



Extragalactic Astronomy Overview

Santiago González-Gaitán

Literature

1. **The Cosmic Perspective** - Bennett, Donahue, Schneider, Voit
2. **Extragalactic Astronomy and Cosmology** - Peter Schneider
3. **Galactic Dynamics** - Binney & Tremaine

Extragalactic Astronomy

I. The Milky Way

II. Galaxies

III. Galaxy evolution



NASA, ESA, STScI/AURA

I. Milky Way: our Galaxy



I. Milky Way: our Galaxy

- a) Size and composition
- b) Observations at multiple wavelengths
- c) Star-gas-star cycle
- d) Stellar orbits and rotation
- e) Galactic center

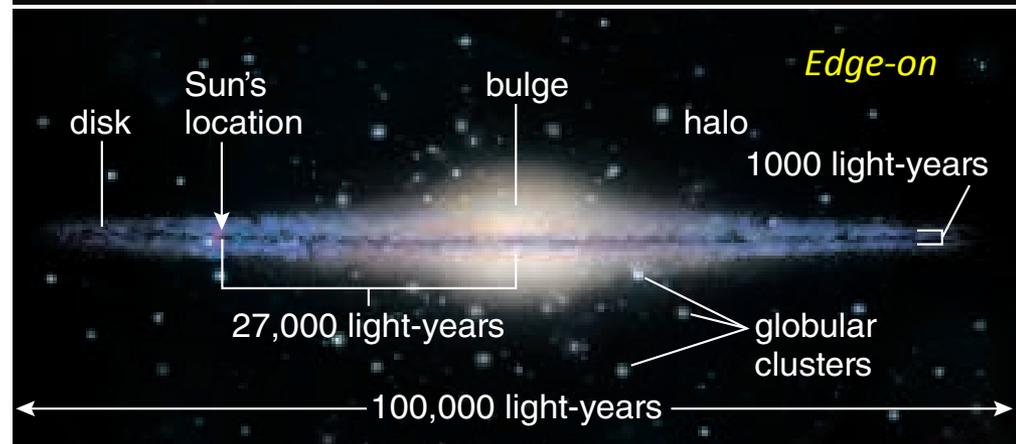
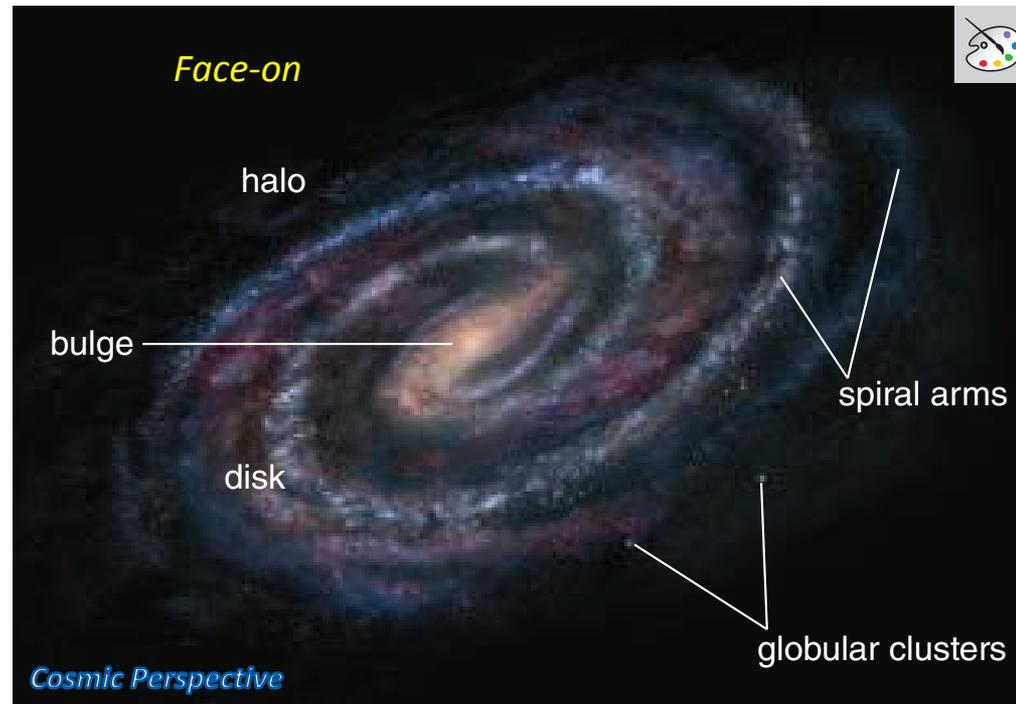
Milky Way size & composition

Difficulties:

- we cannot observe it from an external point of view
- dust obscuration in the center

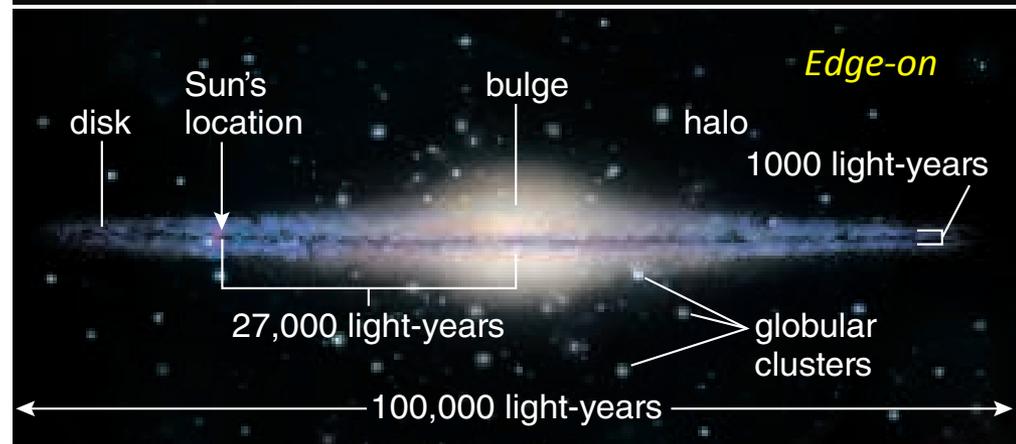
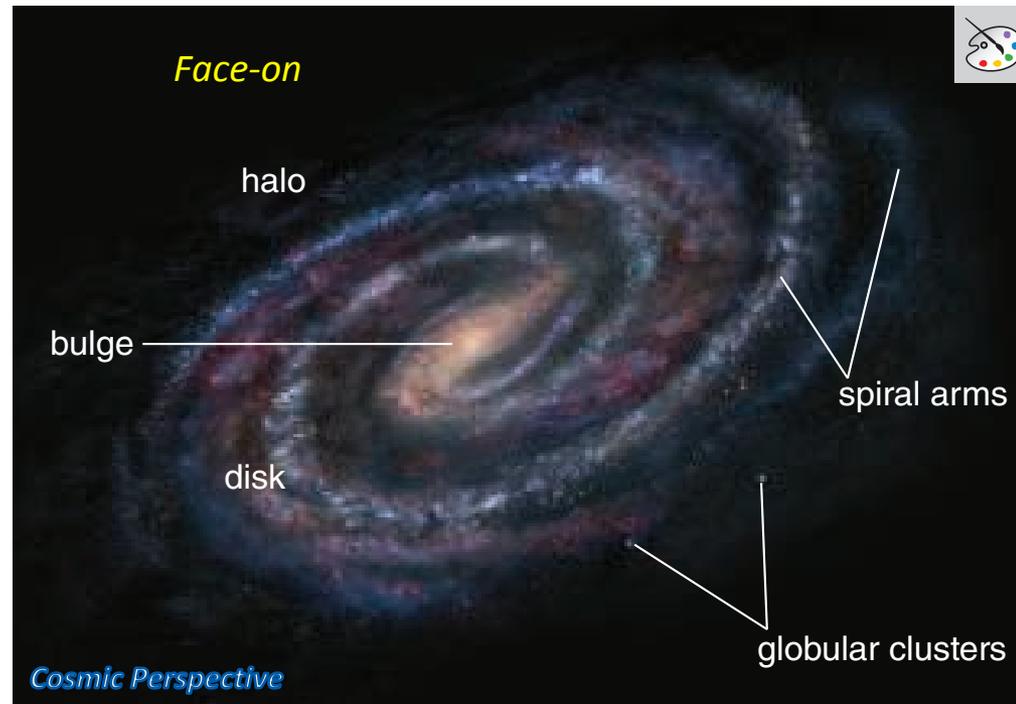
Advantages:

- Study individual objects



Milky Way size & composition

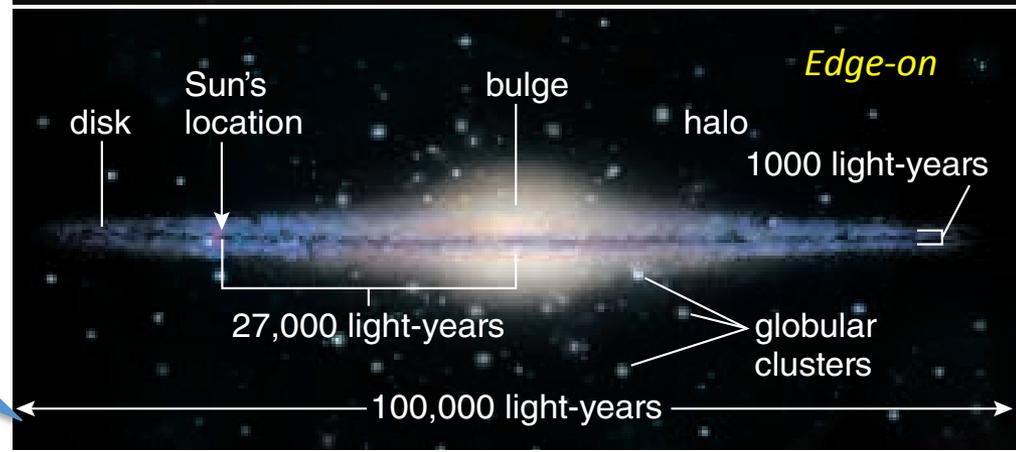
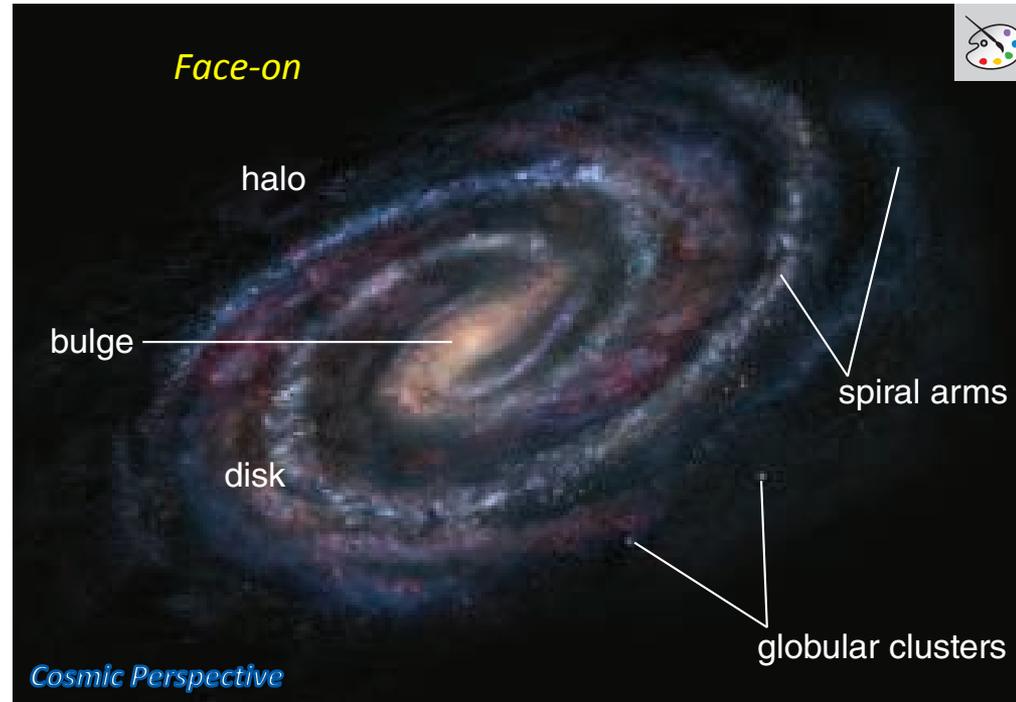
- 100 billion (10^{10}) stars
- Spiral galaxy with arms
- Disk of stars with a bulge
- Dim halo of stars



Milky Way size & composition

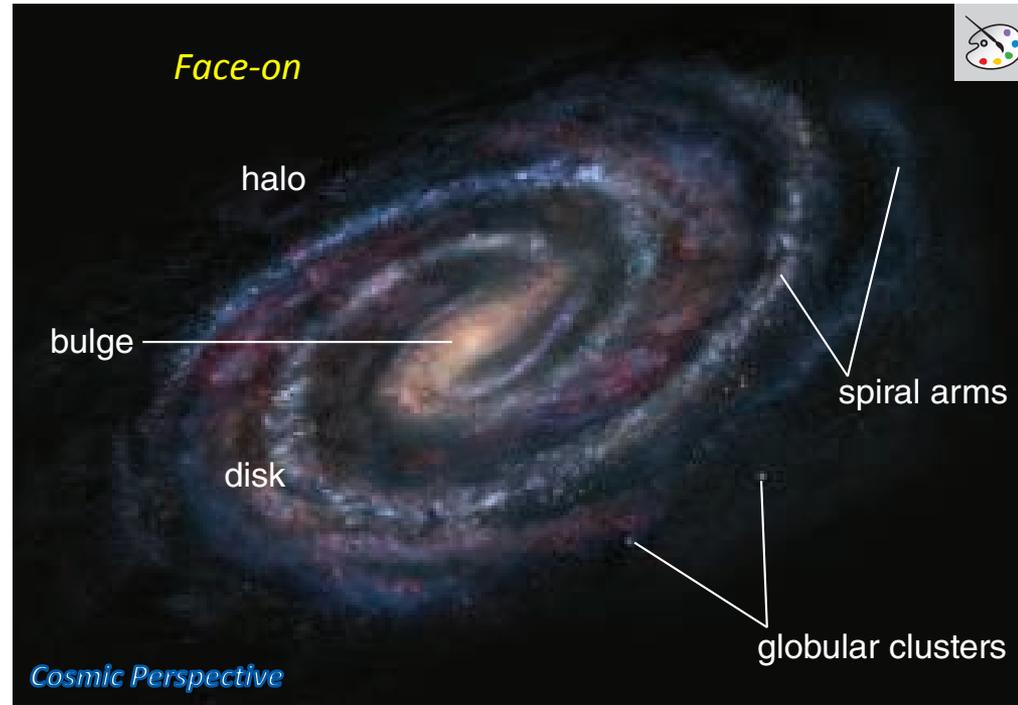
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A light-year (lyr) is the distance traveled by light in one year (9.5×10^{12} km). A parsec is 3.26 lyrs

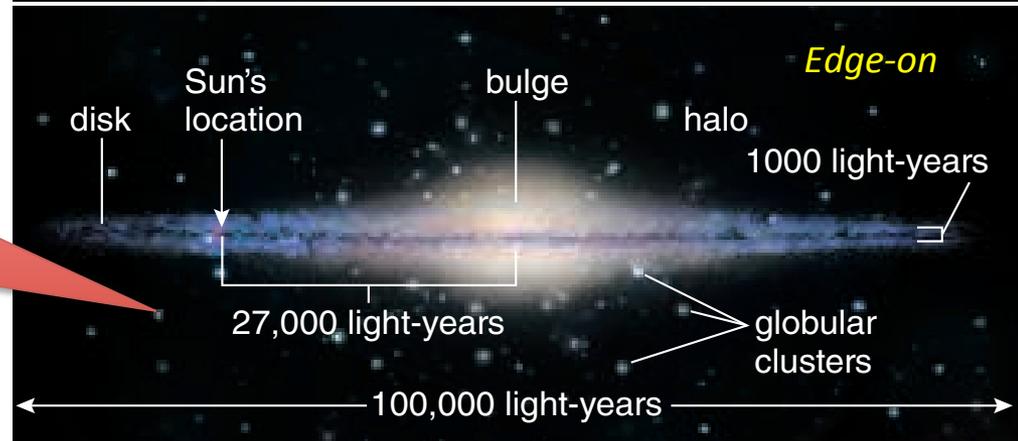


Milky Way size & composition

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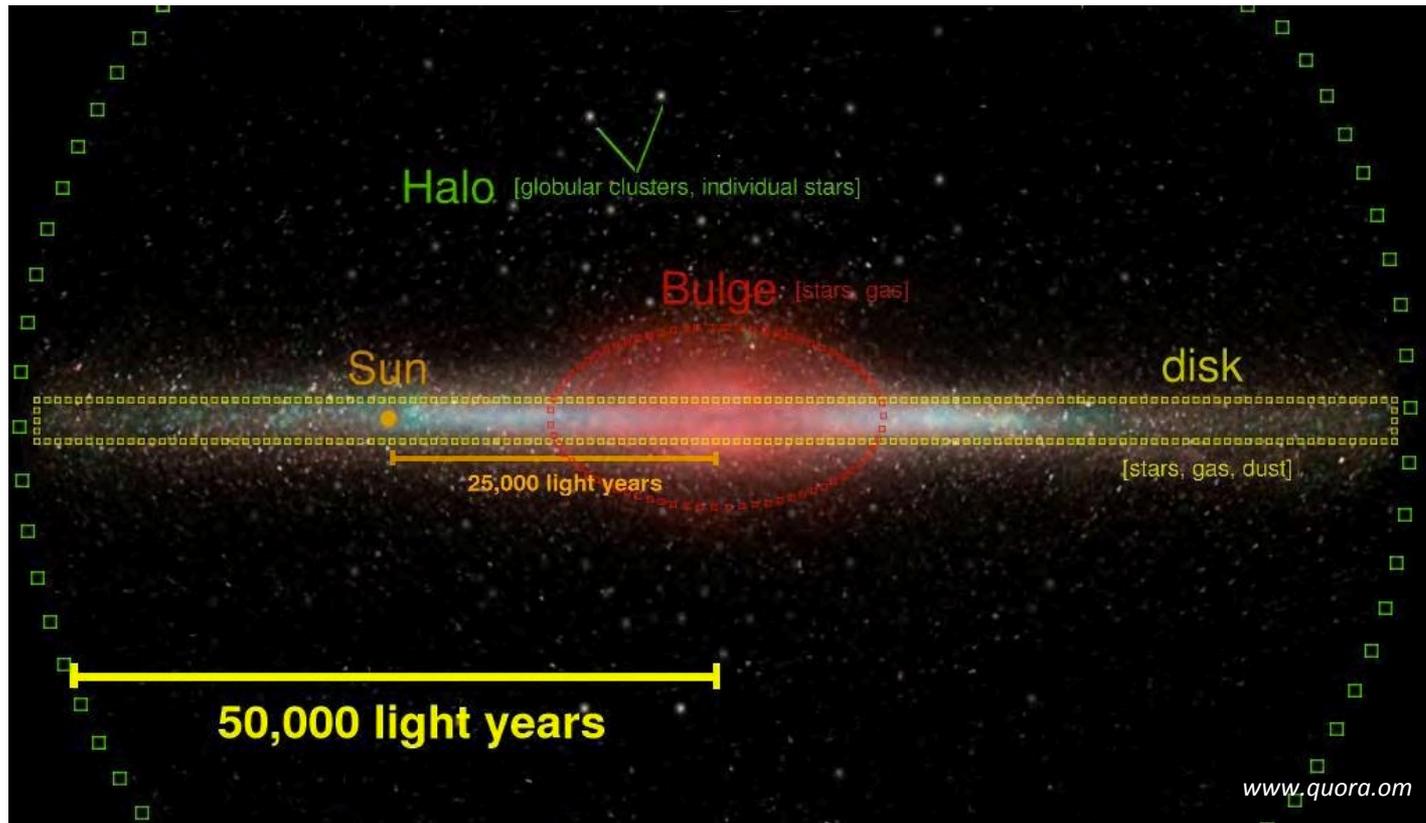


A globular cluster is an ensemble of thousands to millions of old stars packed together



Milky Way composition

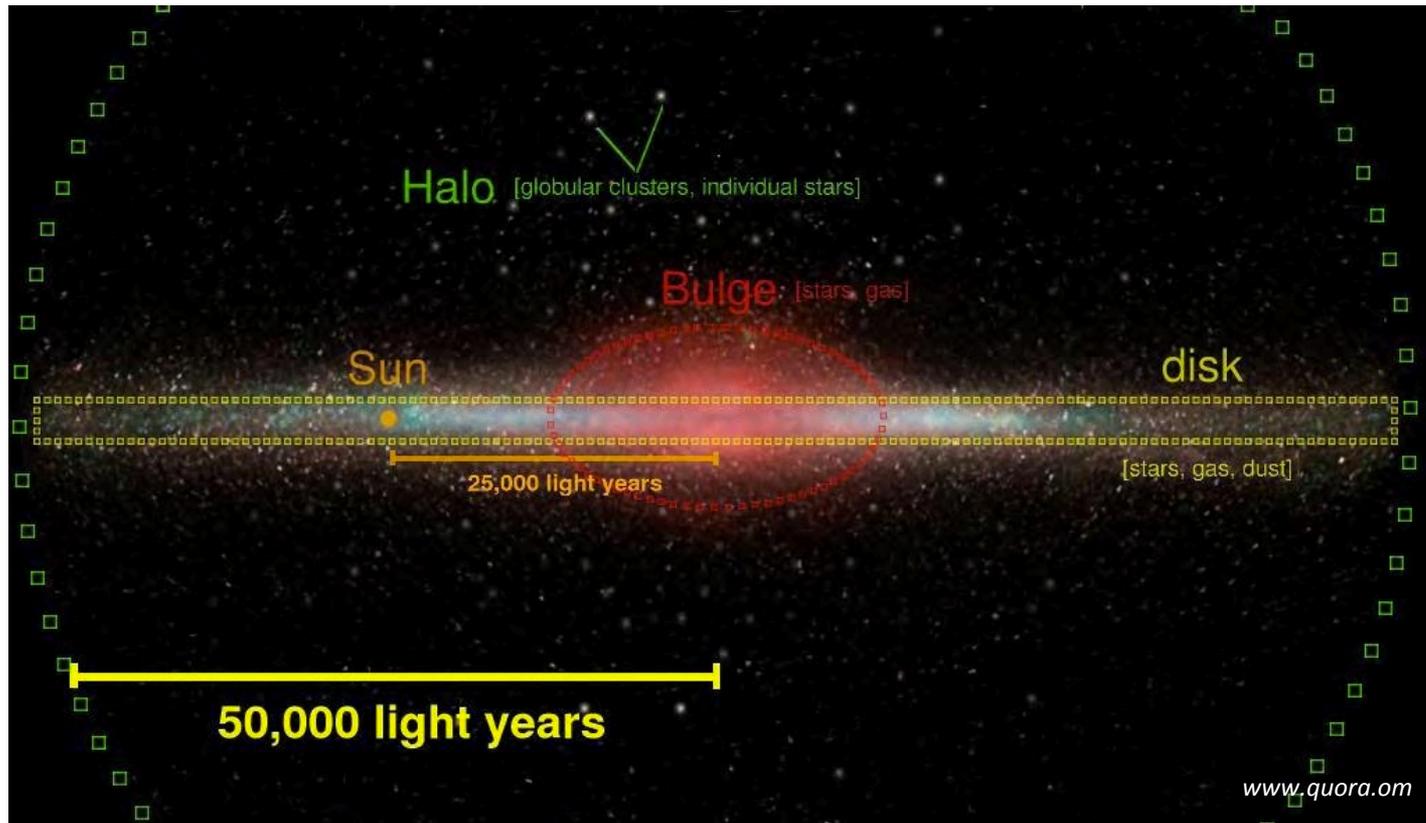
- **Disk:** contains stars, gas and dust
- **Bulge:** contains mostly stars (some gas)
- **Halo:** contains globular clusters and individual stars



Milky Way composition

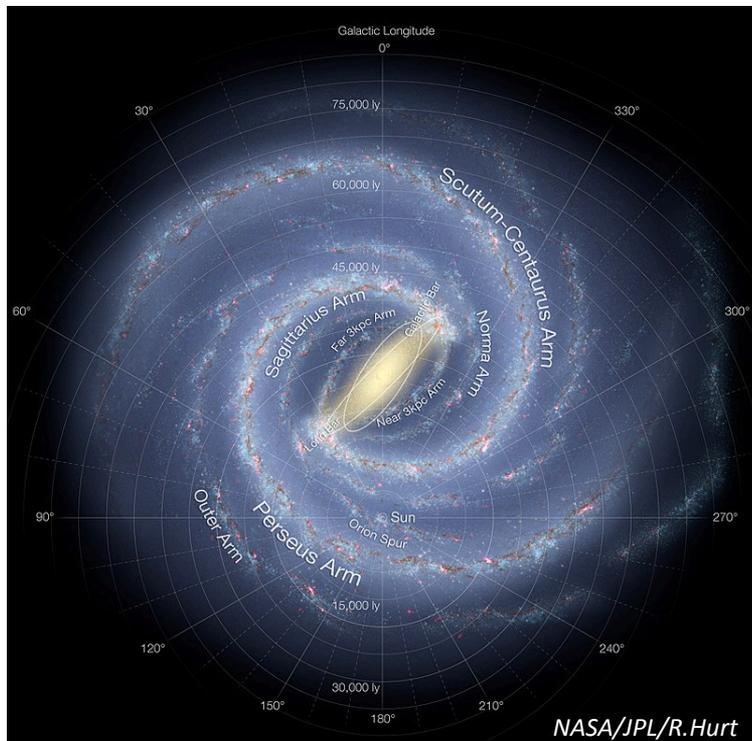
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Intestellar medium:
gas and dust
between stars



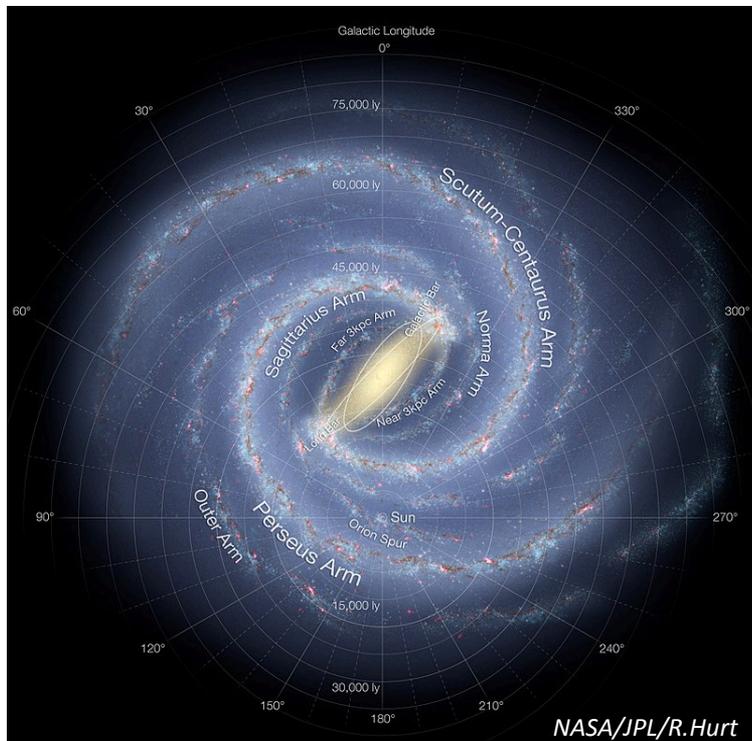
Milky Way composition

- Disk population: younger bluer stars (population I)
- Halo population: older yellow stars (population II)
- Bulge: mixture of both, disk and halo populations



Milky Way composition

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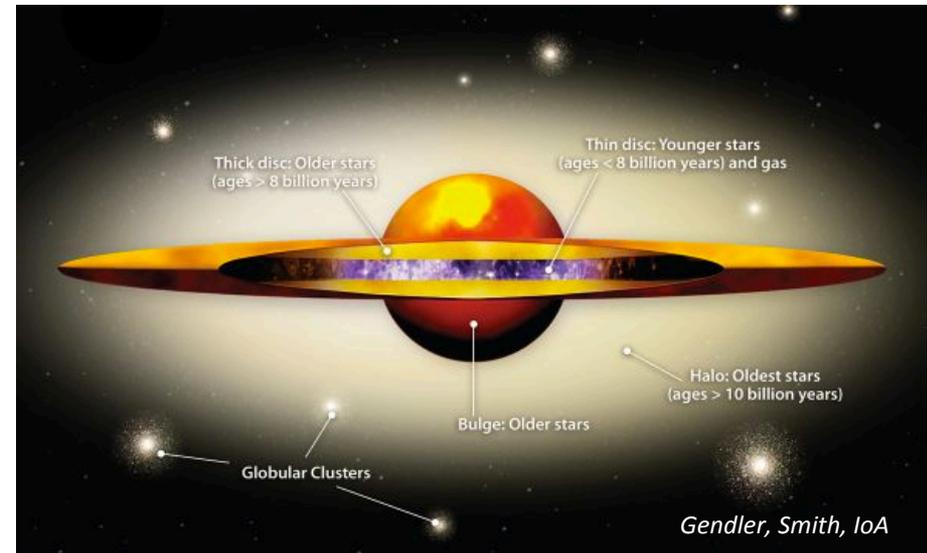
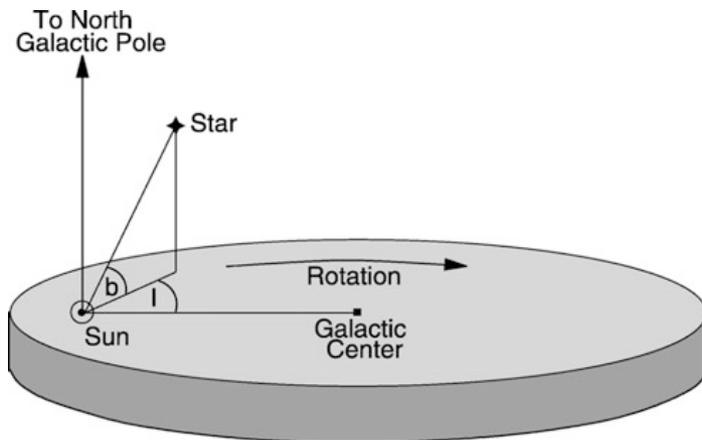


Metallicity is the chemical composition of a star or stellar population: a star with heavier elements is more metal-rich. Recent stars are more metal-rich.

Galactic disk

- Can be divided into thin and thick disks of scale heights (300pc and 1.5kpc): $n(z) \propto \exp\left(-\frac{|z|}{h}\right)$
- Thin disk has younger, metal-rich stars and more gas/dust fractions
- Radial density also decreases exponentially

$$n(R, z) = n_0 \left(e^{-|z|/h_{\text{thin}}} + 0.02e^{-|z|/h_{\text{thick}}} \right) e^{-R/h_R}$$



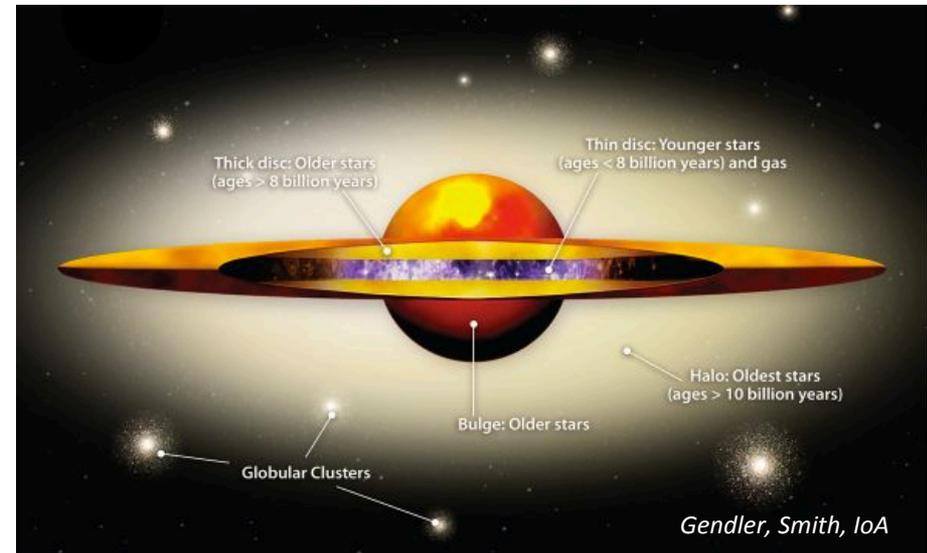
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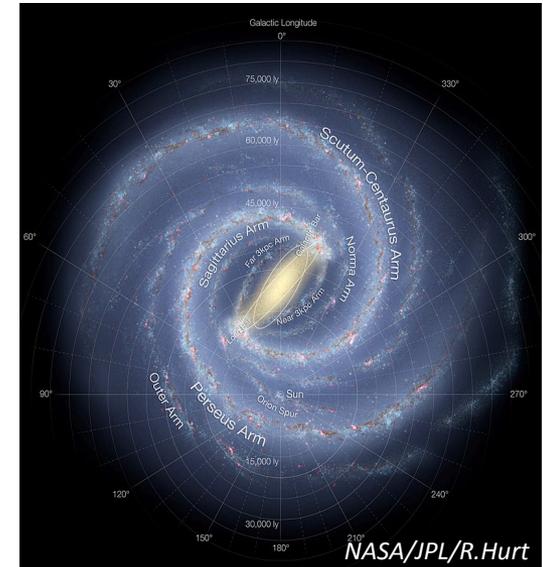
Disk brightness profile is exponential:

$$L(R, z) = \frac{L_0 e^{-R/h_R}}{\cosh^2(z/h_z)}$$



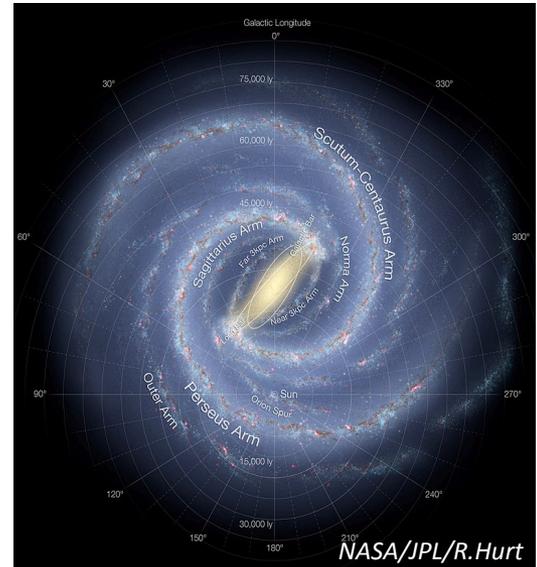
Galactic bulge

- Older stars away from the center
- Bulge has peanut-like bar with characteristic scale length of 1kpc



Galactic bulge

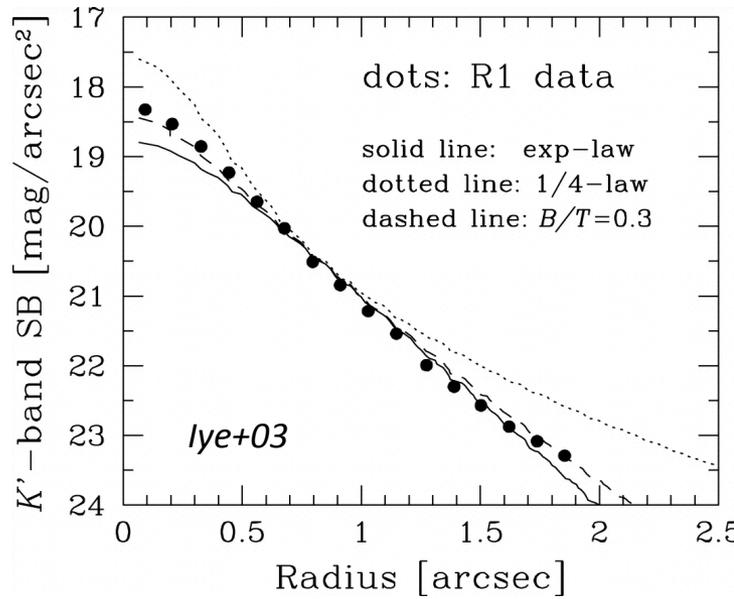
- Older stars away from the center
- Bulge has peanut-like bar with characteristic scale length of 1kpc
- **Bulge brightness** follows a *de Vaucouleurs* profile:



$$I(R) = I_e \exp\left(-7.669 \left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]\right)$$

Surface
brightness:
 $\mu = L/4\pi R^2$

Effective radius:
half of the
luminosity radius



OBSERVATION: Milky Way in multi-wavelength

CHROMOSCOPE
version 1.4.6

OPTICAL

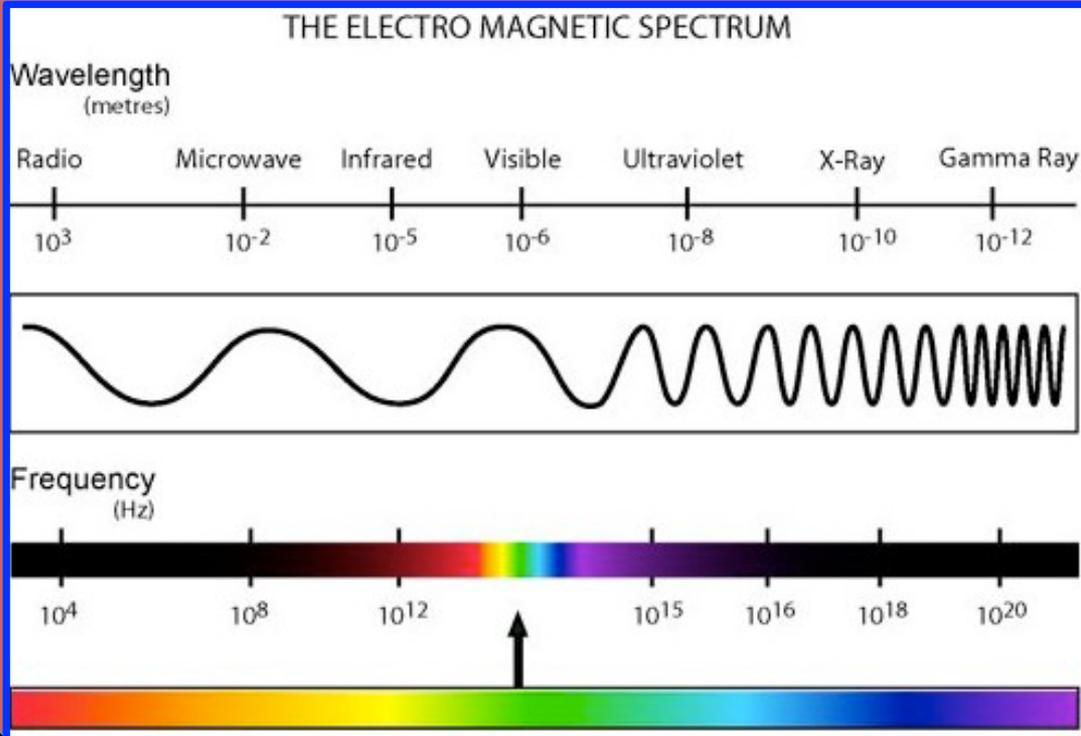
Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio

+
-

OBSERVATION: Milky Way in multi-wavelength

CHROMOSCOPE
version 1.4.6

Gamma ray
X-ray
Visible
Hydrogen α
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OBSERVATION: Milky Way in multi-wavelength

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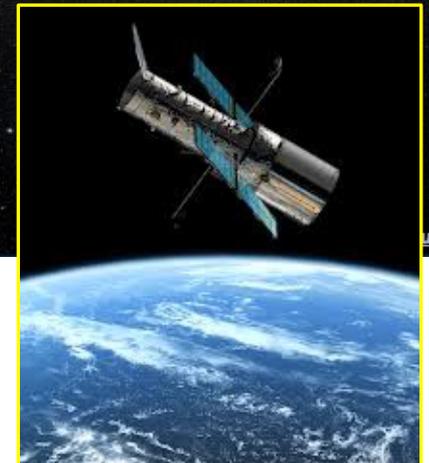
OPTICAL

Gamma ray
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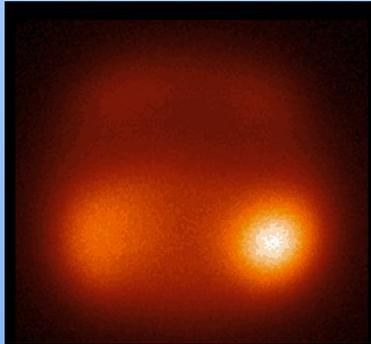


Telescopes

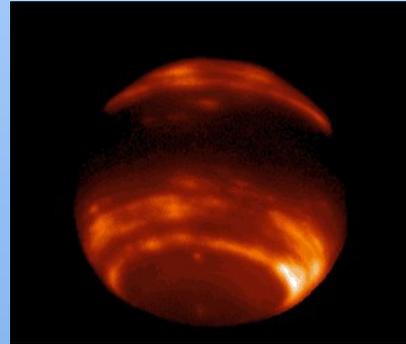
OBSERVATION: Milky Way in multi-wavelength

Why put telescopes in space?

Neptune

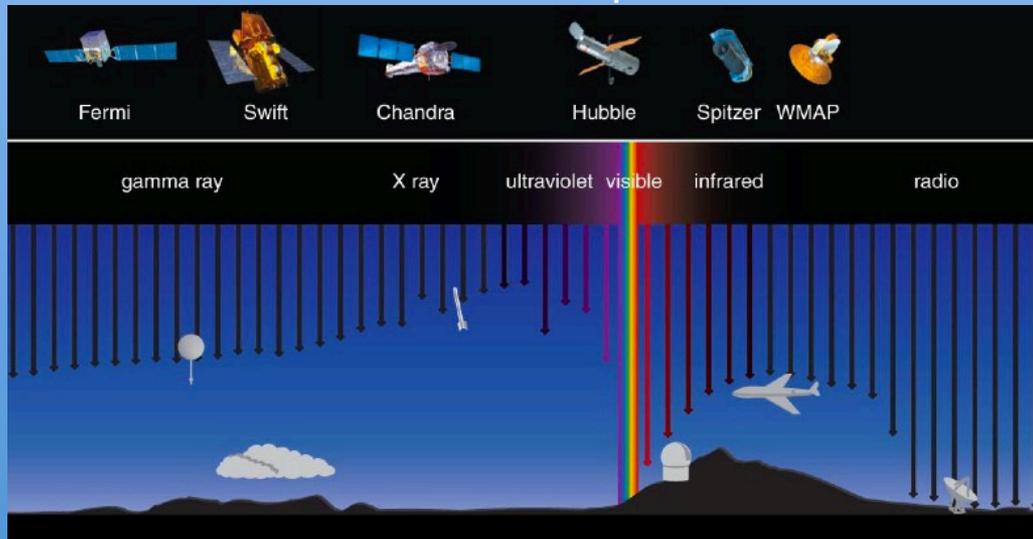


On earth

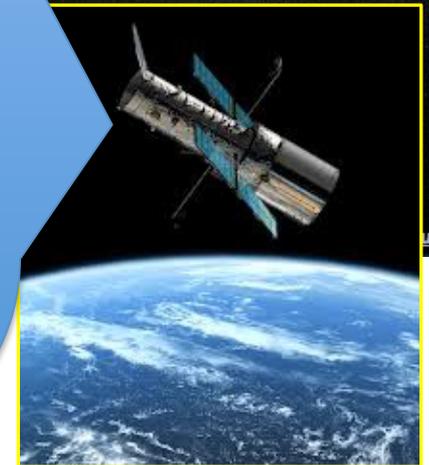


In space

Effect of atmosphere



Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio



OBSERVATION: Milky Way in multi-wavelength

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OPTICAL

Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio



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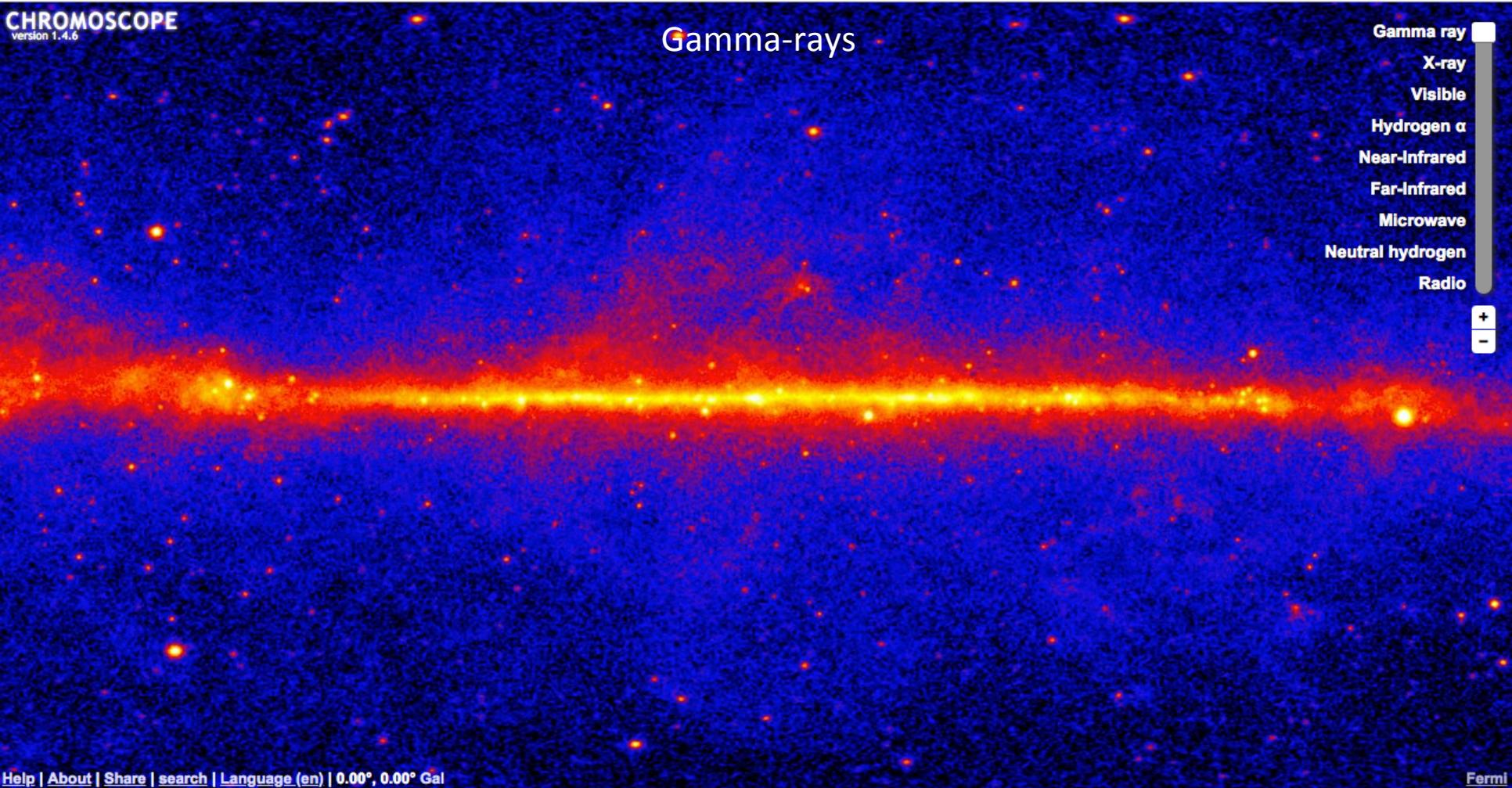
Telescopes

OBSERVATION: Milky Way in multi-wavelength

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Gamma-rays

- Gamma ray
 - X-ray
 - Visible
 - Hydrogen α
 - Near-Infrared
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 - Microwave
 - Neutral hydrogen
 - Radio
- +
-

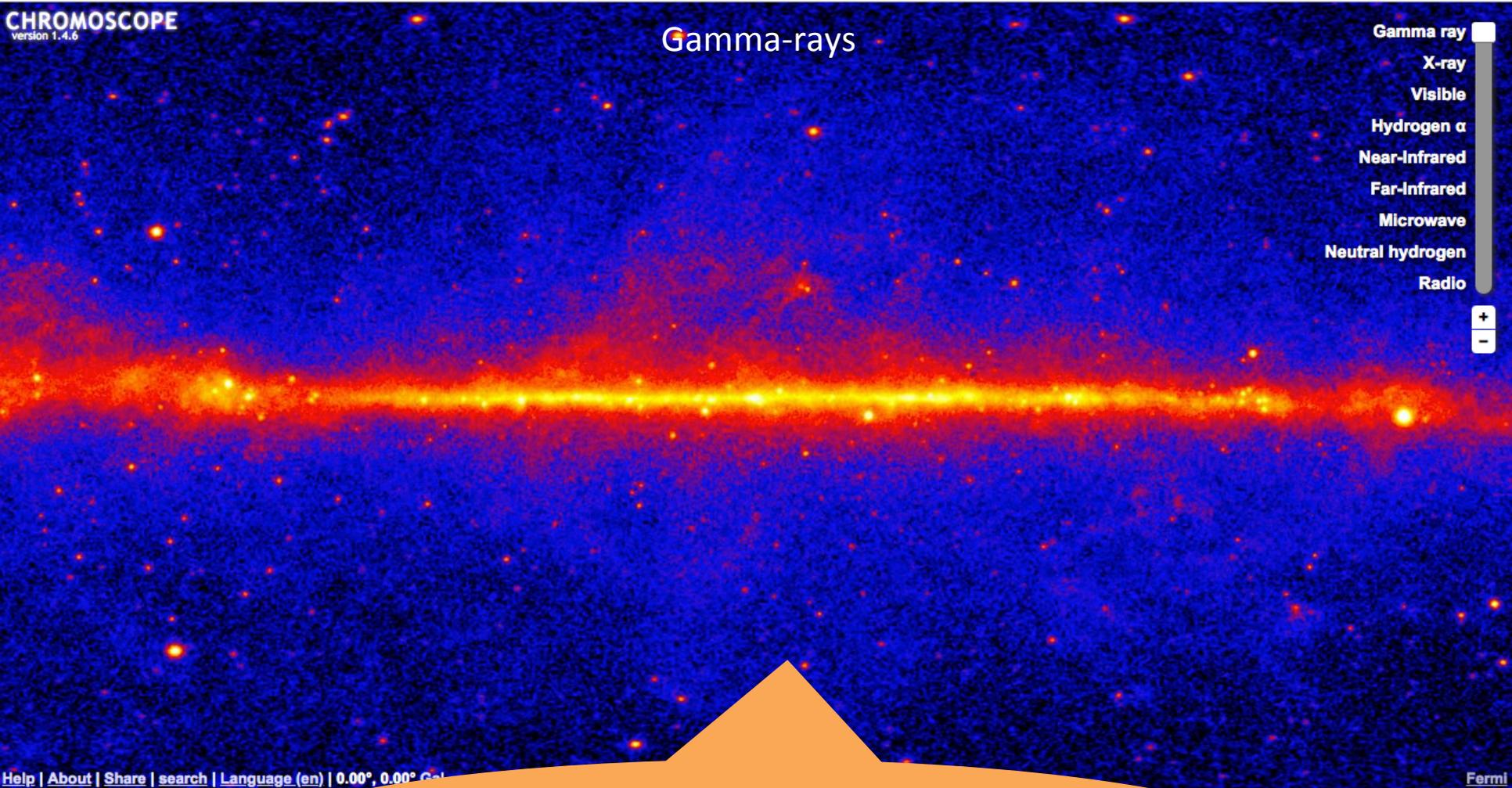


OBSERVATION: Milky Way in multi-wavelength

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Gamma-rays

Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio



The human eye cannot see gamma-rays, UV, IR nor radio, so astronomers use color coding to correspond different emission energy

OBSERVATION: Milky Way in multi-wavelength

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Gamma-rays

- Gamma ray
 - X-ray
 - Visible
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 - Microwave
 - Neutral hydrogen
 - Radio
- +
-

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Fermi

Telescopes



OBSERVATION: Milky Way in multi-wavelength

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X-ray

- Gamma ray
 - X-ray
 - Visible
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 - Near-Infrared
 - Far-Infrared
 - Microwave
 - Neutral hydrogen
 - Radio
- +
-

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ROSAT & Nick Risinger, skysurvey.org

Telescopes



OBSERVATION: Milky Way in multi-wavelength

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OPTICAL

Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
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Radio



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Telescopes

OBSERVATION: Milky Way in multi-wavelength

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Hydrogen- α

Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio

+
-

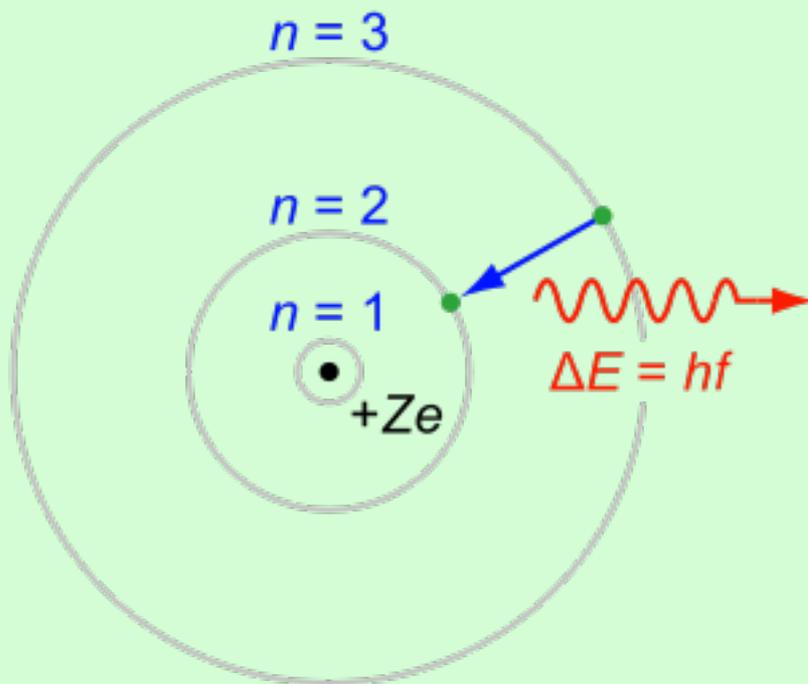
OBSERVATION: Milky Way in multi-wavelength

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Gamma ray
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Neutral hydrogen
Radio

Hydrogen- α

Balmer transition from 3rd to 2nd level
in Hydrogen (656nm)



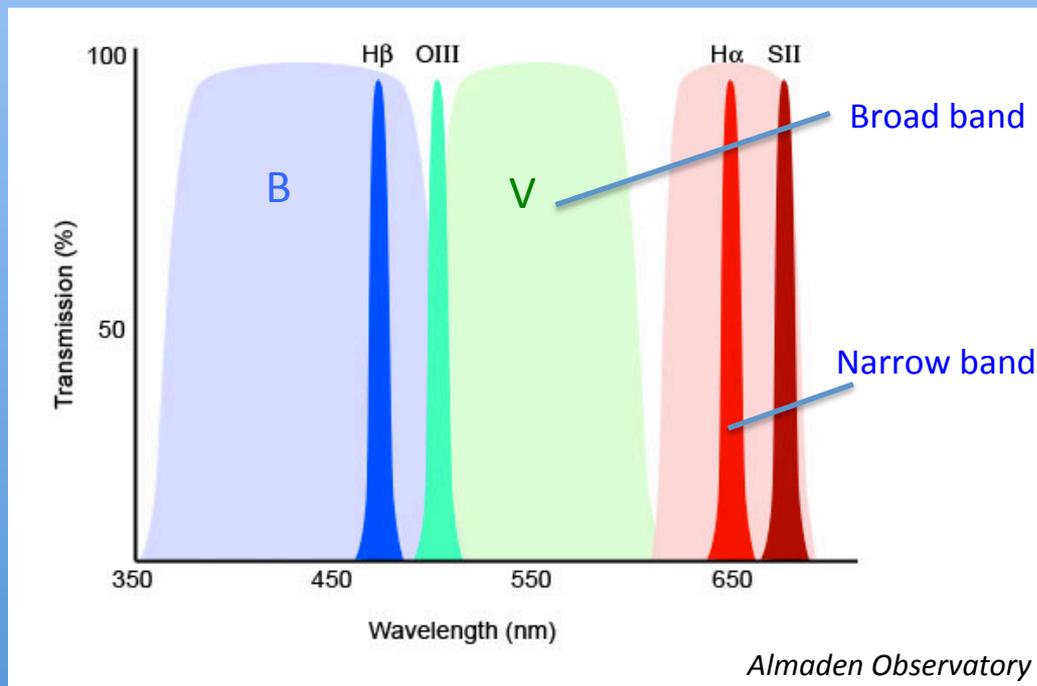
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Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio

Hydrogen- α

Photometry: filter transmissions



Almaden Observatory

OBSERVATION: Milky Way in multi-wavelength

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Hydrogen- α

Gamma ray
X-ray
Visible
Hydrogen α
Near-Infrared
Far-Infrared
Microwave
Neutral hydrogen
Radio

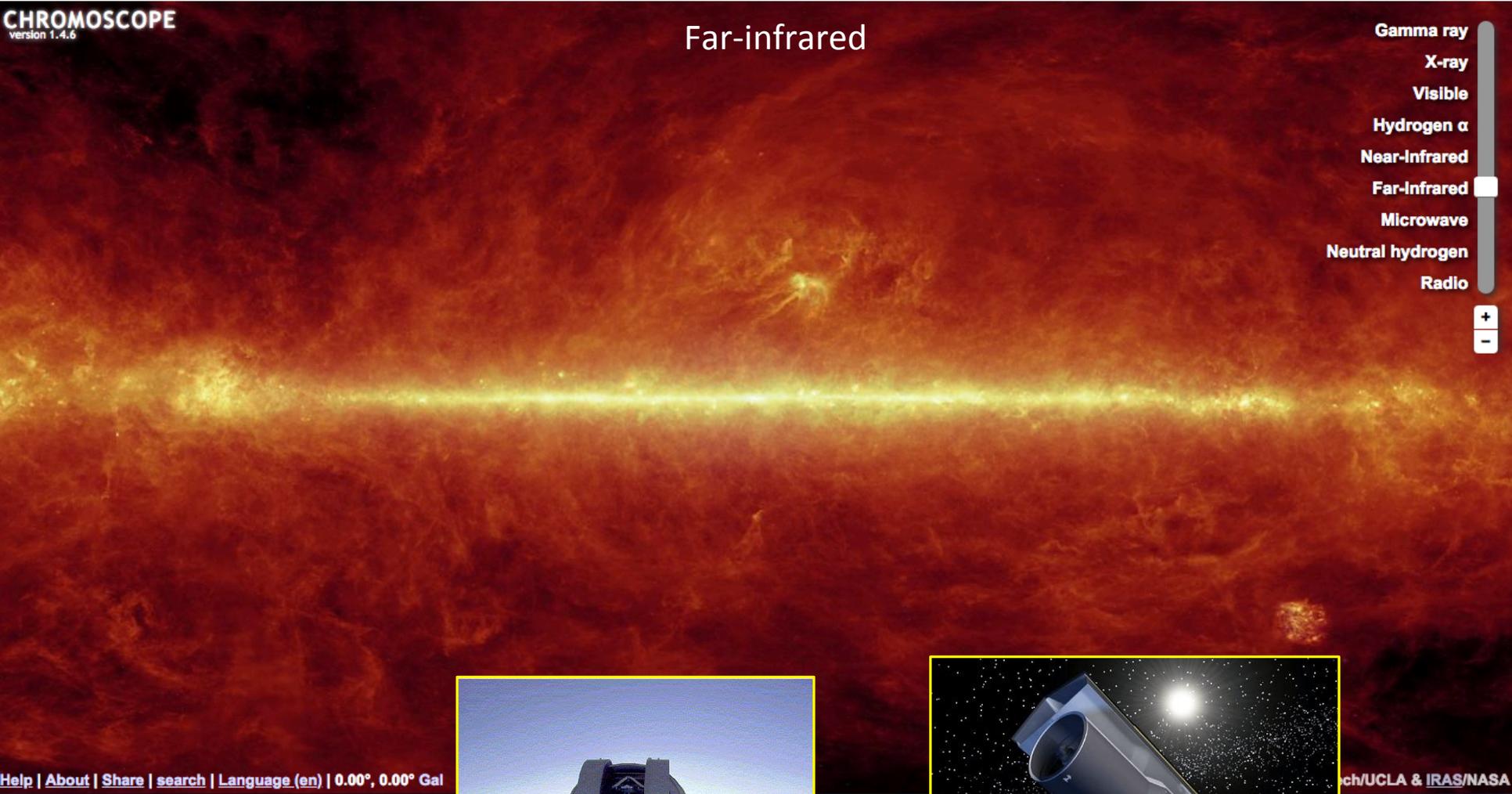
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OBSERVATION: Milky Way in multi-wavelength

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Far-infrared

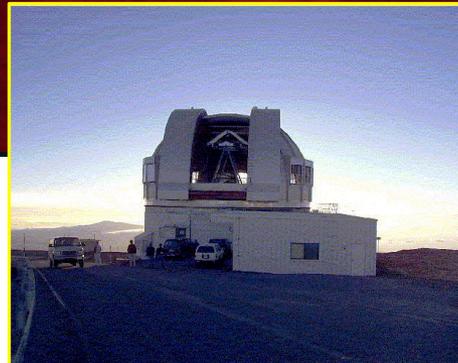
- Gamma ray
 - X-ray
 - Visible
 - Hydrogen α
 - Near-Infrared
 - Far-Infrared
 - Microwave
 - Neutral hydrogen
 - Radio
- +
-



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ch/UCLA & IRAS/NASA

Telescopes



OBSERVATION: Milky Way in multi-wavelength

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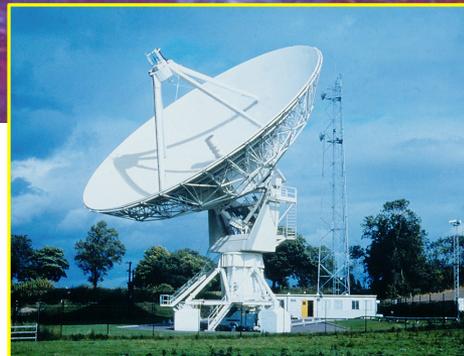
Microwave

- Gamma ray
 - X-ray
 - Visible
 - Hydrogen α
 - Near-Infrared
 - Far-Infrared
 - Microwave
 - Neutral hydrogen
 - Radio
- +
-

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2010) & HI4PI Collaboration

Telescopes



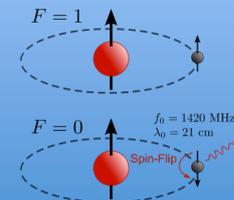
OBSERVATION: Milky Way in multi-wavelength

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Neutral Hydrogen (21cm)

- Gamma ray
 - X-ray
 - Visible
 - Hydrogen α
 - Near-Infrared
 - Far-Infrared
 - Microwave
 - Neutral hydrogen
 - Radio
- +
-

21cm line comes from hyperfine 1s transition of hydrogen



OBSERVATION: Milky Way in multi-wavelength

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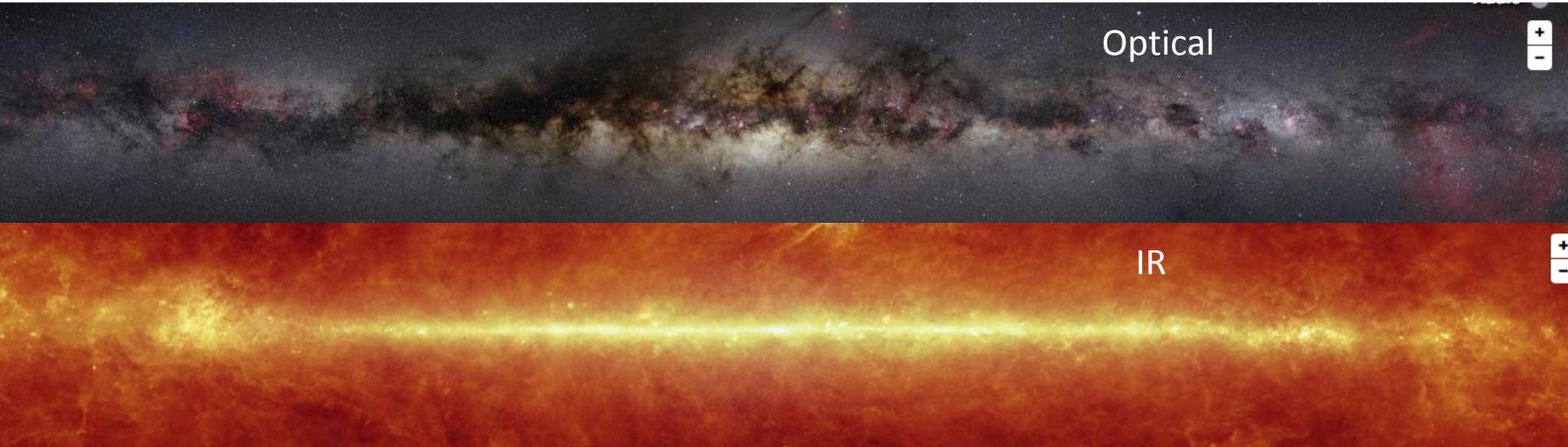
Radio

- Gamma ray
 - X-ray
 - Visible
 - Hydrogen α
 - Near-Infrared
 - Far-Infrared
 - Microwave
 - Neutral hydrogen
 - Radio
- +
-

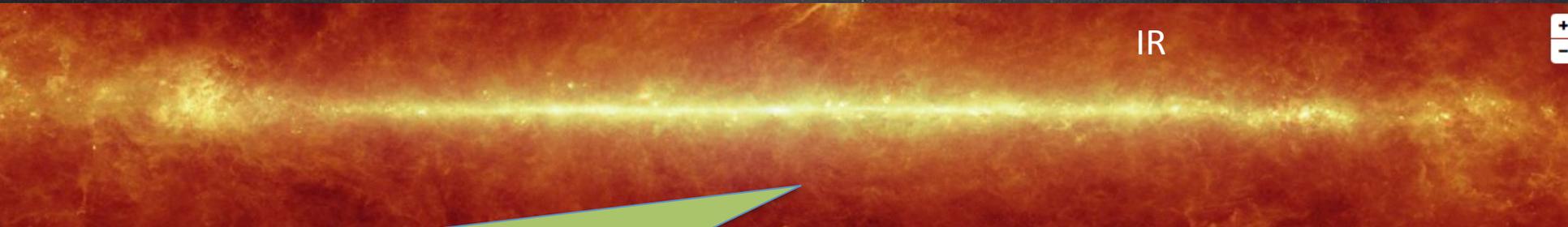
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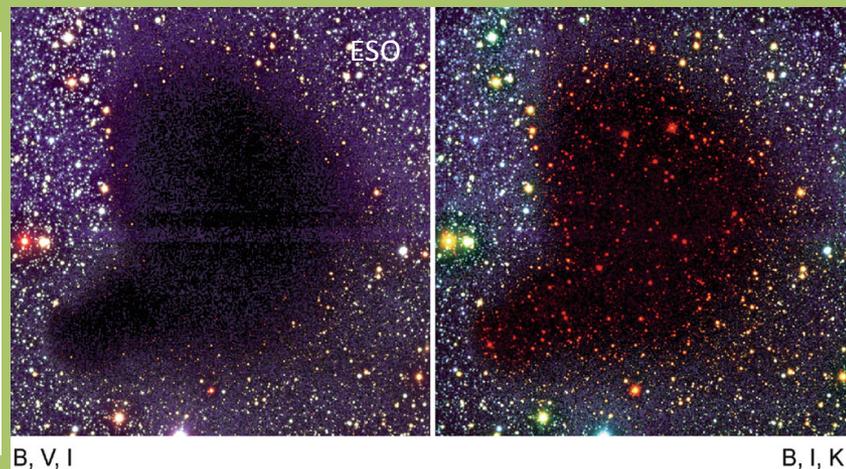
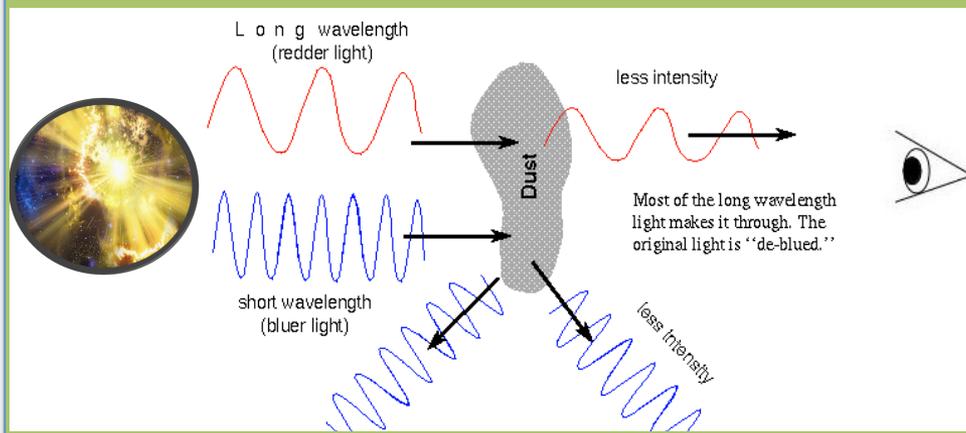
OBSERVATION: Milky Way in multi-wavelength



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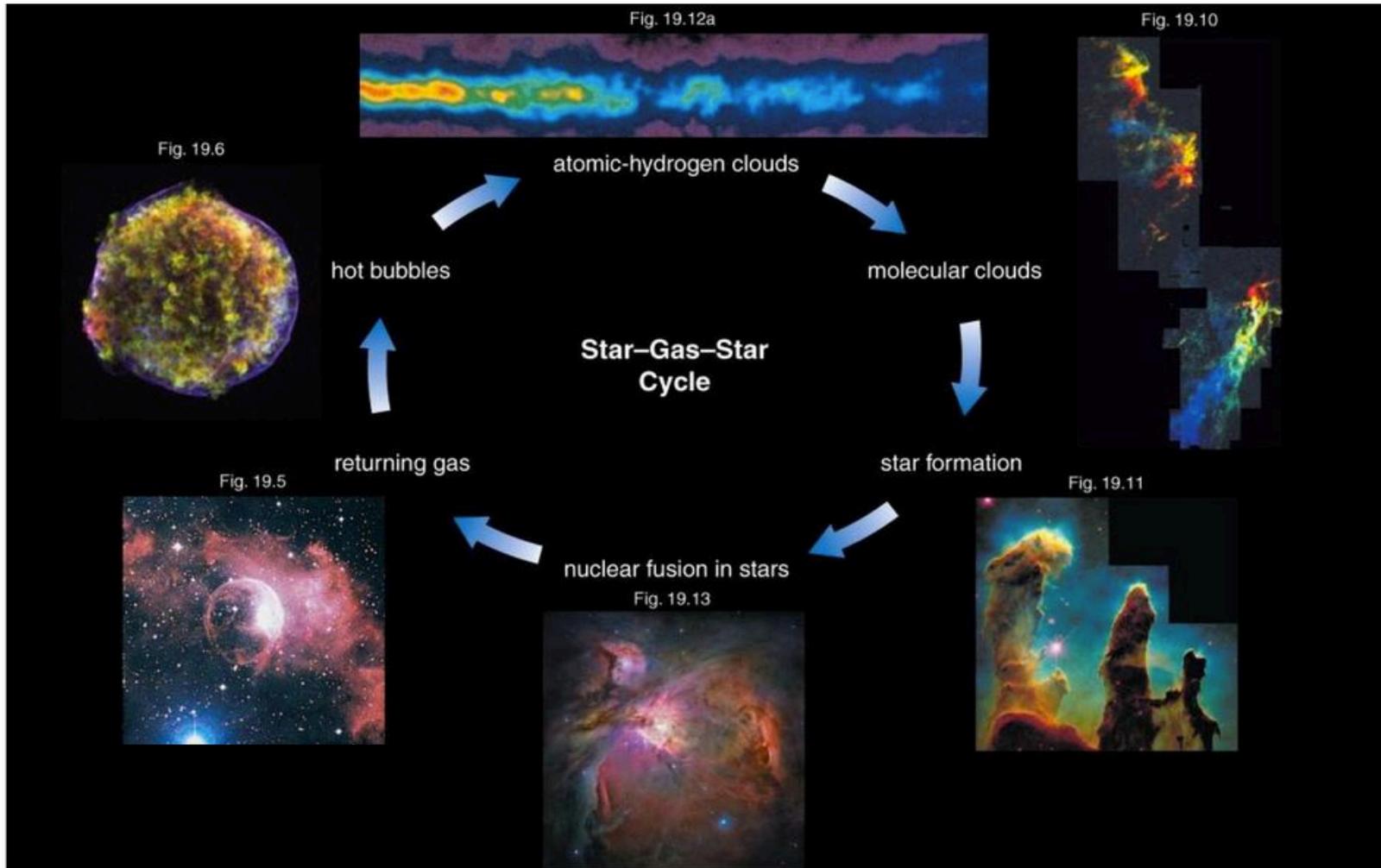


Extinction: absorption of light by dust
Reddening: reemission at longer wavelengths



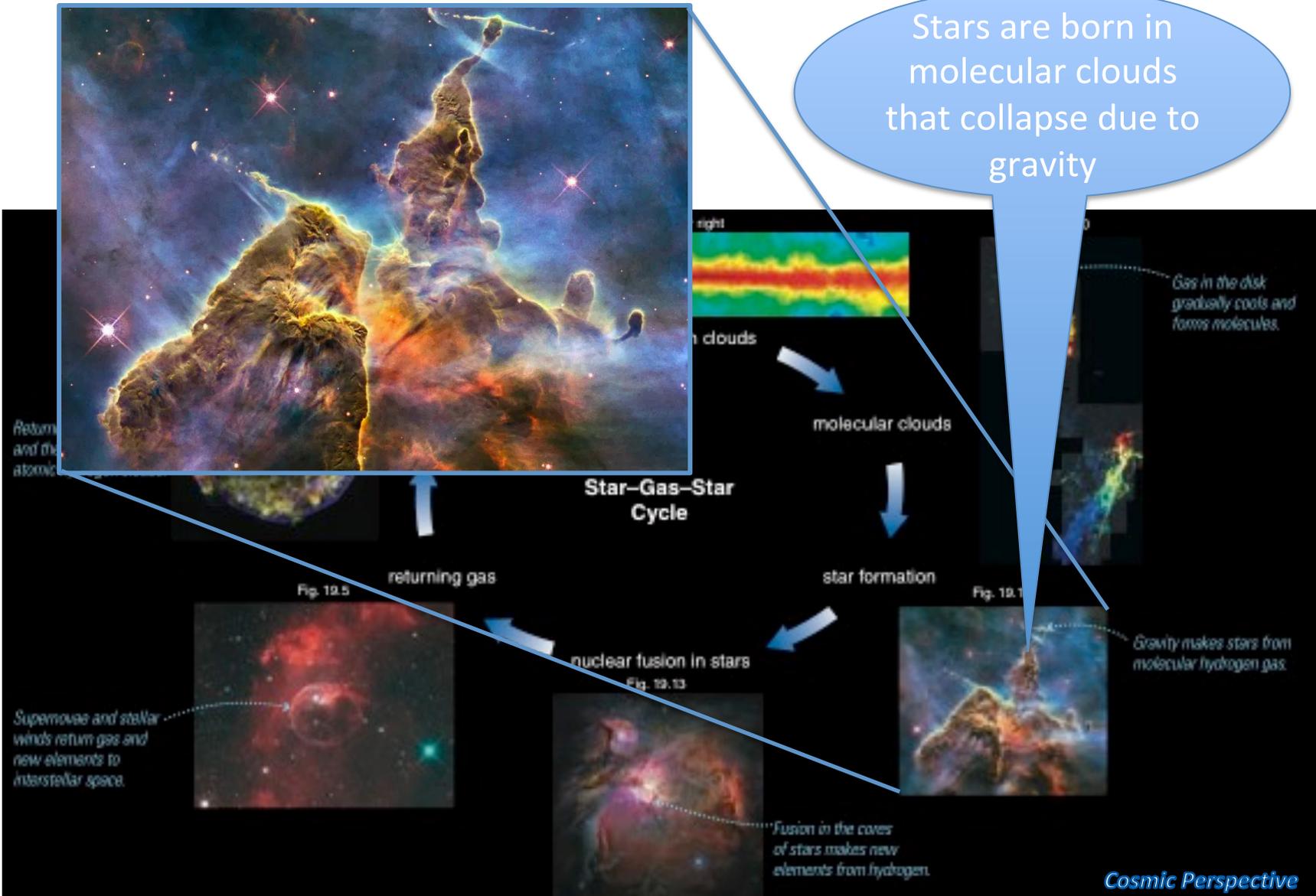
Star-gas-star cycle

Galactic recycling in the disk and interstellar medium: new stars are born from gas and others die enriching the medium with heavier elements



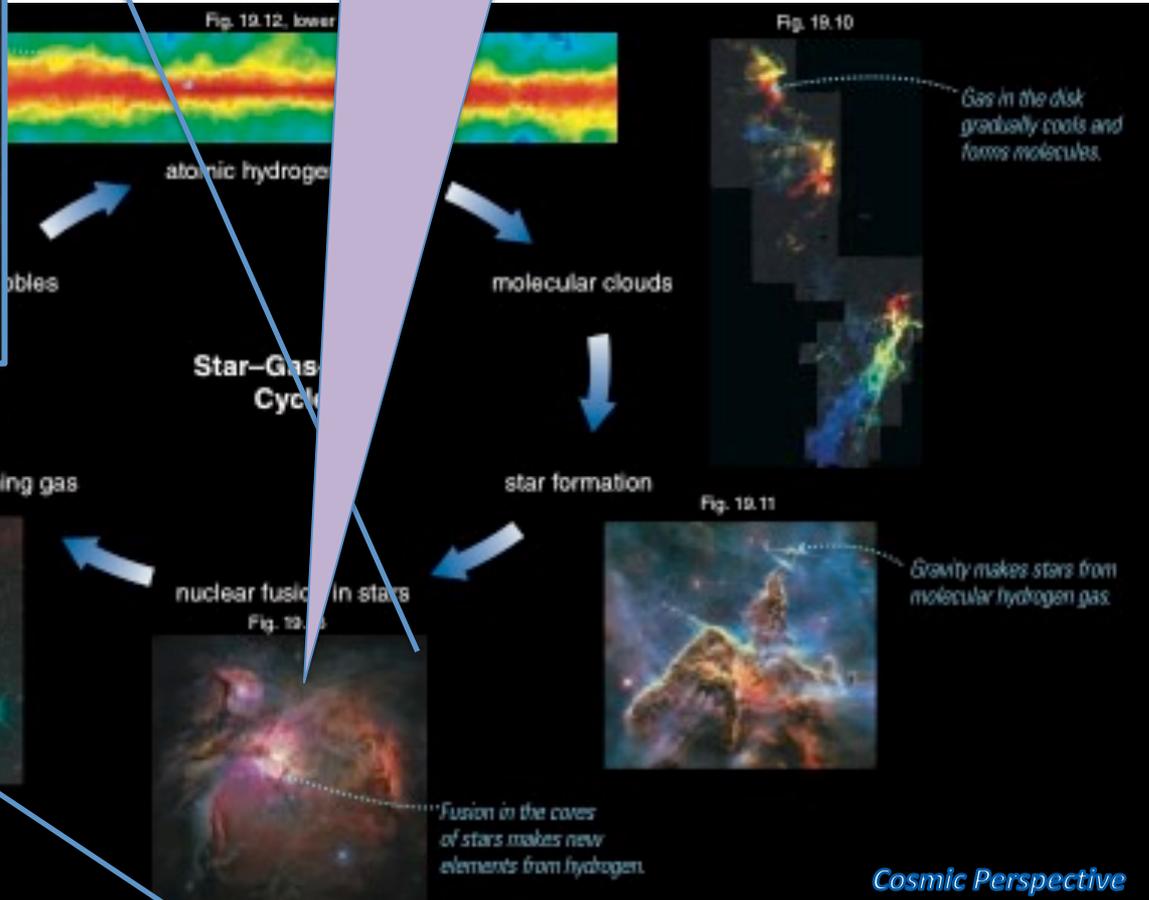
Star-gas-star cycle

Stars are born in molecular clouds that collapse due to gravity



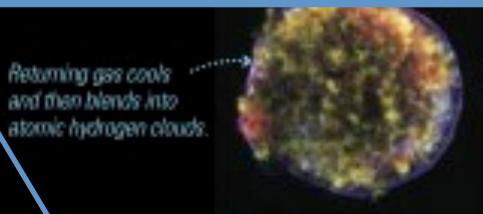
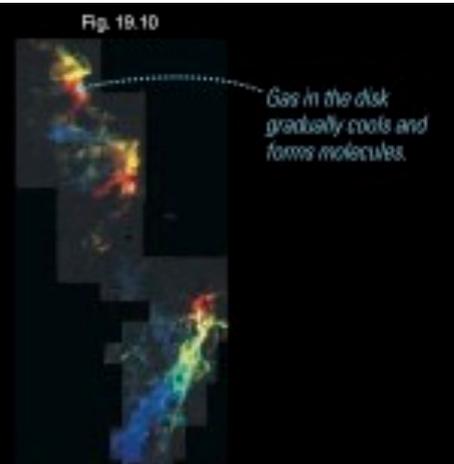
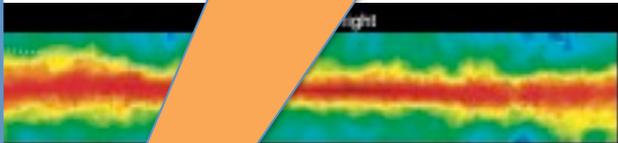
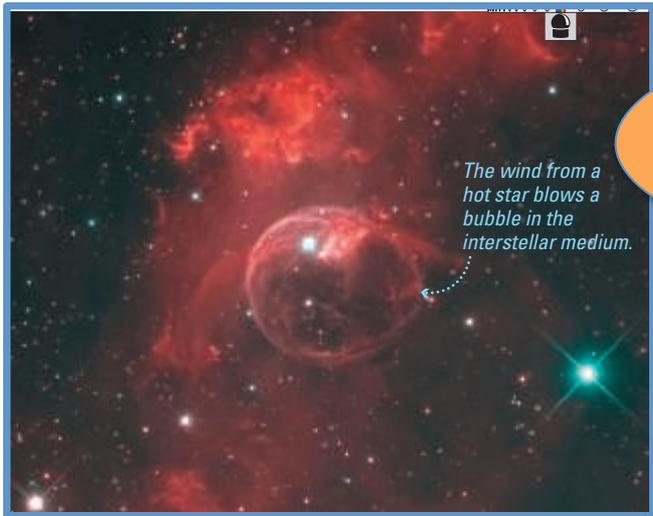
Star-gas-star cycle

During their lives stars generate energy through fusion of lighter elements into heavier ones



Star-gas-star cycle

Stellar winds and stellar deaths like supernovae eject material to environment



hot bubbles

molecular clouds

Star-Gas-Star Cycle

star formation

Fig. 18.11

Gravity makes stars from molecular hydrogen gas.

Fig. 18.5

returning gas

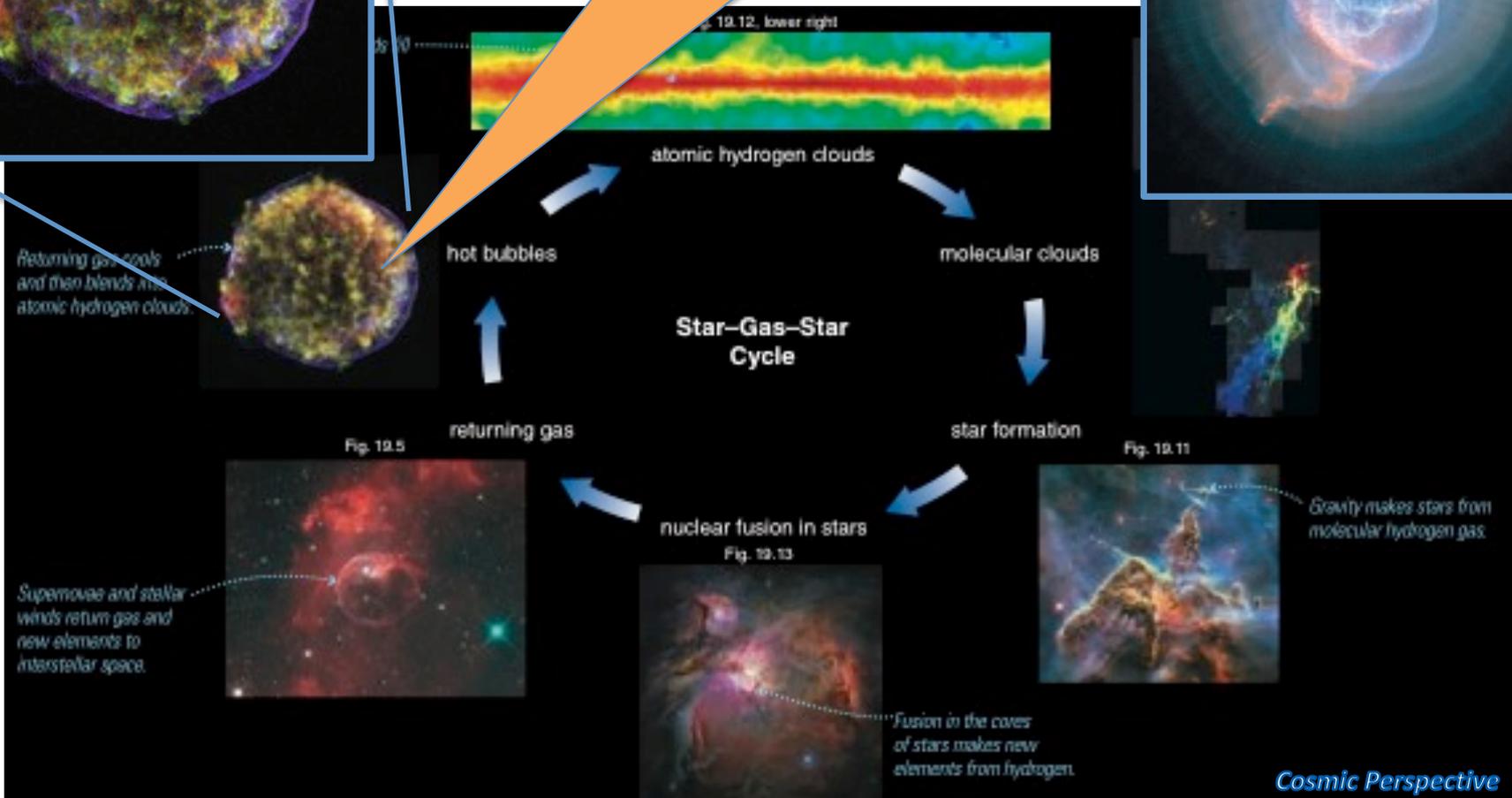
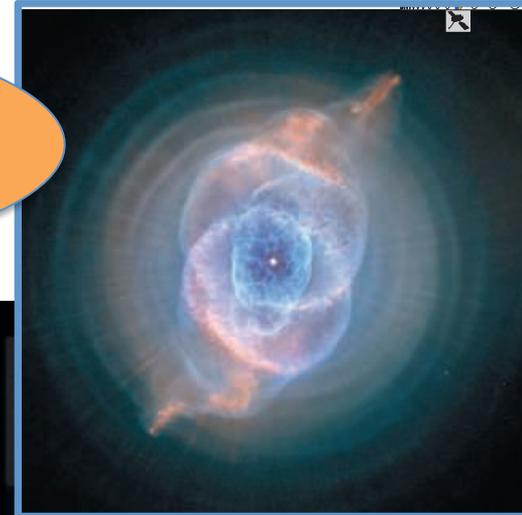
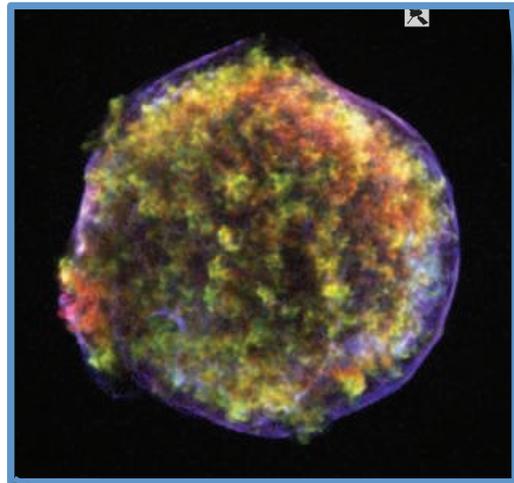
nuclear fusion in stars
Fig. 18.13

Fusion in the cores of stars makes new elements from hydrogen.

Supernovae and stellar winds return gas and new elements to interstellar space.

Star-gas-star cycle

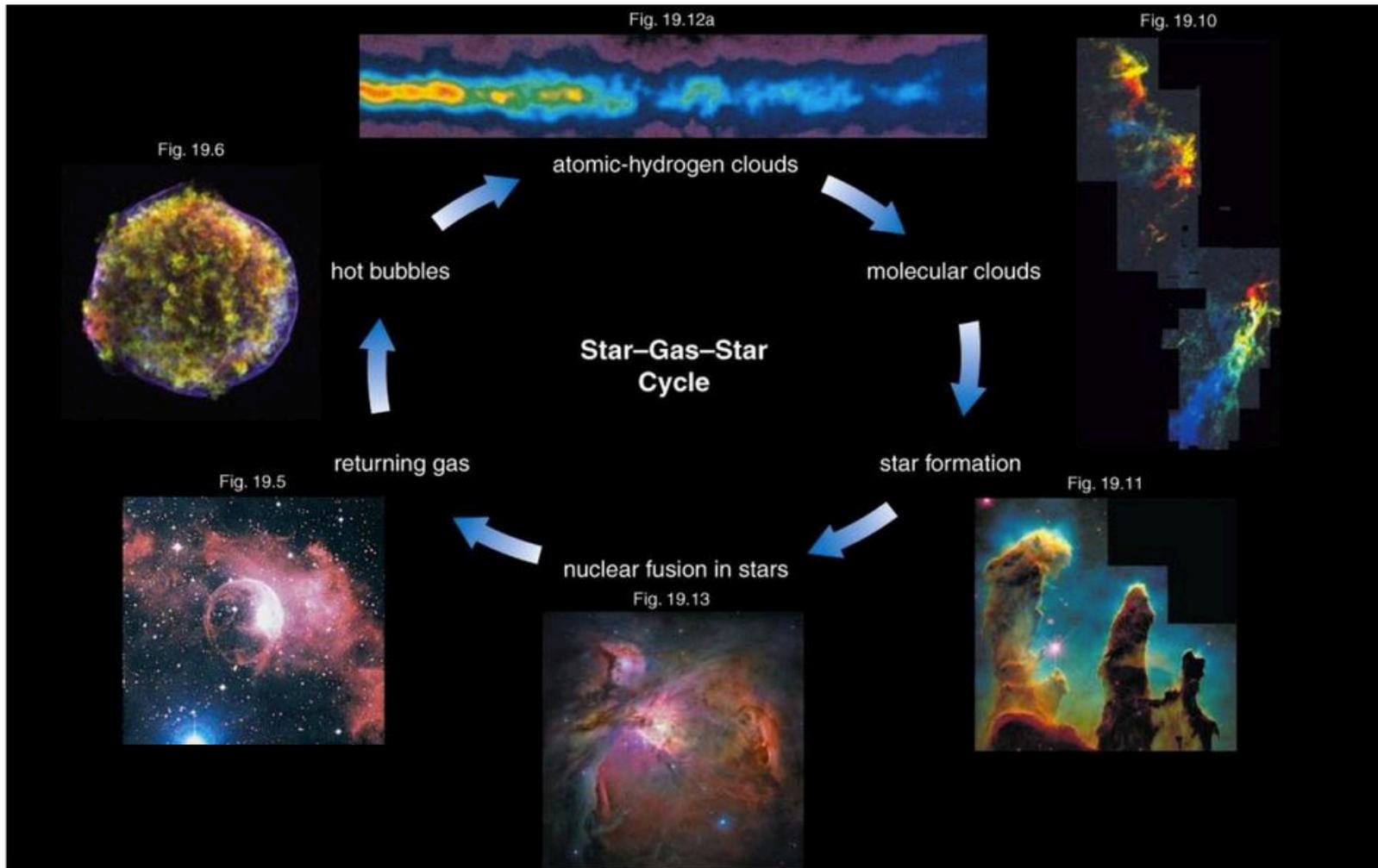
Stellar winds and stellar deaths like supernovae eject material to environment

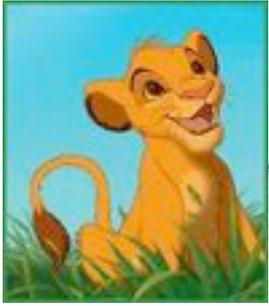


Star-gas-star cycle

Cycle begins again with an enriched material

Duration of cycle might vary from millions to billions of yrs

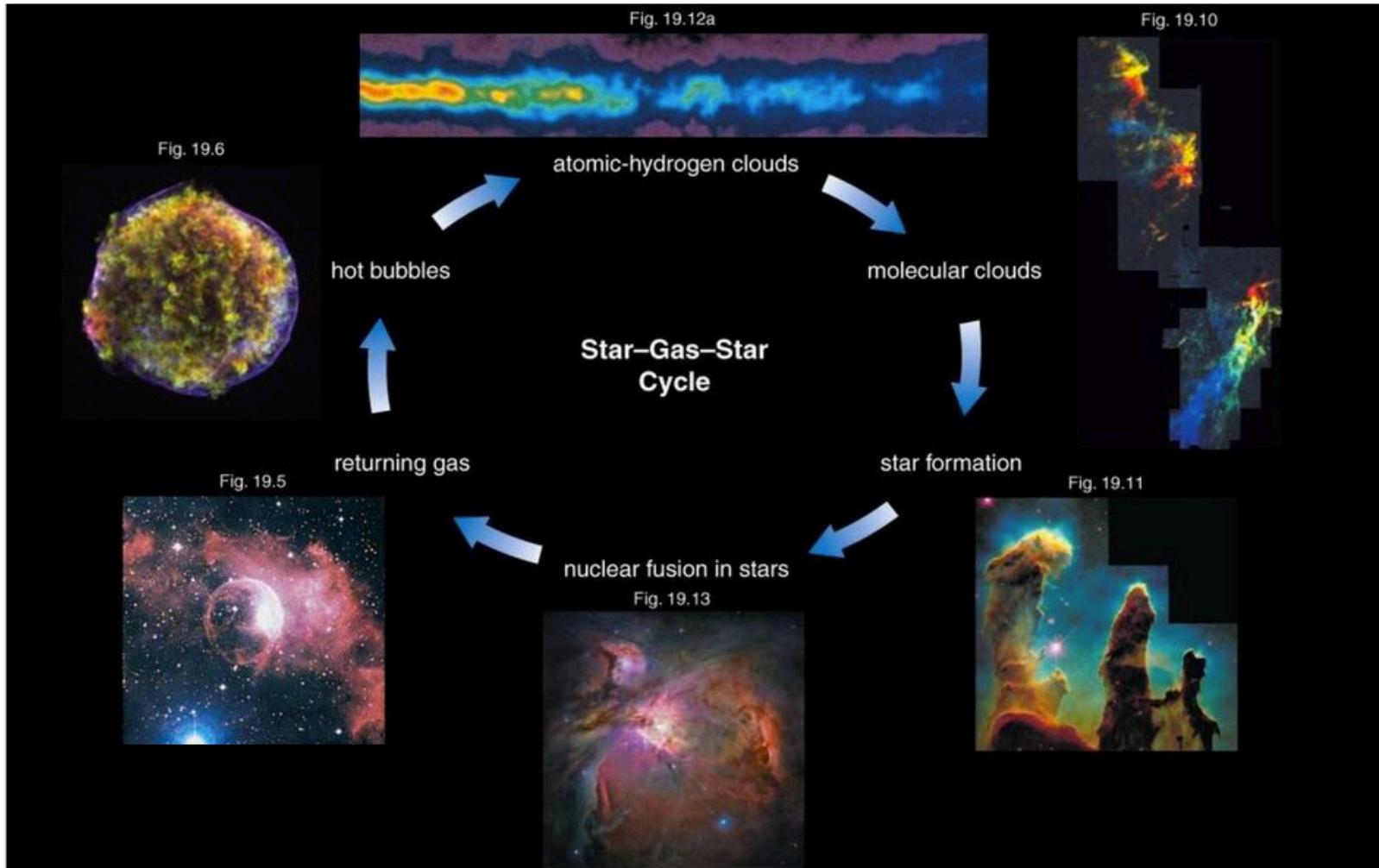




Star-gas-star cycle



It's the circle of life!

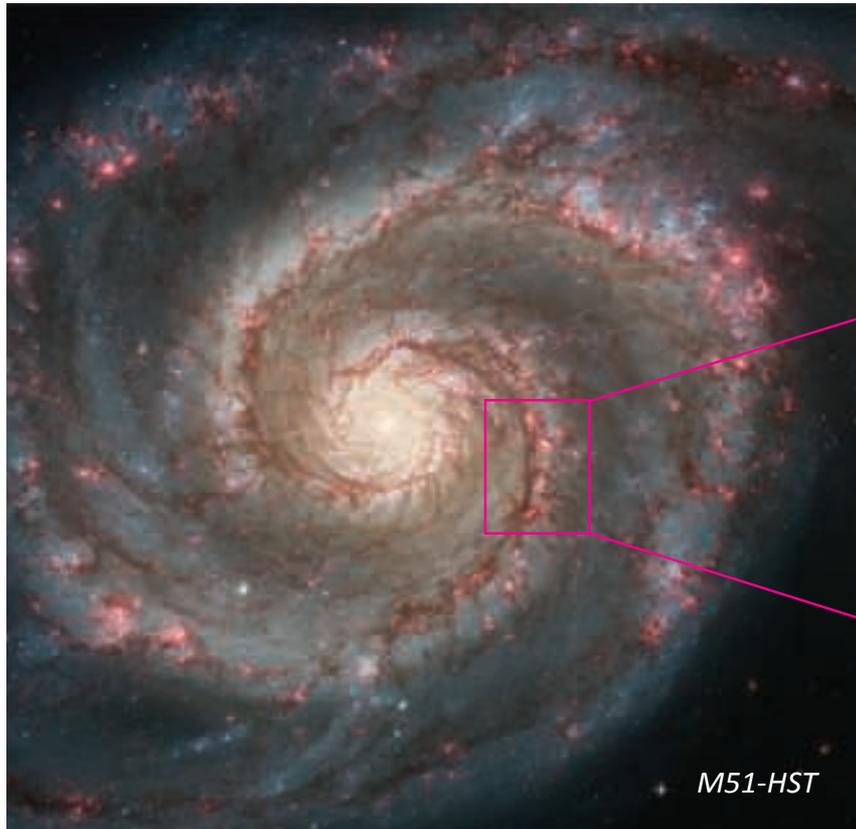


Star formation

Where do stars form? Where do they die? Do stars migrate?

Star forming regions

Stars form in spiral arms where cool molecular gas clouds are abundant



Dark patches on inner edge of spiral arm show where gas clouds are packing together. . .

. . . and compression of these clouds triggers star formation in the arm.

Blue specks are young stars that formed in the spiral arm.

Red patches are ionization nebulae around the hottest, youngest stars.

Flow of gas and stars through spiral arm

Star forming regions

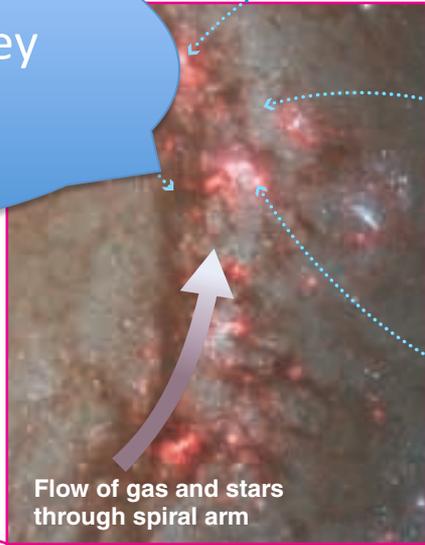
Stars form in spiral arms where cool molecular gas clouds are abundant



Massive stars are hotter (bluer) and live fast: they don't have time to move!

Dark patches on inner edge of spiral arm show where gas clouds are packing together. . .

. . . and compression of these clouds triggers star formation in the arm.



Blue specks are young stars that formed in the spiral arm.

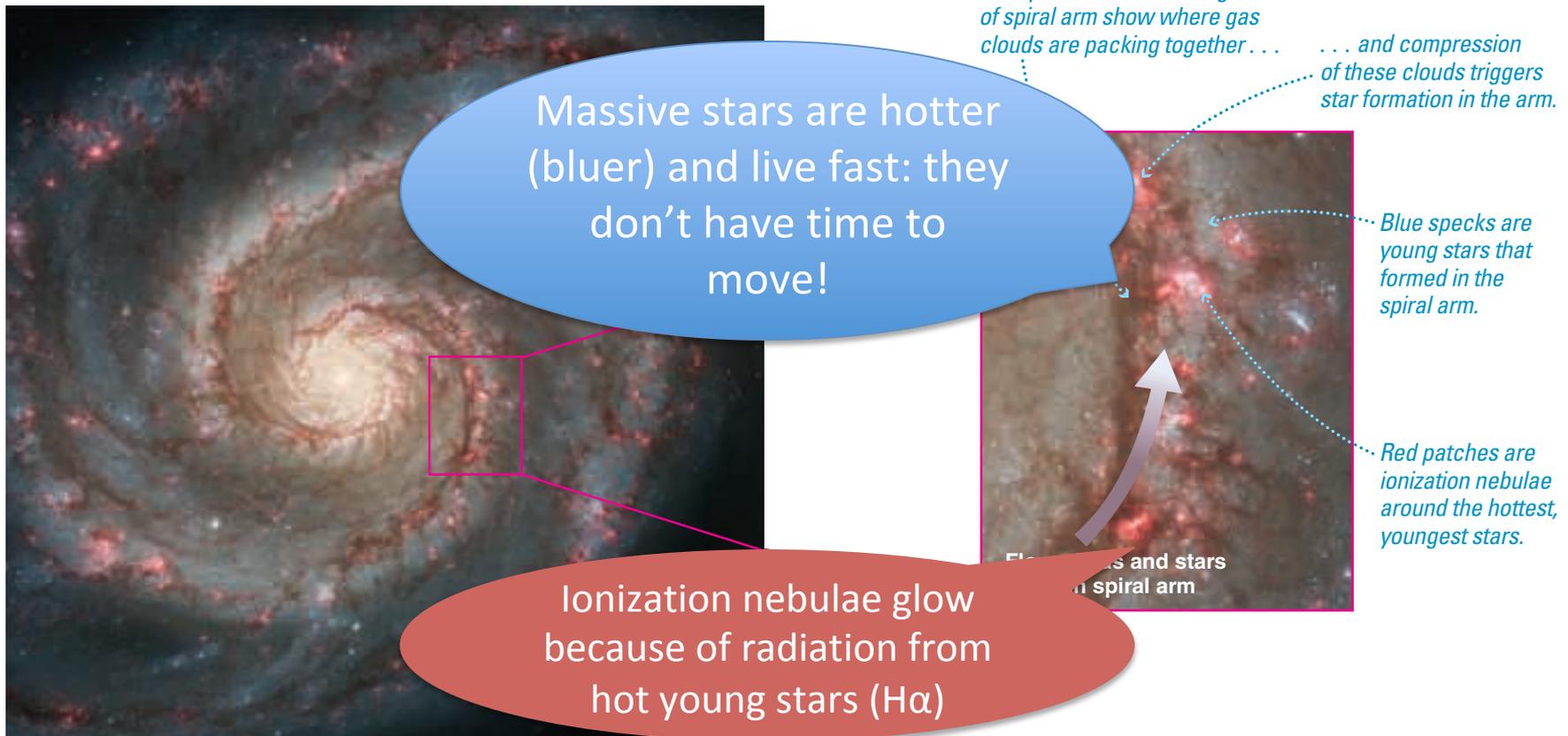
Red patches are ionization nebulae around the hottest, youngest stars.

Flow of gas and stars through spiral arm

M51-HST

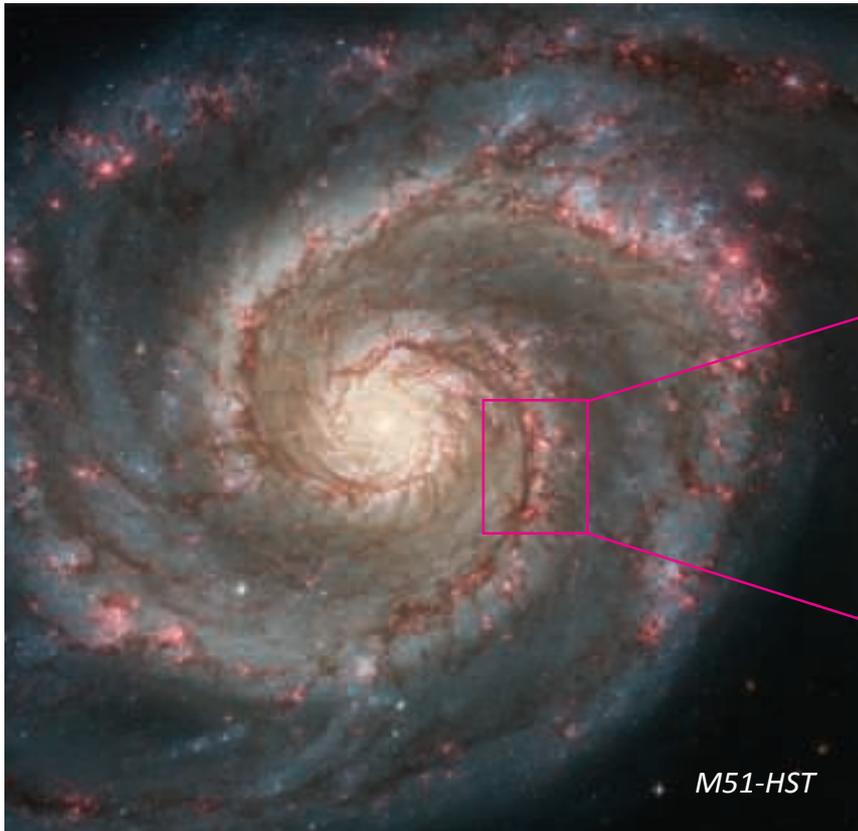
Star forming regions

Stars form in spiral arms where cool molecular gas clouds are abundant



Star forming regions

Stars form in spiral arms where cool molecular gas clouds are abundant



Schmidt-Kennicutt law

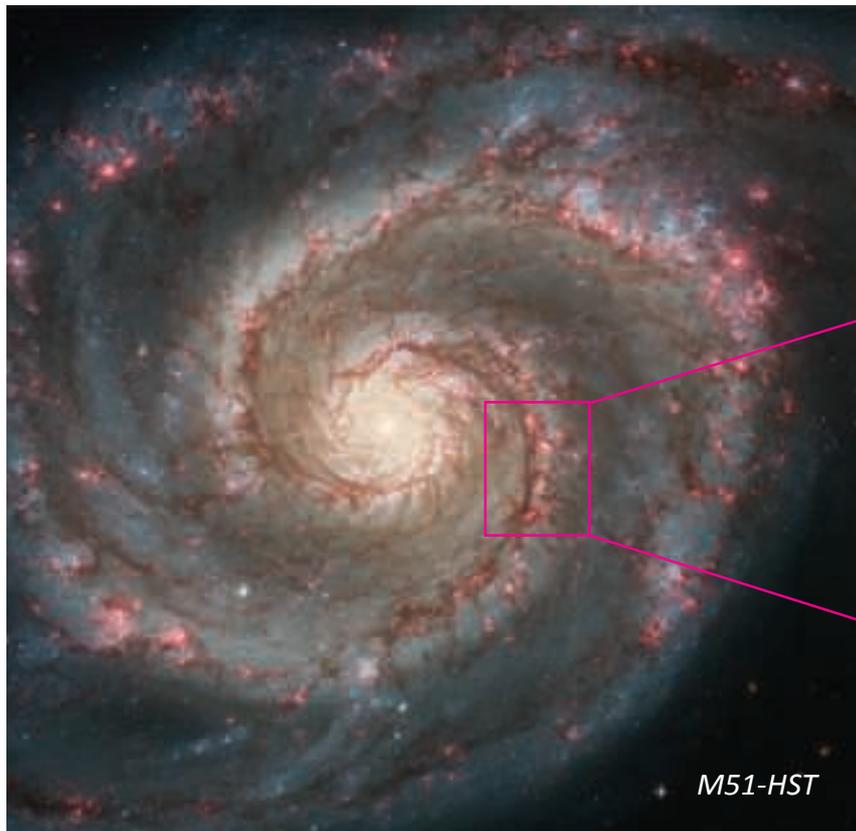
$$\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^N$$

Star formation rate (M/yr) is proportional to gas density

Milky Way forms 1 solar mass per yr

Star migration

Older stars can move away off their birthplace to the bulge or the halo



Dark patches on inner edge of spiral arm show where gas clouds are packing together. . .

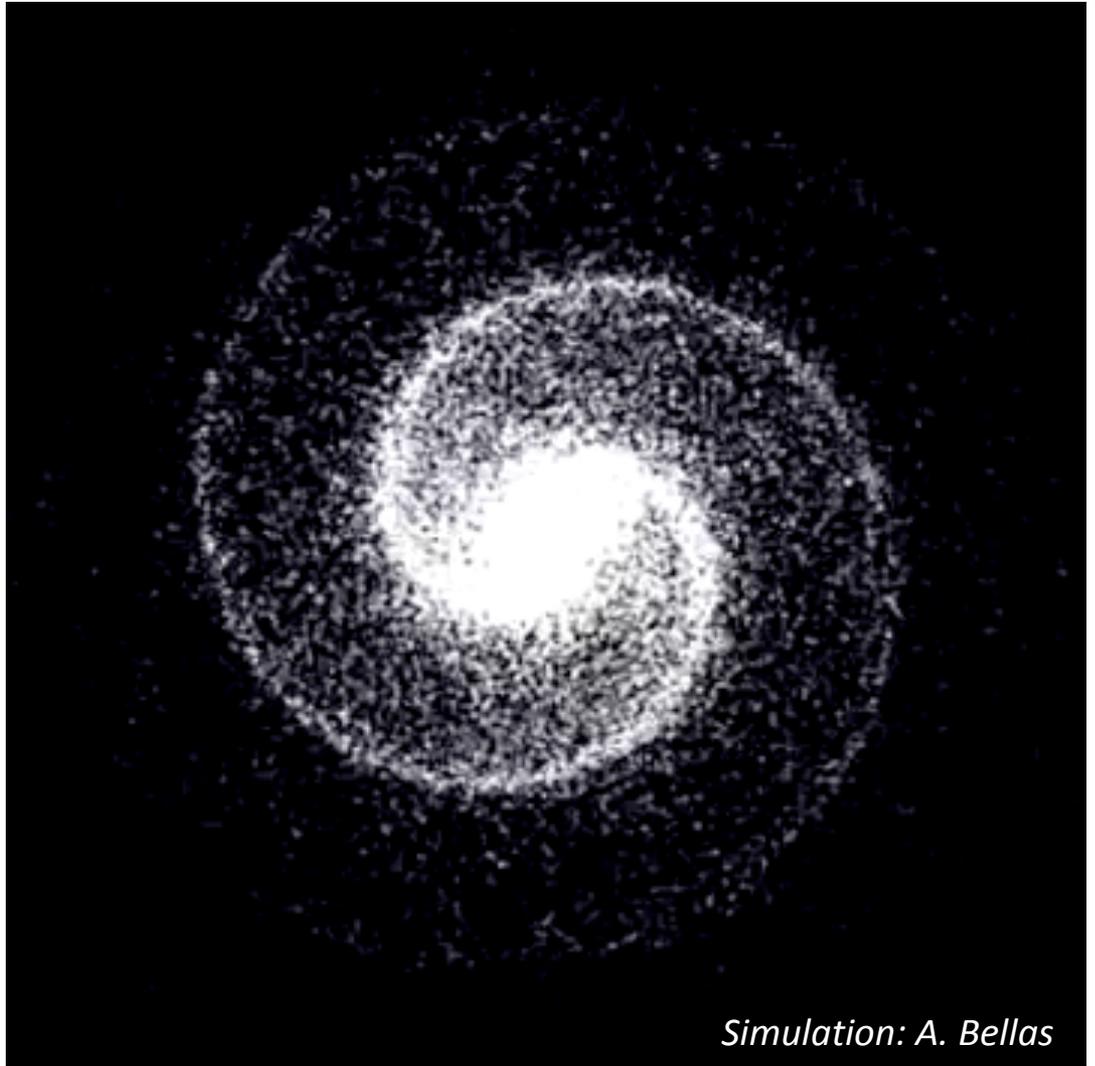
. . . and compression of these clouds triggers star formation in the arm.

Blue specks are young stars that formed in the spiral arm.

Red patches are ionization nebulae around the hottest, youngest stars.

Flow of gas and stars through spiral arm

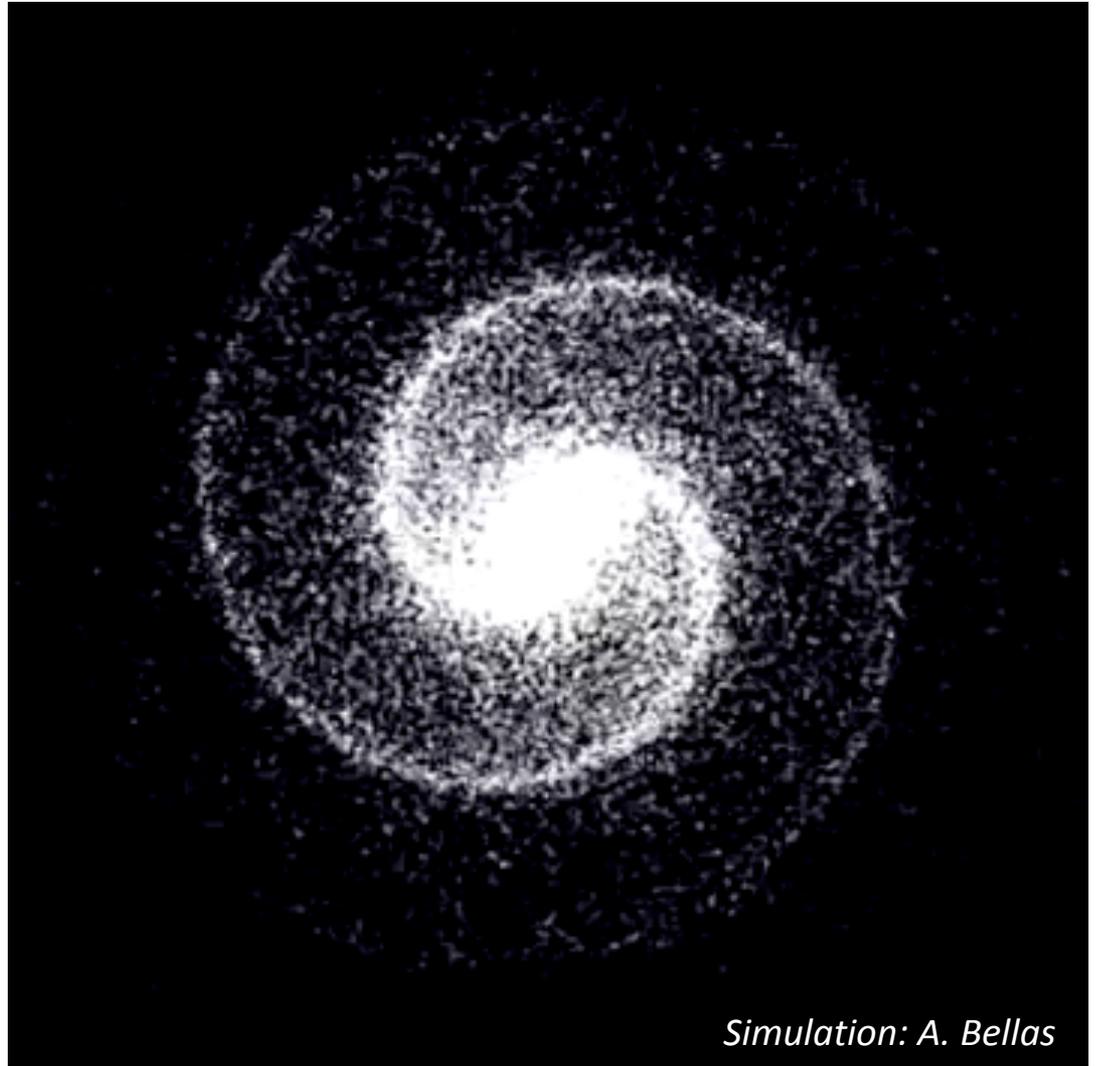
Milky Way rotation



Simulation: A. Bellas

Milky Way rotation

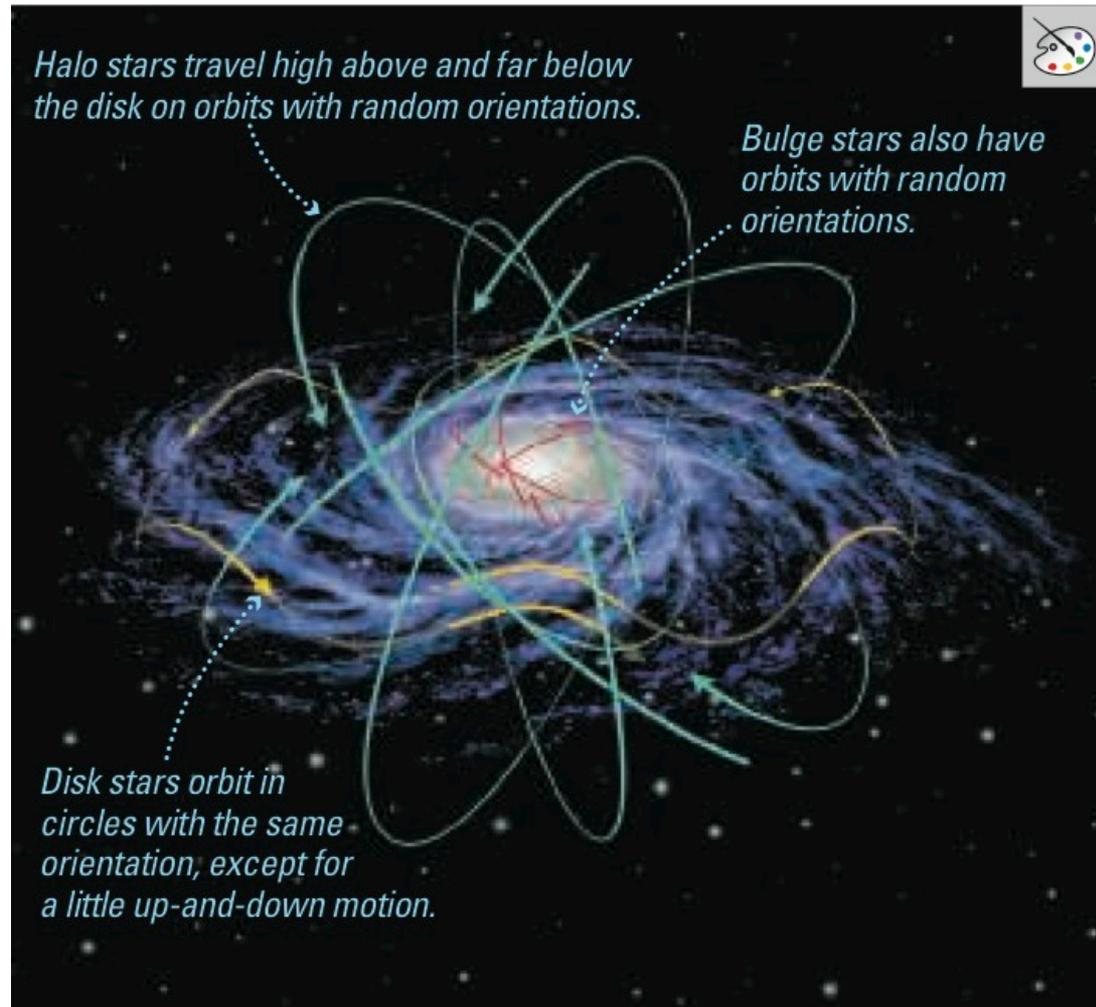
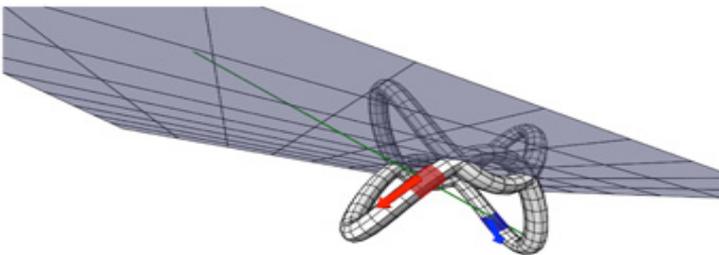
- Orbital velocities of stars closer to the center are similar to stars farther
- Spiral arms are not rigid: spiral density waves
- In the spiral arms, stars and gas move more slowly: denser regions
- Sun orbits at 220km/s and takes about 230 million years to do an orbit



Simulation: A. Bellas

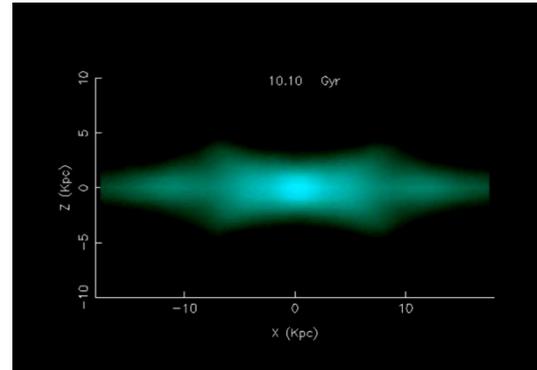
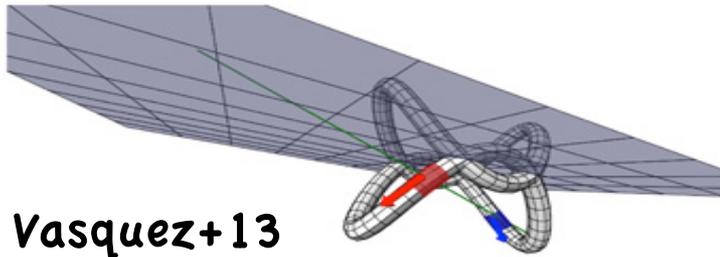
Star orbits

- Disk stars orbit in circles around center due to gravitational pull of center mass (period 200 million yrs)
- Disk stars wobble in the vertical direction due to gravitational pull of disk mass (period 10 millions yrs)
- Halo stars have random orbits around center with large heights
- Bulge stars seem to have two components: ordered and random, or “banana-shape”



MW bulge: X-shape

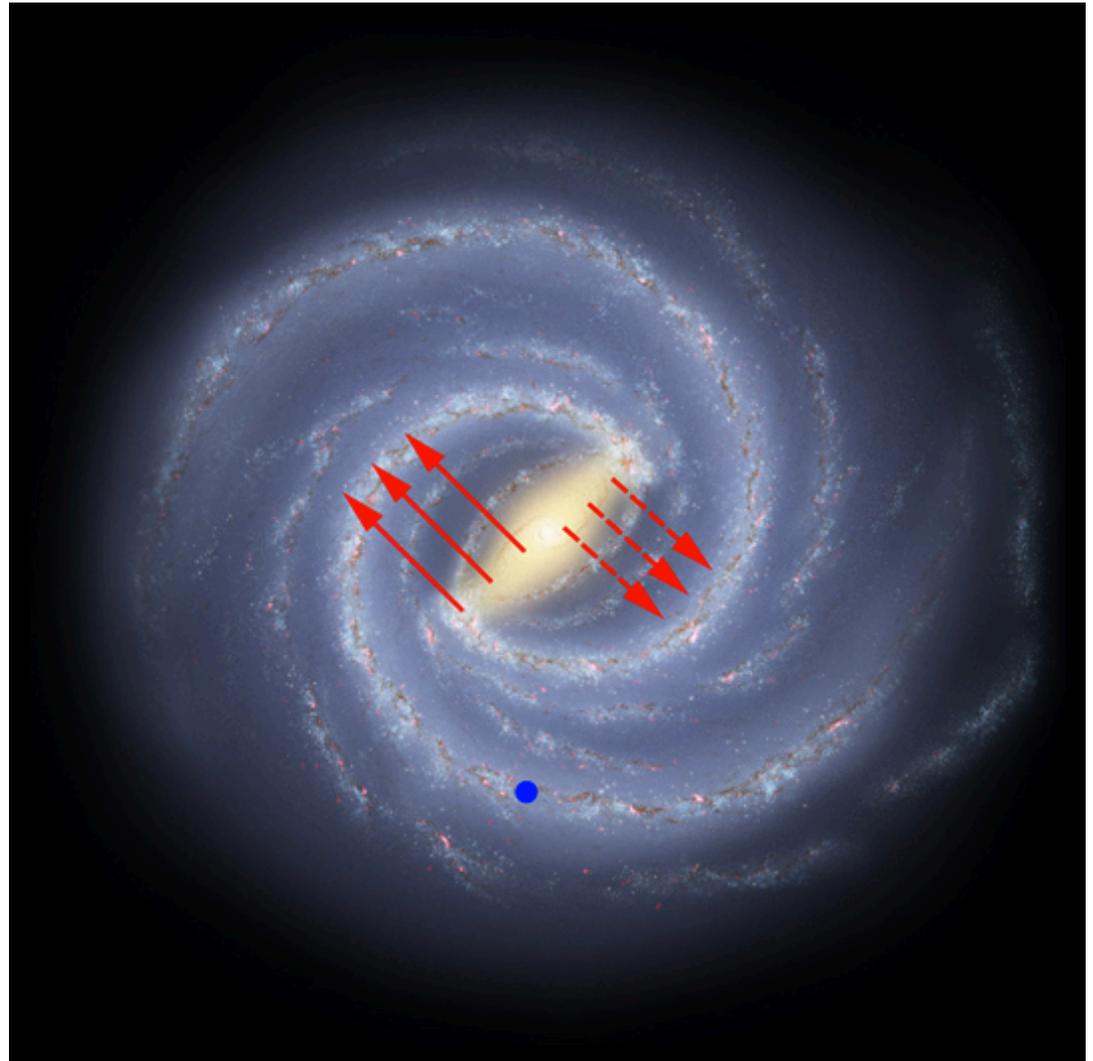
Bulge stars seem to have
“banana-shape” orbits



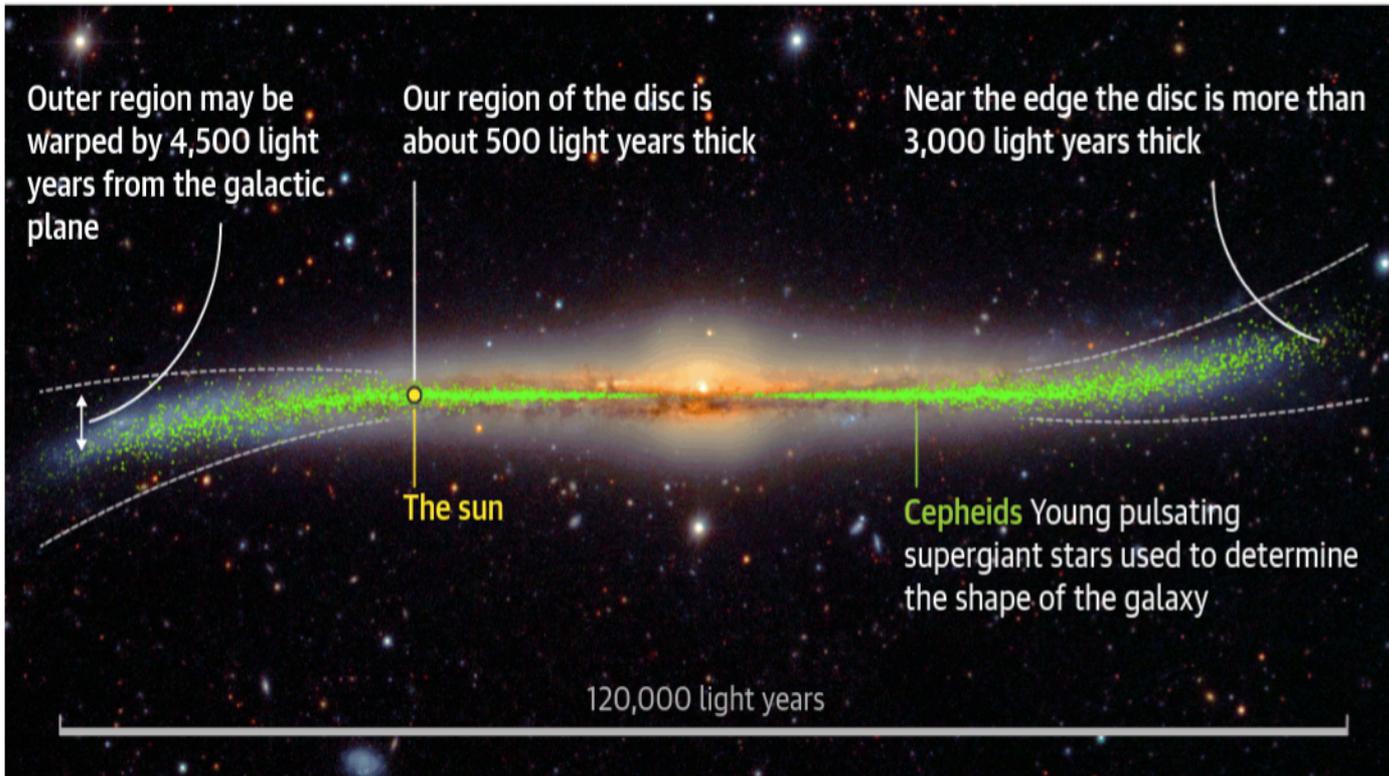
X-shape
bulge

Bar of the Milky Way

- Barred potential explains naturally the bulge stellar orbits we saw
- Explains gas concentrations and non-circular orbits
- Explains asymmetries in stellar counts

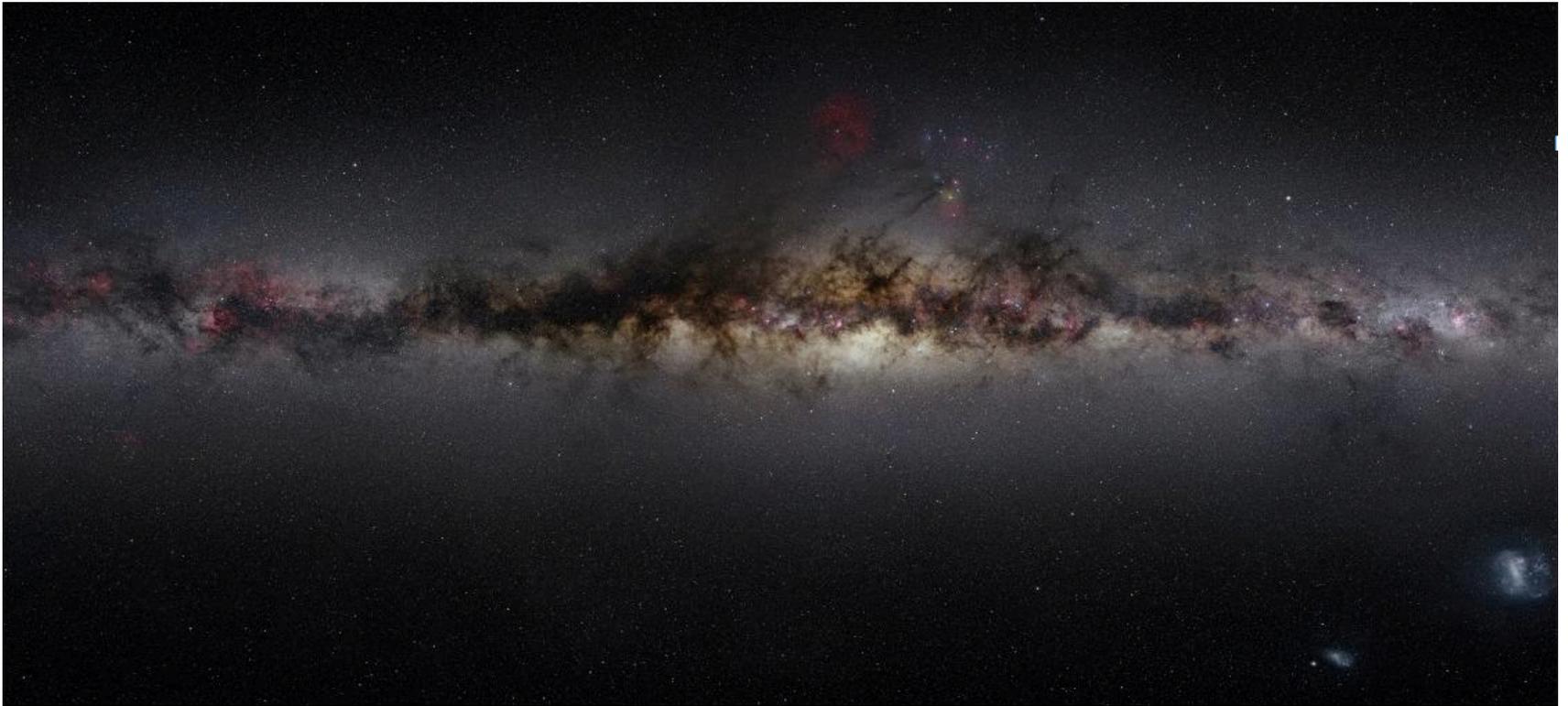


MW disk: warped

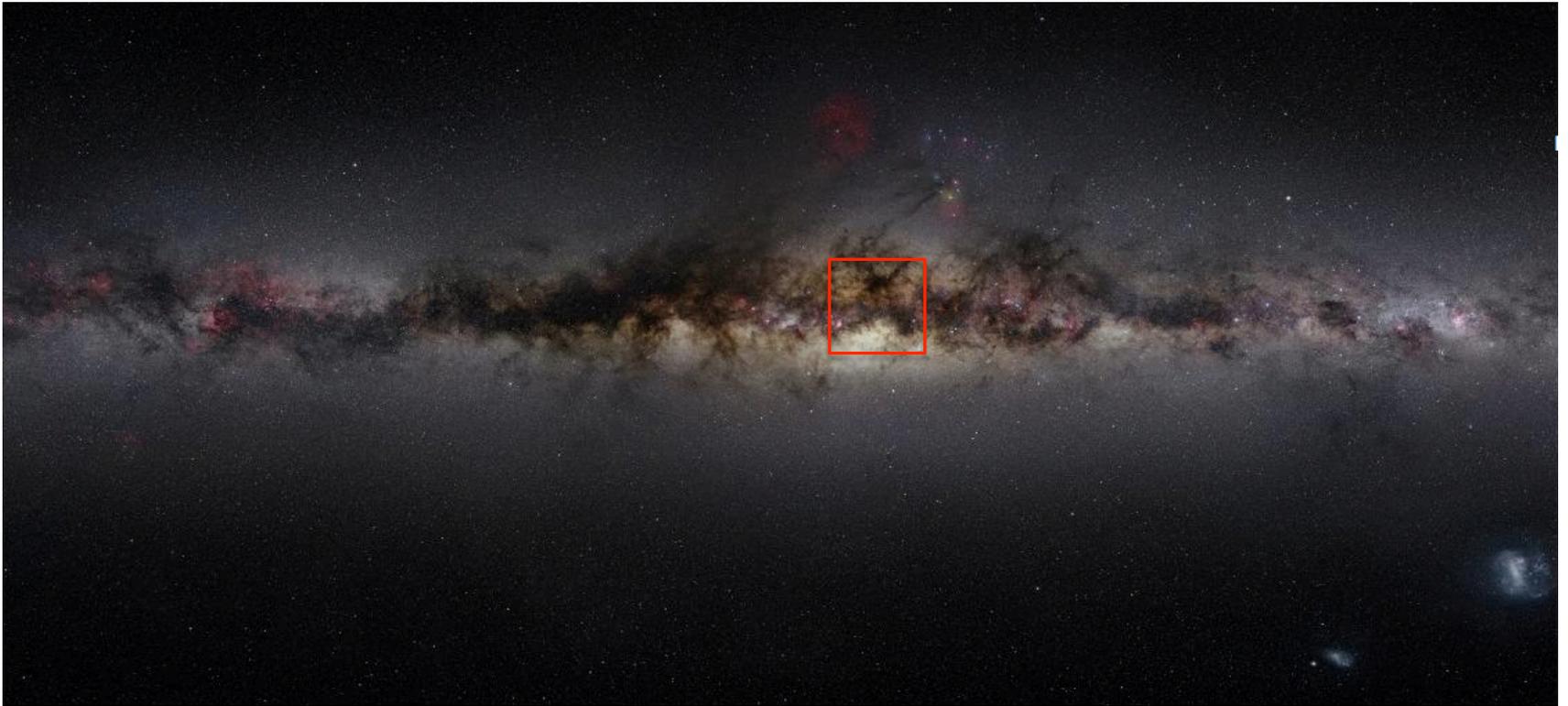


- Warped disk (Skowron+19)
- Precesses due to satellite galaxy (Poggio+20)

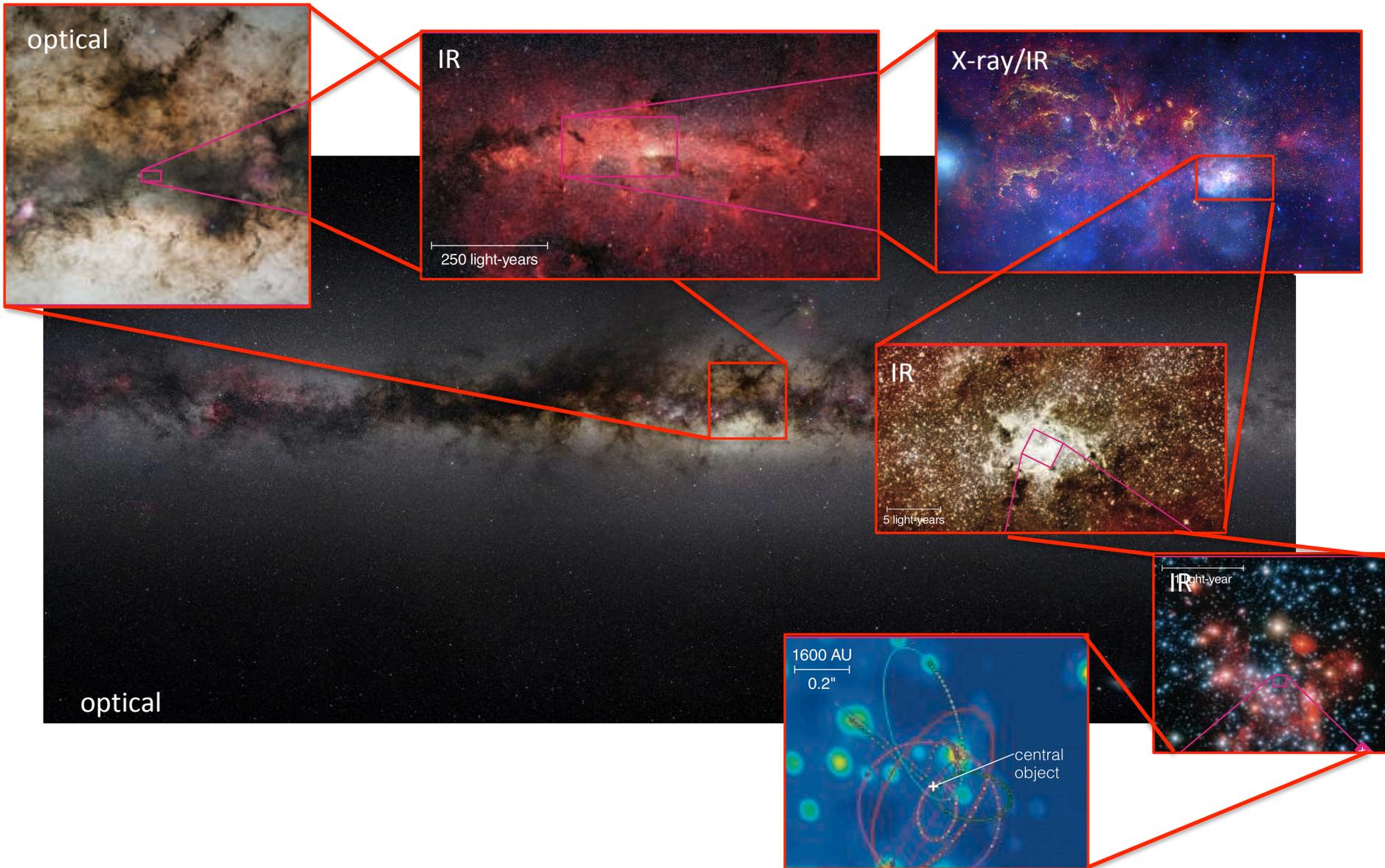
Galactic Center



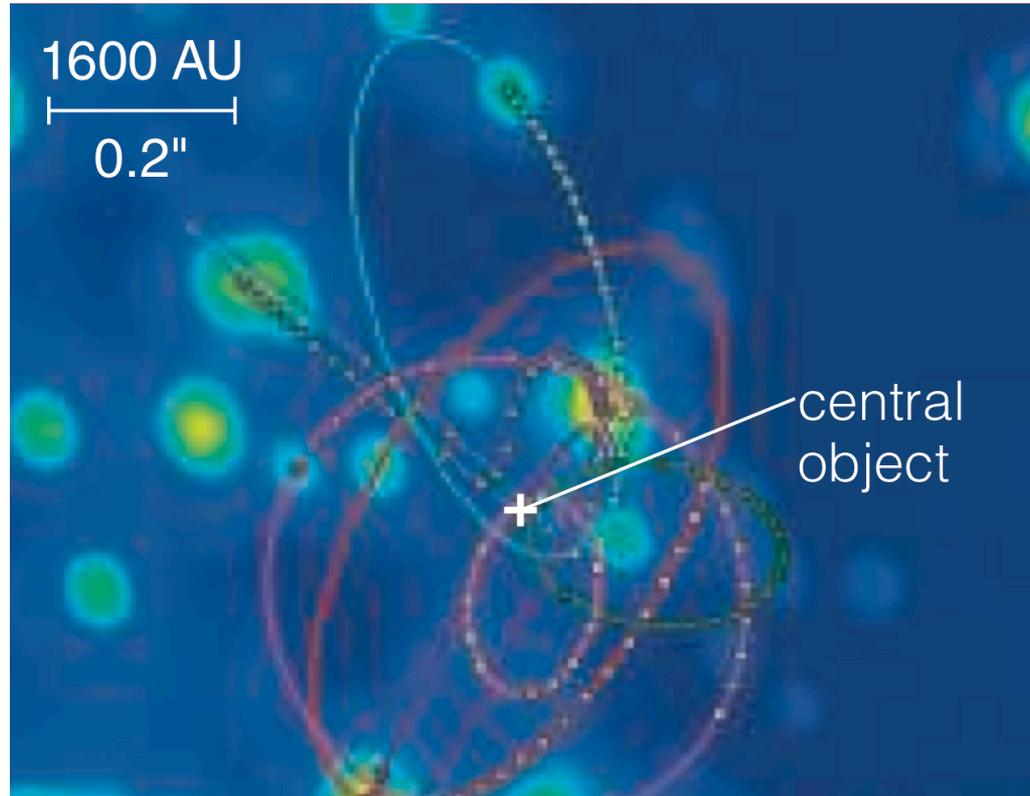
Galactic Center



Galactic Center



Galactic Center



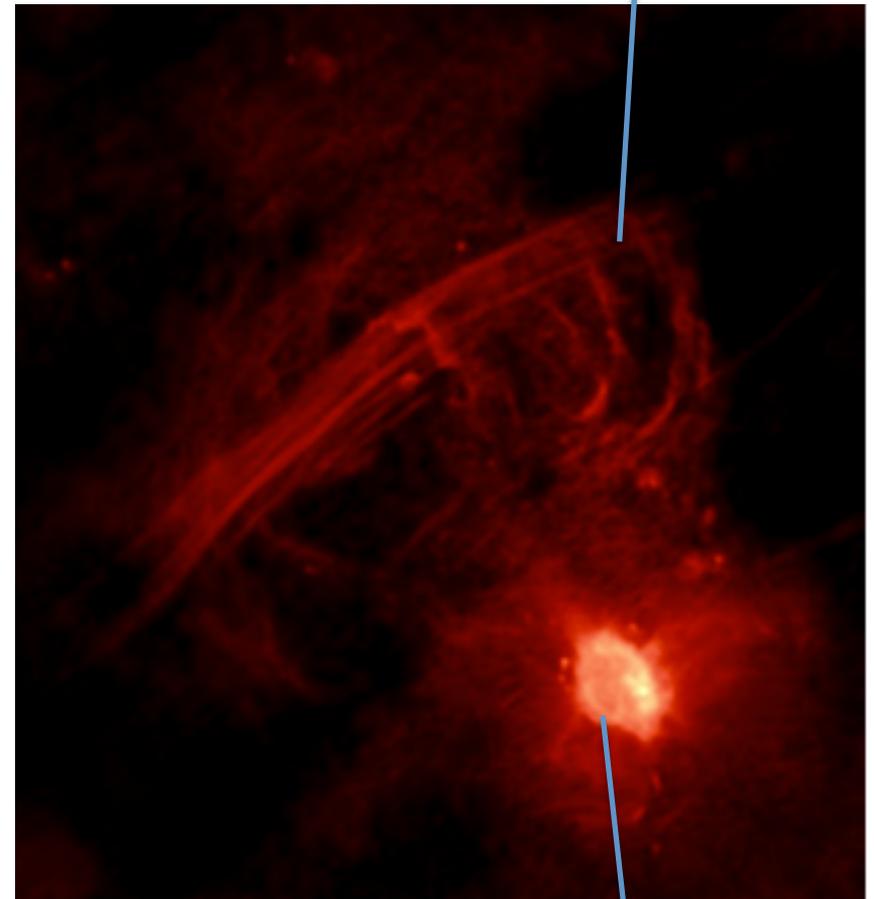
Galactic Center



Galactic Center

- Orbits of stars around a central dense center
- X-ray emission from hot gas
- Radio emission from gas

Emission following magnetic lines



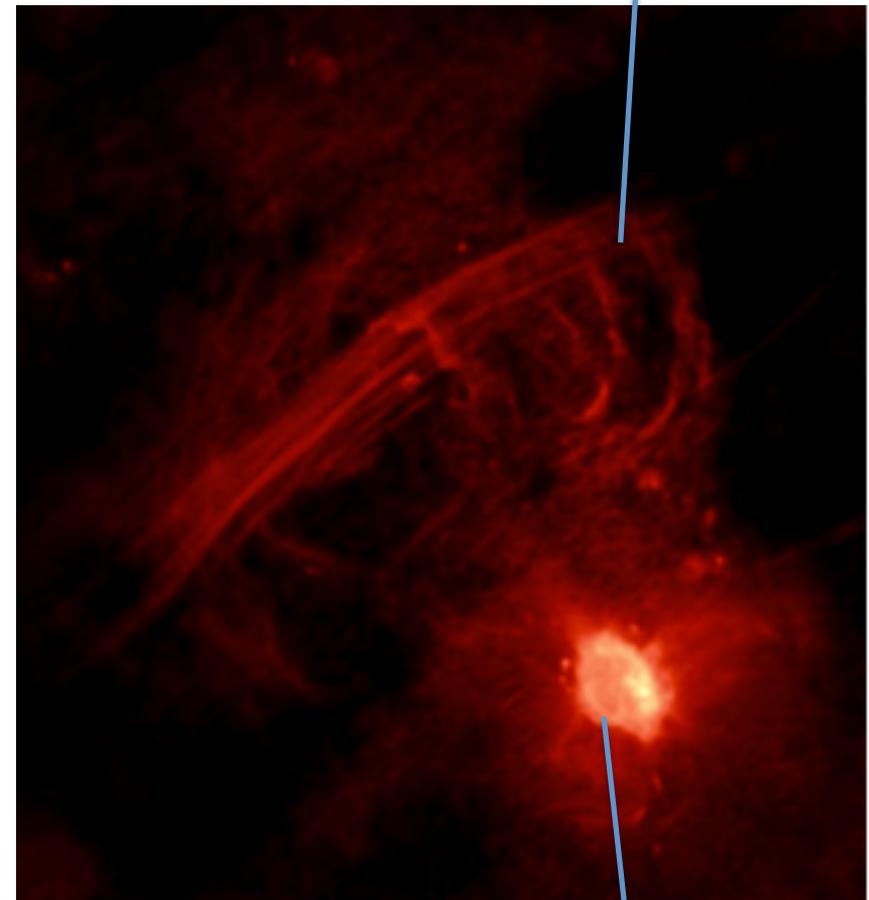
The center of our Galaxy, as seen in the radio.

Sagittarius A*

Galactic Center

- Orbits of stars around a central dense center
- X-ray emission from hot gas
- Radio emission from gas

→ Supermassive black hole in the center
(4.3×10^6 solar masses)



Emission following magnetic lines

The center of our Galaxy, as seen in the radio.

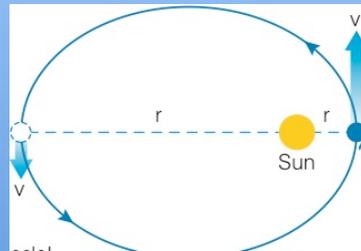
Sagittarius A*

Galactic Center

- Orbits
- a cen
- X-ray
- hot g
- Radio

→ Super
hole in the center
(4.0×10^6 solar masses)

Newton's version
of Kepler's laws:

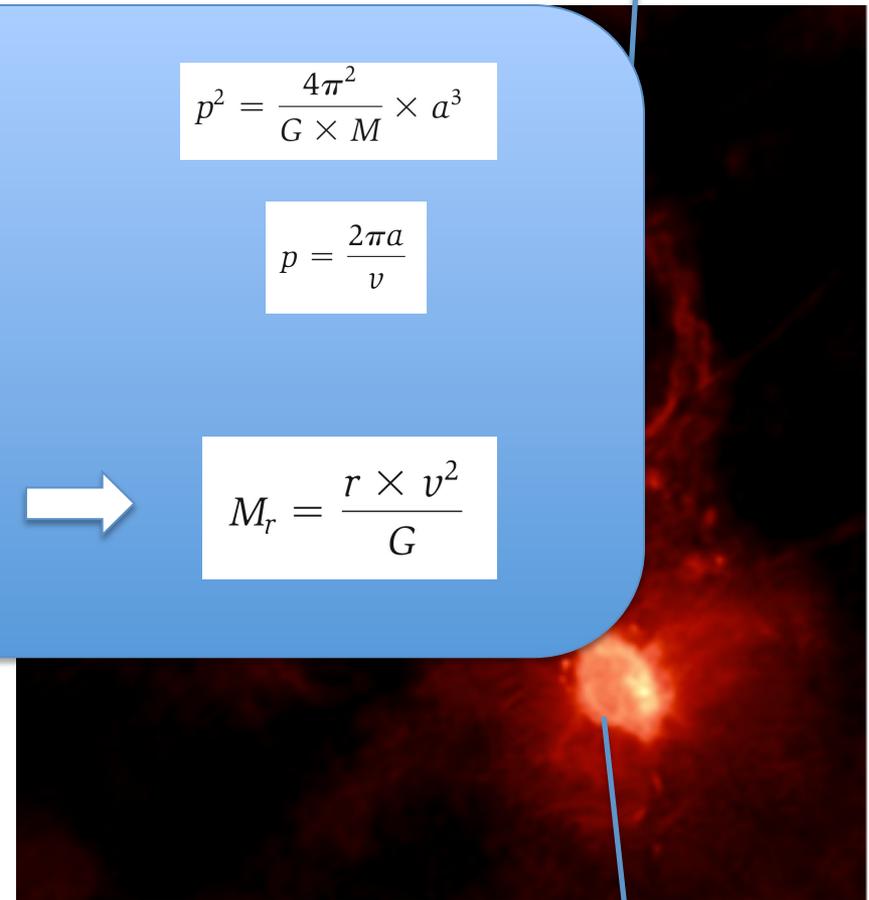


$$p^2 = \frac{4\pi^2}{G \times M} \times a^3$$

$$p = \frac{2\pi a}{v}$$

$$M_r = \frac{r \times v^2}{G}$$

Emission
following
magnetic lines



The center of our Galaxy, as seen in the radio.

Sagittarius A*

Summary

- Milky Way is our galaxy made of billions of stars
- It has a disk with spiral arms and gas and dust where stars form, a halo with old stars and a central elongated bulge with a mix population
- Galactic recycling ensures that new stars are formed from gas enriched from previous generations
- All stars orbit around the center in an orderly fashion in the disk and less so in the bulge and halo
- There is a supermassive black hole at the center