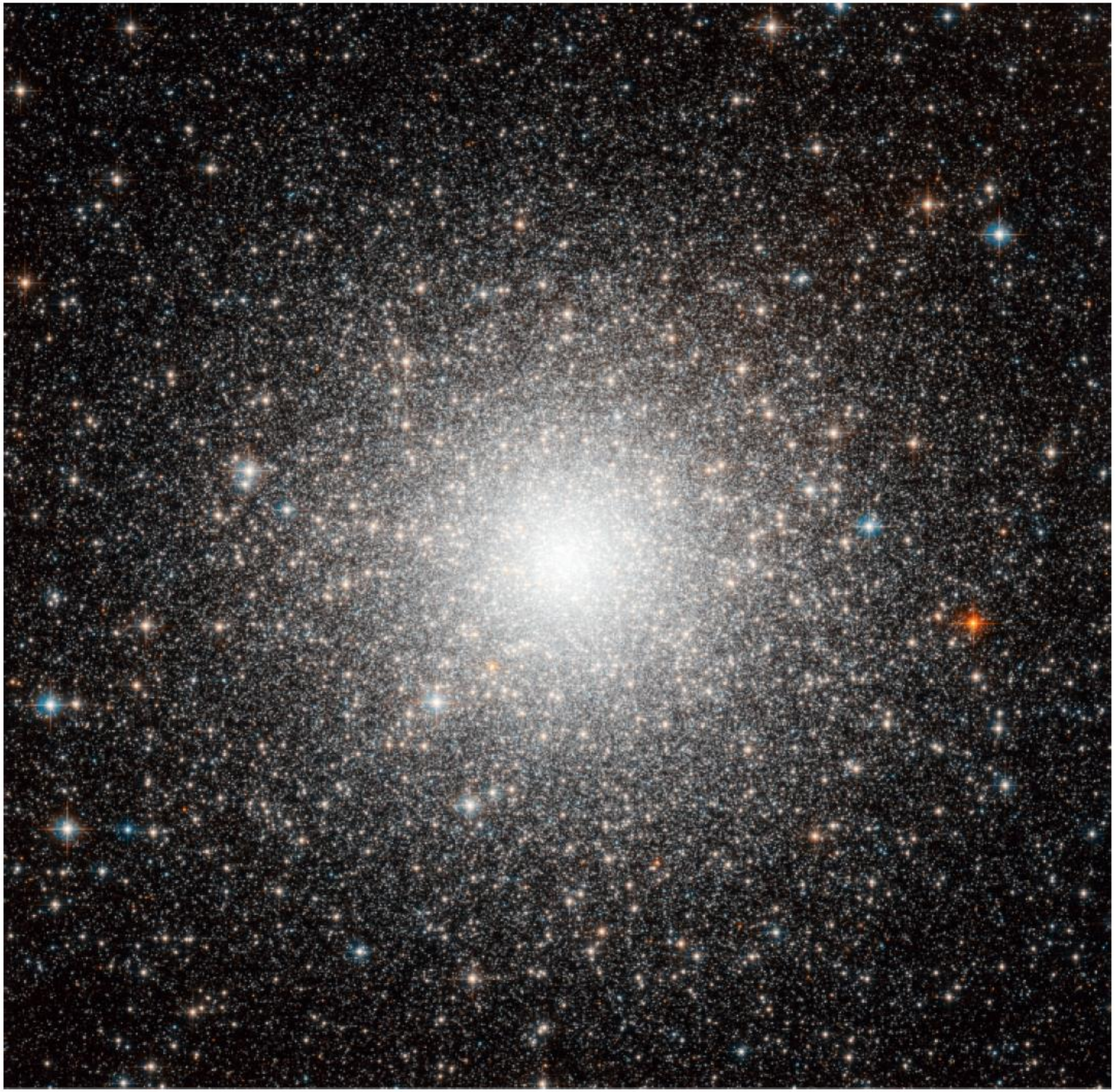
All-sky Gamma Ray emission





Globular clusters
2000 LY
400 LY
Thin layer of dust
Central bar
Nuclear bulge
26,000 LY
Sun
Orion
Cygnus
Perseus



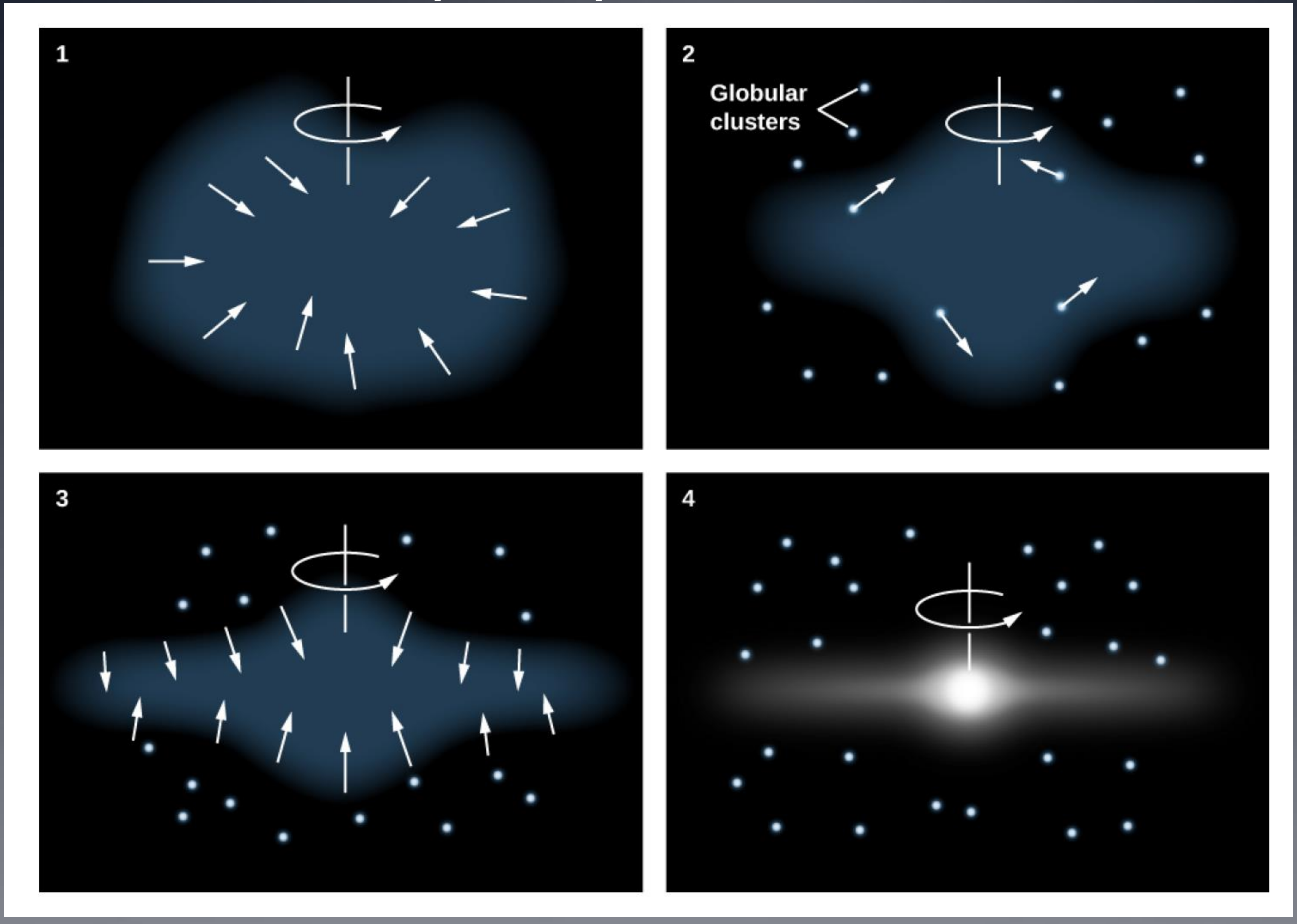

Halo
Bulge
Thick
disk
Thin
disk
Sun
Galactic center



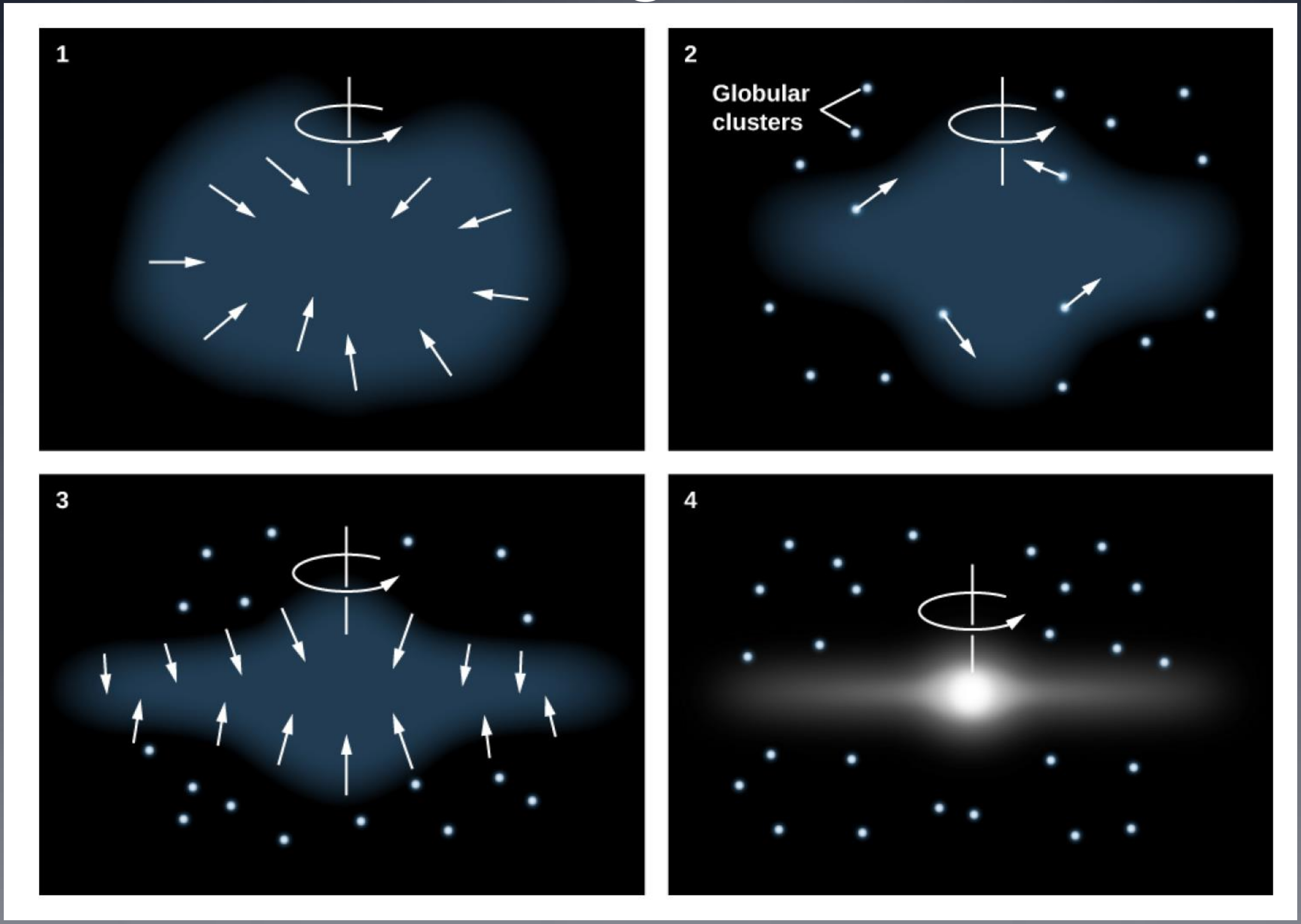
Characteristics of the Milky Way Galaxy

Property	Thin Disk	Thick Disk	Stellar Halo (Excludes Dark Matter)
Stellar mass	$4 \times 10^{10}\ M_{\text{Sun}}$	A few percent of the thin disk mass	$10^{10}\ M_{\text{Sun}}$
Luminosity	$3 \times 10^{10}\ L_{\text{Sun}}$	A few percent of the thin disk luminosity	$8 \times 10^{8}\ L_{\text{Sun}}$
Typical age of stars	1 million to 10 billion years	11 billion years	13 billion years
Heavier-element abundance	High	Intermediate	Very low
Rotation	High	Intermediate	Very low

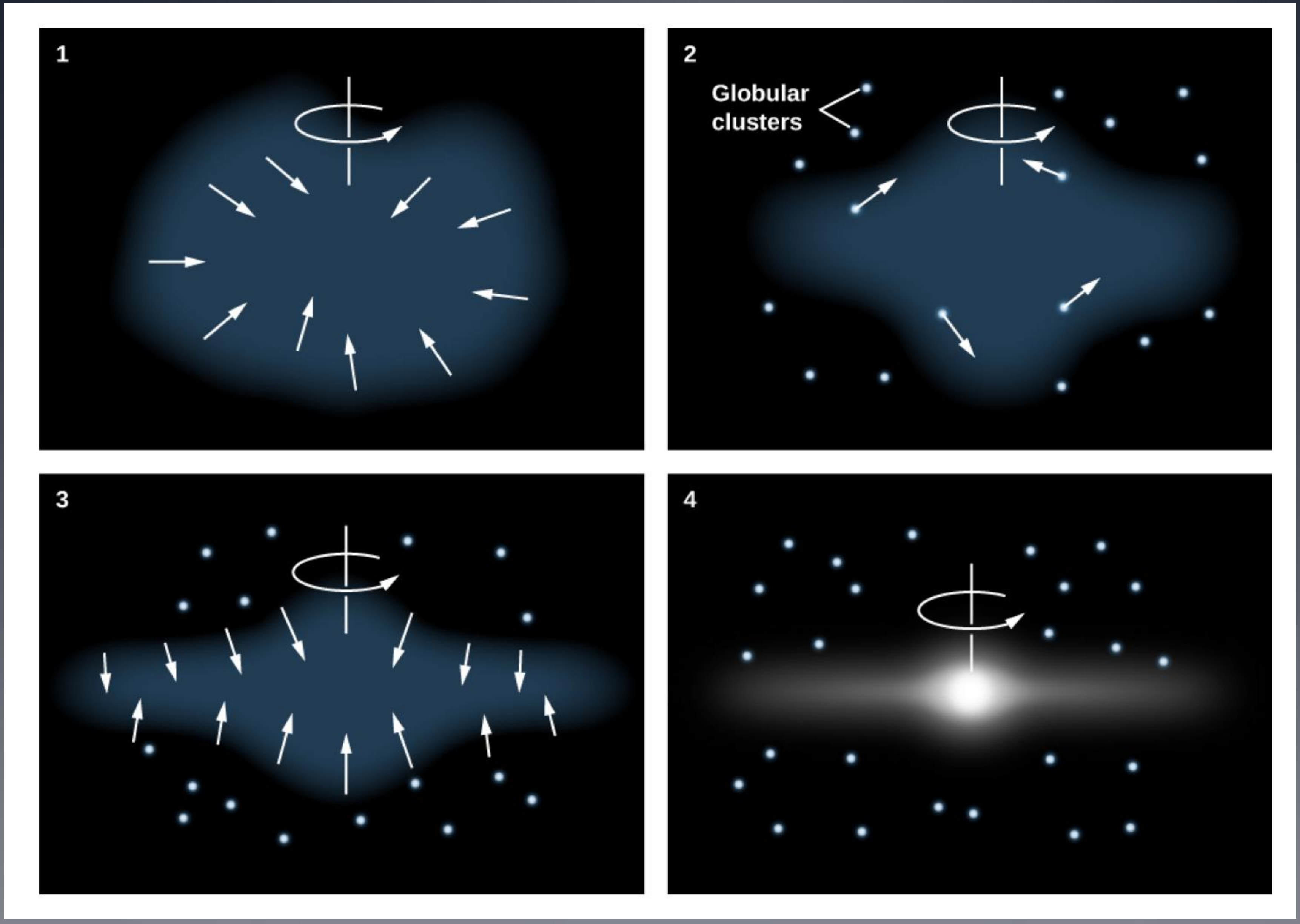
1. Milky Way starts to form



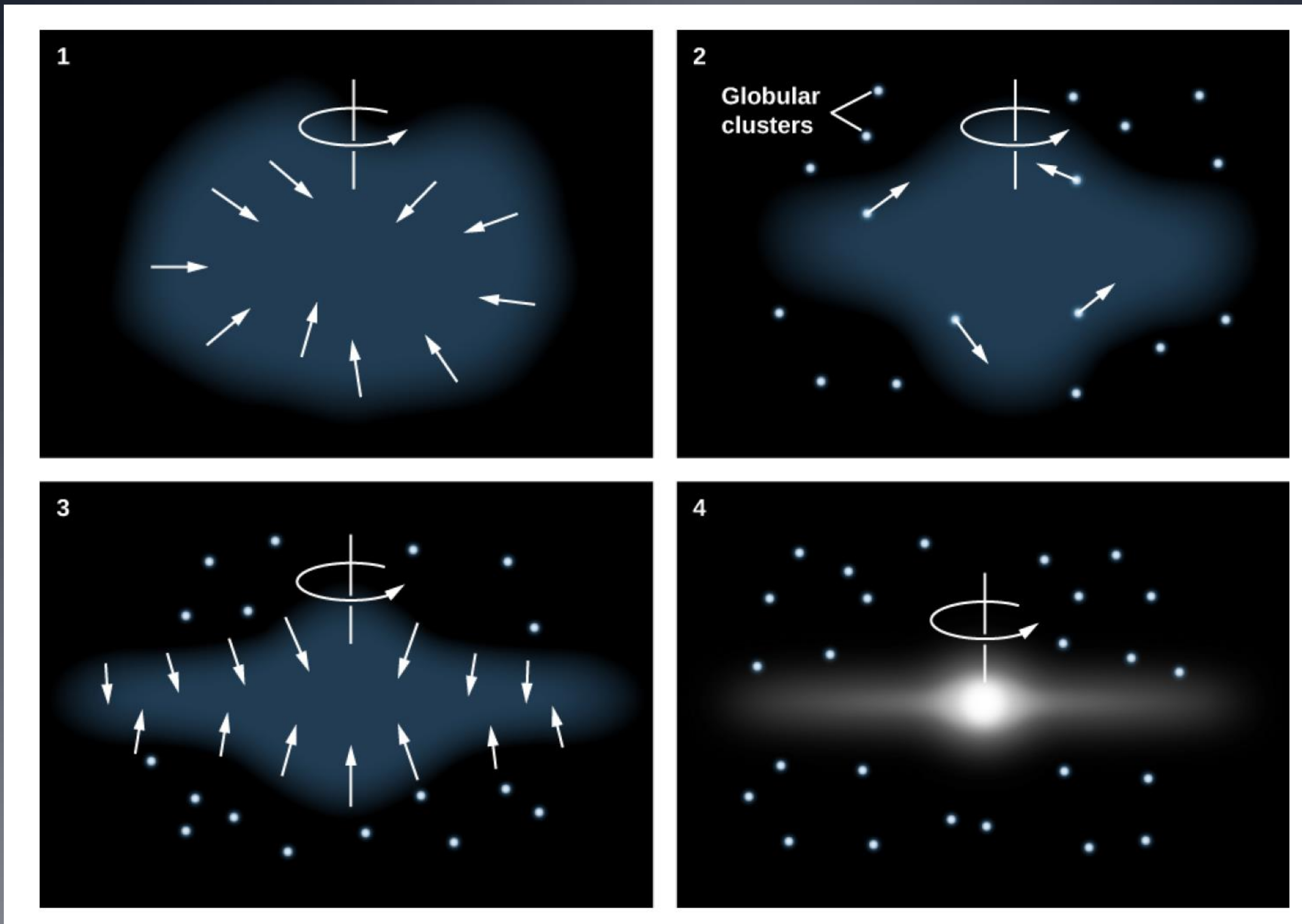
2. First stars in globular clusters



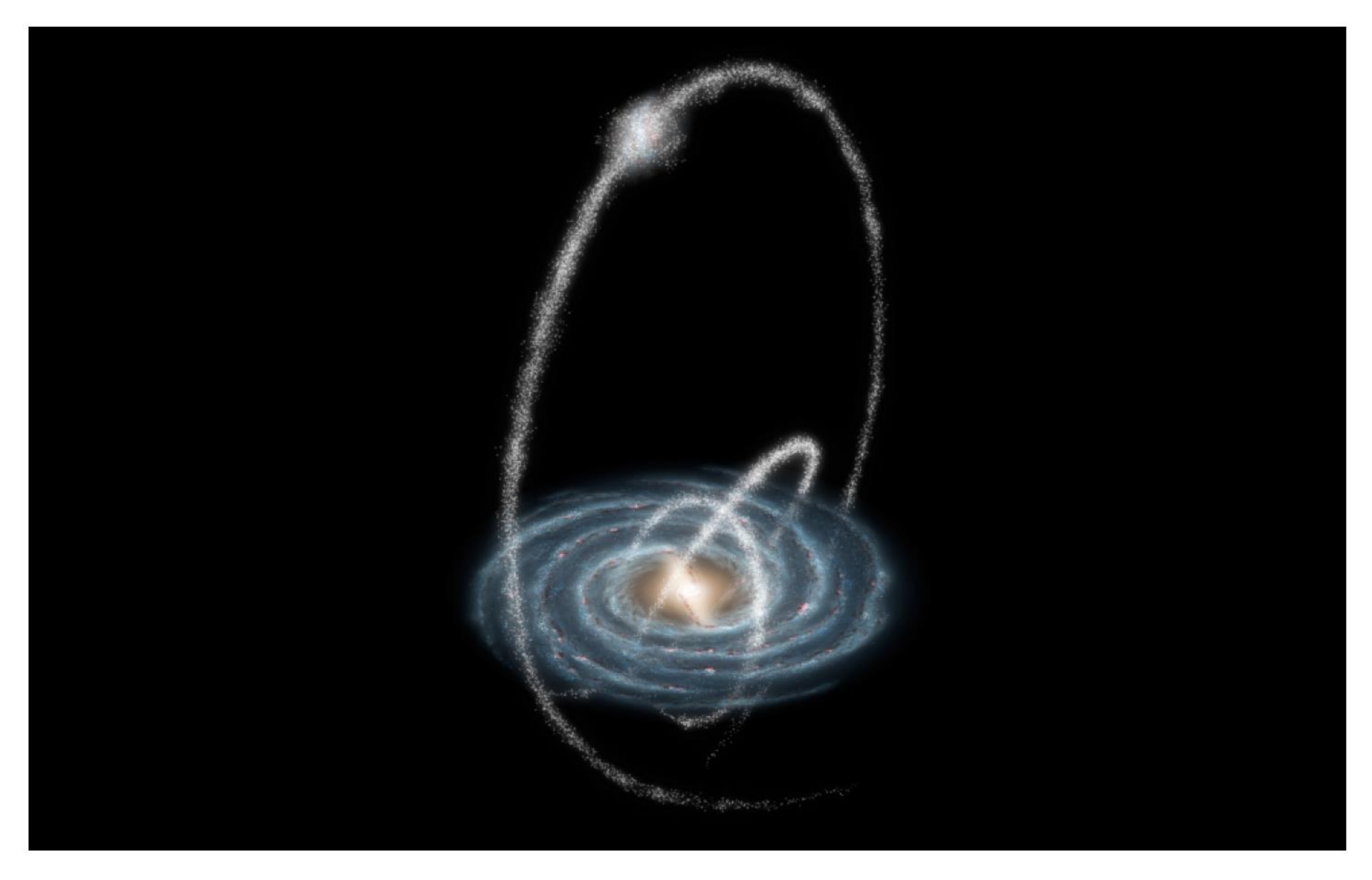
3. Gas collapses into disk (angular momentum)



4. Stars continue to form in galactic disk



Milky Way: historical mergers



Characteristics of the Milky Way Galaxy

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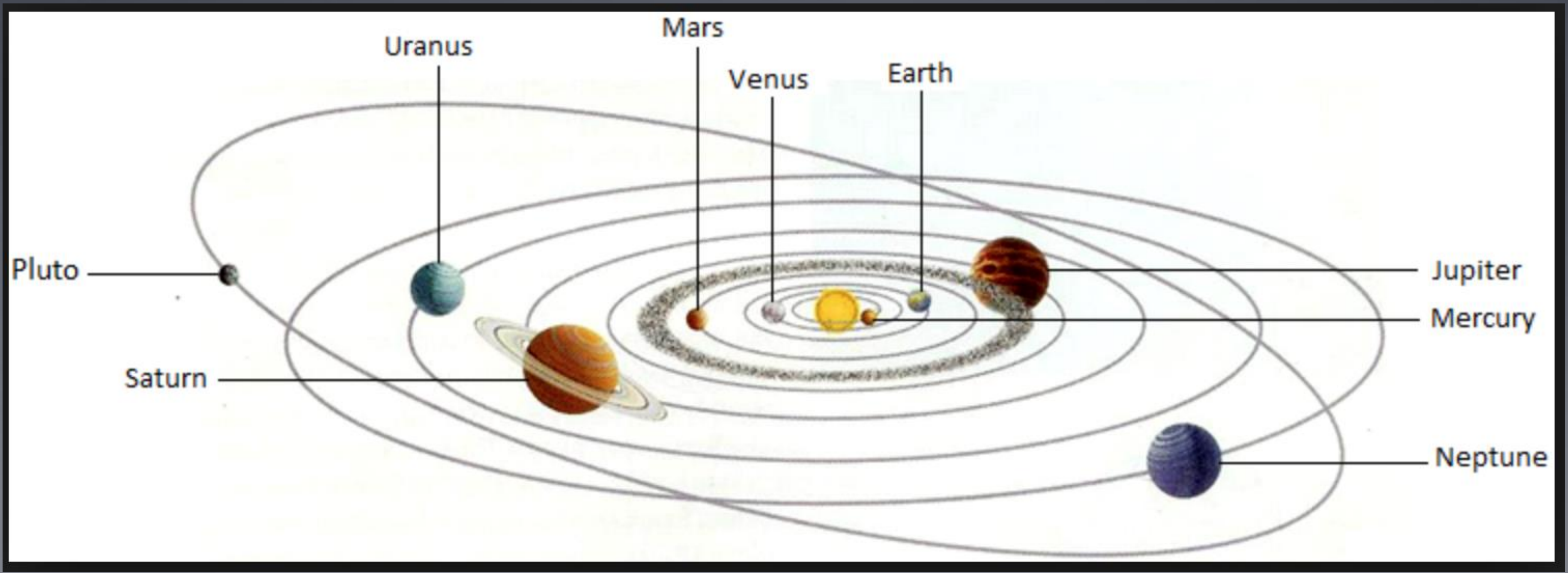
Stellar mass	$4 \times 10^{10}\ M_{\text{Sun}}$	A few percent of the thin disk mass	$10^{10}\ M_{\text{Sun}}$
Luminosity	$3 \times 10^{10}\ L_{\text{Sun}}$	A few percent of the thin disk luminosity	$8 \times 10^{8}\ L_{\text{Sun}}$
Typical age of stars	1 million to 10 billion years	11 billion years	13 billion years
Heavier-element abundance	High	Intermediate	Very low
Rotation	High	Intermediate	Very low

- How to measure the mass of the central supermassive black hole?
- How to measure the mass of the galaxy?
- How to identify spiral arms?

Kepler's laws!

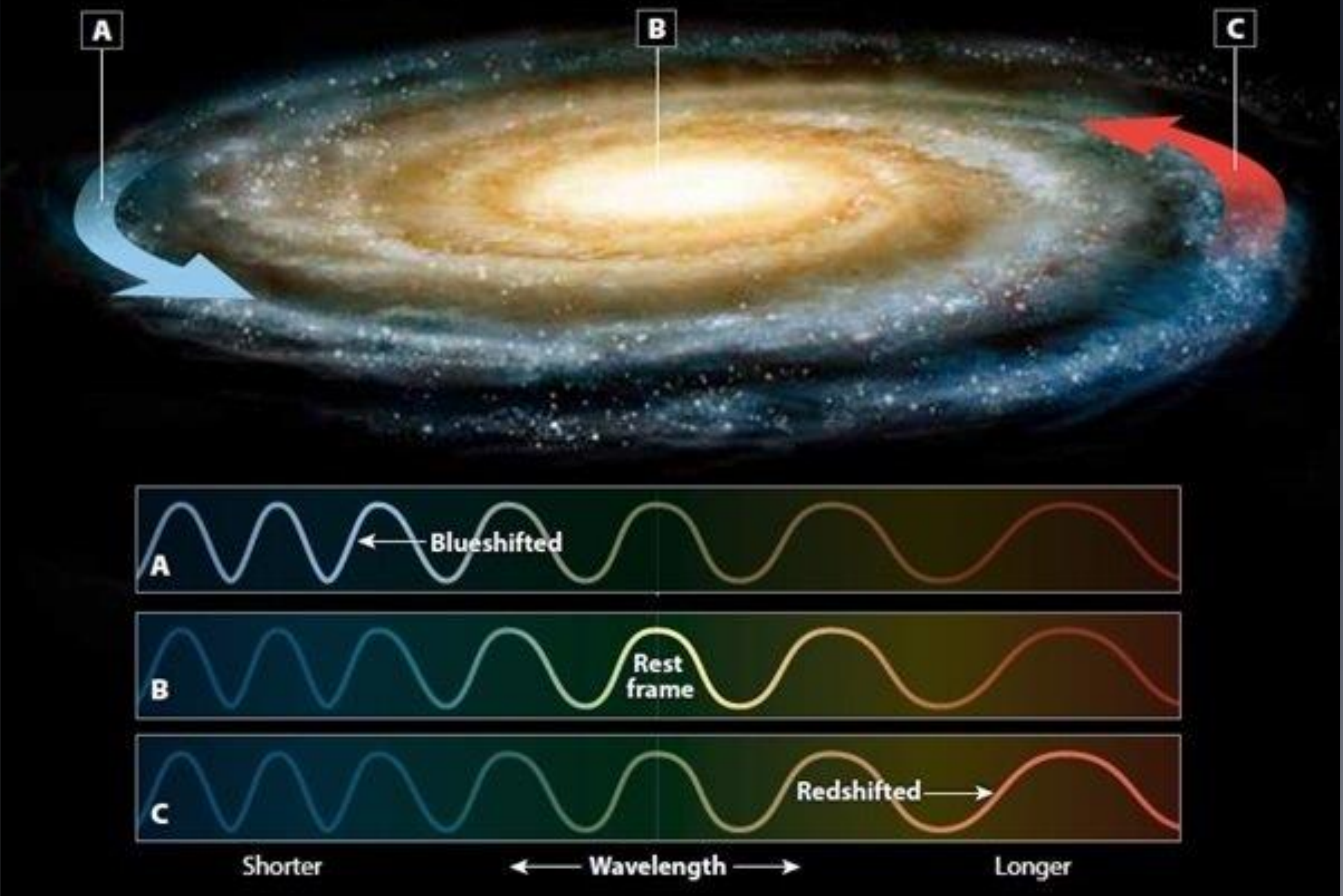


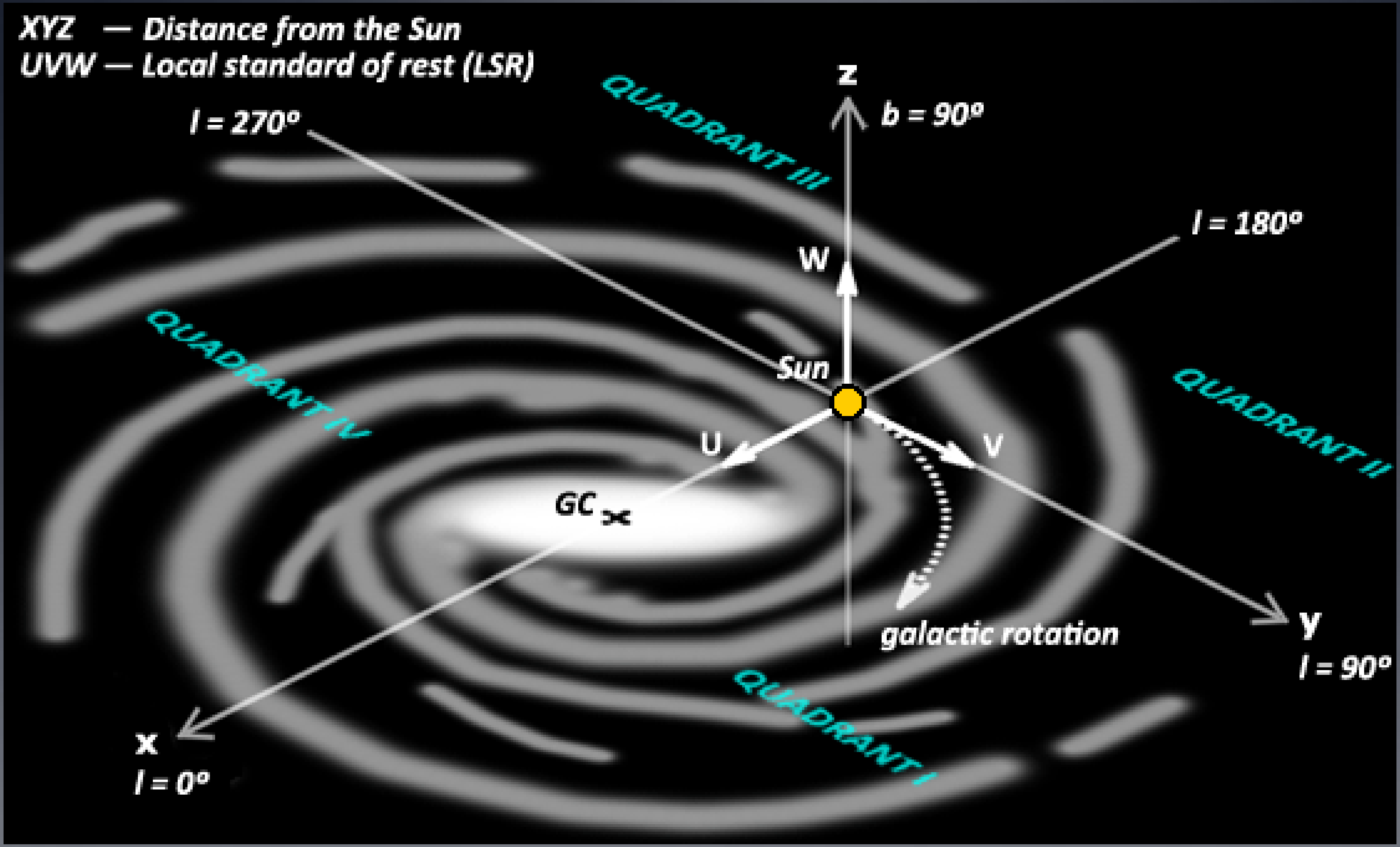
$$T^2 = \frac{4\pi^2}{GM}a^3$$

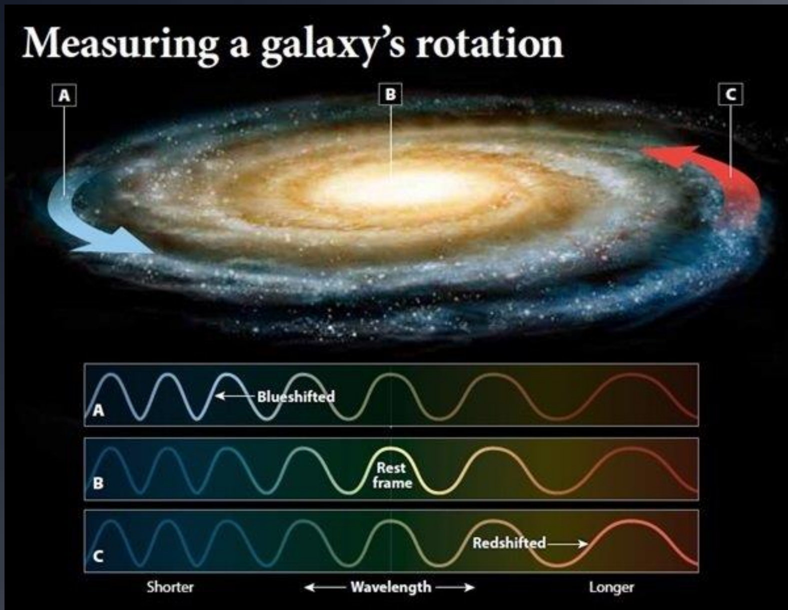
Planetary Data Applied to Kepler's Third Law

Planet	Mean Distance from Sun, r (10^6 km)	Period, T (Earth Years)	r^3/T^2 (10^{24} km^3/yr^2)
Mercury	57.9	0.241	3.34
Venus	108.2	0.615	3.35
Earth	149.6	1.0	3.35
Mars	227.9	1.88	3.35
Jupiter	778.3	11.86	3.35
Saturn	1427	29.5	3.34
Uranus	2870	84.0	3.35
Neptune	4497	165	3.34
Pluto	5900	248	3.33

Measuring a galaxy's rotation

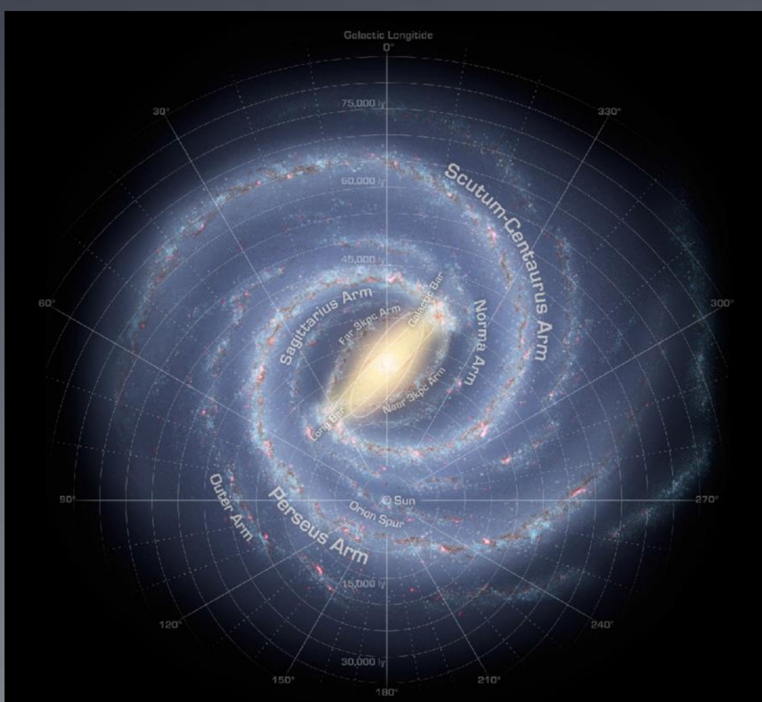



XYZ — Distance from the Sun
UVW — Local standard of rest (LSR)
QUADRANT III
QUADRANT IV
QUADRANT II
QUADRANT I
z
b = 90º
l = 270º
l = 180º
W
Sun
U
V
GC
galactic rotation
y
l = 90º
x
l = 0º

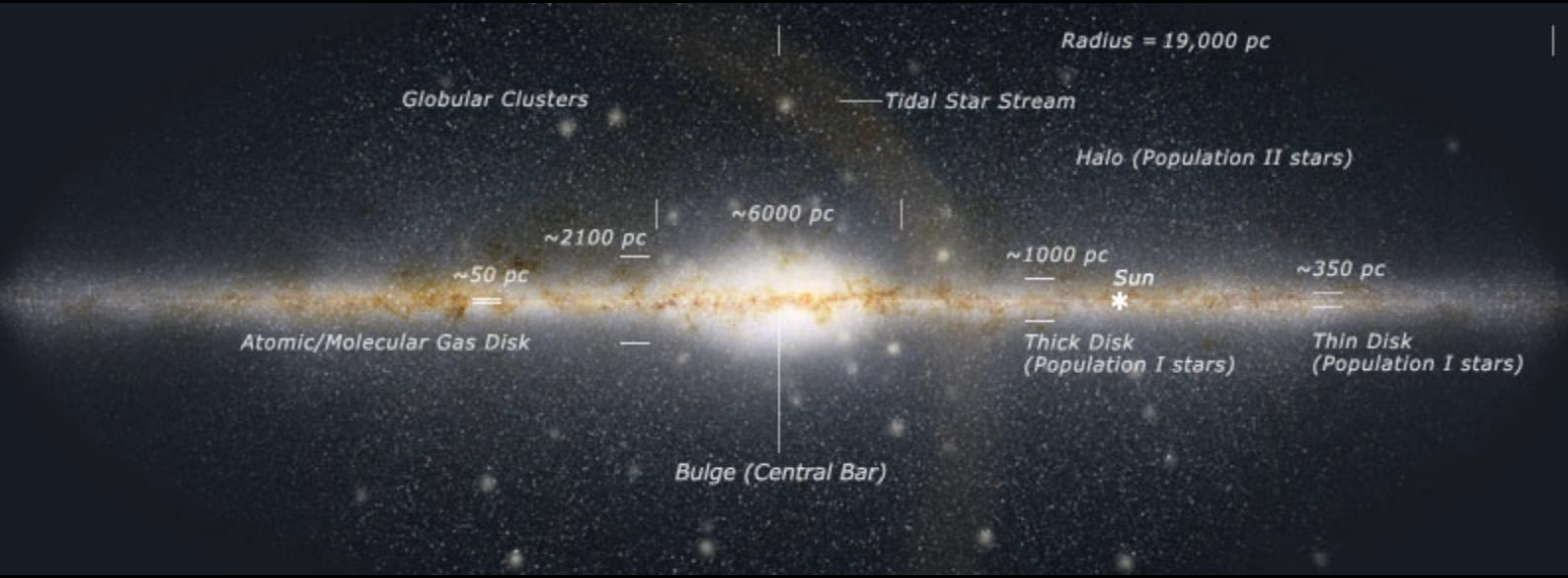


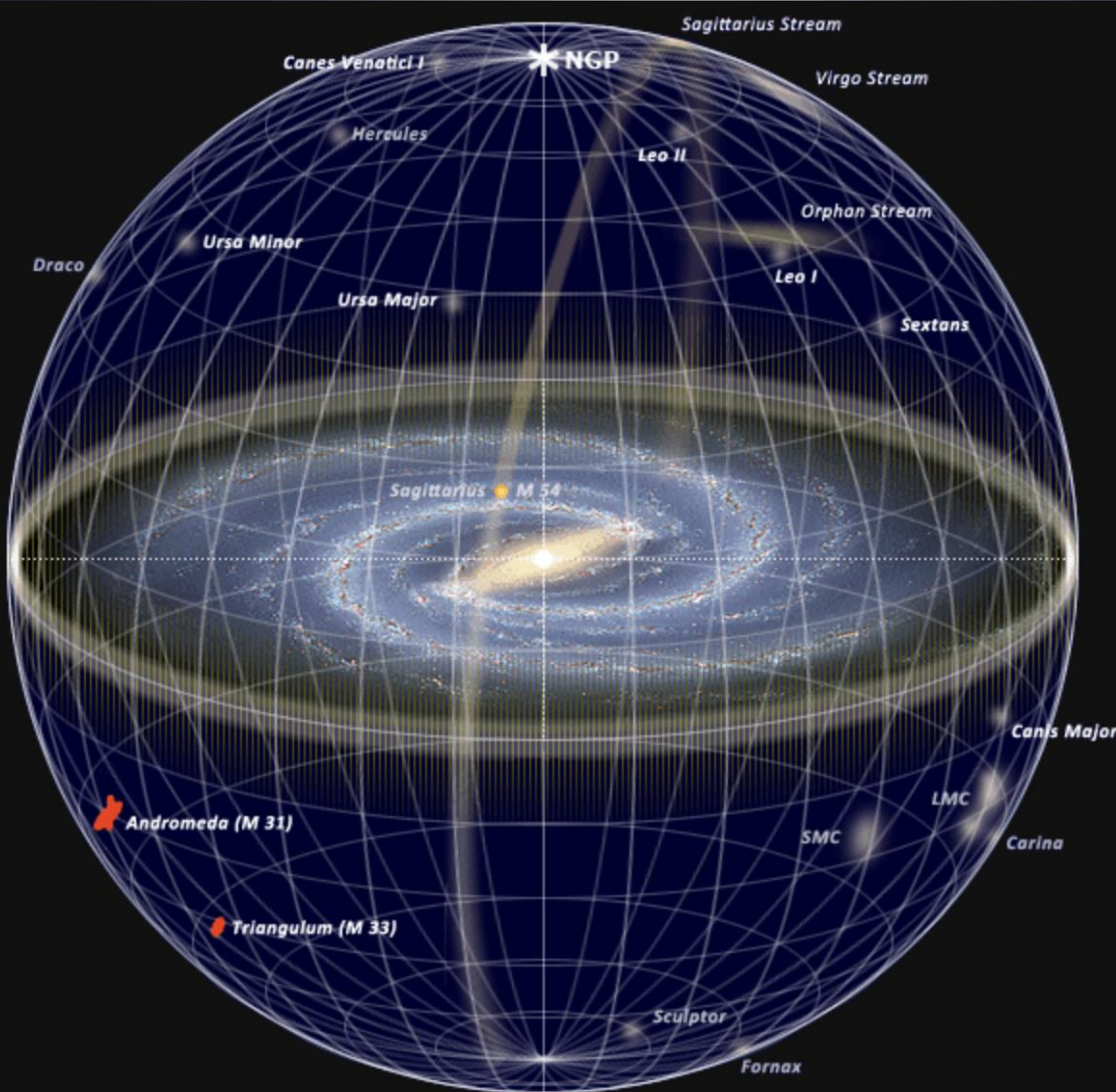
- Stellar density
- Gas density
- Velocities of star and gas

- Spiral structures
- Bar at center

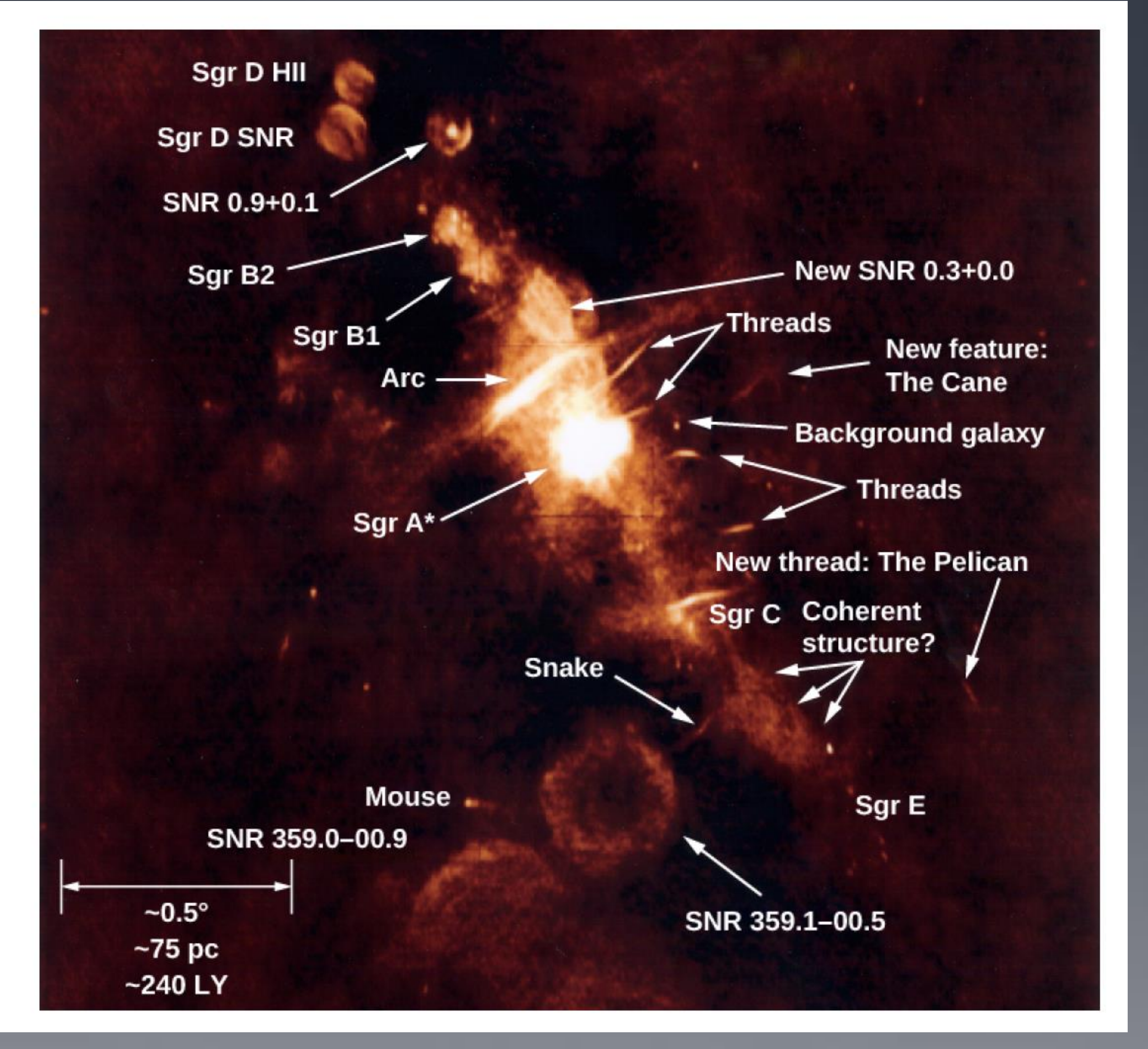


- Sun: 230 km/s
- One "galactic year": 230 million years
  - Sun has had 20 trips around
  - Permian–Triassic extinction event was ~1 galactic year ago
  - Cambrian explosion: 2.4 years ago
- 25,000 light years from galactic center

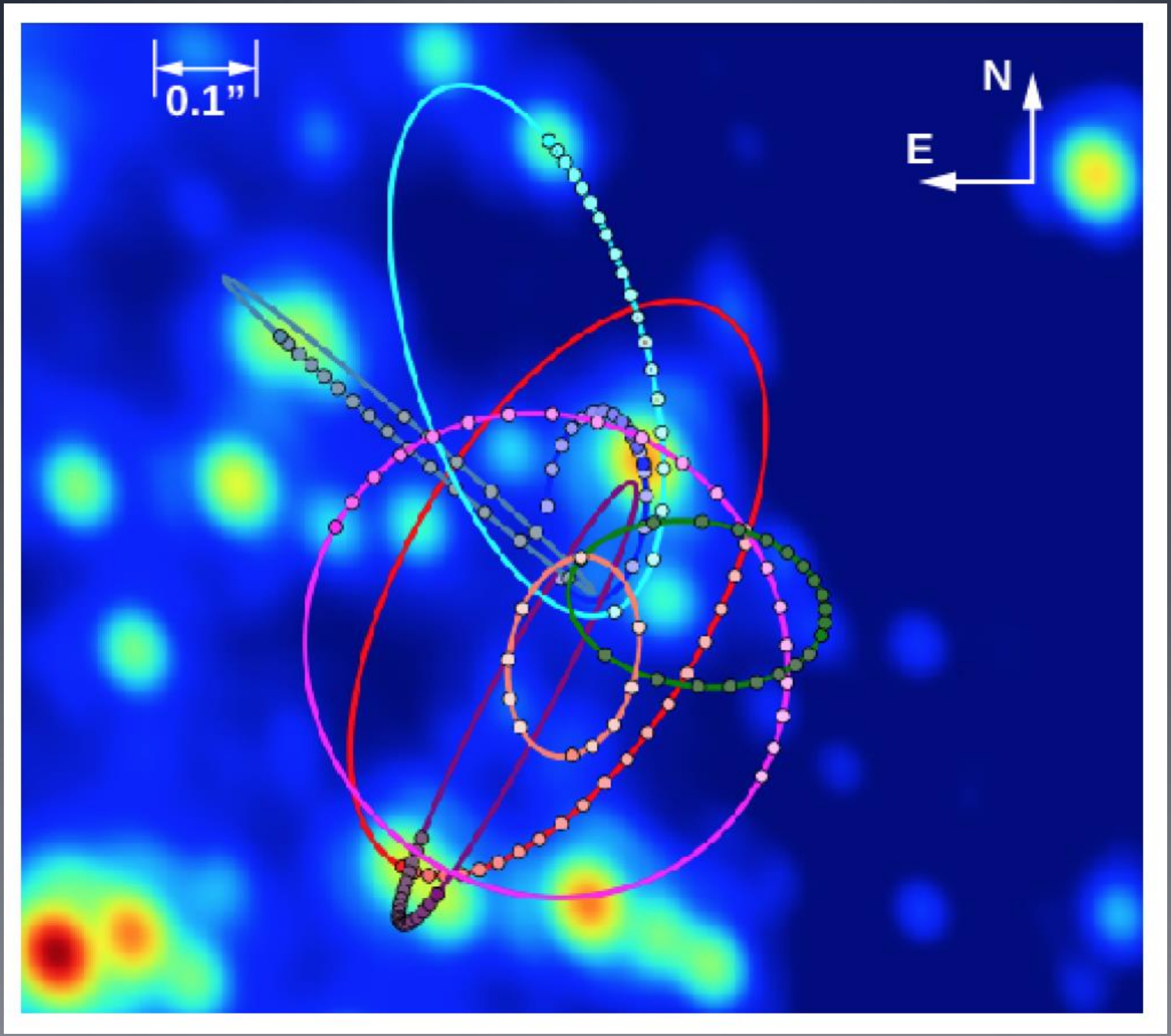

Radius = 19,000 pc
Globular Clusters
Tidal Star Stream
Halo (Population II stars)
~6000 pc
~2100 pc
~1000 pc
~50 pc
Sun
~350 pc
Atomic/Molecular Gas Disk
Thick Disk
(Population I stars)
Thin Disk
(Population I stars)
Bulge (Central Bar)


Sagittarius Stream
Canes Venatici I
NGP
Virgo Stream
Hercules
Leo II
Orphan Stream
Ursa Minor
Draco
Leo I
Ursa Major
Sextans
Sagittarius
M 54
Canis Major
LMC
Andromeda (M 31)
SMC
Carina
Triangulum (M 33)
Sculptor
Fornax

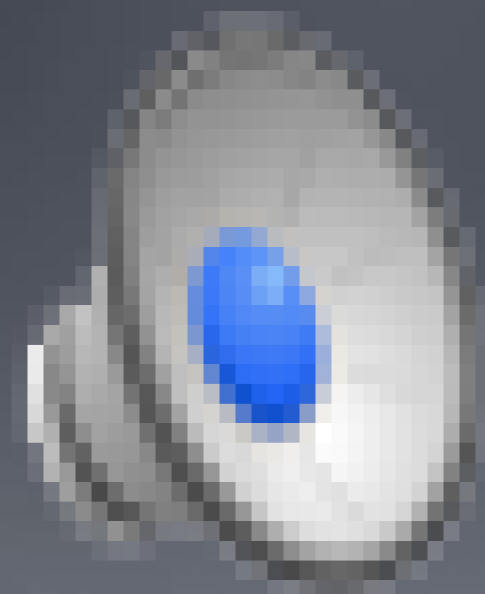
What is at the center of the galaxy?



Galactic center orbits



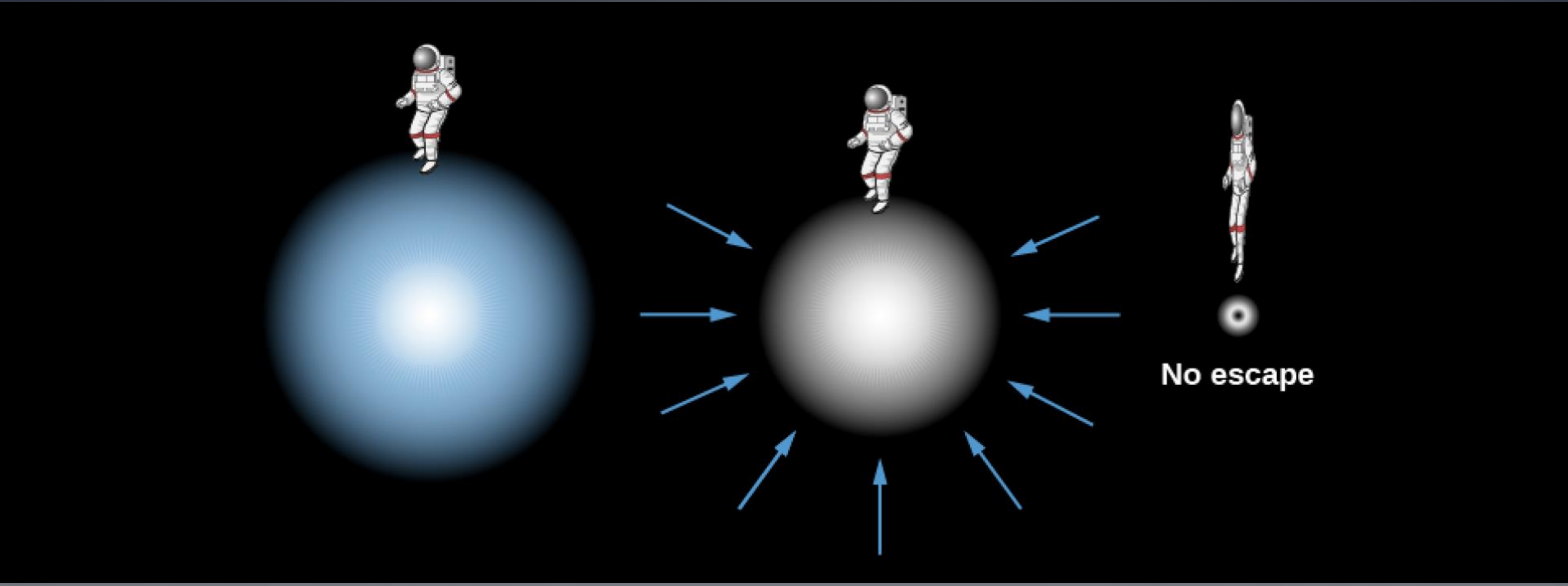
Galactic center orbits



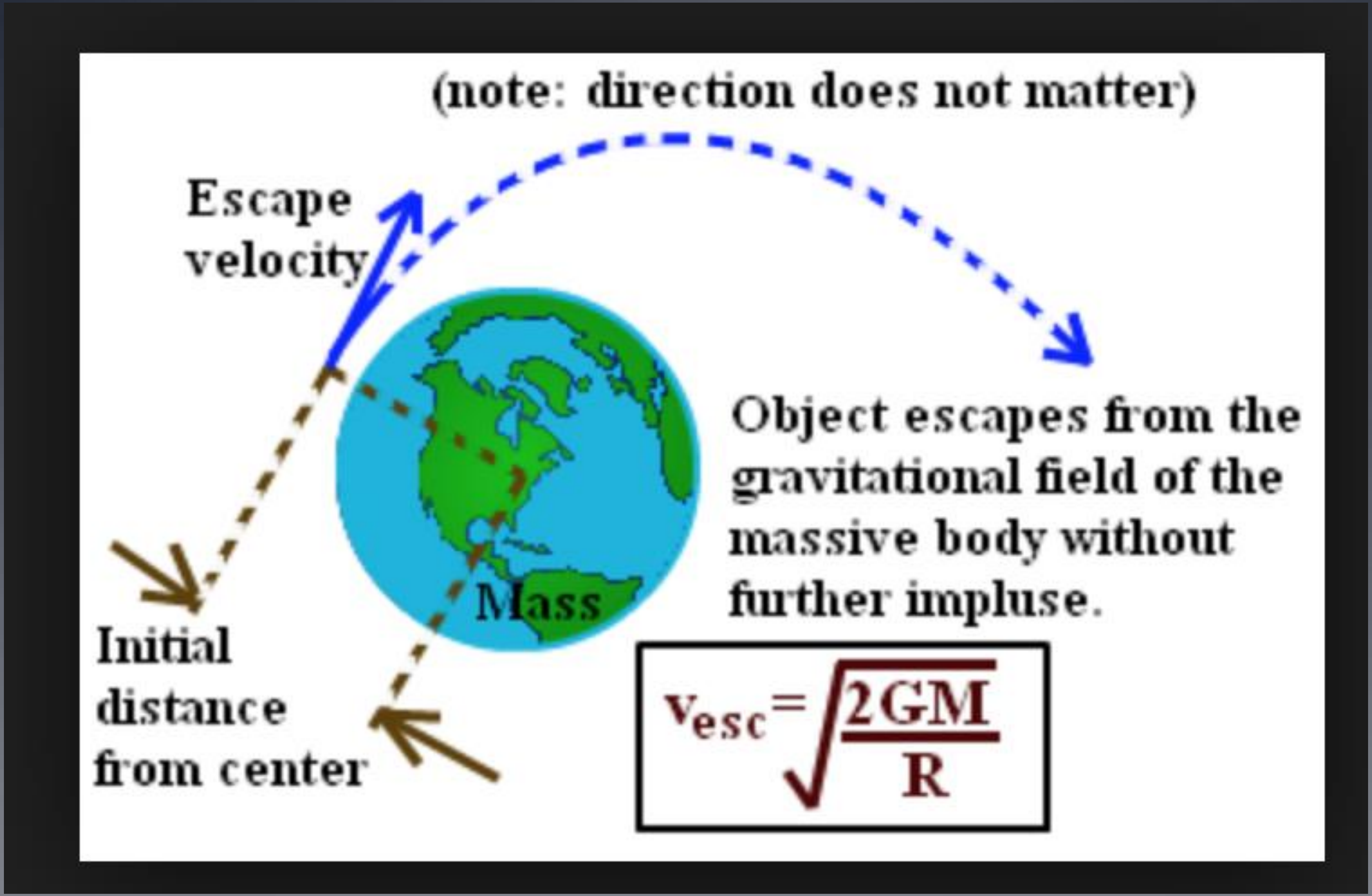
Nobel Prize in Physics (2020): Reinhard Genzel, Andrea Ghez

Event Horizon Telescope:
image of Milky Way black hole

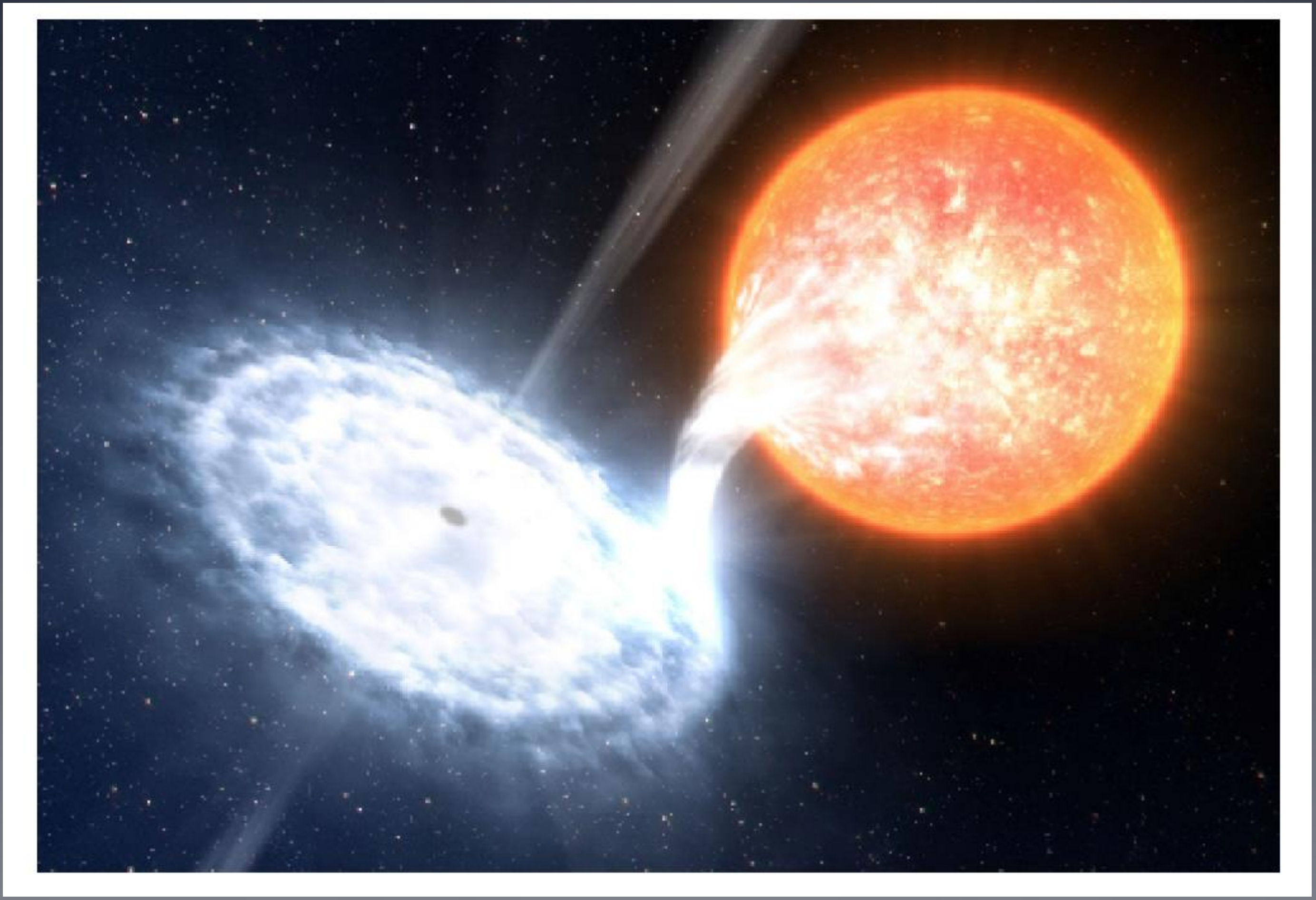
Black holes: gravity high enough (large mass, small volume) that light cannot escape



Black holes: gravity high enough (large mass, small volume) that light cannot escape



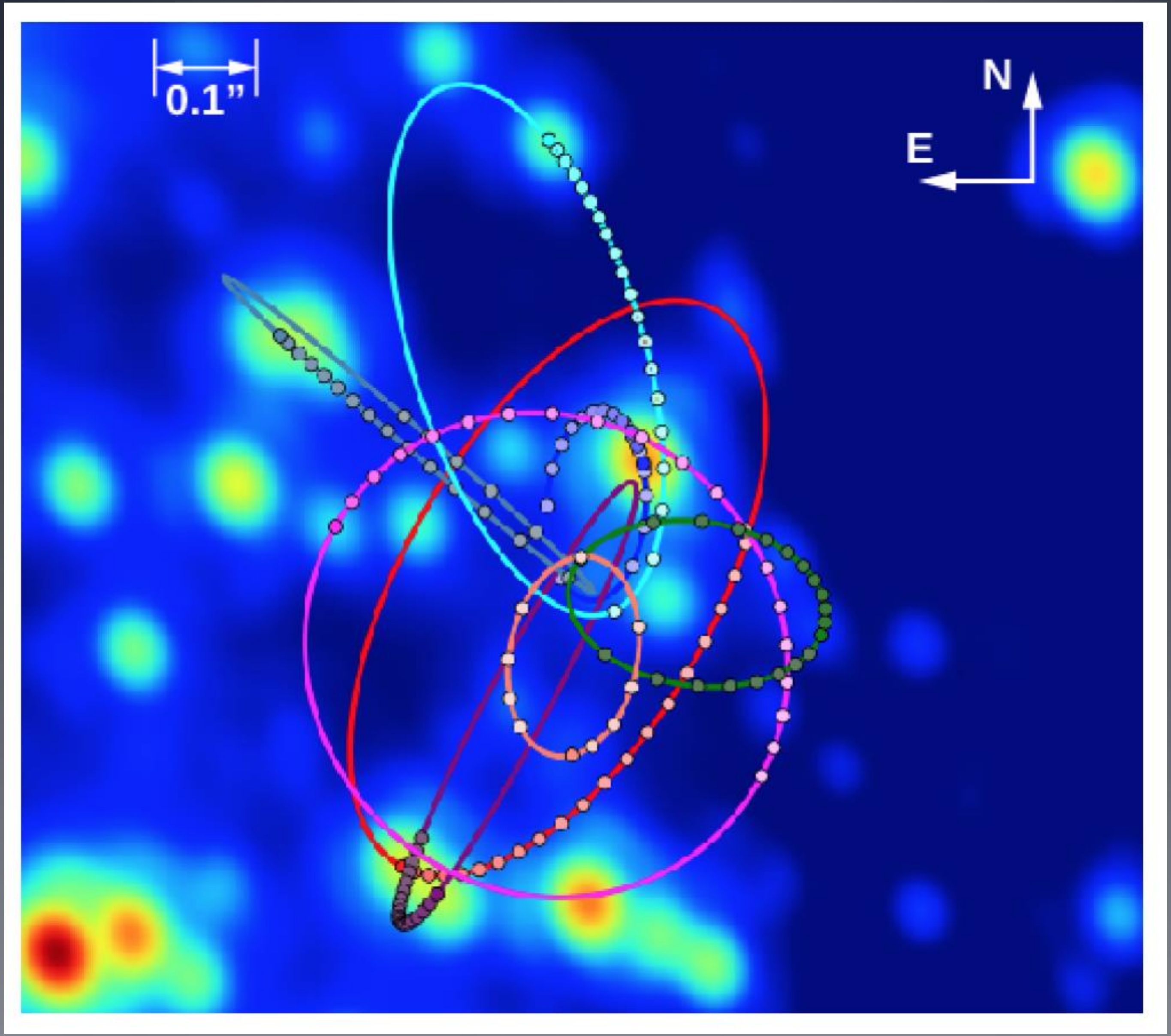
Some black holes accrete:
We can see heated accretion disk

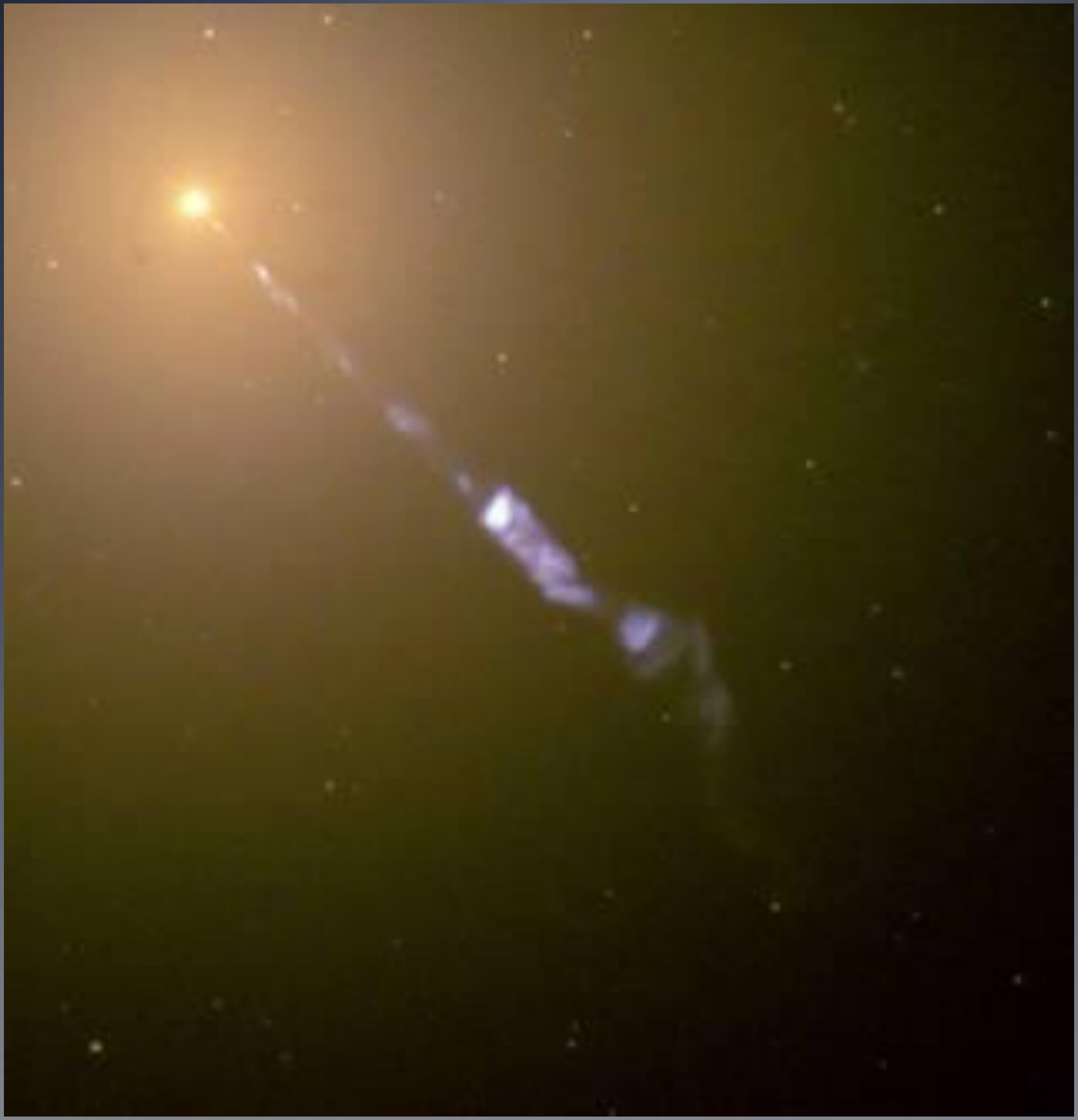


Some Black Hole Candidates in Binary Star Systems

Name/Catalog Designation[2]	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass Estimates (M_{Sun})
LMC X-1	O giant	3.9	10.9
Cygnus X-1	O supergiant	5.6	15
XTE J1819.3-254 (V4641 Sgr)	B giant	2.8	6–7
LMC X-3	B main sequence	1.7	7
4U1543-475 (IL Lup)	A main sequence	1.1	9
GRO J1655-40 (V1033 Sco)	F subgiant	2.6	7
GRS 1915+105	K giant	33.5	14
GS202+1338 (V404 Cyg)	K giant	6.5	12
XTE J1550-564	K giant	1.5	11
A0620-00 (V616 Mon)	K main sequence	0.33	9–13
H1705-250 (Nova Oph 1977)	K main sequence	0.52	5–7
GRS1124-683 (Nova Mus 1991)	K main sequence	0.43	7
GS2000+25 (QZ Vul)	K main sequence	0.35	5–10
GRS1009-45 (Nova Vel 1993)	K dwarf	0.29	8–9
XTE J1118+480	K dwarf	0.17	7
XTE J1859+226	K dwarf	0.38	5.4
GRO J0422+32	M dwarf	0.21	4

Galactic center orbits





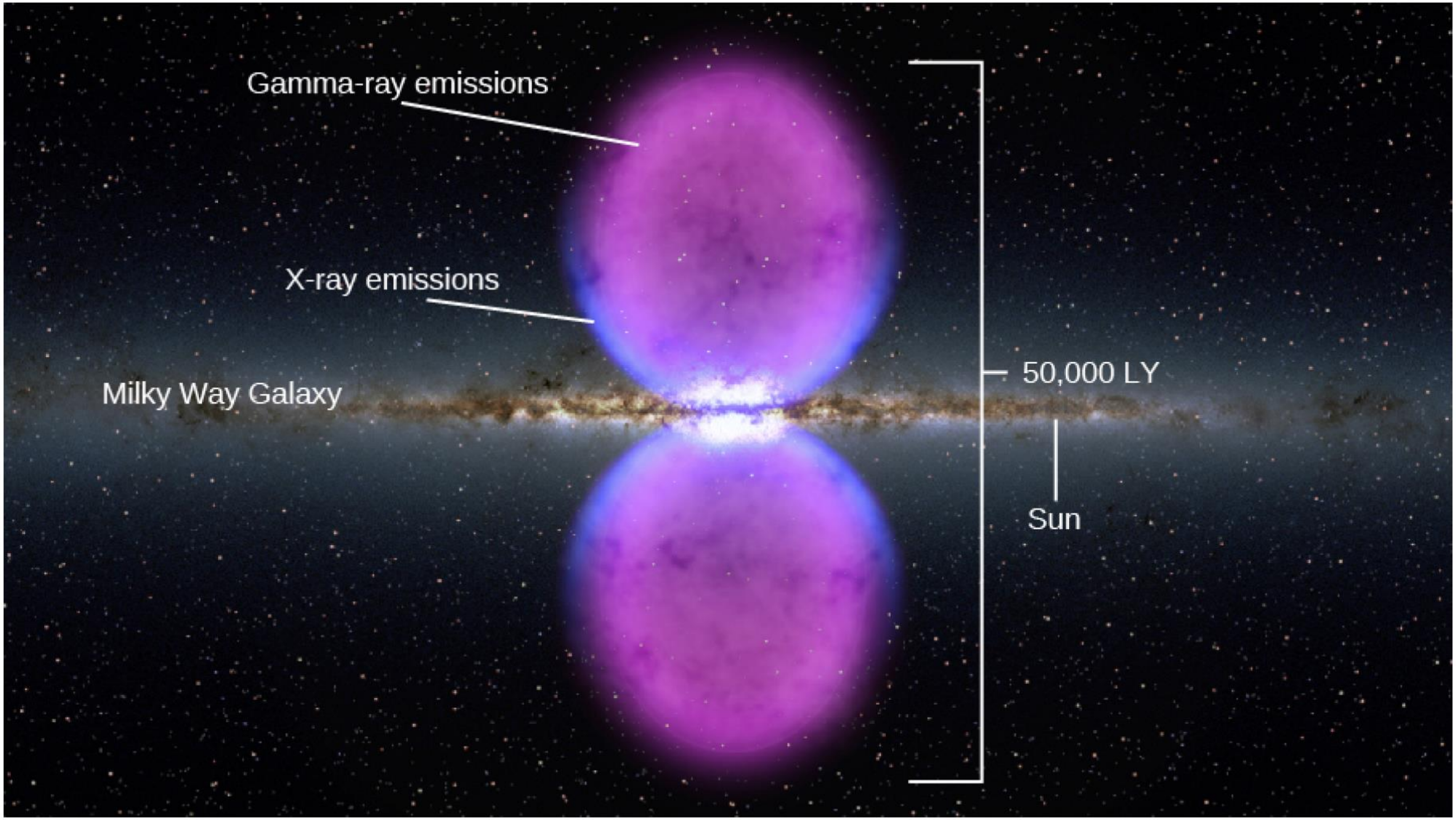
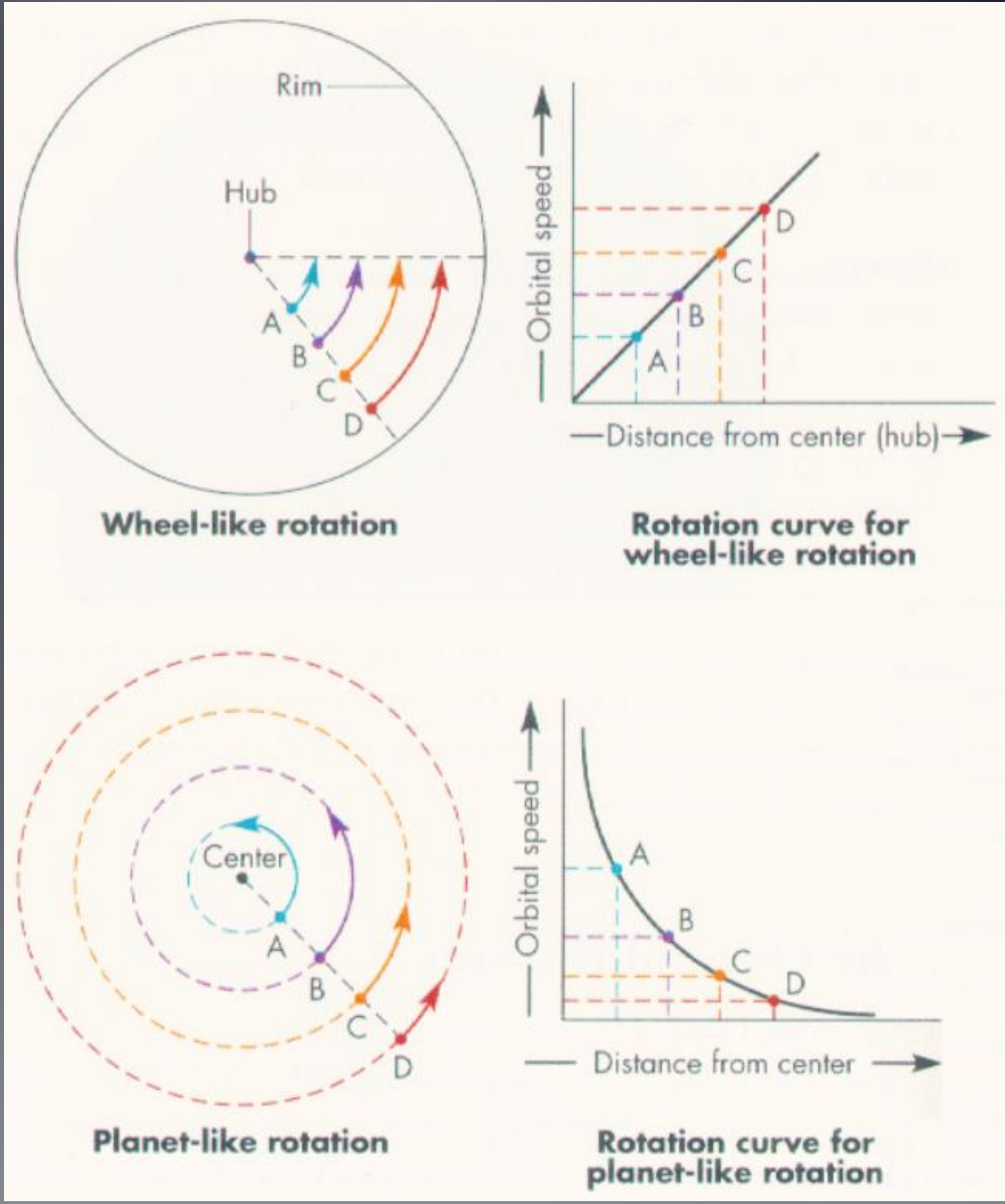
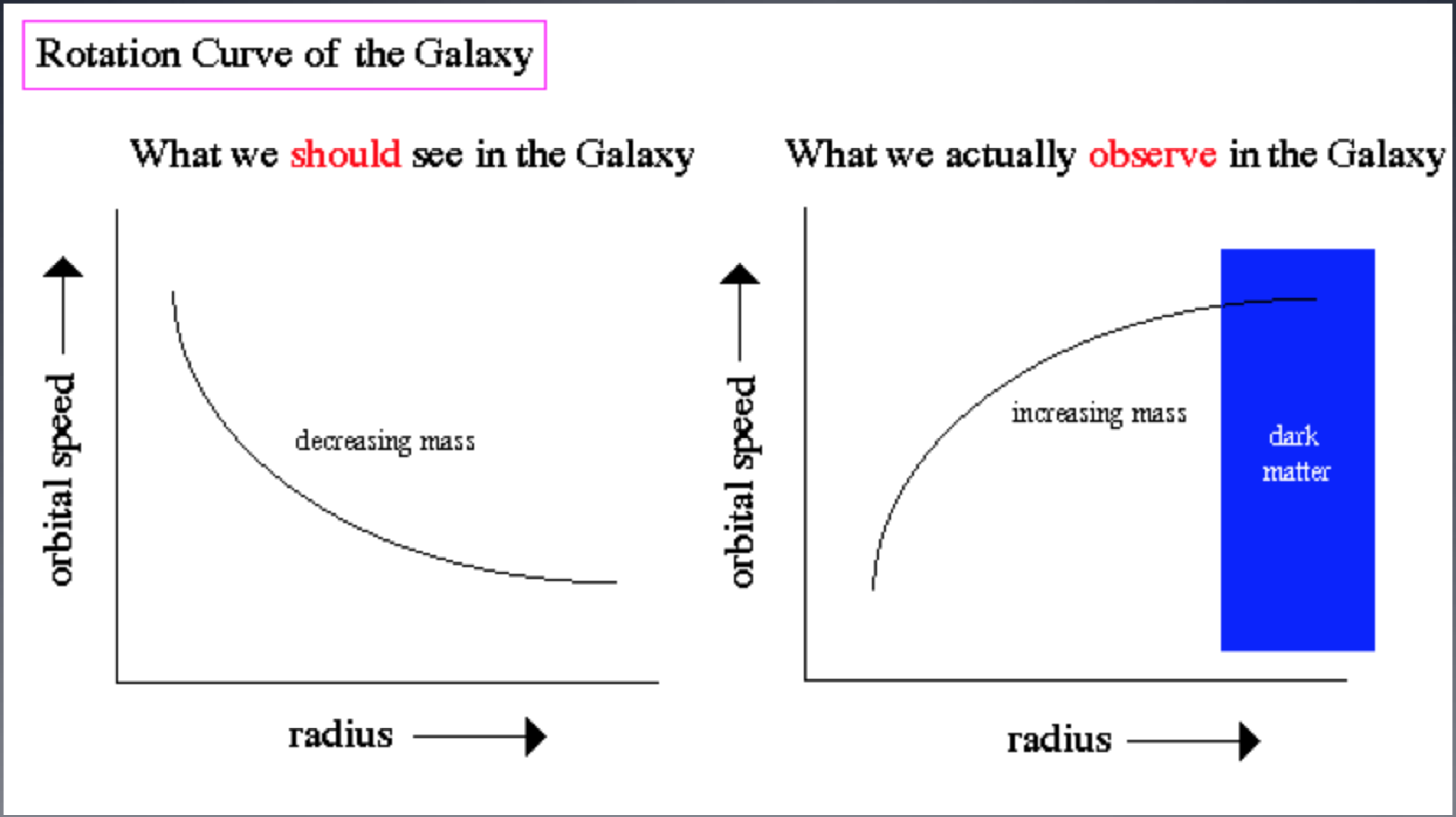


Figure 27.11 Fermi Bubbles in the Galaxy. Giant bubbles shining in gamma-ray light lie above and below the center of the Milky Way Galaxy, as seen by the Fermi satellite. (The gamma-ray and X-ray image is superimposed on a visible-light image of the inner parts of our Galaxy.) The bubbles may be evidence that the supermassive black hole at the center of our Galaxy was a quasar a few million years ago. (credit: modification of work by NASA's Goddard Space Flight Center)

- How to measure the mass of the galaxy?

Kepler's laws!




Rotation Curve of the Galaxy
What we should see in the Galaxy
orbital speed
decreasing mass
radius
What we actually observe in the Galaxy
orbital speed
increasing mass
dark matter
radius

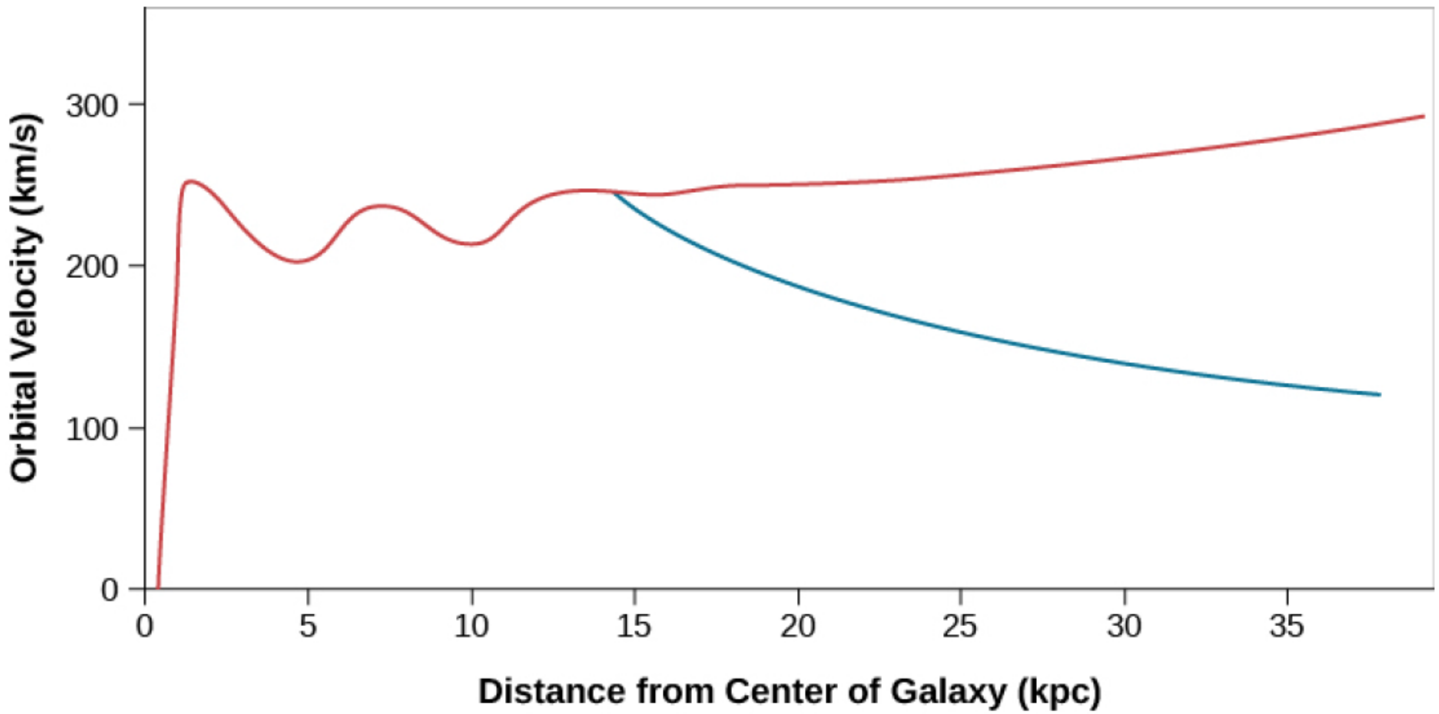
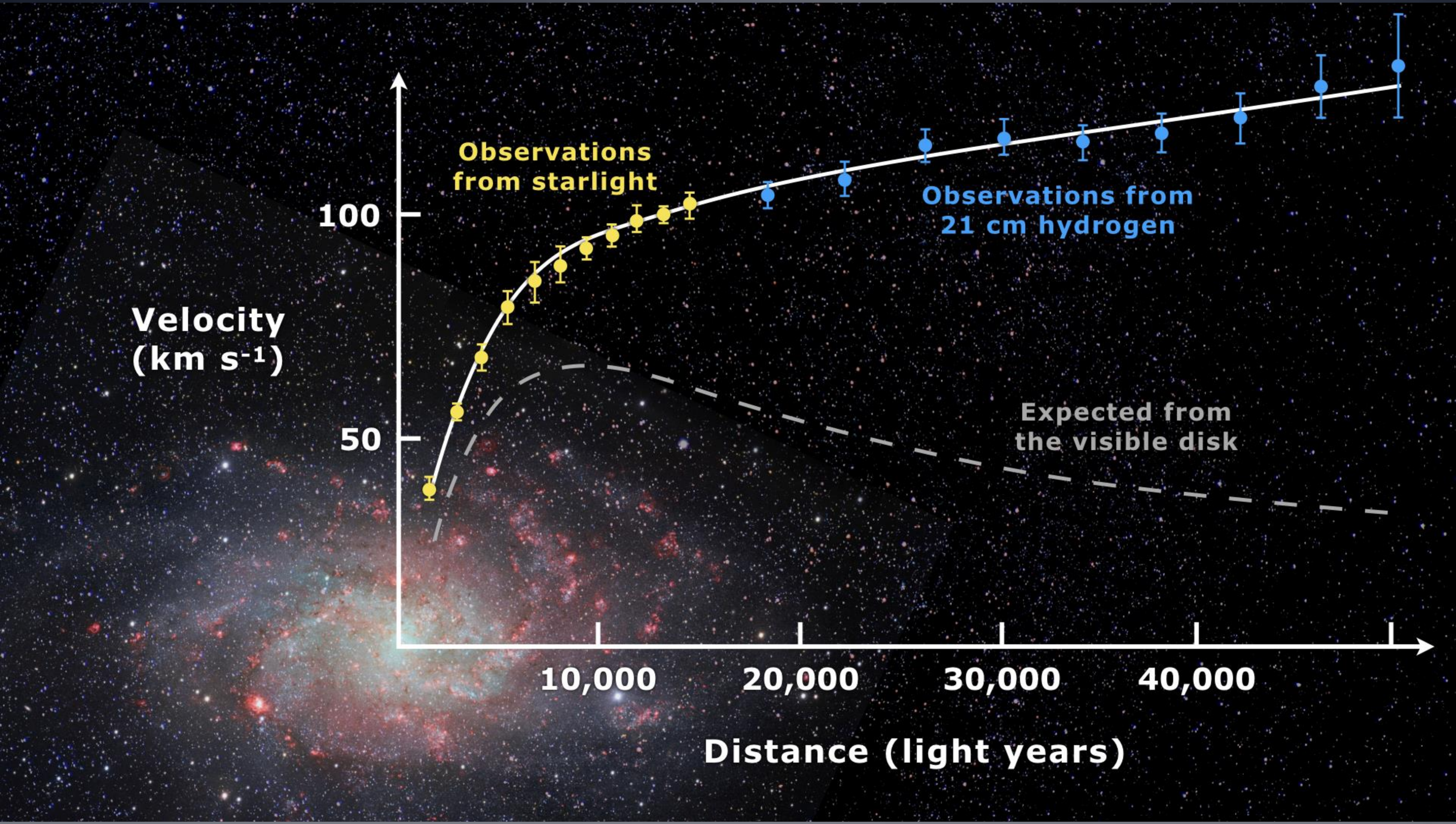


Figure 25.13 Rotation Curve of the Galaxy. The orbital speed of carbon monoxide (CO) and hydrogen (H) gas at different distances from the center of the Milky Way Galaxy is shown in red. The blue curve shows what the rotation curve would look like if all the matter in the Galaxy were located inside a radius of 50,000 light-years. Instead of going down, the speed of gas clouds farther out remains high, indicating a great deal of mass beyond the Sun's orbit. The horizontal axis shows the distance from the galactic center in kiloparsecs (where a kiloparsec equals 3,260 light-years).



Observations from starlight
Observations from 21 cm hydrogen
Expected from the visible disk
100
50
Velocity (km s-1)
10,000
20,000
30,000
40,000
Distance (light years)

Dark Matter!

- We can measure accurately the mass of the galaxy through Kepler's Laws/gravity
- We can measure the mass of stars+gas
- Mass of stars = 0.2 x mass of galaxy

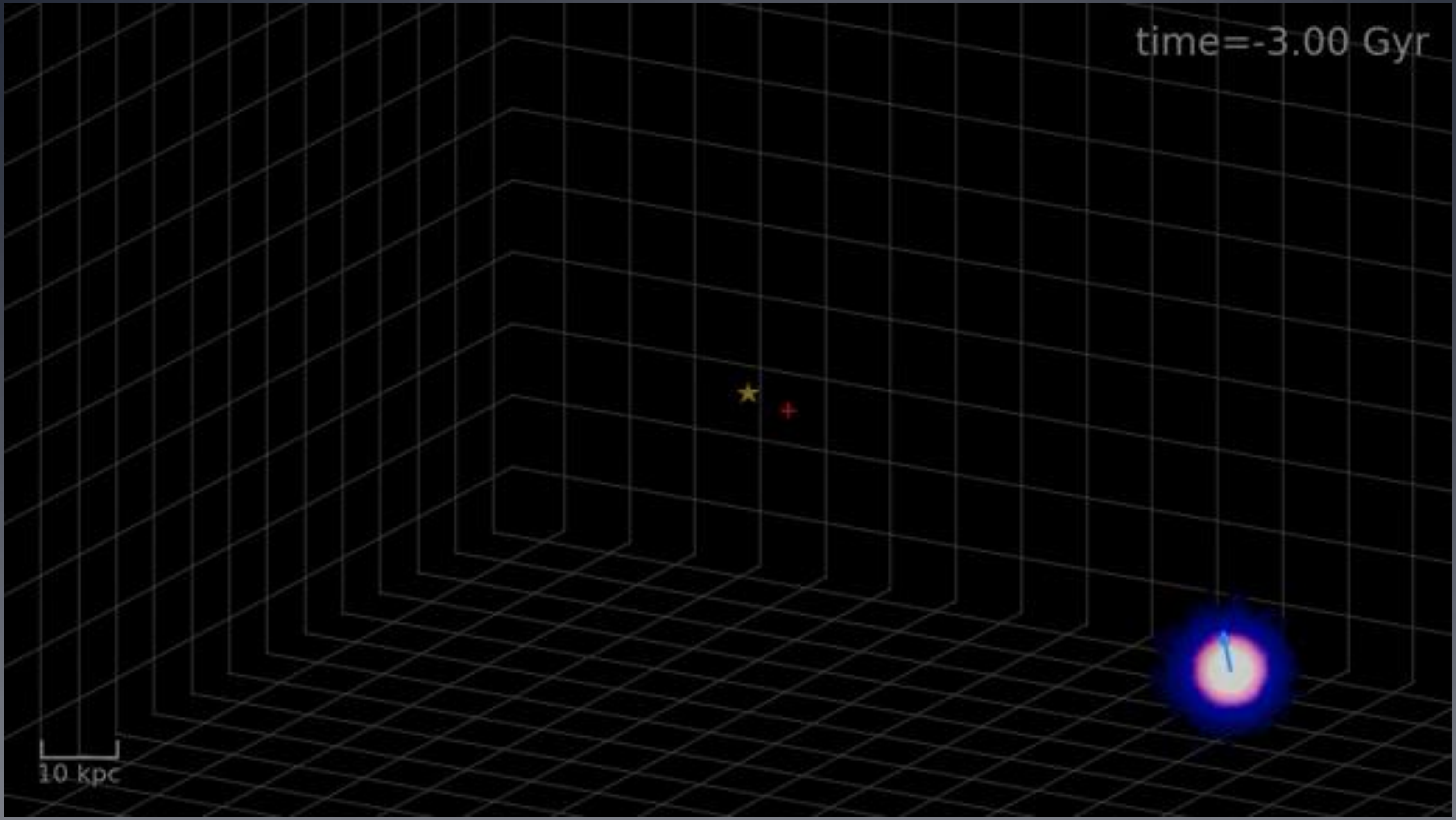
Rule out: black holes, brown dwarfs/planets, interstellar gas

Dark matter: exotic, non-interacting particle

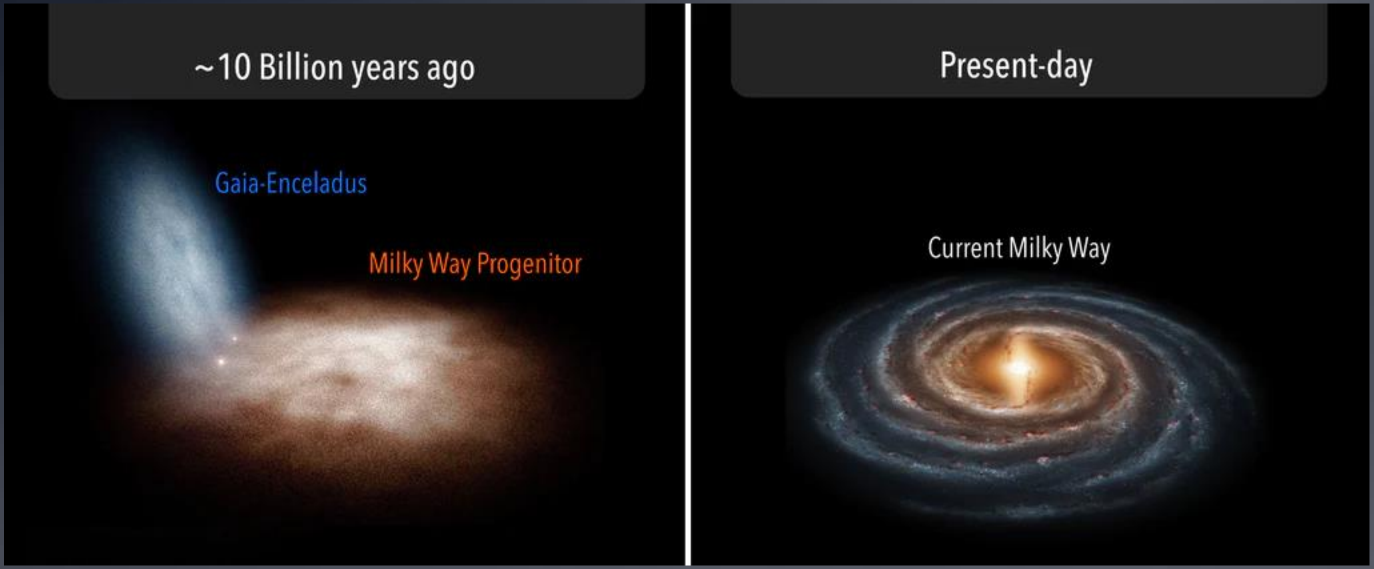
Dark=not interacting; 80% of mass!

Simulations of Milky Way Formation

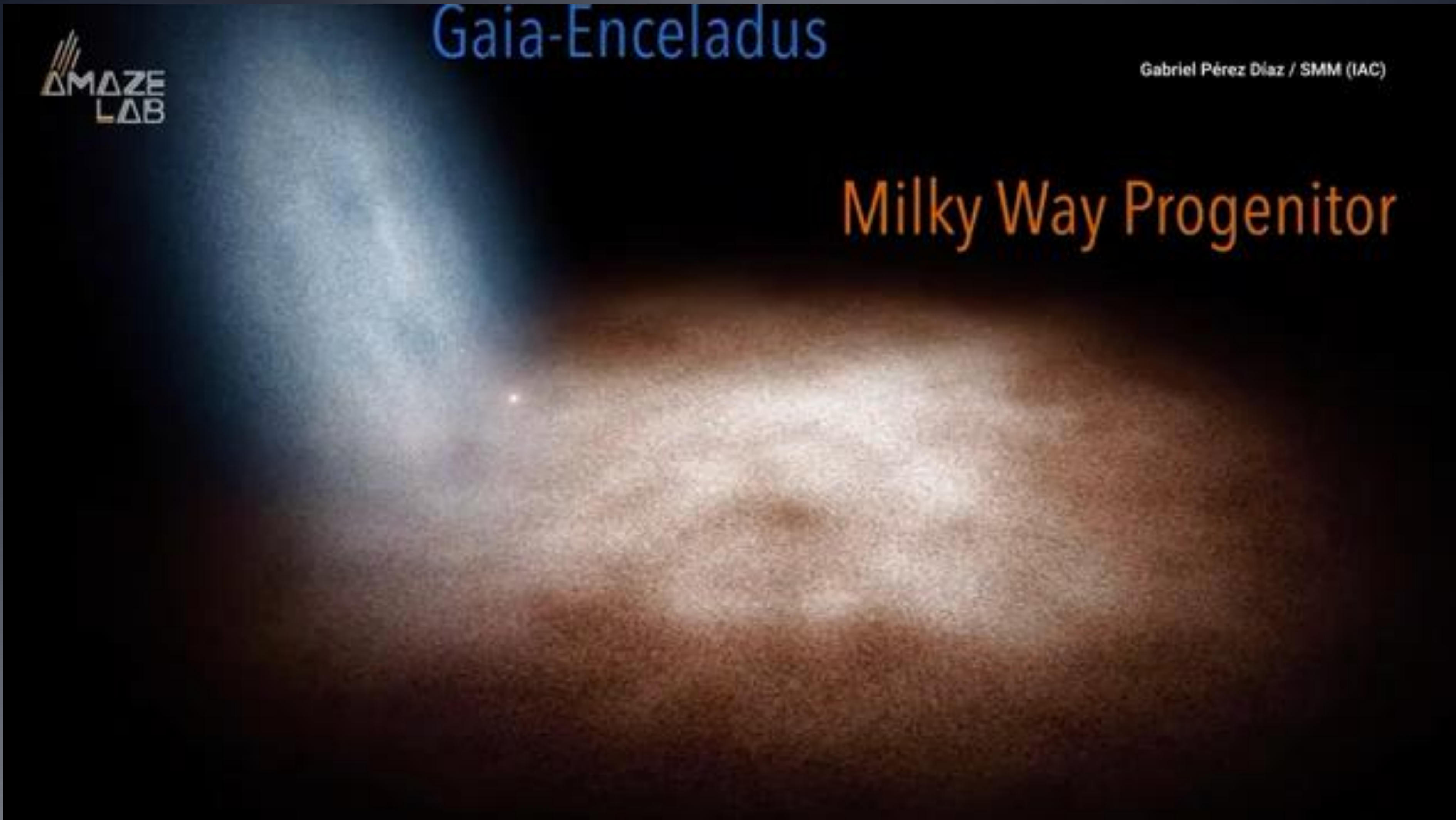
Sagittarius Stream



Last major merger: Gaia-Enceladus Sausage

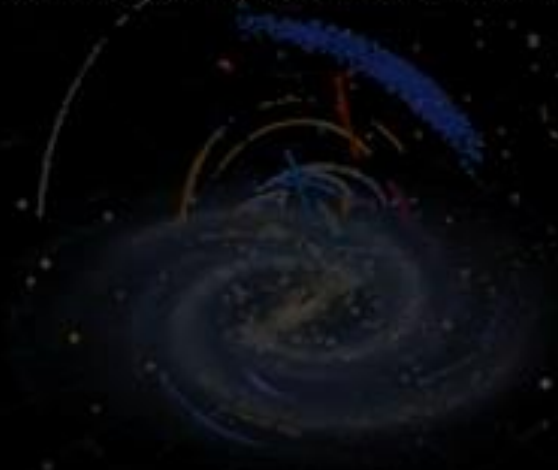


- 8-10 billion years ago
- Stars from "alien" galaxy mixed into Milky Way
- Globular cluster NGC 2068 may be remnant


Gaia-Enceladus
AMAZE LAB
Gabriel Pérez Díaz / SMM (IAC)
Milky Way Progenitor

The Global Dynamic Atlas of the Milky Way mergers:

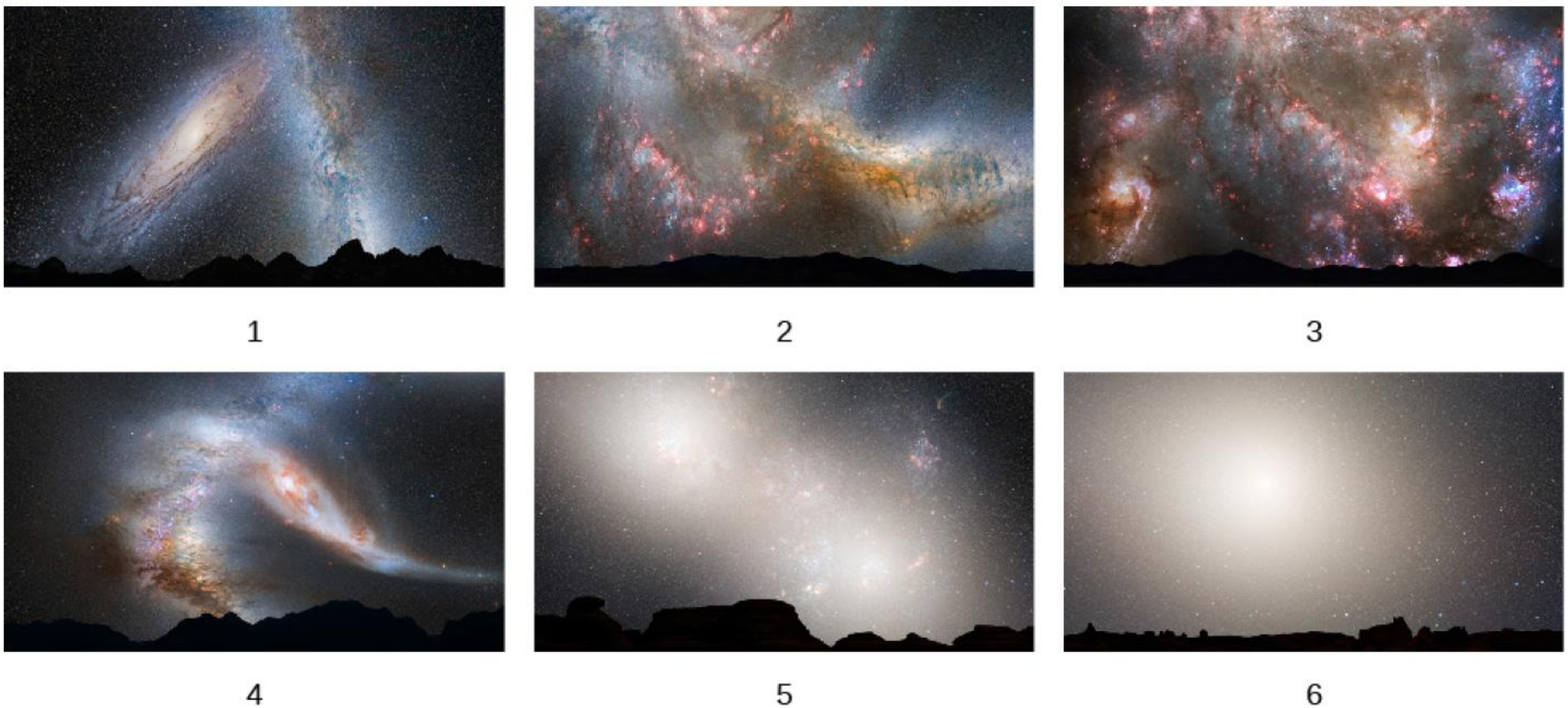
constraints from Gaia EDR3 based orbits of globular clusters, stellar streams and satellite galaxies



K. Malhan et al.

The future: it’s coming right at us!

Collision with Andromeda galaxy: 3 billion years



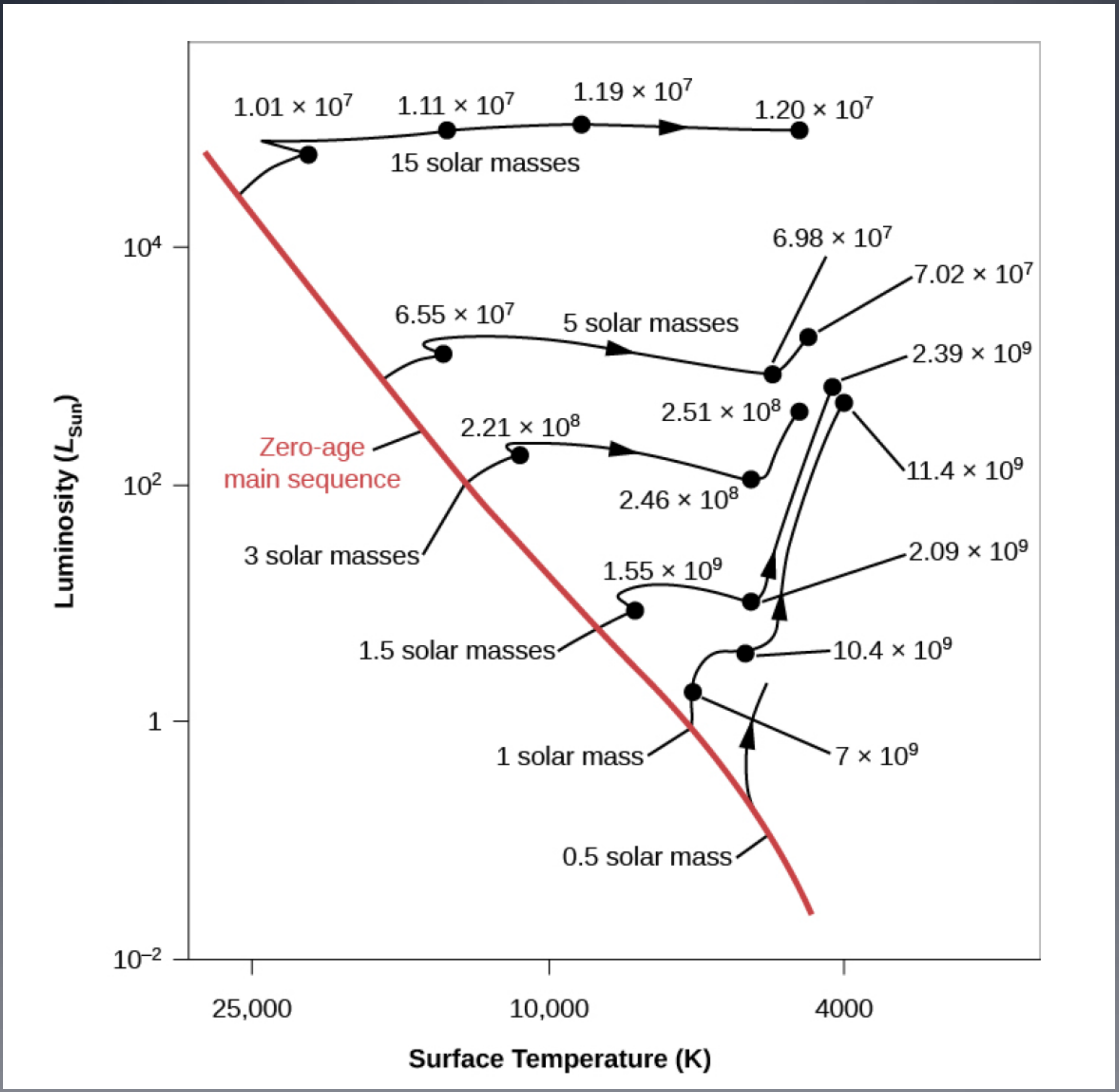
The future: it's coming right at us!

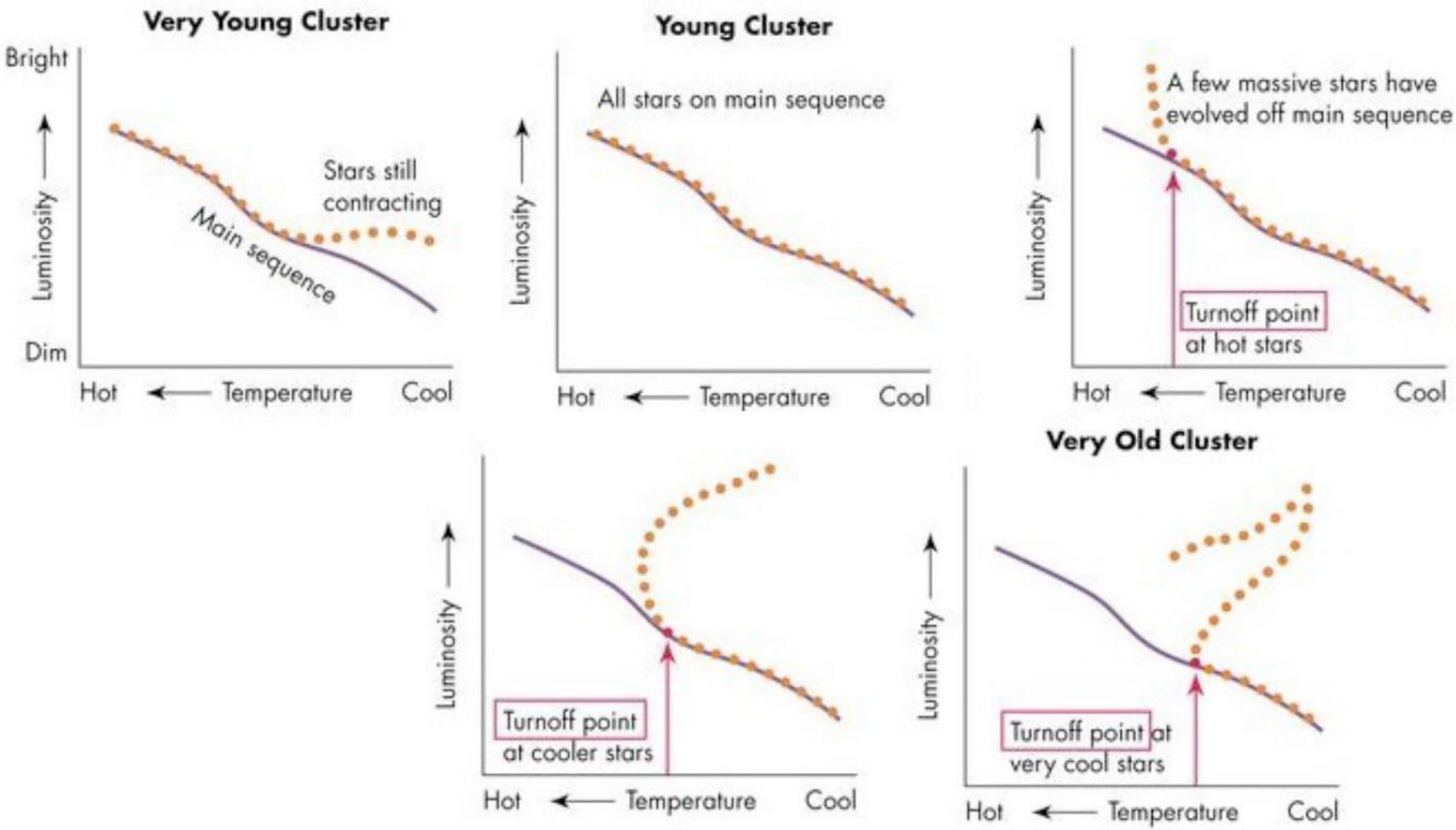
Collision with Andromeda galaxy: 3 billion years

The future: it's coming right at us!
Collision with Andromeda galaxy: 3 billion years

Globular Cluster:
~1 million stars, formed early

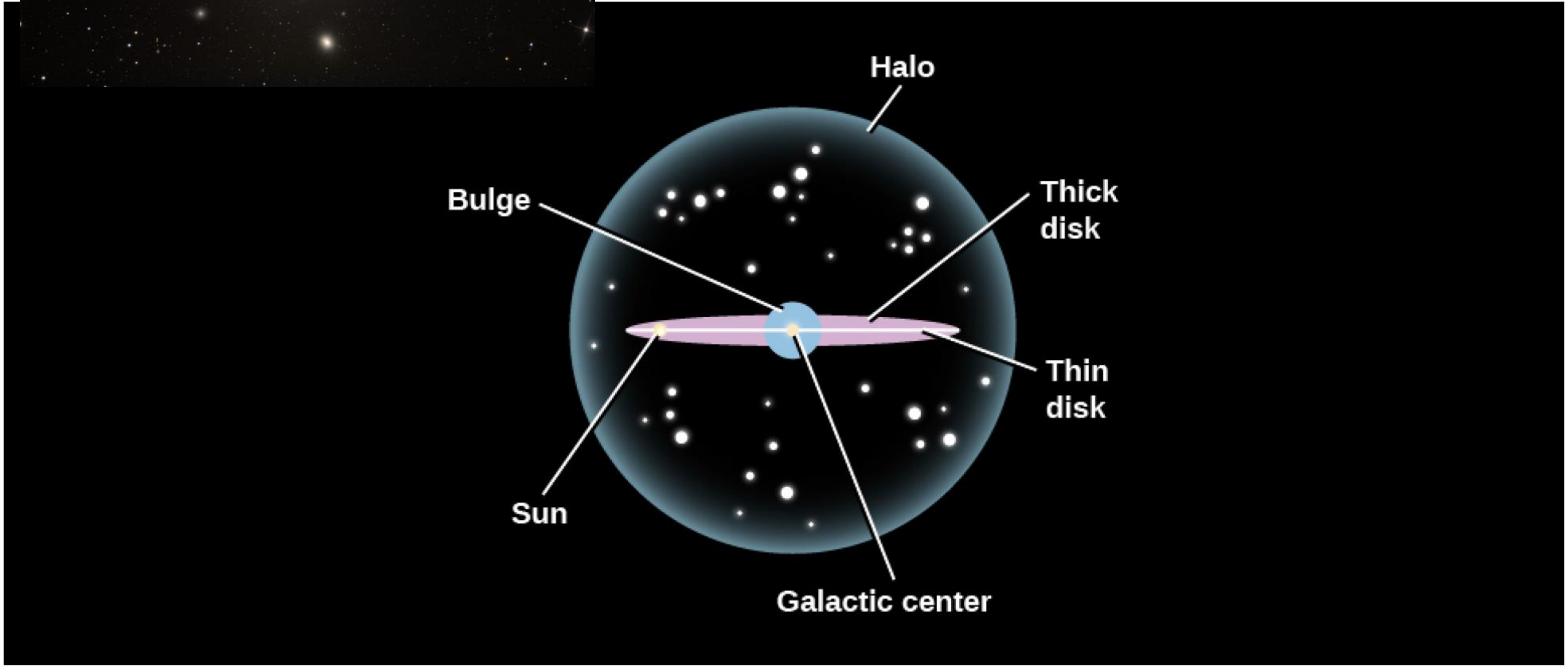
Location of stars tells us age of cluster



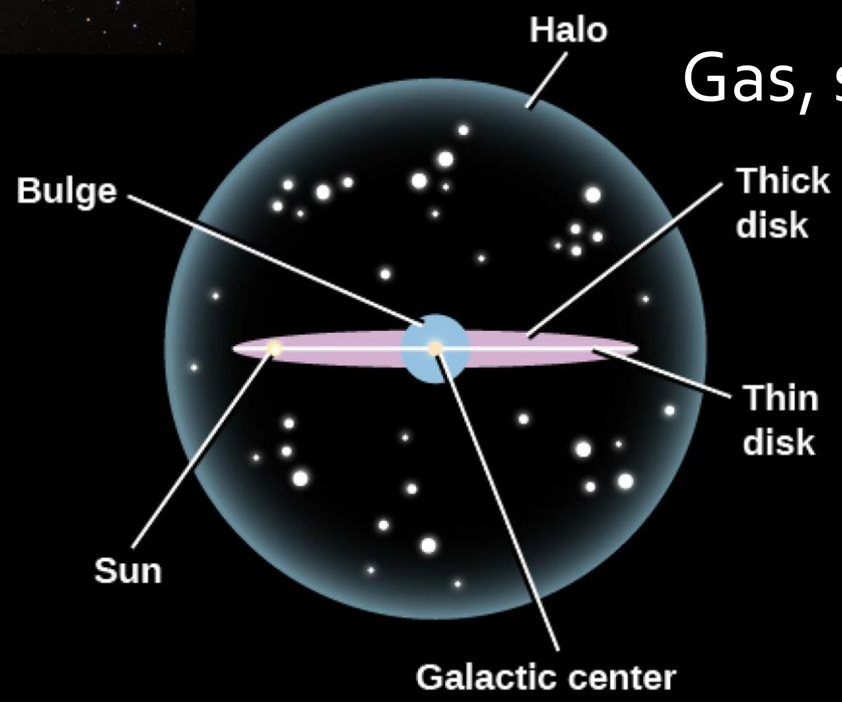


Very Young Cluster
Bright
Dim
Luminosity
Stars still contracting
Main sequence
Hot
Temperature
Cool
Young Cluster
All stars on main sequence
Luminosity
Hot
Temperature
Cool
A few massive stars have evolved off main sequence
Luminosity
Turnoff point at hot stars
Hot
Temperature
Cool
Luminosity
Turnoff point at cooler stars
Hot
Temperature
Cool
Very Old Cluster
Luminosity
Turnoff point at very cool stars
Hot
Temperature
Cool

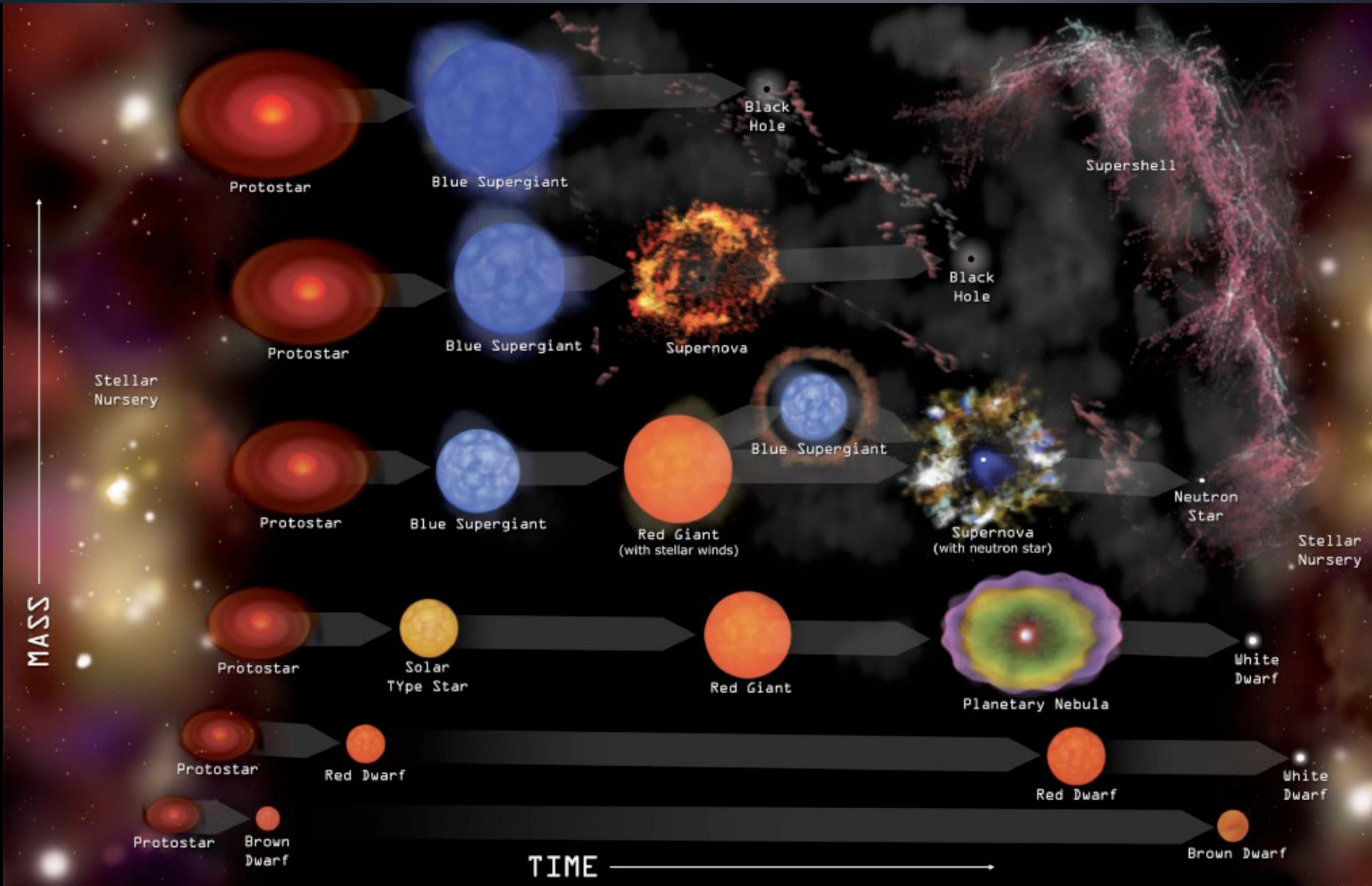
Halo & globular clusters: ~1 million stars, formed early (old stars)



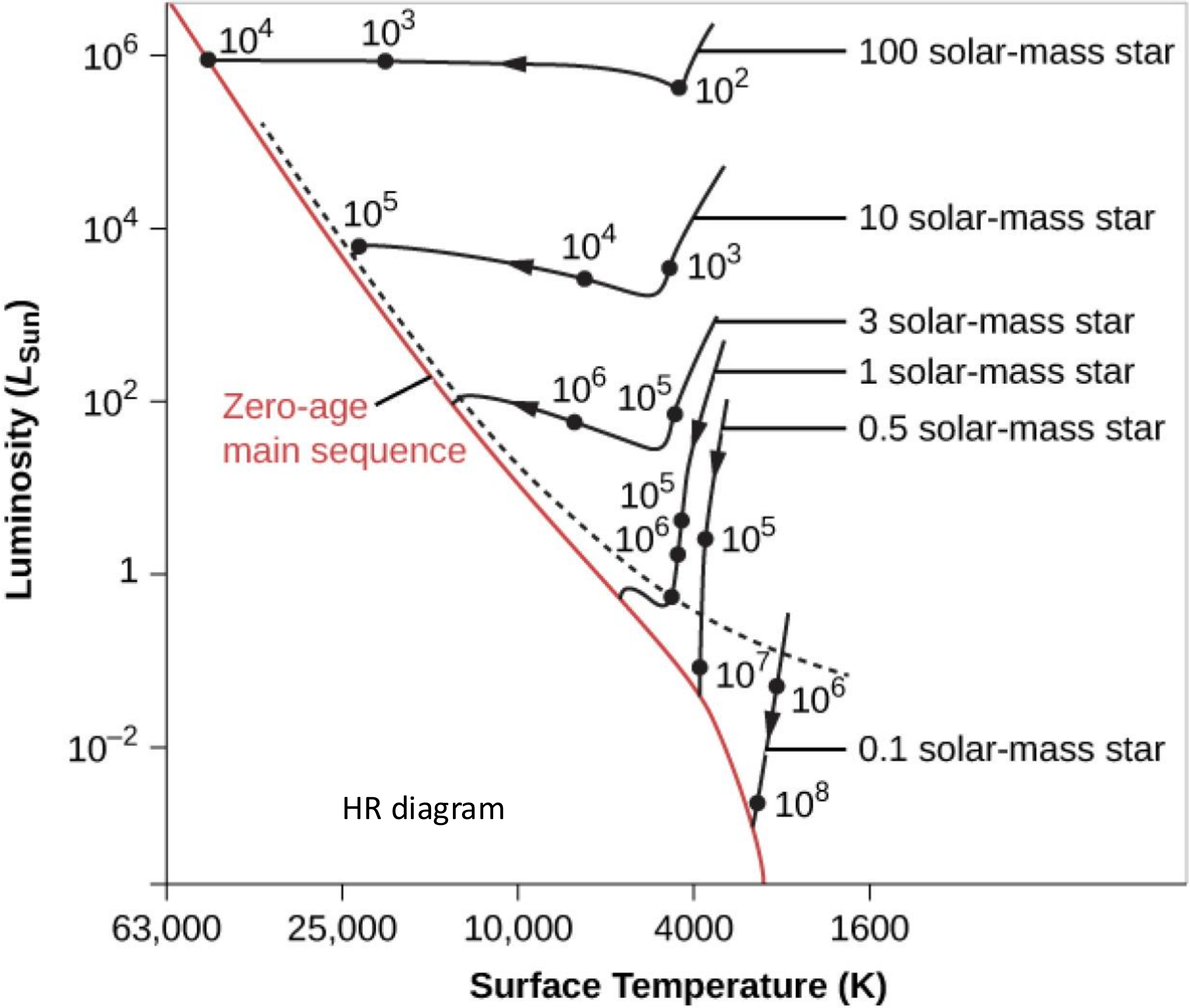
Halo: old stars



Disk:
Gas, still forming stars



Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
TIME
Brown Dwarf


Luminosity (L_{Sun})
10^6
10^4
10^2
1
10^{-2}
Surface Temperature (K)
63,000
25,000
10,000
4000
1600
100 solar-mass star
10 solar-mass star
3 solar-mass star
1 solar-mass star
0.5 solar-mass star
0.1 solar-mass star
Zero-age main sequence
10^4
10^3
10^2
10^5
10^4
10^3
10^6
10^5
10^5
10^6
10^5
10^7
10^6
10^8
HR diagram

Interstellar medium

- Space is not quite empty
  - Hot interstellar medium: 10^{-4} ions per cm^3
  - In this room: 10^{19} molecules/cm^3
  - Best vacuum in lab: 10^{10} molecules/cm^3

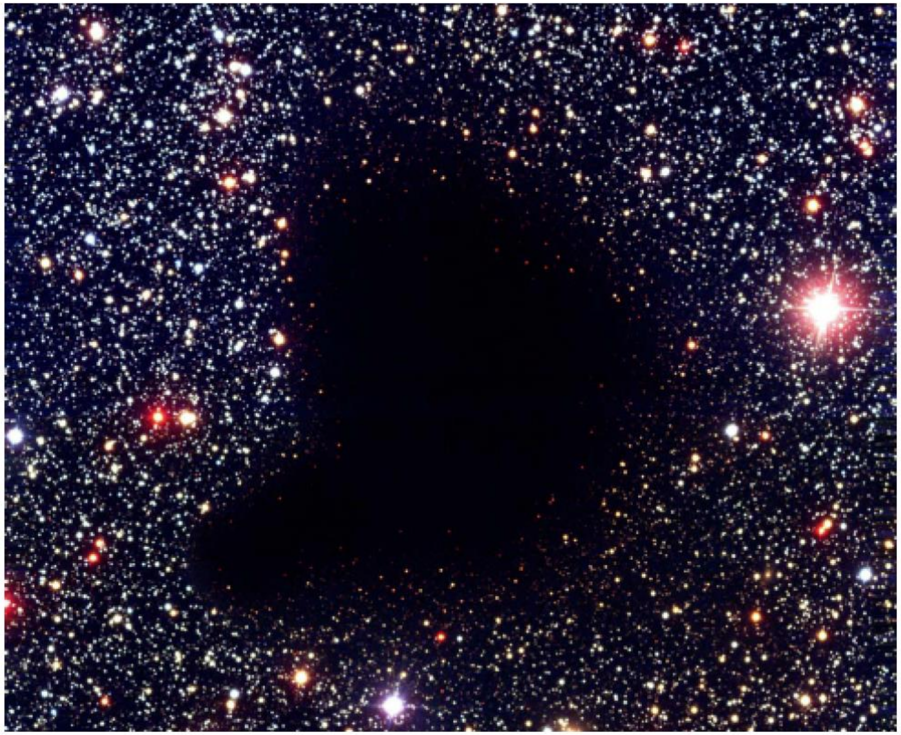
- Some places are denser and colder
  - **Molecular clouds**, where stars form
  - Densities of 10^2-10^6 molecules/cm^3


Orion Nebula
Largest nearby star-forming region

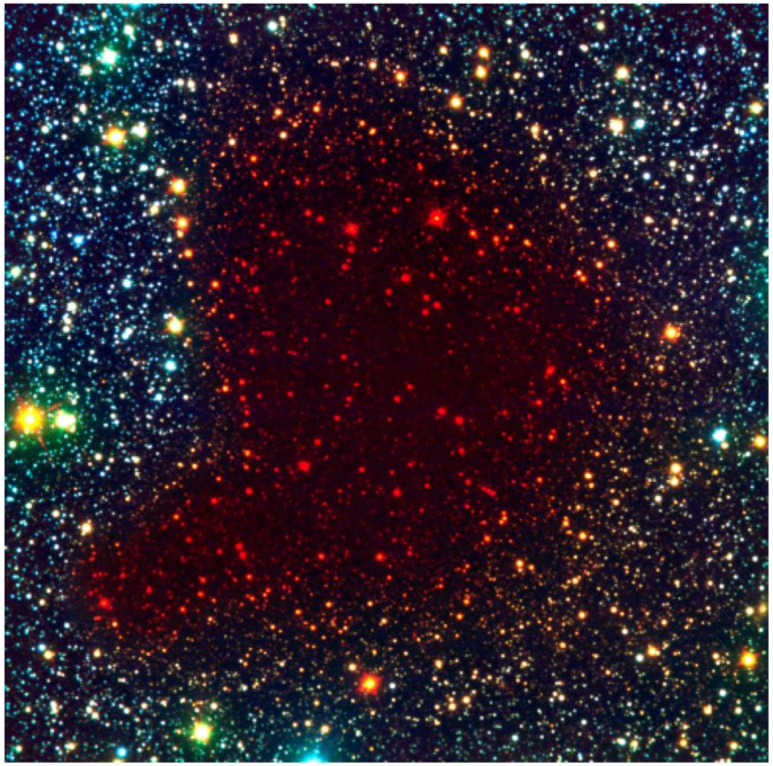
Serpens star-forming region
Courtesy Adam Block via APOD

Interstellar medium, supernova remnants

JWST image of Carina Nebula: hot stars ionize gas



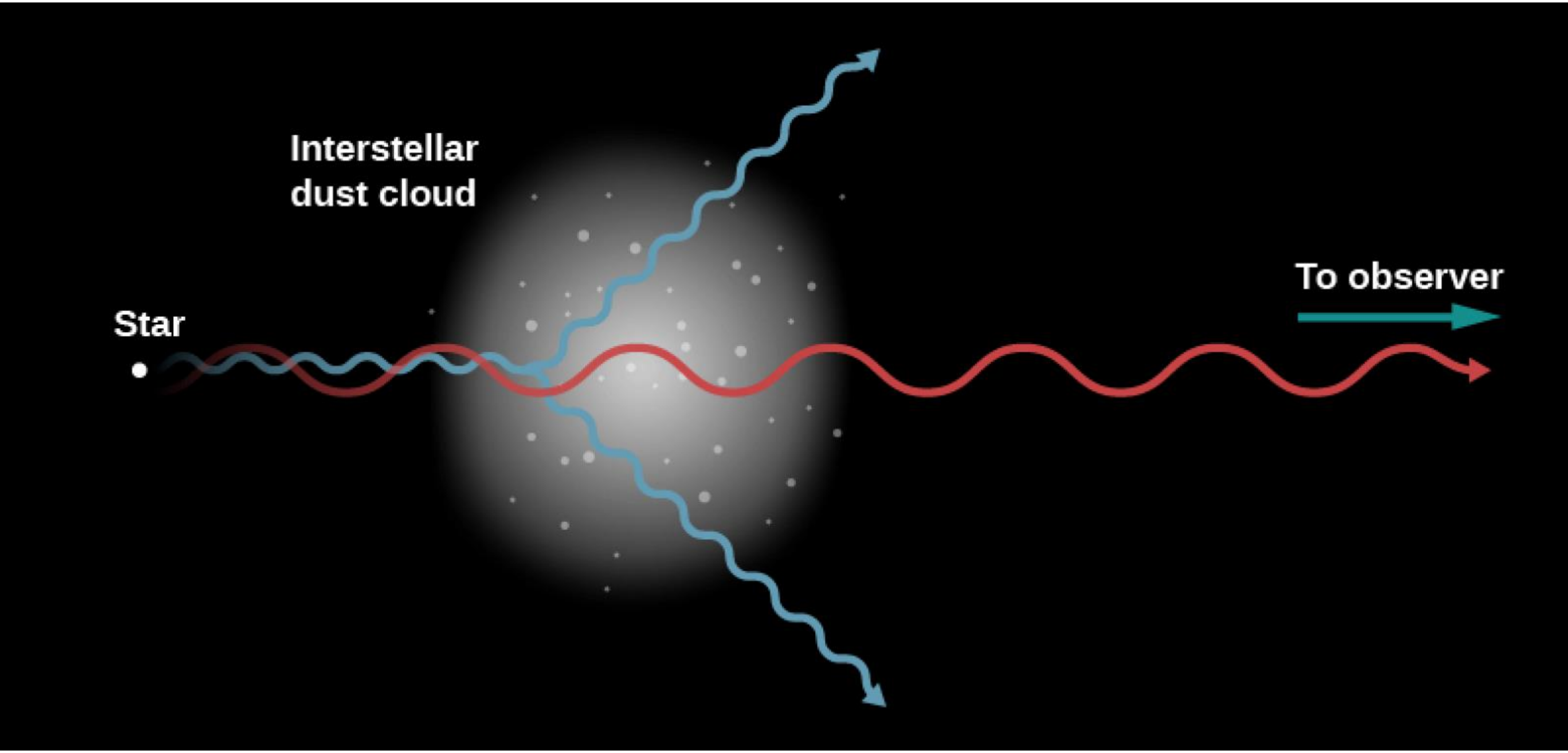
Optical



Near-infrared

Barnard 68: very dusty!

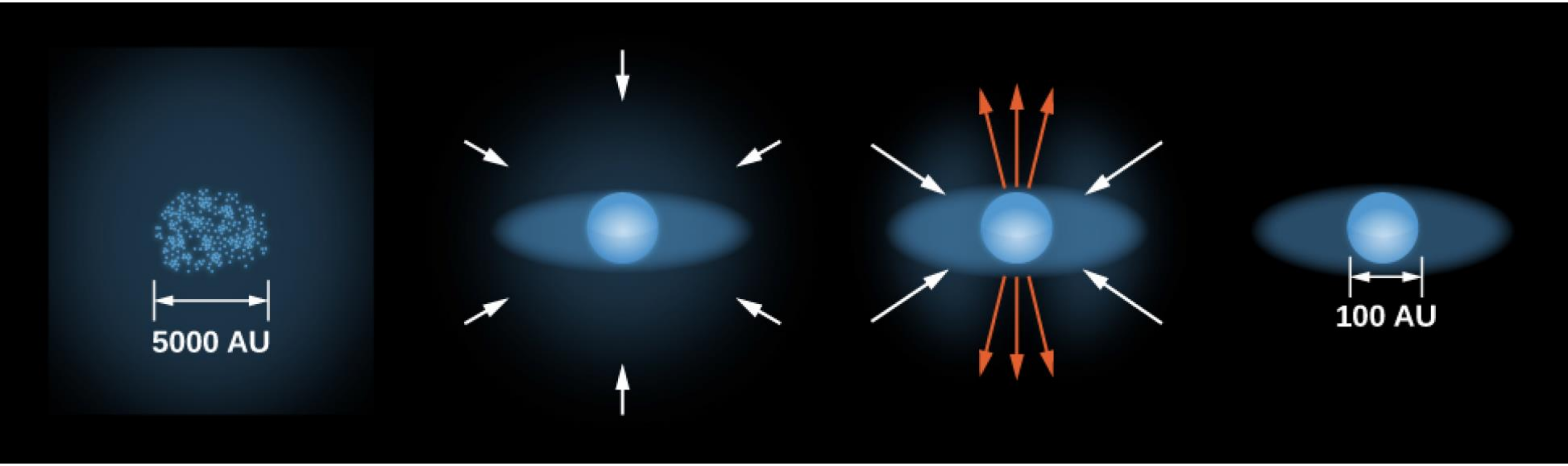
Longer wavelengths look through dust (red objects on right)

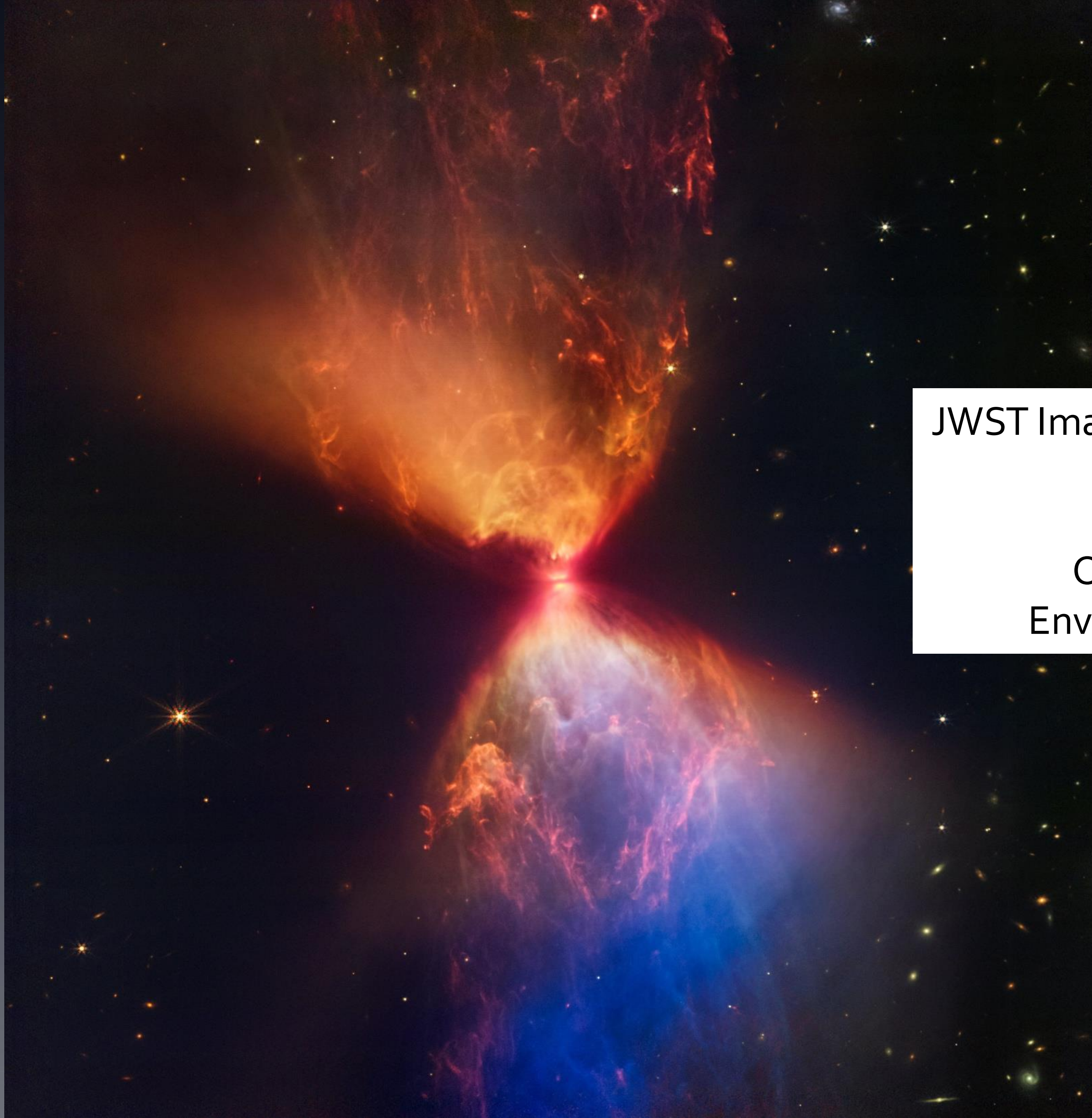


Blue wavelengths: absorbed/scattered by dust
Red wavelengths: pass through dust

Steps of star formation:

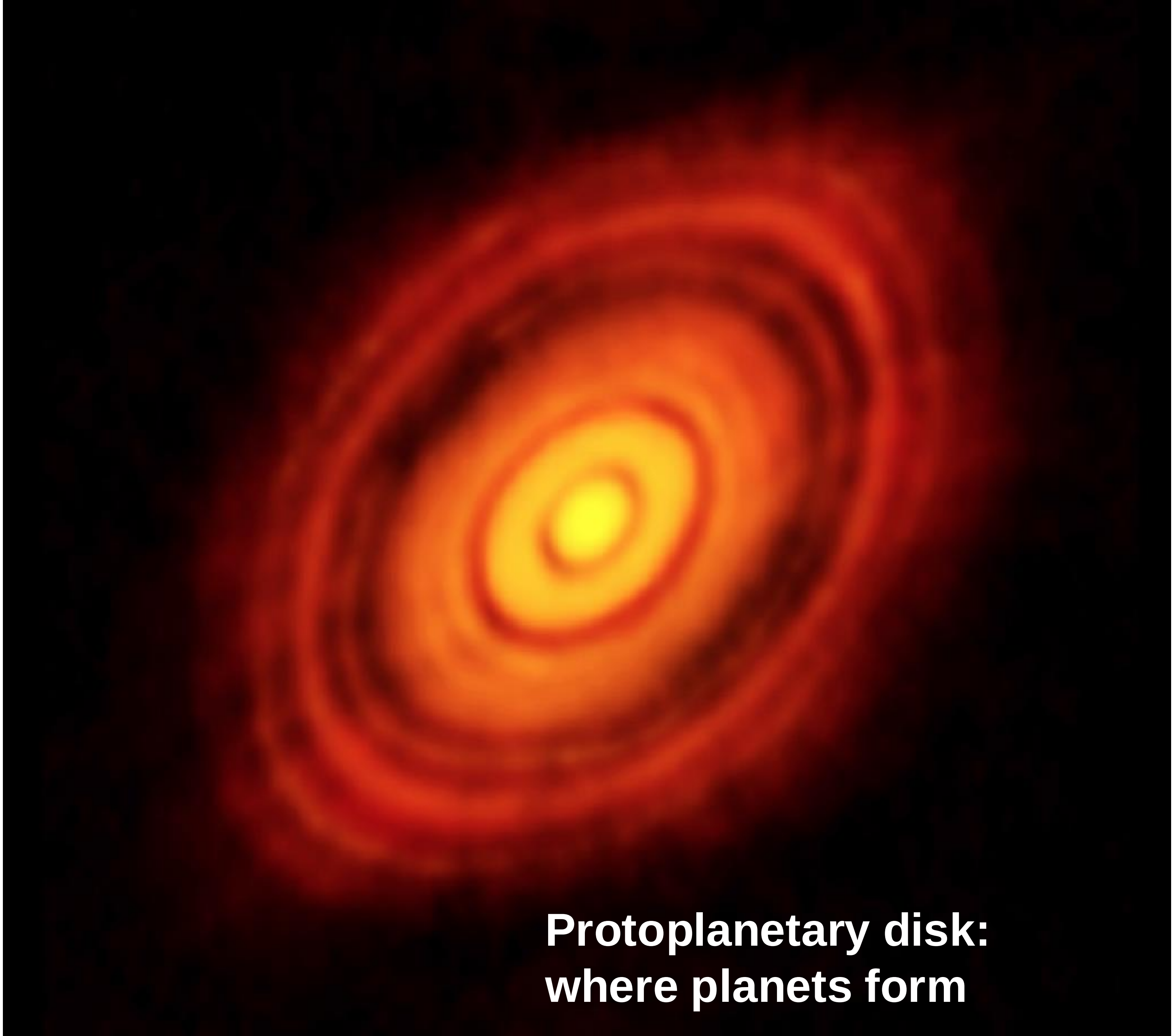
1) Region is dense enough to be gravitationally unstable and collapse
2) Protostar forms, with envelope and disk
3) Star grows, leads to jets and outflows
4) Envelope and disk disappear, leaving behind planets+star





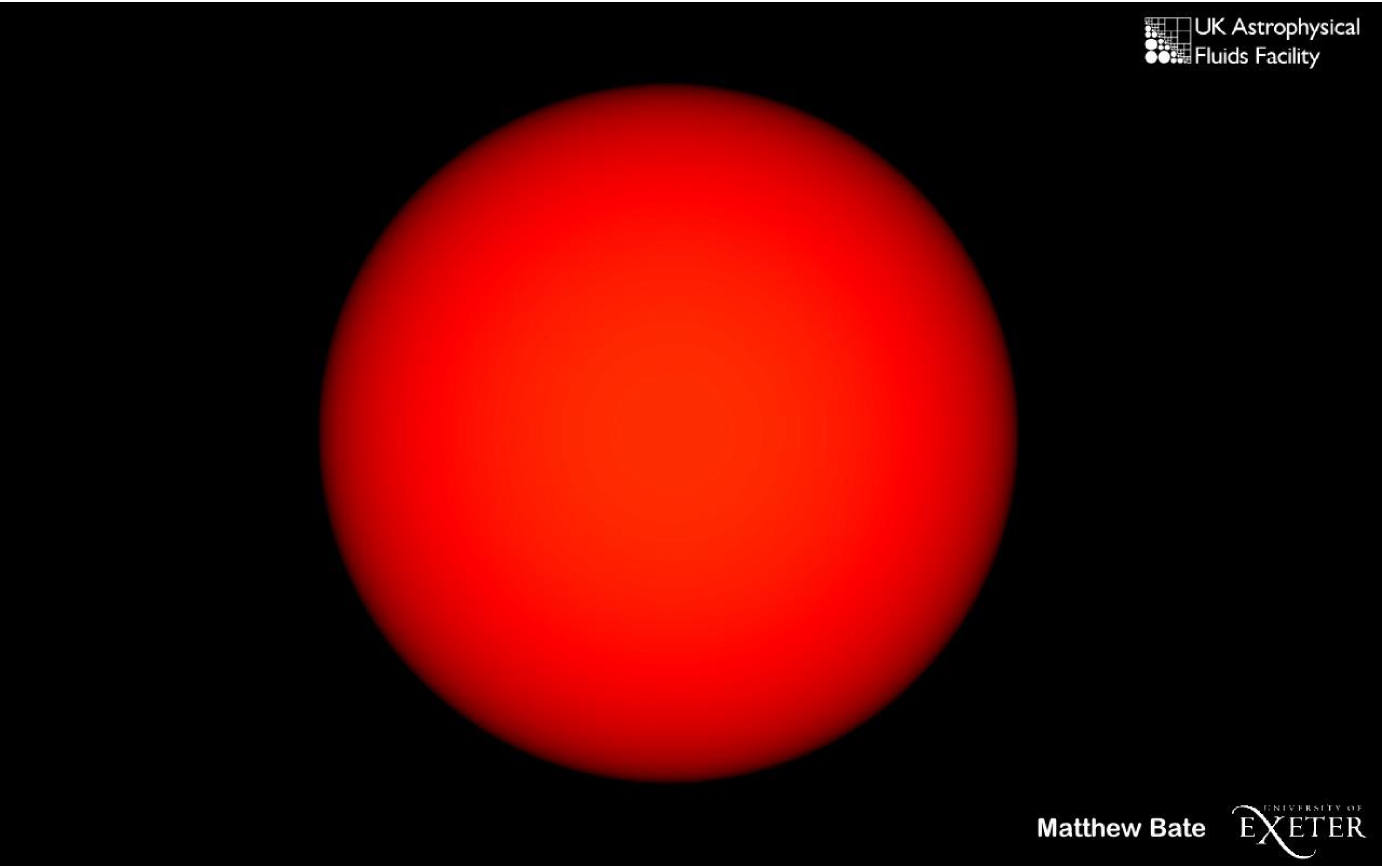
JWST Image of protostar L1527

Disk
Outflow cavity
Envelope extinction

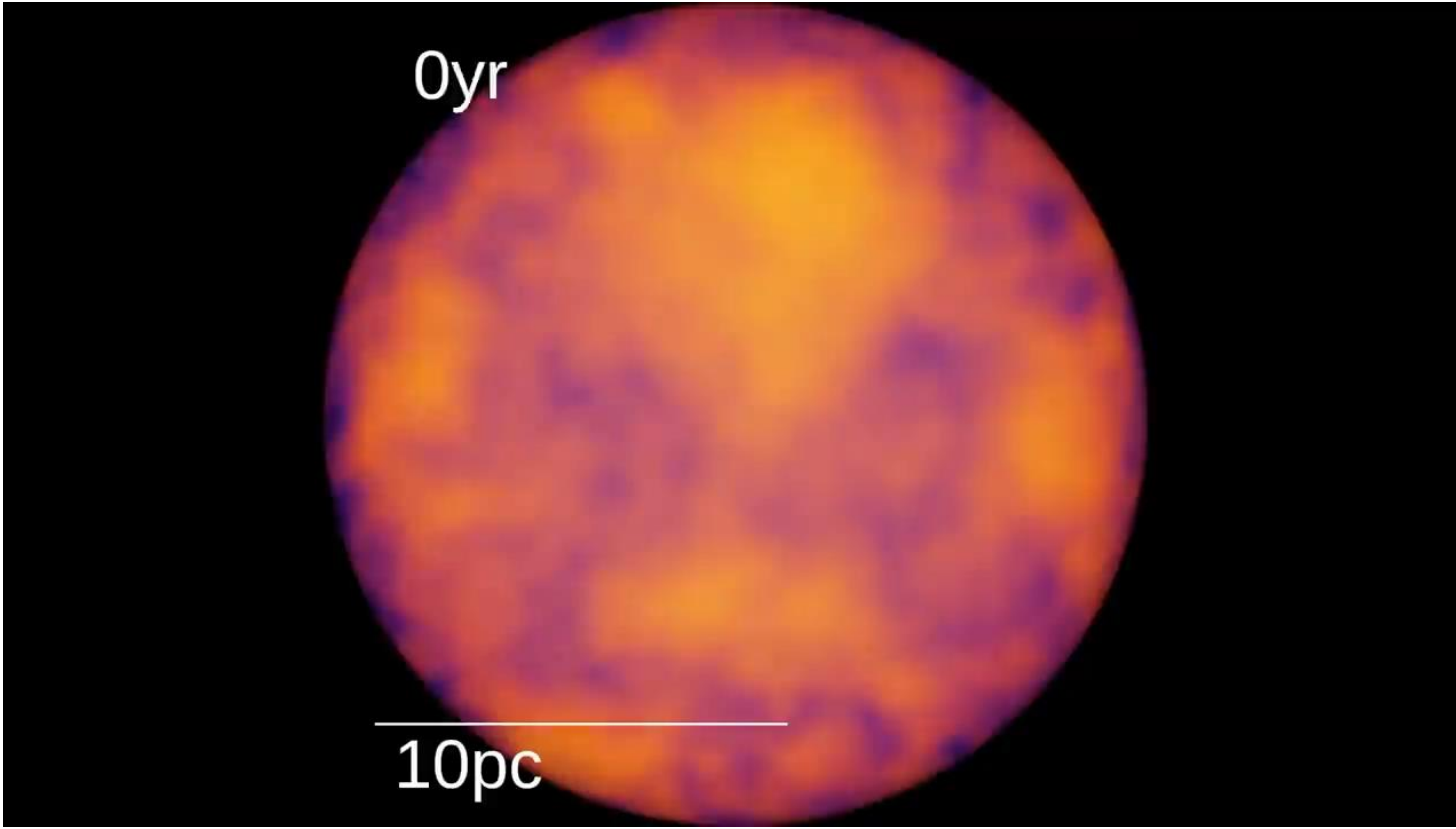


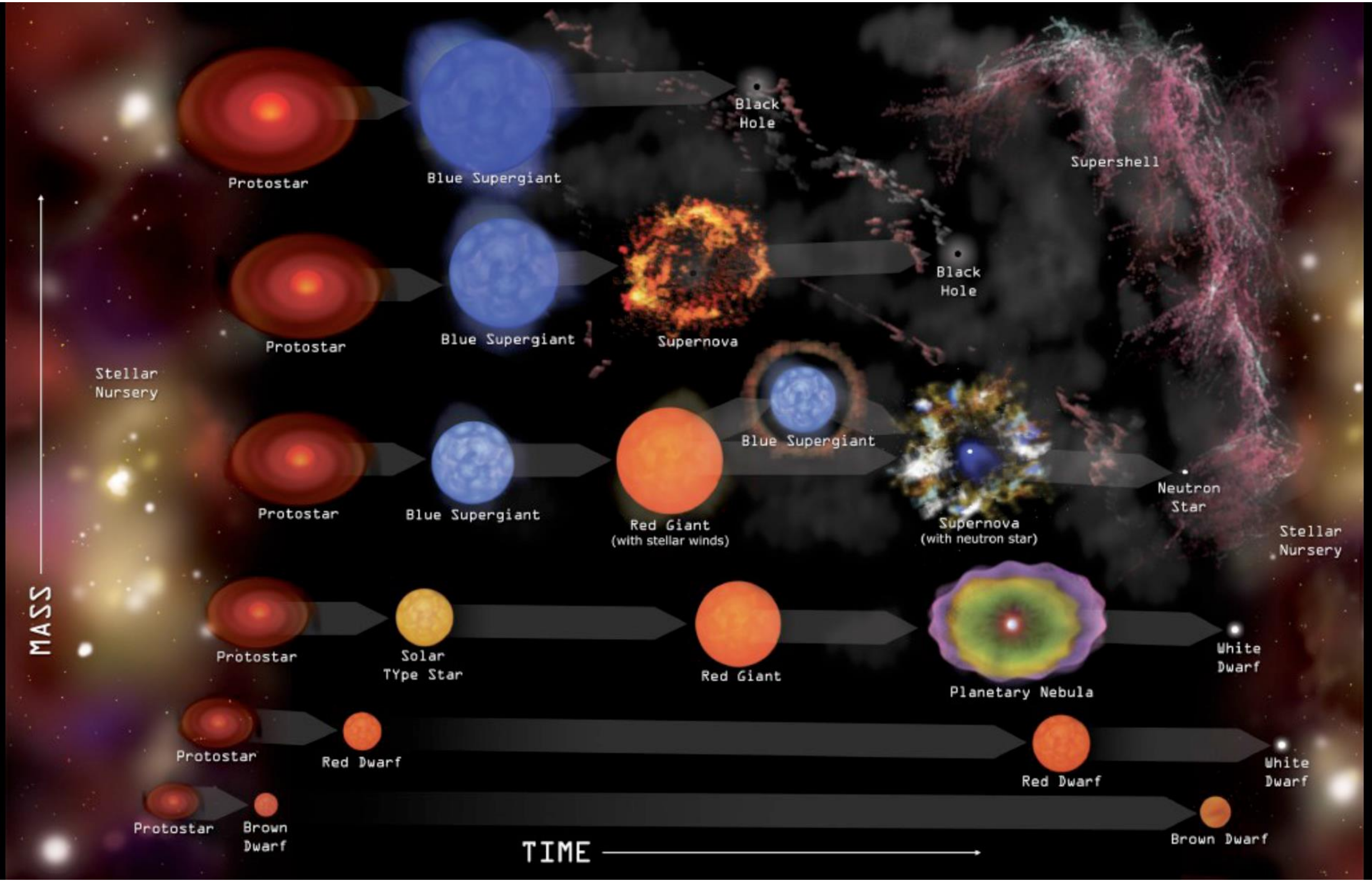
Protoplanetary disk:
where planets form

Simulation of a star-forming region



STARFORGE: Simulation of a star-forming region





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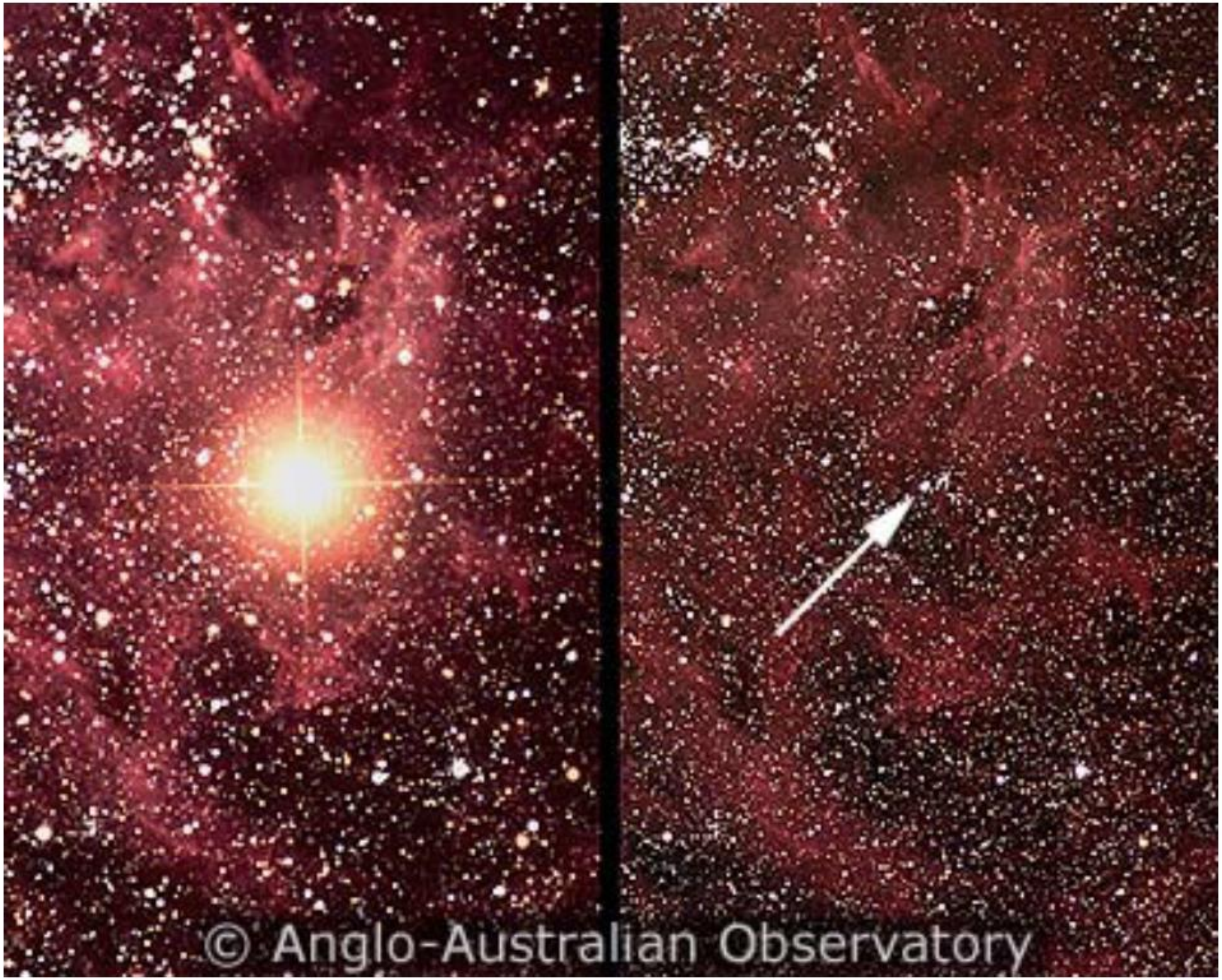
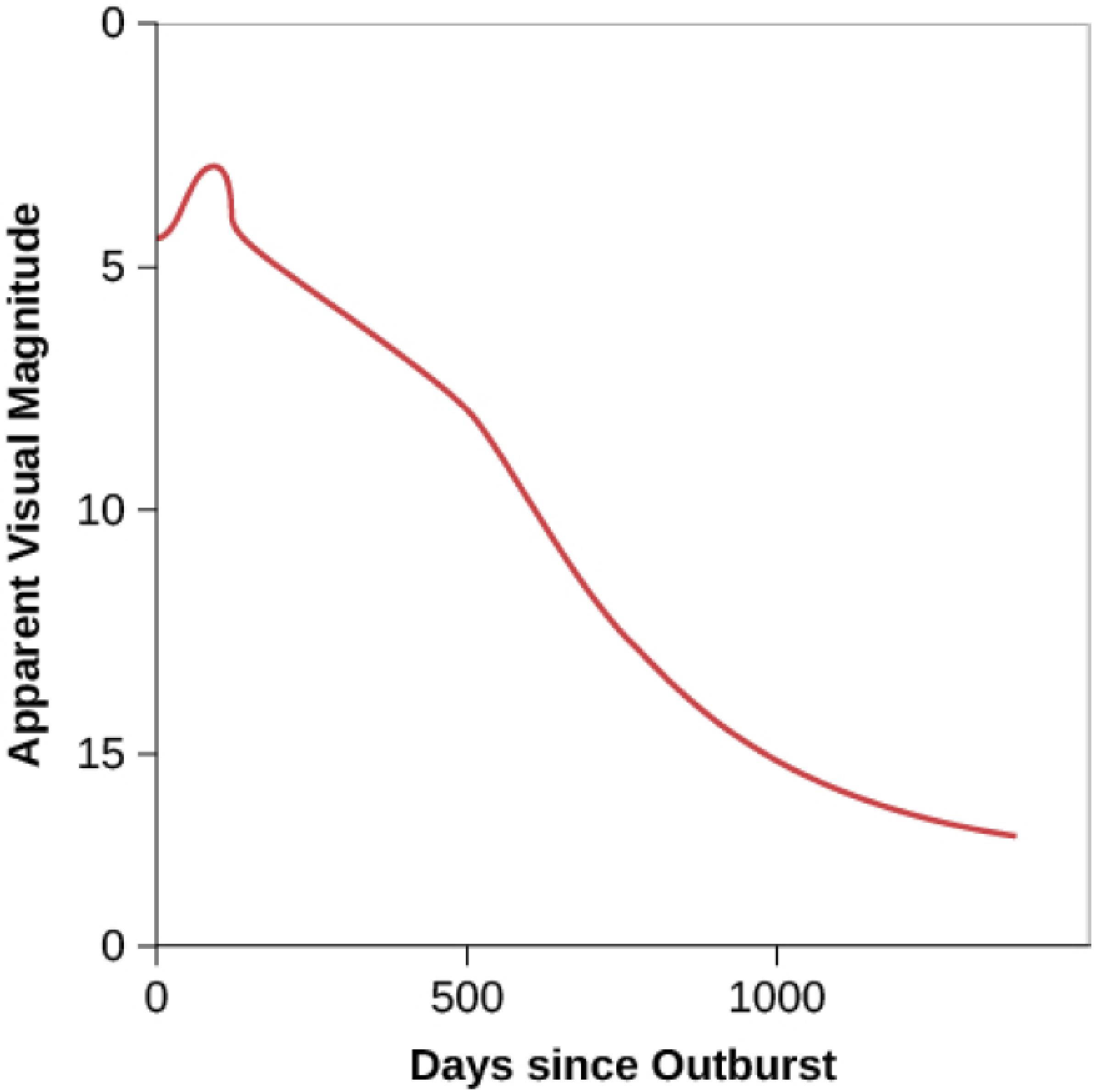
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME

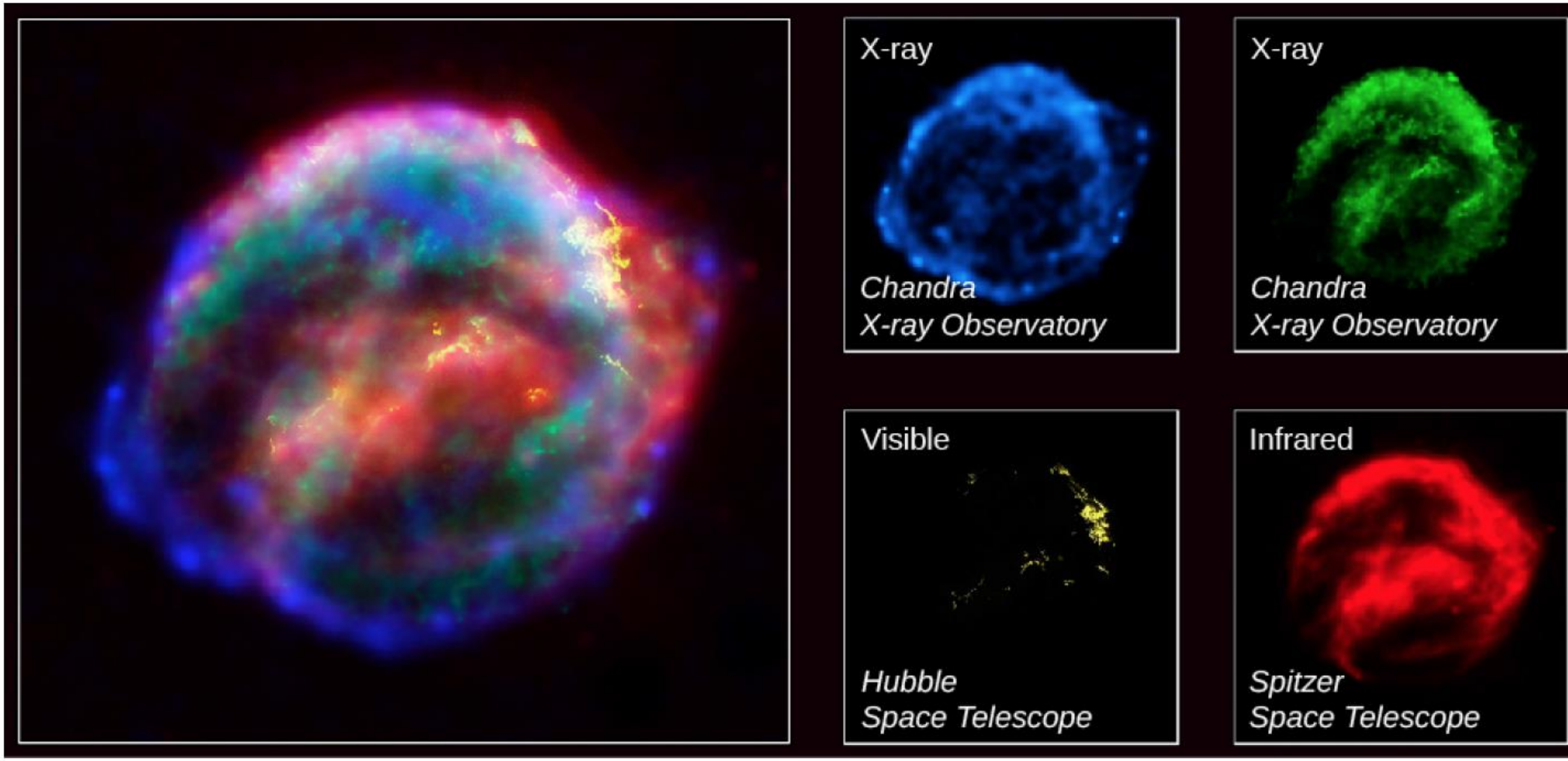
Supernova 1987A (brightest in modern times)



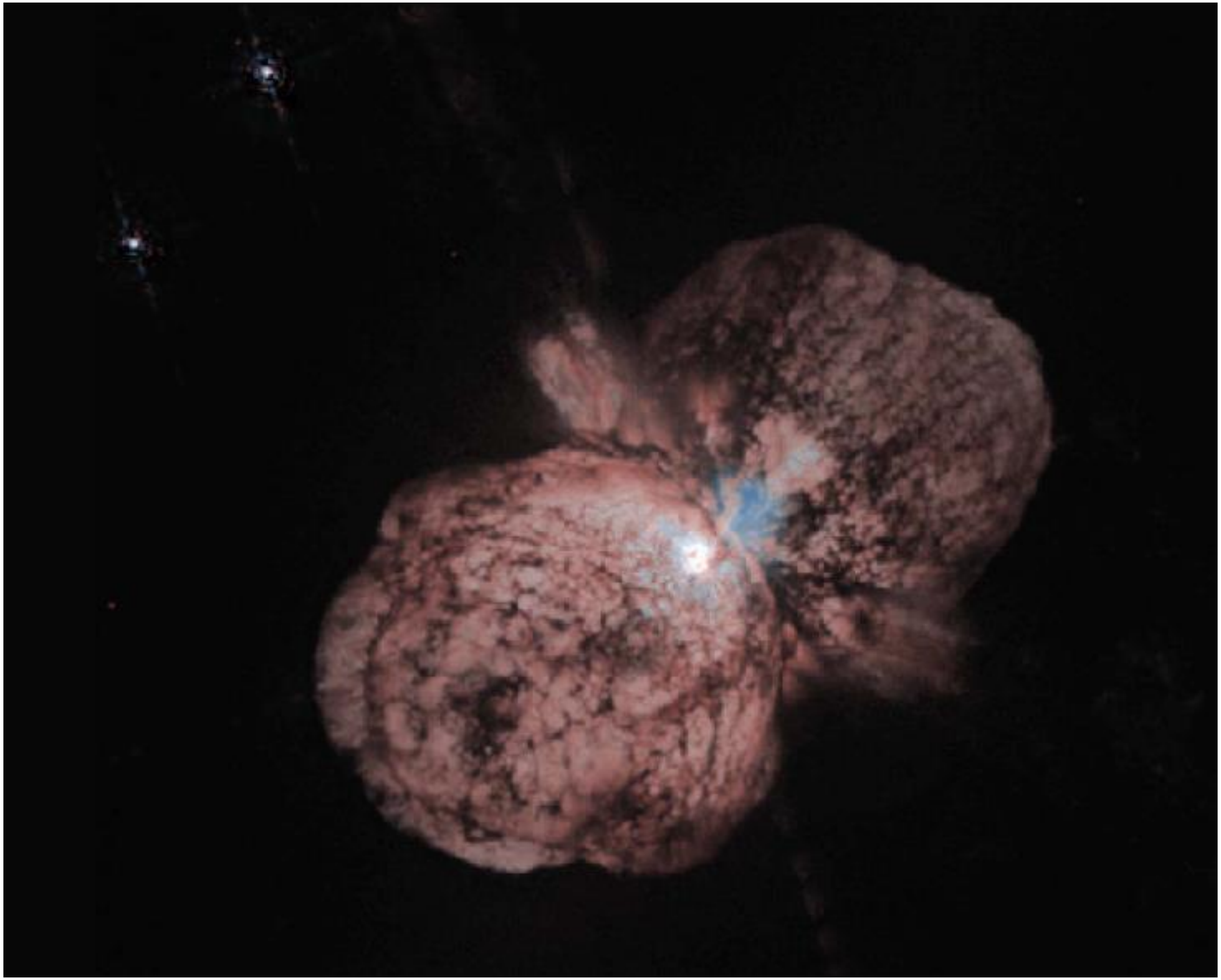
Brightness of supernova with time



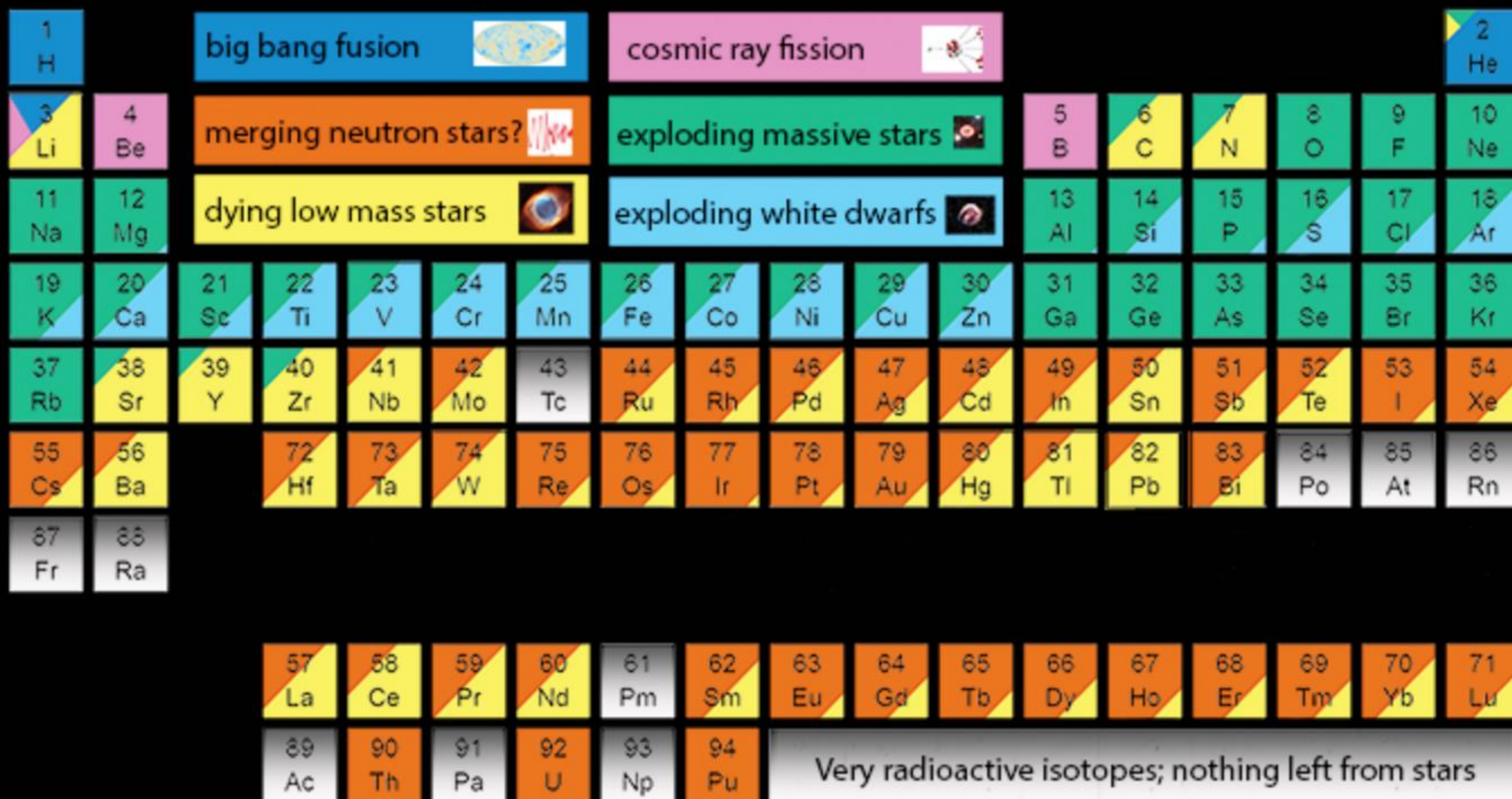
Supernova remnant



Eta Carina: what a 100 Msun star looks like



The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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Next week: galaxy structure and formation