Chap 5: Galaxies (in the Universe Today)

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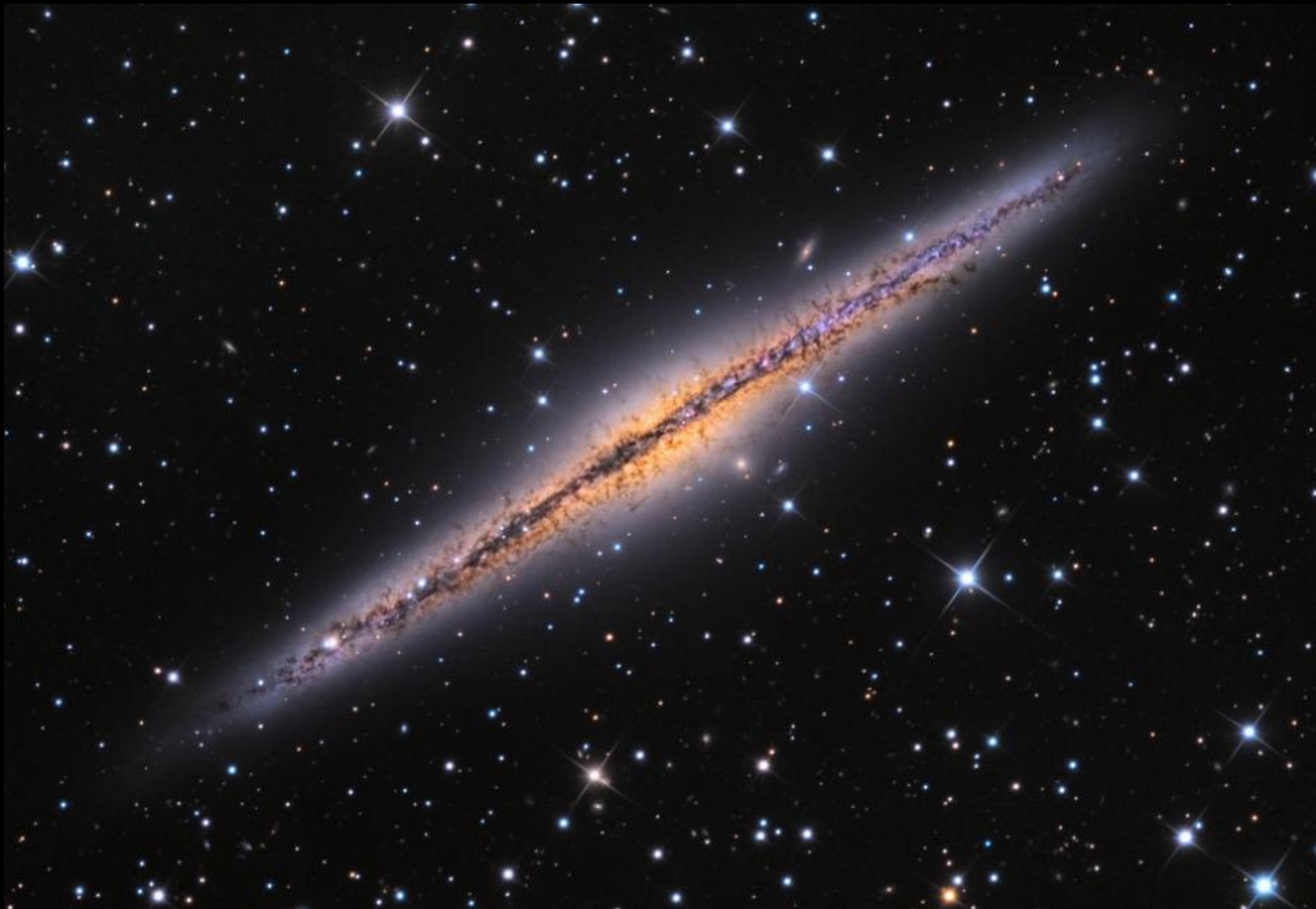
- Nebulae or island universes? How to determine distances to galaxies? What is the distance **ladder**?
- What are the morphologies of galaxies today?
- How morphology is related to the stellar population?
- How orbits of stars and galaxy morphology are intertwined?
- Evidence of dark matter
- Evidence of supermassive black holes & accretion energy

Viewing a Large Spiral Galaxy from Inside - the Milky Way

The Milky Way & Devils Tower, Wyoming

NGC 891 - an edge-on spiral galaxy

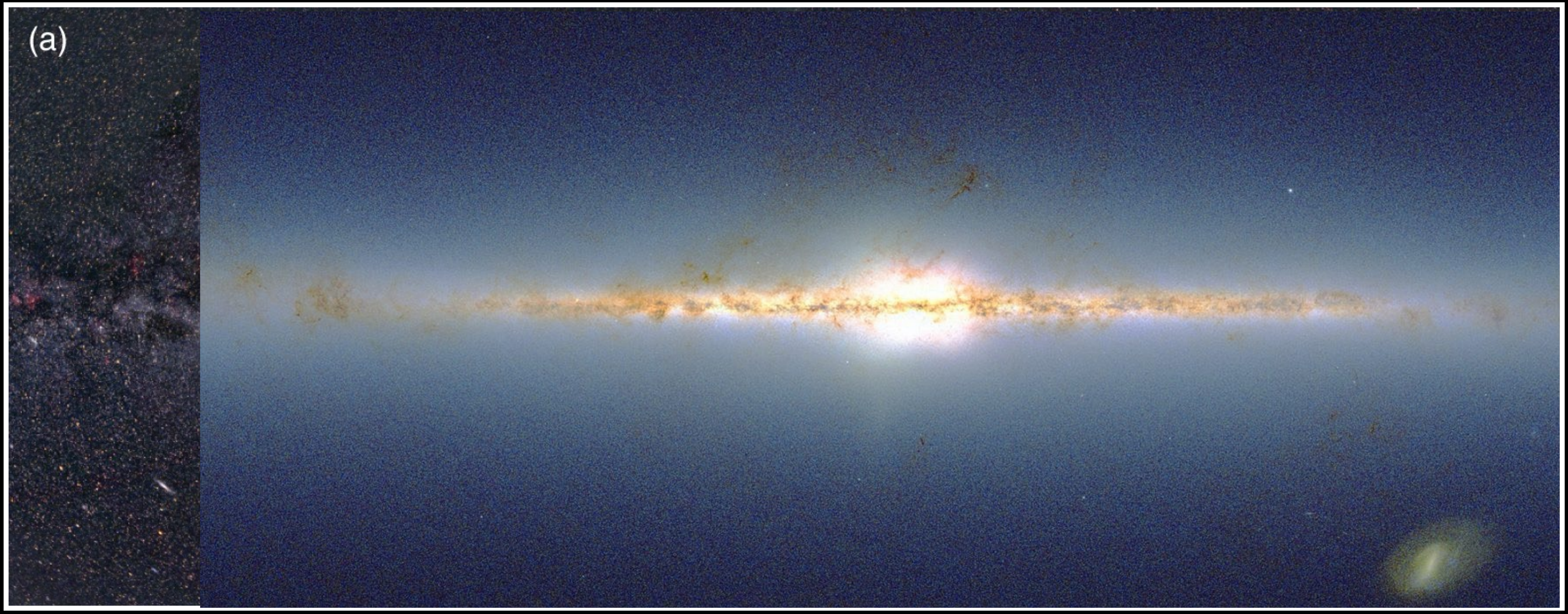


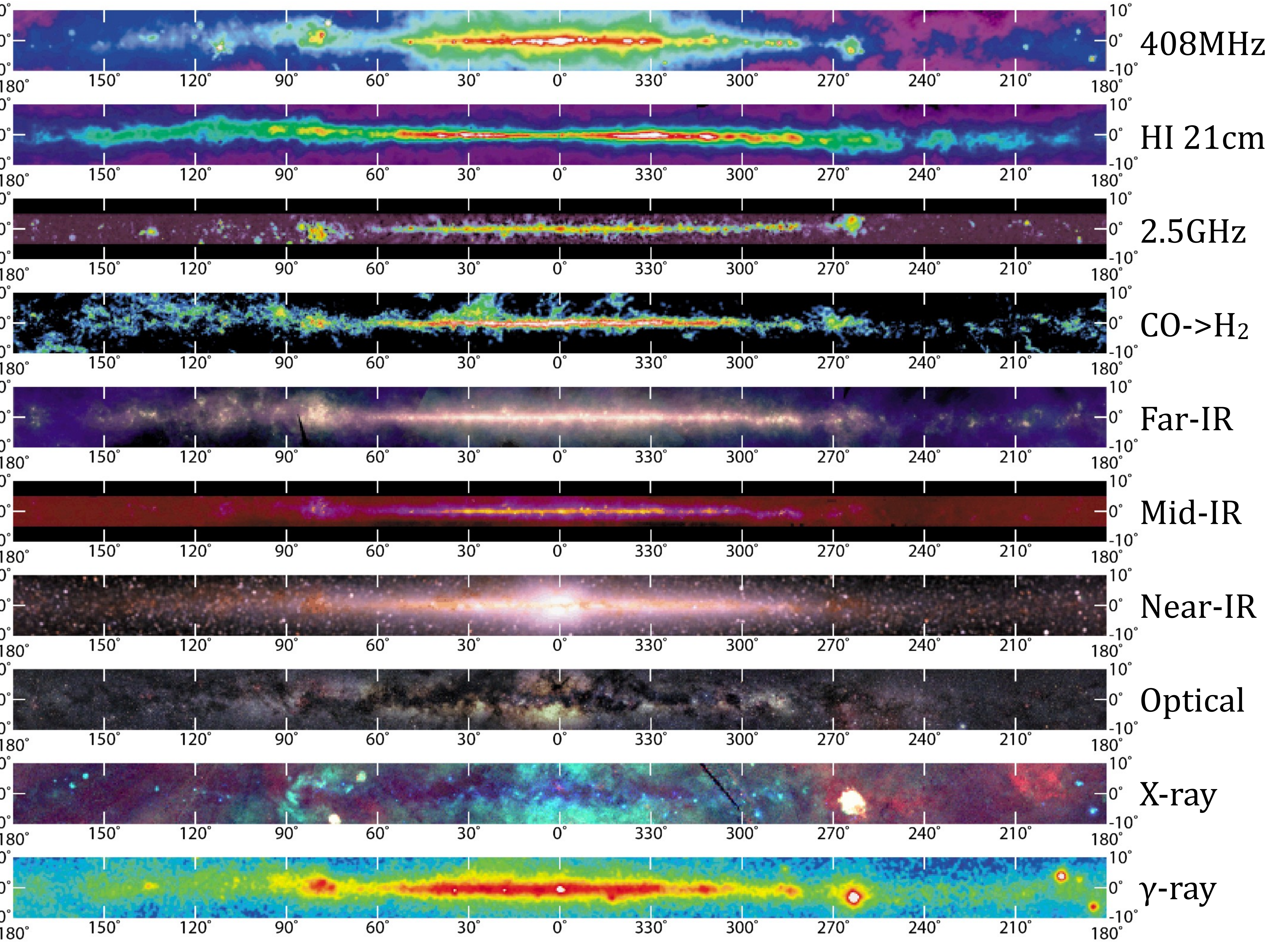
Milky Way compared to NGC 891 (an edge-on Spiral galaxy)

a.

Milky Way in optical vs. infrared wavelengths

- The IR light is less attenuated by dust, revealing the central stellar bulge of the galaxy.
- Illustrating the importance of dust extinction




408MHz
HI 21cm
2.5GHz
CO->H2
Far-IR
Mid-IR
Near-IR
Optical
X-ray
γ-ray
10°
0°
-10°
180°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180°

Nebulae or Island Universes?

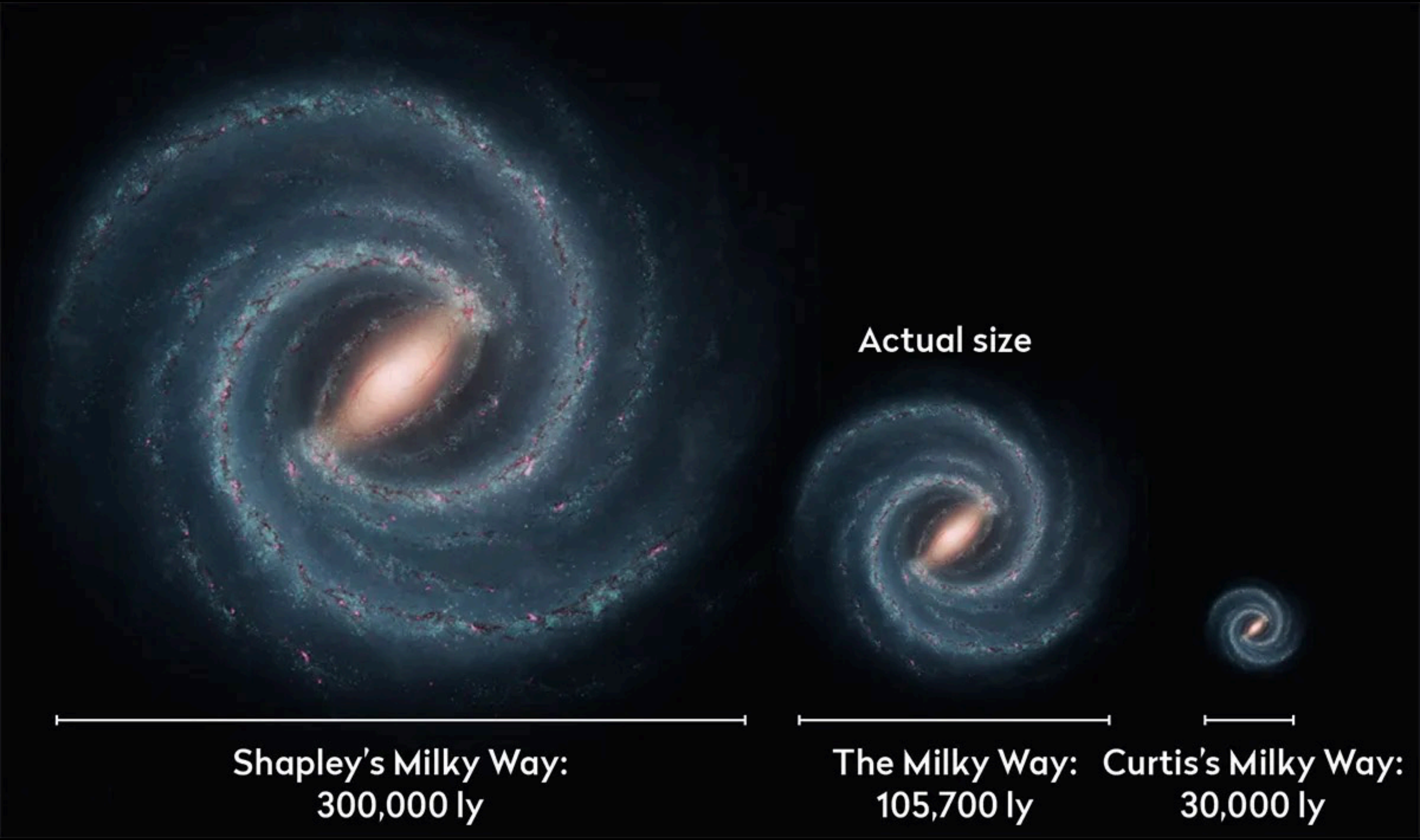
The 1920 Great Debate

The 1920 Great Debate: "Nebulae" or "Island Universes"?

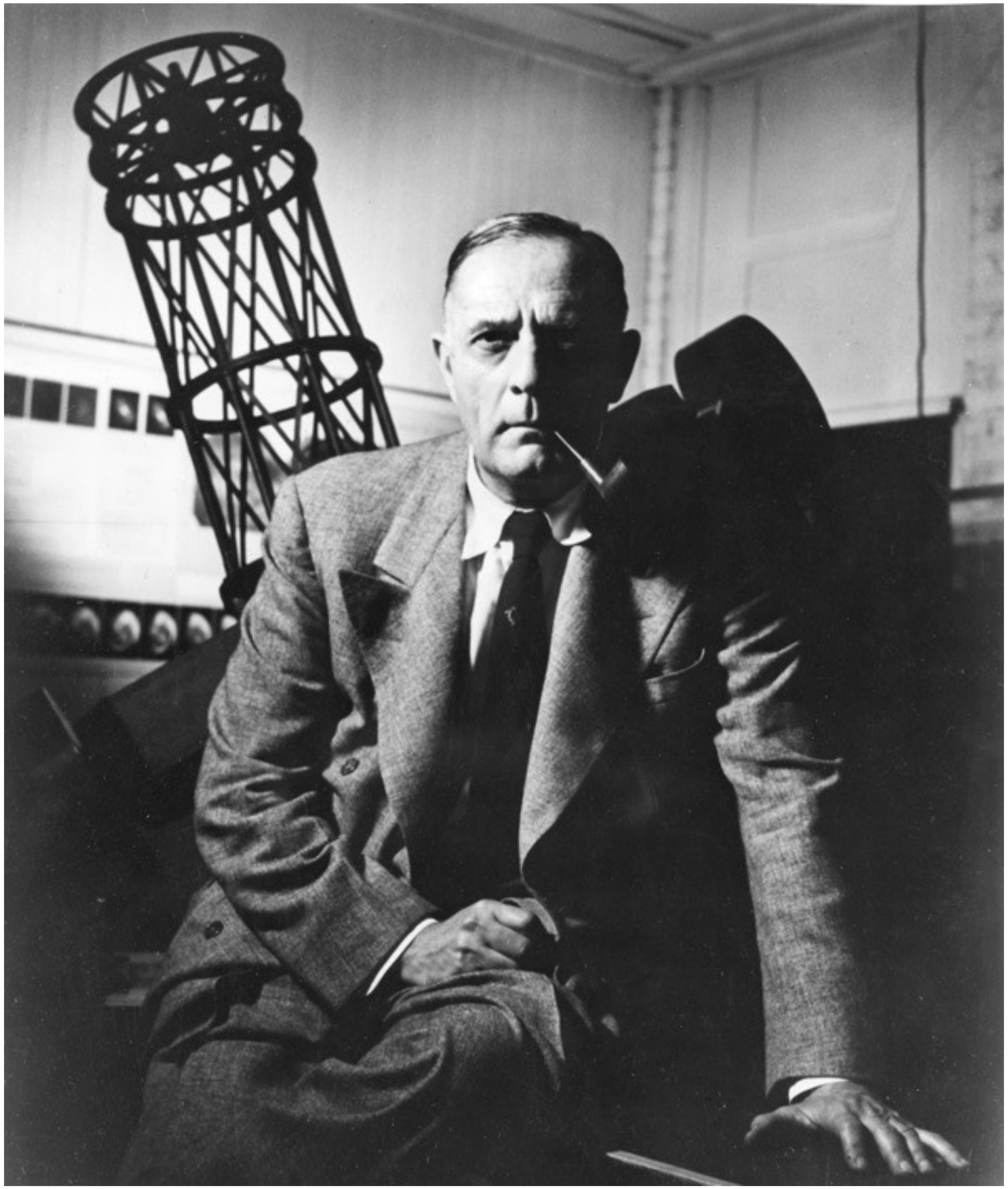
- Charles **Messier** and William and Caroline **Herschel** identified thousands of **fuzzy "nebulae"** in **1700s**.
- Some astronomers thought the nebulae were located in the Milky Way, while others speculated that they were **island universes**.
  - This was an important question as it was widely believed at the time that the **Milky Way was the only galaxy in the universe**.
- This was the subject of the **1920 Great Debate** between Harlow Shapley and Heber Curtis.
  - **Shapley** (1918) calculated the Milky Way to be **100 kpc** across. He argued that **the nebulae were inside the Milky Way**.
  - **Curtis** believed the Milky Way was smaller and therefore the **nebulae were located outside of the Milky Way**.

Baird Auditorium of the Smithsonian Museum of Natural History in Washington, DC,

The "Sizes" of the Milky Way Galaxy



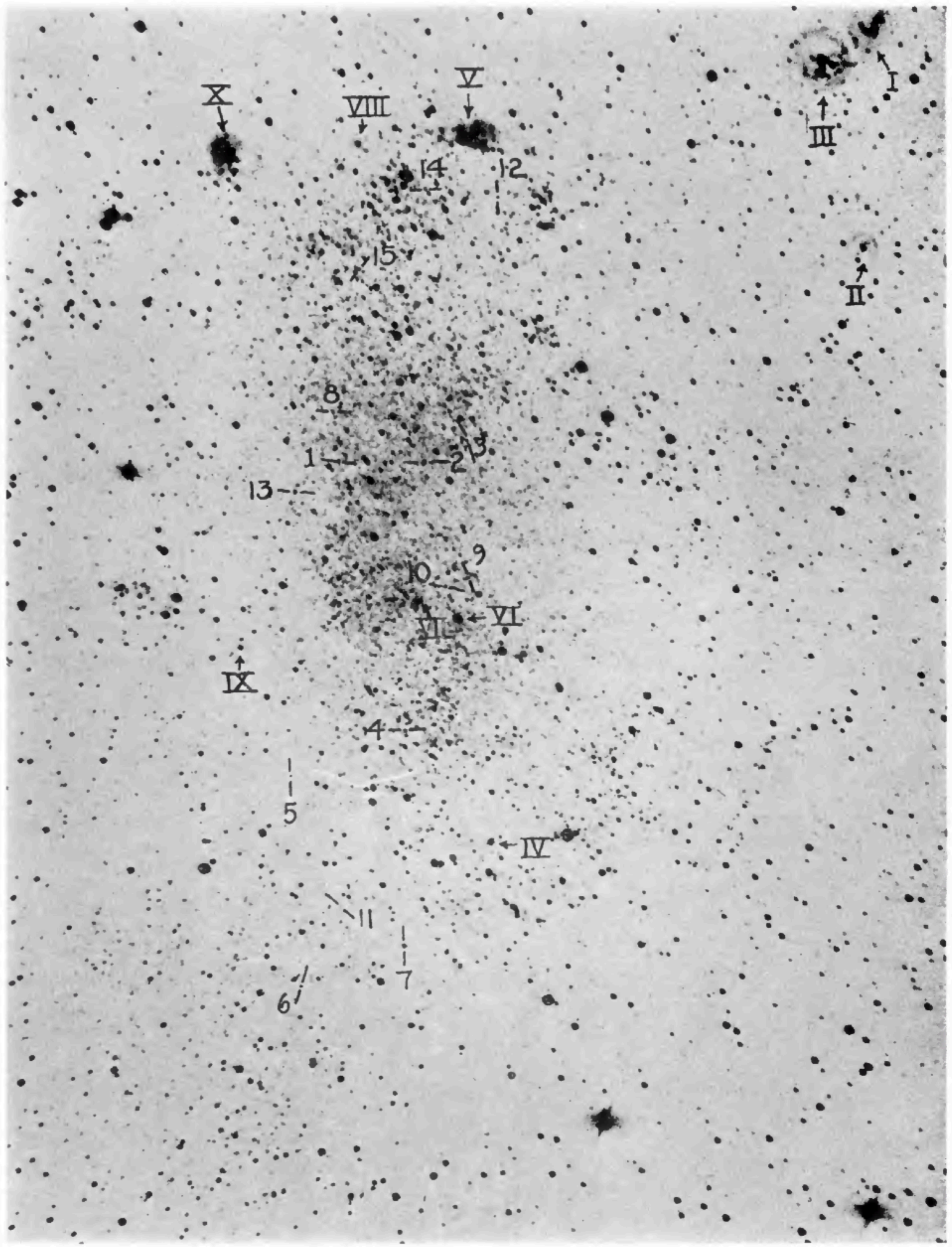
Edwin Hubble (1889-1953)



- Born in **Marshfield, Missouri**
- B.S. & Ph.D. from University of Chicago
- Key accomplishments:
  - NGC 6822 and M31's distances: galaxies are island universes
  - Hubble-Lamaitre law: the expansion of the universe
  - Hubble's sequence of galactic morphology
  - The age of the Crab nebula and its association with SN 1054.
- Photo on the left: portrait in front of the 100-in telescope on Mt Wilson, LA.

The debate was resolved by Hubble's discovery of Cepheids in NGC 6822

The debate was resolved by Hubble's observations of NGC 6822



1925ApJ....62..409H N.G.C. 6822

Negative print of Plate XIV. Variable stars are designated by Arabic figures; nebulae involved in or superposed on the cluster by Roman numerals.

Hubble (1925)

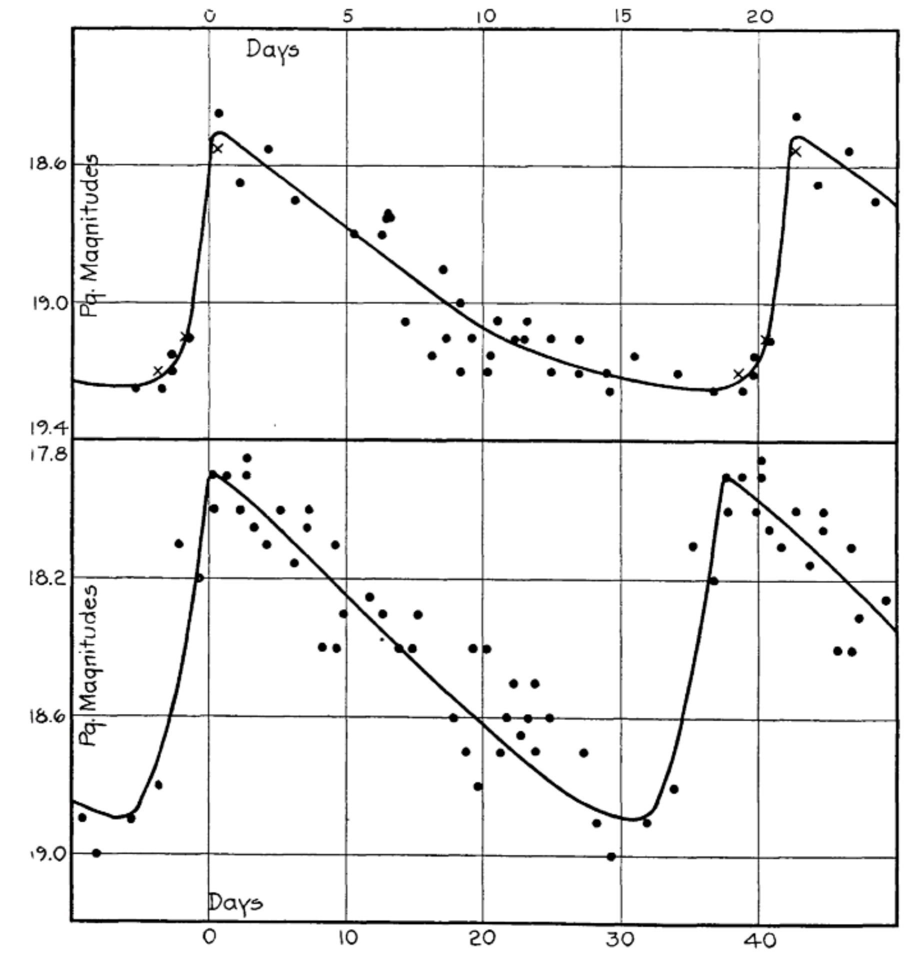


FIG. 1.—Light curves for two Cepheids in N.G.C. 6822. Upper curve, variable No. 6. Period 21.06 days; range 18.5–19.25. Lower curve, variable No. 2. Period 37.45 days; range 17.9–18.9. The three crosses on the rising slope of the upper curve represent observations on successive days and illustrate the rapid brightening of the variables.

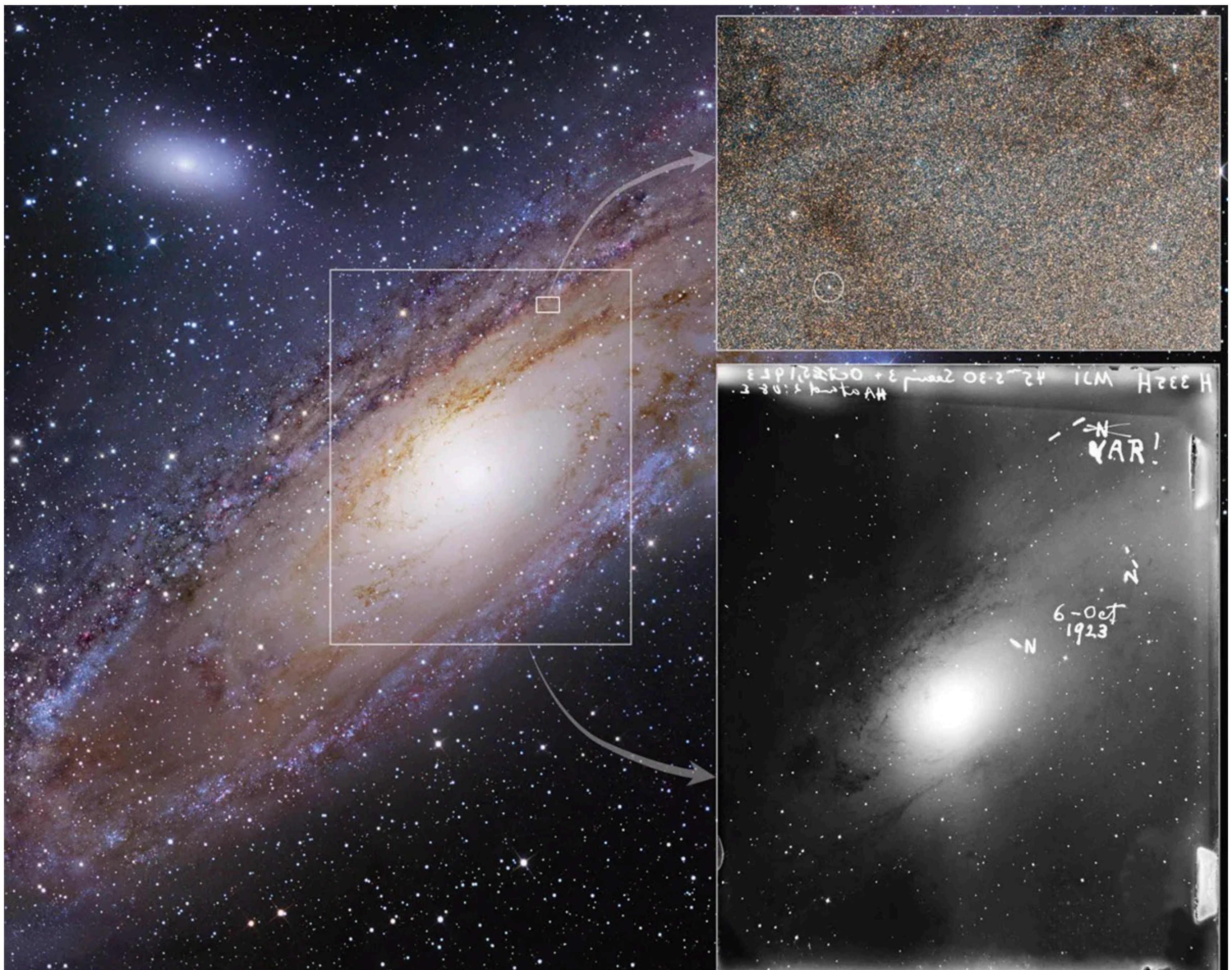
$$m-M=21.65$$

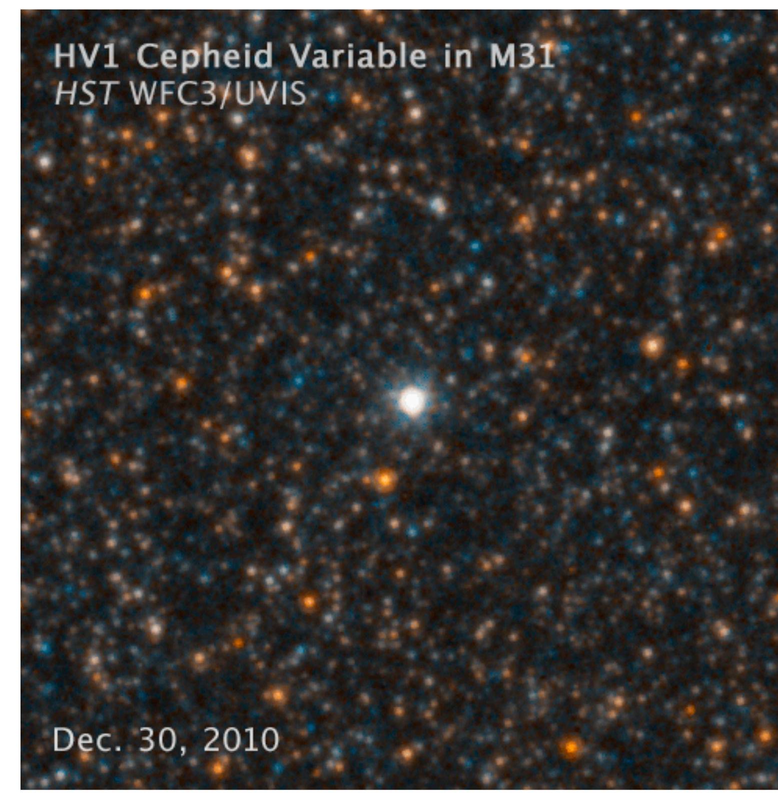
$$\pi=0''.0000468$$

$$\text{Distance}=214{,}000 \text{ parsecs}$$
$$=700{,}000 \text{ light-years}$$

Later, more conclusively by Hubble's observations of M31-V1

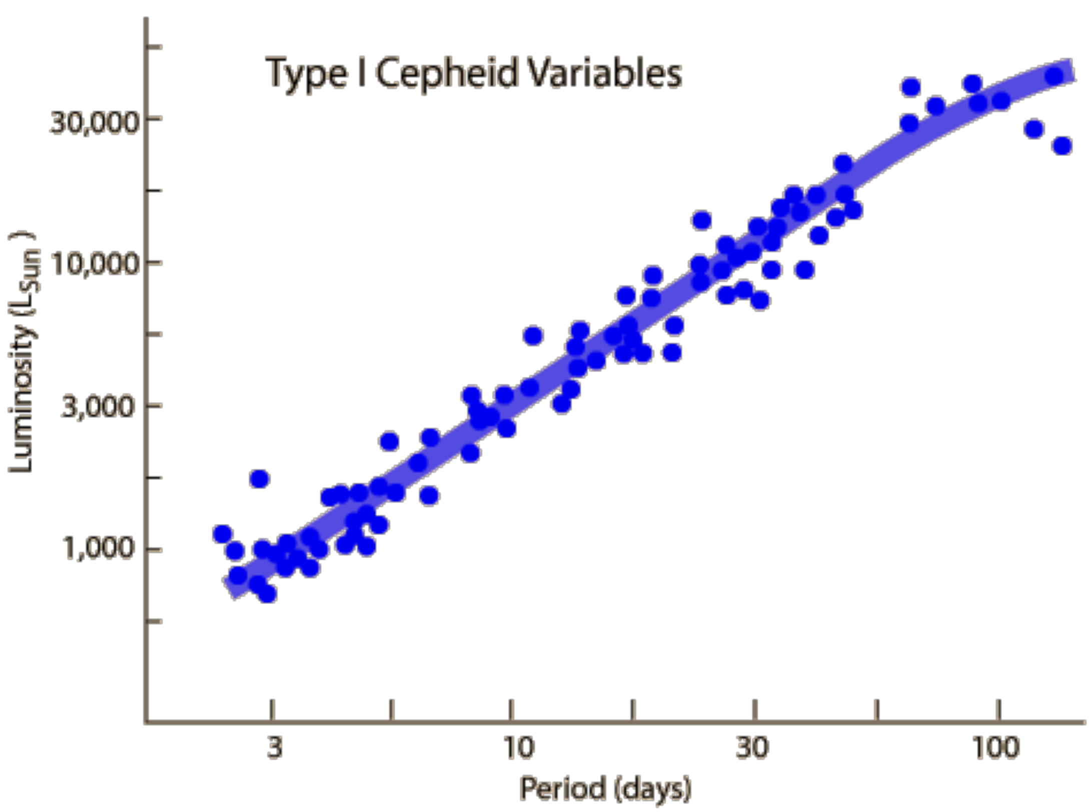
- **Hubble (1929)**: *"A Spiral Nebula as a Stellar System, Messier 31"*
- He discovered a **Cepheid variable** inside of the Andromeda (**M31-V1**).
- He used **Leavitt** (1908)'s **Luminosity-Period relation** to calculate the distance to M31. This distance was much greater than the size of the Milky Way per Shapley.

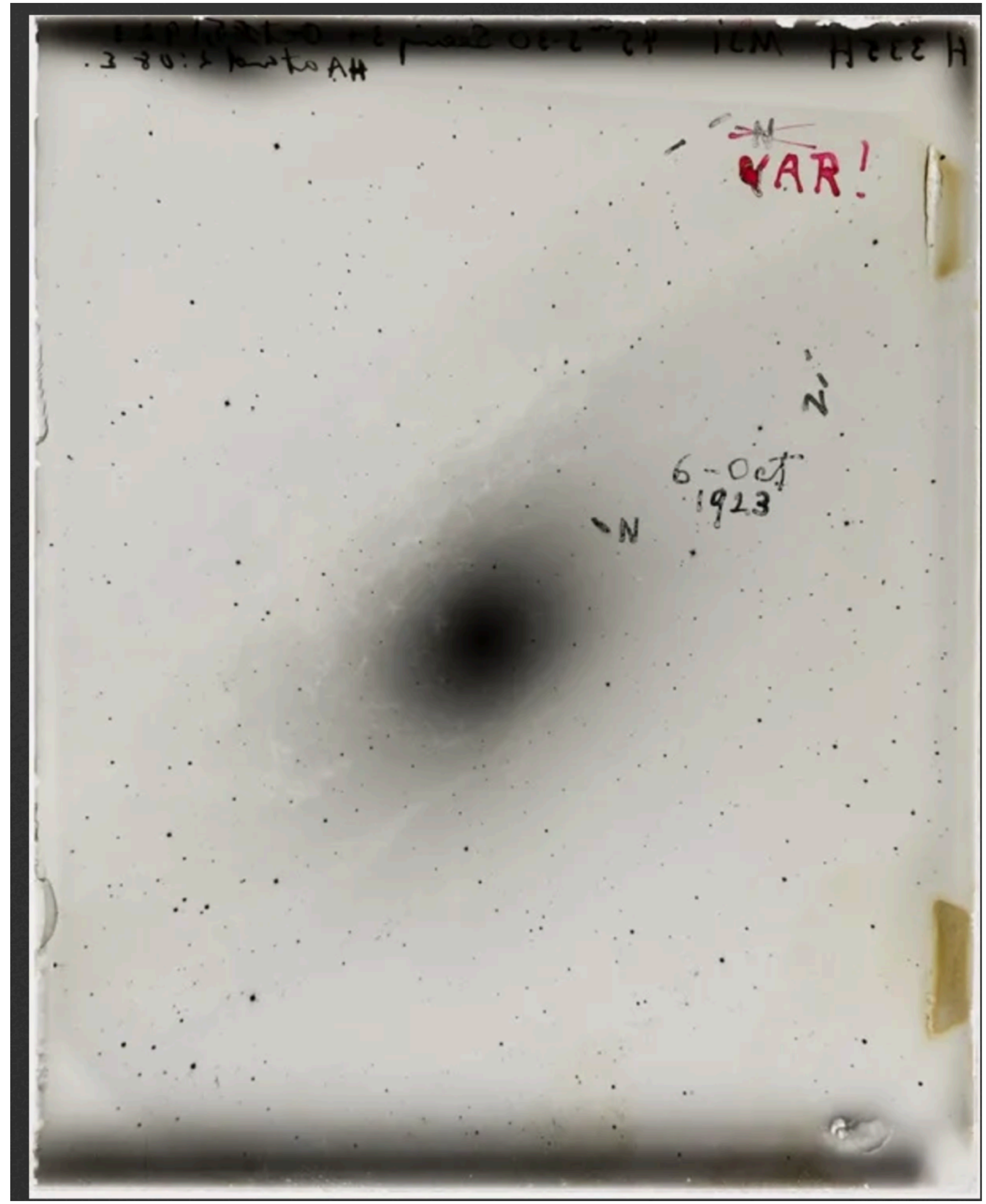




In 1923, Edwin Hubble used a Cepheid to determine distance to M31

- $M_V = -2.43 \log(P_{day}) - 1.62$
  (Type I Cepheids, Fritz et al. 2007)
- This is critical for determining distances to other galaxies:
  $d_{pc} = 10^{\frac{(m-M)+5}{5}}$



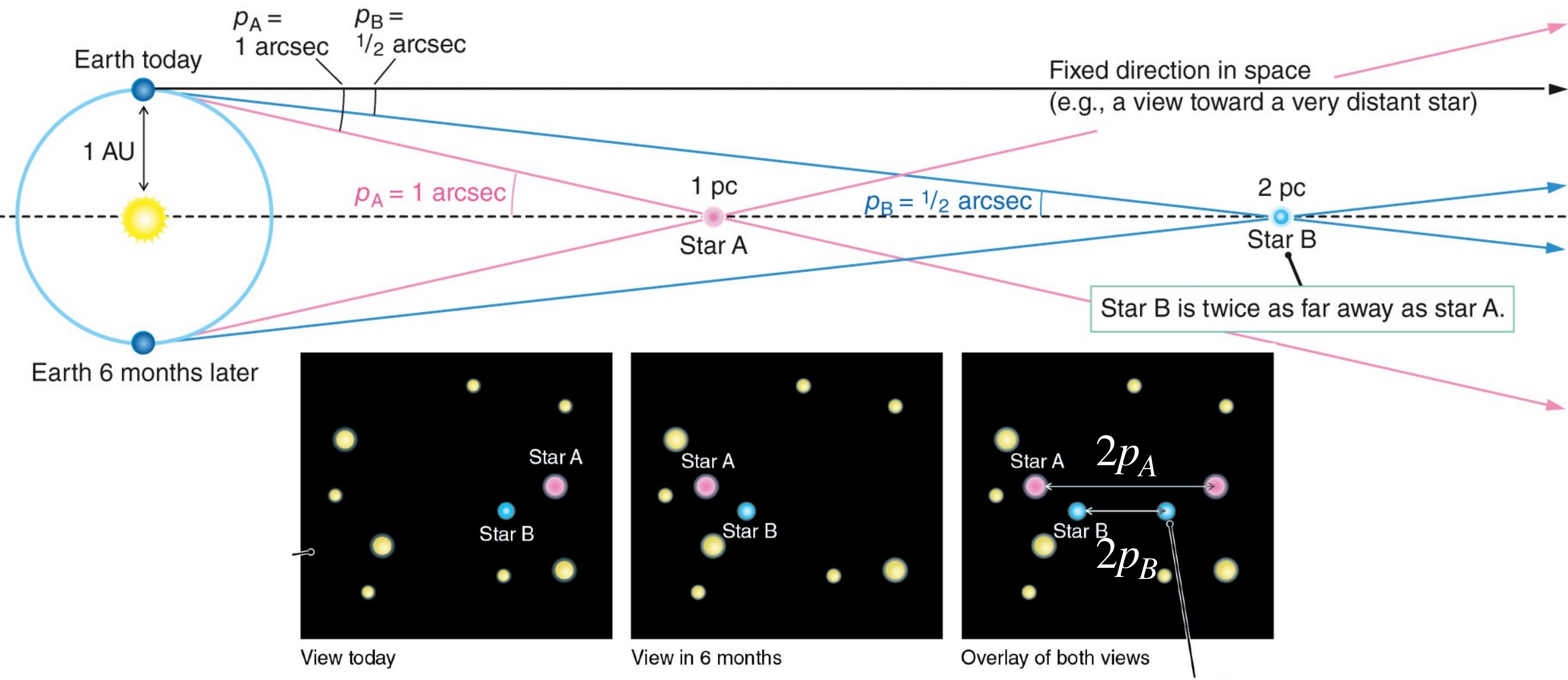


The Distance Ladder

Stellar Parallax - The First Rung of the Ladder

Any directional shift due to a positional shift is a parallax effect, but in **stellar astronomy**, **parallax** is defined as **half of the maximum directional shift** due to Earth's orbital motion.

From this diagram, it's clear that **parallax** is inversely proportional to **distance**: $p \sim 1/d$



Distances to Galaxies

- Finding distances to galaxies requires the use of the **distance ladder** in which short-distance methods are used to calibrate long-distance methods.

- **Parallax** uses geometry to measure the distances to stars.
- **Standard candles** are objects with a luminosity inferred from other properties, so that their brightness and luminosity can be combined to calculate a distance.
  - **Spectroscopic "parallax"** uses the luminosity-spectral type relation of main sequence stars
  - **Cepheid variables** uses the luminosity-period relation of pulsating variable stars.
  - **Type Ia supernovae** uses the luminosity-duration relation.

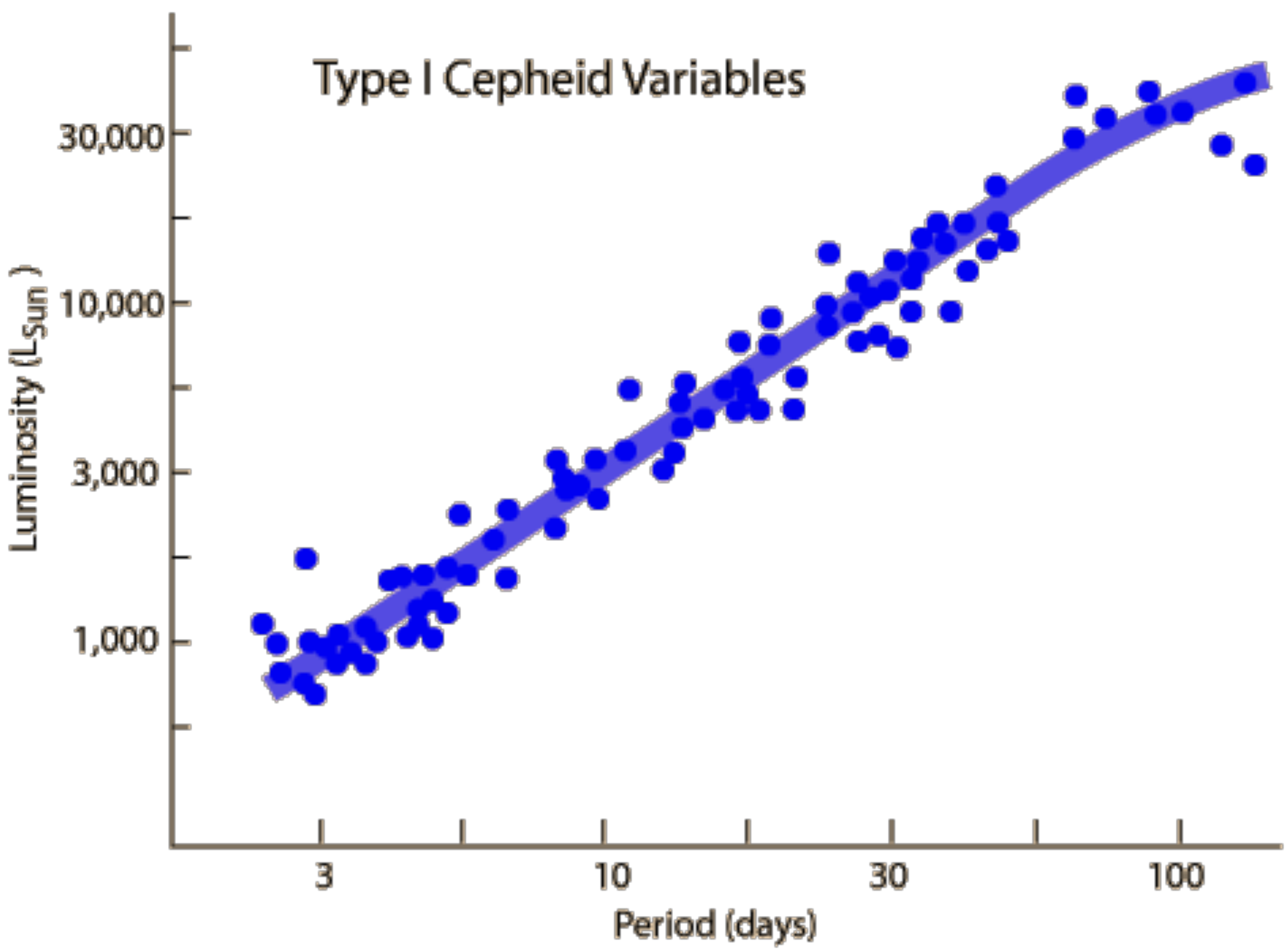
The Standard Candle Methods

- If we had measured or inferred the absolute magnitude of a class of astrophysical objects, we can get the **distance modulus (m-M)** from its apparent magnitude.
- The distance modulus then gives us the **distance**:

$$m - M = 5\ (\log d_{\rm pc} - 1) \Rightarrow d_{\rm pc} = 10^{1+0.2(m-M)}$$

The Standard Candle Method 1 — Cepheids (Leavitt's Law)

- $M_V = -2.43\log(P_{\mathrm{day}}) - 1.62$
  (Type I Cepheids, Fritz et al. 2007)
- This is critical for determining distances to other galaxies: $d_{\mathrm{pc}} = 10^{\frac{(m-M)+5}{5}}$

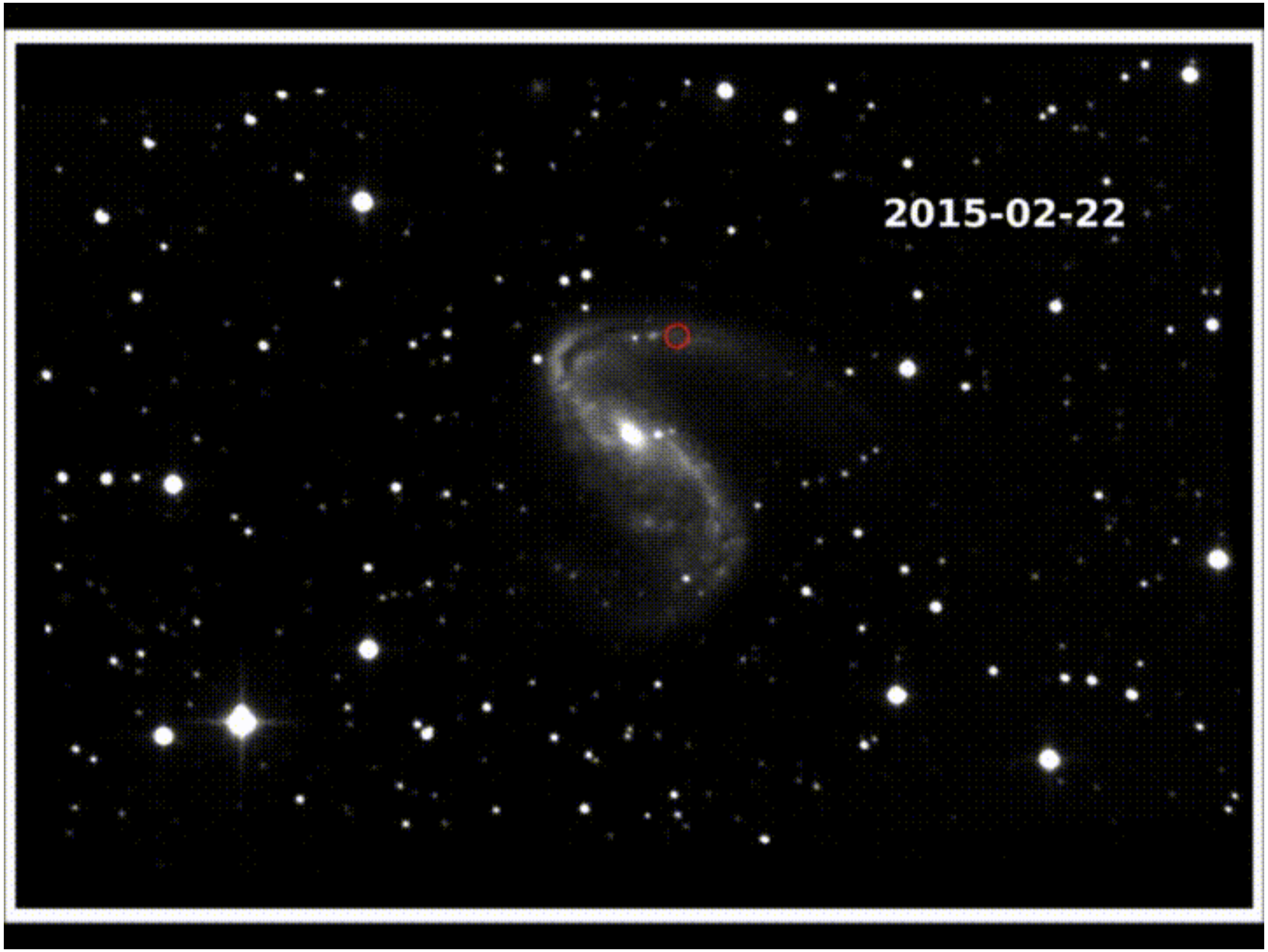


Henrietta Swan Leavitt

Born	July 4, 1868 Lancaster, Massachusetts, U.S.
Died	December 12, 1921 (aged 53) Cambridge, Massachusetts, U.S.
Education	Oberlin College Harvard University (BS)
Known for	Leavitt's law: the period-luminosity relationship for Cepheid variables

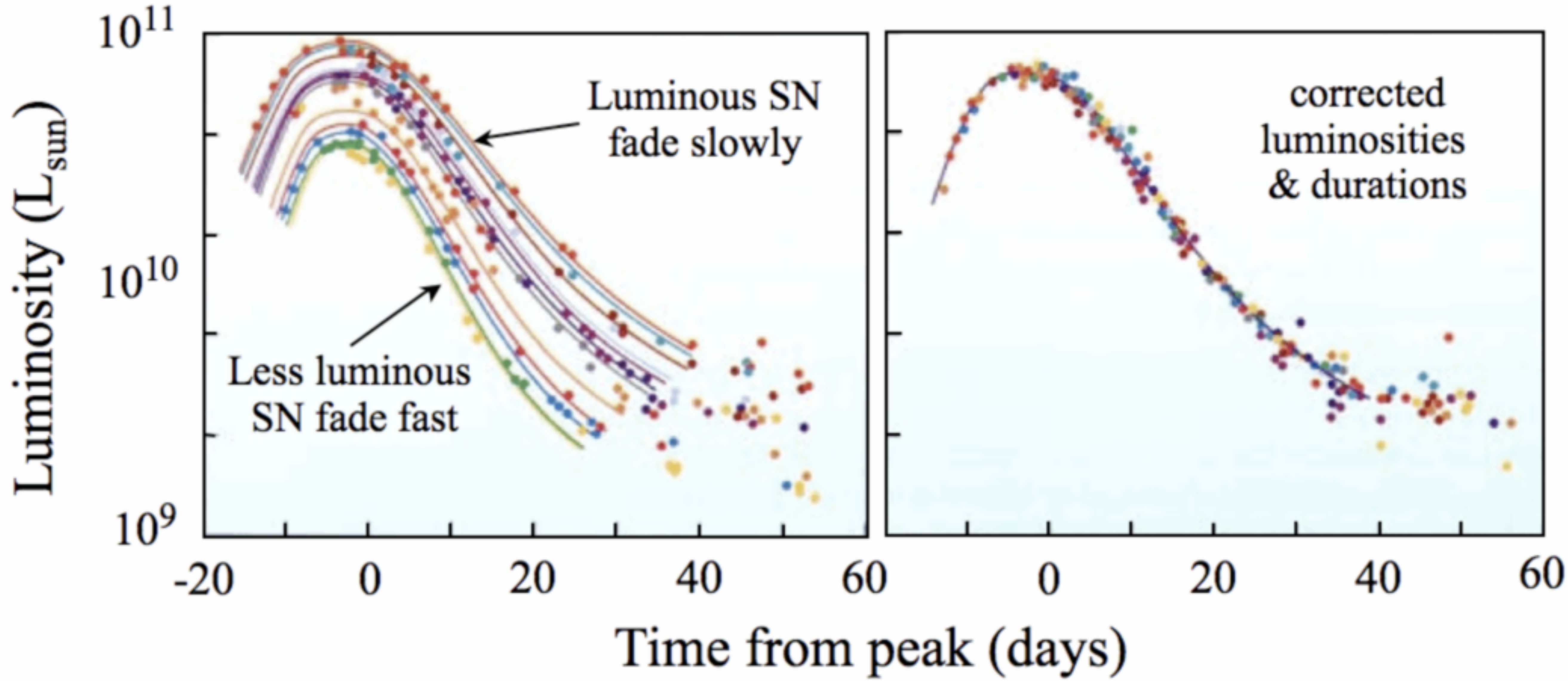
The Standard Candle Method 2 — Type Ia SNe

- Type Ia supernovae (SNe) have been used as standard candles to measure cosmological distances to other galaxies.
- They work as **standard candles** because the white dwarfs have to reach ~1.44 solar masses (**Chandrasekhar limit**) to trigger the thermonuclear explosion, reaching a peak absolute magnitude of **M_V = -19, approximately!**

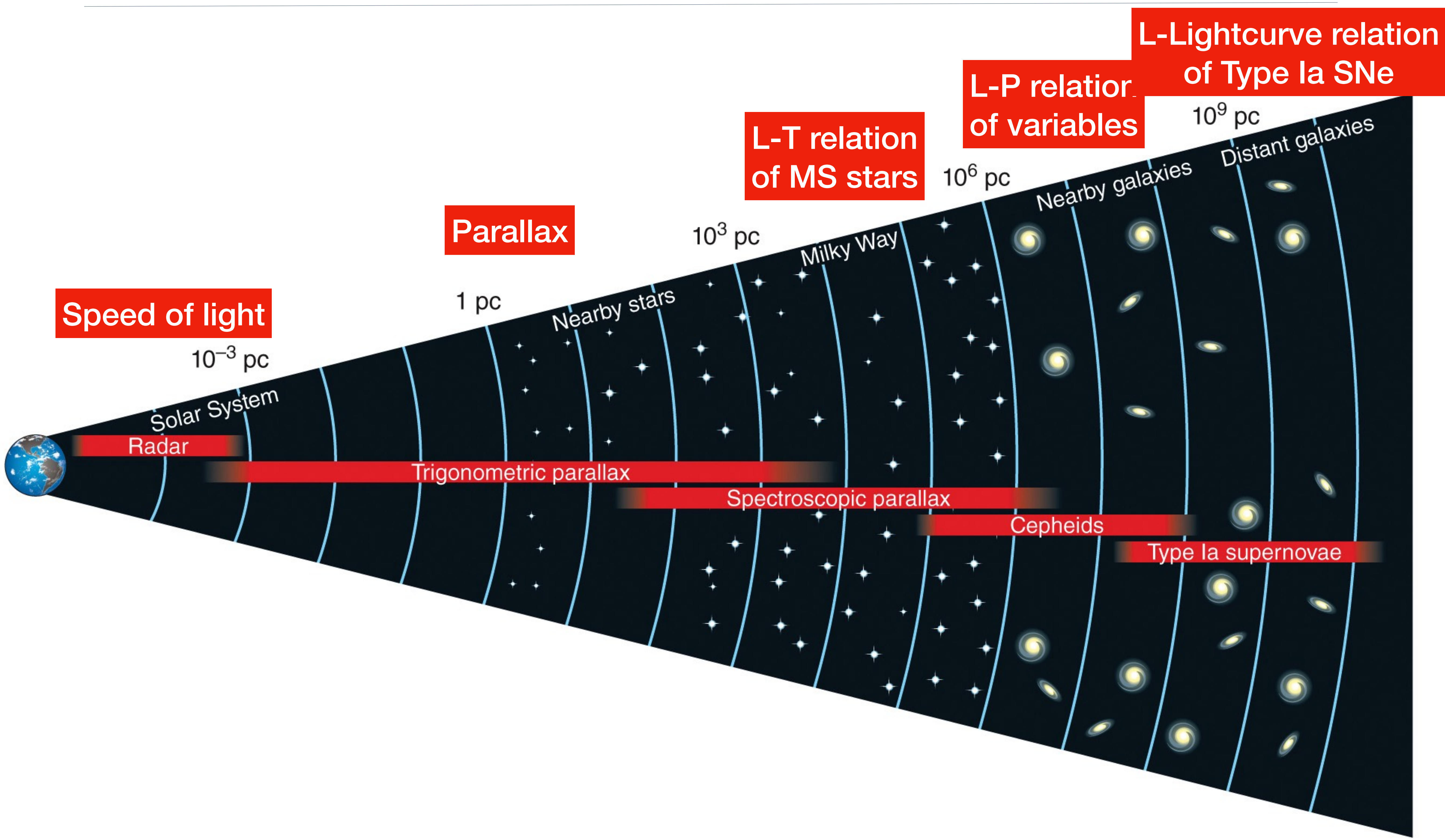


Type Ia SNe - Luminosity-Lightcurve Correlation

- Over just a few days, the explosion releases about the same amount of energy as the Sun does over its entire main-sequence lifetime (10^{44} Joules).
- Type Ia supernovae are excellent **distance indicators** because they are **standard candles** (luminosity can be inferred from the shape of its **light curve** - how long the explosion last and how fast its brightness declines)

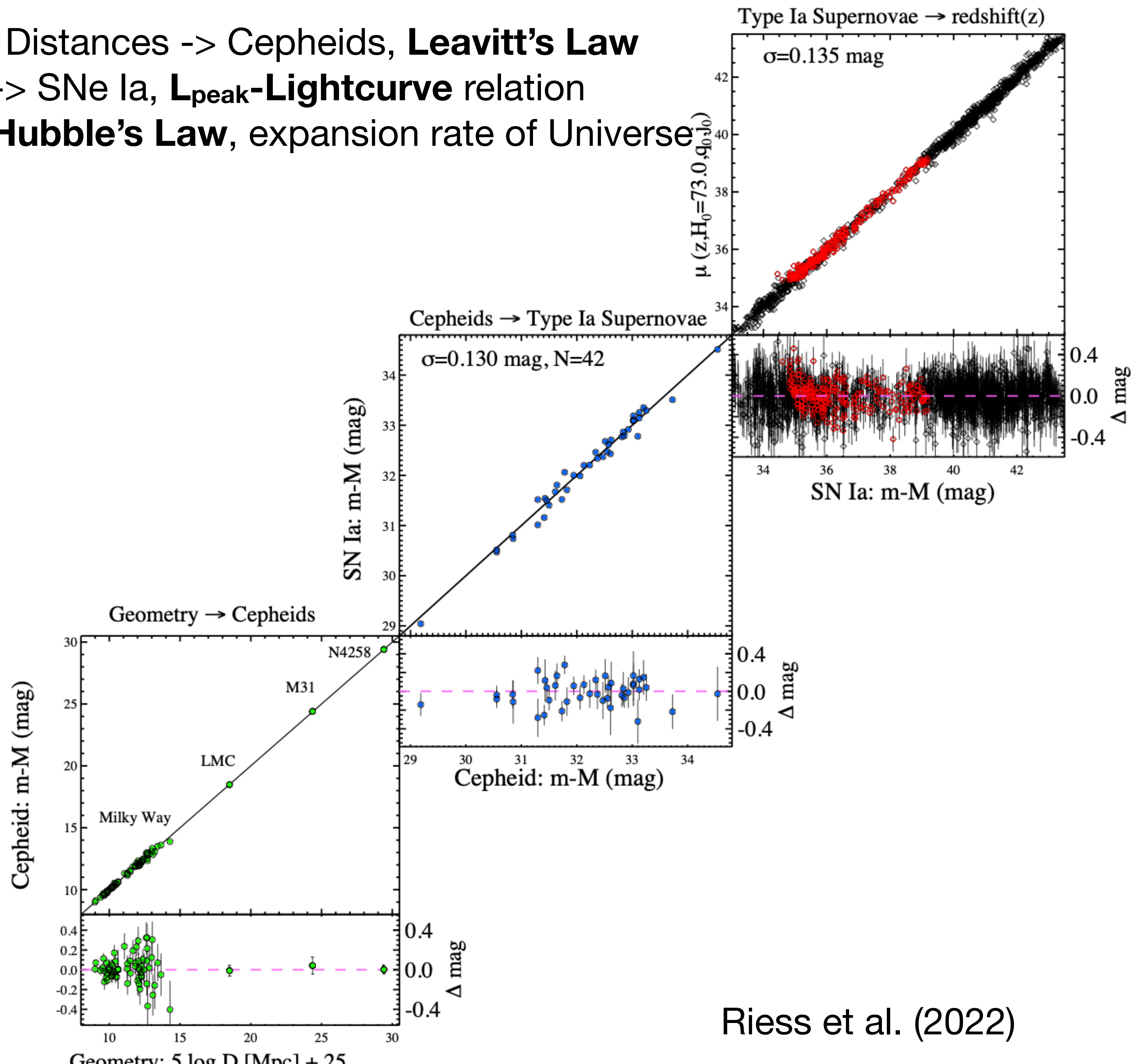


The Distance Ladder from Solar System to Galaxies



Distance Ladder: presented in a more technical Way

1. Geometric Distances -> Cepheids, **Leavitt's Law**
2. Cepheids -> SNe Ia, **L_{peak}-Lightcurve** relation
3. SNe Ia -> **Hubble's Law**, expansion rate of Universe



Riess et al. (2022)

Critical Overlaps: Galaxies with both Cepheids and SNe Ia

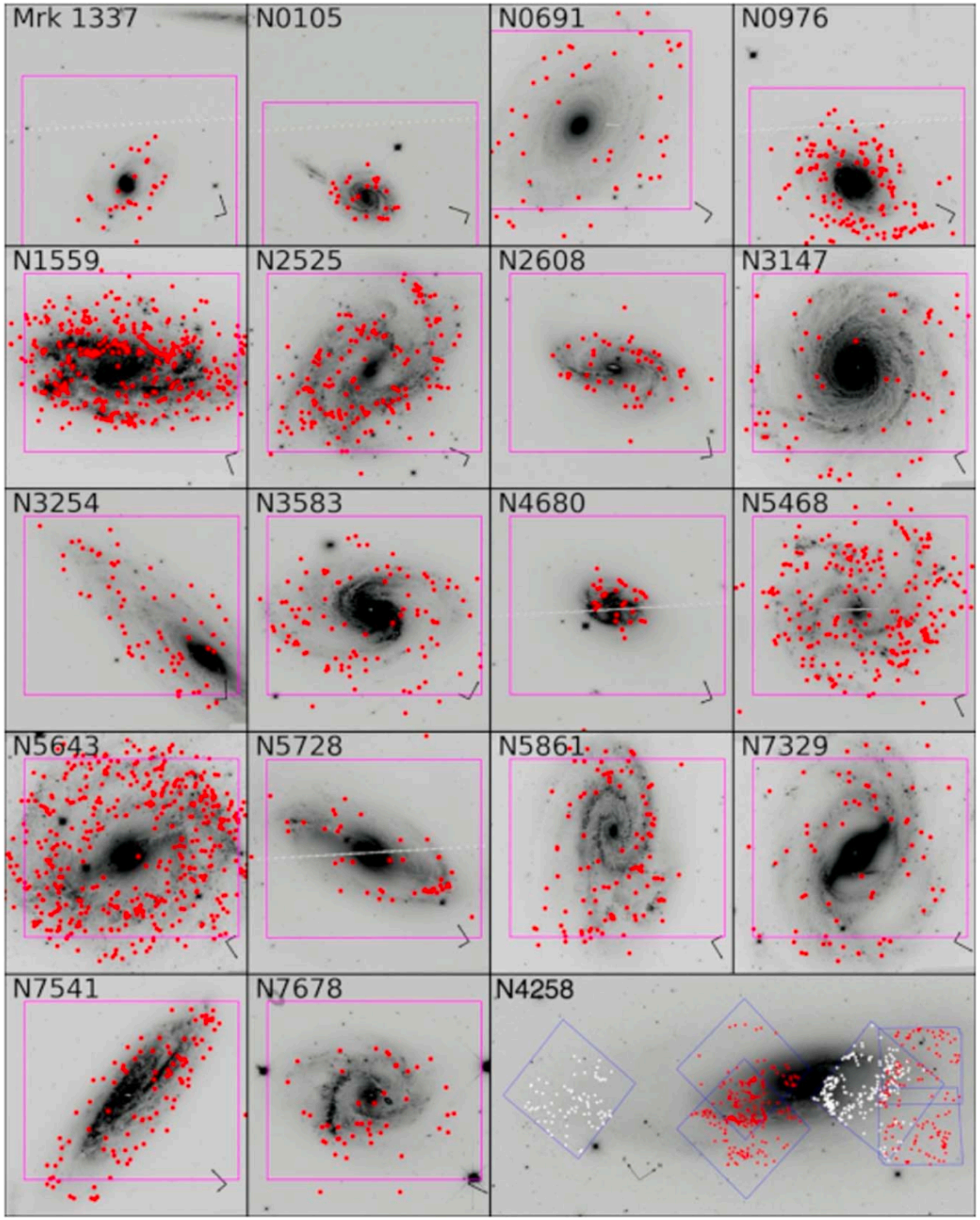
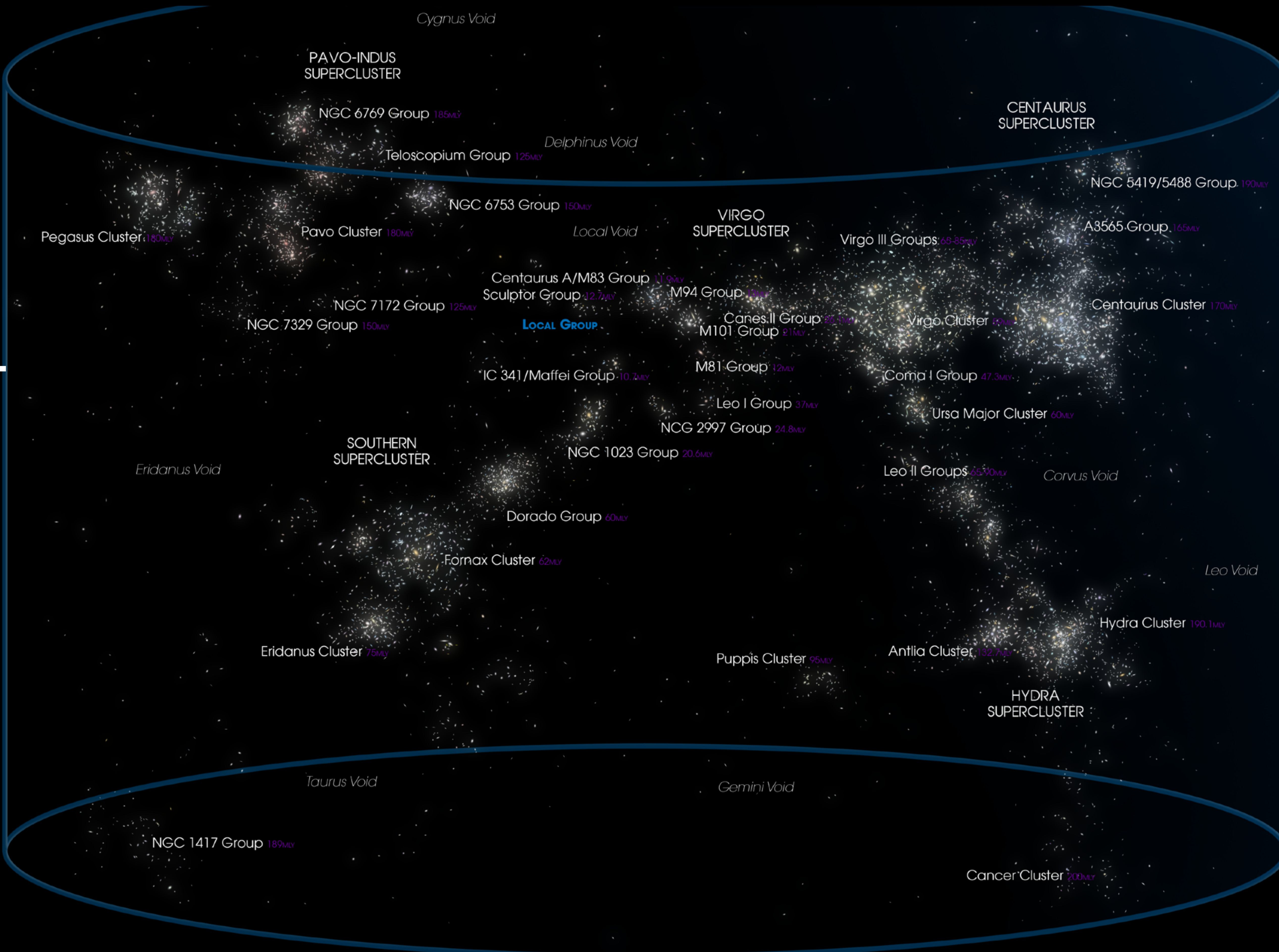


Figure 3. Images of 18 newly observed hosts of 23 SNe Ia and NGC 4258. Each image is of the Cepheid host indicated. The magenta outline shows the 2.′7 × 2.′7 field of the WFC3/NIR observations. Red dots indicate the positions of the Cepheids. Compass indicates north (long axis) and east (short axis). The NGC 4258 image shows Cepheids from Macri et al. (2006) in white and new ones from Yuan et al. (2022) in red.

Riess+2022

10^{17} Solar Masses, 10^5 Member Galaxies, 520 million light years across

LANIAKEA Supercluster

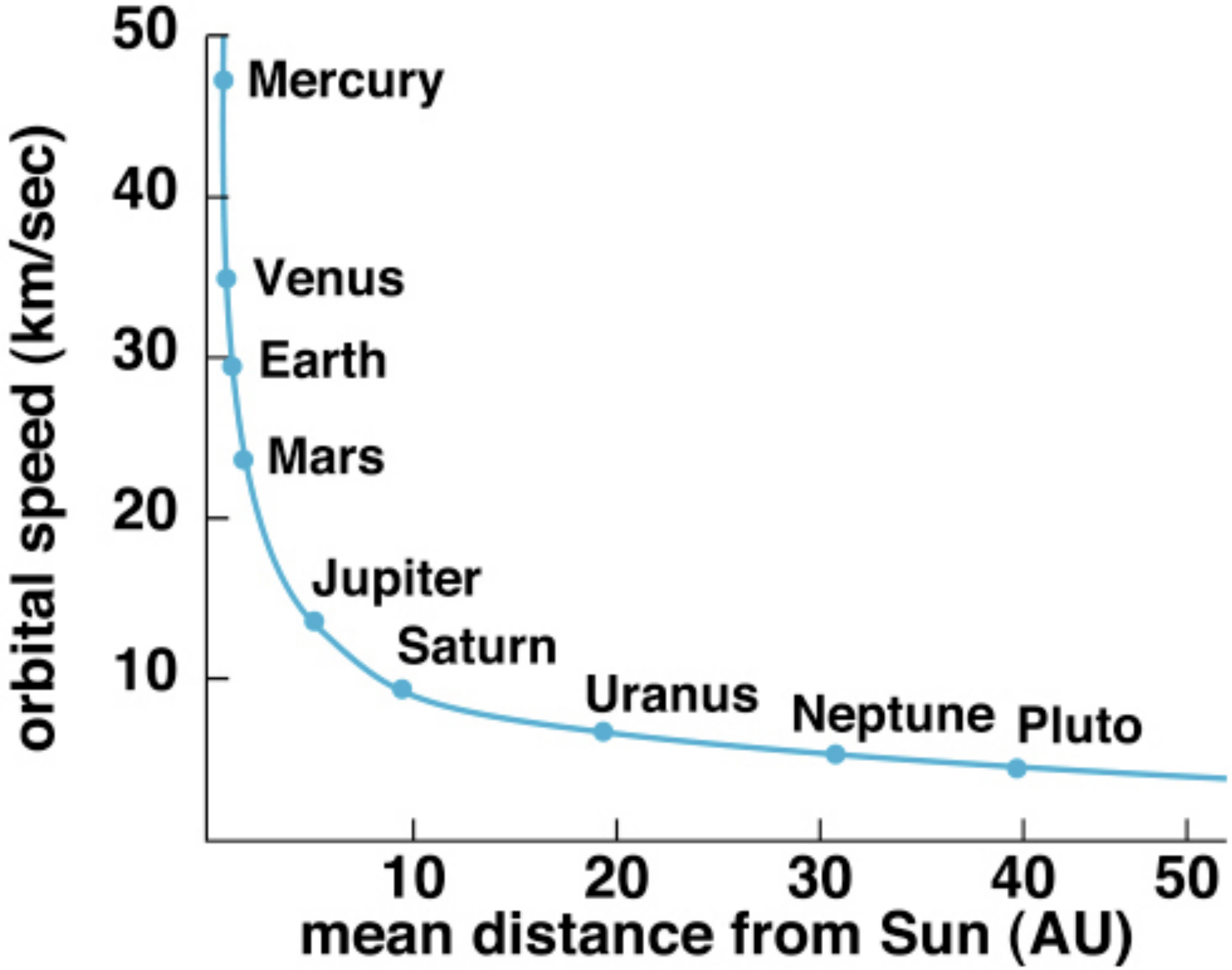


The scope of the known Universe

Homework P3 Hint: Orbital Velocities of Planets

Newton's laws: $GM(r)/r^2 = v^2/r \Rightarrow M(r) = v^2r/G$

$v(r) = \sqrt{GM(r)/r} \Rightarrow v(r) \propto 1/\sqrt{r}$ because the Sun took 99.9% of the mass!



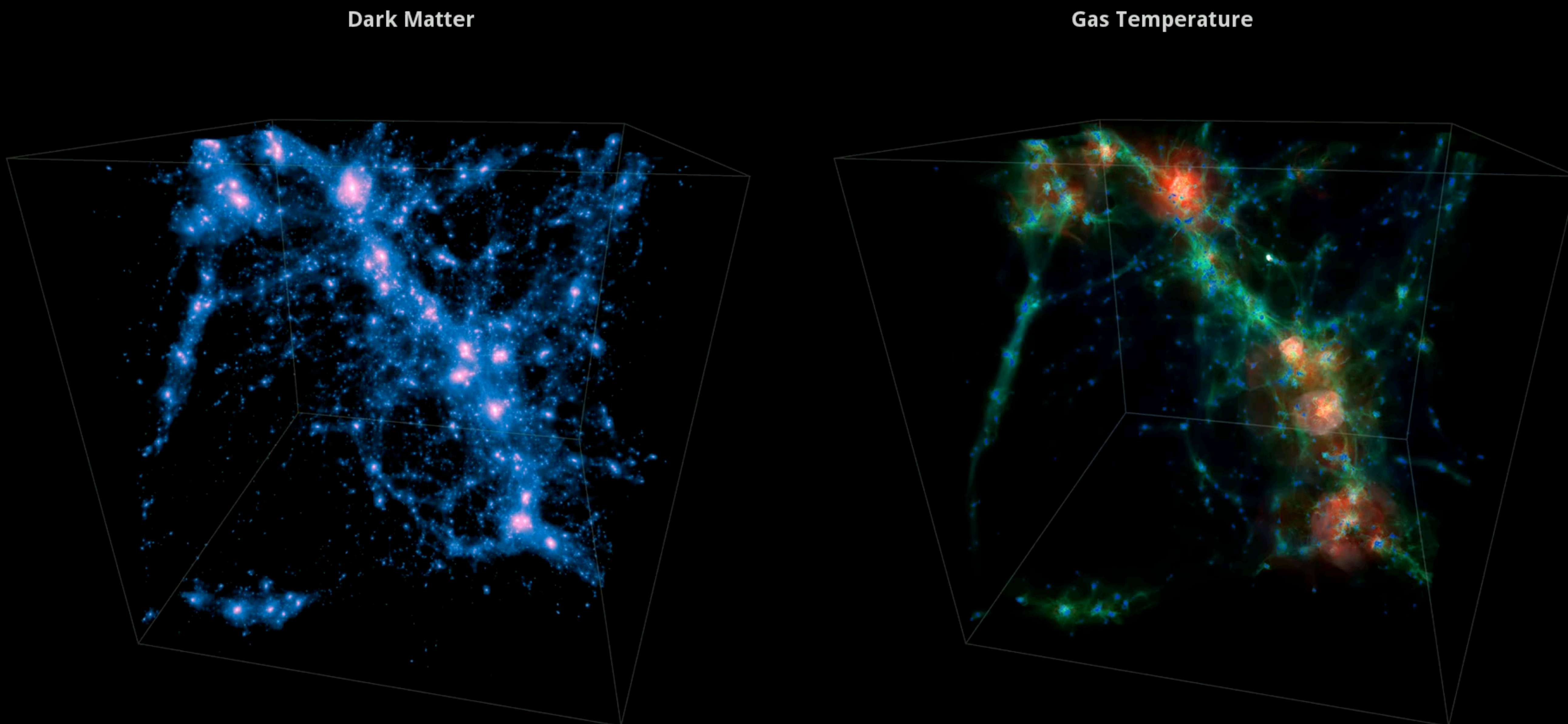
A Universe of Galaxies

- A **galaxy** is a gravitationally bound collection of dust, gas, a million to hundreds of billions of stars, and dark matter.
- A galaxy like the Milky Way contains about 100 billion stars.
- There are hundreds of billions of galaxies in the universe.


JWST

Galaxies evolve over time

Simulation of a Cube 30 Million Light Year Across

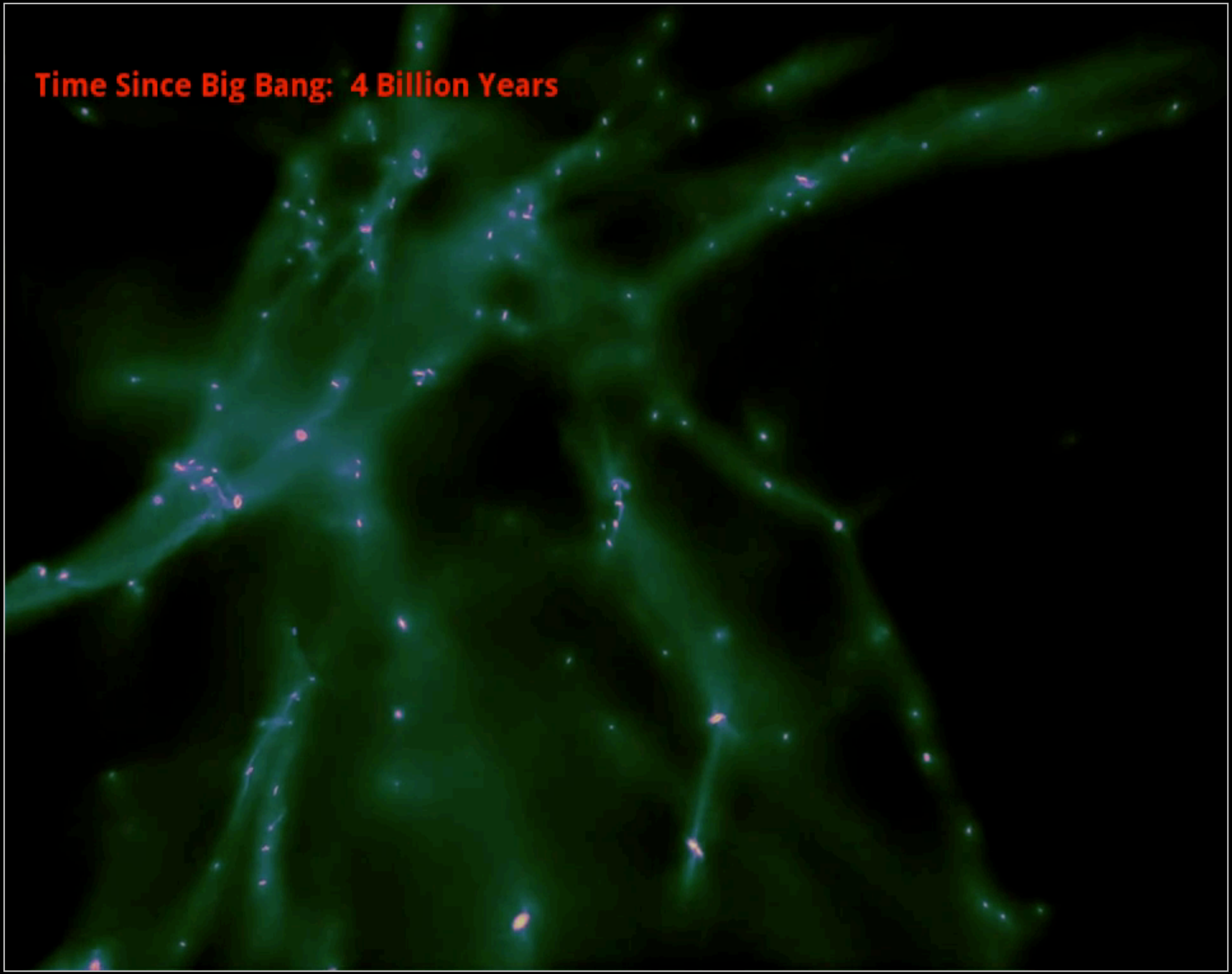


redshift : 1.54
Time since the Big Bang : 4.3 billion years

stellar mass : 27.7 billion solar masses

ILLUSTRIS

Simulation: showing only baryonic components



Galaxy evolution highly depends on environment

Massive Galaxies Today:

Spirals, Ellipticals, Irregulars

Spiral Galaxies

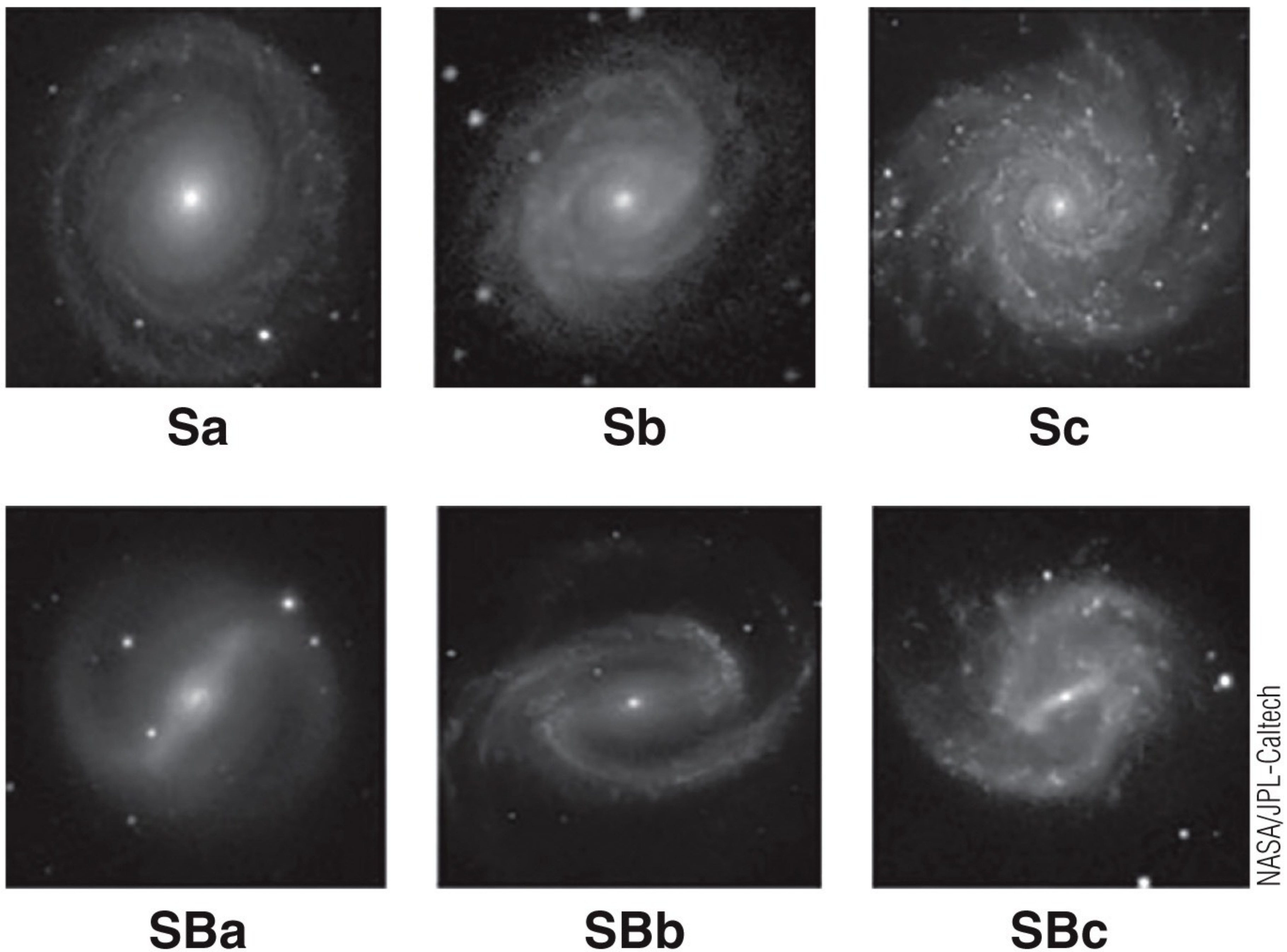
- **Spiral galaxies** have arms that lie in a flat disk and a central bulge that extends above and below the disk.
- There are two types of spirals: **regular** and **barred**.

M101, aka, Pinwheel

Barred Spiral Galaxies: e.g., NGC 1300

Spiral Galaxy Classification: Sa, Sb, Sc & SBa, SBb, SBc

- Spirals are classified by how bright the central bulge is and how tightly wound the arms are.
  - Sa/SBa = **bright** center, **tight** arms
  - Sc/SBc = **dim** center, **open** arms



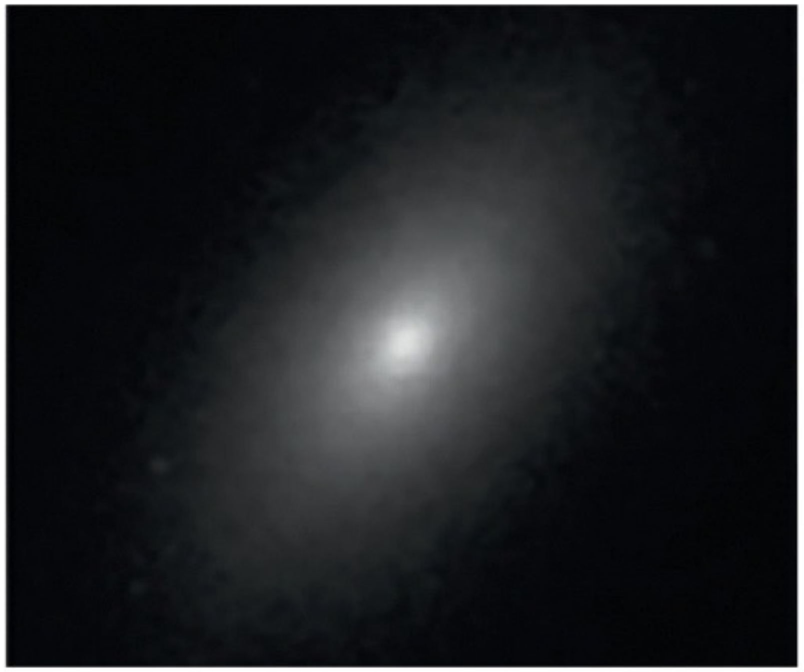
Elliptical Galaxies: e.g., Central Cluster Galaxy in Abell S740

Elliptical Galaxy Classification

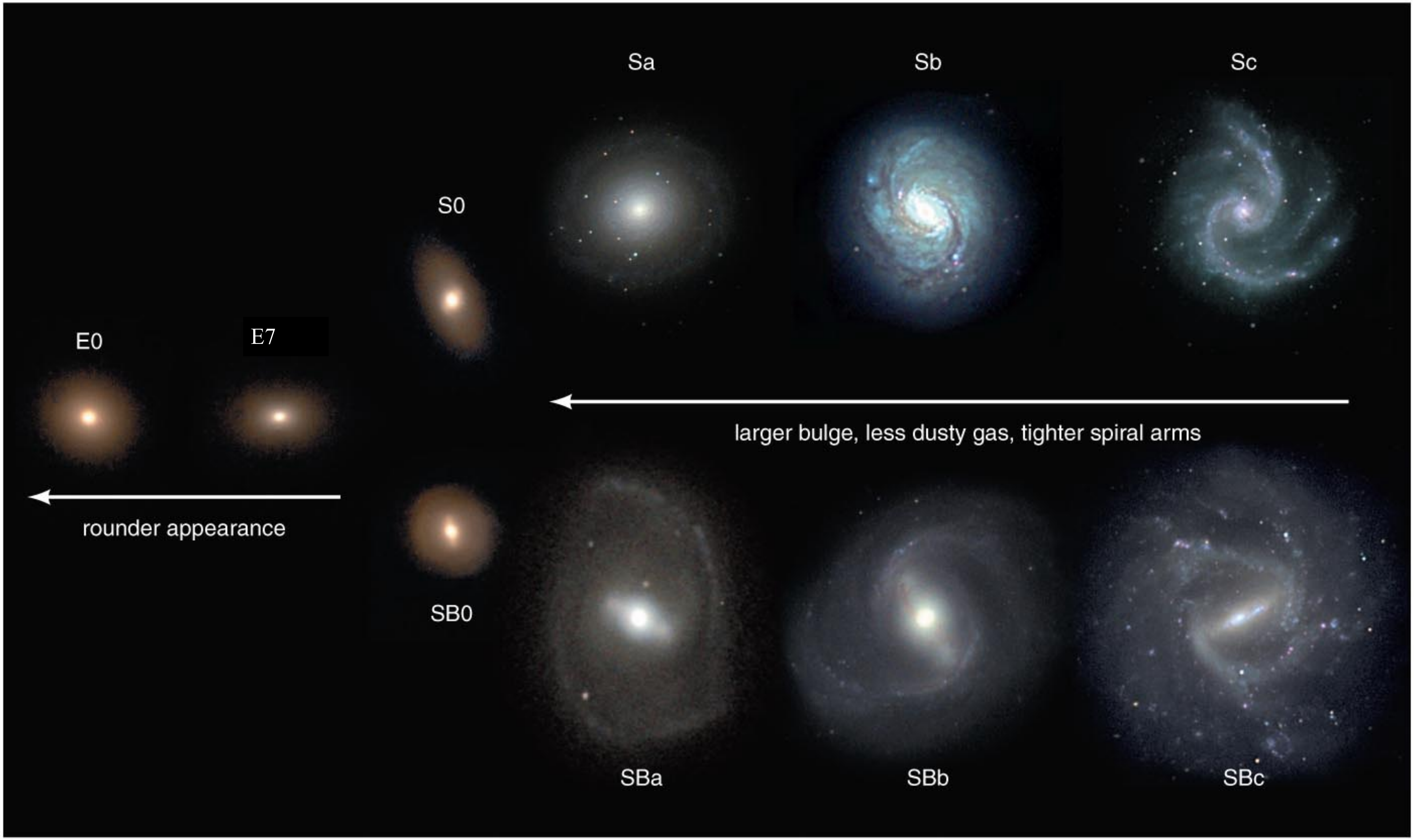
- **Elliptical galaxies** have spherical or ellipsoidal shapes.
- They have subtypes based on roundness.
  - An E0 galaxy is nearly spherical.
  - An E7 galaxy appears flattened.
- Elliptical galaxies appear smooth.
  - They have very little dust.
  - They have an old stellar population.

E0

E3



E5



Spheroid Dominates

Hubble's galaxy classes

Disk Dominates

An important caveat: **geometric** effects on observed morphology

Two spiral galaxies: why they look so different?

Inclination Angle Changes the Appearance of Disk Galaxies

$$\cos i = b/a$$

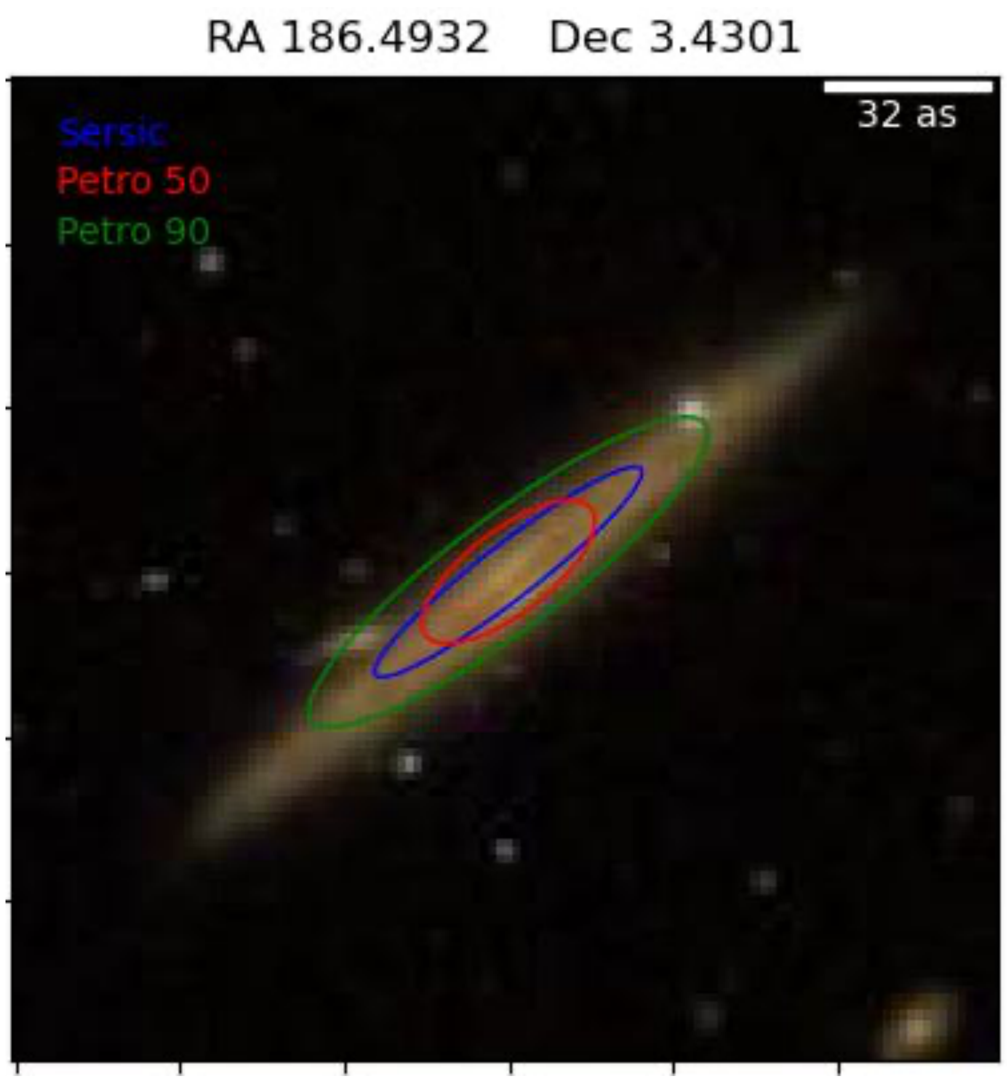
- where b and a are the semi-minor and semi-major axis of the ellipse, and i is the inclination angle

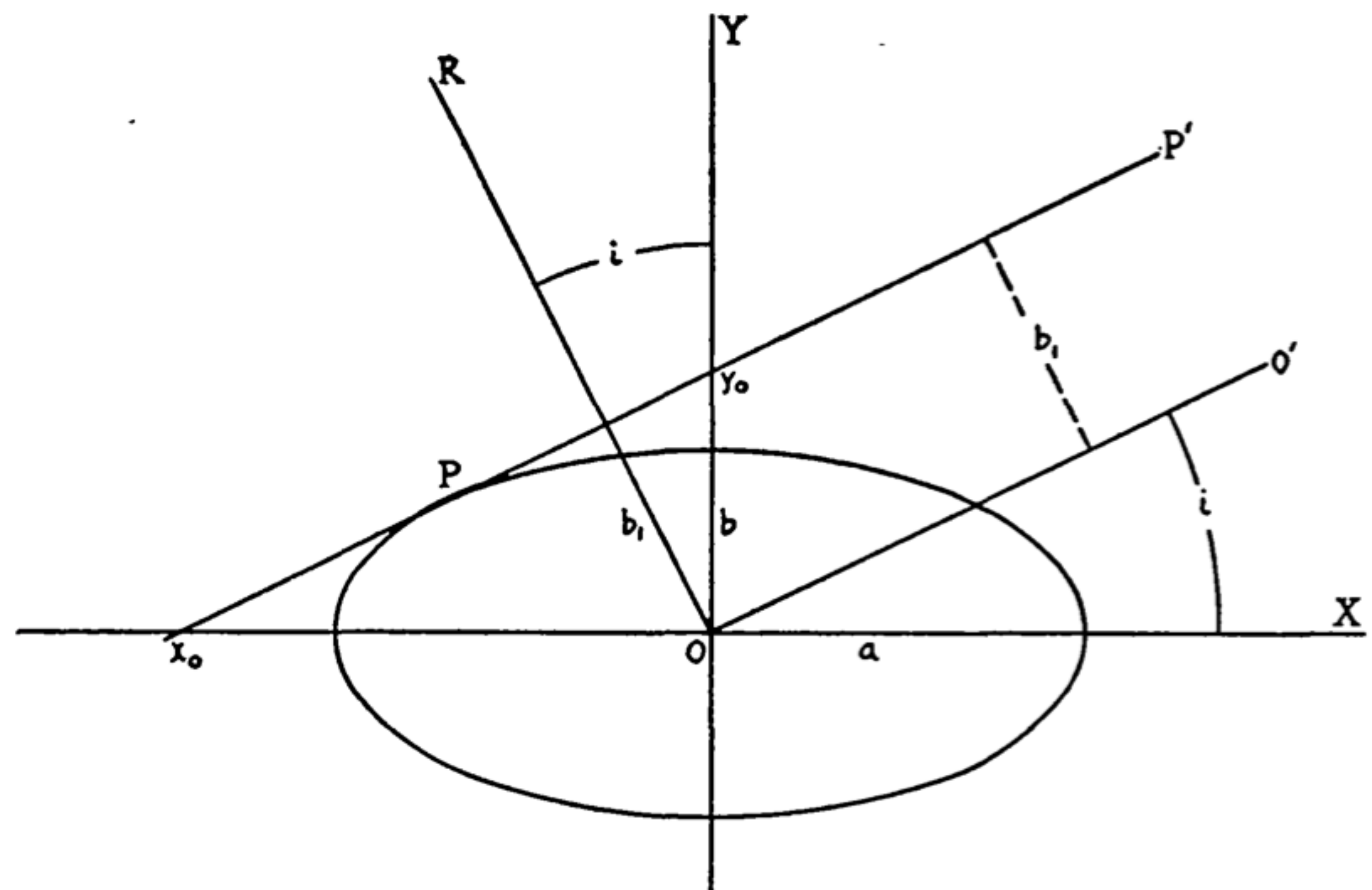
Estimate inclination angle from b/a ratio

Oblate Ellipsoid Model of Disk Galaxies (Hubble 1926)

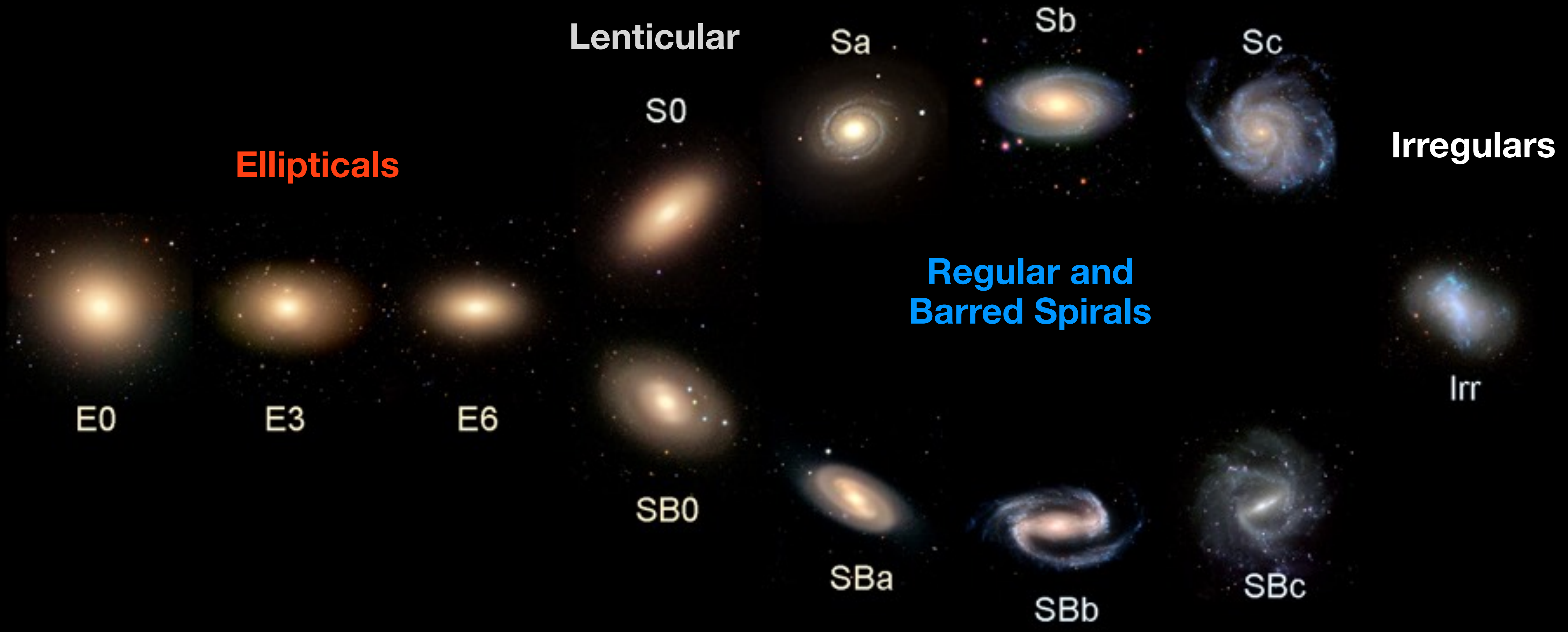
$$\cos^2 i = \frac{(b/a)^2 - q^2}{1 - q^2} .$$

- where q is the intrinsic thickness, the b/a ratio of the disk when viewed edge-on





Hubble's Tuning Fork



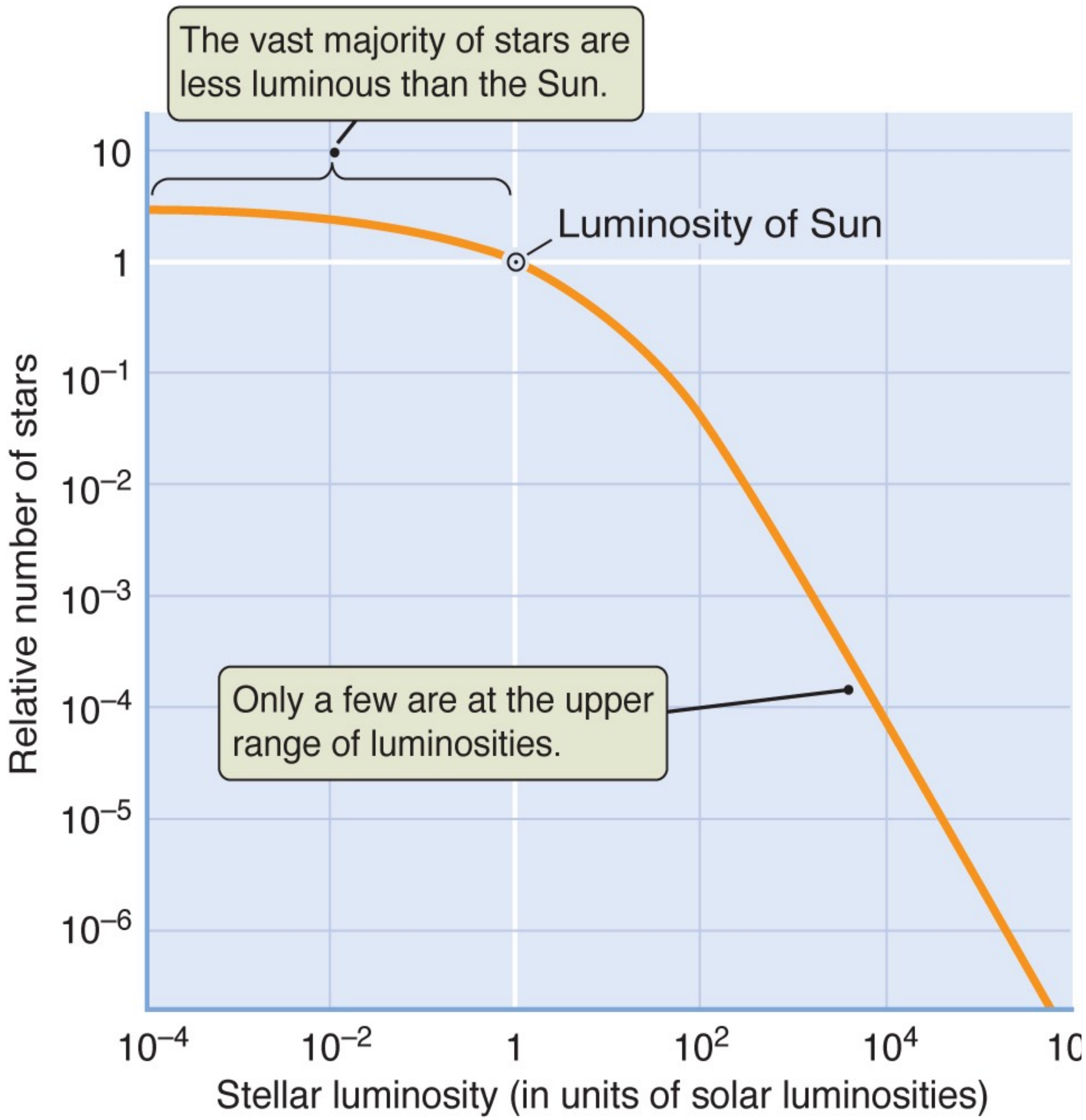
Massive Irregular Galaxies

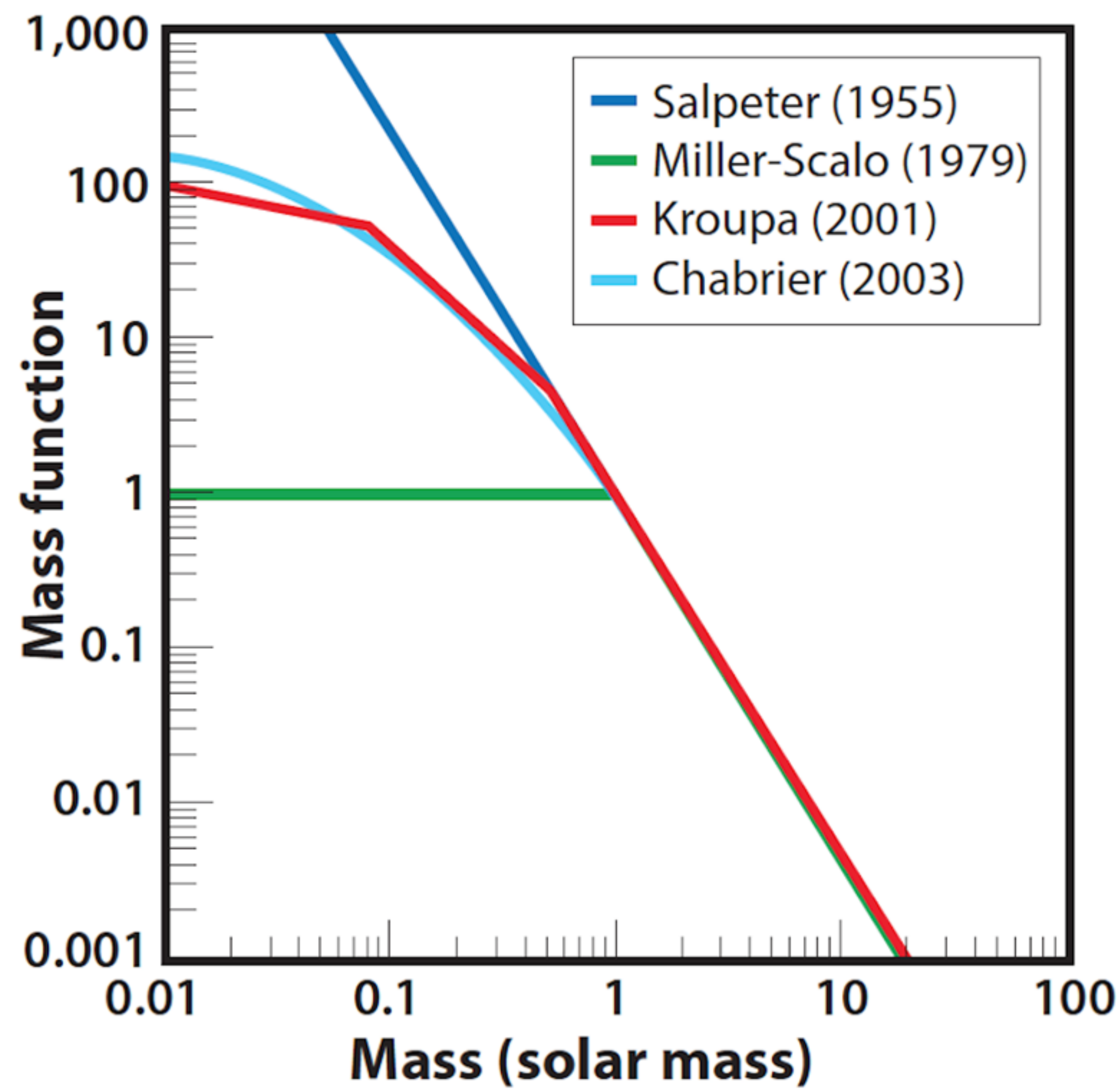
- **Massive irregular galaxies** have no defined shape.
  - They are likely the product of a gravitational interaction between two galaxies (**mergers**).
  - Some are forming stars at such a high rate that they are classified as **starburst galaxies**.

Irregular and Dwarf Galaxies

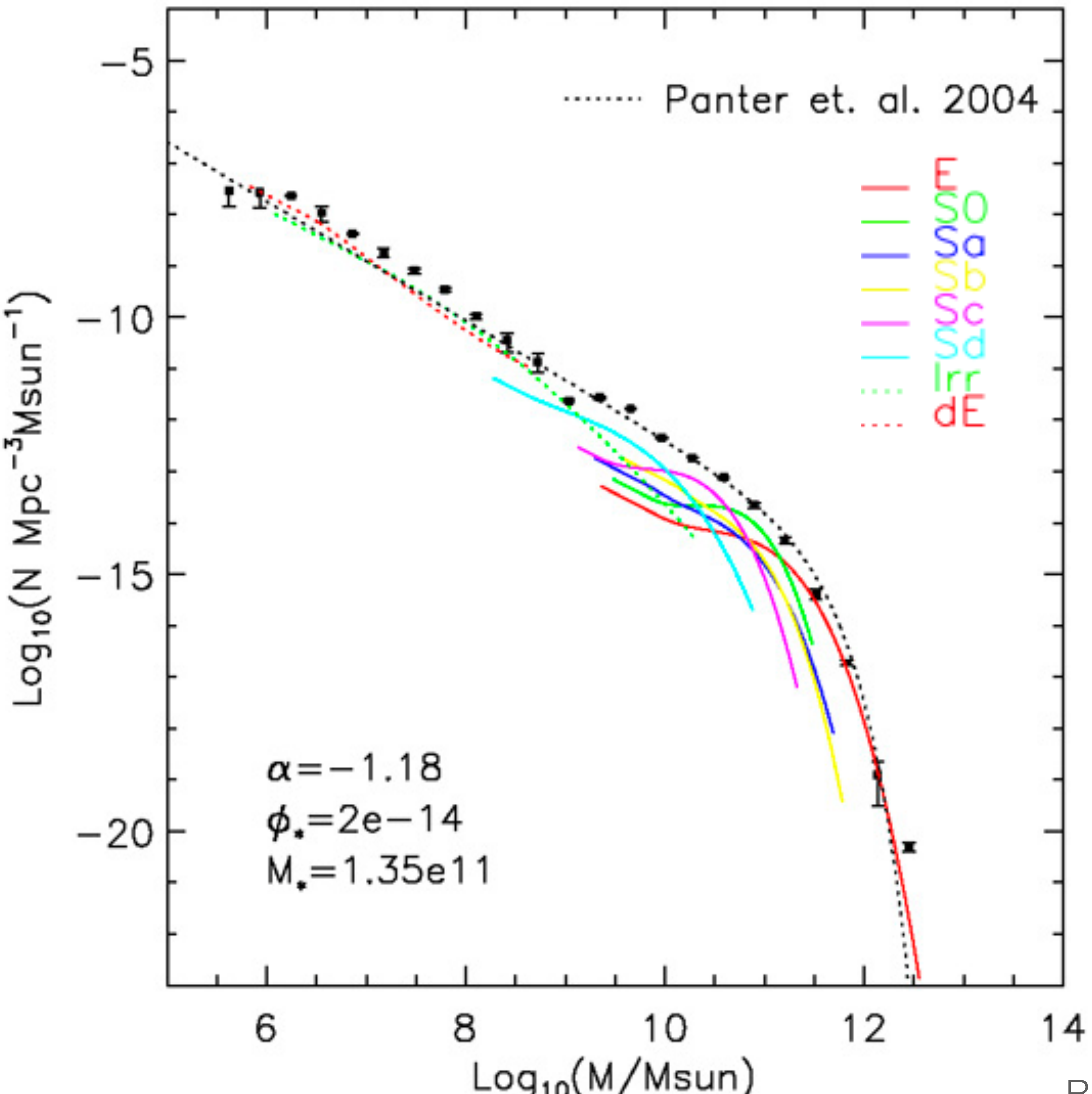
Chap 3-4: The Mass (Distribution) Function of Stars

- *Initial Mass Function* shows the distribution of stellar masses at birth





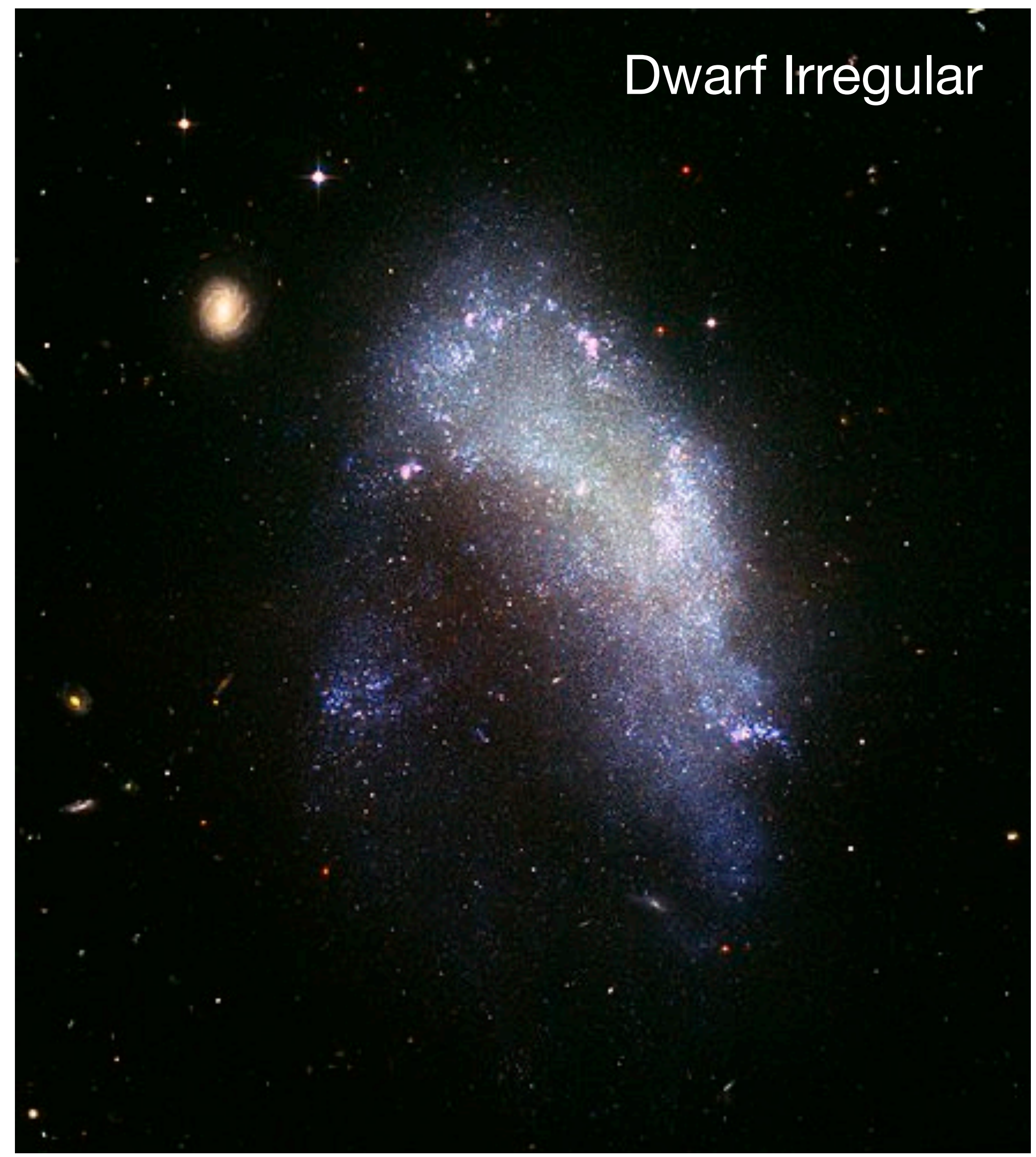
The Mass (Distribution) Function of Galaxies Today



Read & Trentham 2005

Dwarf Galaxies vs. Massive Galaxies

- **Dwarf galaxies** have less than **10% the stellar mass** of the **Milky Way. Their stellar masses range between 10^2 and 10^{10} solar masses.**
- The low surface brightness of dwarf galaxies make them difficult to observe, so we are only detecting the **nearest** dwarfs.



Dwarf Galaxies: A Diverse Population

Bright dwarfs:

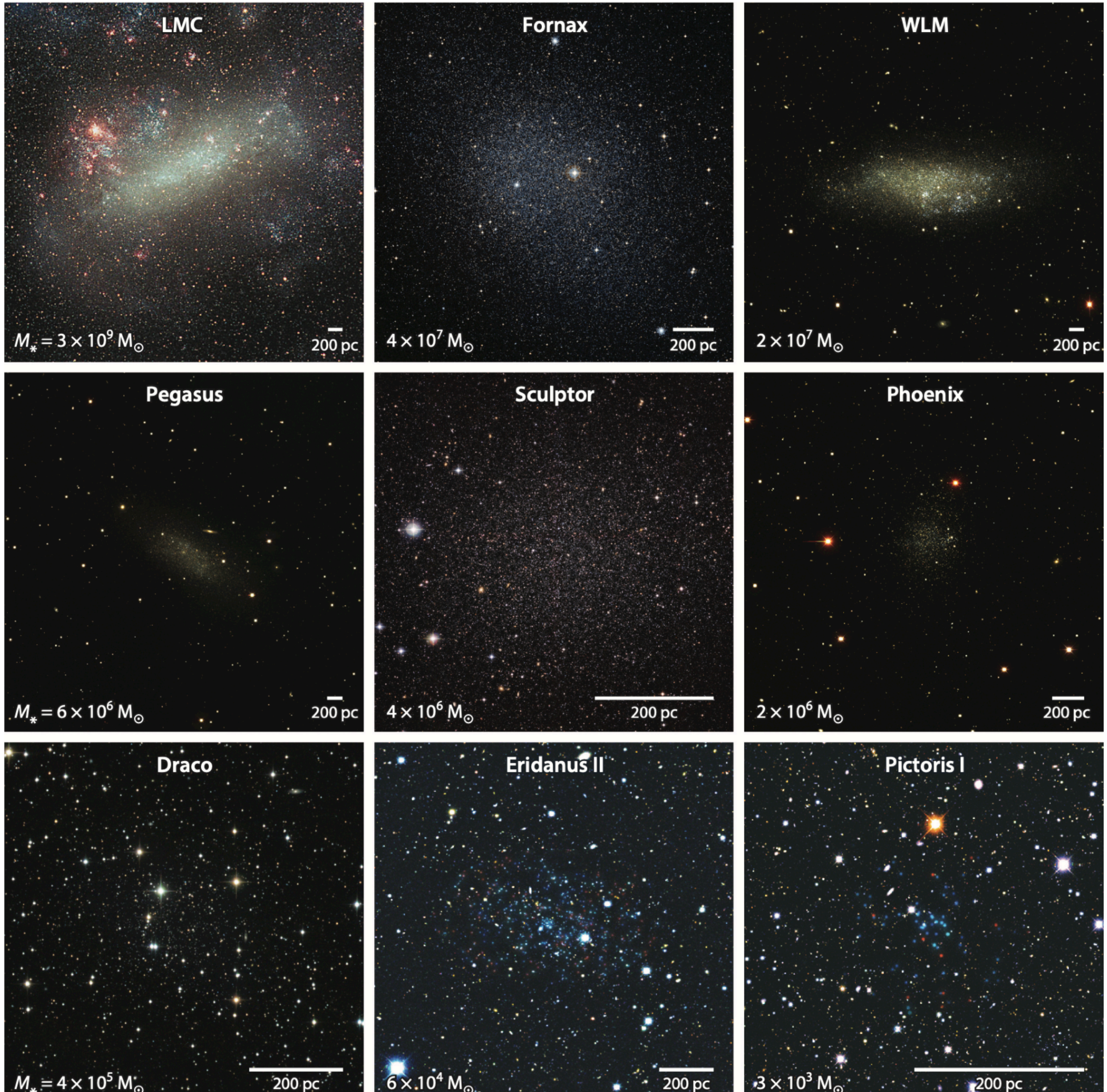
$M_\star \approx 10^8\ \mathrm{M}_\odot$,
$M_{\rm vir} \approx 10^{11}\ \mathrm{M}_\odot$,
$M_\star / M_{\rm vir} \approx 10^{-3}$

Classical dwarfs:

$M_\star \approx 10^6\ \mathrm{M}_\odot$,
$M_{\rm vir} \approx 10^{10}\ \mathrm{M}_\odot$,
$M_\star / M_{\rm vir} \approx 10^{-4}$

Ultra-faint dwarfs:

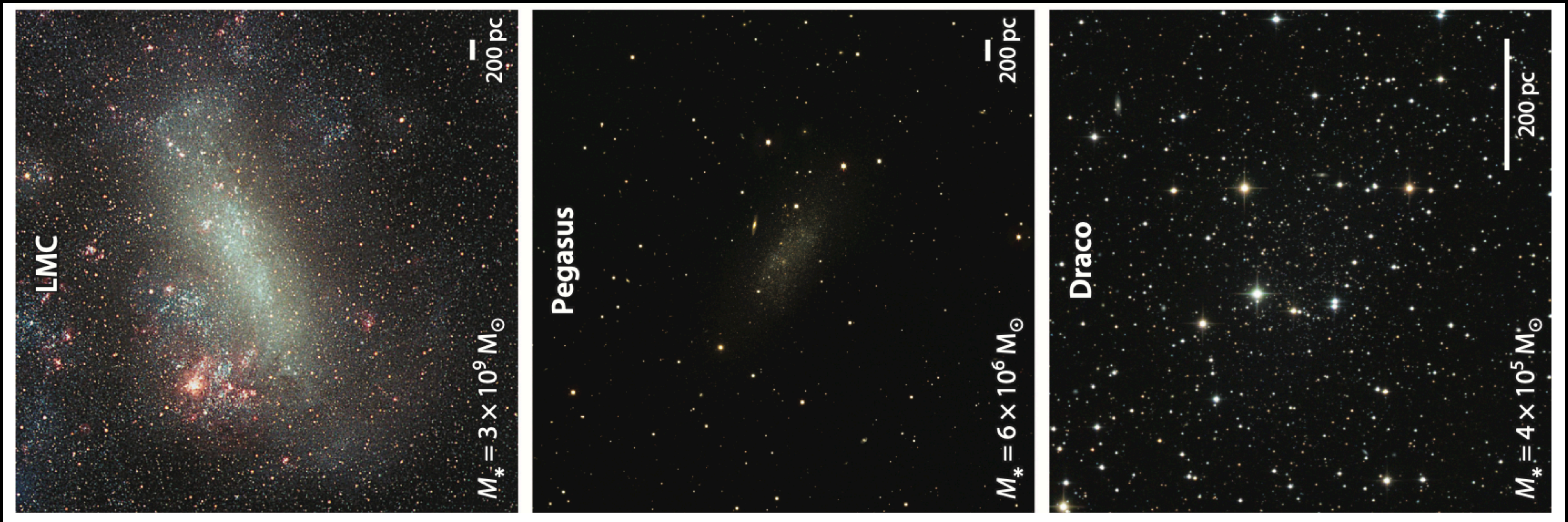
$M_\star \approx 10^4\ \mathrm{M}_\odot$,
$M_{\rm vir} \approx 10^{9}\ \mathrm{M}_\odot$,
$M_\star / M_{\rm vir} \approx 10^{-5}$



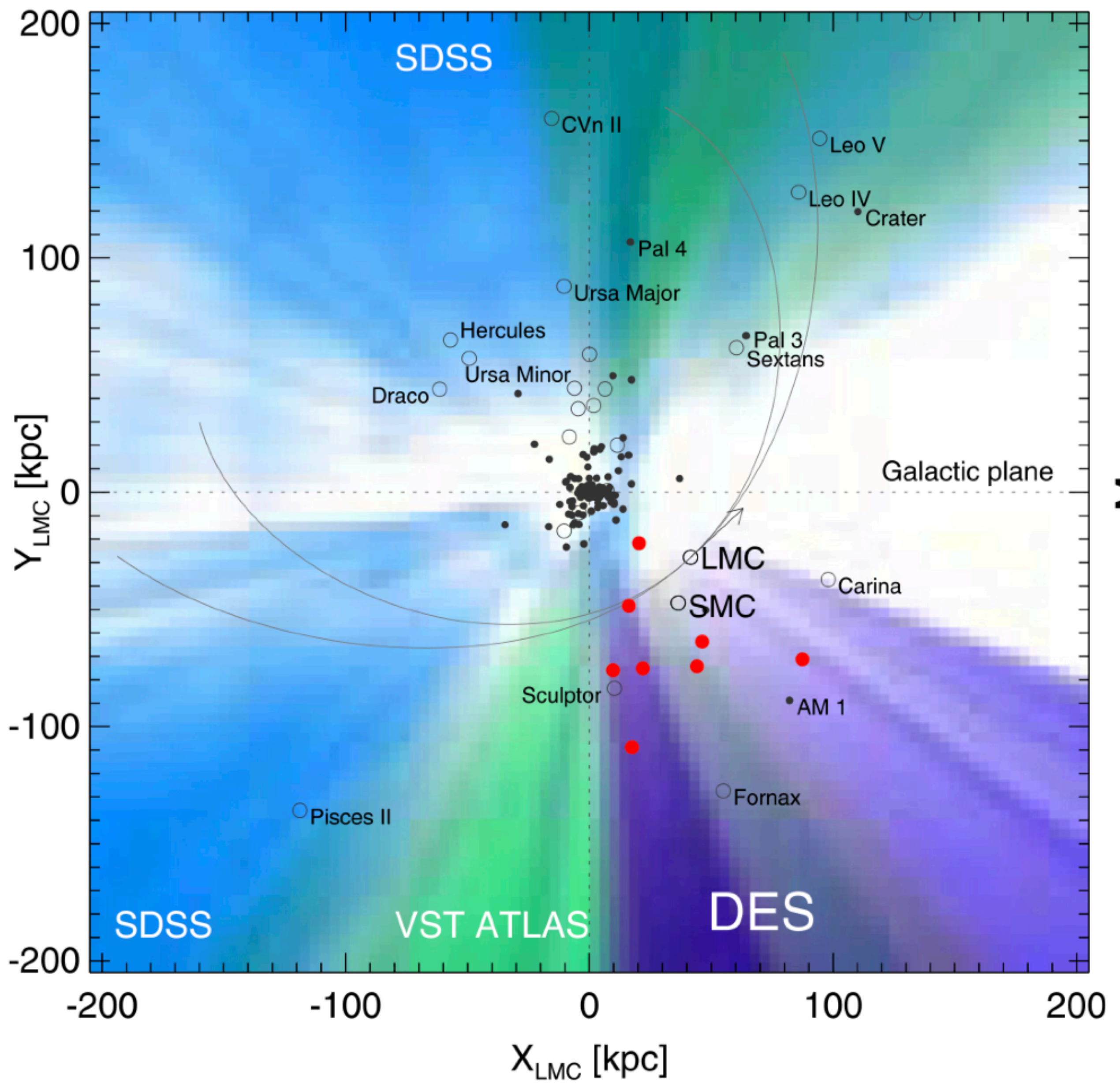
Bullock & Boylan-Kolchin 2017

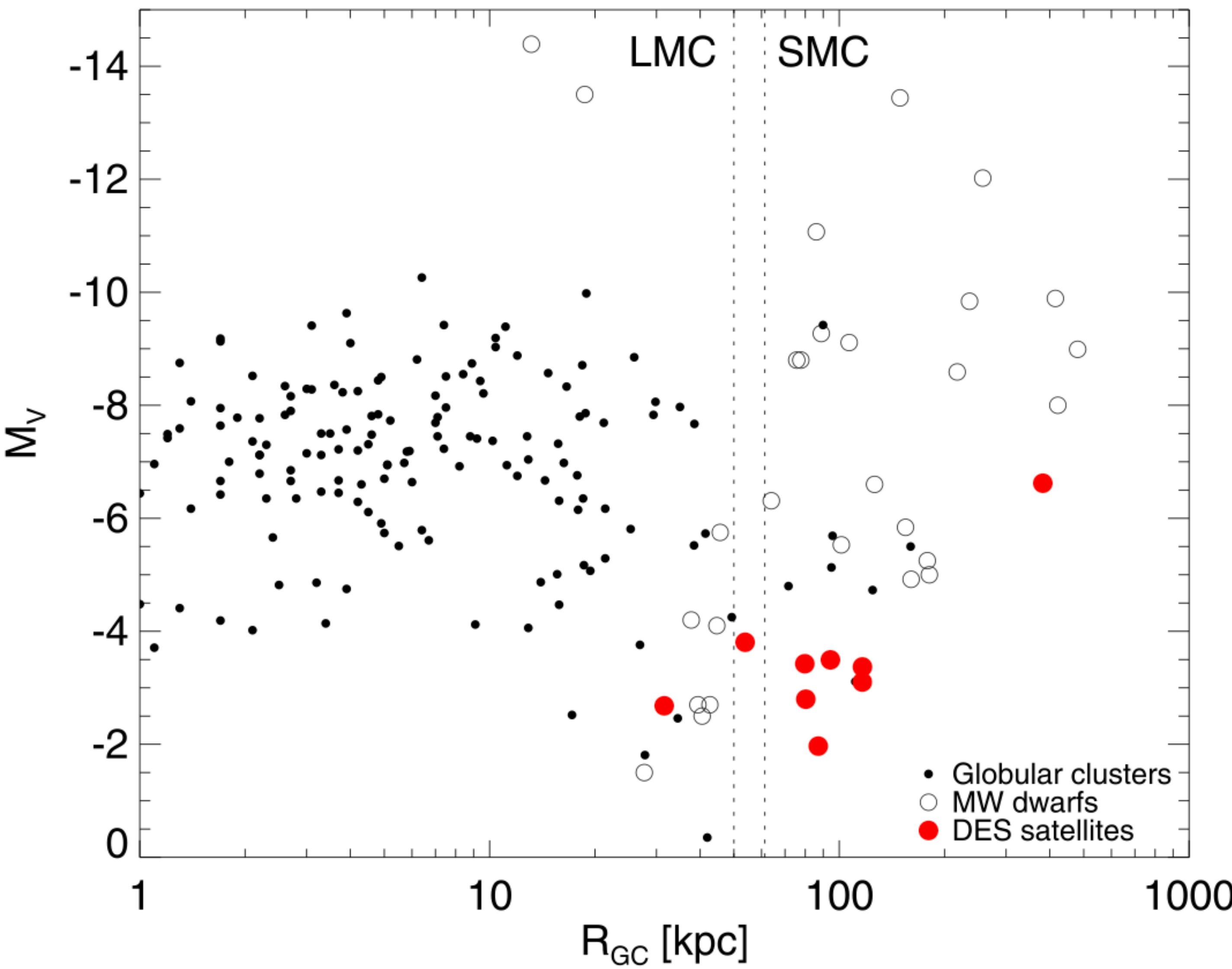
ADOPTED DWARF GALAXY NAMING CONVENTIONS

Bright Dwarfs: $M_\star \approx 10^{7-9}\ \mathrm{M}_\odot$
– the faint galaxy completeness limit for field galaxy surveys
Classical Dwarfs: $M_\star \approx 10^{5-7}\mathrm{M}_\odot$
– the faintest galaxies known prior to SDSS
Ultra-faint Dwarfs: $M_\star \approx 10^{2-5}\mathrm{M}_\odot$
– detected within limited volumes around M31 and the Milky Way



The Distribution of Dwarf Galaxies around the Milky Way

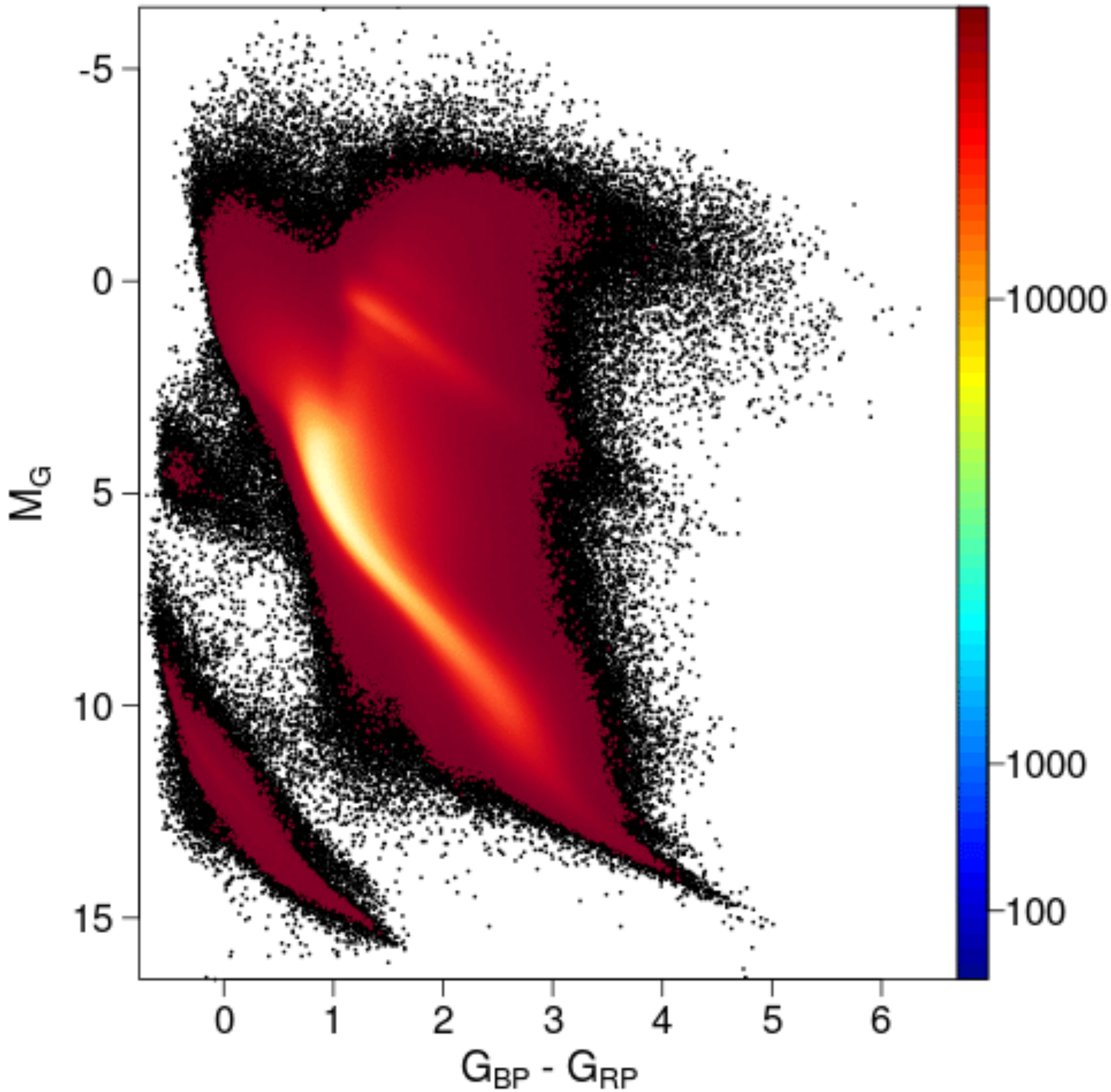




Koposov et al. 2015

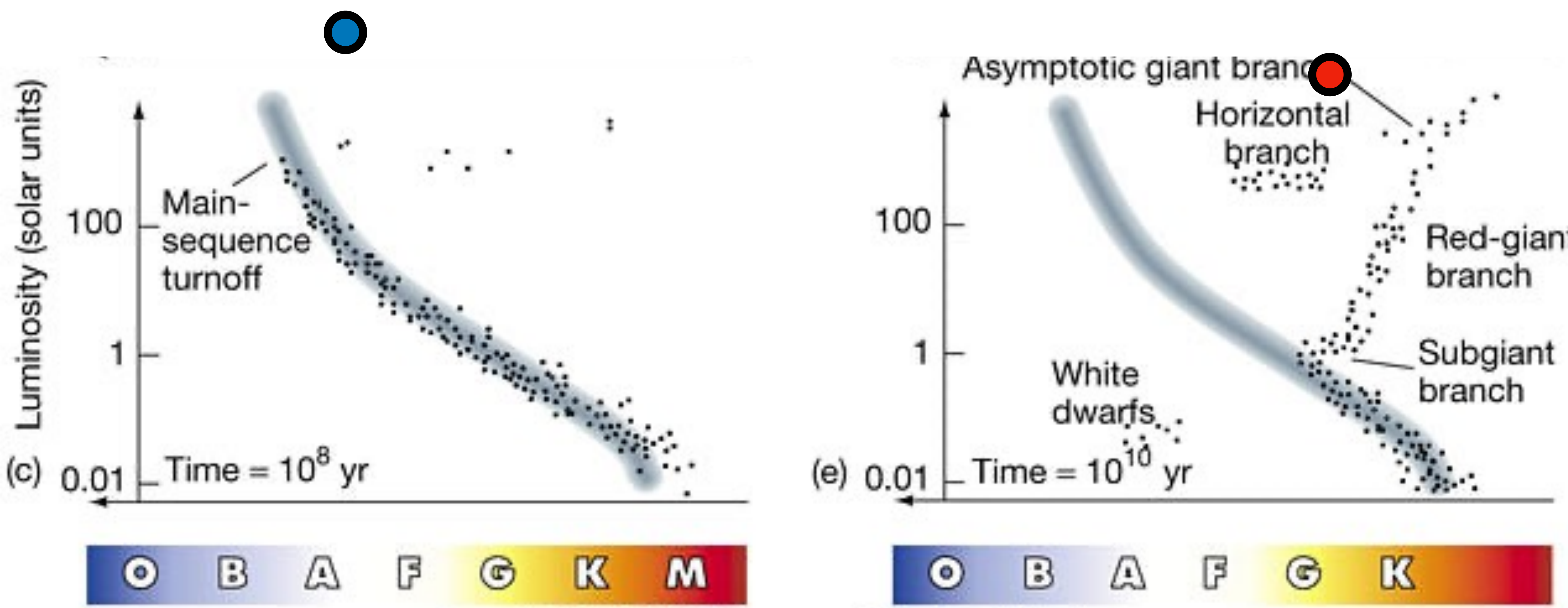
The HR Diagram of Galaxies

HR Diagram is a Color-Magnitude Diagram of Stars



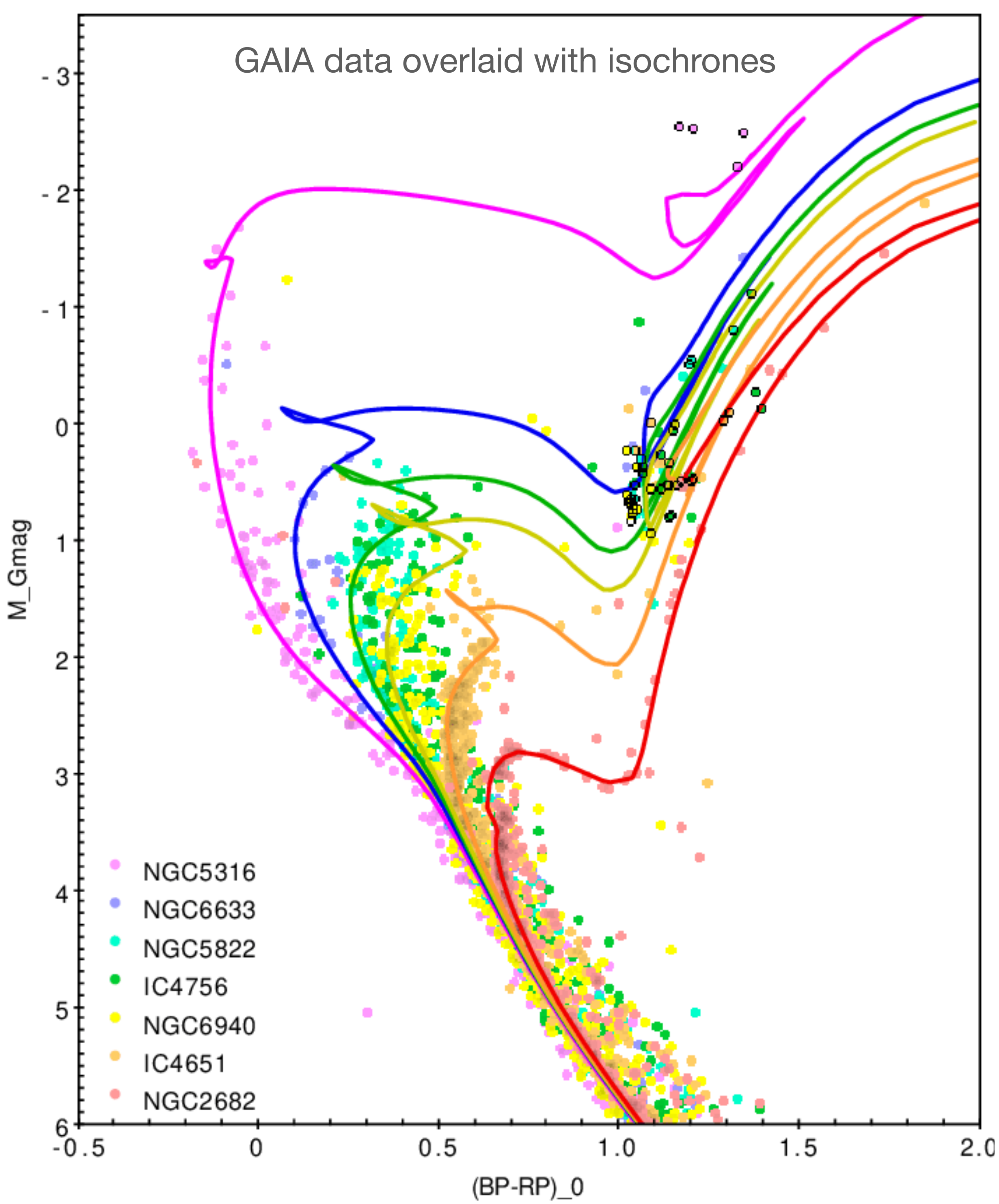
Integrated color and luminosity of simple stellar populations

- Because individual stars are usually unresolved in galaxies, we can only measure the **integrated color** and the **total luminosity** from billions of stars in the same galaxy.
- We can illustrate this process with the HR diagram of star clusters, which represent **simple stellar populations**.
- If you sum up all of the stars in the two clusters below, what would be the resulting **integrated color** and **luminosity**?

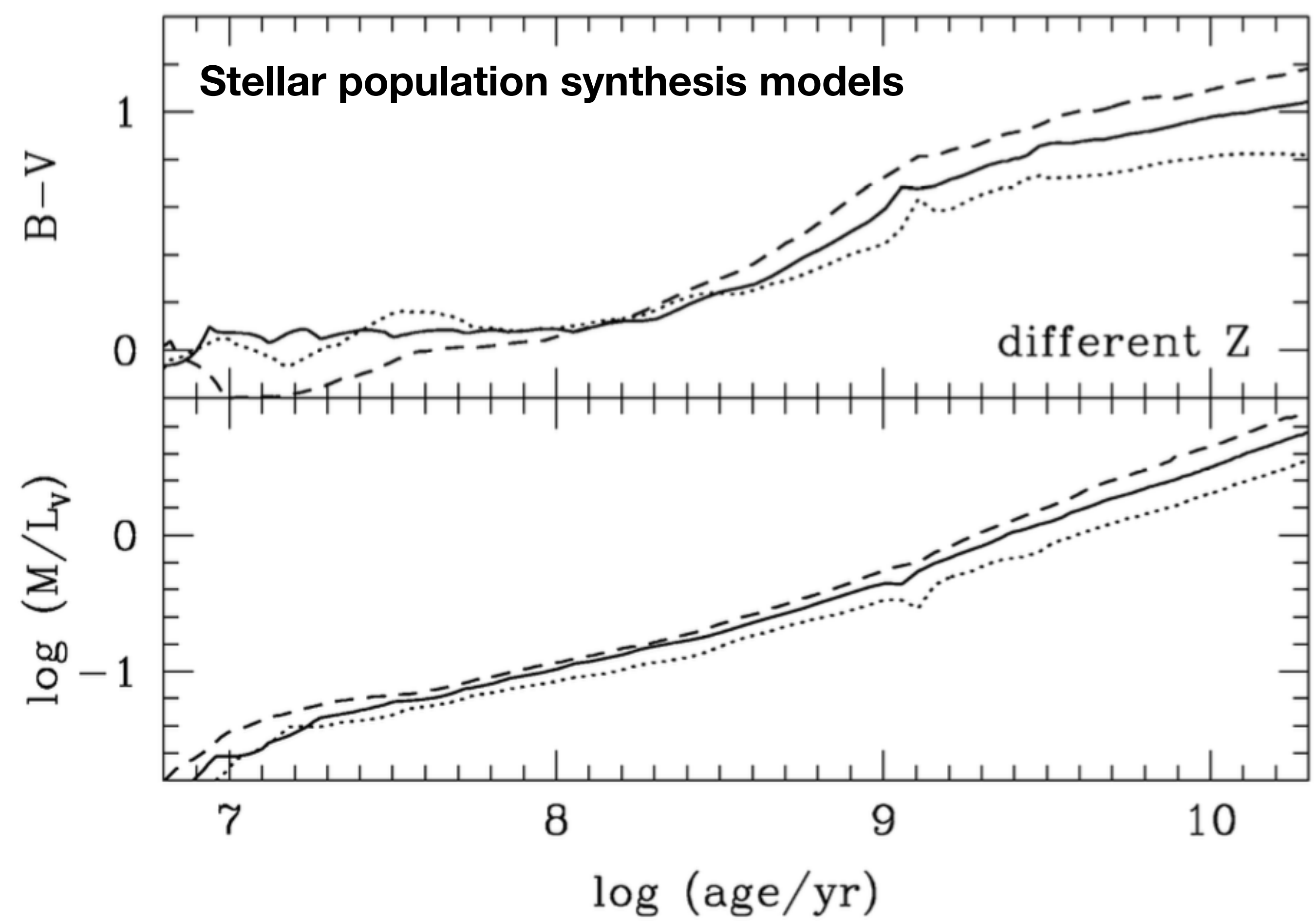


As a stellar population ages, it becomes redder and fainter

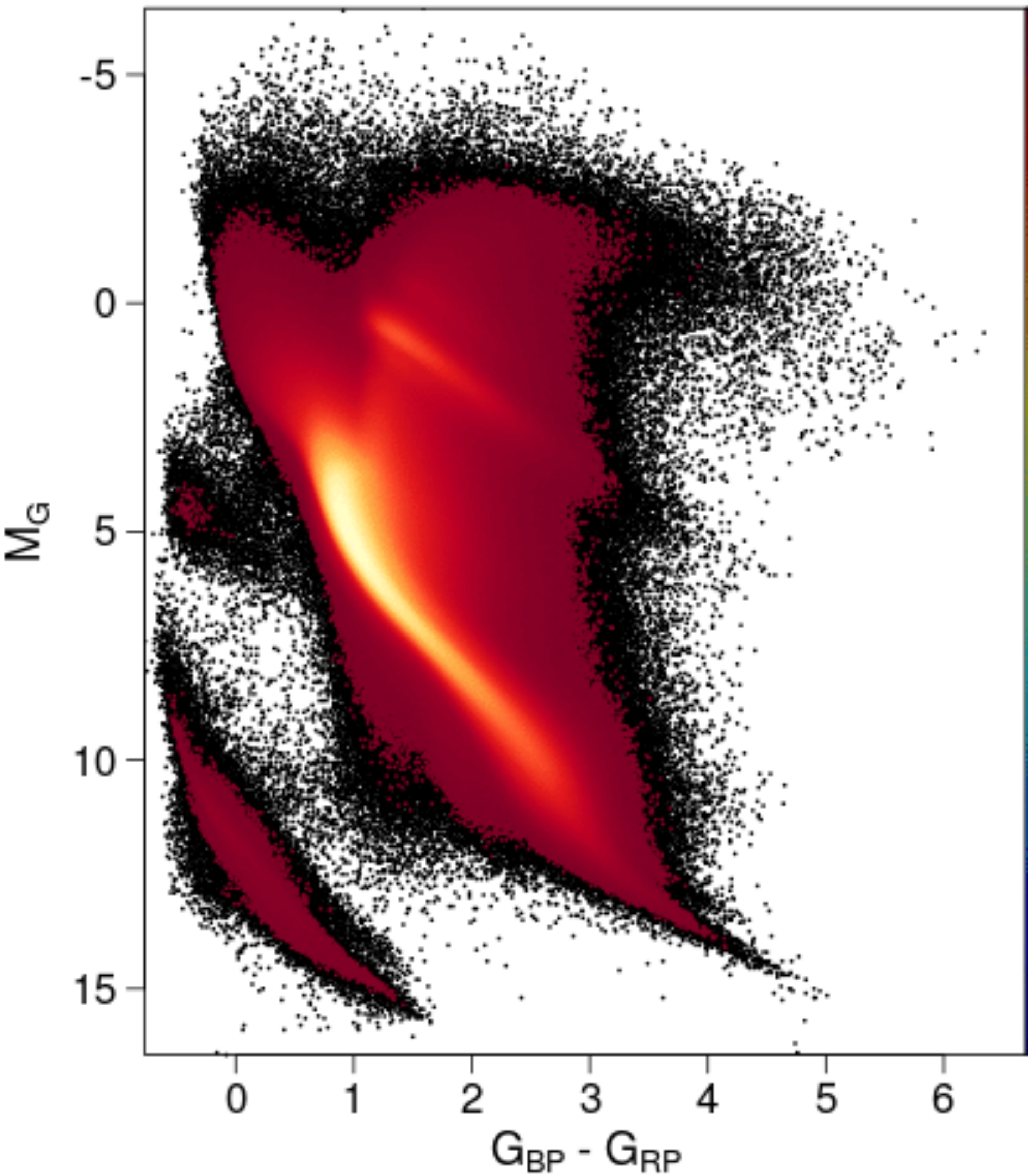
HR diagram of clusters covering a range of ages

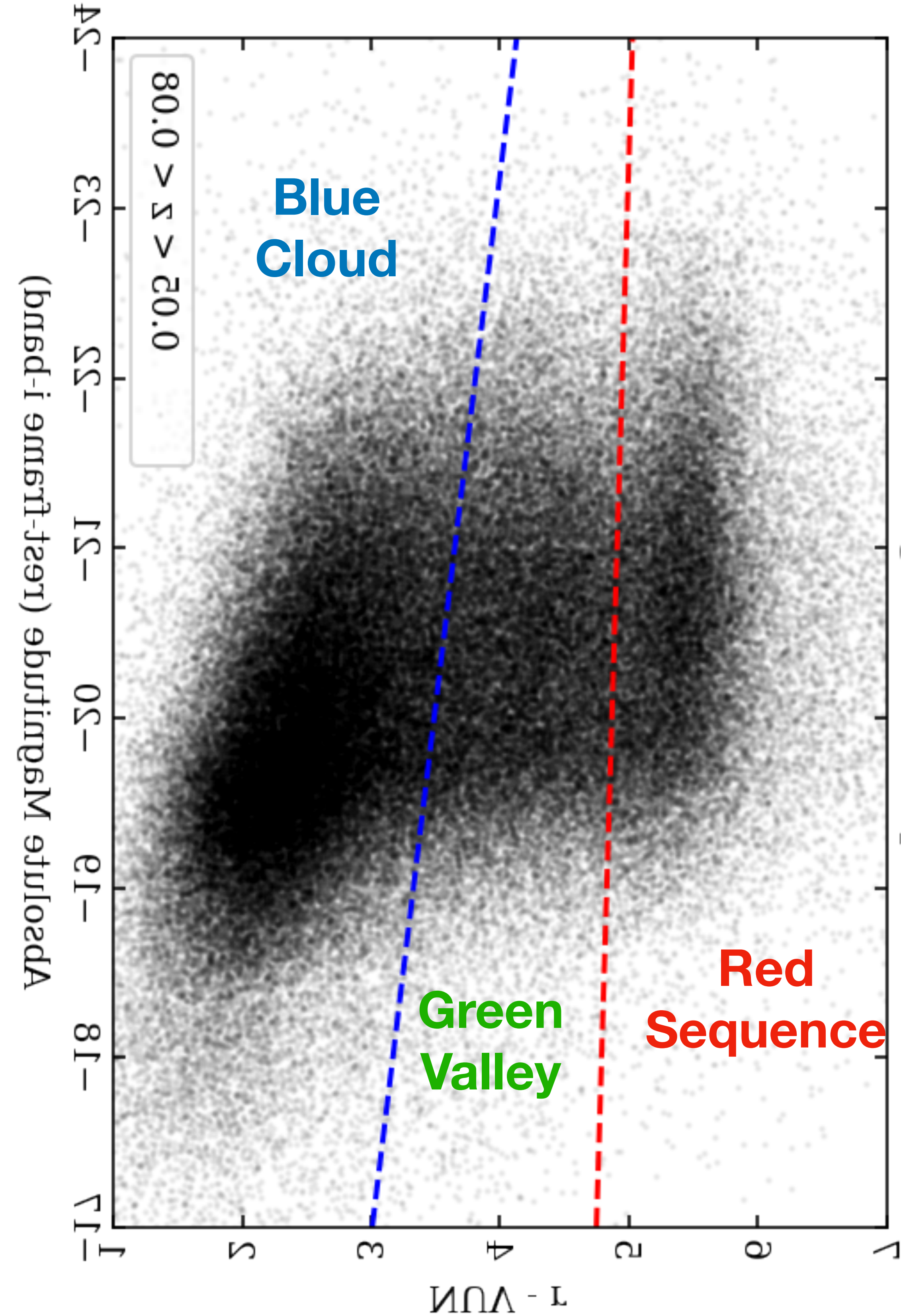


- Stellar population synthesis models follow the **isochrone evolution** of stellar populations and predict the **integrated color** and the **total luminosity** as a function of age.
- The **mass-to-light ratio (M/L)** increases because luminosity decreases faster than mass loss.

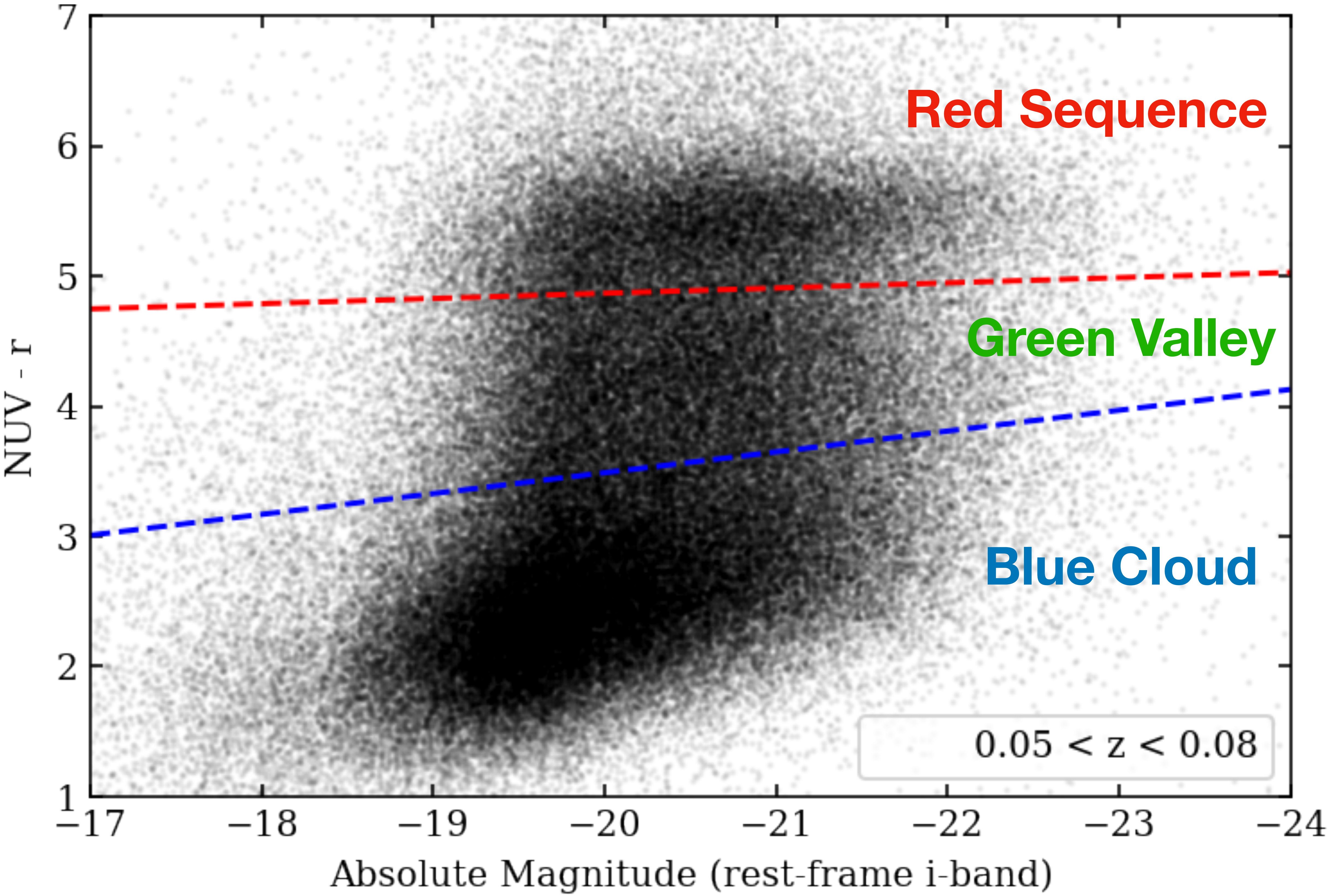


HR Diagram of Stars vs. CM Diagram of Galaxies

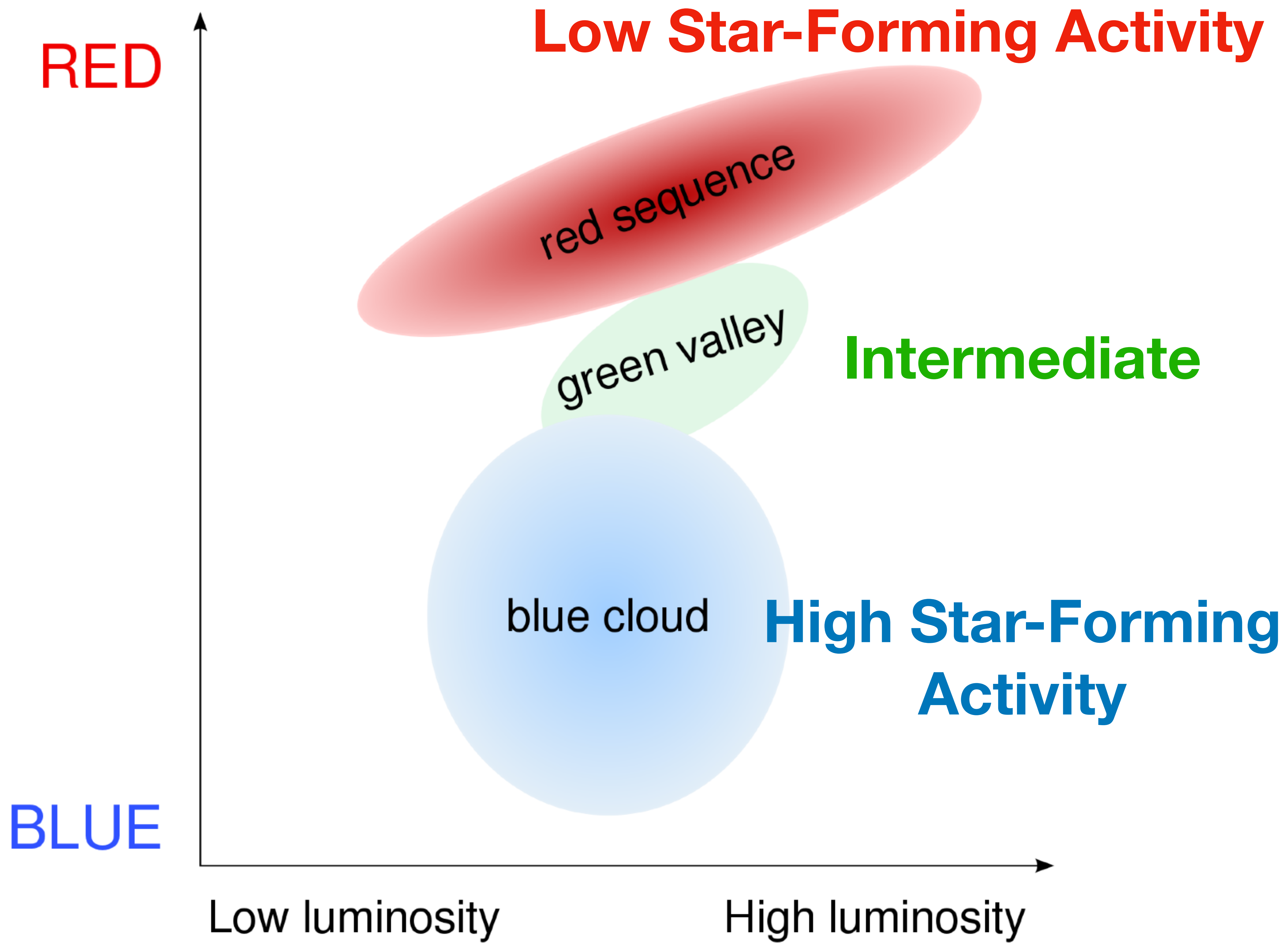




Color-Magnitude Diagram of Galaxies



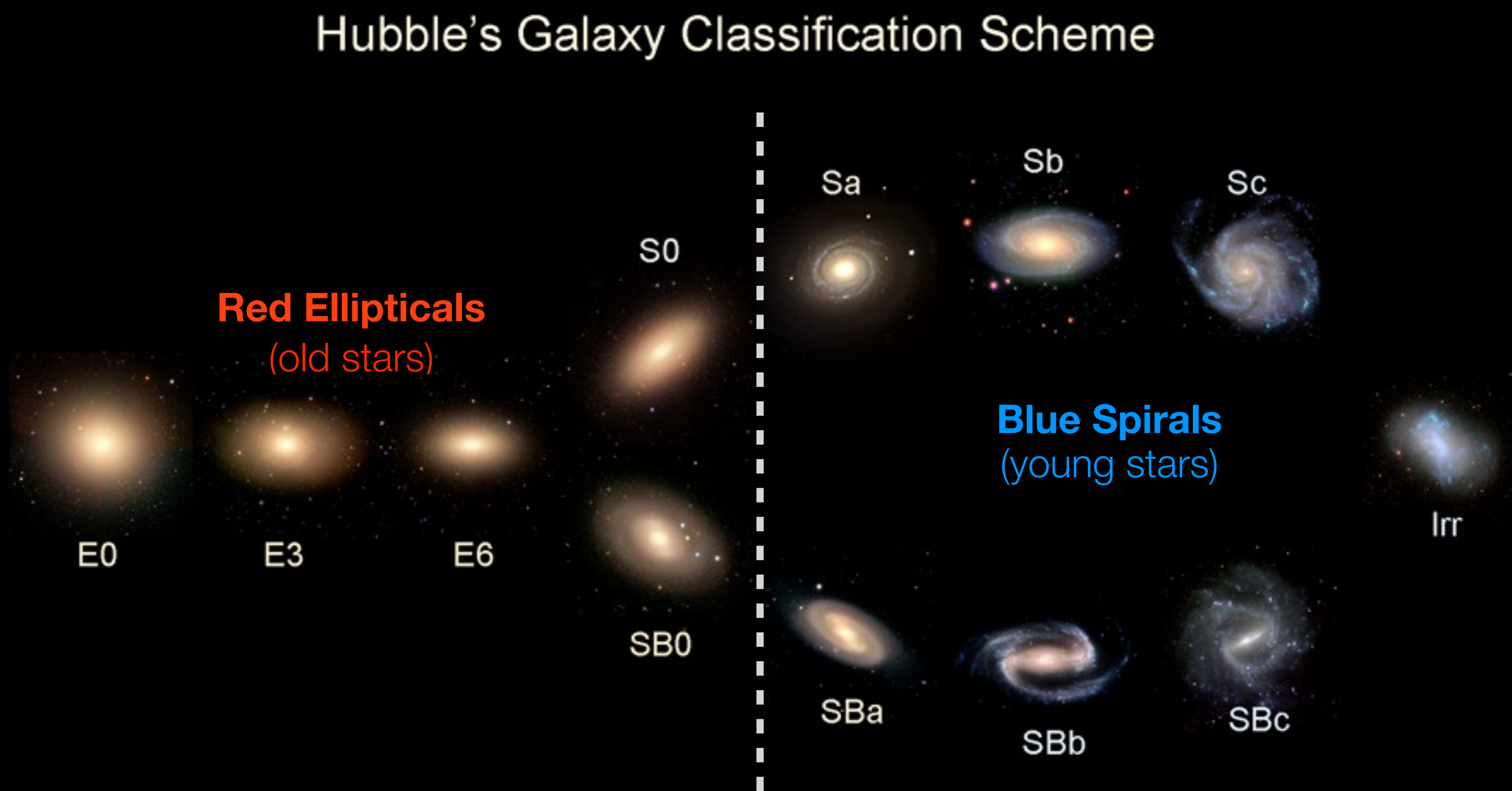
Color-Magnitude Diagram of Galaxies



Integrated Color Naturally Separates Spirals and Ellipticals

http://cosmo.nyu.edu/hogg/aas205/

Galaxies are either blue spirals or red ellipticals



Galaxies in the Current Universe

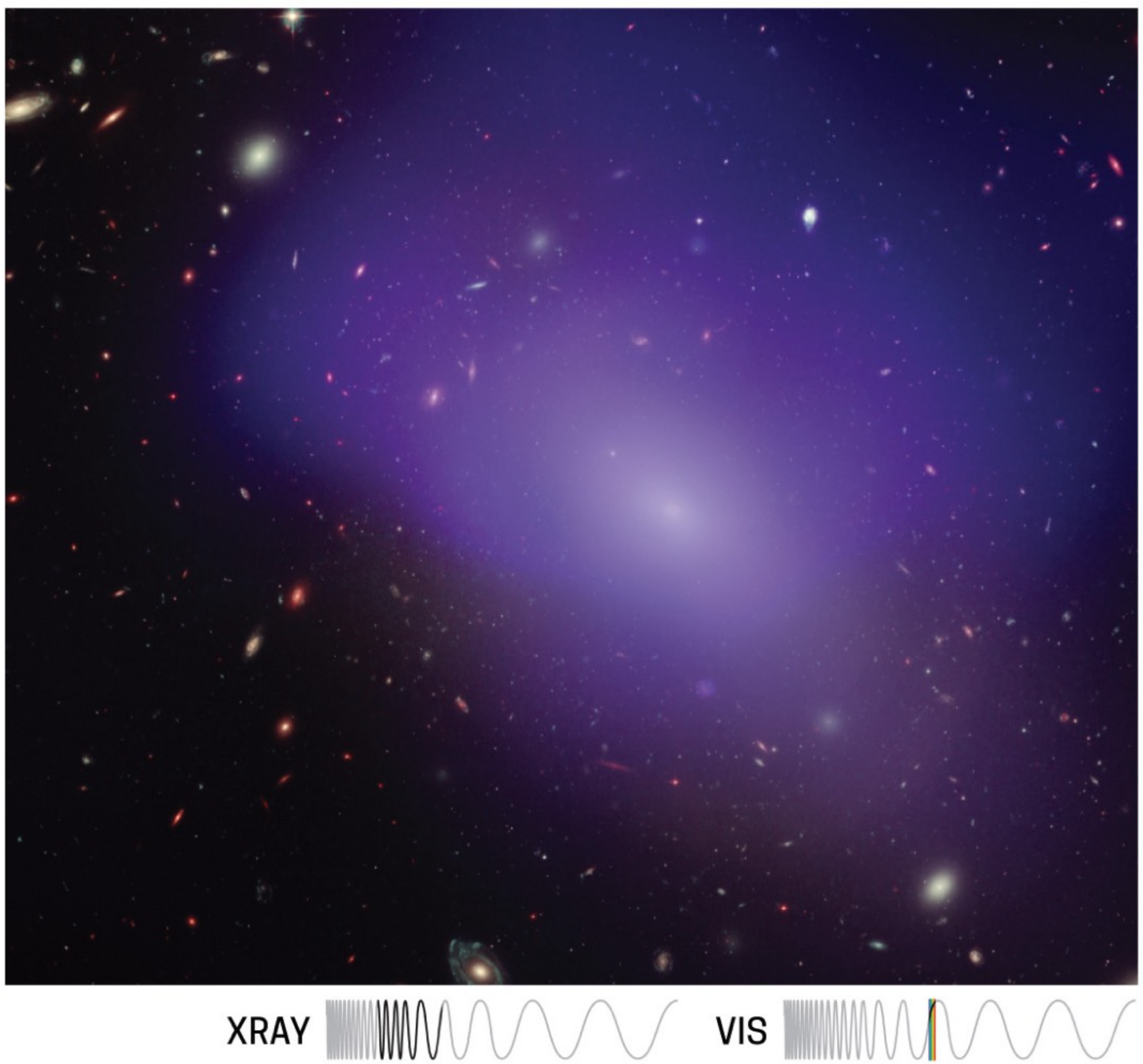
Spiral Galaxies: Ongoing Star Formation in Spiral Arms

- Spiral arms contain cold gas and dust that get compressed into clouds.
  - Cold gas can form into molecular clouds, out of which stars form.
- Star formation occurs in the spiral arms and produces a blue color.
  - Blue light comes only from young stars.

Elliptical Galaxies: Little or No Recent Star Formation

- **Passively evolving**: No star formation has occurred in elliptical galaxies for a long time. Gas in ellipticals is mostly hot and only visible at X-ray wavelengths. Such hot diffuse gas cannot collapse to form stars.
- Do you expect to find Cepheid variables in Elliptical galaxies? Why?
- Do you expect to find Cepheid variables in Spiral galaxies? Why?

NASA, ESA and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration



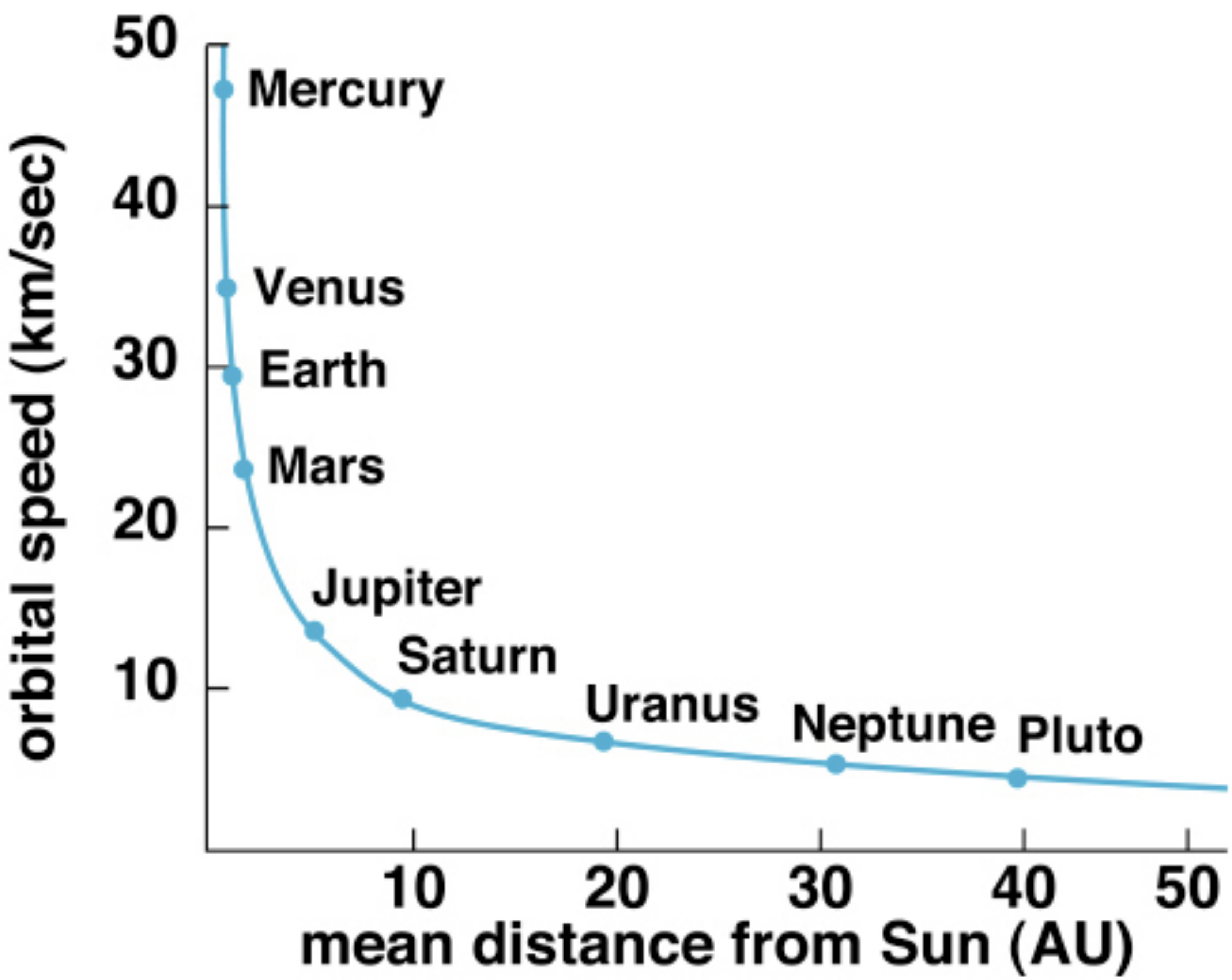
NASA/ESA/STScI/M. West X-ray: NASA/CXC/Penn State/G. Garmire

Evidence of Dark Matter

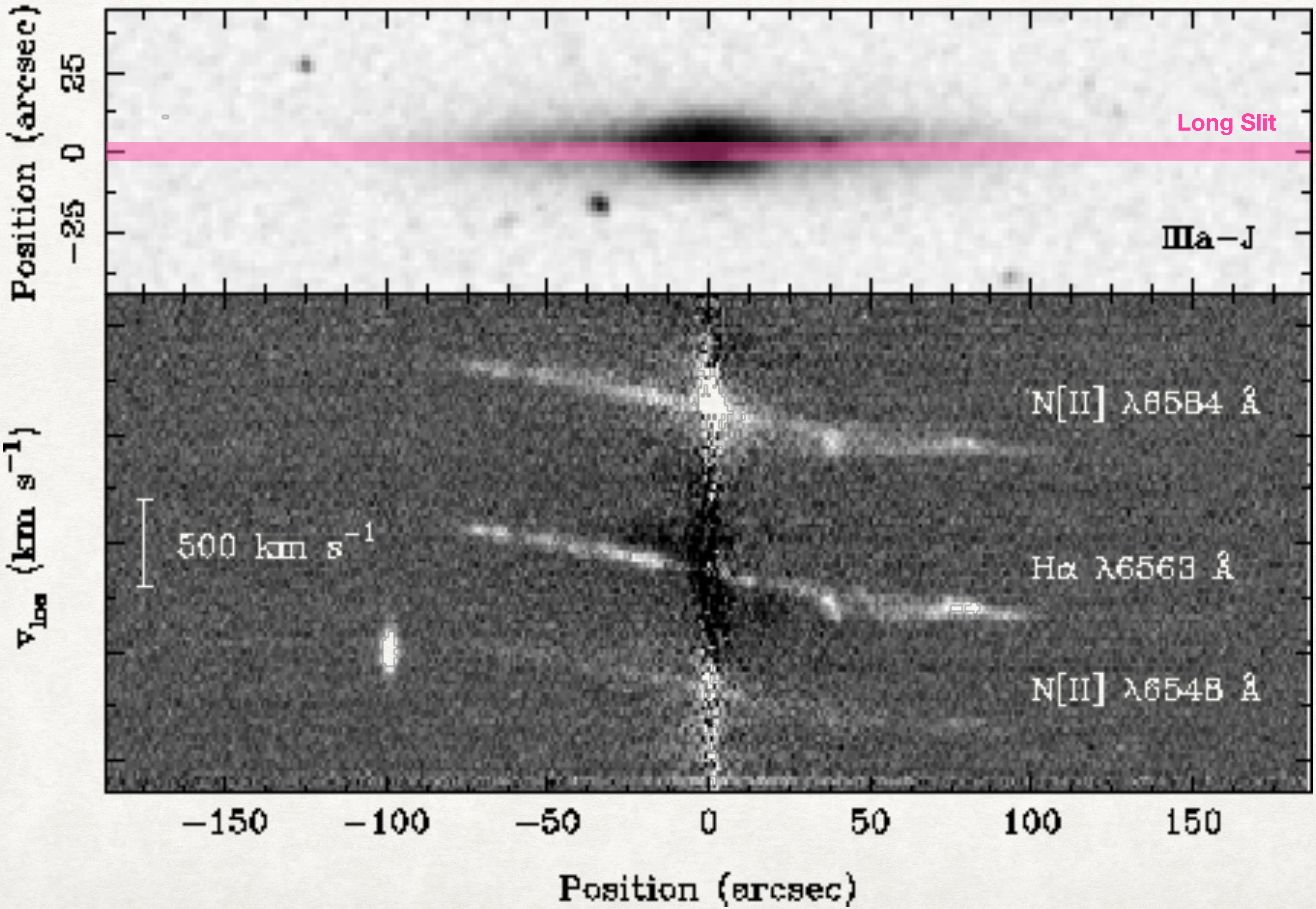
Orbital Velocities of Planets in the Solar System

Newton's laws: $GM(r)/r^2 = v^2/r$

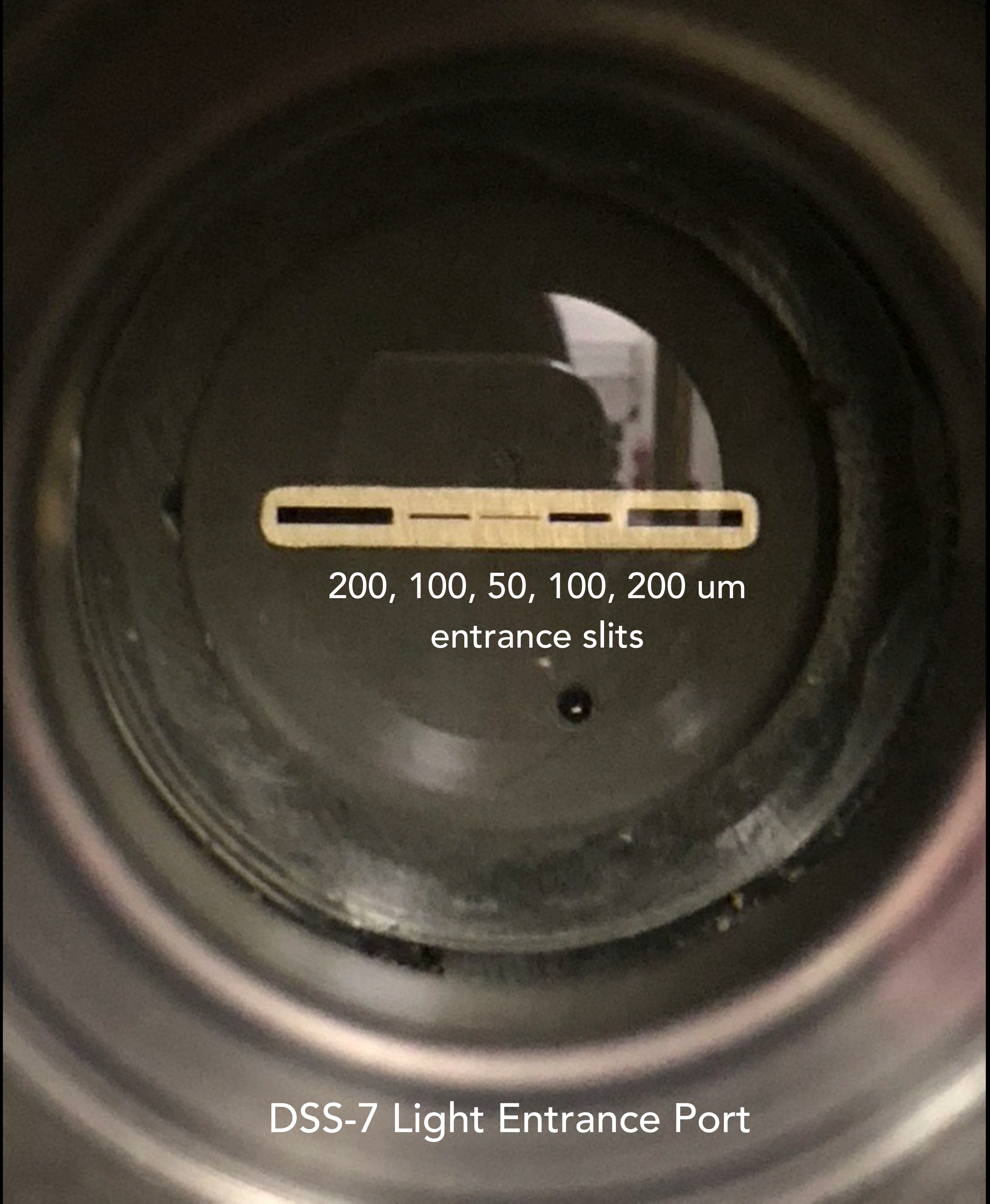
$v(r) = \sqrt{GM(r)/r} \Rightarrow v(r) \propto 1/\sqrt{r}$ because the Sun took 99.9% of the mass!



A LONGSLIT PLACED ALONG A GALAXY'S MAJOR AXIS



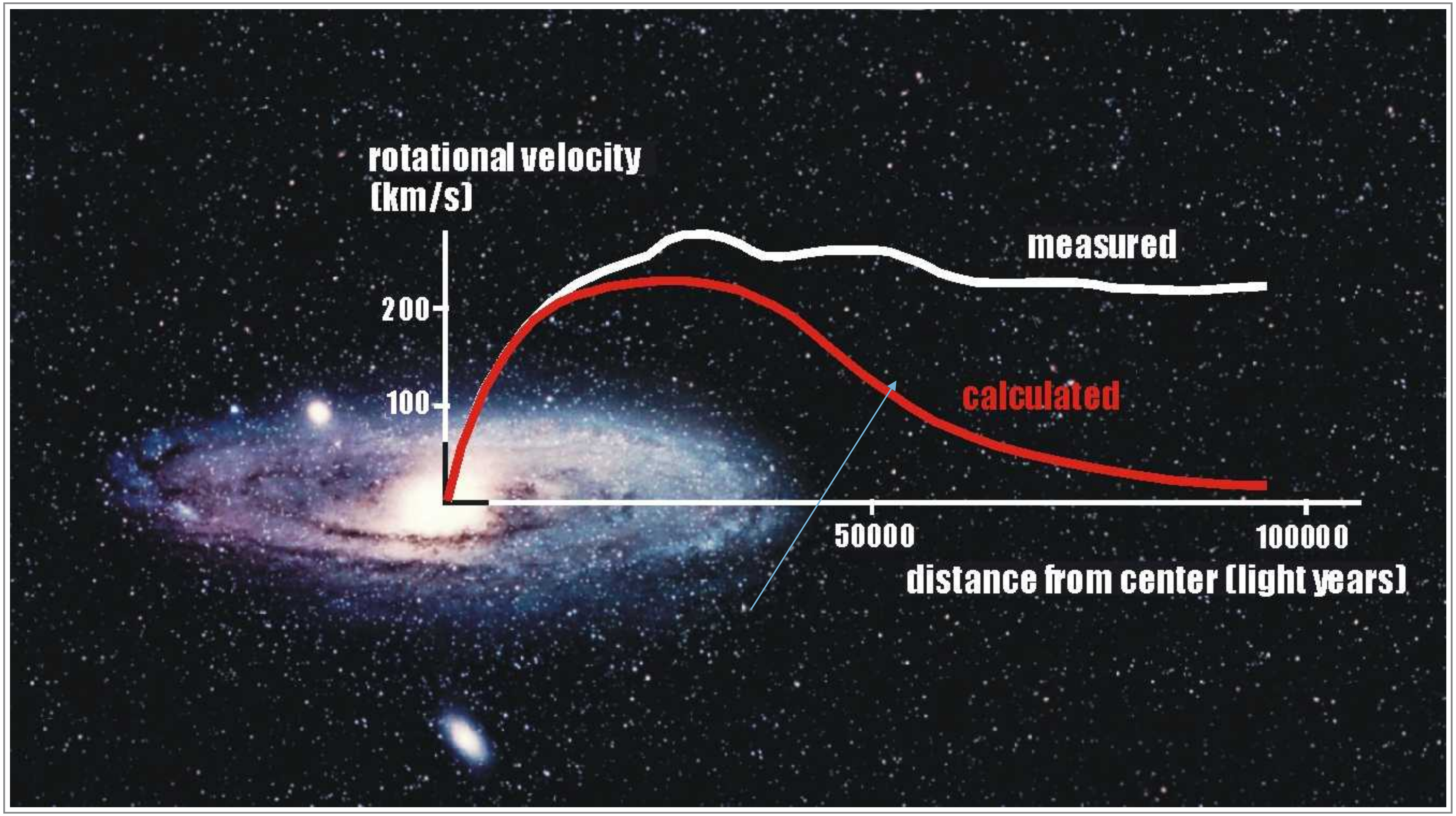
LONG SLITS PLACED AT THE FOCAL PLANE



Evidence of Dark Matter in Disk Galaxies

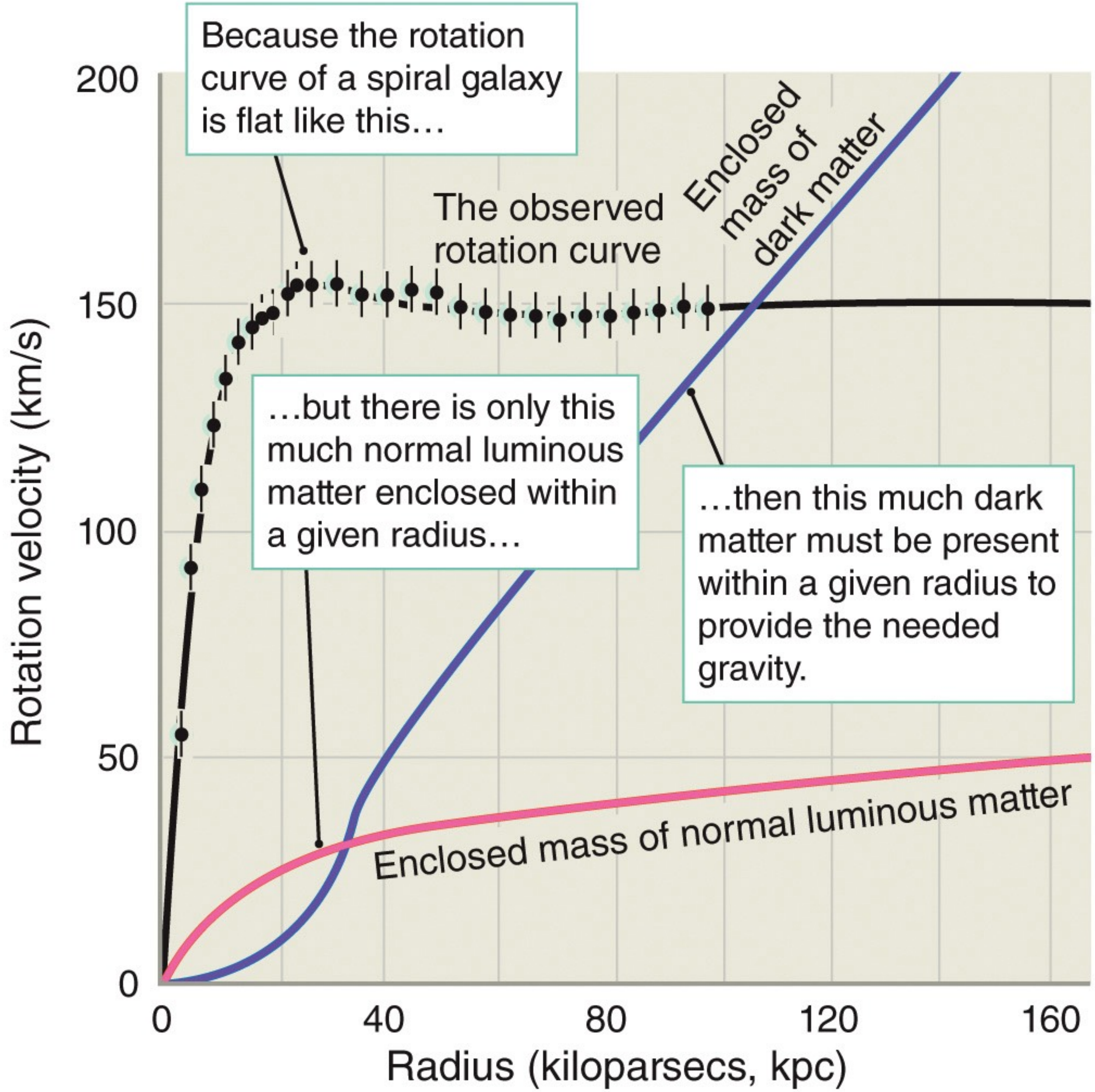
Newton's laws: $GM(r)/r^2 = v^2/r$

$$v(r) = \sqrt{GM(r)/r} \Rightarrow v(r) \propto 1/\sqrt{r} \text{ beyond the boundary of the disk}$$

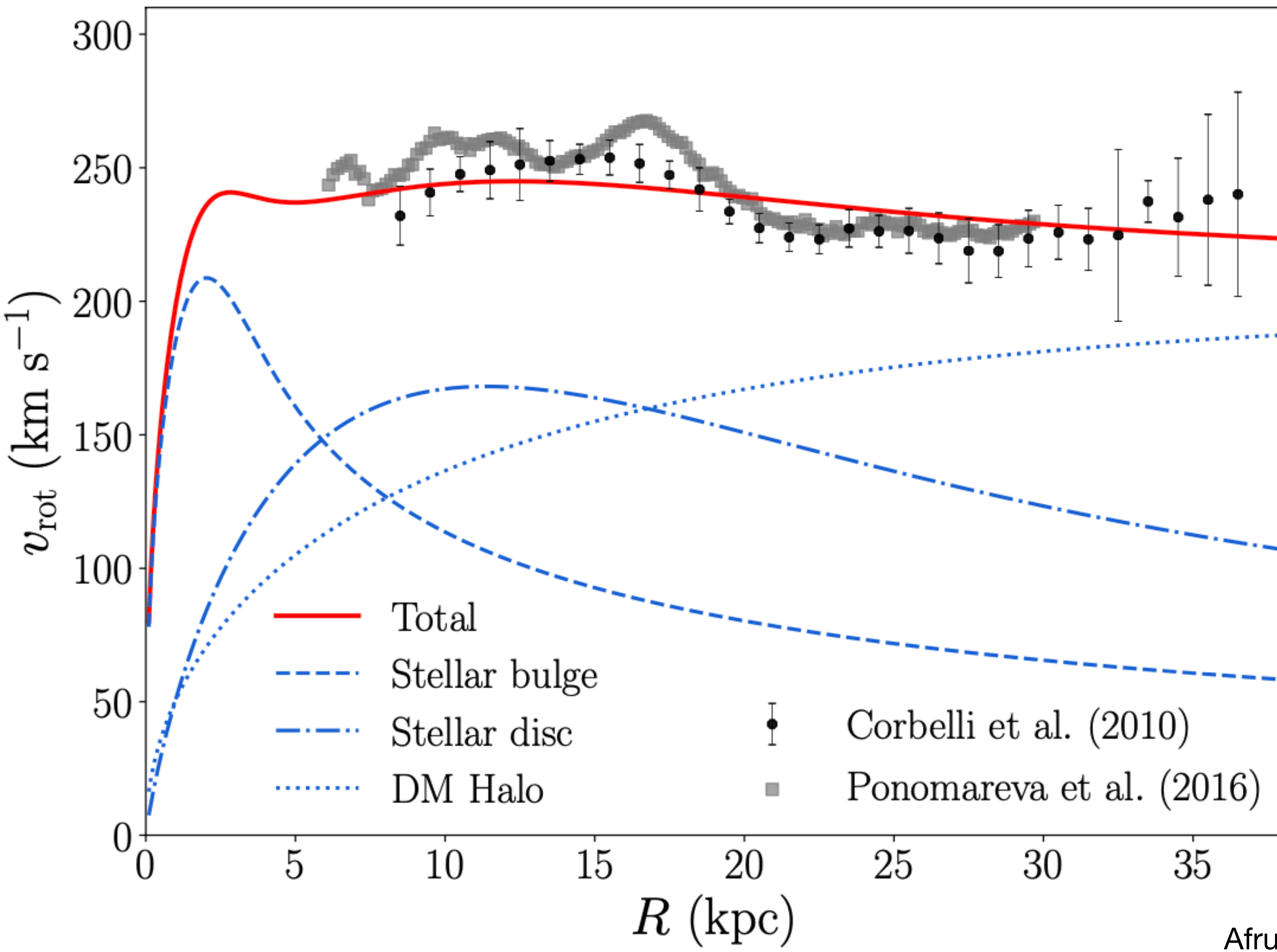


Flat Rotation Curves Provide Evidence for Dark Matter

- If mass distribution follows light distribution, rotation speeds should ***decrease*** at larger radii; But they remain constant!
- There must be an additional source of gravity that does not make light, called **dark matter**.
- Dark matter dominates mass in the outer regions of the galaxy and does not emit or absorb light (**they are not dark, they are transparent!**).



Rotation Curve Decomposition of M31 (Andromeda Galaxy)



Afruni+2021

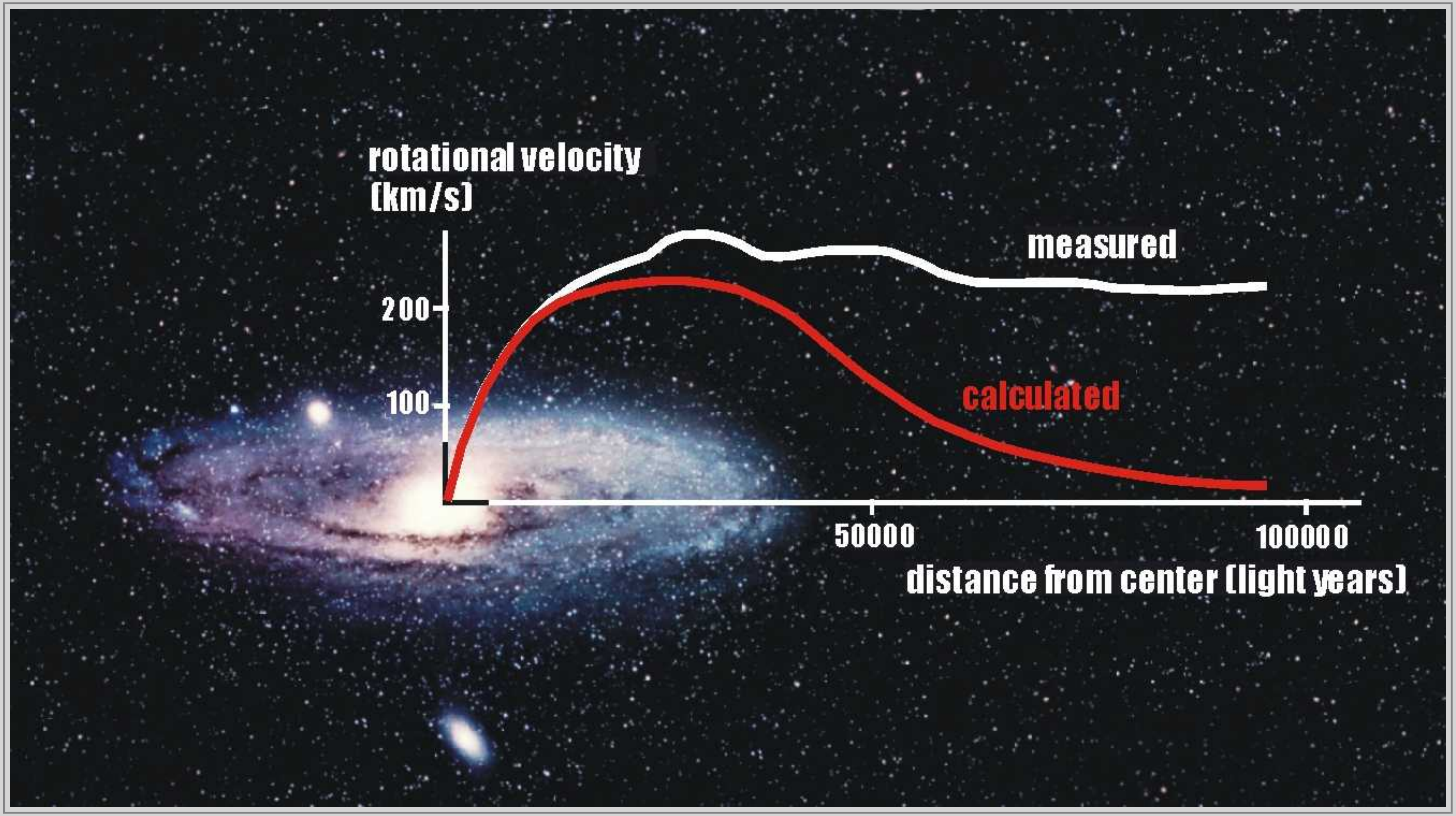
Vera C. Rubin (1928 - 2016) - Dark Matter in Spiral Galaxies

"Her work helped usher in a Copernican-scale change in cosmic consciousness, namely the realization that what astronomers always saw and thought was the universe is just the visible tip of a lumbering iceberg of mystery."

- *New York Times*

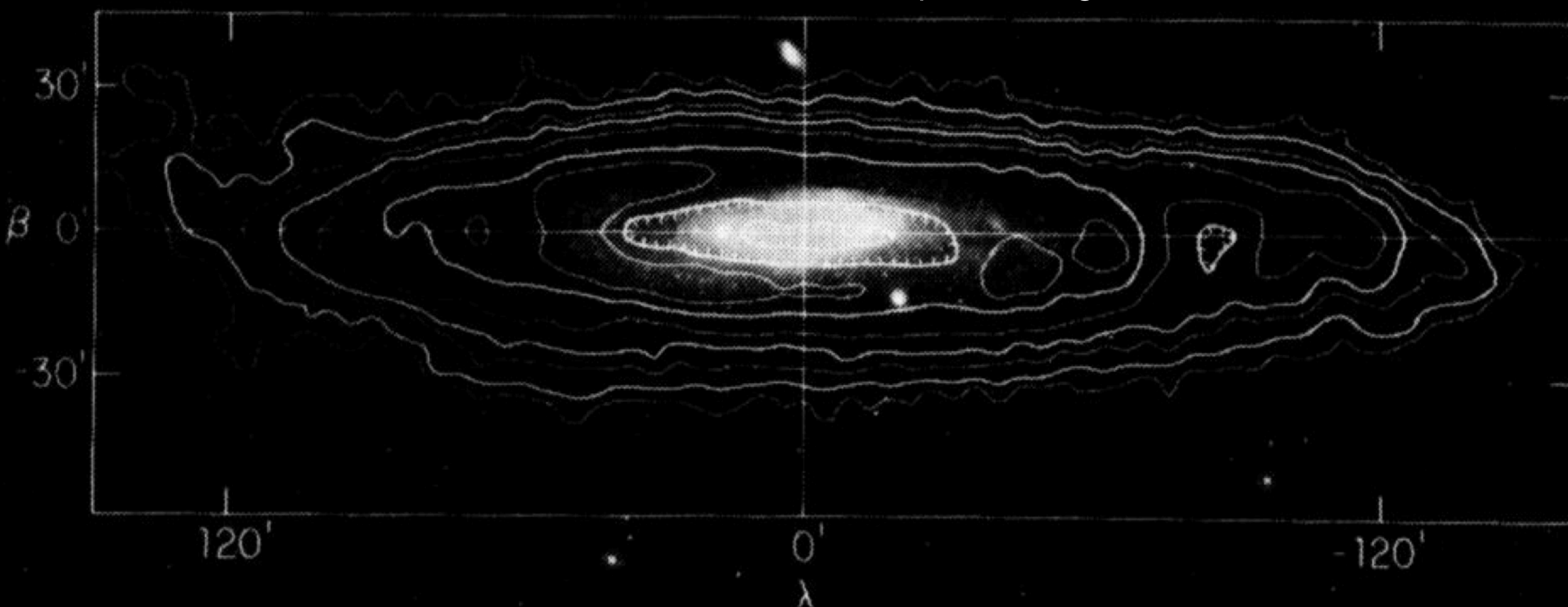
Vera Rubin Observatory (formerly known as LSST)

An important caveat: How to measure rotation velocity at large galacto-centric distances?



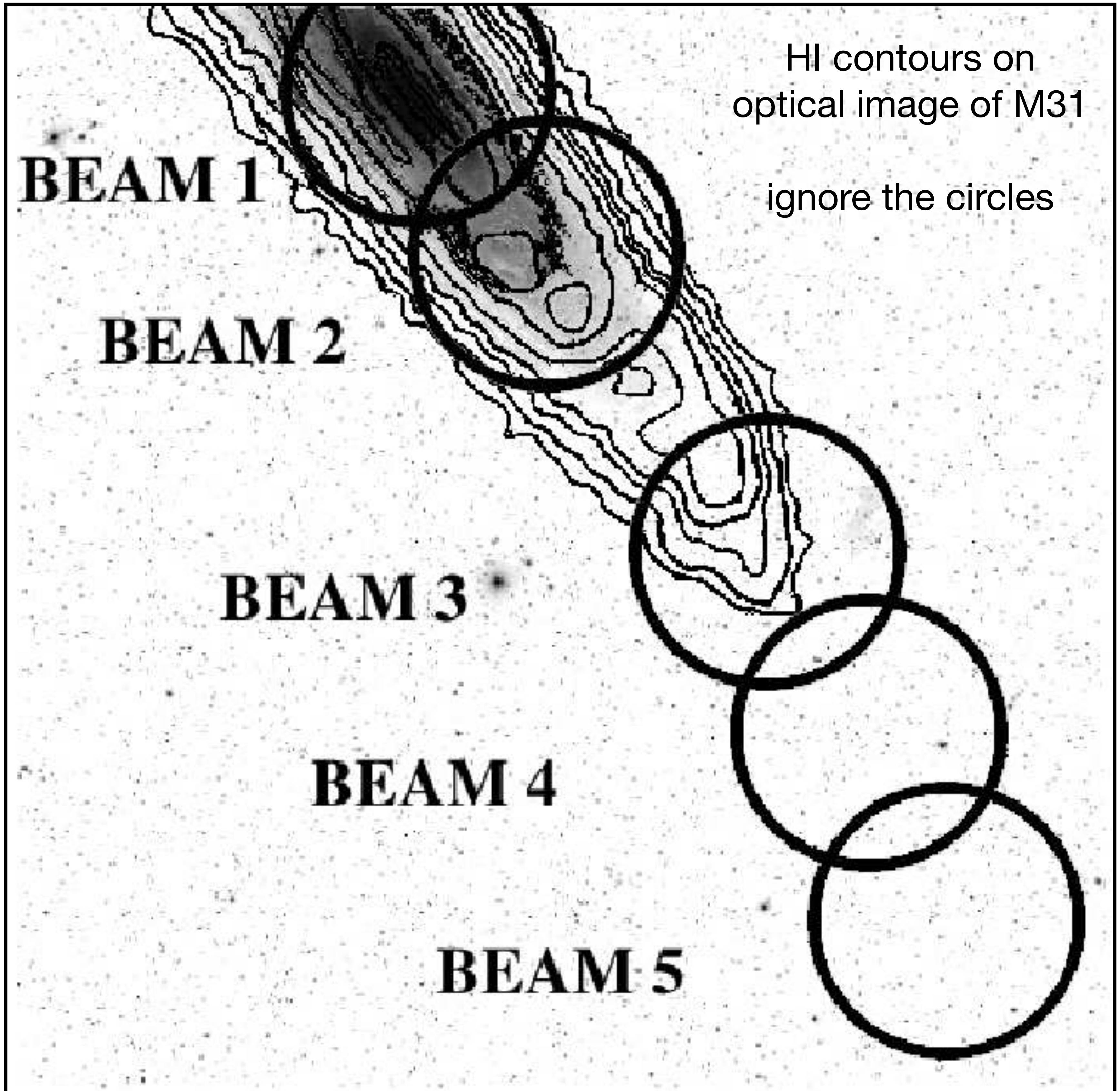
Neutral Hydrogen disk is much more extended than the optical stellar disk

Radio HI contours on optical image



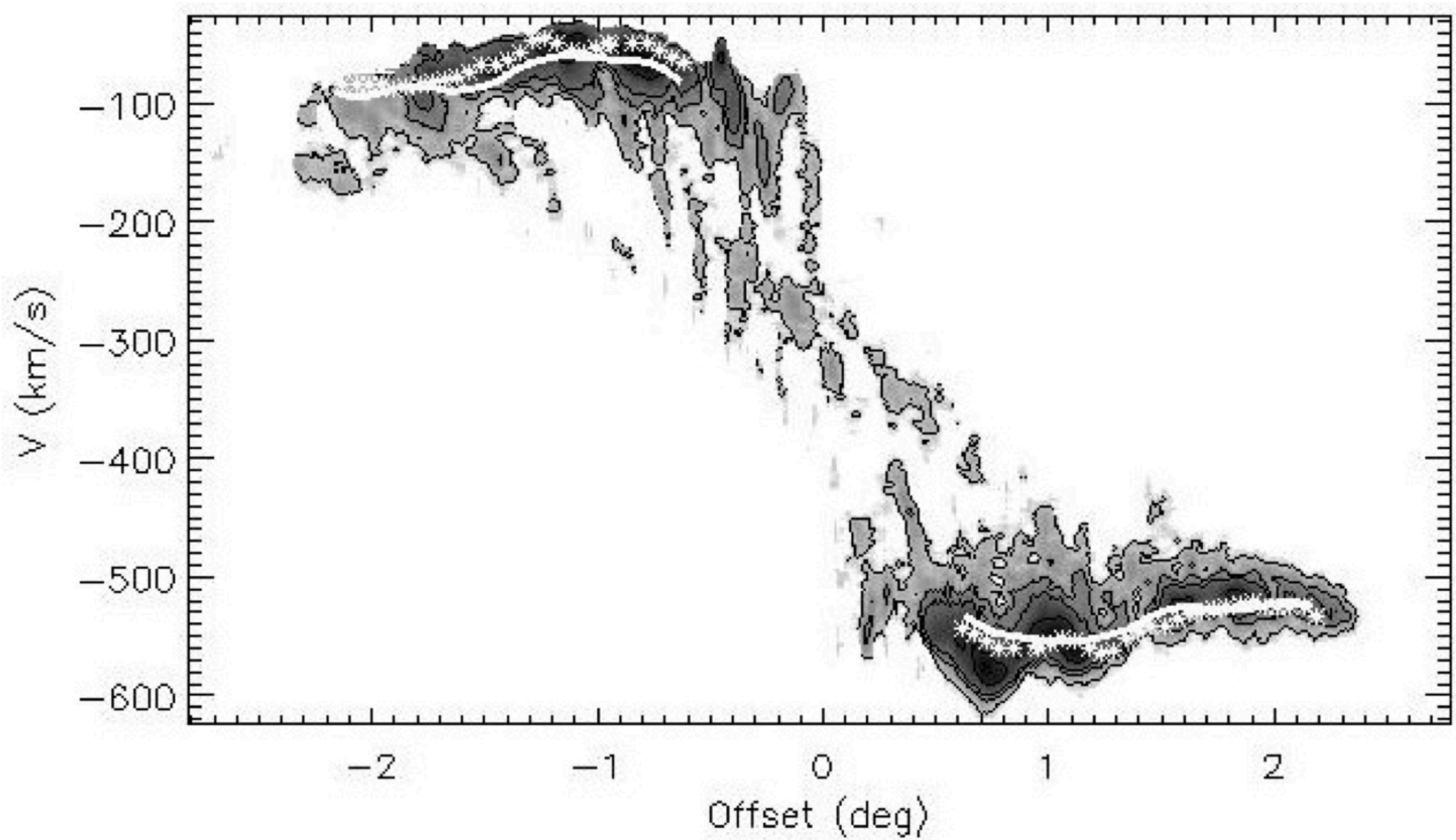
Cram+1980

Neutral Hydrogen disk extends farther out than the optical stellar disk



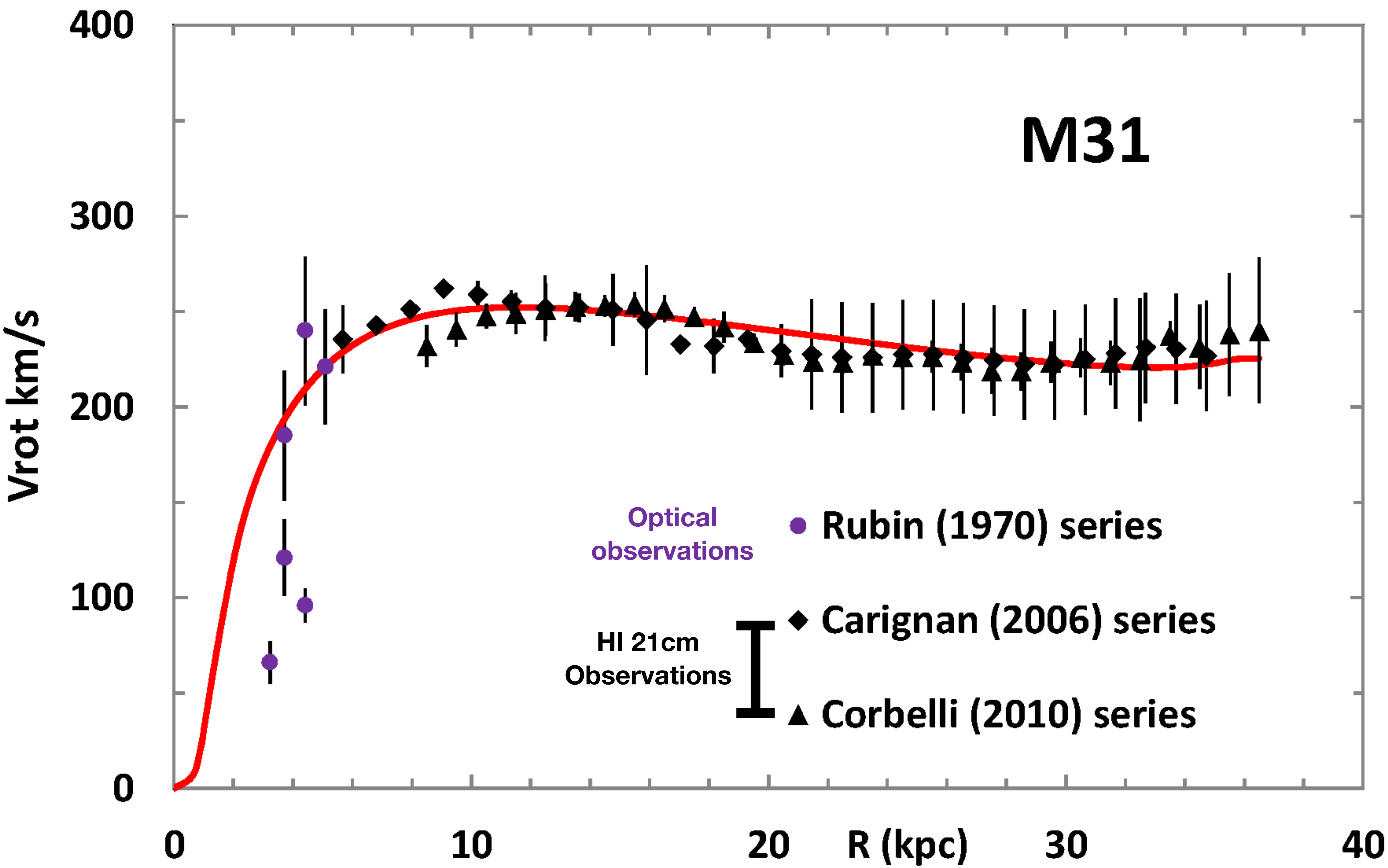
Madson+2001

M31's Rotation Curve Revealed by the HI 21cm Emission Line



Corbelli+2010

M31's Full Rotation Curve: Original Data Sources



The First Observational Evidence of Dark Matter

Zwicky 1933: **velocity dispersion** of galaxies in the Coma Cluster

Virial Theorem: $2K + U = 0 \Rightarrow V^2 = GM/R \Rightarrow \mathbf{M = V^2R/G}$

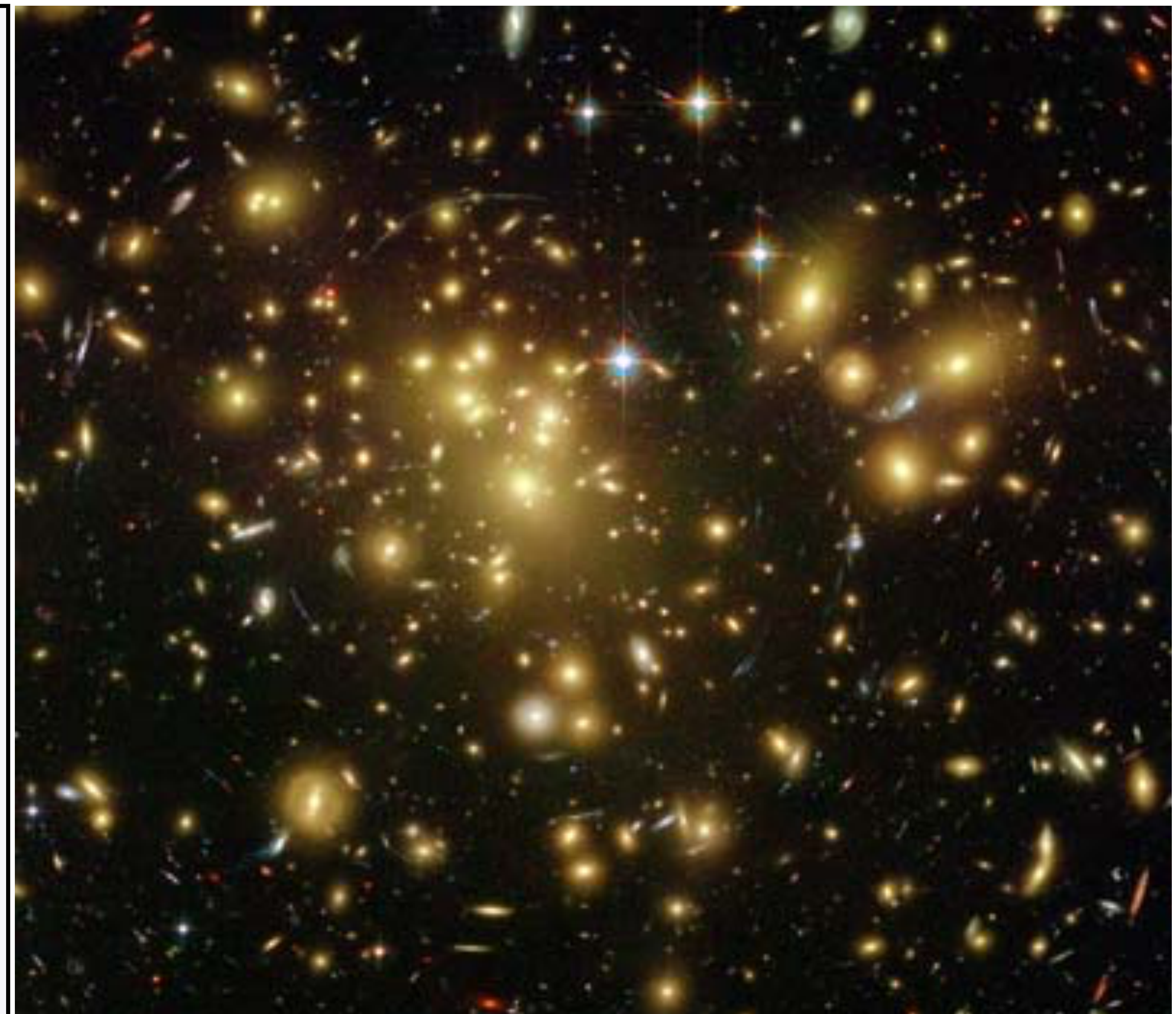
The virial mass is **400x** greater than visible stellar mass

Fritz Zwicky

Zwicky in 1947

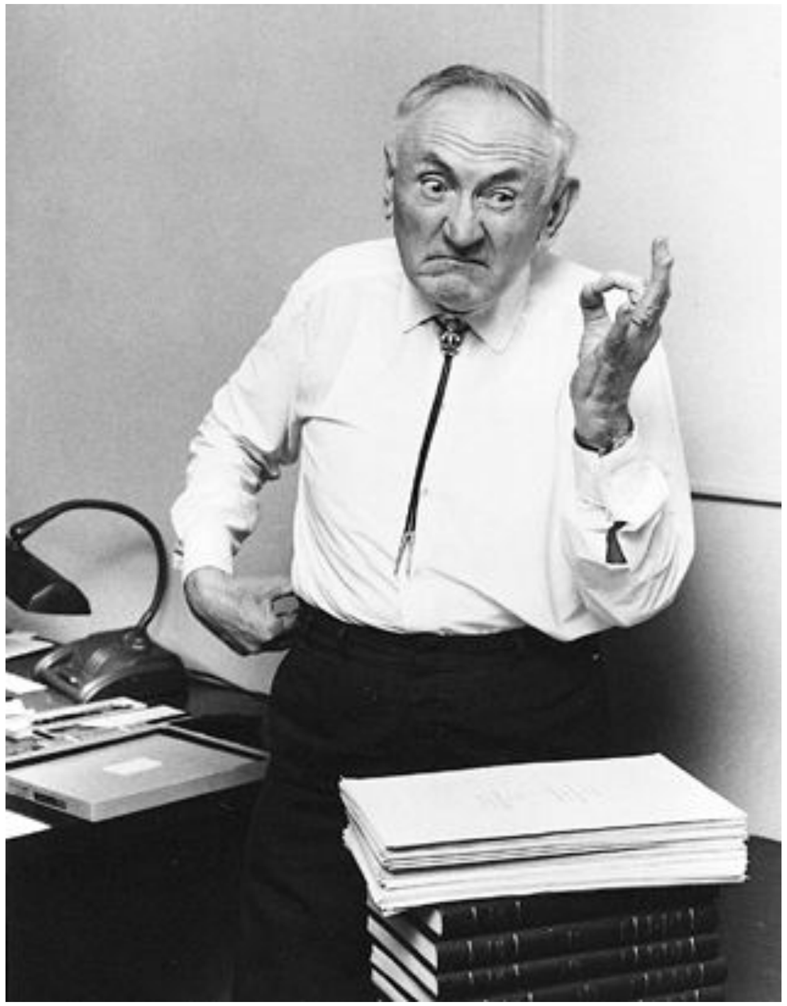
Born February 14, 1898
Varna, Bulgaria

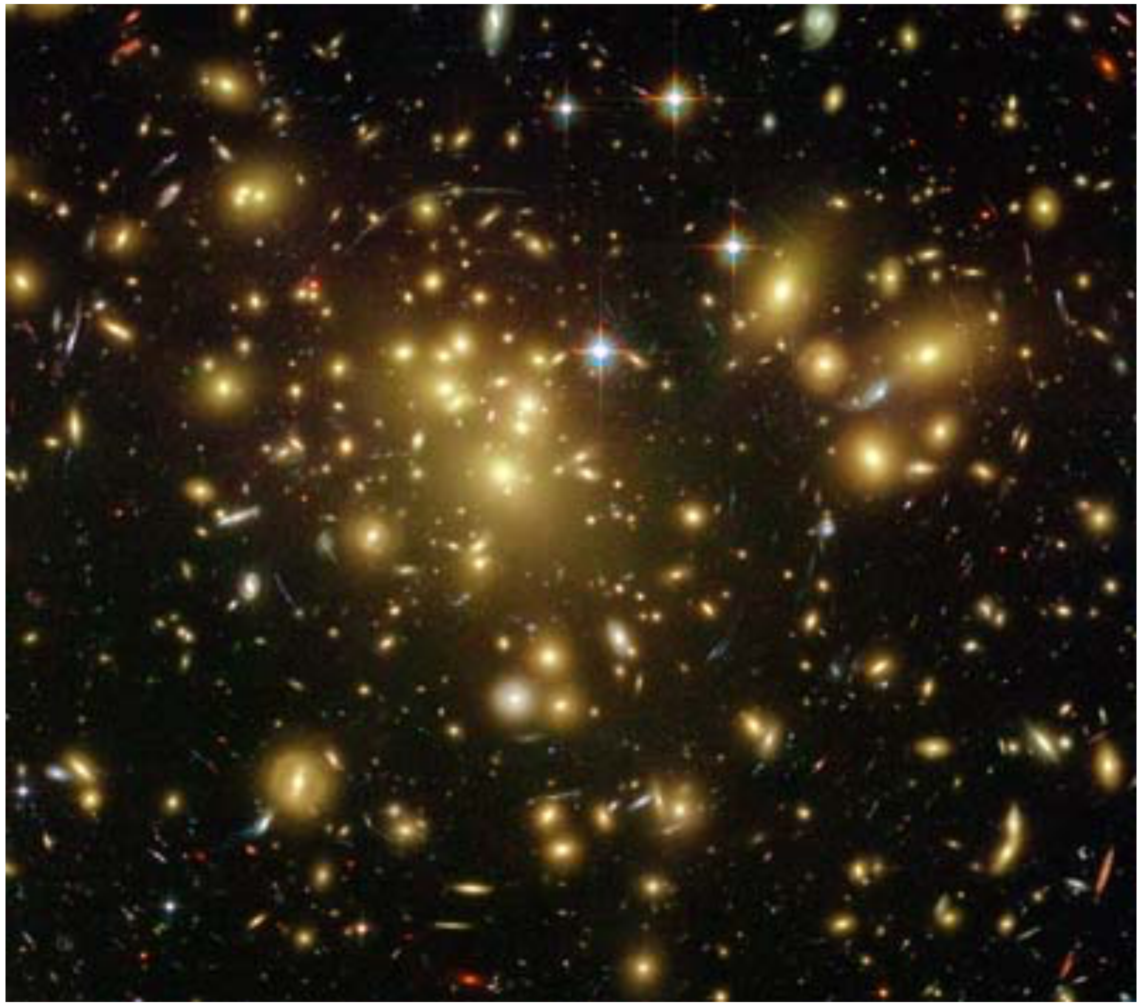
Died February 8, 1974 (aged 75)
Pasadena, California, US



Zwicky (1933) Section 5:
Comments on the Velocity Dispersion in the Coma Cluster of Nebulae

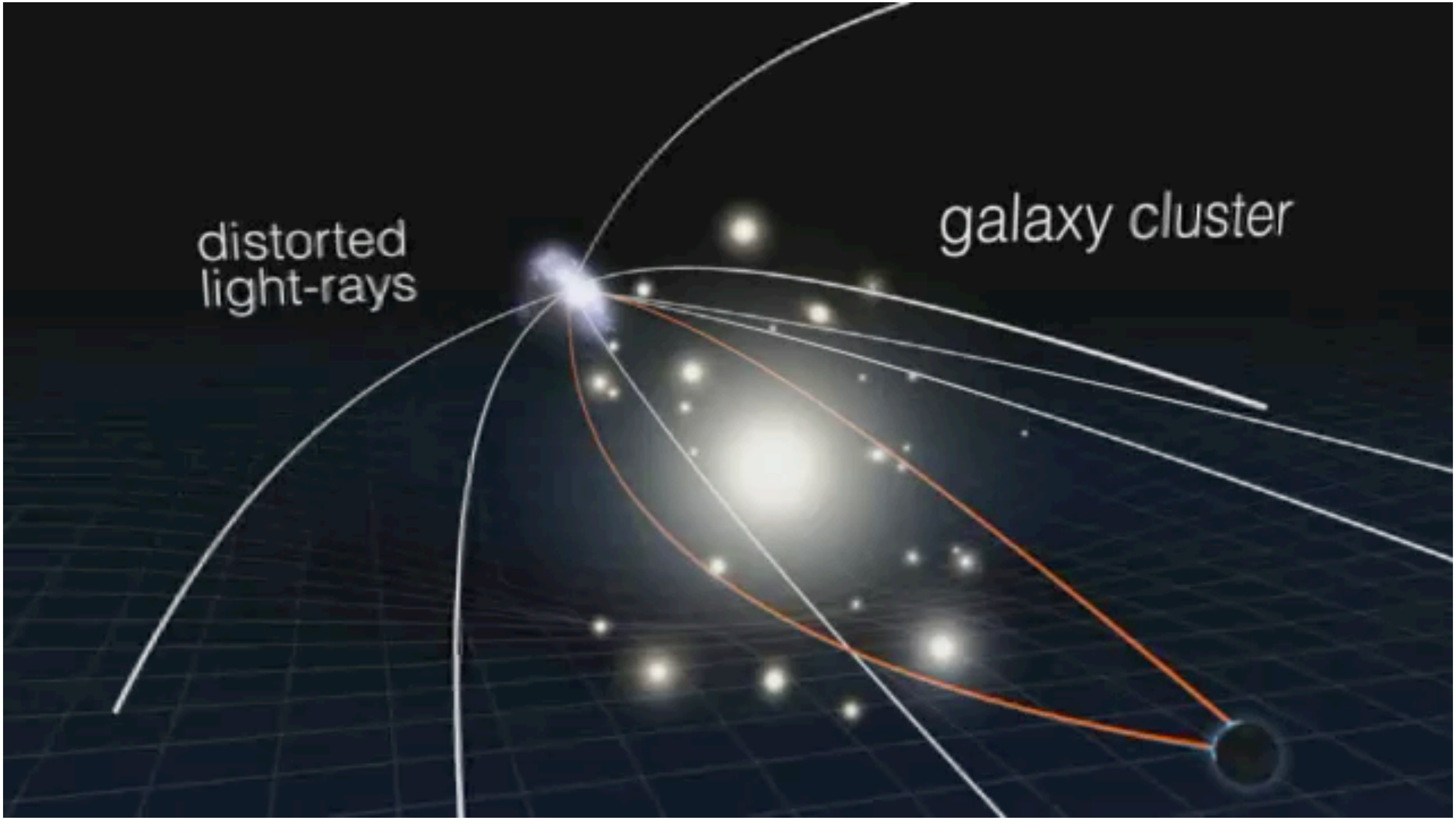
In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter [This would be in approximate accordance with the opinion of Einstein and de Sitter as discussed in Sect. 4.]. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.





Non-Dynamical Evidence for Dark Matter: Gravitational Lensing

Lensing allows us to measure the *total* mass in the foreground lens galaxy or cluster



2024.4.8

Total Solar Eclipse

“the greatest conjunction”

Crowd reaction, Cape Girardeau, MO

ABC News: Total eclipse captures hearts, minds of millions

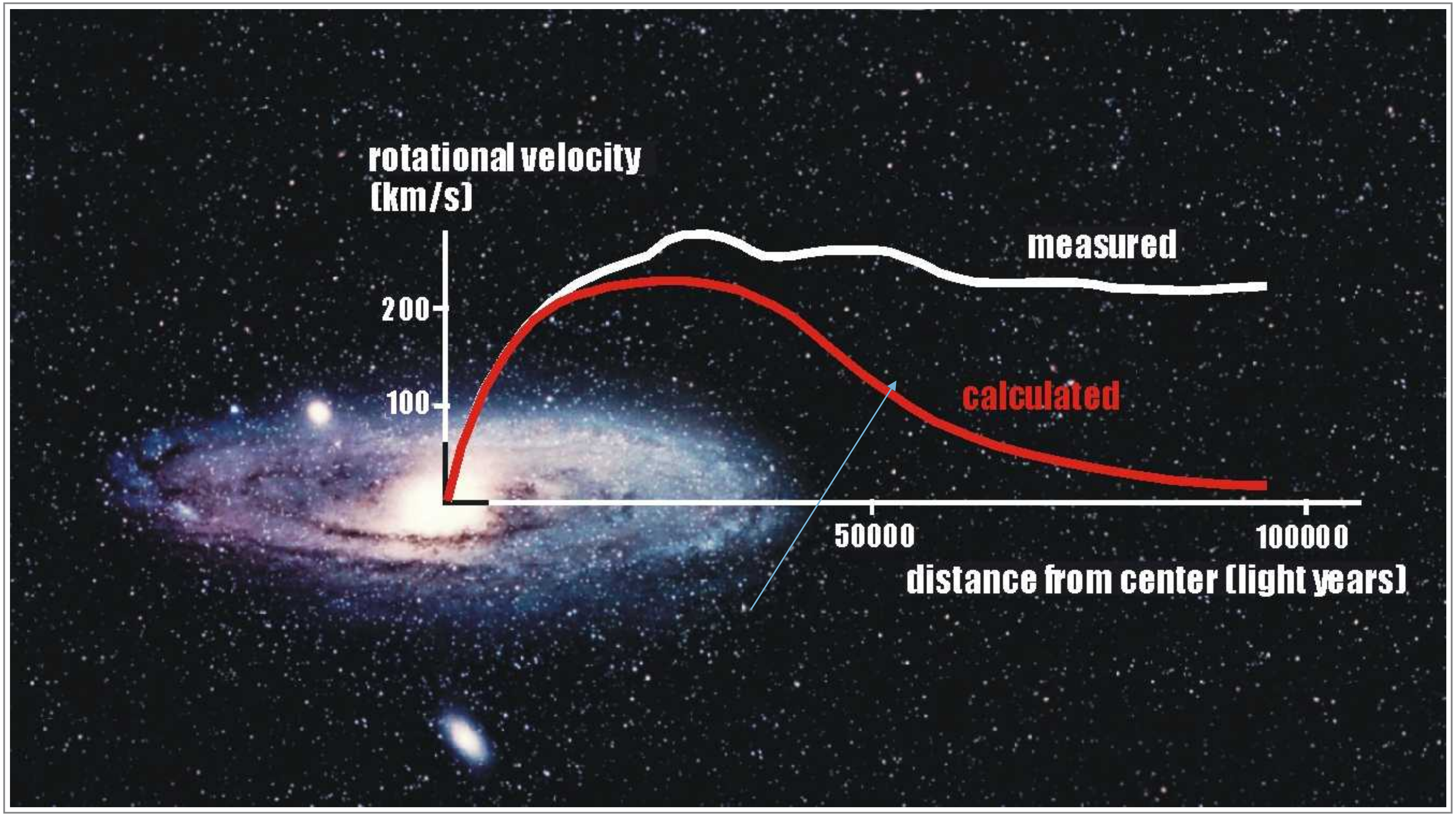
Evidence of Dark Matter (continued)

Method 1: Circular Velocity

Circular motion under gravity alone: $GM(r)/r^2 = v(r)^2/r$, where $M(r)$ is enclosed mass

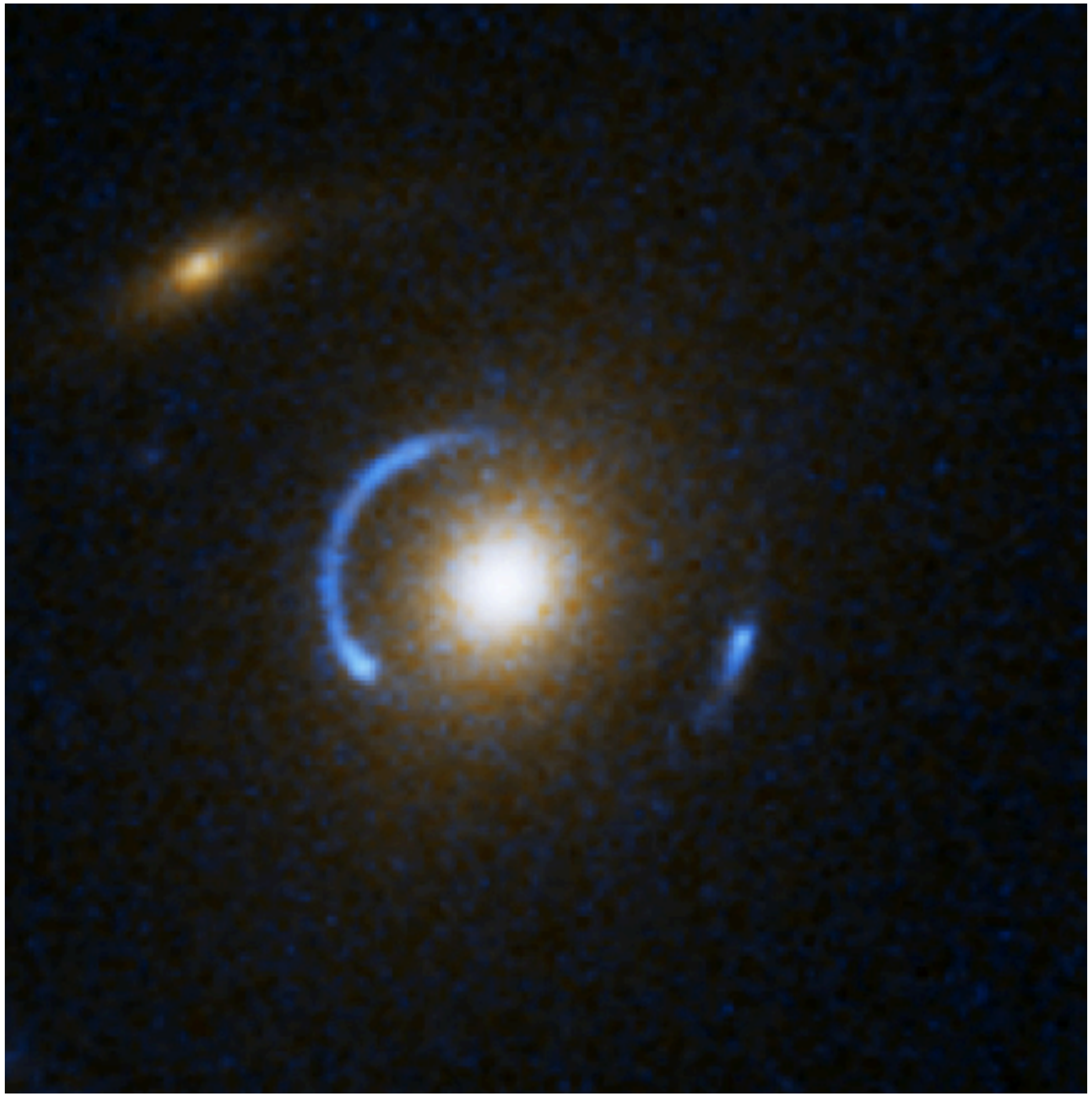
$$v(r) = \sqrt{GM(r)/r} \Rightarrow v(r) \propto 1/\sqrt{r}$$

So beyond the edge of the spiral galaxy, one expects the circular velocity to decline



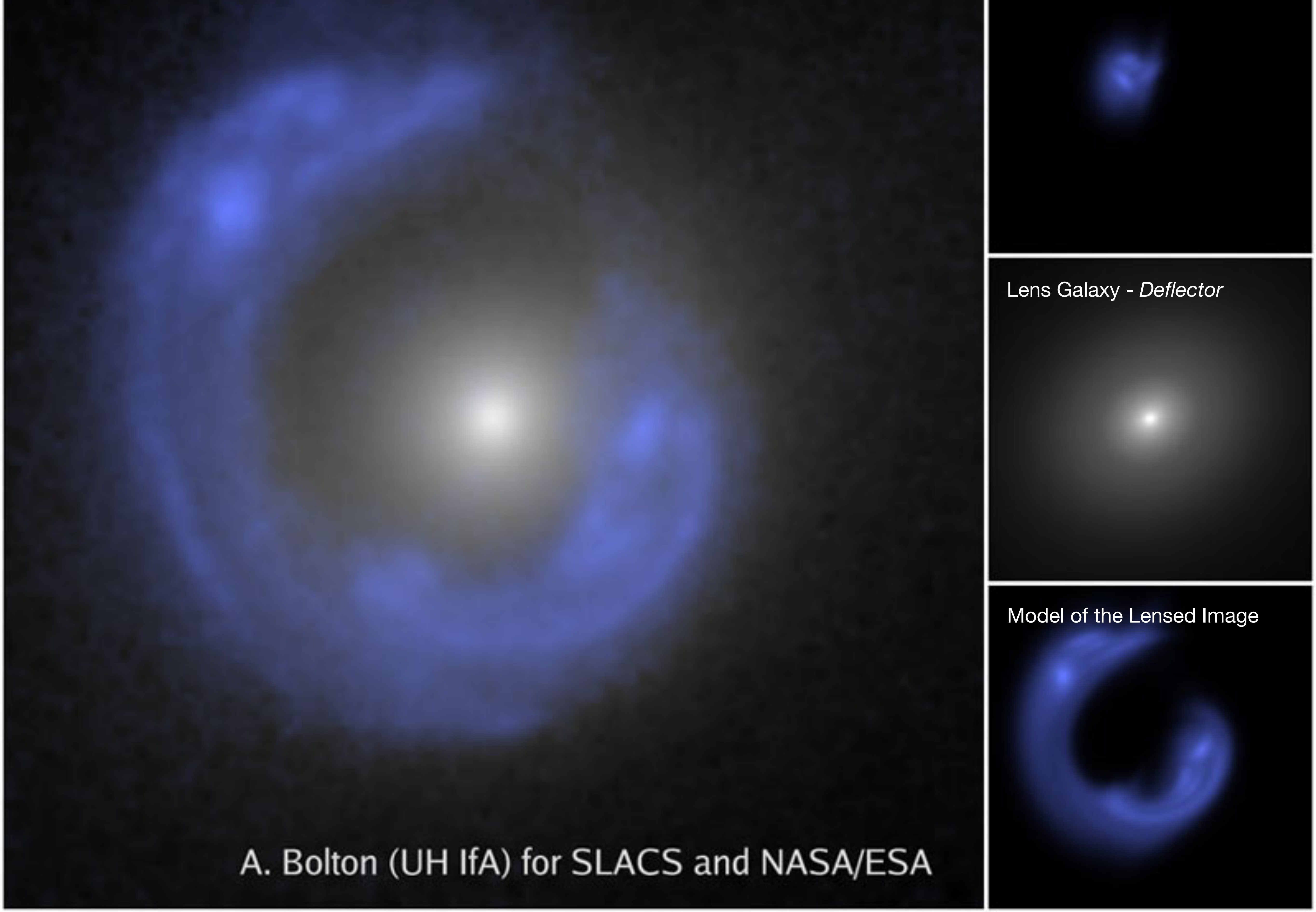
Method 2: Strong Gravitational Lensing

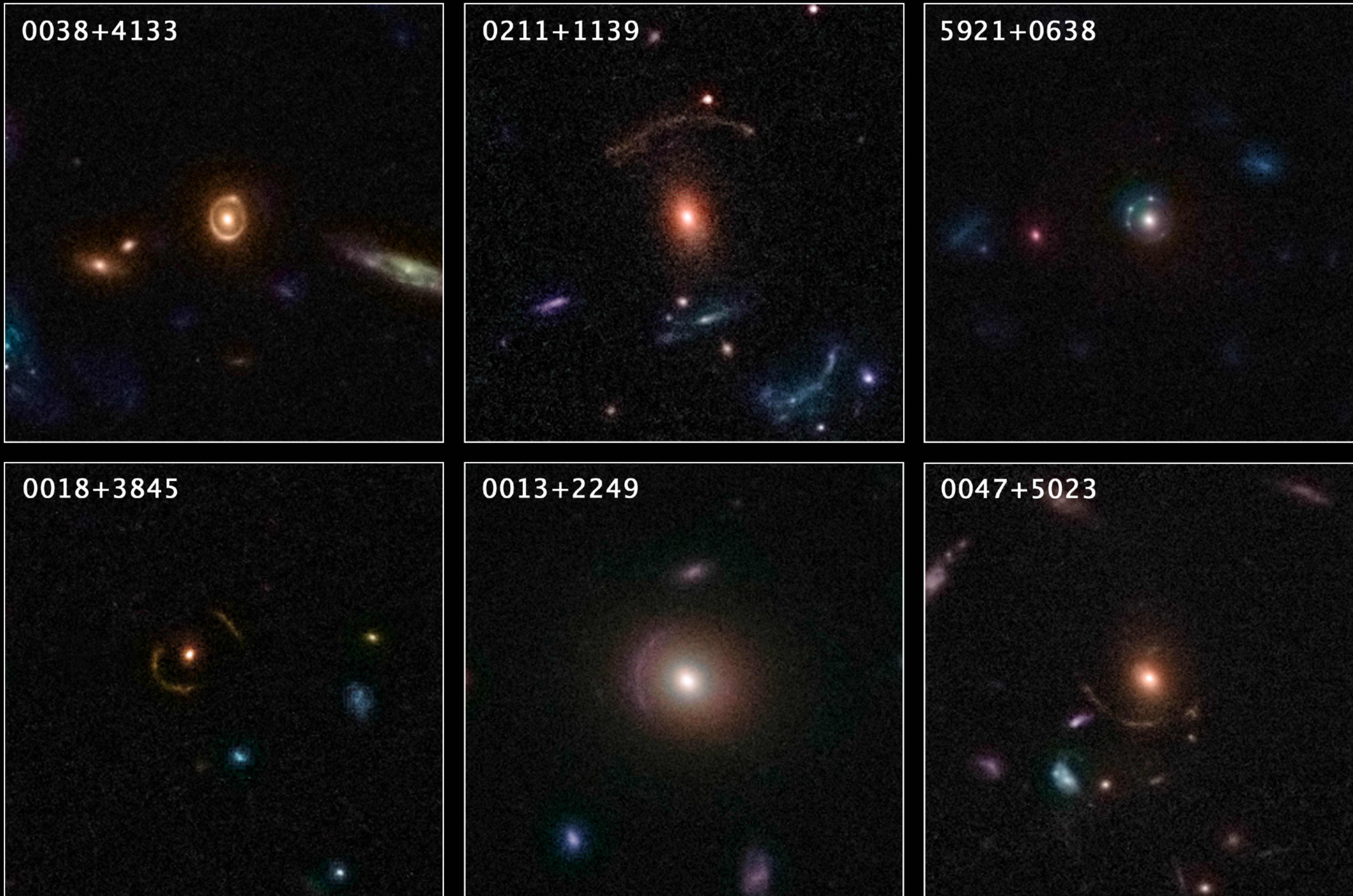
Lensing allows us to measure the *total* mass in the foreground lens galaxy



Various lensing configurations reproduced by a wine glass

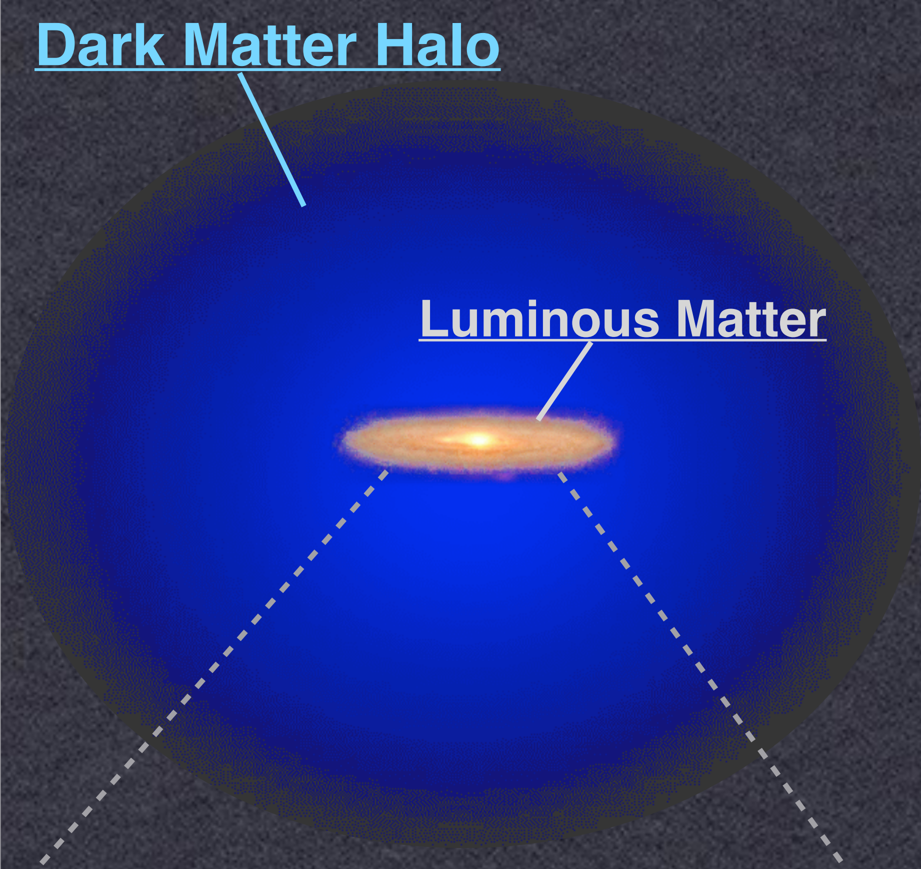
Modeling Strong Gravitational Lensing



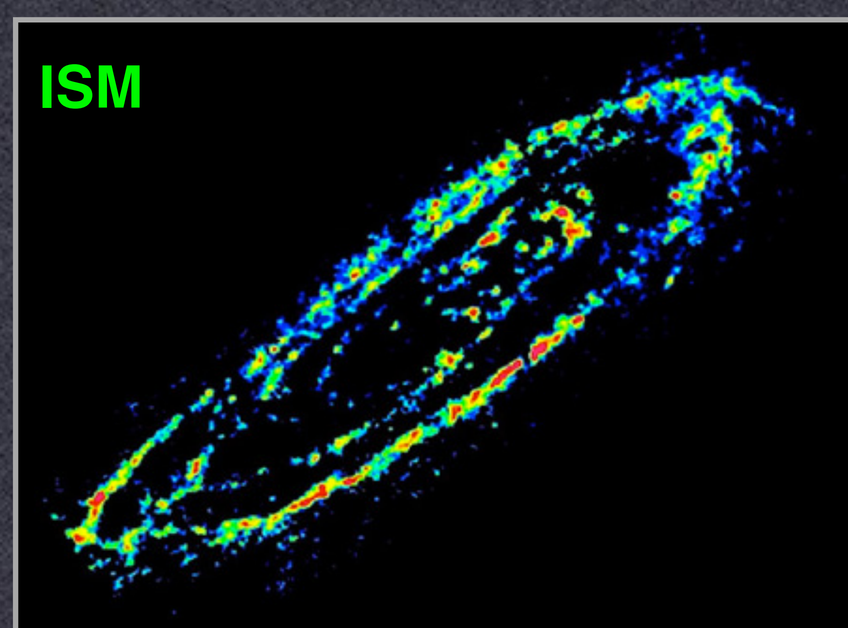


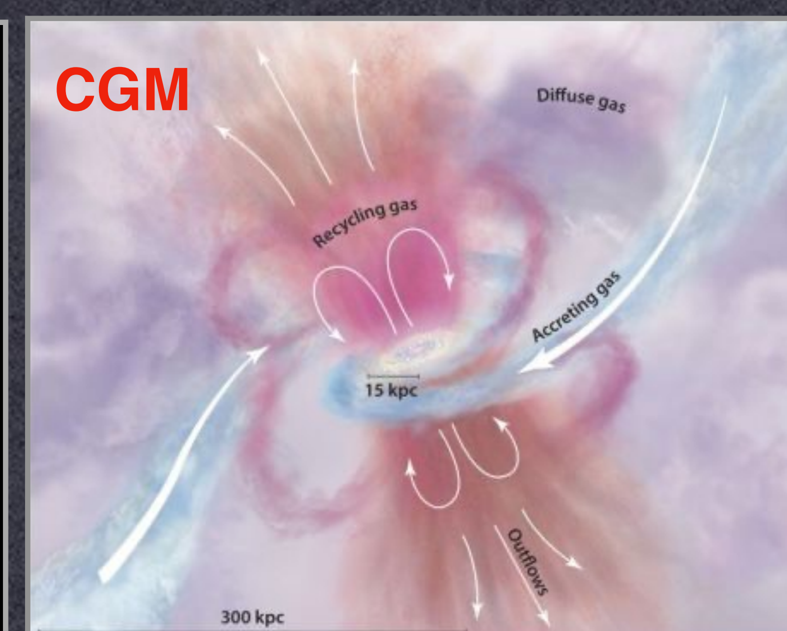
Gravitational Lenses in the COSMOS Survey
Hubble Space Telescope ▪ ACS/WFC

Summary: The Components of M31



- Total Dynamical Mass: $1.2 \times 10^{12}\ M_{\odot}$
- Normal Baryonic Matter (~16% or 1/6)
  - Stellar Mass: $\sim 10^{11}\ M_{\odot}$
  - Interstellar Medium (ISM): $\sim 10^{10}\ M_{\odot}$
    atomic/molecular H, helium
  - Circumgalactic Medium (CGM): $\sim 10^{11}\ M_{\odot}$
    Mostly ionized gas, some at million K
- Dark Matter (~84% or 5/6)
  - Dark Matter Halo Mass: $\sim 10^{12}\ M_{\odot}$





references: Corbelli+2010, Nieten+2005, Lehner+2015

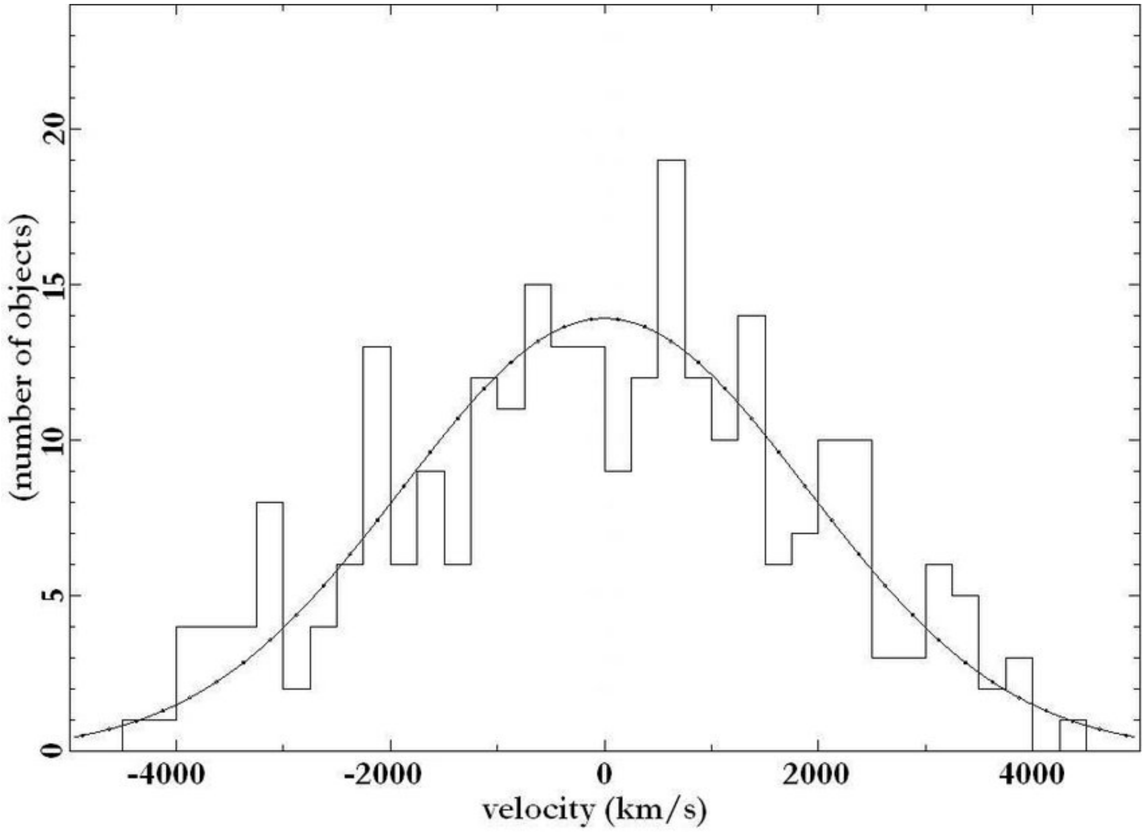
Dark Matter & Normal Matter in Galaxy Clusters

Method 3: Virial Theorem in Coma Cluster

Zwicky 1933: **velocity dispersion** of galaxies in the Coma Cluster

Virial Theorem: $2\bar{K} + \bar{U} = 0 \rightarrow \sigma^2 = GM/R \rightarrow M = \sigma^2 R/G$

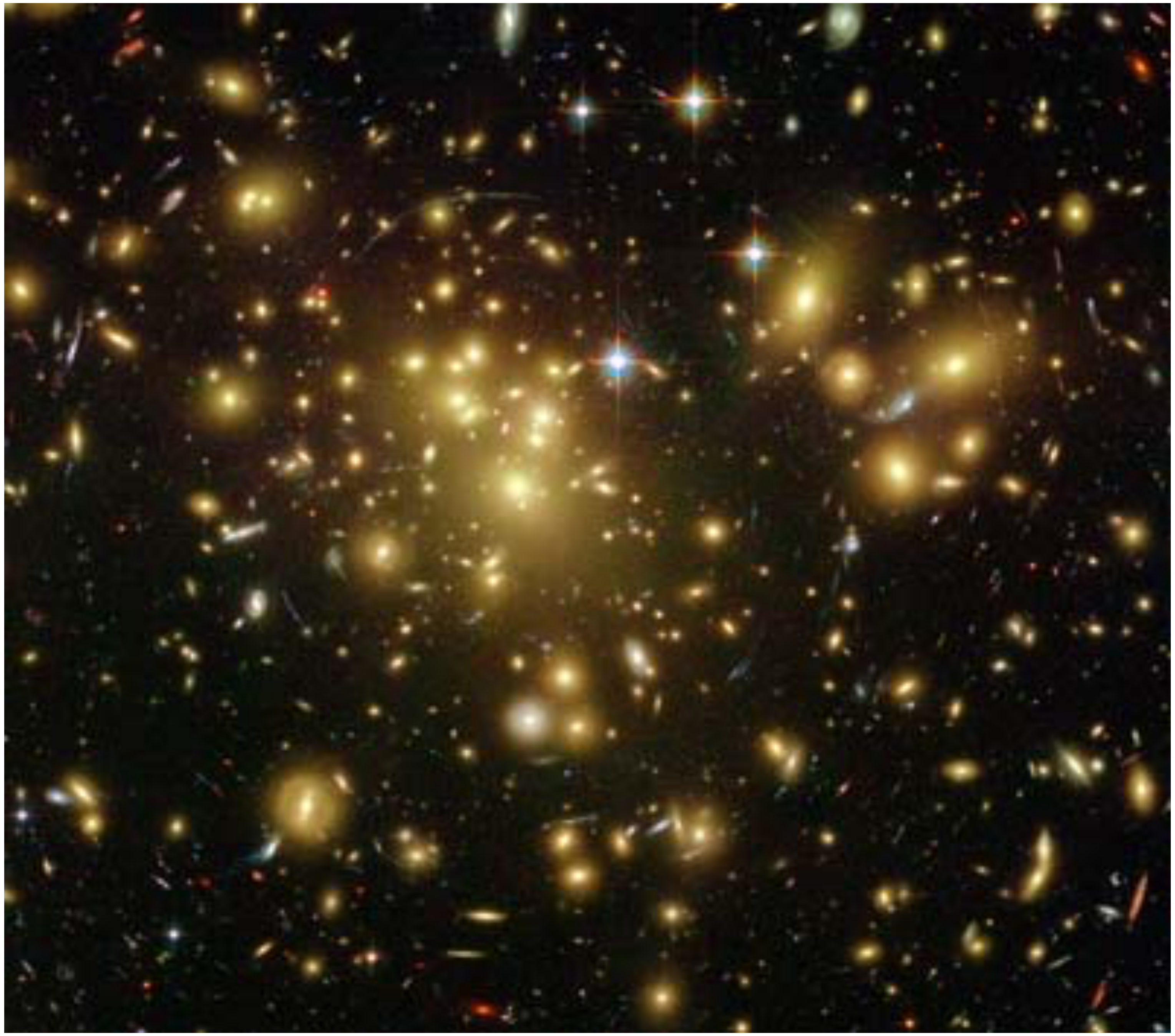
The virial mass is **400x** greater than visible stellar mass



Gaussian Probability Density Function

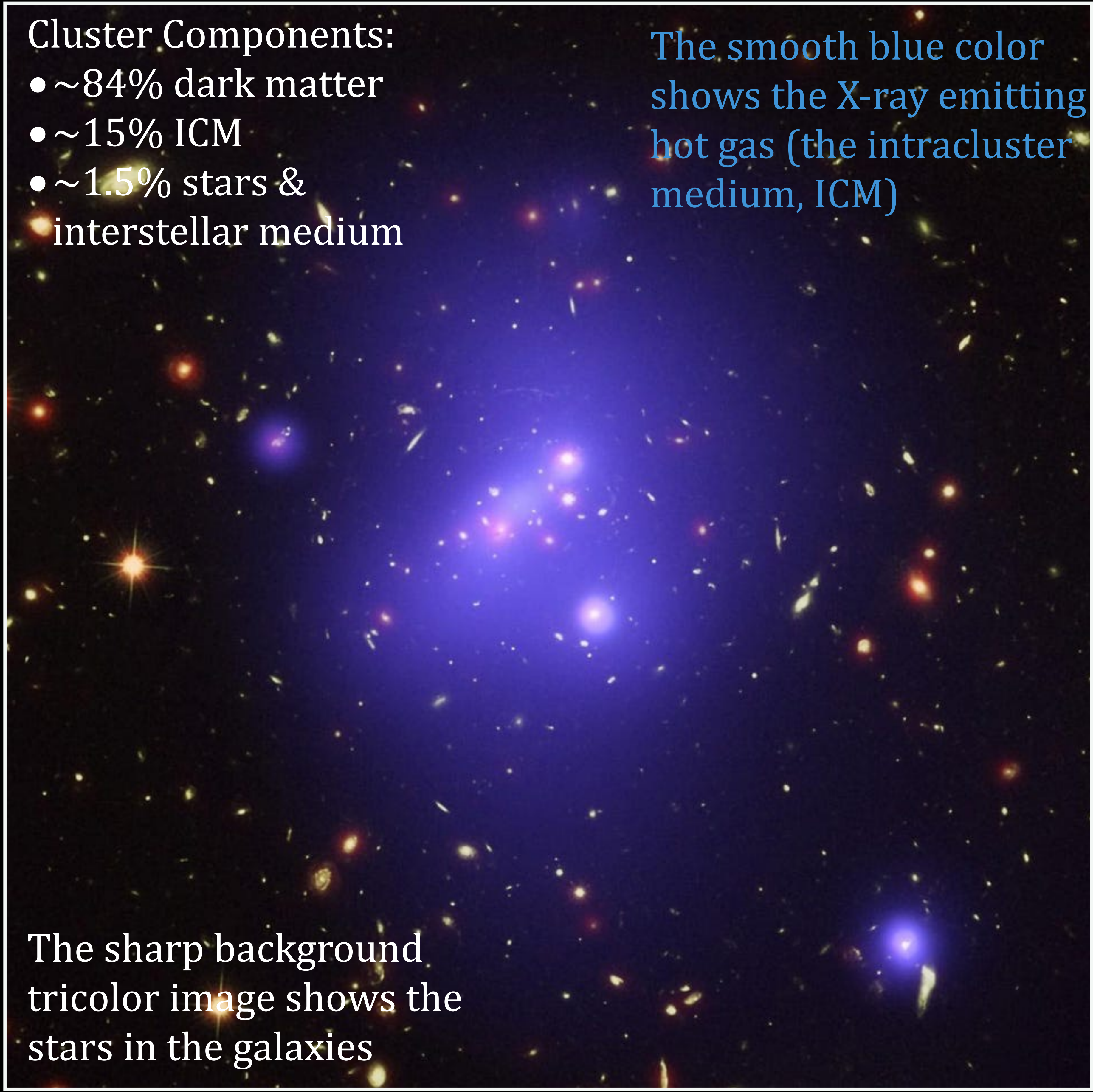
$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where σ is the standard deviation and μ the mean



In galaxy clusters, the mass of the X-ray-emitting plasma in the ICM is ~10x more massive than the stars in the galaxies

Unlike galaxies, most of the normal matter in clusters is in gas instead of stars



IDCS J1426.5+3508

Method 4: Weak Gravitational Lensing

Lensing allows us to measure the *total* mass in the foreground lens galaxy or cluster

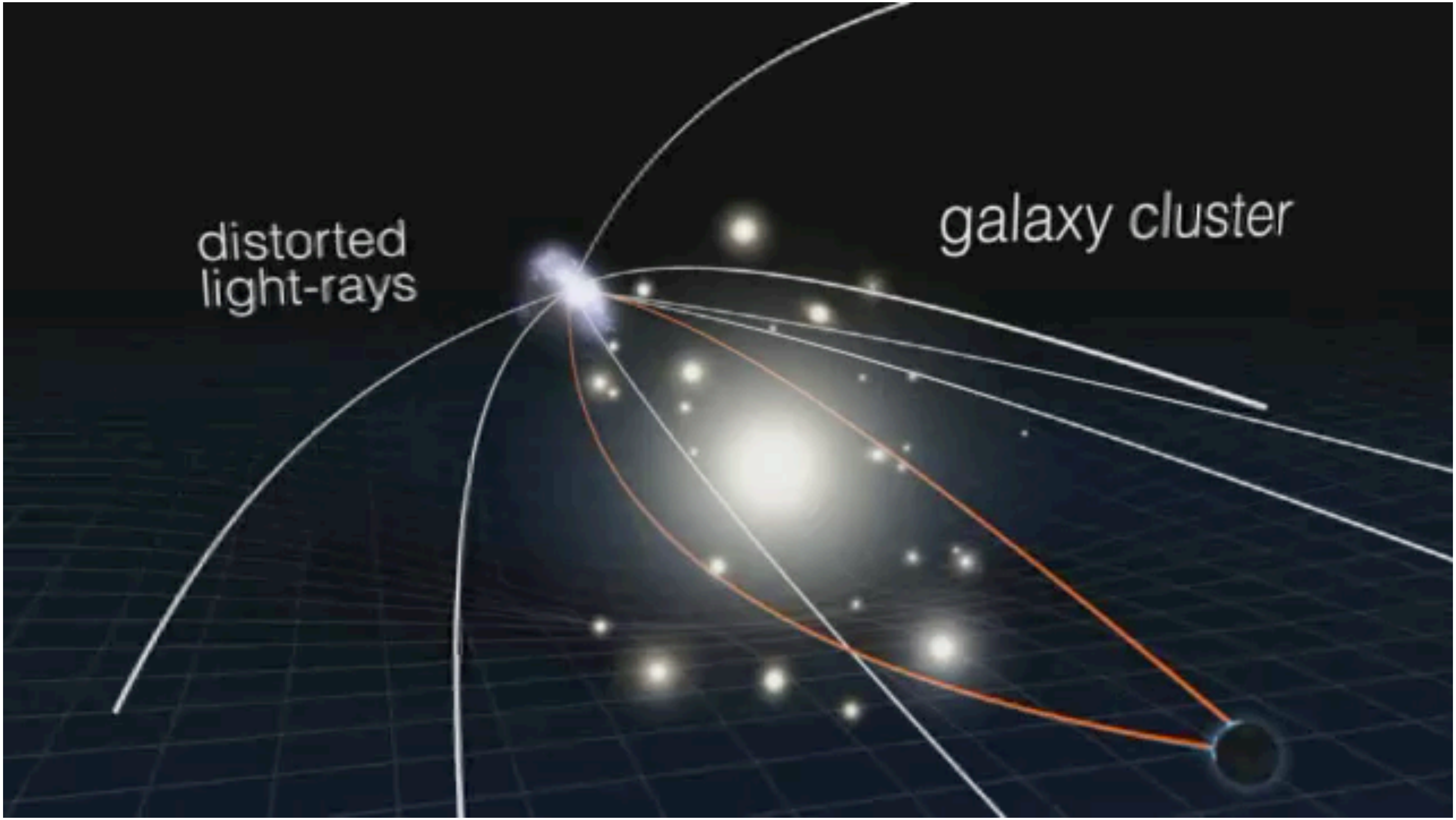
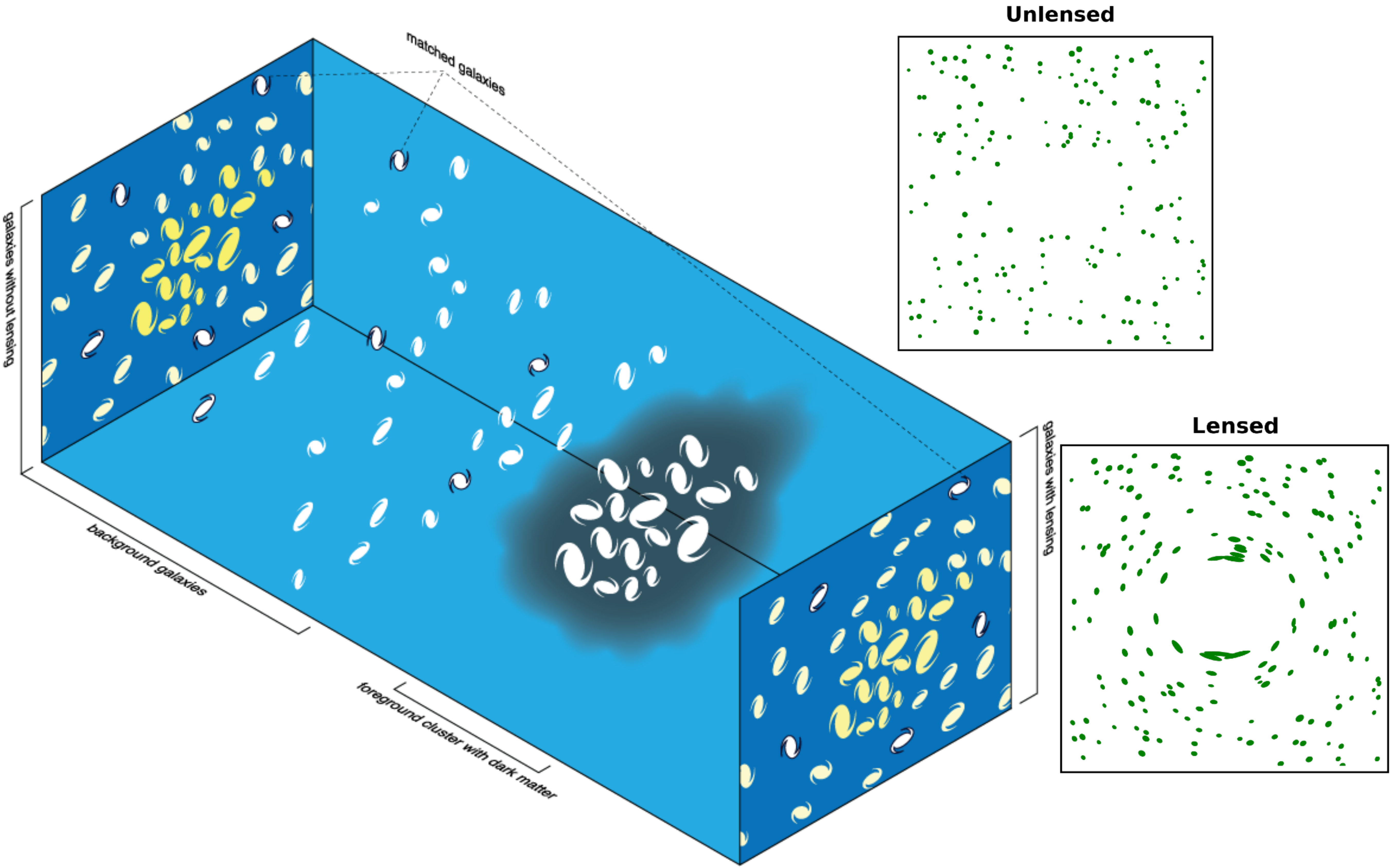
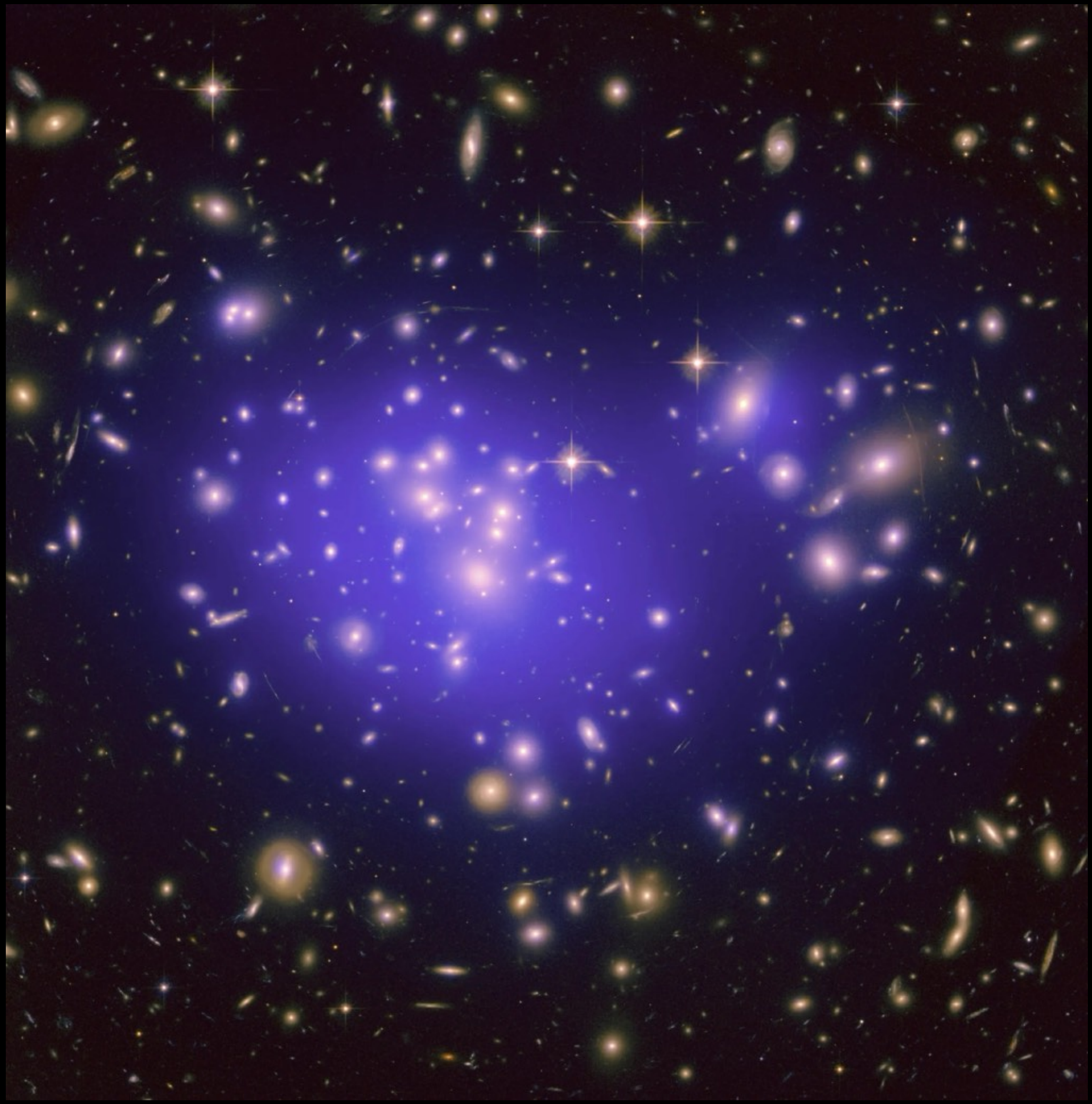


Image distortion due to weak lensing

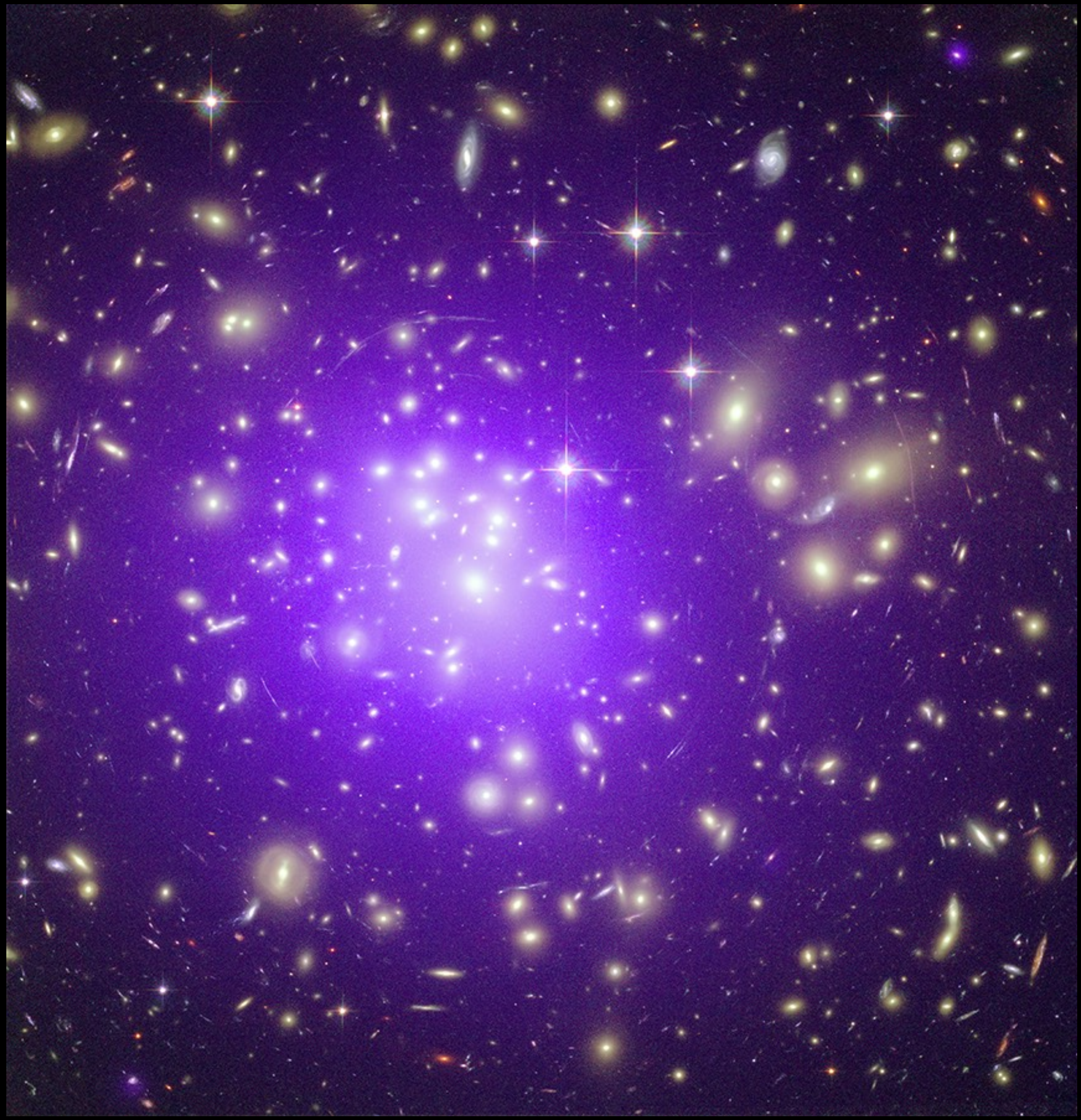


Total mass distribution of a galaxy cluster from weak lensing

Abell 1689 Weak Lensing vs. Optical

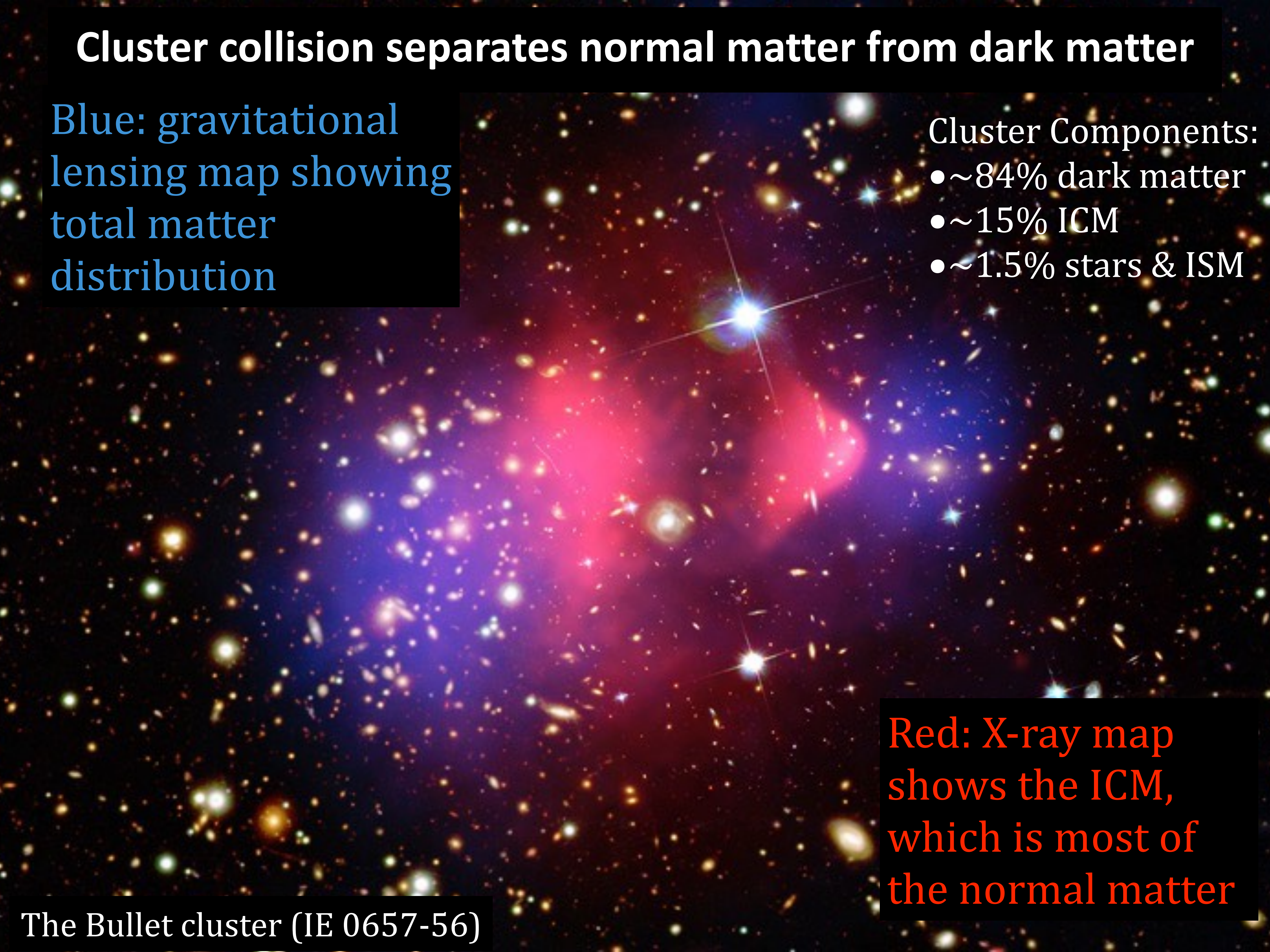


Abell 1689 X-ray vs. Optical

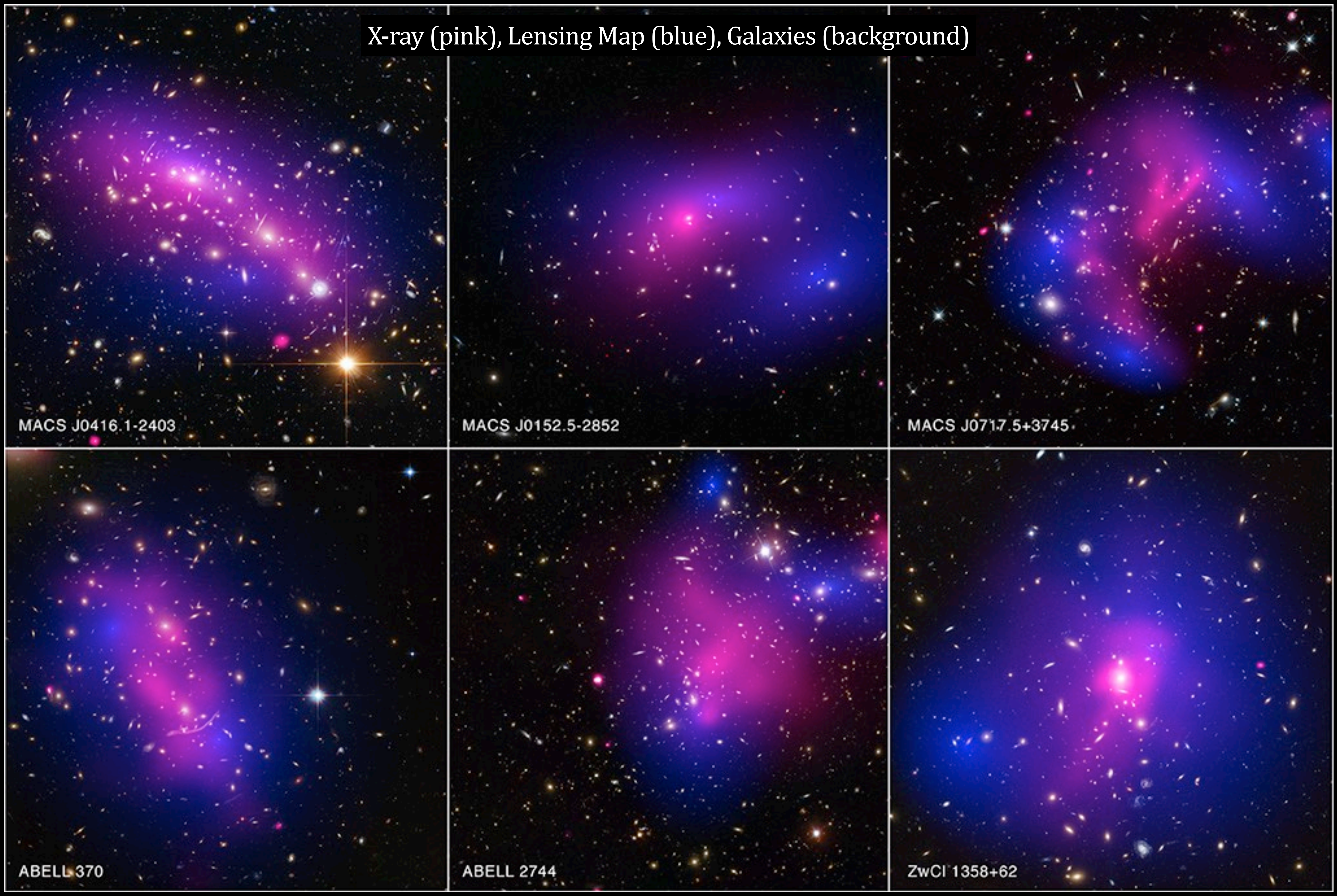


If dark matter and normal matter are distinctly separated in a galaxy cluster, we would expect the mass distribution from lensing to be completely different from the X-ray gas distribution

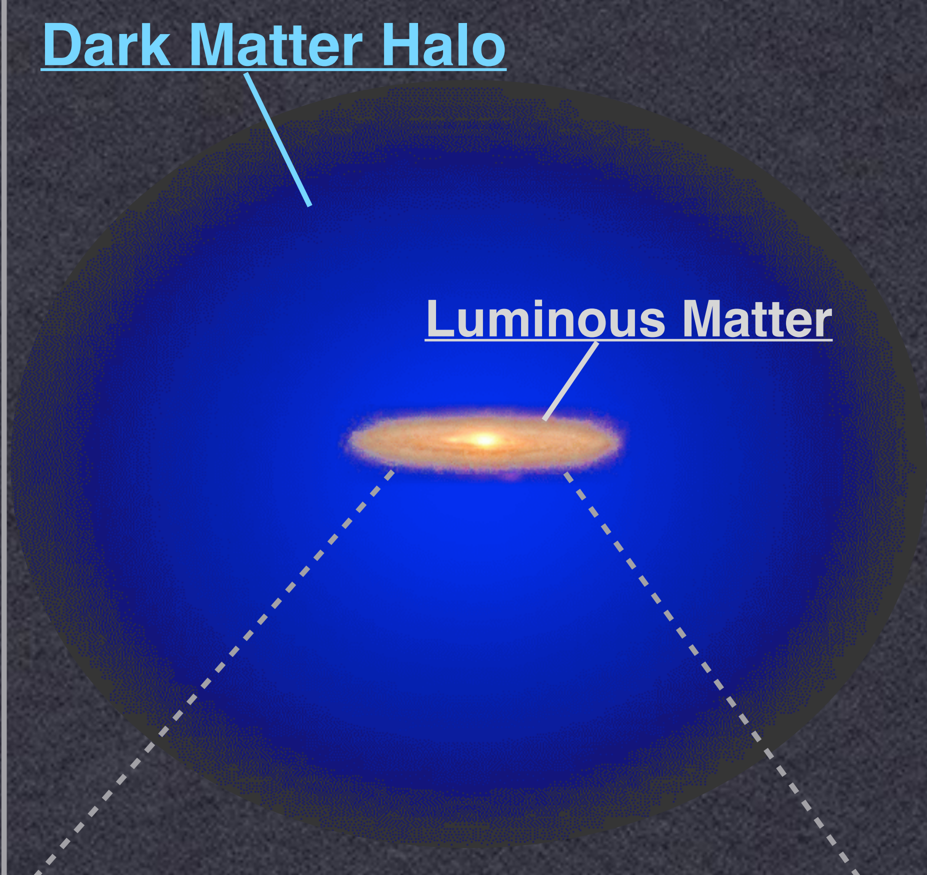
Cluster collision separates normal matter from dark matter



When clusters collide, the ICM could be separated from the dark matter



A Key Component of M31 is Missing …



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    atomic/molecular H, helium
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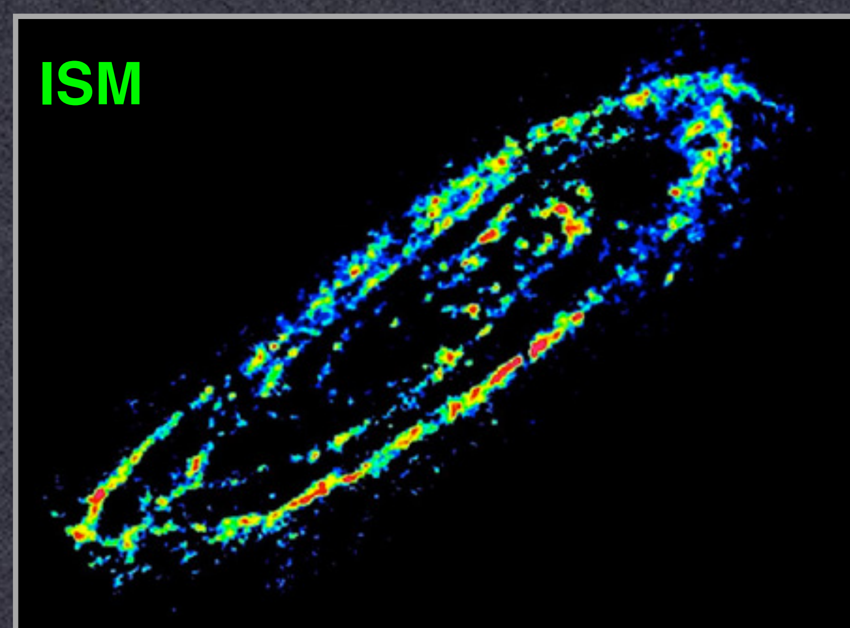
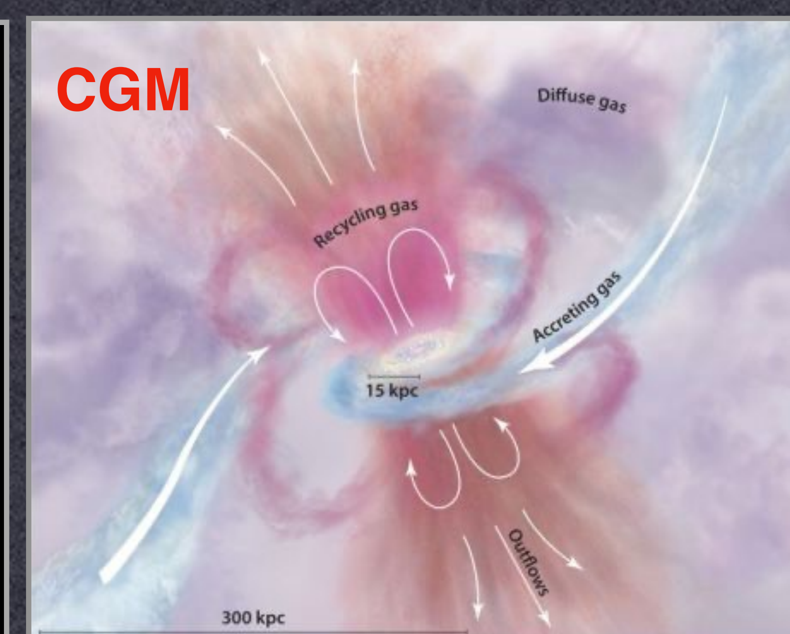




references: Corbelli+2010, Nieten+2005, Lehner+2015

Interstellar (2014)

Hunting for SMBHs in Galaxies
methodology

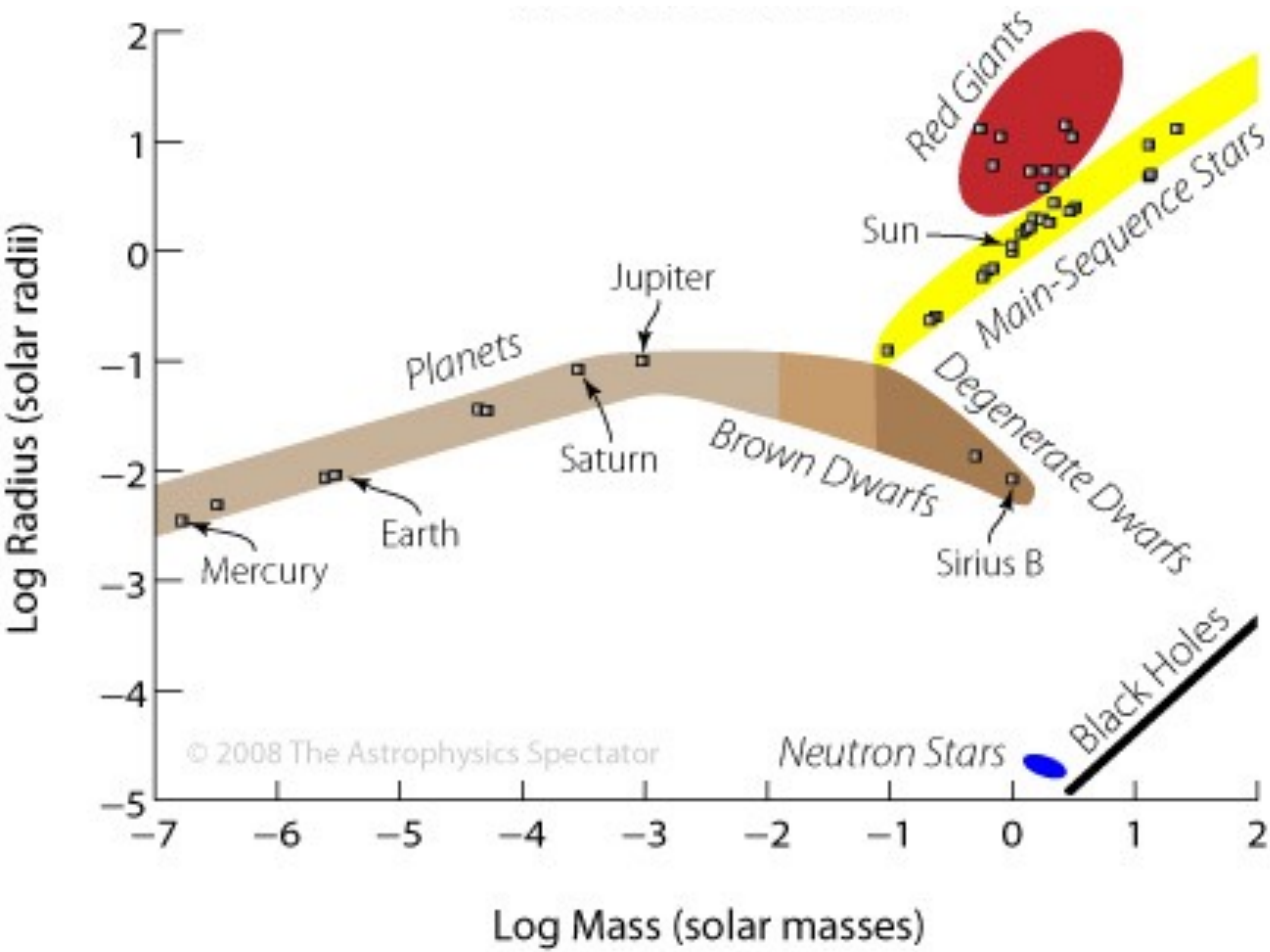
Method 1: Resolving the Event Horizon (Schwarzschild Radius)

- In **1916**, **Karl Schwarzschild** obtained the solution to Einstein's field equation for a **non-rotating, spherically symmetric body**.
- The solution has two singularities, one at r = 0, the other at $\boldsymbol{r = r_s = 2GM/c^2}$, and $\boldsymbol{r_s}$ is called the **Schwarzschild radius**. $\mathbf{r_s}$ defines the **event horizon** of a Schwarzschild black hole:

$$r_s = \frac{2GM_{\rm BH}}{c^2} = 3\,{\rm km}\left(\frac{M_{\rm BH}}{1M_\odot}\right) = 2\,{\rm AU}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$$

- Note the implied **mass-radius relation** for black holes: $r_s \propto M$

Mass-Radius Relations of Planets, Stars, White Dwarfs, Neutron Stars, and Black Holes (from stellar mass to supermassive black holes)



Practice: the Size of a Supermassive Black Hole

- How big are supermassive black holes? We can use the Schwarzschild radius formula if we know the mass of the black hole.
- The black hole in M87 has a mass of 6.6 billion M_{Sun}
- The Schwarzschild radius is:

$$r_s = \frac{2GM_{\mathrm{BH}}}{c^2} = 3\,\mathrm{km}\,\left(\frac{M_{\mathrm{BH}}}{1M_\odot}\right) = 2\,\mathrm{AU}\left(\frac{M_{\mathrm{BH}}}{10^8\,M_\odot}\right)$$

- For M87:

$$r_s = 130\ \mathrm{AU}$$

- This is just about 4 times the radius of Neptune's orbit! or about the same size as the heliosphere (r $\sim$ 123 AU)

Method 1: Resolving the Event Horizon (Schwarzschild Radius)

- In **1916**, **Karl Schwarzschild** obtained the solution to Einstein's field equation for a **non-rotating, spherically symmetric body**.
- The solution has two singularities, one at r = 0, the other at $\boldsymbol{r = r_s = 2GM/c^2}$, and $\boldsymbol{r_s}$ is called the **Schwarzschild radius**. $\mathbf{r_s}$ defines the **event horizon** of a Schwarzschild black hole:

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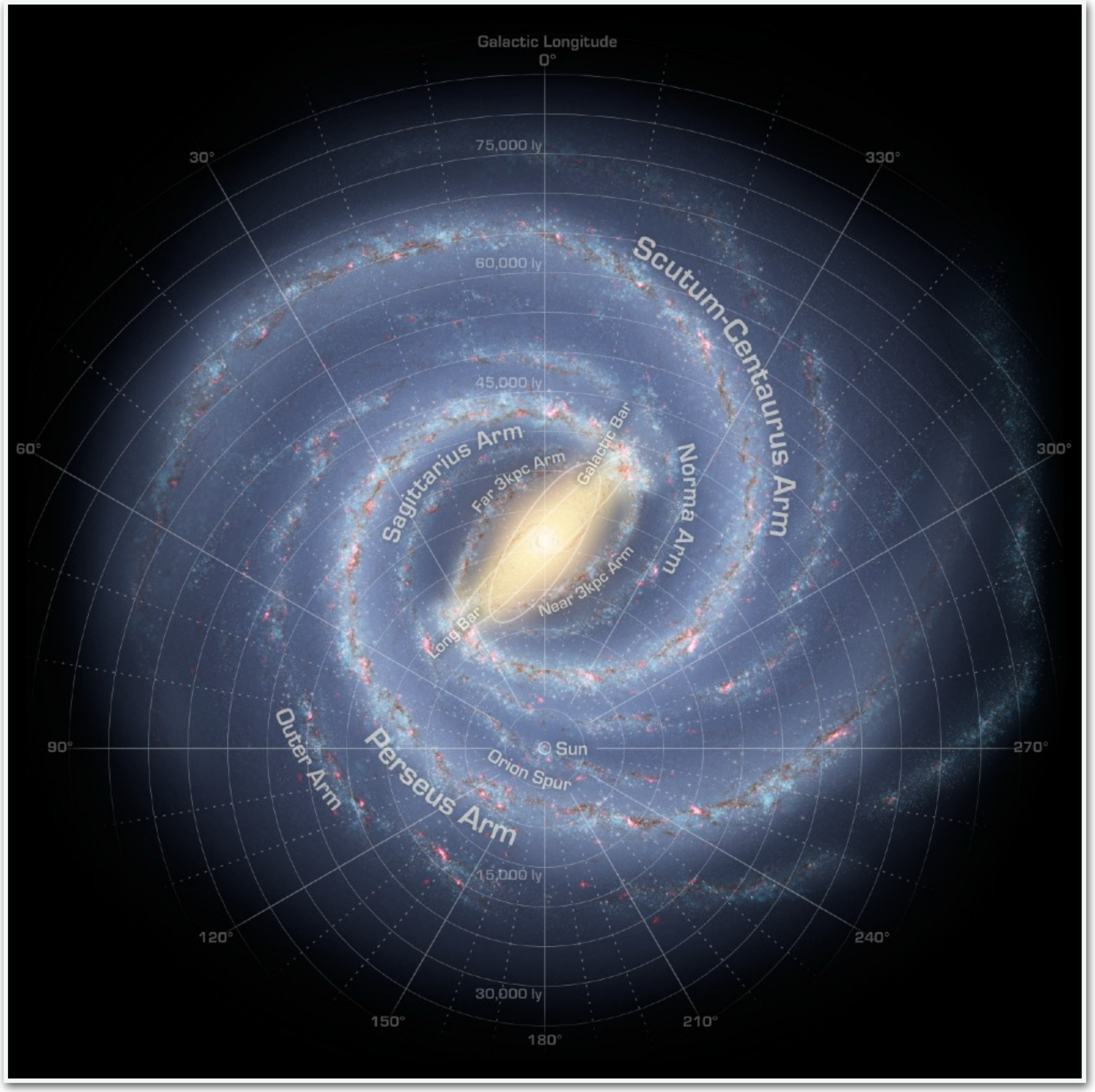
- Note the implied **mass-radius relation** for black holes: $r_s \propto M$

Practice: Can we spatially resolve the SMBH closest to us?

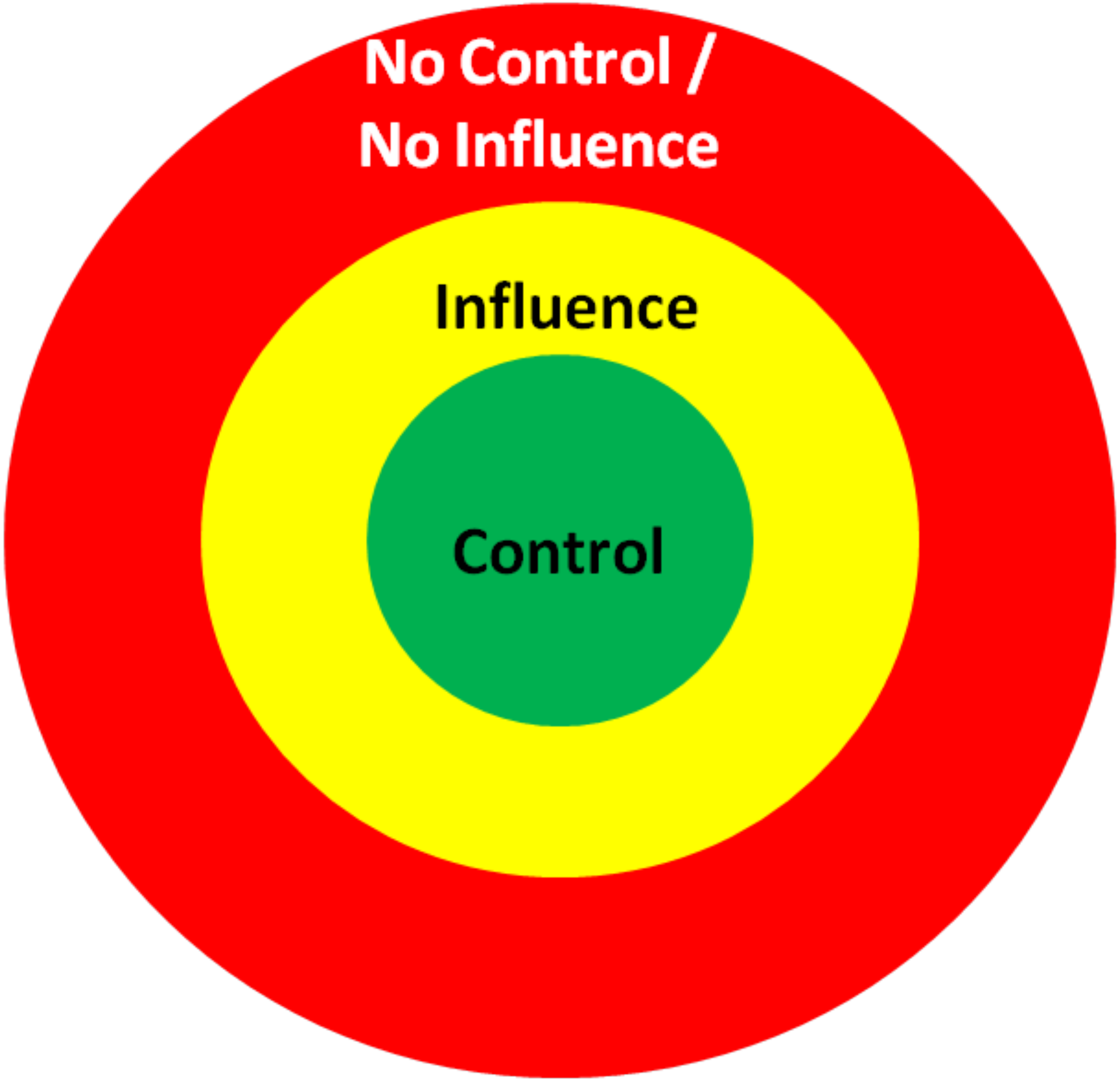
- Our distance to our Milky Way's center is 8 kpc.
- Suppose the SMBH at the center of MW is 1e8 M_{sun}(*much larger than actual mass*), its event horizon would have a radius of 2 AU.
- At this distance, what's the ***angular radius*** of the event horizon?



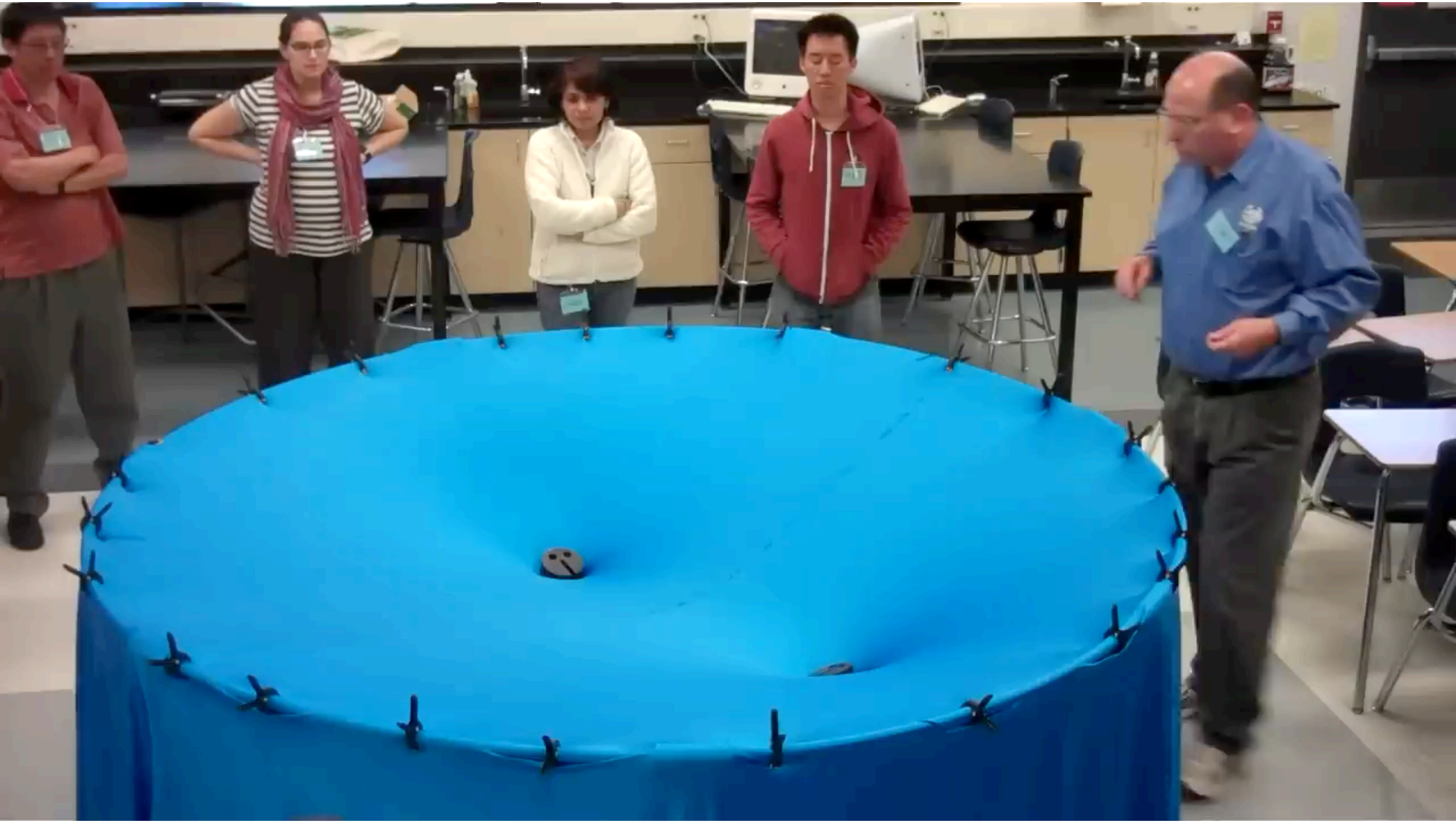
1 AU at 1 pc = 1 arcsec
1 AU at 1 kpc = 1 mas
2 AU at 8 kpc = 0.25 mas
= 250 micro-arcsec

Hubble Space Telescope's
diffraction limit:
lambda/D ~ 52 mas

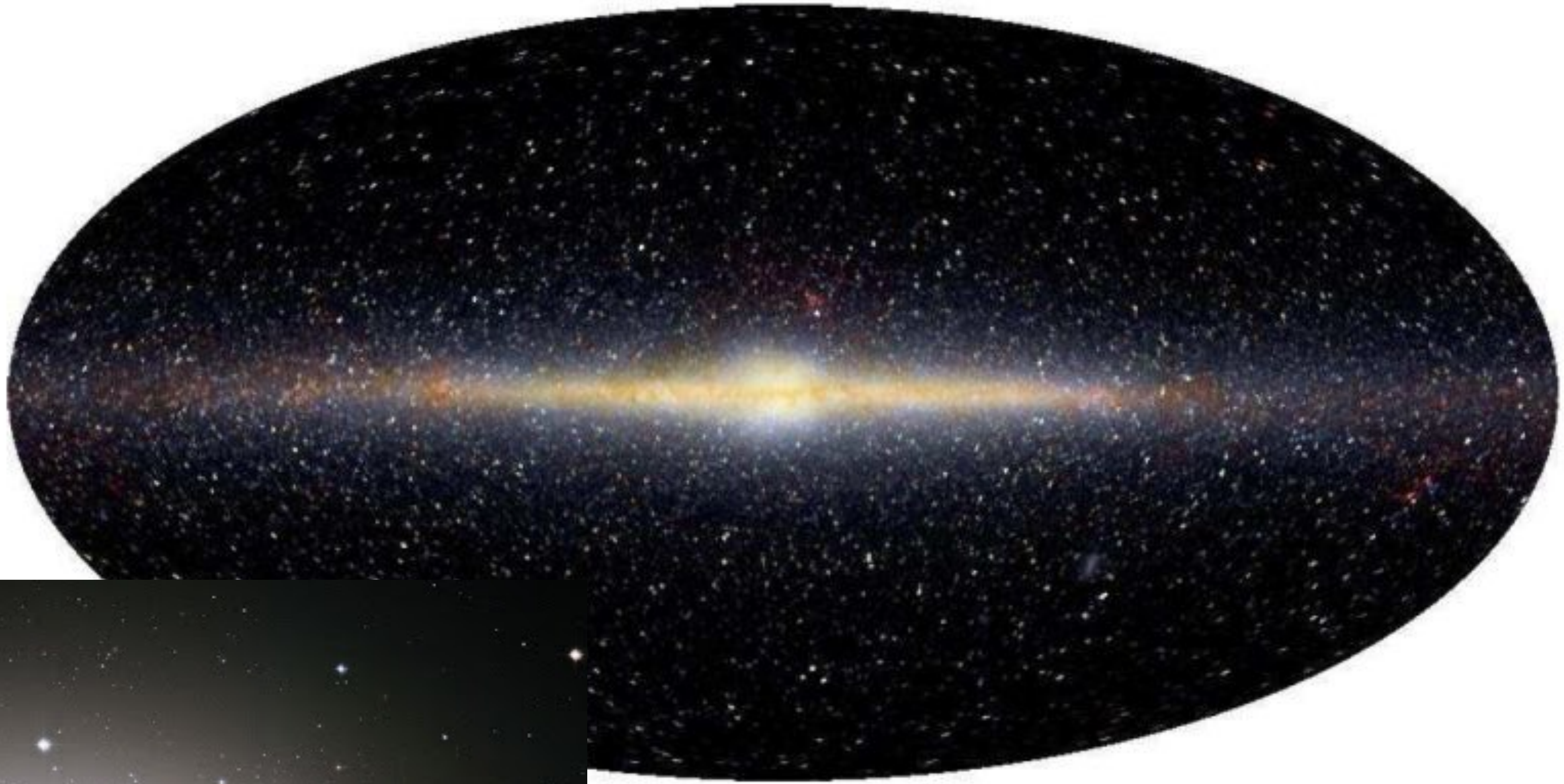
The Sphere of Influence of an Entity is Larger than the Entity Itself



Sphere of Influence of a SMBH inside a Galactic Bulge



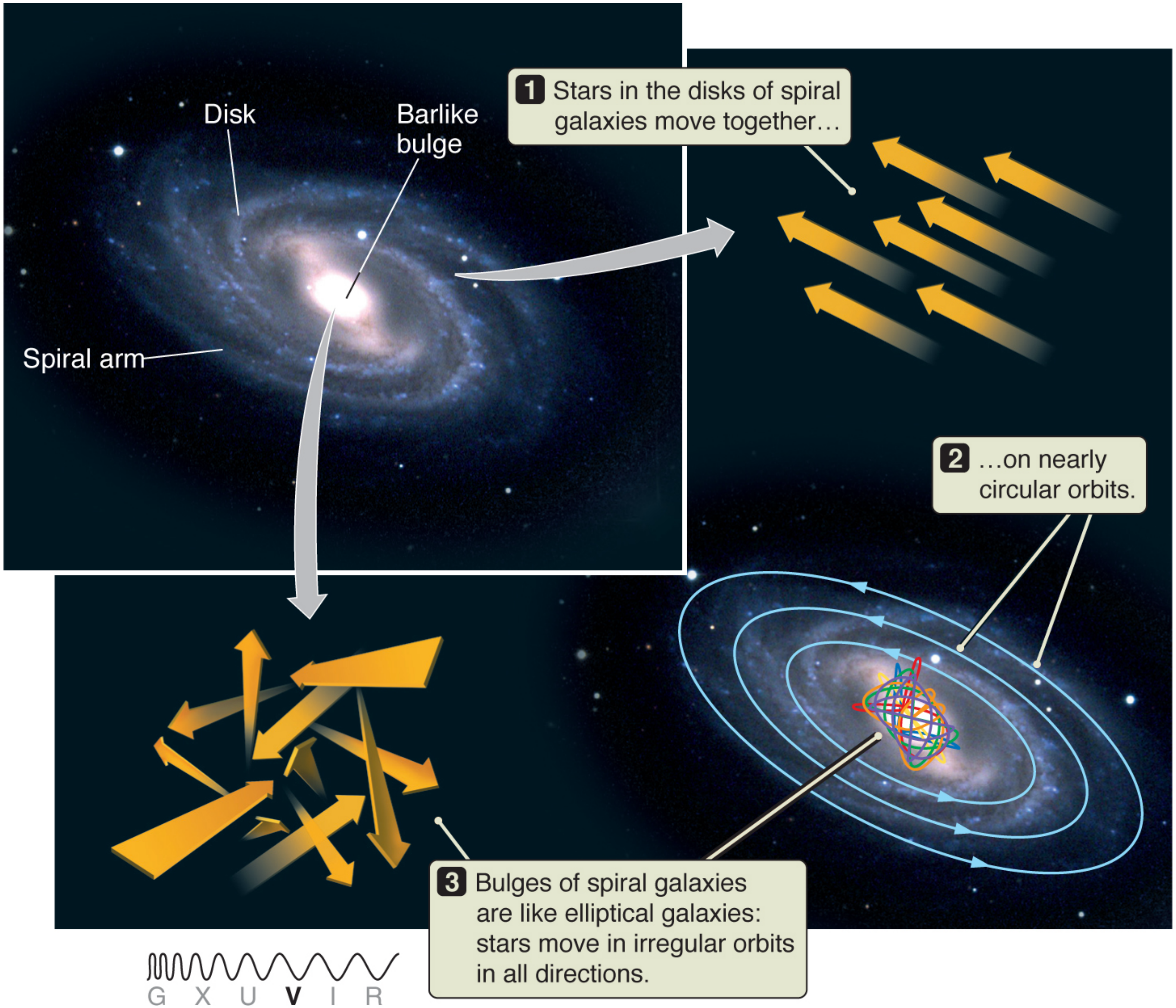
The Central SMBH live inside a Stellar Bulge made of stars on randomly oriented orbits



The Milky Way Galaxy

The Sombrero Galaxy

Spiral Galaxies:
Regular Circular Orbits of Disk Stars + Irregular Orbits of Bulge stars

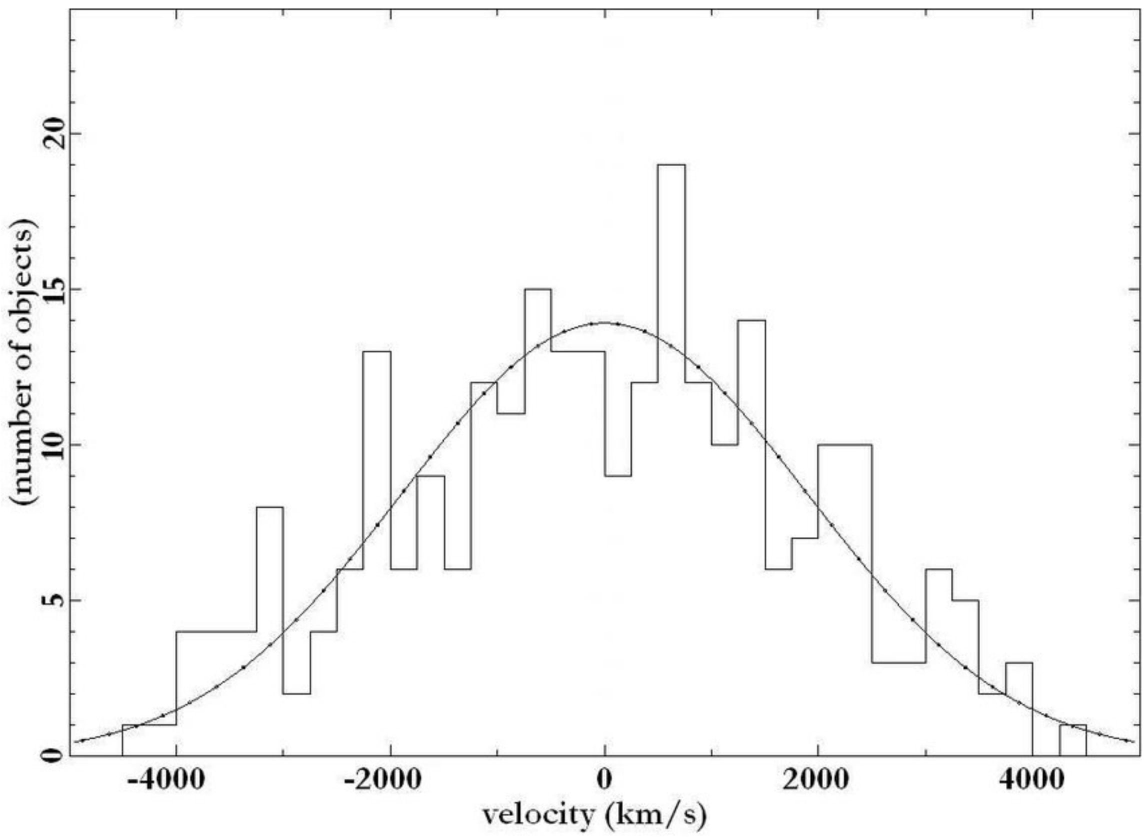


Recall Velocity Dispersion of Galaxies in a Cluster

Zwicky 1933: **velocity dispersion** of galaxies in the Coma Cluster

Virial Theorem: $2\bar{K} + \bar{U} = 0 \rightarrow \sigma^2 = GM/R \rightarrow M = \sigma^2 R/G$

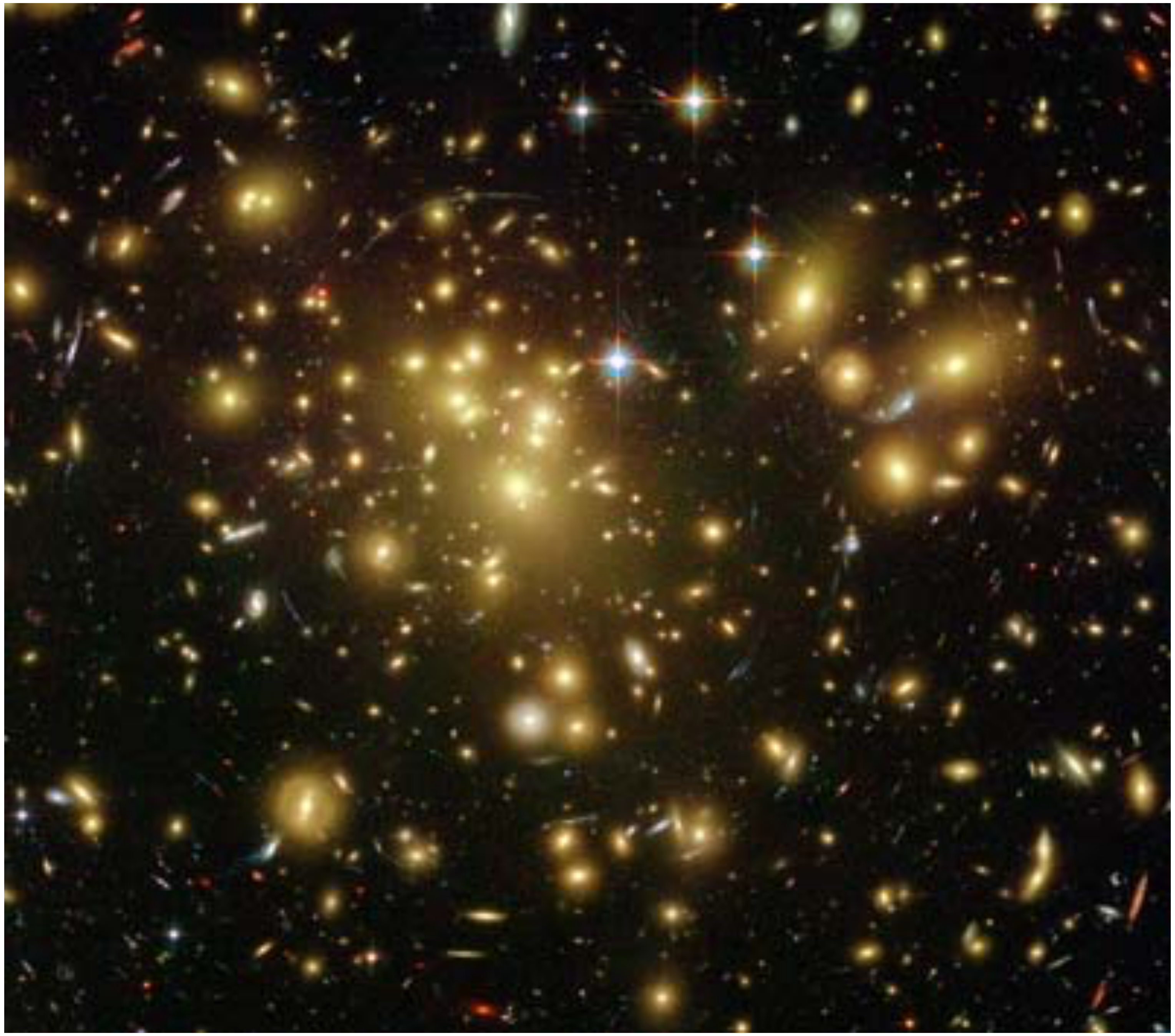
The virial mass is **400x** greater than visible stellar mass



Gaussian Probability Density Function

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where σ is the standard deviation and μ the mean



Method 2: Resolve the Sphere of Influence of a SMBH

- The **Schwarzschild radius** defines the **event horizon** of a Schwarzschild blackhole:

$$r_s = \frac{2GM_{\rm BH}}{c^2} = 3\,{\rm km}\left(\frac{M_{\rm BH}}{1M_\odot}\right) = 2\,{\rm AU}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$$

- The **sphere of influence** of a black hole defines the region around the BH where its gravity strongly affect the kinematics of stars:

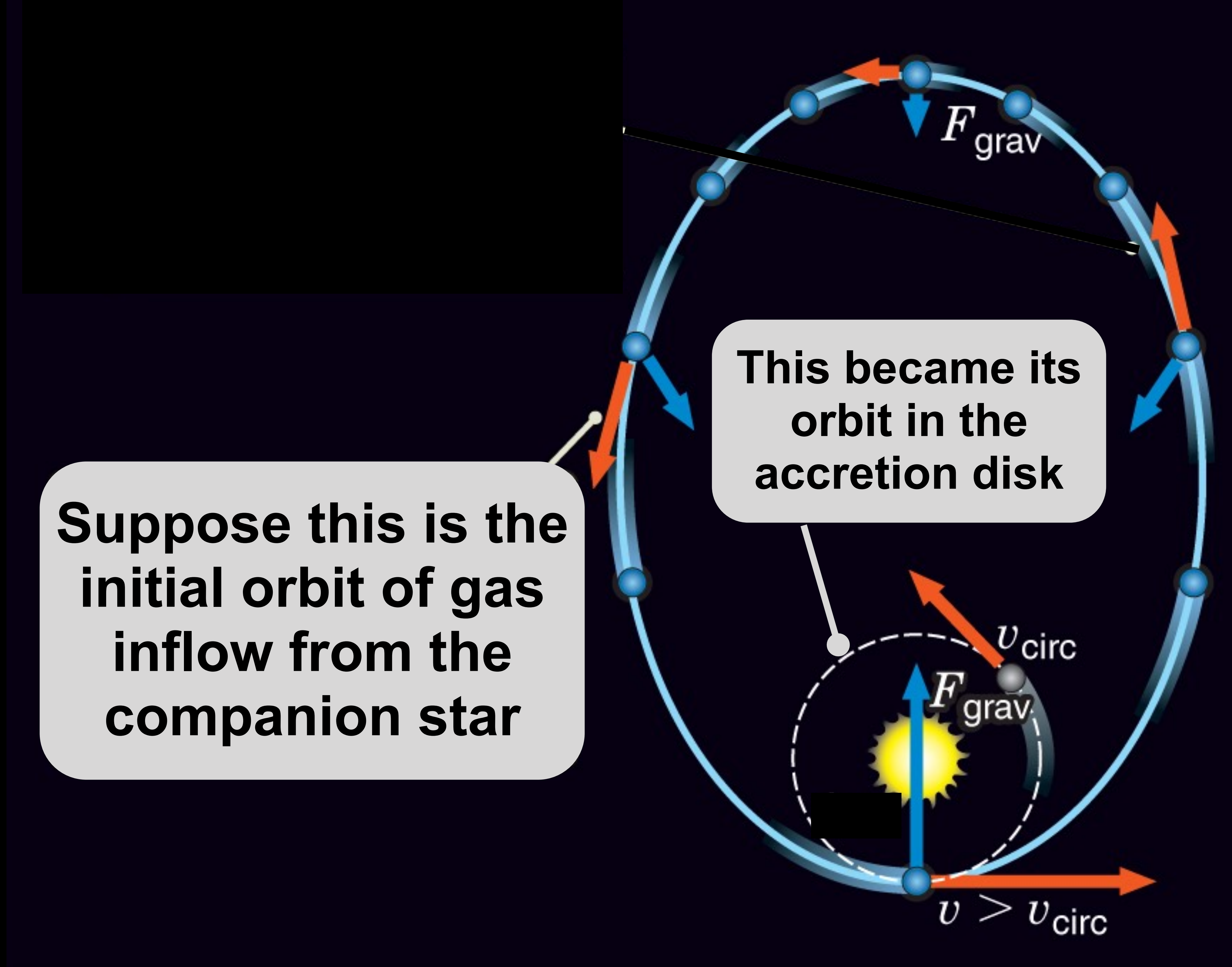
$$\frac{GM_{\rm BH}}{r^2} \geq \frac{\sigma_*^2}{r} \Rightarrow$$

$$r < r_* = \frac{GM_{\rm BH}}{\sigma_*^2} = 11\,{\rm parsec}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{200\,{\rm km/s}}{\sigma_*}\right)^2$$

- For a 10^8 M_{sun} BH inside a stellar bulge that has a velocity dispersion σ_* of 200 km/s, the radius of **the sphere of influence** is ***a million times*** greater than the radius of **the event horizon**.

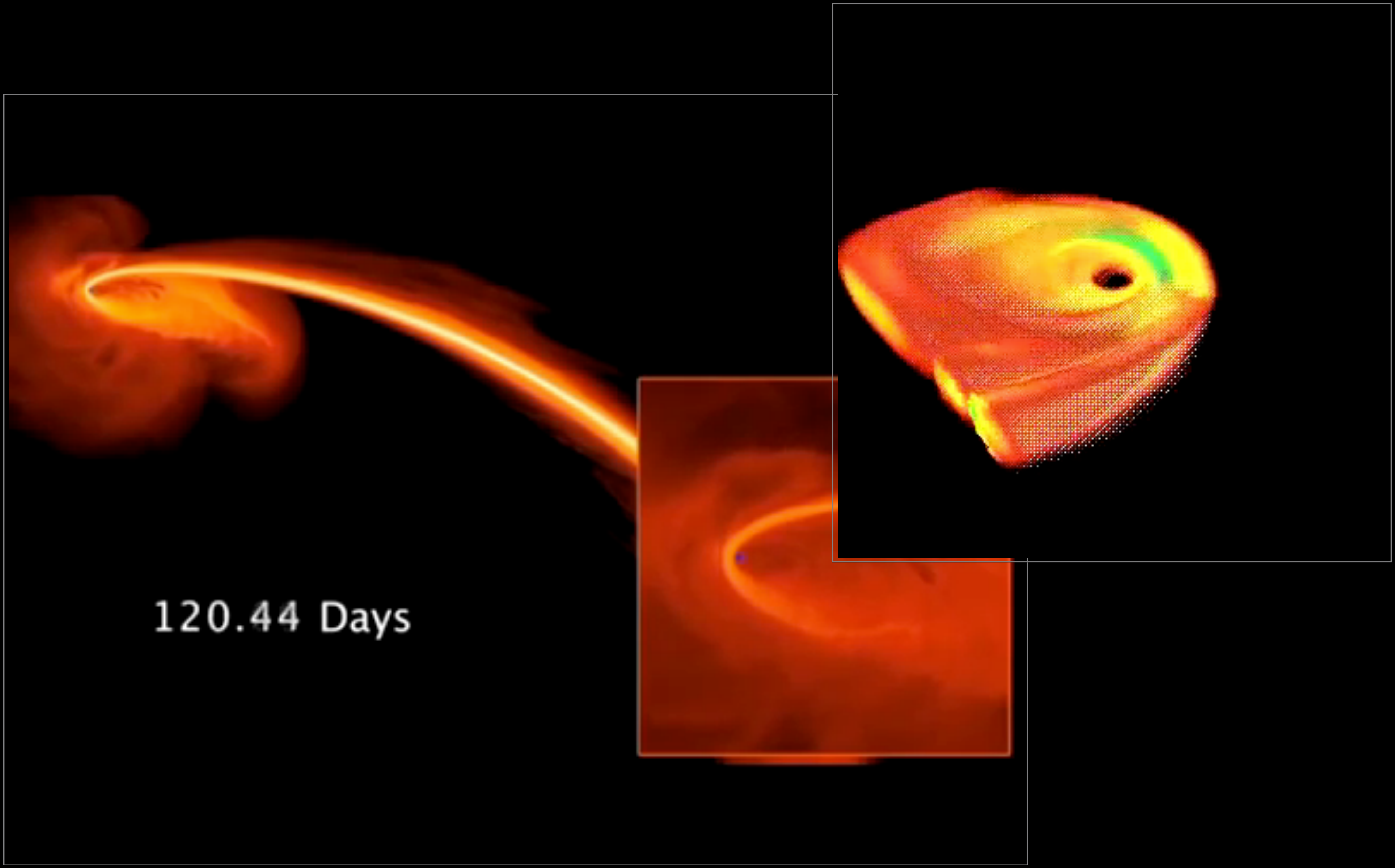
- **But note that the sphere of influence is still *tiny* compared to the size of the galaxy, which is at least ~10 kpc in radius (1000x larger), depending on how you define its boundary.**

Method 3: Detect Enormous Accretion Energy

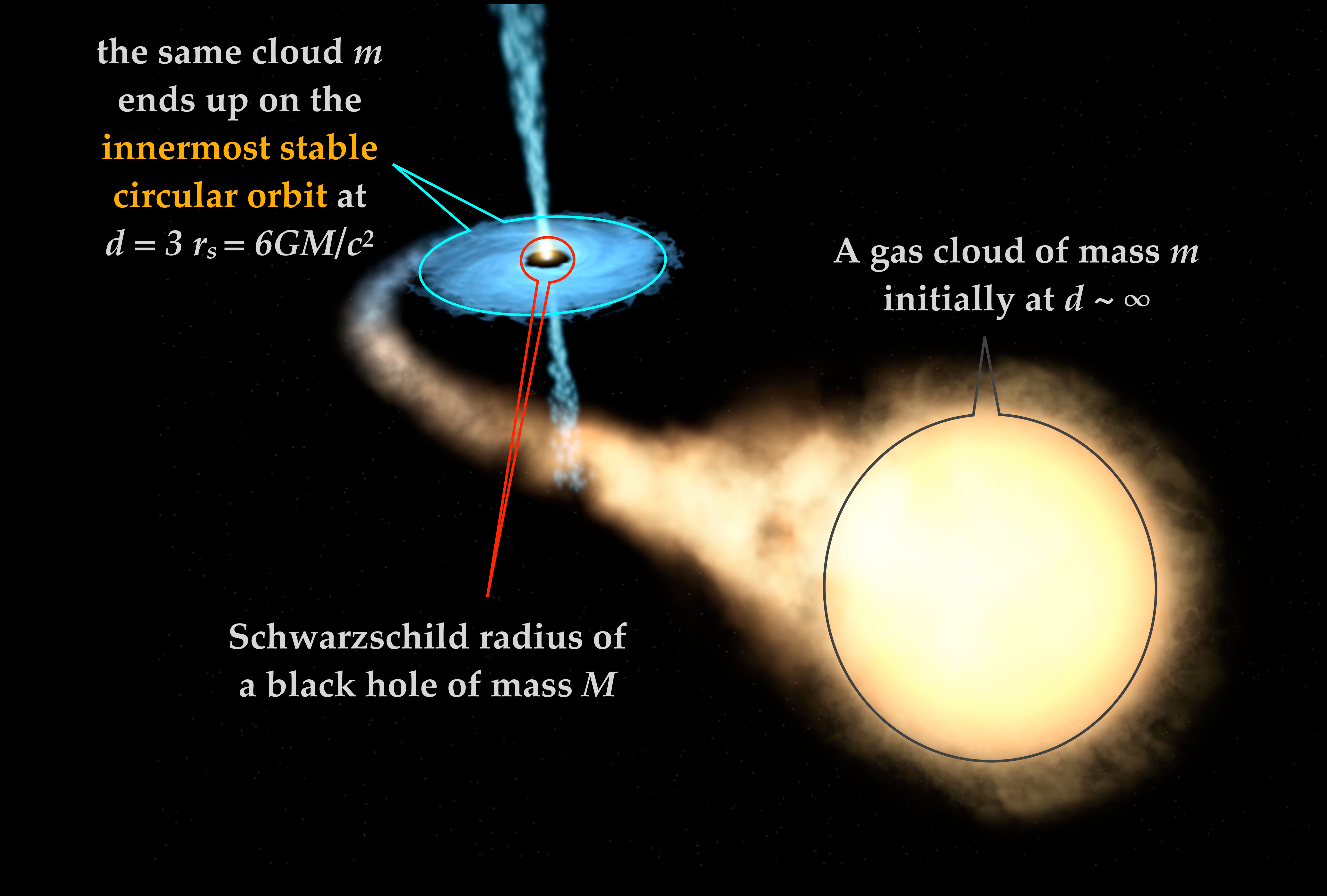


How gravitational accretion produces energy?

Simulation of the formation of an accretion disk



The accretion disk around a black hole has an inner edge



Energy Release from Black Hole Accretion

- Initial energy of a gas cloud m before accretion:

  $$K + U = mv^2/2 - GMm/d = 0$$

  because $v = 0$ at $d = \infty$.

- Final energy at the last stable orbit at $d = 3\,r_s = 6GM/c^2$:
  We can use either Virial Theorem (2 K + U = 0) or Newton's law and circular orbits to obtain the following

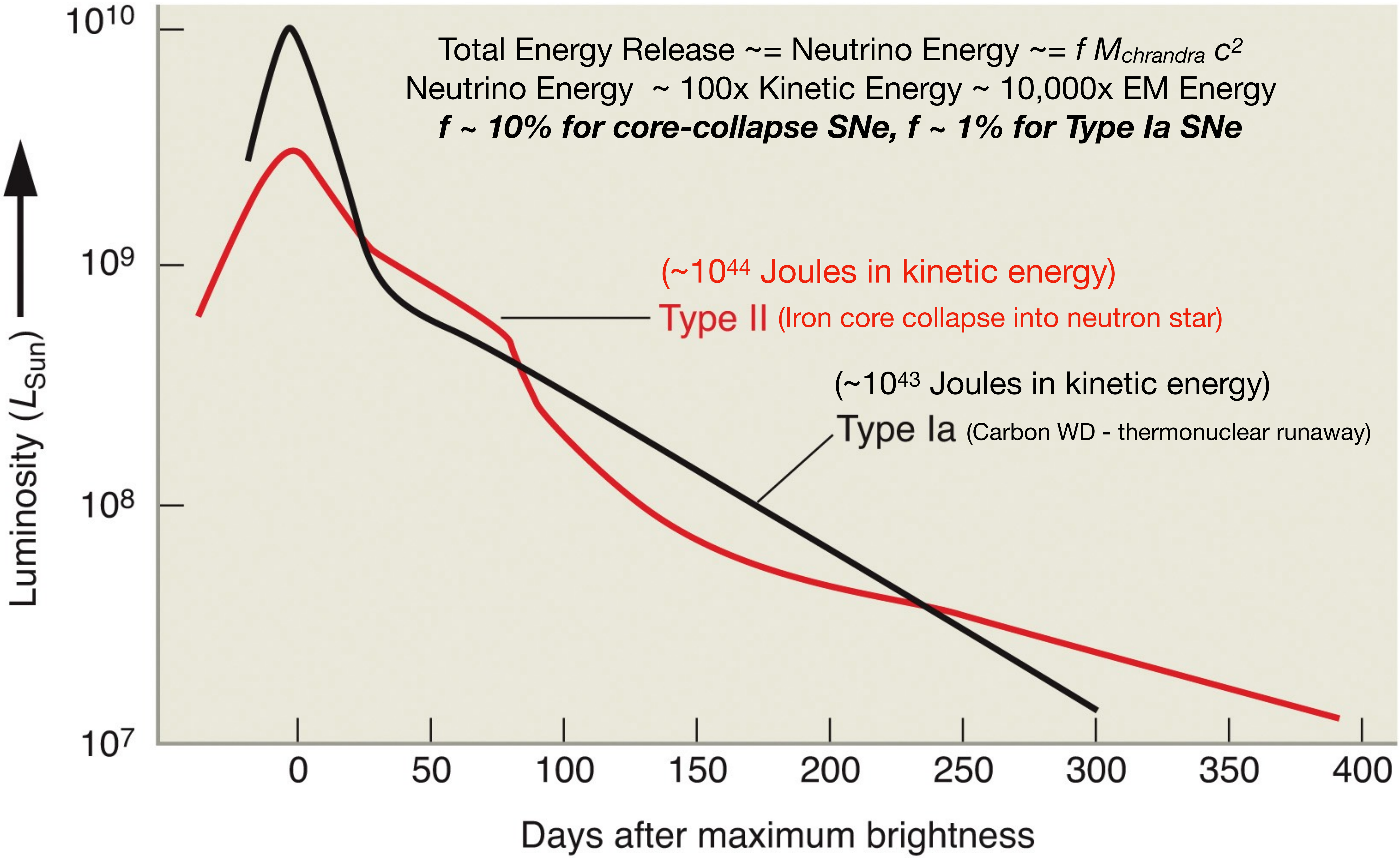
  $$K + U = U/2 = -GMm/2d = -mc^2/12$$

- The difference between the initial energy and the final energy must be released to allow accretion to occur. So the amount of energy released is $mc^2/12$ during the accretion of mass m.

- This shows that roughly **10% (~1/12) of the rest mass** is converted into energy. For comparison, the pp chain converts **0.7%** of the rest mass into energy (because $\delta m/m = 0.7\,\%$ between 4xH and 1xHe).

- This is huge! Just 1 Solar mass is accreted in a year, the released energy would be as luminous as 10^{12} Suns combined!

This explains the 10% mass-energy conversion factor of Type II SNe



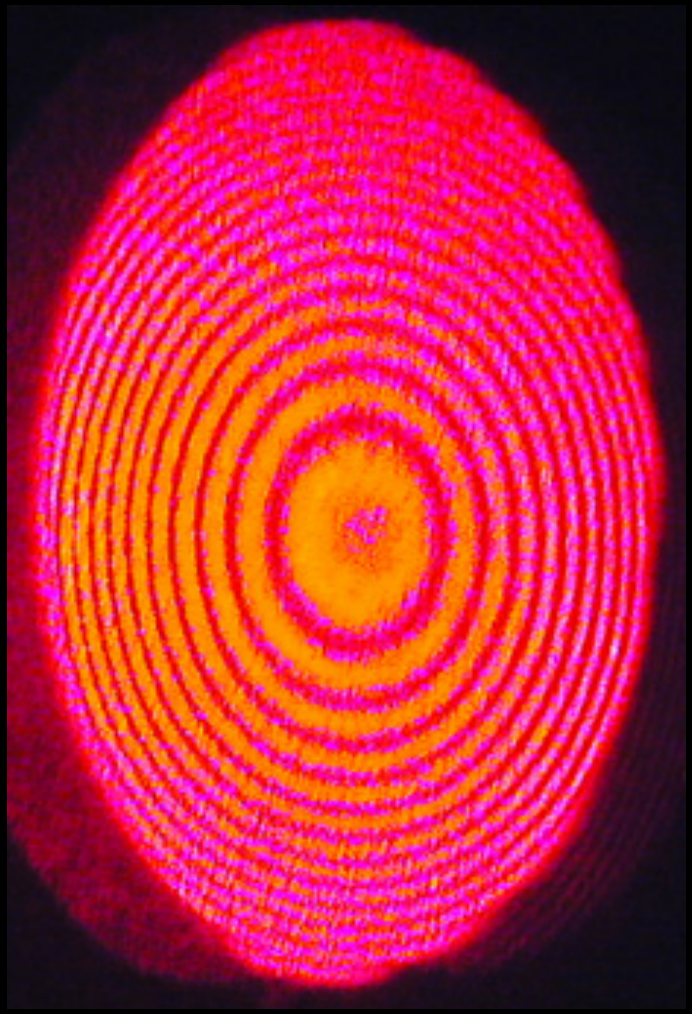
Summary: Tools for detecting supermassive black holes

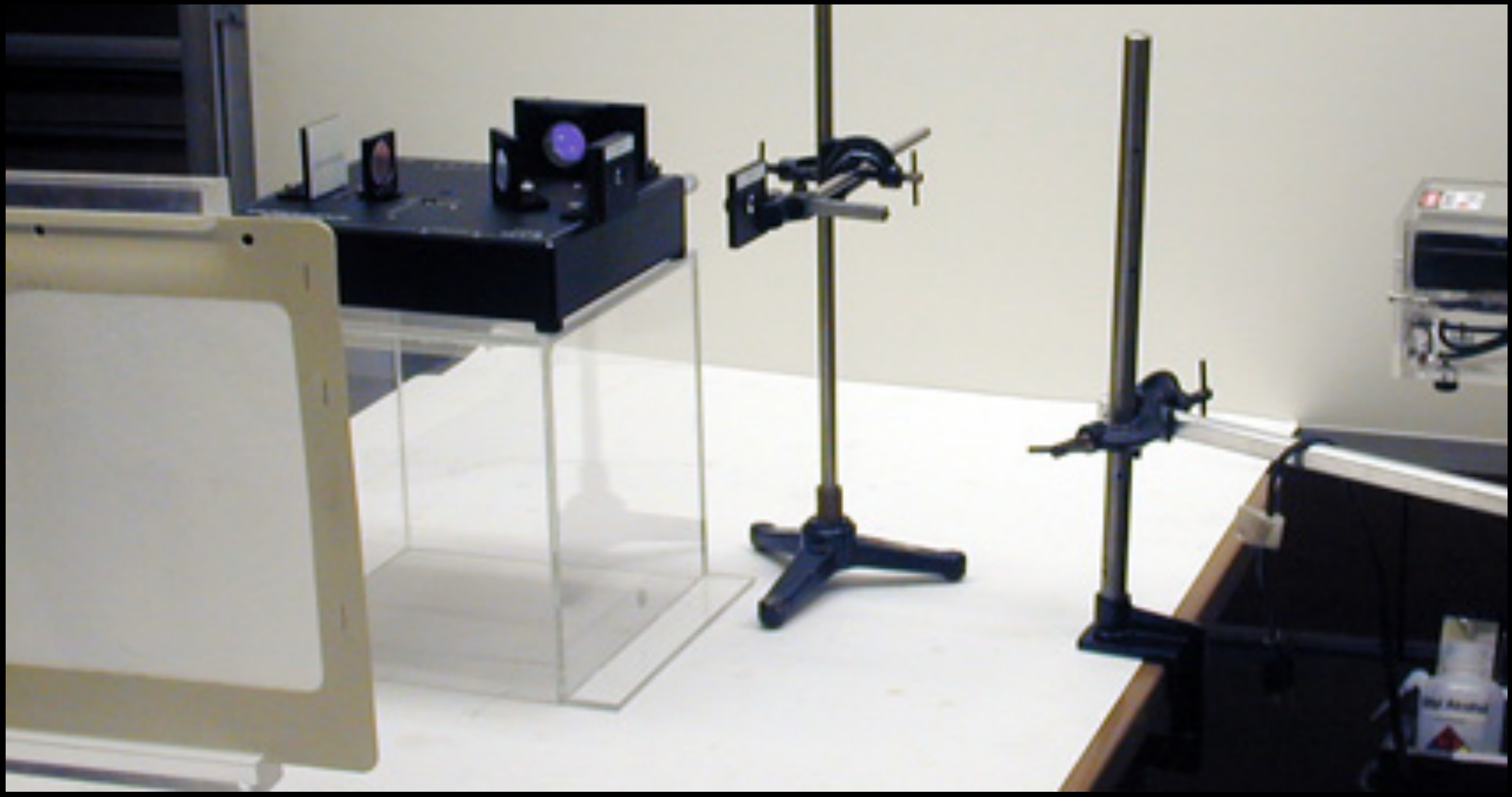
- **Resolve the event horizon**
  - $r_s = \frac{2GM_{\rm BH}}{c^2} = 3\,\mathrm{km}\left(\frac{M_{\rm BH}}{1M_\odot}\right) = 2\,\mathrm{AU}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$
  - Aperture synthesis with a network of radio observatories
  - Minimizing the diffraction limit: $\theta = \lambda/D$
- **Resolve the sphere of influence**
  - $r_* = \frac{GM_{\rm BH}}{\sigma_*^2} = 11\,\mathrm{parsec}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{200\,\mathrm{km/s}}{\sigma_*}\right)^2$
  - Studies of Stellar and Gas Kinematics
  - Adaptive Optics or Space Telescopes like HST
- **Detect the incredible energy generation from accretion**
  - $L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,\mathrm{yr}^{-1}}\right)$
  - Studies of Active Galactic Nuclei (AGN)
- **Detect the gravitational wave generated from BH mergers**
  - Gravitational wave detectors like the Pulsar Timing Array

Evidence of SMBHs in the Nearest Massive Galaxies

Resolving the event horizon

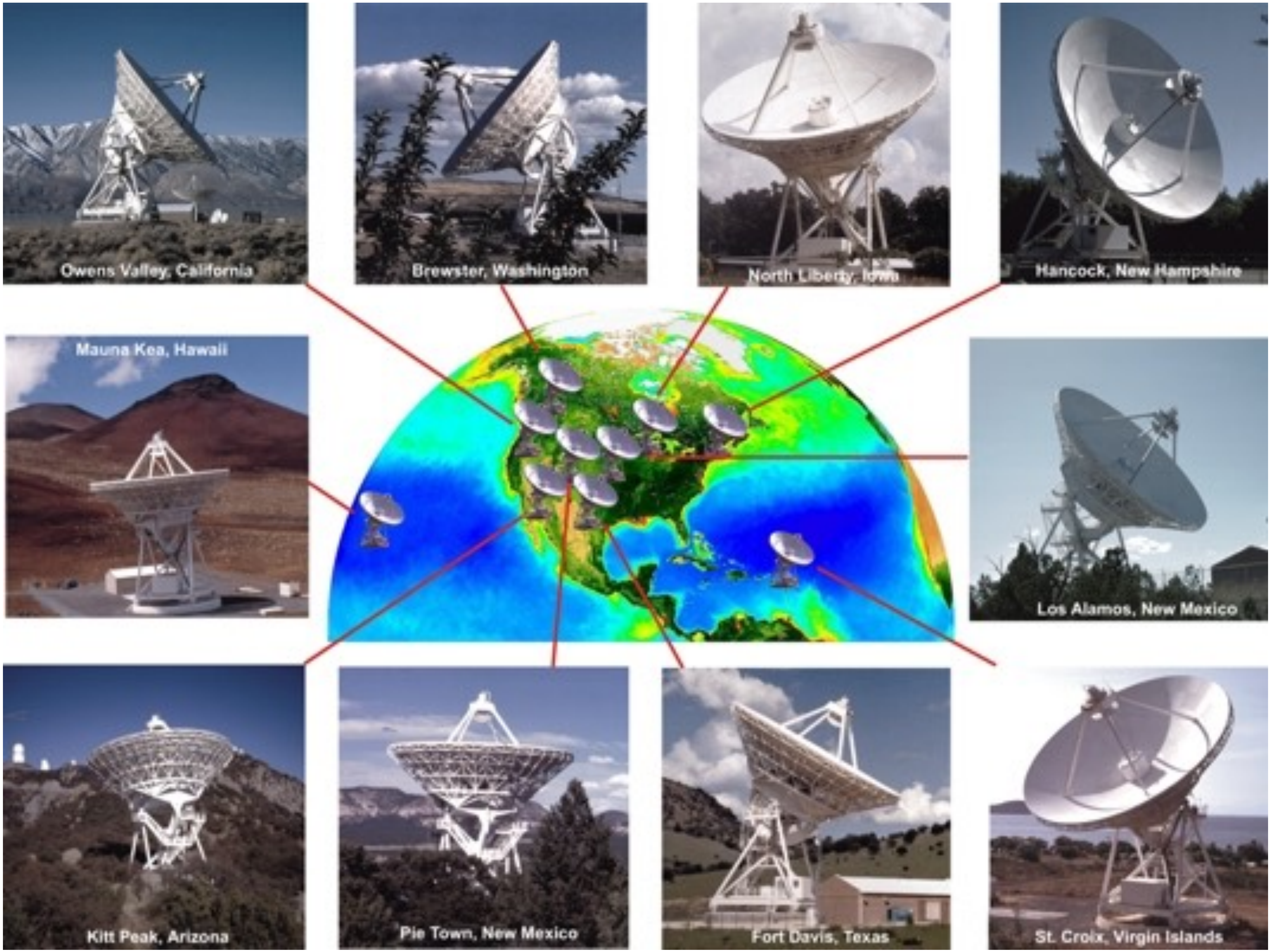
Michelson interferometer (demo)





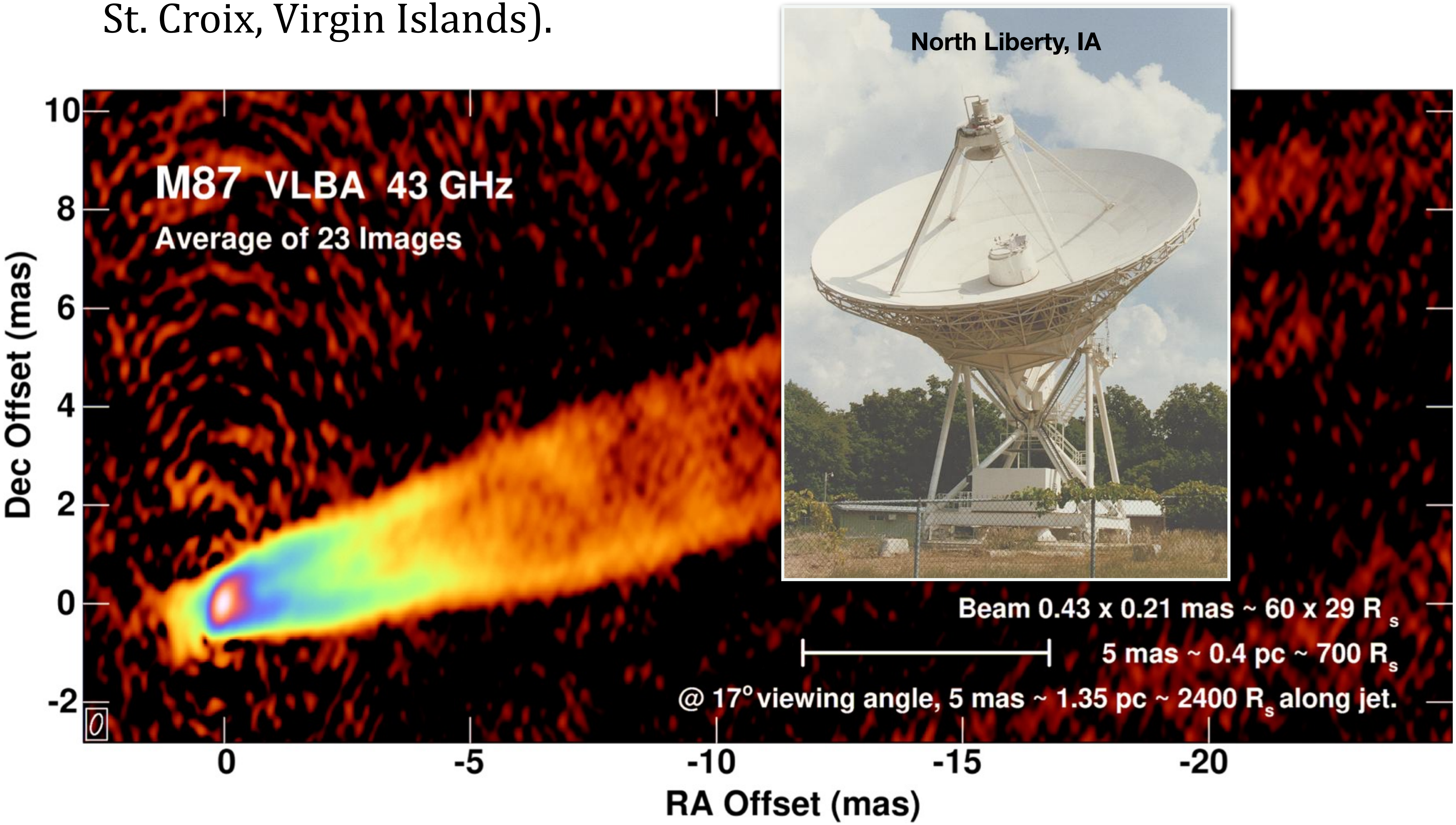
The Very Large Array (VLA)

The Very Long Baseline Array (VLBA)



Now the North Liberty Station of the Very Long Baseline Array

- The VLBA is an interferometer consisting of 10 identical 25-meter antennas, separated by distances from 200km to transcontinental 8600 km (with the longest baseline between Mauna Kea, Hawaii and St. Croix, Virgin Islands).



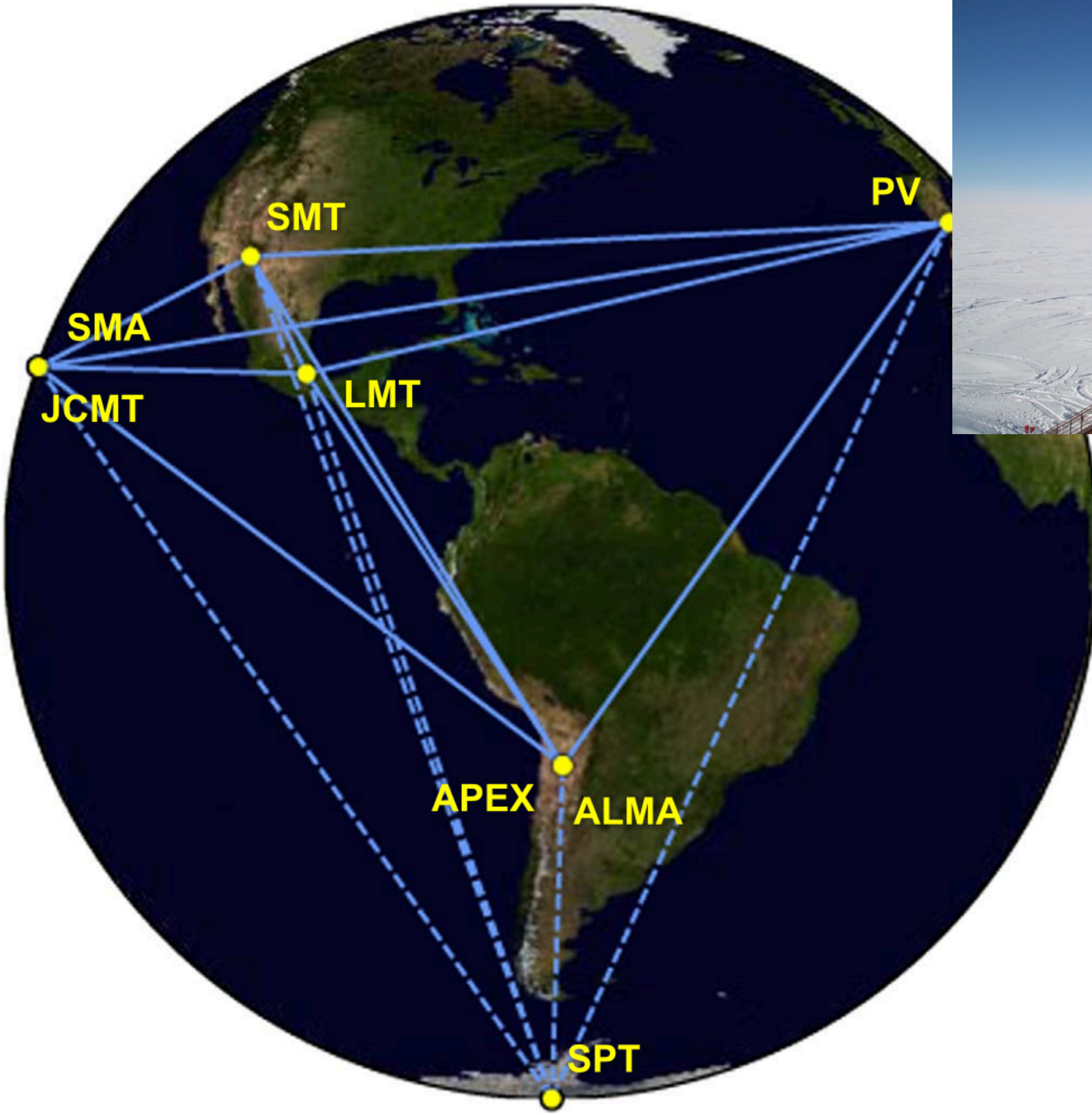
The Univ. of Iowa North Liberty Radio Observatory in 1973

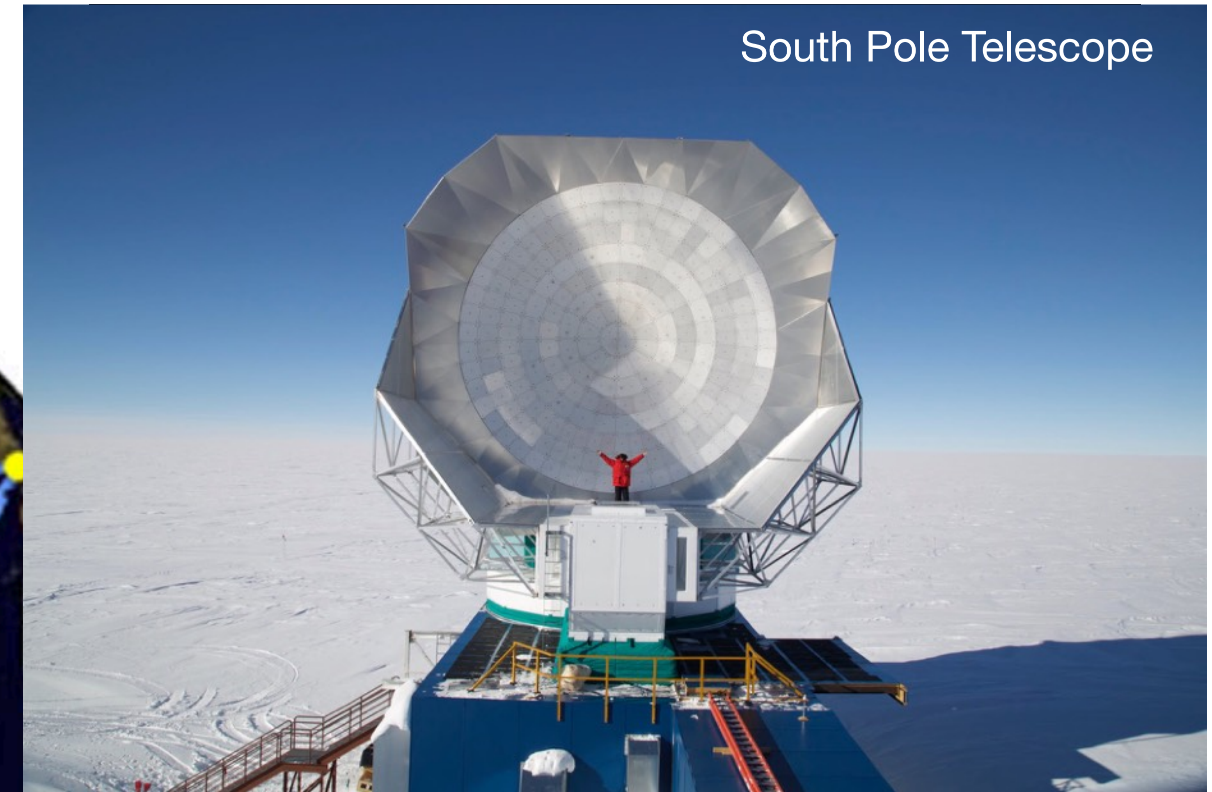

Mehaffey Bridge Rd NE
VLBA North Liberty Station

Angular resolution required to resolve the event horizon of M87*

Discerning the fingers of an astronaut at the distance of the moon

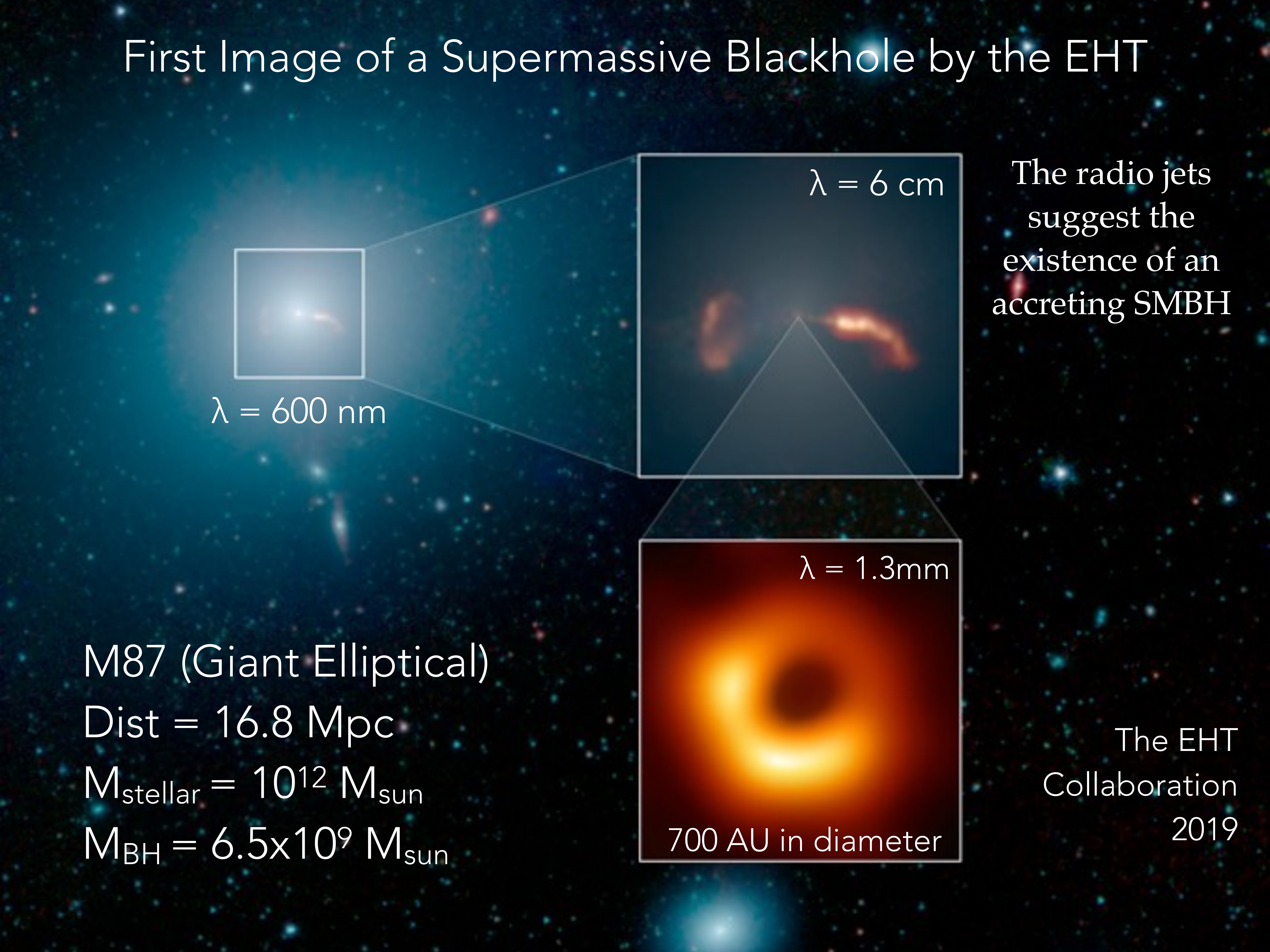
The Event Horizon Telescope



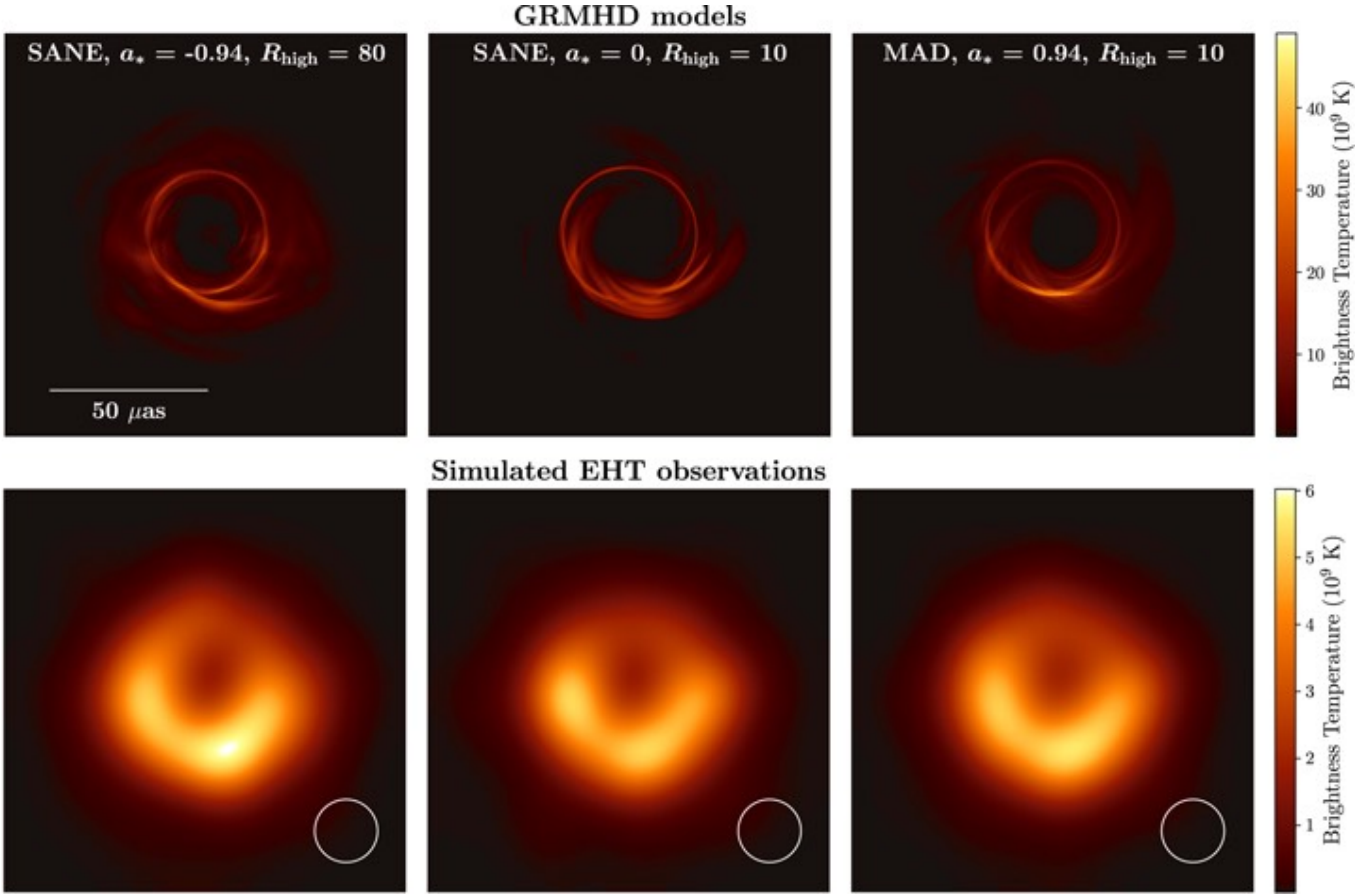


Wavelength: 1.3 mm
Frequency: 231 GHz
Theoretical diffraction limit: 25 microarcsec

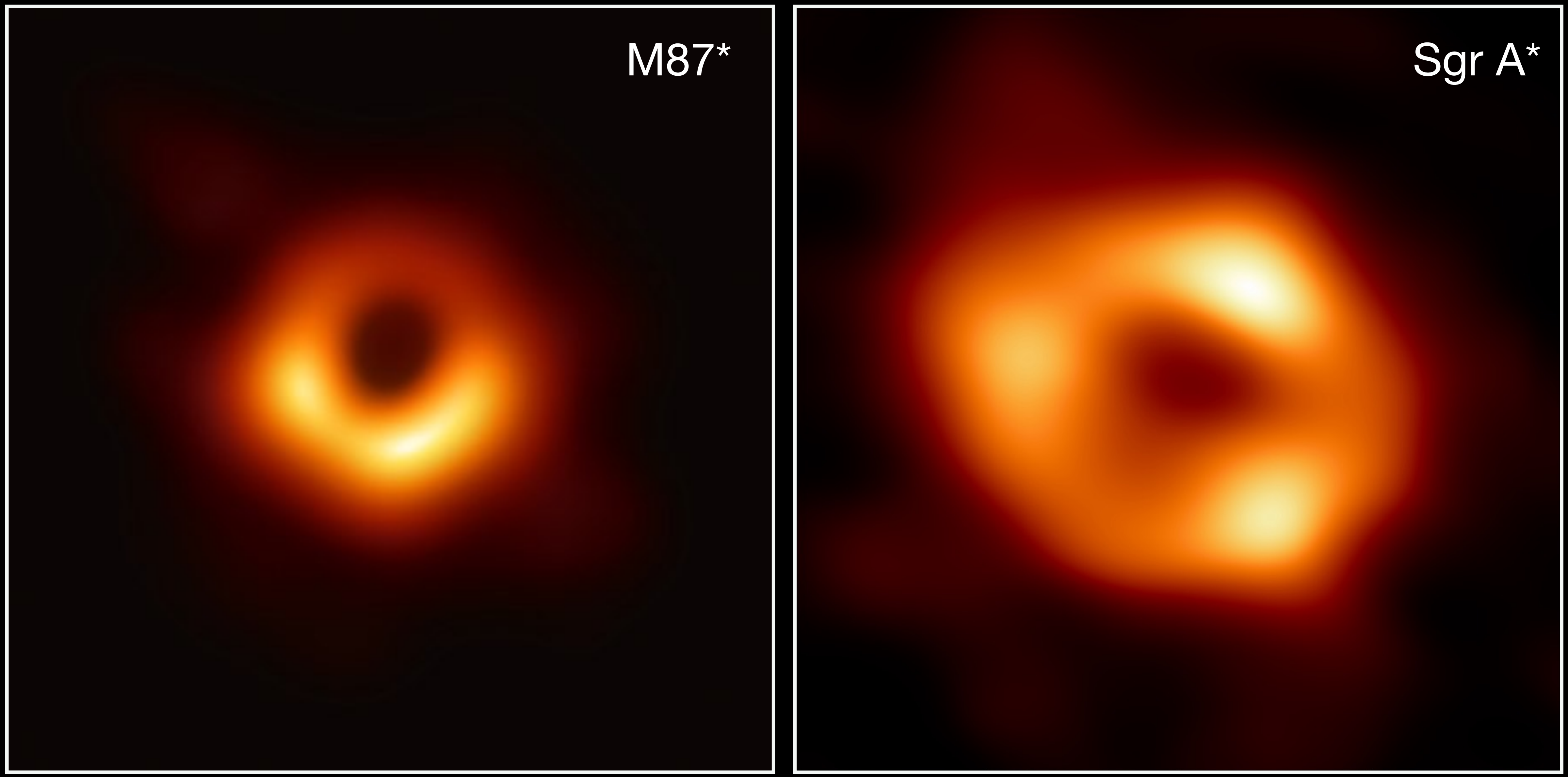
https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT


First Image of a Supermassive Blackhole by the EHT
λ = 600 nm
λ = 6 cm
The radio jets suggest the existence of an accreting SMBH
λ = 1.3mm
700 AU in diameter
M87 (Giant Elliptical)
Dist = 16.8 Mpc
$M_{stellar} = 10^{12}\ M_{sun}$
$M_{BH} = 6.5 \times 10^{9}\ M_{sun}$
The EHT Collaboration 2019

GRMHD simulations of different spin parameters and accretion flows



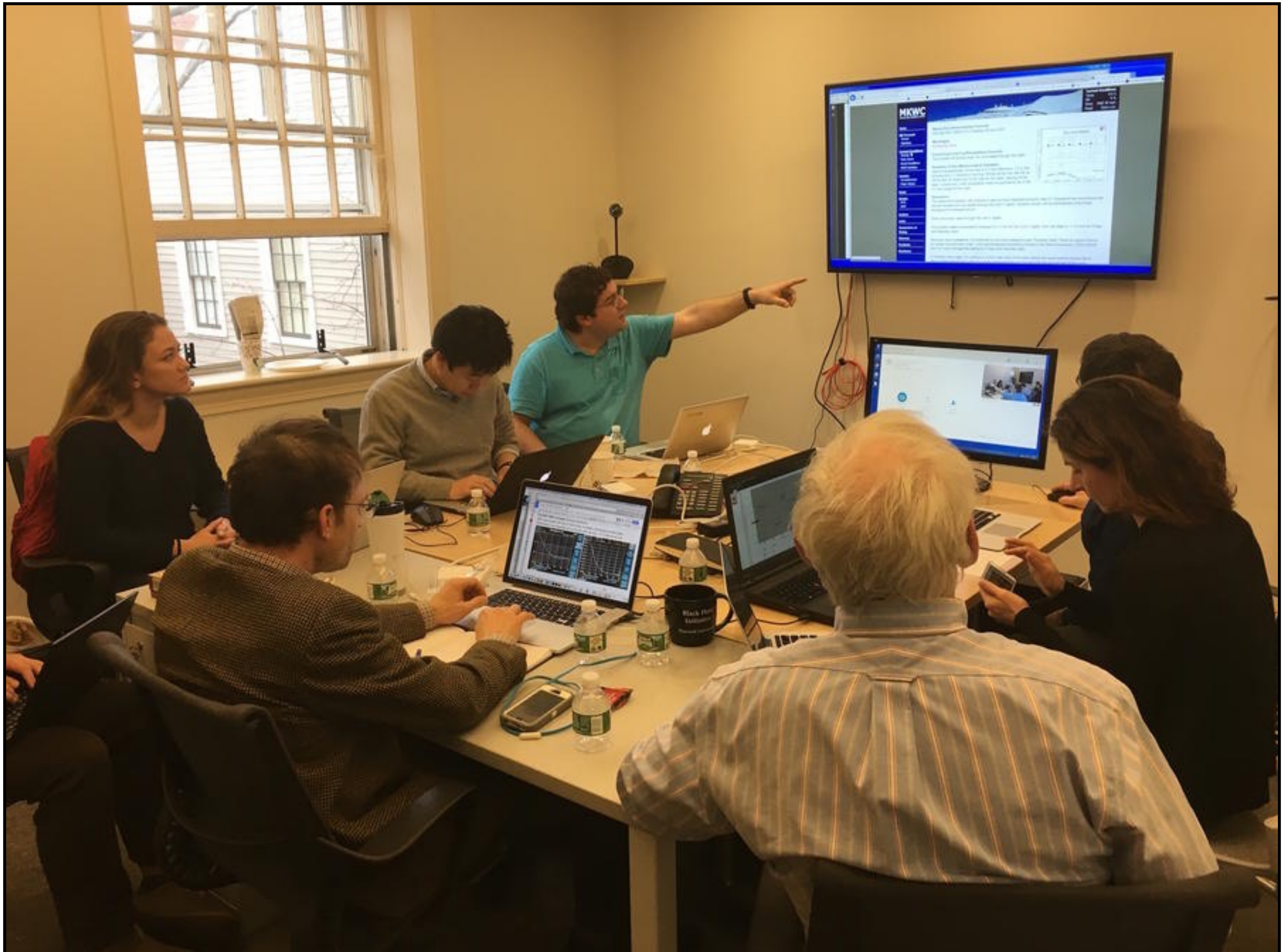
Directly Imaging the Event Horizon of SMBHs



Event Horizon Telescope


5 petabytes (PB) of data

"More than **200 members from 59 institutes in 20 countries and regions** have devoted years to the effort, all unified by a common scientific vision."



The Astrophysical Journal Letters, 875:L1 (17pp), 2019 April 10 https://doi.org/10.3847/2041-8213/ab0ec7

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
Received 2019 March 1; revised 2019 March 12; accepted 2019 March 12; published 2019 April 10

Abstract

When surrounded by a transparent emission region, black holes are expected to reveal a dark shadow caused by gravitational light bending and photon capture at the event horizon. To image and study this phenomenon, we have assembled the Event Horizon Telescope, a global very long baseline interferometry array observing at a wavelength of 1.3 mm. This allows us to reconstruct event-horizon-scale images of the supermassive black hole candidate in the center of the giant elliptical galaxy M87. We have resolved the central compact radio source as an asymmetric bright emission ring with a diameter of 42 ± 3 μas, which is circular and encompasses a central depression in brightness with a flux ratio $\gtrsim$10:1. The emission ring is recovered using different calibration and imaging schemes, with its diameter and width remaining stable over four different observations carried out in different days. Overall, the observed image is consistent with expectations for the shadow of a Kerr black hole as predicted by general relativity. The asymmetry in brightness in the ring can be explained in terms of relativistic beaming of the emission from a plasma rotating close to the speed of light around a black hole. We compare our images to an extensive library of ray-traced general-relativistic magnetohydrodynamic simulations of black holes and derive a central mass of $M = (6.5 \pm 0.7) \times 10^9 M_\odot$. Our radio-wave observations thus provide powerful evidence for the presence of supermassive black holes in centers of galaxies and as the central engines of active galactic nuclei. They also present a new tool to explore gravity in its most extreme limit and on a mass scale that was so far not accessible.

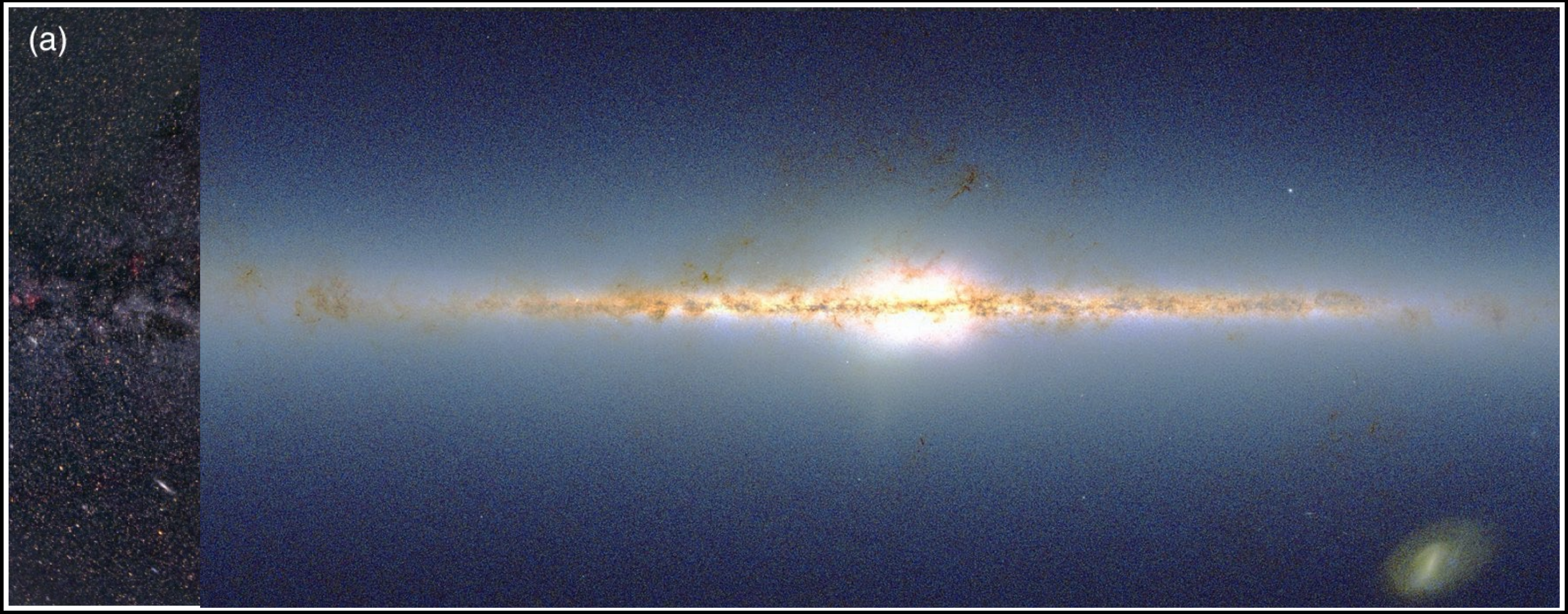
Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: individual (M87) – galaxies: jets – gravitation

Weighing the SMBH in the Milky Way

resolving the sphere of influence

Milky Way in optical vs. infrared wavelengths

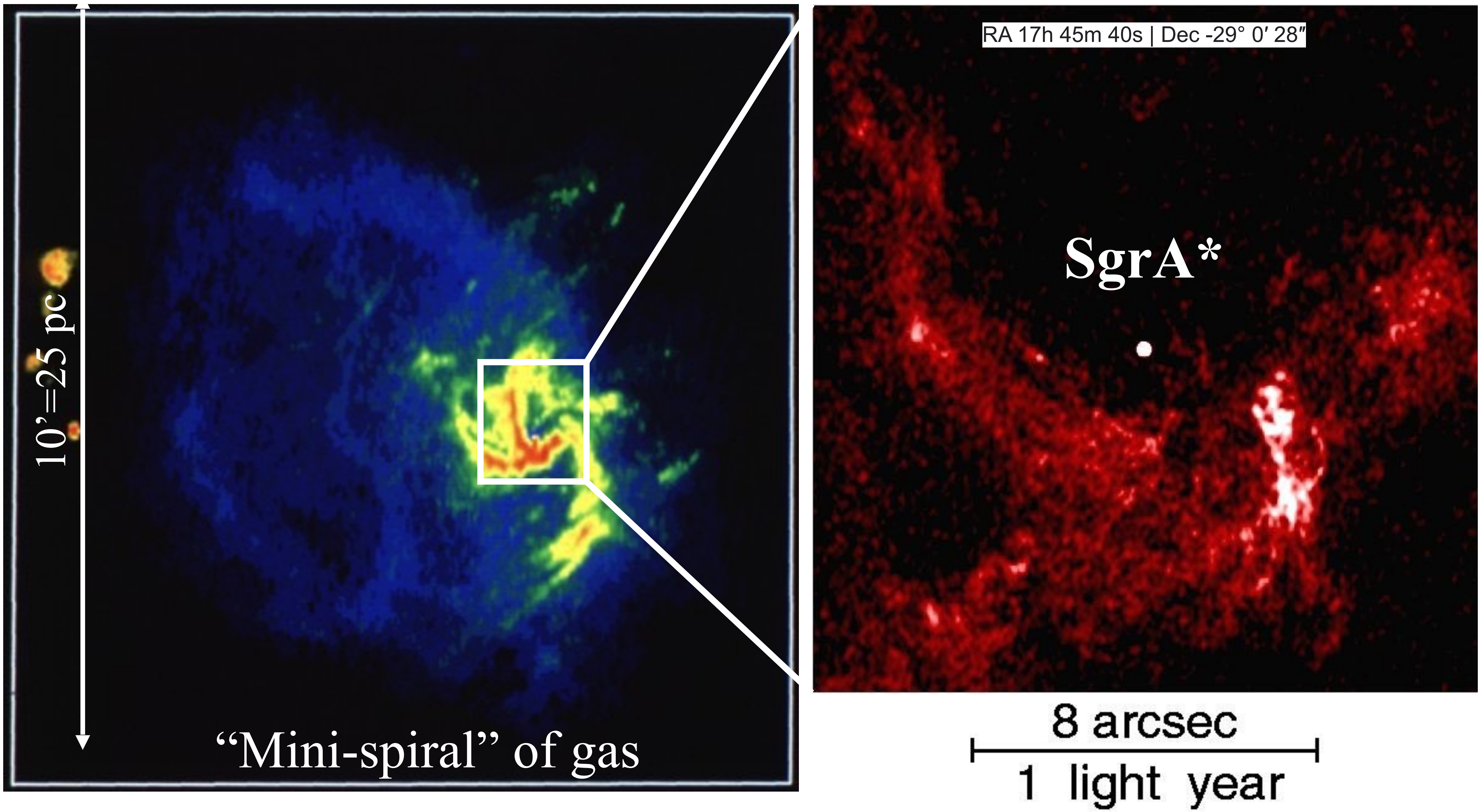
- The IR light is less attenuated by dust, revealing the central stellar bulge of the galaxy.
- Illustrating the importance of dust extinction



Pinpoint the Galactic Center:

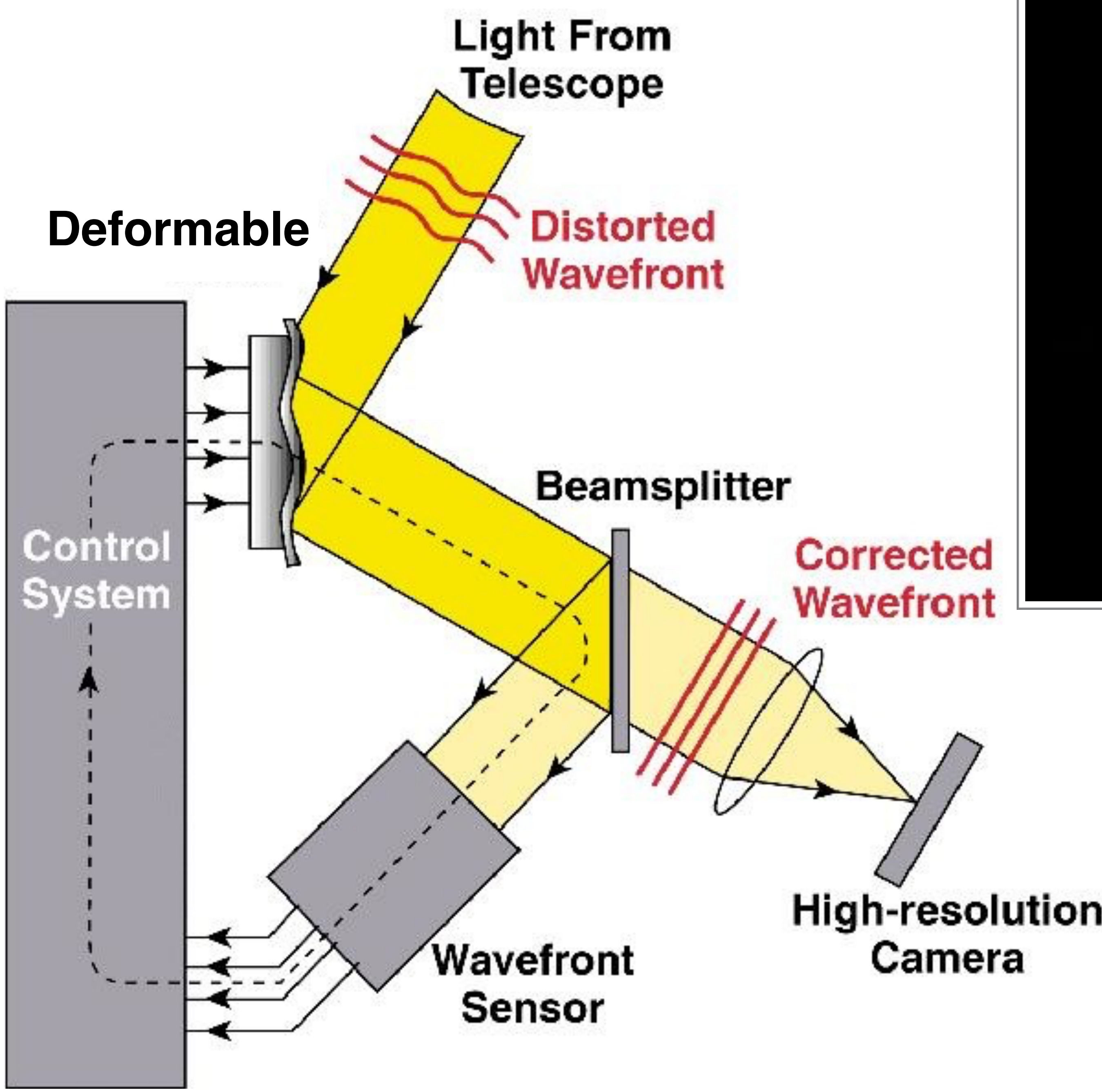
Radio images of the Galactic central region shows an unusually bright single point source surrounded by extended spirals.

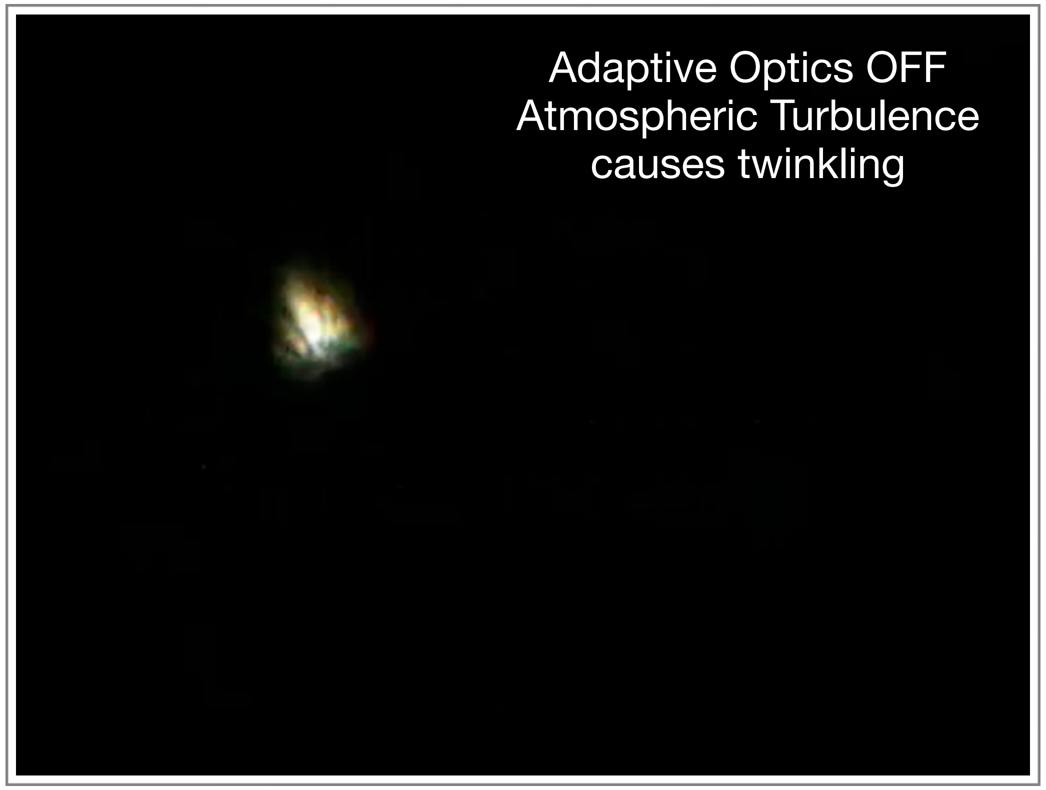
Think about why do we need radio observations?

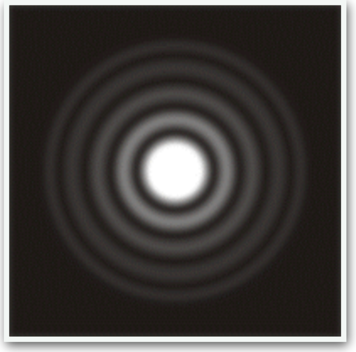


6 cm VLA image (Ekers et al. 1983)

Ground-based optical and near-IR telescopes need Adaptive Optics to reach diffraction limit because of atmospheric turbulence

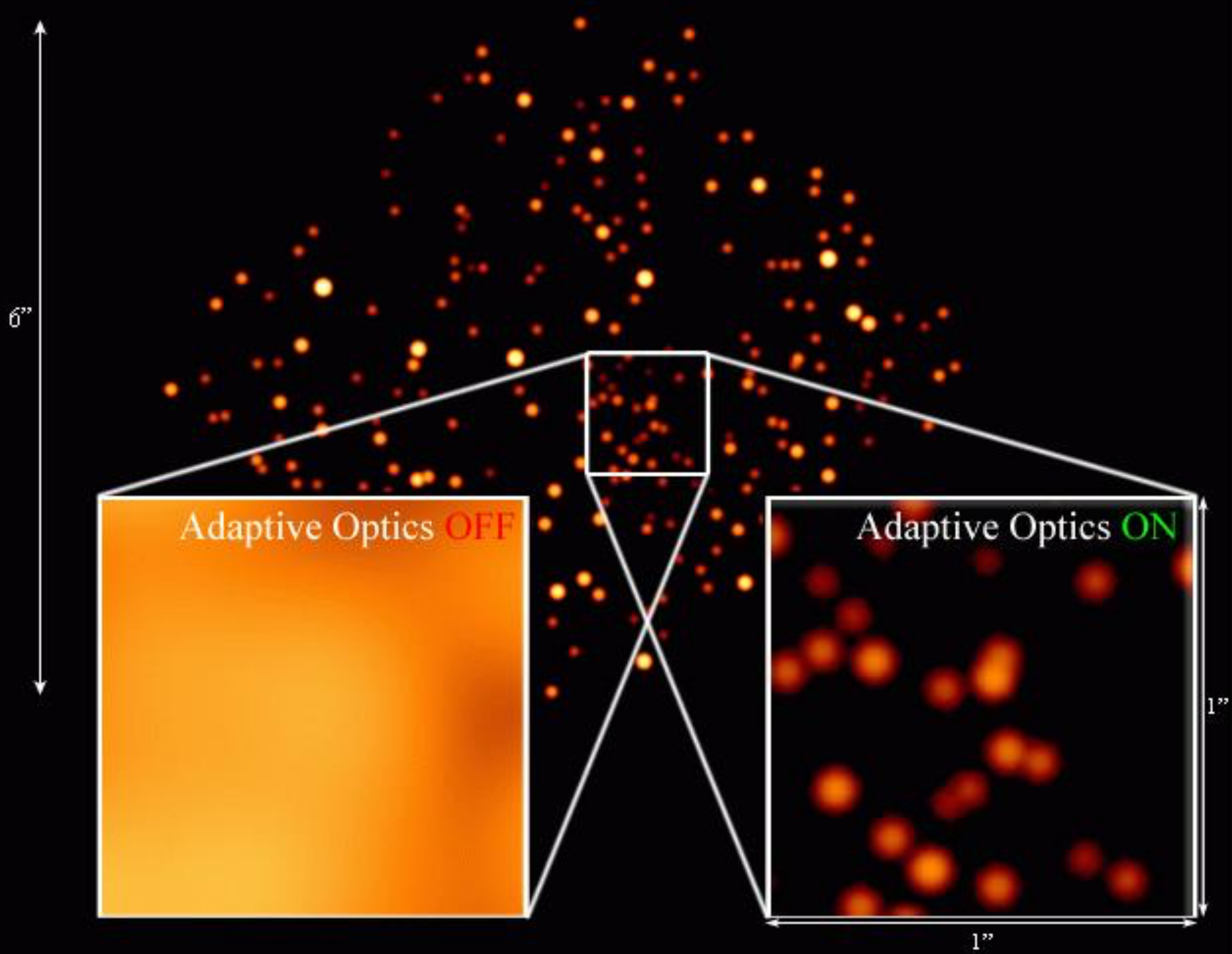




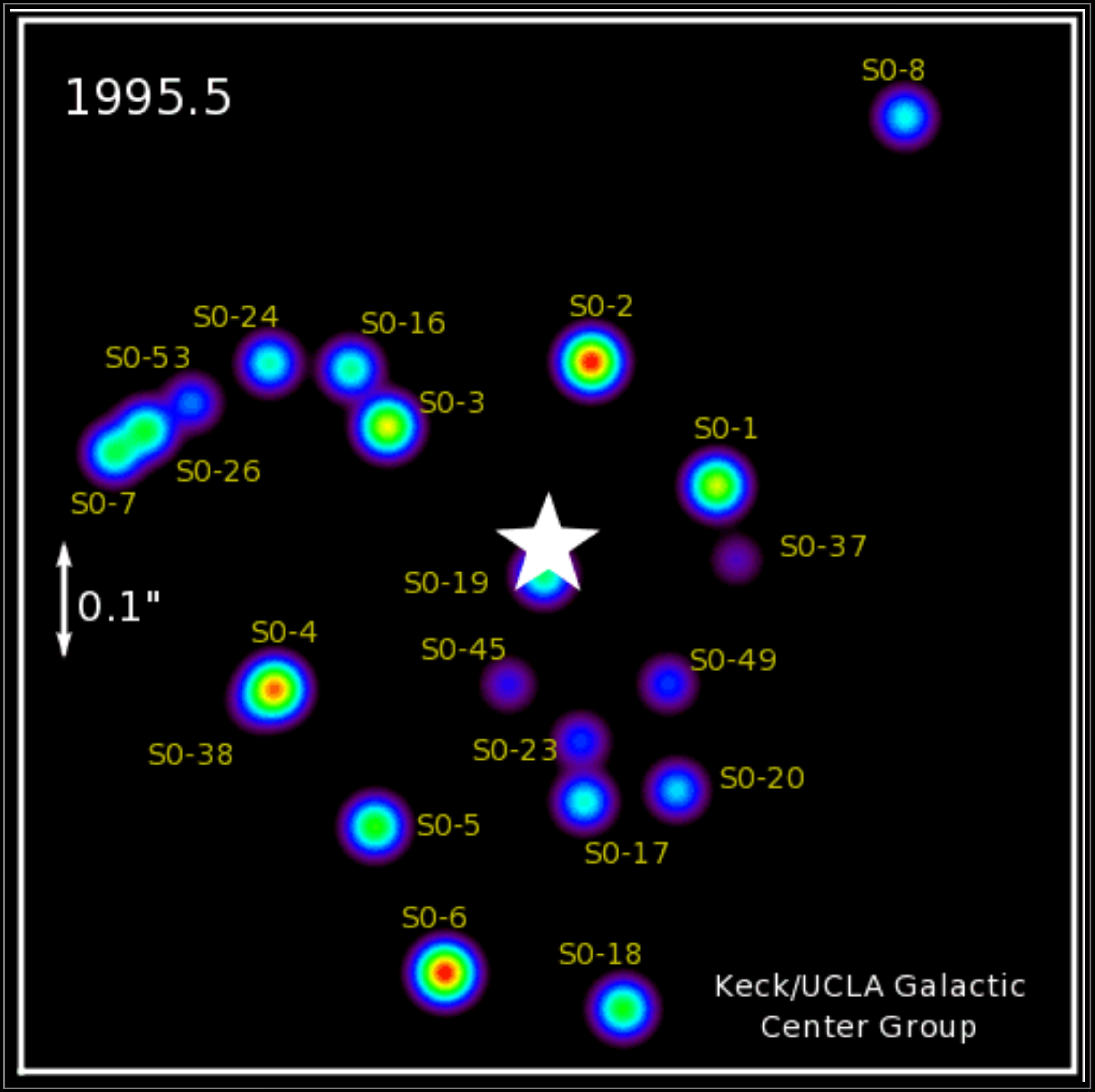


Adaptive Optics ON
reaching diffraction limit

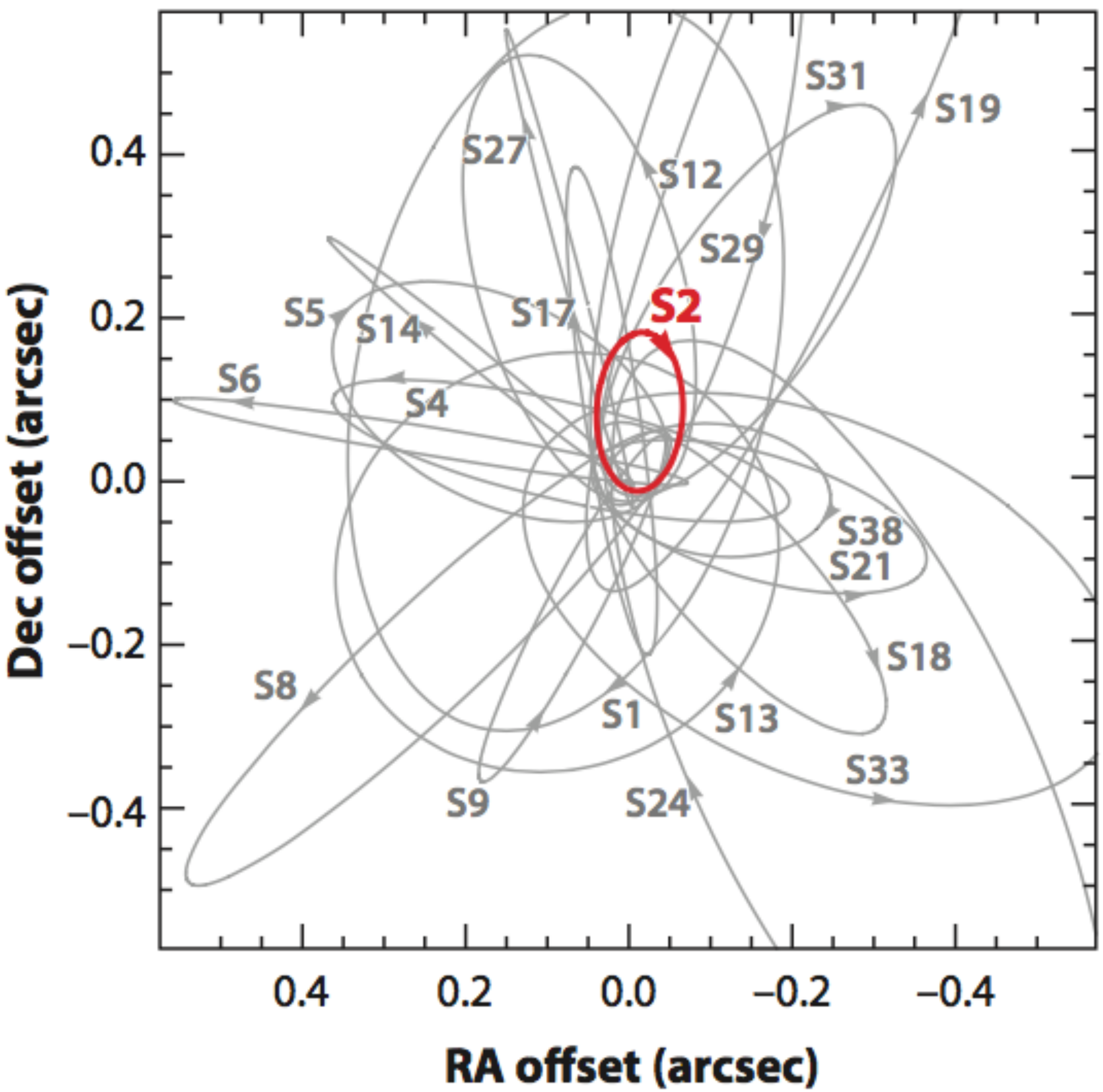
The Galactic Center at 2.2 microns



Resolving individual stars near Sgr A* with IR Adaptive Optics



Mass and distance of the SMBH in the Milky Way Galaxy

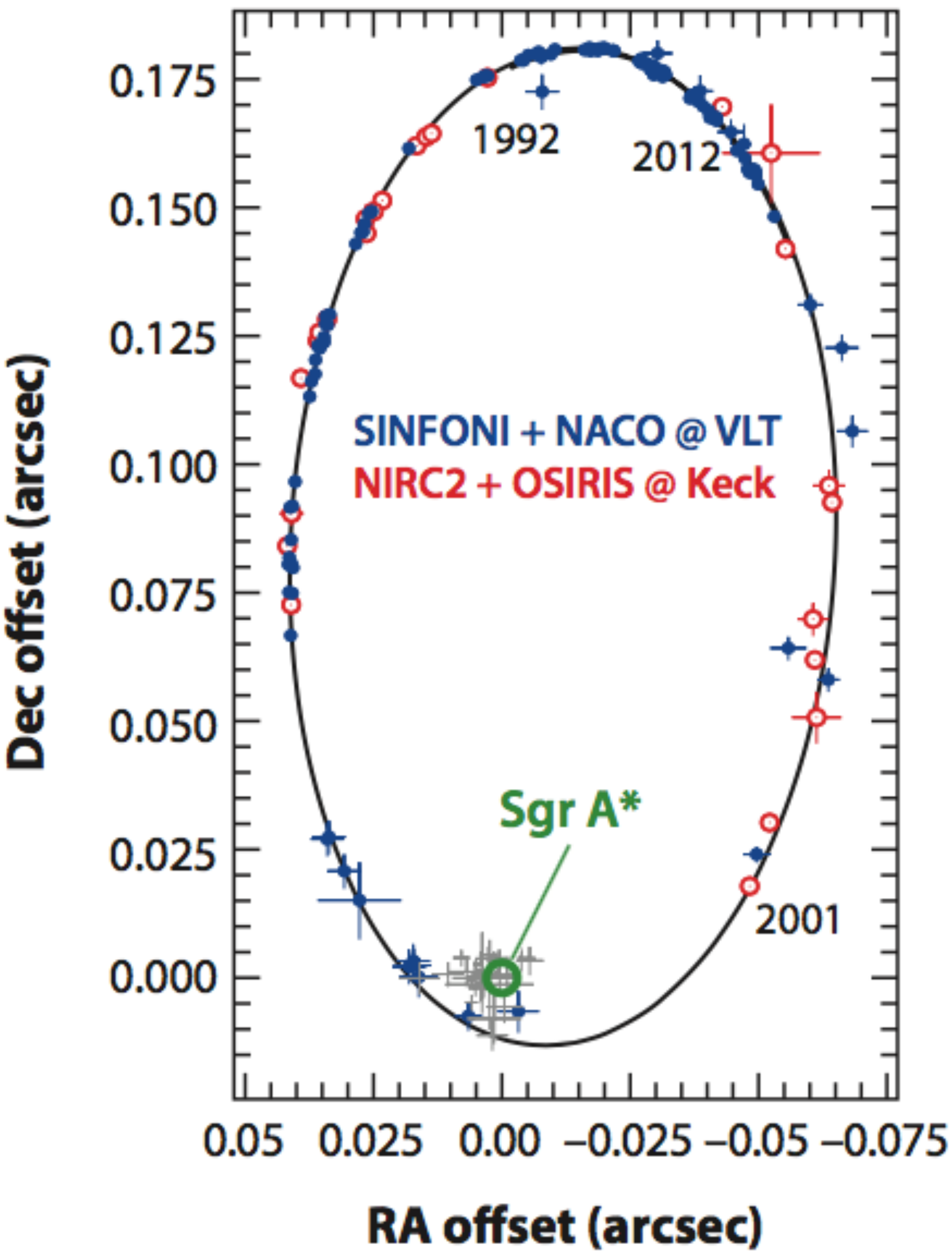


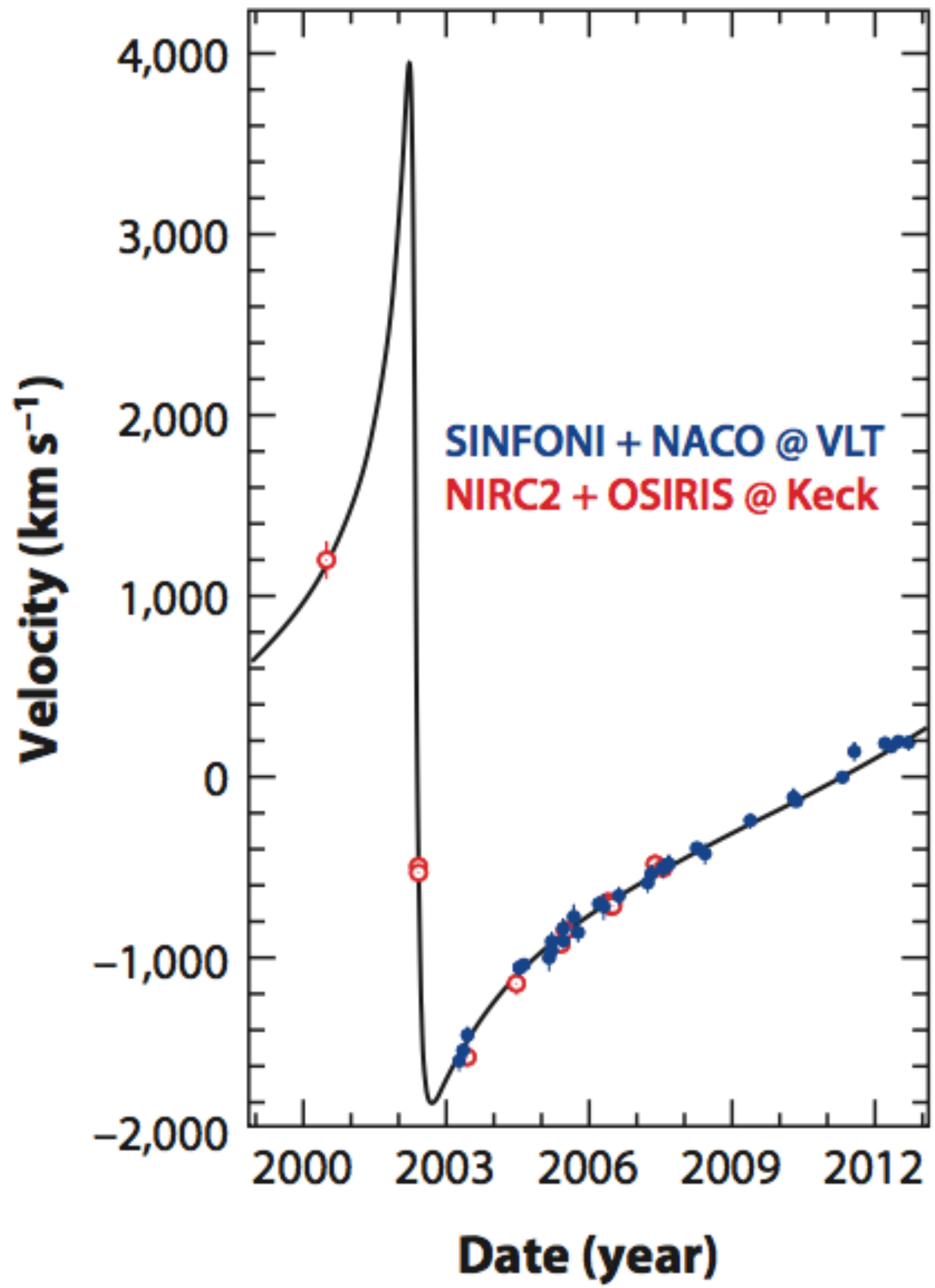
By monitoring **individual star's orbits and their velocities,** we can measure both the mass and the distance of the SMBH:

Mass: 4 million M_{sun}
Distance: 8.3 kpc

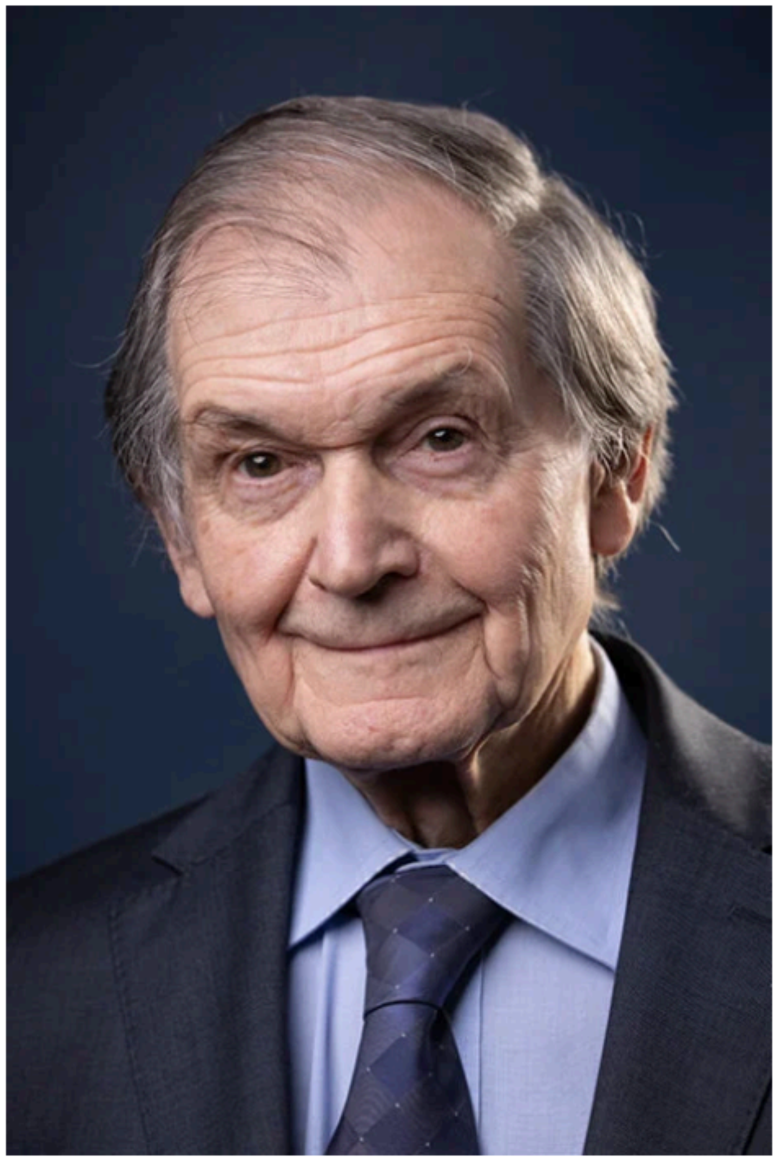
Data from Genzel's & Ghez's Groups

Mass and distance of the SMBH in the Milky Way Galaxy





The Nobel Prize in Physics 2020



Roger Penrose

Prize share: 1/2

Reinhard Genzel

Prize share: 1/4

Andrea Ghez

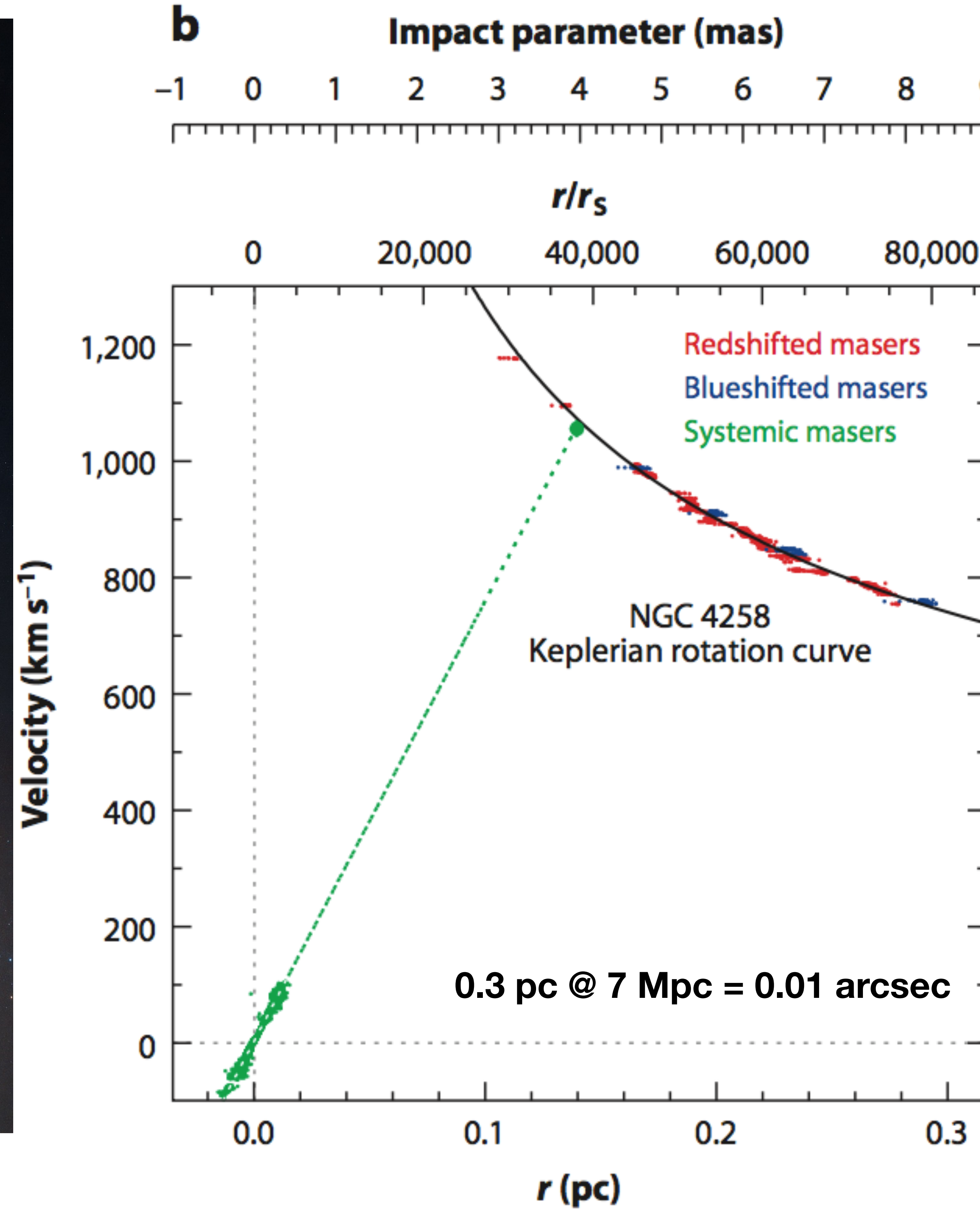
Prize share: 1/4

Weighing SMBHs in Other Galaxies

resolving the sphere of influence

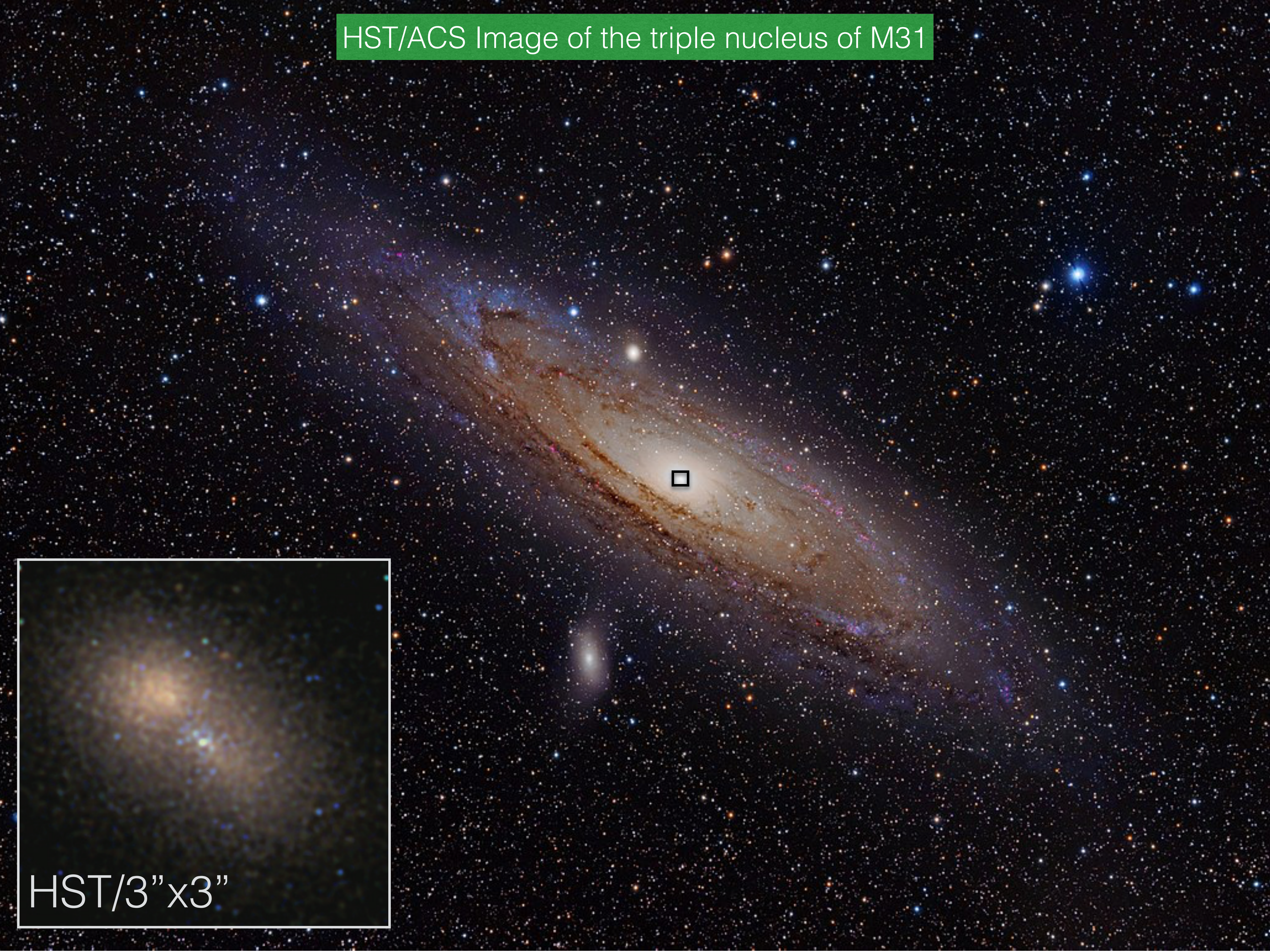

NGC 4258
Distance: 7 Mpc
Angular size: 18’x7’
SAB galaxy
accreting SMBH (4e7 M_{sun})

NGC 4258: Keplerian Disk of H_2O Masers w/i the central pc

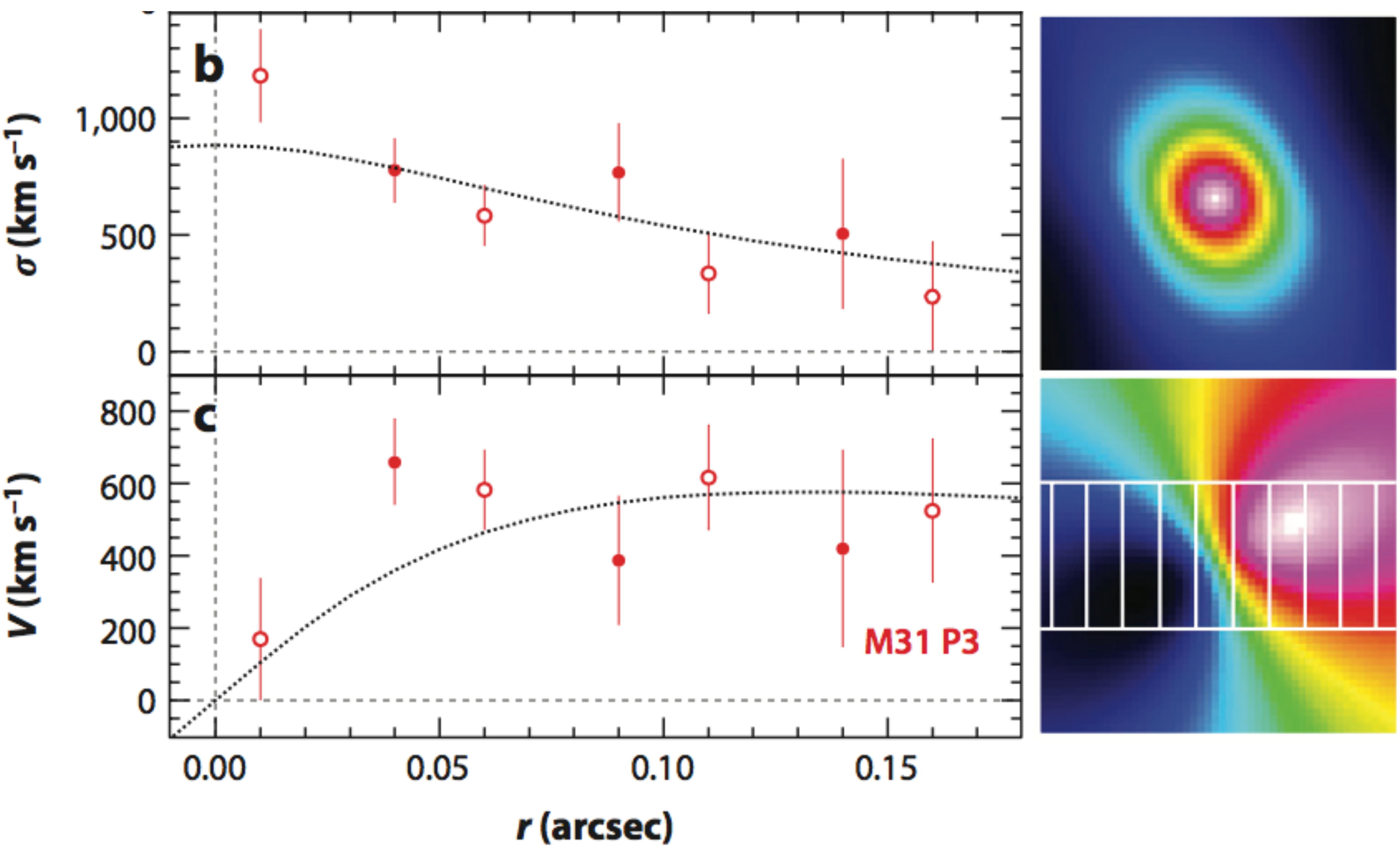


Kormendy & Ho 2013, with data from Argon+07, Moran 08

HST/ACS Image of the triple nucleus of M31

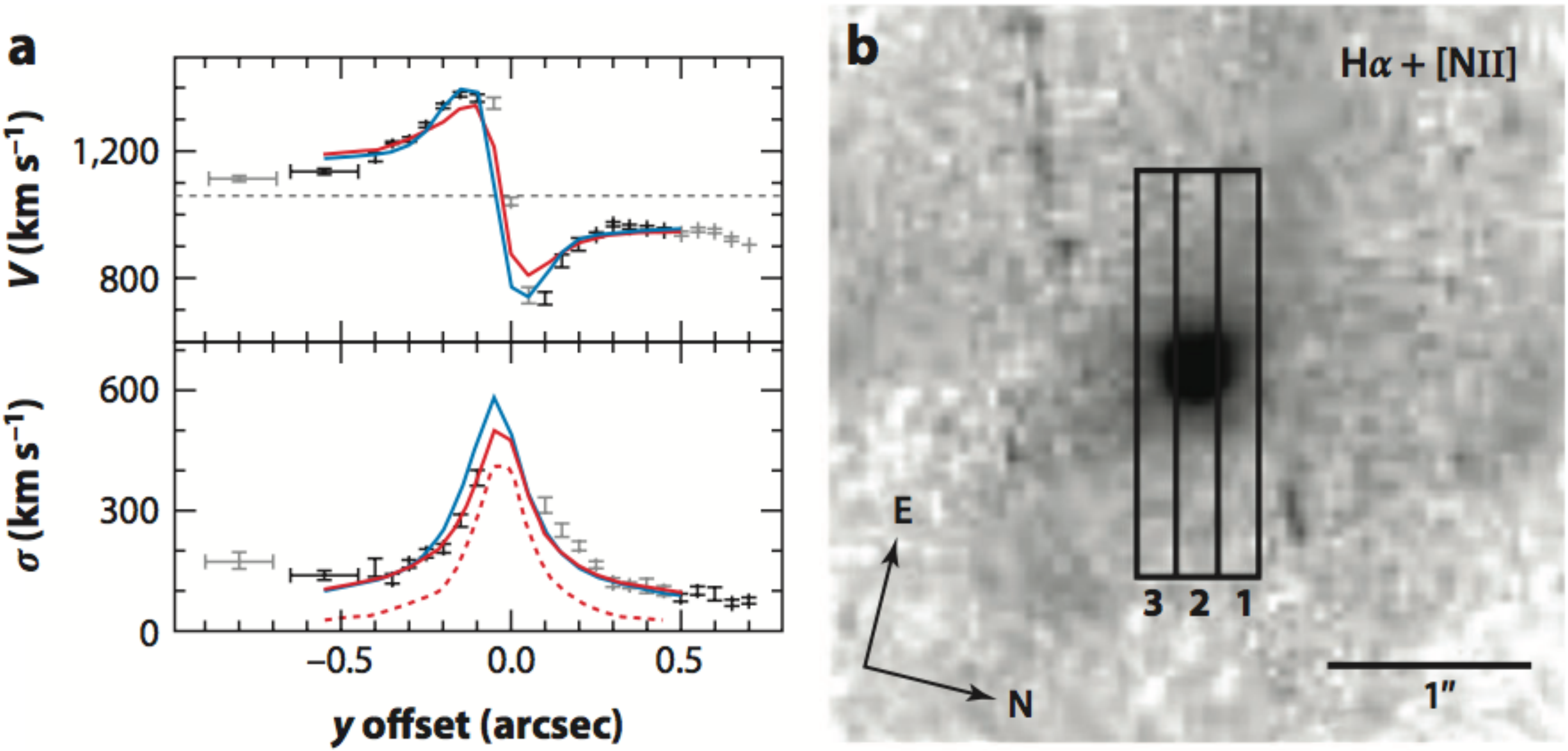


Elevated Stellar Velocity Dispersion in the Sphere of Influence



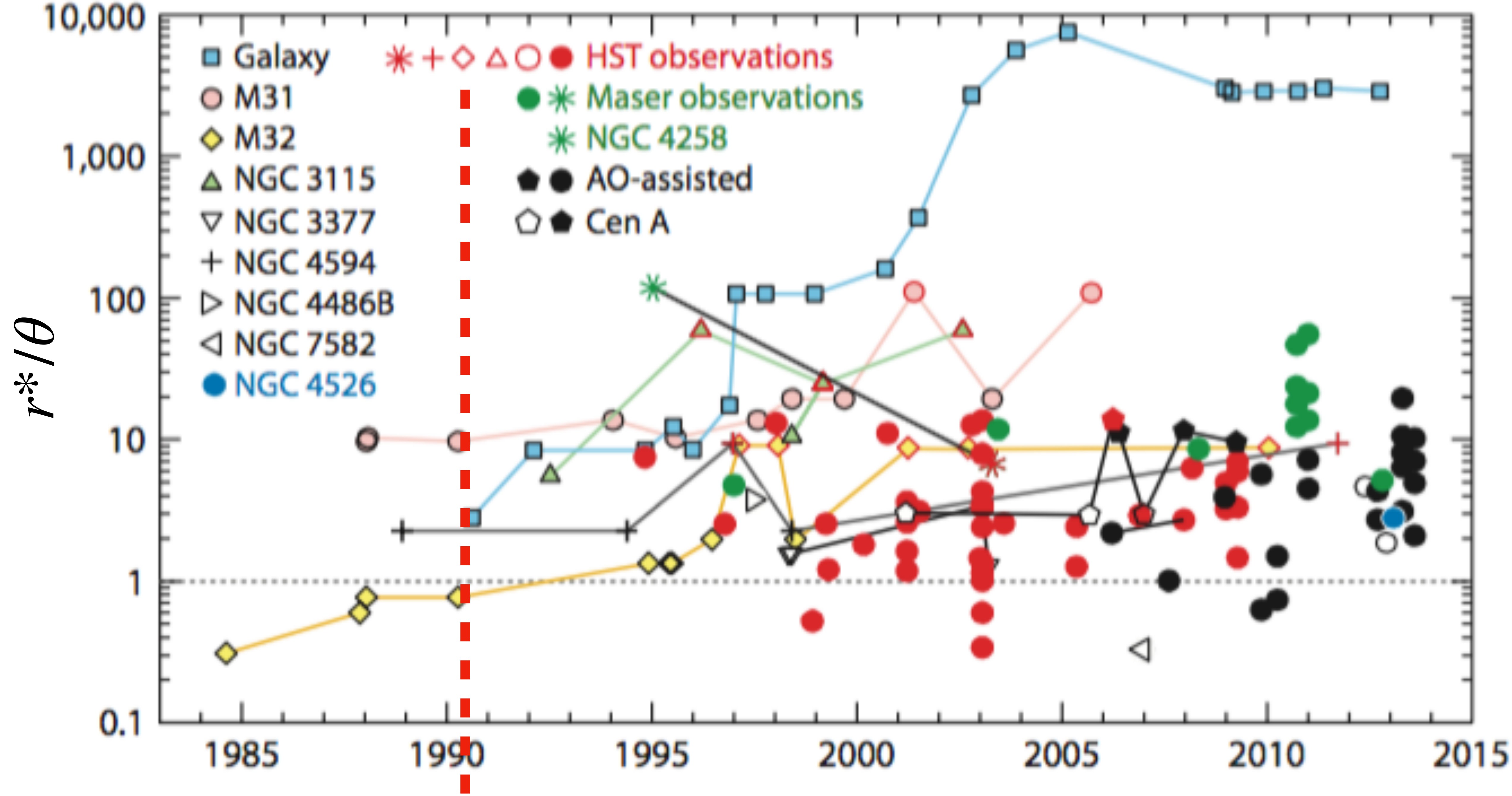
Bender+05

Elevated Gas Velocity Dispersion in the Sphere of Influence



NGC 4374, HST/STIS, Walsh+2010

Making Progress in Resolving the Sphere of Influence



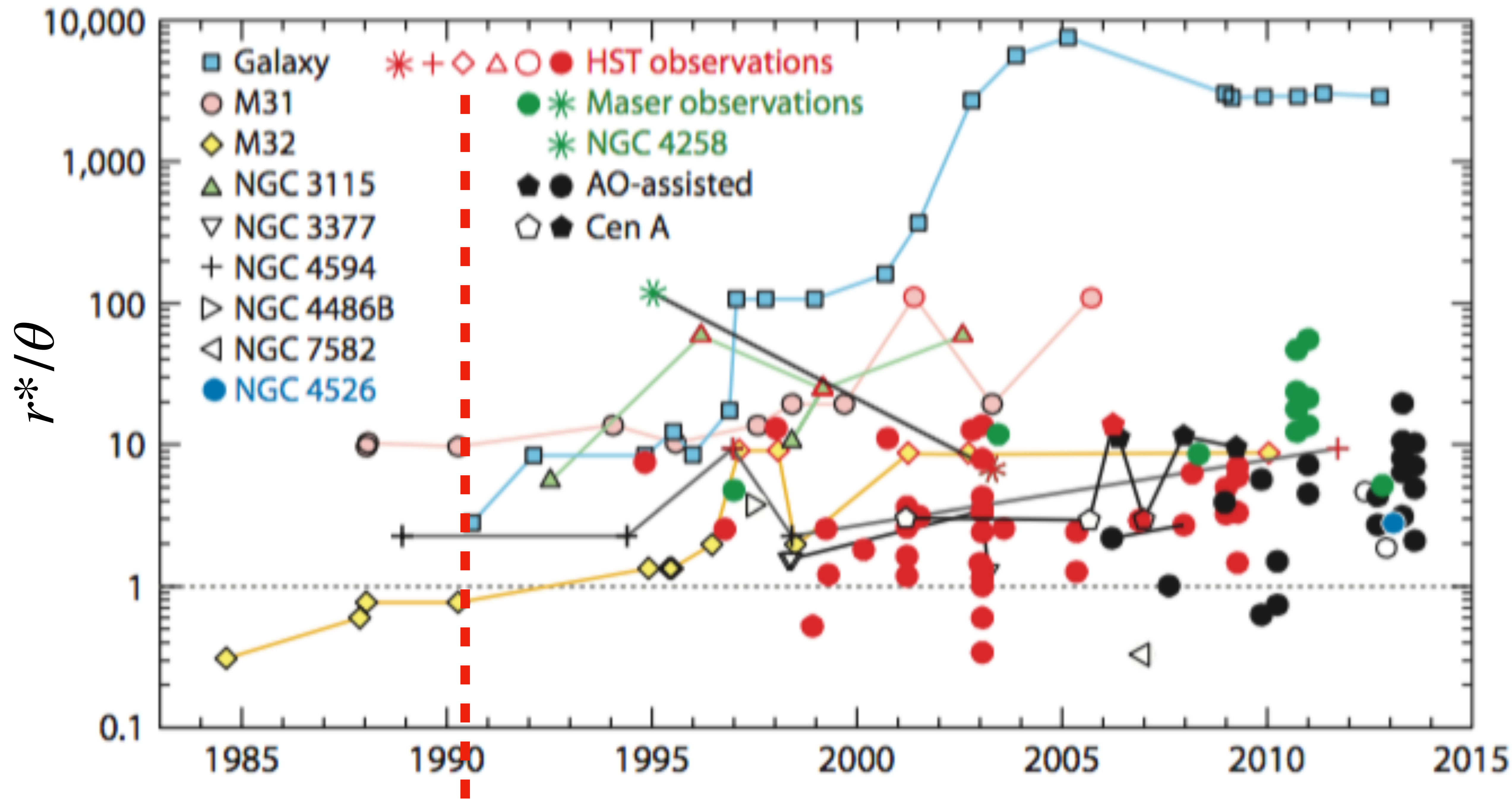
Thanks to Hubble & Adaptive Optics

Kormendy & Ho 2013

Tools for detecting Supermassive Black Holes (>10^3 M_{sun})

- **Resolve the event horizon**
  - $r_s = \frac{2GM_{BH}}{c^2} = 3\,\mathrm{km}\left(\frac{M_{BH}}{1M_\odot}\right) = 2\,\mathrm{AU}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)$
  - Aperture synthesis with a network of radio observatories
  - Minimizing the diffraction limit: $\theta = \lambda/D$
- **Resolve the sphere of influence**
  - $r_* = \frac{GM_{BH}}{\sigma_*^2} = 11\,\mathrm{parsec}\left(\frac{M_{BH}}{10^8 M_\odot}\right)\left(\frac{200\,\mathrm{km/s}}{\sigma_*}\right)^2$
  - Studies of Stellar and Gas Kinematics
  - Adaptive Optics or Space Telescopes like HST
- **Detect the incredible energy generation from accretion**
  - $L_{bol} = 0.1\dot{M}_{BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{BH}}{1\,M_\odot\,\mathrm{yr}^{-1}}\right)$
  - Studies of Active Galactic Nuclei (AGN)
- **Detect the gravitational wave generated from BH mergers**
  - Gravitational wave detectors like the Pulsar Timing Array

Making Progress in Resolving the Sphere of Influence



Thanks to Hubble & Adaptive Optics

Kormendy & Ho 2013

Evidence of SMBHs in Active Galaxies

Detecting gravitational accretion power

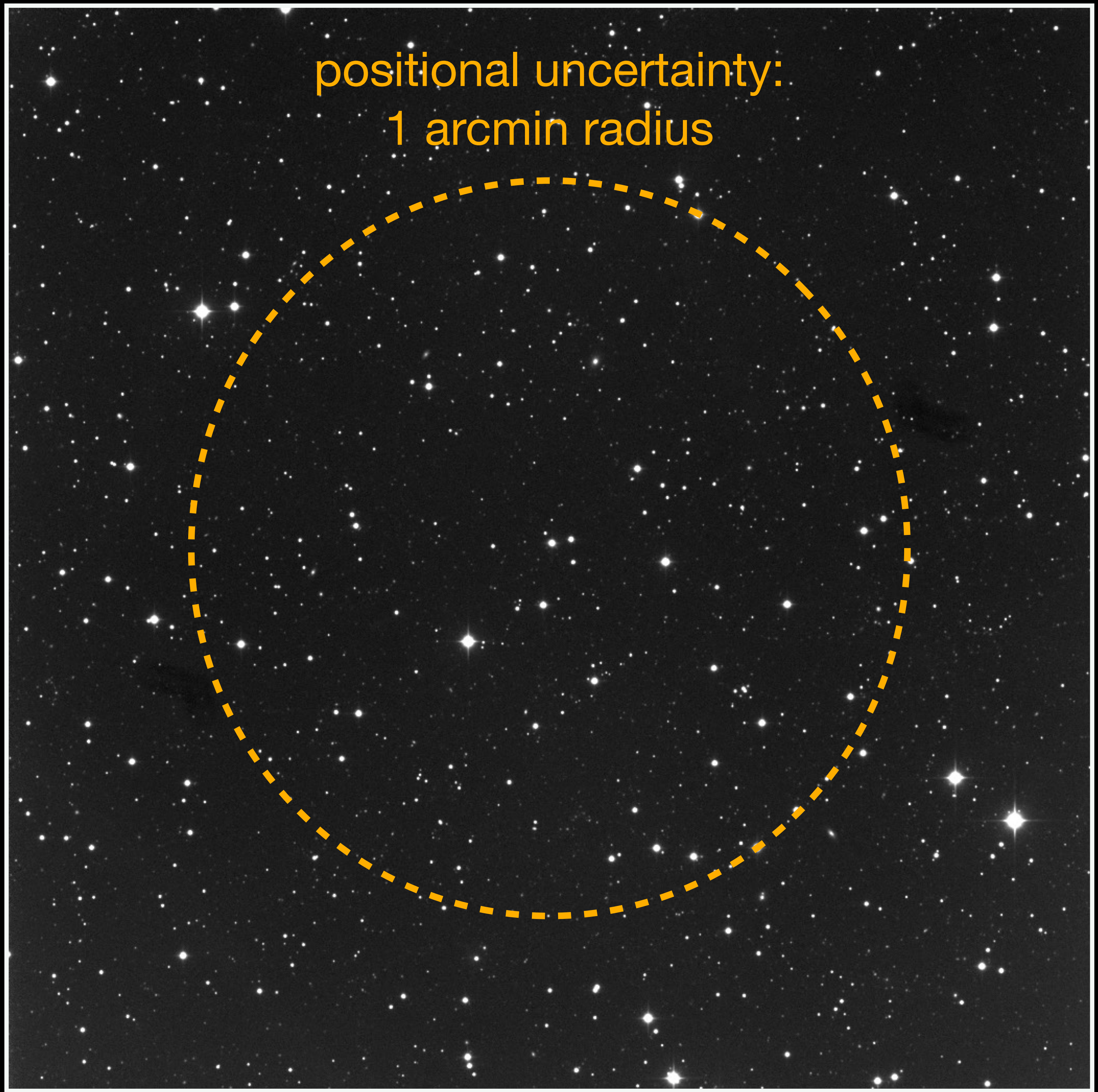
Discovery of Quasars: the Cambridge Interferometer

After WWII, **Martin Ryle and Antony Hewish** (1974 Nobel Prize) took 5 truckloads of surplus equipment from the Royal Aircraft Establishment, including several **3-7.5 m Würzburg radio antennae** to build the Cambridge interferometer

Würzburg-Riese at Military History Museum, Gatow Airport, Berlin

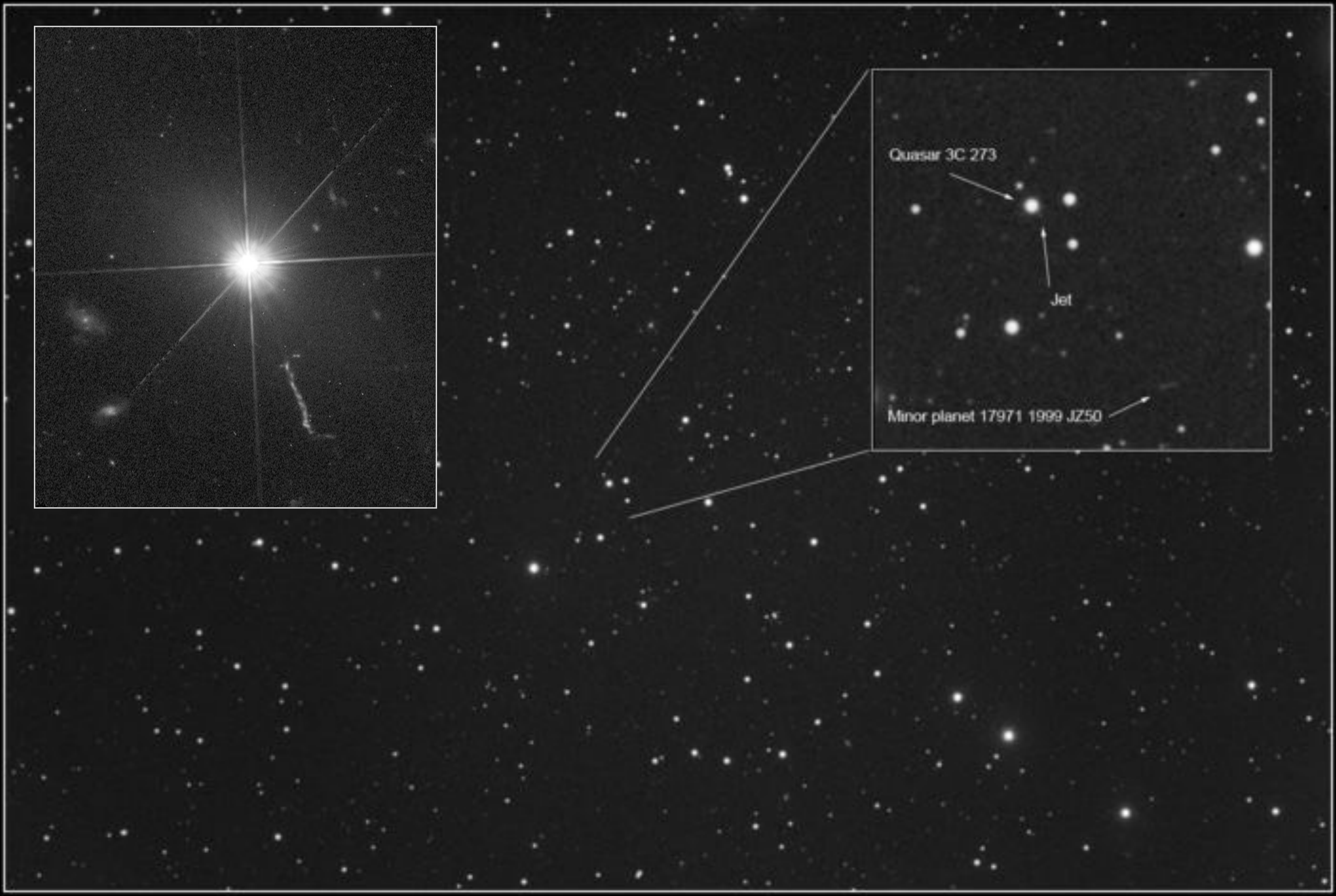
Discovery of 3C 273: the First Quasar

Edge *et al* (1959) - 1′



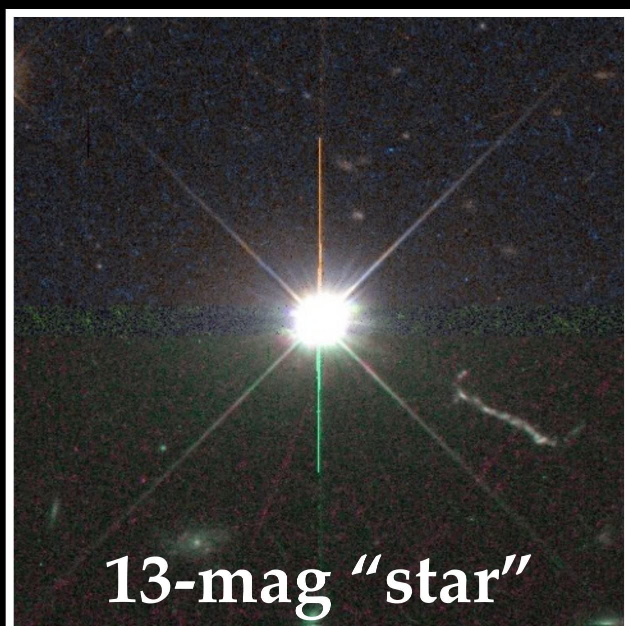
Hazard *et al* (1963) - lunar occultation, 1″

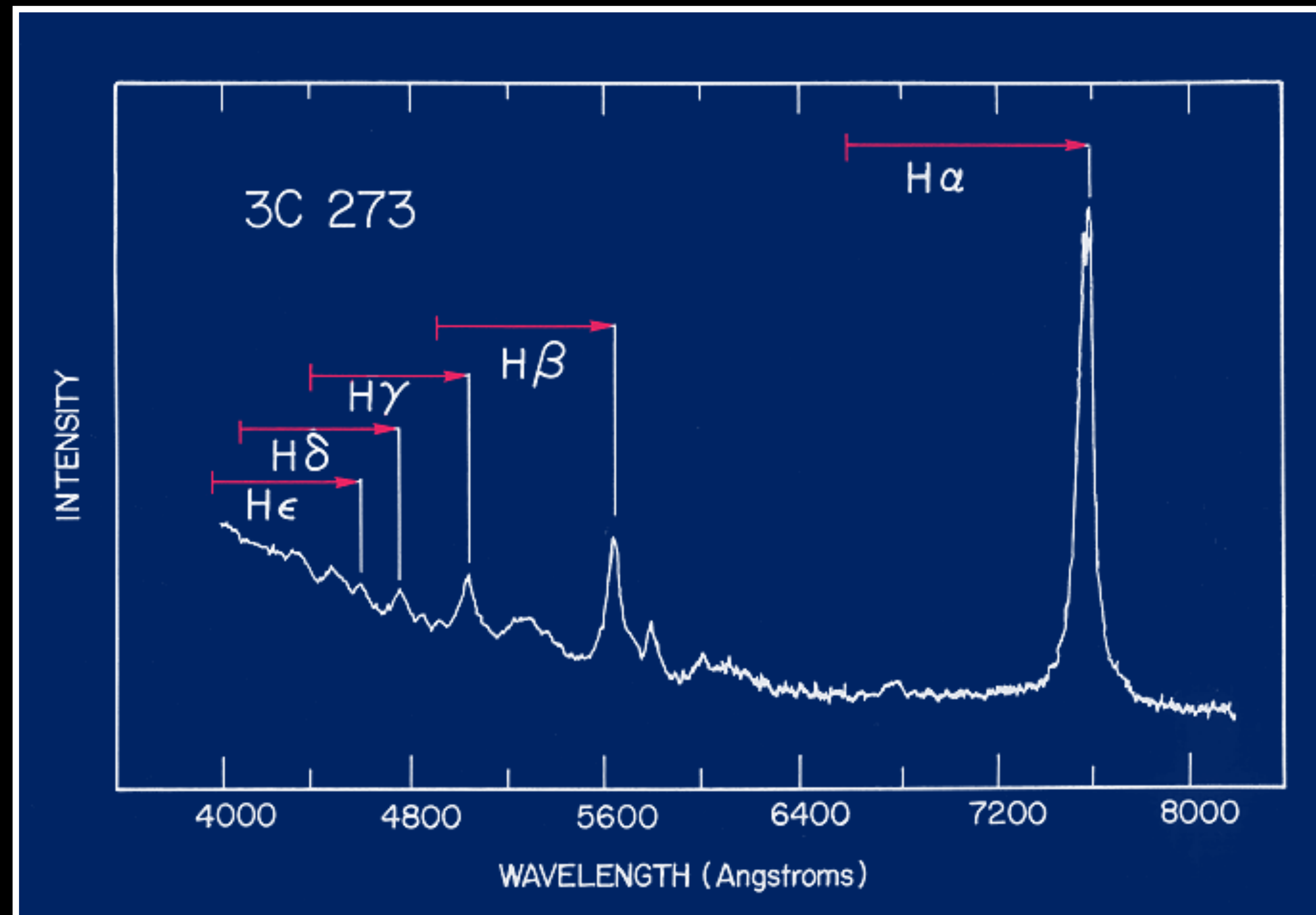
Optical Counterpart of 3C273

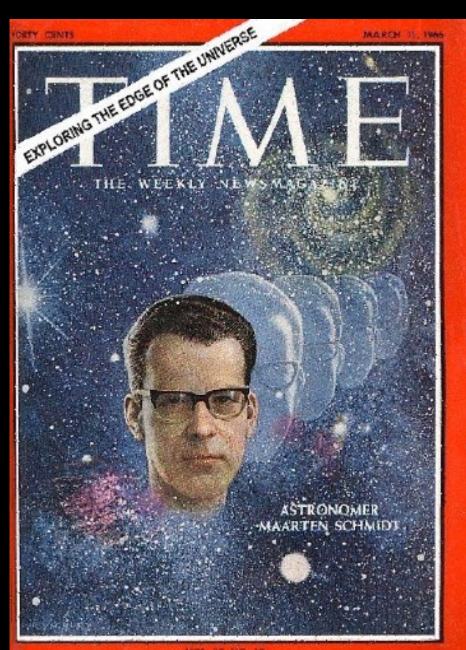


Quasar 3C 273 w/Jet & MP 17971 1999 JZ50

Discovery of 3C 273: the First Quasar



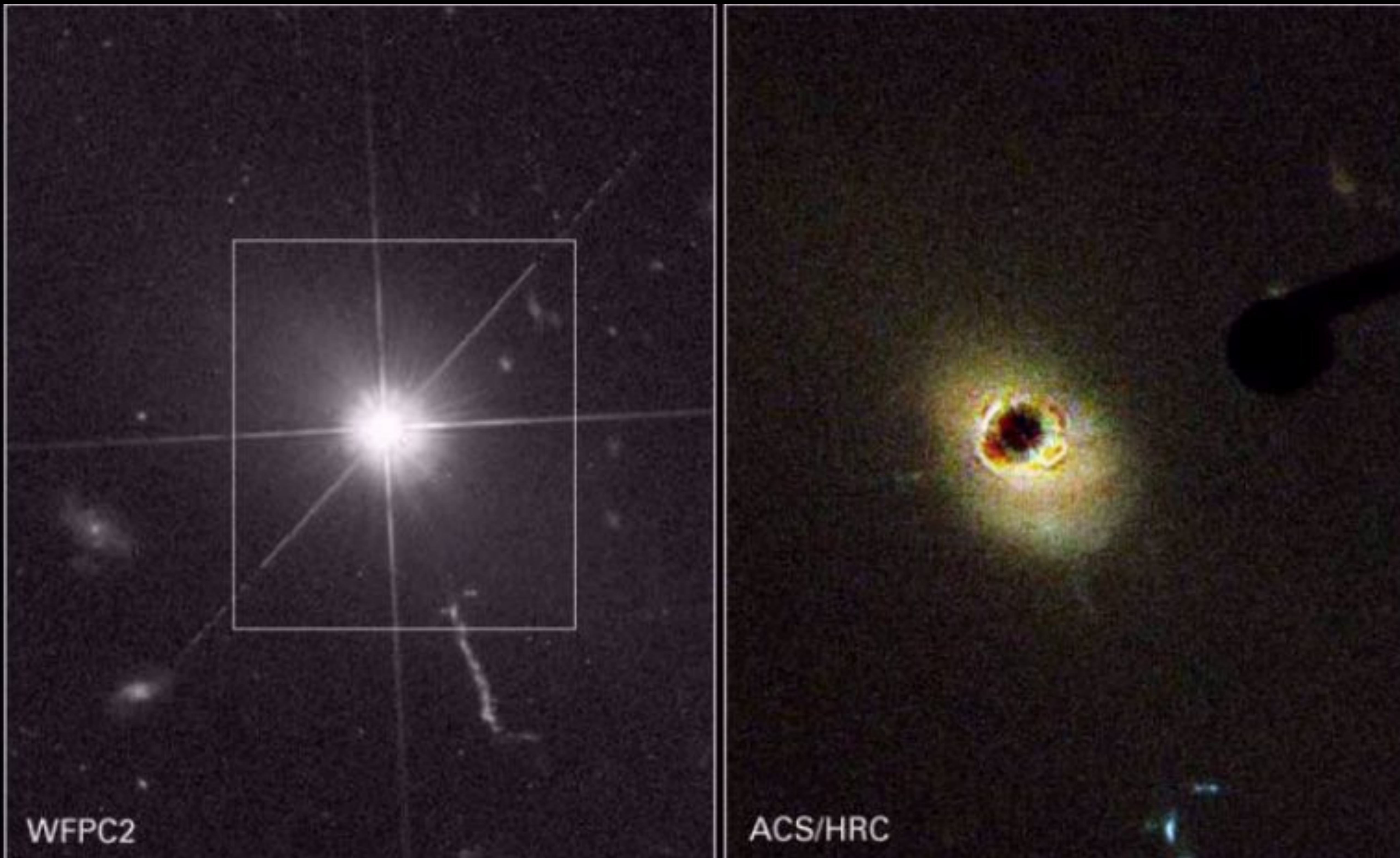




z = 0.158 (760 Mpc)

Schmidt (1963)

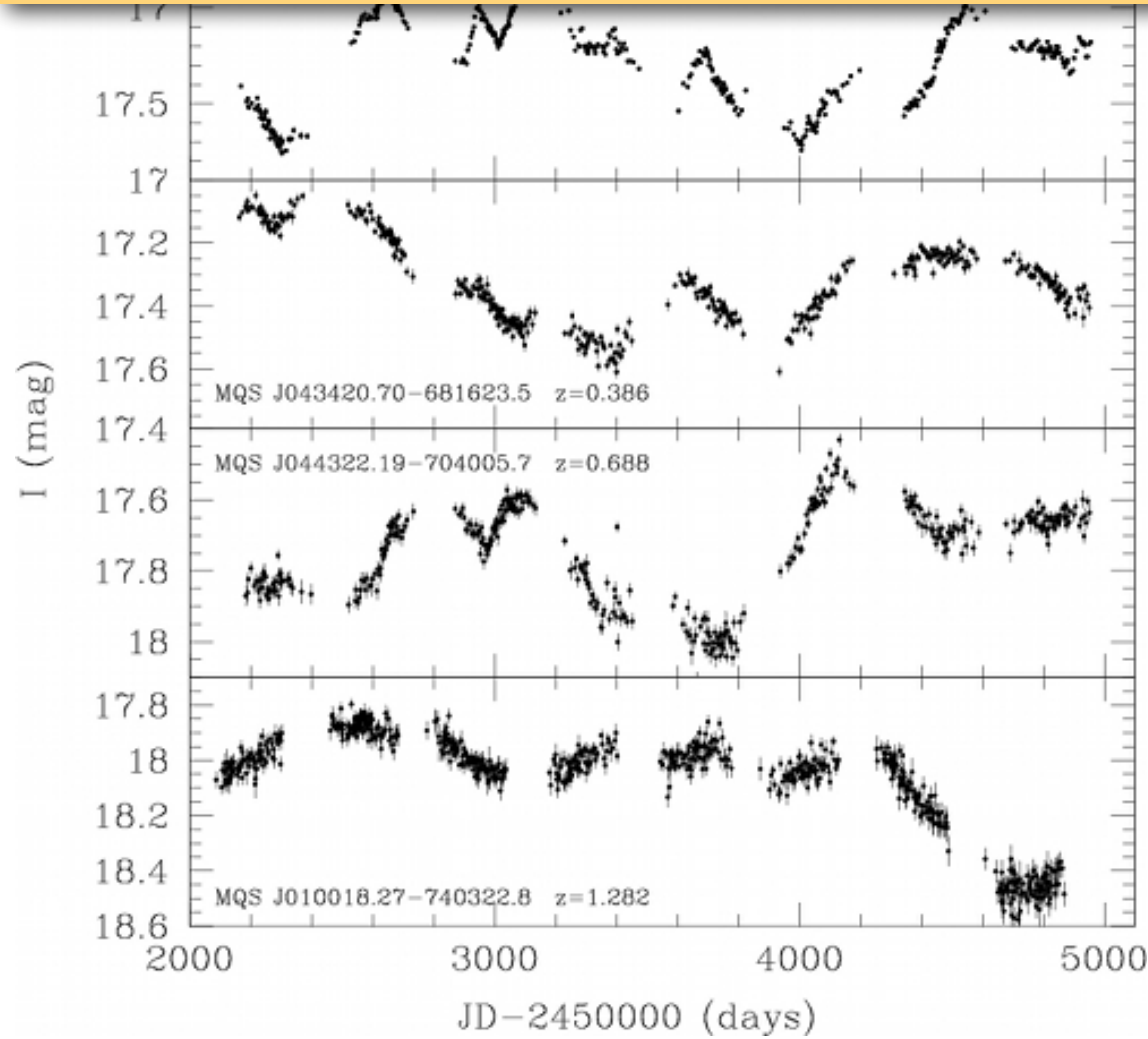
HST coronagraphic image reveals the host galaxy of 3C273



NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA STScI-PRC03-03

Quasars Show Rapid Variations in Brightness

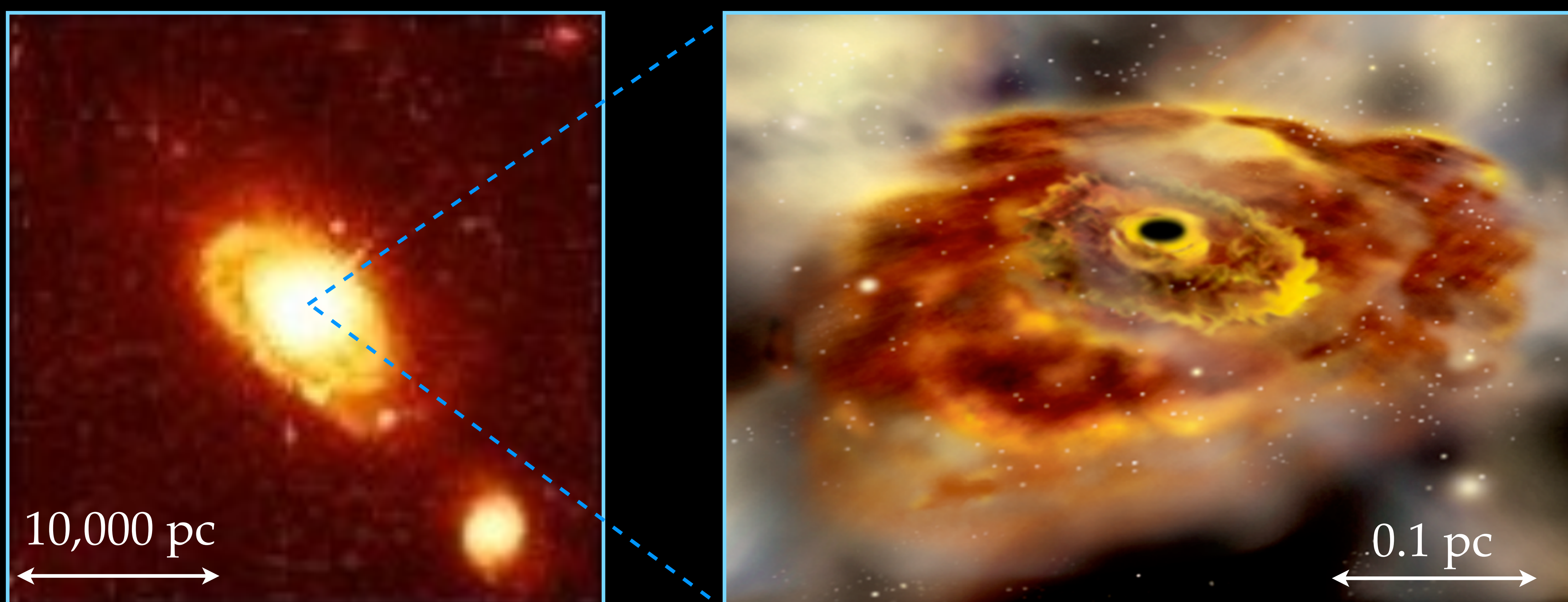
$c \times 1$ **week = 0.006 pc = 1212 AU**



What Could Power Quasars?

Accreting supermassive black holes

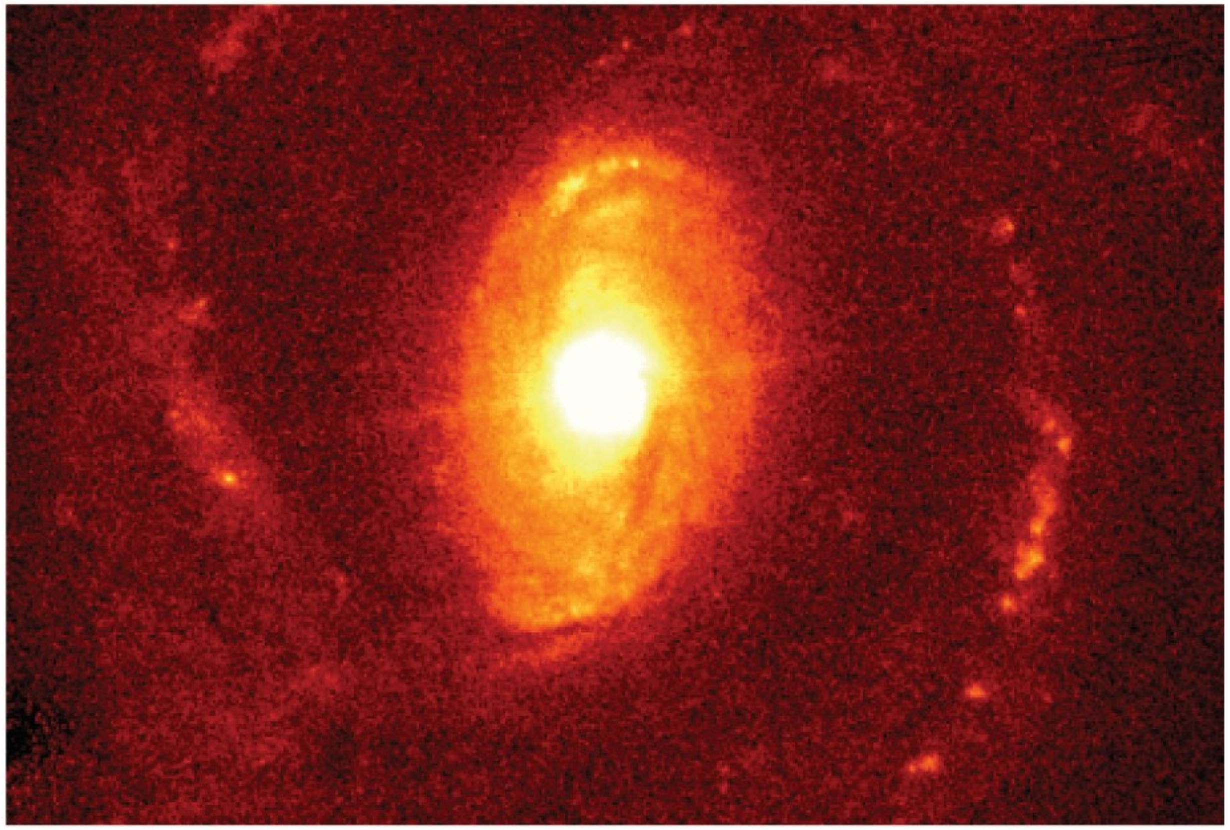
$$L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,{\rm yr}^{-1}}\right)$$

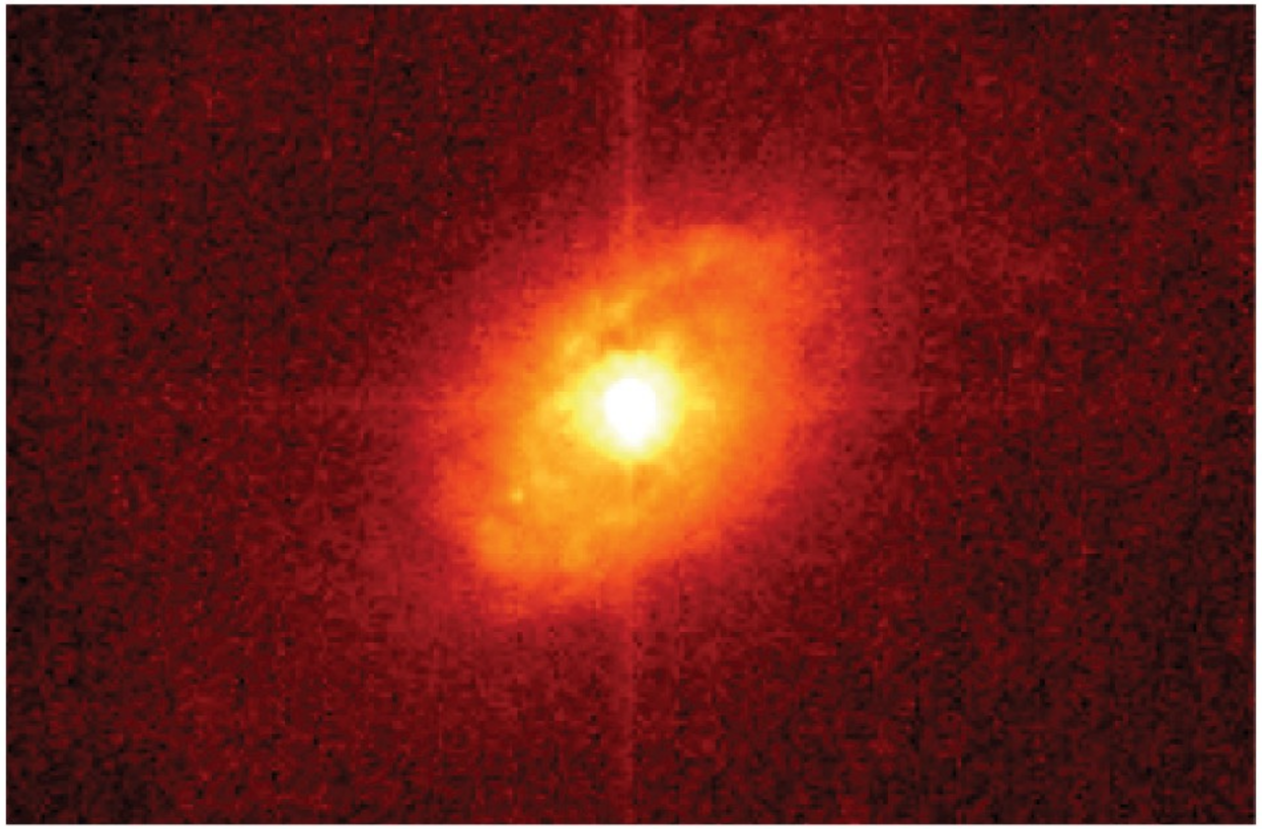


Hoyle et al (1964), Lynden-Bell (1969)

Active Galactic Nuclei: a Rare but Important Class of Galaxies

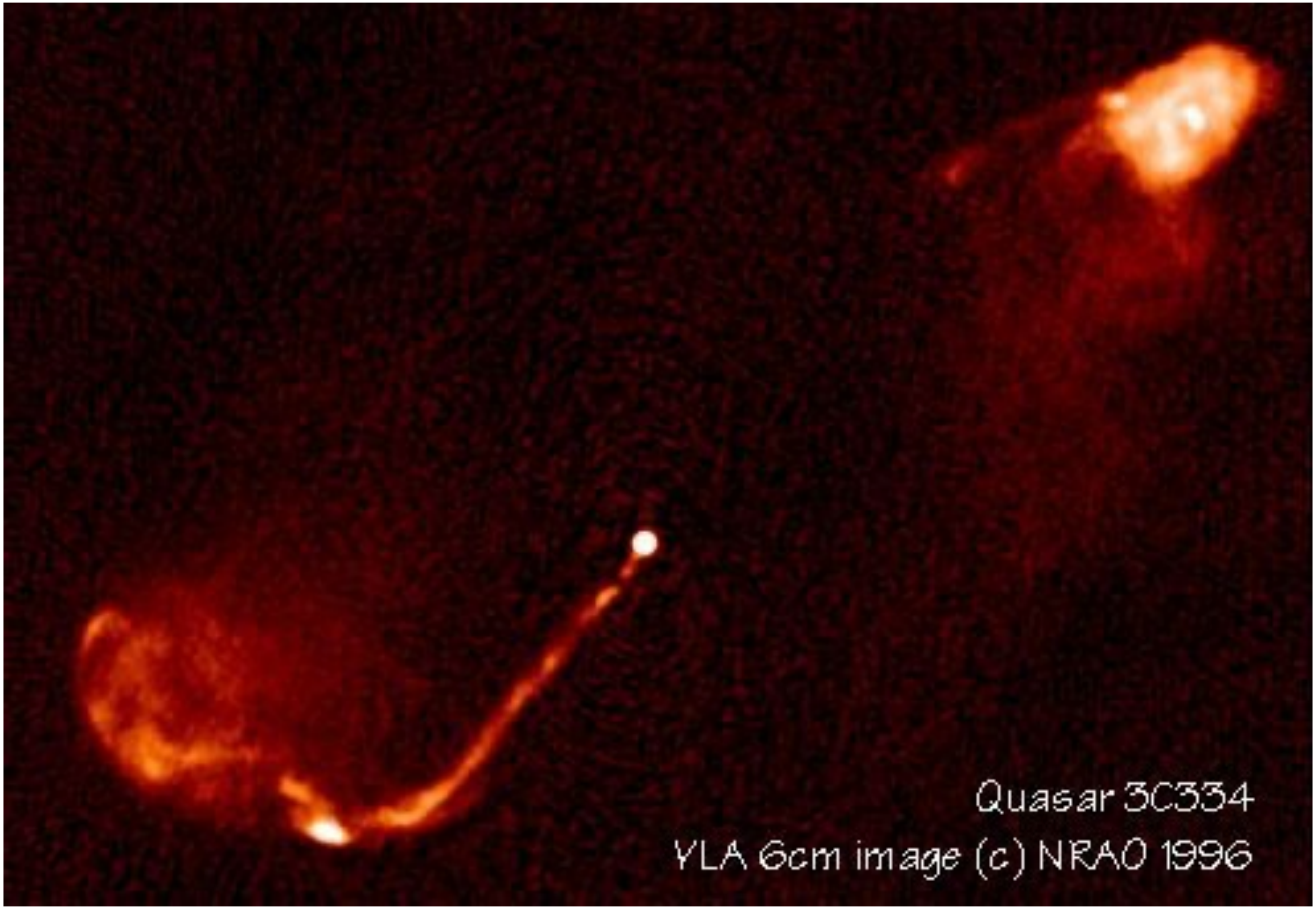
- **Quasars** are only a subset of **active galactic nuclei (AGN)**.
  - The luminosity of a quasar can be as large as the rest of the galaxy.
  - The most luminous AGN are called **quasars**, the less luminous AGN are called **Seyferts**.
- All **AGN** are powered by central **supermassive black holes** with accretion disks.





Radio-Loud Quasars: Radio Jets and Lobes

- **Radio-loud Quasars** show large jets and lobes of radio emission, powered by the central engine.

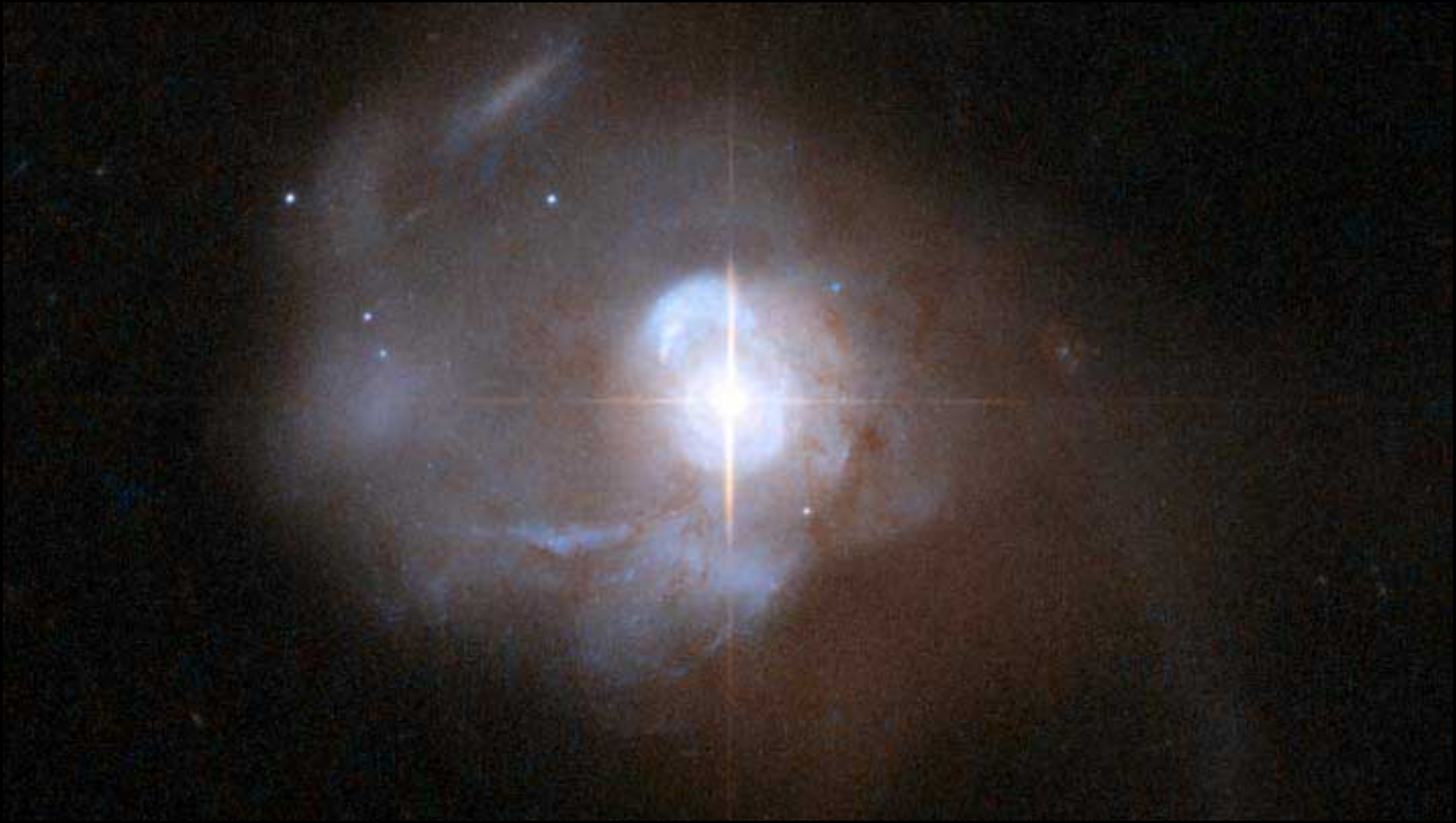


Radio Galaxies: Similar Radio Jets and Lobes

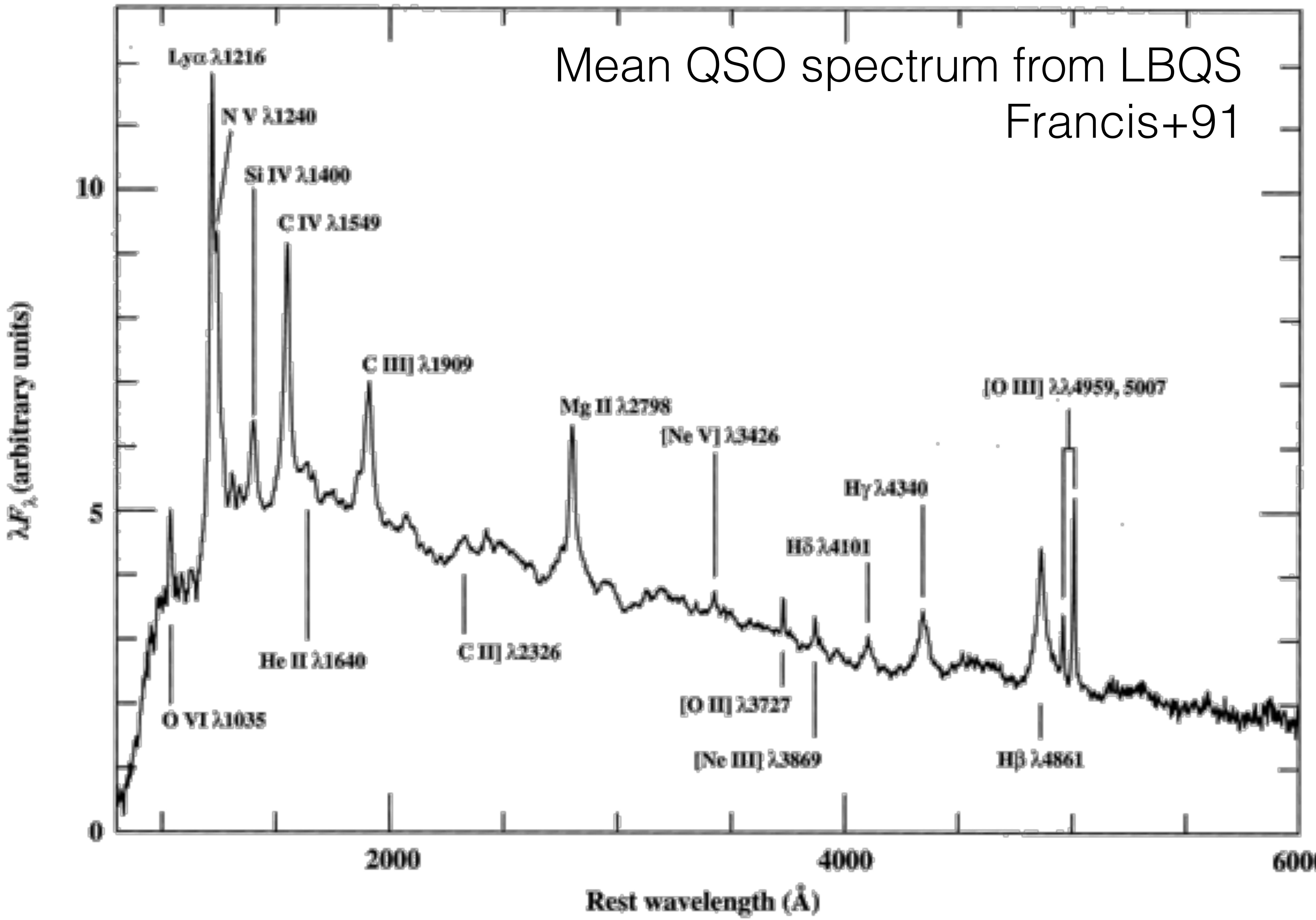
- **Radio galaxies** are ***elliptical galaxies*** that have large jets and lobes of radio emission, powered by the central engine.
- Their radio properties are similar to radio-loud quasars but they do NOT show the central brilliant point source

Centaurus A (distance 3.4 Mpc)

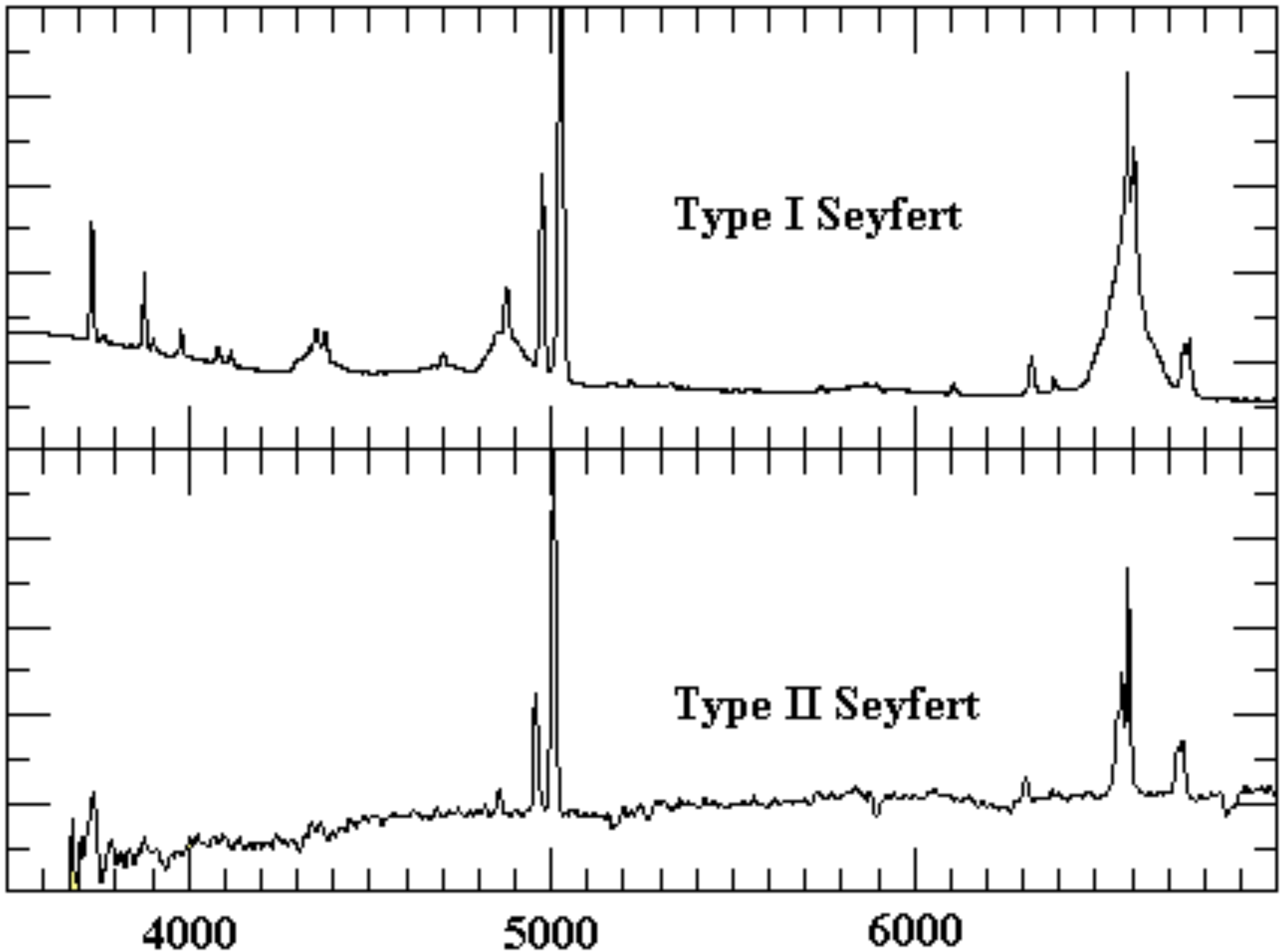
Mrk 231: a Type 1 Seyfert



NGC 1672: a Type 2 Seyfert



Mean QSO spectrum from LBQS
Francis+91
Lyα λ1216
N V λ1240
Si IV λ1400
C IV λ1549
C III] λ1909
Mg II λ2798
[Ne V] λ3426
[O III] λλ4959, 5007
Hγ λ4340
Hδ λ4101
He II λ1640
C II] λ2326
O VI λ1035
[O II] λ3727
[Ne III] λ3869
Hβ λ4861
λF_λ (arbitrary units)
0
5
10
2000
4000
6000
Rest wavelength (Å)

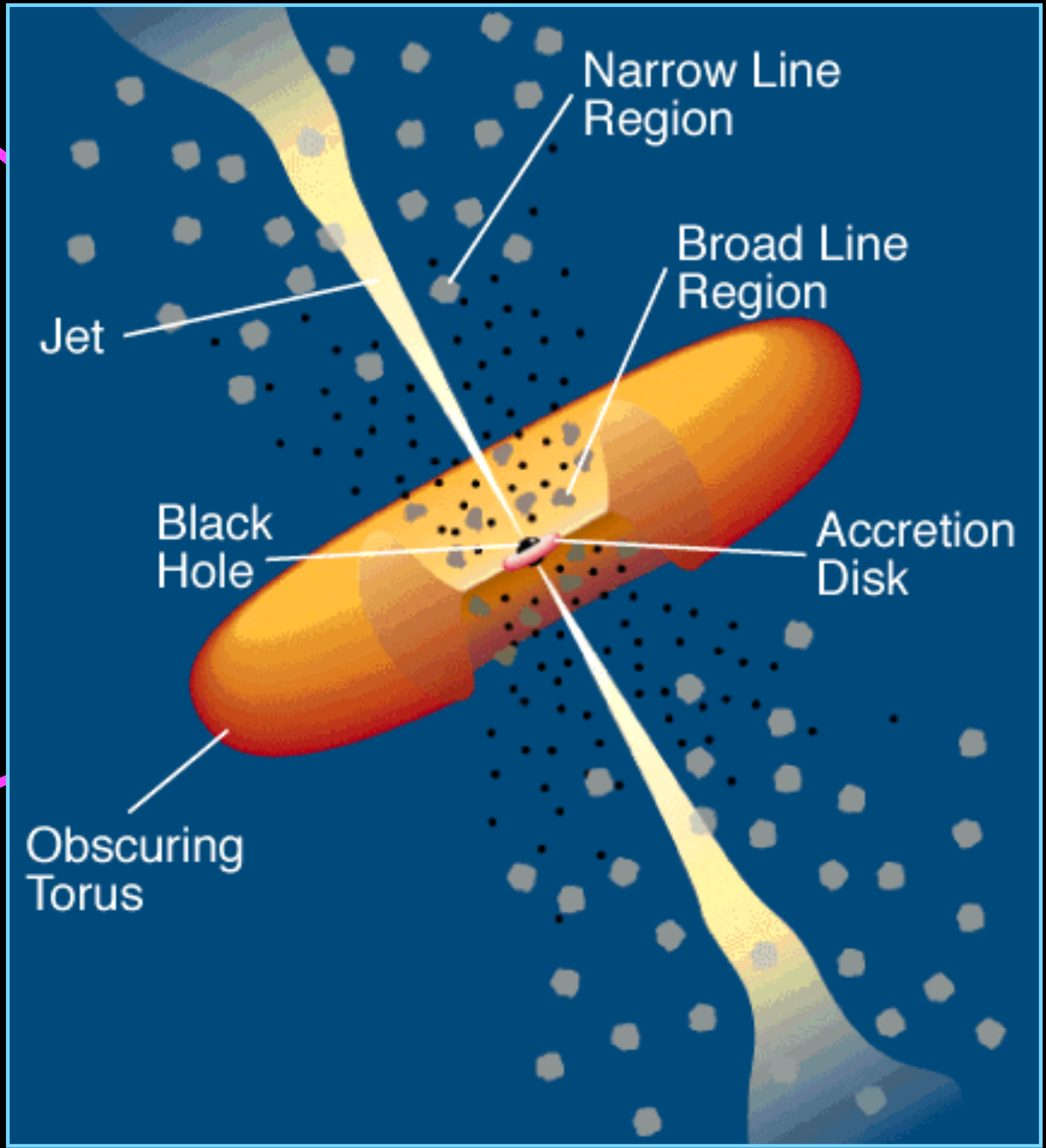


Type I Seyfert
Type II Seyfert
4000
5000
6000

Could Quasars & Radio Galaxies be the same type of objects but viewed at different angles?

Could Type 1 & Type 2 Seyferts be the same type of objects but viewed at different angles?

Seyfert 1s
Quasars



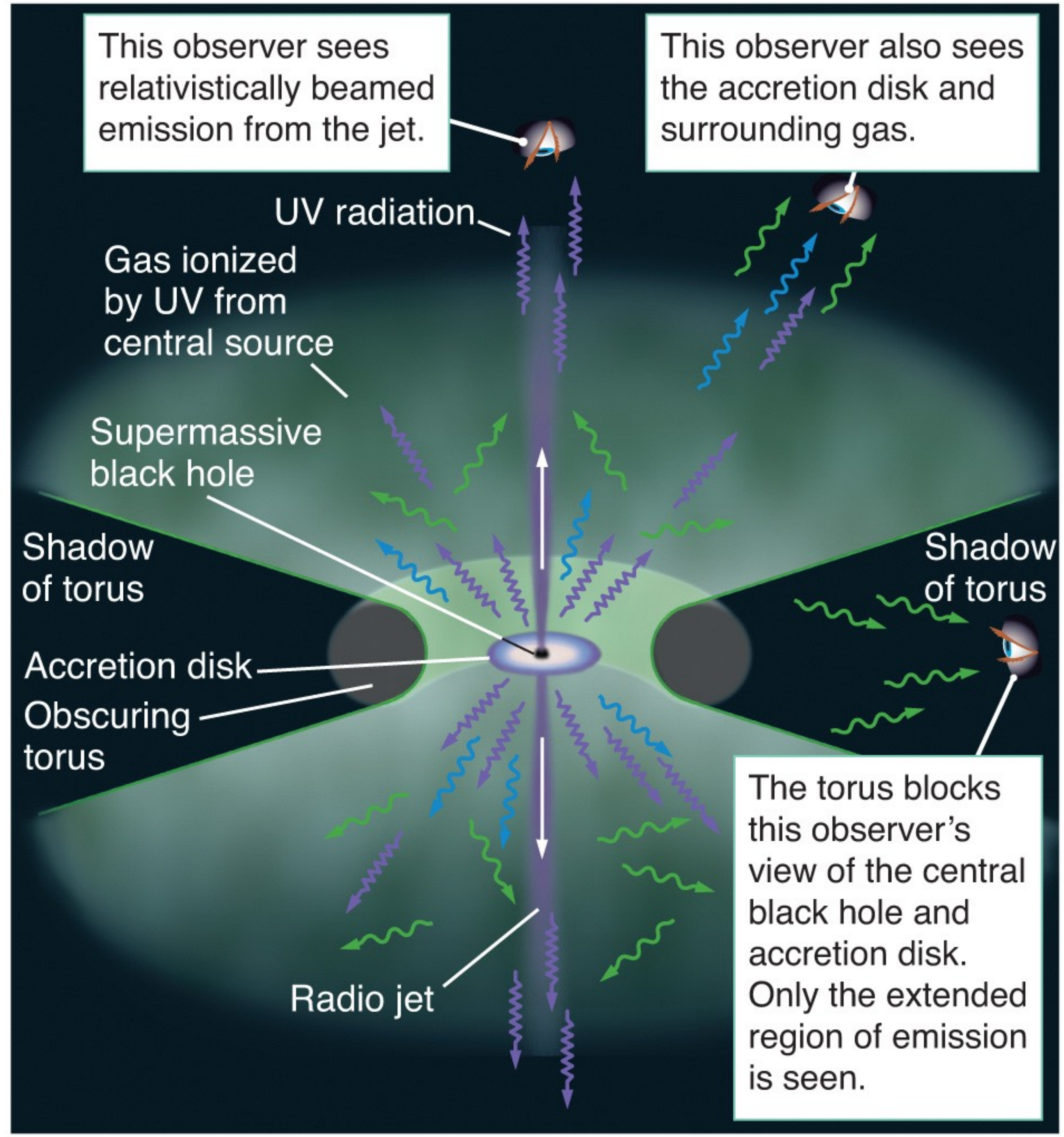
Seyfert 2s
Radio
Galaxies

Torus Size ~ 5 pc

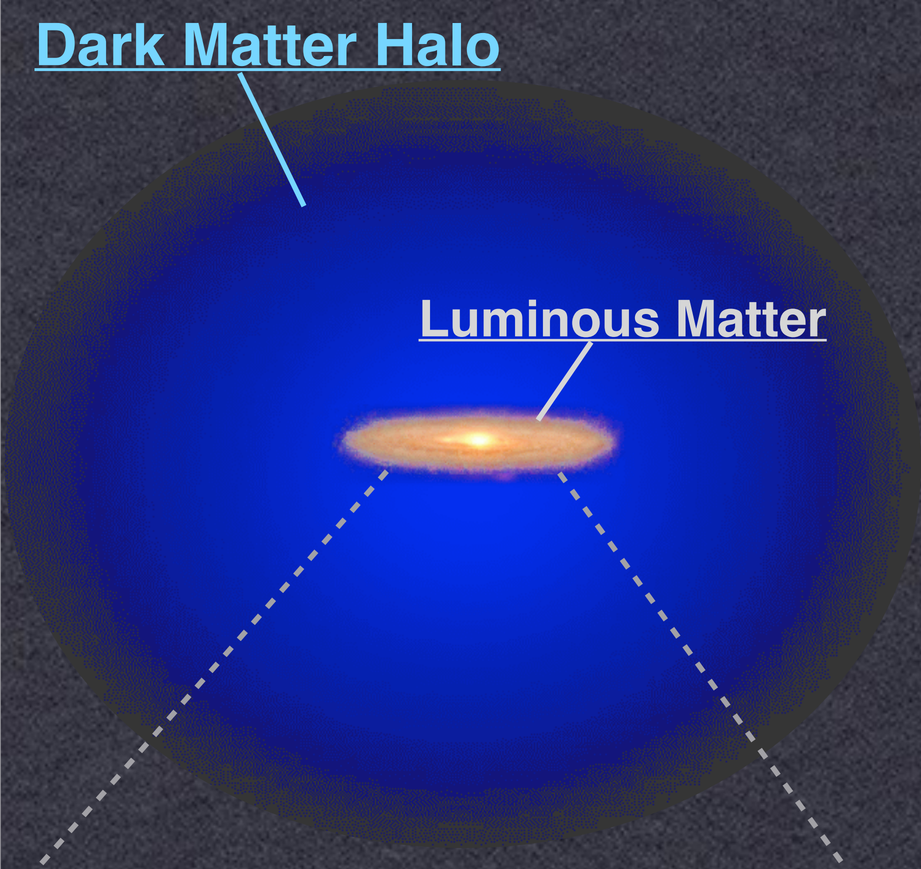
Urry & Padovani 1995

Unified Model of AGN: applicable to both Seyferts and Quasars/RGs

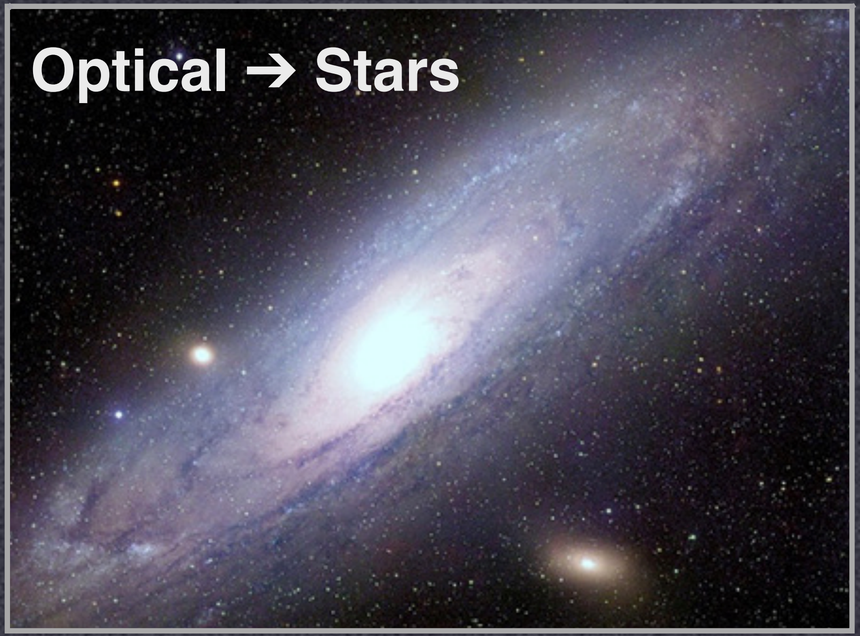
- The **unified model of AGN** attempts to explain the different types of AGN.
- What we see depends on our viewing angle of the AGN.
  - **Edge on**: viewing emission from the torus
  - **Face on**: viewing emission from the accretion disk and jet
  - ***Blazar*** when viewing straight down the jet

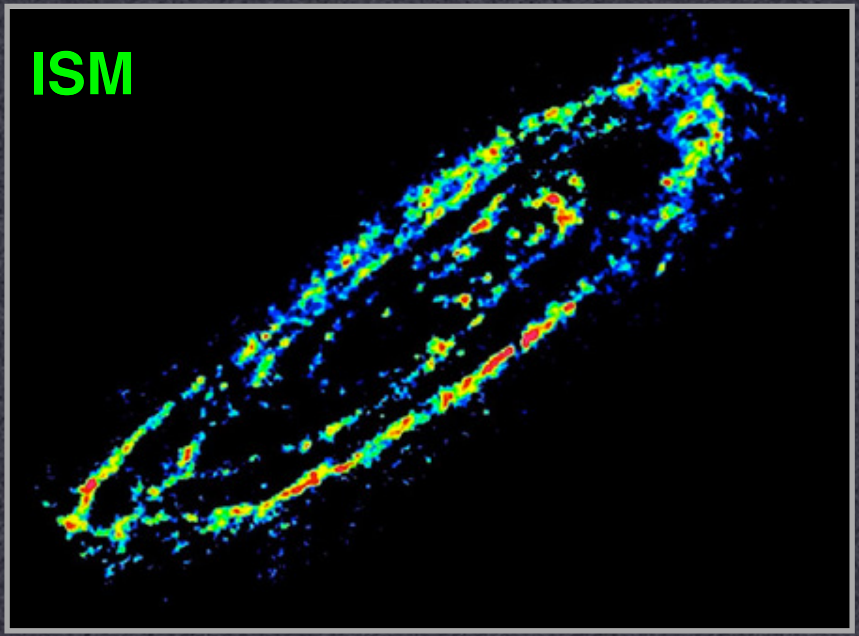


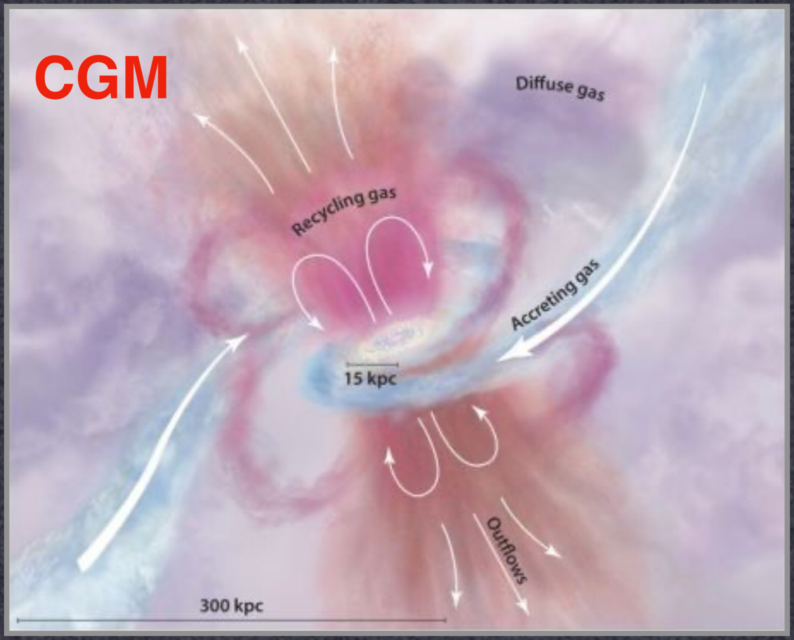
Summary: Components of M31



- Total Dynamical Mass: $1.2 \times 10^{12}\ M_\odot$
- Normal Baryonic Matter (~16% or 1/6)
  - Stars: $\sim 10^{11}\ M_\odot$
  - Interstellar Medium (ISM): $\sim 10^{10}\ M_\odot$
  - Circumgalactic Medium (CGM): $\sim 10^{11}\ M_\odot$ mostly ionized gas, some at million K
- Supermassive Black Hole ($\sim 10^{8}\ M_\odot$)
- Dark Matter (~84% or 5/6)
  - Halo Mass: $\sim 10^{12}\ M_\odot$







references: Corbelli+2010, Nieten+2005, Lehner+2015, Bender+2005

Chap 5: Galaxies - Summary

- How to determine distances to galaxies? What is the distance ladder?
- What are the morphologies of galaxies today?
- How morphology is related to the stellar population?
- How orbits of stars and galaxy morphology are intertwined?
- Evidence of dark matter
- Evidence of supermassive black holes & accretion energy

Chap 5 Galaxies: Key Equations

- **Period-Luminosity relation** of Cepheids: $M_V = -2.43\log(P_{\rm day}) - 1.62$
- **Distance modulus**: $m - M = 5\log d_{\rm pc} - 5 \Rightarrow d_{\rm pc} = 10^{1+0.2(m-M)}$
- **Virial Mass**: $M_{\rm vir} = \bar{v}^2 R/G$
- **Keplerian rotation curve**:
  $v(r) = \sqrt{GM(r)/r} \Rightarrow v(r) \propto 1/\sqrt{r}$ when *M(r)* no longer increases
- The **Schwarzschild radius**:
  $$r_s = \frac{2GM_{\rm BH}}{c^2} = 3\,{\rm km}\left(\frac{M_{\rm BH}}{1M_\odot}\right) = 2\,{\rm AU}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$$
- The **sphere of influence:**
  $$r_* = \frac{GM_{\rm BH}}{\sigma_*^2} = 11\,{\rm parsec}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{200\,{\rm km/s}}{\sigma_*}\right)^2$$
- Black hole **accretion energy** generation rate**:**
  $$L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,{\rm yr}^{-1}}\right)$$