ASTR 511
Galactic Astronomy

Lecture 03
History of Galactic Astronomy

Prof. James Davenport (UW)

Winter 2023

Q: What are the “important” components of the Milky Way?

Q: What are the “important” components of the Milky Way?

- Disk
- Spiral Arms
- Bulge
- Bar
- Halo
- Dark Matter
- Lots of other stuff…

https://en.m.wikipedia.org/wiki/File:Milky_Way_Galaxy.jpg

Goal Today…

- Some vague review of when we discovered things we think we know now
- Understand how NEW this model is
- Appreciate how clever our predecessors were (humility & call to action!)
- A plea to you: READ OLD PAPERS!

https://en.m.wikipedia.org/wiki/File:Milky_Way_Galaxy.jpg

Ancient History

Fajada Butte (New Mexico)

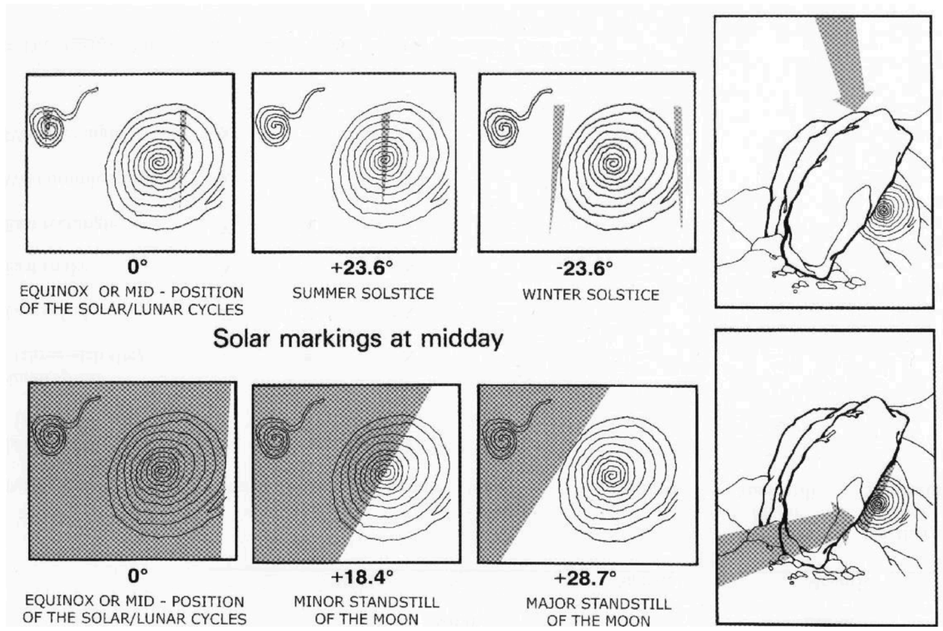


Figure 2. Diagram of shadow and light markings on the Sun Dagger petroglyph at key points in the solar and lunar cycles; sun and moon declinations in degrees . © Solstice Project

https://solsticeproject.org/wp-content/uploads/2021/12/85-SofaerWeinerStone2017_ChacoShrineAlignments_Word.pdf

Ancient History

“Archeoastronomy”

Nabata Playa (southern Egypt)

Pre-20th century [edit]

- 5th century BC — Democritus proposes that the bright band in the night sky known as the Milky Way might consist of stars.
- 4th century BC — Aristotle believes the Milky Way to be caused by "the ignition of the fiery exhalation of some stars which were large, numerous and close together" and that the "ignition takes place in the upper part of the atmosphere, in the region of the world which is continuous with the heavenly motions".[1]
- 964 — Abd al-Rahman al-Sufi (Azophi), a Persian astronomer, makes the first recorded observations of the Andromeda Galaxy[2] and the Large Magellanic Cloud[3][4] in his *Book of Fixed Stars*, and which are the first galaxies other than the Milky Way to be observed from Earth.
- 11th century — Al-Biruni, another Persian astronomer, describes the Milky Way galaxy as a collection of numerous nebulous stars.[5]
- 11th century — Alhazen (Ibn al-Haytham), an Arabian astronomer, refutes Aristotle's theory on the Milky Way by making the first attempt at observing and measuring the Milky Way's parallax.[6] and he thus "determined that because the Milky Way had no parallax, it was very remote from the Earth and did not belong to the atmosphere".[7]
- 12th century — Avempace (Ibn Bajjah) of Islamic Spain proposes the Milky Way to be made up of many stars but that it appears to be a continuous image due to the effect of refraction in the Earth's atmosphere.[1]
- 14th century — Ibn Qayyim al-Jawziyya of Syria proposes the Milky Way galaxy to be "a myriad of tiny stars packed together in the sphere of the fixed stars" and that these stars are larger than planets.[8]
- 1521 — Ferdinand Magellan observes the Magellanic Clouds during his circumnavigating expedition.
- 1610 — Galileo Galilei uses a telescope to determine that the bright band on the sky, the "Milky Way", is composed of many faint stars.
- 1612 — Simon Marius using a moderate telescope observes Andromeda and describes as a "flame seen through horn".
- 1750 — Thomas Wright discusses galaxies and the flattened shape of the Milky Way and speculates nebulae as separate.
- 1755 — Immanuel Kant drawing on Wright's work conjectures our galaxy is a rotating disk of stars held together by gravity, and that the nebulae are separate such galaxies; he calls them *Island Universes*.
- 1774 — Charles Messier releases a preliminary list of 45 Messier objects, three of which turn out to be the galaxies including Andromeda and Triangulum. By 1781 the final published list grows to 103 objects, 34 of which turn out to be galaxies.
- 1785 — William Herschel carried the first attempt to describe the shape of the Milky Way and the position of the Sun in it by carefully counting the number of stars in different regions of the sky. He produced a diagram of the shape of the galaxy with the solar system close to the center.
- 1845 — Lord Rosse discovers a nebula with a distinct spiral shape.

https://en.wikipedia.org/wiki/Timeline_of_knowledge_about_galaxies,_clusters_of_galaxies,_and_large-scale_structure

Galileo (1610)

Widely cited as the first discovery that the Milky Way is made up of stars

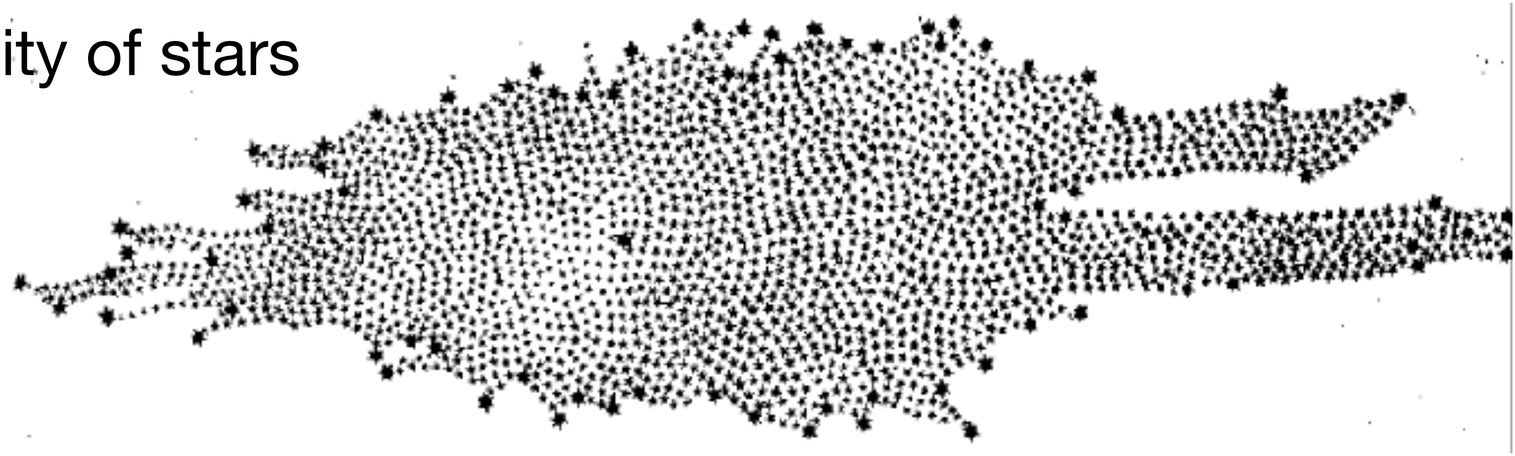
Nebula of Orion.

Nebula of Praesepe.

https://www.reed.edu/math/wieting/mathematics537/SideriusNuncius.pdf

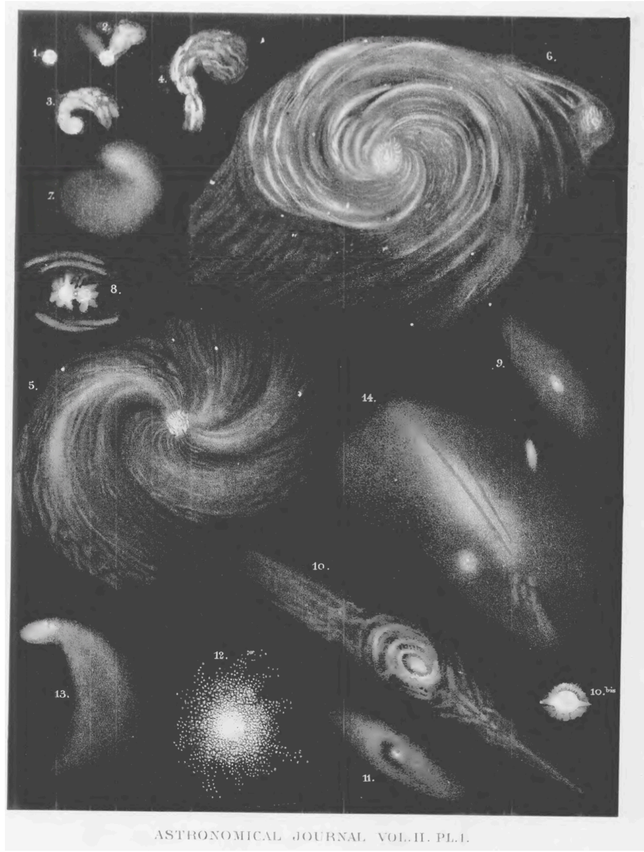
1785: William & Catherine Herschel

- Counting stars along many lines of sight
- Assumes a fairly uniform density of stars (like a forest)
- No concept of dust or extinction



1800’s

- Big telescopes being built (up to 72” diameter!), detailed sketches of nebulae
- William Parsons, 3rd Earl of Rosse (1850)
  - “Observations on the Nebulae”
- Stephen Alexander (1852)
  - “On the origin of the forms and the present condition of some of the clusters of stars, and several of the nebulae”



1900’s

Where is the Sun within the Milky Way?

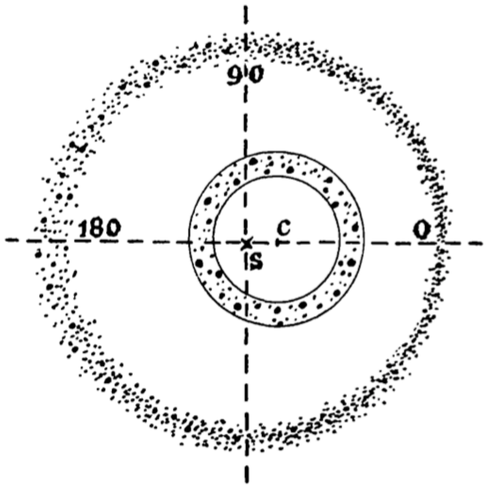


FIG. 1.

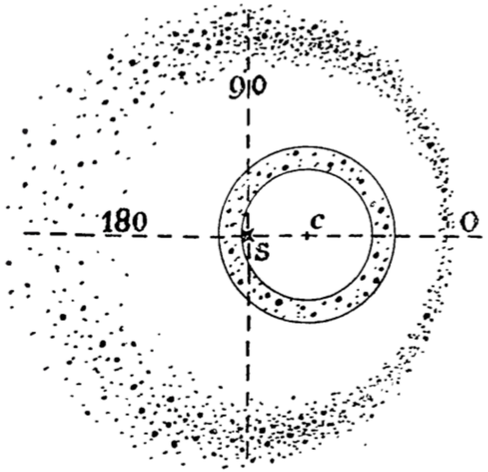


FIG. 2.

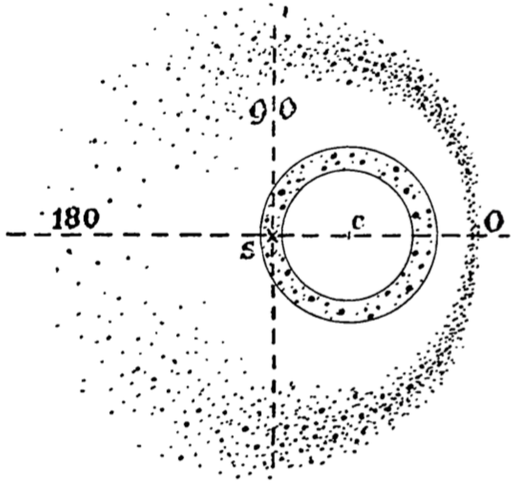
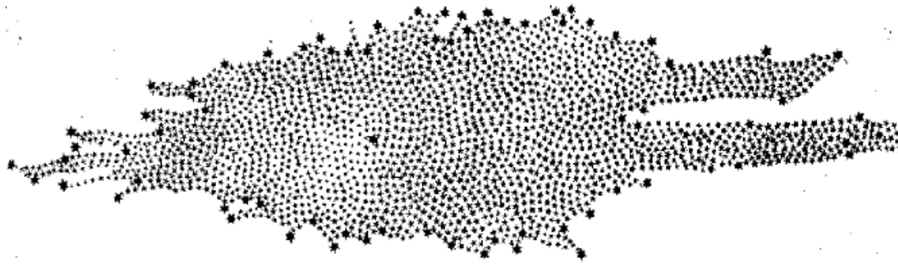


FIG. 3.

Easton (1900)



1900’s

First speculative drawing of Milky Way including spiral arms

Easton (1900)

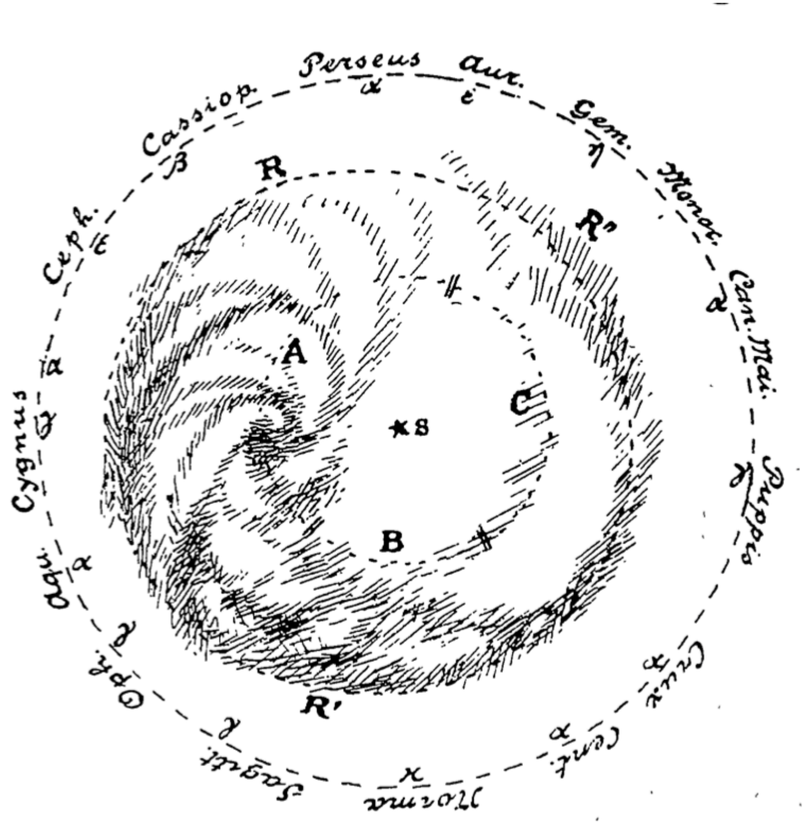


FIG. 6.

ness of the secondary branch near *Cygnus;* the dark spaces surrounded by luminous streams between *α Cygni* and *β Cassiopeiae*, etc.; the "lateral offsets" of the Milky Way; the connection of the clusters and the bright stars in *Taurus* and *Orion* with the nebulosities related to the Milky Way; the very faint region in *Perseus*, etc.—while retaining the advantages offered by the annular segments. I wish to insist upon the fact that Fig. 6 *does not pretend to give an even approximate representation of the Milky Way*, seen from a point in space situated on its axis. It only indicates in a general way how the stellar accumulations of the Milky Way might be distributed so as to produce the galactic phenomenon, in its general structure and its principal details, as we observe it.

The 1920s

- Have photography & spectroscopy (RVs)
- some proper motions & parallaxes for very nearby things
- dynamics arguments starting to be used to discuss structure and formation of MWY
- **LOTS of work focusing around star clusters & pulsating stars (Leavitt & Pickering 1912)**
- Oort (PhD thesis!) 1927 on “stars of high velocity” (some halo stars!)

Clusters

Shapley (1930)

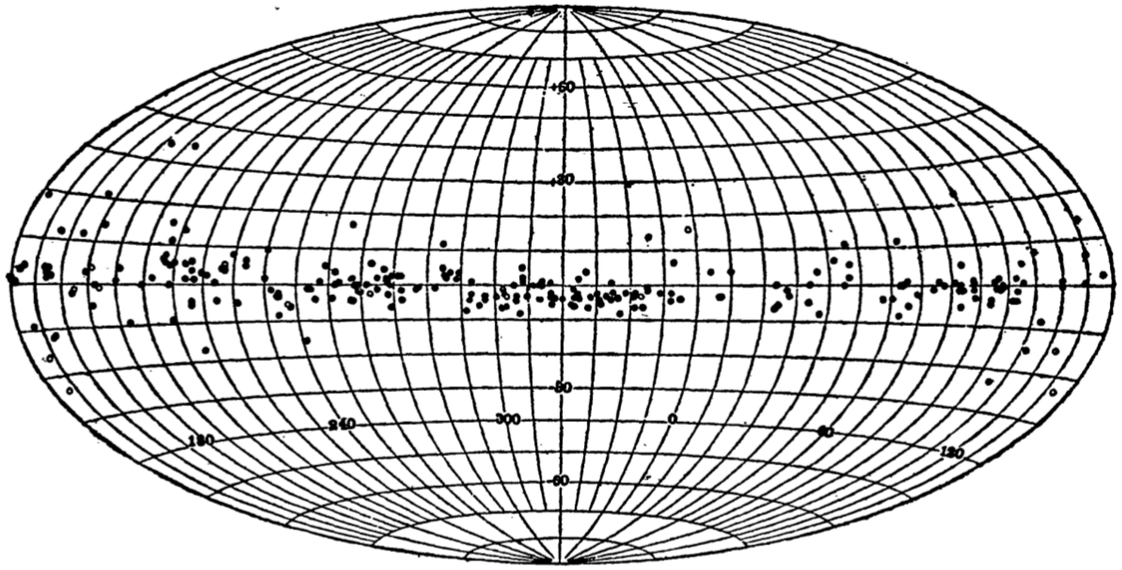


FIGURE II, 2.

Distribution of galactic clusters in galactic coordinates. Cluster classes are indicated as follows: c, ○; d, ⊕; e, ◑; f, ◒; g, ●.

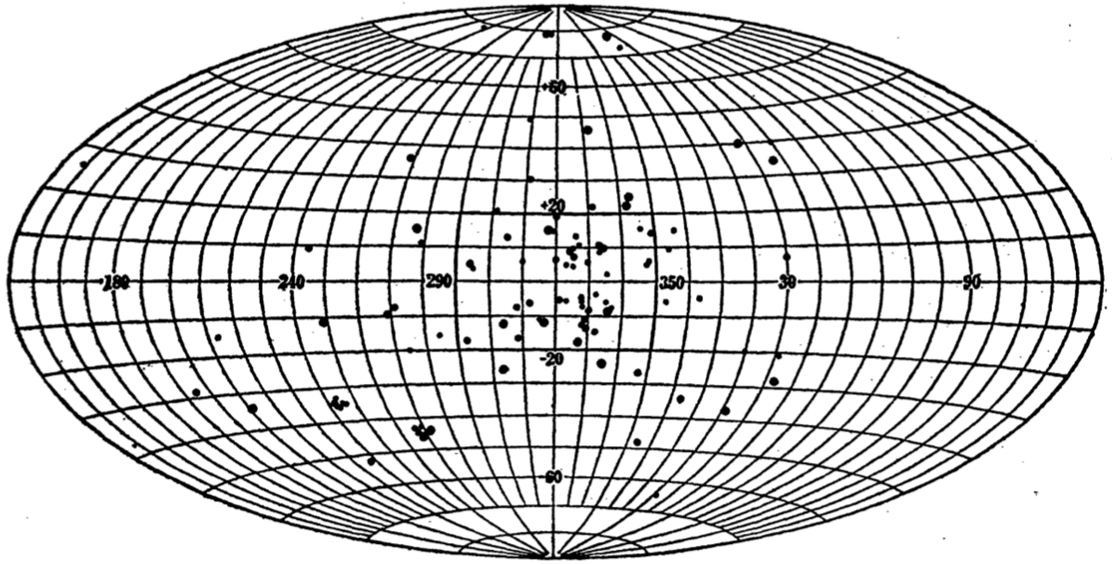
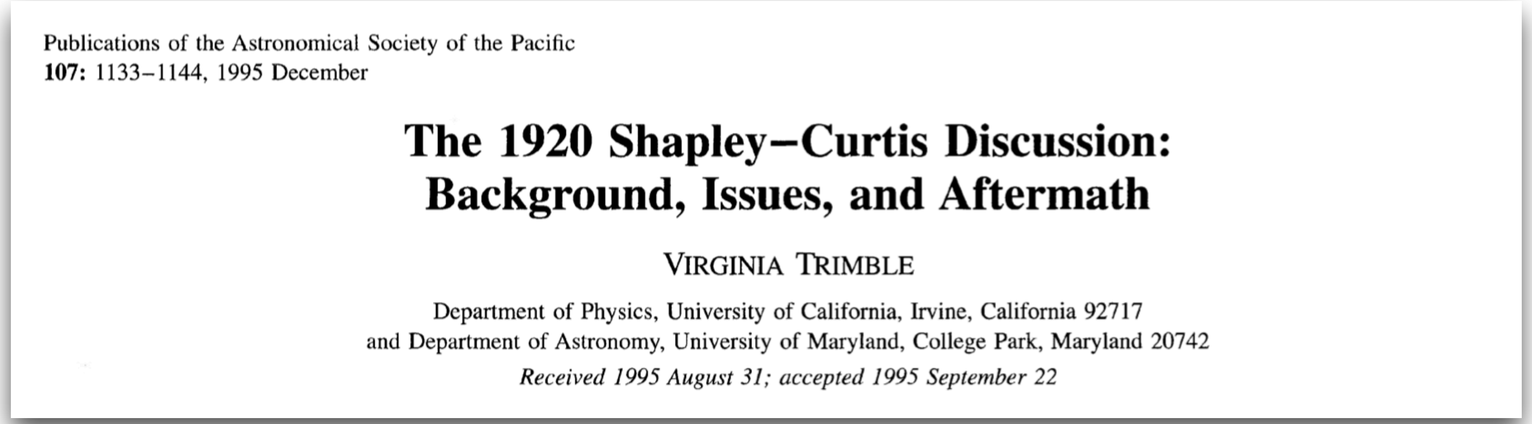


FIGURE II, 4.

Distribution of globular clusters in galactic coordinates.

The “Great Debate”

- Interesting review of the “Great Debate” by Trimble (1995)
  - Now *itself* a bit of history



Publications of the Astronomical Society of the Pacific
107: 1133–1144, 1995 December

The 1920 Shapley–Curtis Discussion: Background, Issues, and Aftermath

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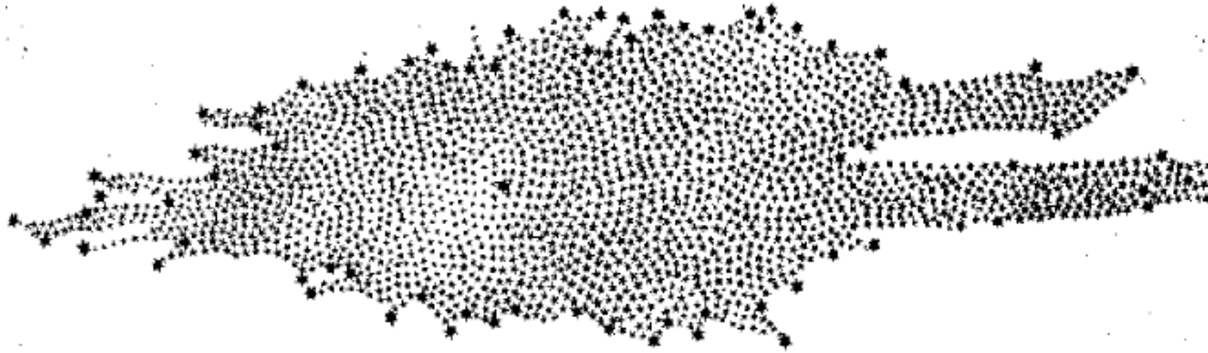
Received 1995 August 31; accepted 1995 September 22

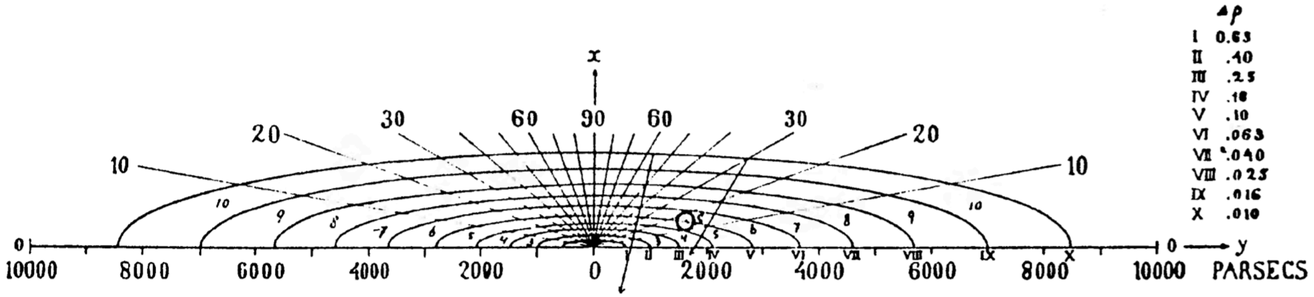
The “Great Debate”

- Held in 1920 on the “distance scale of the Universe”
  - **Harlow Shapley** (Milky Way is *huge*, other “nebulae” look small, must not be galaxies like ours)
  - **Heber Curtis** (“Kapteyn’s model”, MWY is small, Andromeda is VERY far away, comparable to MWY in size)

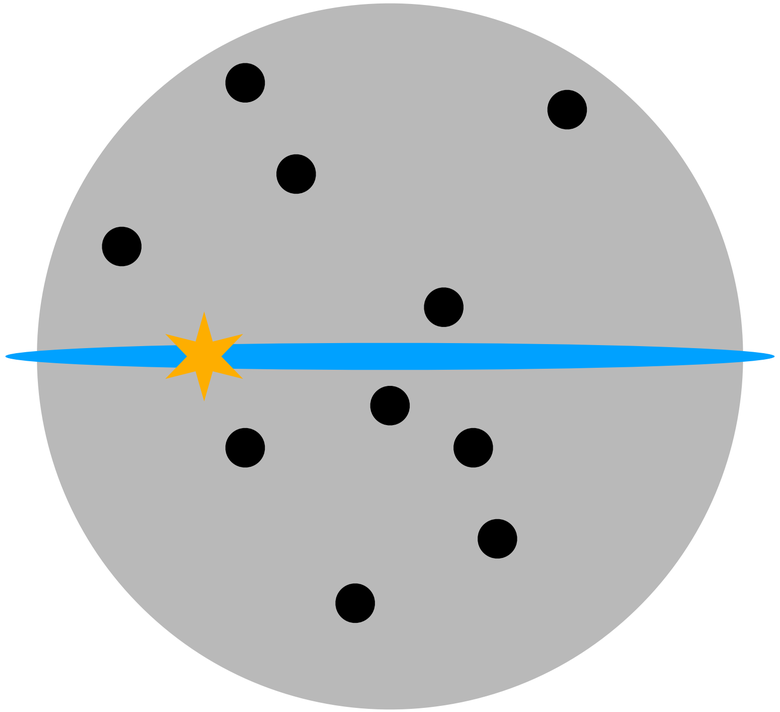
The “Great Debate”

Heber Curtis & the “Kapteyn Universe” model



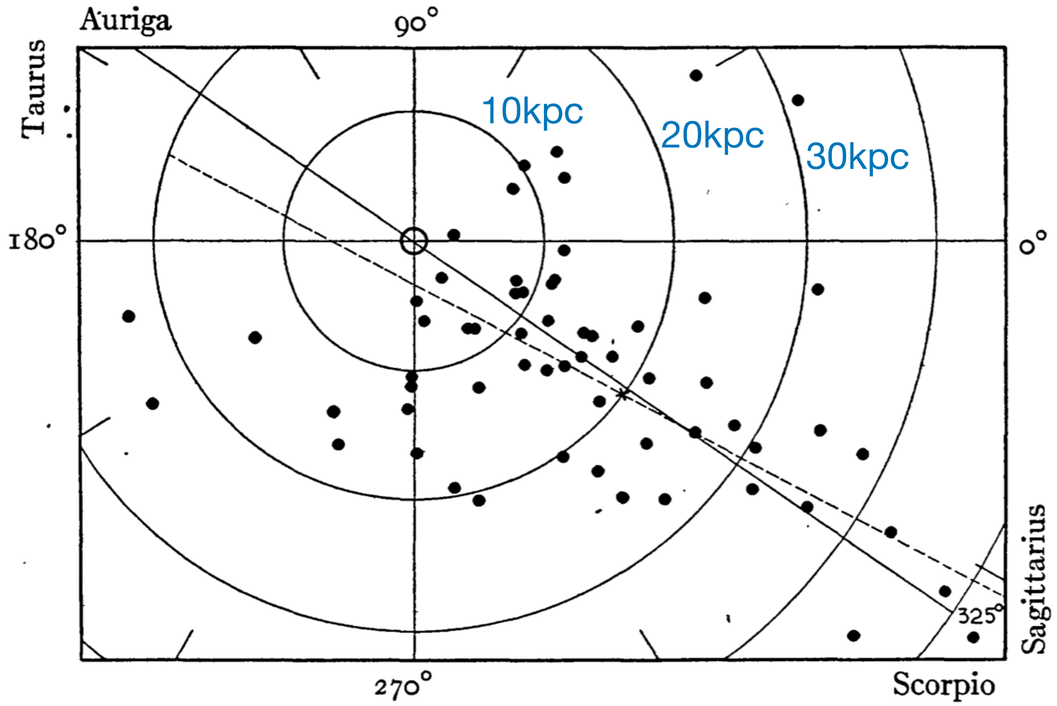


The “Great Debate”



GC system NOT centered on us!

Harlow Shapley’s model



- Globular Clusters

Shapley (1919)

The “Great Debate”

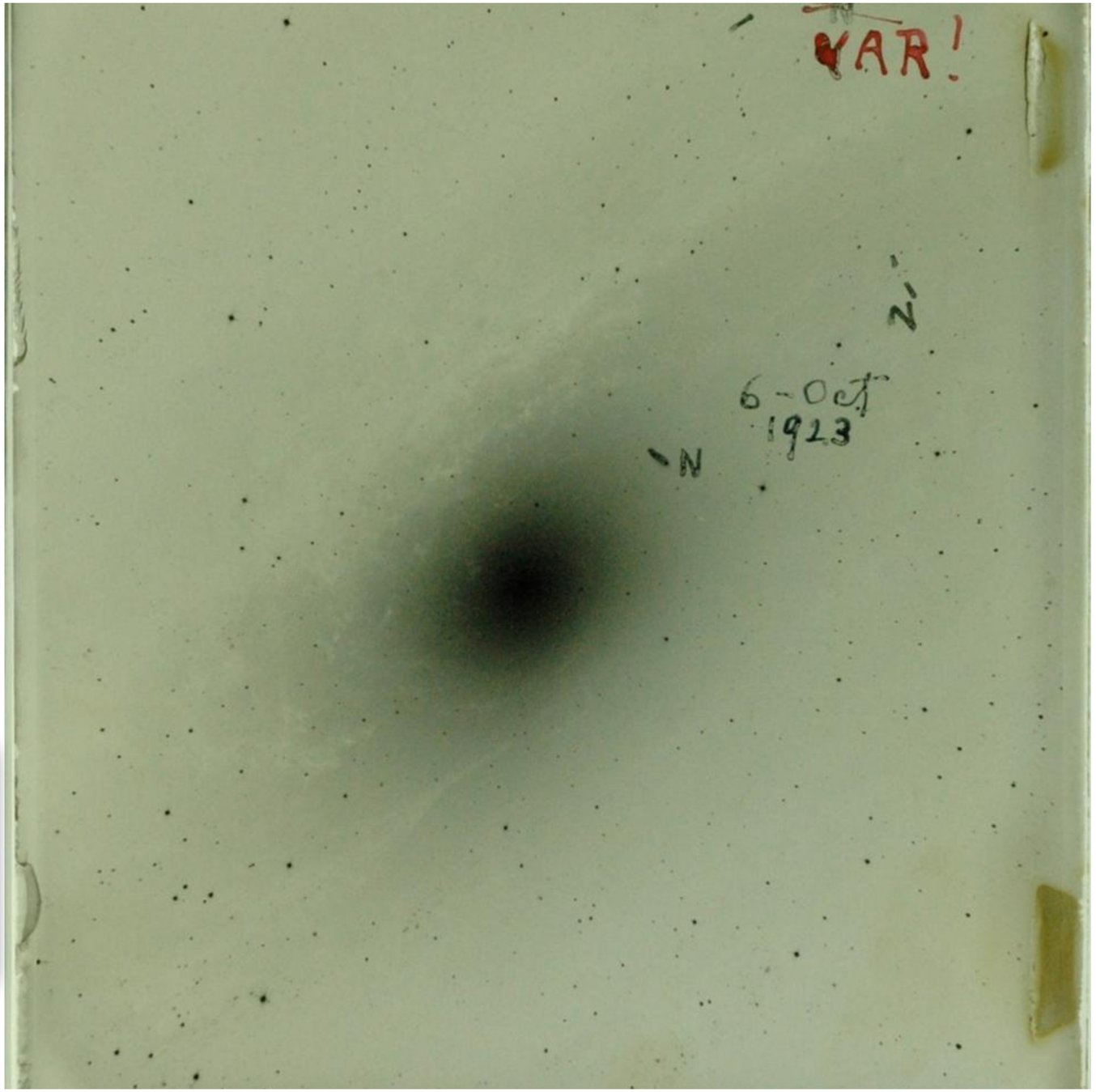
- Held in 1920 on the “distance scale of the Universe”
  - **Harlow Shapley** (Milky Way is *huge*, other “nebulae” look small, must not be galaxies like ours)
  - **Heber Curtis** (“Kapteyn’s model”, MWY is small, Andromeda is VERY far away, comparable to MWY in size)
- Not the fierce brawl you might imagine… it was really 2 dudes giving 30 min talks
- They BOTH got parts of the picture very wrong, and some things right
- Field didn’t seem to coalesce on either model quickly

The “Great Debate”

- Hubble starts finding Cepheids (1923)
- 1925: Hubble “solves”the debate for M31 & M33
  - Announced at AAS 33 in DC!
- 1926: starts studying *hundreds* of galaxies, classifying them…

greater reliability of the magnitude determinations. When this is done, the resulting values of M—*m* are −21·8 and −21·9 for M 31 and M 33 respectively. These must be corrected by half the average ranges of the Cepheids in the two spirals, and the final values are then on the order of −22·3 for both nebulæ. The corresponding distance is about 285,000 parsecs *. The greatest uncertainty is probably in the zero-point of Shapley's curve.

Distance to M31 ~3x too small



https://obs.carnegiescience.edu/hubbles-famous-m31-var-plate

Other Debates…

- In the same 1925 volume, here's Malmquist whinging for 3 pages about units for distance
  - why is absolute magnitude tied to a distance of 10 pc, not 1 pc?!
  - Shame the "Siriometer" died out, lol
    - (d=2.64 pc)

In accepting a definitive unit of length, the system of absolute magnitudes is also fixed. For there is not the least reason for giving up the usual definition, viz. that the absolute magnitude is equal to the apparent magnitude *at unit distance*. This consistent definition is, however, not adhered to by the decision of the question at the meeting of the International Astronomical Union in Rome, May 1922. Here the parsec was adopted as unit of length, but the absolute magnitude was defined as the apparent magnitude at ten parsecs distance! Such a compromise must, of course, be considered as wholly unnecessary and moreover, inconvenient, and this is another reason not to consider this decision as the definite one. Then the question must first be discussed before it can be considered as mature for decision. I hope that this little contribution may initiate such a discussion.

K. G. MALMQUIST.

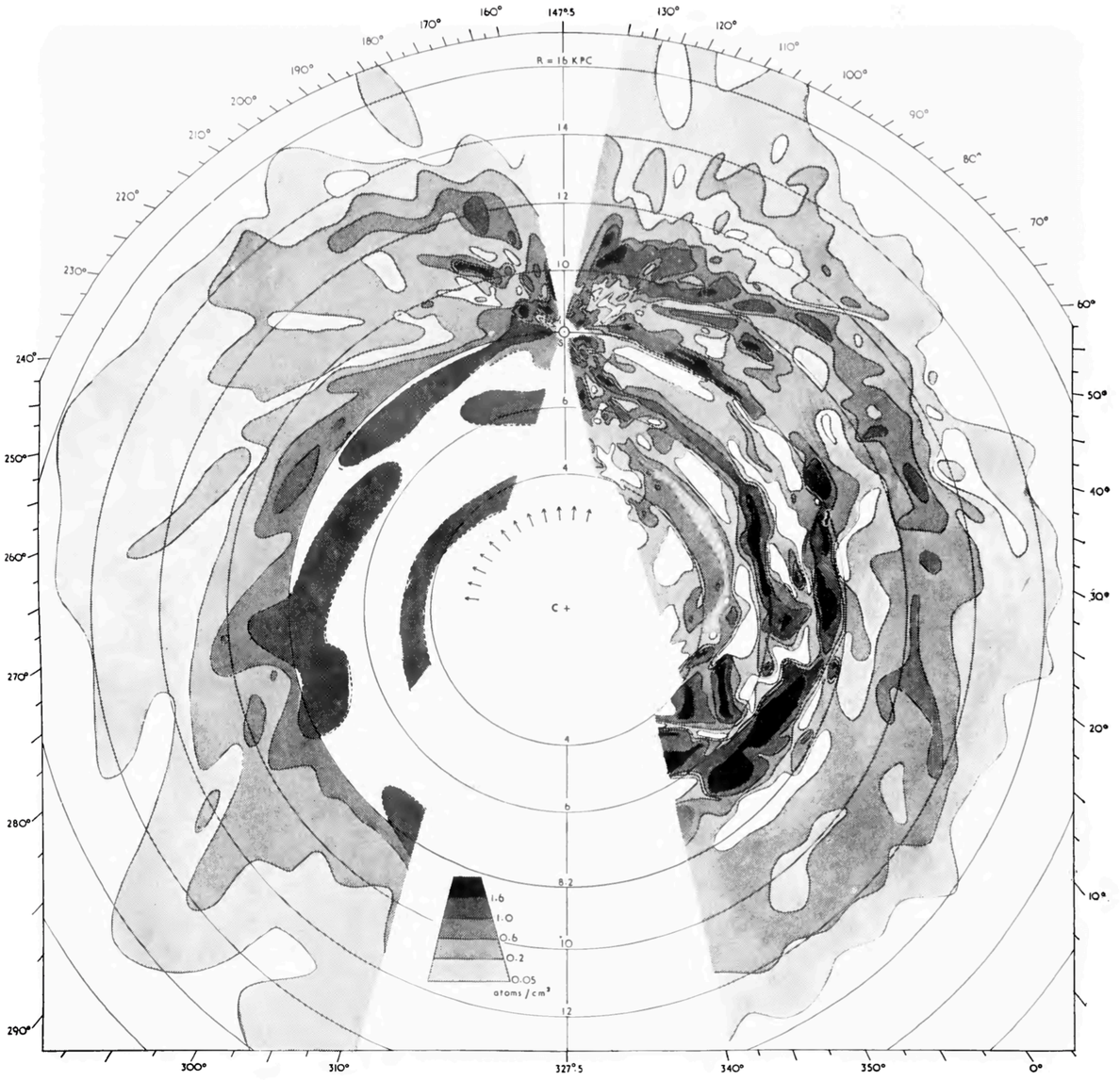
Spiral Arms

- Described in 1850's for *other* "nebulae"
- Early speculation about MWY spiral structure at least as early as 1900
- Once we realized that DUST was in the way, and Milky Way was a normal galaxy (mid 1920's) thoughts about spiral structure immediately began to take shape

FIG. 6.

Spiral Arms

- First detection claimed by Morgan+1952
- Oort+1958 give nice overview of state of understanding. Optical AND Radio playing a key role
  - Multiple spiral arms noted!
  - Note: Sun at 8kpc!



https://ui.adsabs.harvard.edu/abs/1958MNRAS.118..379O/abstract

Rotation (1927)

- Oort (again!)
- Galaxy rotates
- Rotates differentially
- The “Oort Constants” (A and B) named after him

1927 April 14 Volume III. No. 120.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

Observational evidence confirming Lindblad's hypothesis of a rotation of the galactic system, by *J. H. Oort.*

1. *Introduction.*

It is well known that the motions of the globular clusters and RR Lyrae variables differ considerably from those of the brighter stars in our neighbourhood. The former give evidence of a systematic drift of some 200 or 300 *km/sec* with respect to the bright stars, while their peculiar velocity averages about 80 *km/sec* in one component, which is nearly six times higher than the average velocity of the bright stars.

Because the globular clusters and the bright stars seem to possess rather accurately the same plane of symmetry, we are easily led to the assumption that there exists a connection between the two. But what is the nature of the connection?

In order to explain the rotation there must be near the centre an attracting mass of at least 8×10^{10} times the mass of the sun. There remains the difficulty why we do not observe this large mass. Near 6000 parsecs KAPTEYN and VAN RHIJN find an almost negligible density, whereas it *should* be very much greater than in our neighbourhood. Part of the dis-

longitudes were combined. Discussing various galactic regions separately KREIKEN finds indications of a centre near 314° longitude, at a distance of 2270 parsecs *) which is in the right direction, but certainly at too small a distance and too little defined. **) The most probable explanation is that the decrease of density in the galactic plane indicated for larger distances is mainly due to obscuration by dark matter. Such a hypothesis receives considerable support from the marked avoidance of the galactic plane by the globular clusters, a phenomenon for which up to the present time no other well defensible explanation has been put forward. ***)

Oort (1927)

Rotation (1927)

- Oort (again!)
- Galaxy rotates
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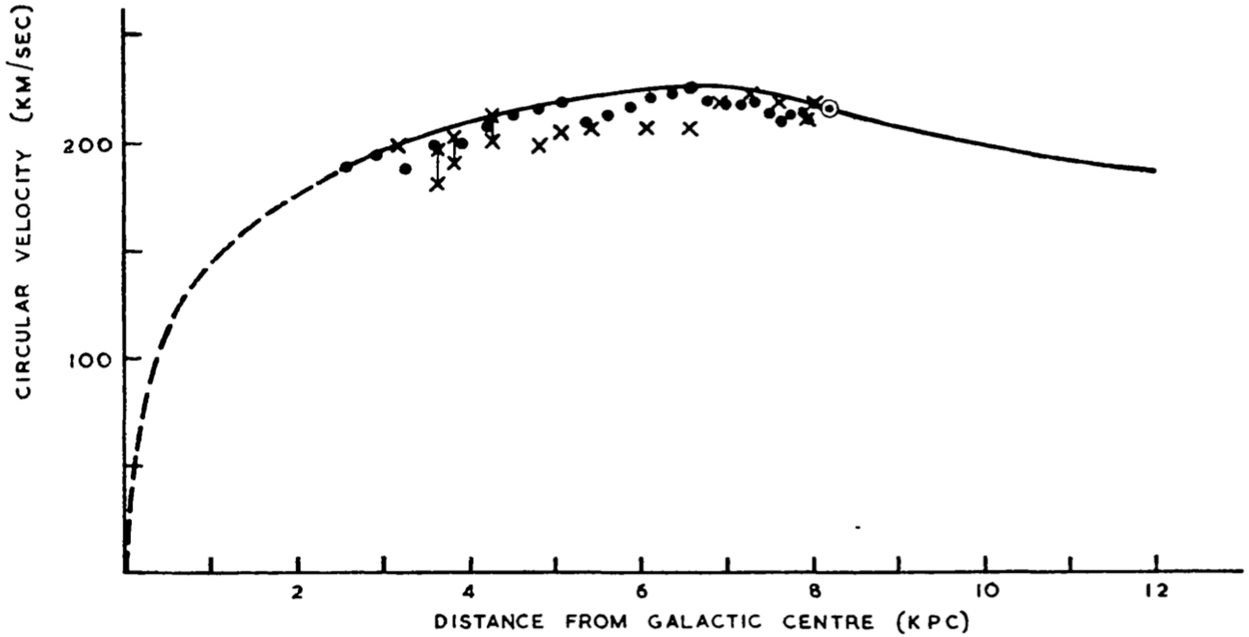


FIG. 2.—*Variation of circular velocity with distance from the galactic centre* (7, 8). *Observational points from the northern* (●) *and southern* (×) *sectors have been included, except in the innermost region, where expansion makes the interpretation more difficult.*

https://ui.adsabs.harvard.edu/abs/1958MNRAS.118..379O/abstract

Dark Matter

- Oort (1932) notes problems with orbital velocities of stars perpendicular to the galactic plane
- Fritz Zwicky (1933) studying Coma galaxy cluster notes velocities too high
- Problems with galactic dynamics, rotation of galaxies, velocities of galaxy clusters noted for MANY years from the late 1950s to the 1970s
- Vera Rubin and others estimate mass structure of other galaxies

Dark Matter

This ratio seems too high

Stars	0.05
Gas (HI, HII, He)	0.03
Total	0.08

Thus, we can account for only 60 percent of the total mass density in the Galactic plane near the vicinity of the sun. Fully 40 percent of the matter has not yet been found in observable form. Perhaps this missing mass is in the form of undetected stars; these might be cool, faint "black dwarfs," which emit all their radiation in the unobserved infrared region. In this connection it should be remembered that we have no firm data on the luminosity function for stars with $M_{vis} > 20$; large numbers of these stars could contribute substantially to the mass density if in fact they exist. Perhaps the missing mass is in the form of molecular hydrogen, H_2, which is extremely hard to observe spectroscopically because all the absorption lines originating from the ground state of the molecule lie in the far infrared or ultraviolet regions and are extremely weak. We have at present no observational information about the density of interstellar H_2, but it is tempting to believe that much of the "missing matter" might be in this form.

Could we have made a mistake? The star density is probably accurate enough. As pointed out previously, however, the gas density might be (though probably is not) as high as $0.05\mathfrak{M}_\odot$ per cubic parsec. Even so, this still leaves $0.05\mathfrak{M}_\odot$ per cubic parsec unaccounted for, an amount somewhat larger than our present estimate of the gas density. The elimination of this discrepancy will represent a major step forward in our understanding of the interstellar medium.

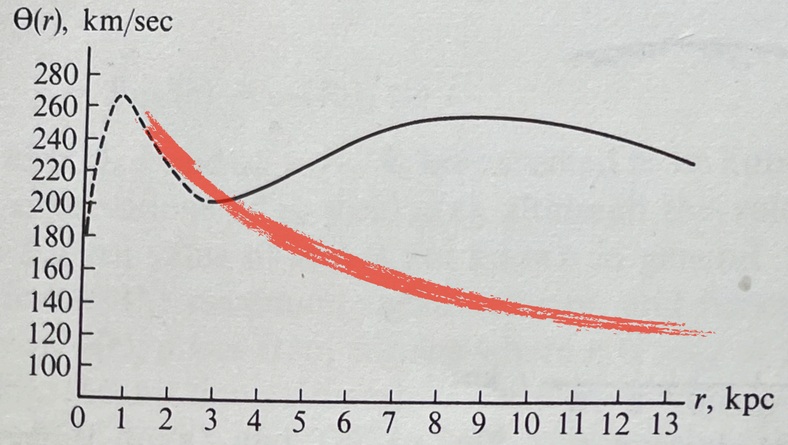
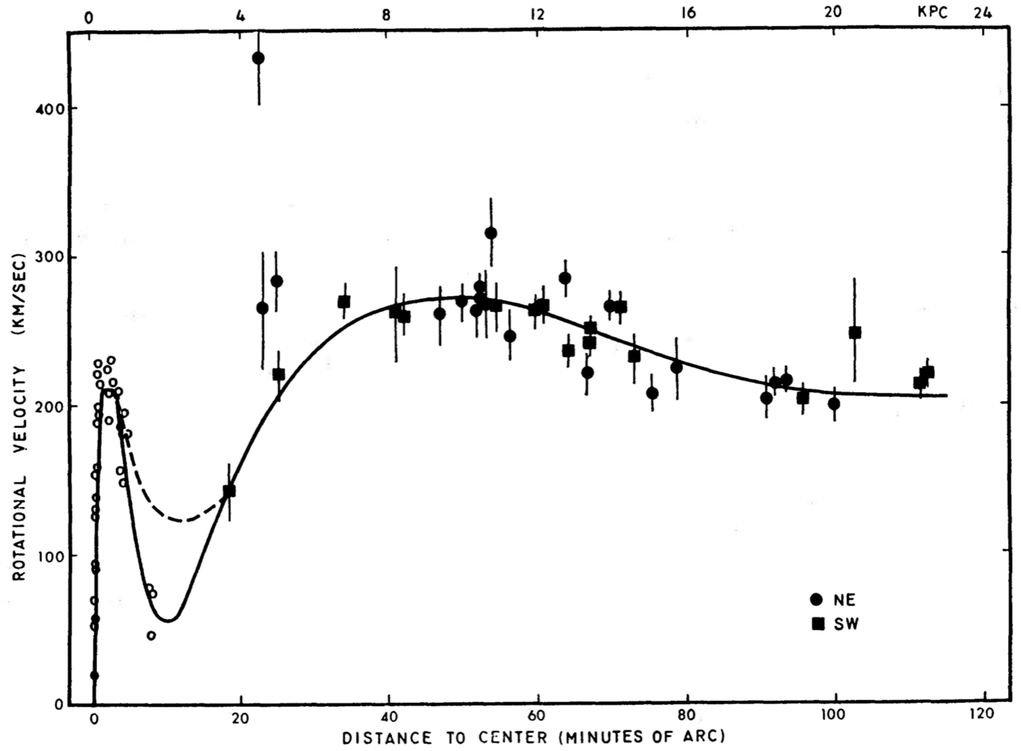


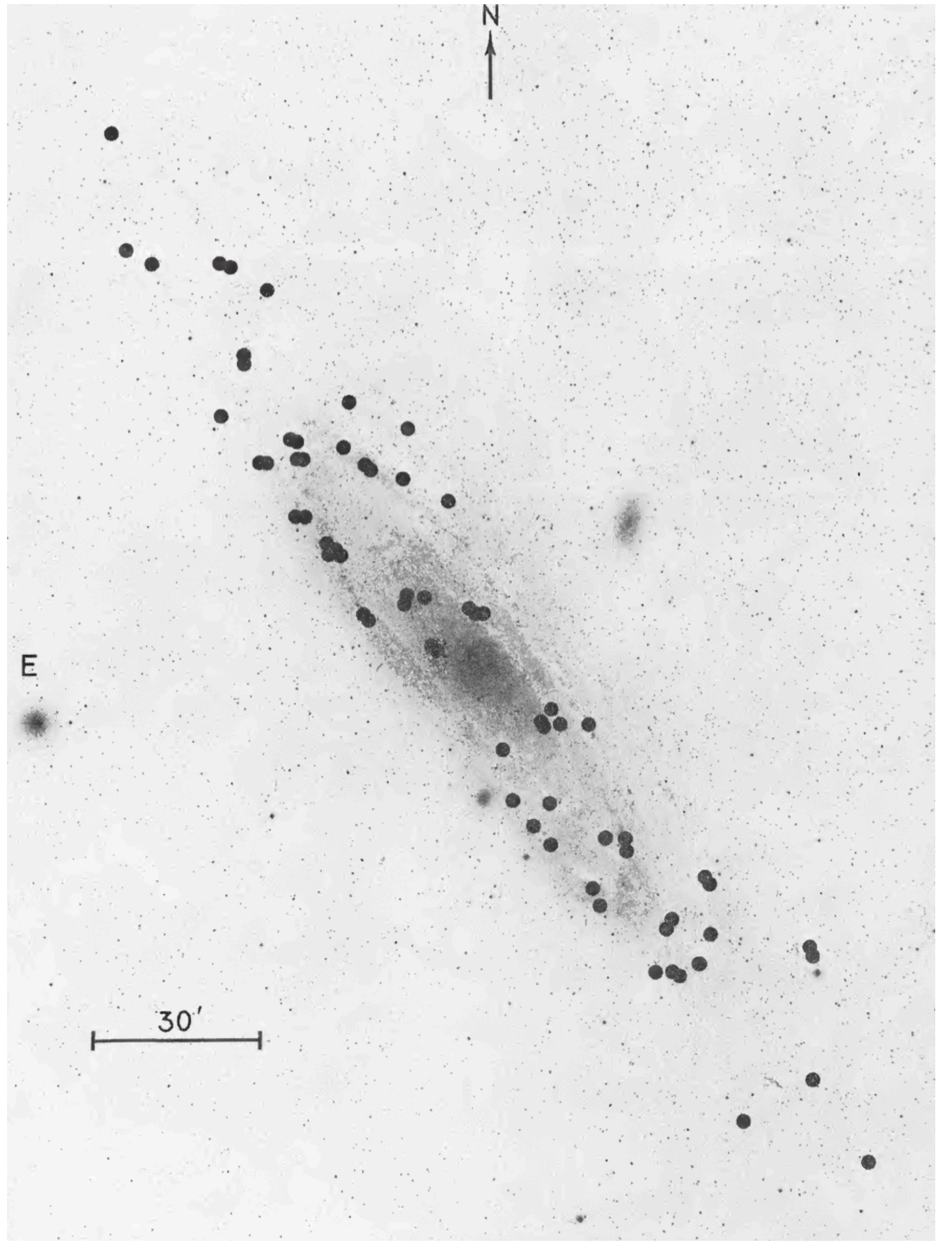
FIG. 8-18. The rotation curve $\Theta(r)$ based on the most recent values for Θ_0 and R_0. Rotation velocities for $r < R_0$ were obtained from radio observations and values for $r > R_0$ were derived from optical observations. (From G. Contopolous and B. Strömgren, *Tables of Plane Galactic Orbits*, New York: NASA Institute for Space Studies, 1965, by permission.)

1965: Milky Way rotation curve isn't quite right

Dark Matter

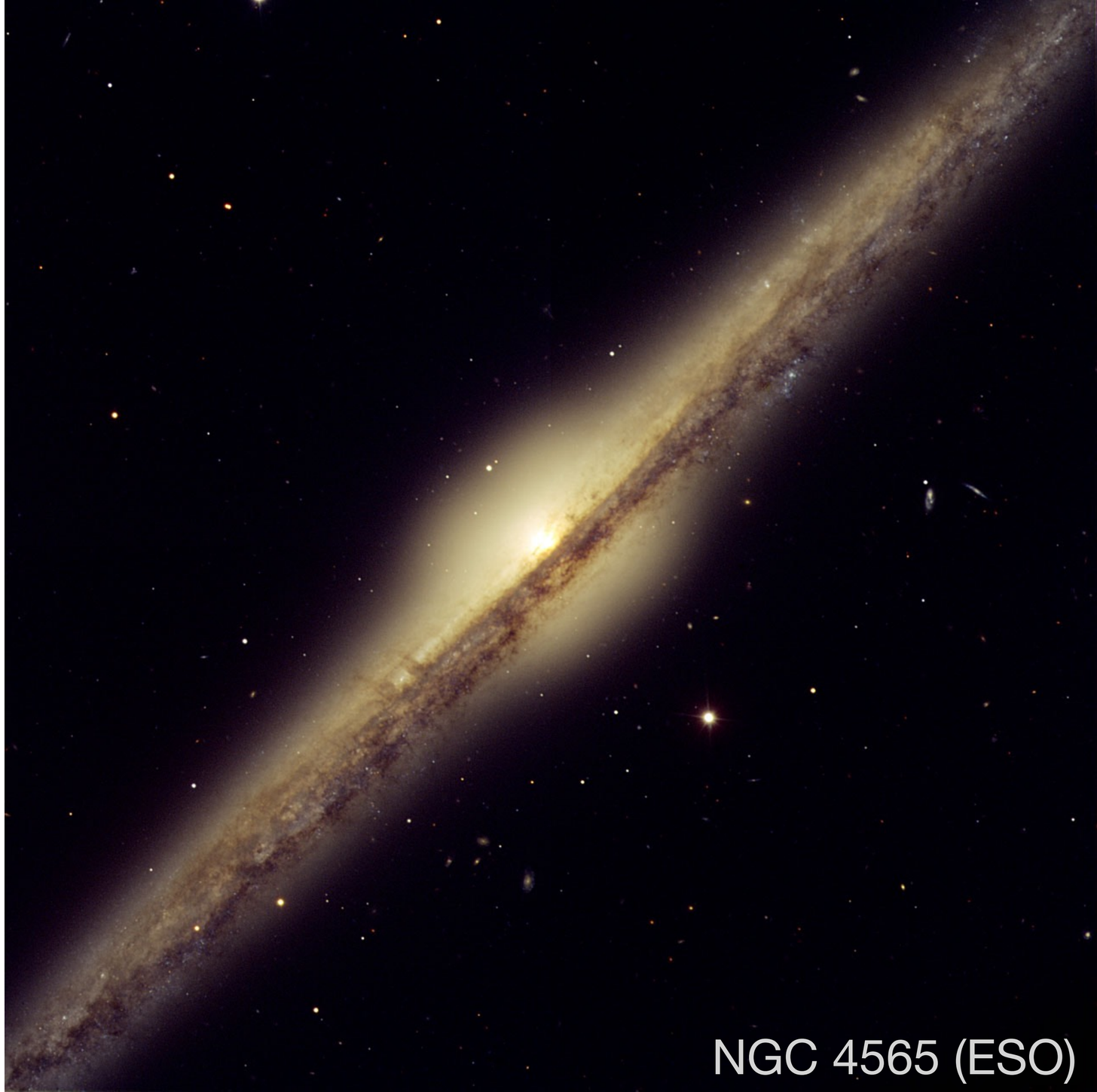
- Rubin & Ford (1970) a canonical paper on the Andromeda “Nebula” (M31)





The Bulge

- Thickness or high density region (bulge) obvious since antiquity
- Distance to galactic center hotly debated (STILL)
- Radio source (Sag A) detected by Pawsey+1955



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Constellation	I.A.U. No.	Observer's Catalogue No.	Position (1950 Epoch) R.A.	Position (1950 Epoch) Dec.	Flux Density Frequency (Mc/Sec)	Flux Density Watts M^{-2} $(C/Sec)^{-1}$ $\times 10^{-24}$	Remarks
Sagittarius	17S2A	M 17−2B BSS 68 NRL 5	$17^h44^m \pm 2^m$ $17^h42^m \pm 1^m$ $17^h42^m.5 \pm 0^m.2$	$-30° \pm 1°$ aa $-28°.5 \pm 0°.2$ bb $-29°01' \pm 5'$ y	100 101 400 1200 3200	1.2 r 3 b 14 bb 26 aa 4.8 y	May be associated with the galactic nucleus; the presence of neighboring intense emission regions makes the measurements of flux density difficult
		BSS 120	$18^h16^m \pm 4^m$	$-8° \pm 2°$ r	100	1.5 r	

NGC 4565 (ESO)

The Bulge

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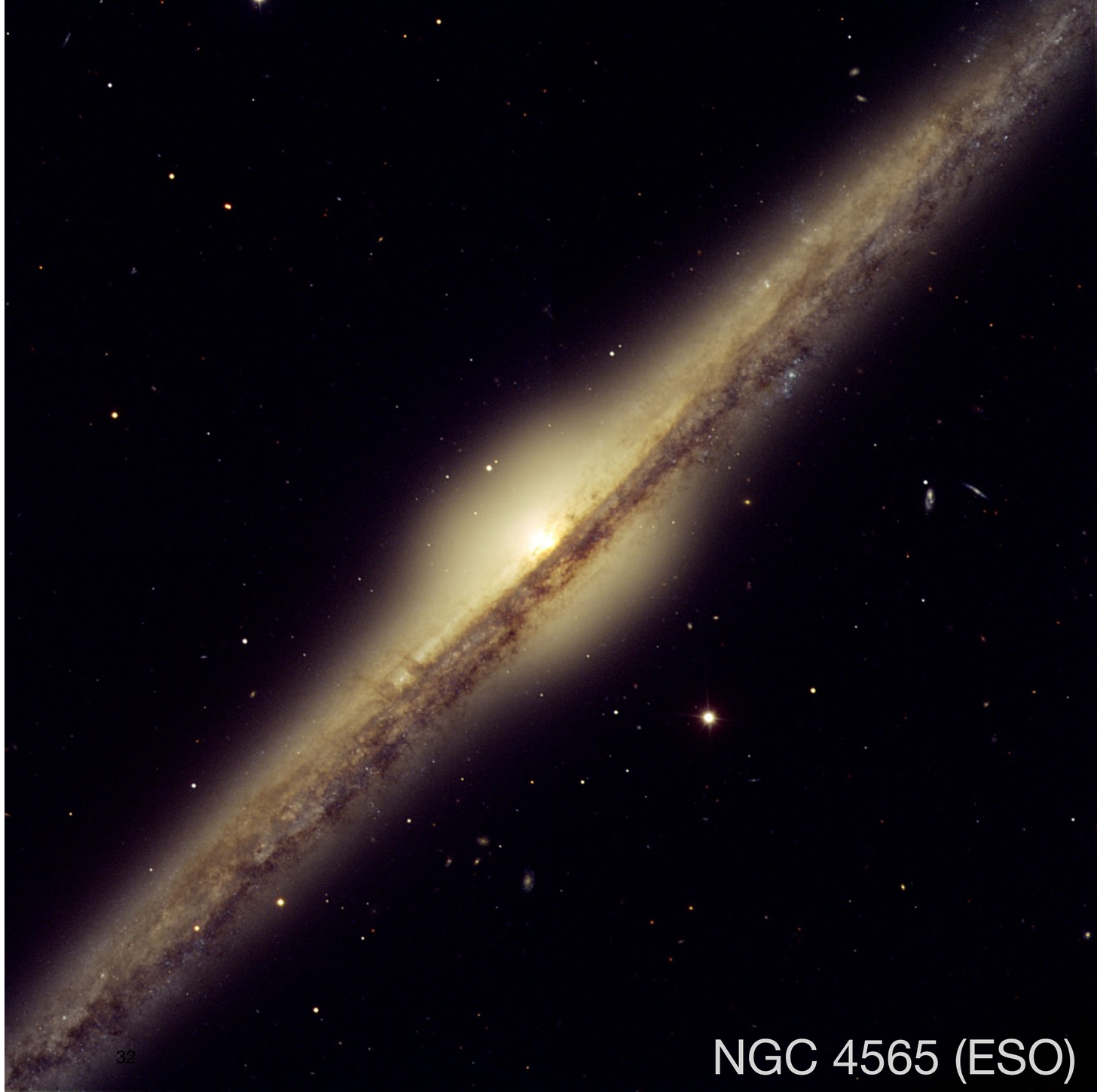
NGC 4565 (ESO)

The Bulge

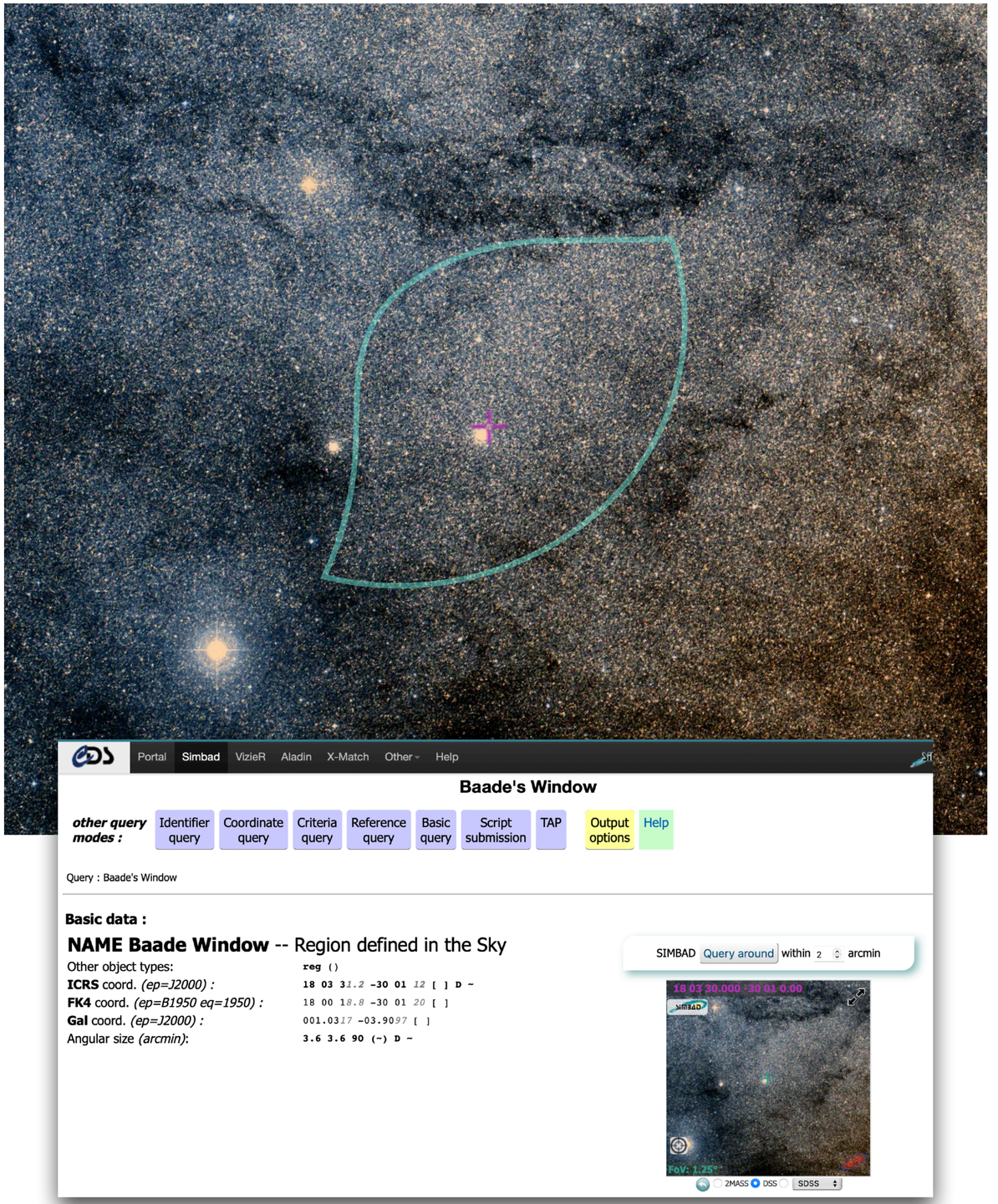
- Nuclear star clusters are quite small (relative to disk)
- SO much extinction (once we figured out dust)
  - **~25 magnitudes of dust!**
  - Can only study in Radio/IR
- How do we see the bulge stars?!
  - **WINDOWS!**



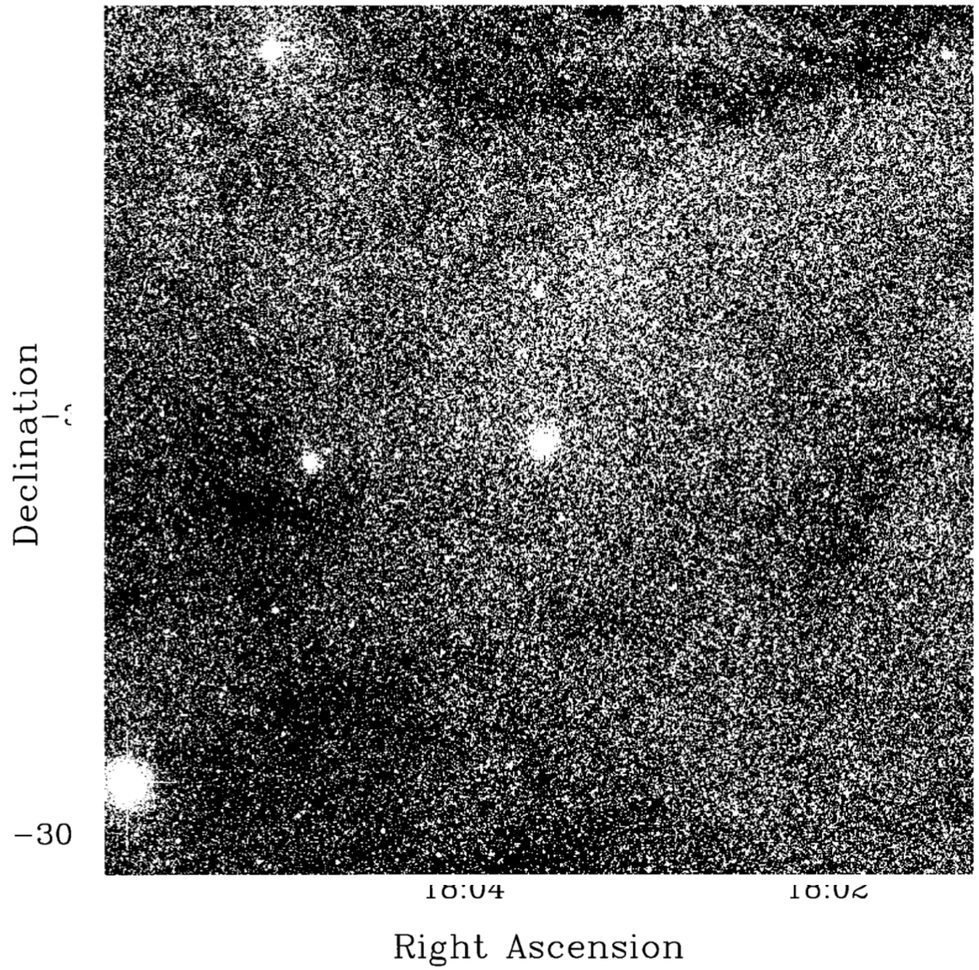
NGC 4565 (ESO)

Baade’s Window

- First discovered by W. Baade (1946)
- About 1deg wide “window” of low extinction, can see star clusters & variable stars (RR Lyr), like those in Globular Clusters
- Can tell stars are older/redder
- Speculates the halo (galactic corona) may be an extension of the bulge
- ~4 other good “windows”



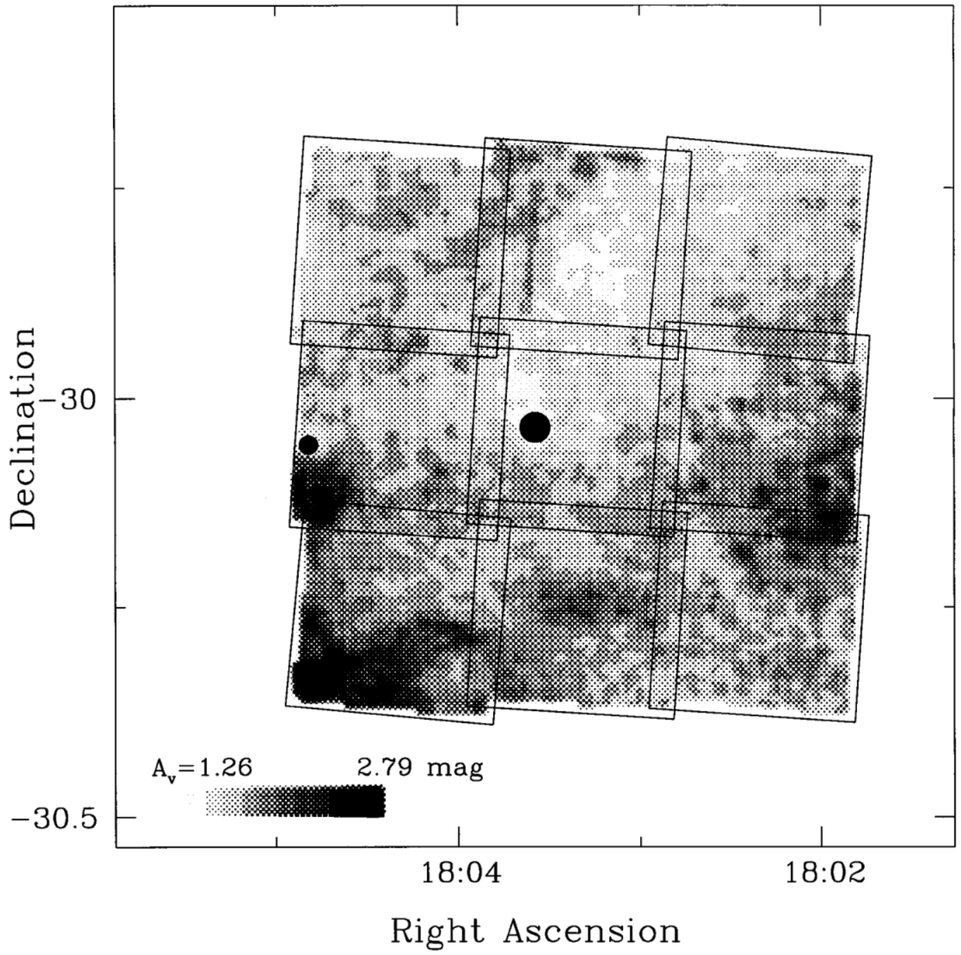
Baade's Window



Stanek (1996)

OGLE data

Baade's Window

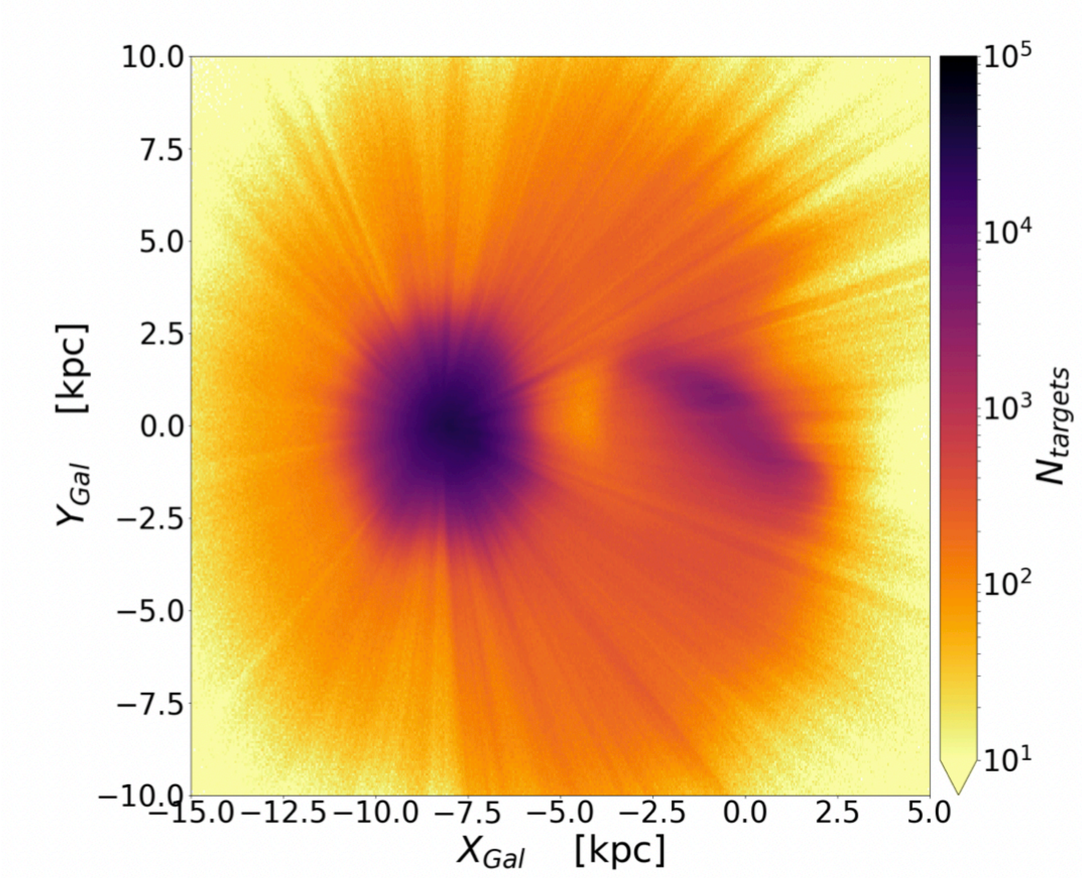


Stanek (1996)

OGLE data

The Bar

https://en.m.wikipedia.org/wiki/File:Milky_Way_Galaxy.jpg



https://ui.adsabs.harvard.edu/abs/2019A%26A...628A..94A/abstract

The Bar

In this model the negative velocities in the direction of the centre are interpreted not as an expanding arm or ring, but as indicating that the gas is streaming along the bar from the nucleus outward at velocities of the order of 60 to 70 km/sec, the line-of-sight component being 53 km/sec in the direction of the nucleus (Oort, Kerr, and Westerhout 1958). Such a flow pattern, which is strongly suggested by the narrow dust lanes commonly observed along the bars of barred spirals, was directly detected by recent spectroscopic observations of several systems described in another communication.

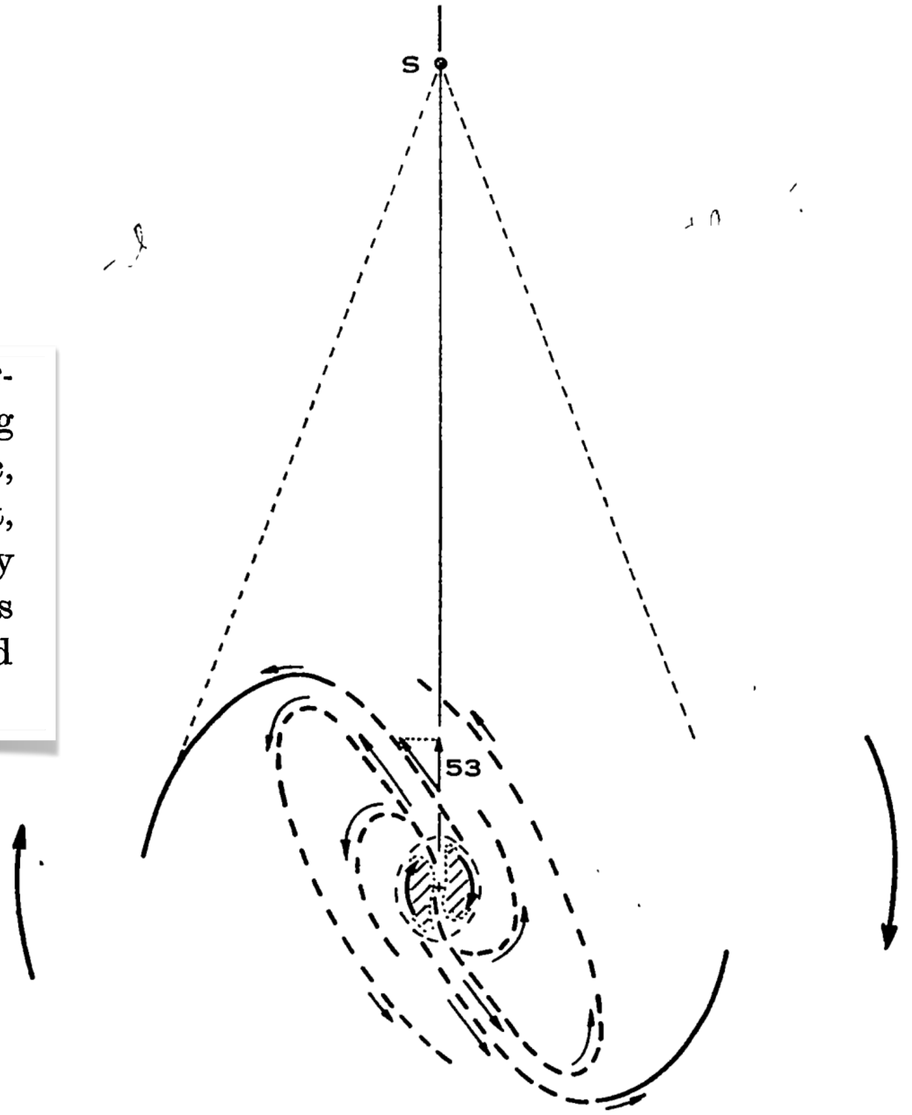


Fig. 1.—Possible structure of inner regions of the Galaxy consistent with SAB(rs) structure of outer regions. Compare with photograph of NGC 4303. Dashes show main gas and dust streams superimposed on general rotation.

de Vaucouleurs (1964)

The Bar

DIRECT EVIDENCE FOR A BAR AT THE GALACTIC CENTER

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Blitz & Spergel (1991)

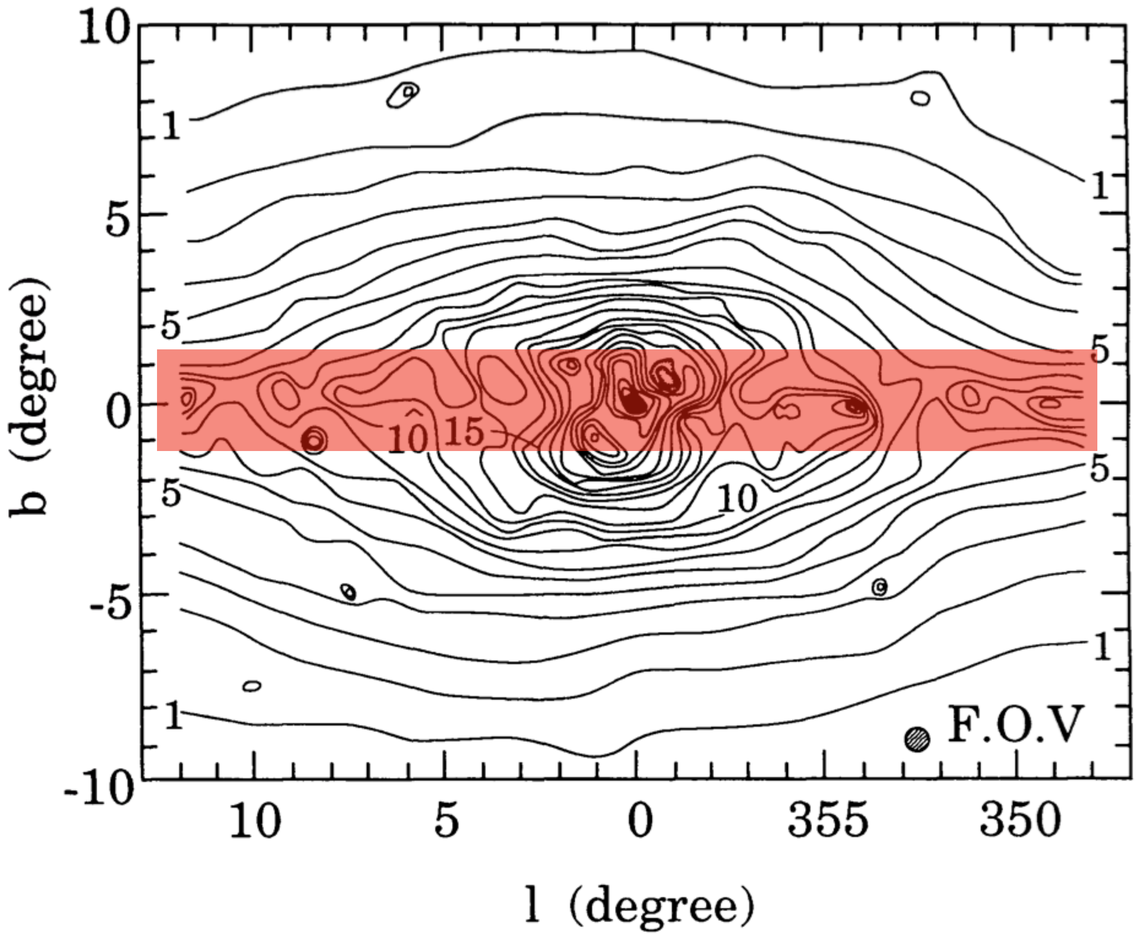
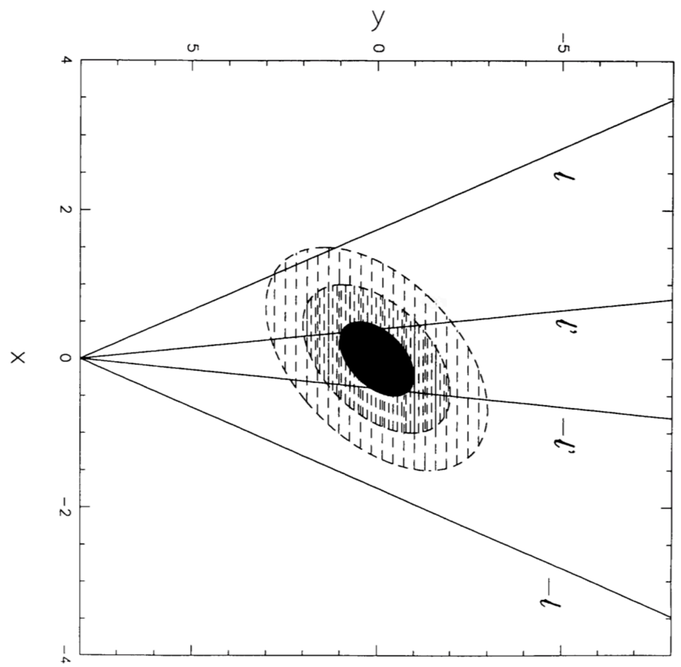
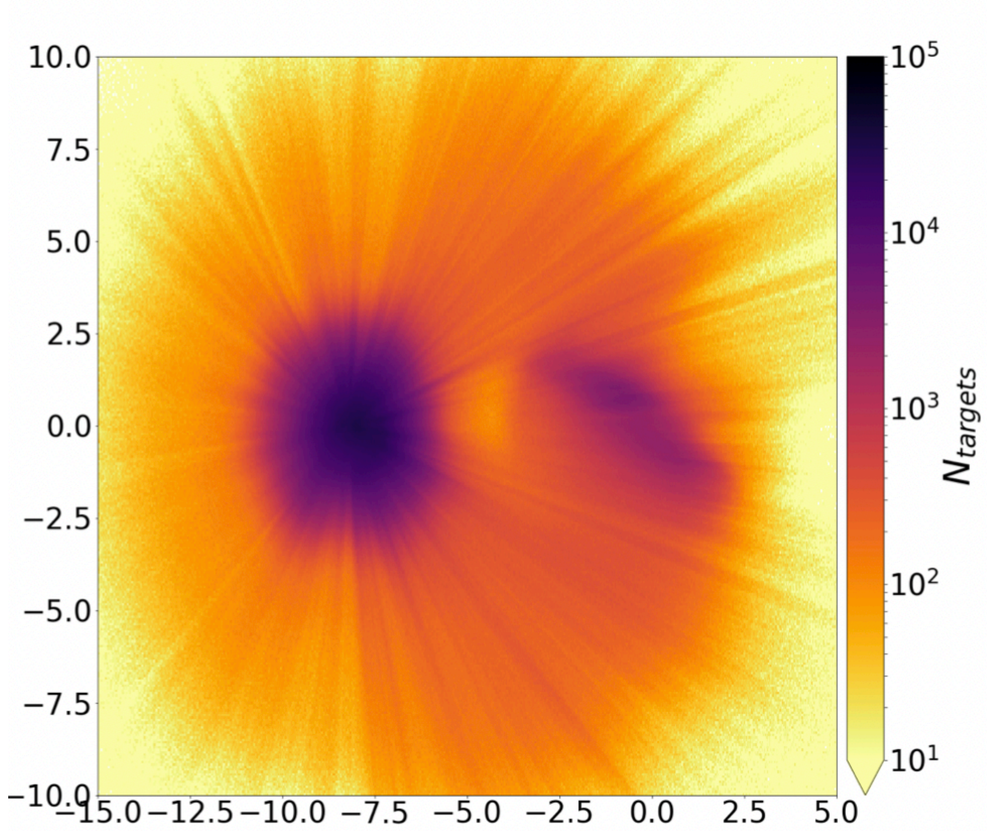


FIG. 2.—Contour map of 2.4 μm surface brightness of the region around the Galactic center taken from Matsumoto et al. (1982). The lowest contour and the contour interval are in steps of 1.0×10^{-10} W cm^2 μm^{-1} sr^{-1}.

The Bar

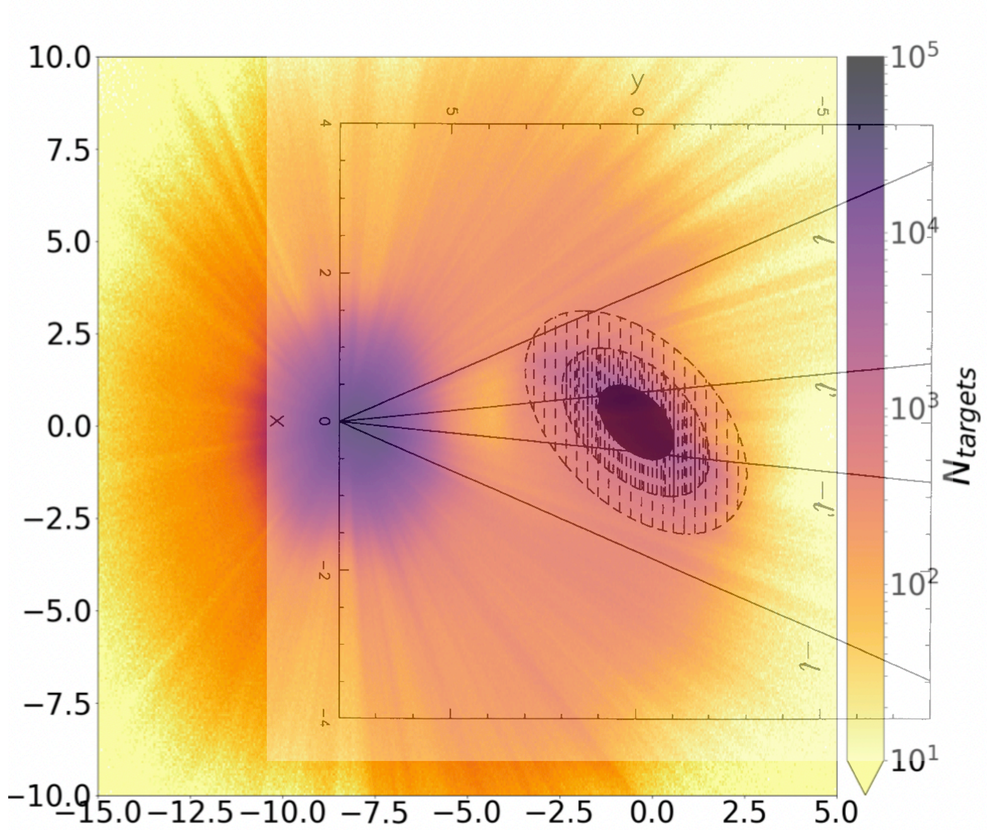


Blitz & Spergel (1991)



Anders+2019

The Bar



Blitz & Spergel (1991)

Anders+2019

Next time:

- Clusters & “Simple Stellar Populations”
  - HW2 will be posted next week!

https://apod.nasa.gov/apod/ap051004.html