III : Real-life black holes

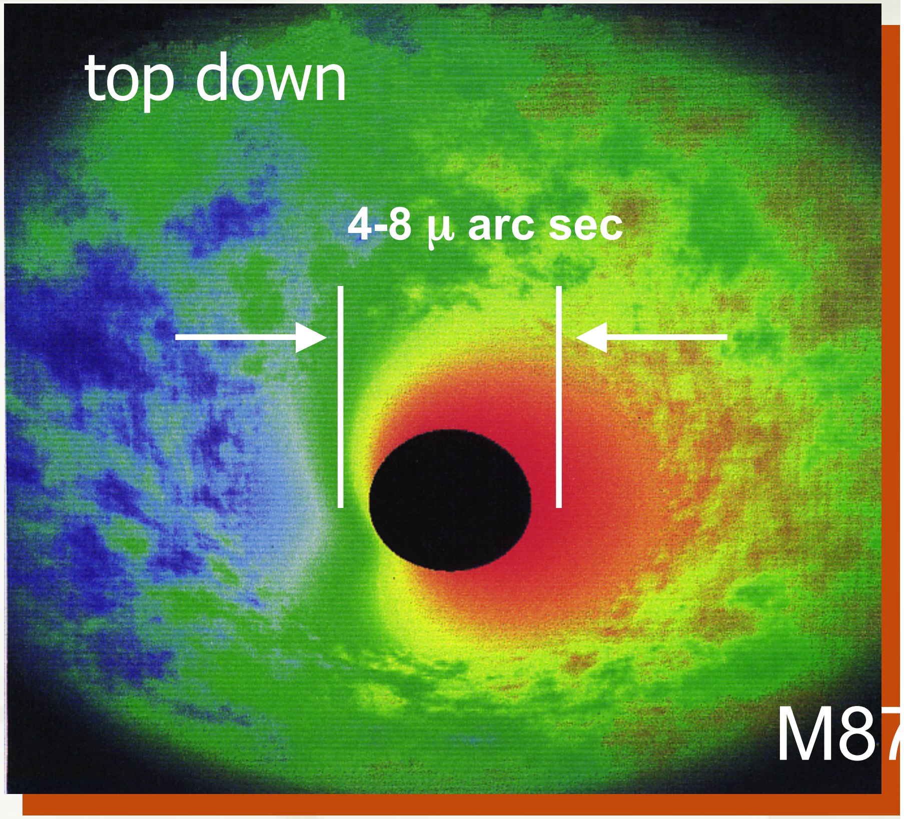
- So much for theory – what about reality
- Thought to be two (maybe three?) classes of black hole in nature
  - **"Stellar mass black holes"** – left over from the collapse/implosion of a massive star (about 10 solar masses)
  - **"Supermassive black holes"** – giants that currently sit at the centers of galaxies (range from millions to billions of solar masses)
  - **"Intermediate-mass black holes"** – suggested by very recent observations (hundreds to thousand of solar masses)

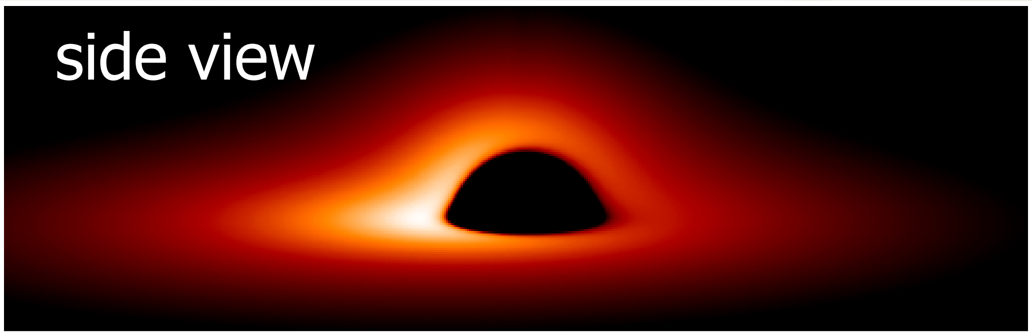
Why Do We Think Black Holes are Real

- In binary stars can determine the mass of the stars by measuring their orbits- Keplers laws
- In x-ray binaries one of the stars is 'normal' the other has strange properties (emits lots of x-rays and is very small and other things)
- Mass of the the 'strange' star is larger than a neutron star can be (maximum mass of a neutron star is set by quantum mechanics (!))
- So lots of mass and very small leads to the idea of a black hole

Images of a Black Hole

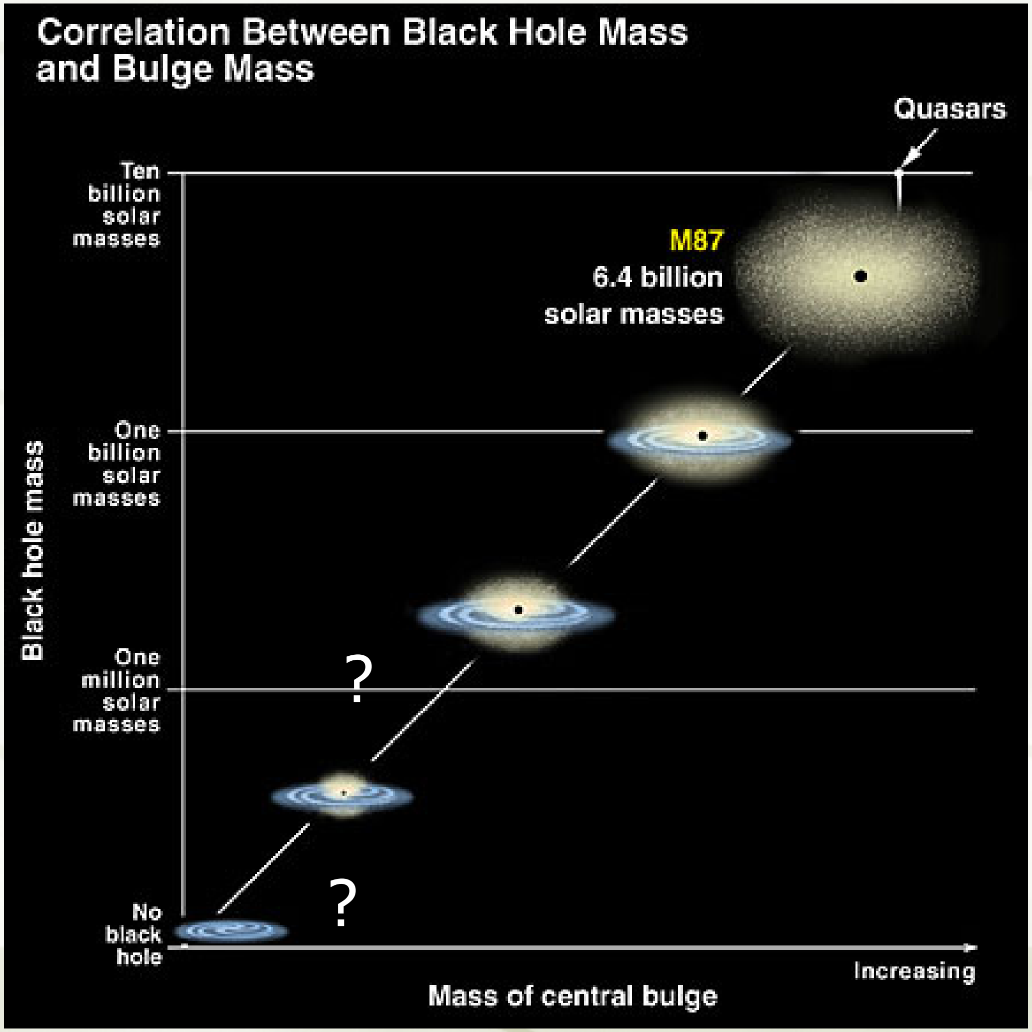
- A theoretical calculation of what the region near a black hole might look like
- The red/blue represent the Doppler shift and the asymmetries the effect of GR





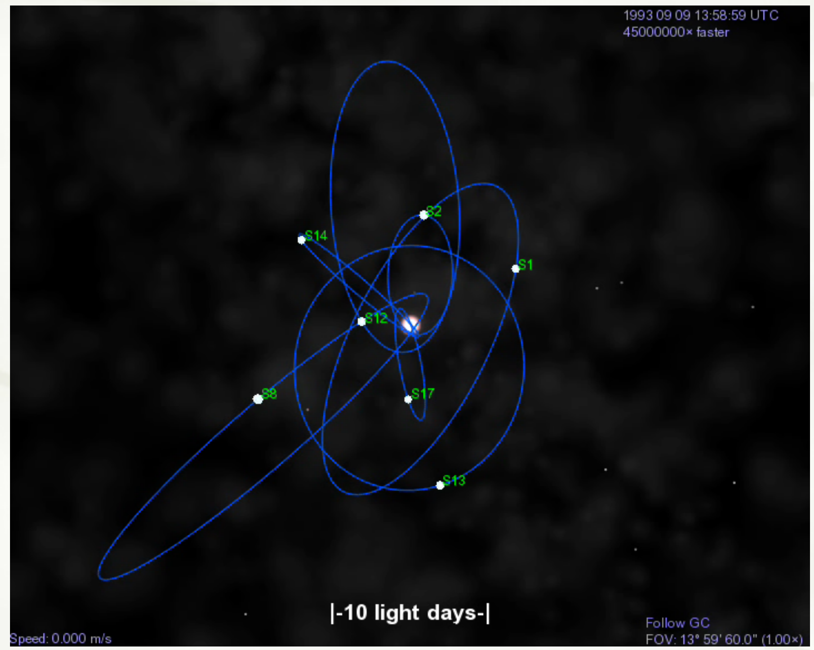
Supermassive black holes (SMBHs)

- Found in the centers of most big galaxies
- Mass of black hole and galaxy are correlated



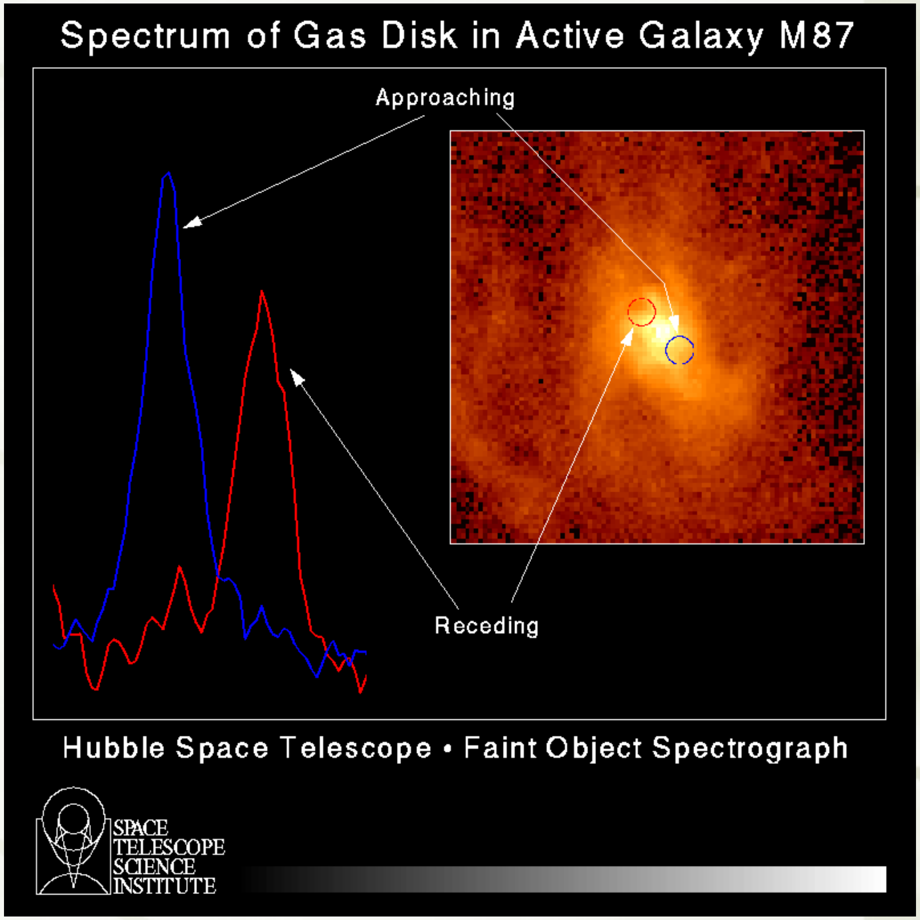
*Center of the Milky Way: Sgr A**

- The center of our own Galaxy
  - Can directly observe stars orbiting an unseen object
  - Need a black hole with mass of 3.7 million solar masses to explain stellar orbits
  - Best case yet of a black hole.



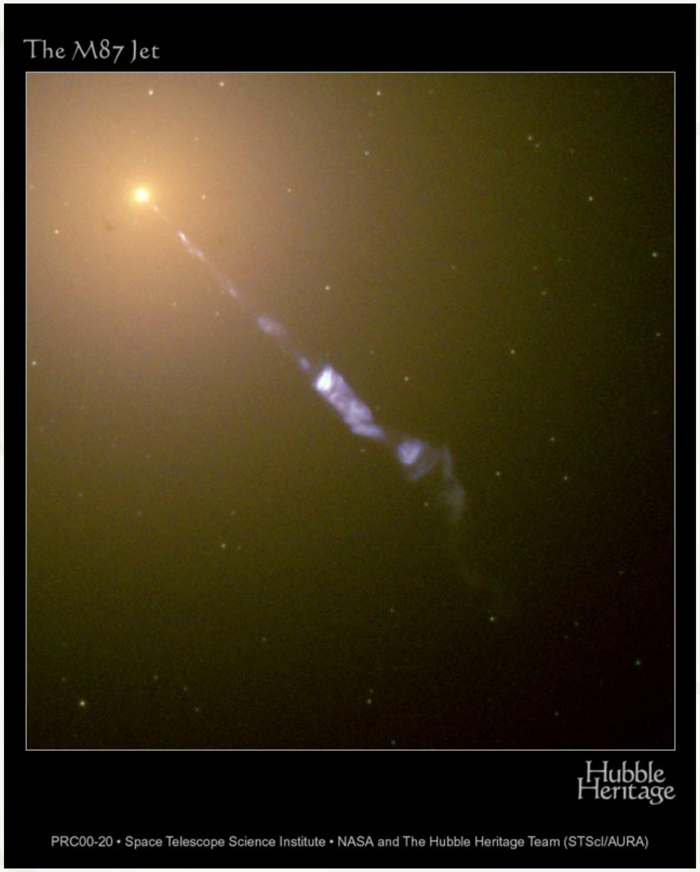
M87

- Another example – the SMBH in the galaxy M87
  - Can see a gas disk orbiting galaxy's center
  - Measure velocities using the Doppler effect (red and blue shift of light from gas)
  - Need a 3 **b**illion solar mass SMBH (Keplers Laws) to explain gas disk velocities

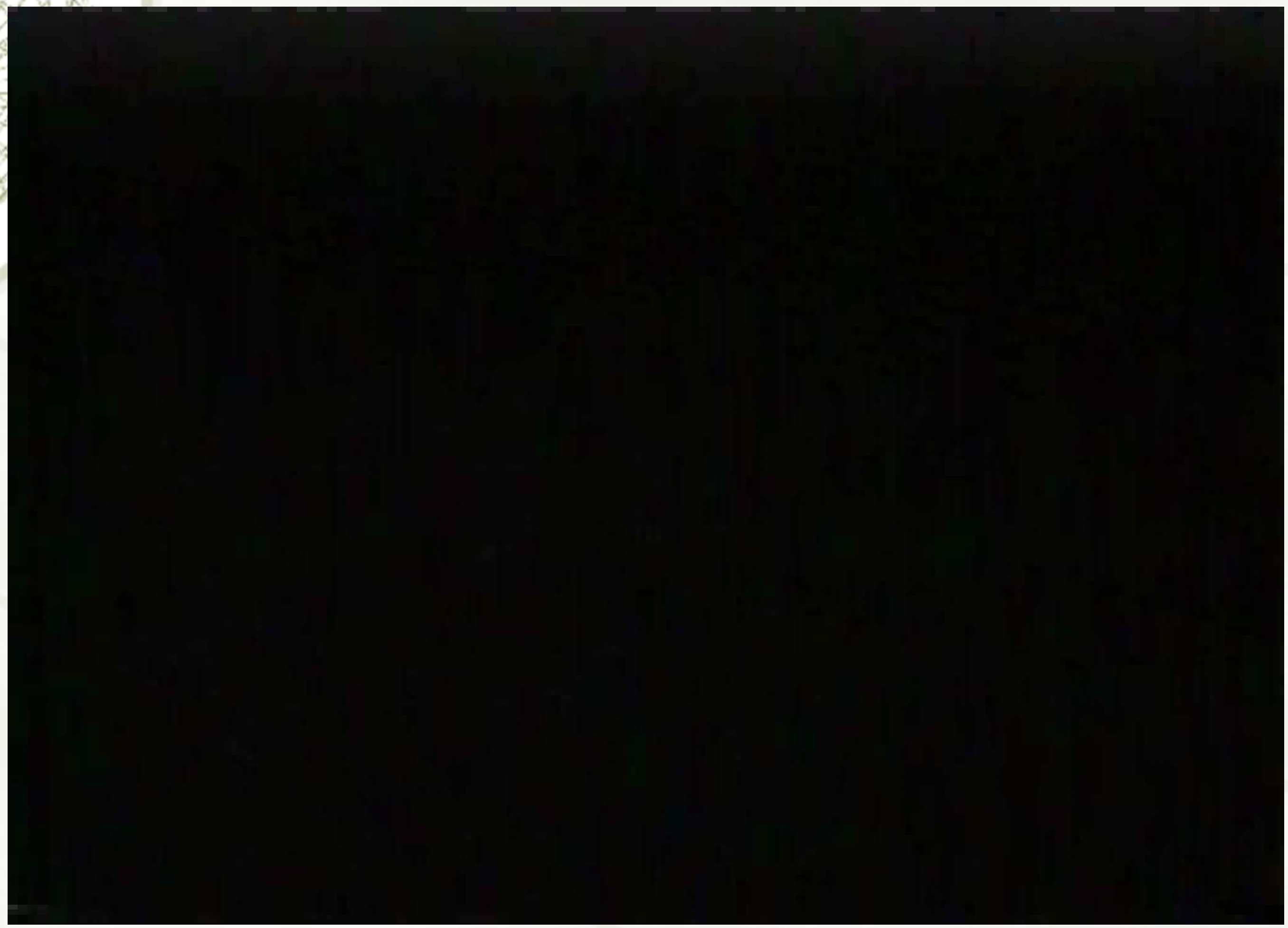


Active Galactic Nuclei

- M87 shows signs of “central activity”
- The Jet
  - Jet of material "squirted" from vicinity of SMBH
  - Lorentz factor of >6
  - Powerful (probably as powerful as galaxy itself)
- What powers the jet?
  - Accretion power
  - Extraction of spin-energy of the black hole



Artist's conception of M87 system



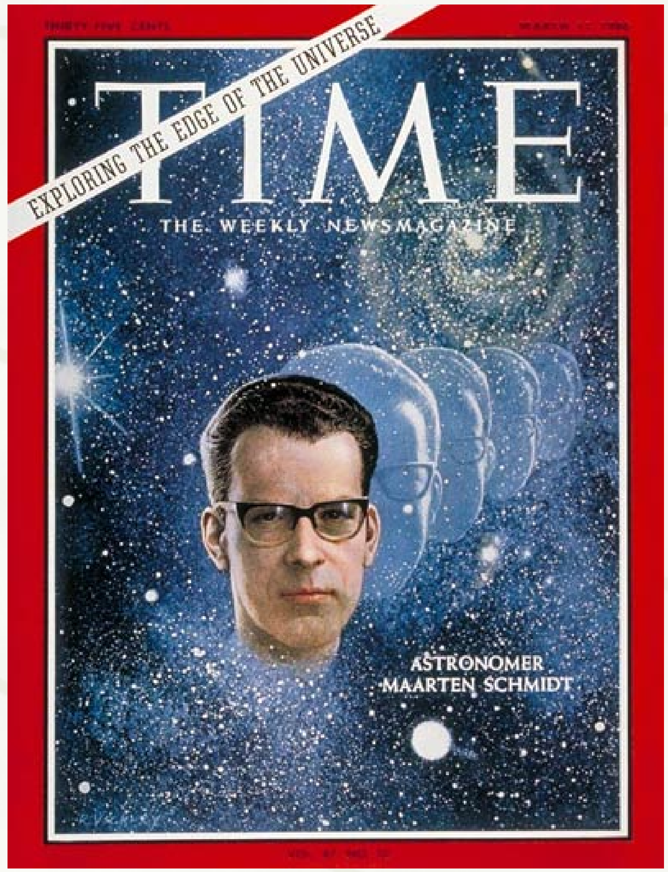
MUSE: Supermassive Black Hole
("Black Holes and Revelations" 2009)

Active Galaxies

- M87 is example of an "active galactic nucleus"
  - Material flows (accretes) into black hole
  - Energy released by accretion of matter powers energetic phenomena
    - Emission from radio to gamma-rays
    - Jets
  - More numerous in the young universe than today

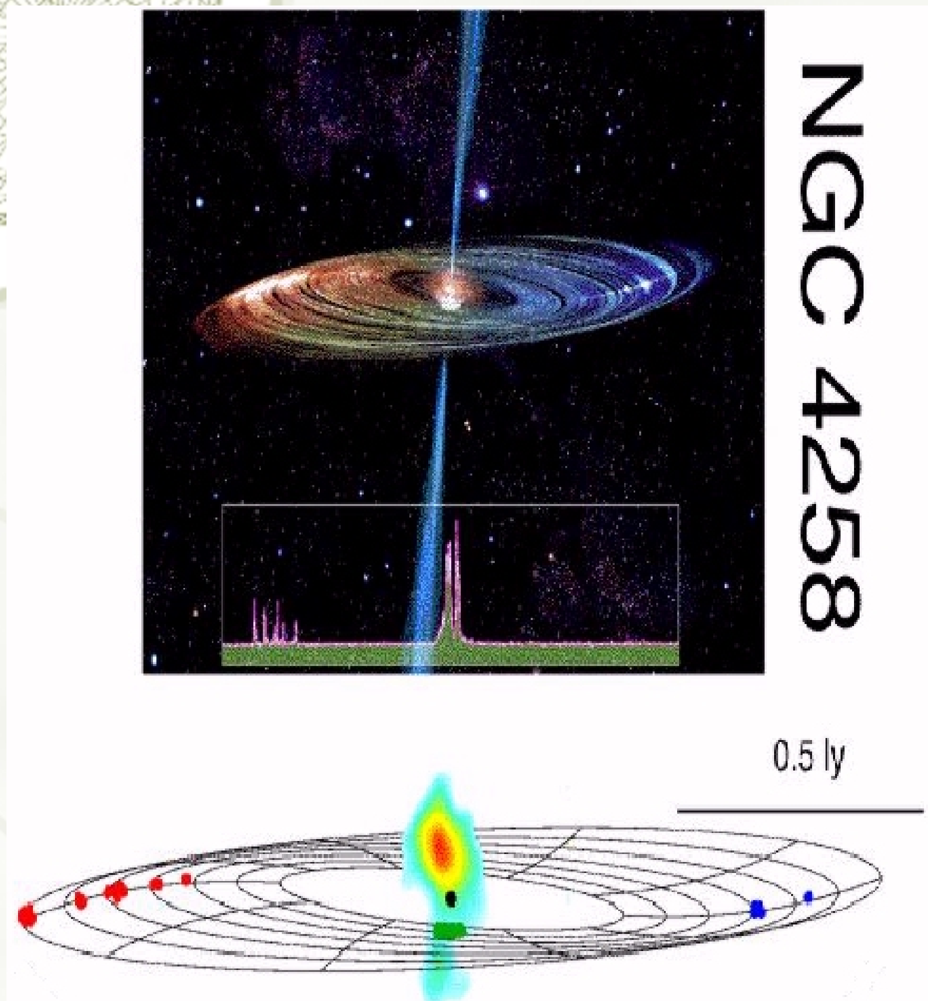
- Particularly powerful active galactic nuclei are sometimes called **Quasars- can be up to 10^{14} x more luminous that the sun**

1966 Cover, discovery of QSOs



quasars can be seen at redshifts >6

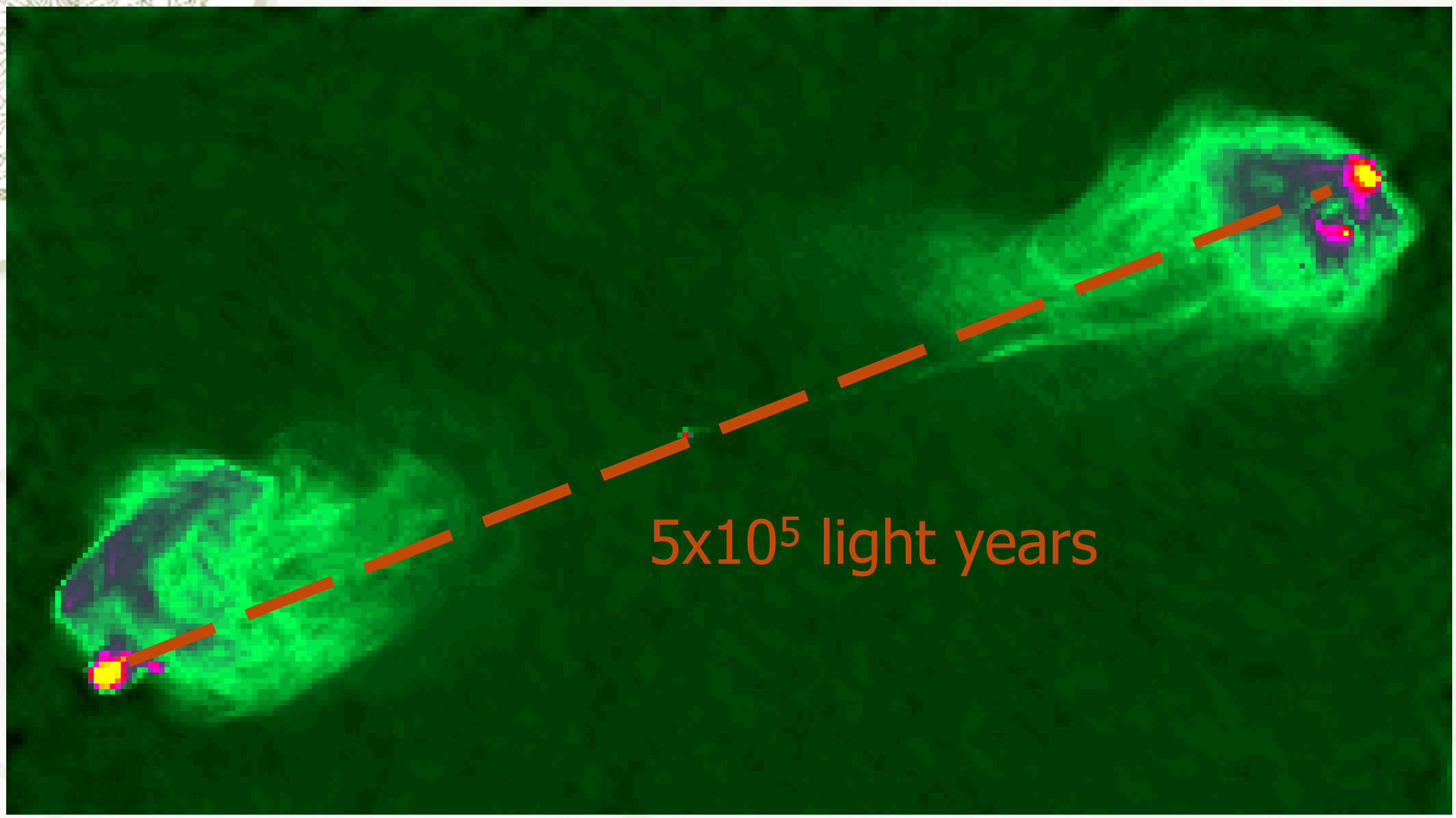
Water masers and dynamics in NGC 4258



Masers reveal a tiny warped disk around a massive black hole
Use Kepler's Laws to get mass (need velocities and distances from BH)

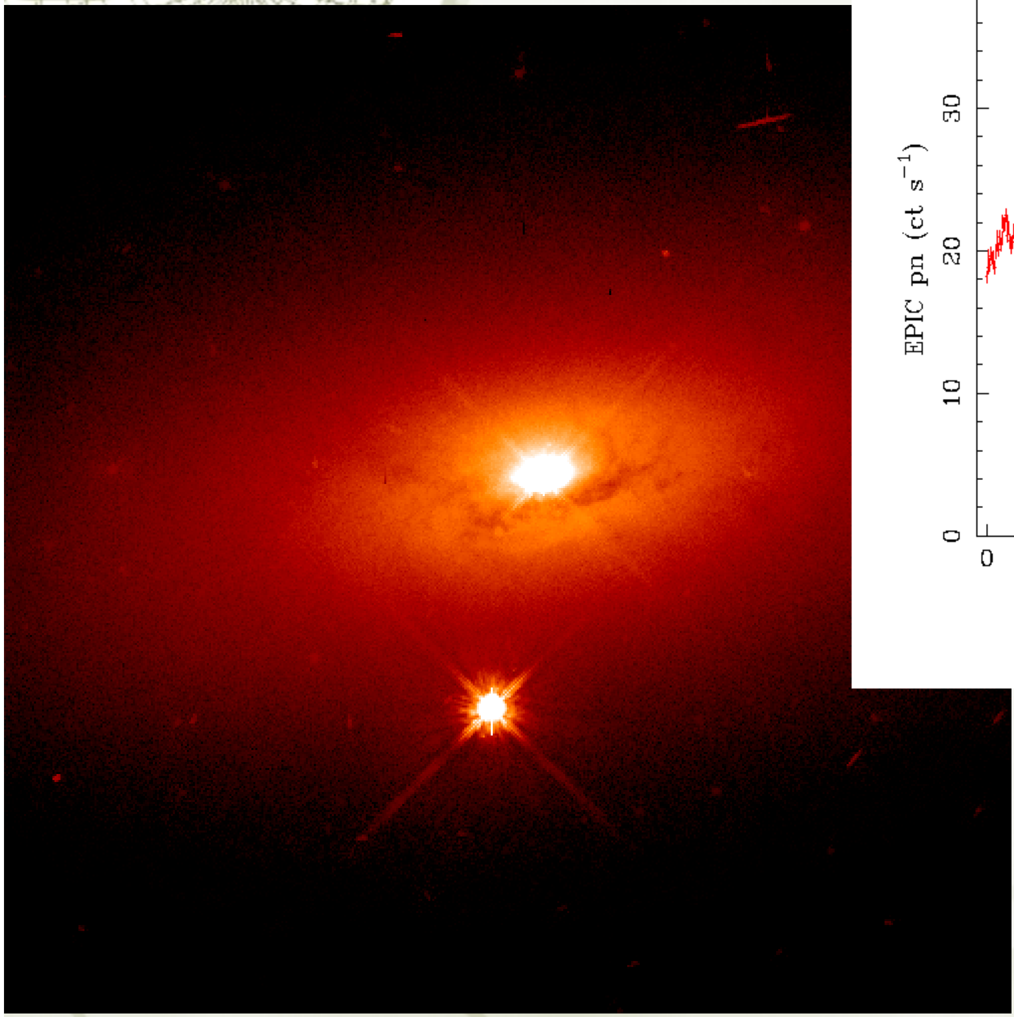
Miyoshi et al 1995;
Greenhill et al 1996;
Herrnstein et al. 1998

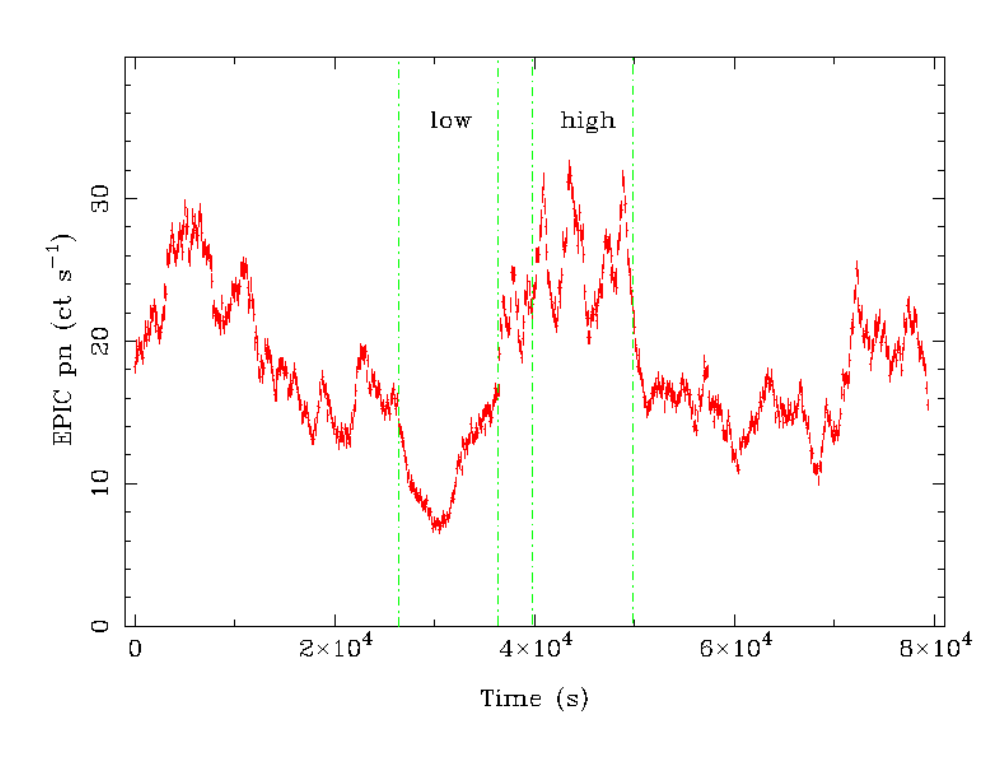
The powerful radio-galaxy Cygnus-A



Radio image with the
Very Large Array in New Mexico

Another example… the "Seyfert galaxy" MCG-6-30-15





time variability of source luminosity ~10^{10} Suns- intensity changing on timescales of minutes

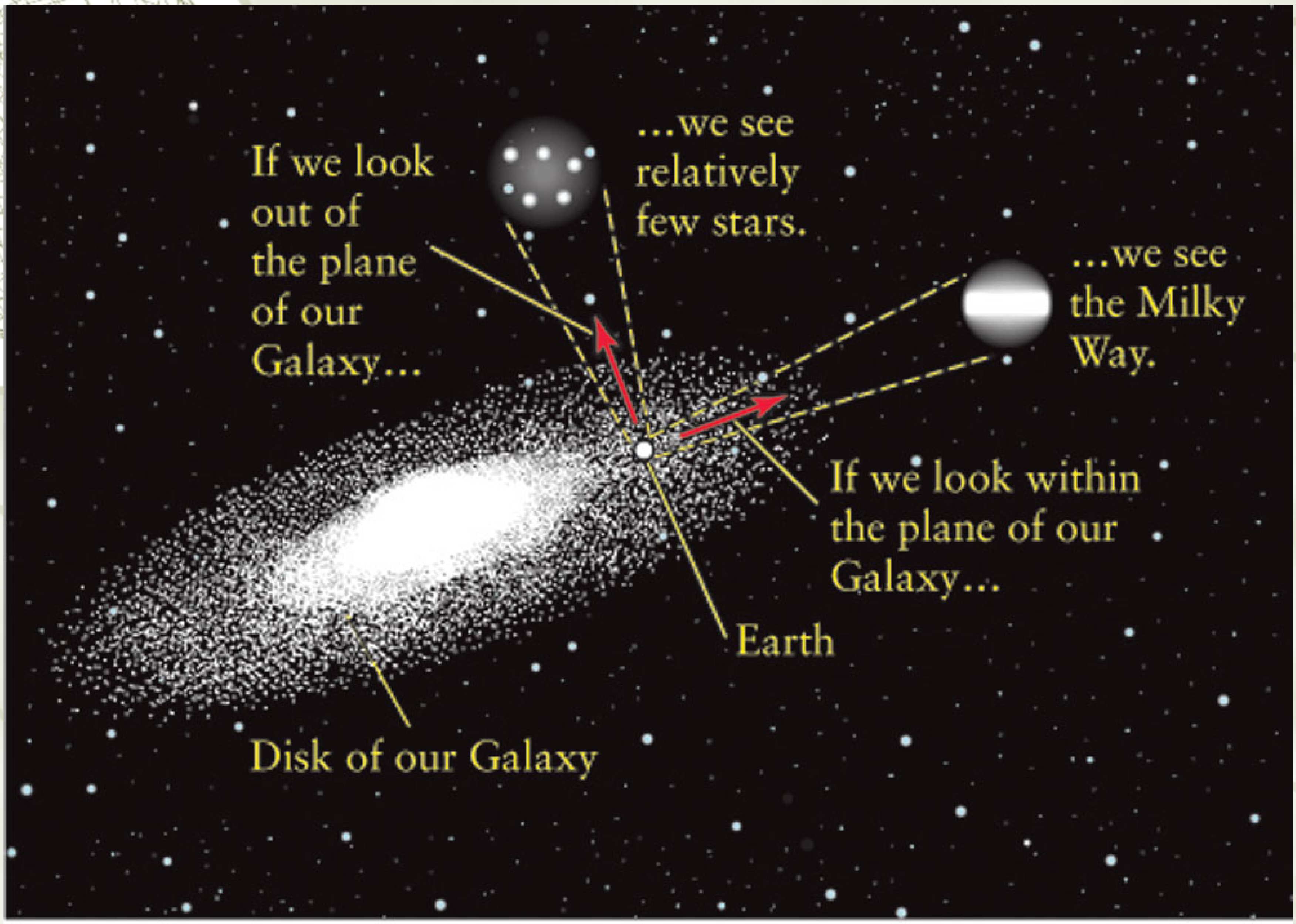
Lecture 13 :
The extragalactic universe I

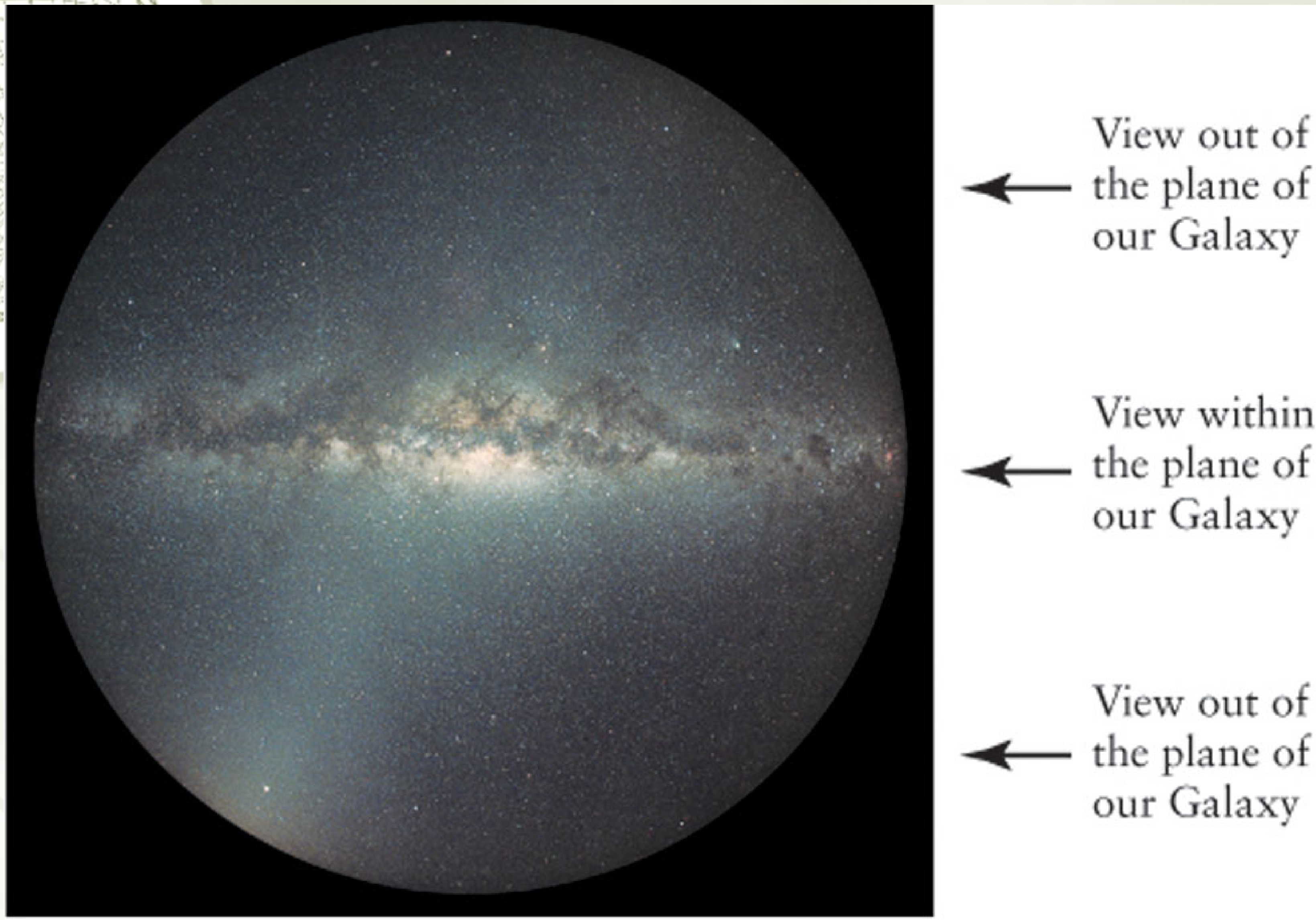
- Our place in the Galaxy
- The Great Debate
- Measuring distance in astronomy
  - Parallax and Cepheids
- Hubble's (first) great discovery

© Sidney Harris

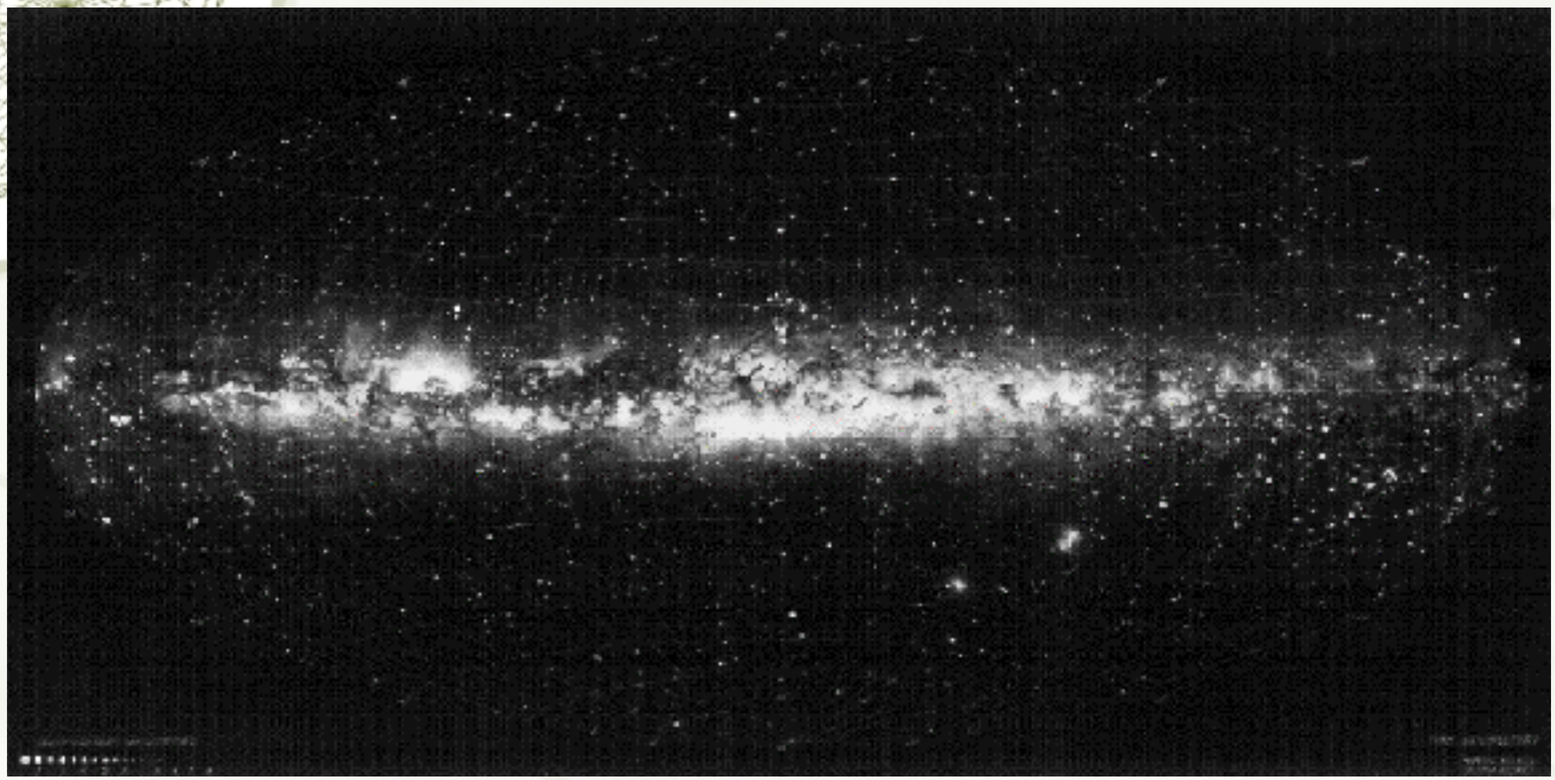
I : Our place in the Galaxy

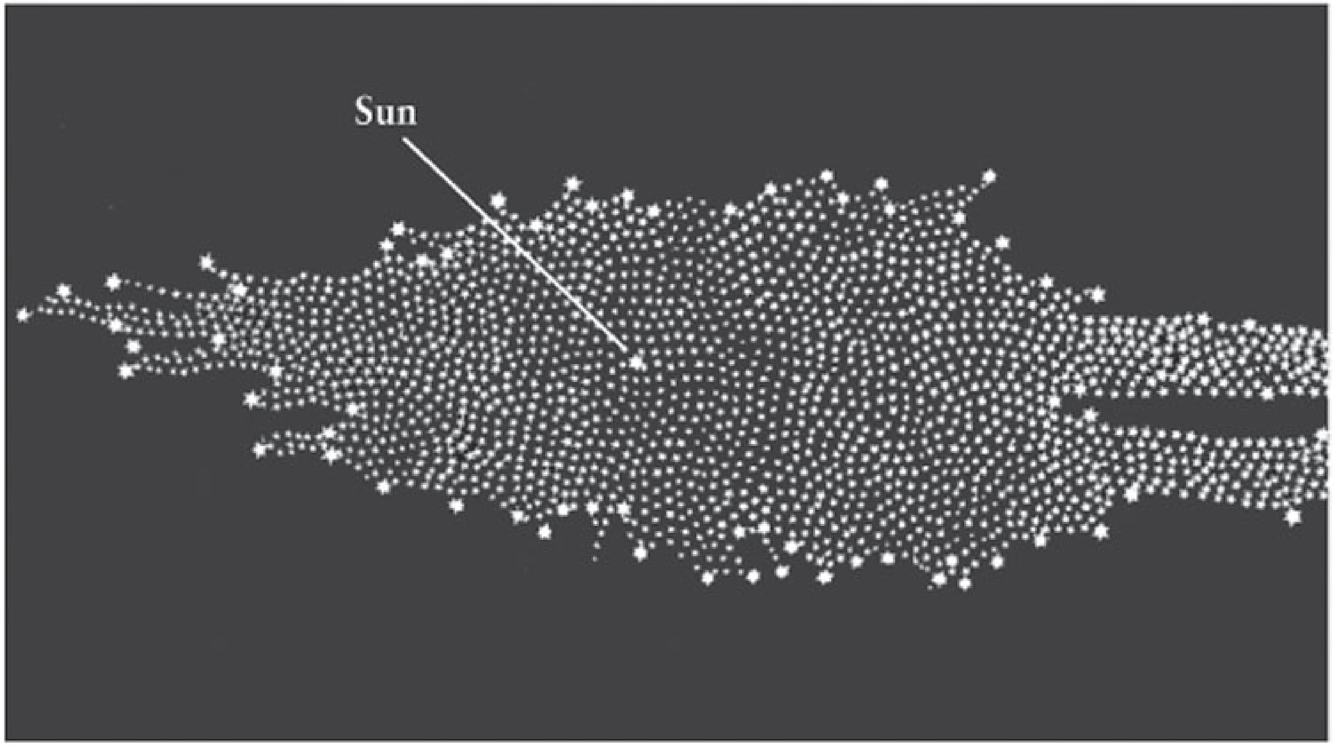
- We live in a large disk galaxy
  - We live in the disk, towards the edge (8kpc~25,000lyr out)
  - Projected onto the sky, this disk of stars looks like a band of light that rings the sky… the Milky Way
- This realization came somewhat slowly…
  - Disk-like nature of galaxy realized by Thomas Wright (1780); refined by Kant
  - First attempt to map out galaxy made by William Herschel (1785); refined by Kapteyn in 1920
  - Herschel came to the conclusion that we sit at the center of the Galactic disk.   In fact, he was wrong… had not accounted absorption by dust!


If we look out of the plane of our Galaxy…
…we see relatively few stars.
…we see the Milky Way.
If we look within the plane of our Galaxy…
Earth
Disk of our Galaxy
(a)

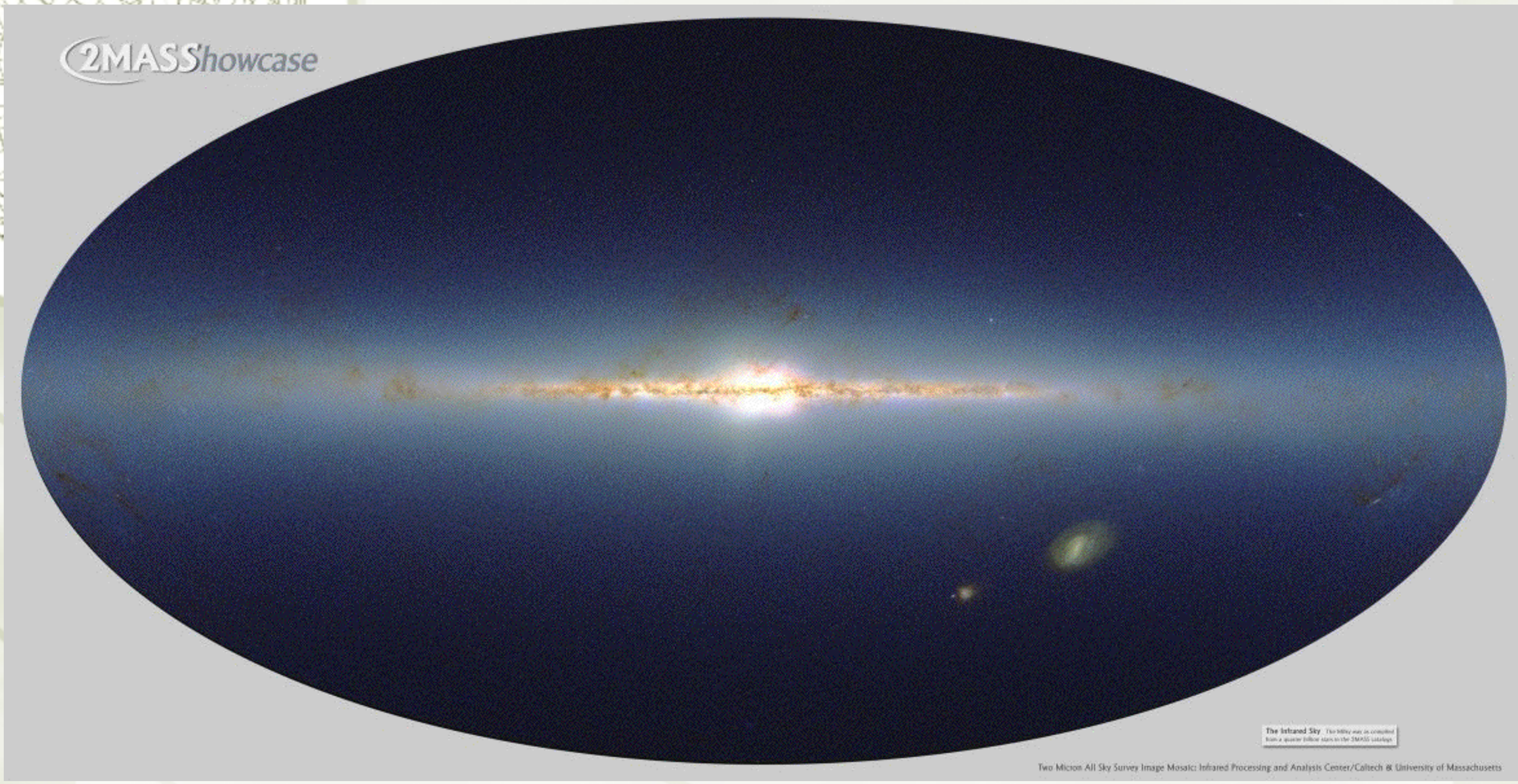

View out of the plane of our Galaxy
View within the plane of our Galaxy
View out of the plane of our Galaxy

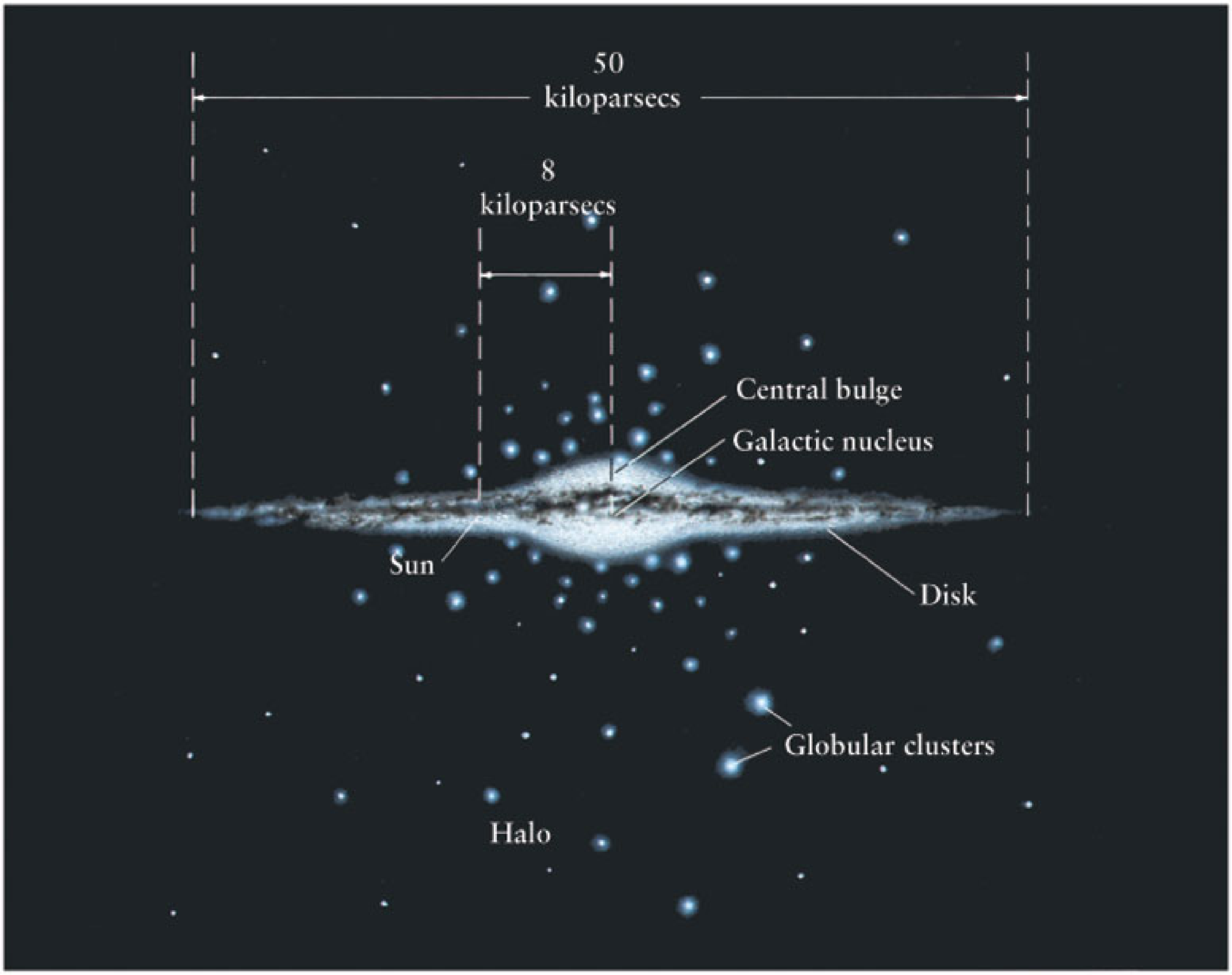
(b)



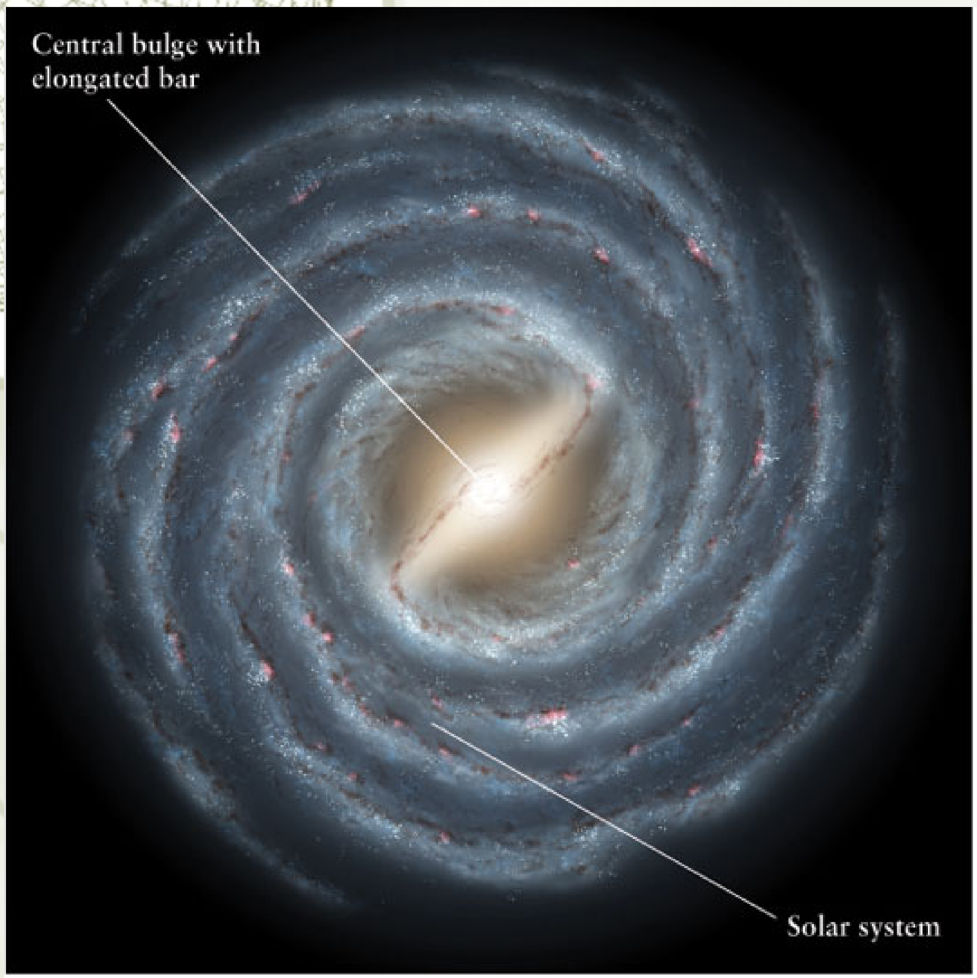


Herschel’s map of the Galaxy

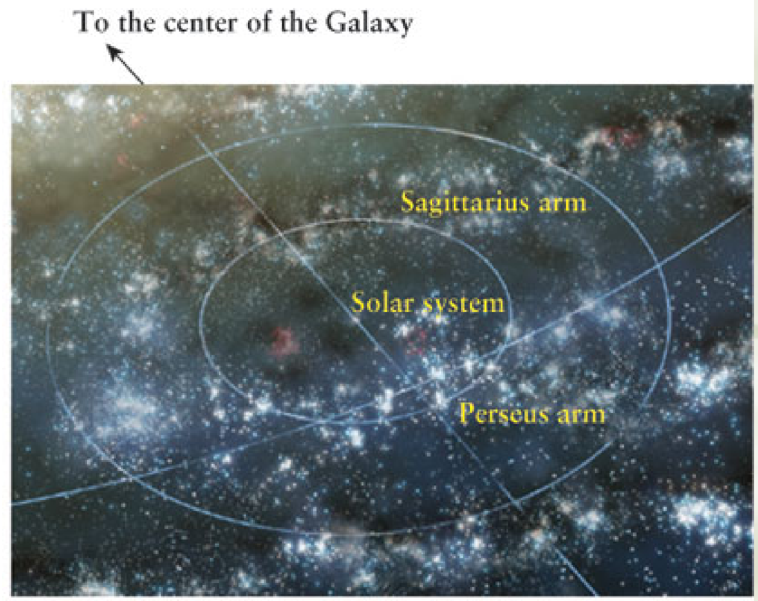

2MASSShowcase
The Infrared Sky
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts



1 kiloparsec=3.26x10^{3} lightyears=3.08x10^{19}m



(a) The structure of the Milky Way's disk



(b) Closeup of the Sun's galactic neighborhood

II : The Great Debate… “what are spiral nebulae?”

- Early 20th century…
  - Knew that we lived in a large disk galaxy
  - But what was the nature of the larger Universe?
  - Two opposing ideas:
    - Our galaxy is alone, sitting in the middle of otherwise empty space
    - Our galaxy is one of many galaxies that fill space (so-called “Island Universes”)
  - The debate rapidly focused on the nature of **nebulae**

- Nebulae have been studied for ages
- Messier (1780)
  - Systematically catalogued over 100 bright nebulae
  - Main reason for doing this was so that comet hunters knew which “fuzzy patches= nebulae” to ignore!
  - But what were these nebulae? Possibilities:
    - Glowing patches of gas (e.g., Orion)
    - Clusters of many stars within our Galaxy (e.g., the Globular cluster M13)
    - Whole other galaxies!!
  - Of special interest were the “spiral nebulae” that showed Milky Way like spiral structure… the brightest spiral nebulae was the **Andromeda nebula**

Messier actually cared about comets

Credit : A. Dimai

The Orion Nebula (M42)

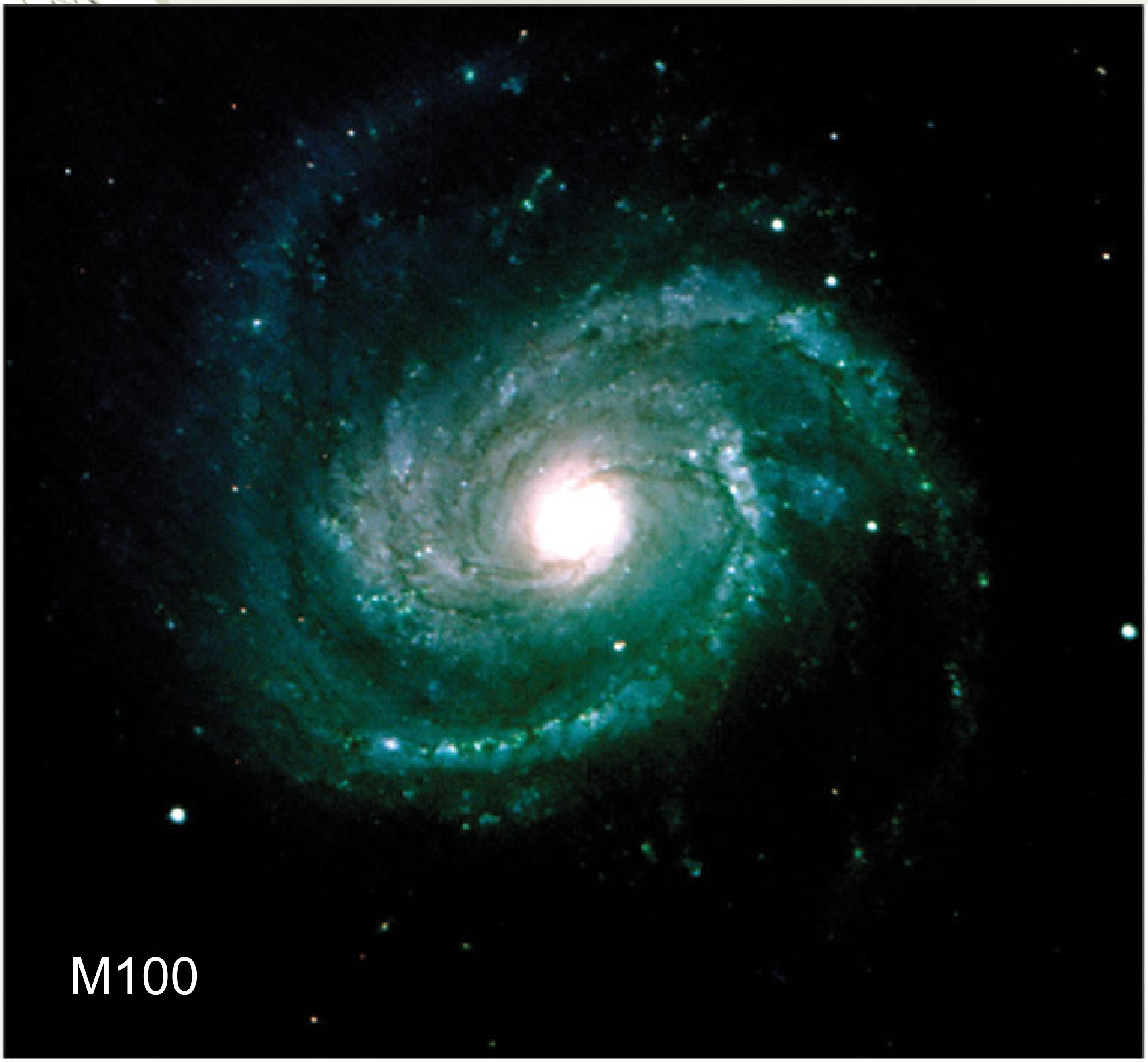
The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

ESO PR Photo 03a/01 (15 January 2001)

© European Southern Observatory

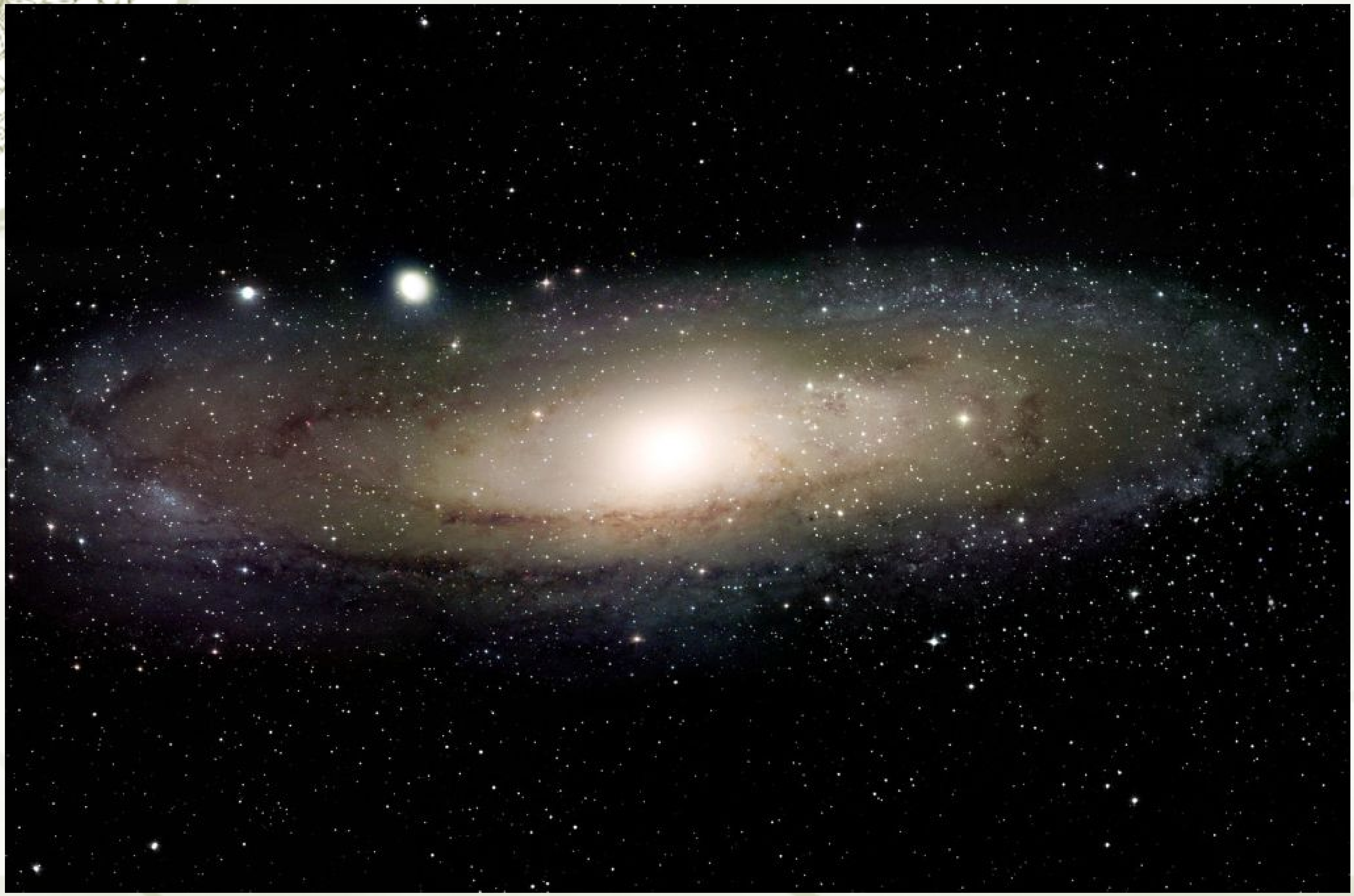
Globular cluster (M13)

Credit: Yuugi Kitahara


M100

- Two misleading events…
  - Van Maanen reported observations showing that the spiral structure in the Andromeda nebula was rotating.
    - If Andromeda was outside of our galaxy, the rotation would have to be much faster than speed of light!
    - Argued for Andromeda being inside of our Galaxy
  - 1885 : A “new star” appeared in Andromeda nebula
    - This was interpreted as a stellar nova
    - Scaling from known nearby novae, it was concluded that Andromeda lay will inside our Galaxy
    - It wasn’t realized at the time that this was actually a **supernova**, not a regular nova.
- 1920 : The two points of view were debated by Shapley & Curtis in the “Great Debate” (see article by V. Trimble on web site)

Andromeda “Nebula” (M31)



Nova and SuperNova

- A nova is a strong, rapid increase in the brightness of a star. The word comes from the latin for "new star".
- Nova are typically due to transient accretion onto white dwarfs of different types producing a thermonuclear run-away can reoccur
- ~30-50 occur per year in Milkyway
- Their peak brightness is

$1\text{-}4\text{x}10^5\ L_\odot$

Supernova is the explosion of a star- 2 types massive star and white dwarf explosion

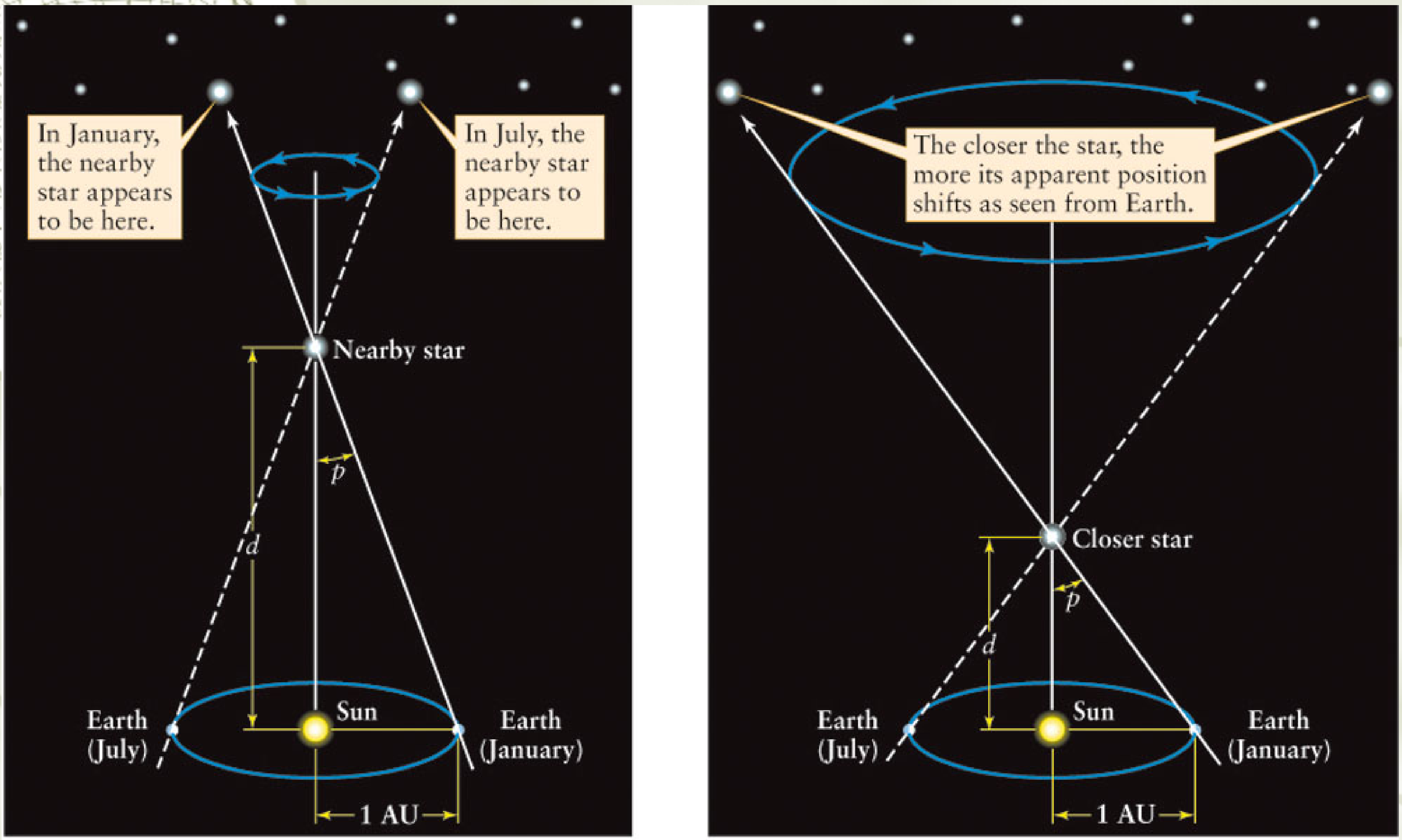
~1/100 years/galaxy

Peak brightness $\sim 5\text{x}10^9 L_\odot$

Only firmly distinguished in 1933

III : Measuring distances in astronomy

- The <u>**distance**</u> to any astronomical object is the most basic parameter we want to know
  - Require knowledge of distance in order to calculate just about any other property of the object
  - Distance is often difficult to determine!
- Most direct method for measure distances to "nearby" stars uses an effect called <u>**parallax**</u> <u>(remember lecture 3??)</u>
  - As Earth orbits Sun, we view a star along a slightly different line of sight
  - This causes the star to **appear** to move slightly with respect to much more distant stars
  - We can currently use this technique to measure stellar distances out to ~3000 light years from Earth

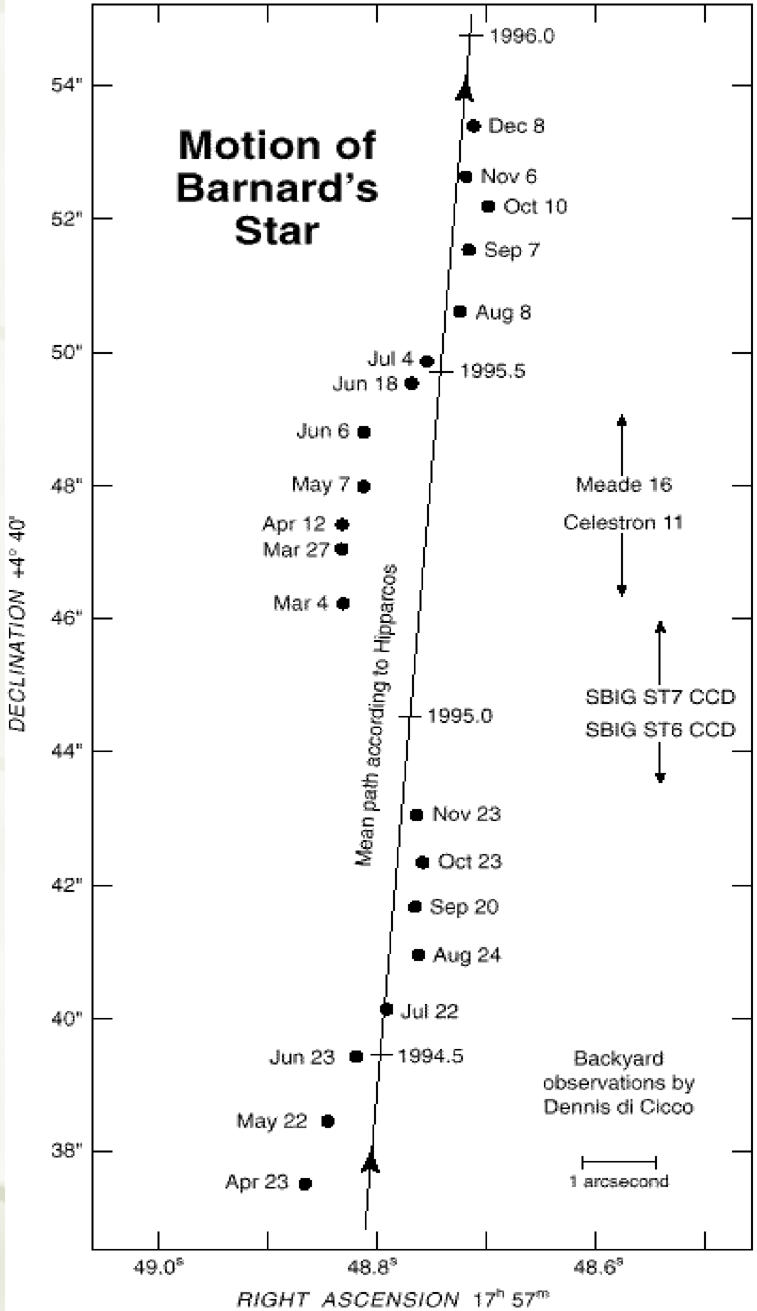


(a) Parallax of a nearby star

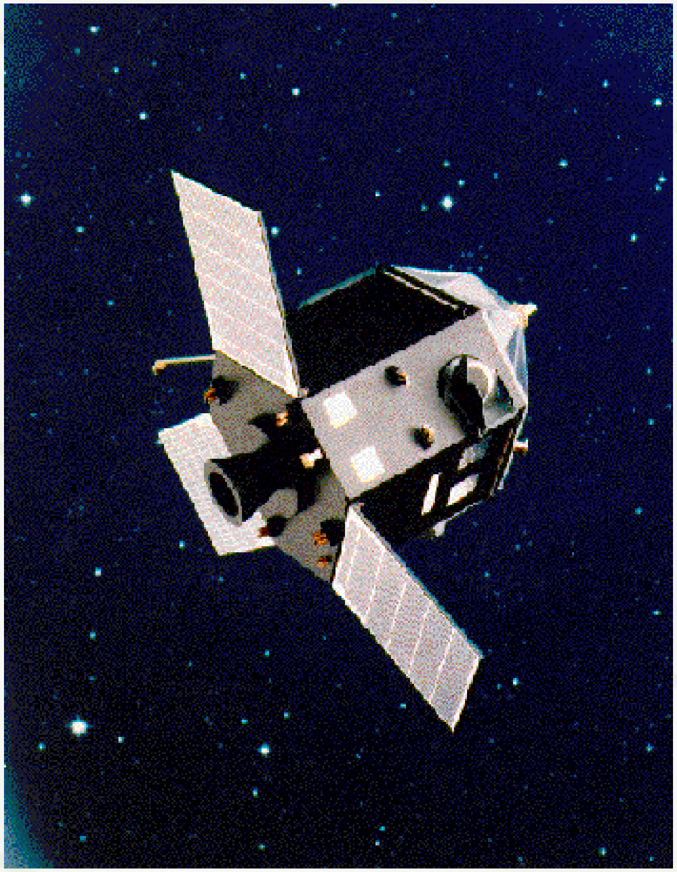
(b) Parallax of an even closer star

- If star wobbles with amplitude of 1 arc-second, then it is at distance of **1 parsec** (definition of parsec).
- 1pc = 3.26 lt-yr
- In general,

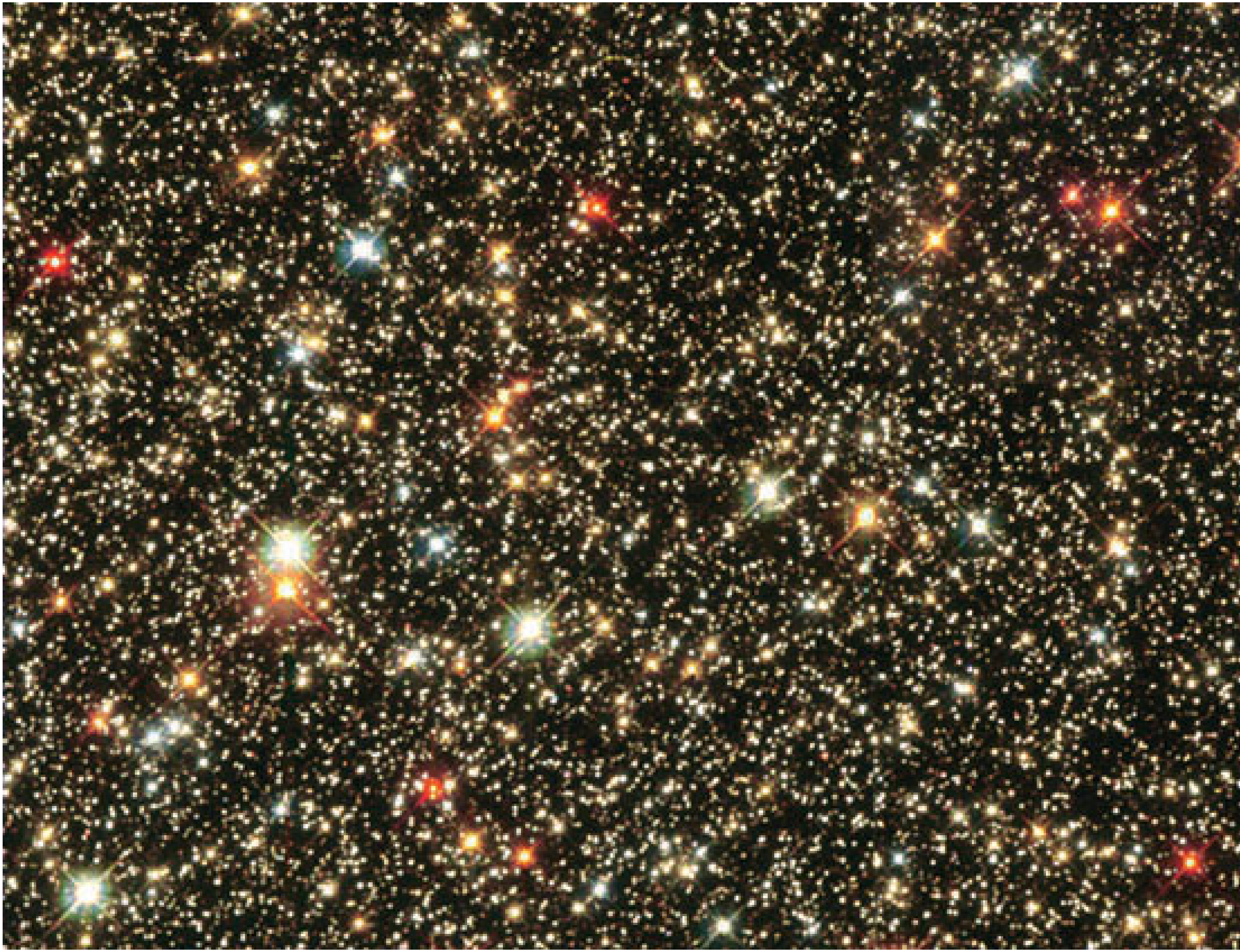
$$D(\text{pc}) = \frac{1}{\theta_{wobble}(\text{arcsec})}$$



- Until 1990s, could only detect parallax out to 50pc.
- Hipparcos satellite
  - Designed to measure parallax of stars
  - Can detect wobble out to distance of about 1kpc (1000pc)
  - Used to map out locations of nearby stars.
- GAIA satellite
  - Due to launch 2012
  - Can map out positions and motions of stars across the whole galaxy!!

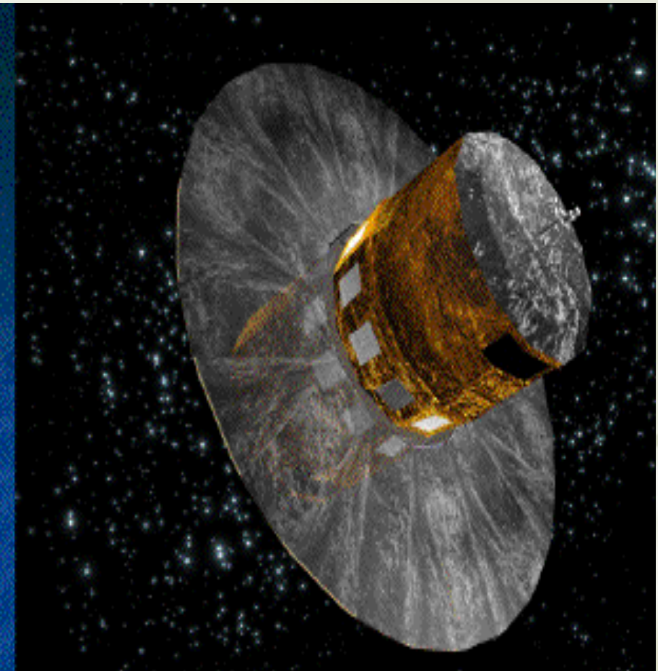


Hipparcos (ESA)



Gaia

- Gaia will achieve:
  - astrometry measurements with an accuracy of about 10 – 200 μas
  - a catalogue of approximately one billion stars to magnitude 20.
  - astrometric measurements of some 500,000 distant quasars



Launch: Dec 2012

angular size of thumbnail at the distance of the moon

3-D view of Milkway

Beyond parallax?

- Definition : The **observed flux** of a star is the energy received from the star per unit time per unit area.
- Definition : The **luminosity** of a star is the energy per unit time (i.e. power) emitted by the star
- If the star is at distance D and emits equally in all directions (i.e. it emits isotropically), then the observed flux F and luminosity L are related by

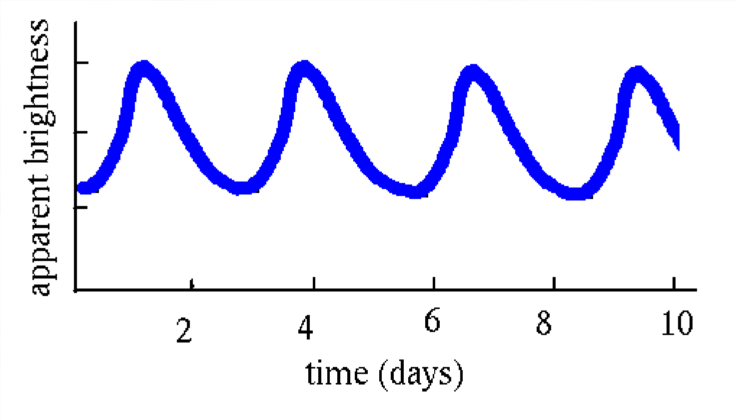
$$L = 4\pi D^2 F \quad \text{or} \quad F = \frac{L}{4\pi D^2}$$

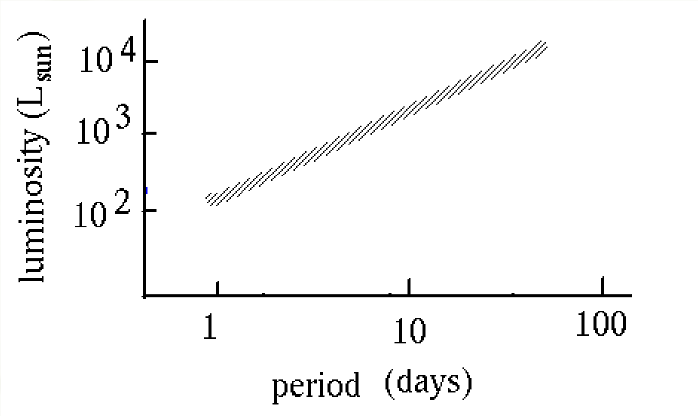
- Suppose we know the luminosity of some object… then we can use its measured flux to determine the distance! Objects with known luminosities are called **standard candles**.

Cepheid variables

Henrietta Leavitt
ph.credit: AAVSO

- Henrietta Leavitt discovered (1912) that a certain class of variable stars called Cepheids had properties that meant they could be used as standard candles
  - She studied Cepheids that are close enough for parallax to be measured… found that the luminosity is related to the period of fluctuations in brightness
  - So, if you measure the period of a Cepheid, you can determine its luminosity. Measuring flux then gives you distance, even if its too far for parallax!





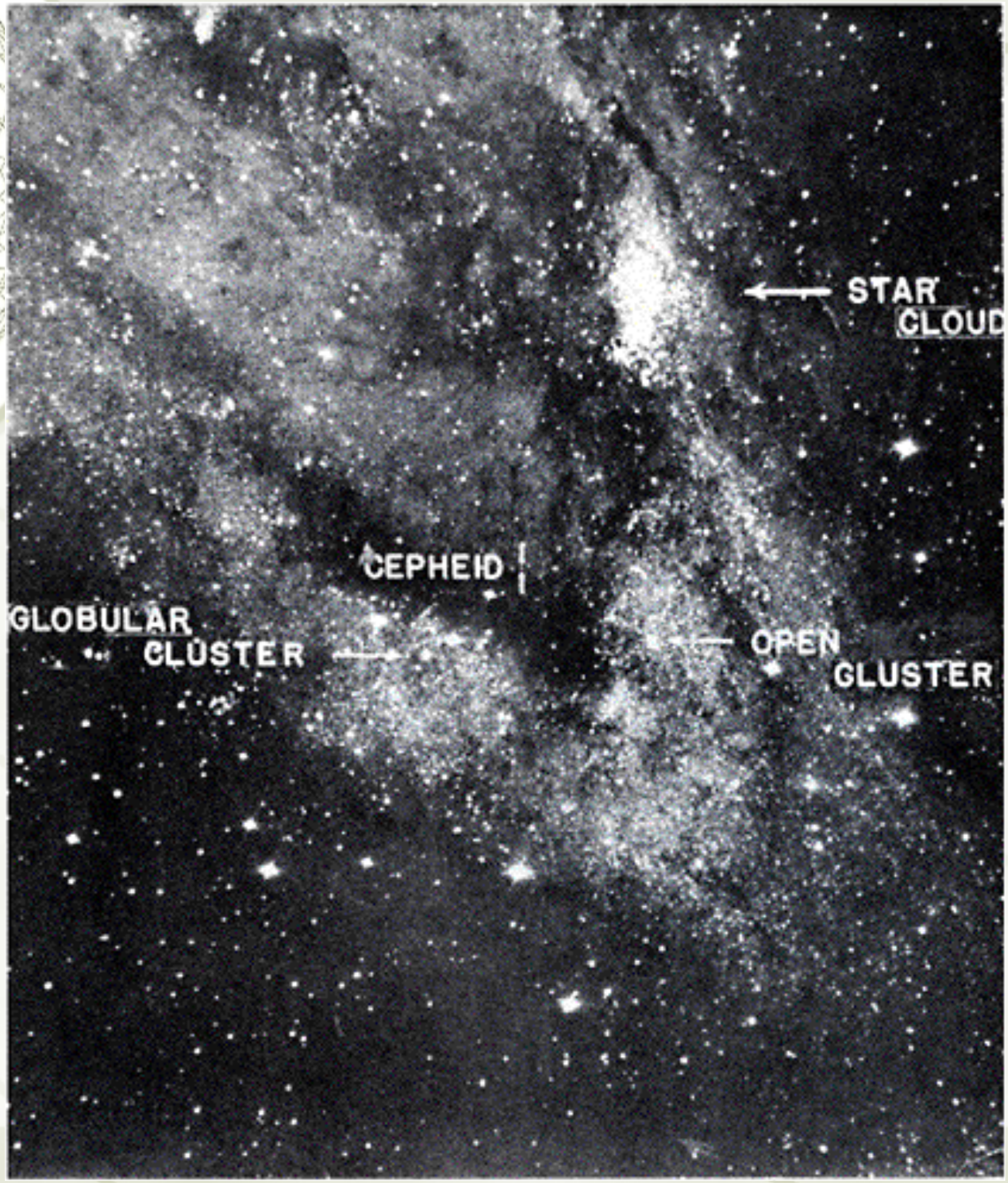
graphics: University of Oregon Astronomy Dept

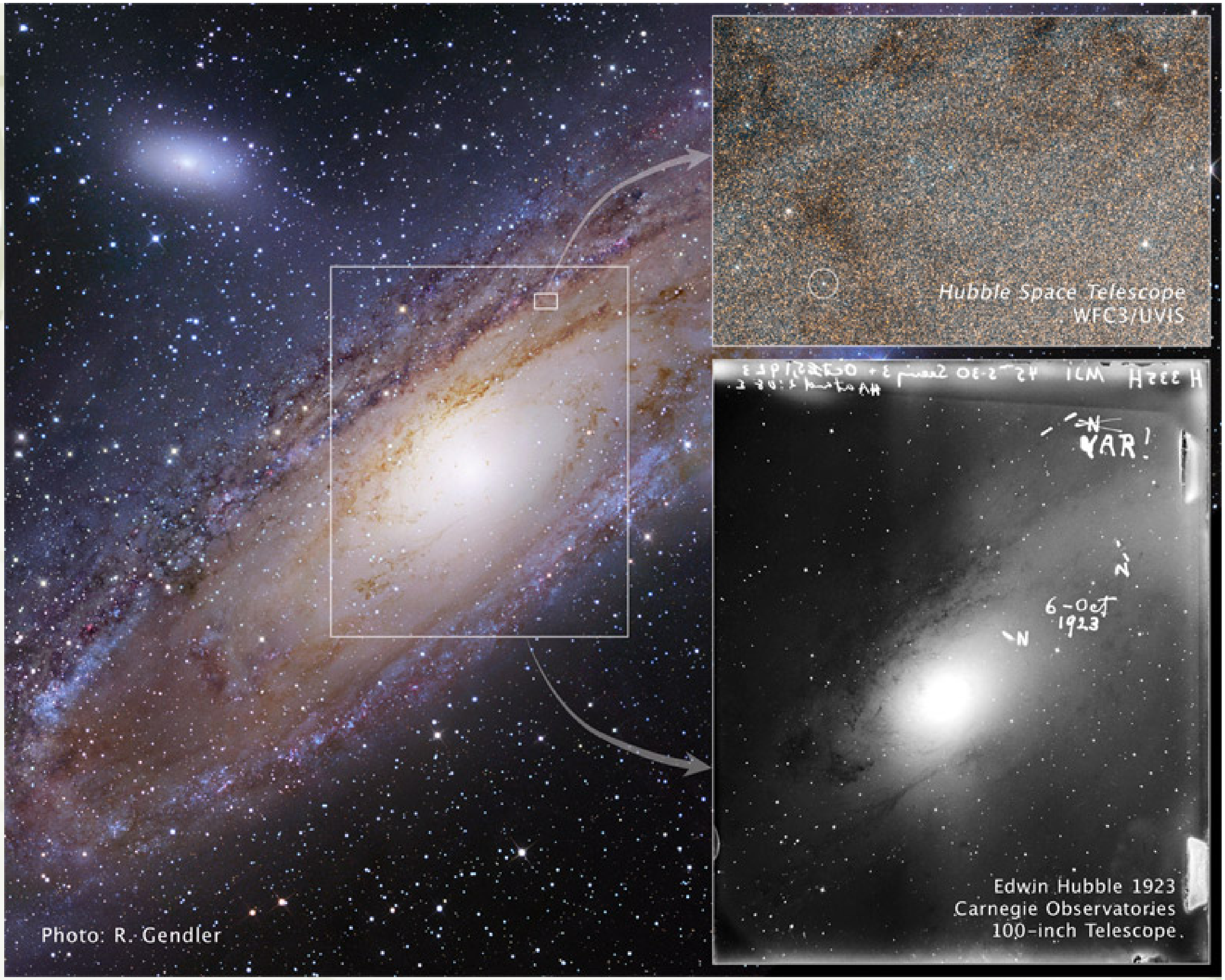
Edwin Hubble

Hubble's observations

- Hubble found Cepheid Variables in Andromeda
  - Measured period and flux, and hence distance
  - Concluded that Andromeda must be well outside of the Milky Way Galaxy
  - Thus, the Great Debate was settled… the MW is just one of many many many galaxies

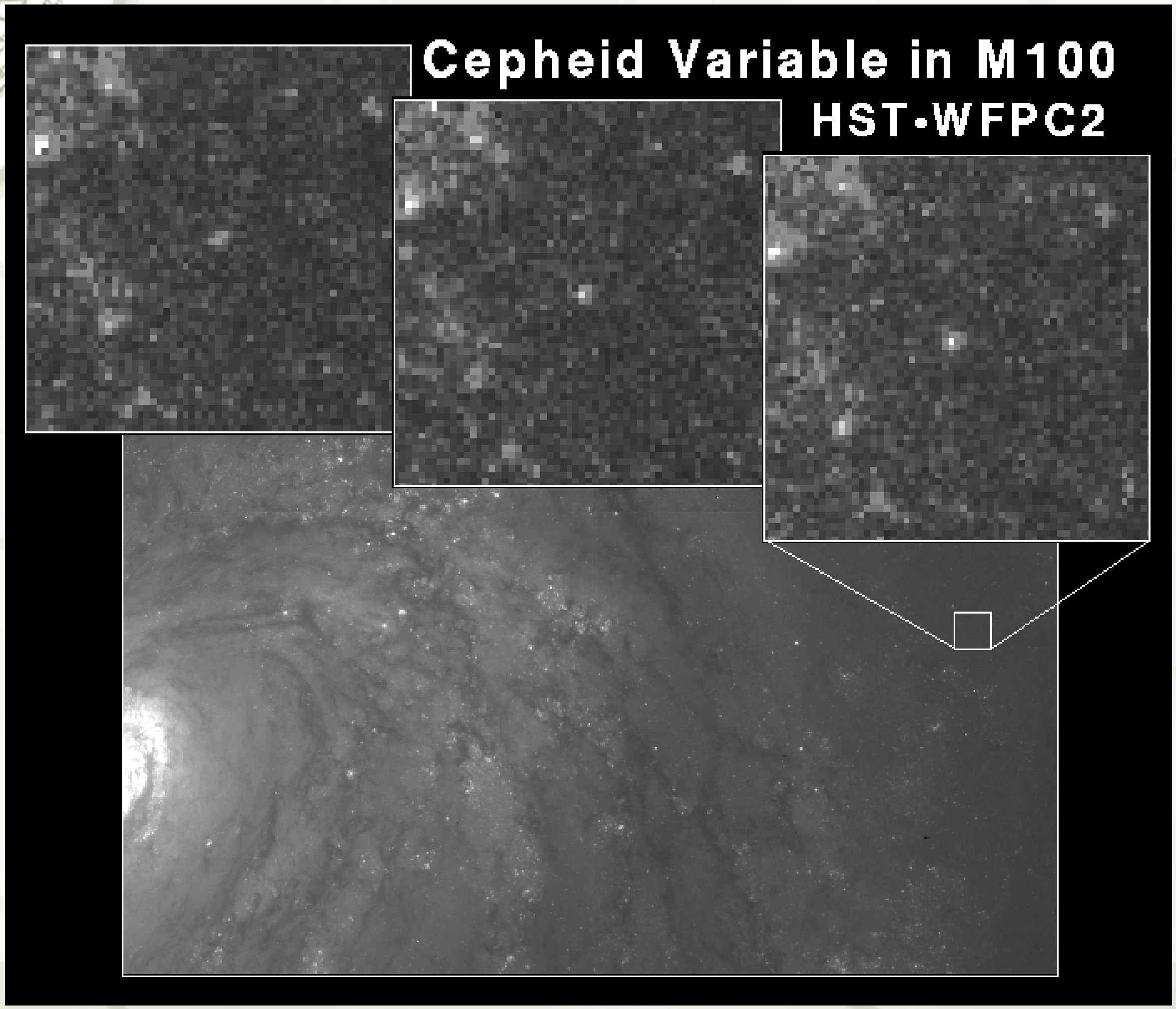
- Modern measurements
  - Distance to Andromeda 744 ± 33 kpc 4%error
  - About 2x MW diameter
- The other big galaxy in the local group is M33 which is at 968 ± 50 kpc


STAR
CLOUD
CEPHEID
GLOBULAR
CLUSTER
OPEN
CLUSTER

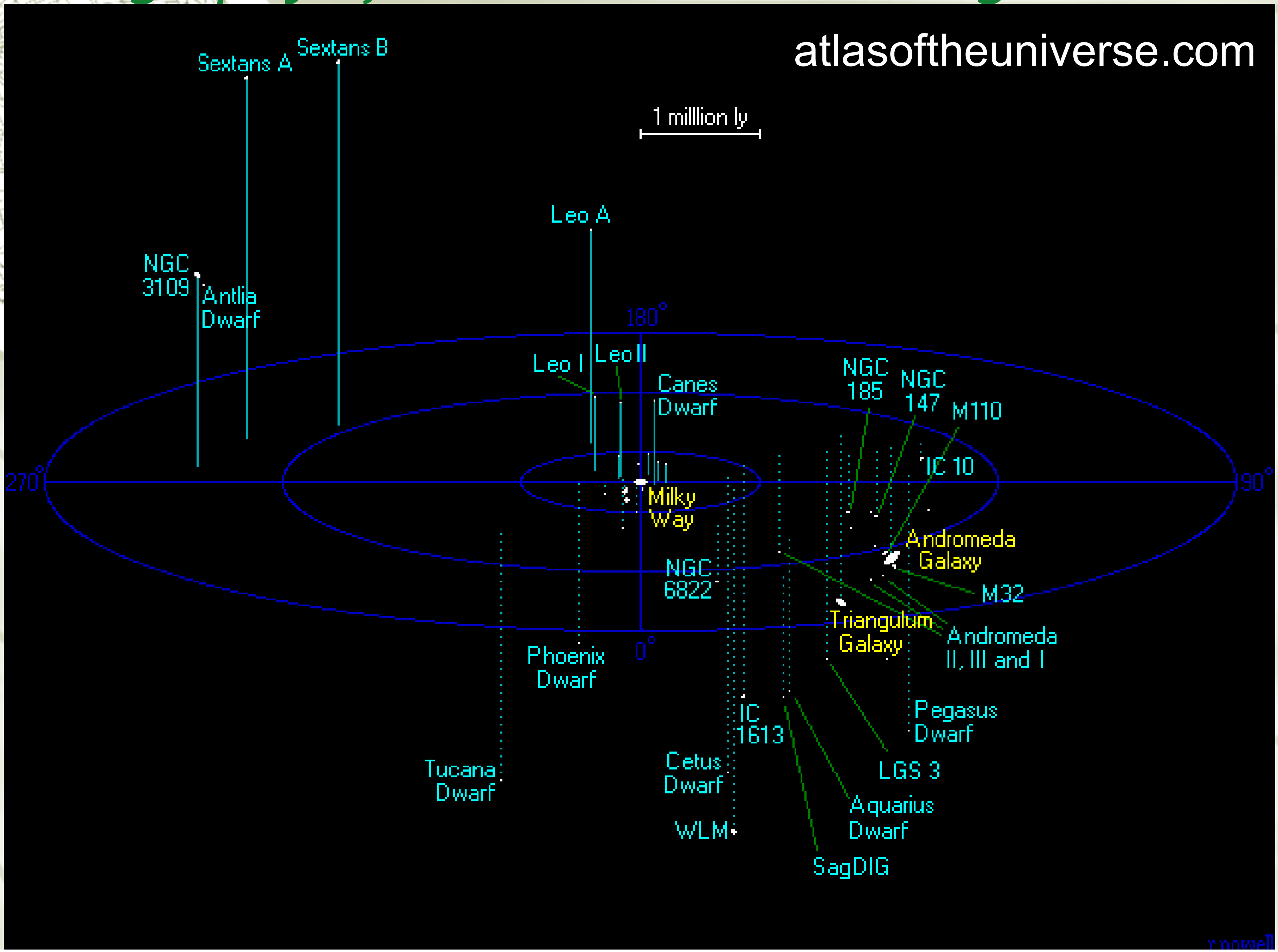


- Hubble's original Cepheid observed with Hubble Space Telescope

*Cepheids in the **Virgo galaxy cluster** with Hubble Space Telescope (16 Mpc away…)*

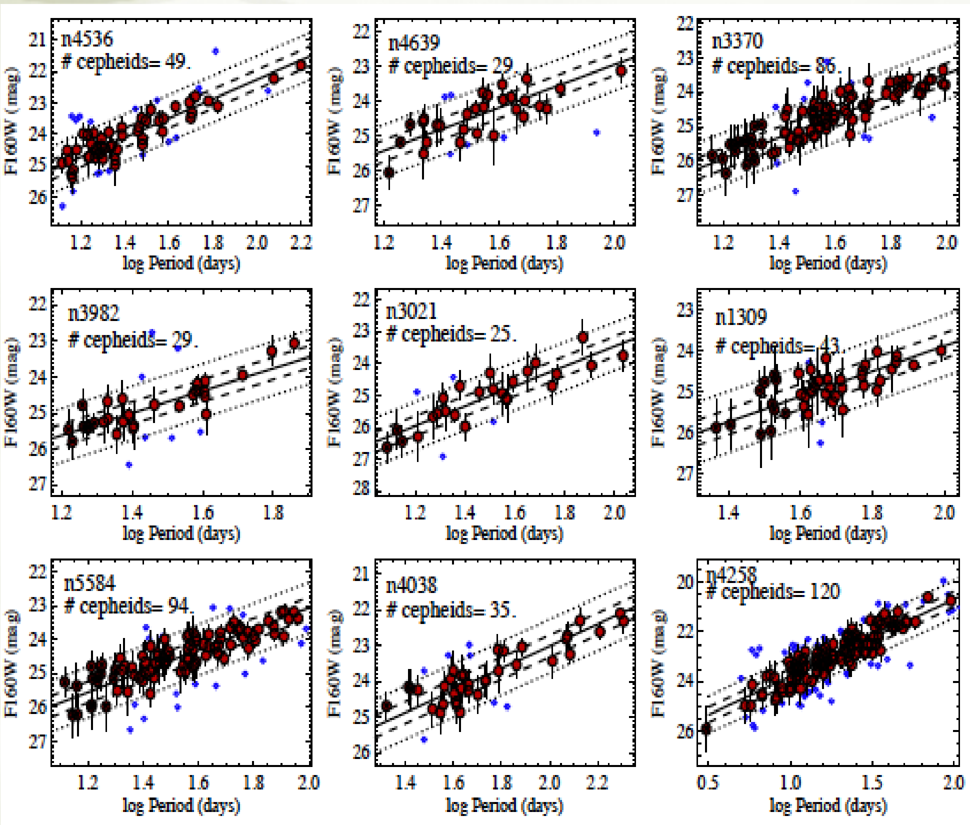


Geography of our Astronomical Neighborhood



Modern Cepheid Data

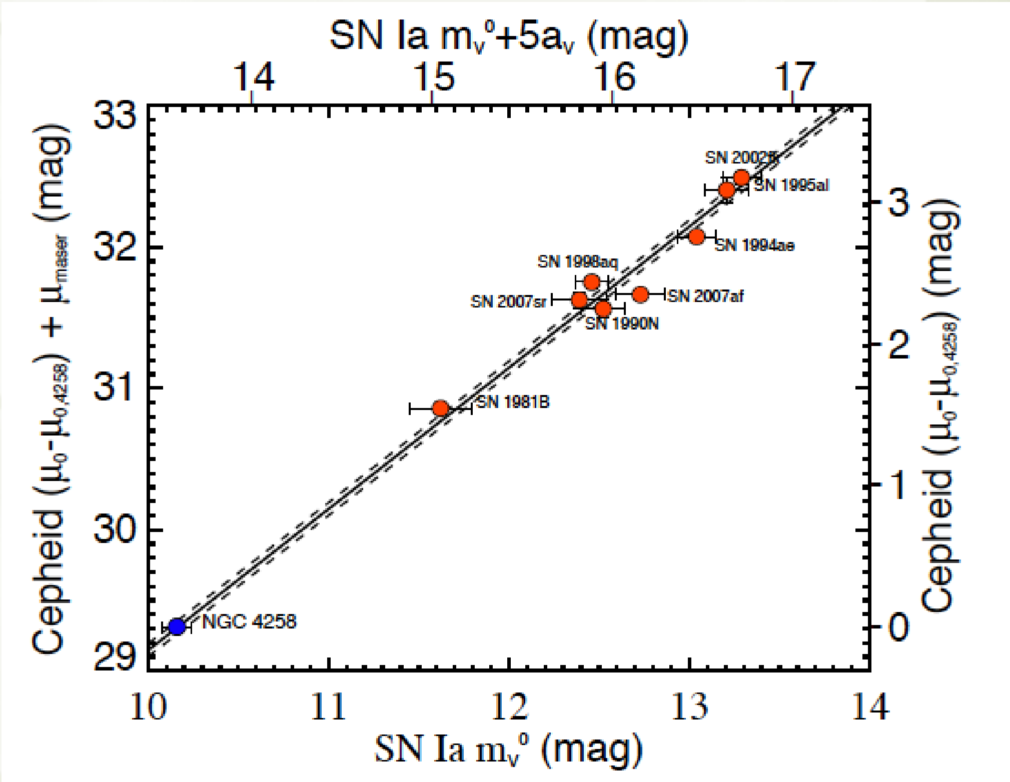
Have 30-300 Cepheids per galaxy- Reiss et al 2011



Other techniques include eclipsing binaries, planetary nebulae, long-period variables, RR Lyrae stars,

What About Going Further

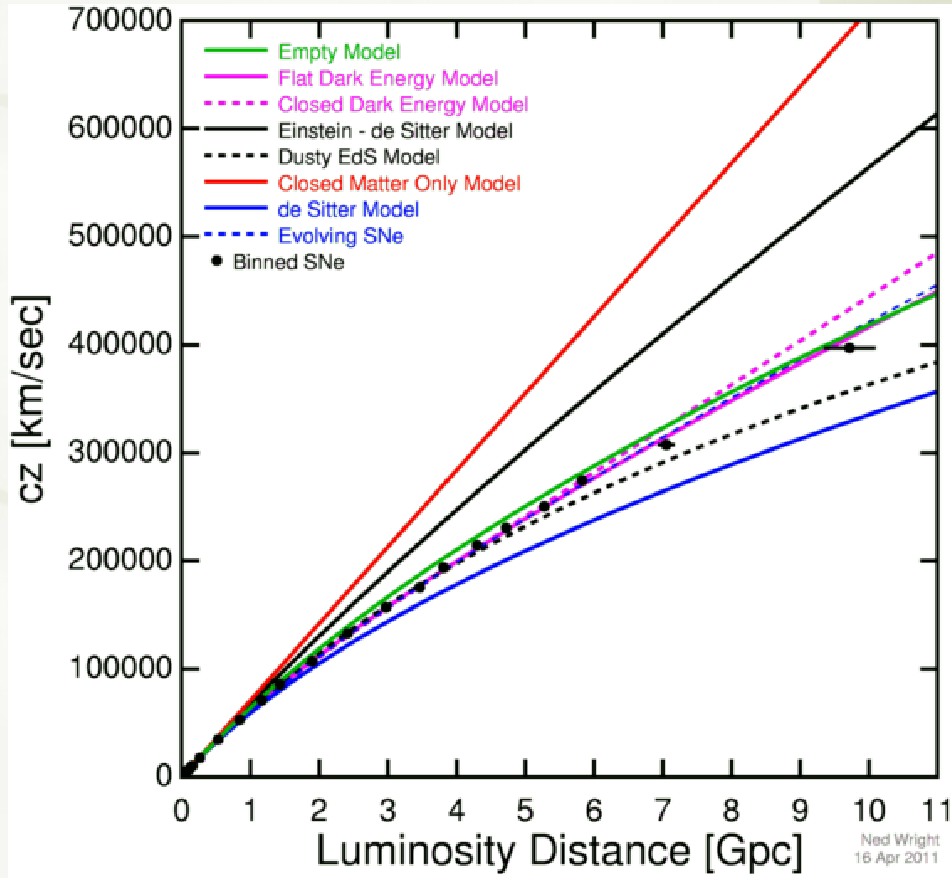
- Need brigher 'standardizable' candles
- Turns out that type I SuperNova (SNIa) can be made standard candles (Nobel Prize 2011)
- This allow 'absolute' distances to ~5000 Mpc



Comparison of SN Ia and Cepheid distances

Peak Into Future Lecture

- Using type Ia SN to determine relationship between redshift and distance



http://www.astro.ucla.edu/~wright/sne_cosmology.html

Singularity

- The center of the black hole… the place into which all of the matter making the black hole has been crushed
- General Relativity gives nonsense answers here (infinite density, infinite spacetime curvature)… **so GR must break down here**
- Some new theory of **quantum gravity** is needed