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

I. Milky Way: our Galaxy

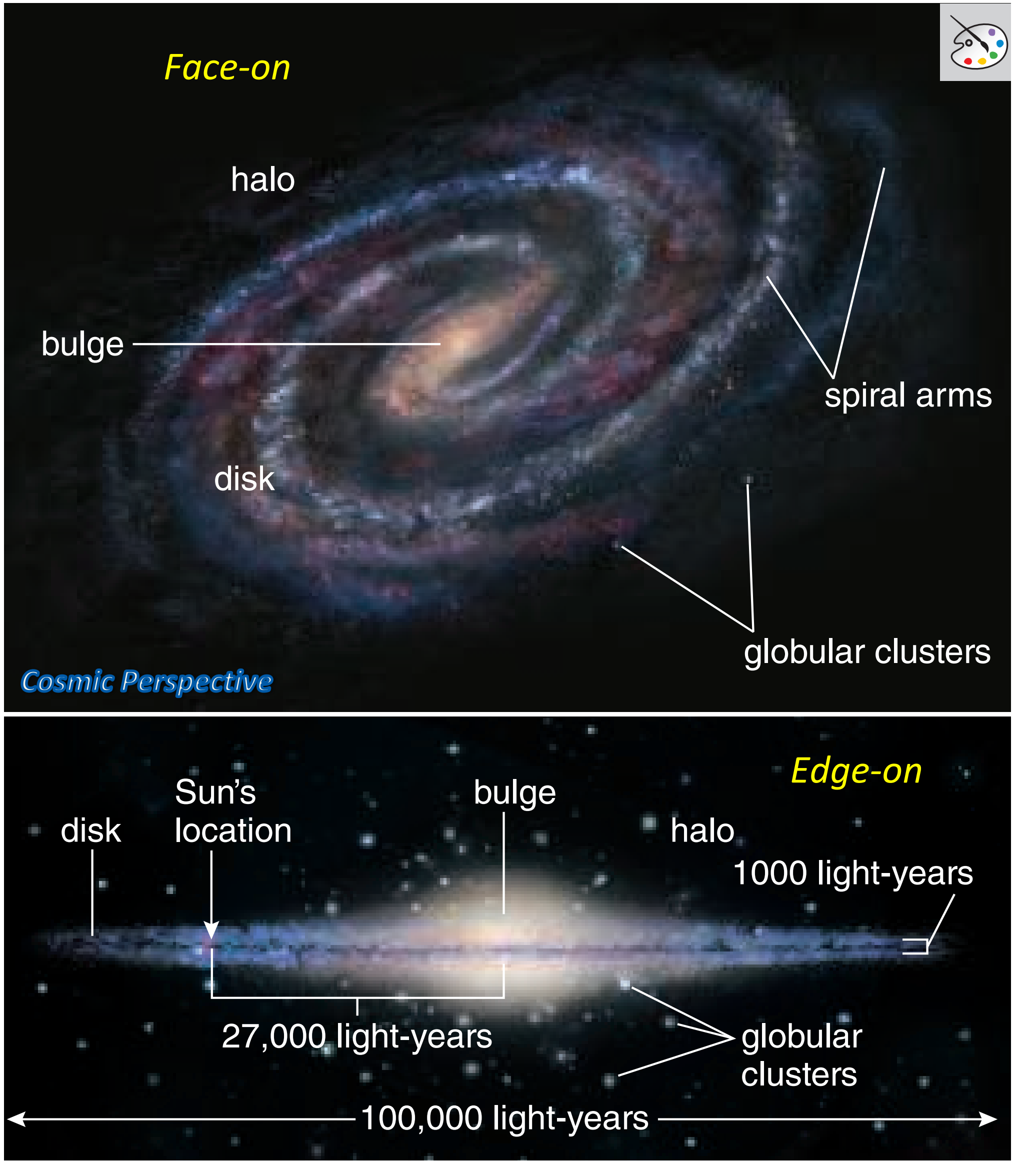
I. Milky Way: our Galaxy

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

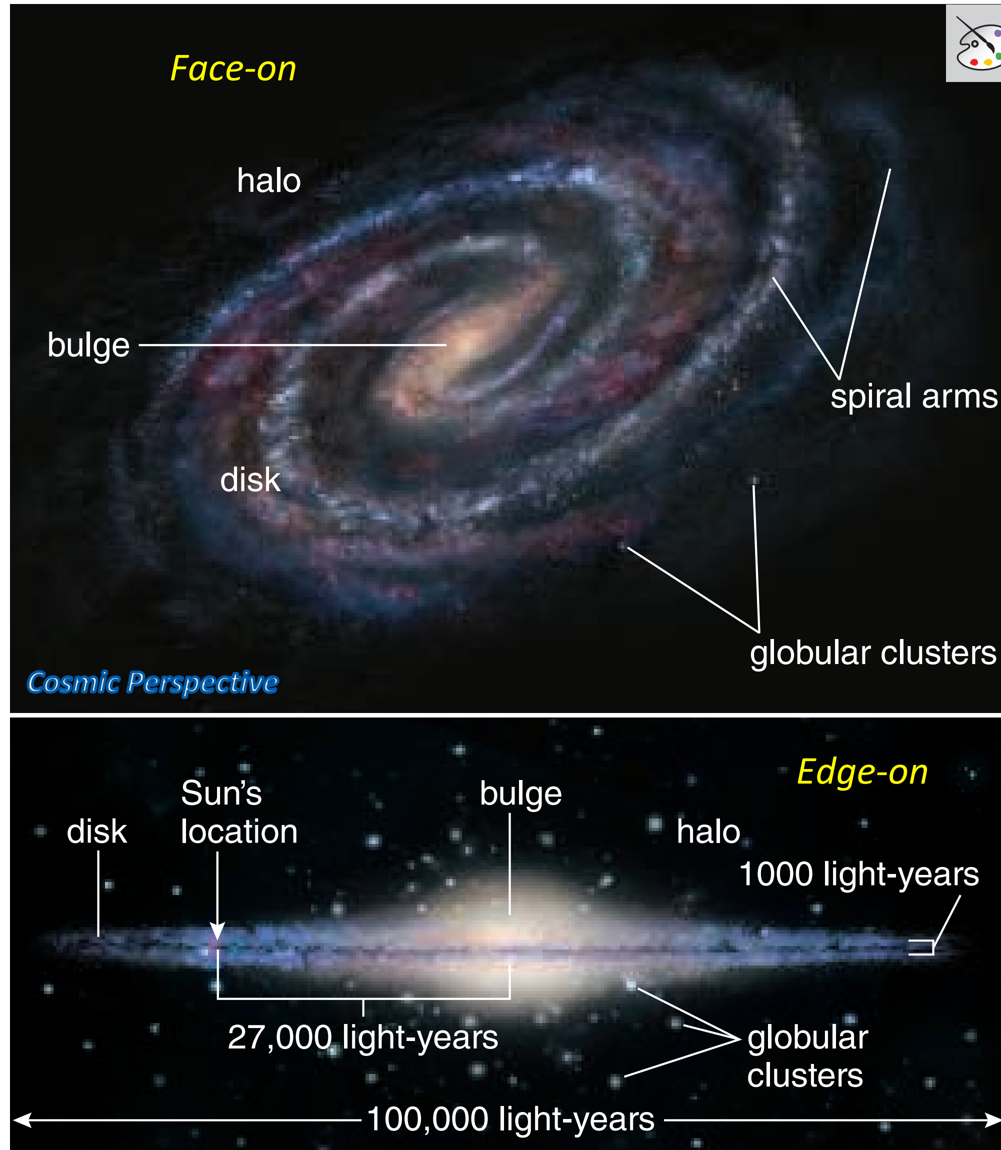
Difficulties:
- we cannot observe it from an external point of view
- dust obscuration in the center

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



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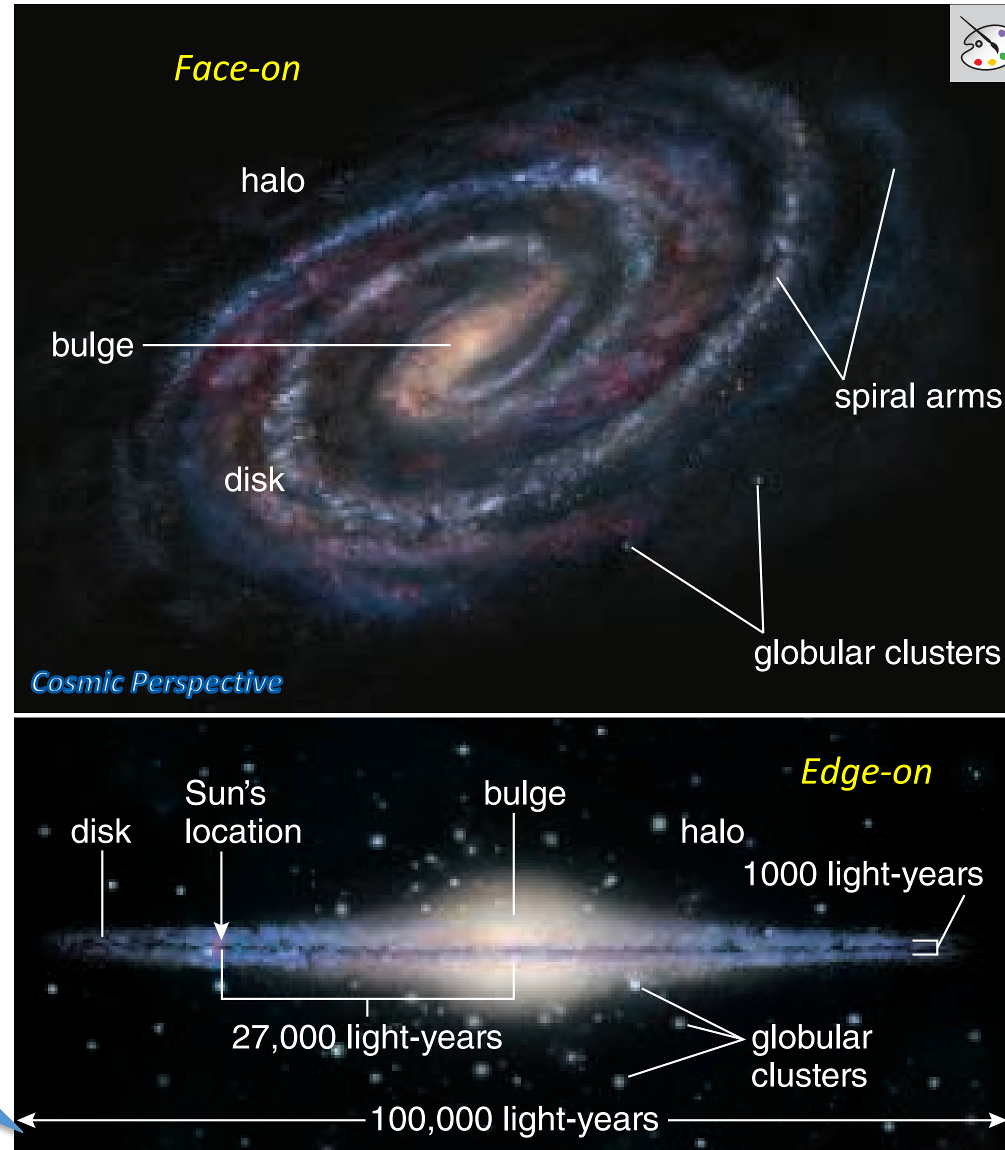
A light-year (lyr) is the distance traveled by light in one year (9.5×10^{12} km). A parsec is 3.26 lyrs



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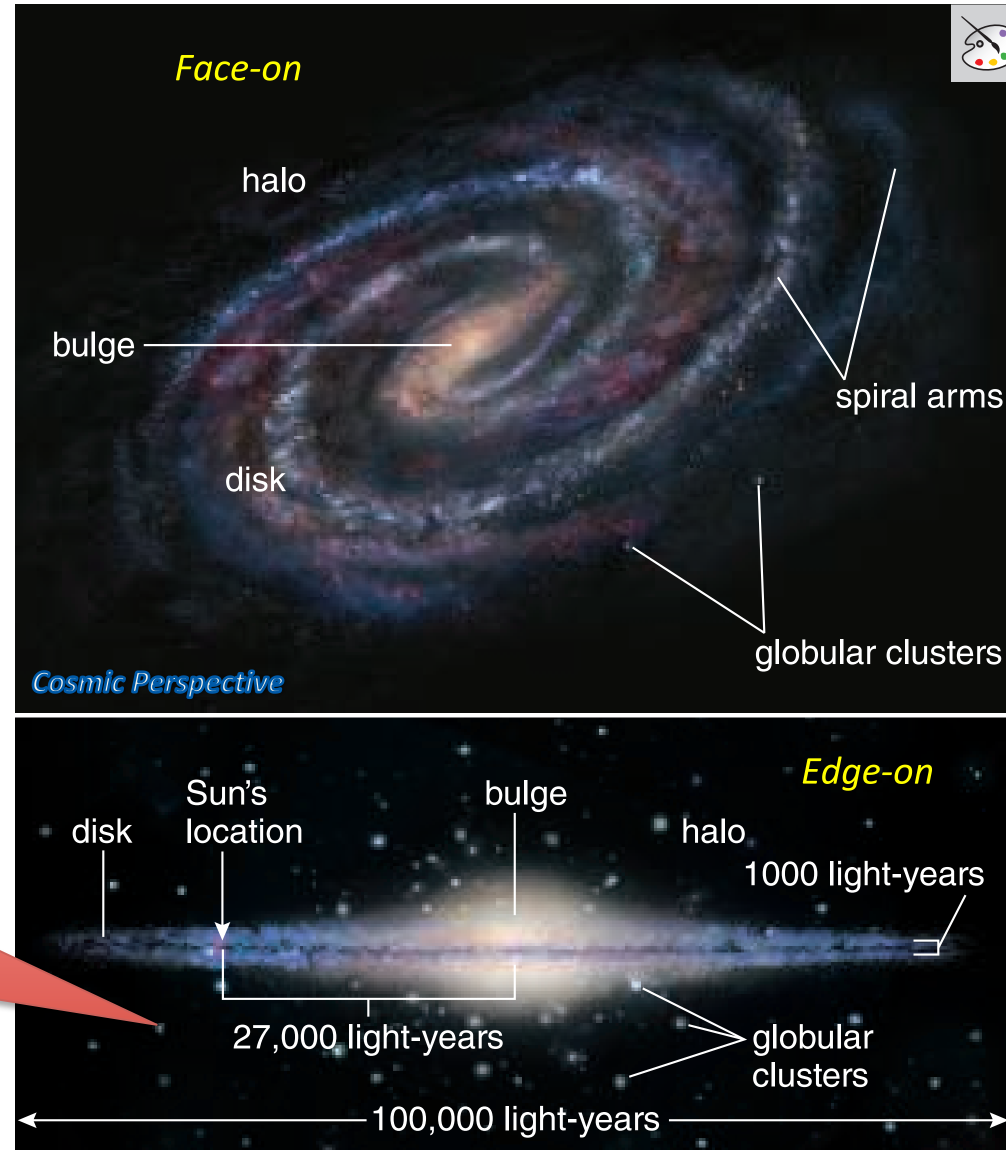
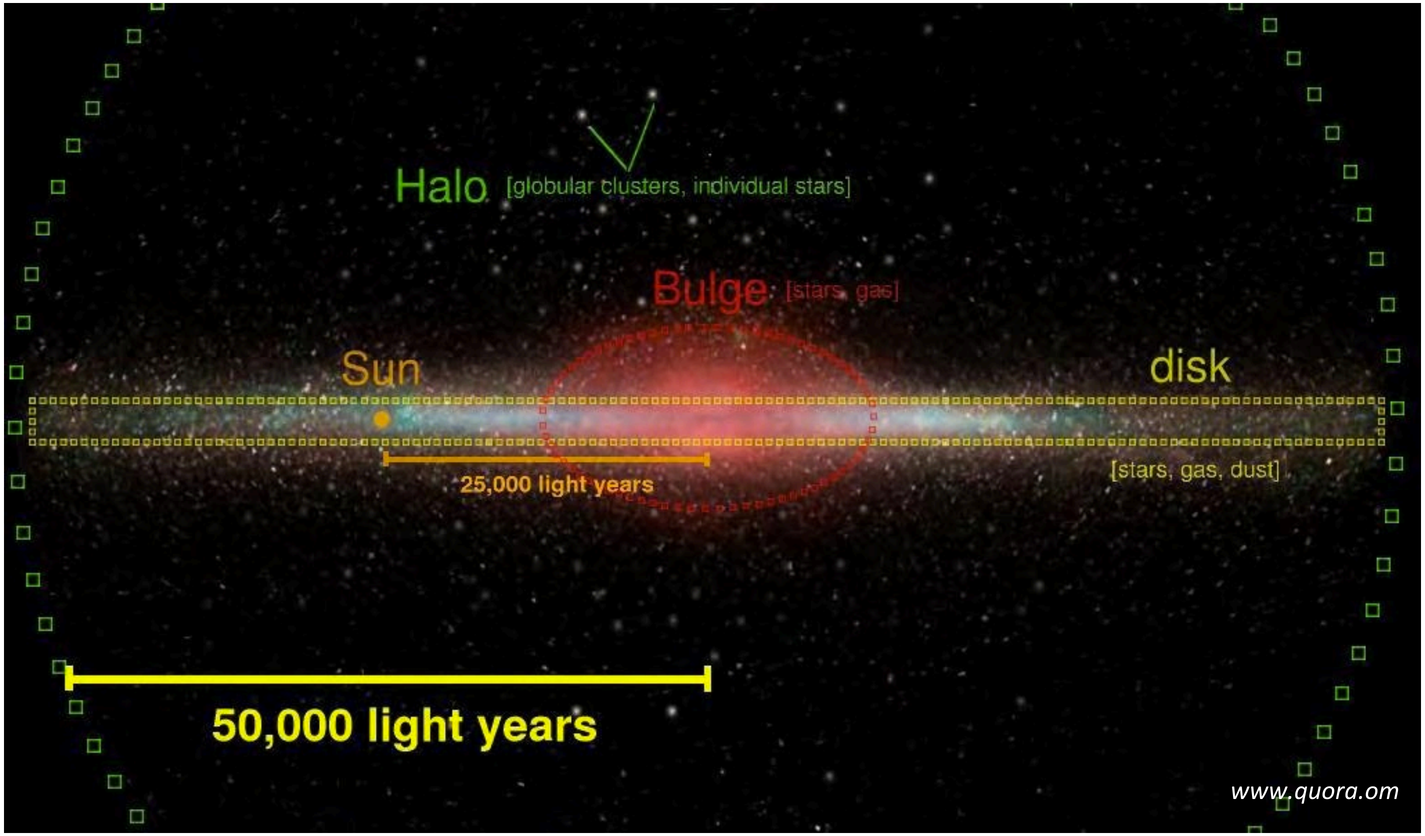


A globular cluster is an ensemble of thousands to millions of old stars packed together

Milky Way composition

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



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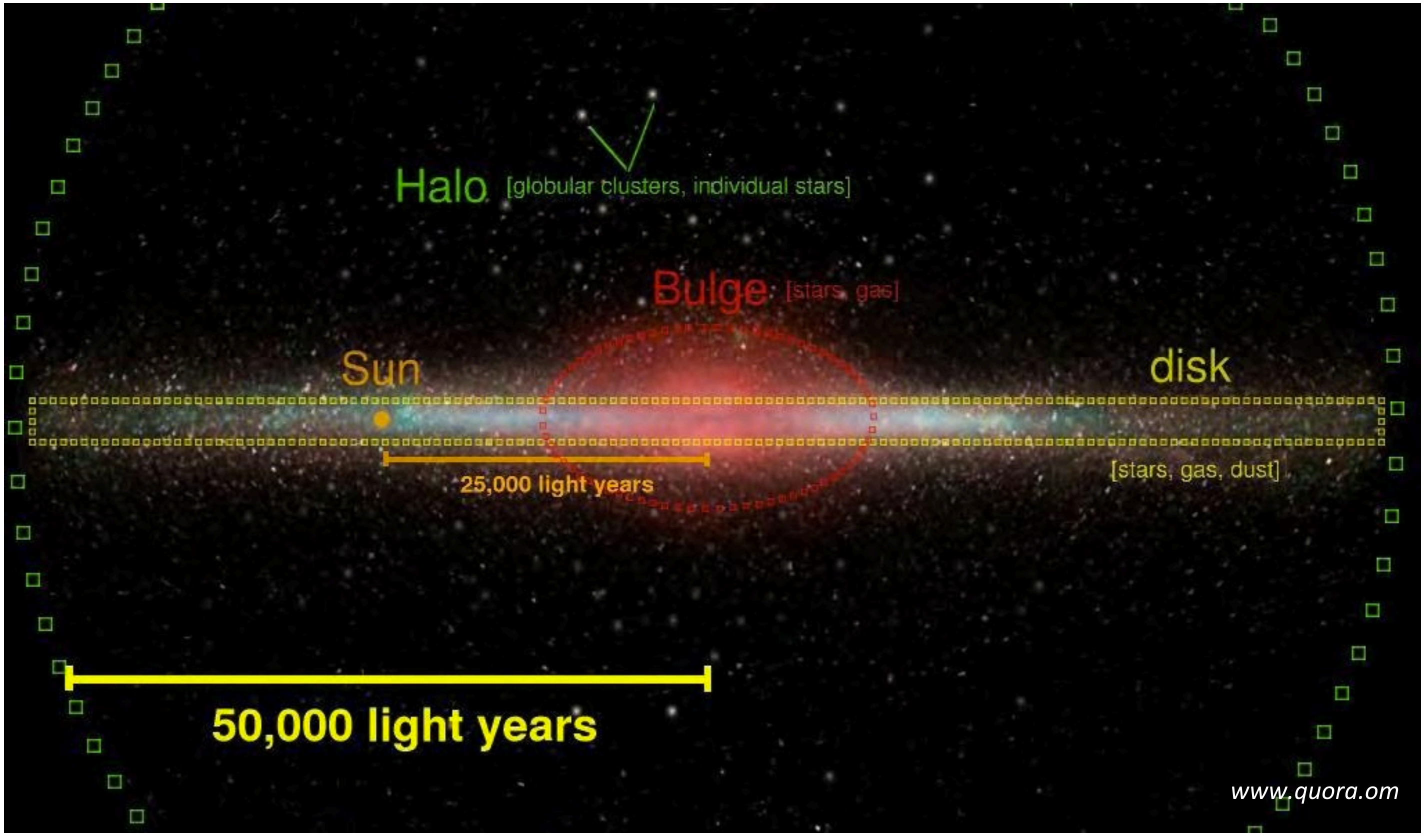
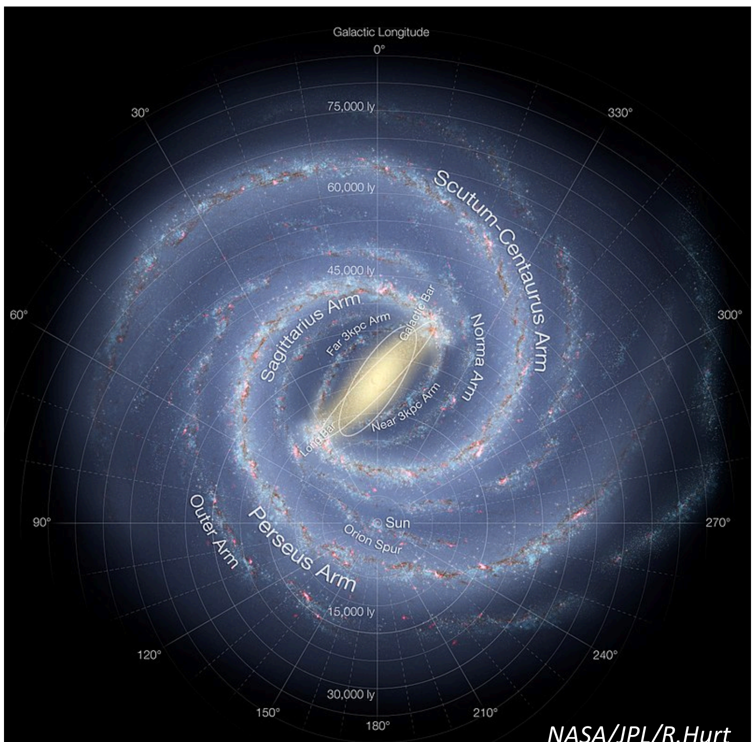
Intestellar medium: gas and dust between stars



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



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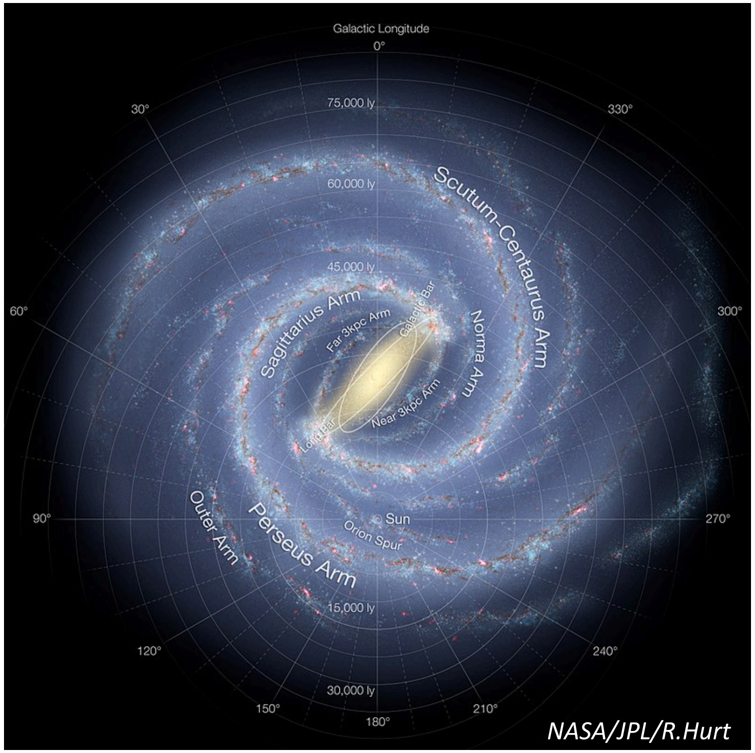
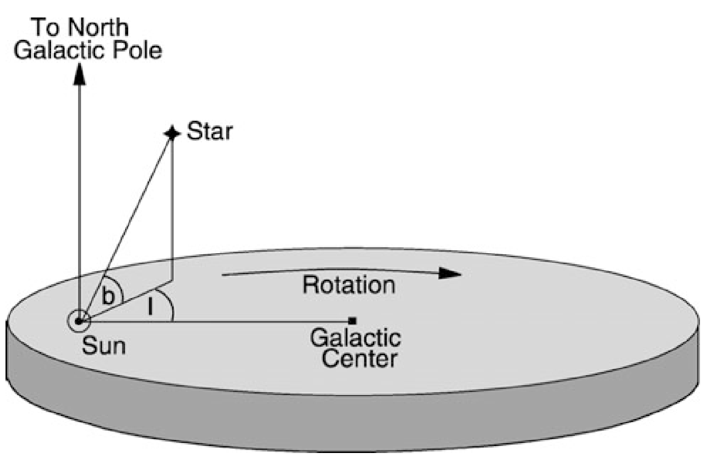
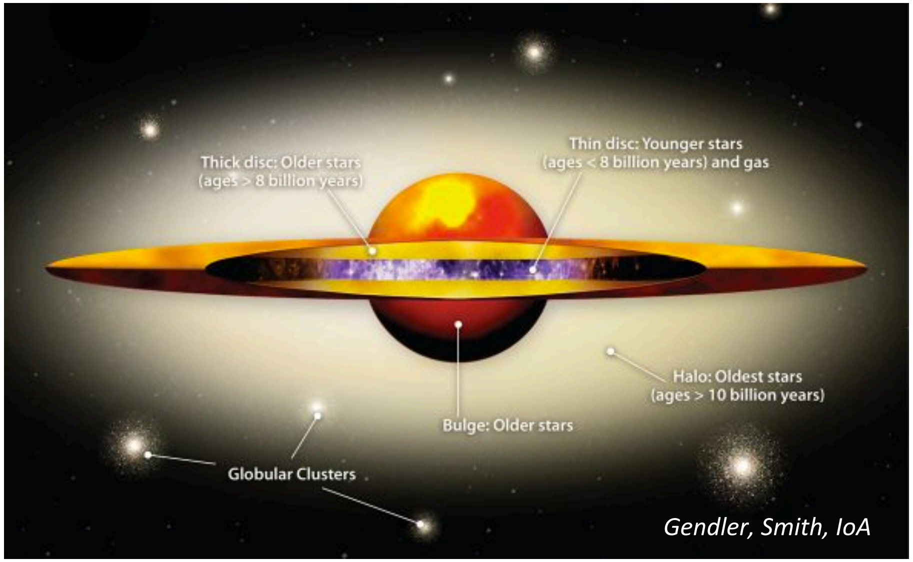


Galactic disk

- 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

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





Gendler, Smith, IoA

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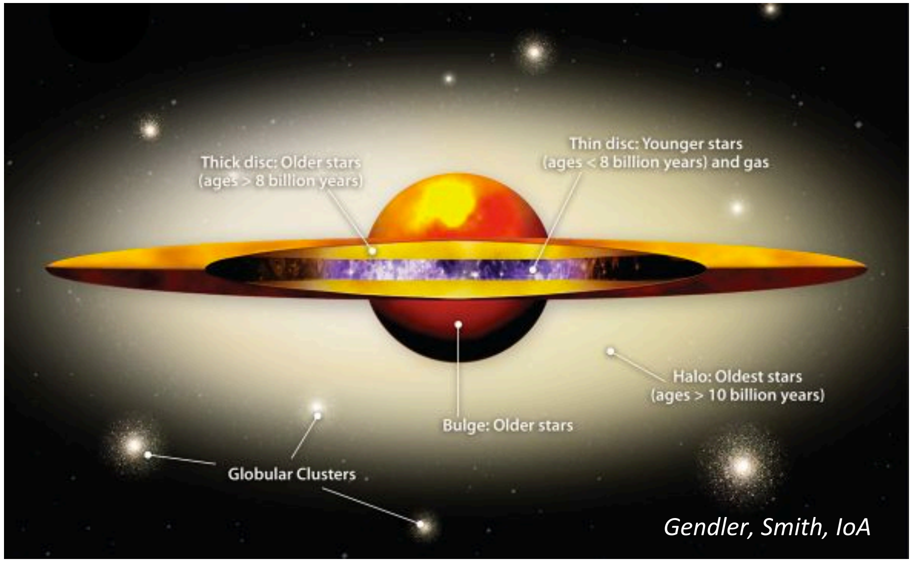
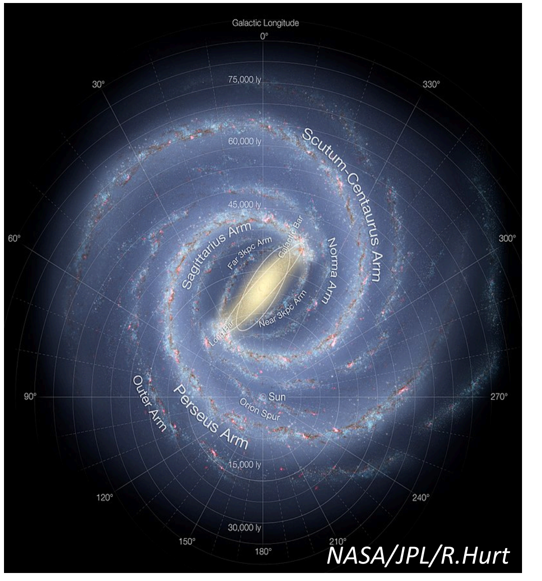
Disk brightness profile is exponential:

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



Galactic bulge

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



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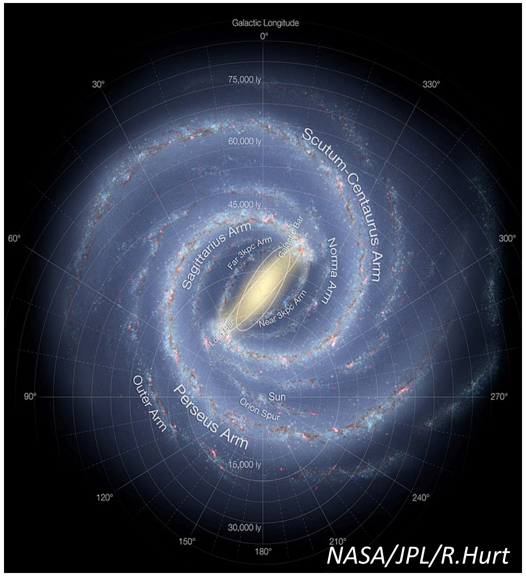
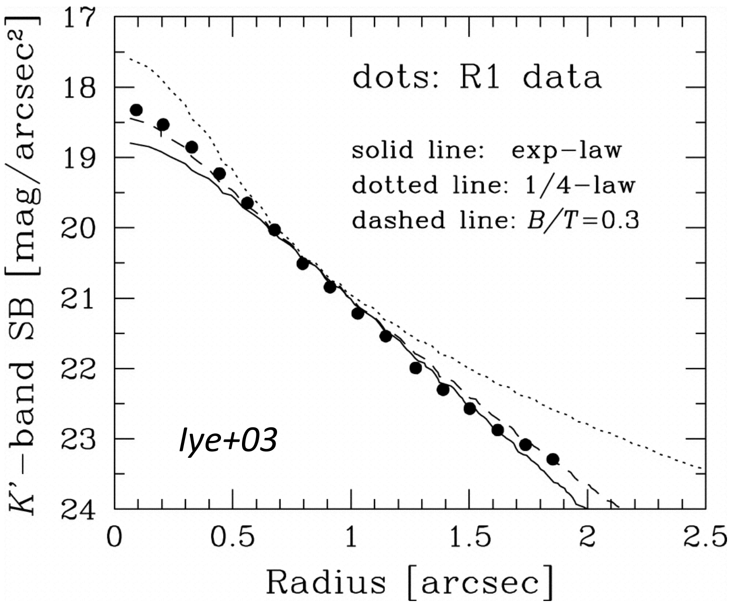
- Bulge has peanut-like bar with characteristic scale length of 1kpc
- **Bulge brightness** follows a *de Vaucouleurs* profile:



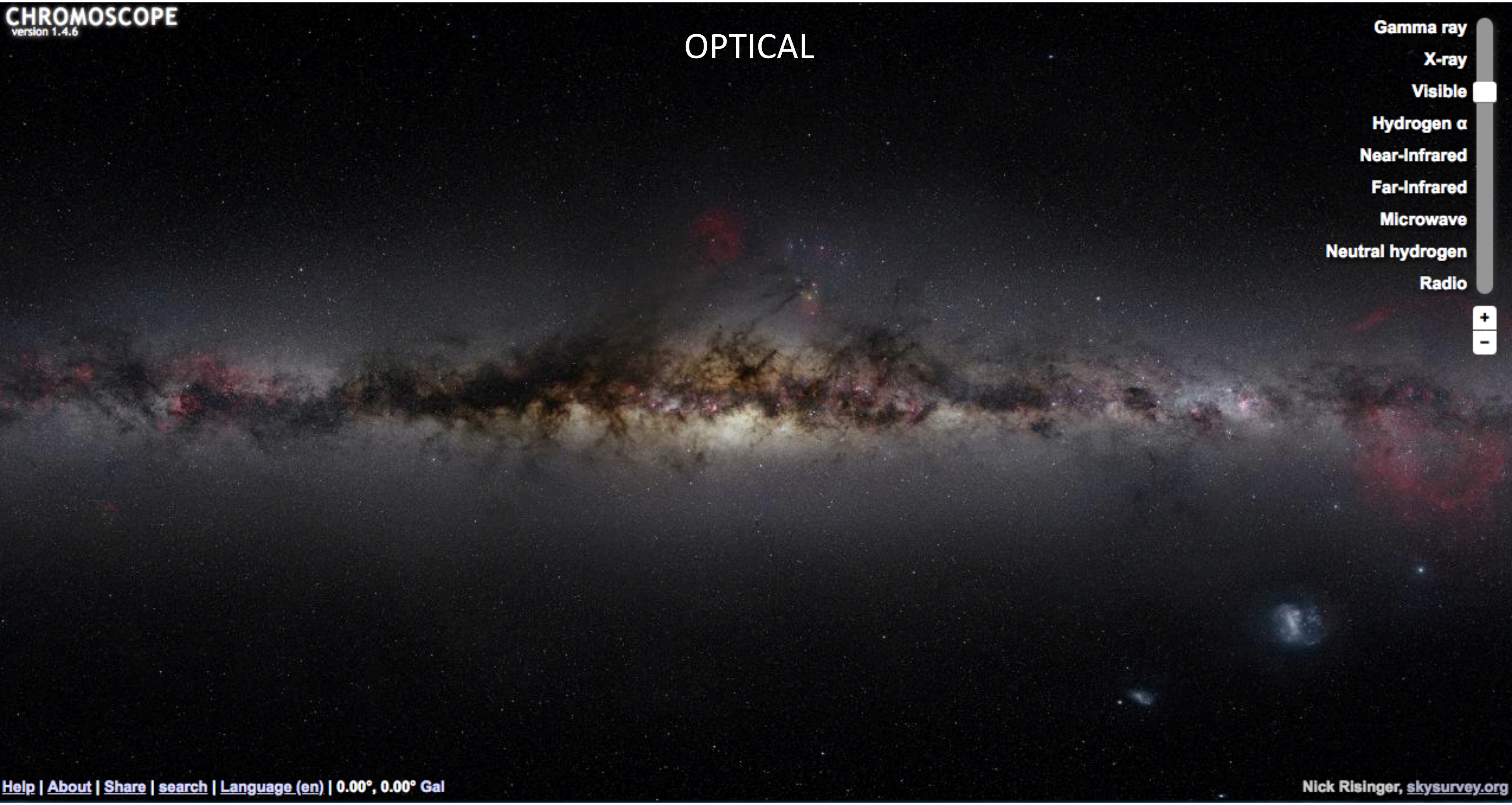
$$\boxed{I(R) = I_{\rm e} \exp\left(-7.669\left[(R/R_{\rm e})^{1/4} - 1\right]\right)}$$

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

Effective radius: half of the luminosity radius



OBSERVATION: Milky Way in multi-wavelength



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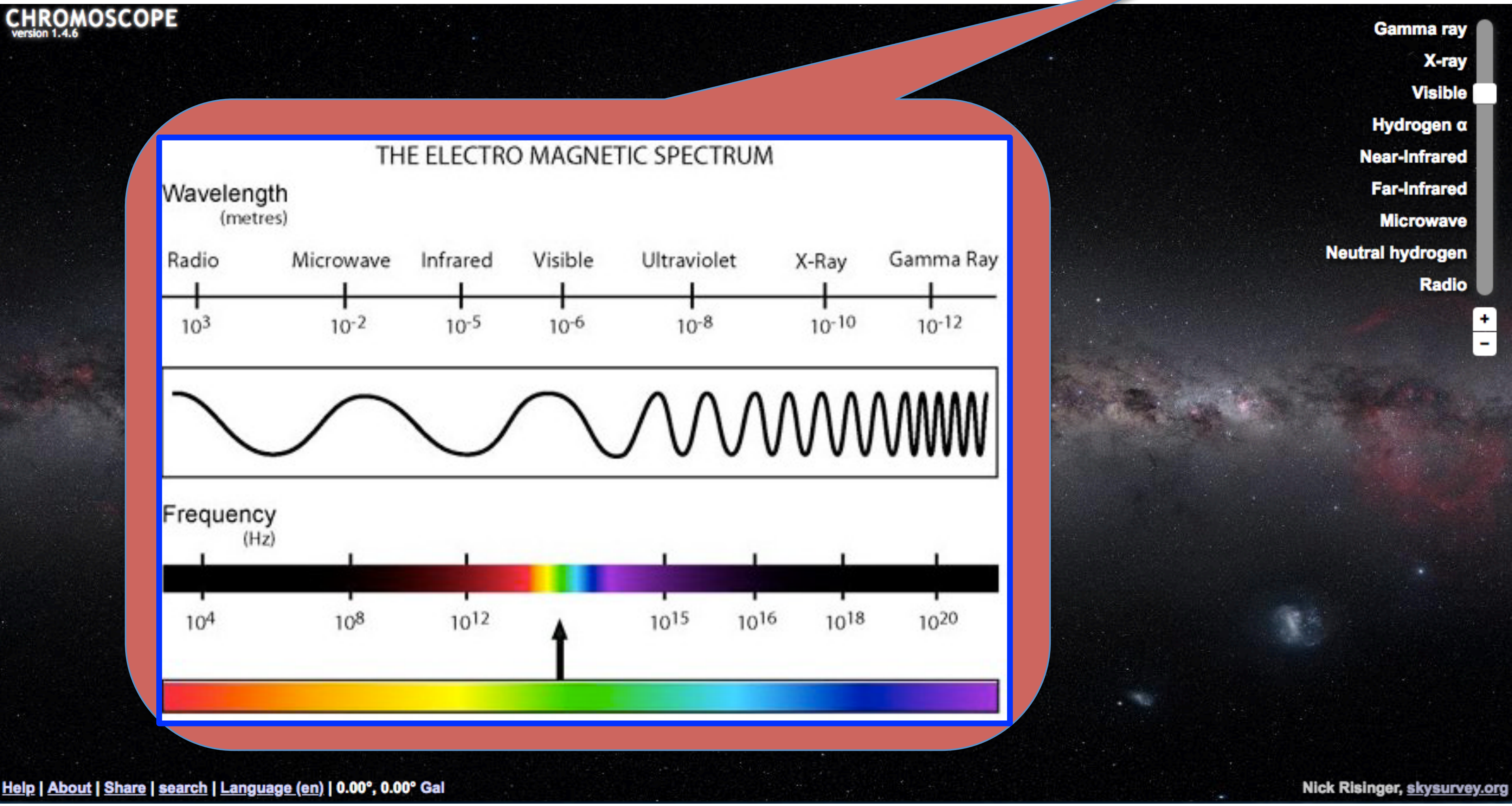

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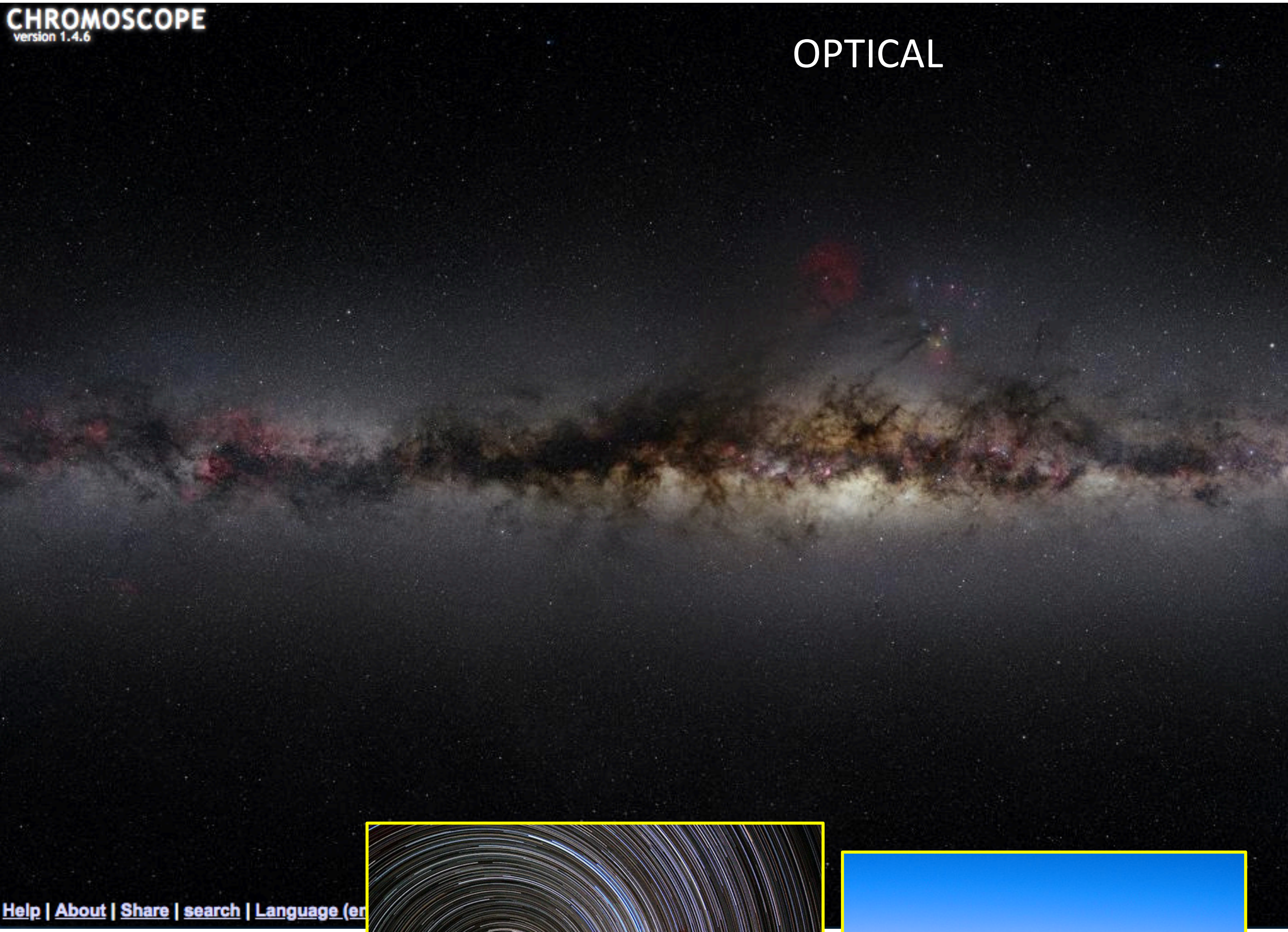
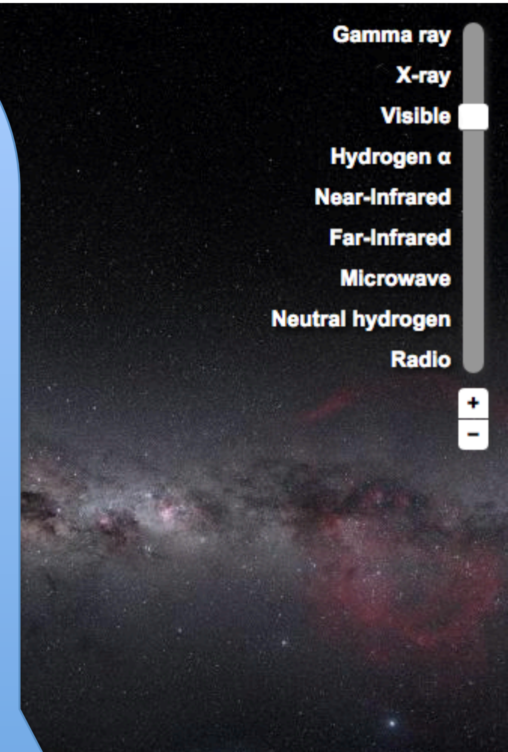


OPTICAL

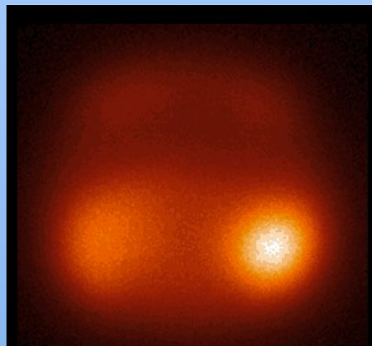
Telescopes

OBSERVATION: Milky Way in multi-wavelength

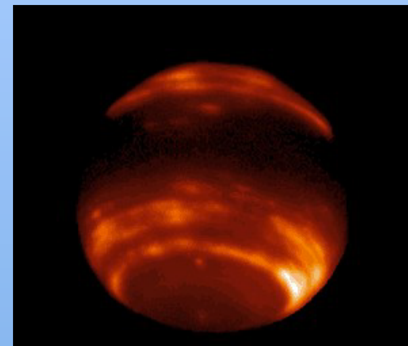


Why put telescopes in space?

Neptune

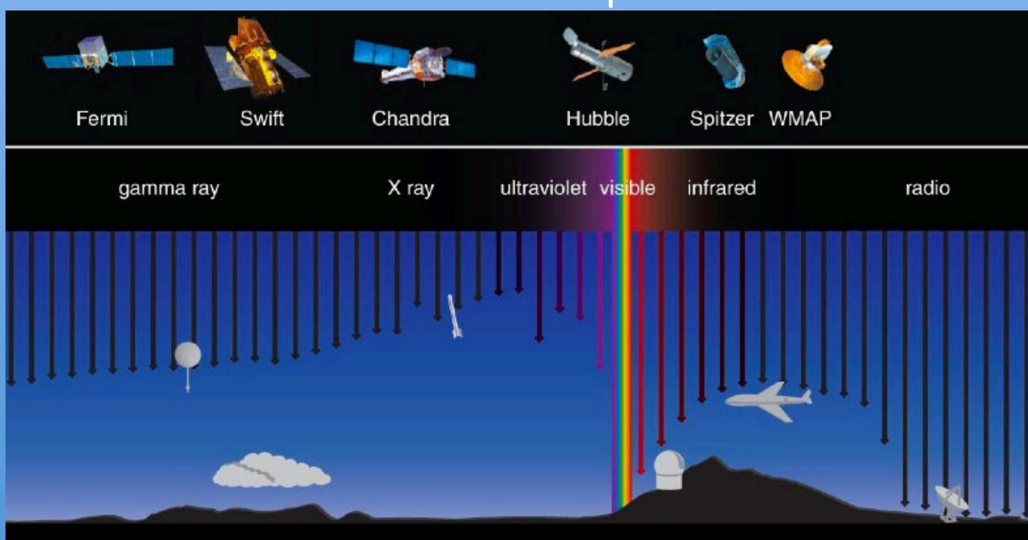


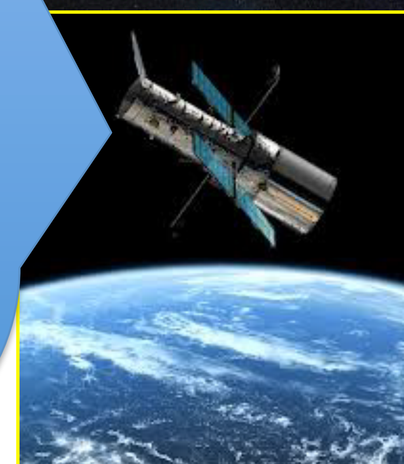
On earth



In space

Effect of atmosphere





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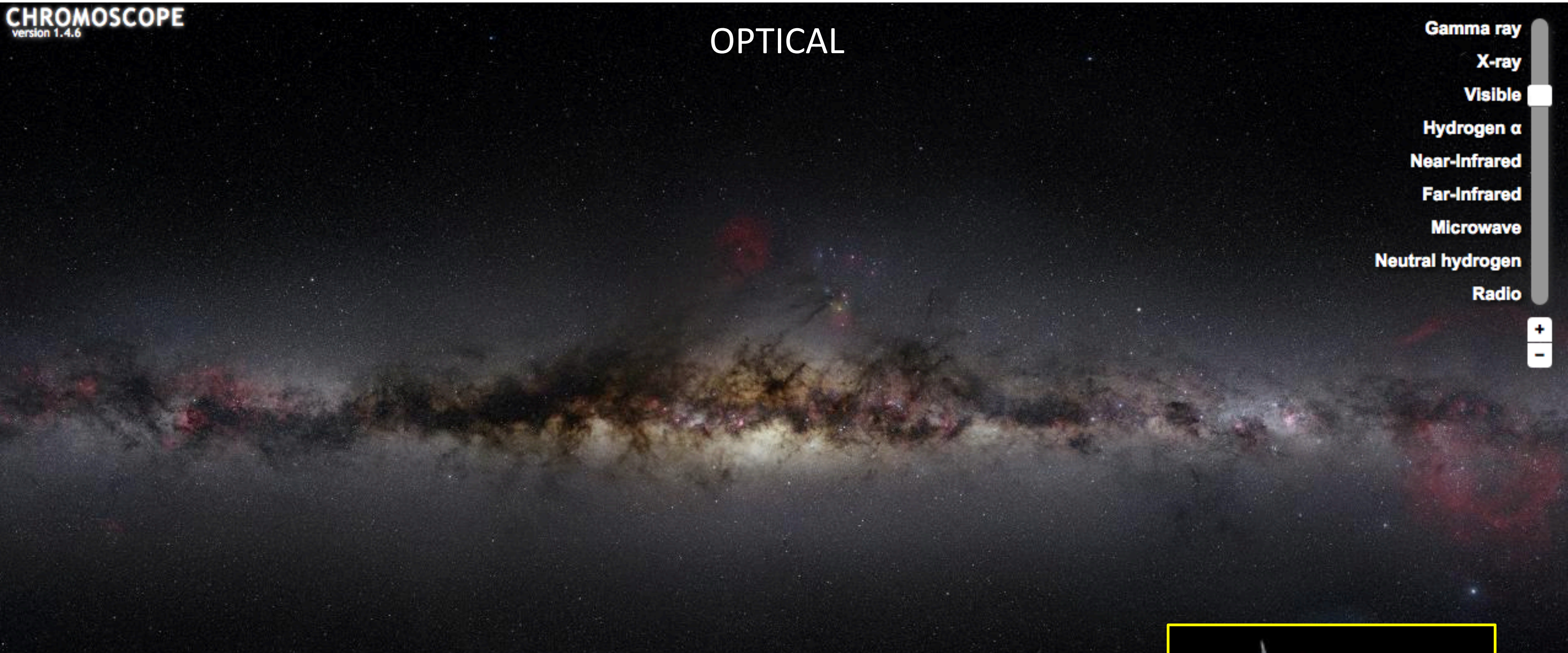

Telescopes

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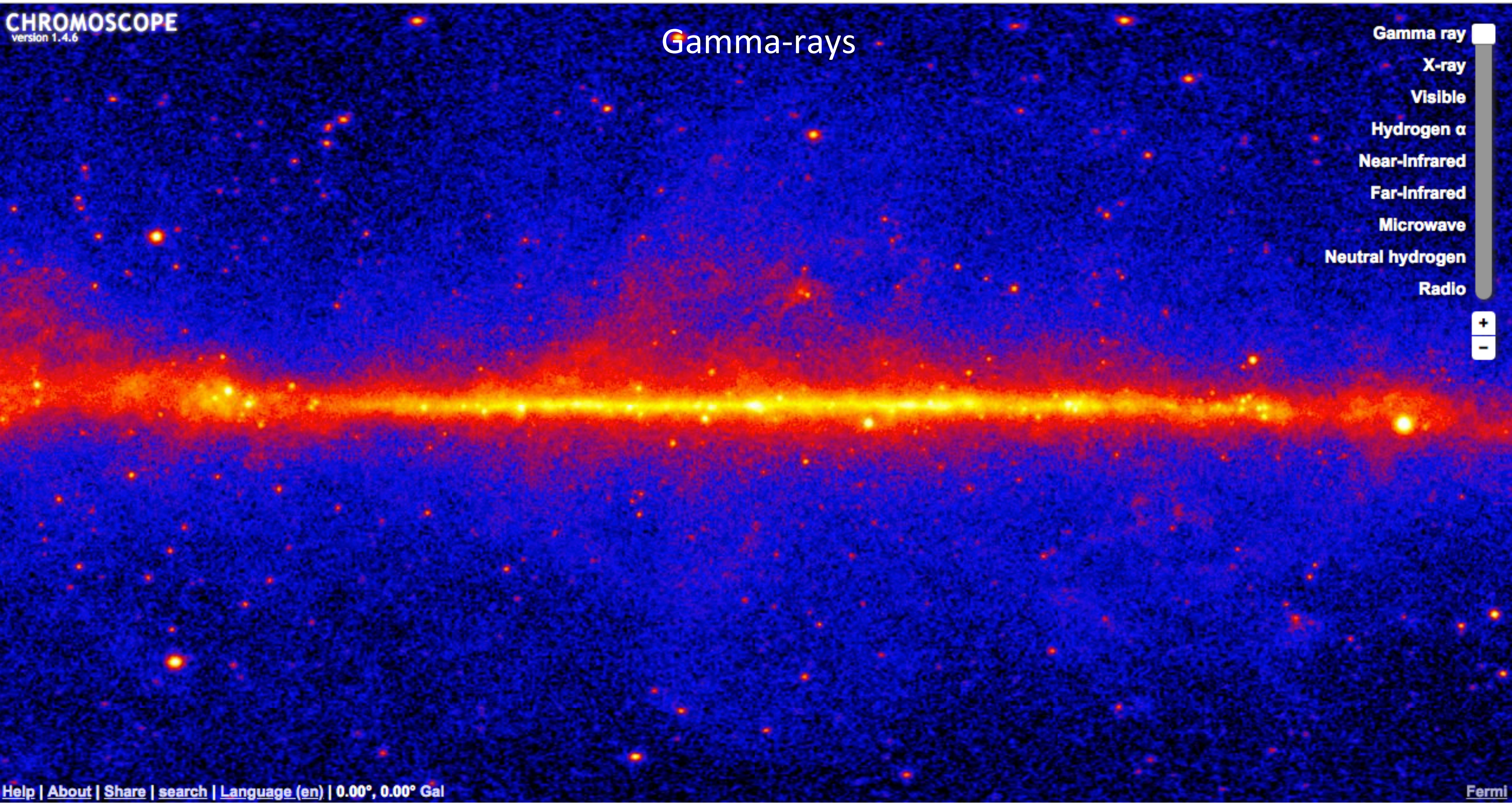

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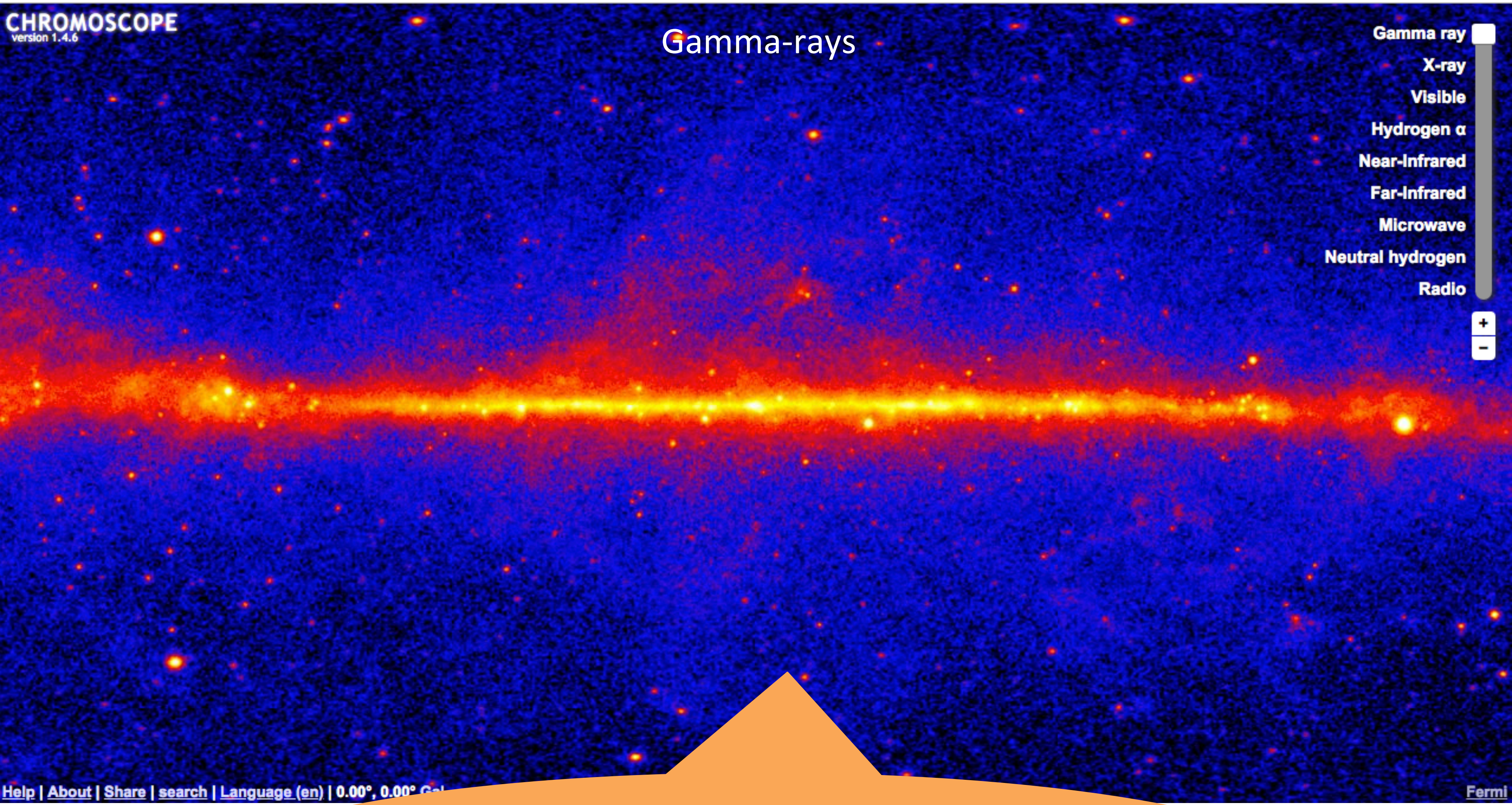
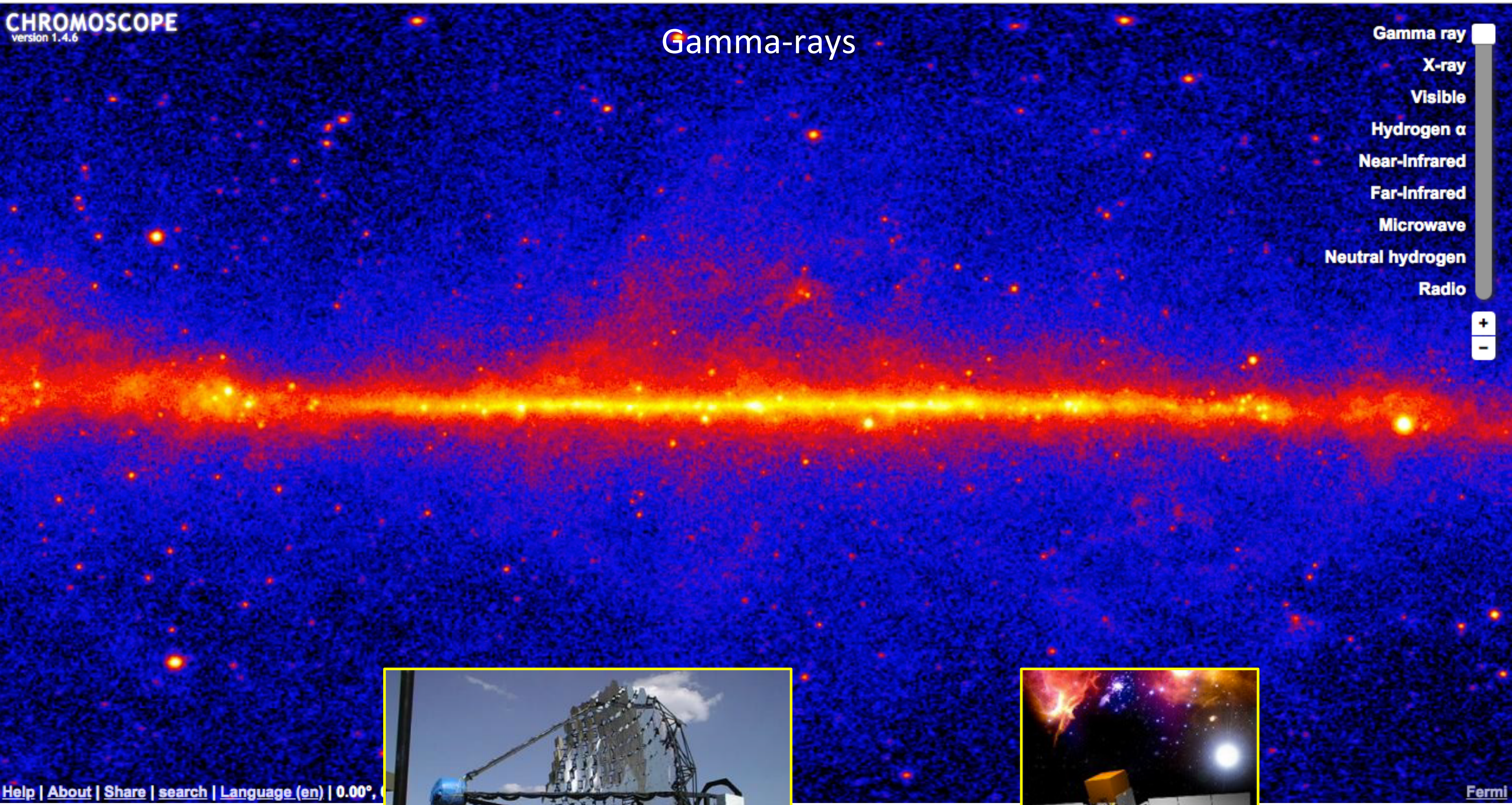


The human eye cannot see gamma-rays, UV, IR nor radio, so astronomers use color coding to correspond different emission energy

OBSERVATION: Milky Way in multi-wavelength



Telescopes

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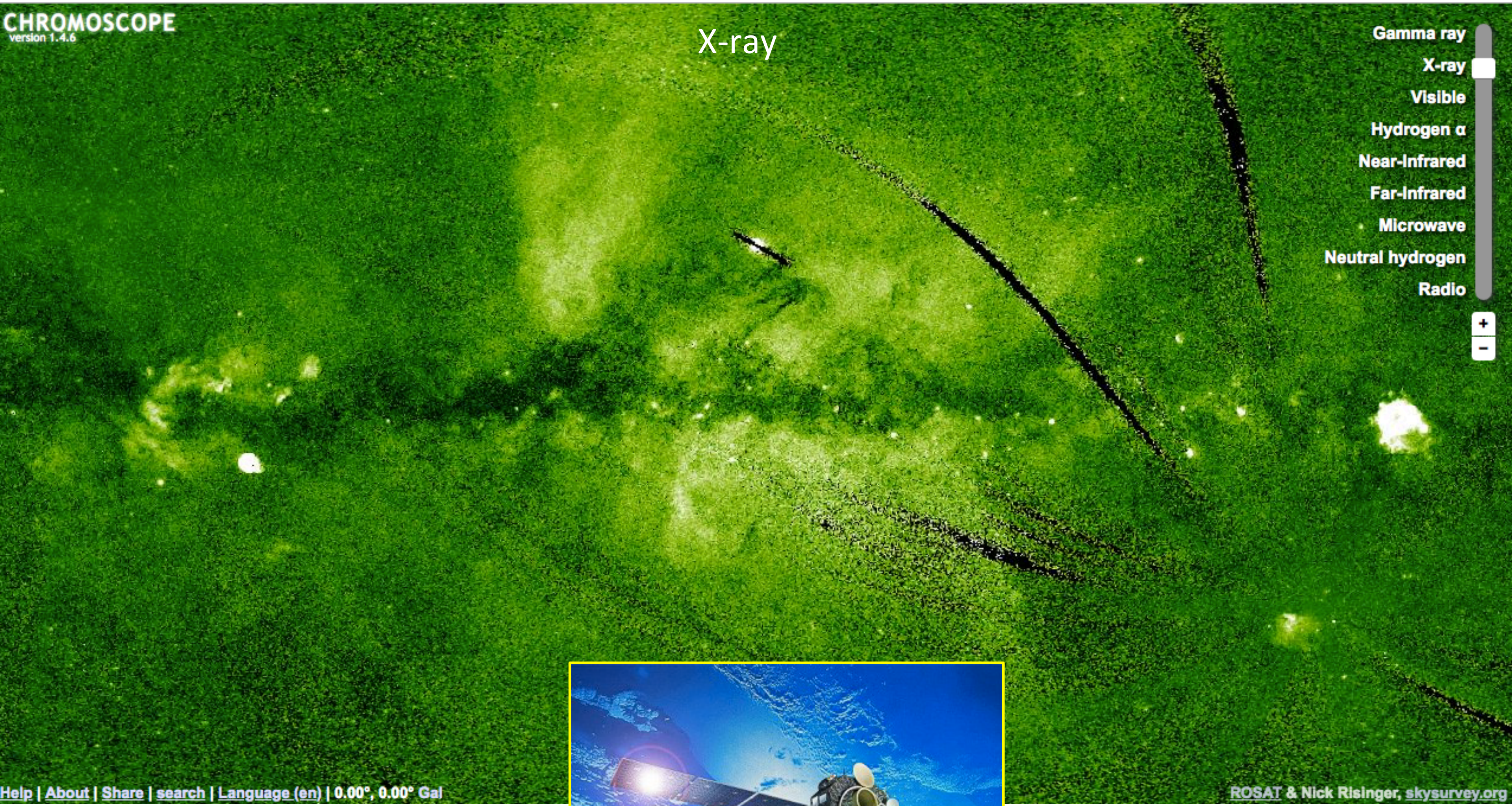

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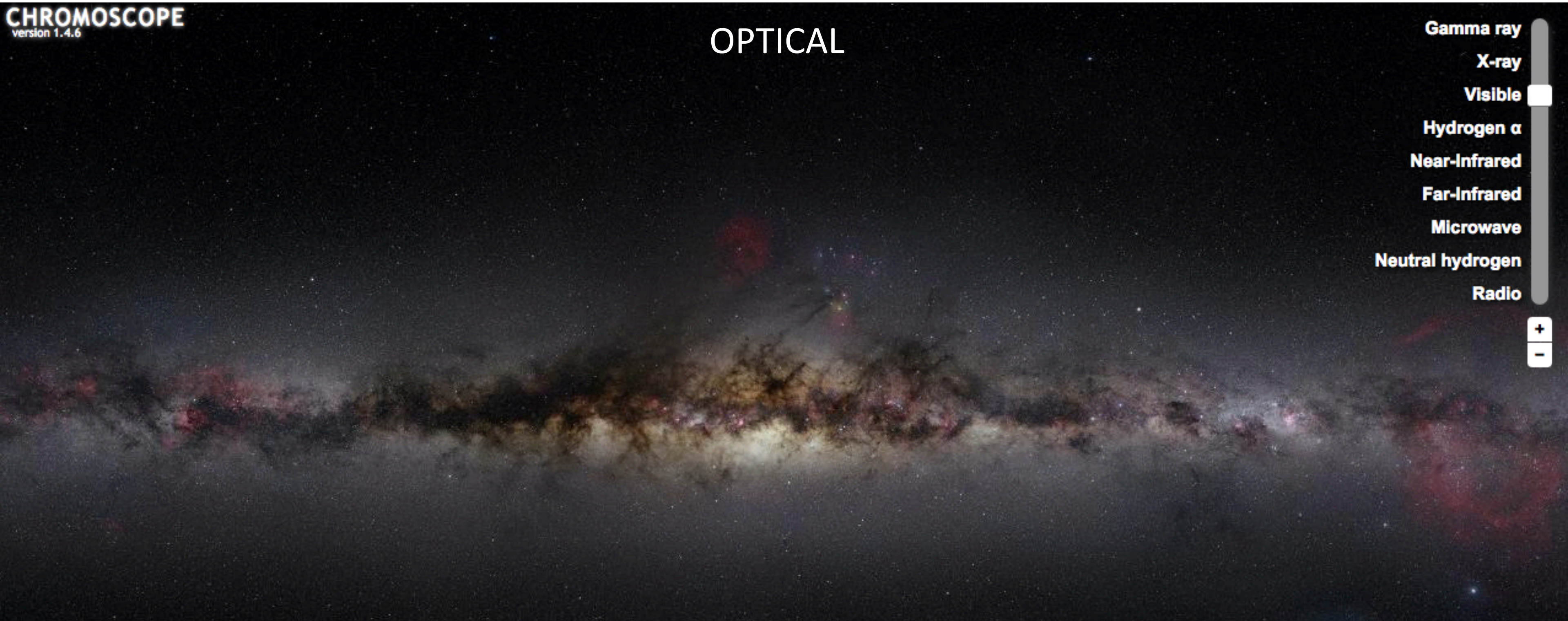

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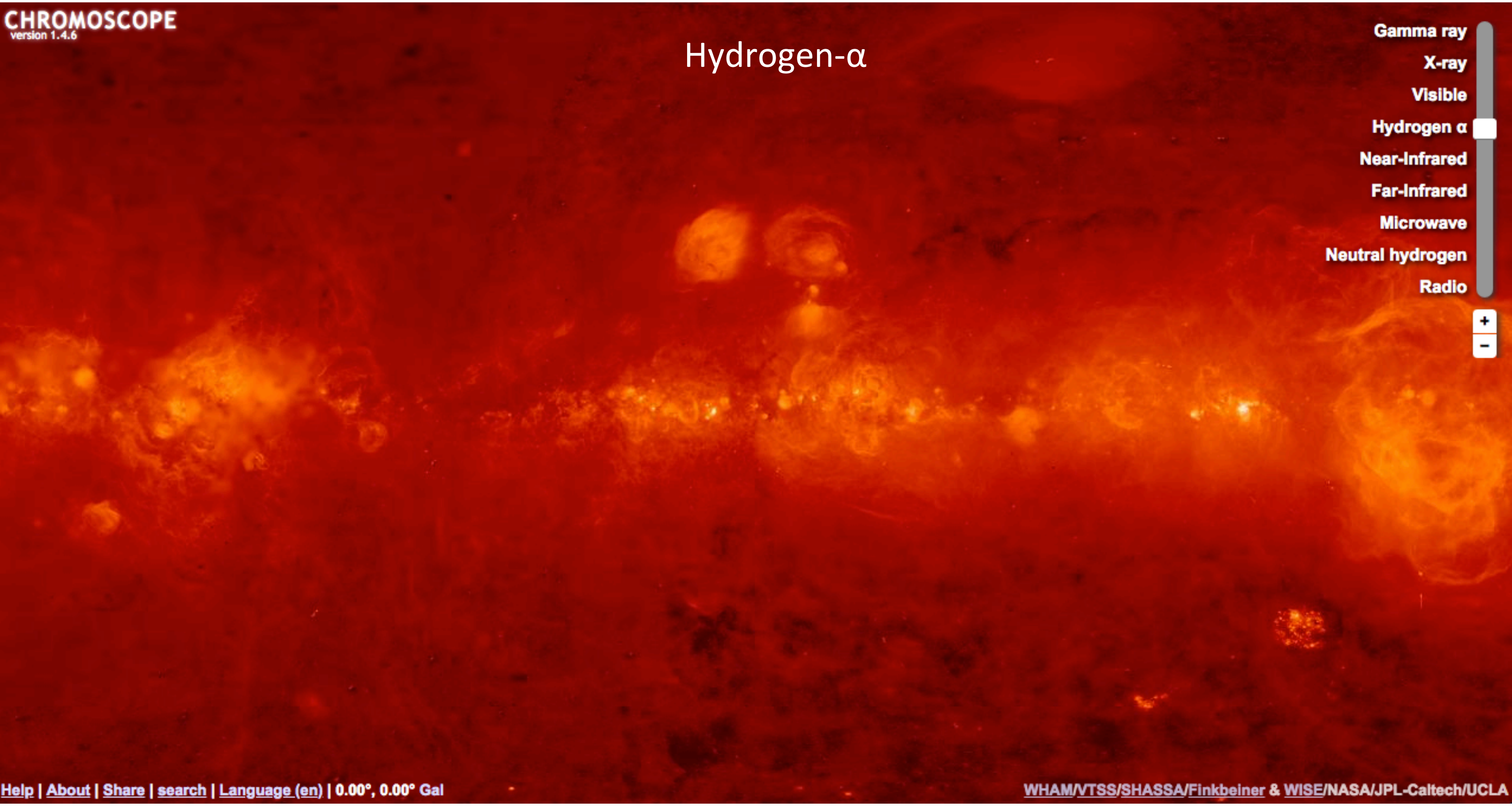

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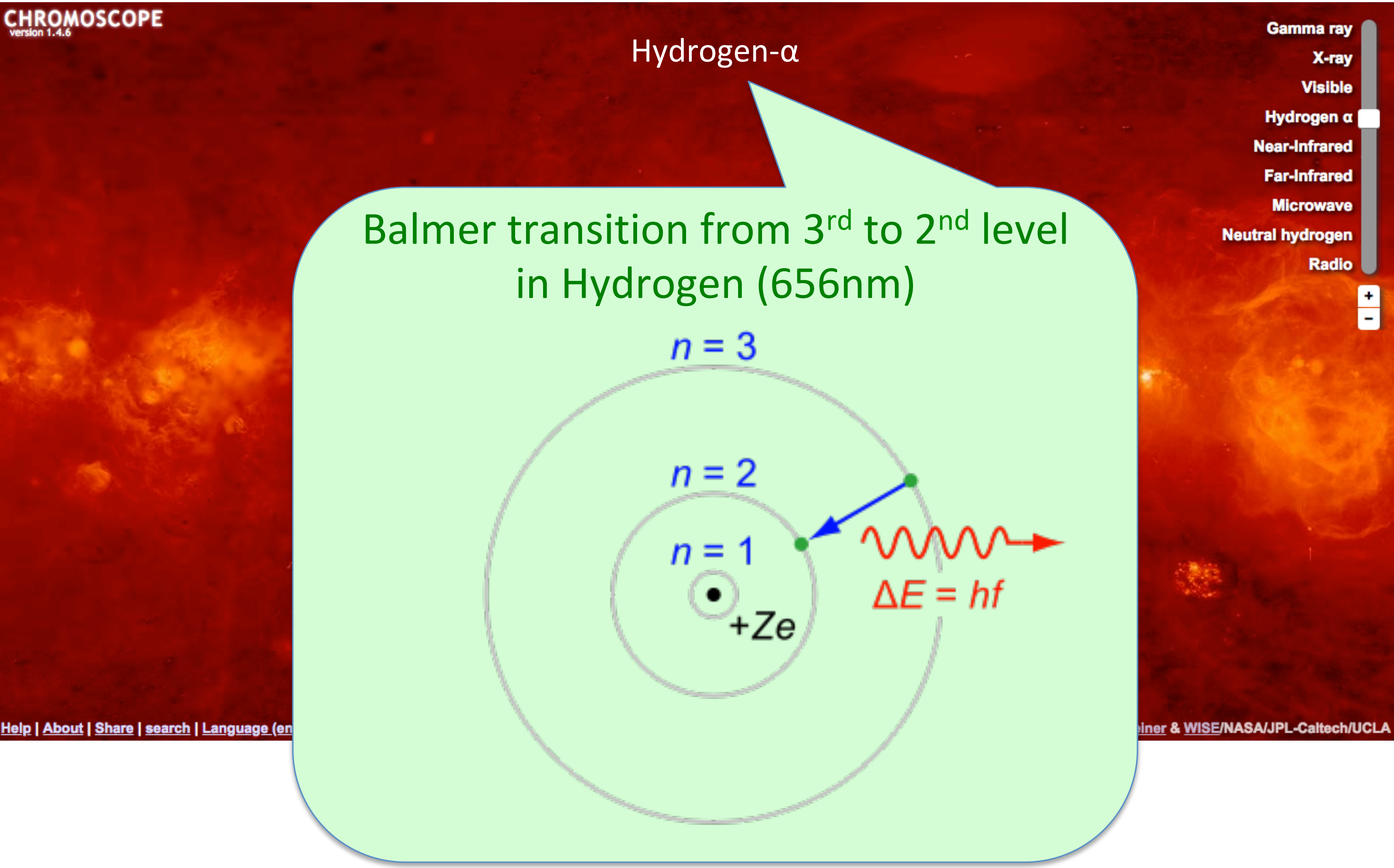

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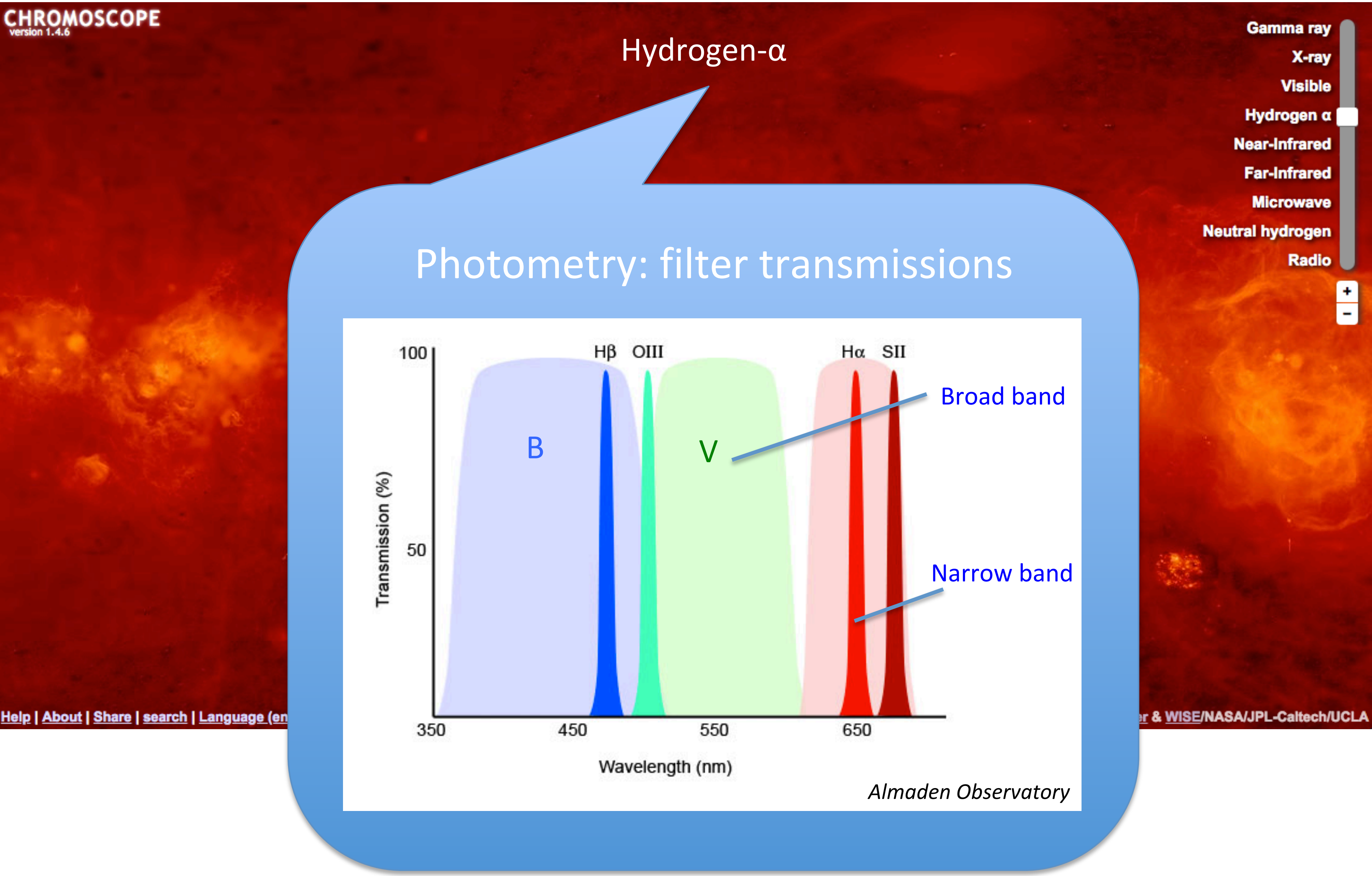

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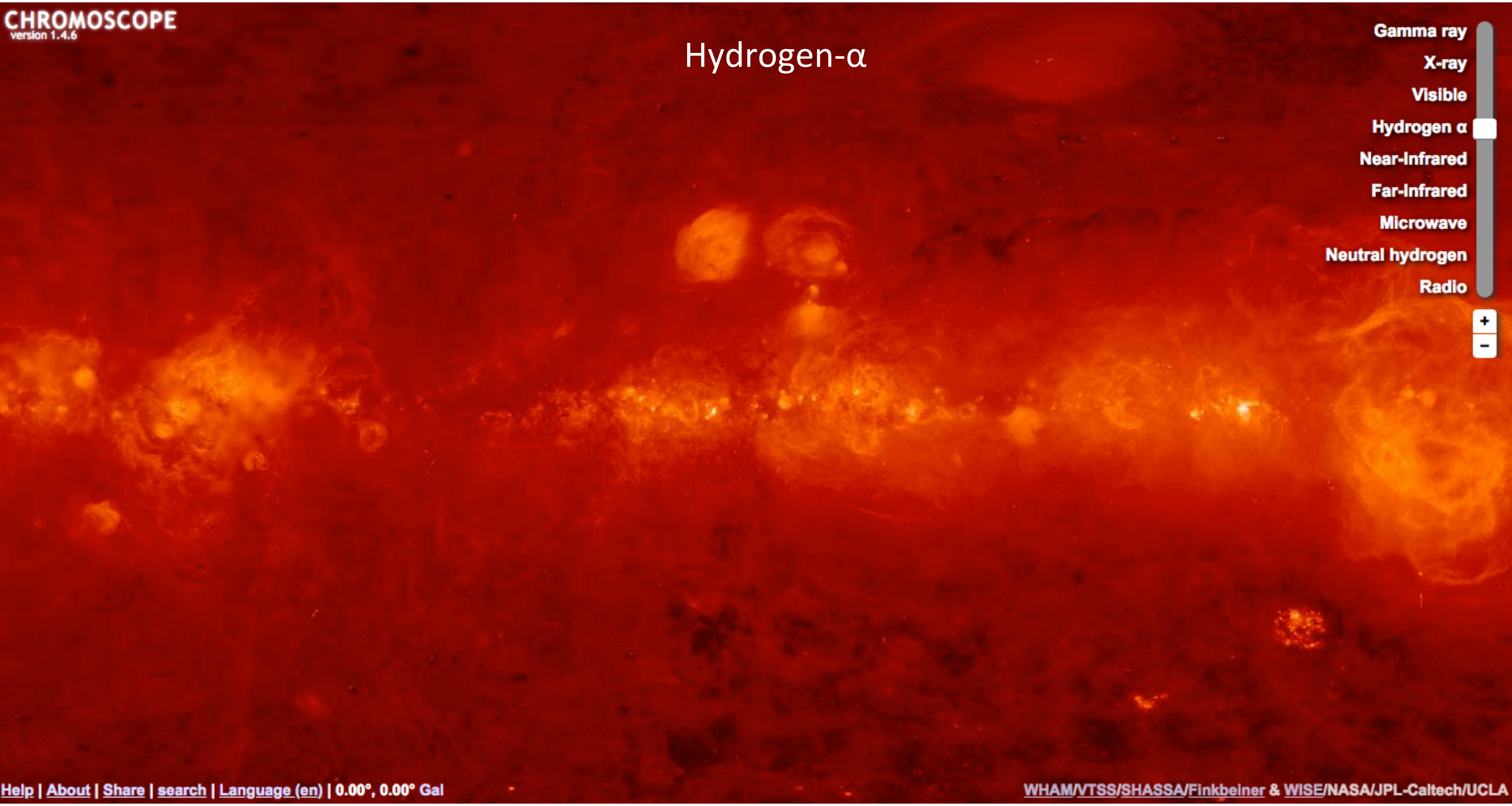

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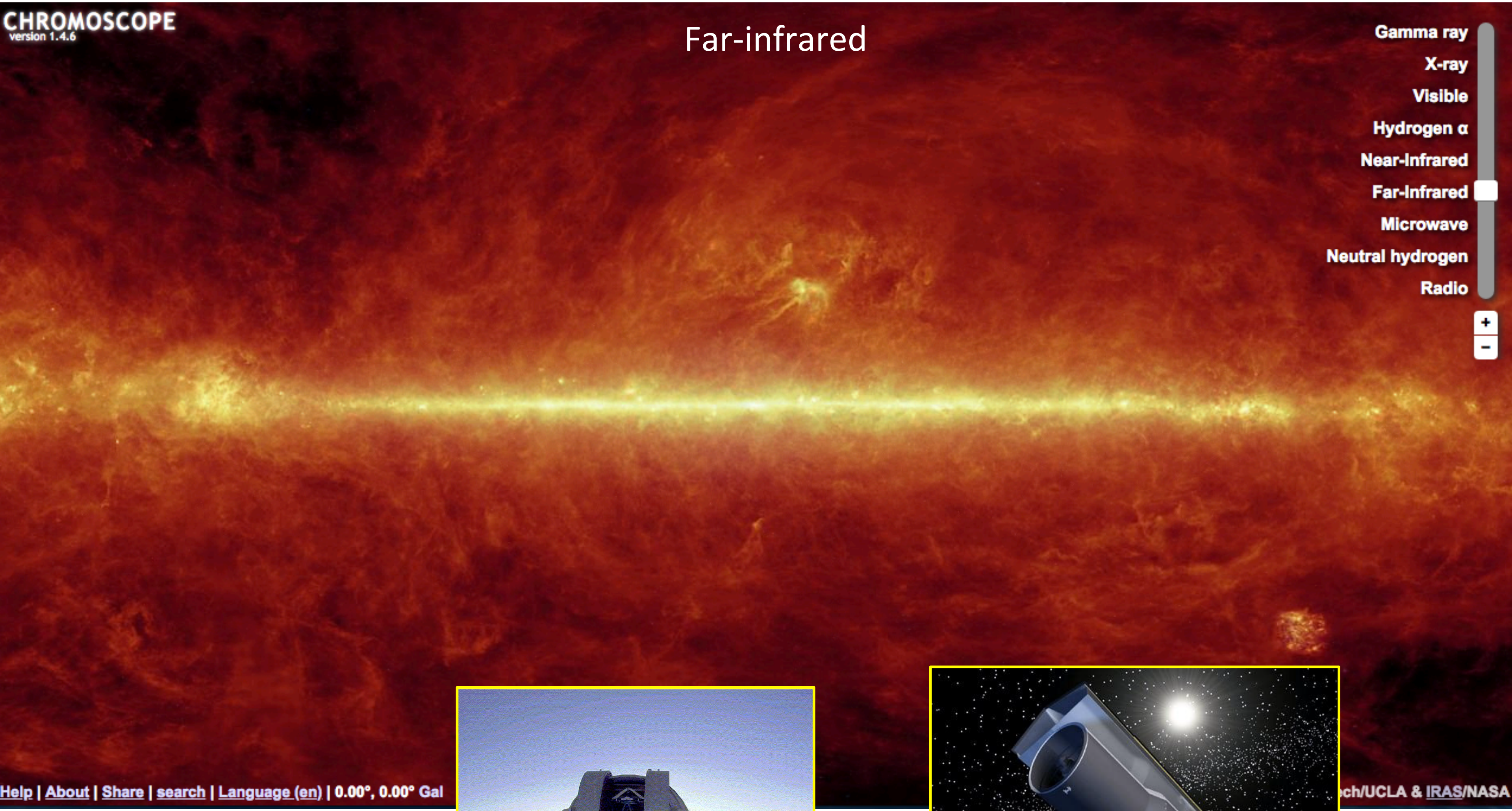

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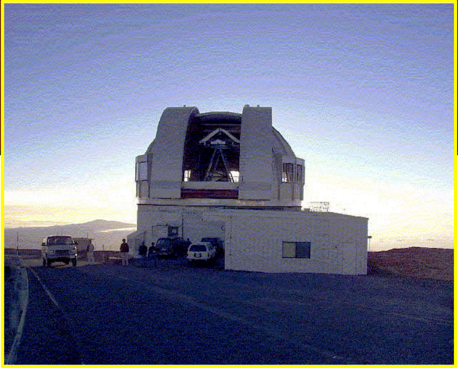

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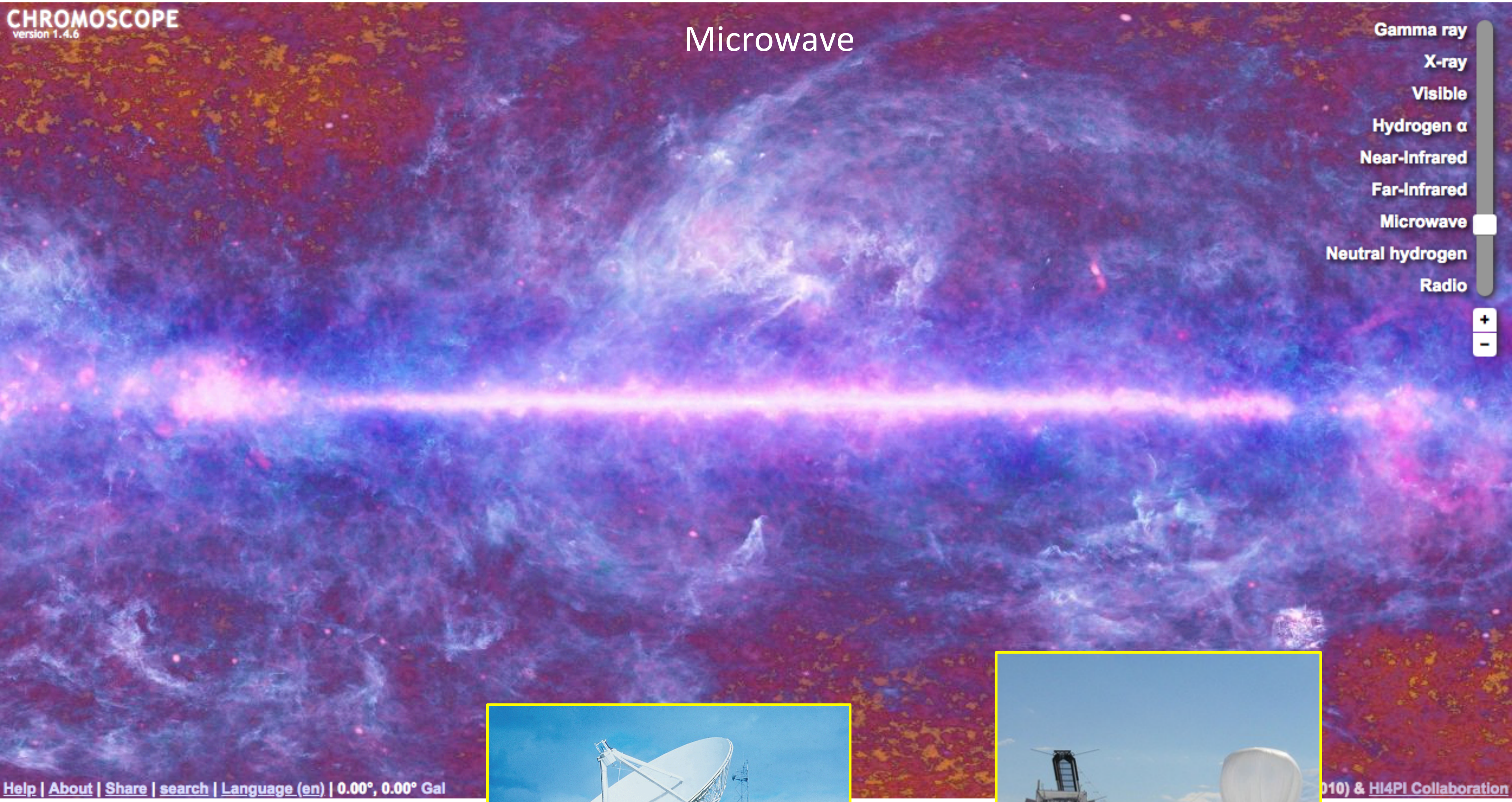

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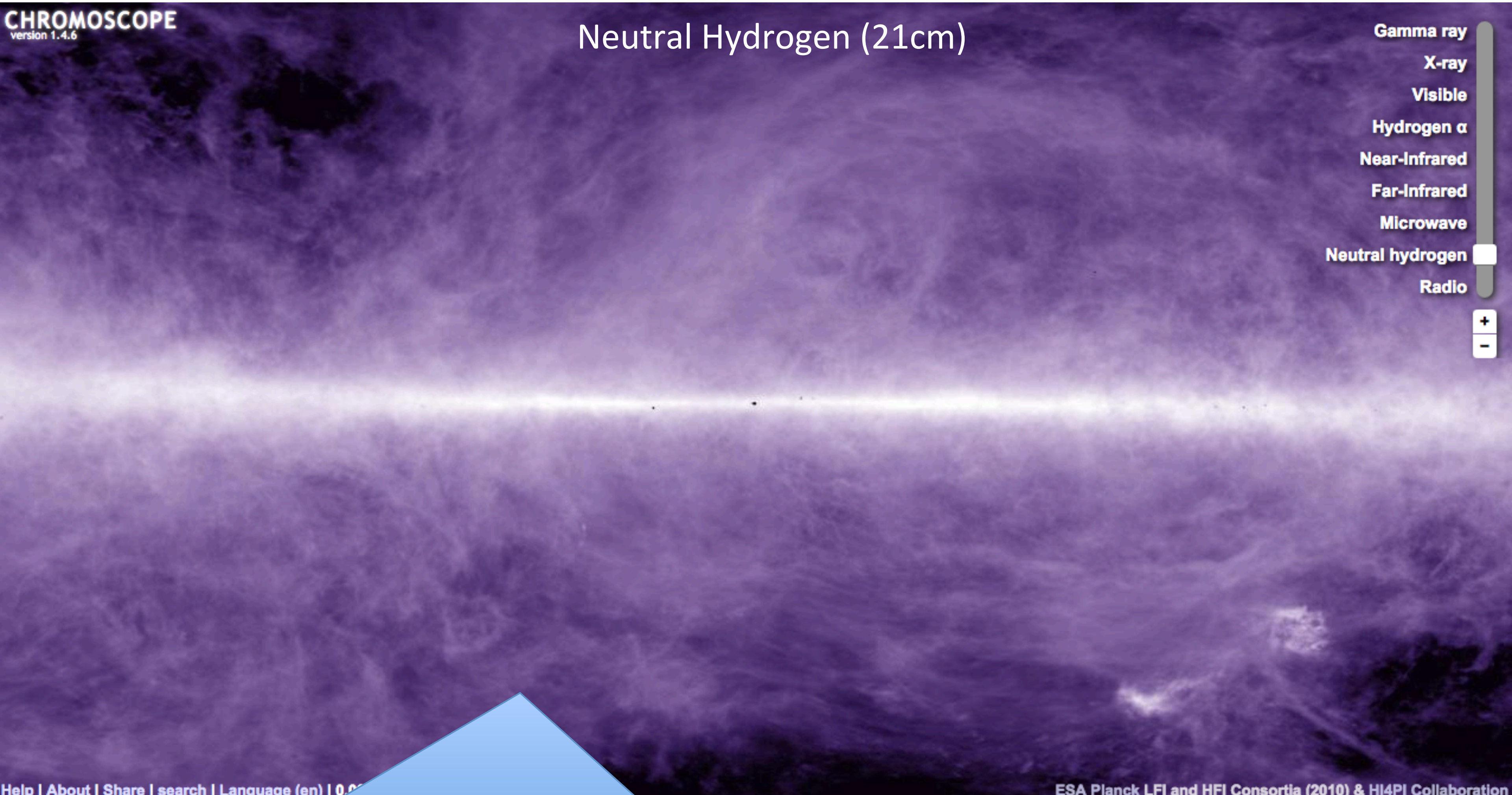
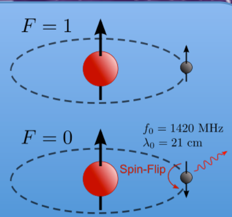


21cm line comes from hyperfine 1s transition of hydrogen



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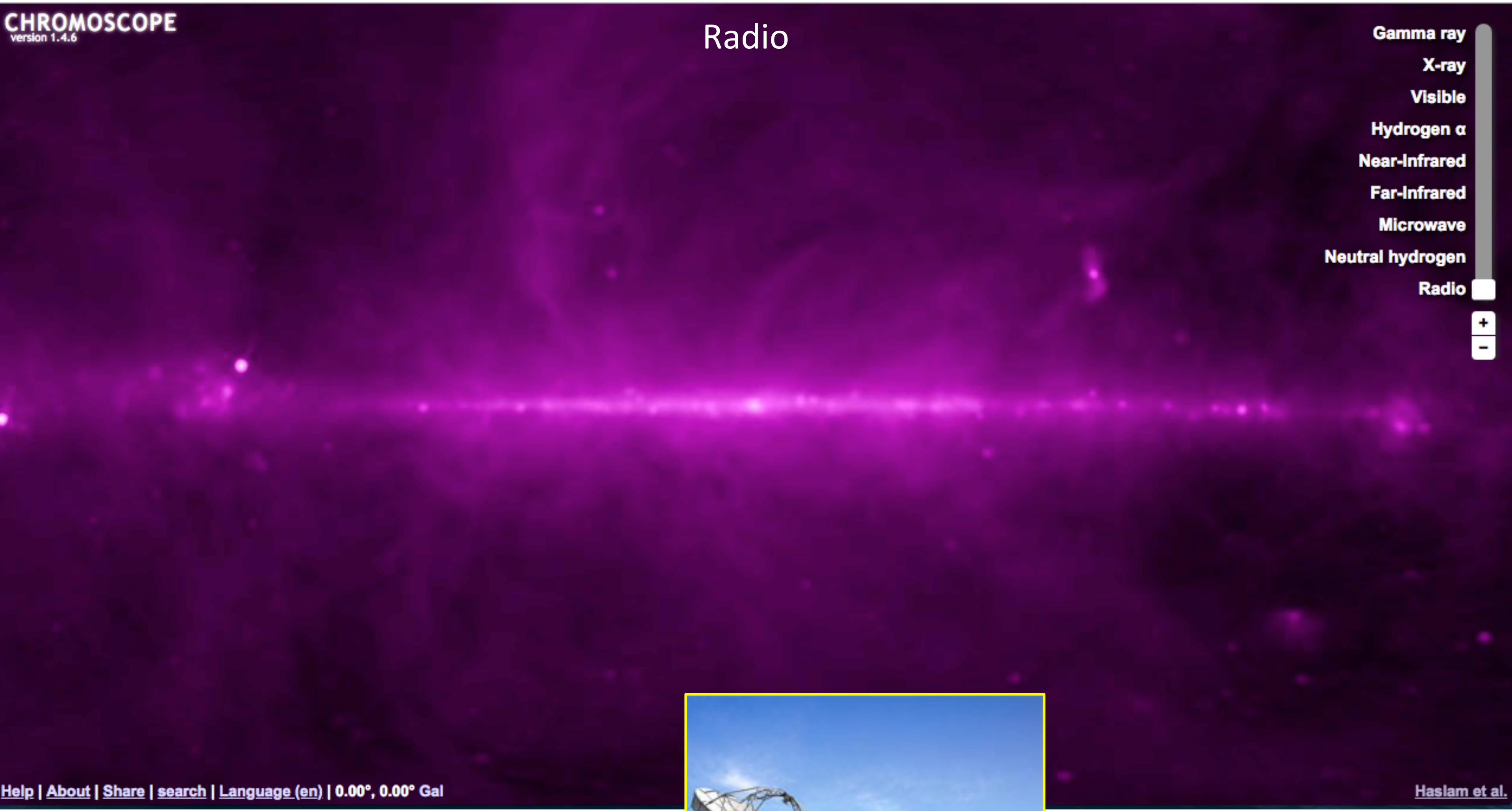

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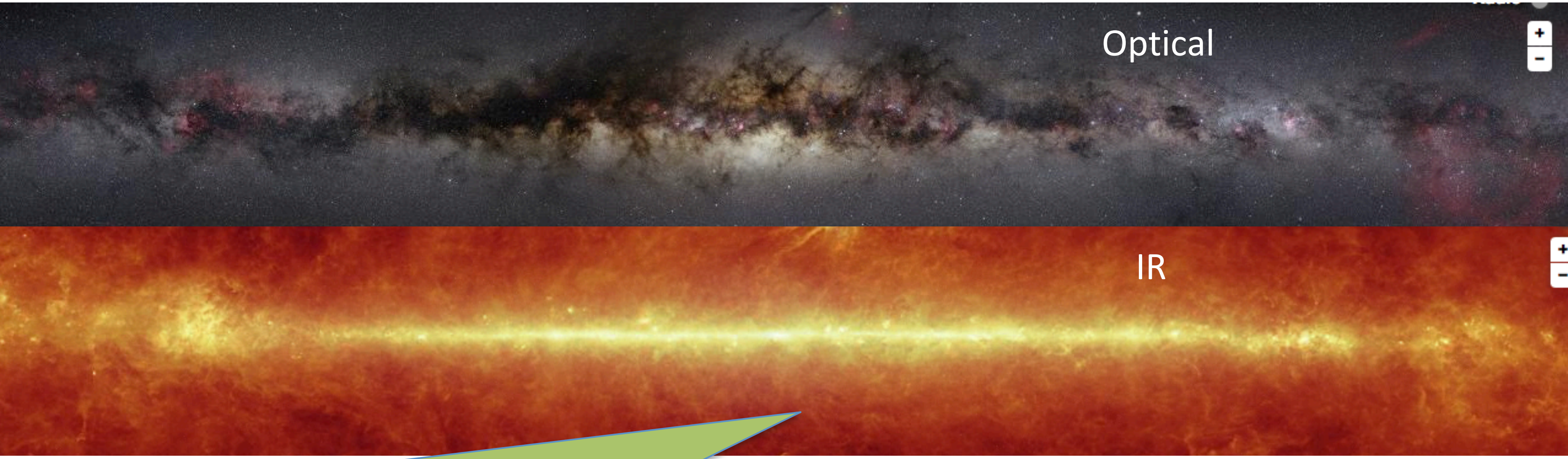
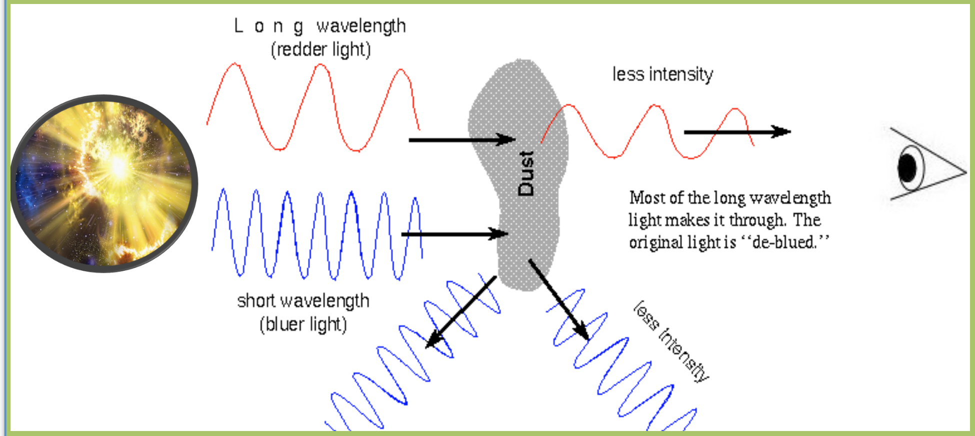
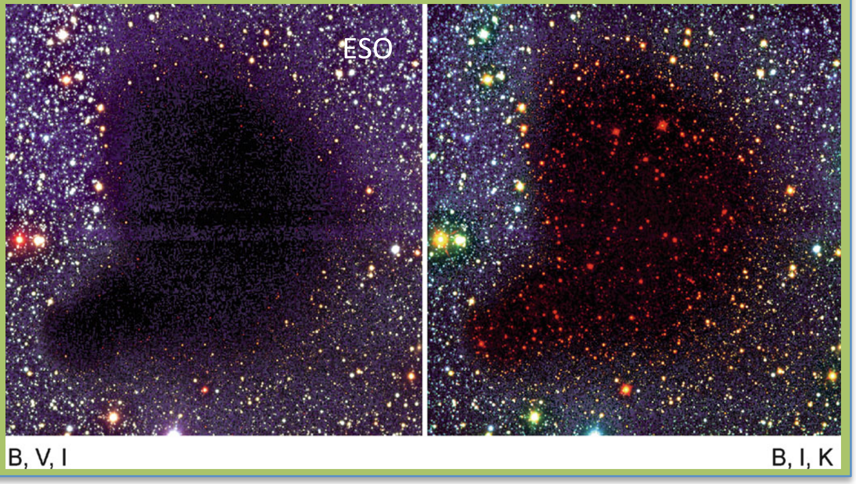


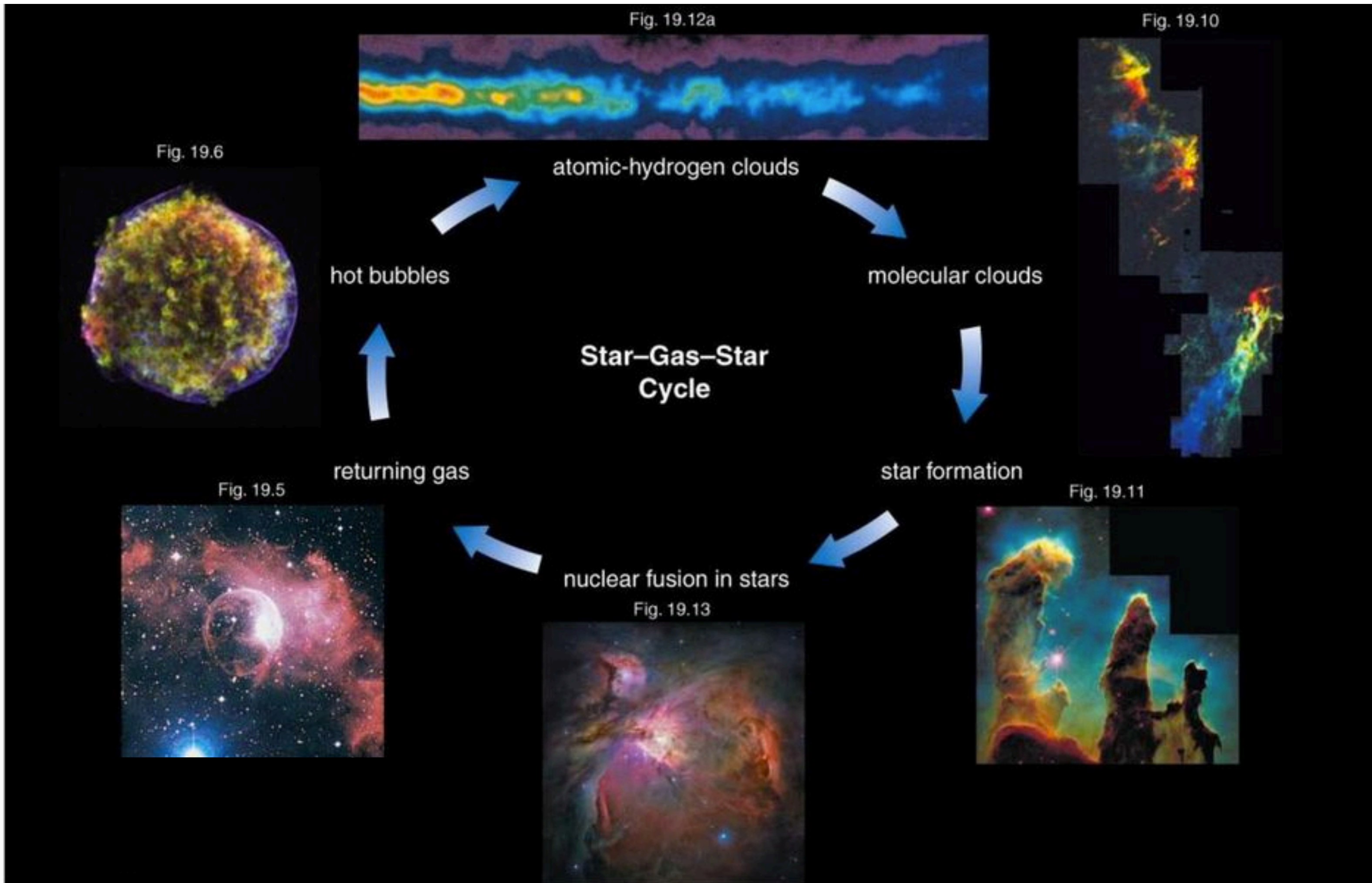
Extinction: absorption of light by dust
Reddening: reemission at longer wavelengths





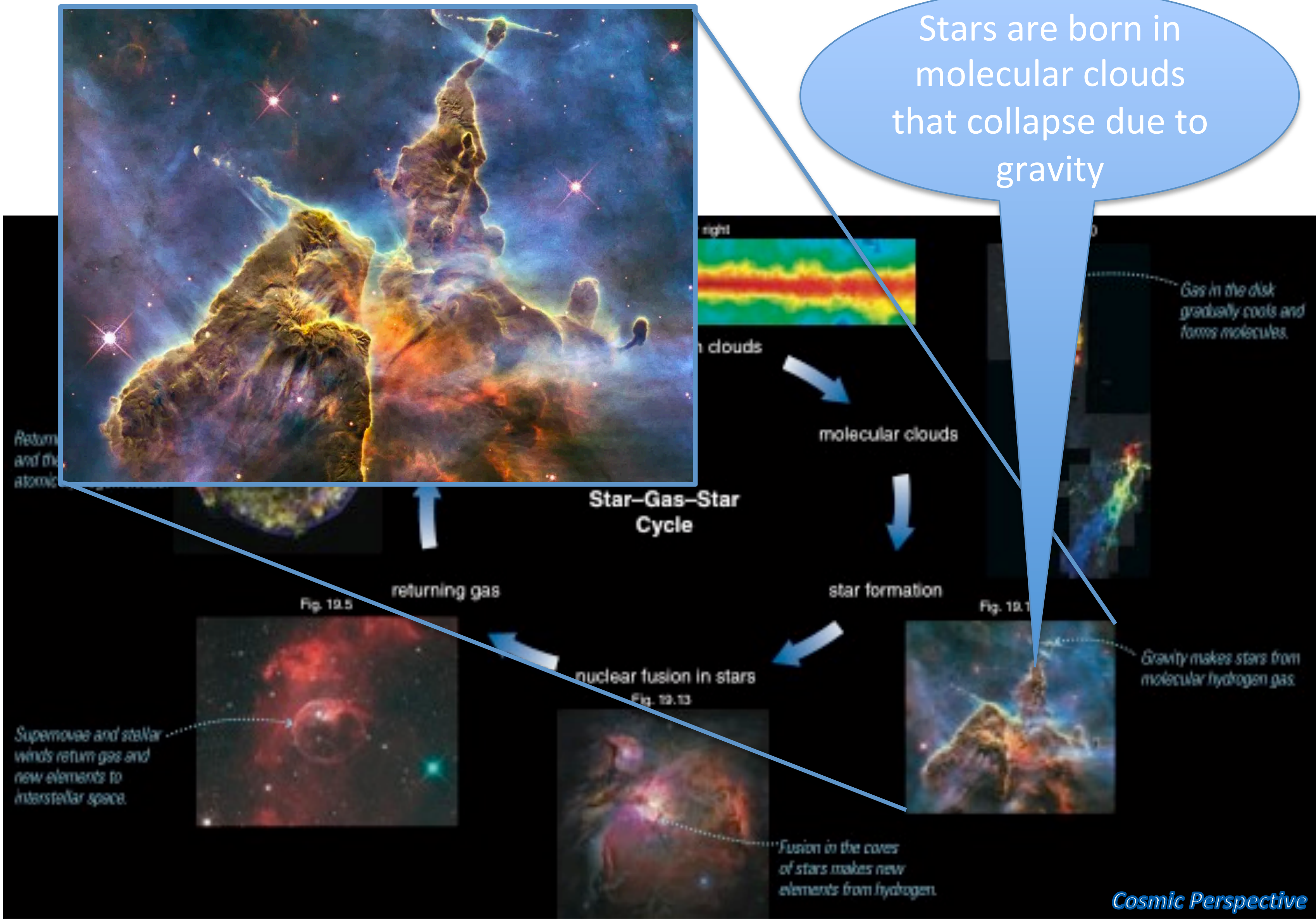
Star-gas-star cycle

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



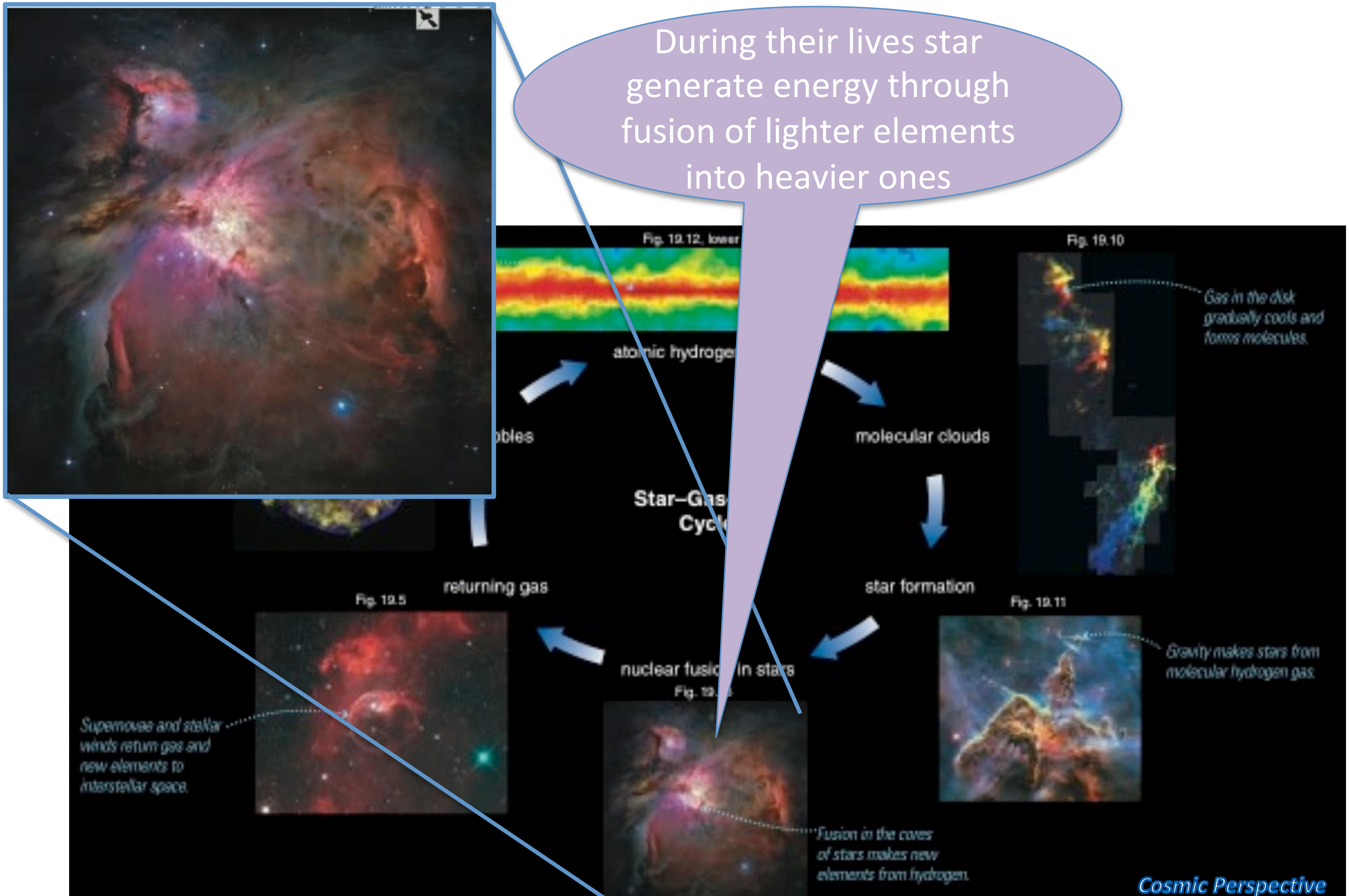
Star-gas-star cycle

Stars are born in molecular clouds that collapse due to gravity



Star-gas-star cycle

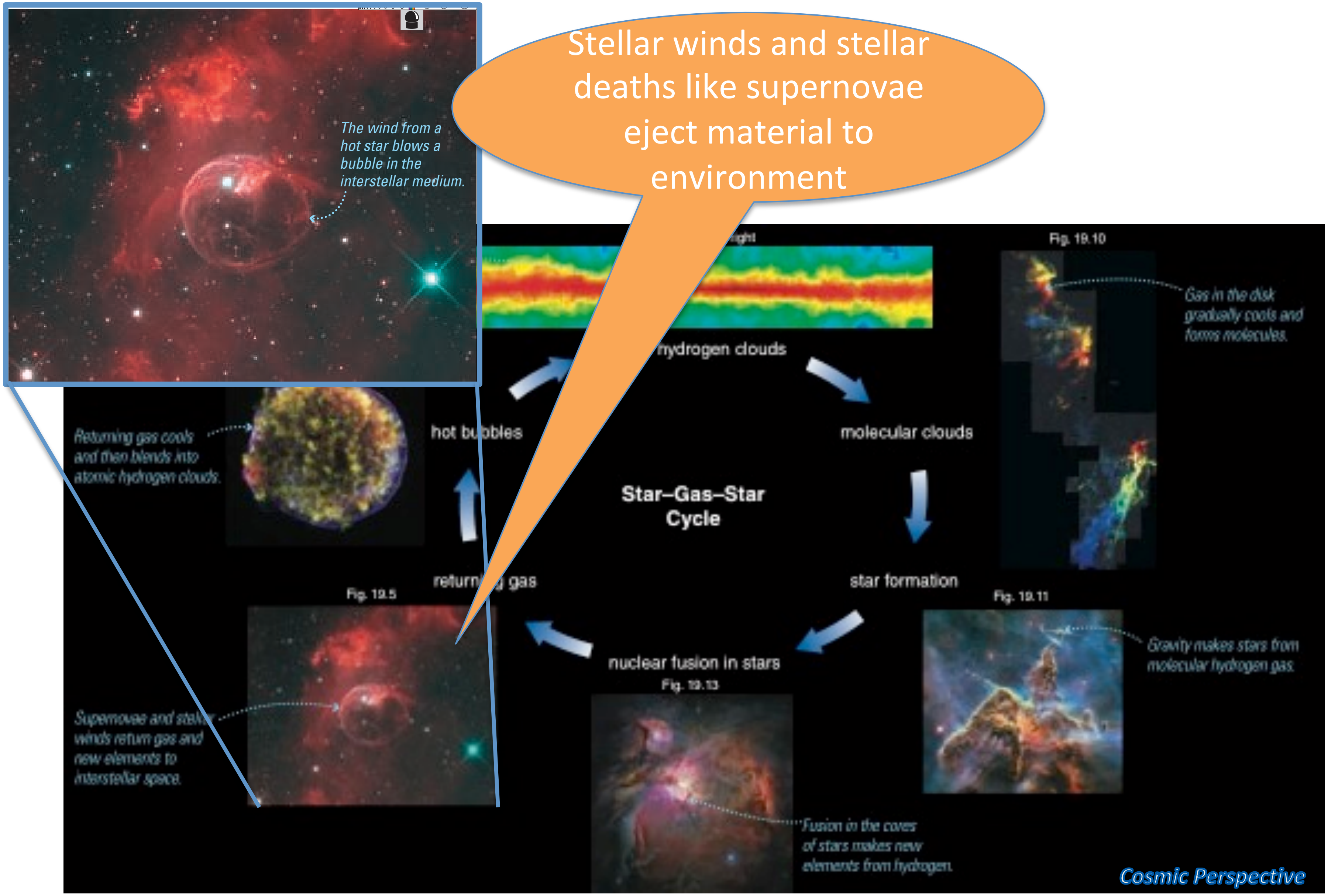
During their lives star generate energy through fusion of lighter elements into heavier ones



Cosmic Perspective

Star-gas-star cycle

Stellar winds and stellar deaths like supernovae eject material to environment



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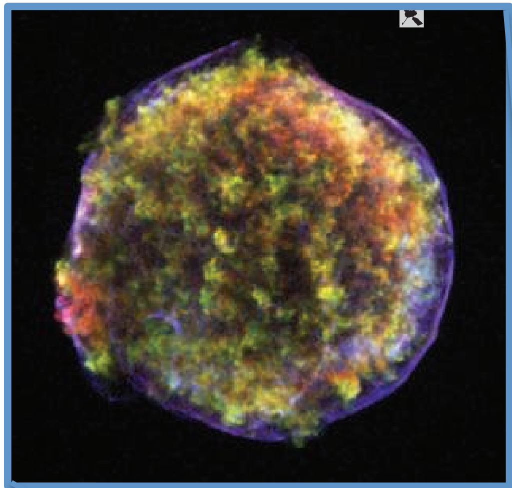

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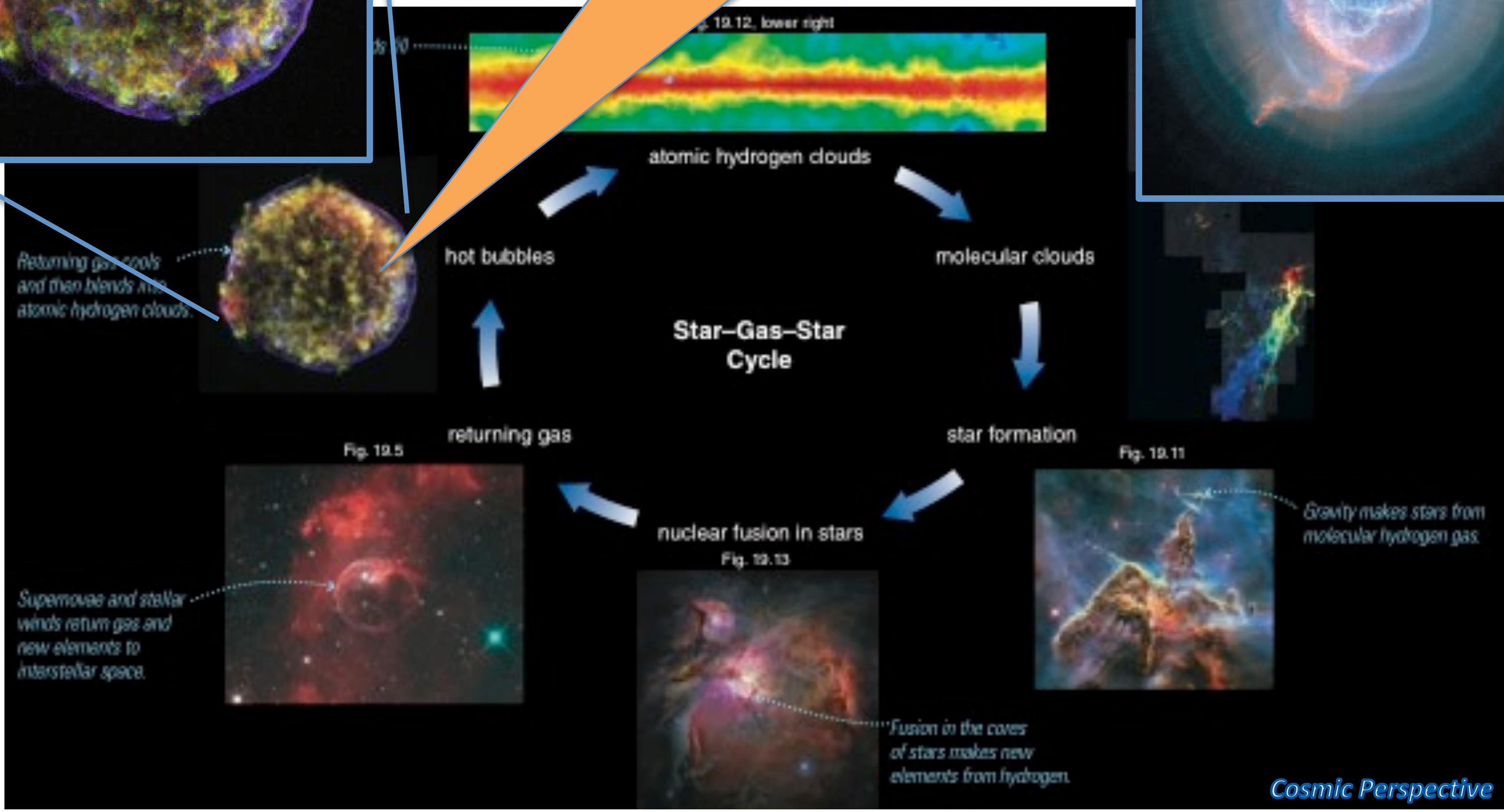
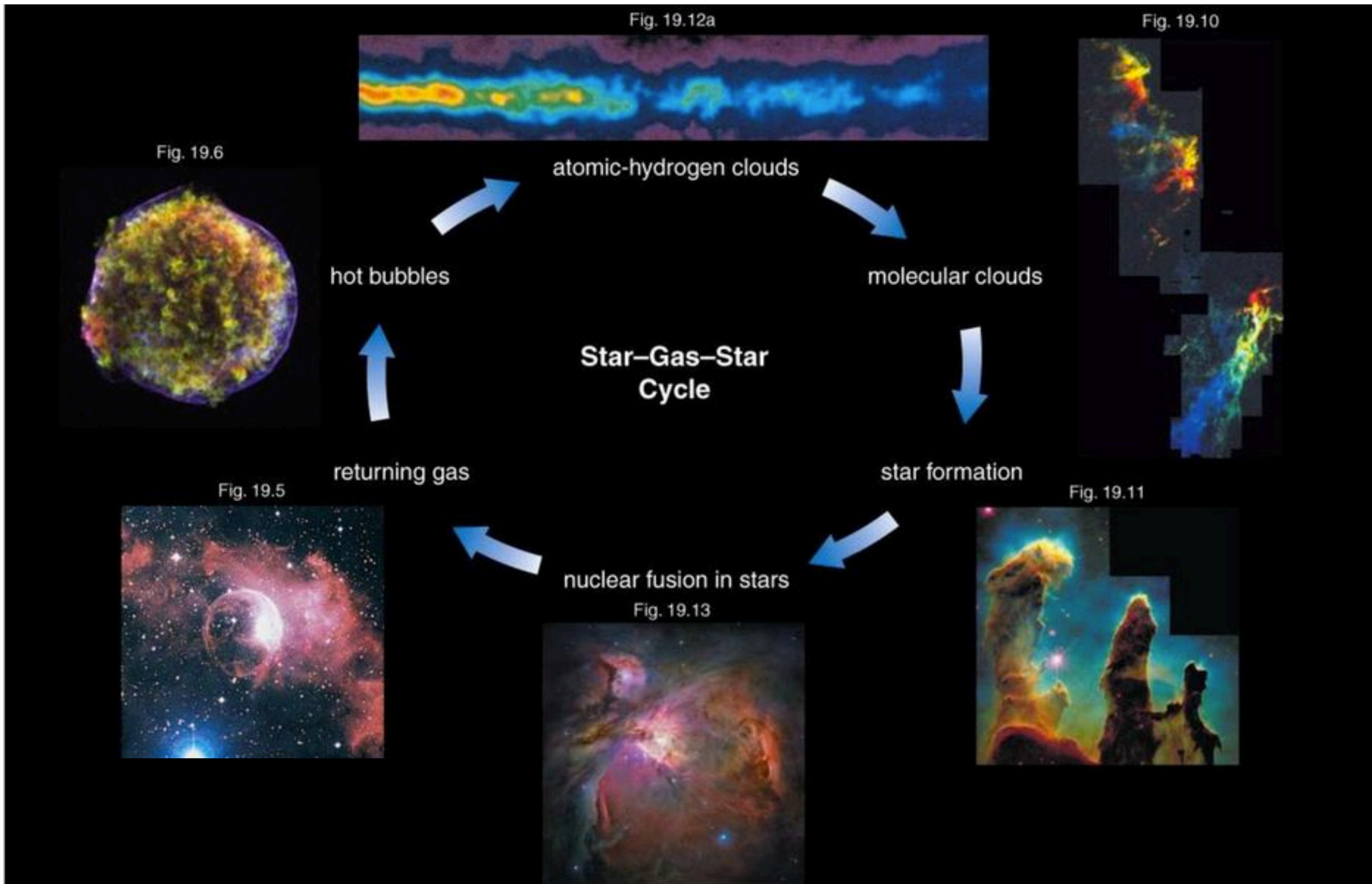


Star-gas-star cycle

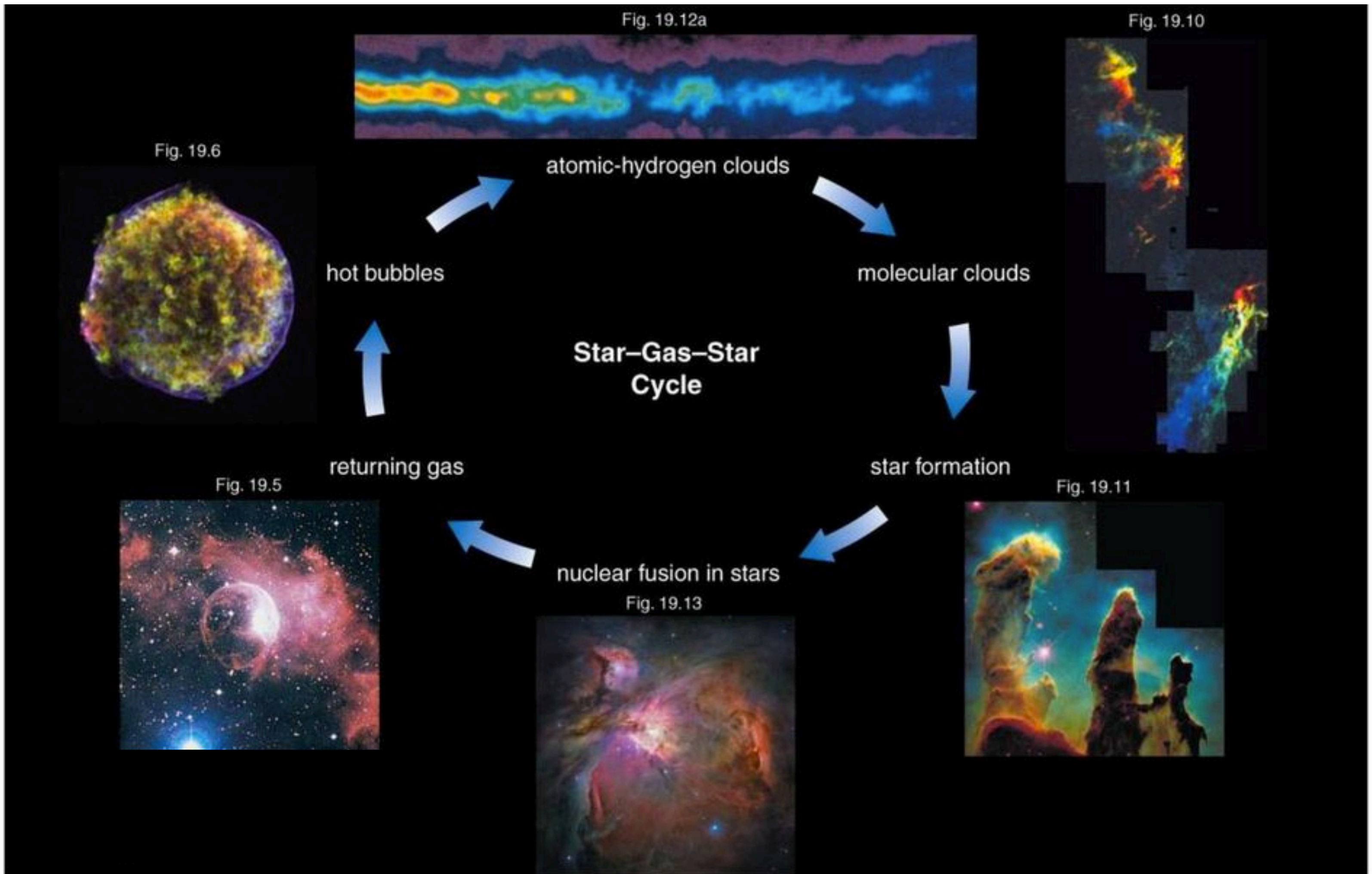
Cycle begins again with an enriched material

Duration of cycle might vary from millions to billions of yrs



Star-gas-star cycle

It's the circle of life!

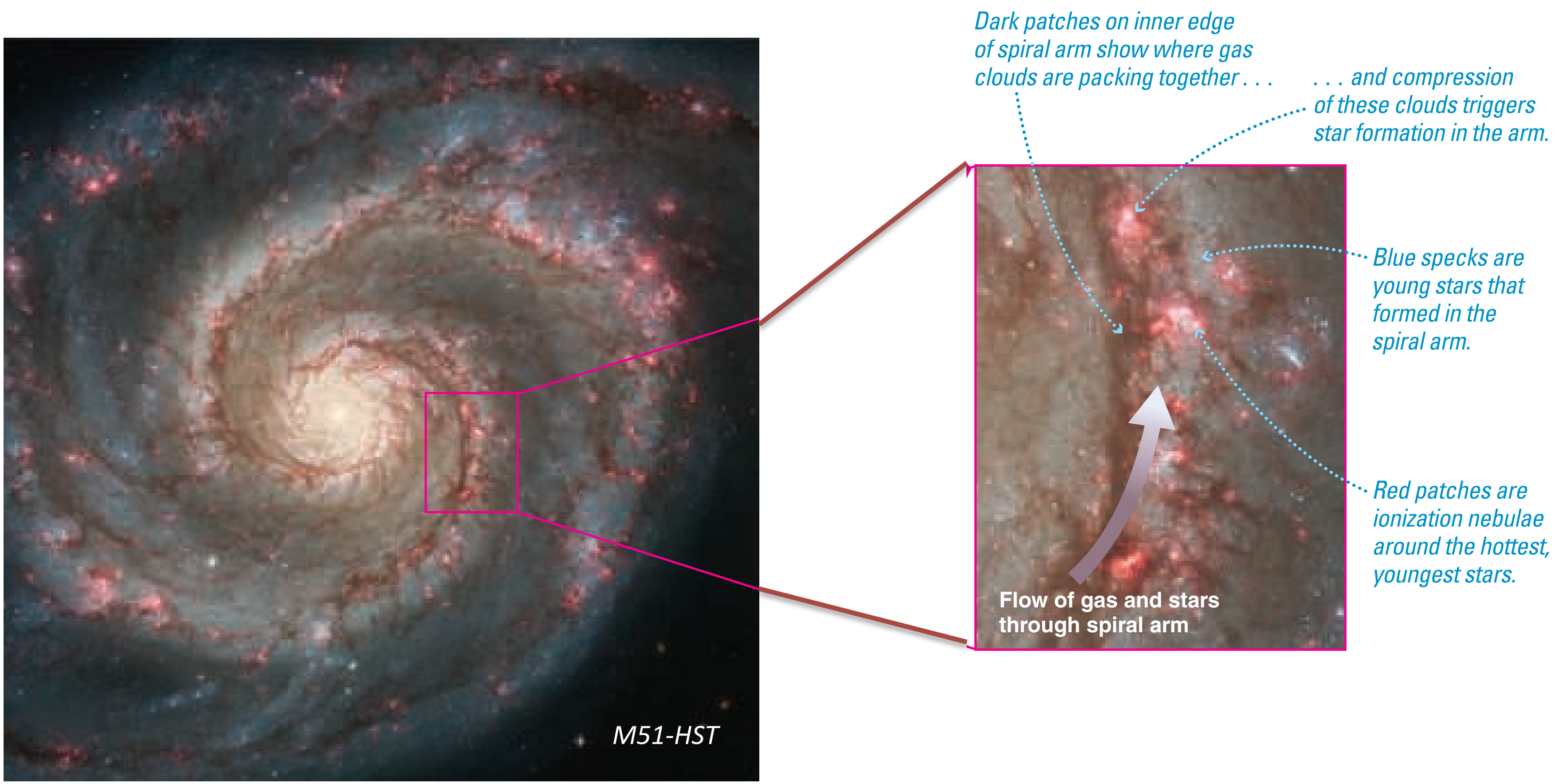


Star formation

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



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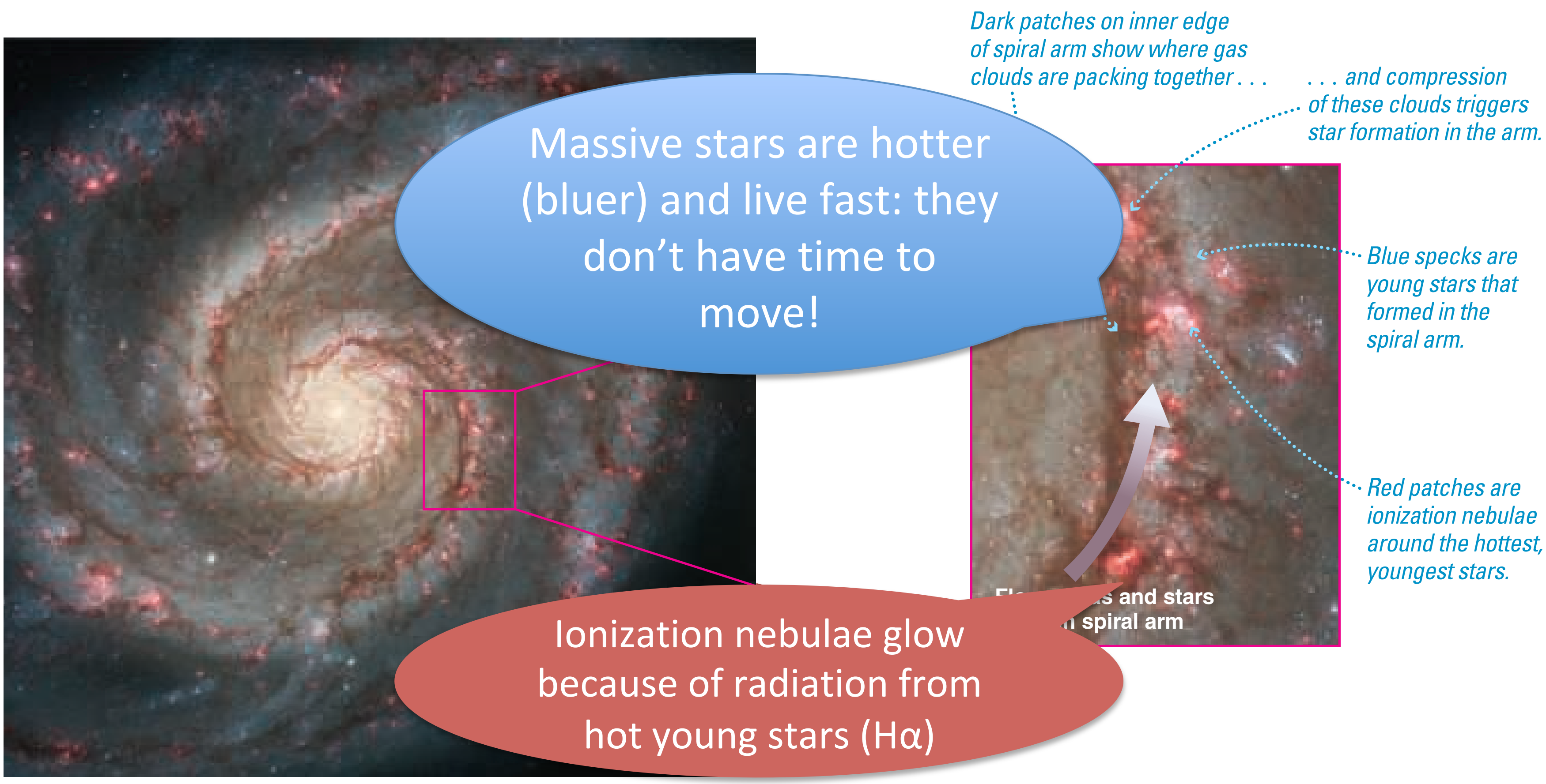

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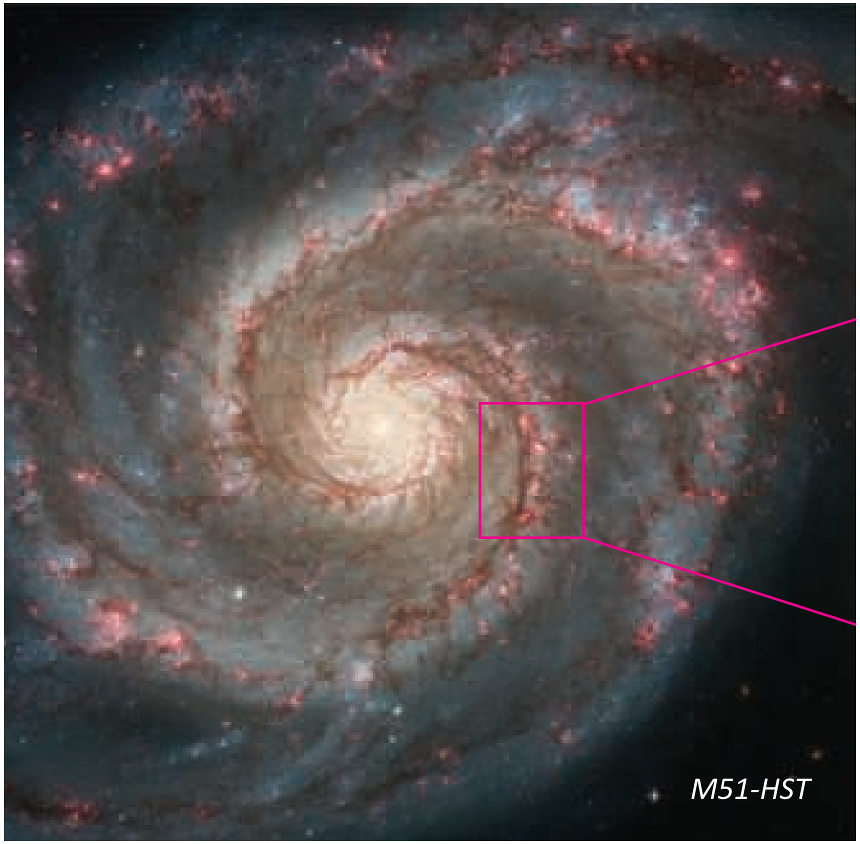


Schmidt-Kennicut law

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

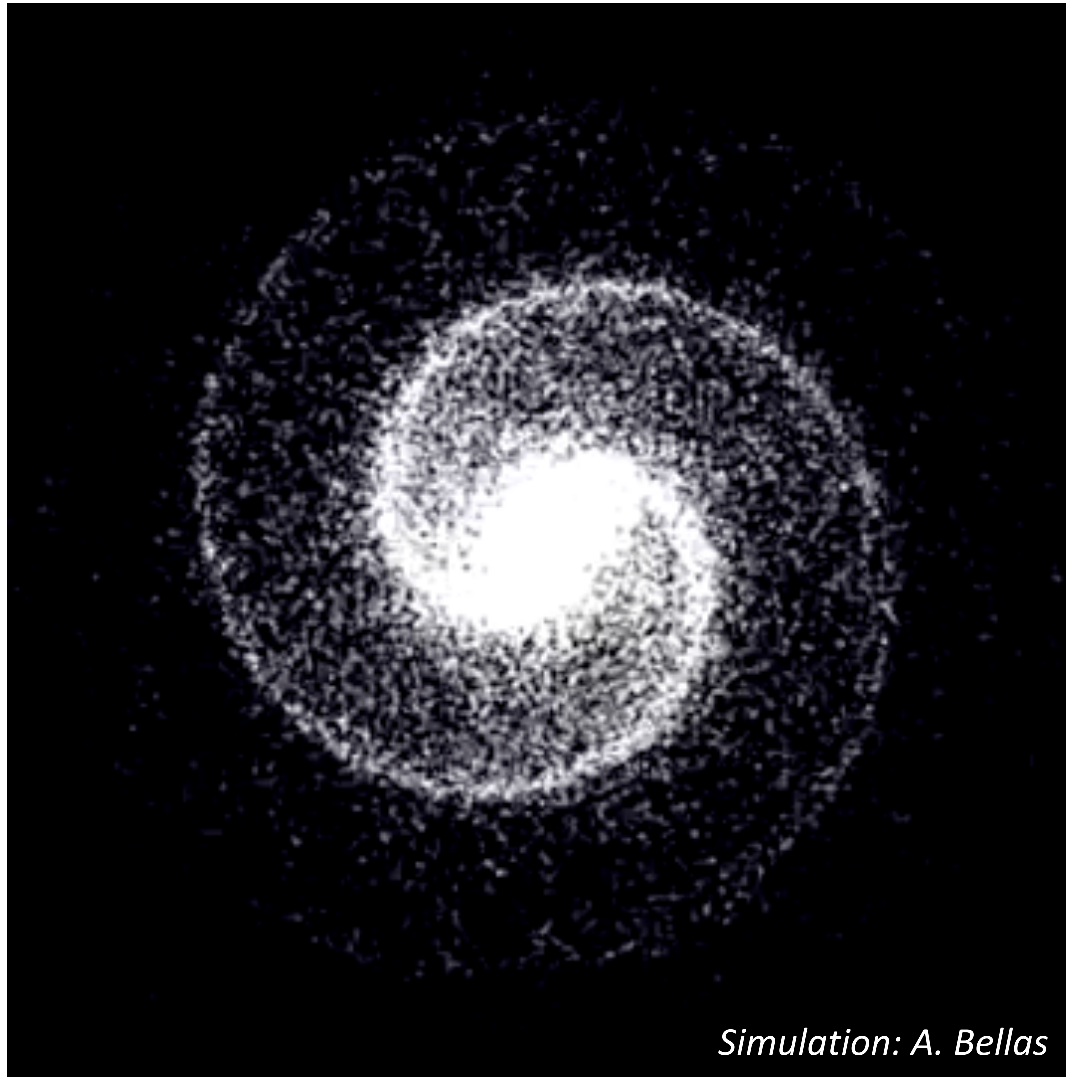
Star formation rate (M/yr) is proportional to gas density

Milky Way forms 1 solar mass per yr

Star migration

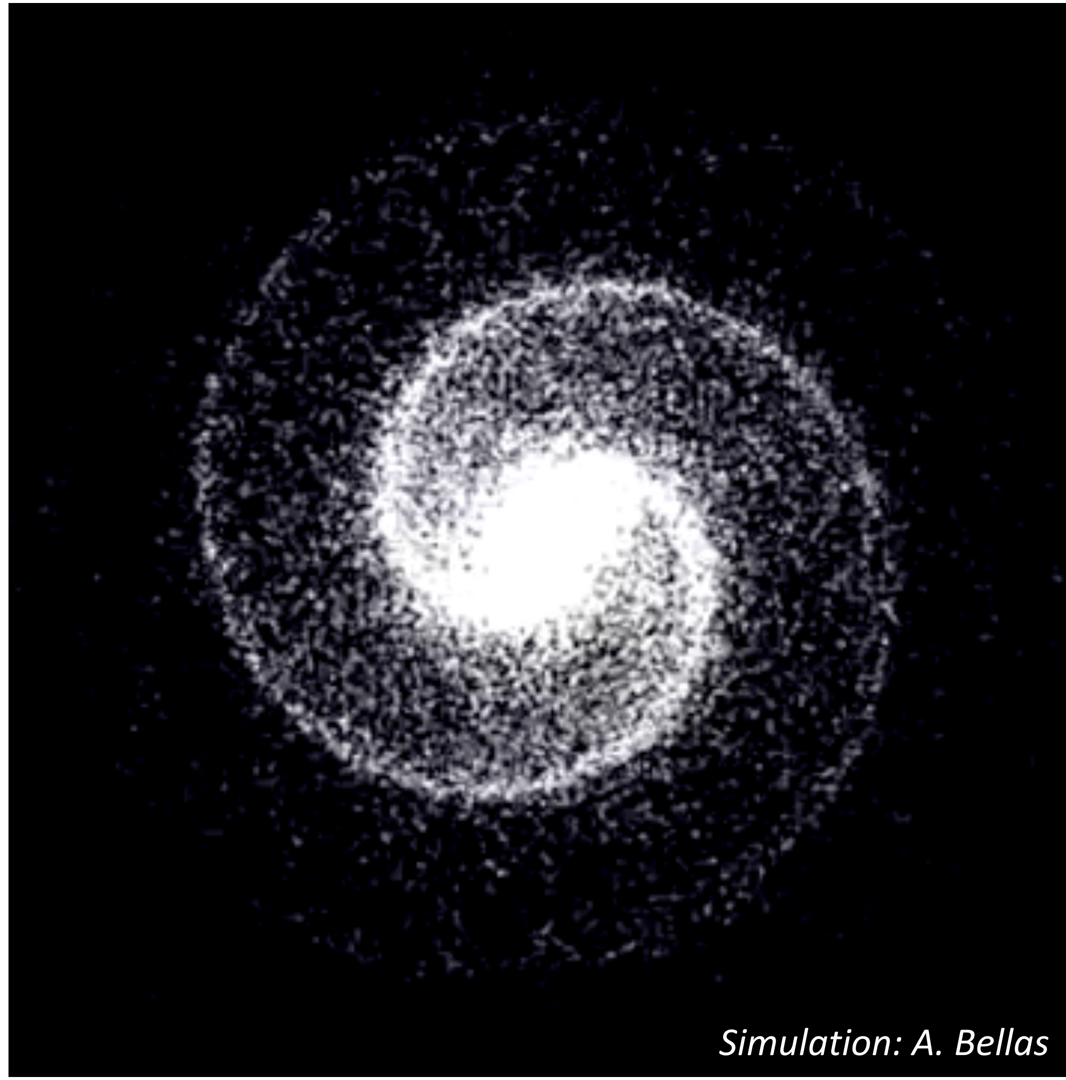
Older stars can move away off their birthplace to the bulge or the halo

Milky Way rotation



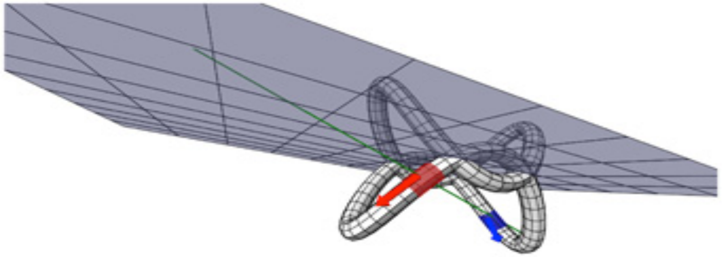
Milky Way rotation

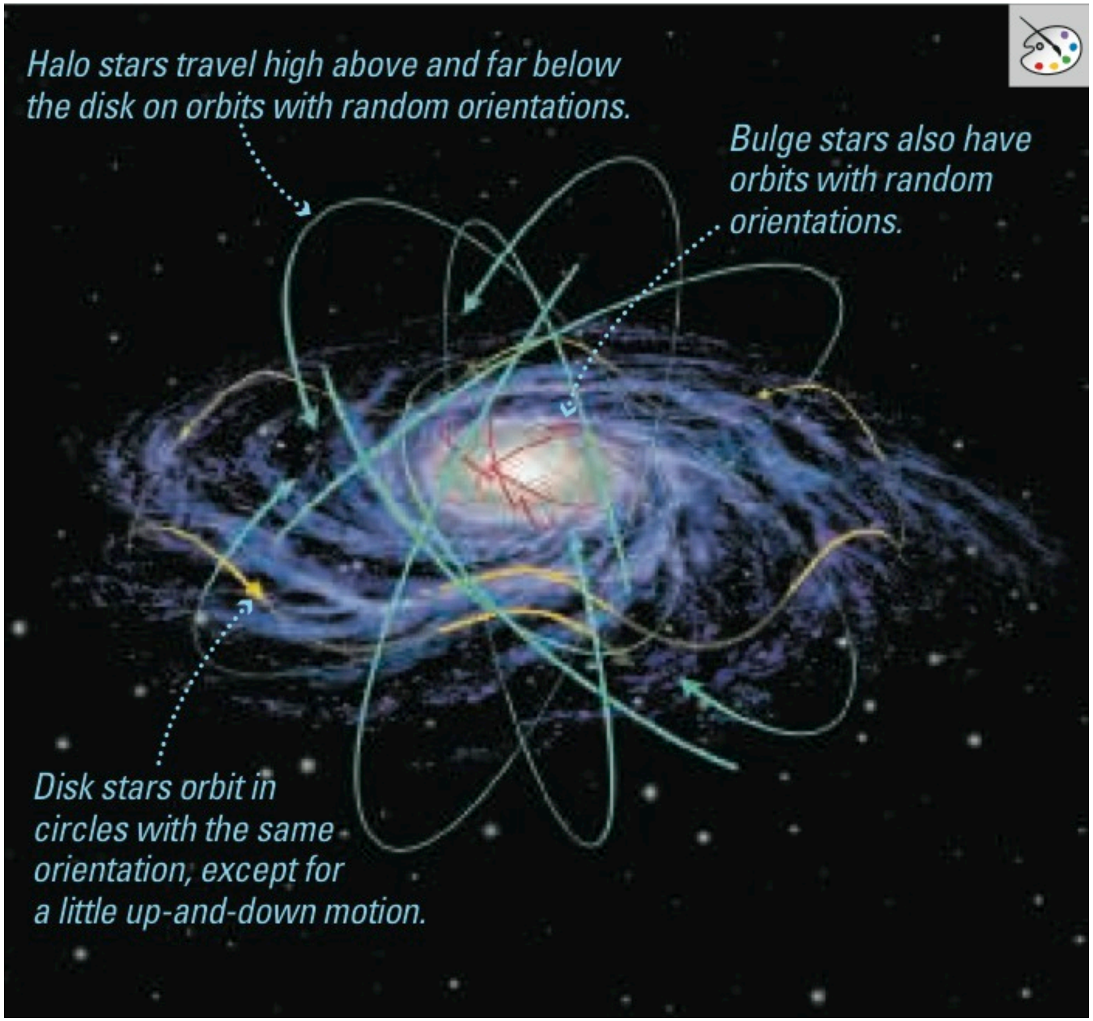
- Orbital velocities of stars closer to the center are similar to stars farther
- Spiral arms are not rigid: spiral density waves
- In the spiral arms, stars and gas move more slowly: denser regions
- Sun orbits at 220km/s and takes about 230 million years to do an orbit


Simulation: A. Bellas

Star orbits

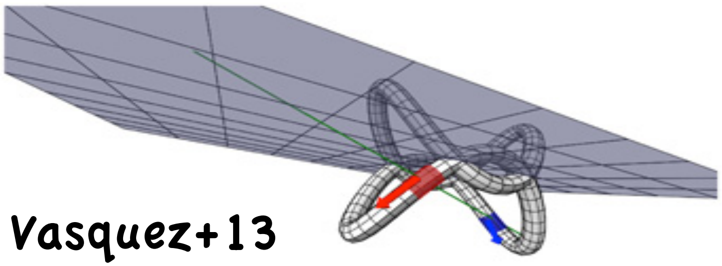
- Disk stars orbit in circles around center due to gravitational pull of center mass (period 200 million yrs)
- Disk stars wobble in the vertical direction due to gravitational pull of disk mass (period 10 millions yrs)
- Halo stars have random orbits around center with large heights
- Bulge stars seem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



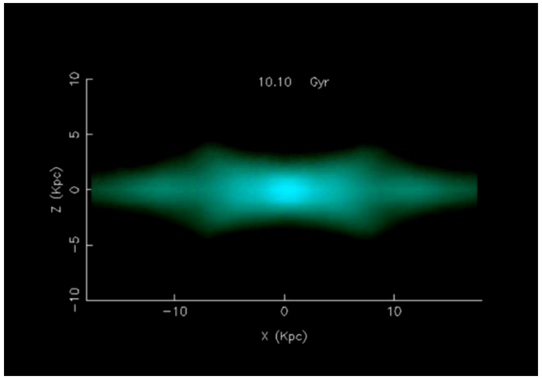


MW bulge: X-shape

Bulge stars seem to have "banana-shape" orbits



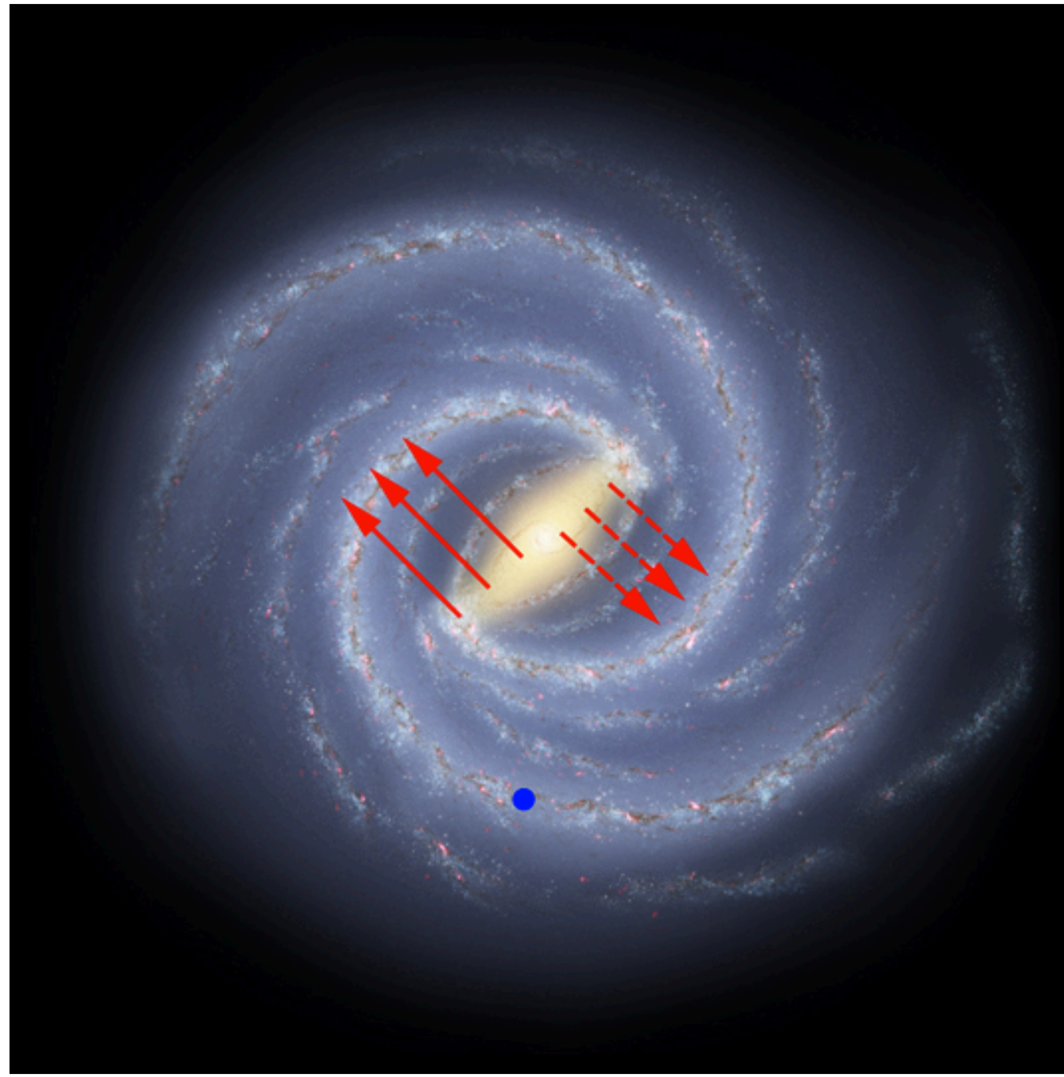
Vasquez+13



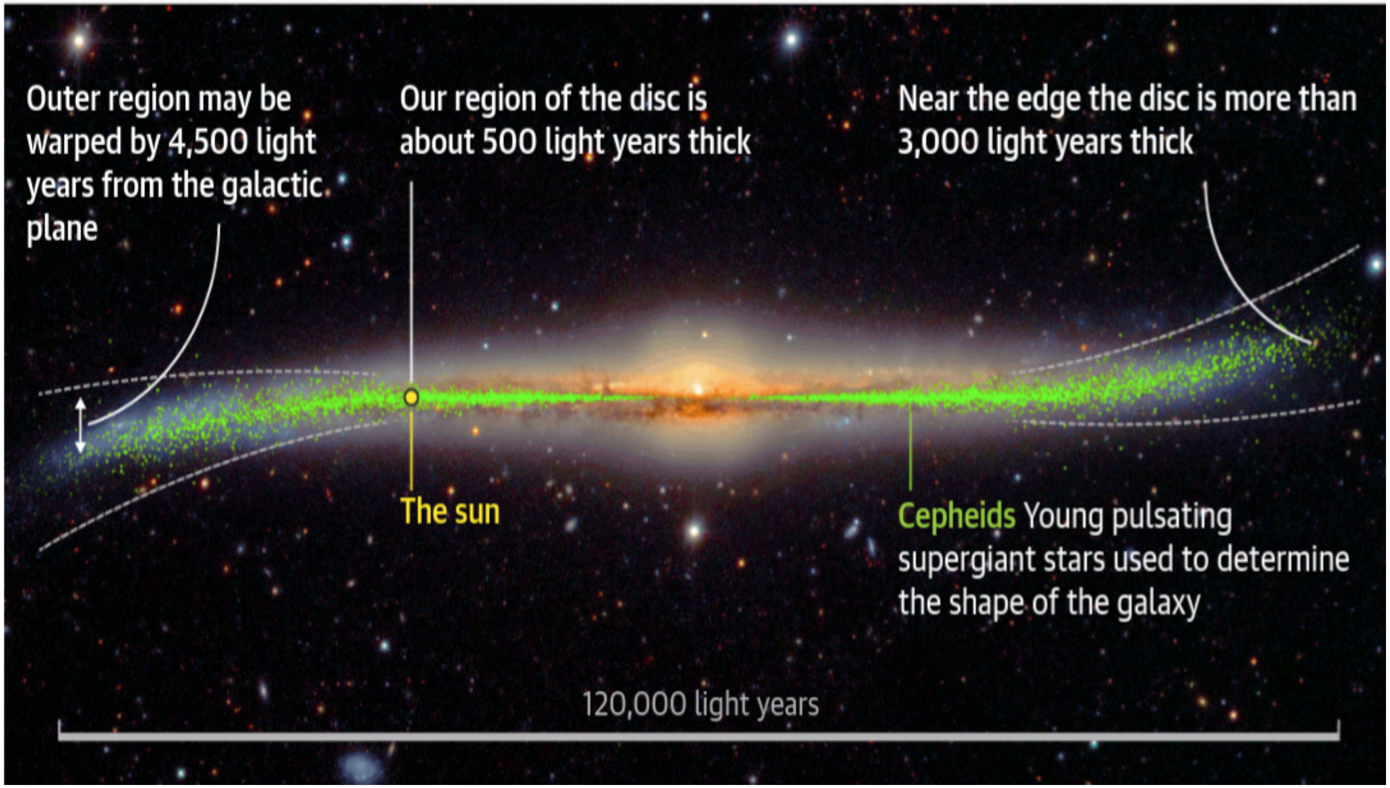
X-shape bulge

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

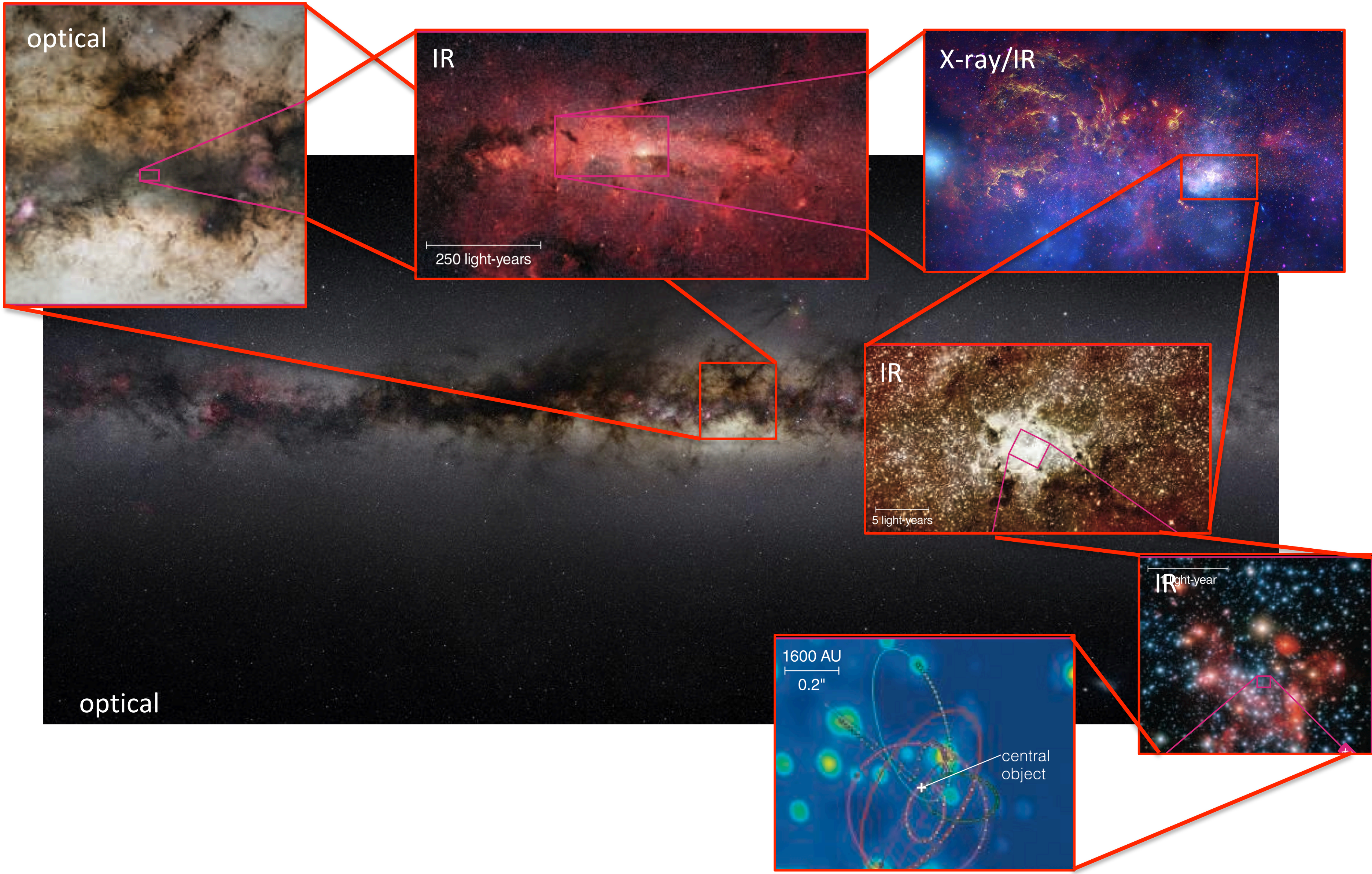


- Warped disk (Skowron+19)
- Precesses due to satellite galaxy (Poggio+20)

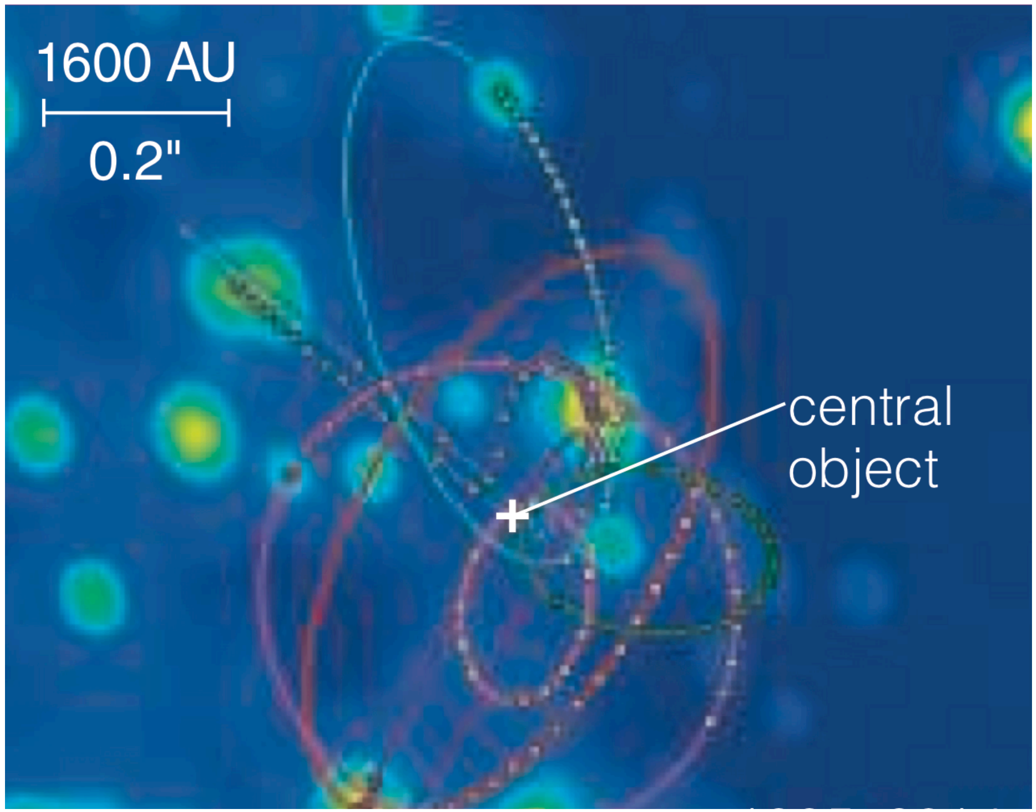
Galactic Center

Galactic Center

Galactic Center



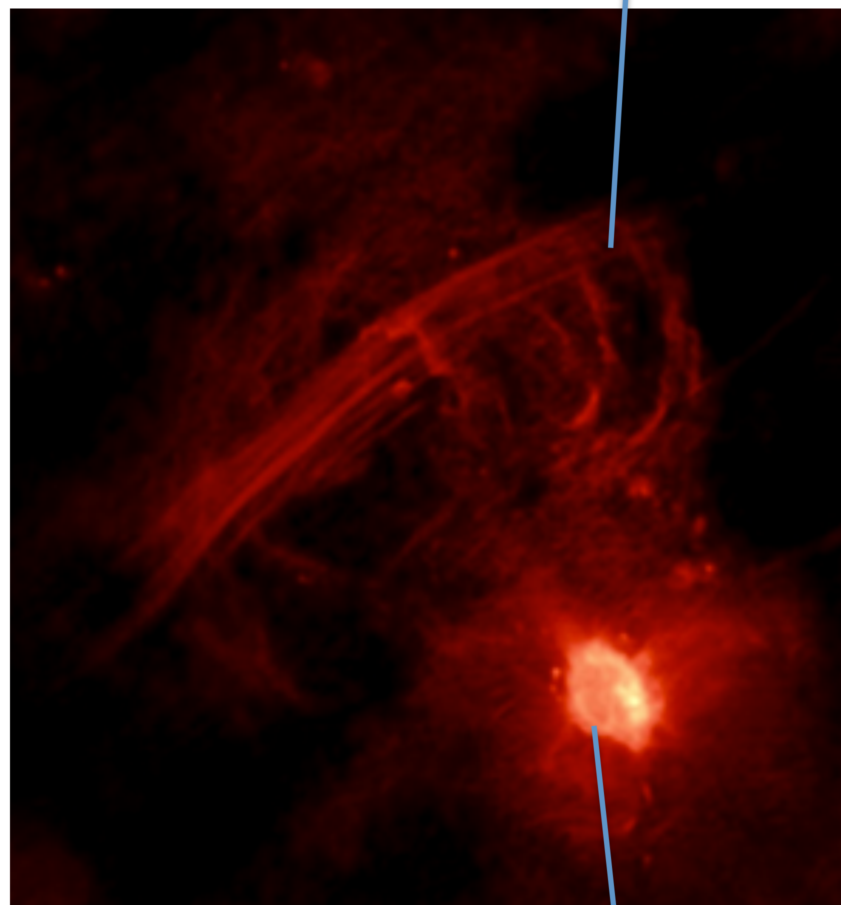
Galactic Center



Galactic Center

Galactic Center

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

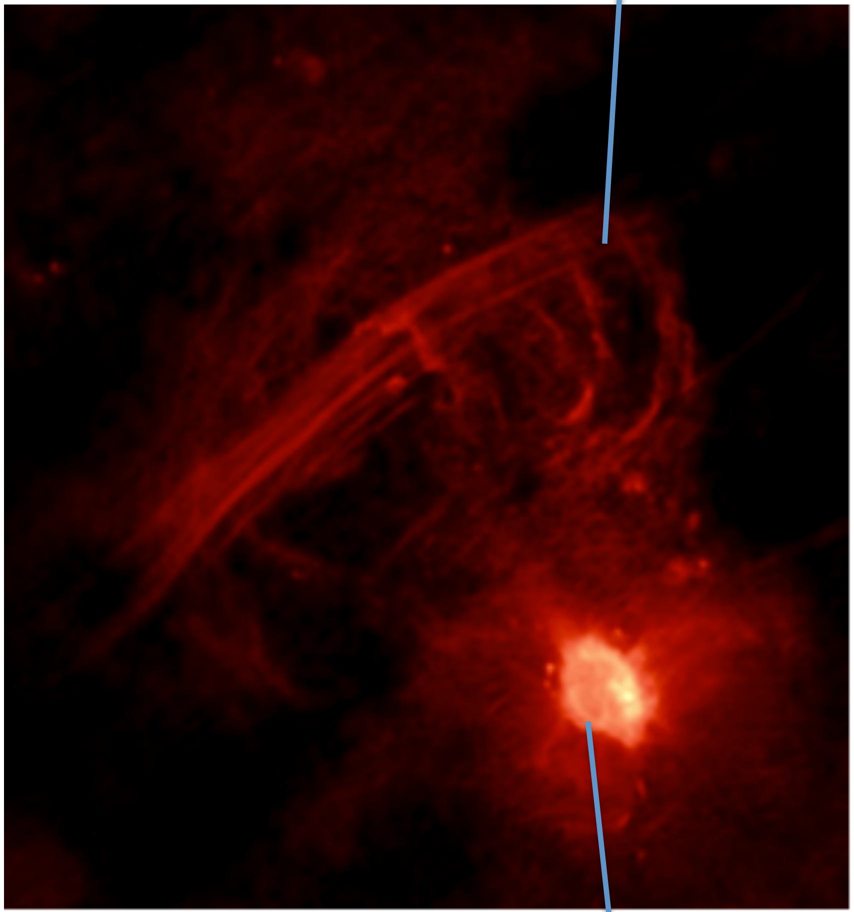


The center of our Galaxy, as seen in the radio.

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)



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

Galactic Center

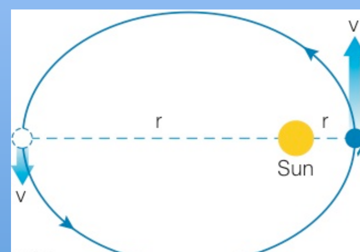
- Orbits
  a cen
- X-ray
  hot g
- Radio

➔ Supe
hole in the center
(4.0x10^6 solar masses)

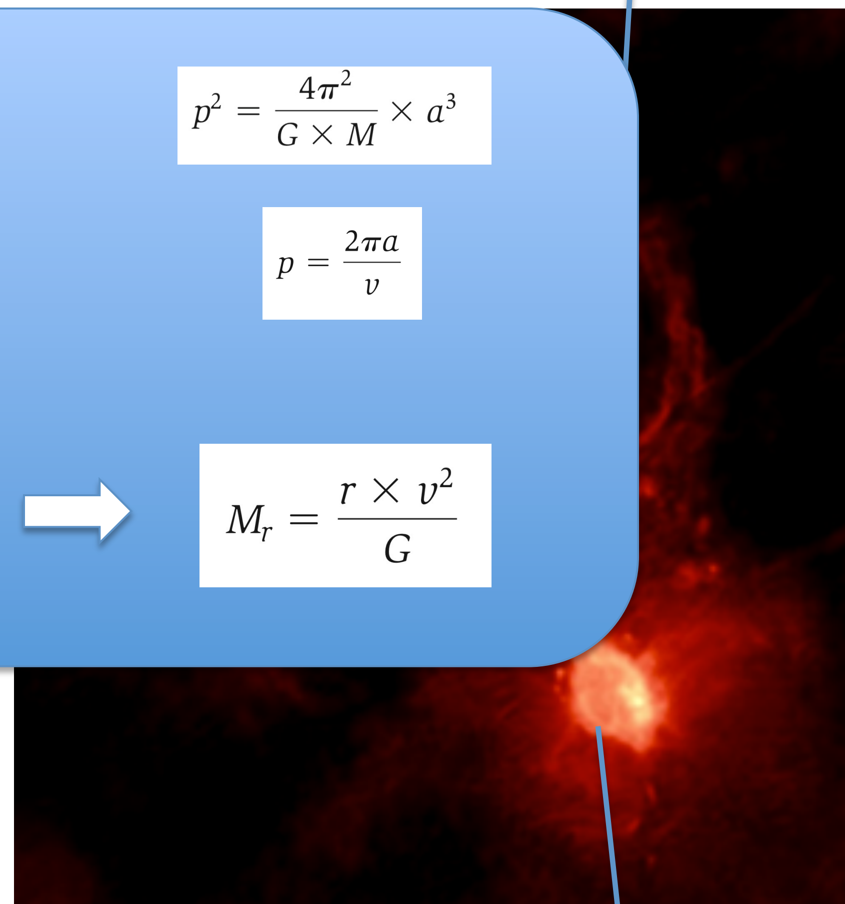
Newton's version of Kepler's laws:

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

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



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



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

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