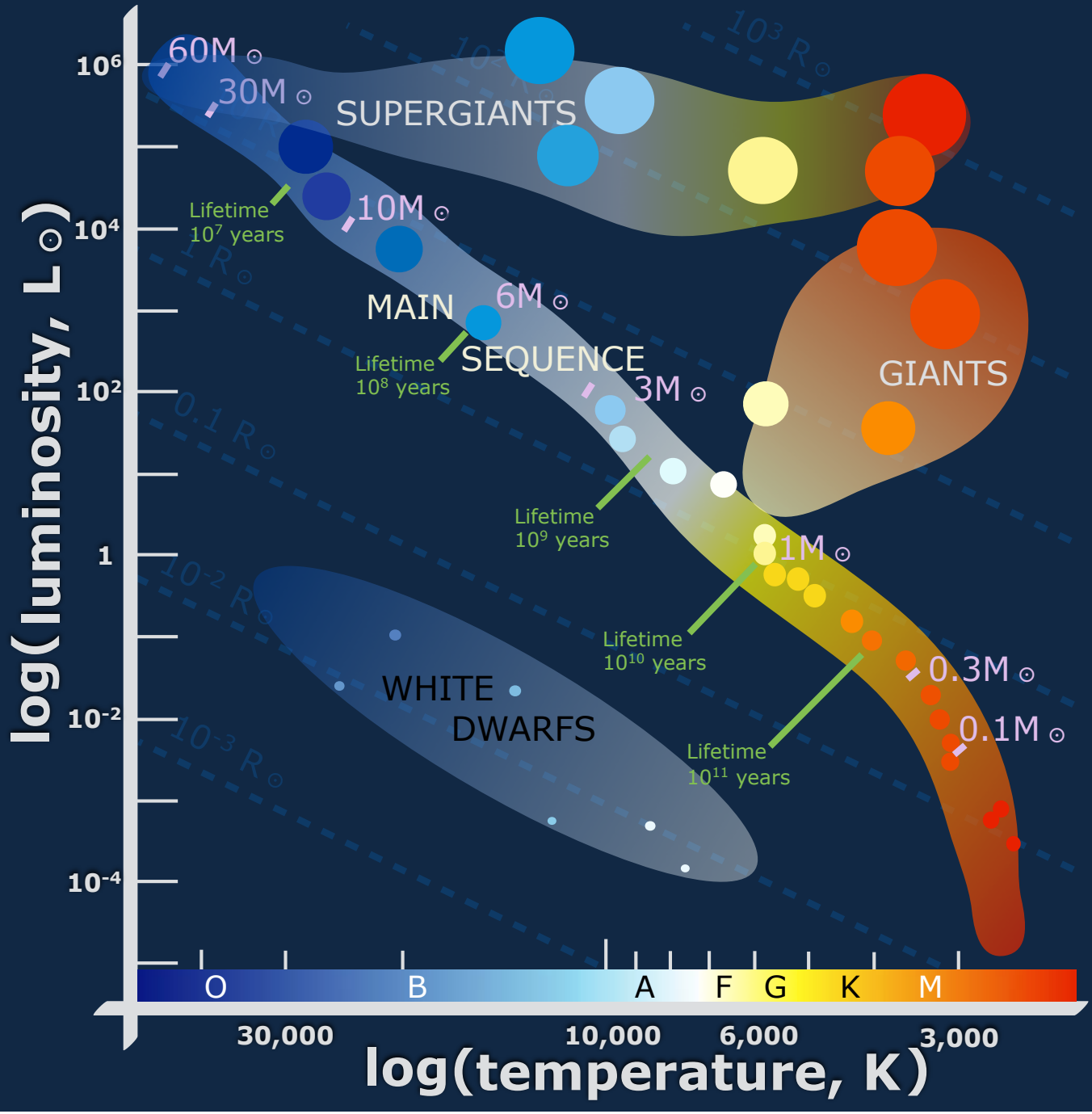
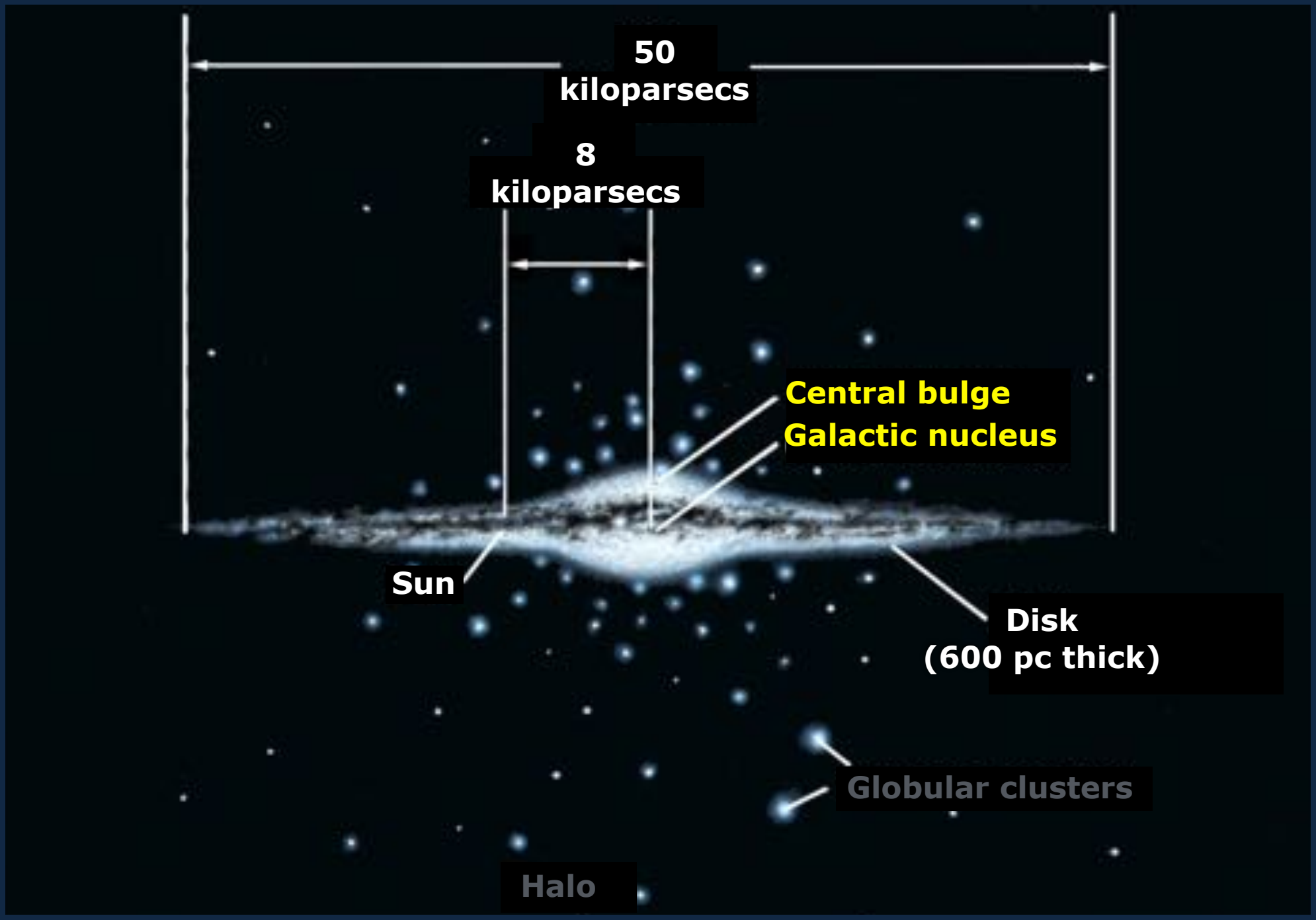
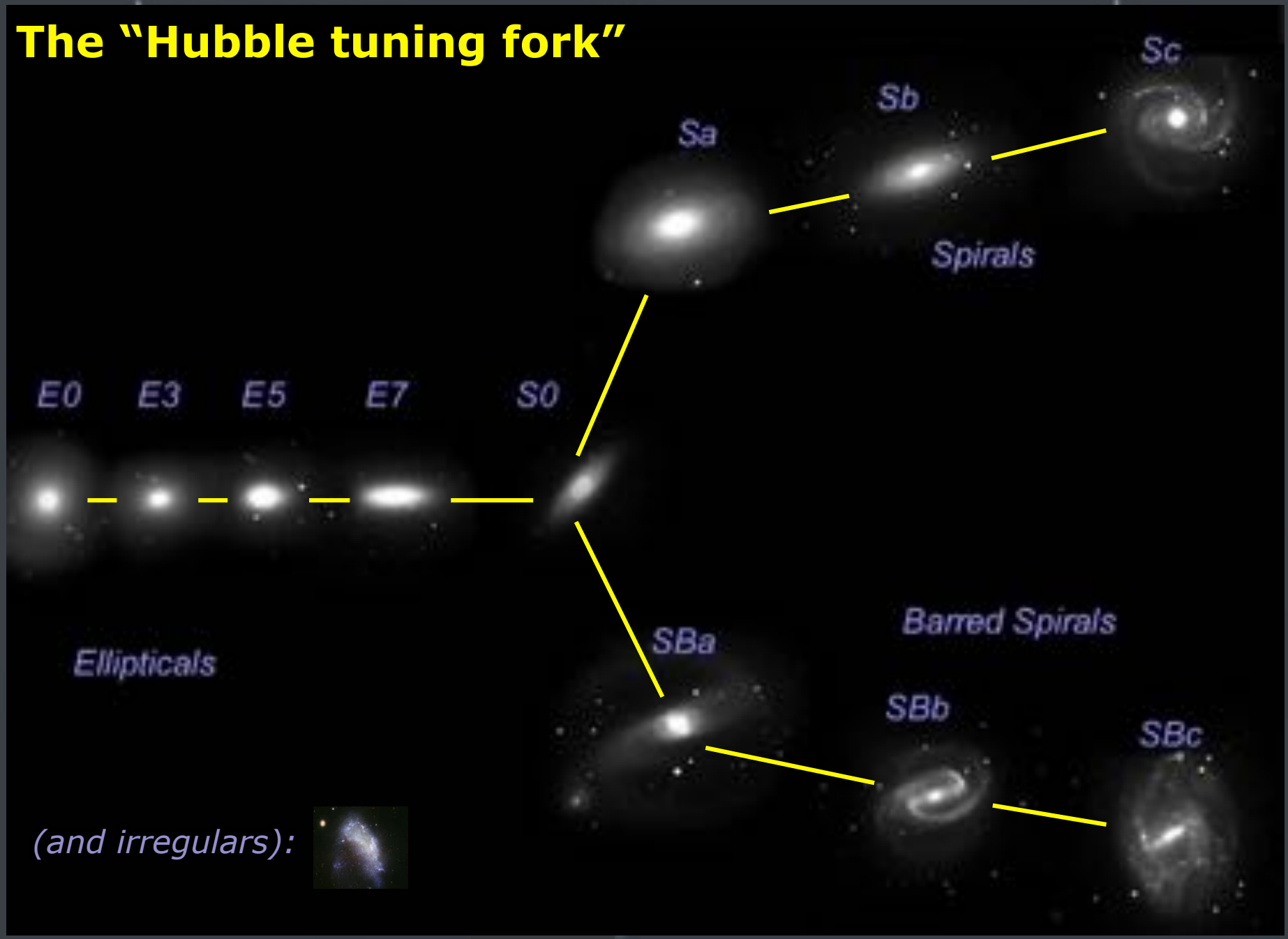
The Contents of Our Galaxy



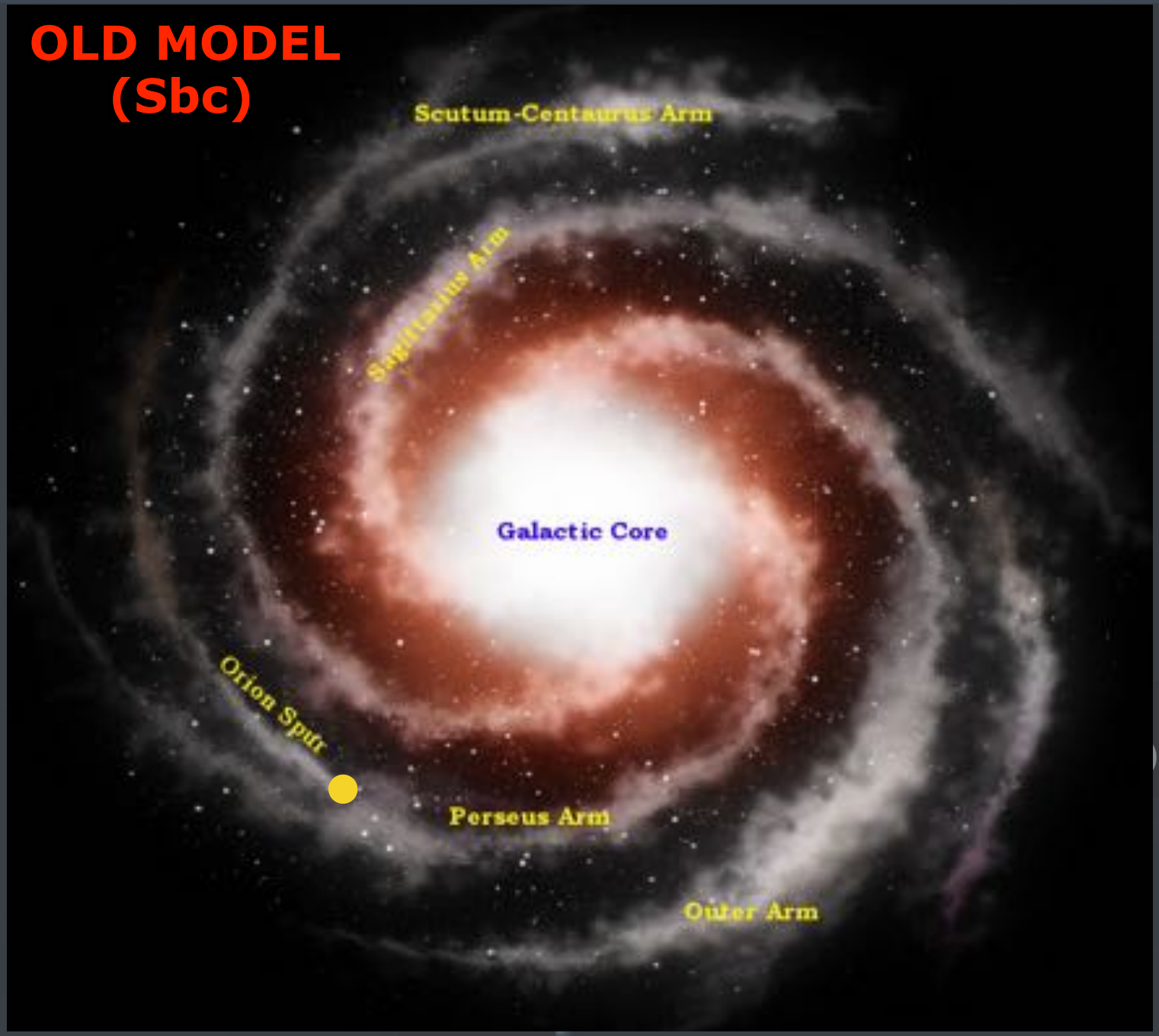
The Milky Way - Morphology



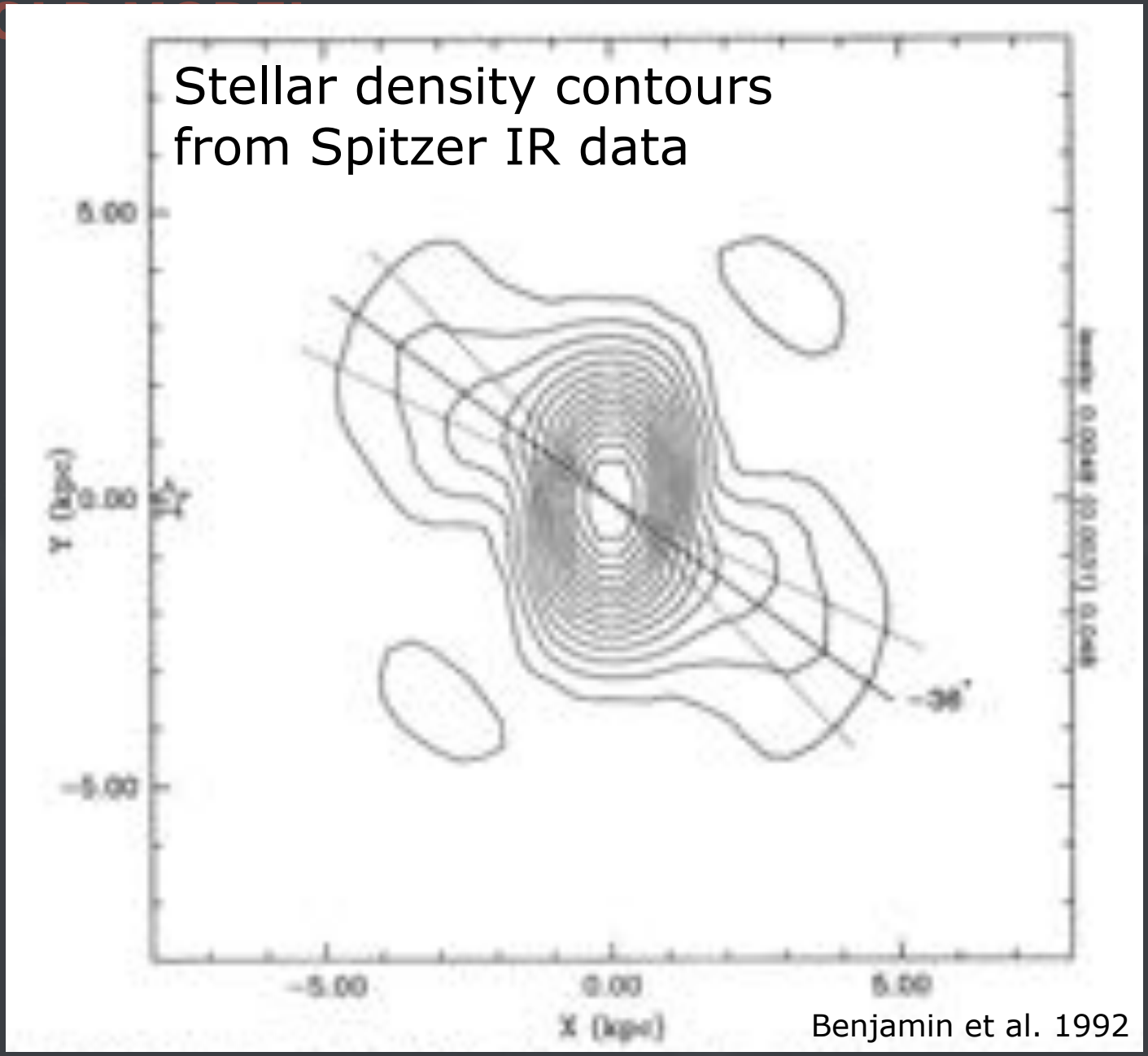
The Milky Way - Morphology



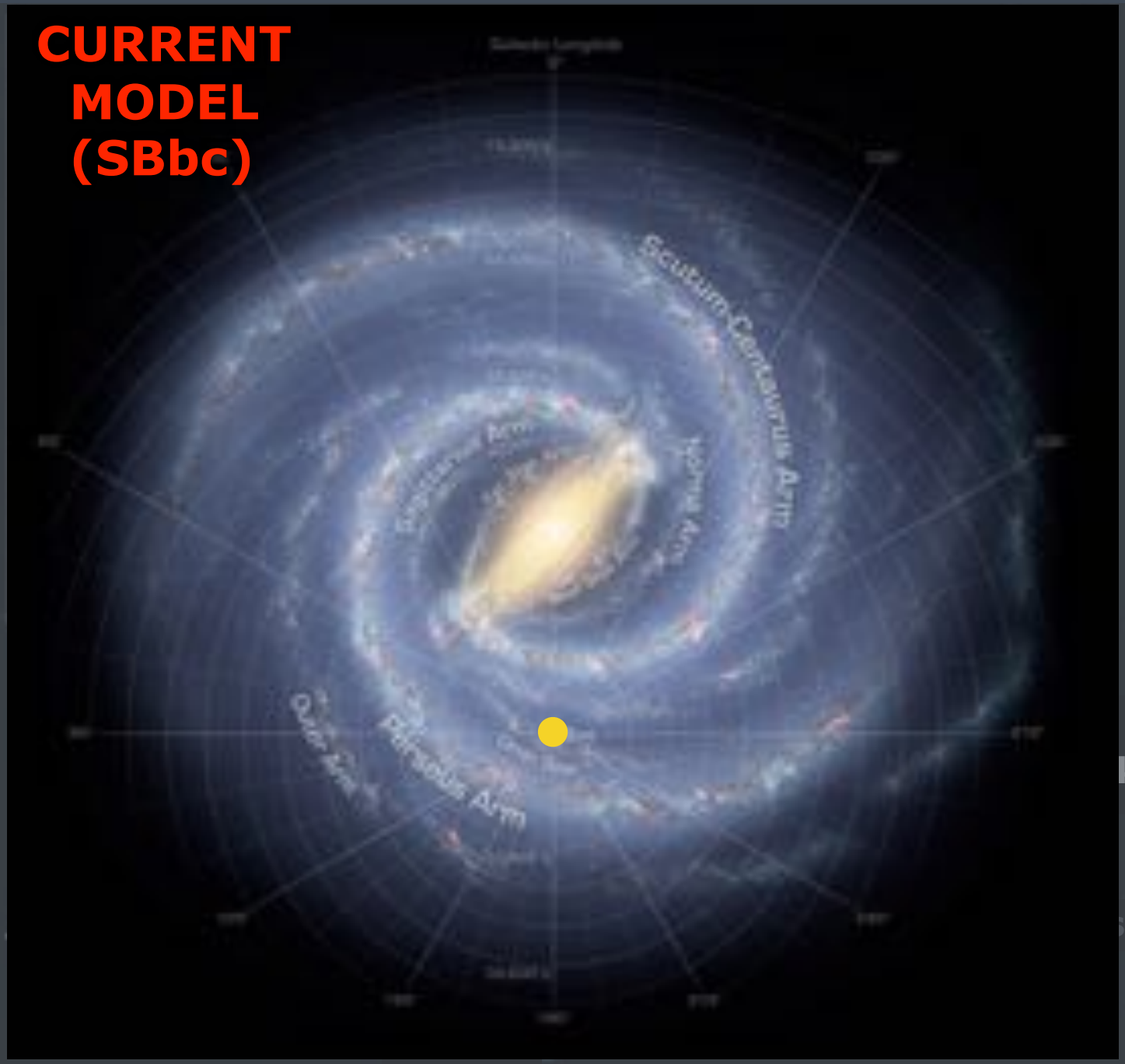
The Milky Way - Morphology



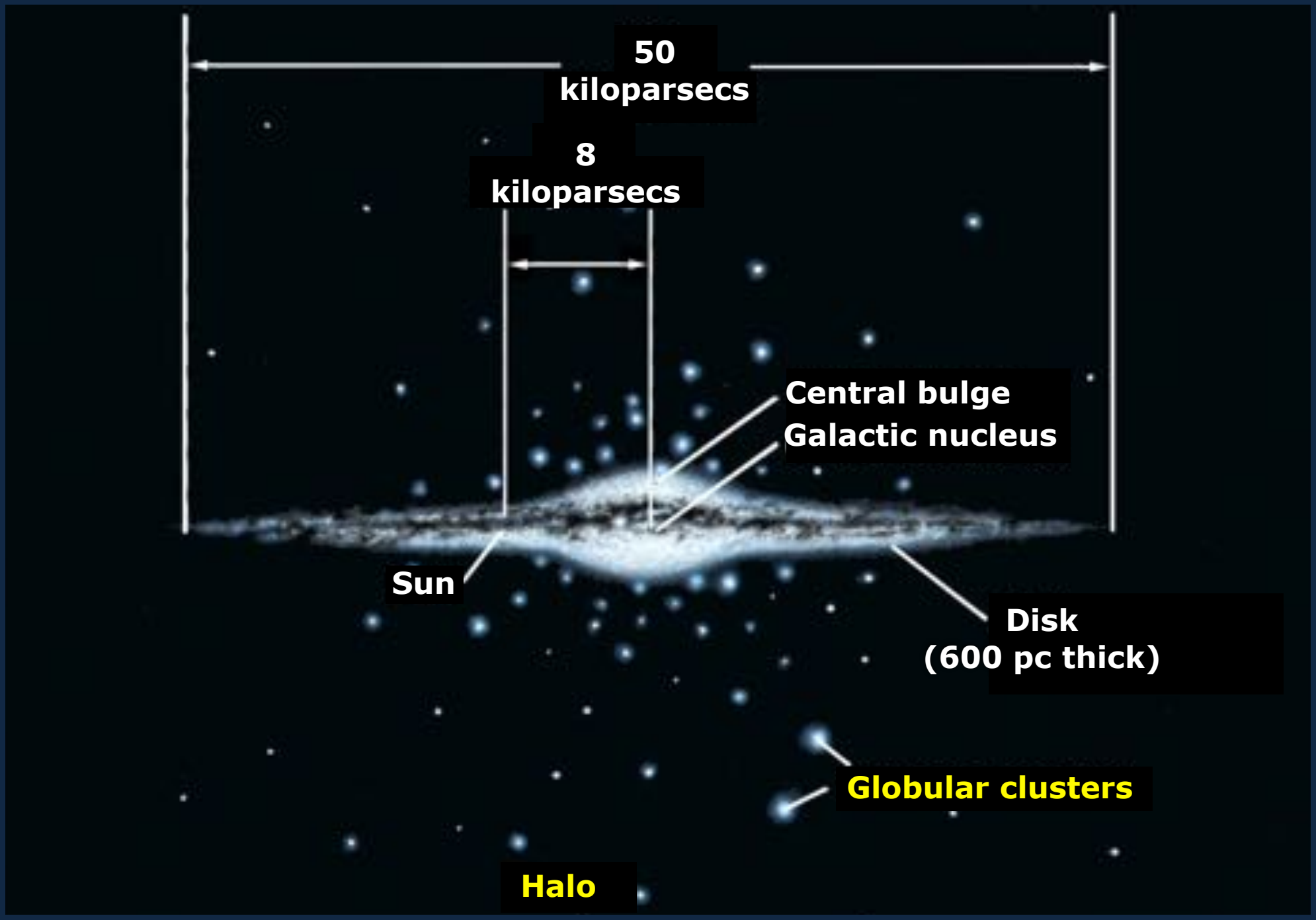
The Milky Way - Morphology



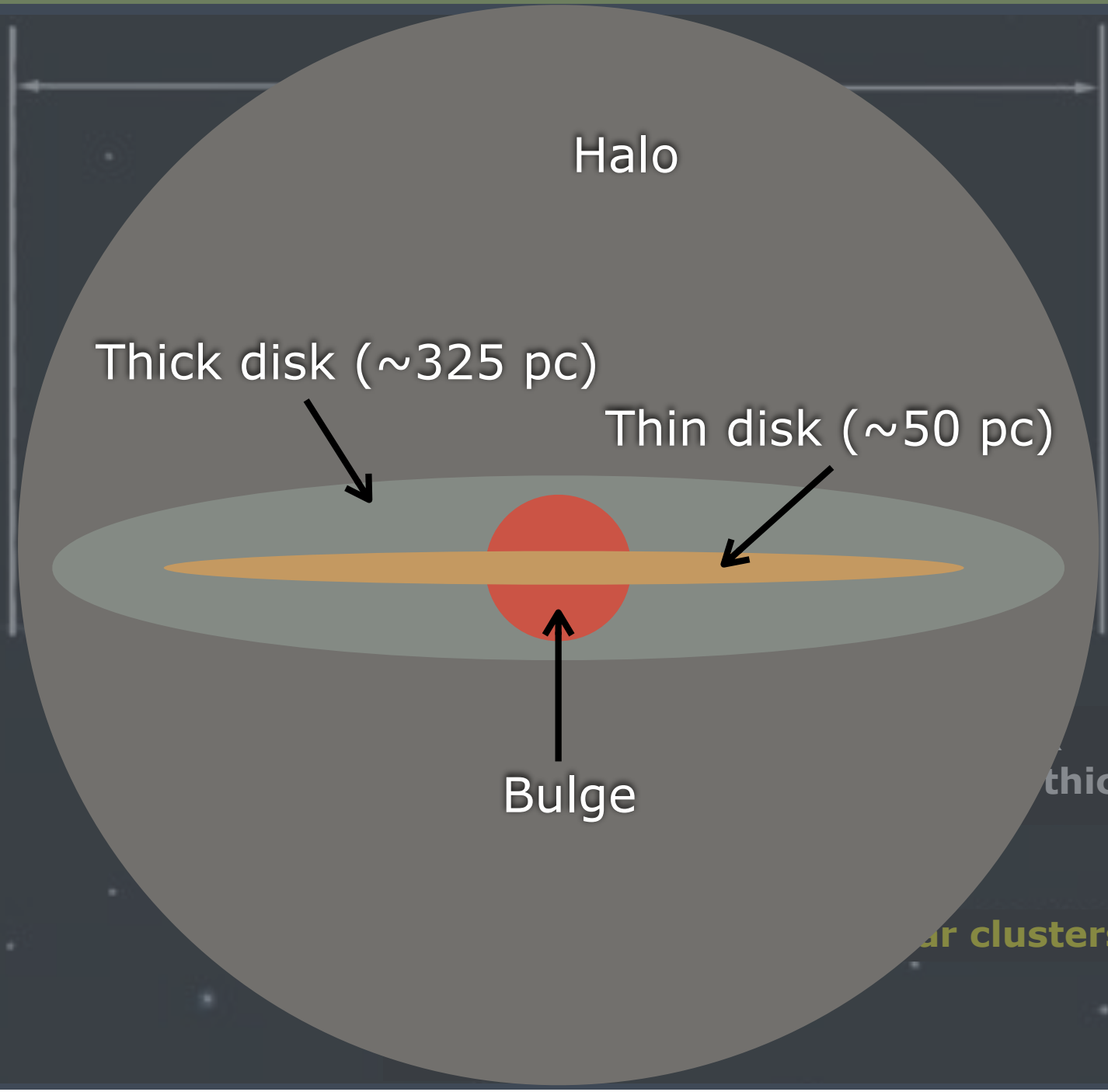
The Milky Way - Morphology



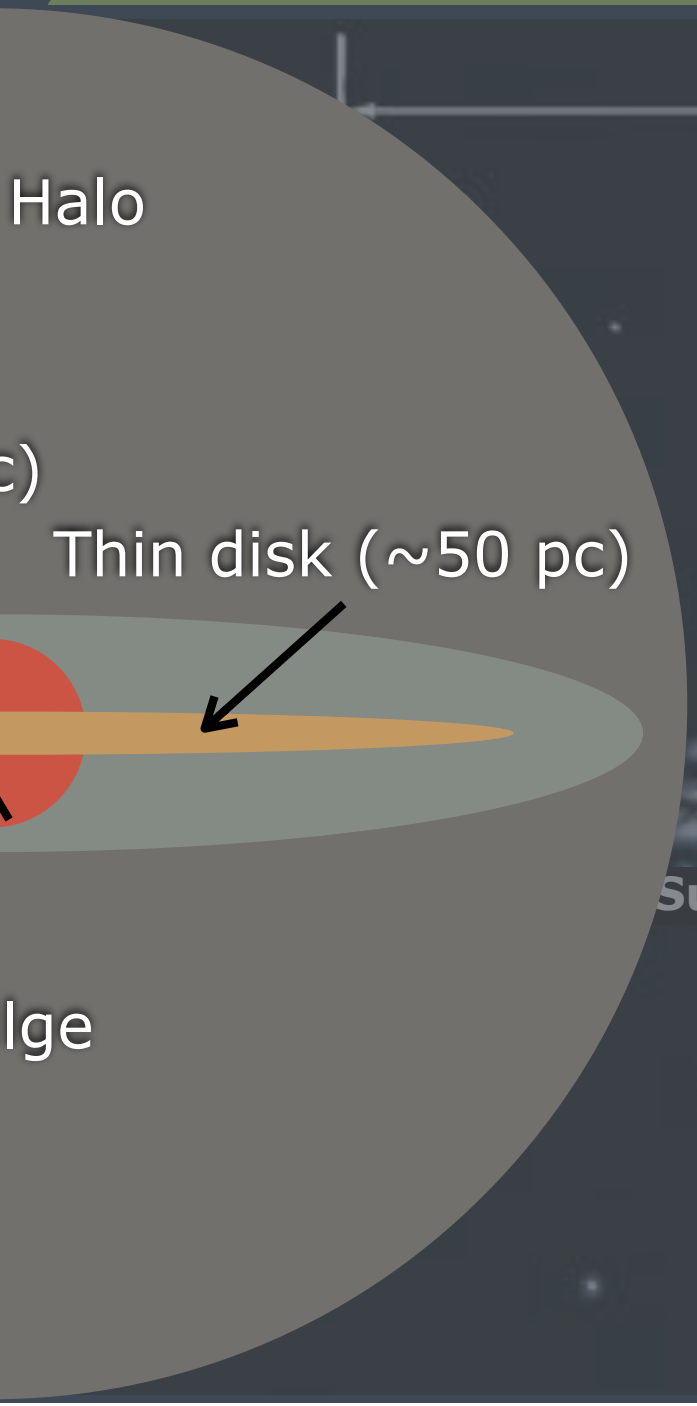
The Milky Way - Morphology

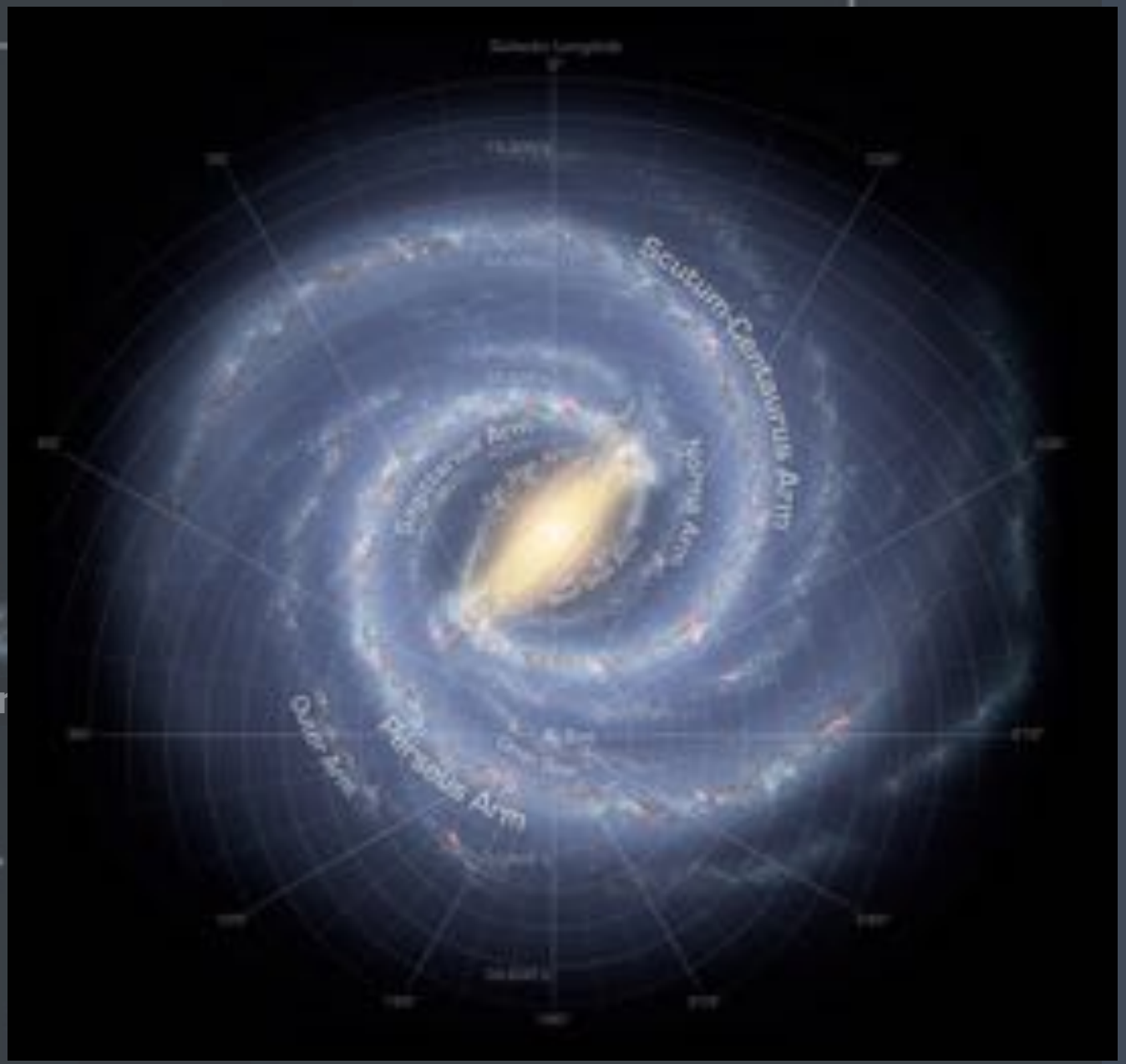


The Milky Way - Morphology



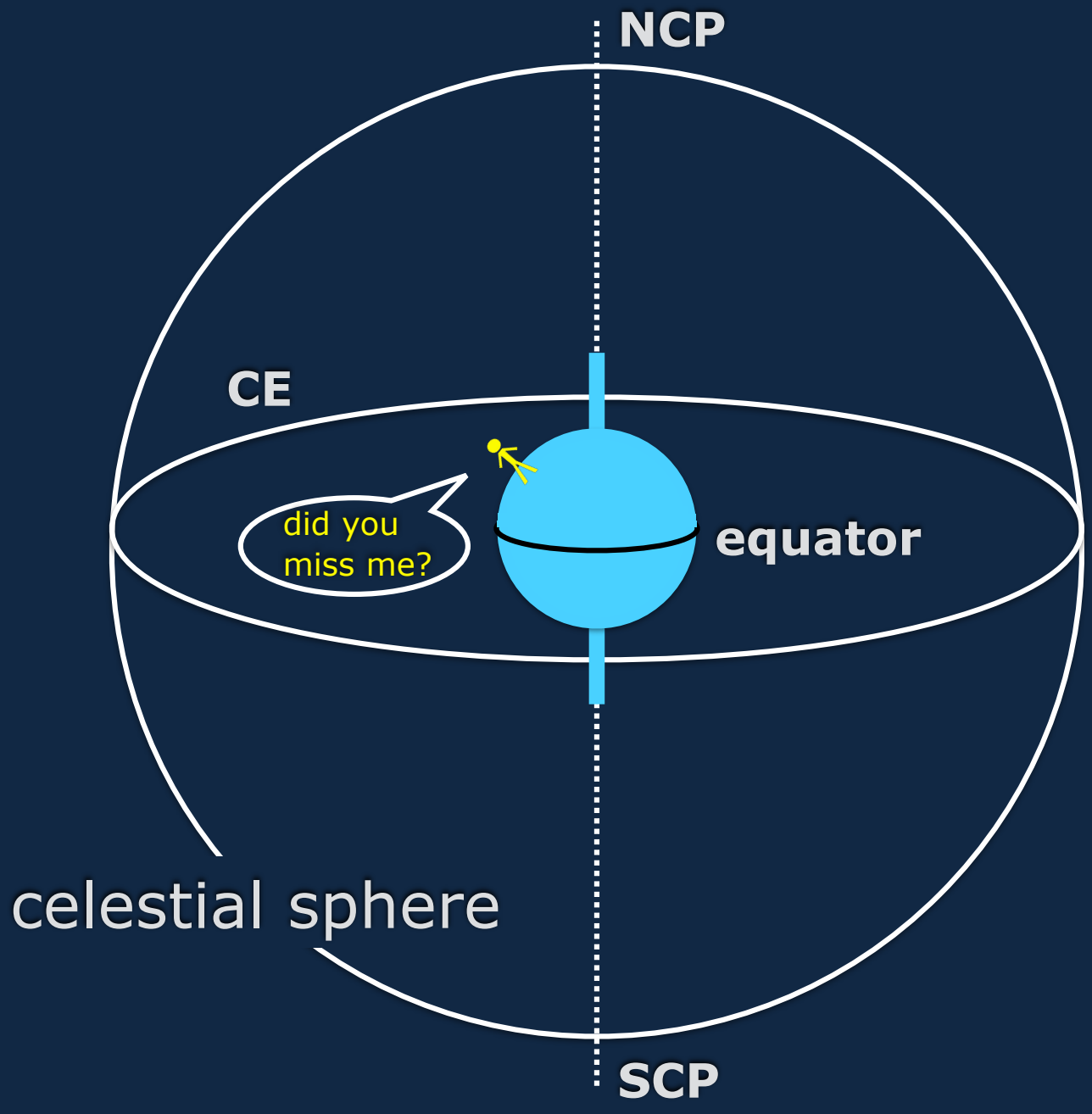
The Milky Way - Morphology



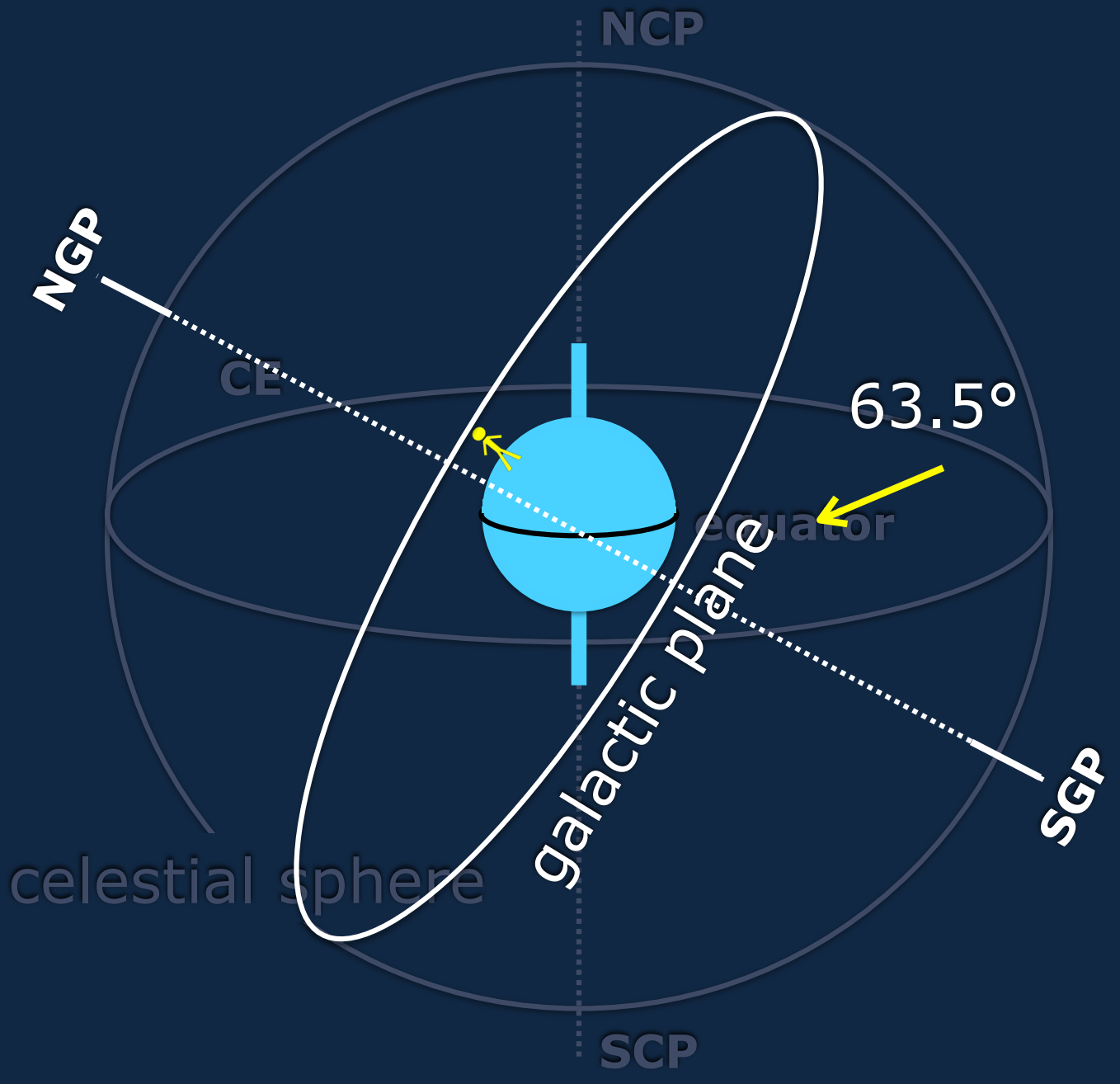


Halo

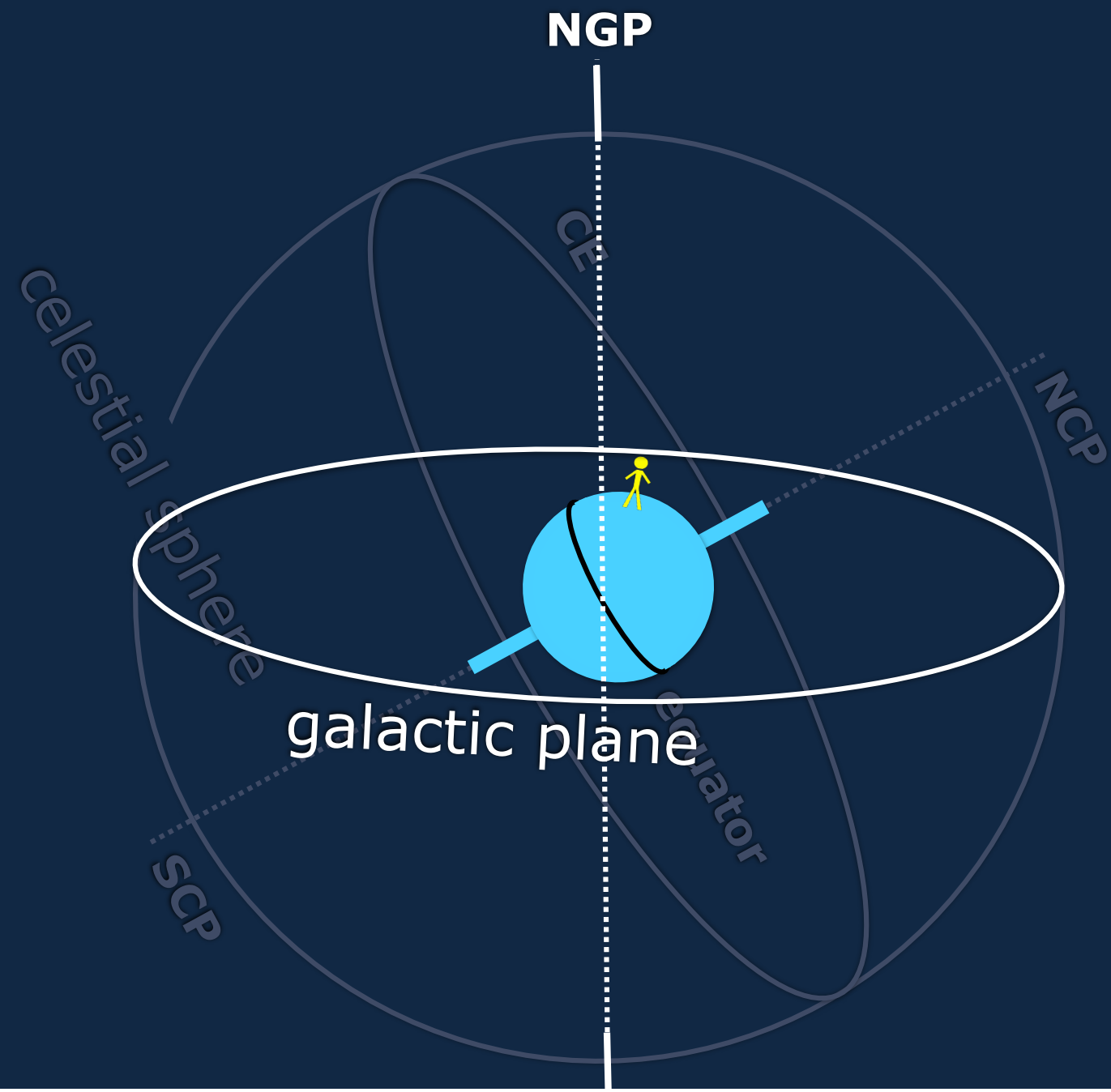
The Milky Way - Galactic coordinates



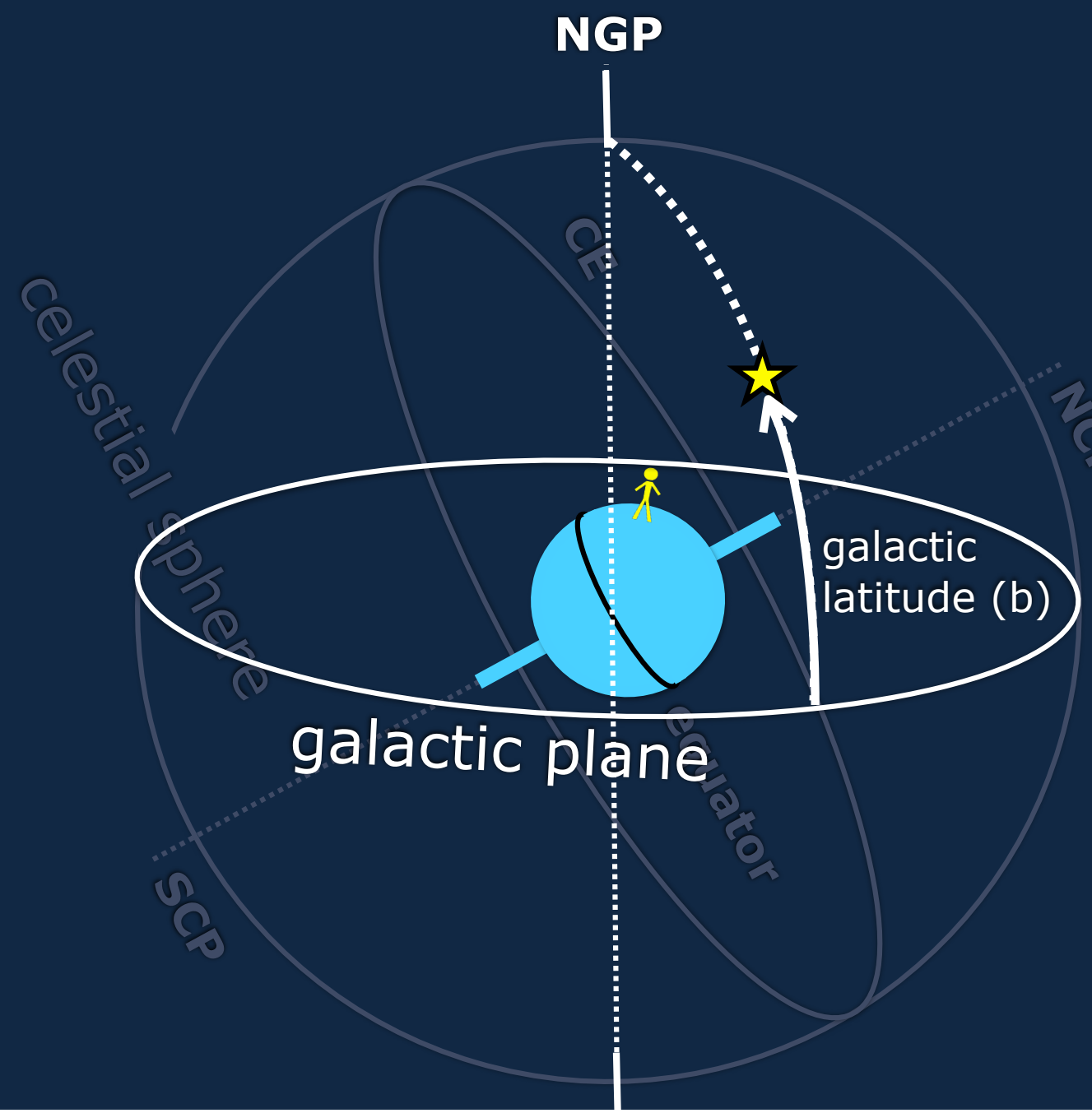
The Milky Way - Galactic coordinates



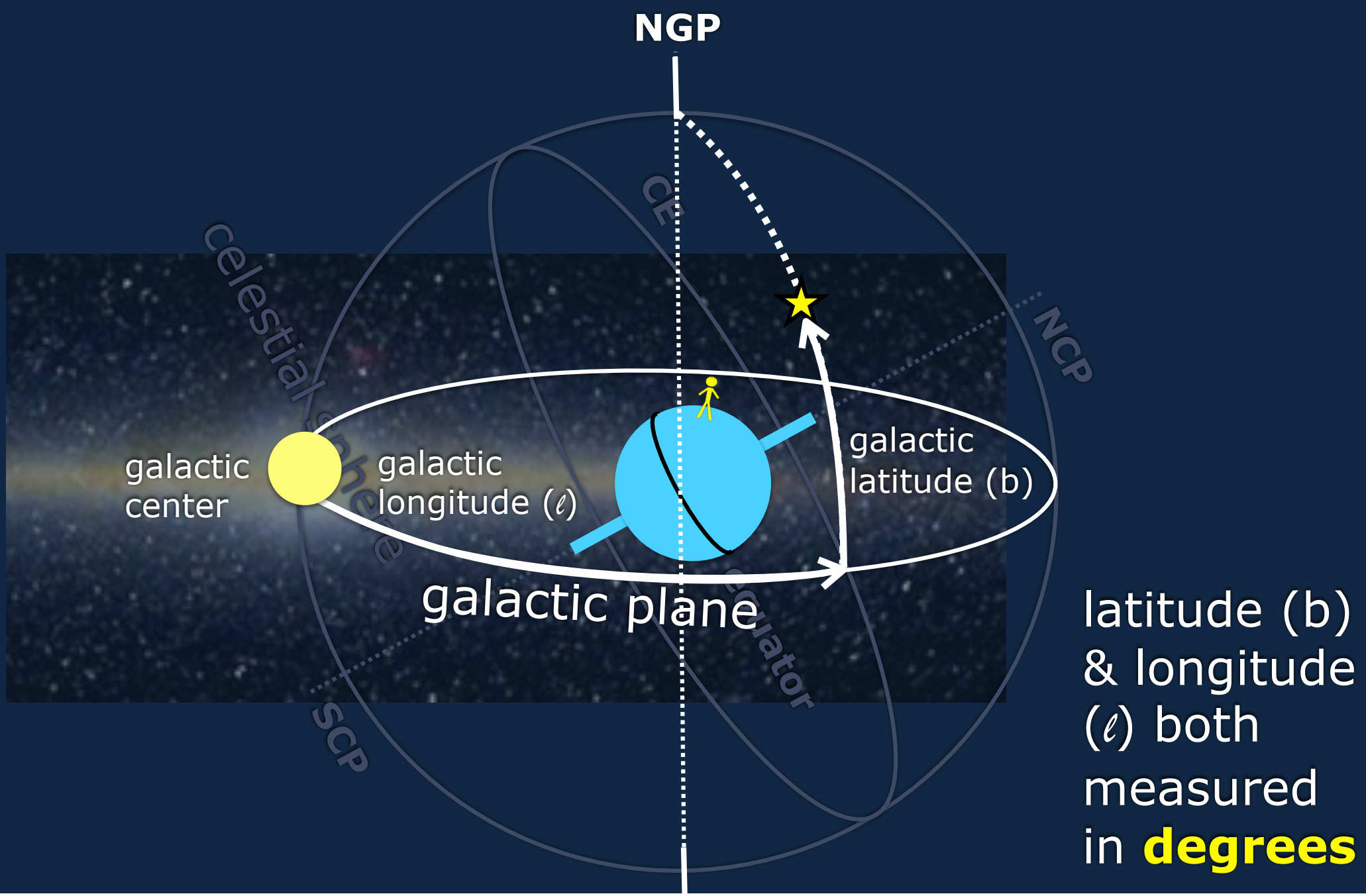
The Milky Way - Galactic coordinates



The Milky Way - Galactic coordinates



The Milky Way - Galactic coordinates



latitude (b) & longitude (ℓ) both measured in **degrees**

The Milky Way - Galactic coordinates

Quick Question

Which hemisphere(s) were these photos taken in?

A) X is South, Y is North

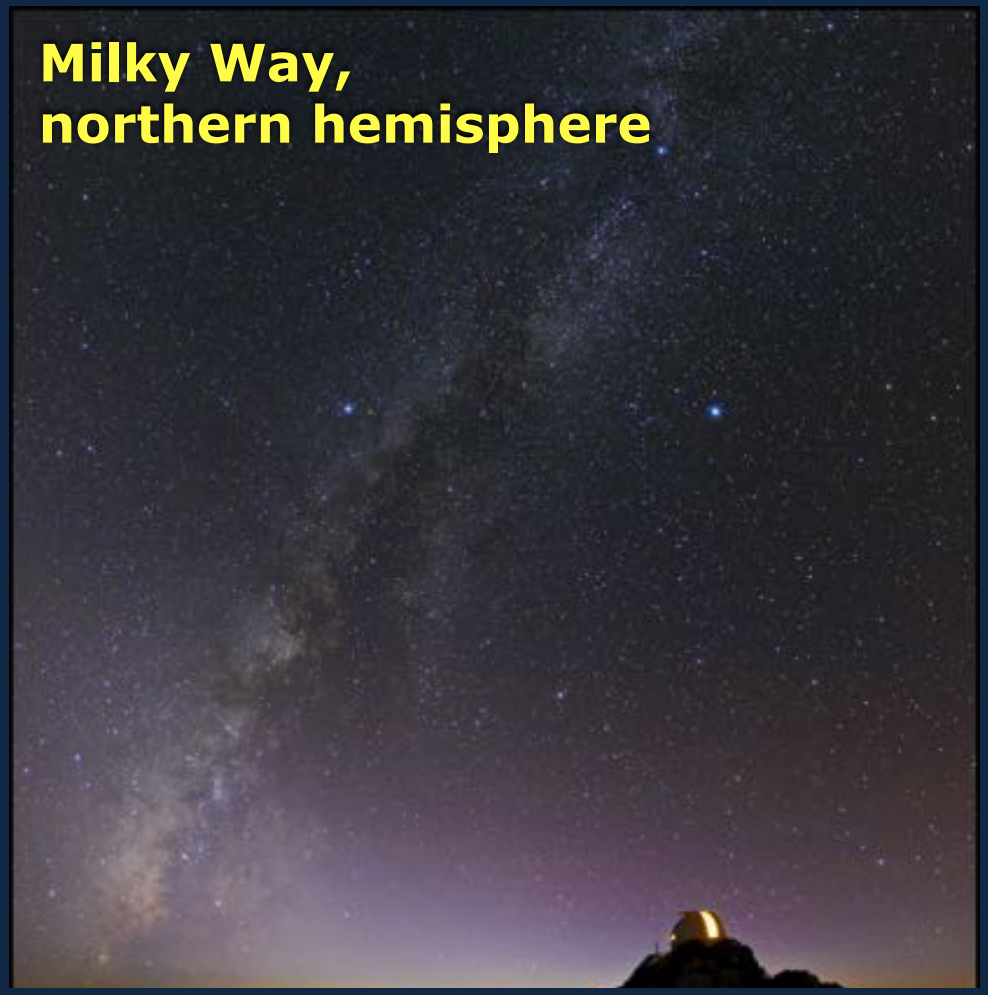
B) X is North, Y is South

C) both are South

D) both are North

The Milky Way - Galactic coordinates

Southern hemisphere faces the Galactic center; makes for much more dramatic Milky Way views…

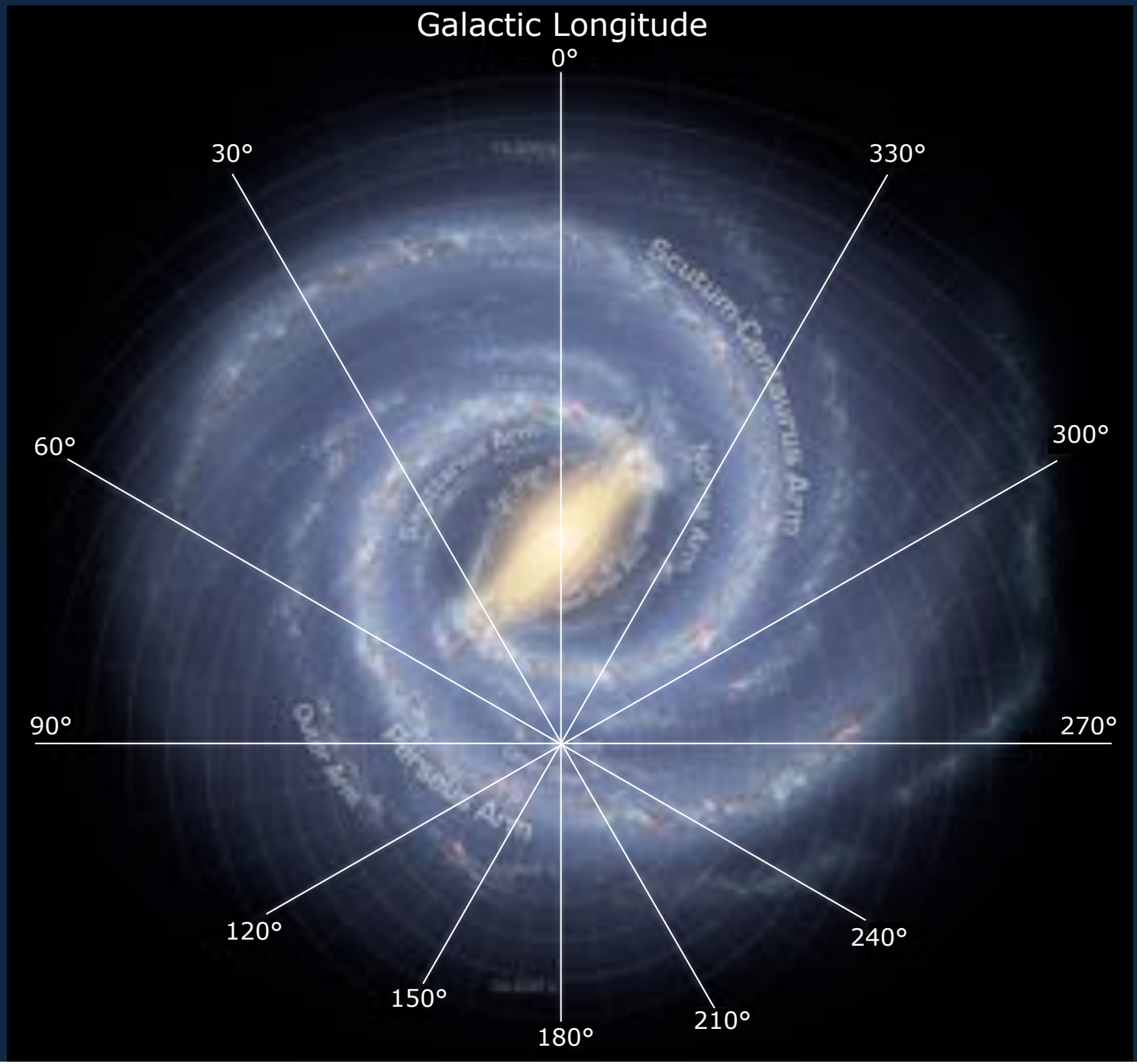


The Milky Way - Galactic coordinates

Southern hemisphere faces the Galactic center; makes for much more dramatic Milky Way views…

…and "dark constellations"

The Milky Way - Galactic coordinates



The Milky Way

1) **Dust**

2) Gas

3) Stars

The Milky Way - Dust

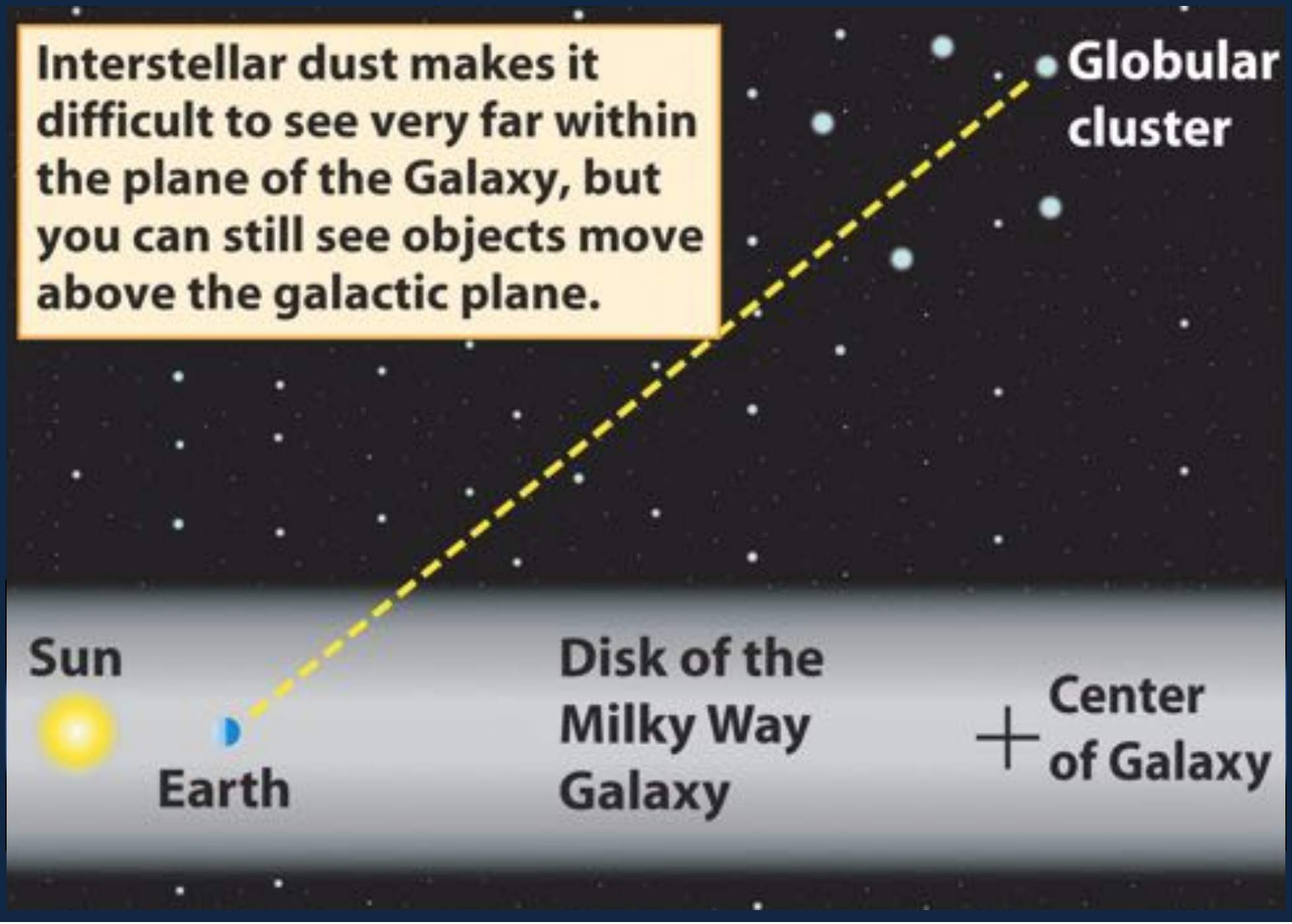
In the visible regime, dust shows up as dark clouds…

The Milky Way - Dust

In the infrared…

IR emission at 25, 60, and 100 microns

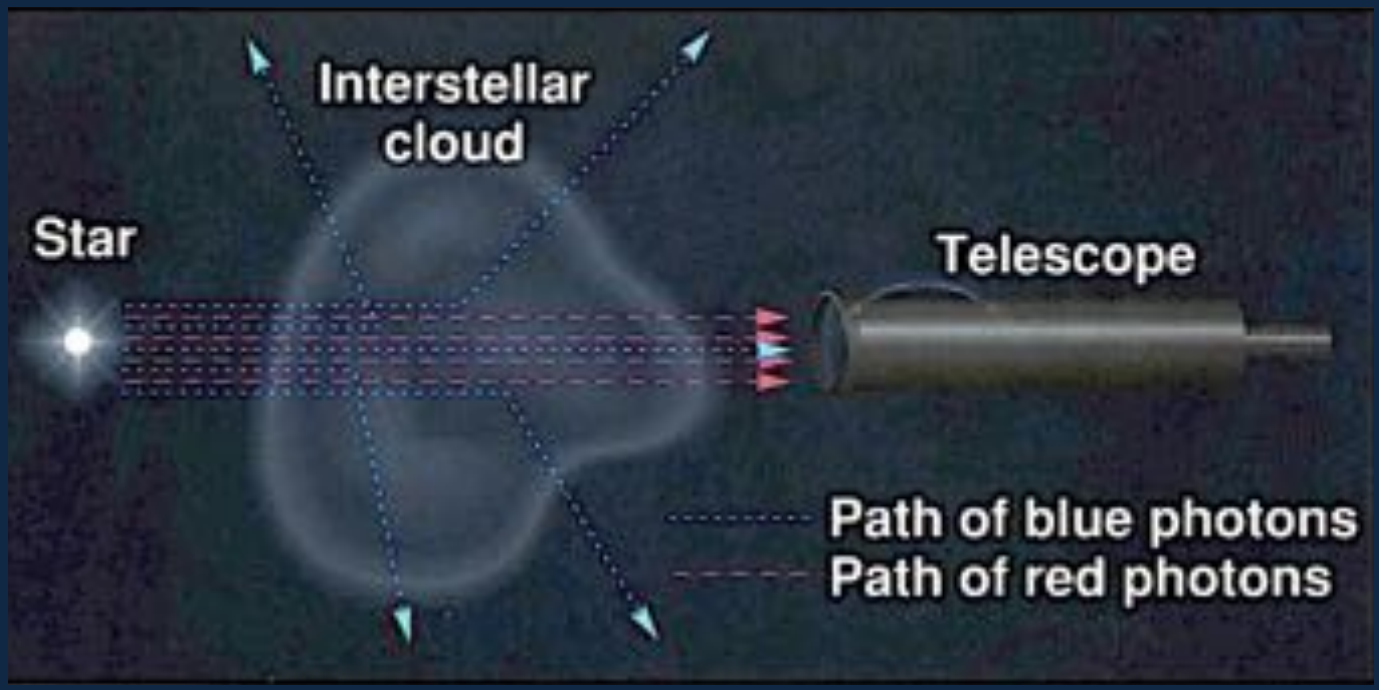
The Milky Way - Dust

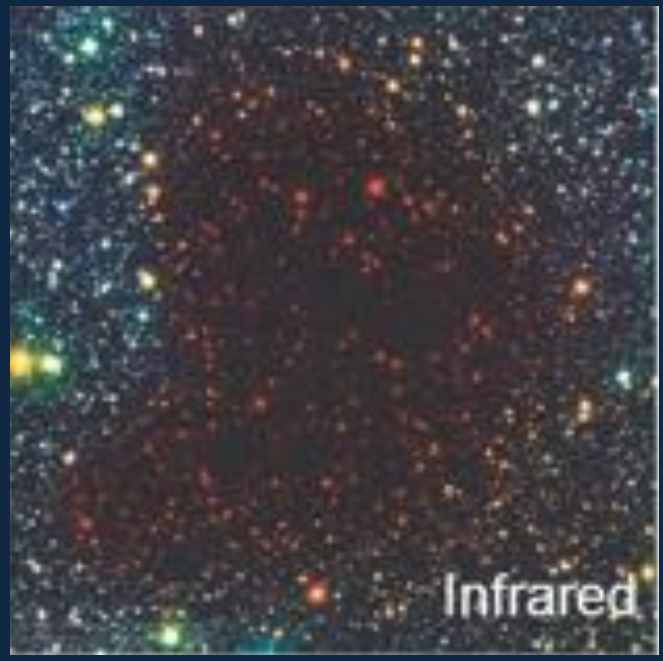


The Milky Way - Dust

Reddening

Dust preferentially scatters **blue** light; objects viewed through dust clouds appear **redder**

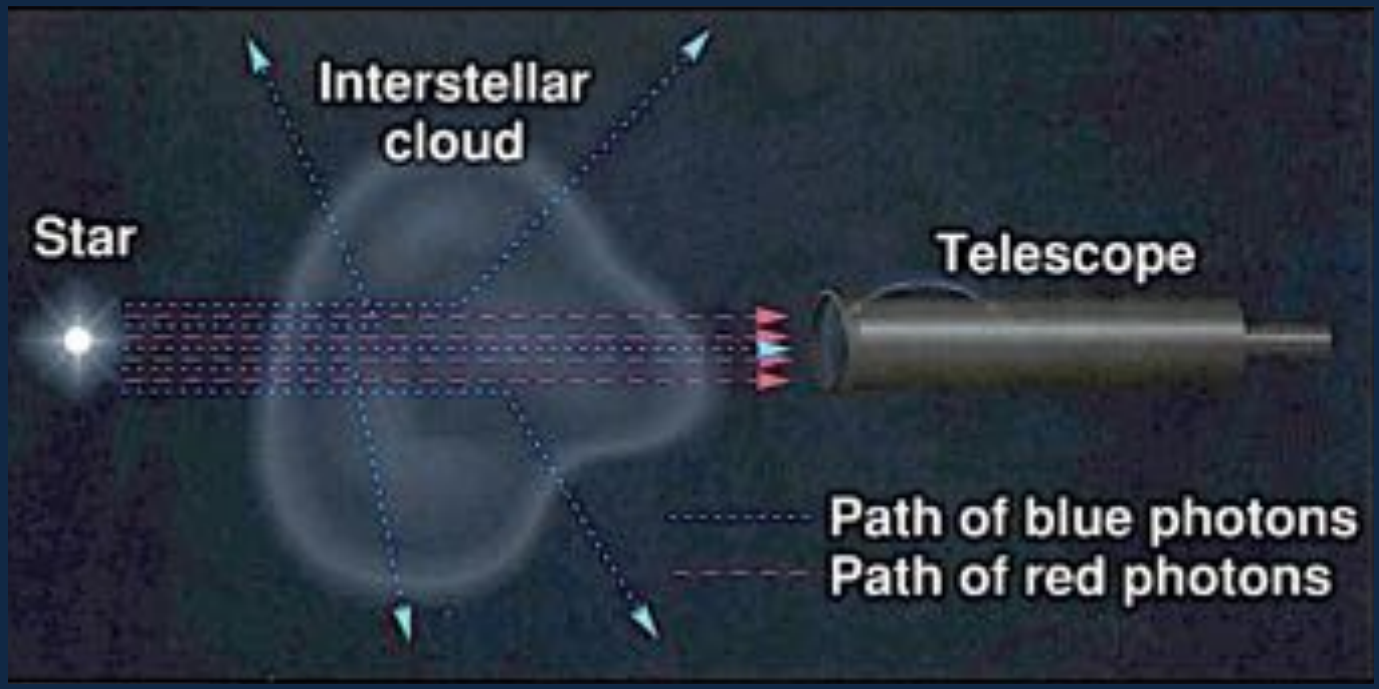




The Milky Way - Dust

Reddening

Dust preferentially scatters **blue** light; objects viewed through dust clouds appear **redder**



$$m_X - M_X = 5(\log(d) - 1) + A_X$$

("extinction" in X)

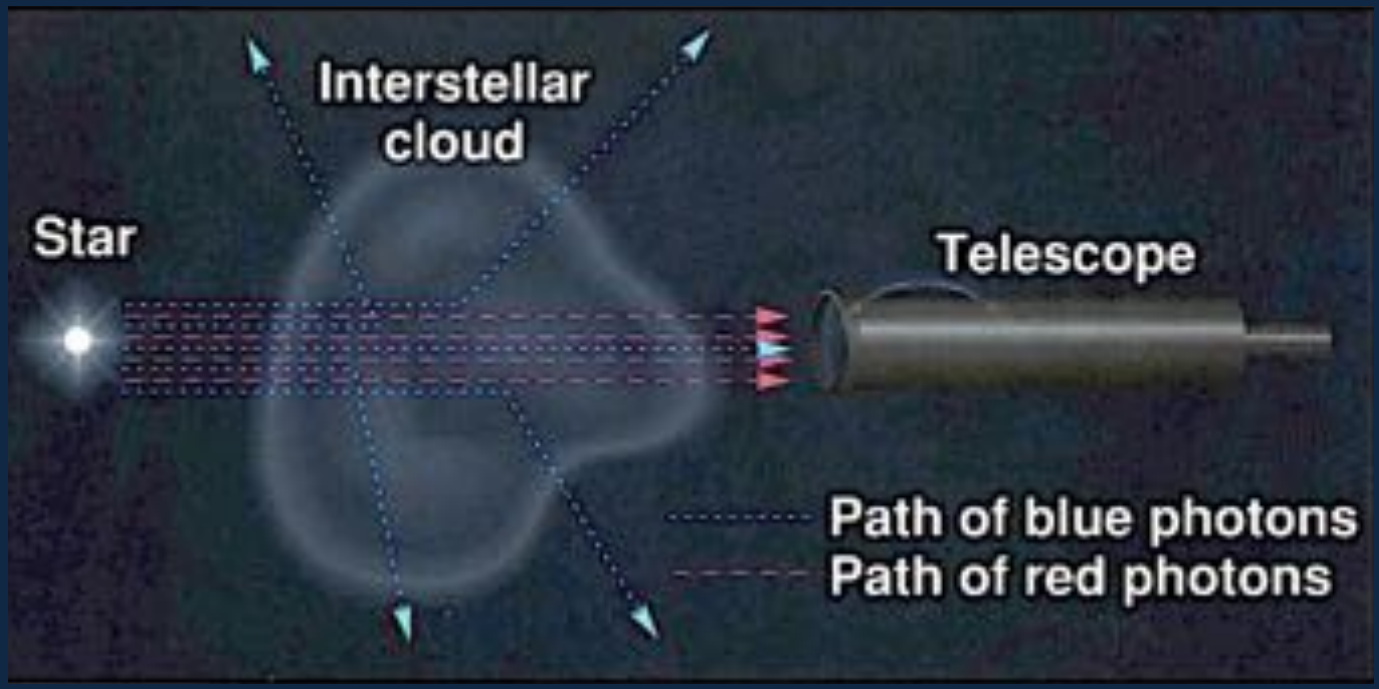
$$E(B\text{-}V) = (B\text{-}V)_{observed} - (B\text{-}V)_{normal}$$

$A_V = 3.1 \times E(B\text{-}V)$

The Milky Way - Dust

Reddening

Dust preferentially scatters **blue** light; objects viewed through dust clouds appear **redder**



$$A_V = 3.1 \times E(B\text{-}V)$$

total-to-selective extinction ratio $\mathbf{R_V}$

(correlated with average size of dust grains)

(average in MW is 3.1; ranges from ~2.5-6)

The Milky Way - Dust

Quick Question

You obtain photometry and spectroscopy of a star and find that it's a very red Cepheid with a low Galactic latitude. You also try to estimate its distance (D_{actual}) using the apparent magnitude in a specific visual band, X (D_X) and the distance modulus equation: $m_X - M_X = 5(\log(d) - 1)$.

Which of the following is true?

A) $D_{actual} = D_X$

B) $D_{actual} > D_X$

C) $D_{actual} < D_X$

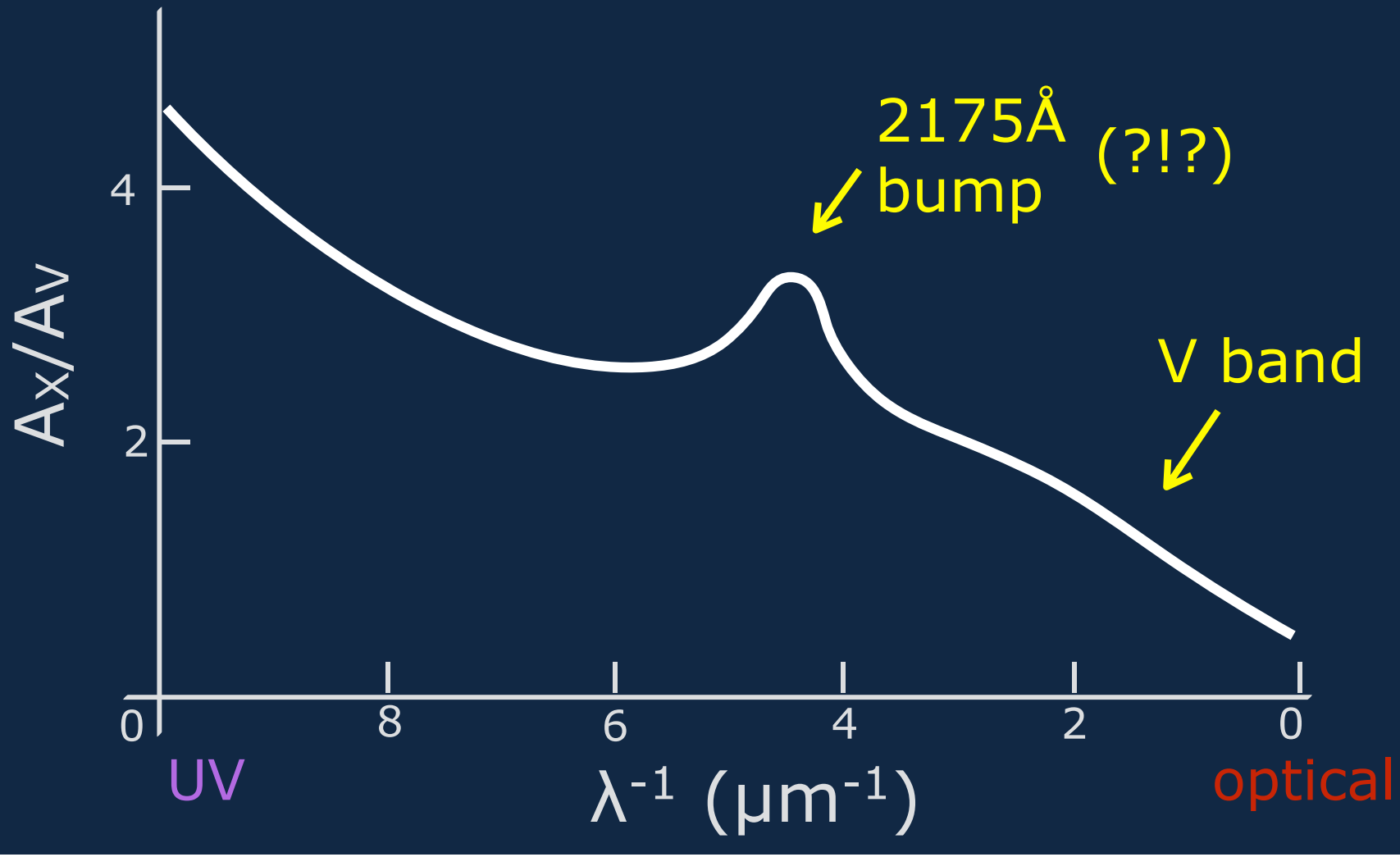
D) depends on which band X is

The Milky Way - Dust

Reddening & Extinction

Find E(B-V) from:

- 2175Å bump

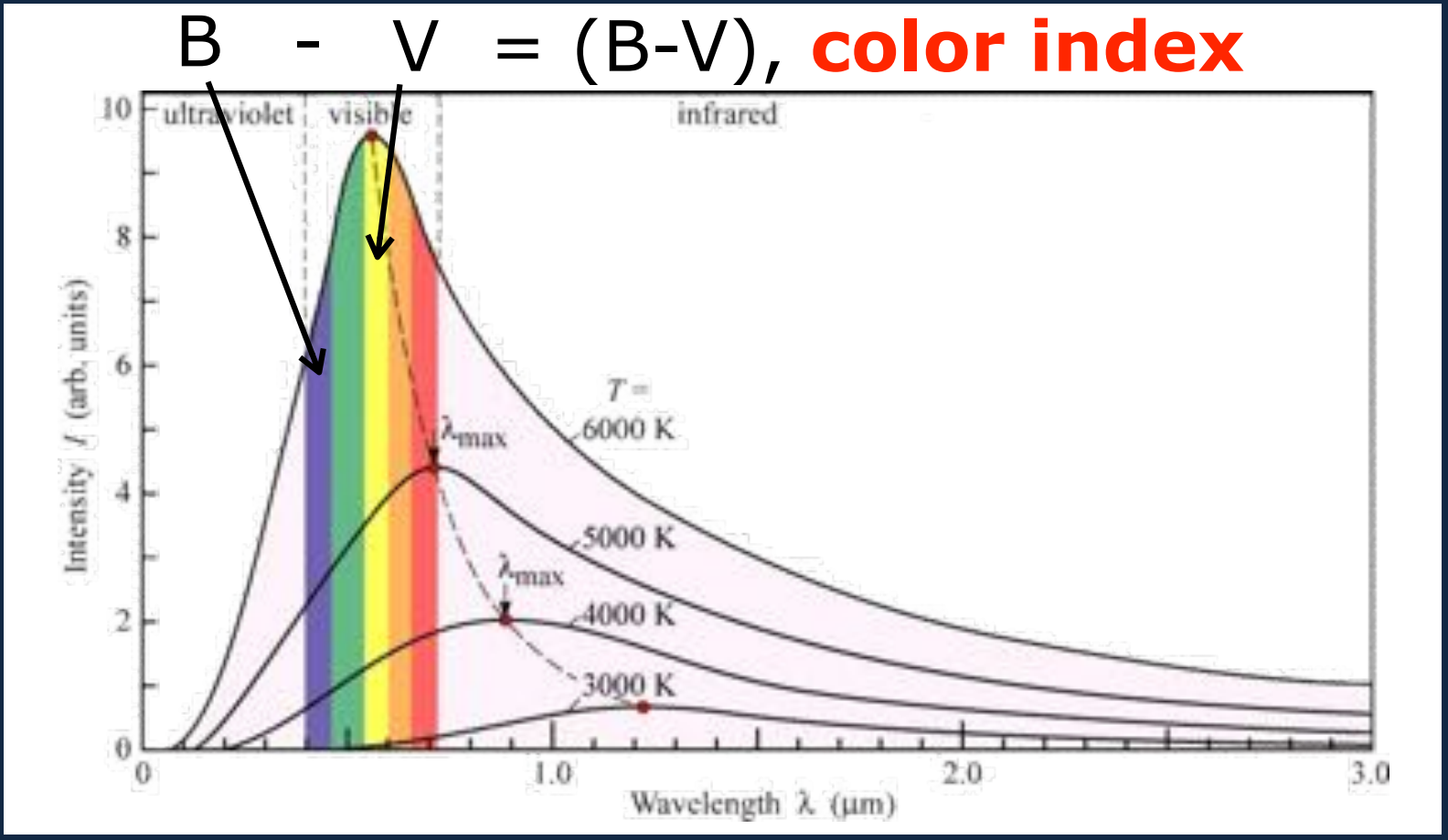


The Milky Way - Dust

Reddening & Extinction

Find E(B-V) from:

- 2175Å bump
- spectral type of star and observed B-V

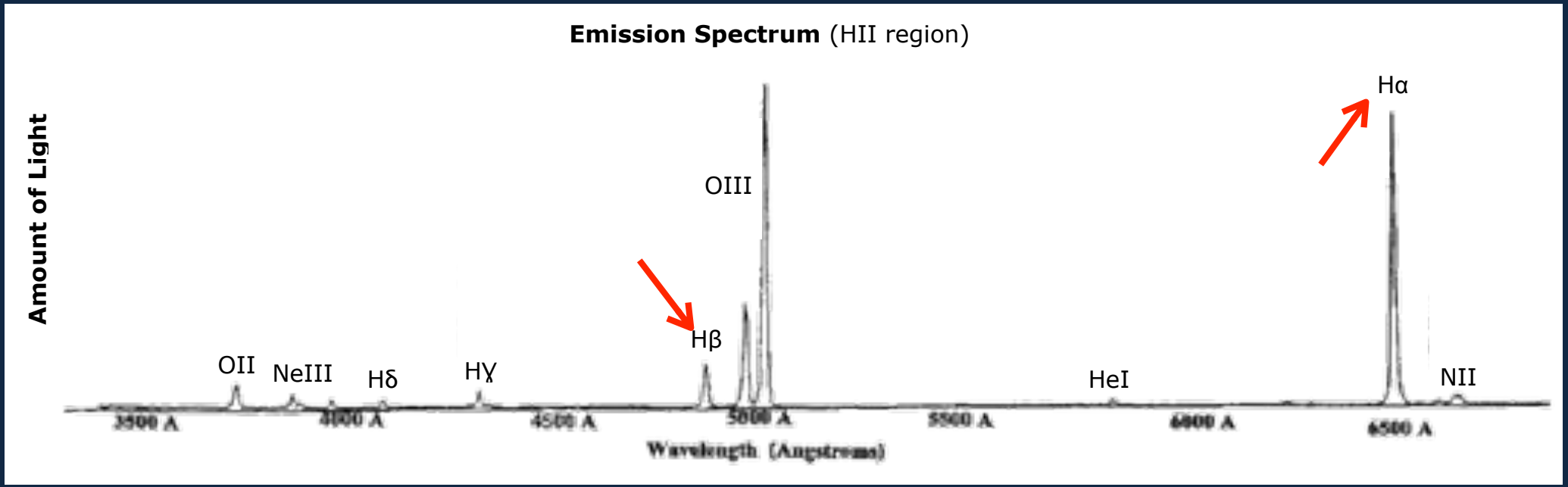


The Milky Way - Dust

Reddening & Extinction

Find E(B-V) from:

- 2175Å bump
- spectral type of star and observed B-V
- Hα/Hβ ratio [normal ~ 3]

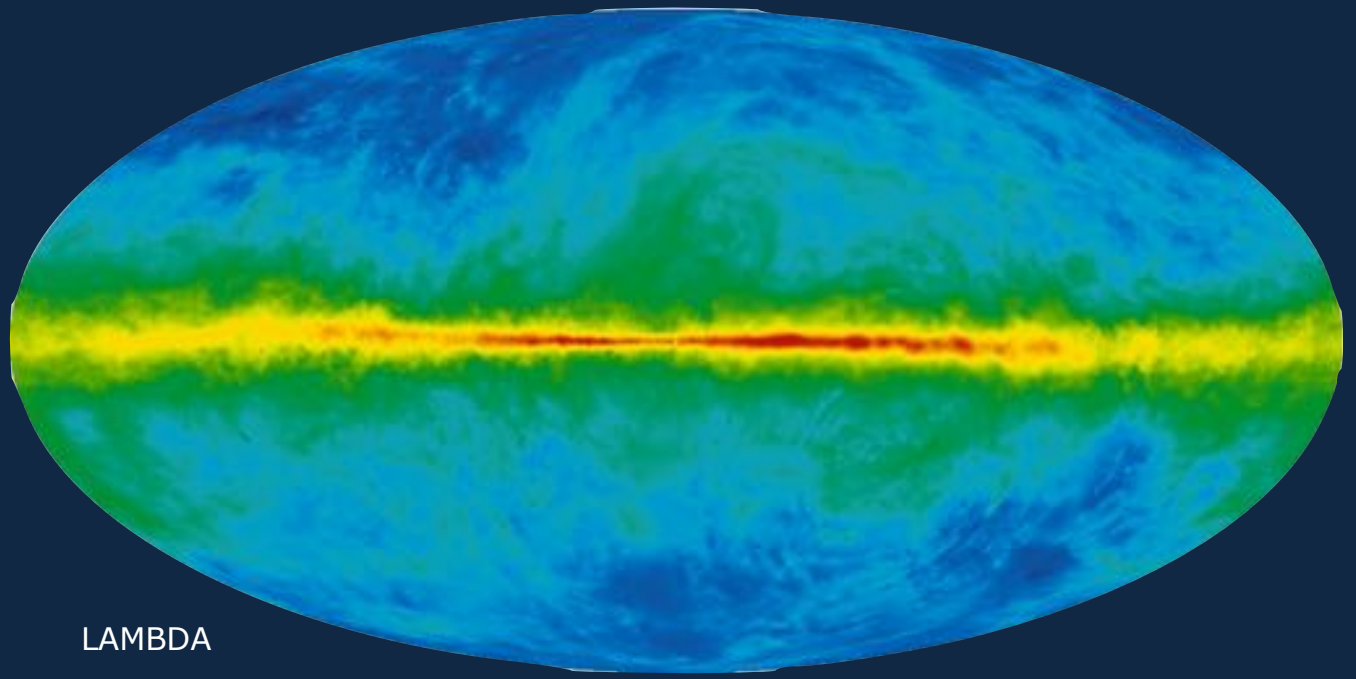


The Milky Way - Dust

Reddening & Extinction

Find E(B-V) from:

- 2175Å bump
- spectral type of star and observed B-V
- Hα/Hβ ratio [normal ~ 3]
- HI maps N_H/E(B-V) = $5x10^{21}$ atoms/cm^2/mag



LAMBDA

The Milky Way - Gas

1) Dust

   — concentrated in Galactic disk
   — results in reddening (E(B-V), A_V)

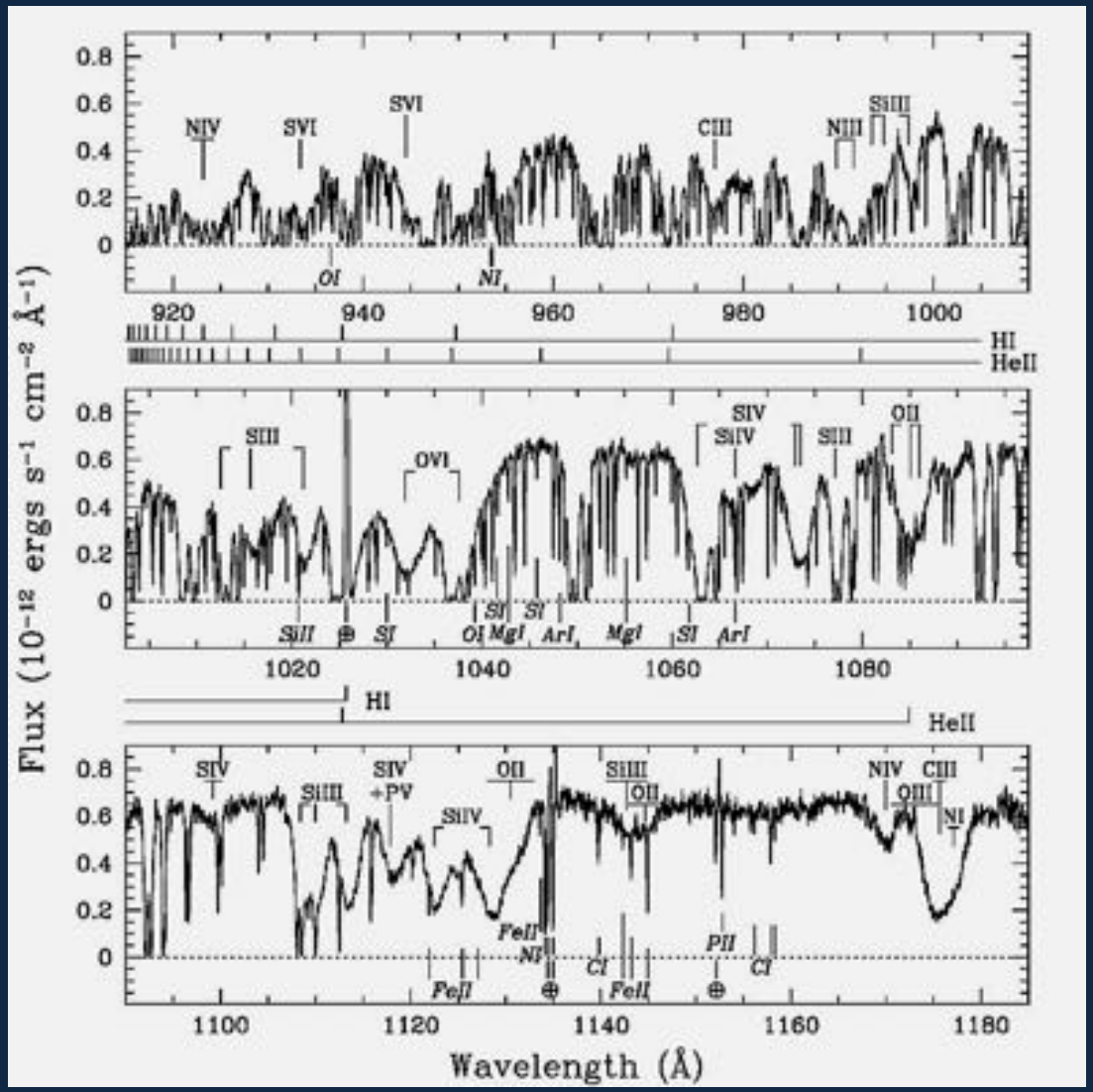
2) **Gas**

3) Stars

The Milky Way - Gas

Interstellar Gas

- UV/optical absorption lines, CaI, CaII, NaI

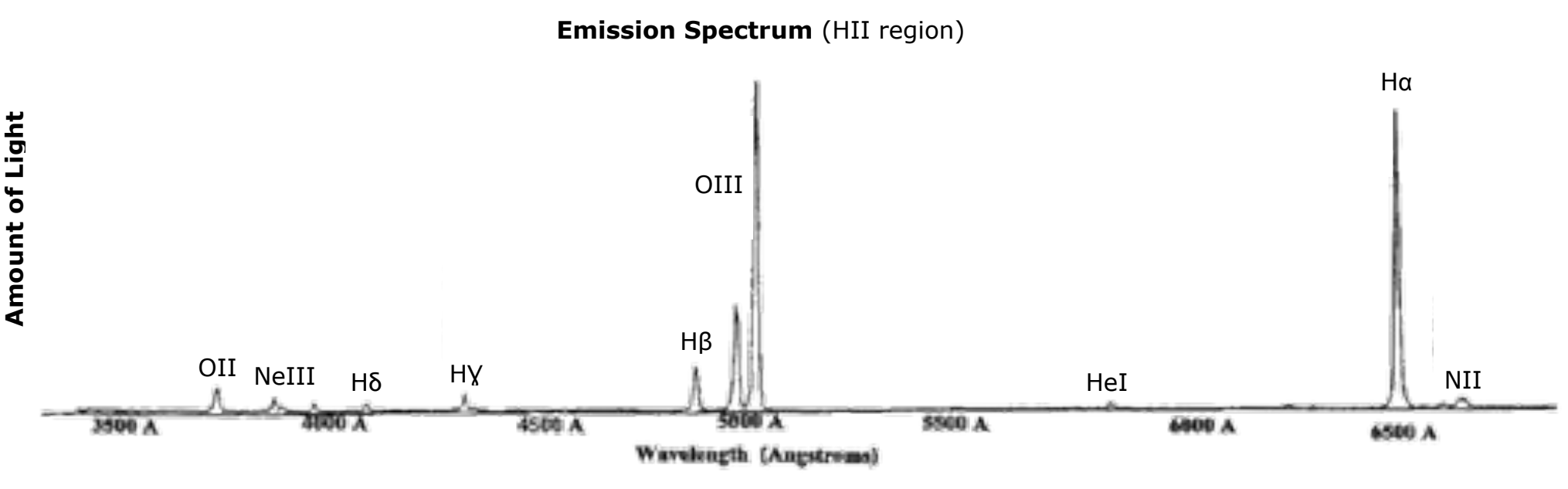


The Milky Way - Gas

Interstellar Gas

- UV/optical absorption lines, CaI, CaII, NaI
- HII regions (recombination around hot star)
  T~10,000K, ρ ~ 5000 ions m^{-3}

X I - neutral atom
X II - singly-ionized atom
X III - double-ionized atom

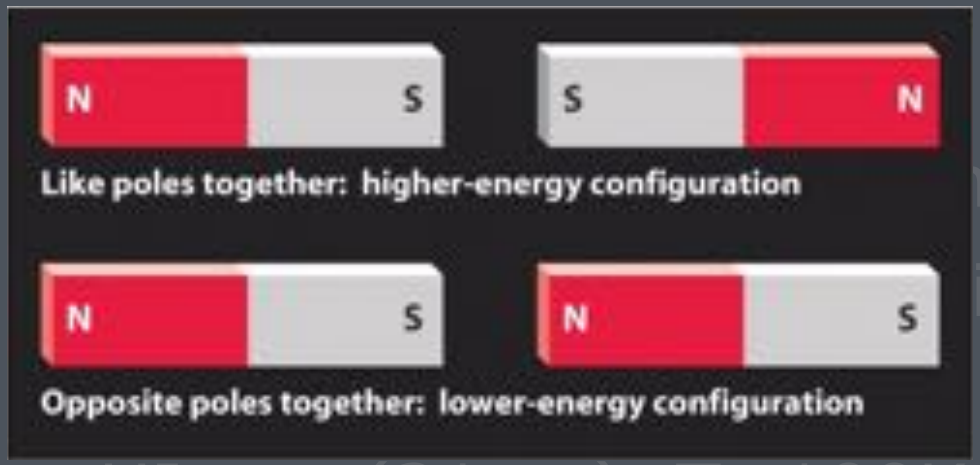


The Milky Way - Gas

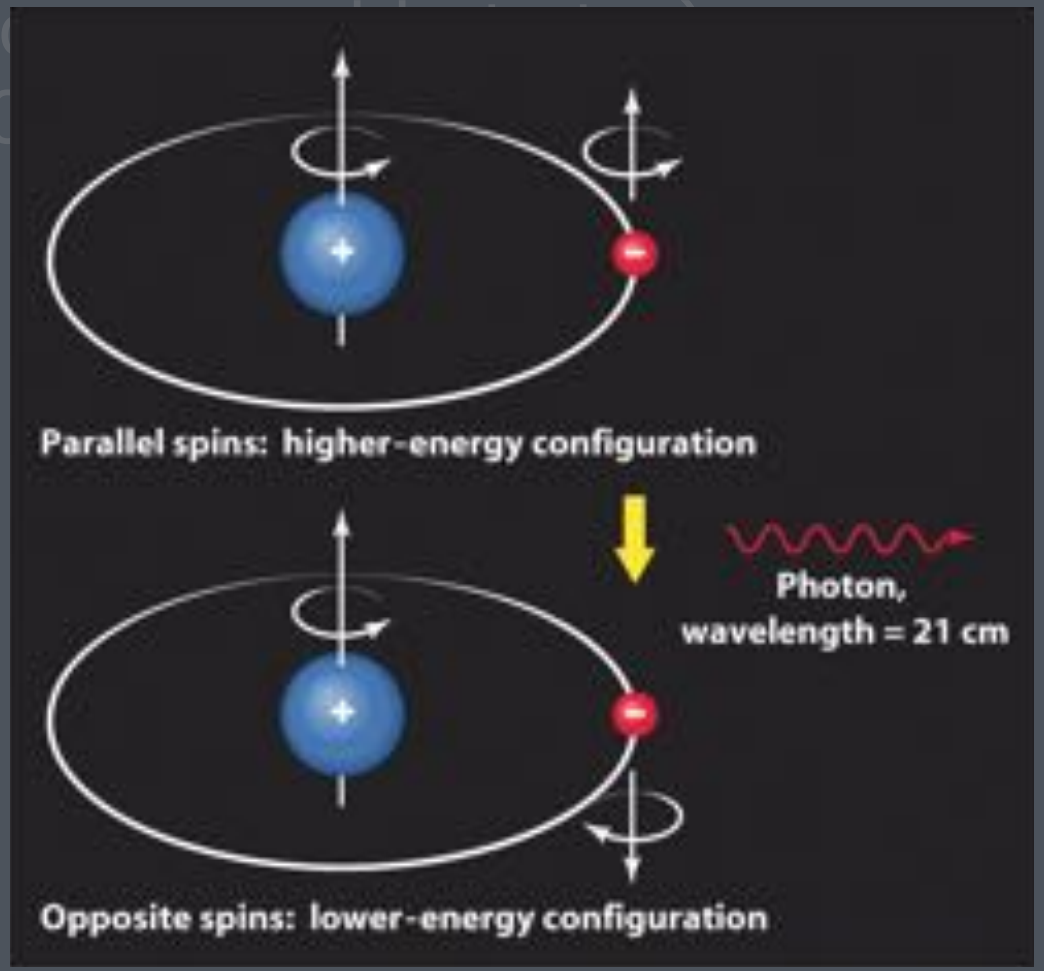
Interstellar Gas

- UV/optical absorption lines, CaI, CaII, NaI
- HII regions (recombination around hot star) T~10,000K, $\rho \sim 5000$ ions m^{-3}
- HI gas (21cm), T~100K, $\rho \sim 10^6$ ions m^{-3}

The spin-flip transition in H emits 21cm radio waves



The magnetic energy of two bar magnets depends on their relative orientation.



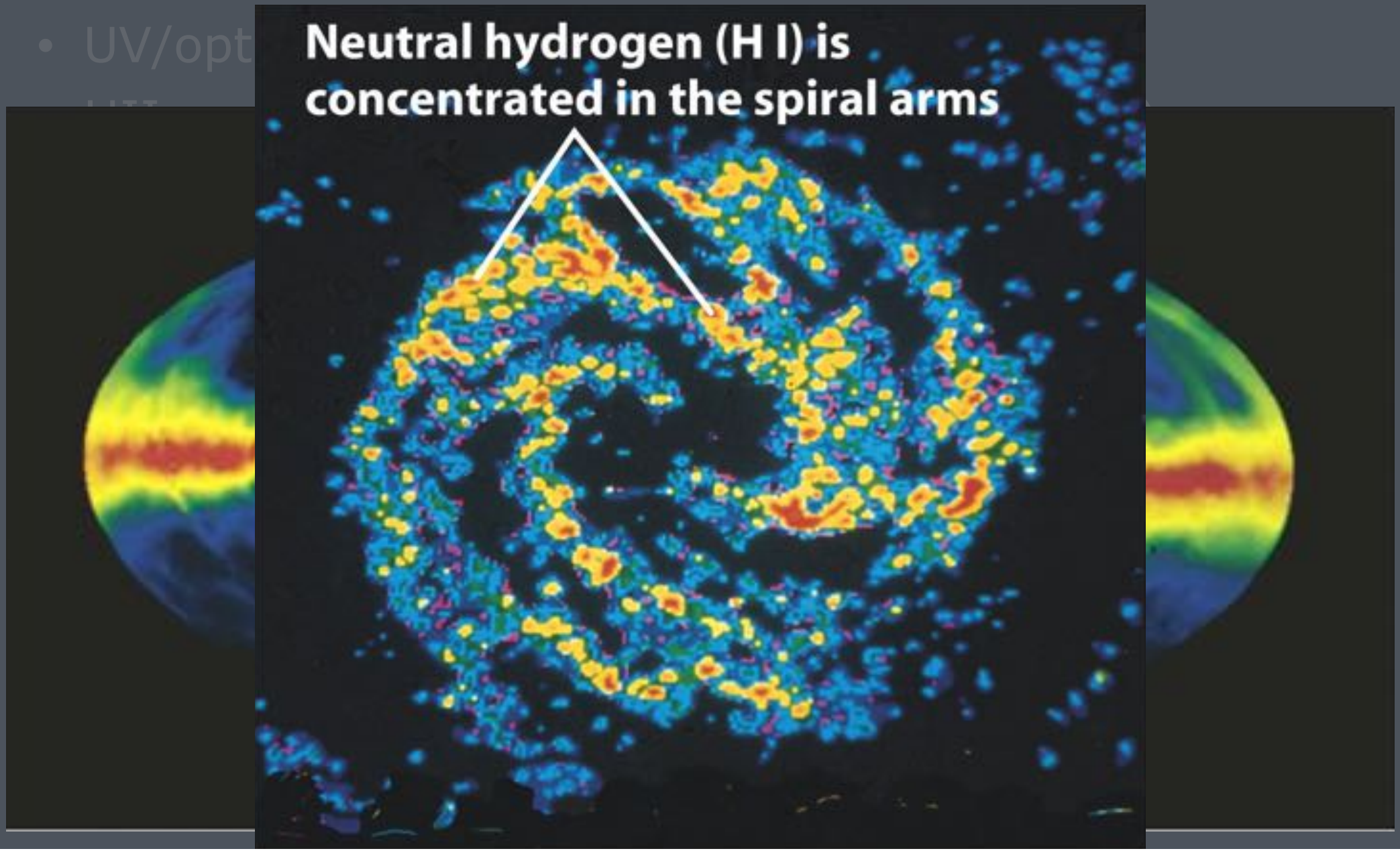
The magnetic energy of a proton and electron depends on their relative spin orientation.

The Milky Way - Gas

The spin-flip transition in H emits 21cm radio waves

Interstellar Gas

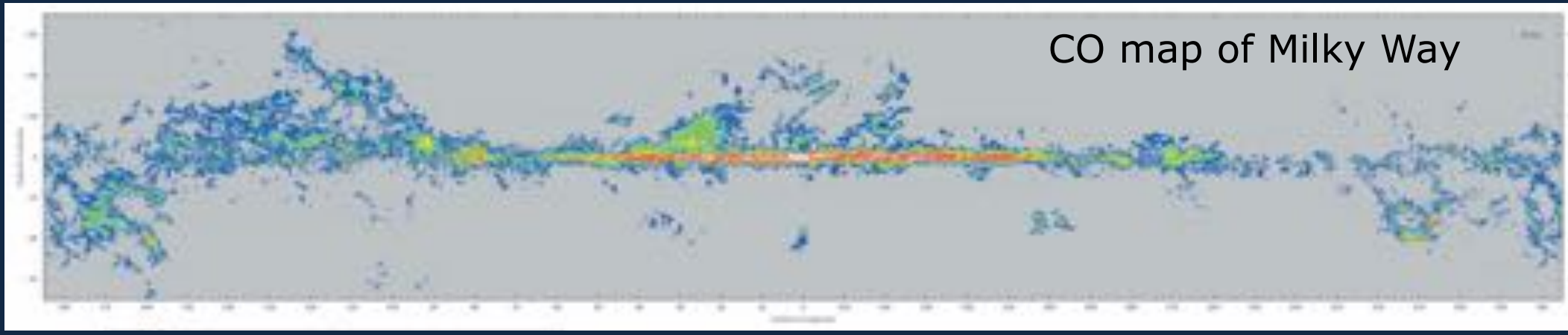
- UV/opt



The Milky Way - Gas

Interstellar Gas

- UV/optical absorption lines, CaI, CaII, NaI
- HII regions (recombination around hot star) T~10,000K, ρ ~ 5000 ions m^{-3}
- HI gas (21cm), T~100K, ρ ~ 10^6 ions m^{-3}
- molecular clouds (radio); H_2, OH, CO, NH_3; T~10K, ρ ~10^9 ions m^{-3}

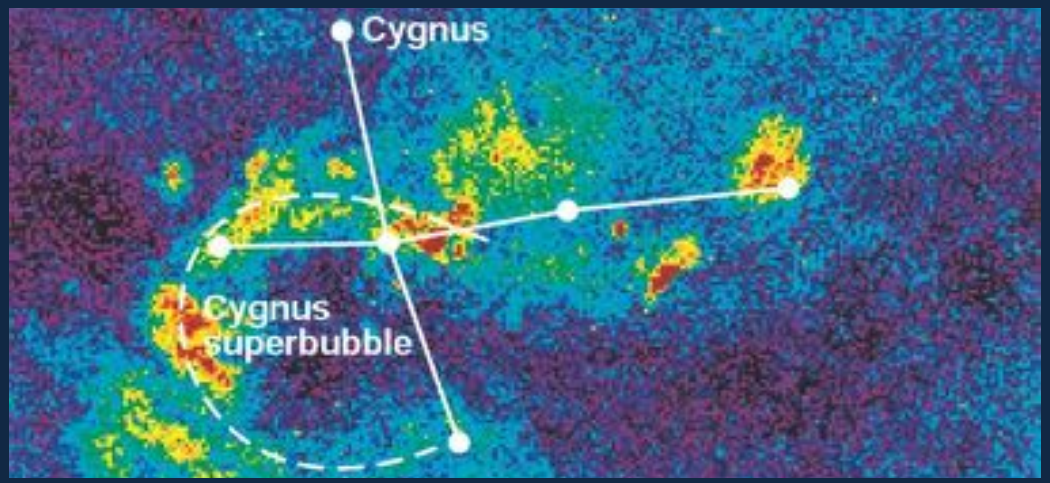


Dame et al. 2001

The Milky Way - Gas

Interstellar Gas

- UV/optical absorption lines, CaI, CaII, NaI
- HII regions (recombination around hot star) T~10,000K, ρ ~ 5000 ions m^{-3}
- HI gas (21cm), T~100K, ρ ~ 10^6 ions m^{-3}
- molecular clouds (radio); H_2, OH, CO, NH_3; T~10K, ρ ~10^9 ions m^{-3}
- X-ray (hot "coronal" gas); T~10^6K, ρ < 10^4 particles m^{-3}



The Milky Way - Stars

1) Dust

— concentrated in Galactic disk
— results in reddening (E(B-V), A_V)

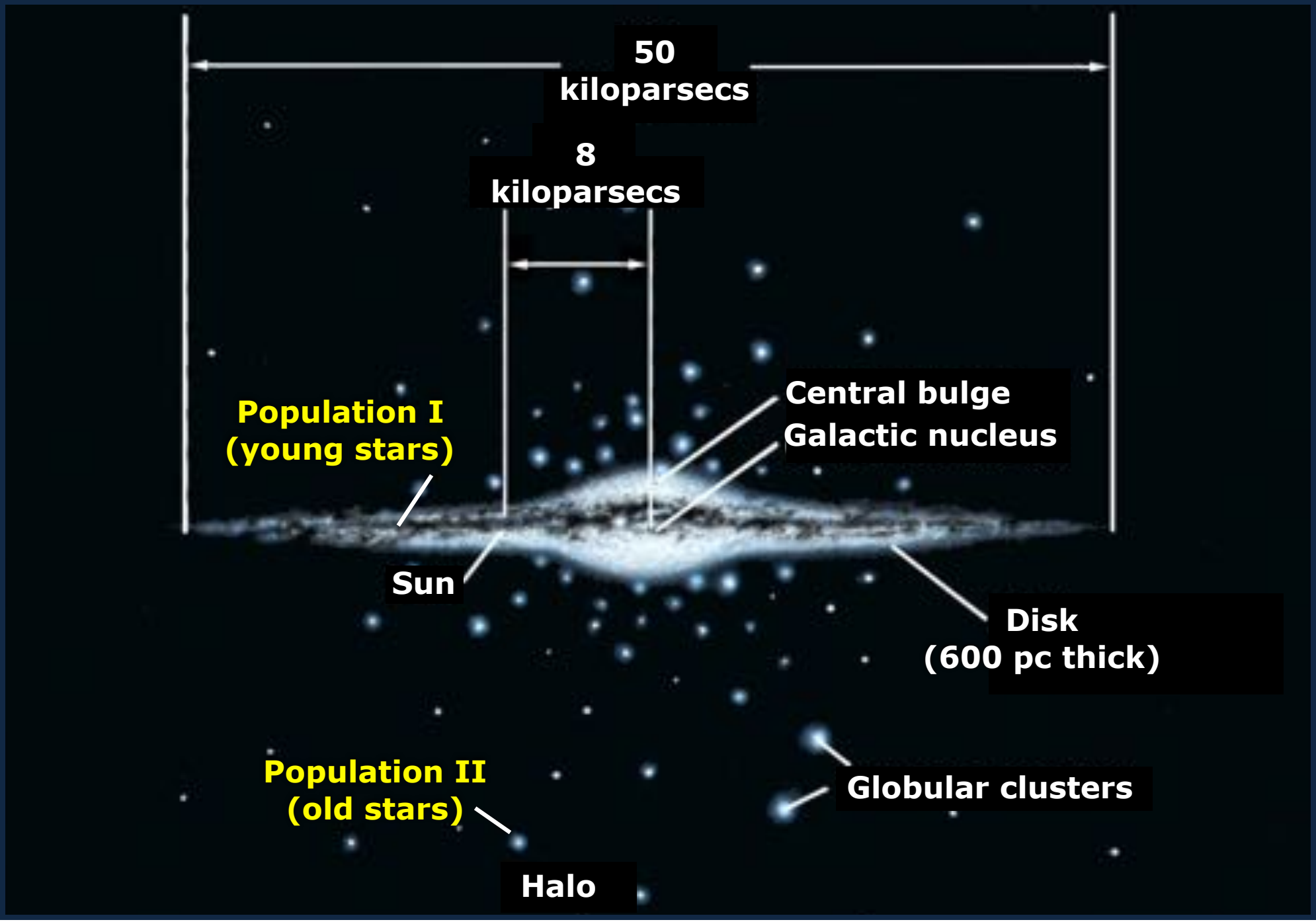
2) Gas

— HI clouds & molecular clouds (radio)

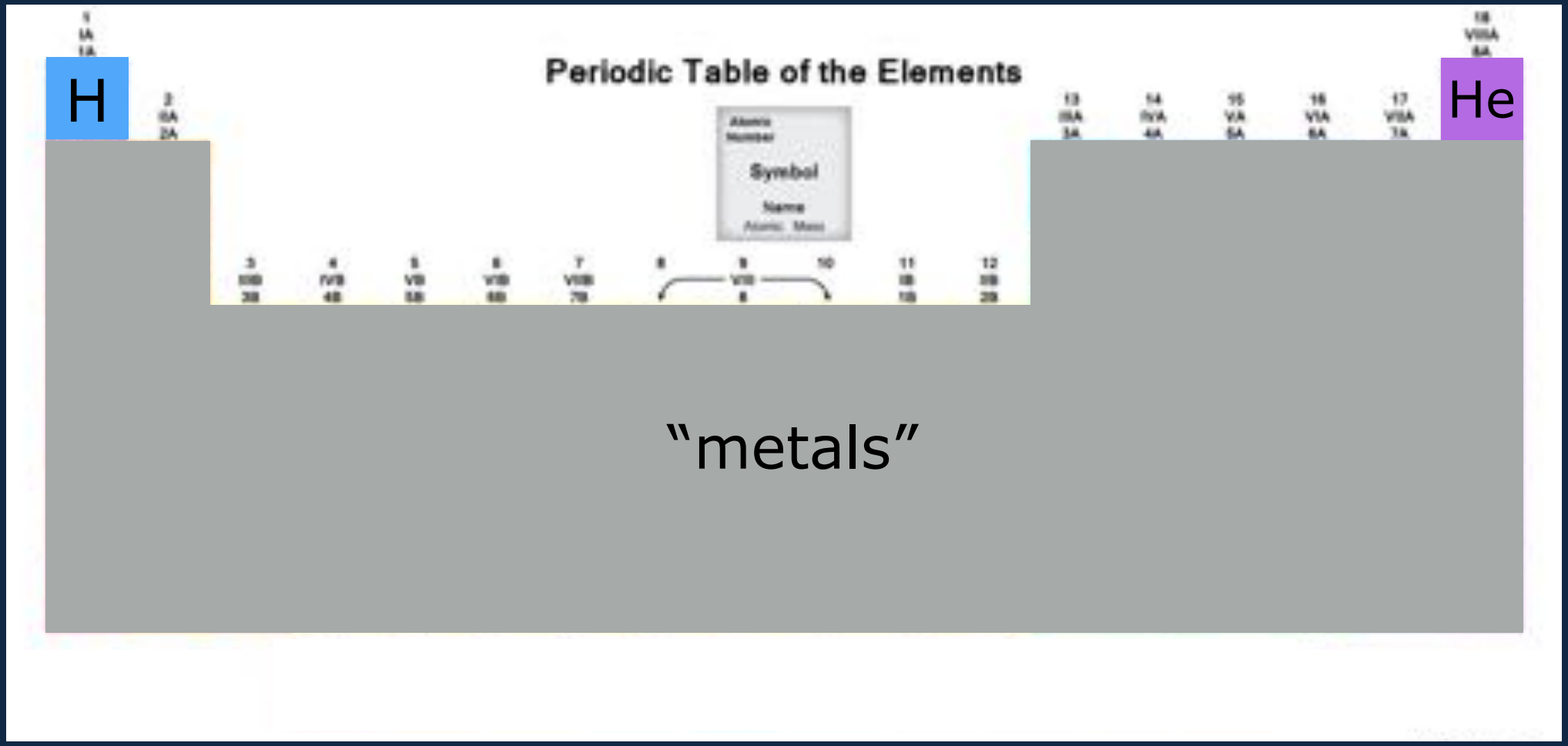
— coronal gas (X-ray) & HII regions (UV/opt)

3) **Stars**

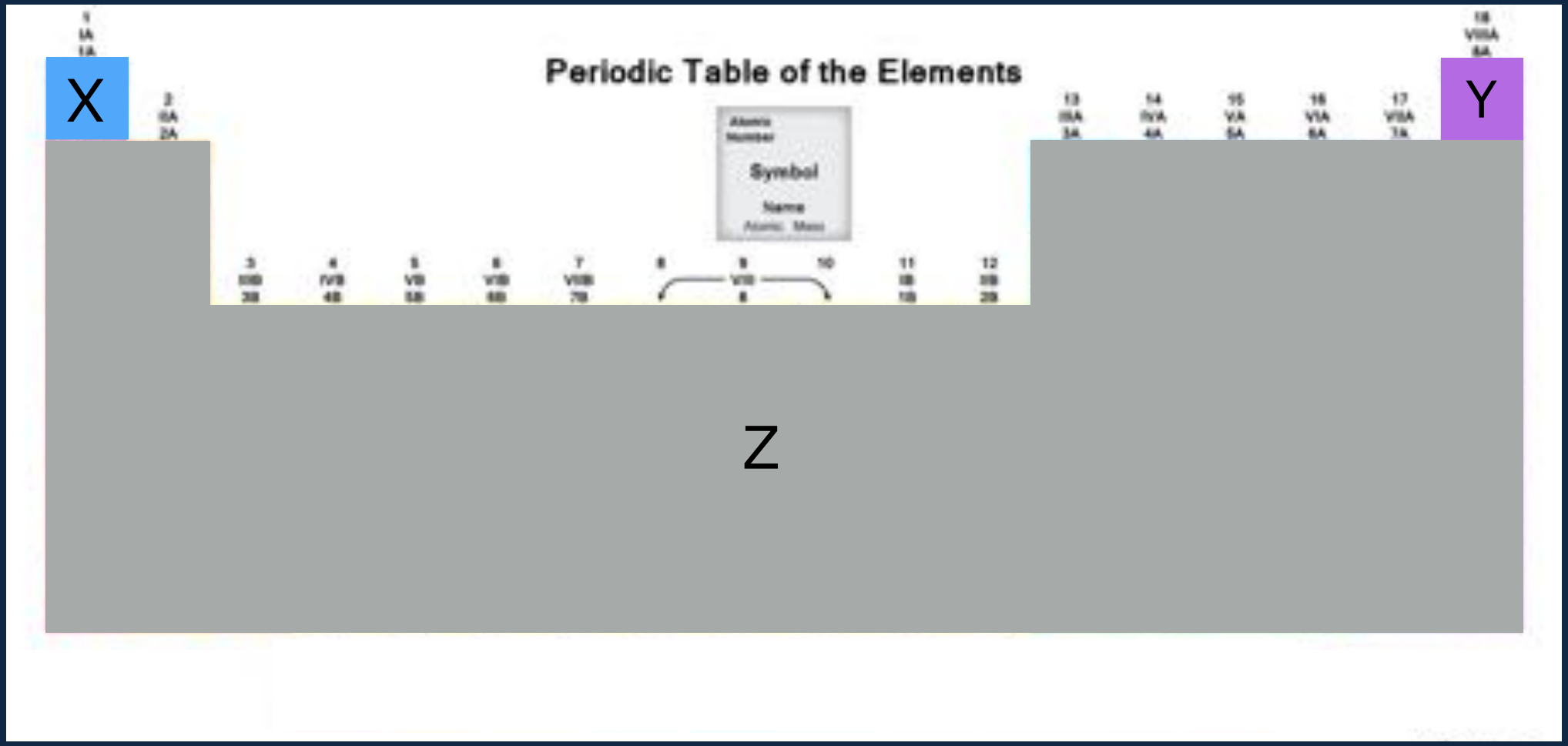
The Milky Way - Stars



The Milky Way - Stars



The Milky Way - Stars

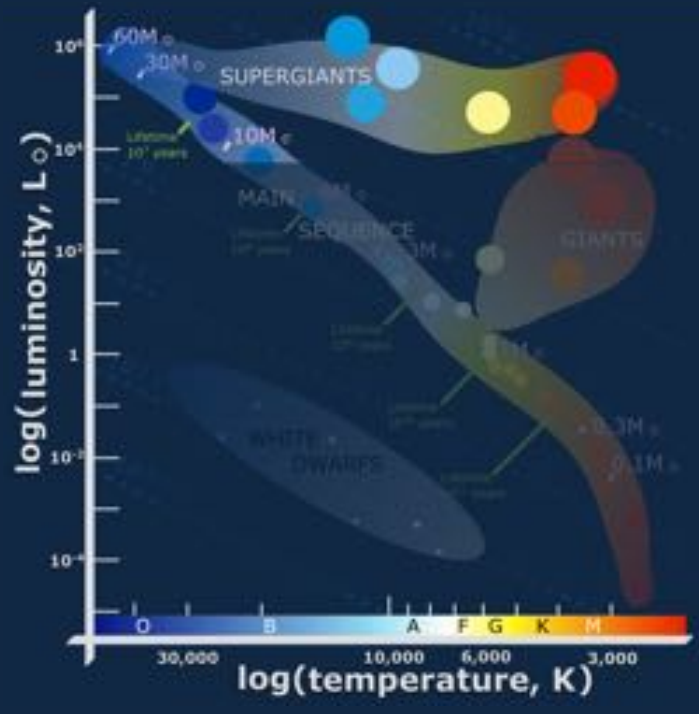


H = 'X' **He = 'Y'** **metal = 'Z' = 0.02**

The Milky Way - Stars

Stellar Populations

	d (pc)	Age (10^9 y)	Z	Distr
Population I (young)				
Extreme	120	< 0.1	0.04	patchy, disk
Older	160	0.1 - 10	0.03	patchy, disk



The Milky Way - Stars

Stellar Populations

	d (pc)	Age (10^9 y)	Z	Distr
Population I (young)				
Extreme	120	< 0.1	0.04	patchy, disk
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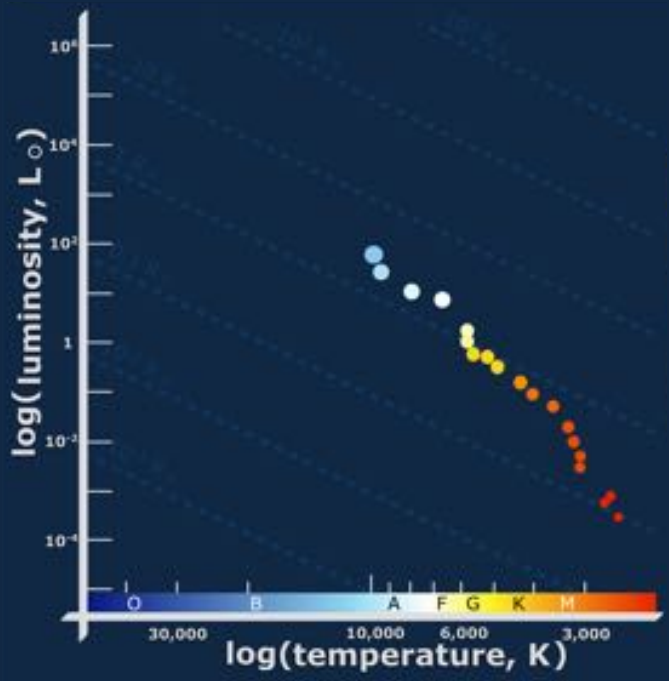
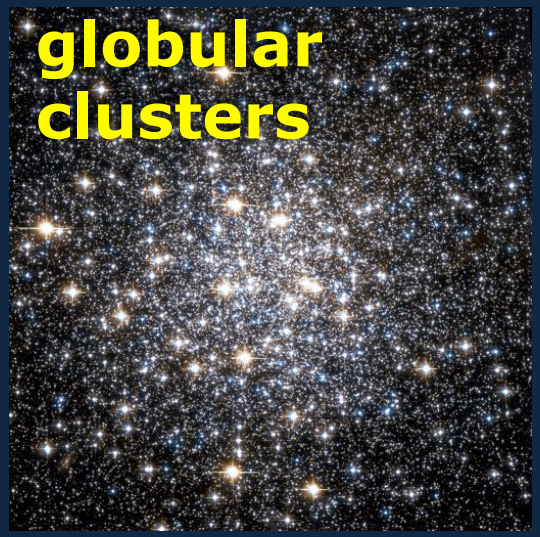
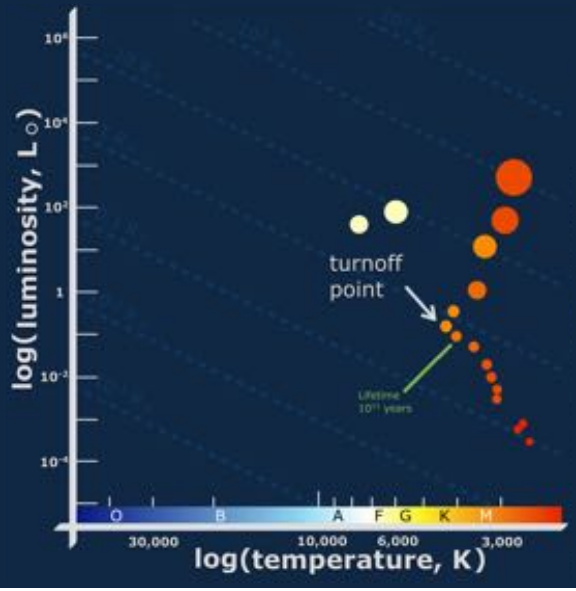


The Milky Way - Stars

Stellar Populations

	d (pc)	Age (10^9 y)	Z	Distr
Population II (old)				
Disk	400	3-10	0.02	smooth
Intermed	700	10	0.01	smooth
Halo	2000	>10	0.003	smooth





The Milky Way - Stars

Stellar Populations

	d (pc)	Age (10^9 y)	Z	Distr
Population II (old)				
Disk	400	3-10	0.02	smooth
Intermed	700	10	0.01	smooth
Halo	2000	>10	0.003	smooth
Population III				

"the first stars"…

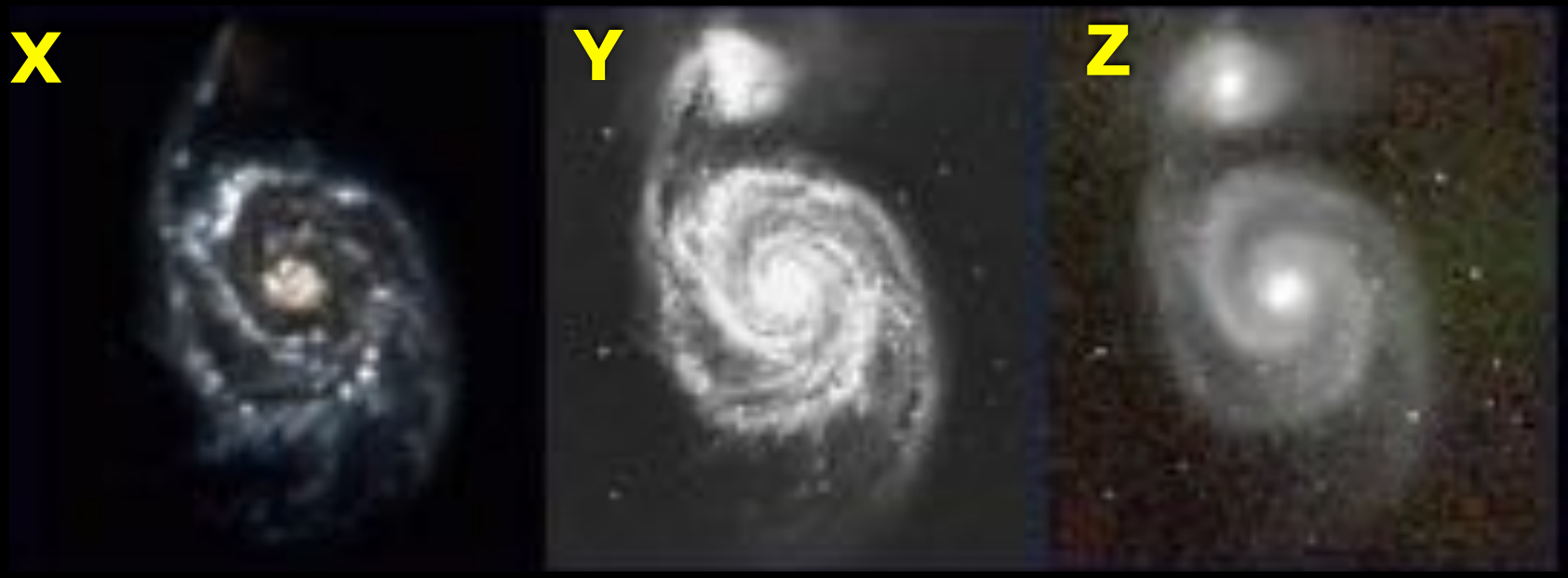
Hypothetical "metal-free" first generation of stars in the early universe…

The Milky Way - Stars

The Milky Way - Stars

Quick Question

Below are three images of the star-forming spiral galaxy M51. What wavelength was each taken in?



A) X=IR, Y=visual, Z=UV

B) X=visual, Y=IR, Z=UV

C) X=UV, Y=IR, Z=visual

D) X=UV, Y=visual, Z=IR

The Milky Way

1) Dust
   — concentrated in Galactic disk
   — results in reddening (E(B-V), A_V)
2) Gas
   — HI clouds & molecular clouds (radio)
   — coronal gas (X-ray) & HII regions (UV/opt)
3) Stars
   — Population I (disk)
   — Population II (disk & halo)

Total mass of the Milky Way?

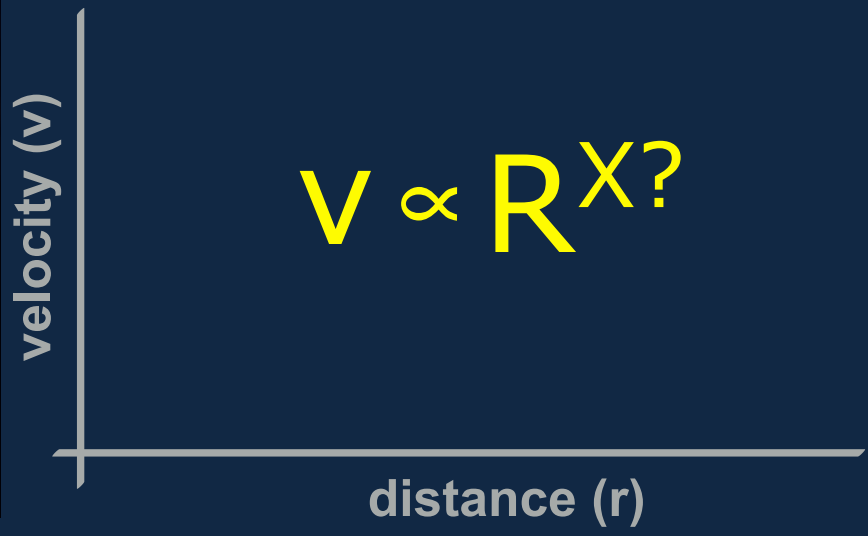
The Milky Way

Total mass of the Milky Way?

Dust + Gas + Stars

=

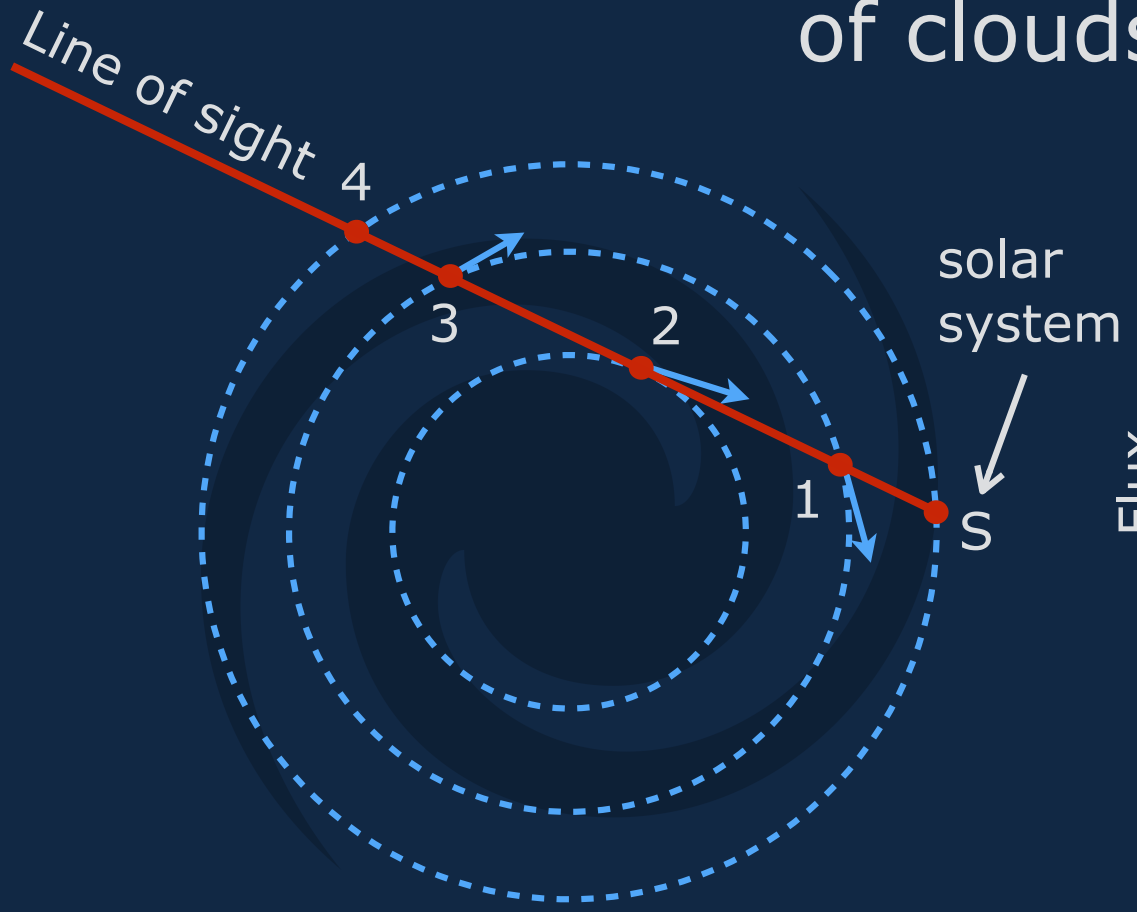
estimated mass, predicted **velocity curve** for a spiral galaxy

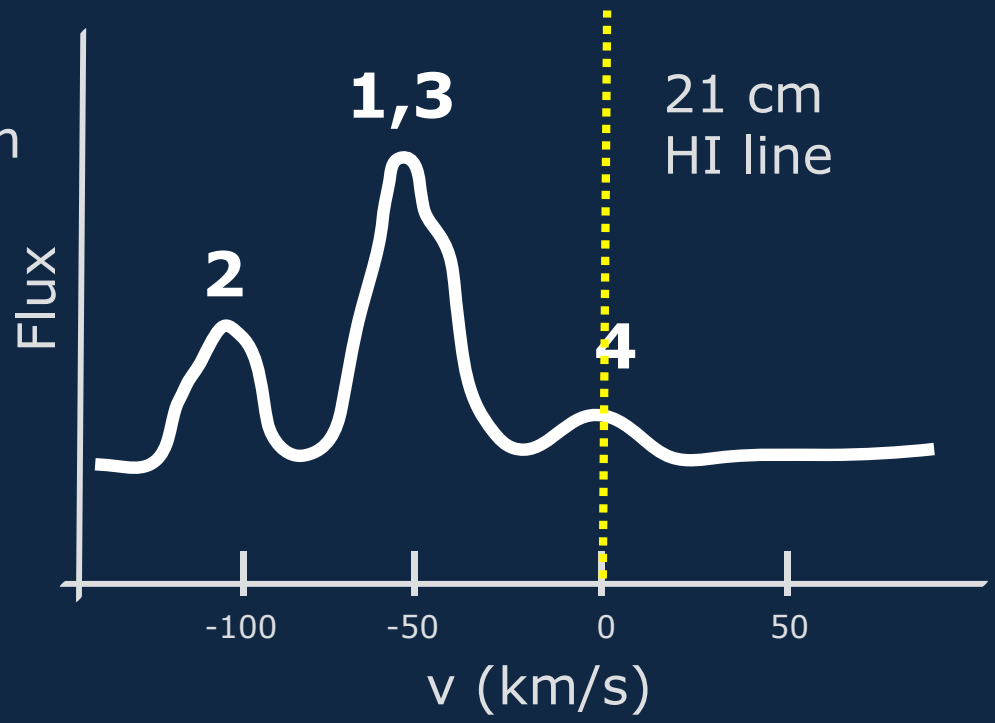


$V \propto R^{X?}$

The Milky Way - Mass

Spiral arms can be traced from the positions of clouds of atomic hydrogen.

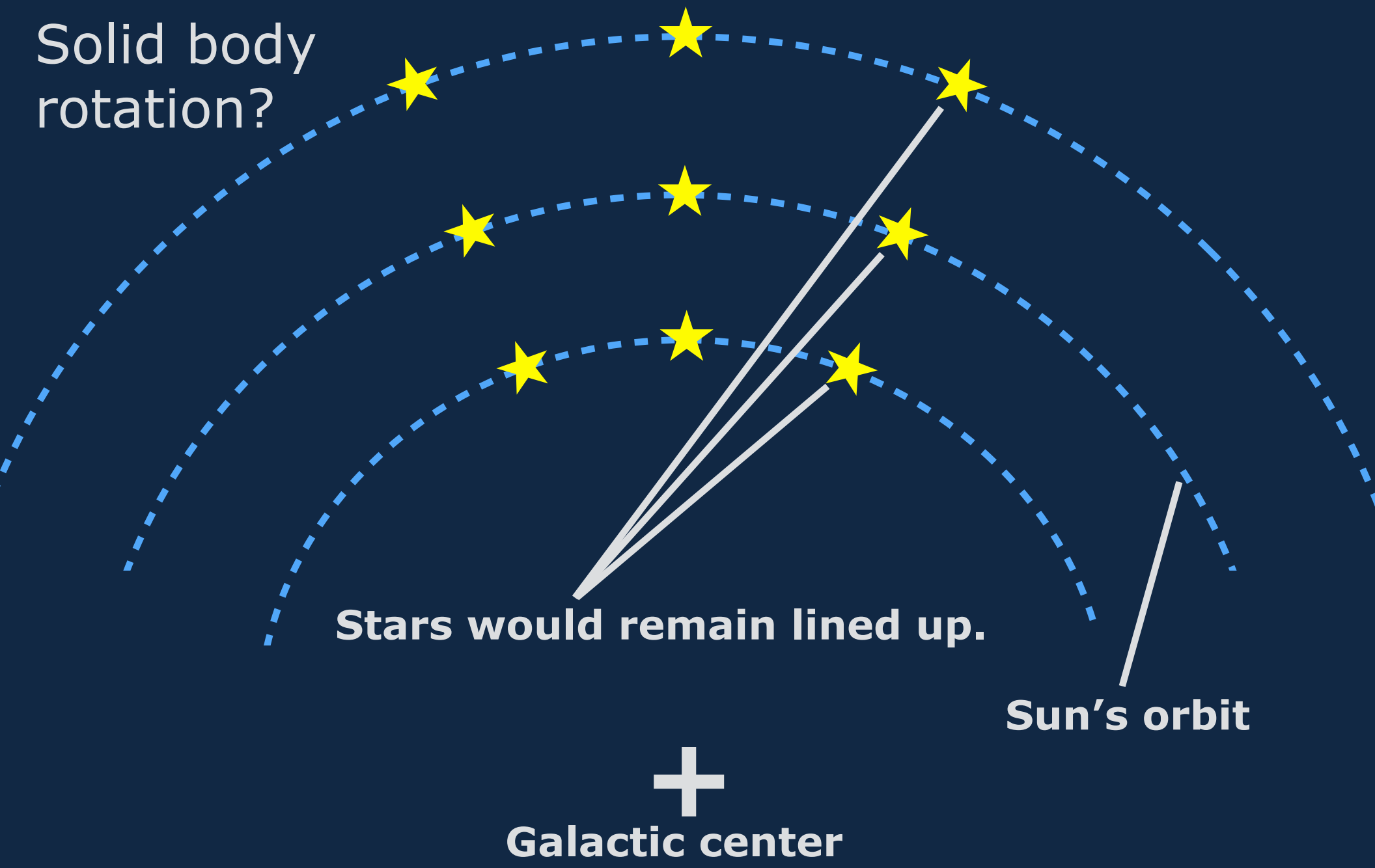




- 1 and 3 are approaching us: moderate blueshift
- 2 is approaching us at a faster speed; larger blueshift
- 4 is neither approaching nor receding

The Milky Way - Mass

Solid body rotation?



The Milky Way - Mass

Solid body

$v \propto R$

Sun's orbit

+

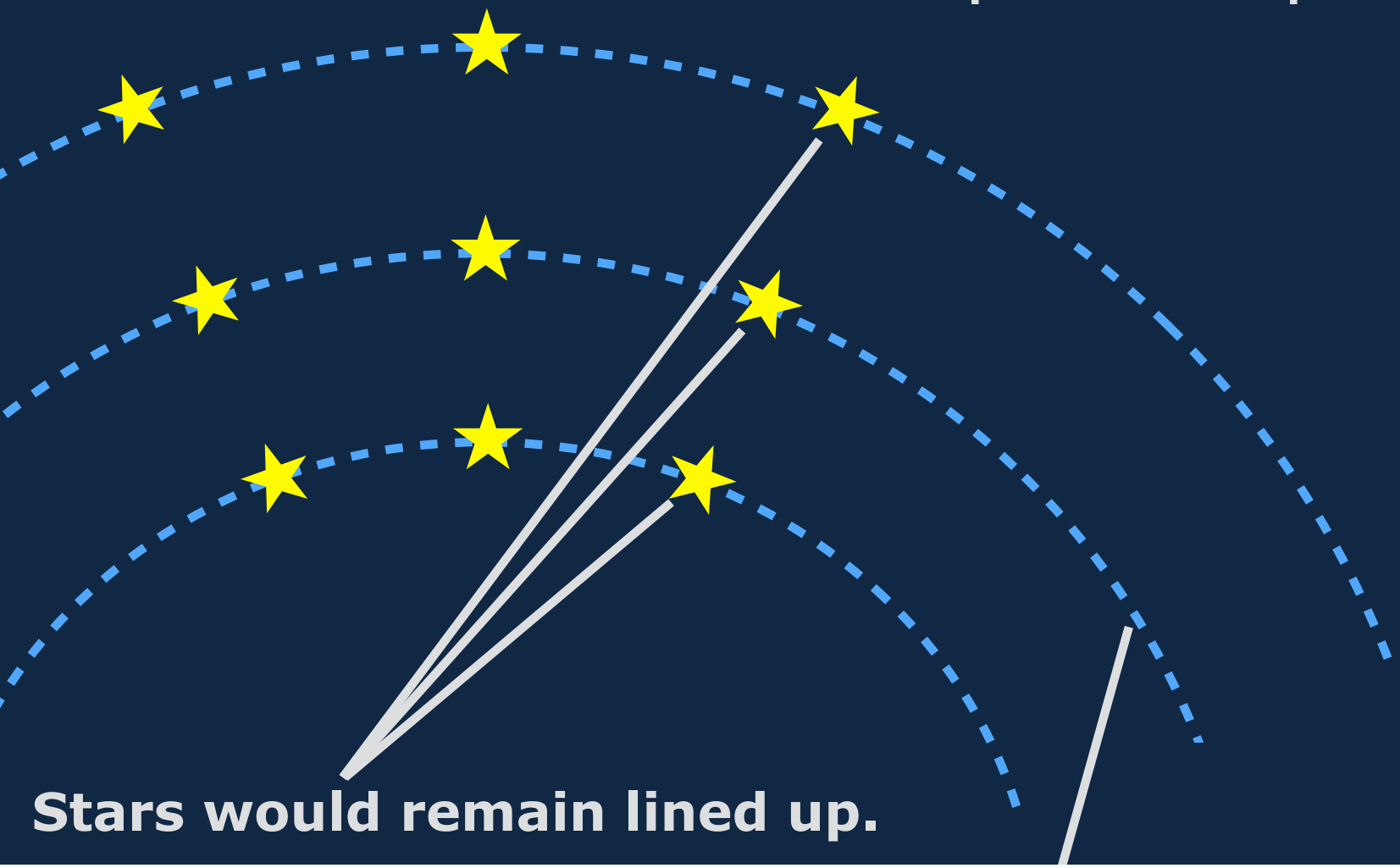
Galactic center

The Milky Way - Mass

Solid body rotation?

centrifugal force = gravitational force

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

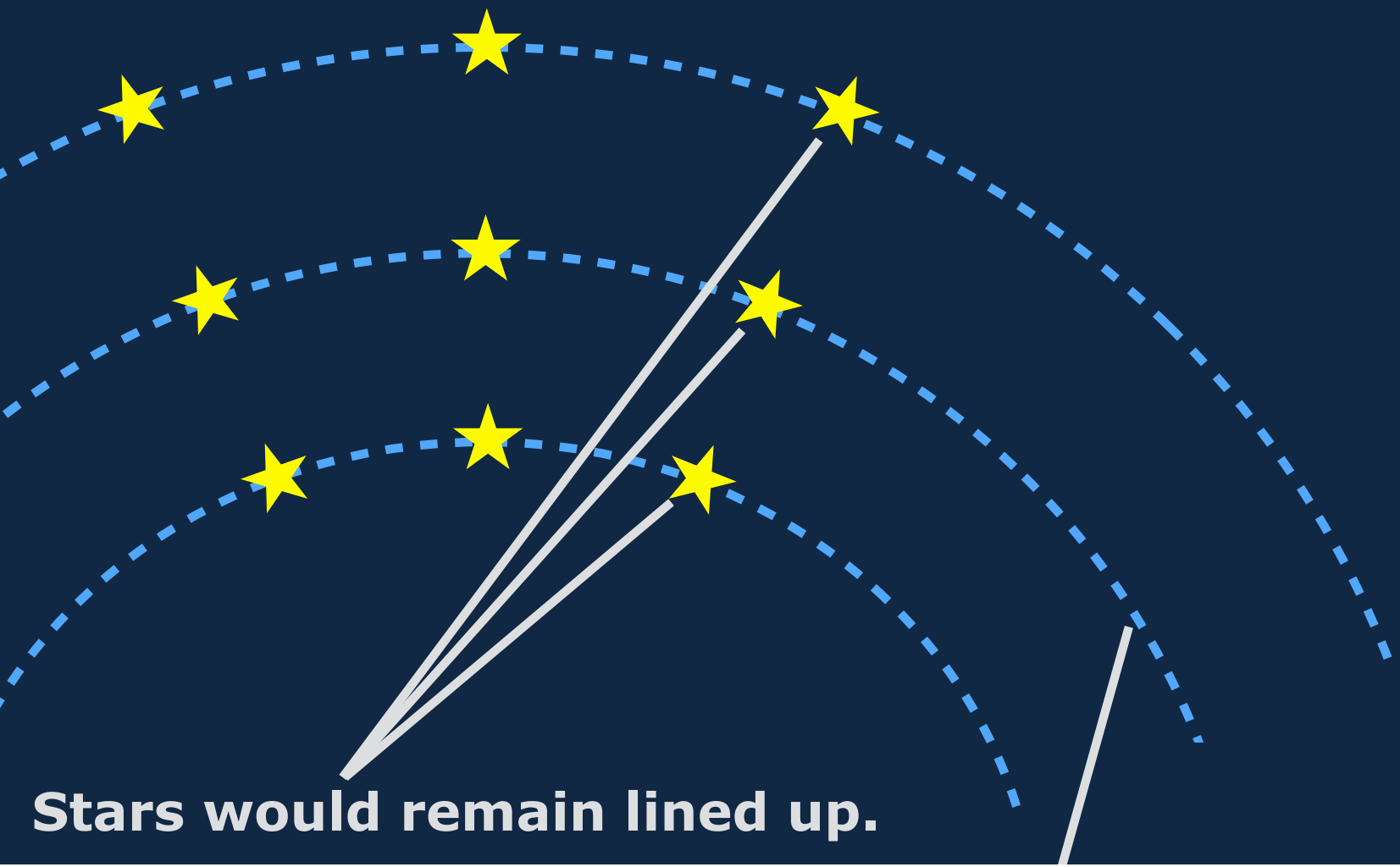


Stars would remain lined up.

The Milky Way - Mass

Solid body rotation?

$v \propto r$



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The Milky Way - Mass

Solid body rotation?

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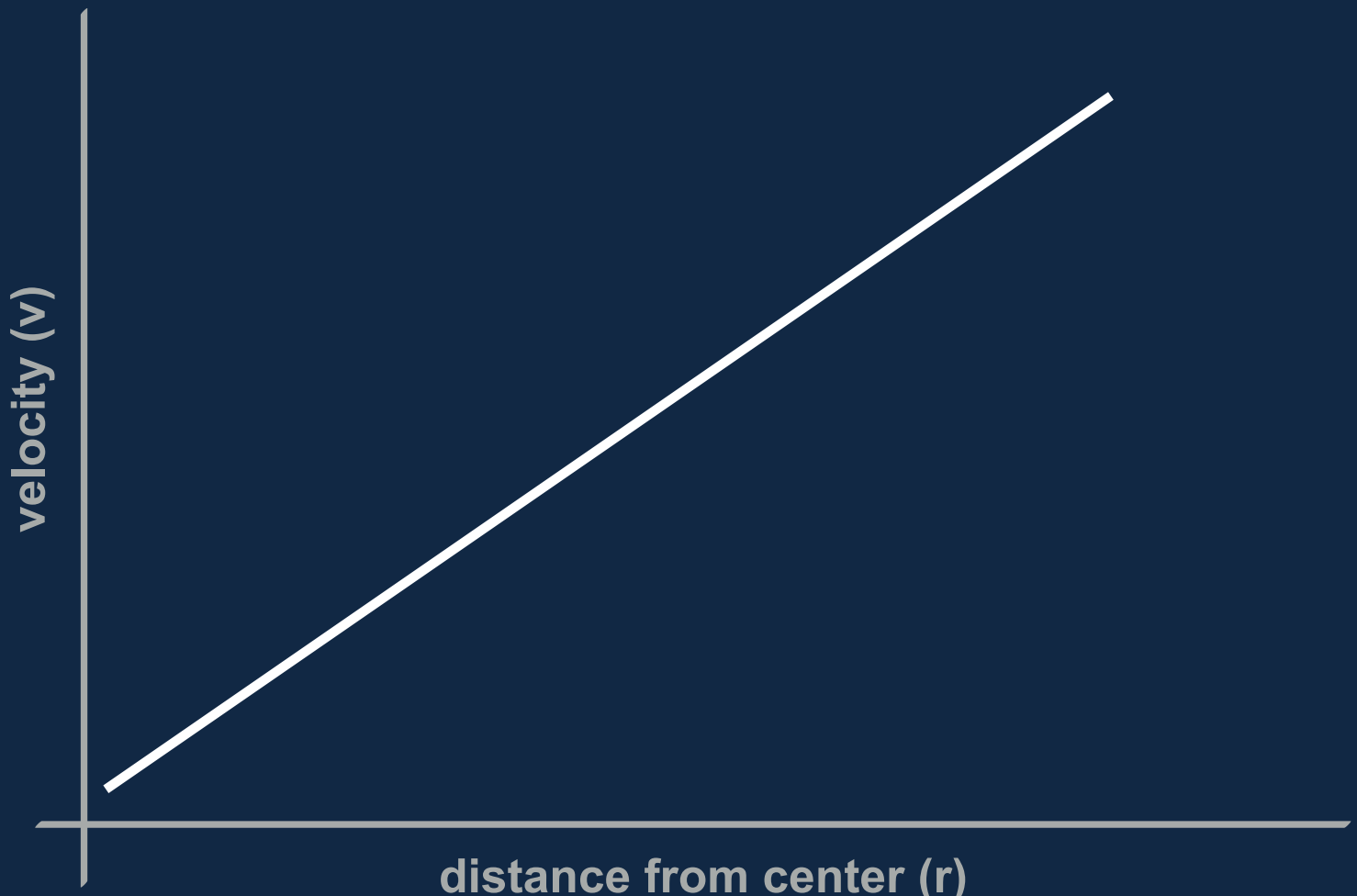
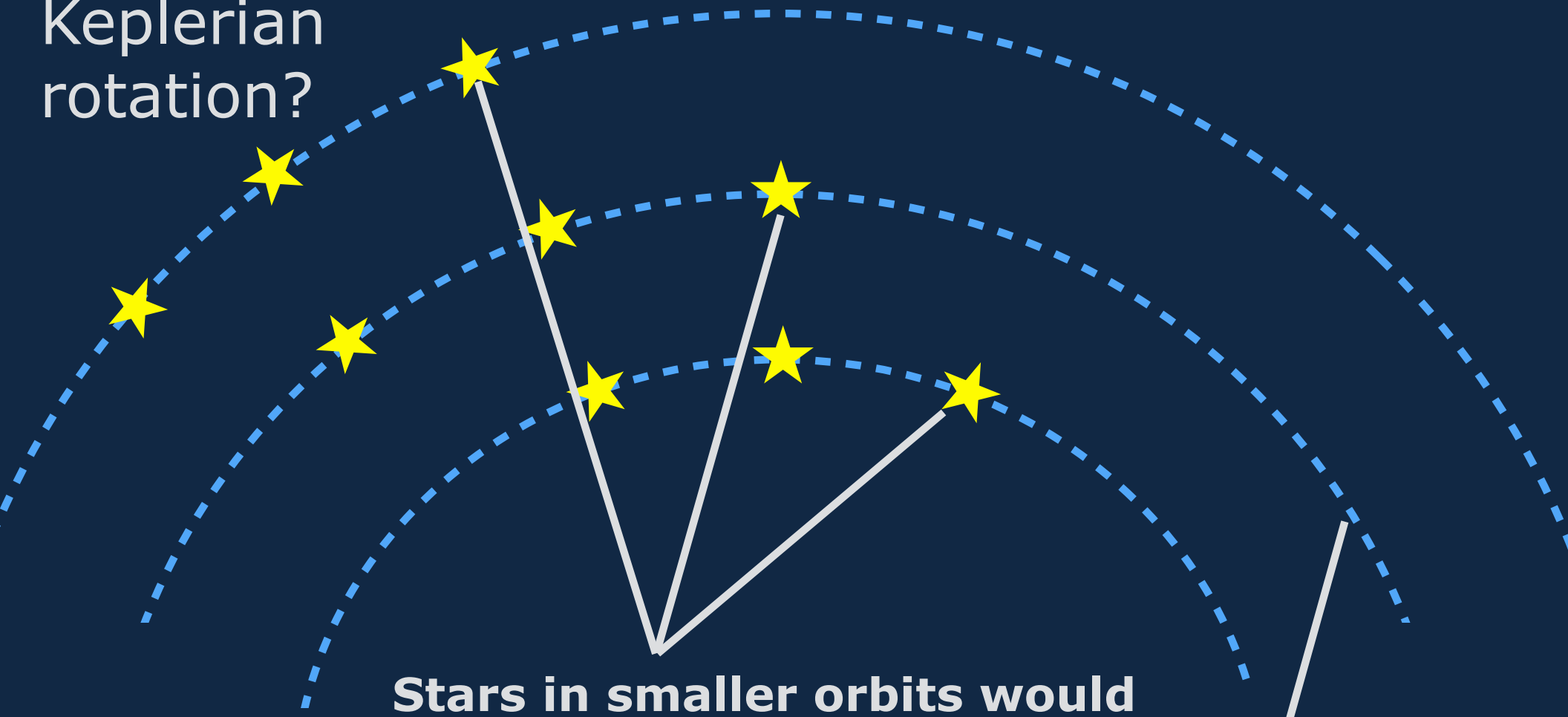


rotation curve

The Milky Way - Mass

Keplerian rotation?



Stars in smaller orbits would rapidly overtake those in larger orbits.

Sun's orbit

+

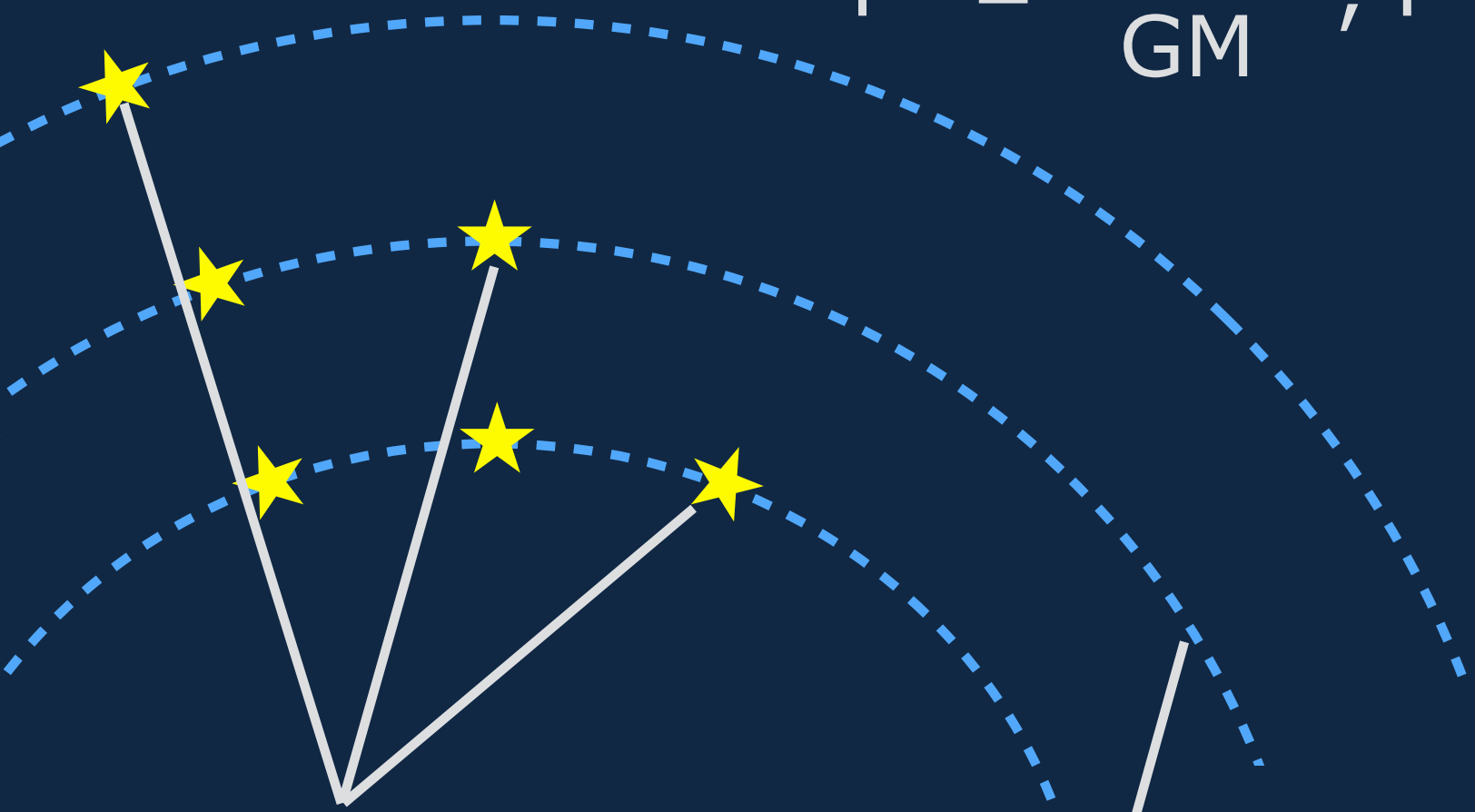
Galactic center

The Milky Way - Mass

Keplerian rotation?

Kepler's 3rd Law:

$$P^2 = \frac{4\pi^2 r^3}{GM}, \quad P = \frac{2\pi r}{v}$$



Stars in smaller orbits would rapidly overtake those in larger orbits.

Sun's orbit

The Milky Way - Mass

Keplerian rotation?

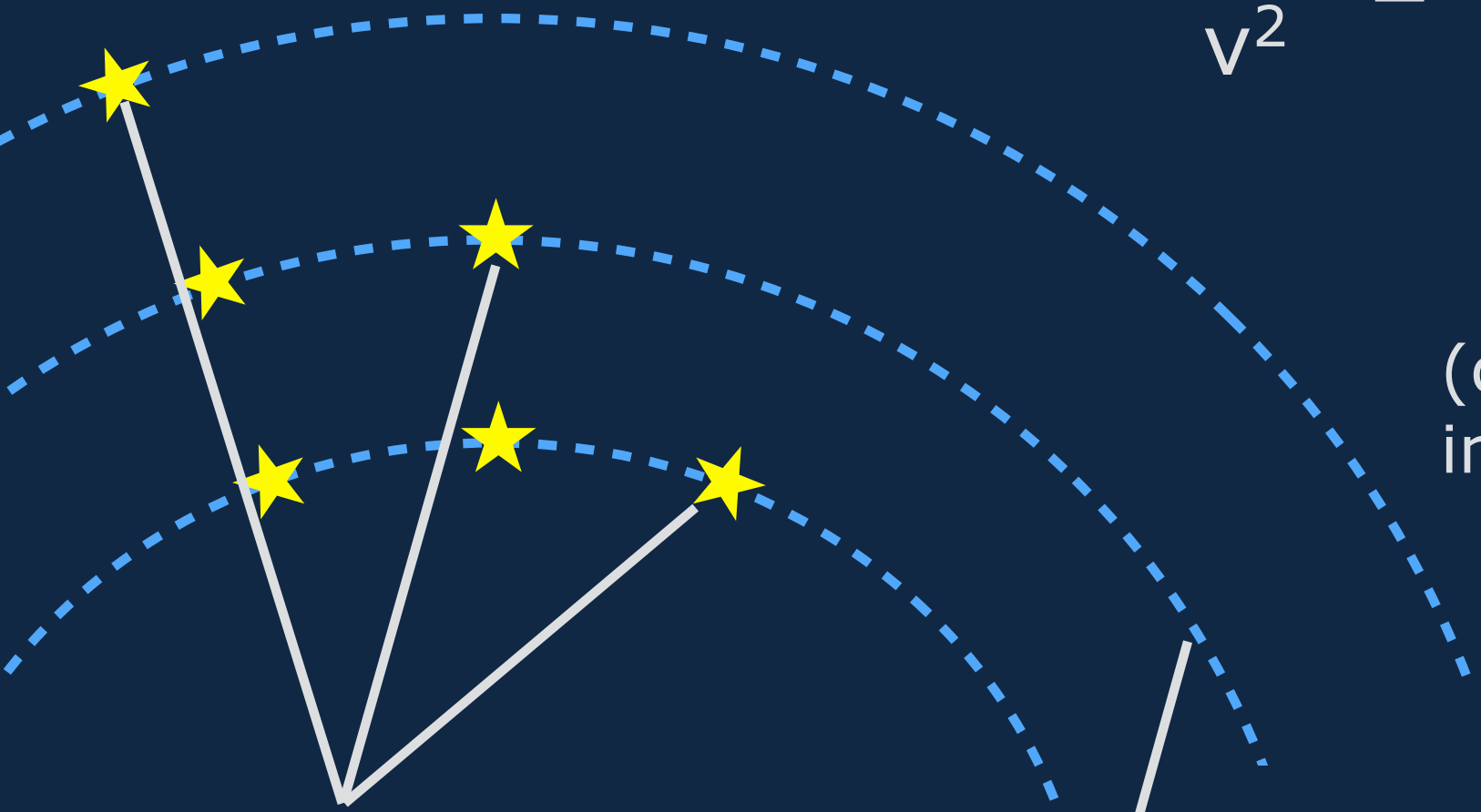
Kepler's 3rd Law:

$$\frac{1}{v^2} = \frac{r}{GM}$$

G = const

M = const

(concentrated in center)



Stars in smaller orbits would rapidly overtake those in larger orbits.

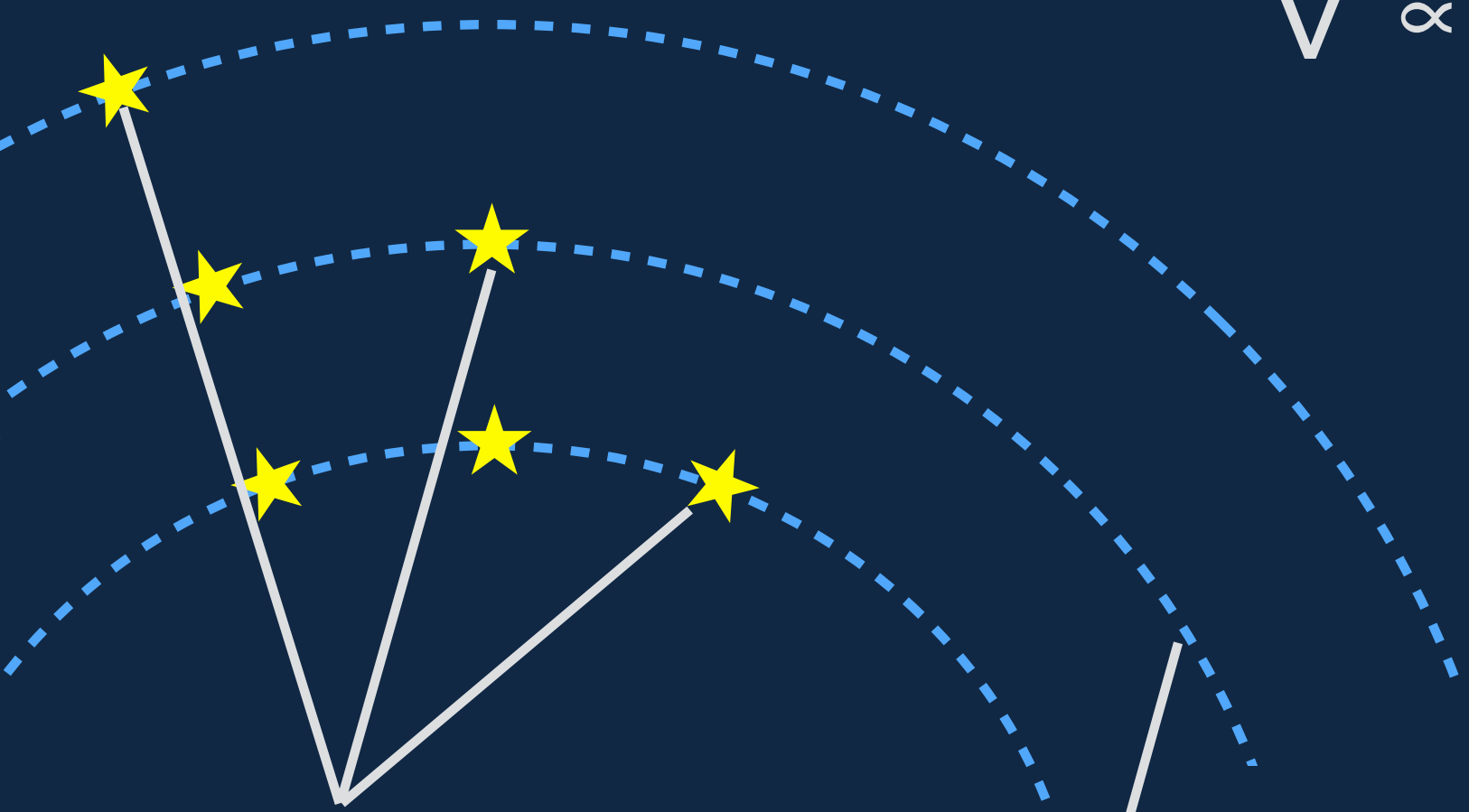
Sun's orbit

The Milky Way - Mass

Keplerian rotation?

Kepler's 3rd Law:

$$v \propto r^{-1/2}$$



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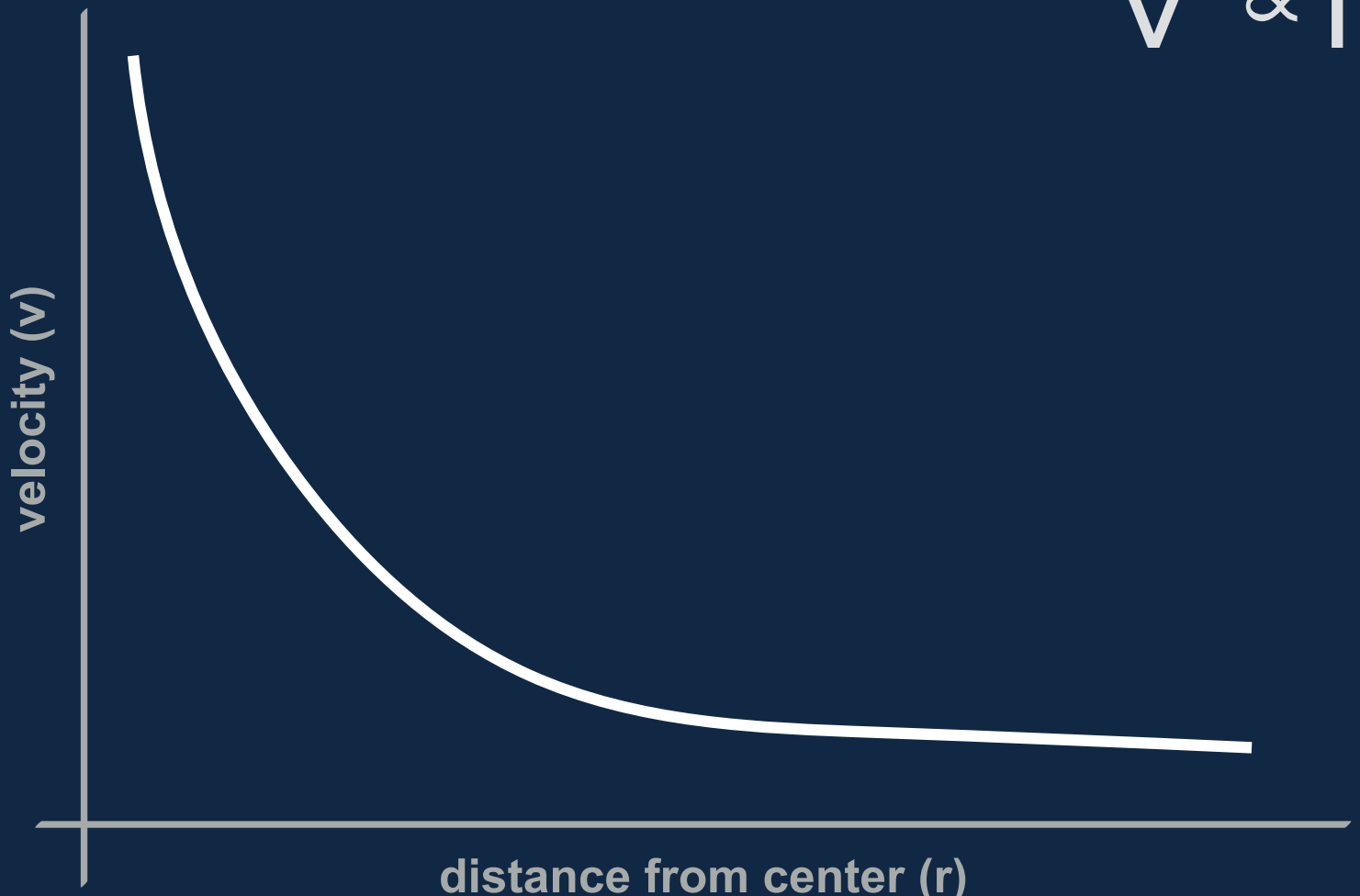
Sun's orbit

The Milky Way - Mass

Keplerian rotation?

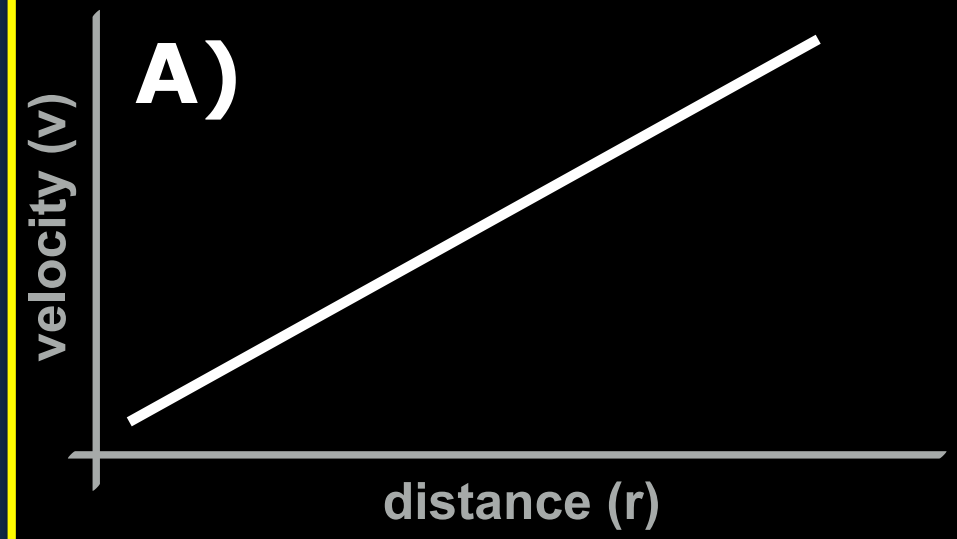
$$v \propto r^{-1/2}$$

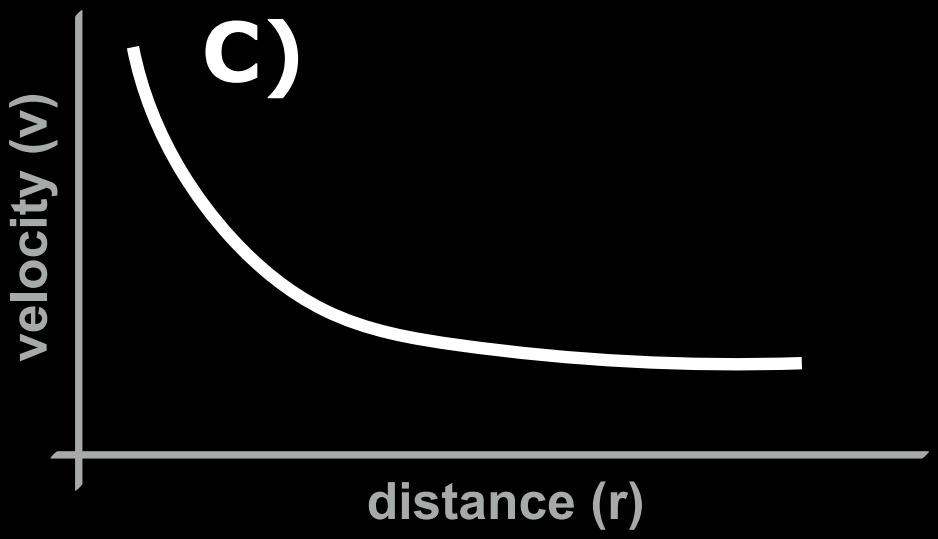


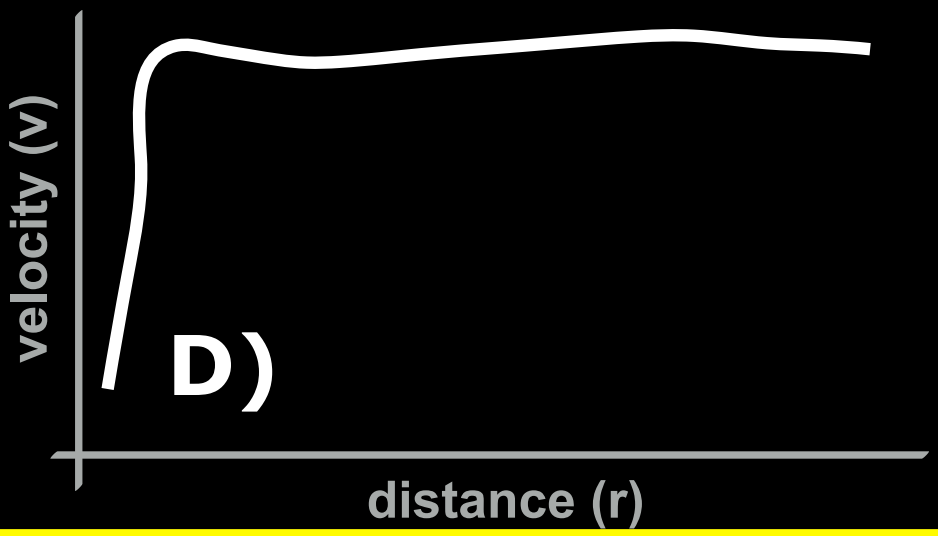
rotation curve

Quick Question

How do we expect the MW velocity curve to look?



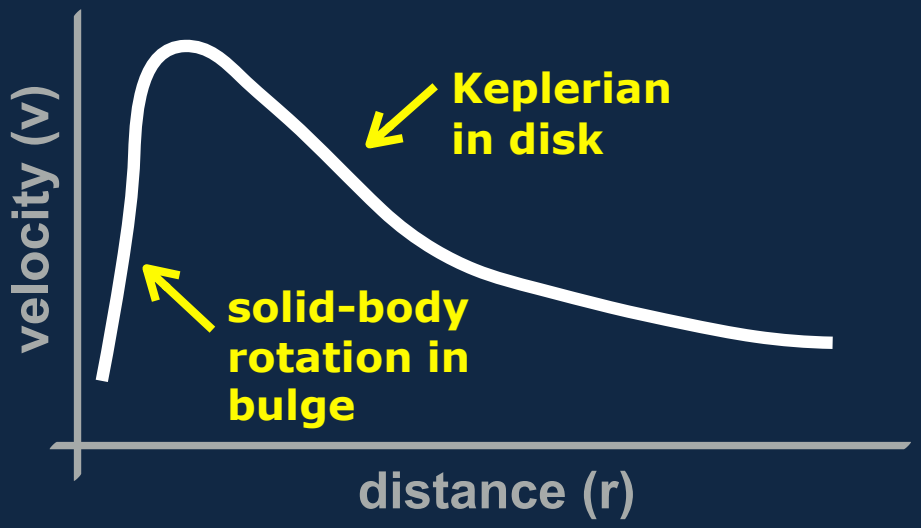


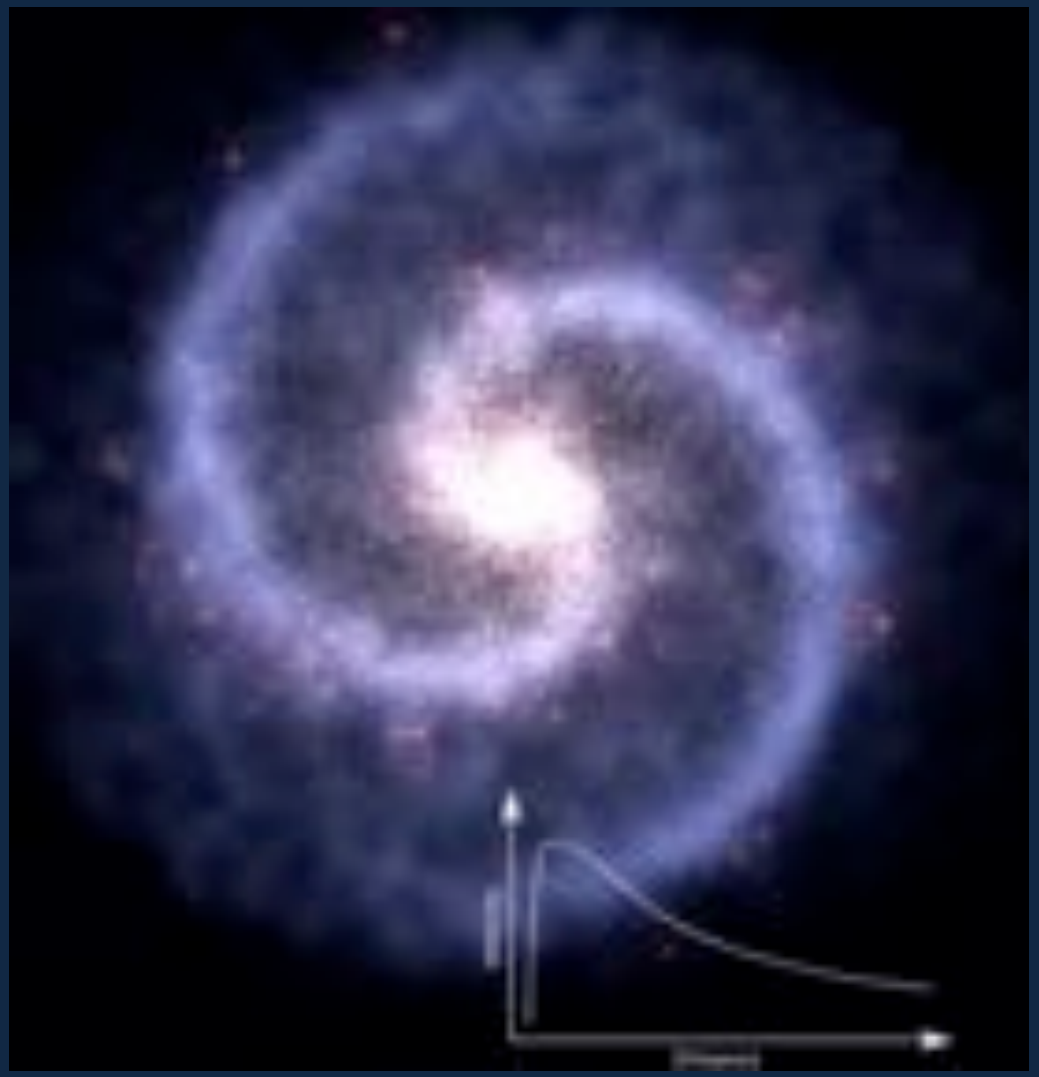


The Milky Way - Mass

Rotation Curve

Observations of the Milky Way and other spiral galaxies should follow predicted rotation curve…



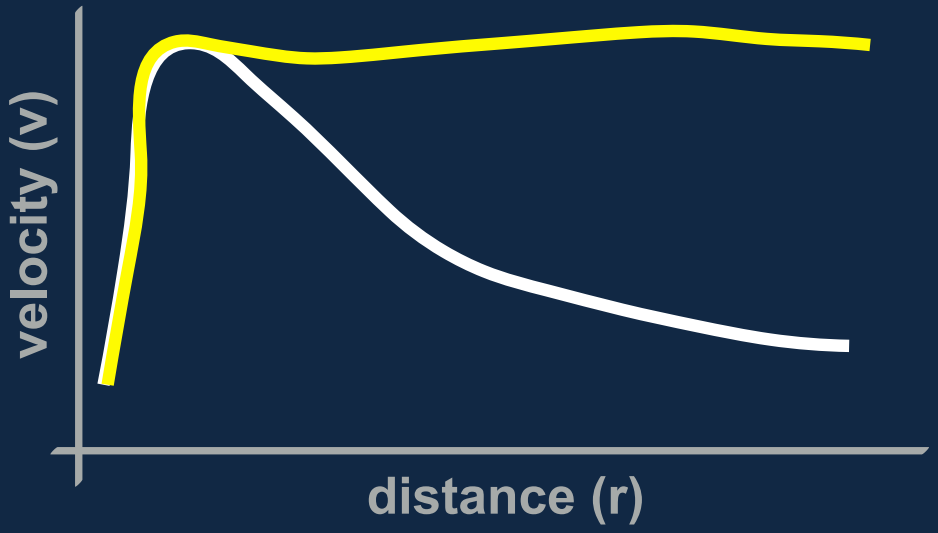


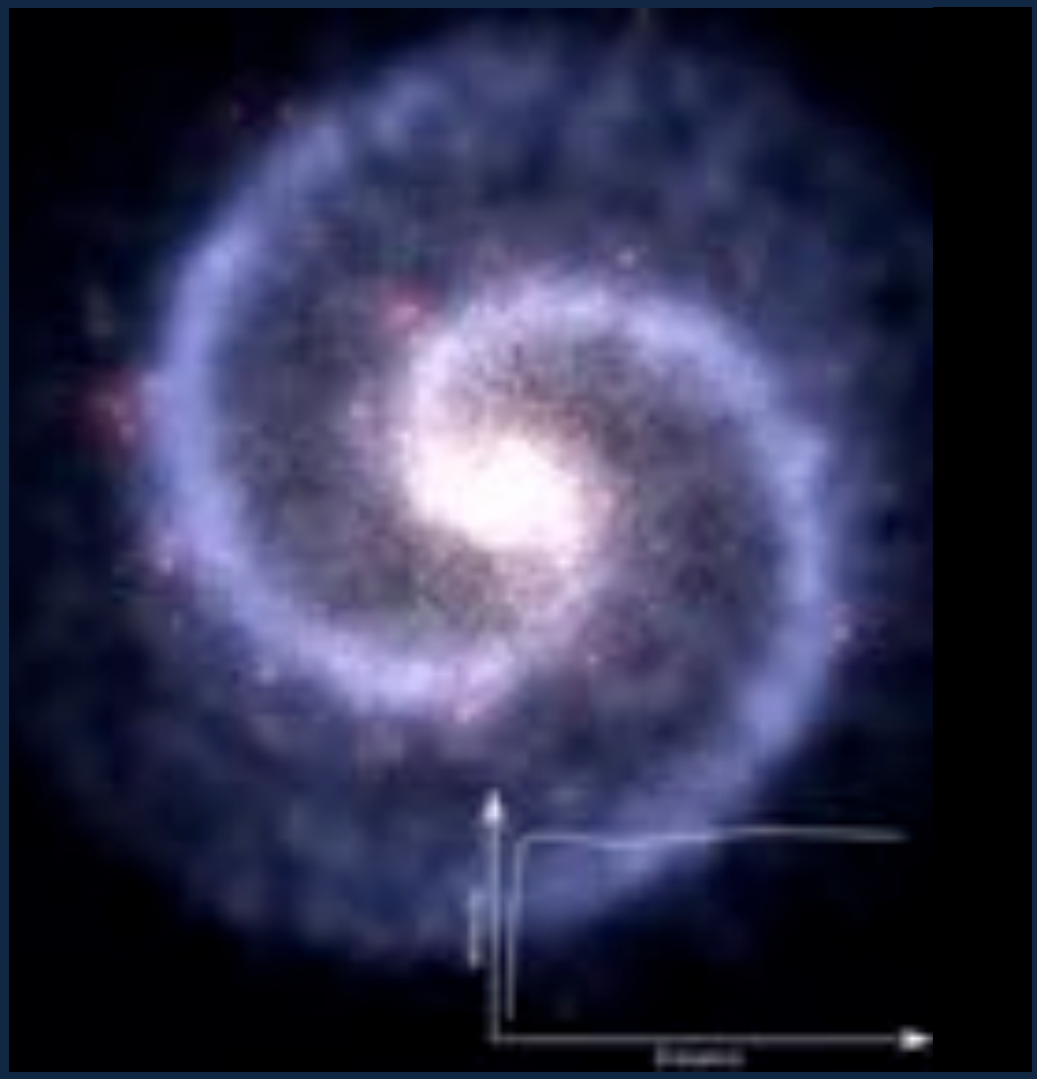
The Milky Way - Mass

Rotation Curve

Observations of the Milky Way and other spiral galaxies should follow predicted rotation curve…

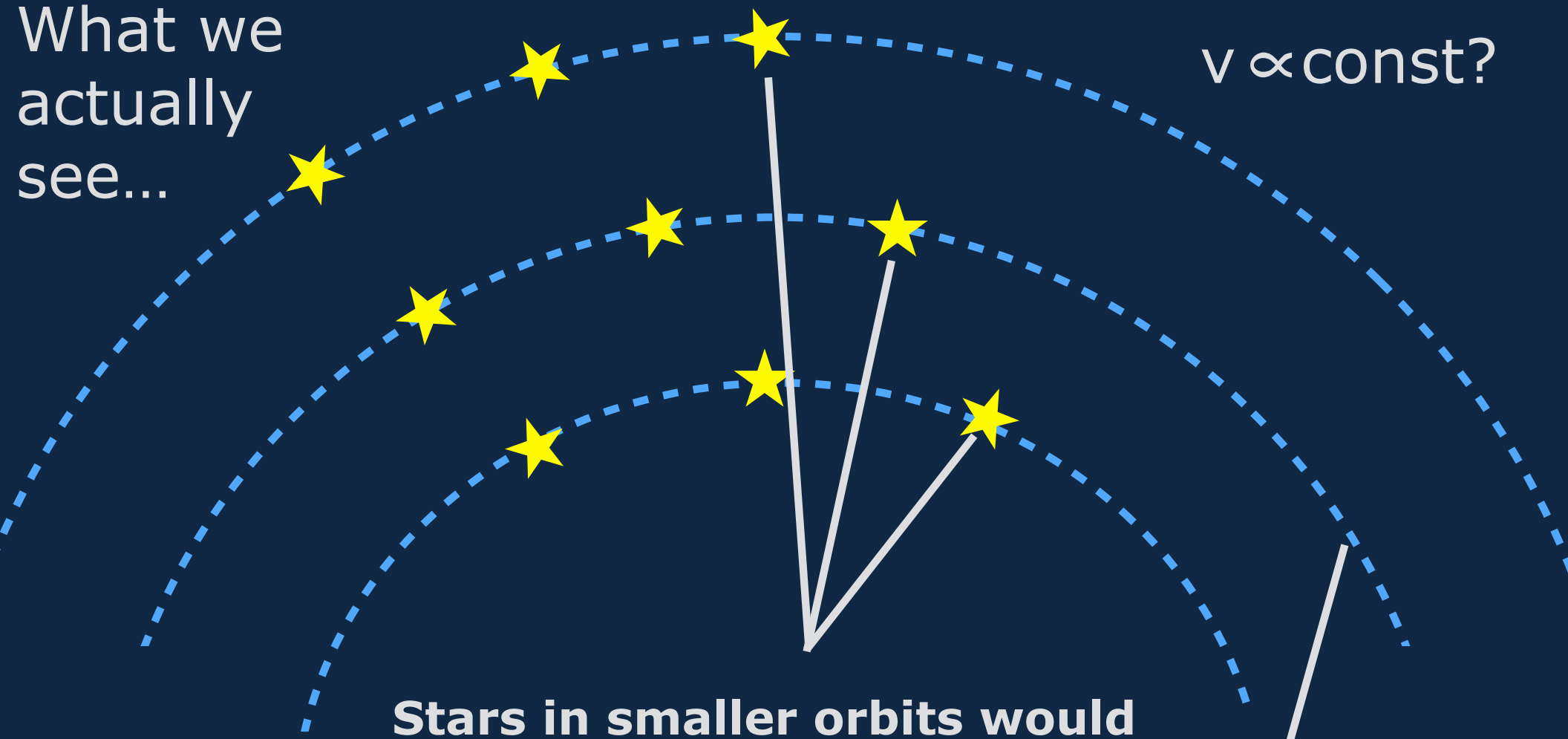
…instead we see this:





The Milky Way - Mass

What we actually see…

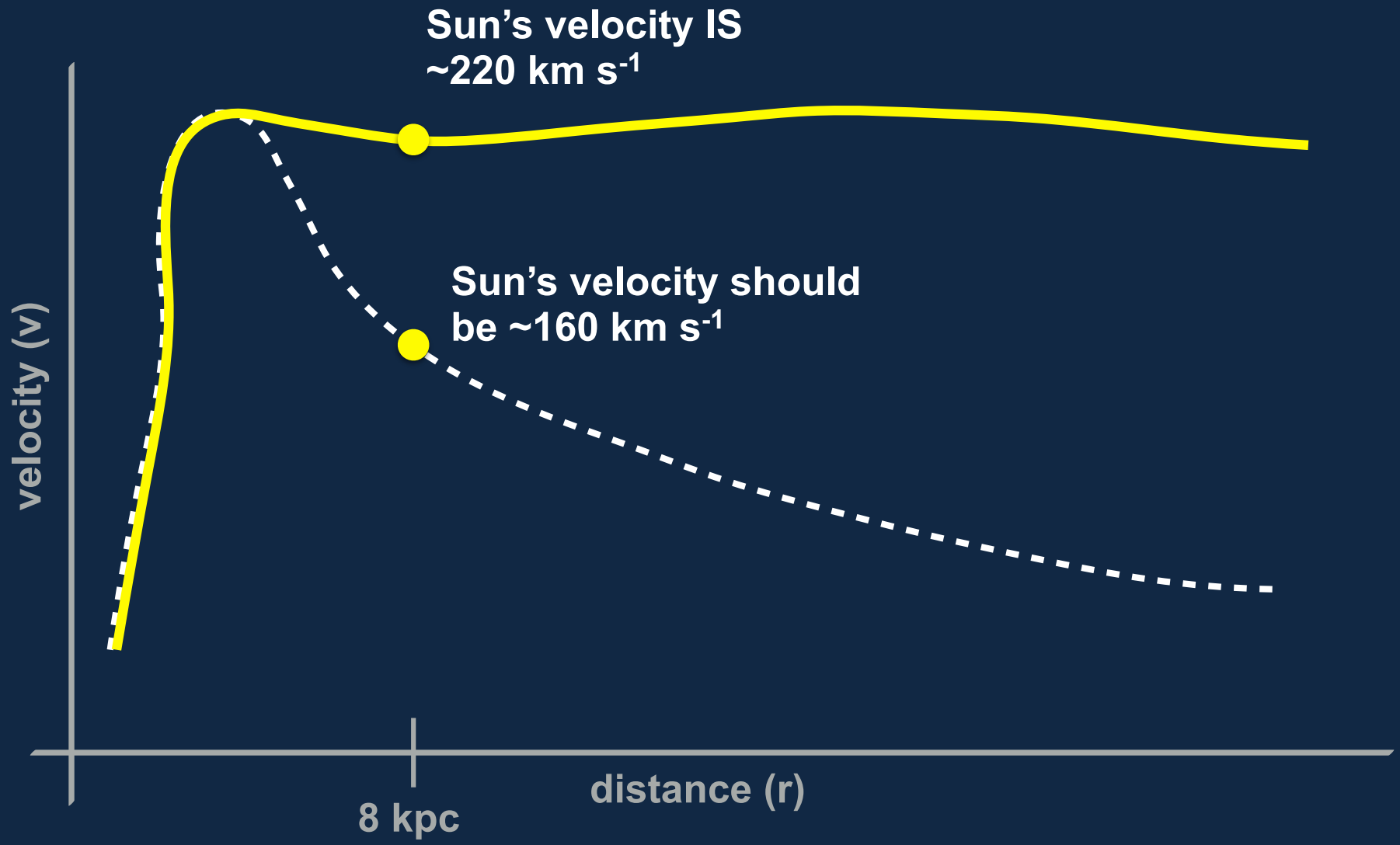


+

Galactic center

The Milky Way - Mass

Rotation Curve

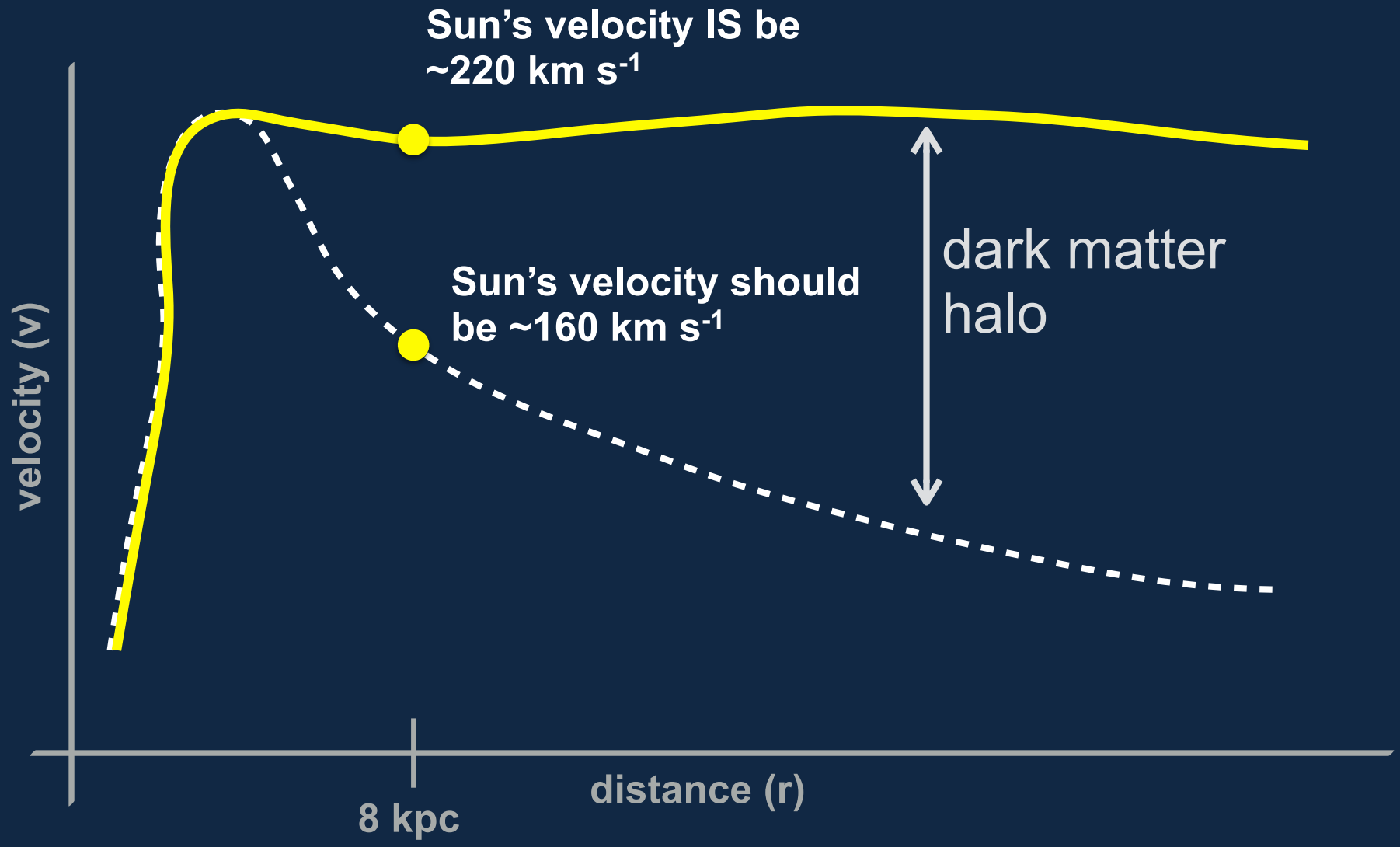


Discussion Question

What's going on?

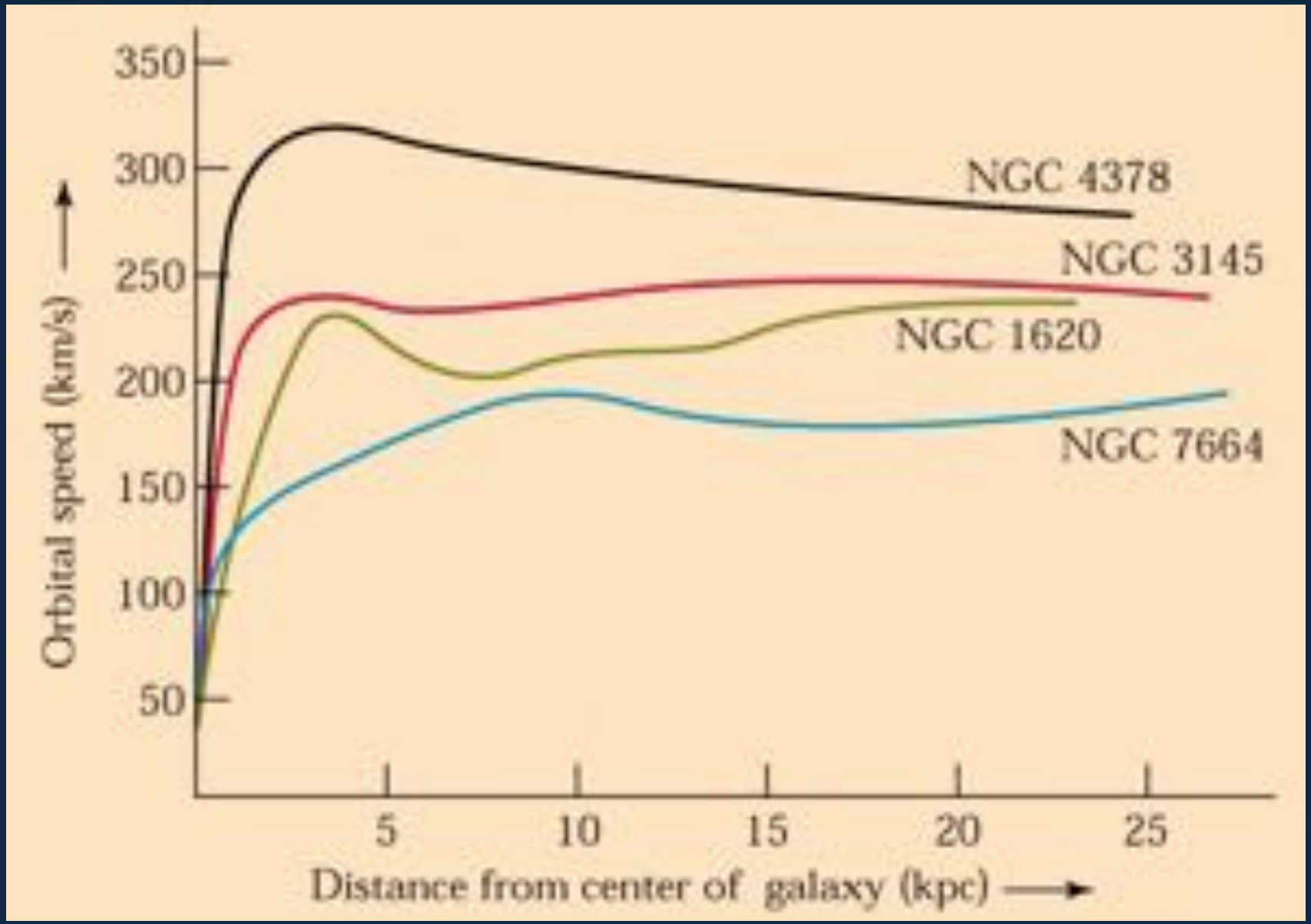
The Milky Way - Dark Matter

Rotation Curve



The Milky Way - Dark Matter

Rotation Curve



The Milky Way – Dark Matter

— researched rotation curves of galaxies in 1970's
— commonly credited with discovery of dark matter
— recognized with over a dozen international research prizes (but never the Nobel)
(out of 207 Nobel Physics Laureates, 2 are women…)

The Milky Way - Dark Matter

What is it?

The composition of dark matter remains unknown…

~~Massive astrophysical compact halo objects (MACHOs)~~

Dim star-sized objects made of baryonic matter (black holes, neutron stars, dim dwarfs and planets)

— we should see them “backlit” by background stars

— theory of Big Bang nucleosynthesis doesn’t predict enough baryons

— no evidence of gravitational interactions with compact dark objects

— fluctuations in cosmic microwave background suggest dark matter is non-baryonic

The Milky Way - Dark Matter

What is it?

The composition of dark matter remains unknown…

~~Massive astrophysical compact halo objects (MACHOs)~~

Dim star-sized objects made of baryonic matter (black holes, neutron stars, dim dwarfs and planets)

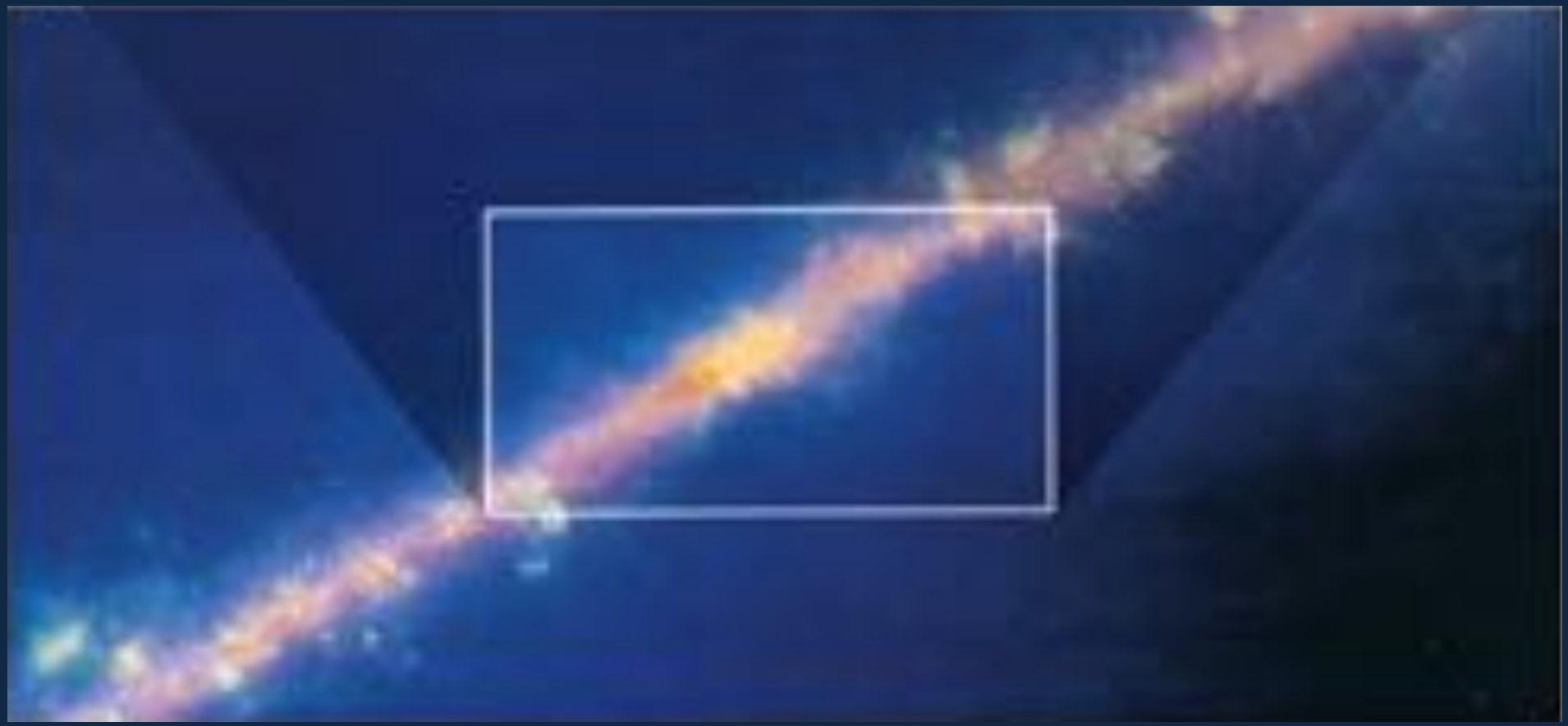
Weakly interactive massive particles (WIMPs)

Non-baryonic subatomic particles; neutrinos? Predictions from supersymmetry?

— no direct or confirmed indirect detections yet…

The Milky Way - Galactic Center

The nucleus of the Galaxy has been studied via its radio, **IR**, and X-ray emission…



Wide-angle view in IR

The Milky Way - Galactic Center

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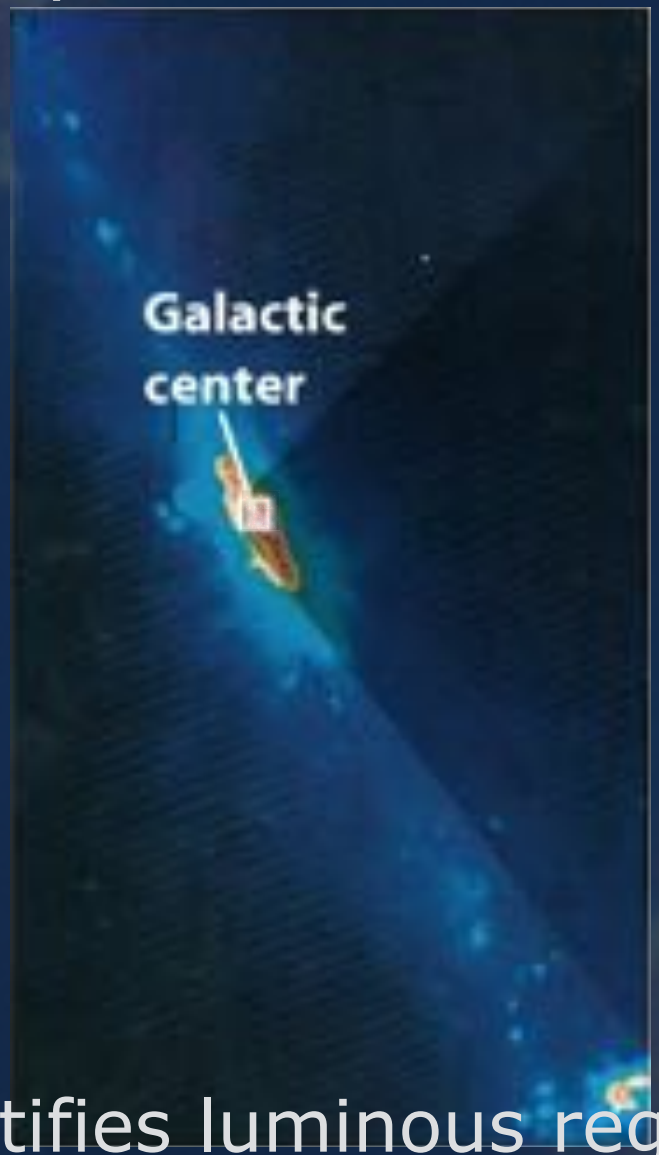


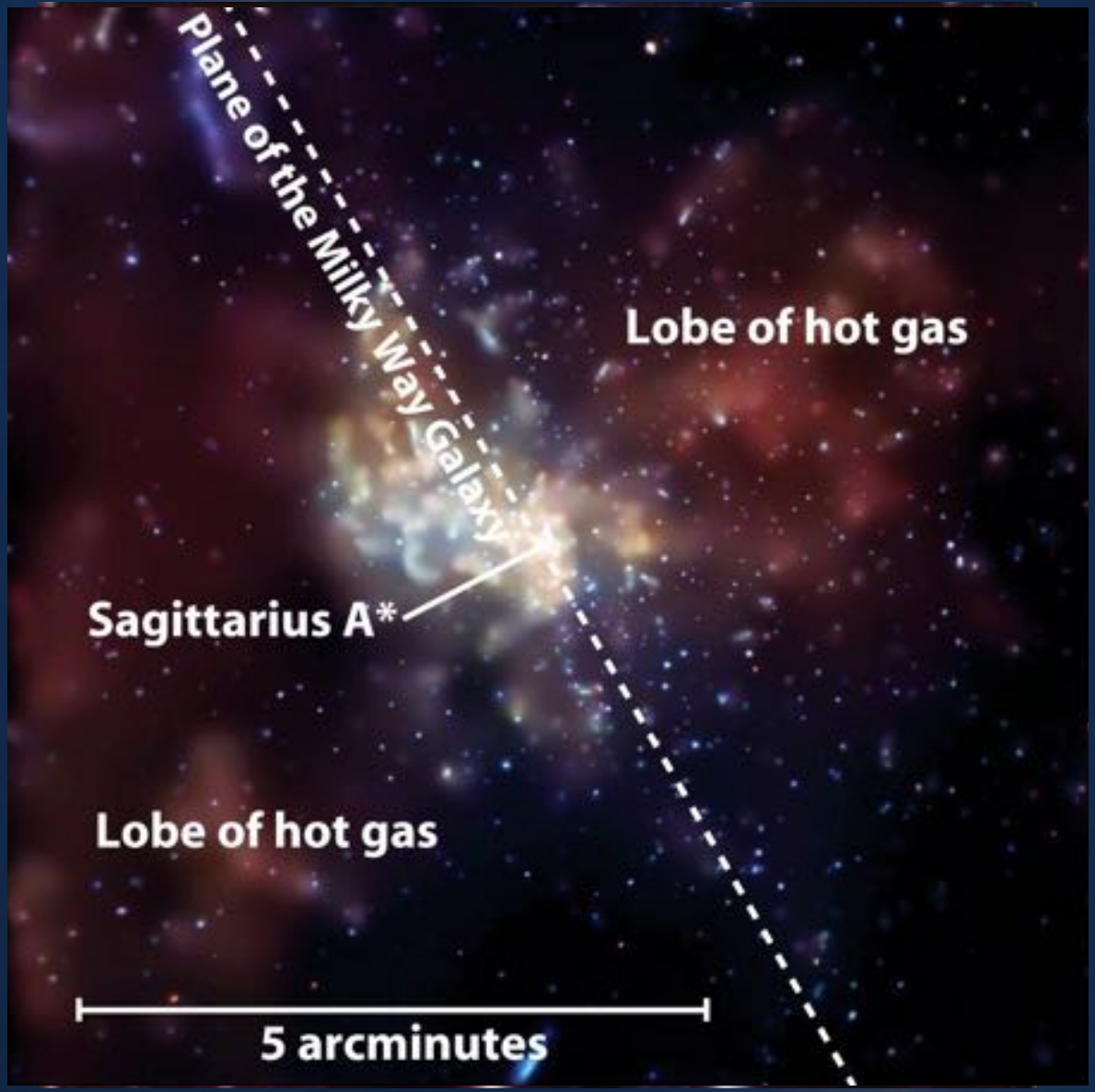
Close-up identifies luminous region in center…

The Milky Way - Galactic Center

The nucleus of the Galaxy has been studied via its radio, **IR**, and X-ray emission…

The Milky Way - Galactic Center

The nucleus of the Galaxy has been studied via its radio, IR, and **X-ray emission**…



The Milky Way - Galactic Center

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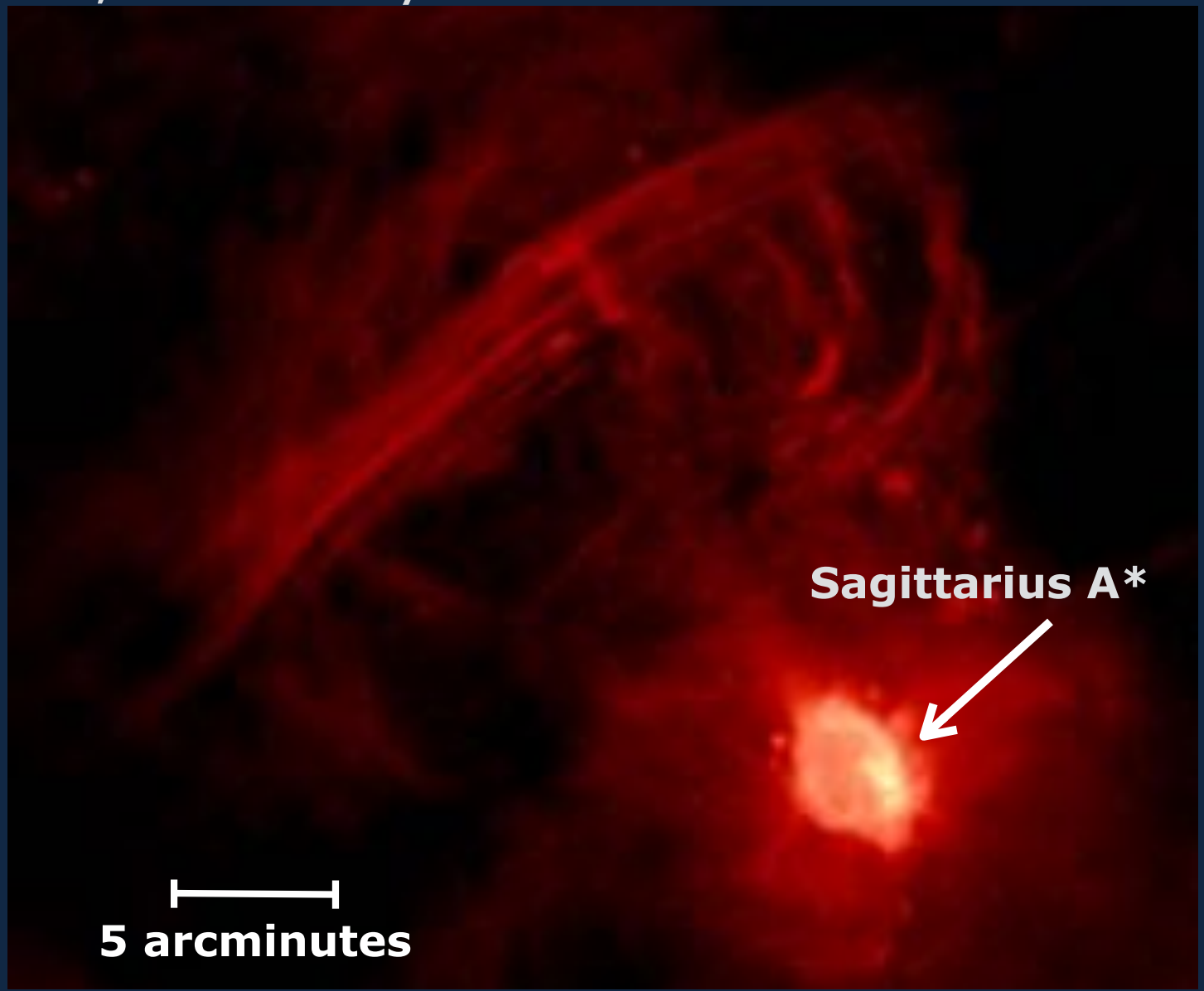
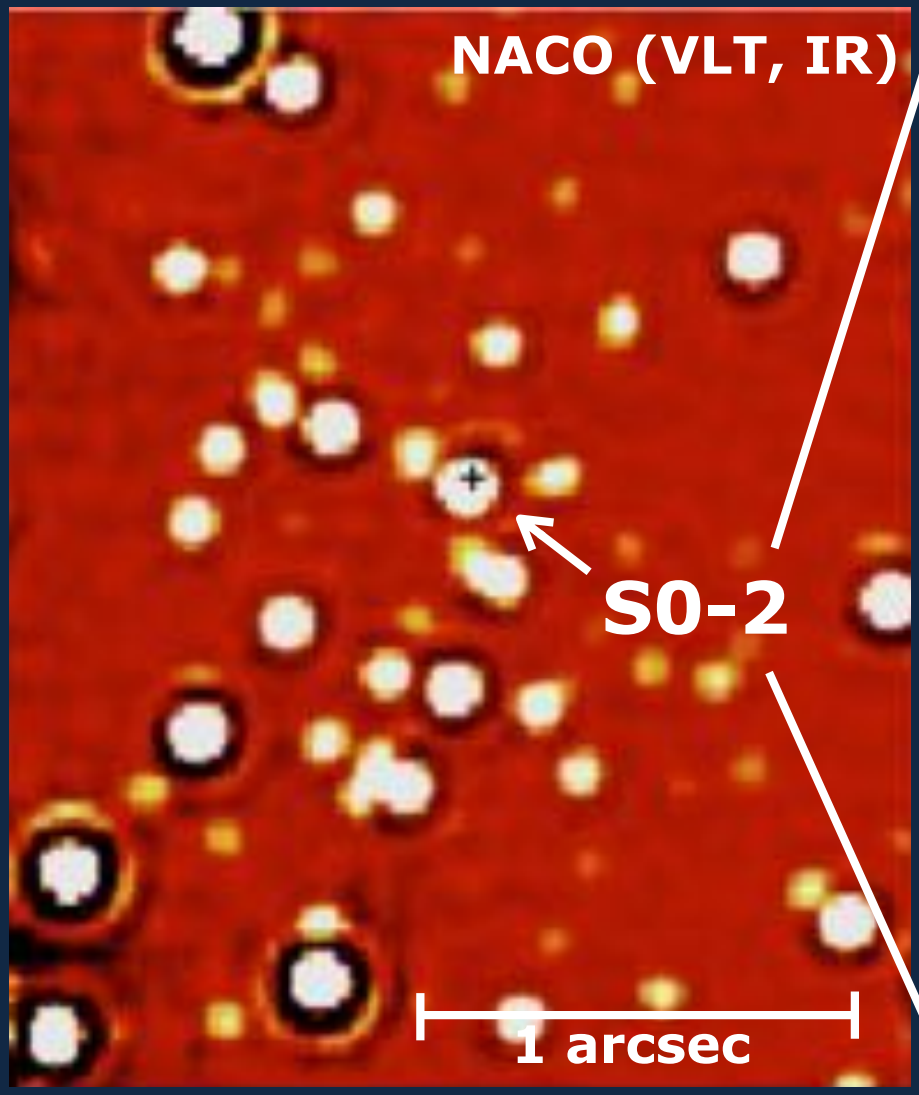
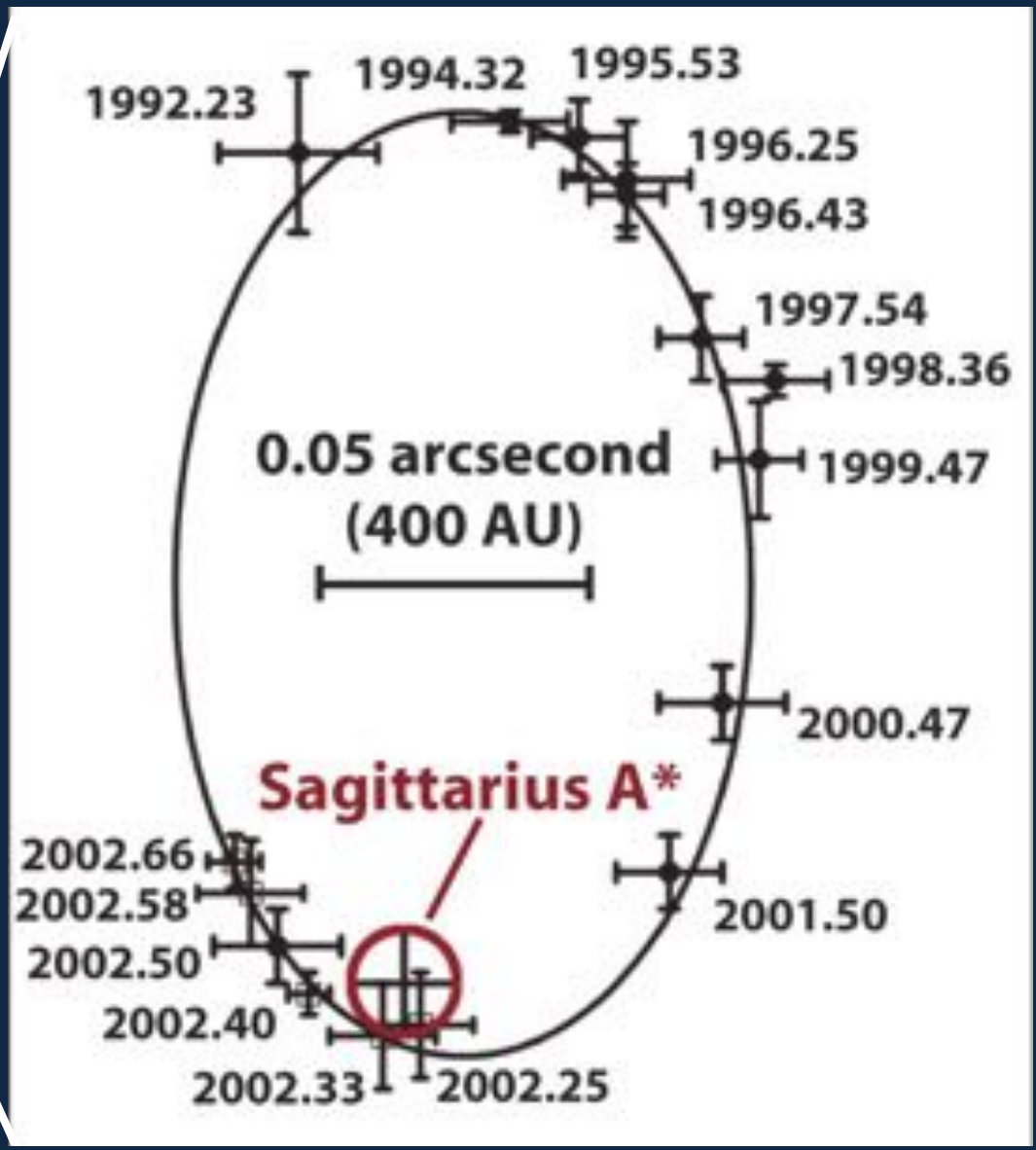


The Milky Way - Galactic Center

The "+" marks Sgr A*, a supermassive black hole with $M \sim 3.6 \times 10^6 M_\odot$





The Milky Way - Galactic Center

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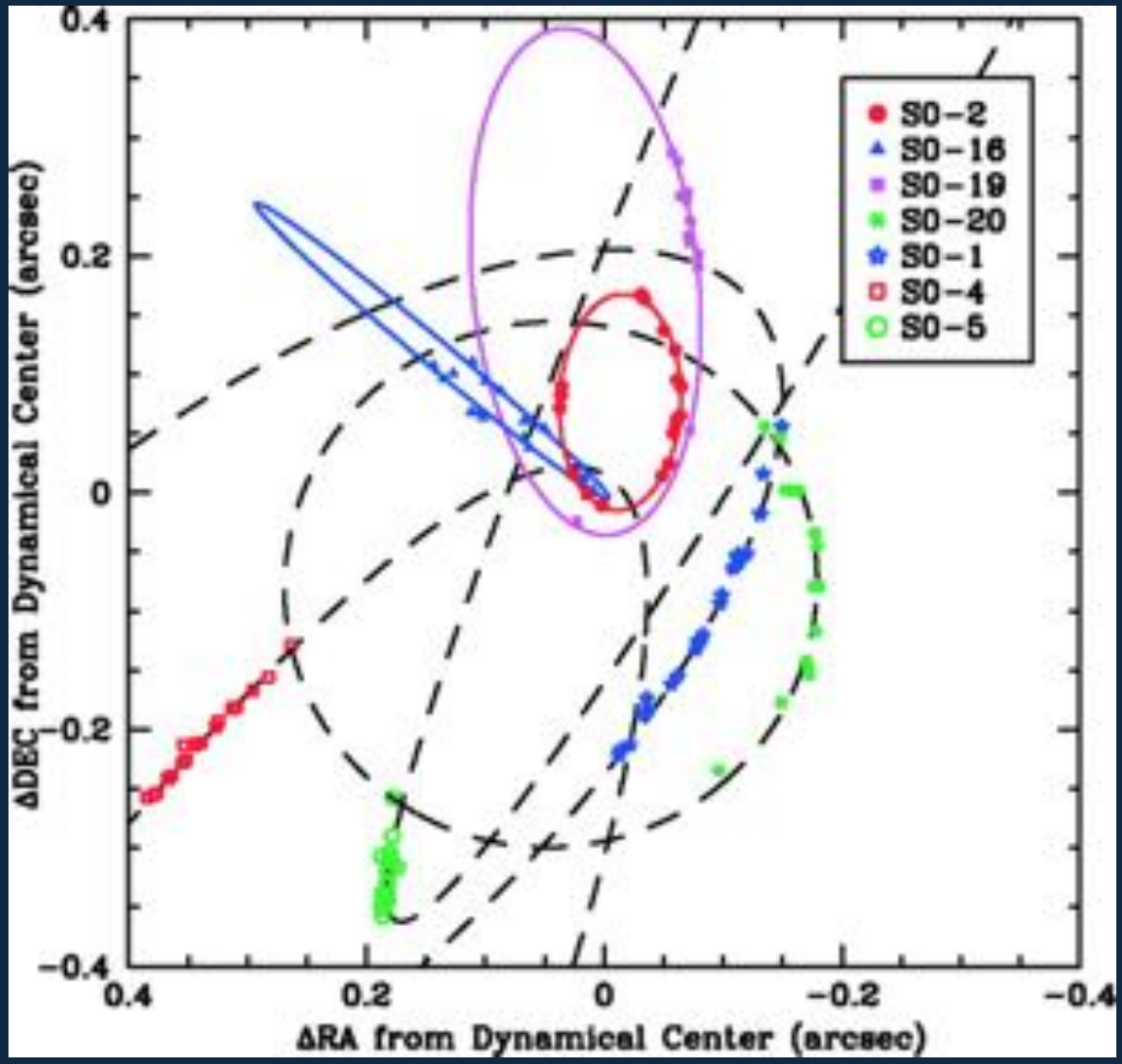

The Milky Way - Galactic Center

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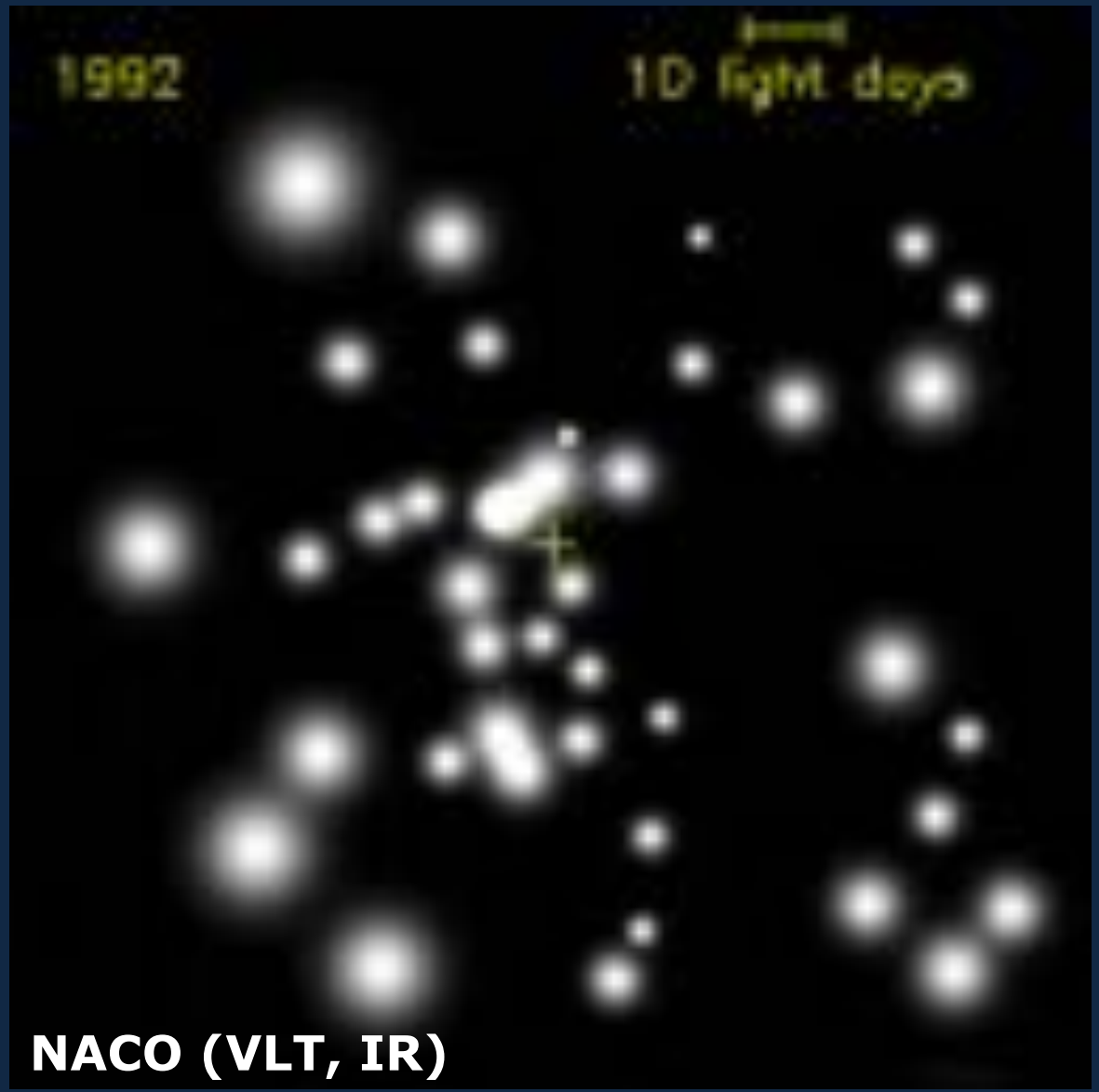


The Milky Way - Galactic Center

The "+" marks Sgr A*, a supermassive black hole with $M \sim 3.6 \times 10^6 M_\odot$

Discussion Question

How do we know that Sag A* is a supermassive black hole?

Discuss, then list reasons

The Milky Way - Galactic Center

Evidence for SMBH:

- stationary (at dynamic center of MW)
- high-energy X-ray source
- small (< solar system from radio)
- no visible object in optical or IR
- motions of nearby stars (1000's of km/s) imply mass

How does an SMBH form?

- stars in center are < 1000AU apart (200,000AU near sun)
- SN chain reaction could produce many stellar BHs
- collisions between BHs cause monster supermassive BH

The Milky Way - Galactic Center

Evidence for SMBH:

- stationary (at dynamic center of MW)
- high-energy X-ray source

New Result Today: binary SMBH??

UW grad student (Trevor Dorn-Wallenstein) discovered what may be the first case of a binary SMBH in a distant galaxy behind M31.

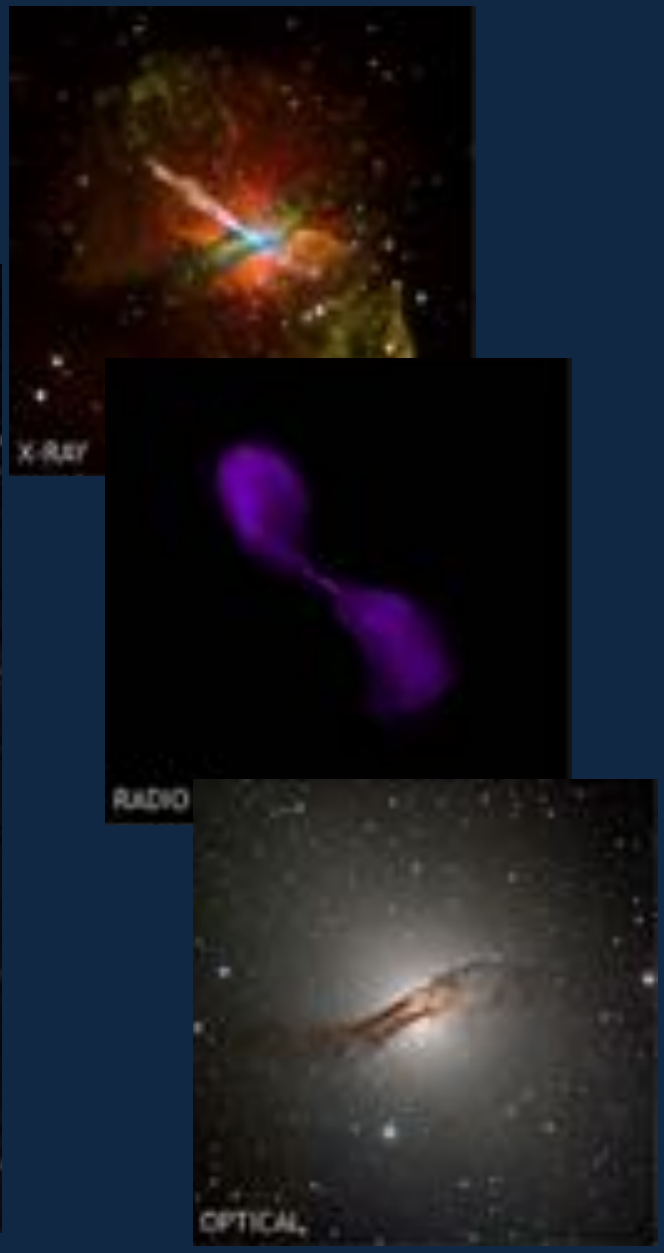
Check out UW news page!

- collisions between BHs cause monster supermassive BH

The Milky Way - Galactic Center

Does the Milky Way have an **active galactic nucleus**?

AGN = hot accretion disk &
(sometimes) relativistic jets



The Milky Way - Galactic Center

Does the Milky Way have an **active galactic nucleus**?

AGN = hot accretion disk &
(sometimes) relativistic jets

No

The Milky Way - Galactic Center

Does the Milky Way have an **active galactic nucleus**?

AGN = hot accretion disk &
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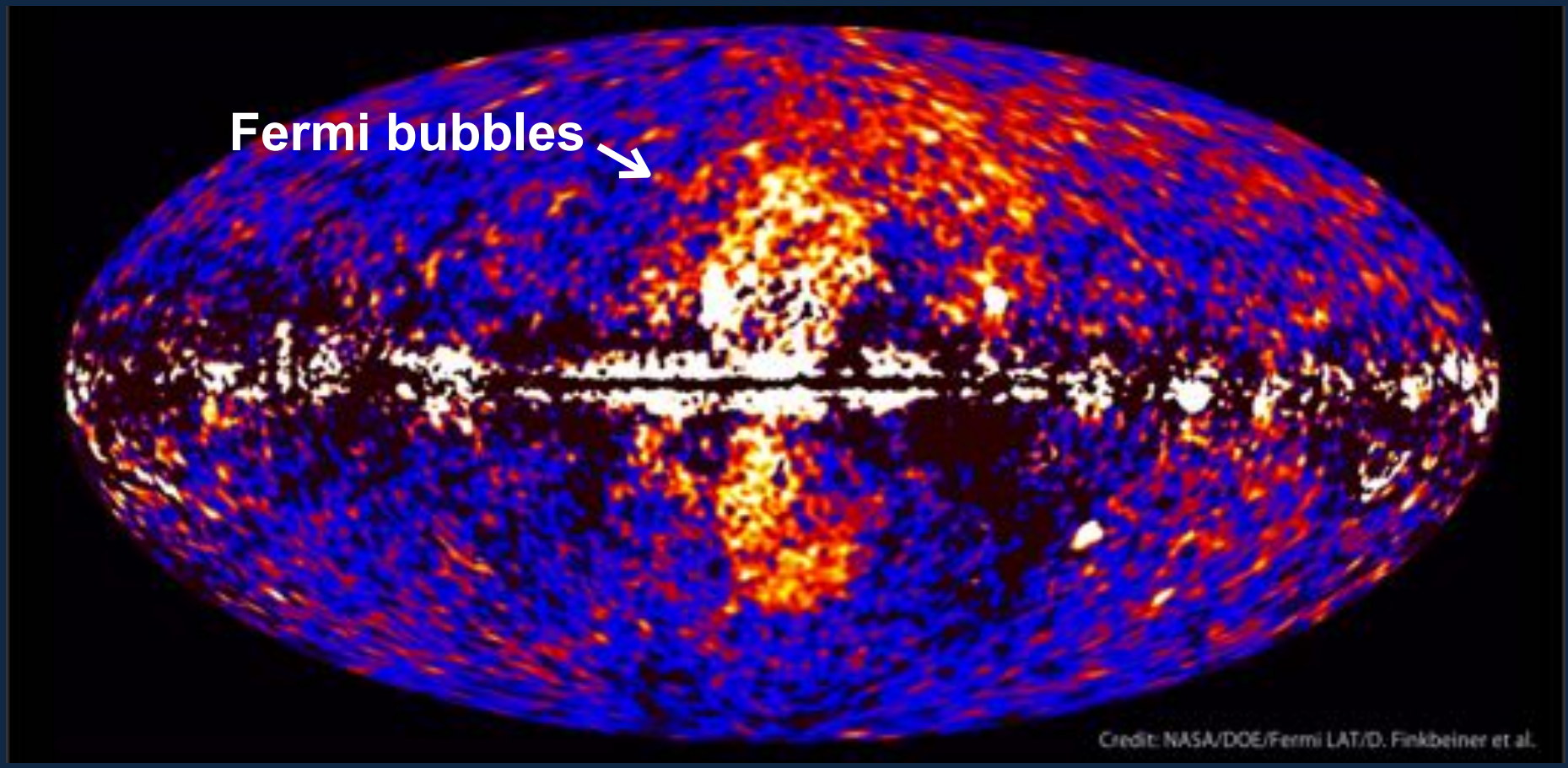

red: gamma-ray
blue: microwave

Not now…

The Milky Way - Galactic Center

Does the Milky Way have an **active galactic nucleus**?

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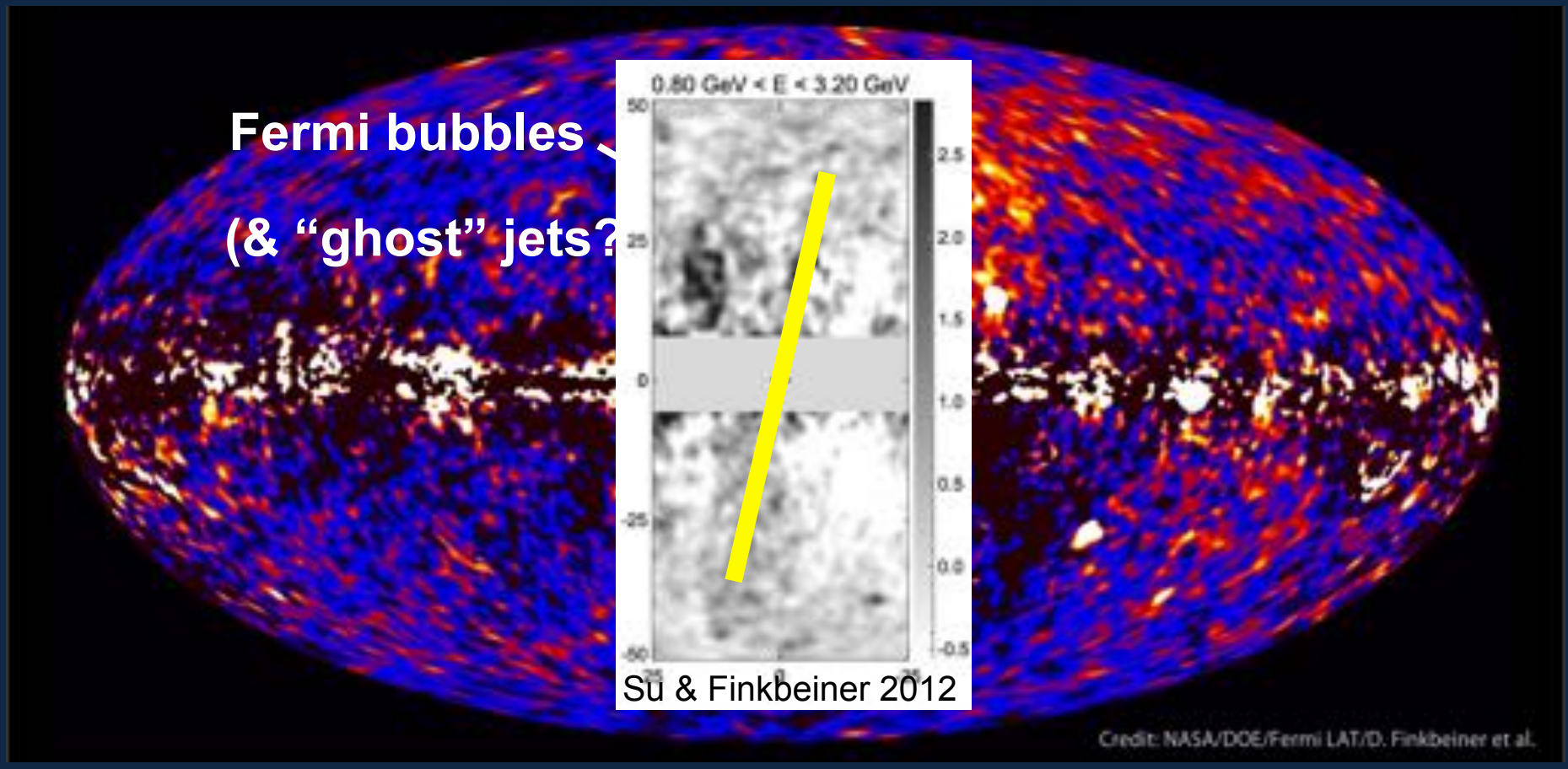
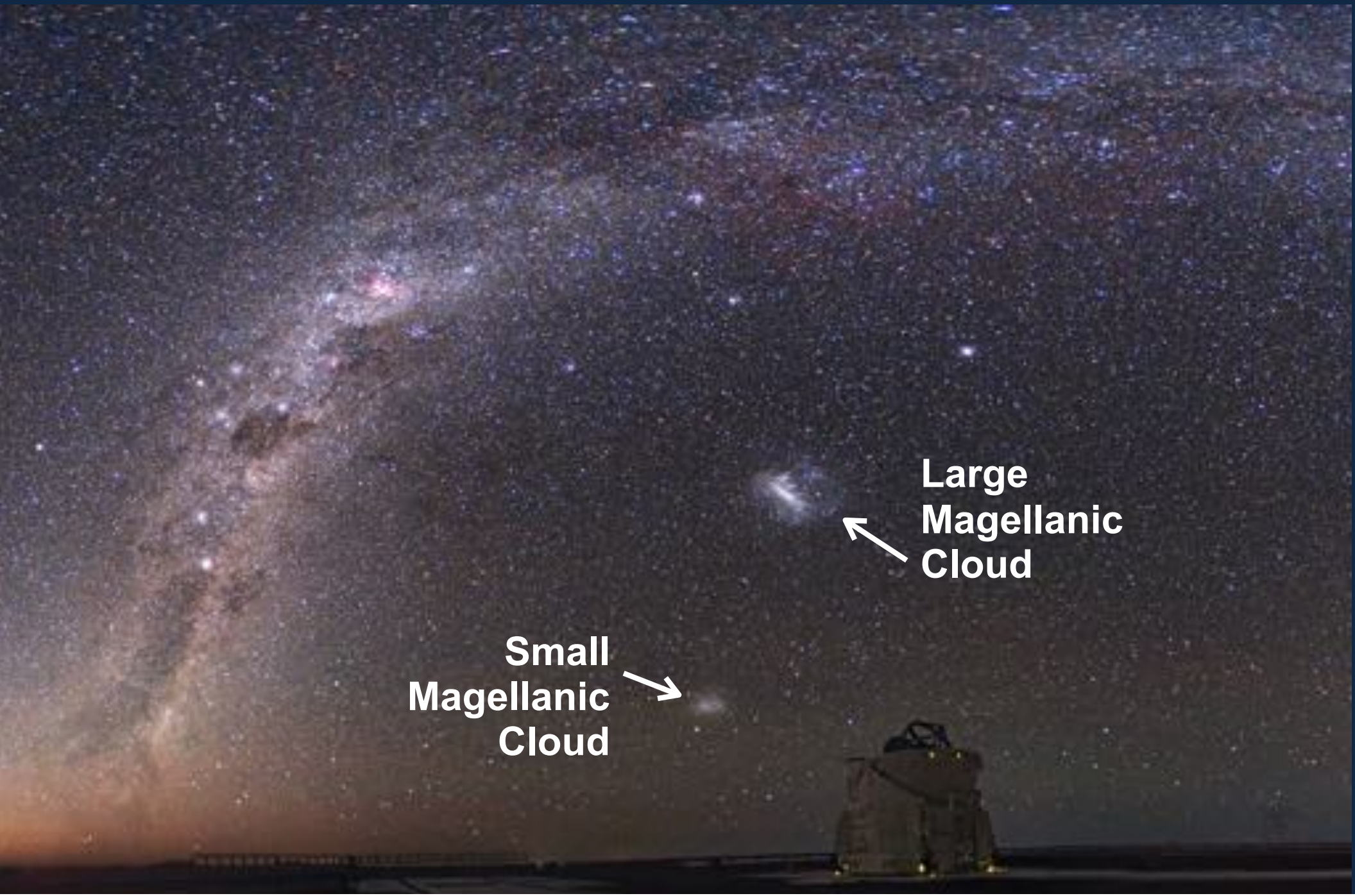
(sometimes) relativistic jets



red: gamma-ray
blue: microwave

Not now…

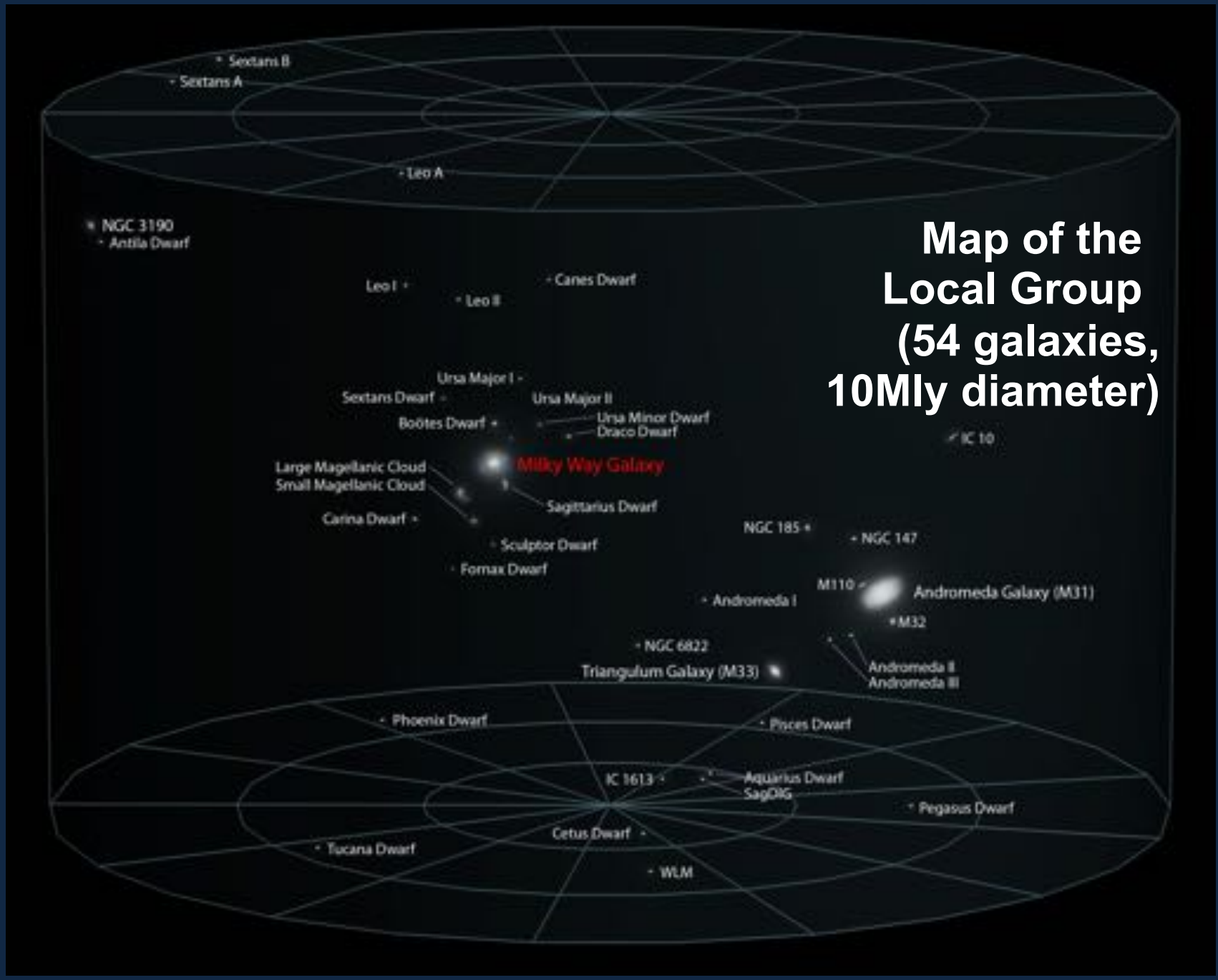
The Milky Way - Neighborhood...



The Milky Way - Neighborhood...

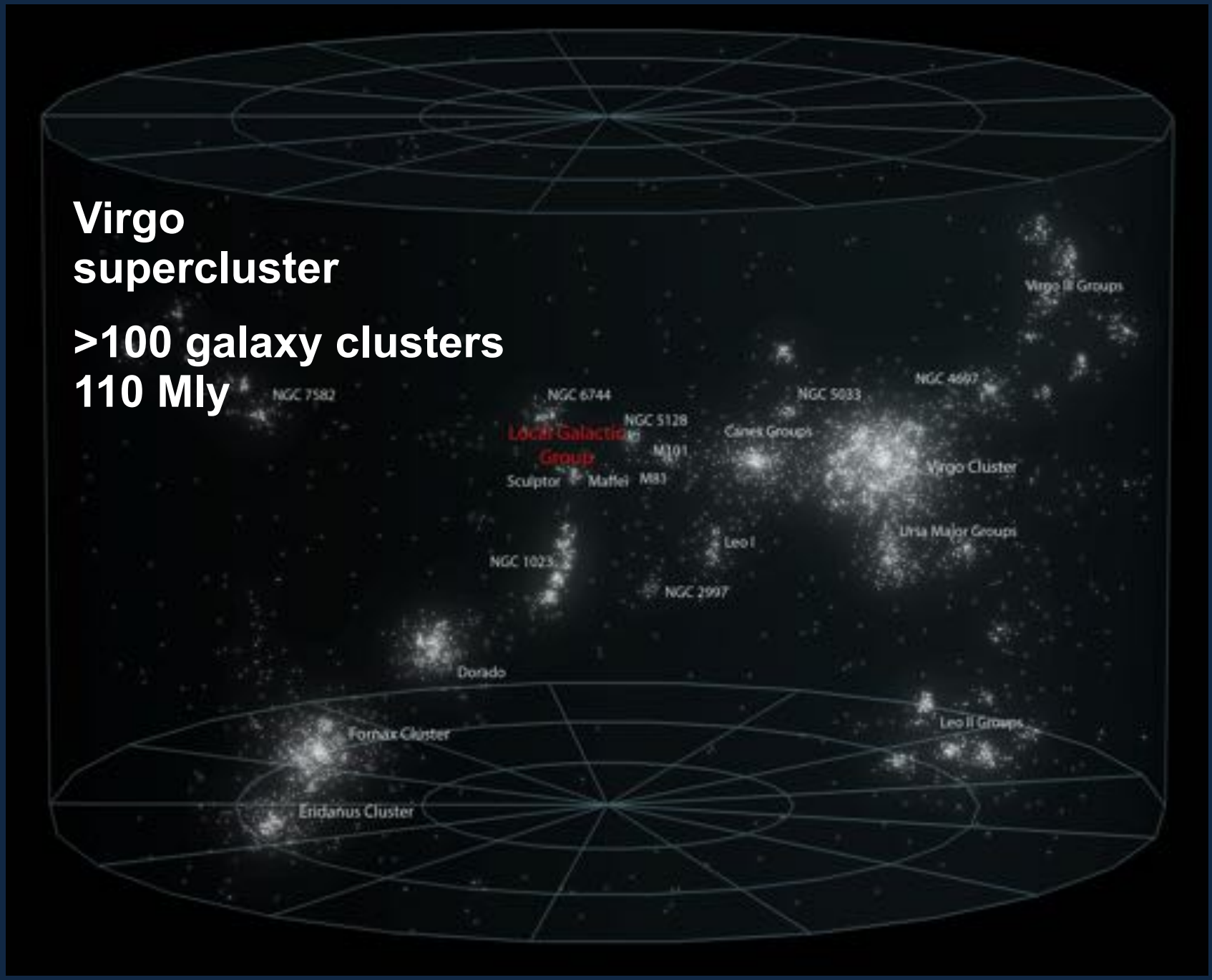
We can see the effect of the Magellanic Clouds' orbits on the Milky Way's disk… **(also dark matter!)**

The Milky Way - Neighborhood...

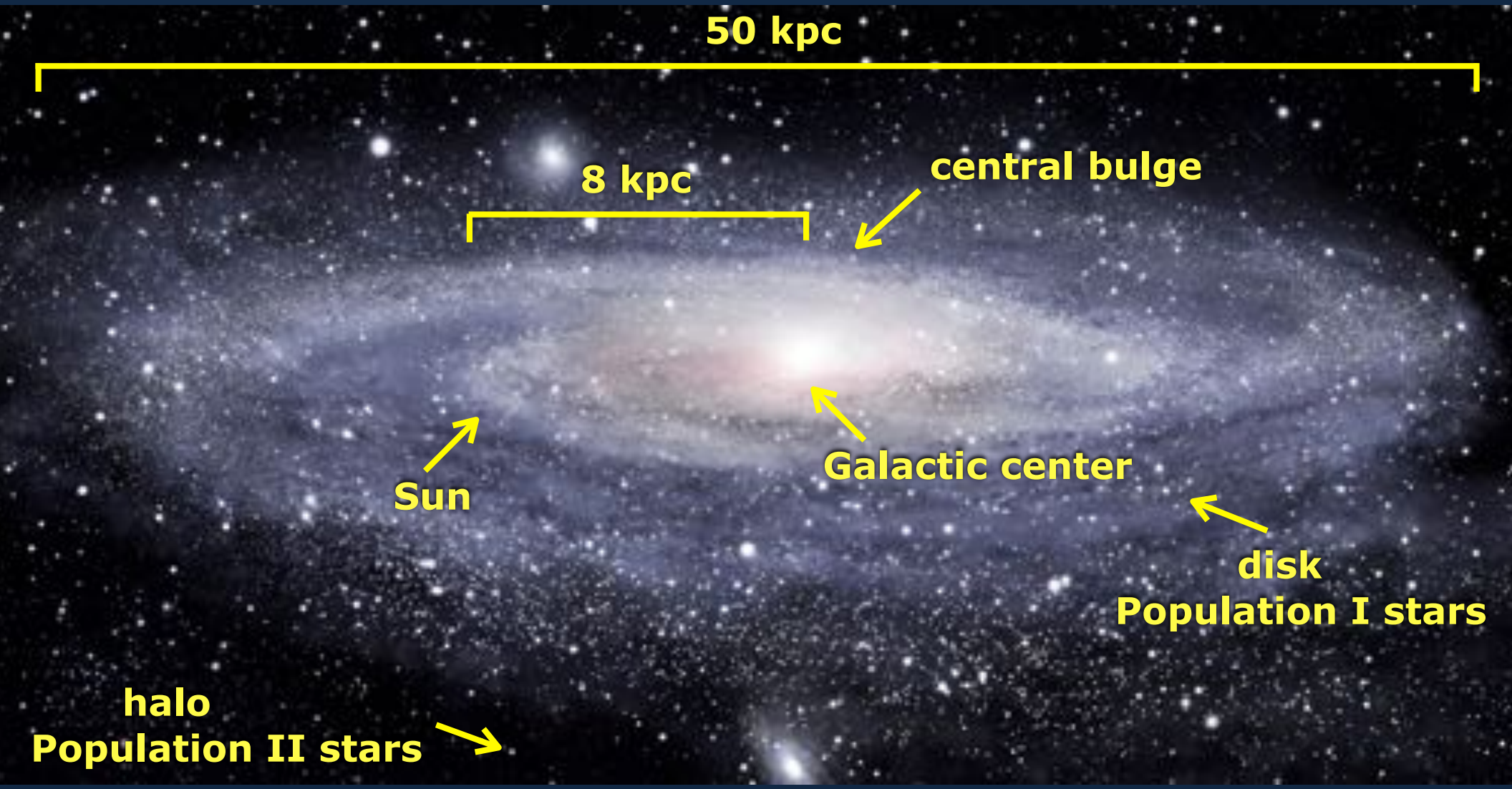


Map of the Local Group (54 galaxies, 10Mly diameter)

The Milky Way - Neighborhood...



The Milky Way



Next Week

Tuesday, Dec 5: review, HW#4 due

(*no late submissions*; solutions will be posted immediately for studying)

Thursday, Dec 7: Exam #2

in PAA A102 again!