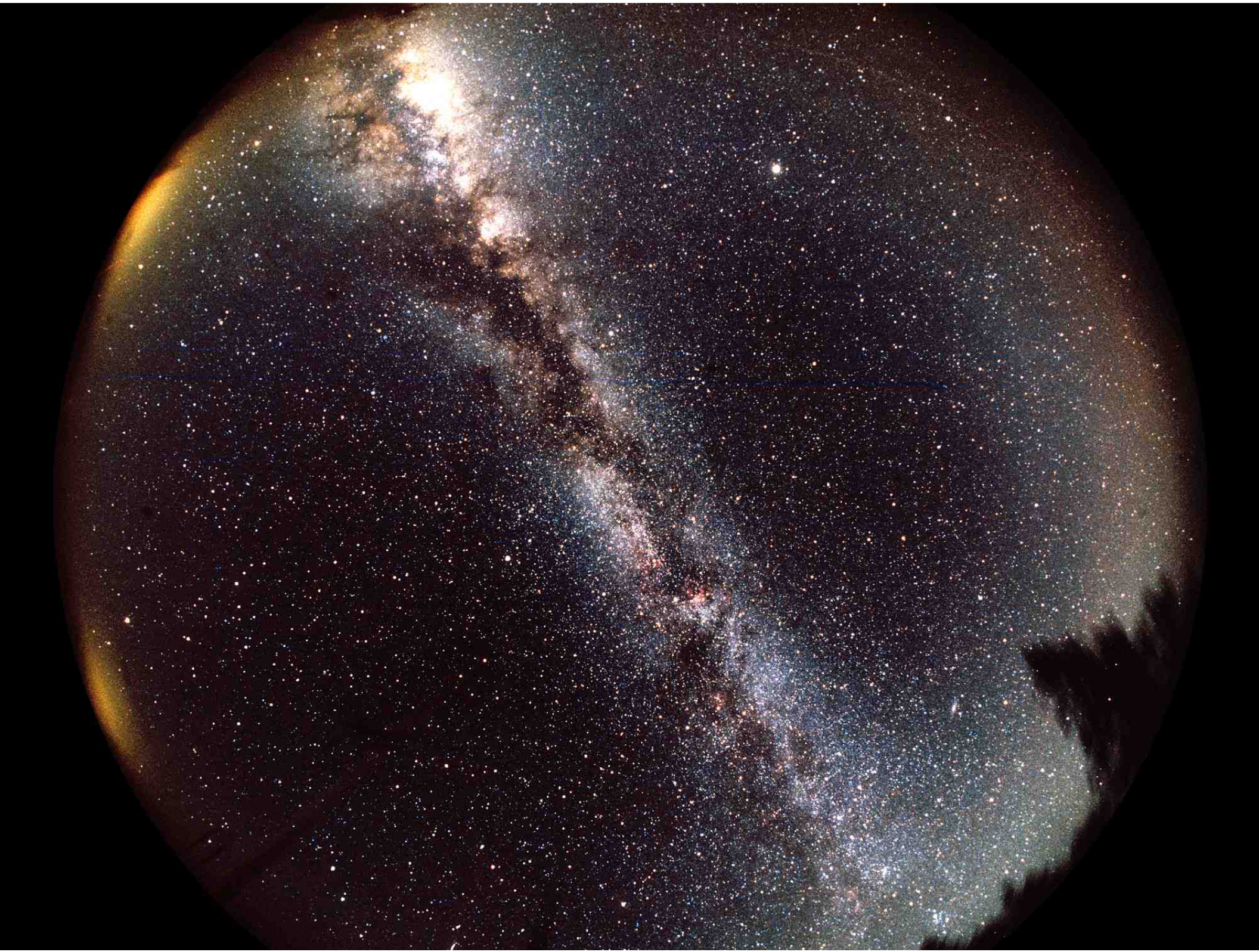

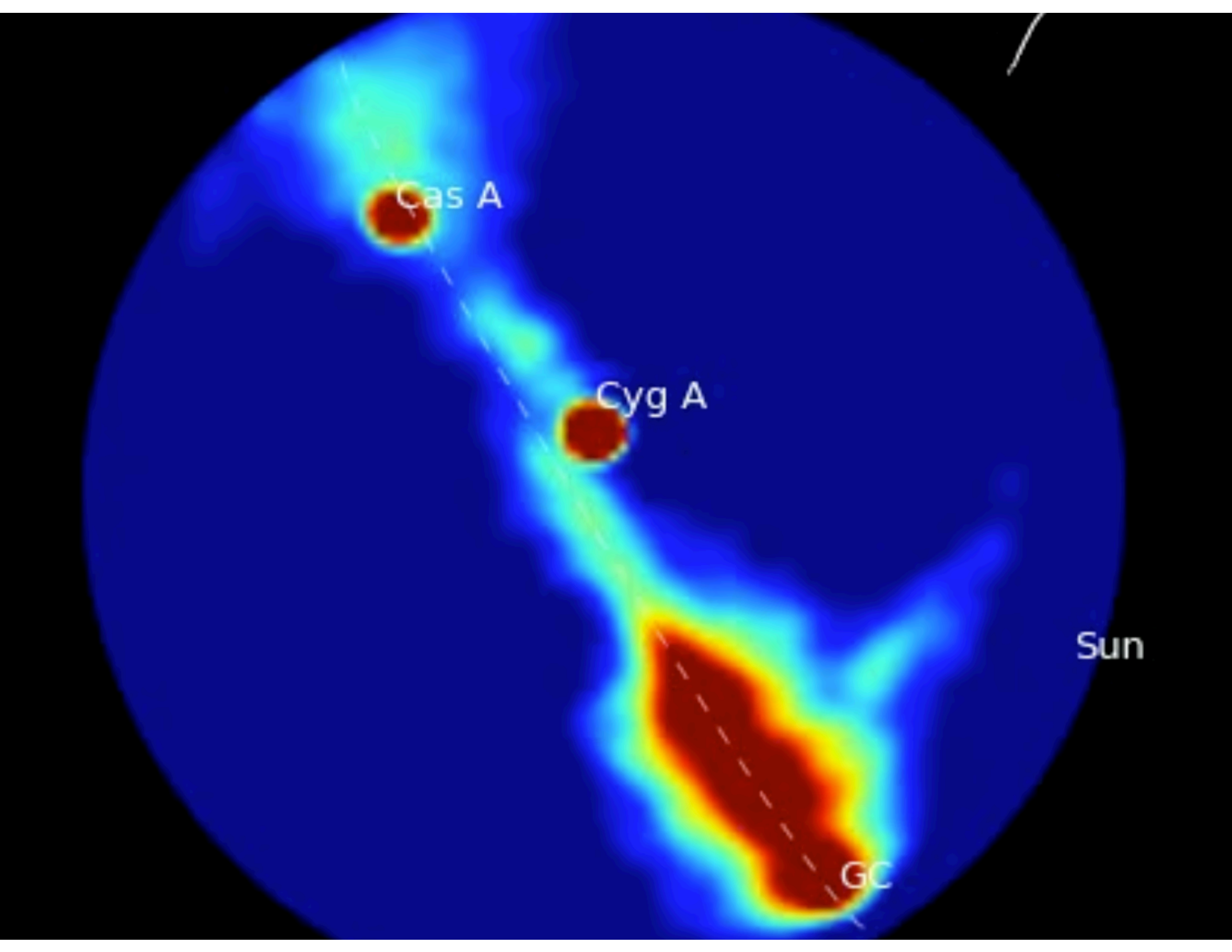
Cas A
Cyg A
Sun
GC

Science at Low Frequencies II

December 2 – 4, 2015
Phillips Technology Institute
2350 Alamo Ave
Albuquerque, NM

SCIENTIFIC ORGANIZING COMMITTEE:

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K. Dwarakanath (RRI)
George Heald (ASTRON/ Groningen)
Melanie Johnston-Hollitt (VUW/ MWA)
Namir Kassim (NRL)
Scott Ransom (NRAO)
Anna Scaife (Manchester)
Frank Schinzel (UNM)
Greg Taylor (UNM, chair)
Cathryn Trott (ICRAR/Curtin)

LOCAL ORGANIZING COMMITTEE:

Ken Obenberger (UNM / AFRL)
Frank Schinzel (UNM)
Kevin Stovall (UNM)
Greg Taylor (UNM, chair)

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*Walter Brisken (NRAO)
Jack Burns (Colorado)
*Jayaram Chengalur (TIFR)
Tracy Clarke (NRL)
Paul Demorest (NRAO)
Jayce Dowell (UNM)
Francesco de Gasperin (Hamburg)
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Vibor Jelic (ASTRON)
Emanuela Orru' (ASTRON)
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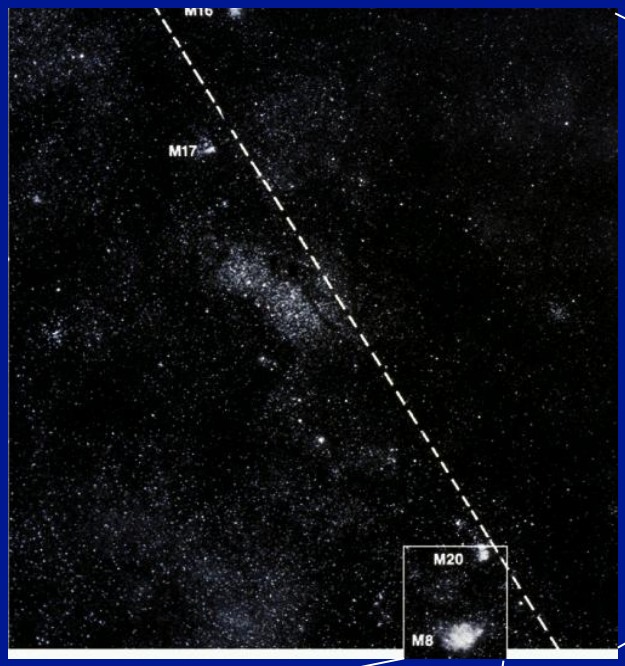
Steven Tingay (Curtin)
Randall Wayth (ICRAR)
Reinout van Weeren (CfA)
Stephen White (AFRL)
Cathie Zheng (VUW)

* TBC

UNM NRAO LWA Long Wavelength Array

The Milky Way Galaxy



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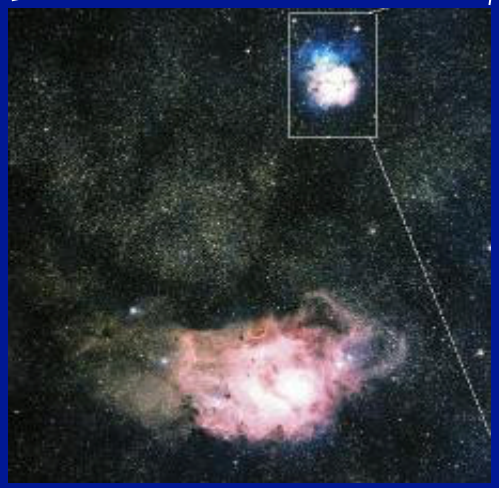
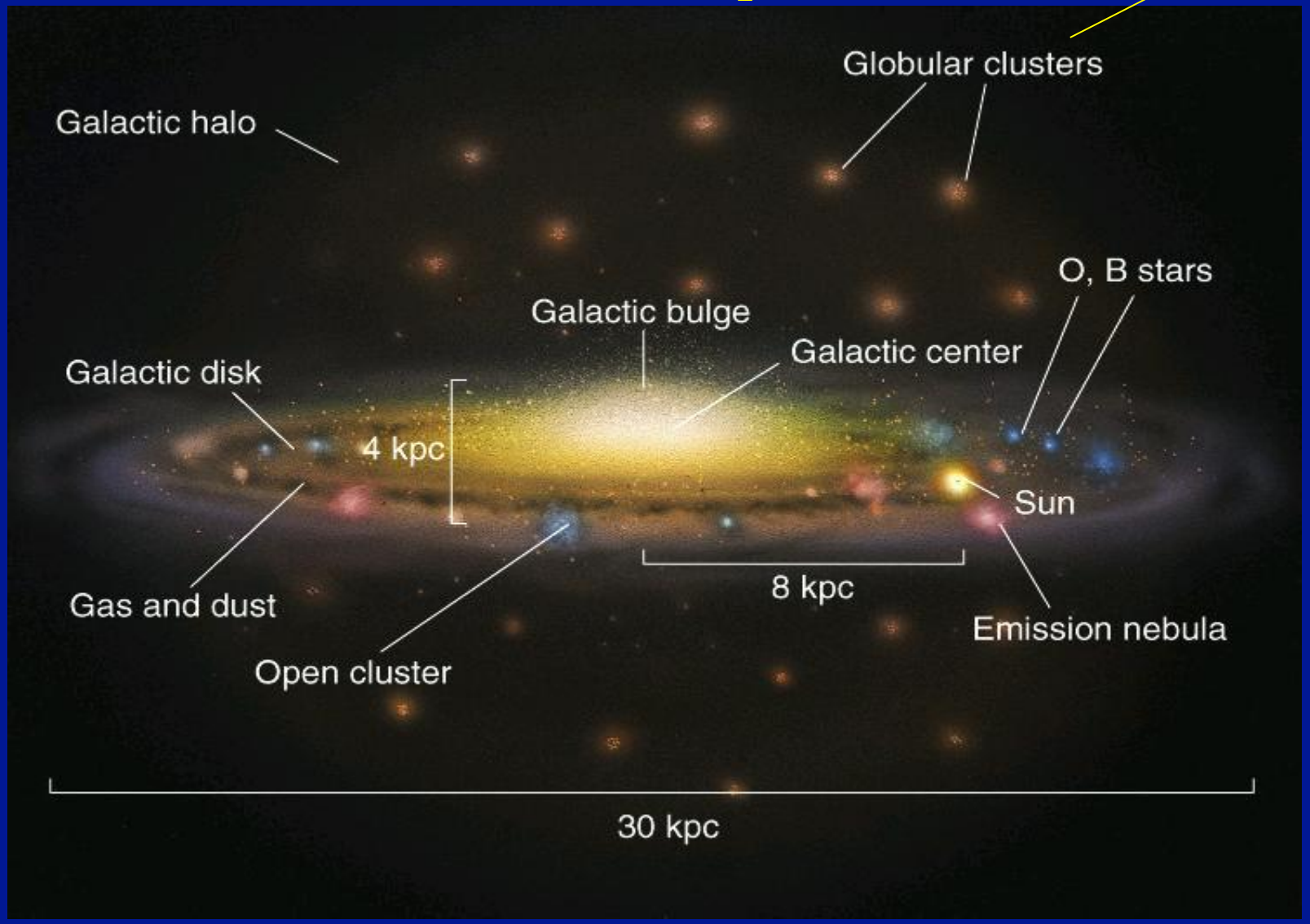


a

d

Take a Giant Step Outside the Milky Way

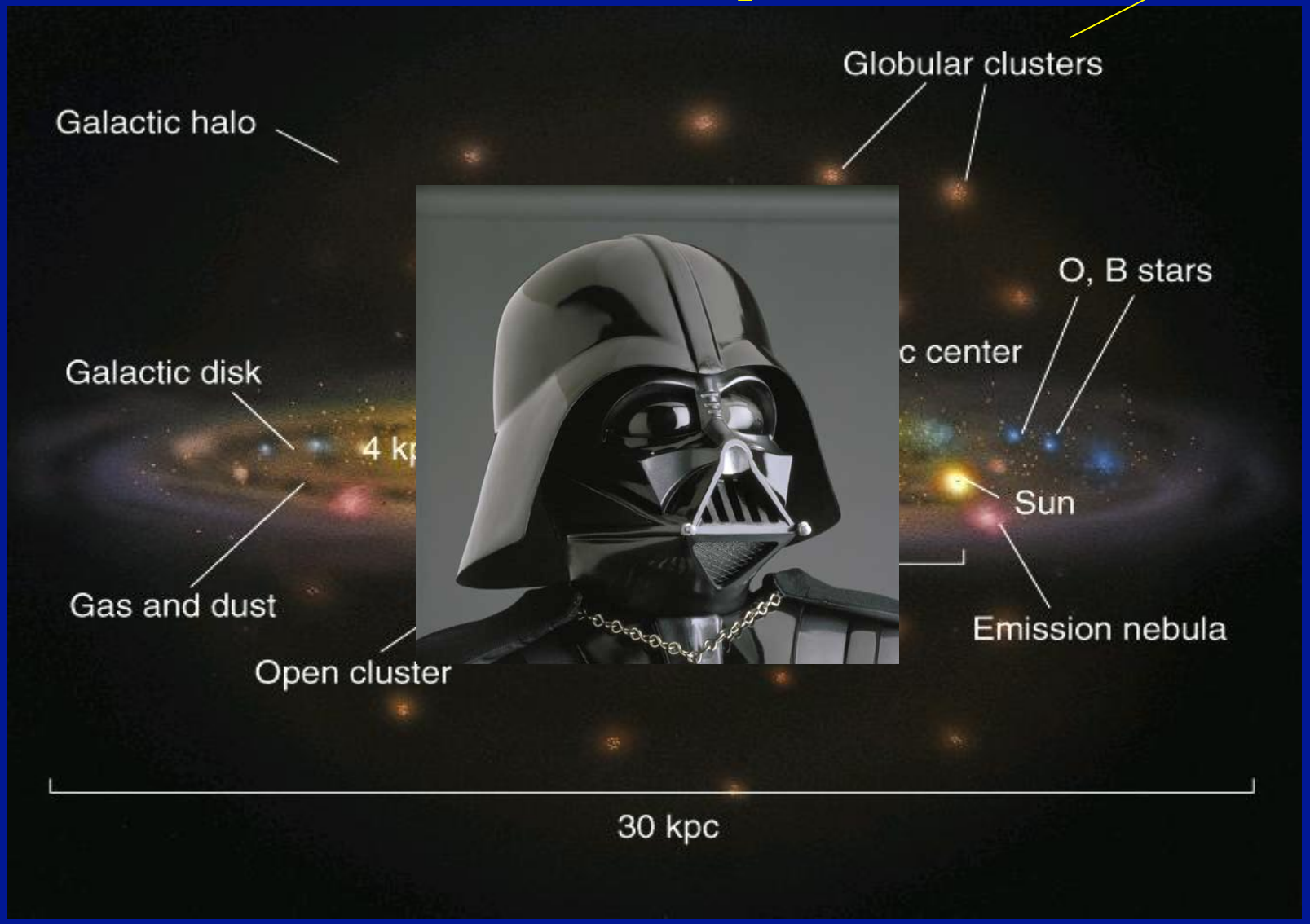
Artist's Conception



Example (not to scale)

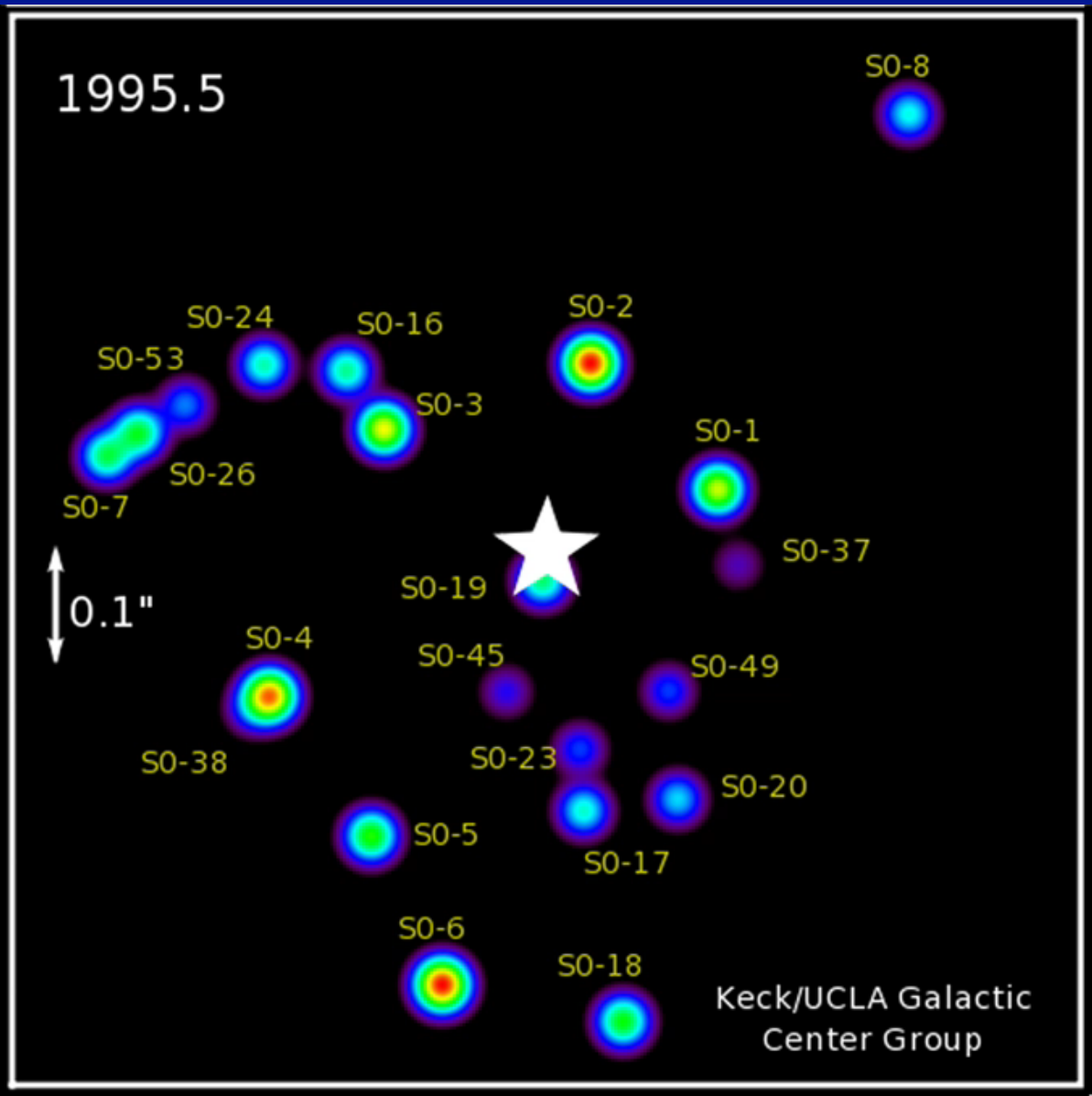
Take a Giant Step Outside the Milky Way

Artist's Conception



Example (not to scale)

Supermassive (4 million solar mass) Black Hole at the Galactic Center

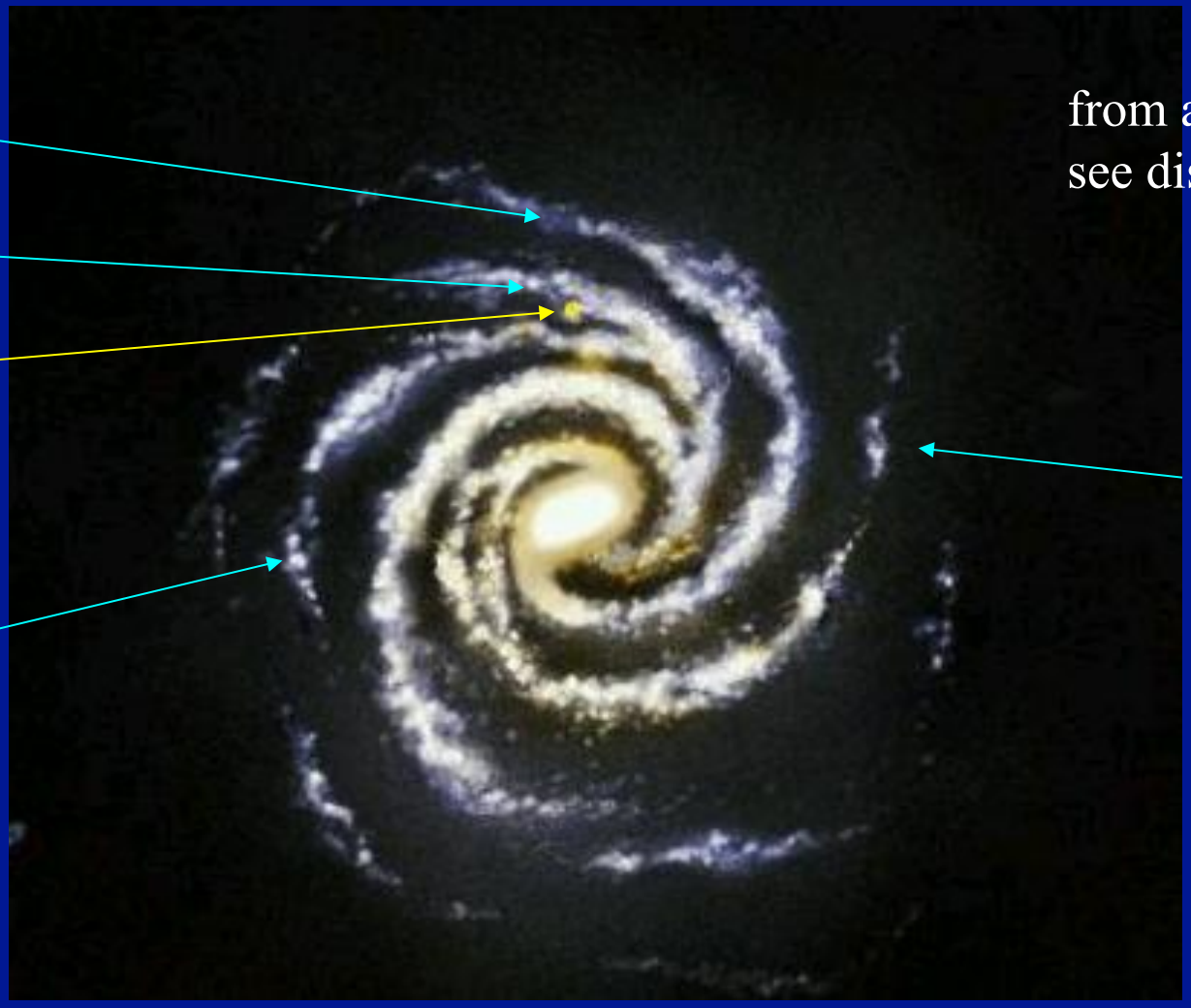


Perseus arm

Orion arm

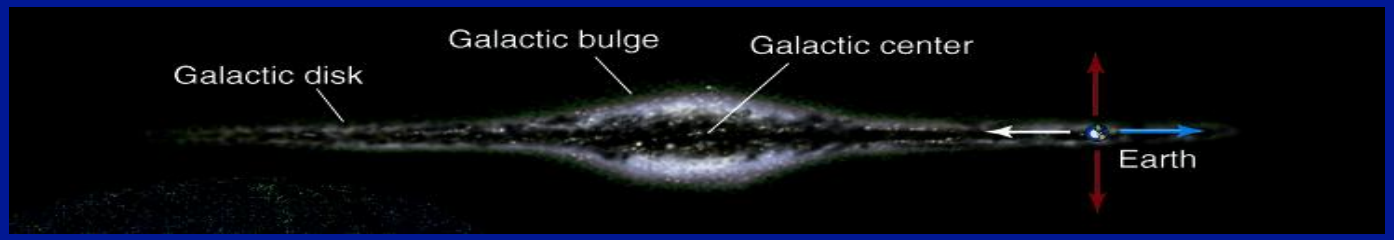
Sun

Carina arm



from above ("face-on")
see disk and bulge

Cygnus arm



from the side
("edge-on")

Another galaxy: NGC 4414. The Milky Way roughly resembles it.

M51

The Three Main Structural Components of the Milky Way

1. Disk

- 30,000 pc diameter (or 30 kpc)

- contains young and old stars, gas, dust. Has spiral structure

- vertical thickness roughly 100 pc - 2 kpc (depending on component. Most gas and dust in thinner layer, most stars in thicker layer)

2. Halo

- at least 30 kpc across

- contains globular clusters, old stars, little gas and dust, much "dark matter"

- roughly spherical

3. Bulge

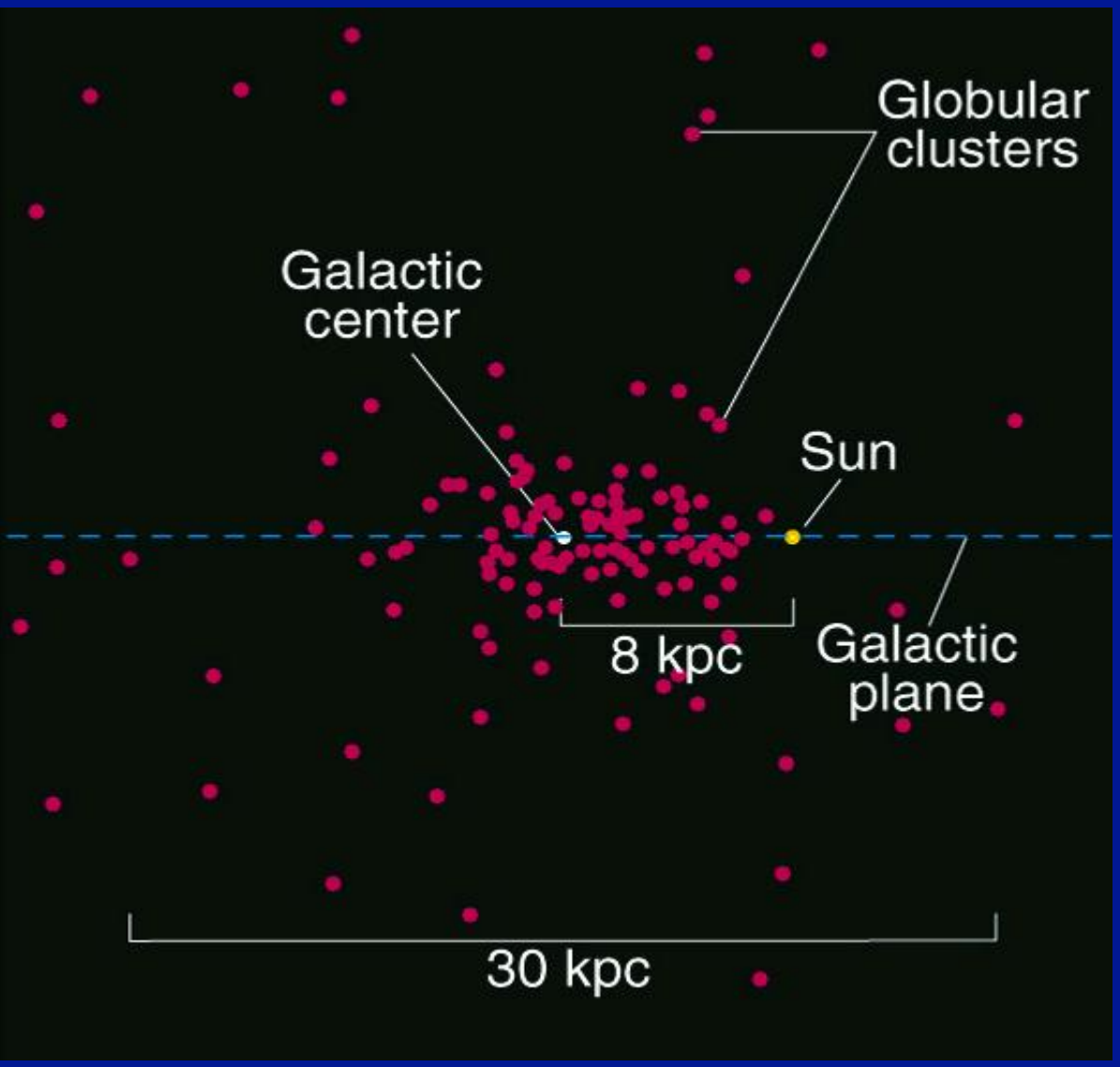
- About 4 kpc across

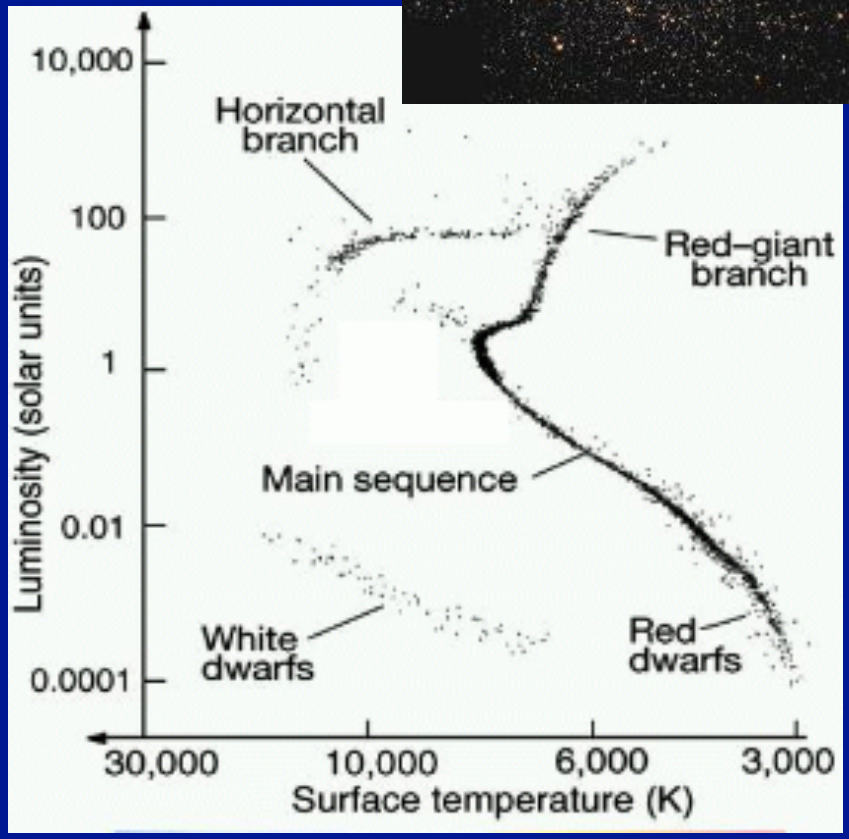
- old stars, some gas, dust

- central black hole of 4×10^6 solar masses

- spherical

Shapley (1917) found that Sun was not at center of Milky Way

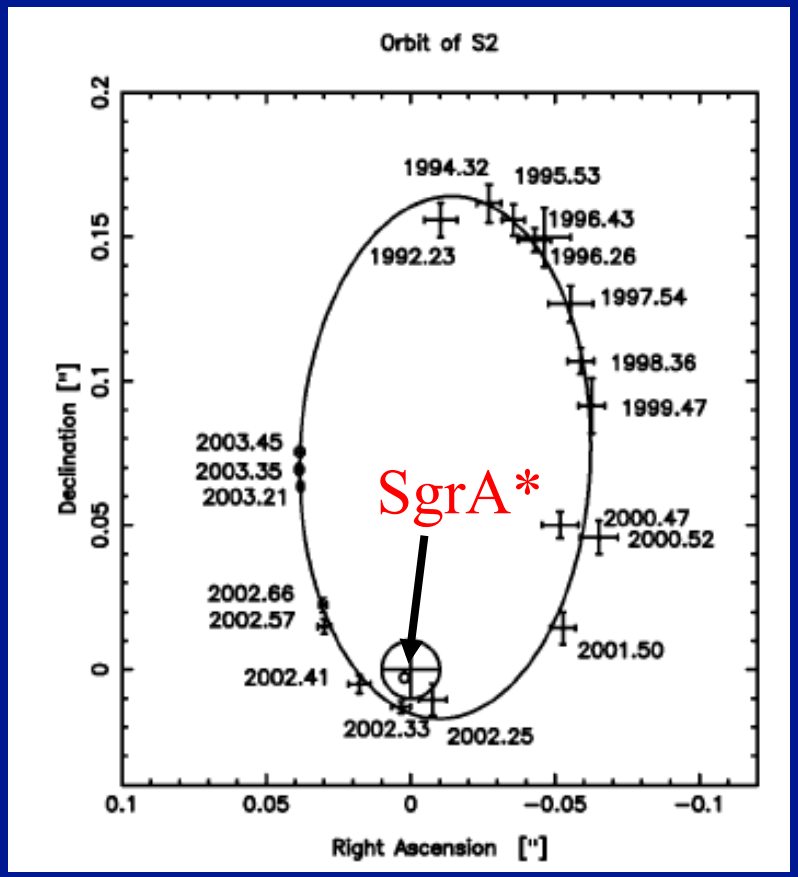




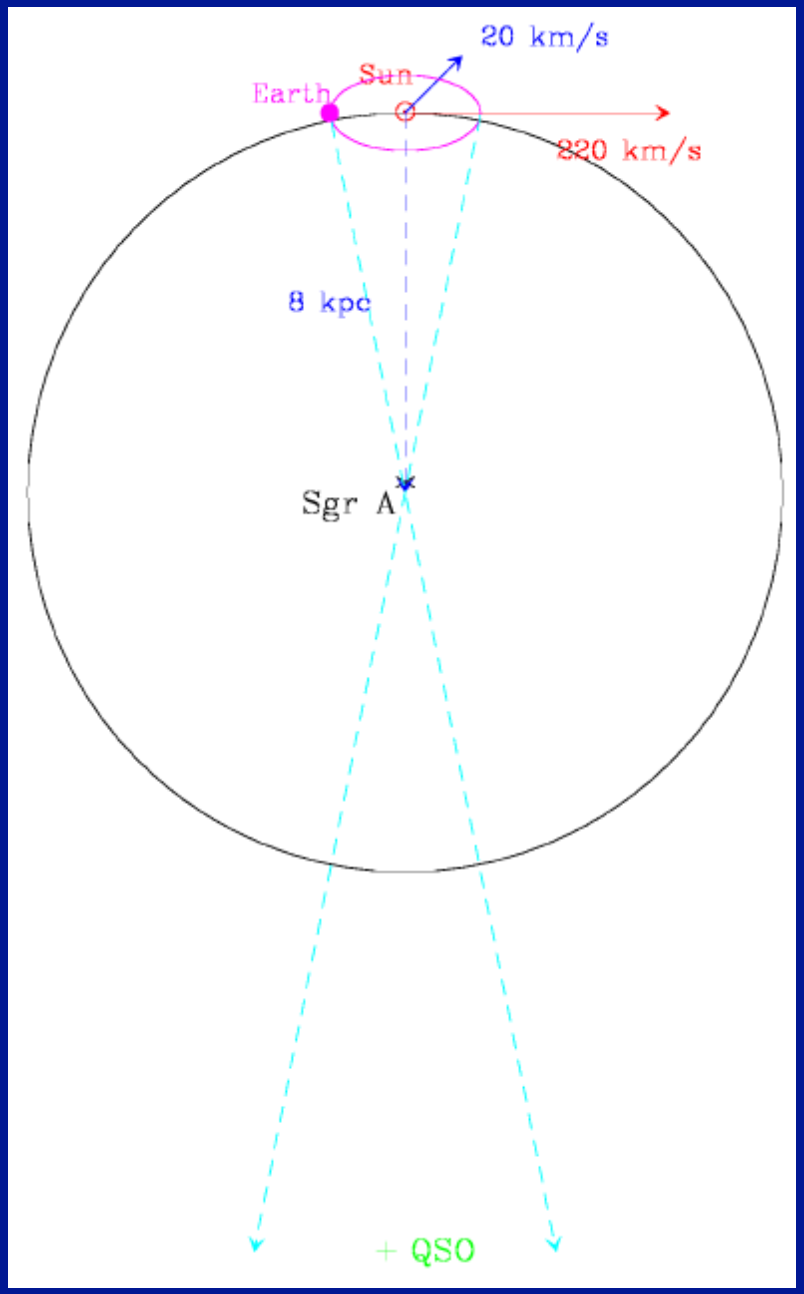
Shapley used distances to variable "RR Lyrae" stars (a kind of Horizontal Branch star) in Globular Clusters to determine that Sun was 16 kpc from center of Milky Way. Modern value 8 kpc.

Precise Distance to Galactic Center

Distance = 7.94 +/- 0.42 kpc

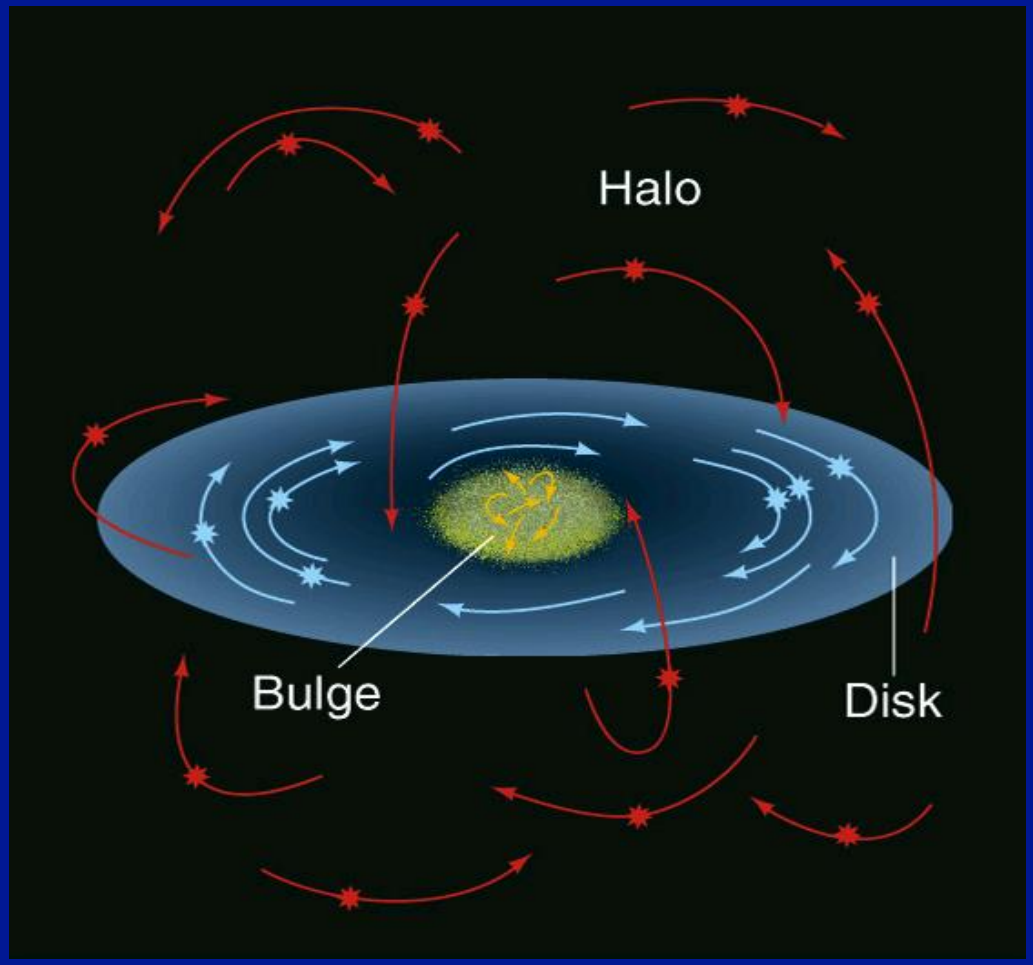


Eisenhauer et al. 2003



Orbital motion 6.37 mas/yr

Stellar Orbits



Halo: stars and globular clusters swarm around center of Milky Way. Very elliptical orbits with random orientations. They also cross the disk.

Bulge: similar to halo.

Disk: rotates.

Clicker Question:

Where is our solar system located?

A: near the center of the Milky Way Galaxy in the bulge.

B: 4 kpc from the center of the Milky Way in the halo.

C: 8 kpc from the center of the Milky Way in the disk.

D: 20 kpc from the center of the Milky Way in the disk.

Clicker Question:

What lurks at the center of our galaxy?

A: A 3 million solar mass black hole.

B: A giant star cluster.

C: A 30 solar mass black hole.

D: Darth Vader

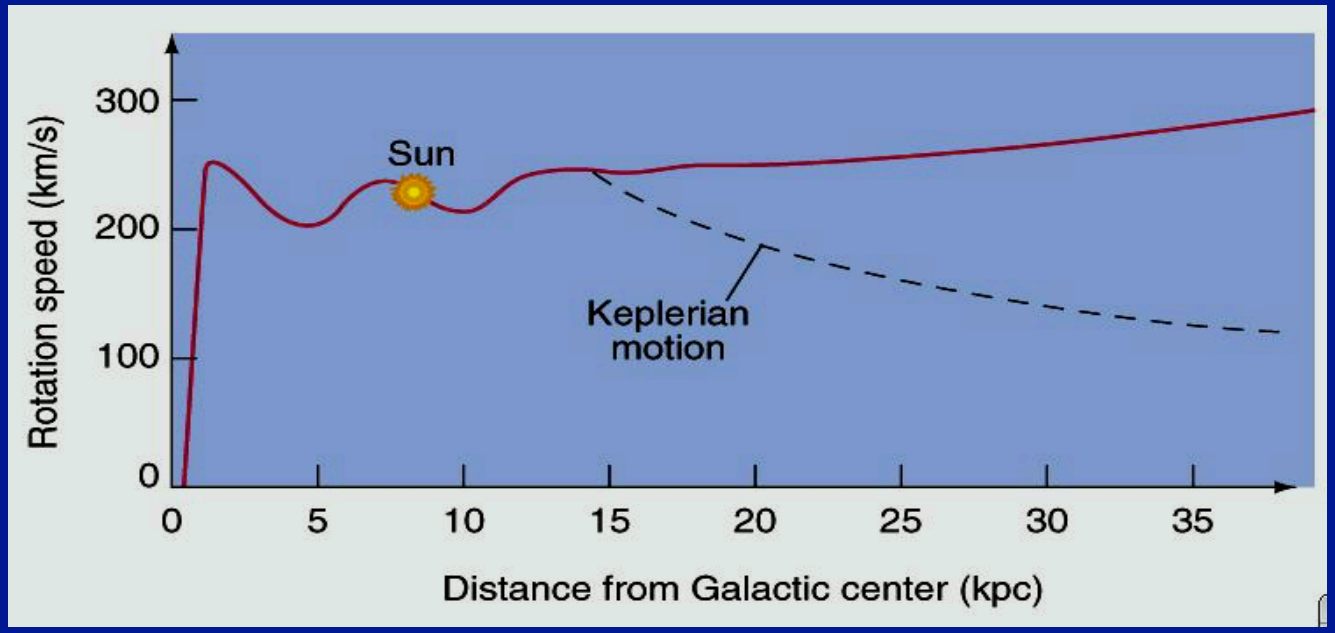
Rotation of the Disk

Sun moves at 220 km/sec around center. An orbit takes 240 million years.

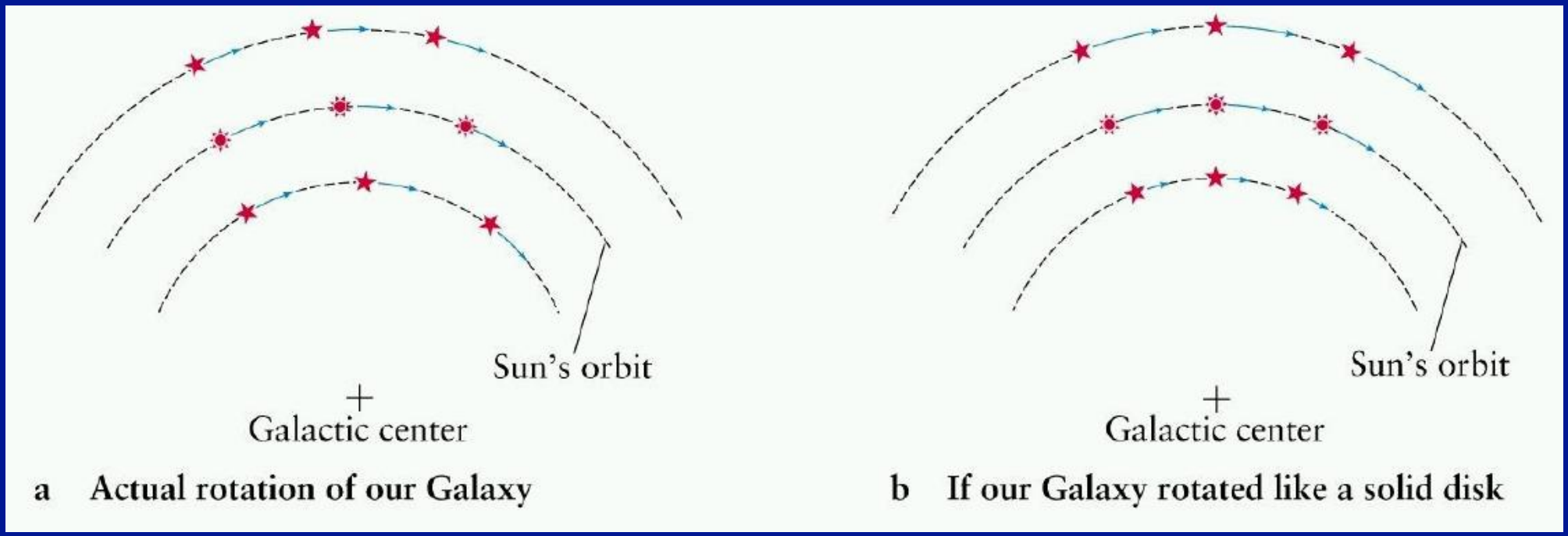
Stars closer to center take less time to orbit. Stars further from center take longer.

=> rotation not rigid like a phonograph record or a merry-go-round. Rather, "differential rotation".

Over most of disk, rotation velocity is roughly constant.



The "rotation curve" of the Milky Way



a **Actual rotation of our Galaxy**

b **If our Galaxy rotated like a solid disk**

Spiral Structure of Disk

Spiral arms best traced by:

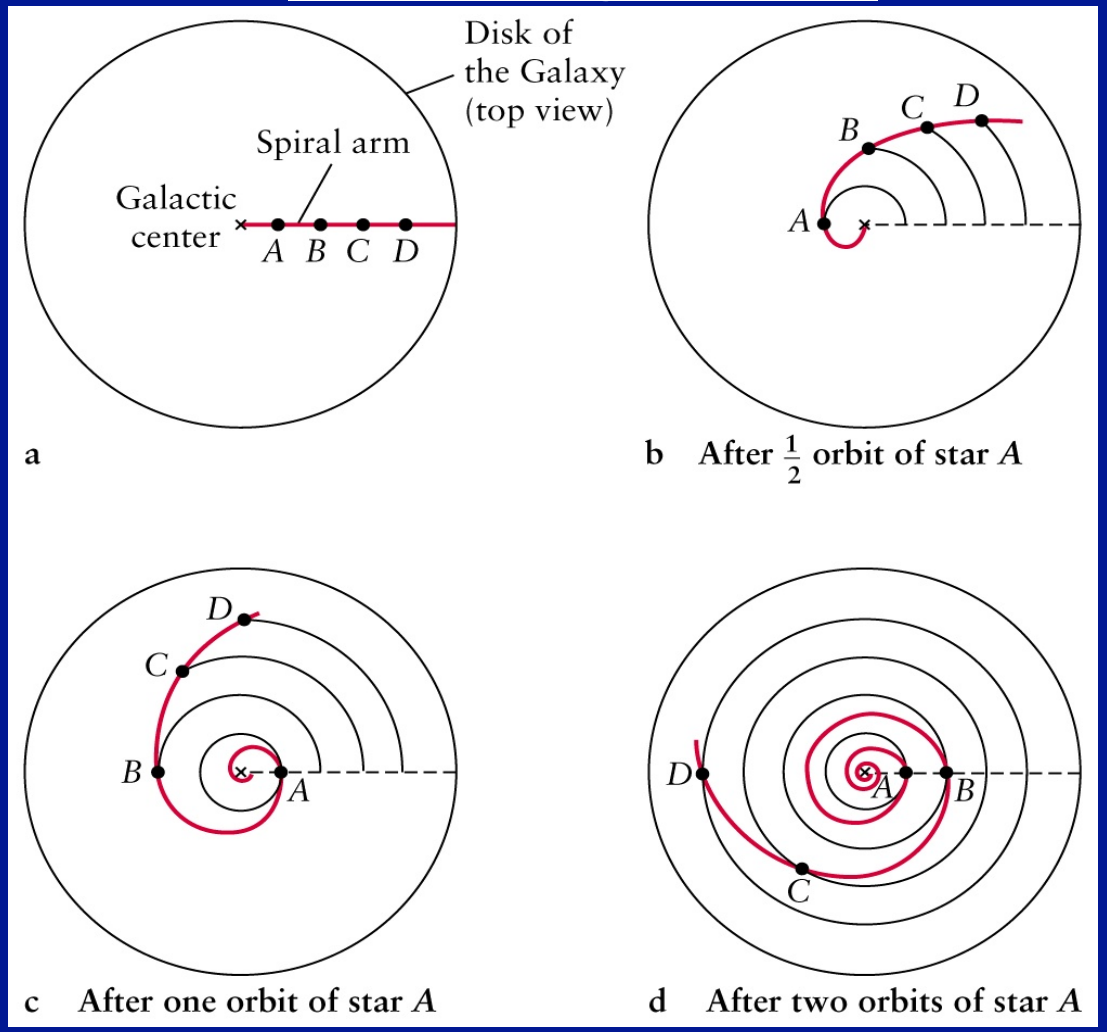
Young stars and clusters
Emission Nebulae
HI
Molecular Clouds
(old stars to a lesser extent)

Disk not empty between arms, just less material there.

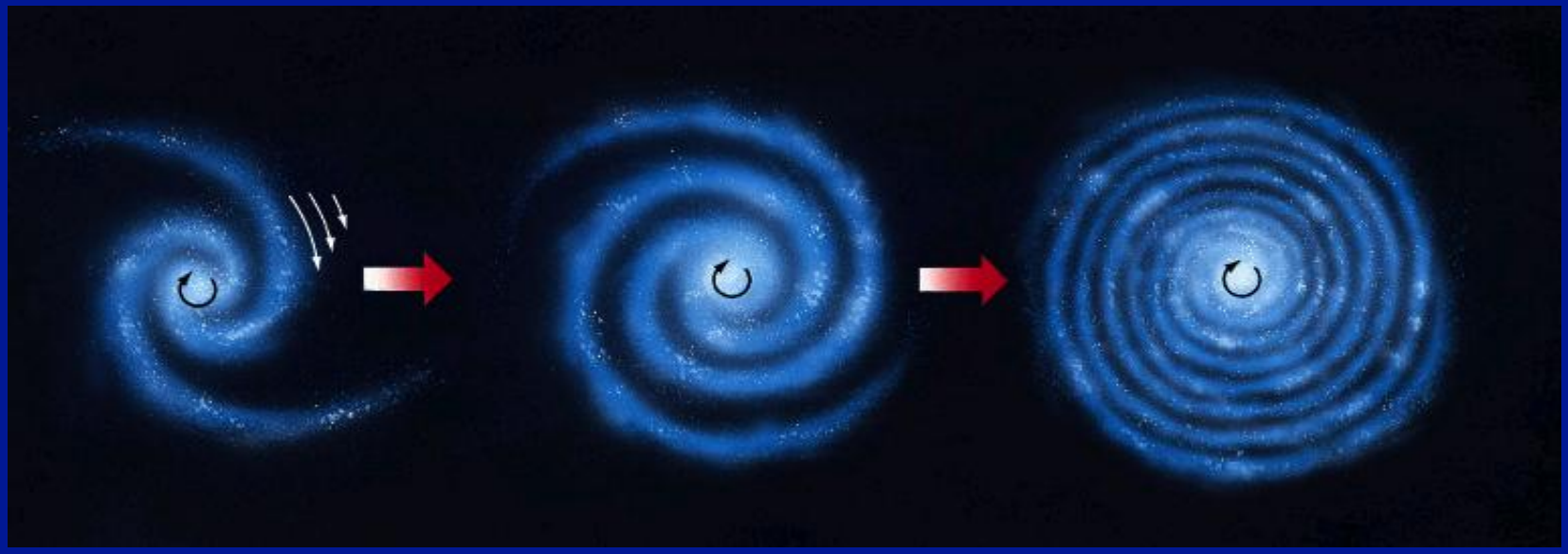
Problem: How do spiral arms survive?

Given differential rotation, arms should be stretched and smeared out after a few revolutions (Sun has made 20 already):

The Winding Dilemma



The spiral should end up like this:



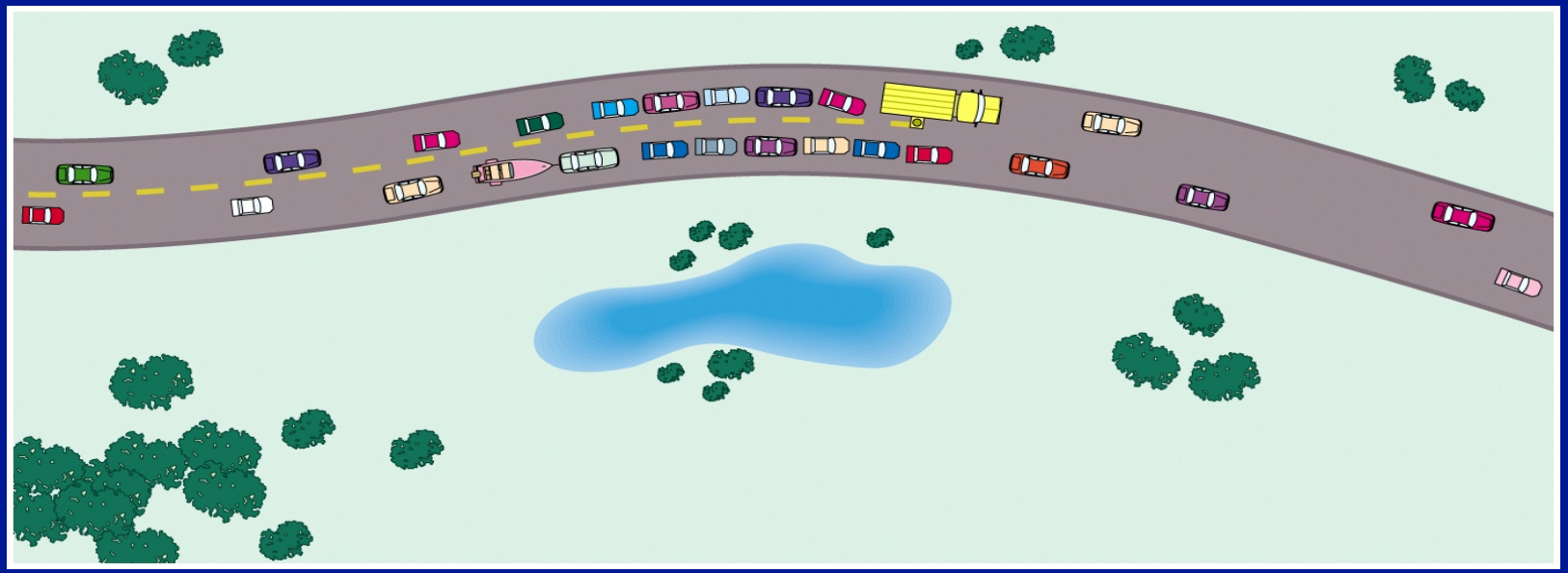
Real structure of Milky Way (and other spiral galaxies) is more loosely wrapped.

Proposed solution:

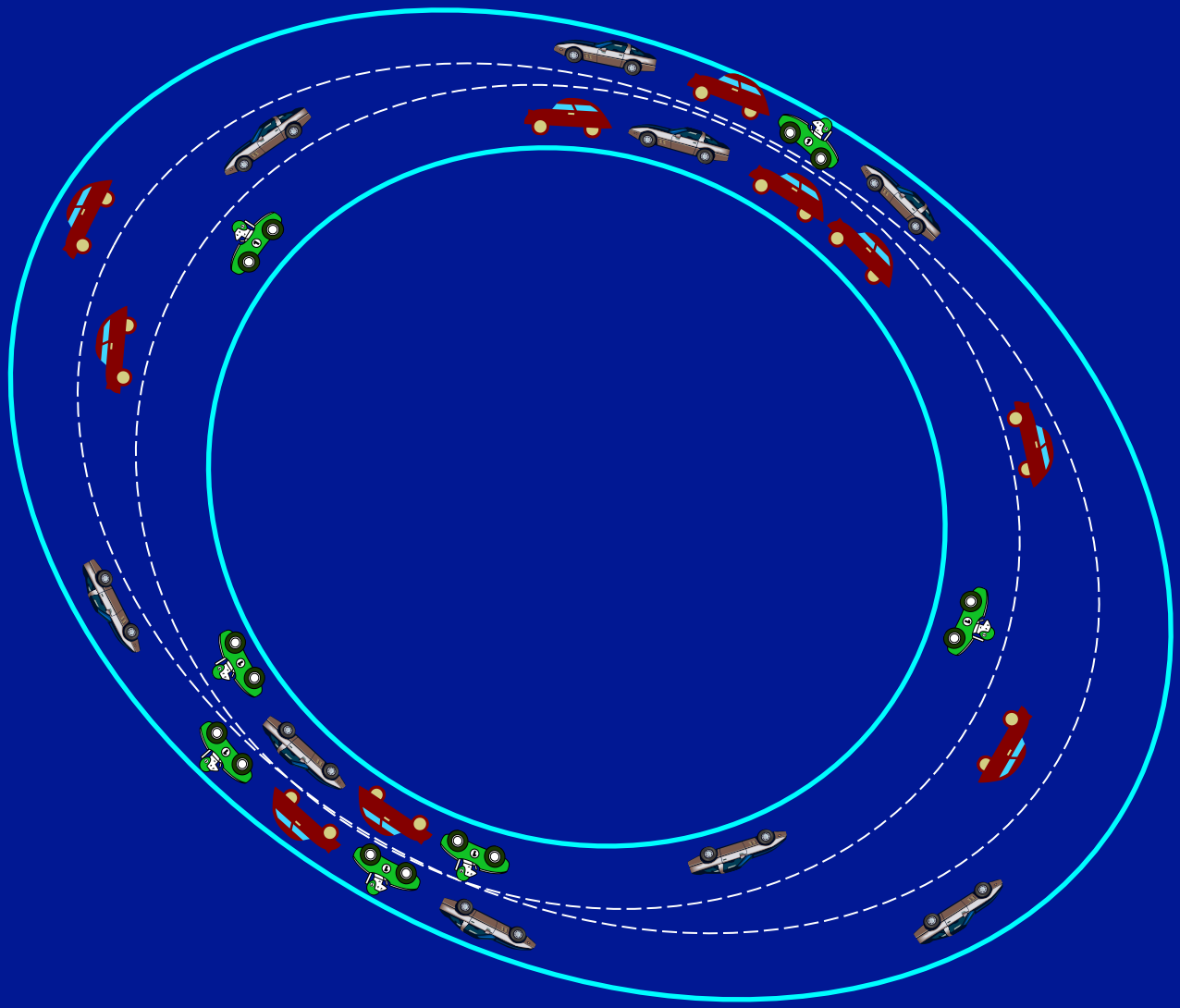
Arms are not material moving together, but mark peak of a compressional wave circling the disk:

A Spiral Density Wave

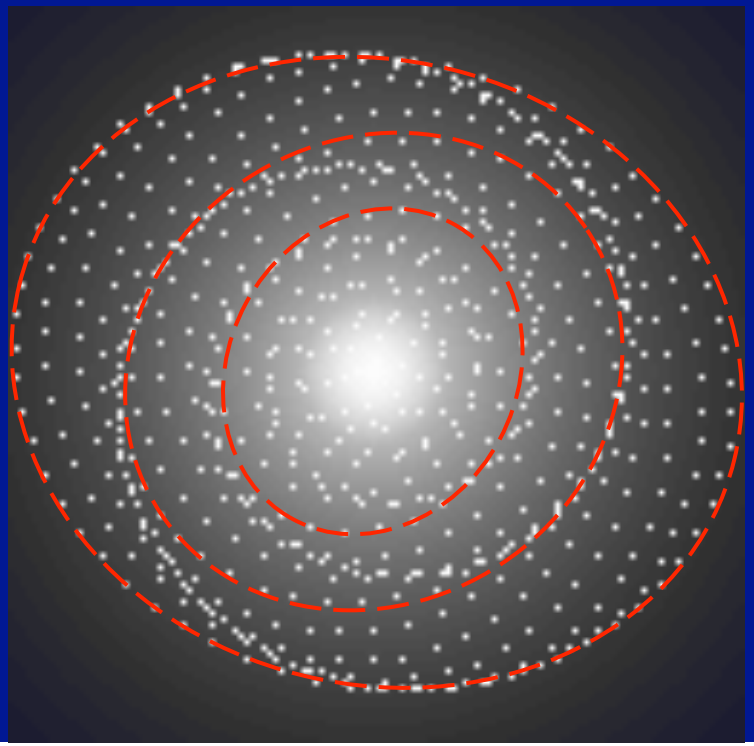
Traffic-jam analogy:

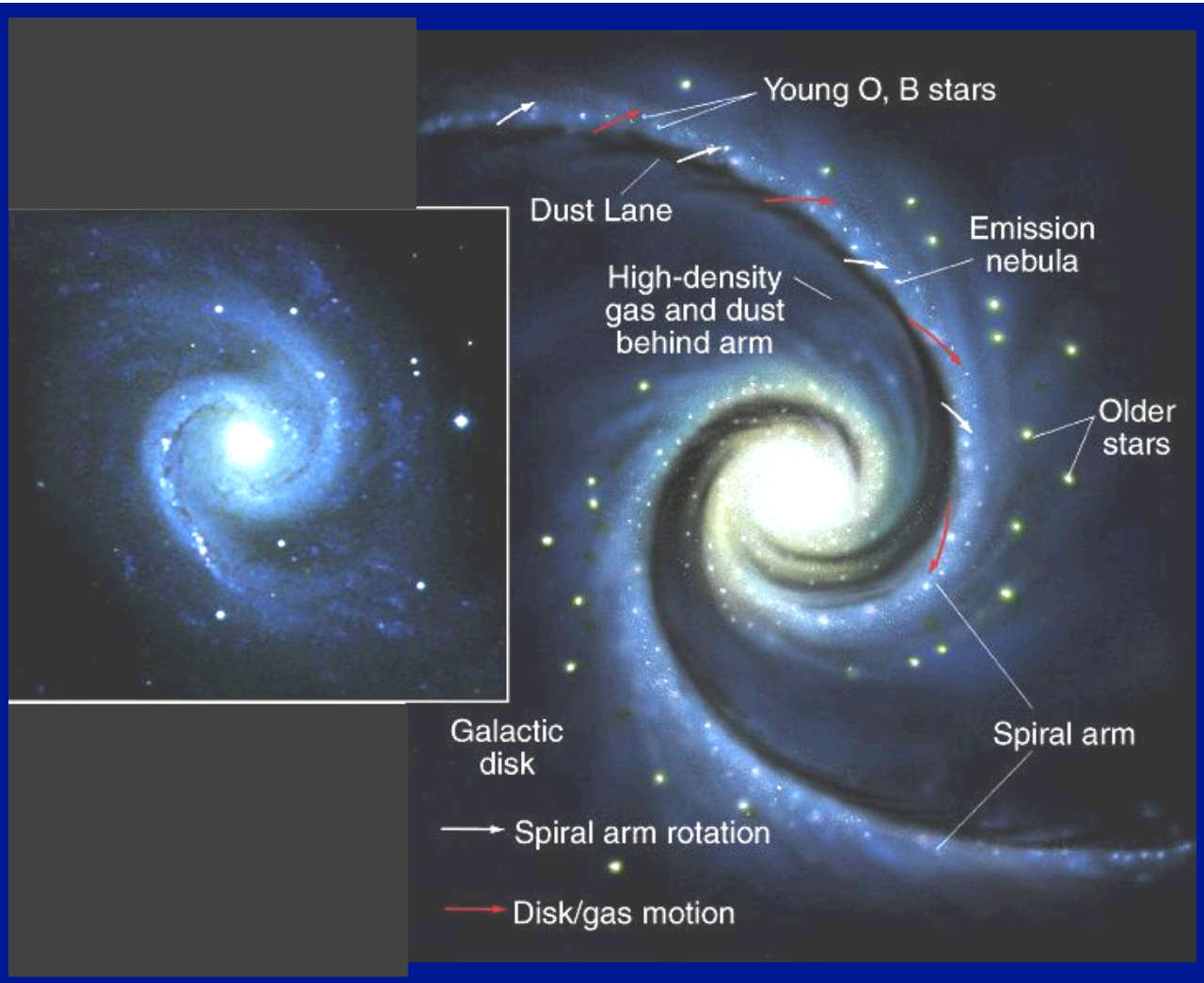


Traffic jam on a loop caused by merging



Now replace cars by stars and gas clouds. The traffic jams are actually due to the stars' collective gravity. The higher gravity of the jams keeps stars in them for longer. Calculations and computer simulations show this situation can be maintained for a long time.





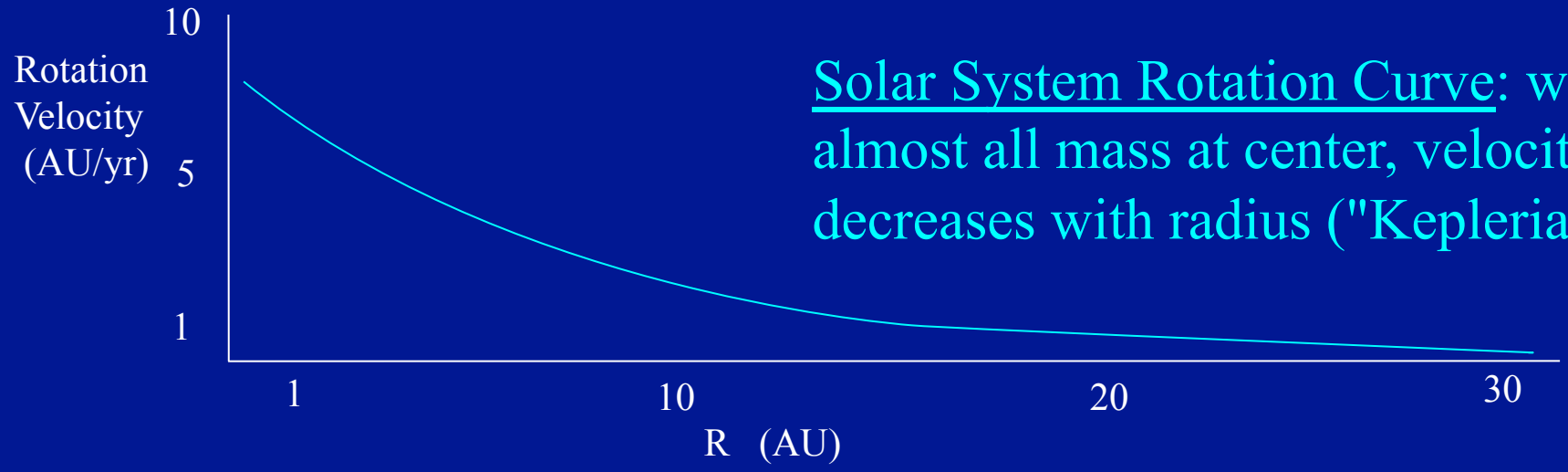
Molecular gas clouds pushed together in arms too => high density of clouds => high concentration of dust => dust lanes.

Also, squeezing of clouds initiates collapse within them => star formation. Bright young massive stars live and die in spiral arms. Emission nebulae mostly in spiral arms.

So arms always contain same types of objects, but individual objects come and go.

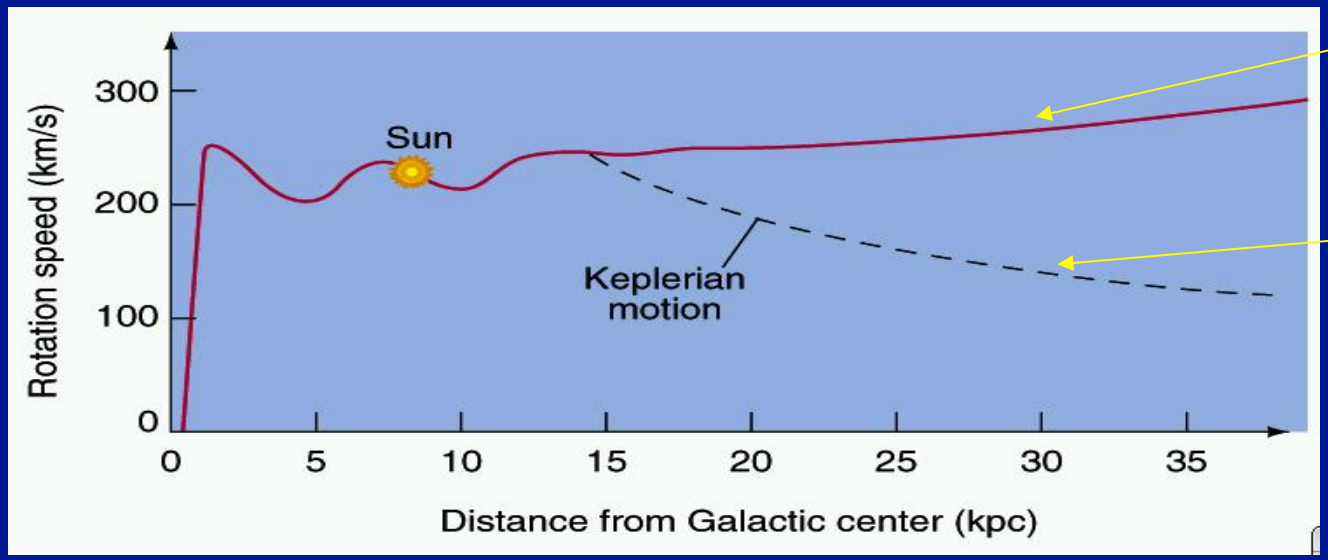
90% of Matter in Milky Way is Dark Matter

Gives off no detectable radiation. Evidence is from rotation curve:



Solar System Rotation Curve: when almost all mass at center, velocity decreases with radius ("Keplerian")

Milky Way Rotation Curve



observed curve

Curve if Milky Way ended where visible matter pretty much runs out.

Not enough radiating matter at large R to explain rotation curve => "dark" matter!

Dark matter must be about 90% of the mass!

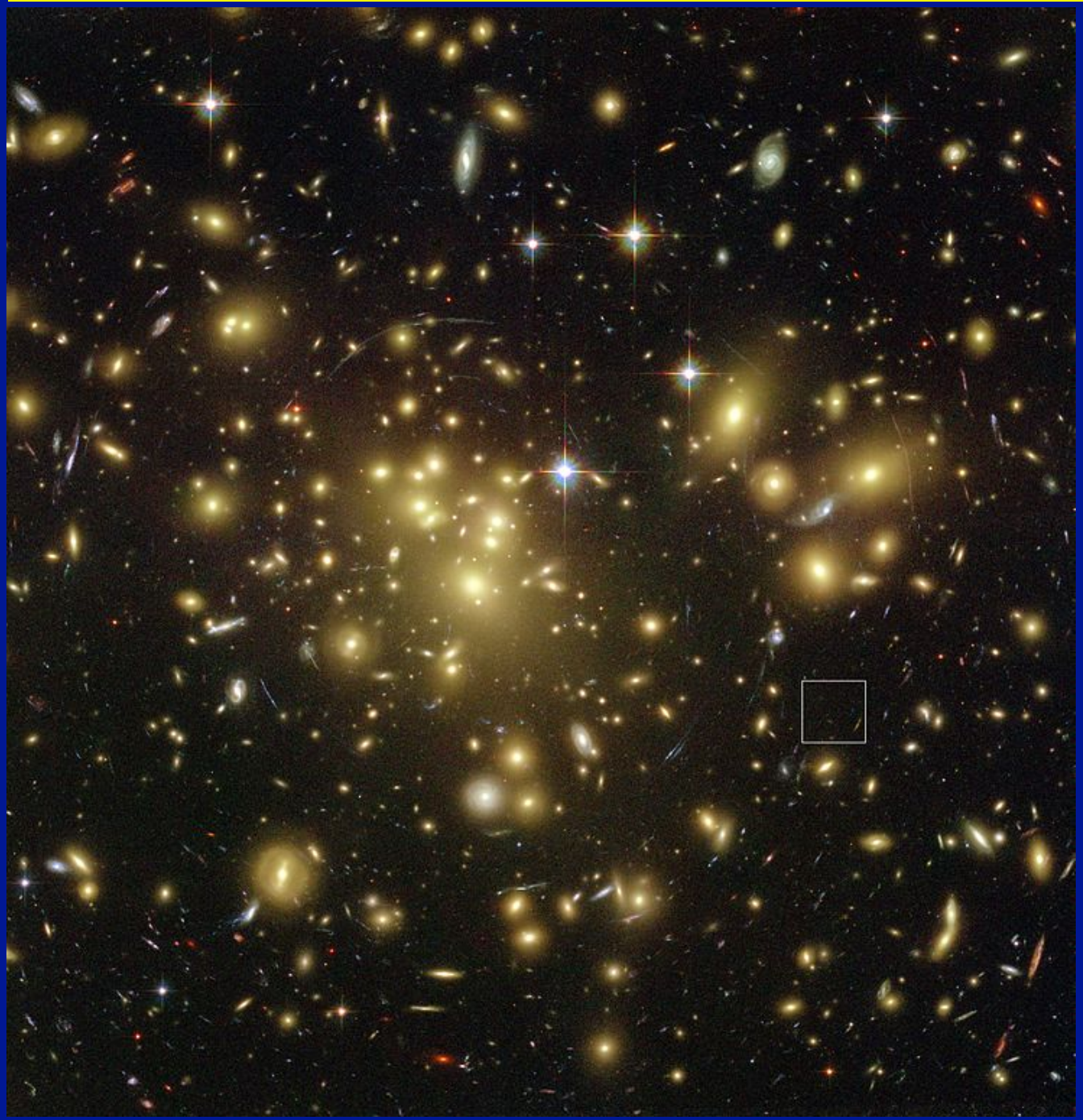
Composition unknown. Probably mostly exotic particles that don't interact with ordinary matter at all (except gravity). Some may be brown dwarfs, cold white dwarfs …

Most likely it's a dark halo surrounding the Milky Way.
Or we need a new theory of gravity.

Mass of Milky Way

6×10^{11} solar masses within 40 kpc of center.

More Evidence for Dark Matter - Abell 1689



Clicker Question:

How long does it take our solar system to orbit once around the Milky Way?

A: 1 year

B: 2 million years

C: 250 million years

D: 250 billion years (longer than the age of the universe)

Clicker Question:

What makes up most of the mass (90%) of the Milky Way Galaxy?

A: hydrogen gas

B: stars

C: dead stars (white dwarfs, neutron stars, and black holes)

D: we don’t know

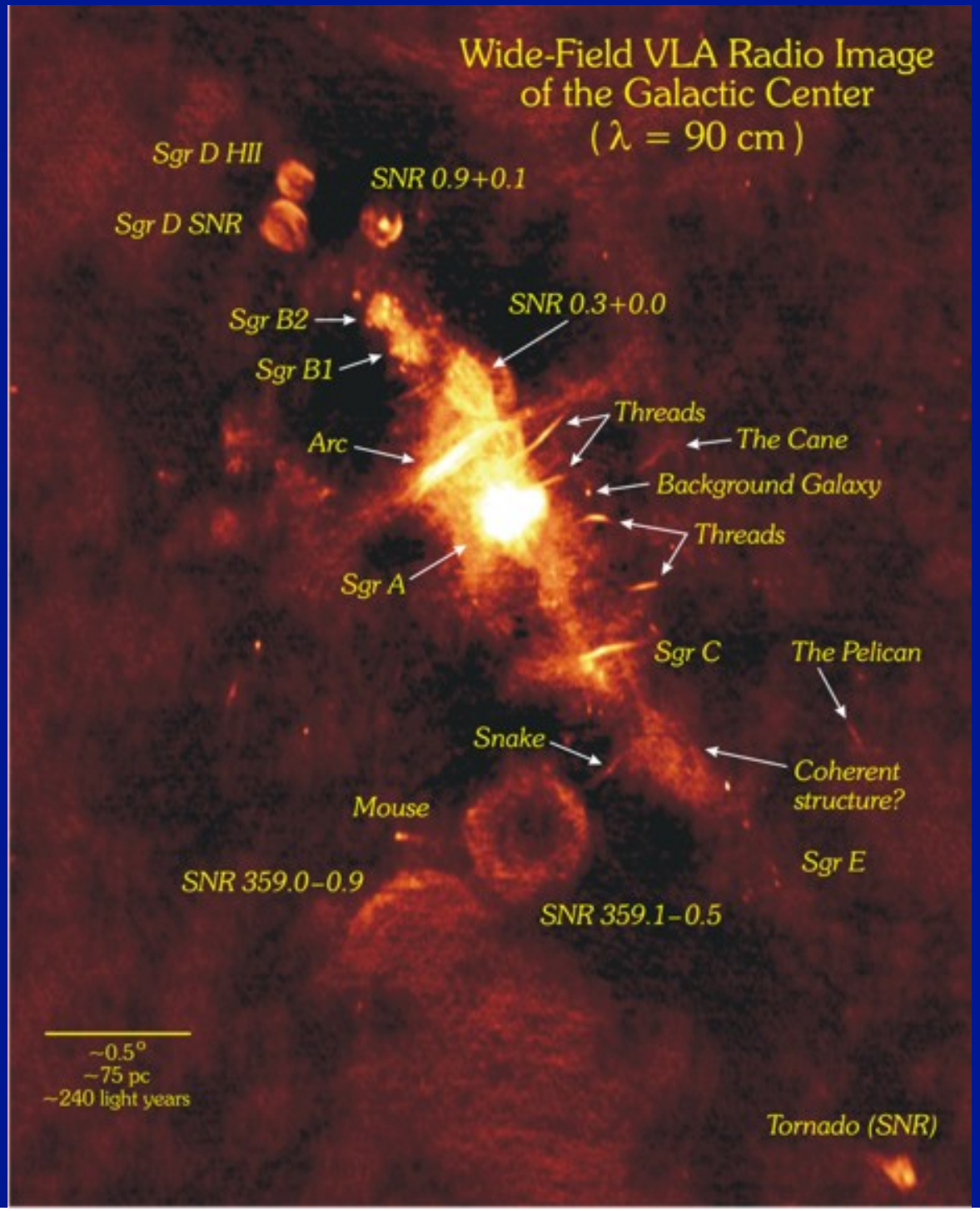
The Center of the Milky Way Galaxy

NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)

Spitzer Space Telescope • IRAC

ssc2006-02a

Seeing into the center of the Milky Way



Seeing into the center of the Milky Way