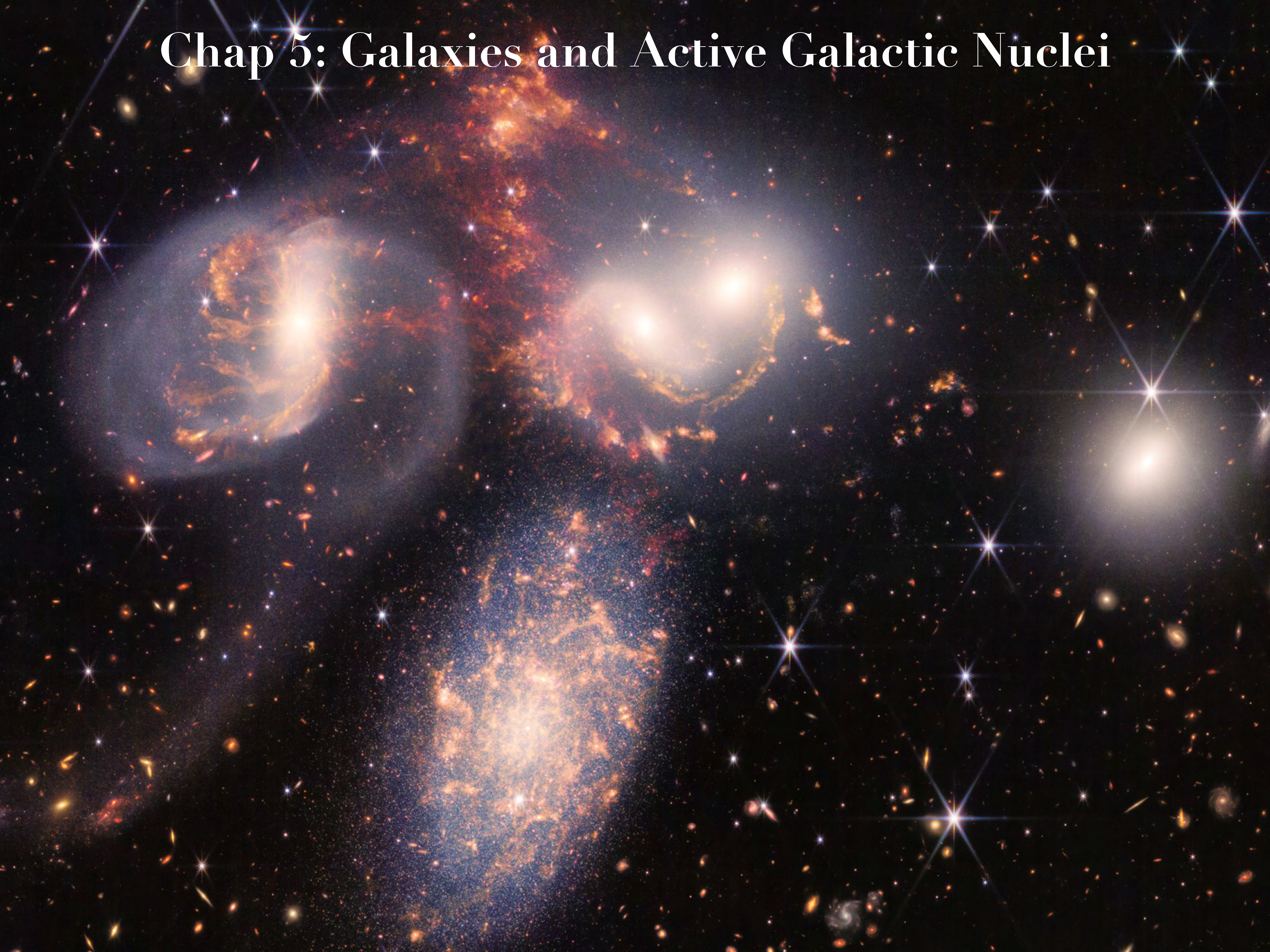
Chap 5: Galaxies and Active Galactic Nuclei

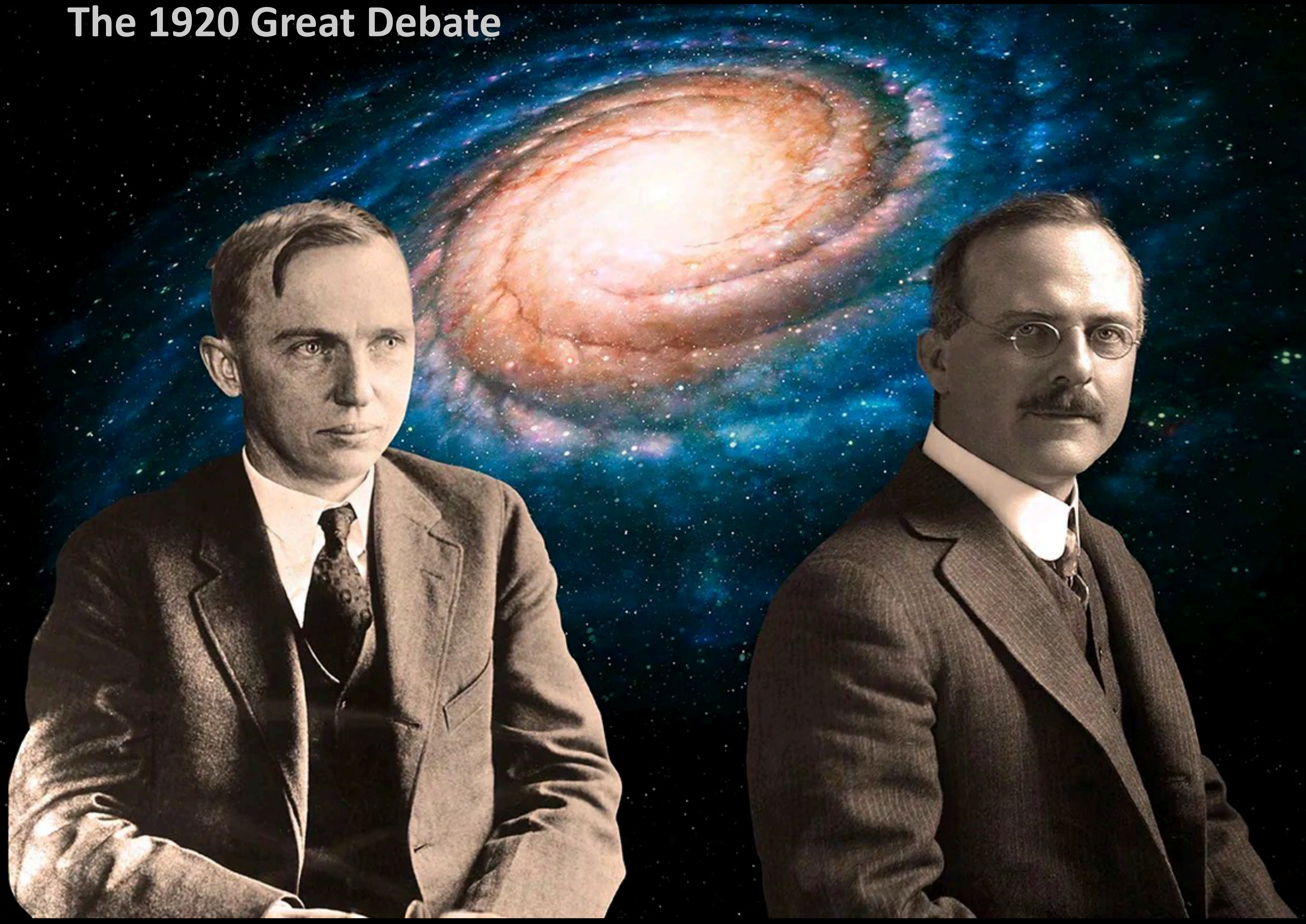


Chap 5: Galaxies and Active Galactic Nuclei

- Astronomers' distance ladders to reach beyond 100 Mpc
- Evidence of dark matter in galaxies and clusters
- Complex stellar population in galaxies (MW as example)
- Evidence of supermassive black holes at the centers of massive galaxies
- The color-magnitude diagram
- How morphology is related to the stellar population?

Nebulae or Island Universes?

The 1920 Great Debate

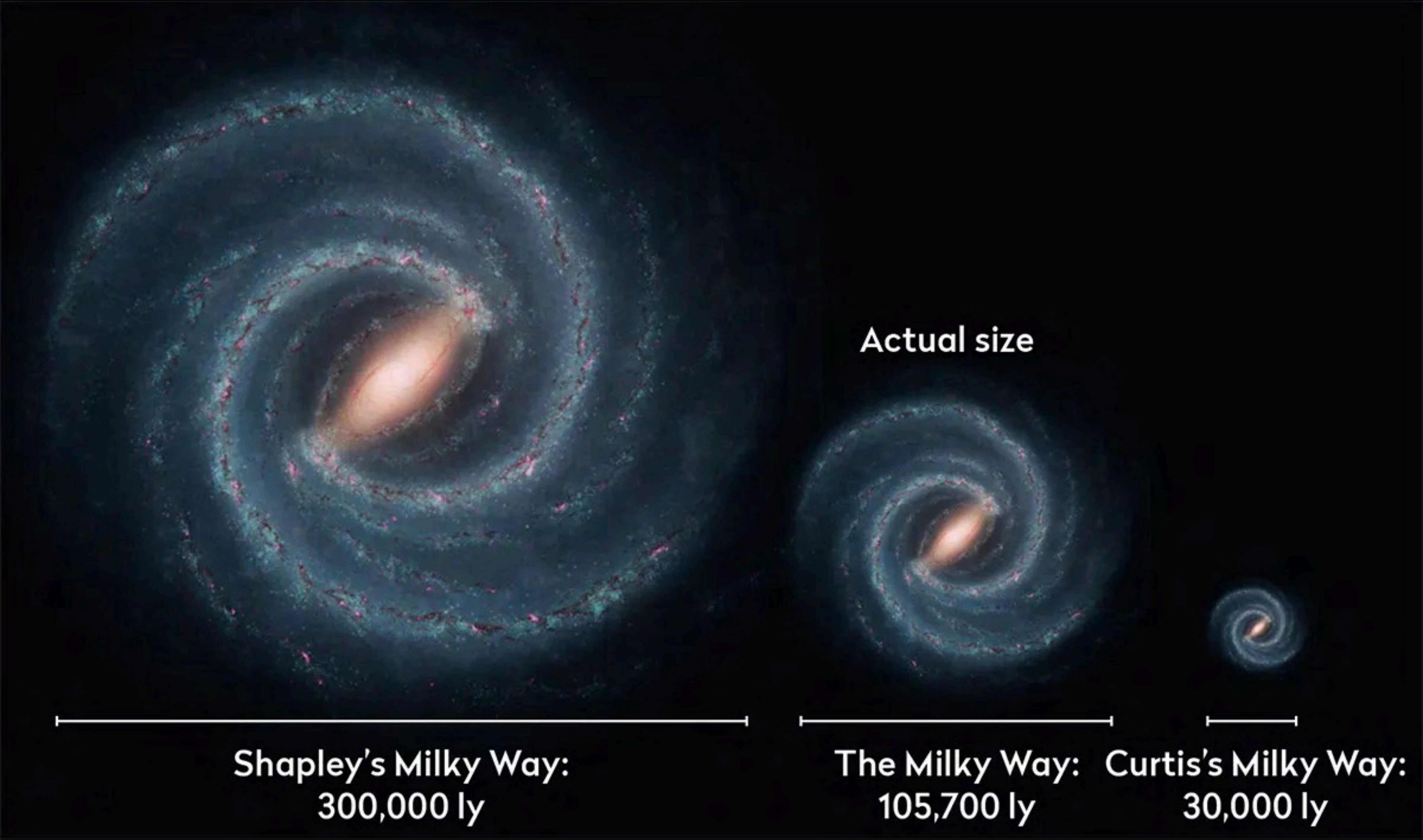


The 1920 Great Debate: "Nebulae" or "Island Universes"?

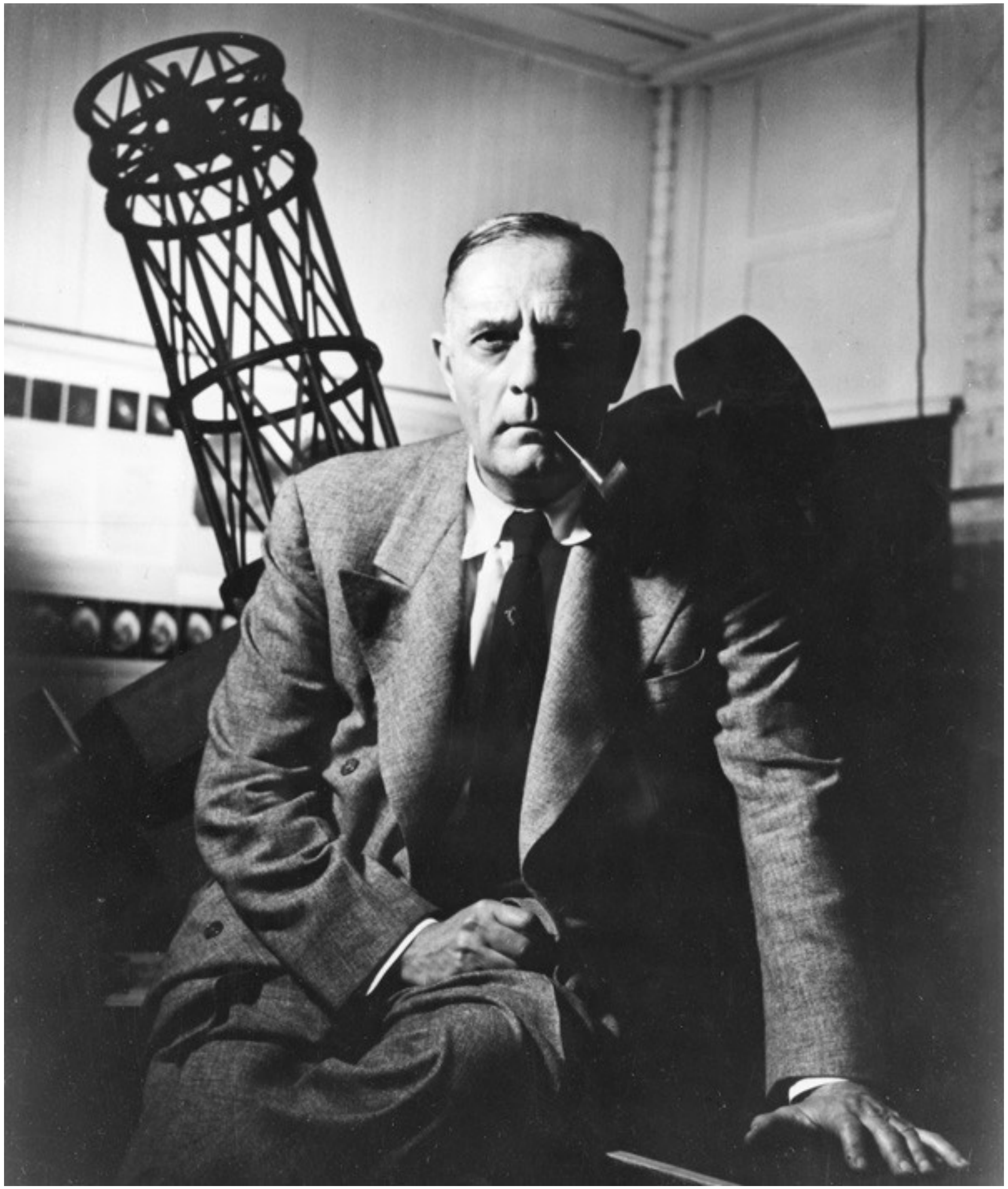
- Charles **Messier** and William and Caroline **Herschel** identified thousands of **fuzzy "nebulae"** in **1700s**.
- Some astronomers thought the nebulae were located in the Milky Way, while others speculated that they were **island universes**.
  - This was an important question as it was widely 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



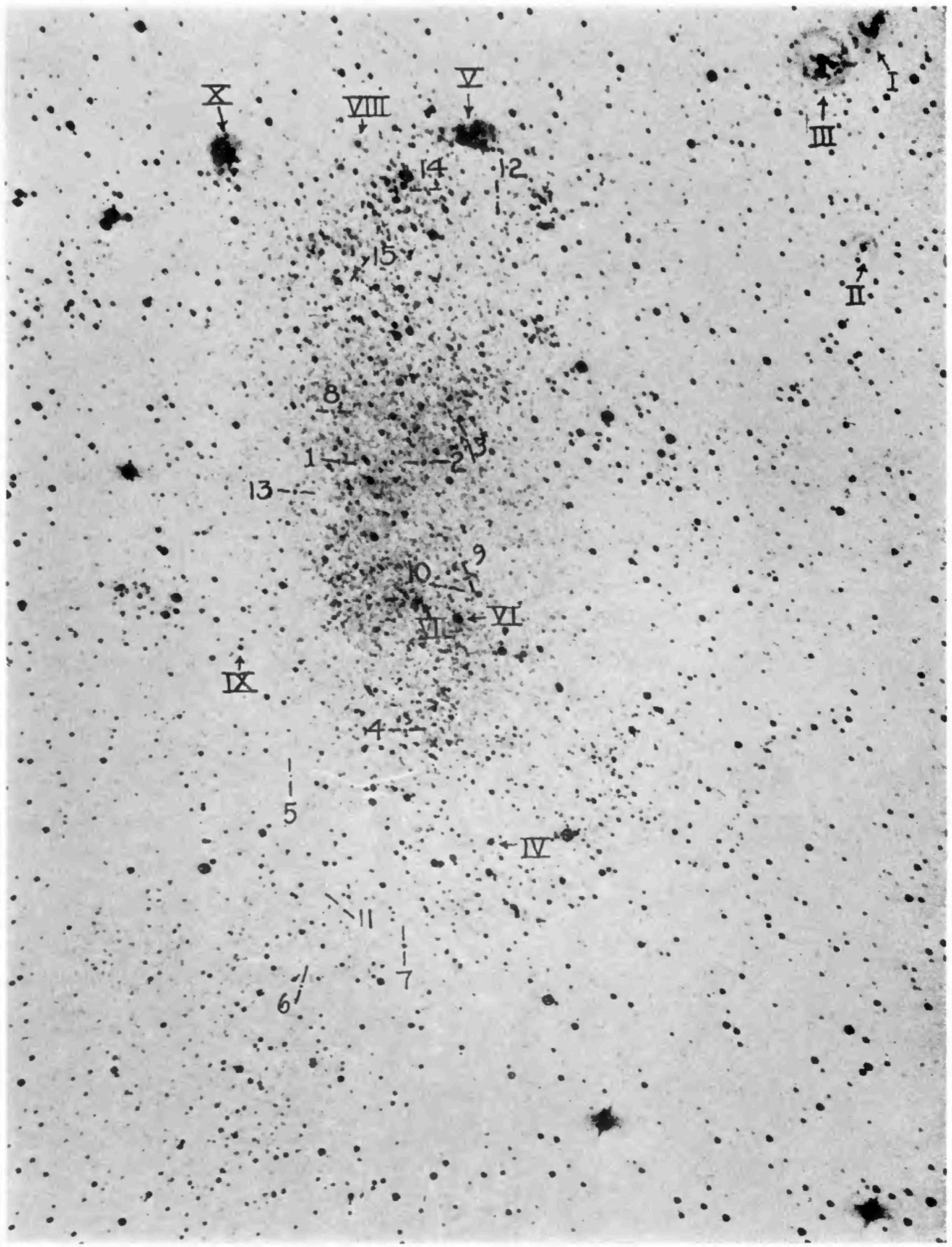
Edwin Hubble (1889-1953)



- 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)

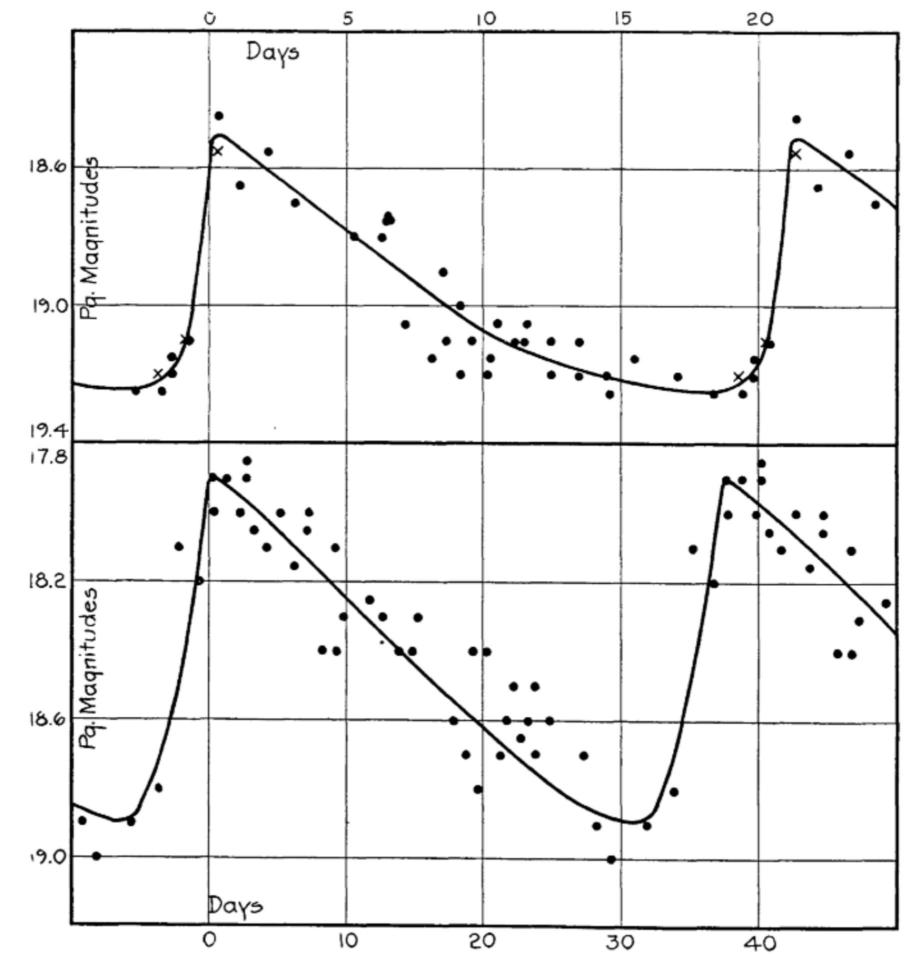


FIG. 1.—Light curves for two Cepheids in N.G.C. 6822. Upper curve, variable No. 6. Period 21.06 days; range 18.5–19.25. Lower curve, variable No. 2. Period 37.45 days; range 17.9–18.9. The three crosses on the rising slope of the upper curve represent observations on successive days and illustrate the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

$$m - M = 21.65 .$$

$$\pi = 0.''00000468$$

Distance = 214,000 parsecs

= 700,000 light-years

The Universe of Galaxies


GC 6753 Group 150MLY
VIRC
SUPERC
Local Void
Centaurus A/M83 Group 11.9MLY
Sculptor Group 12.7MLY
M94 Group
5MLY
Local Group
Ca
M101 G
M81 Gro
IC 341/Maffei Group 10.7MLY
Leo

The scope of the known Universe

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.

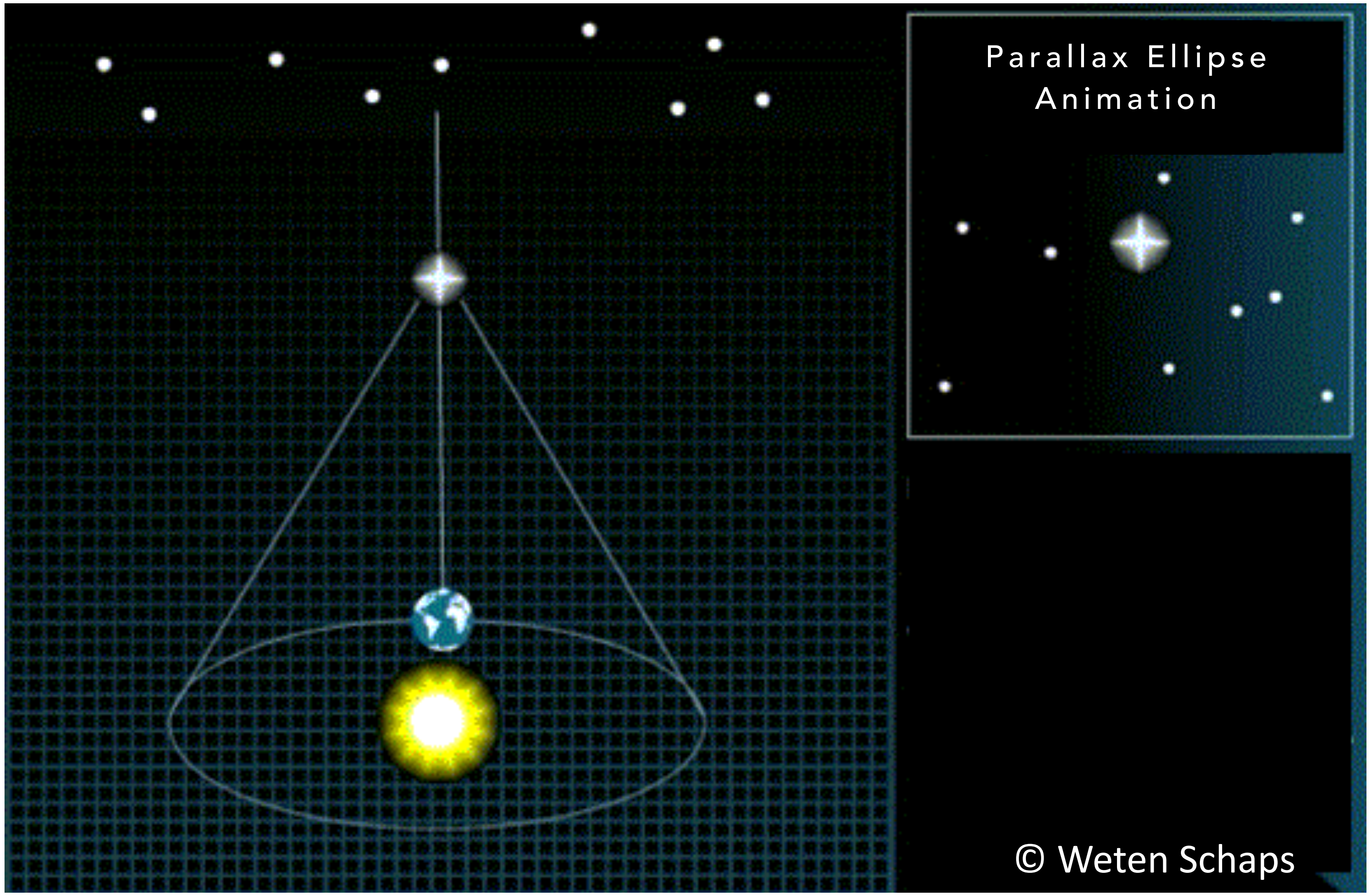

How did we measure distances to galaxies?
JWST

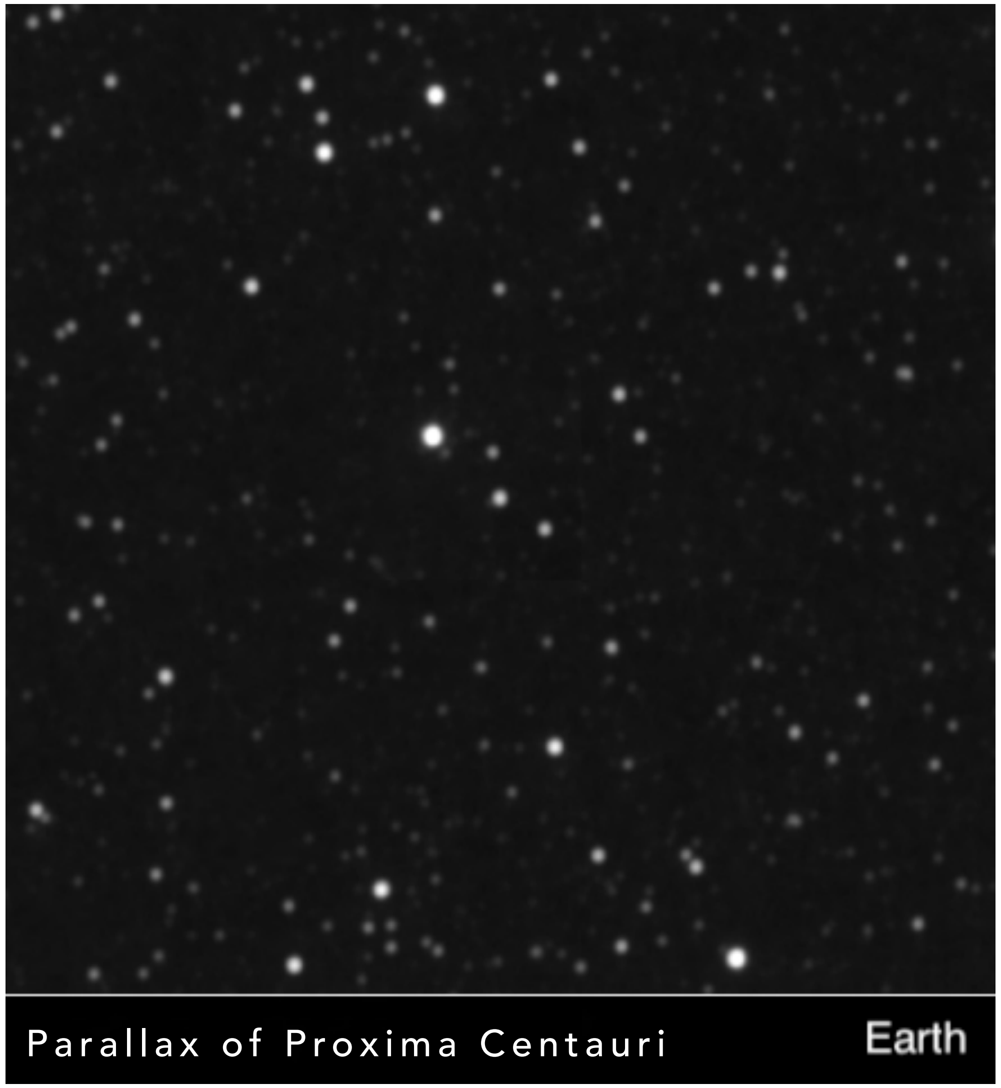
The Distance Ladder

Geometric methods to measure distances (up to 10 Mpc)

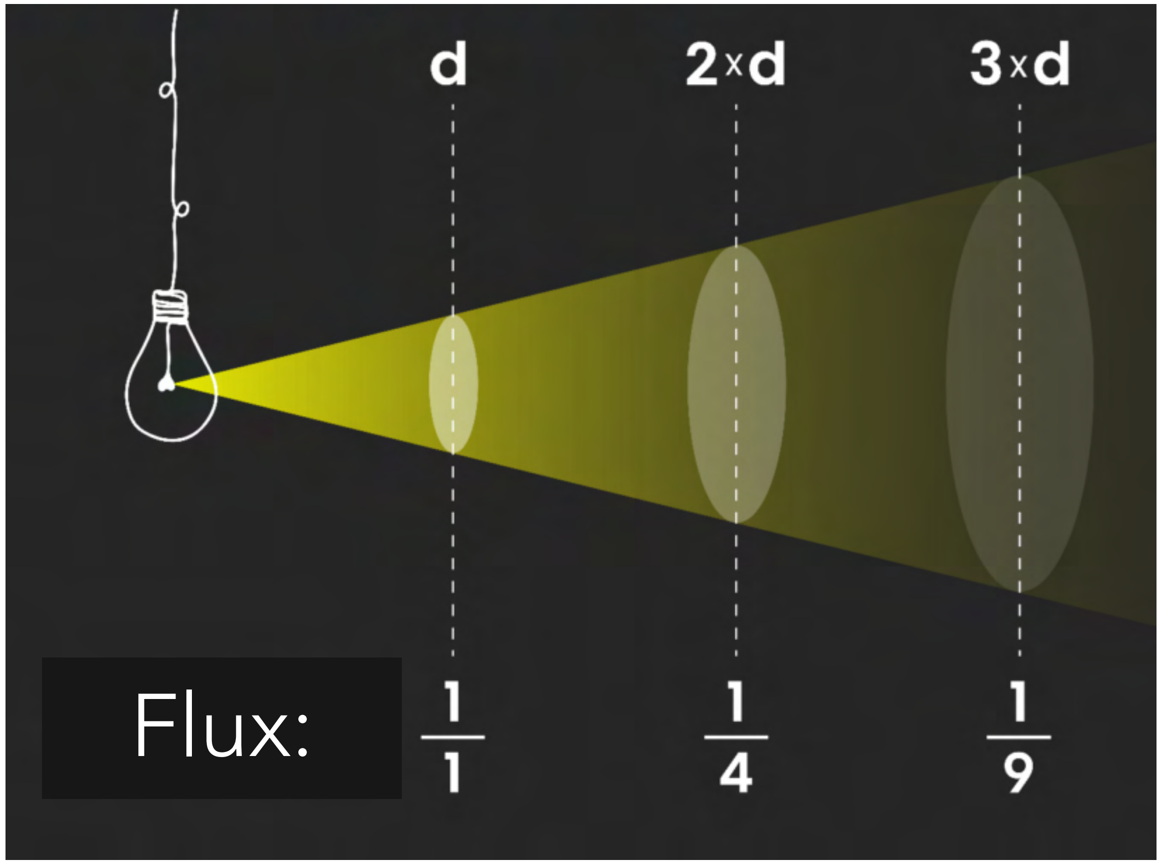
Distances from parallax, radial velocities and proper motions:

- $D = l/\theta$ is the **parallax** method (Hipparchus, 150 BC)
- $D = \dot{l}/\dot{\theta}$ is the **expanding parallax** method
- $D = \int \dot{l} dt \Big/ \int \dot{\theta} dt$ the **expanding atmosphere** method





Distance from Luminosity and Flux: the Inverse Square Law



- **Apparent magnitude**

  $m = -2.5 \log F/F_{\rm ref} + m_{\rm ref}$

- **Absolute magnitude**

  $M = -2.5 \log F_{10\rm pc}/F_{\rm ref} + m_{\rm ref}$

- **Inverse square law**

  $L = 4\pi(10{\rm pc})^2 F_{10\rm pc} = 4\pi d_{\rm pc}^2 F$

  which gives $F_{10\rm pc} = F d_{\rm pc}^2/(10{\rm pc})^2$

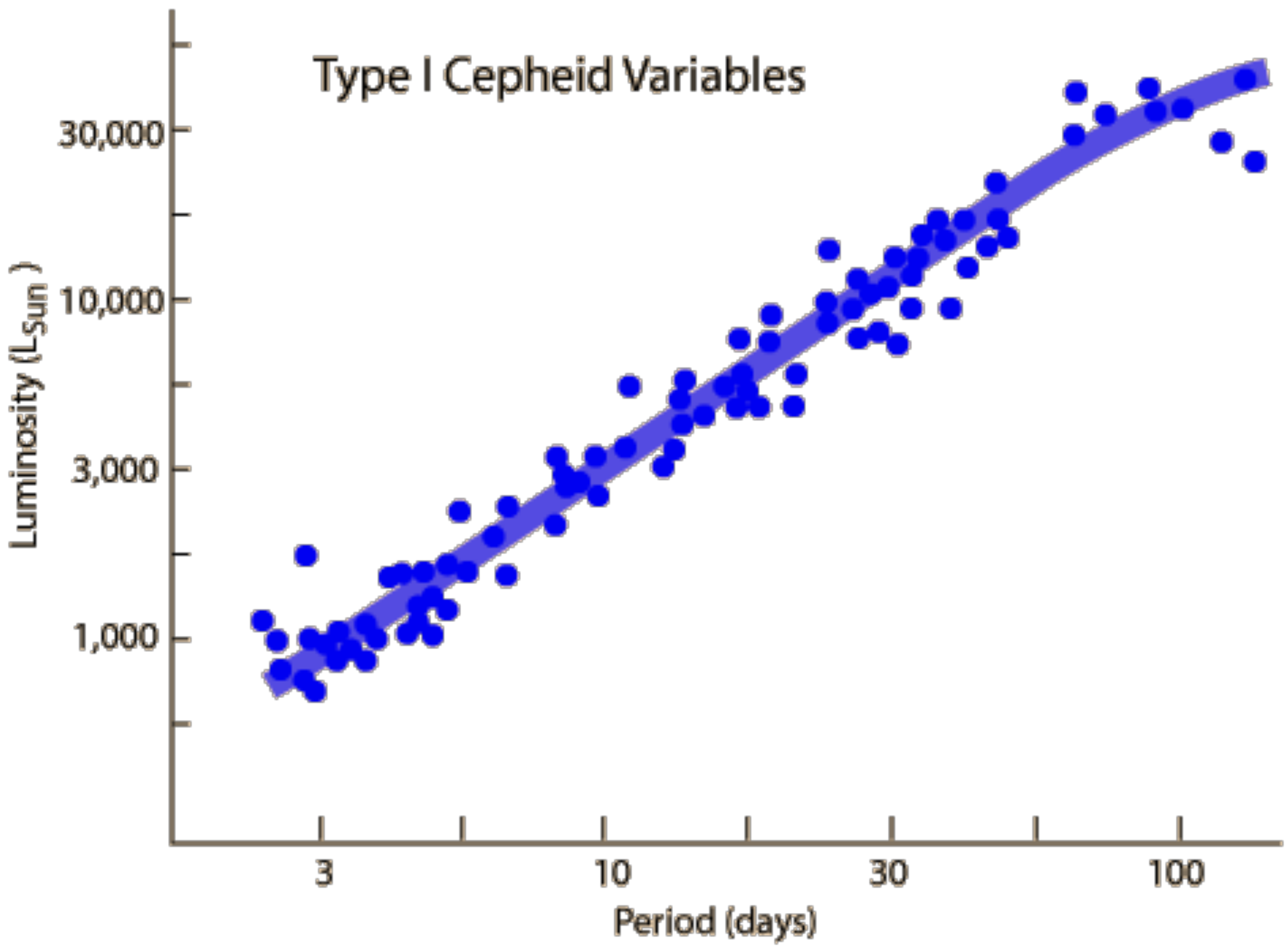
- **Distance modulus and distance:**

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

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

Luminosity must be *predictable* from a distance-independent observable

- $M_V = -2.43\log(P_{\mathrm{day}}) - 1.62$
  (Type I Cepheids, Fritz et al. 2007)
- **Absolute magnitude** of a 10-day period Cepheid is -4.05

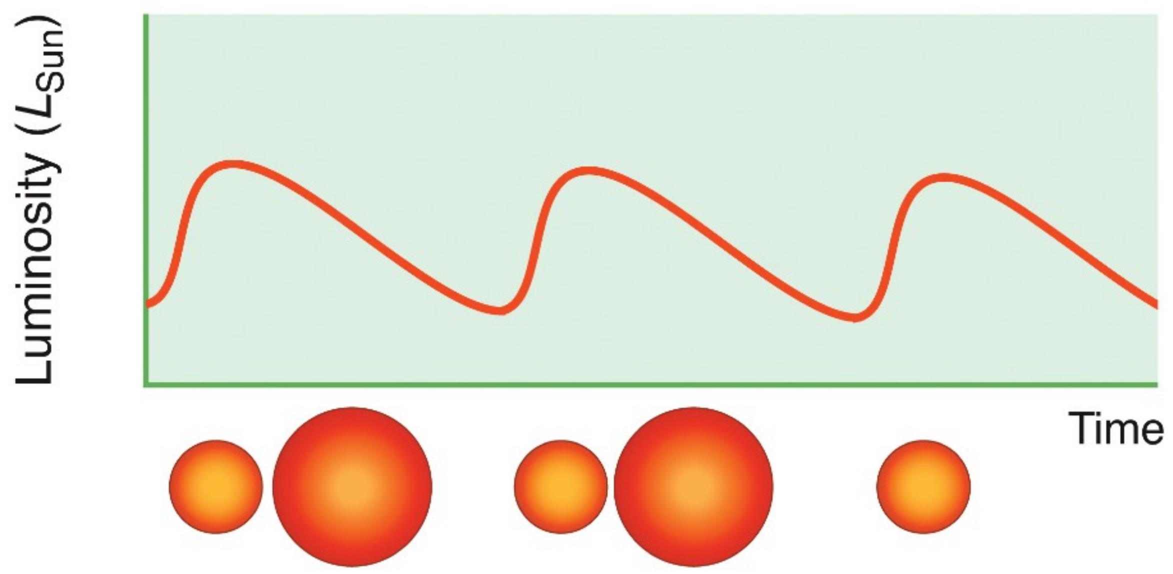


Henrietta Swan Leavitt

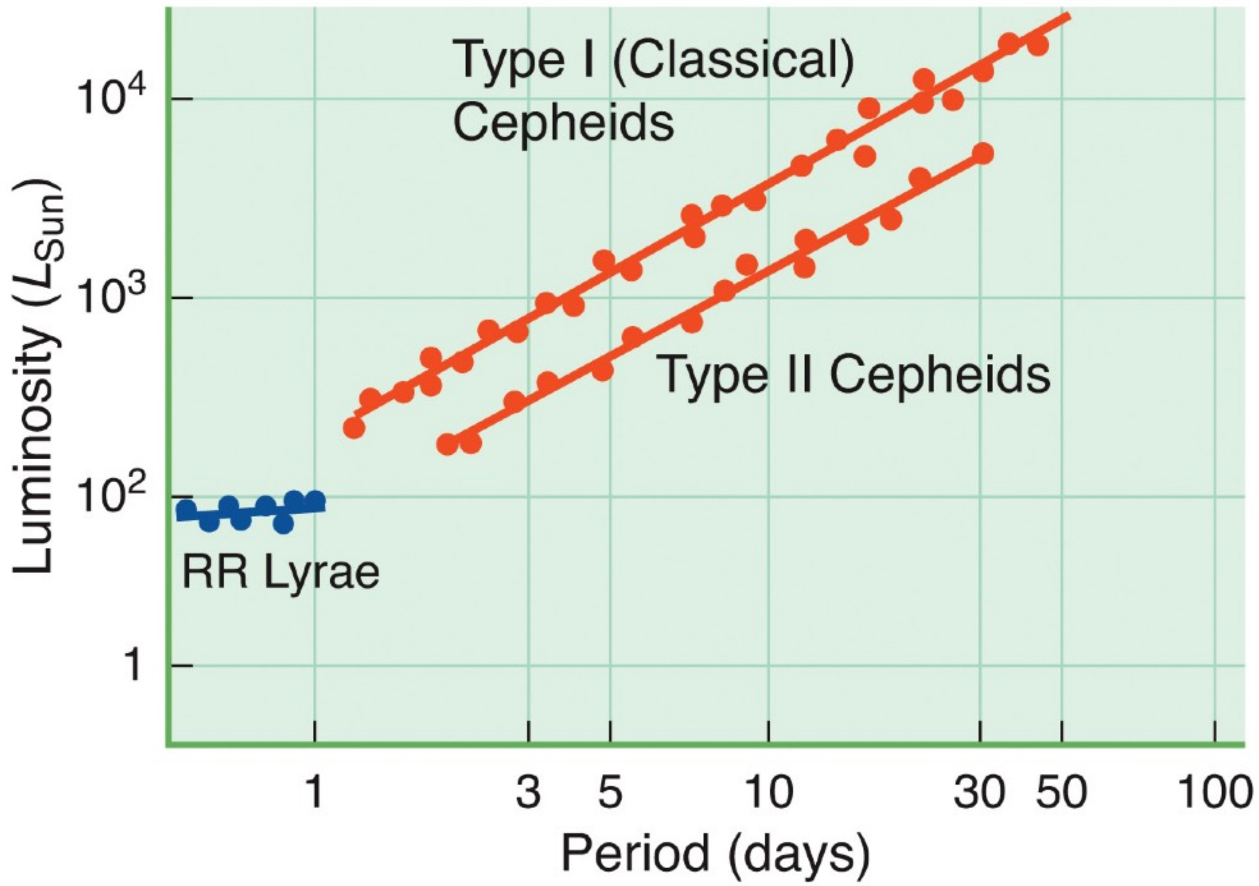
Born	July 4, 1868 Lancaster, Massachusetts, U.S.
Died	December 12, 1921 (aged 53) Cambridge, Massachusetts, U.S.
Education	Oberlin College Harvard University (BS)
Known for	Leavitt's law: the period-luminosity relationship for Cepheid variables

How to Tell Apart the Different Types of Pulsating Variable Stars?

- **Type I Cepheid variables**
  - Classic Cepheid variables are high-mass stars becoming supergiants.
  - They have periods from 1 to 100 days.
- **RR Lyrae variables & Type II Cepheid variables**
  - These are low-mass stars on the horizontal branch.
  - They are less luminous than Cepheid variables.
  - They follow different L-P relations



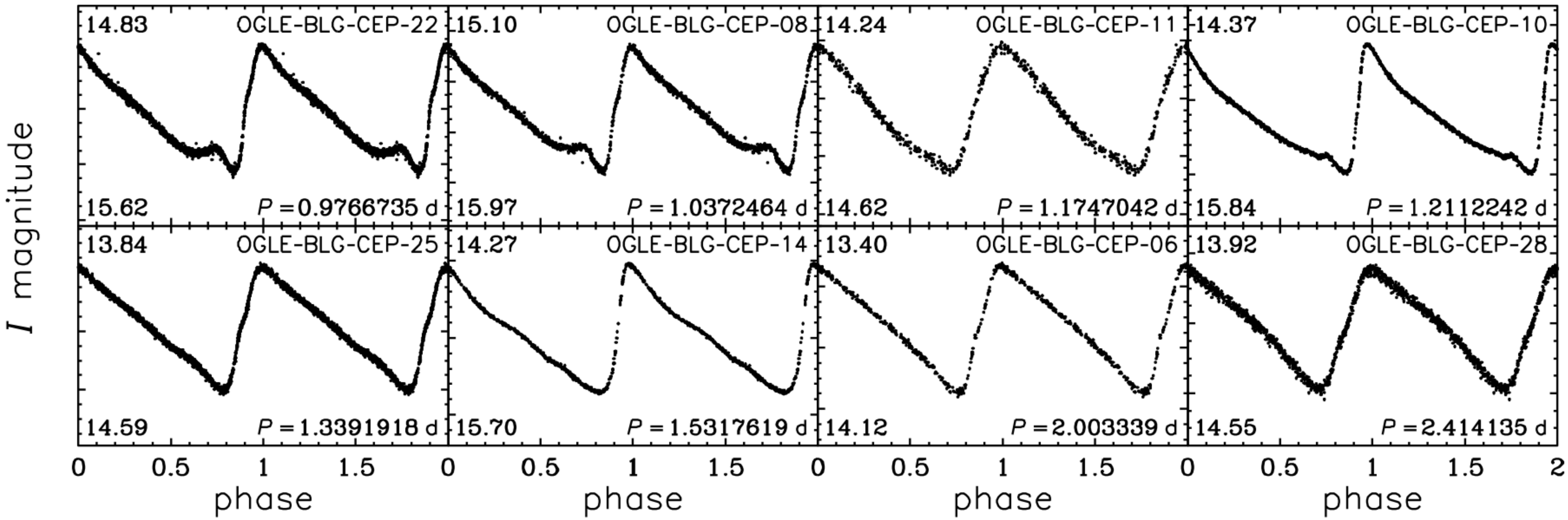
Luminosity vs. time



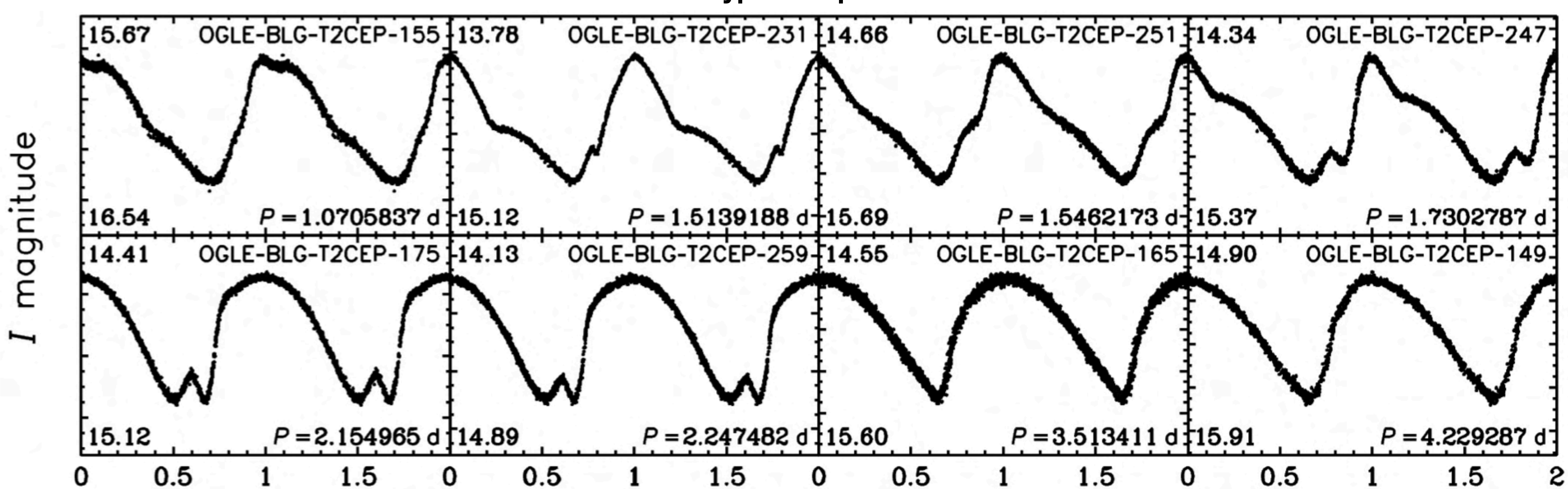
Period-luminosity relationship

Cepheids Light Curves - Type I vs. Type II Cepheids

Classical (or Type I) Cepheids

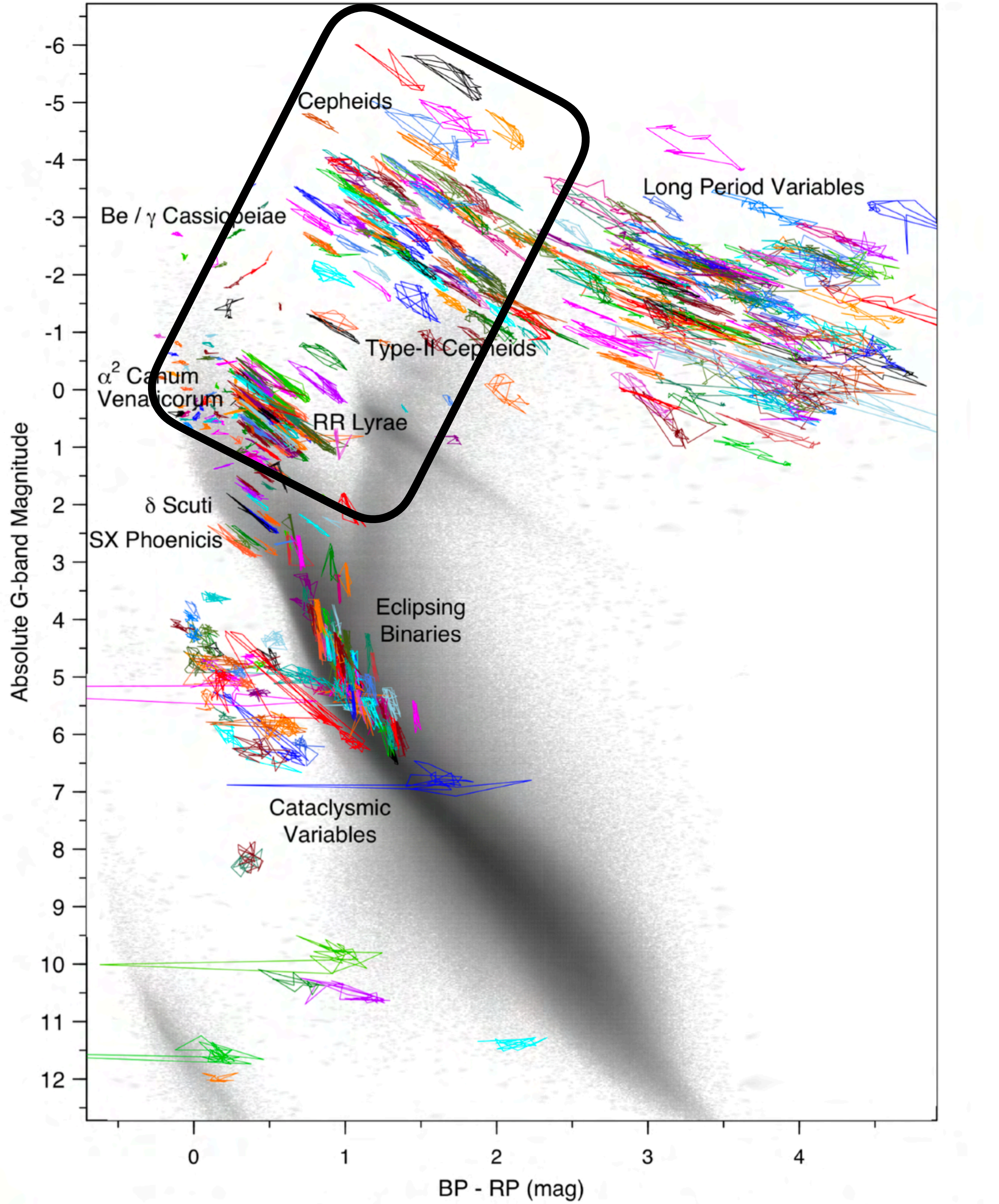


Type II Cepheids



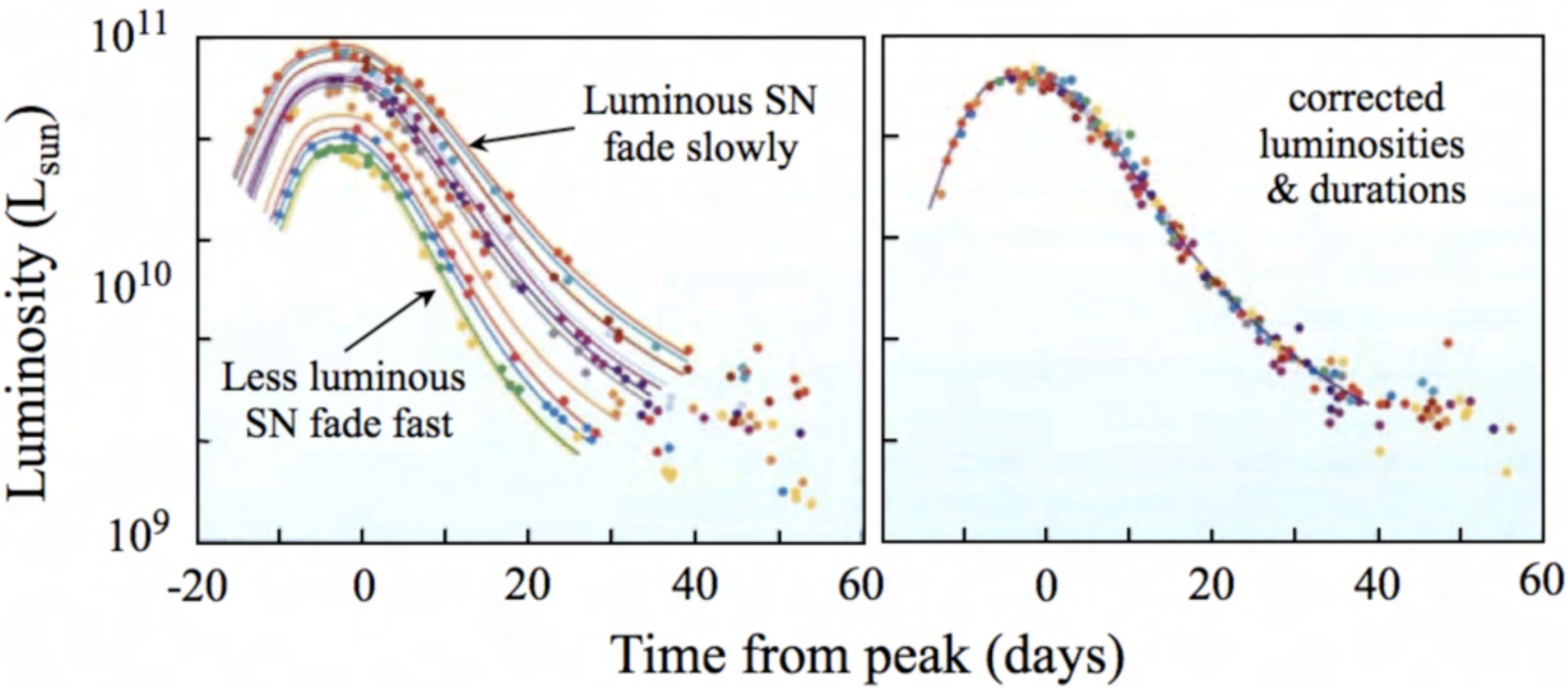
https://arxiv.org/abs/1112.1406

If you know their distances, you can put them on the HR diagram



Standard Candle II - Type Ia SNe (Phillips 1993 Law)

- **Type Ia supernovae** are excellent distance indicators because their luminosity can be inferred from the shape of its light curve, in particular, **how fast its brightness declines in the first 15 days**
- Peak *B*-band **absolute magnitudes** reaches about **-19.5**

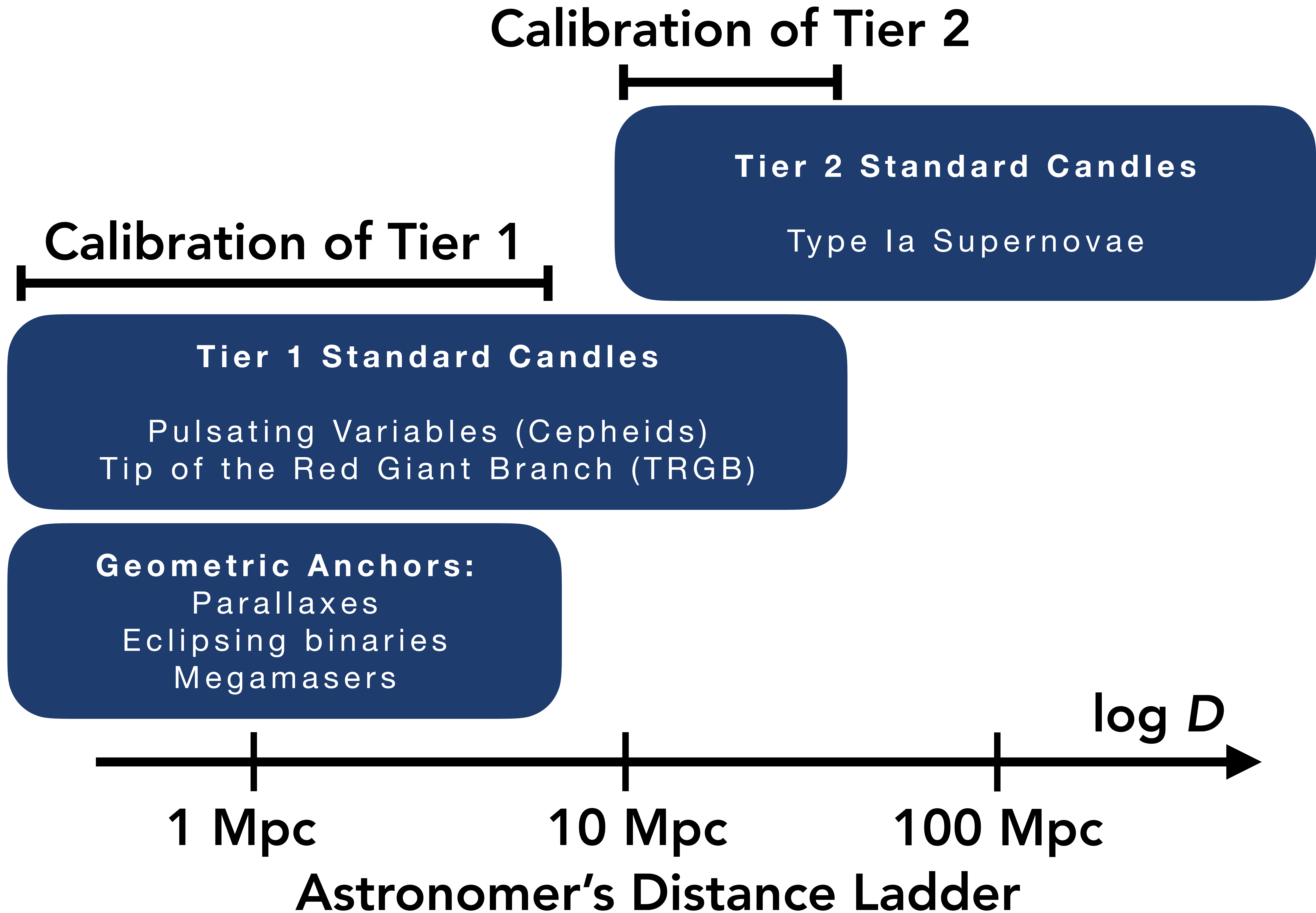


Astronomer's Distance Ladder

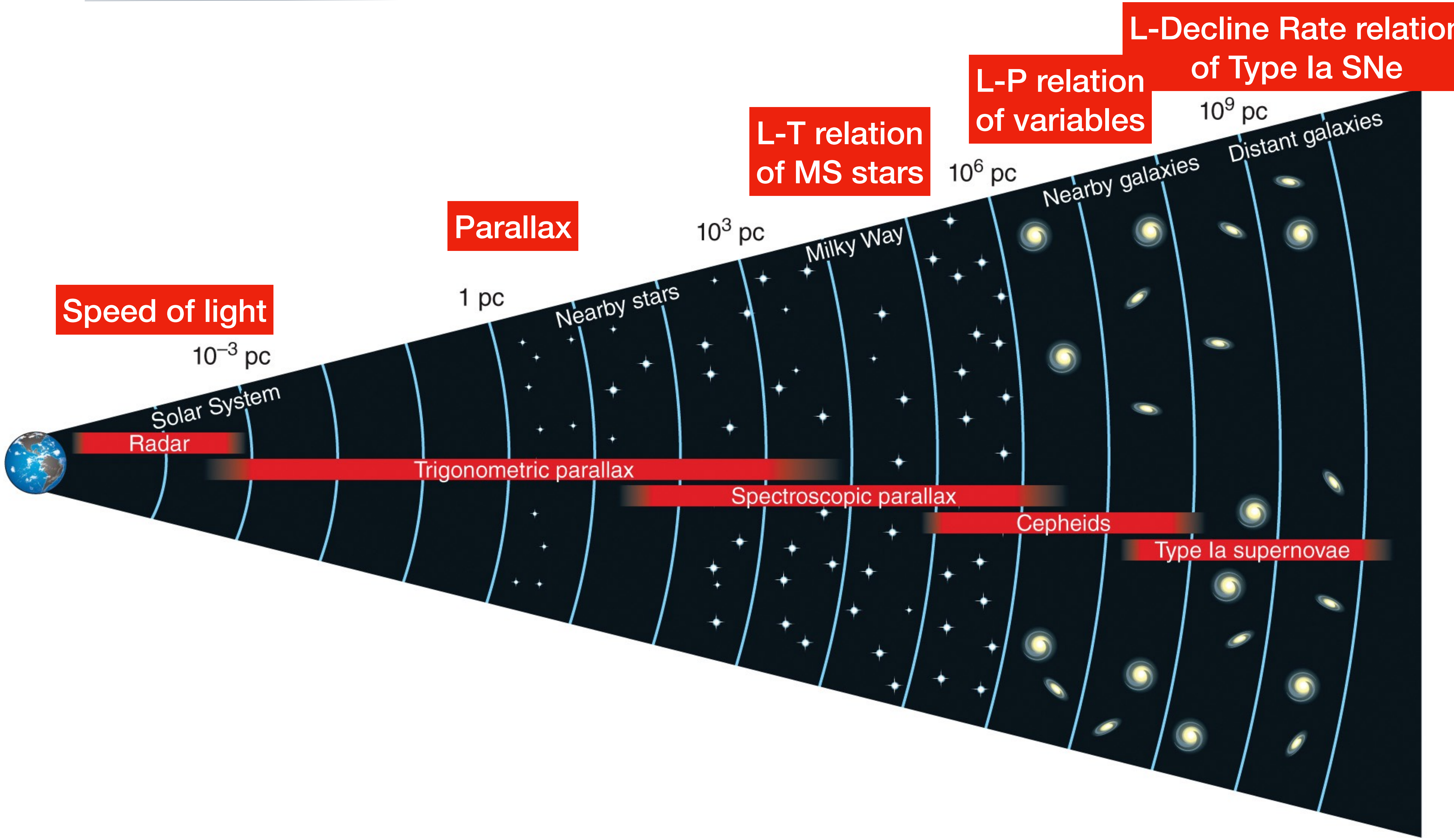
- Finding distances to galaxies requires the use of the **distance ladder** in which short-distance methods are used to calibrate long-distance methods.

- **Geometric method** uses geometric relations to measure distances:
  - e.g., Parallax, expansion parallax, expanding atmosphere

- **Standard candles** are objects with a luminosity inferred from other properties, so that their brightness and luminosity can be combined to calculate a distance.
  - **Cepheid variables** uses the luminosity-period relation of pulsating variable stars.
  - **Type Ia supernovae** uses the luminosity-duration relation.


Calibration of Tier 2
Tier 2 Standard Candles
Type Ia Supernovae
Calibration of Tier 1
Tier 1 Standard Candles
Pulsating Variables (Cepheids)
Tip of the Red Giant Branch (TRGB)
Geometric Anchors:
Parallaxes
Eclipsing binaries
Megamasers
log D
1 Mpc
10 Mpc
100 Mpc
Astronomer's Distance Ladder

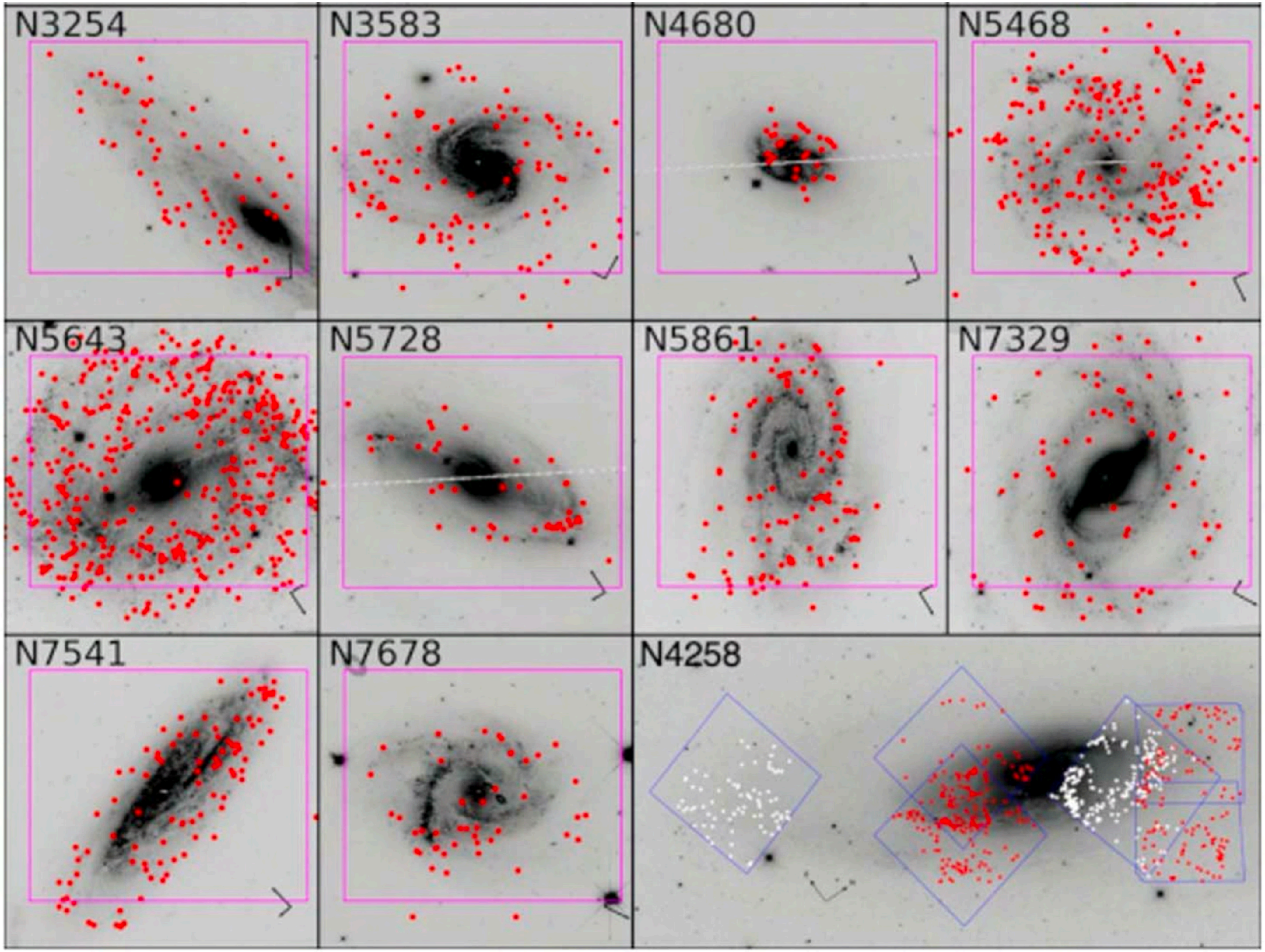
The Distance Ladder from Solar System to Galaxies



Critical Overlaps between Adjacent Rungs in a Distance Ladder

- Galaxies with geometric distances to calibrate Leavitt's Law of Cepheids

- SNe Ia Host Galaxies with Cepheid distances to calibrate Phillips Law of SNe



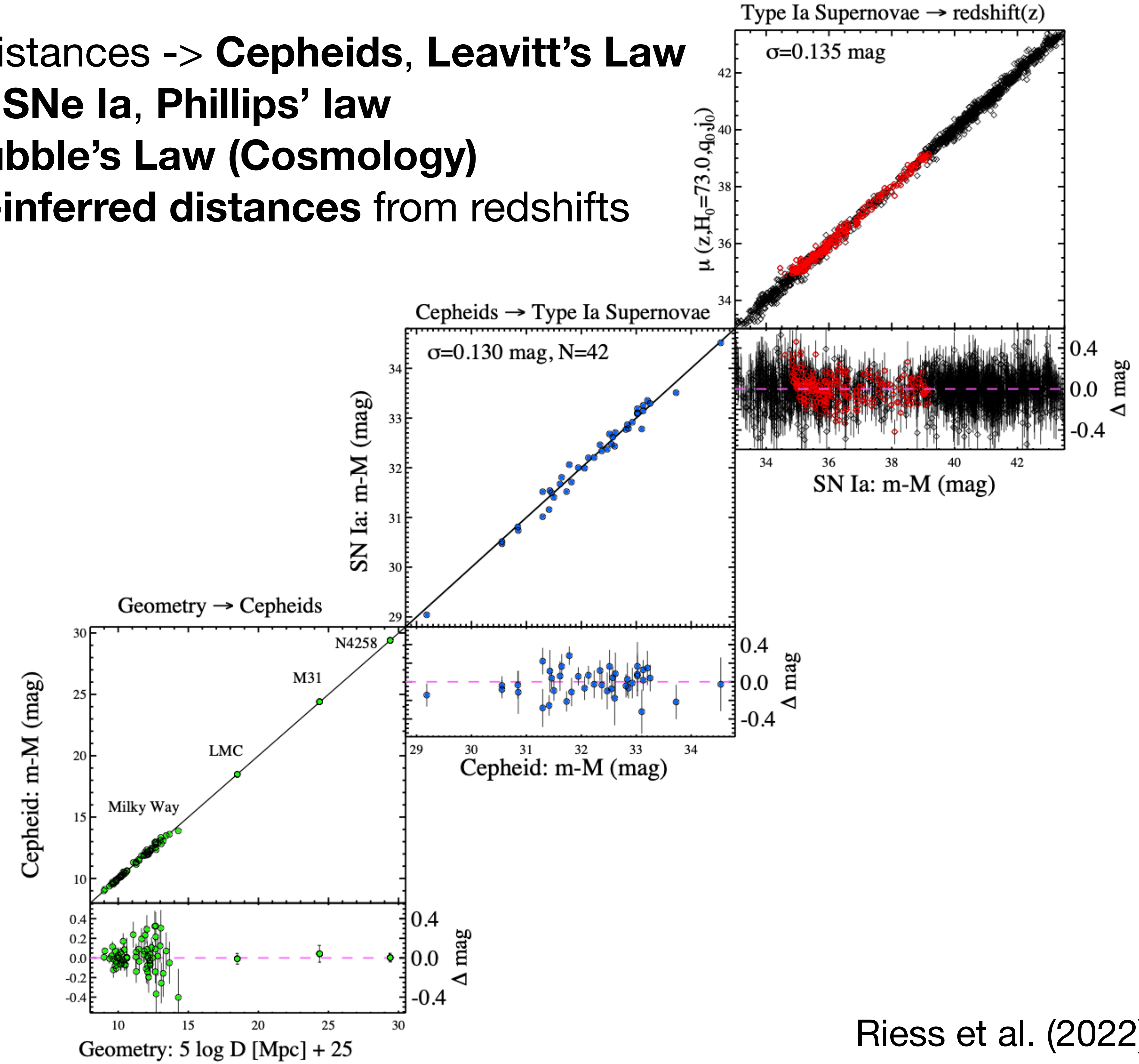
Riess+2022

To measure distances beyond 100 Mpc, astronomers need to combine a number of distance indicators

DISTANCE RANGE	**D < 7Mpc**	**D < 40Mpc**	**10 < D < 600 Mpc**
DISTANCE METHOD	Geometric methods: parallax, eclipsing binaries, megamasers	Tier 1 standard candles: Cepheids, Helium-flash limit stars (TRGB)	Tier 2 standard candles: Type Ia Supernovae HI Disk Galaxies
NUMBER OF GALAXIES	N = 4 MW, SMC, LMC, NGC4258	N = 76 (ceph) N = 558 (TRGB) limited by resolving individual stars	N ~ 1,000 (SNe) N ~ 30,000 (disks) Hubble's law no longer holds beyond 600 Mpc

Distance Ladder -> Cosmology (Hubble's Law) -> Distances from redshift

1. Geometric Distances -> **Cepheids, Leavitt's Law**
2. Cepheids -> **SNe Ia, Phillips' law**
3. SNe Ia -> **Hubble's Law (Cosmology)**
4. **Cosmology-inferred distances** from redshifts



Riess et al. (2022)

Hint of Missing Matter in Galaxy Clusters

Zwicky (1933)

Fritz Zwicky

Zwicky in 1947

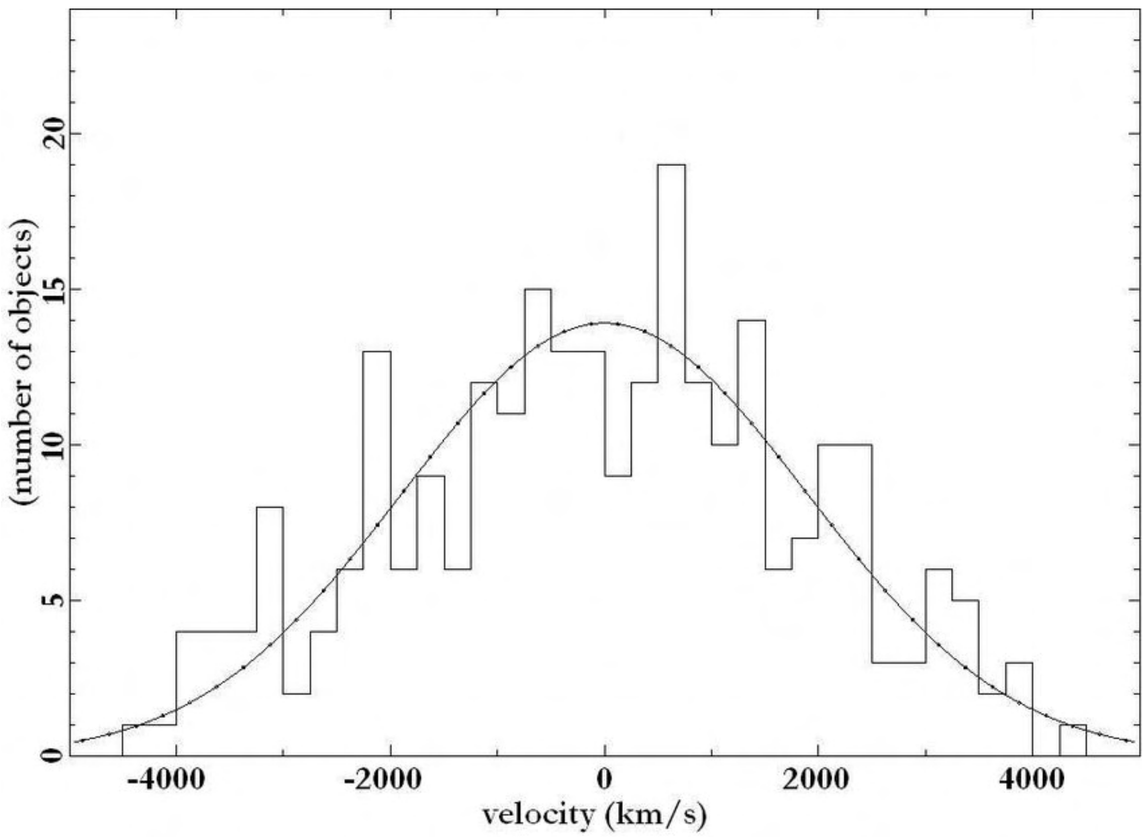
Born	February 14, 1898 Varna, Bulgaria
Died	February 8, 1974 (aged 75) Pasadena, California, US

Virial Theorem applied to the Coma Cluster

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

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

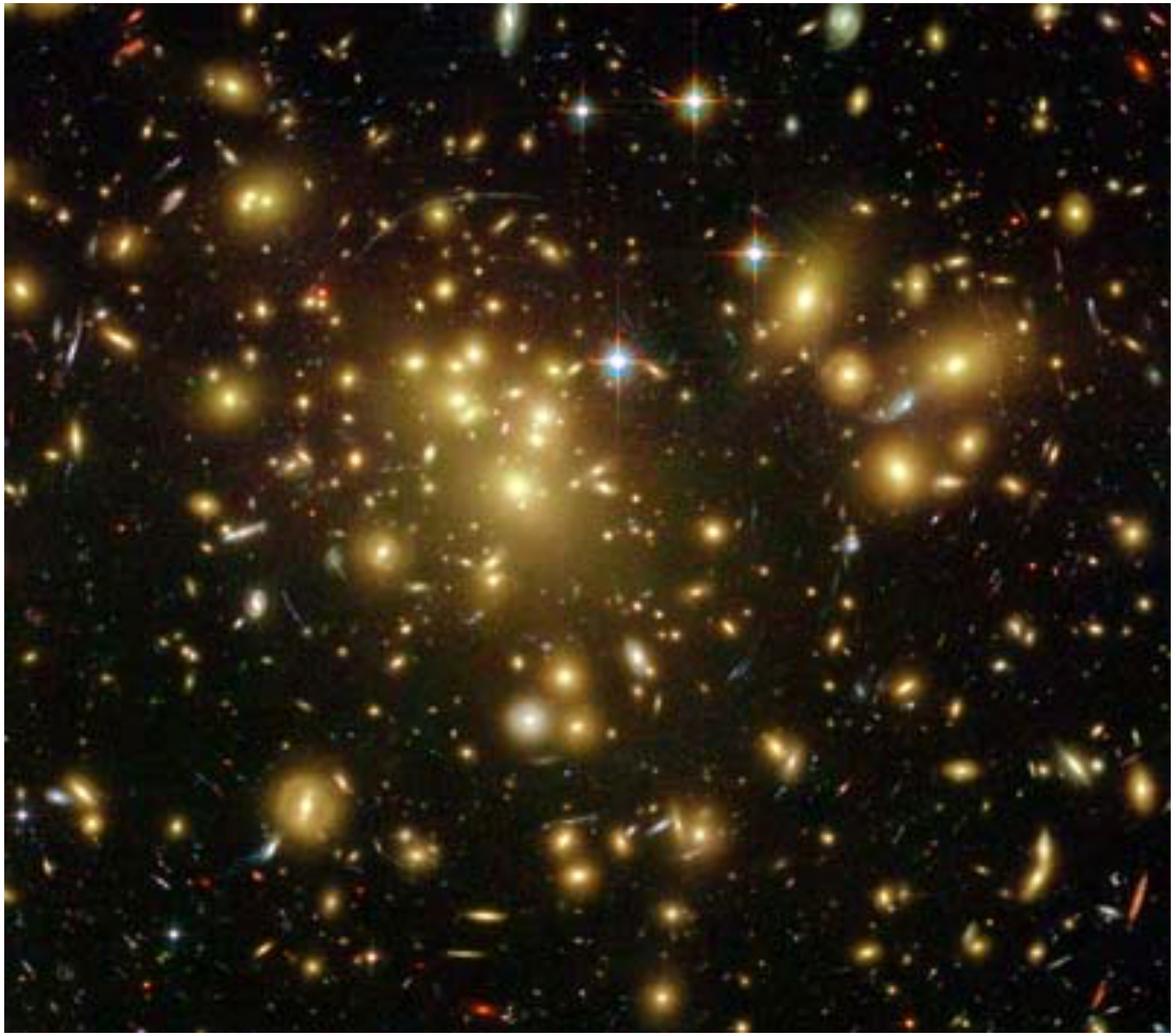
virial mass is **~100x** greater than **stellar mass**



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



Evidence of Dark Matter in Galaxies

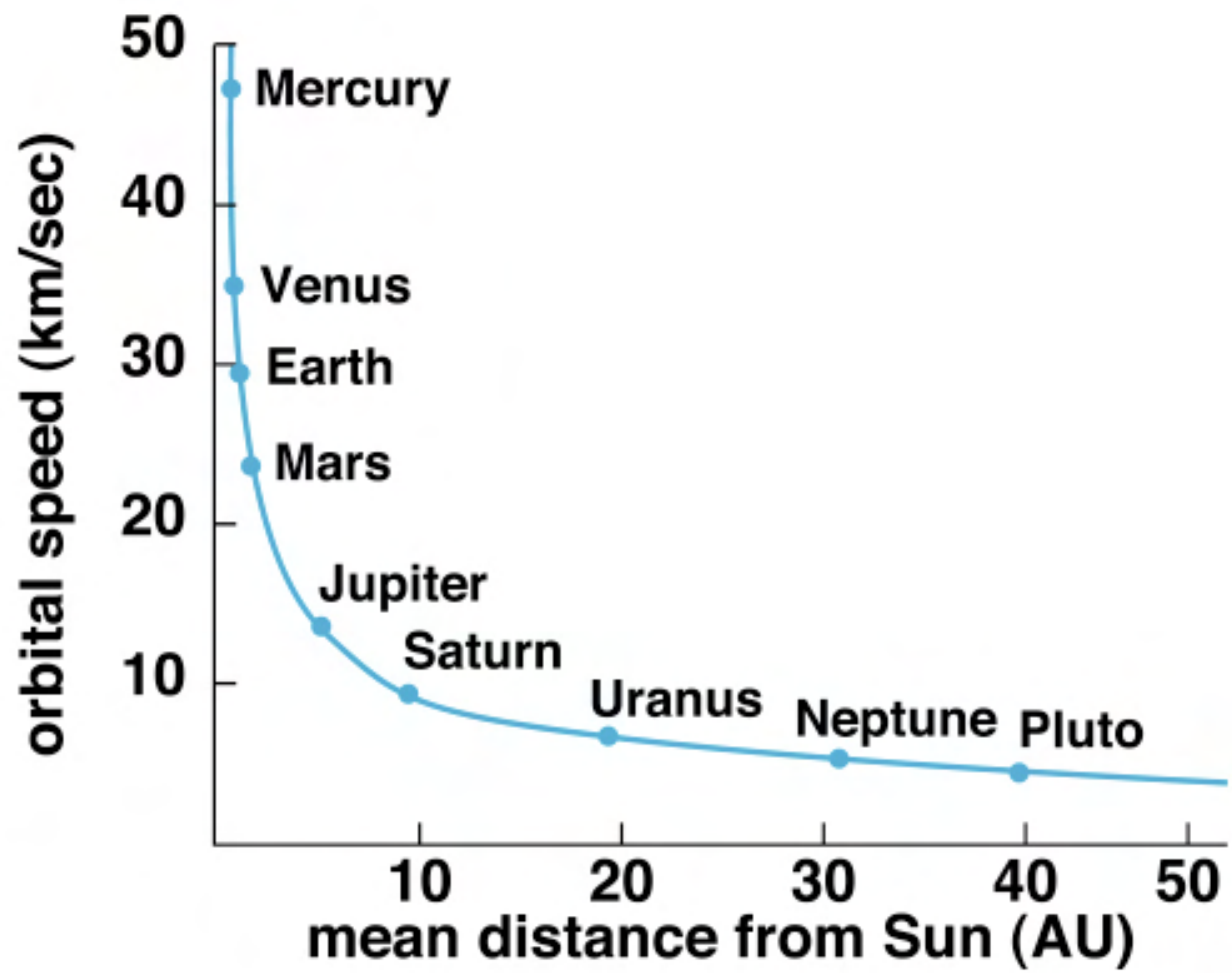
Method 1: Rotation Curves of Disk Galaxies

Vera Rubin (1928-2016)'s "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*

Orbital Velocities of Planets in the Solar System

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

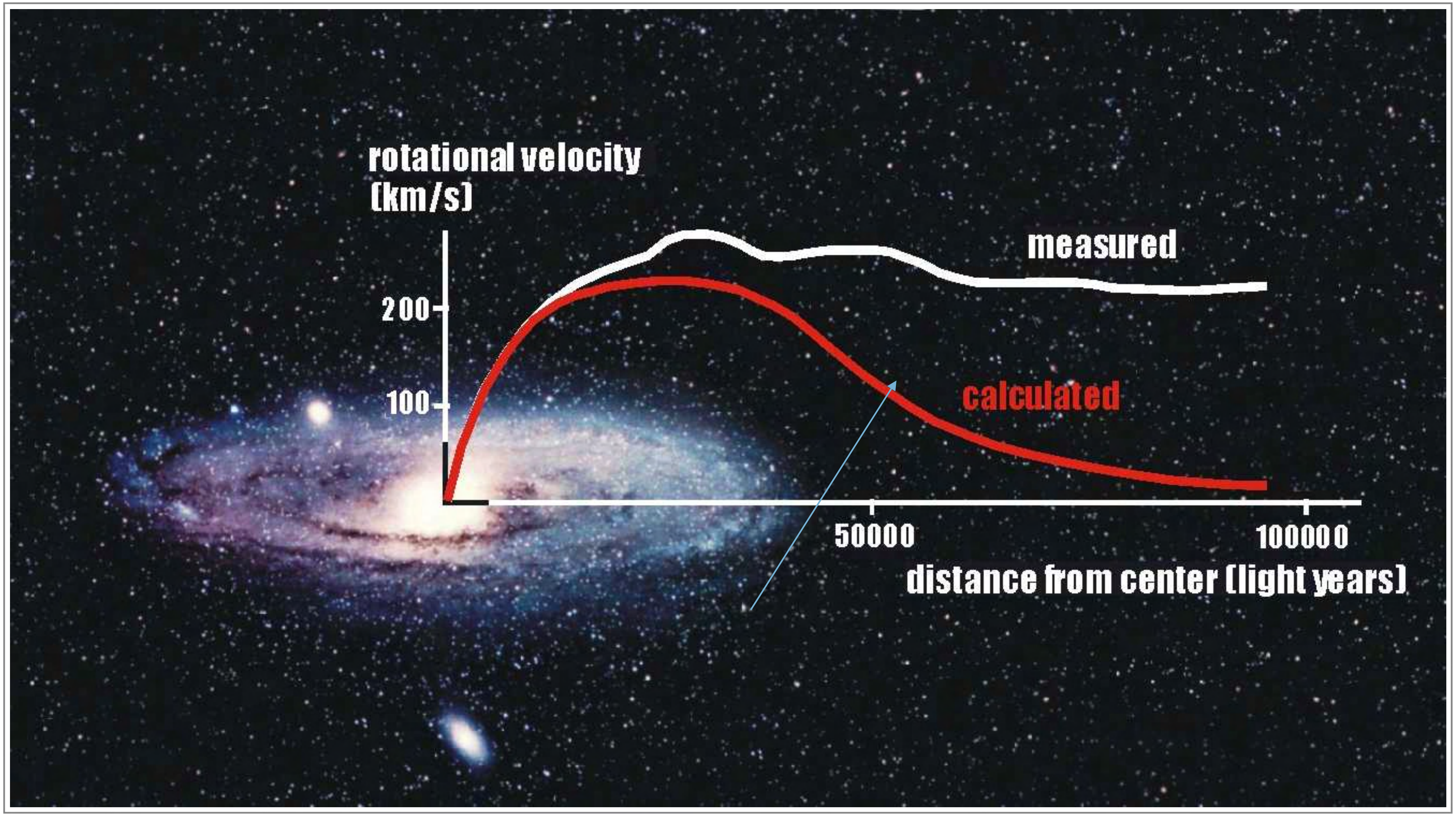
$v(r) = \sqrt{GM(r)/r} \Rightarrow v(r) \propto 1/\sqrt{r}$ because the Sun took 99.9% of the mass!



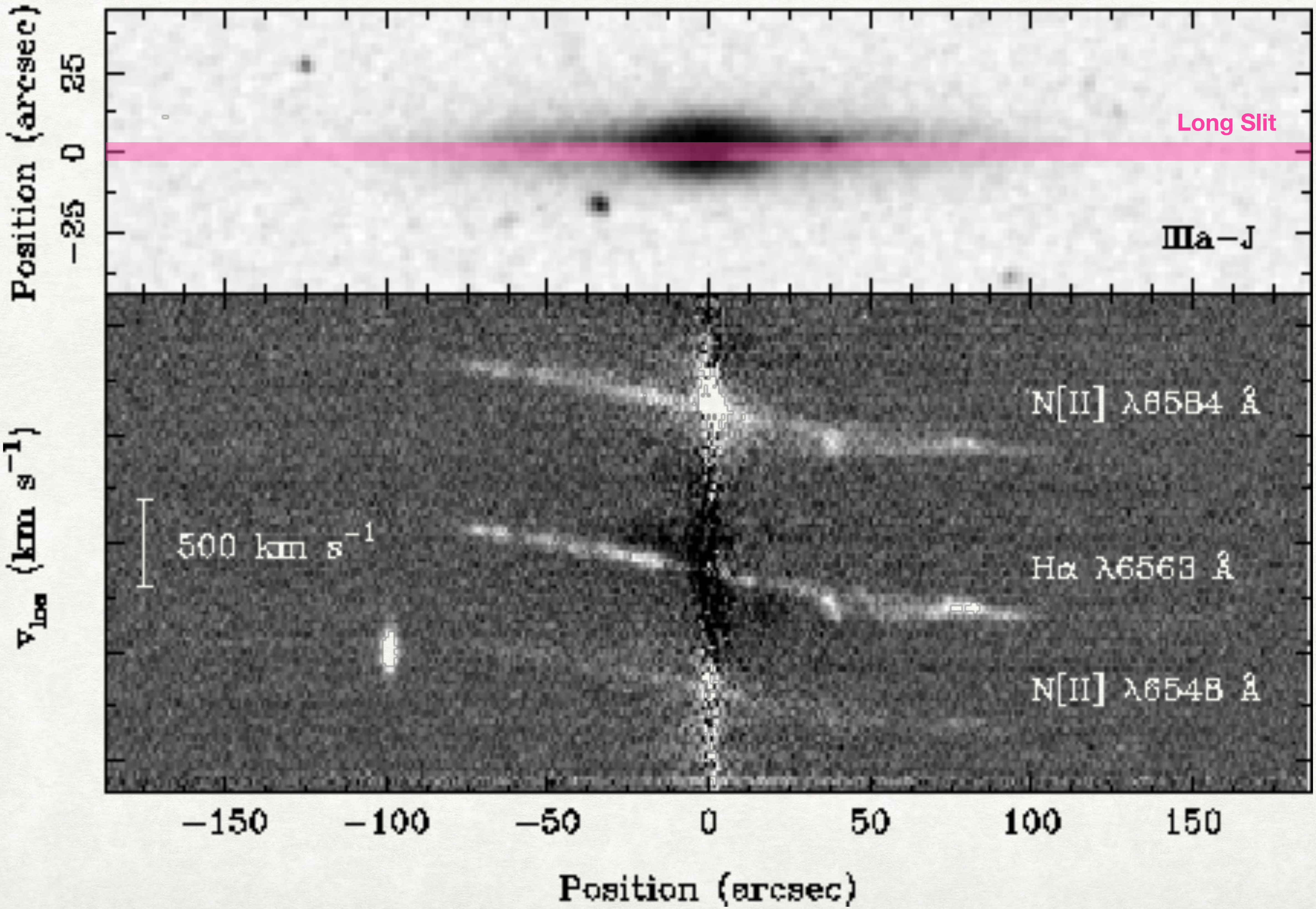
Flat Rotation Curve: Missing Matter in Disk Galaxies

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

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

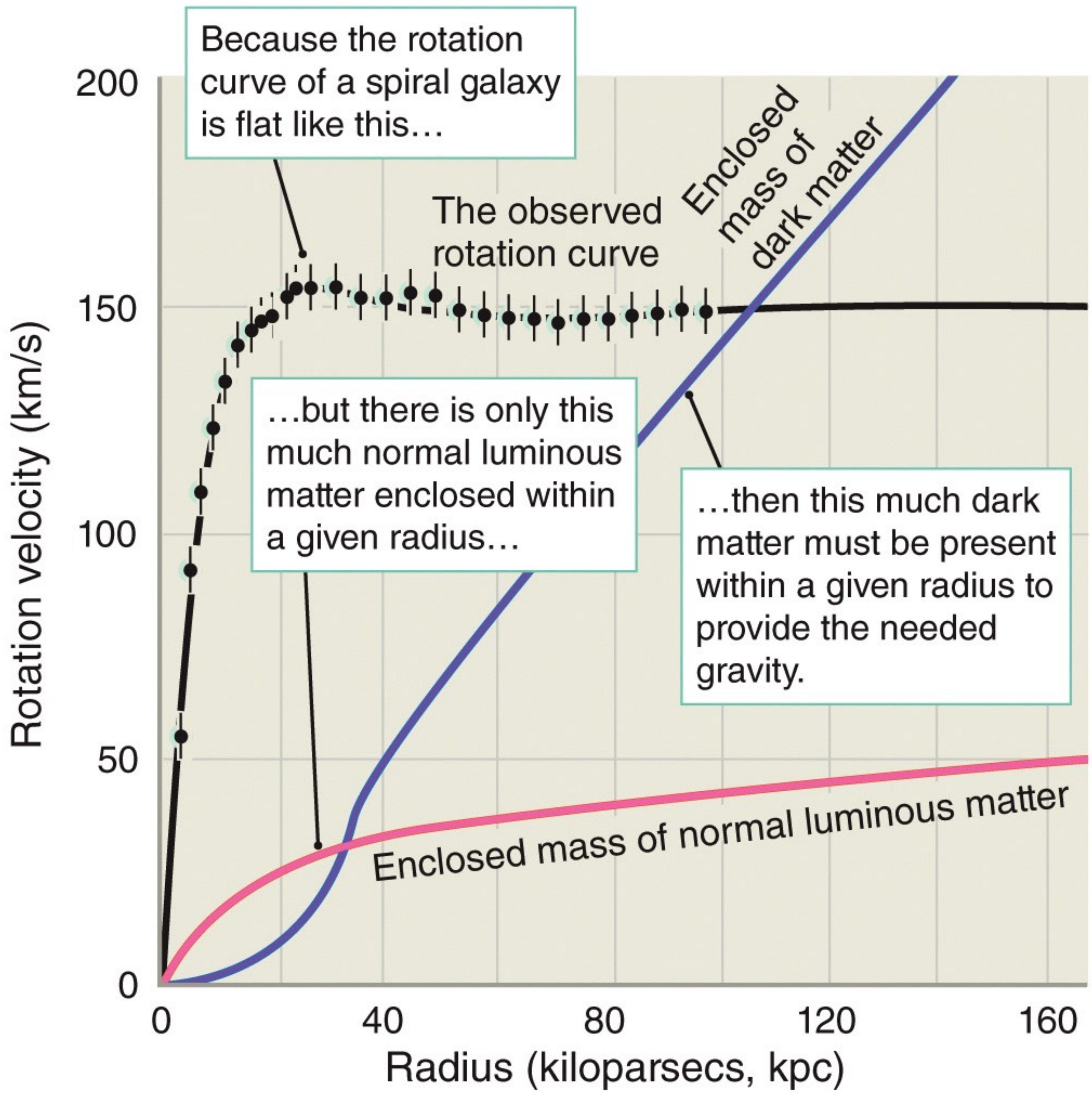


HOW DO WE MEASURE ROTATION CURVES?

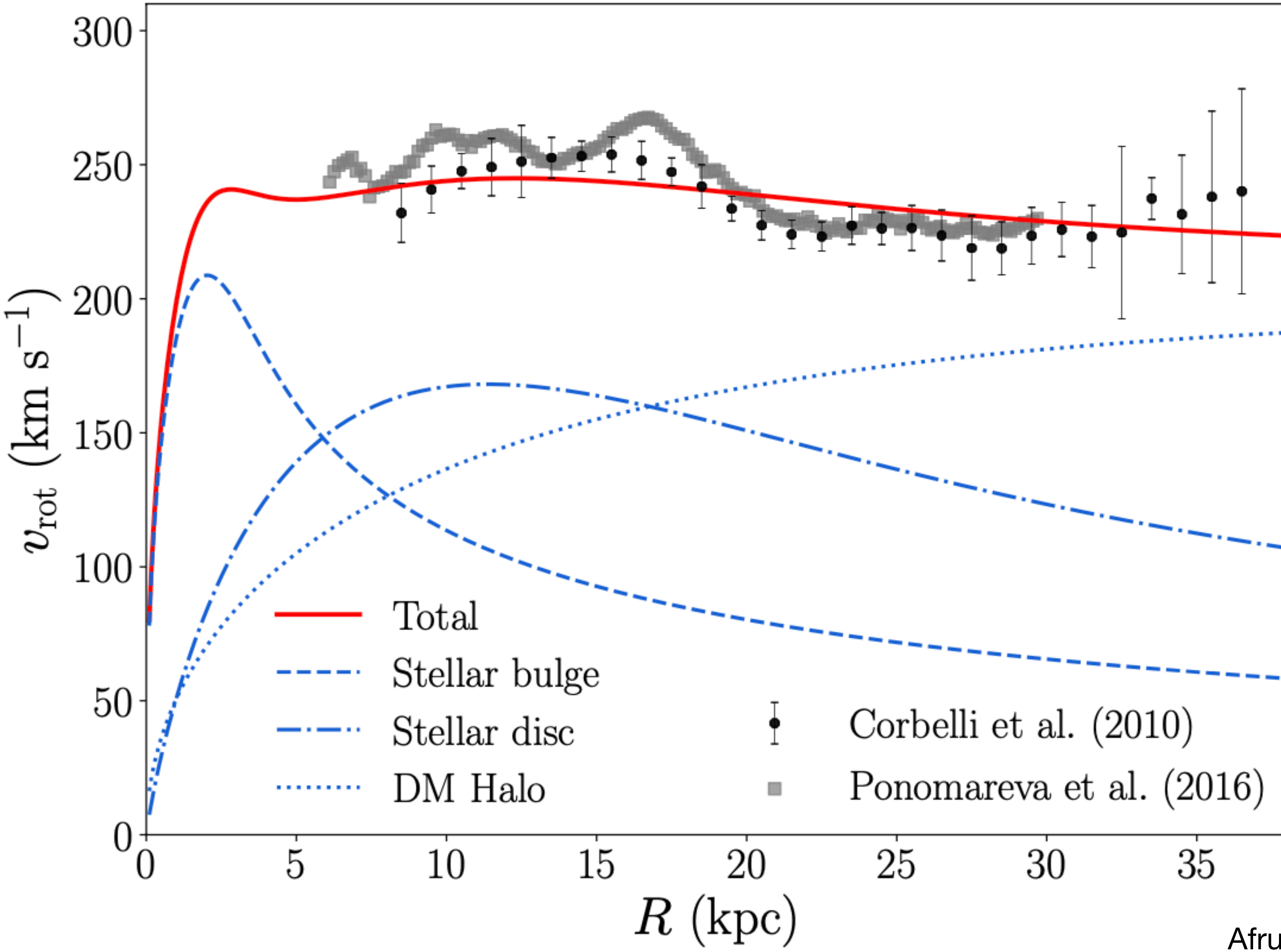


Flat Rotation Curves Provide Evidence for Dark Matter

- 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!**).



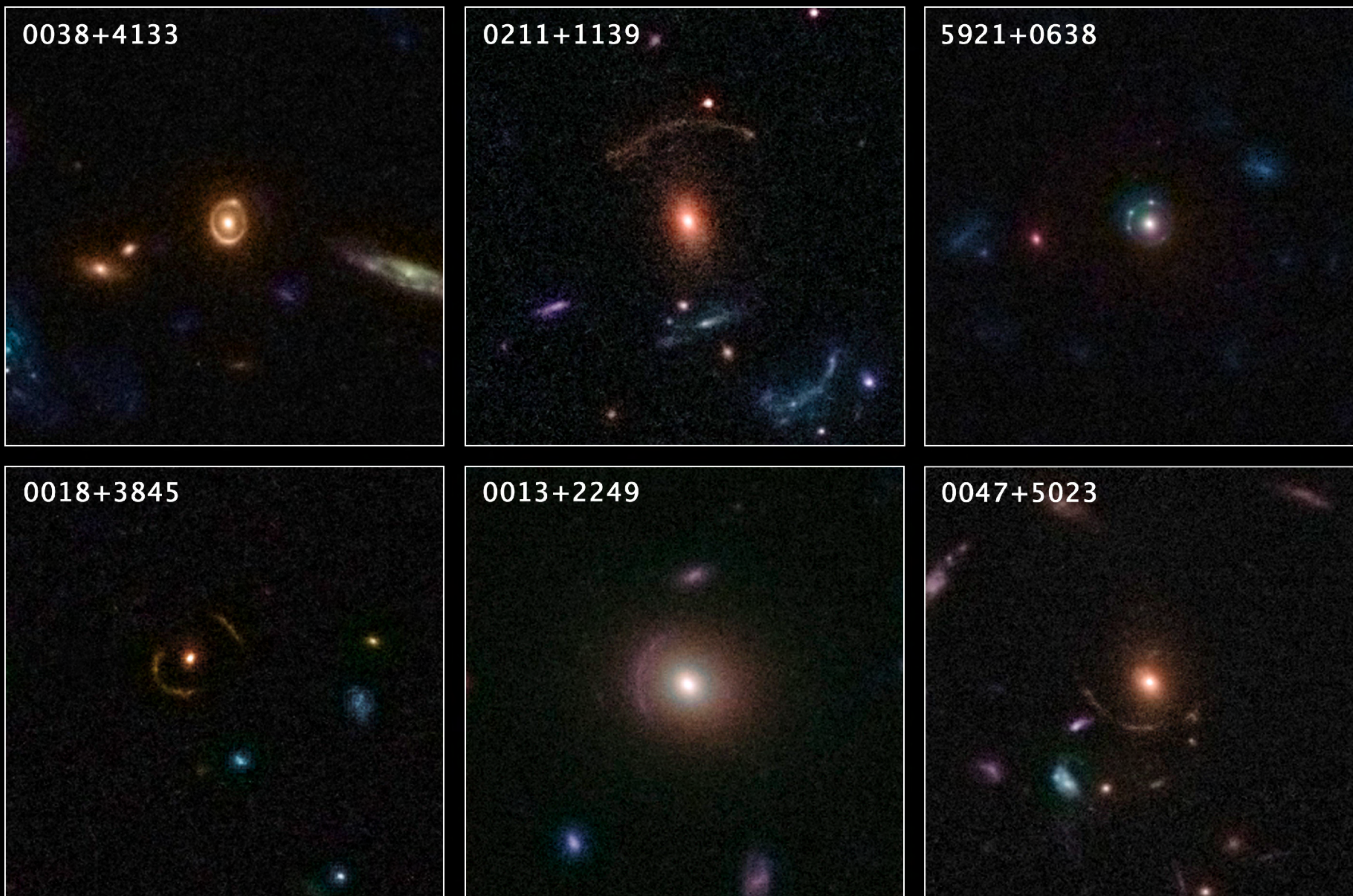
Rotation Curve Decomposition of M31 (Andromeda Galaxy)

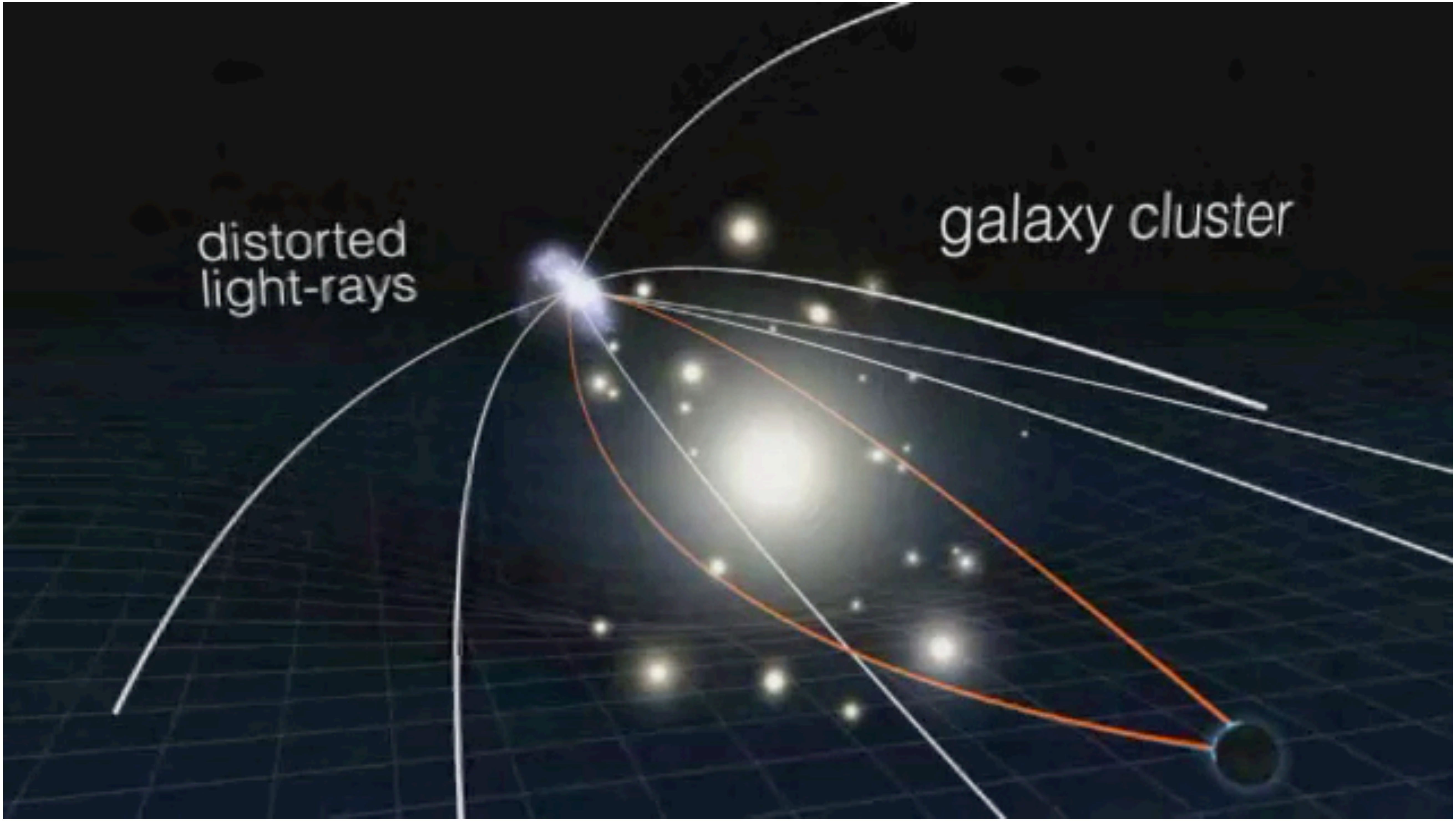


Afruni+2021

Method 2: Strong Gravitational Lensing

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



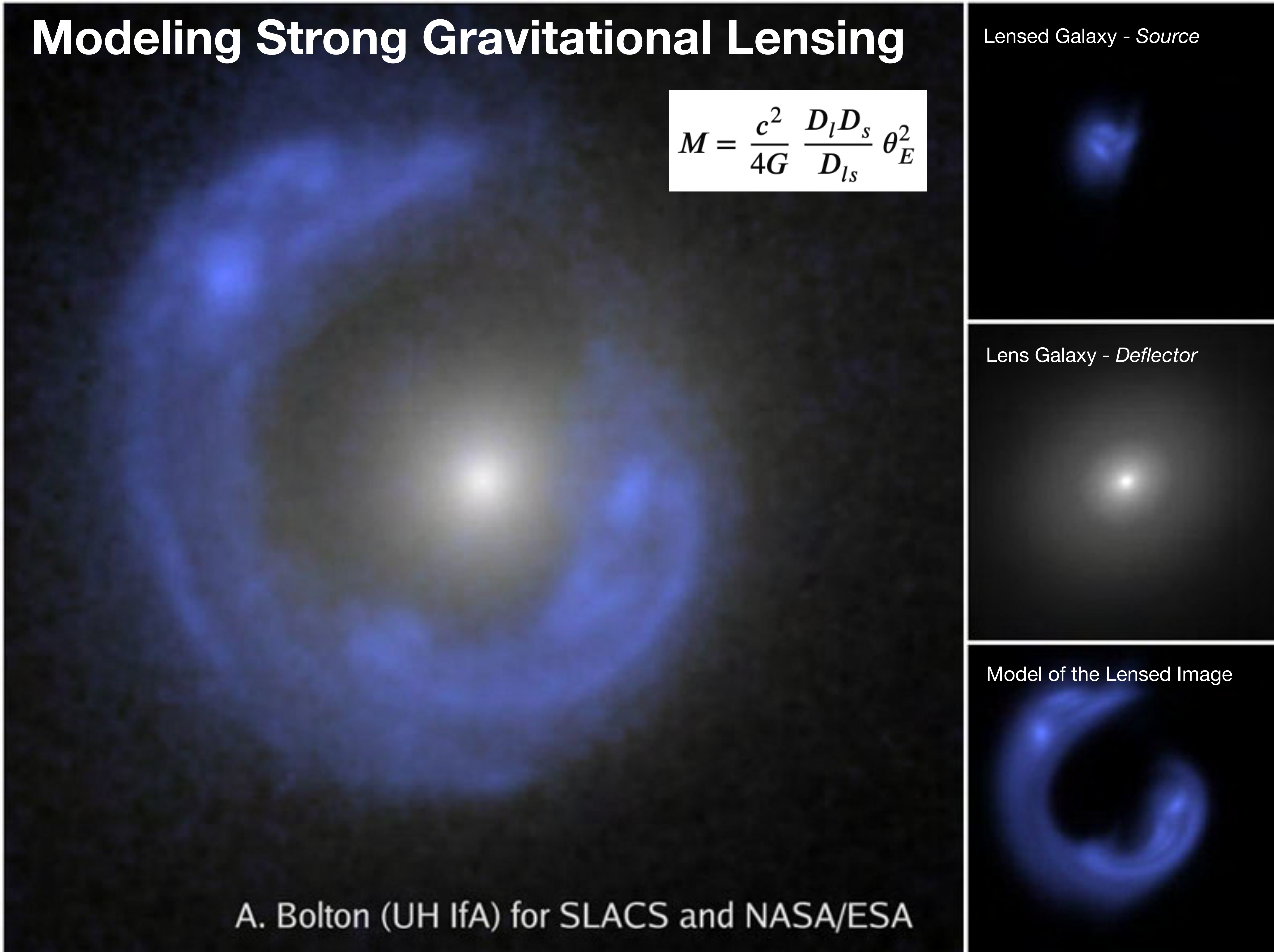


Angular extent of the lensed images gives the *total* enclosed mass of the lens:

$$M = \frac{c^2}{4G} \frac{D_l D_s}{D_{ls}} \theta_E^2$$

Modeling Strong Gravitational Lensing

$$M = \frac{c^2}{4G}\,\frac{D_l D_s}{D_{ls}}\,\theta_E^2$$

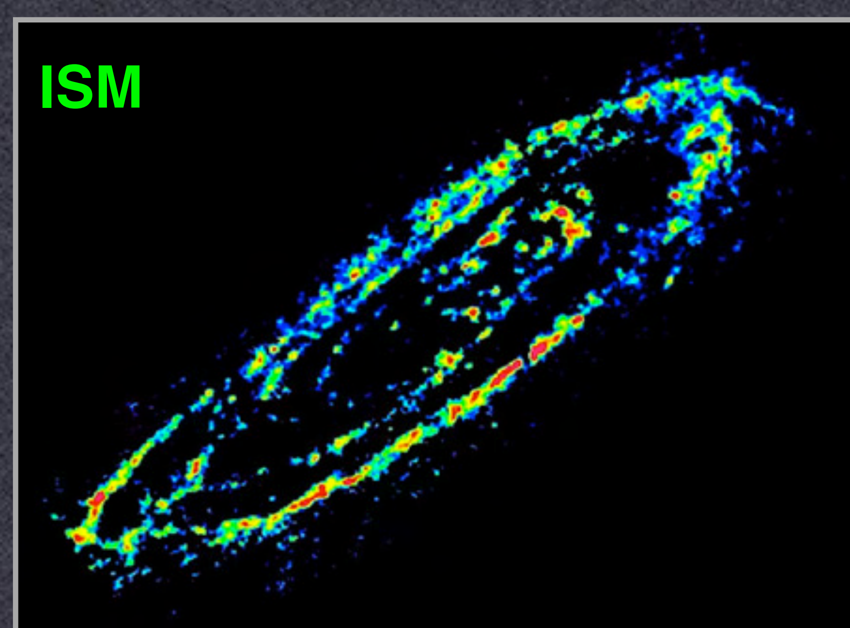


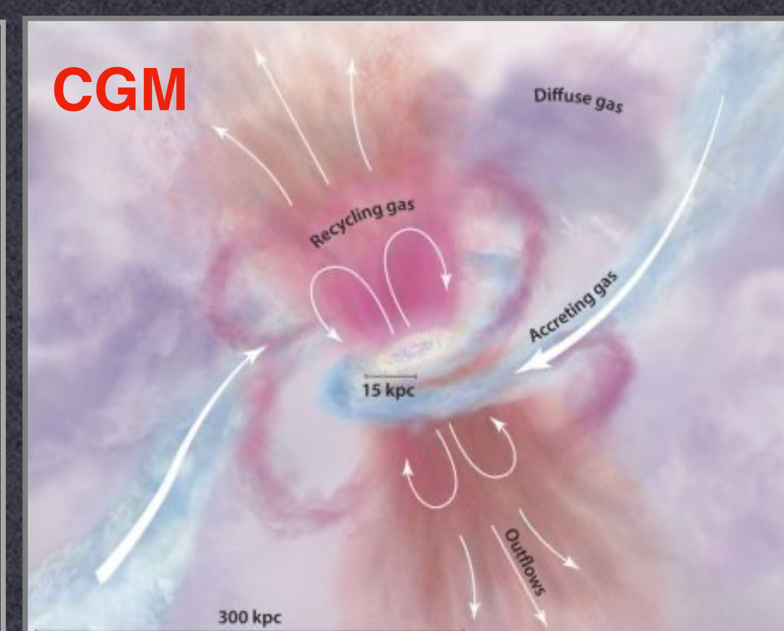
Various lensing configurations reproduced by a wine glass

Various lensing configurations reproduced by a wine glass

Summary: Matters in Disk Galaxy 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

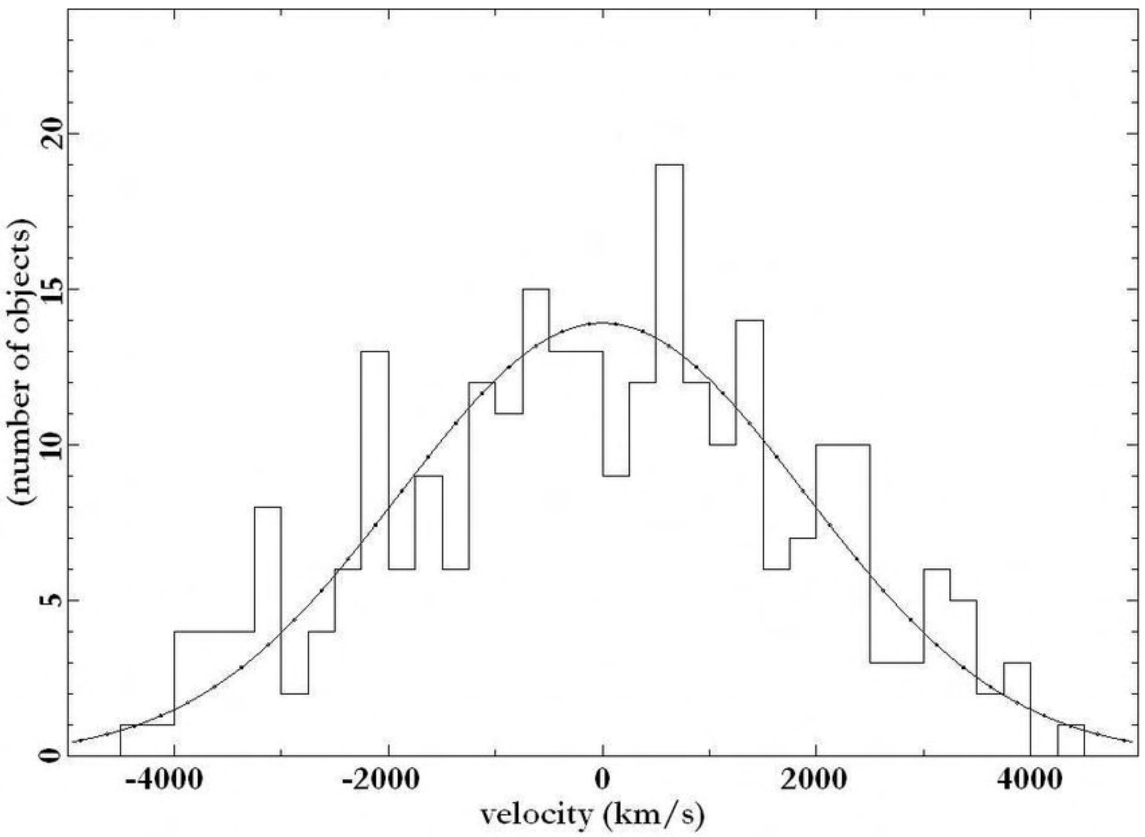
Dark Matter &
“Hidden” Normal Matter in
Galaxy Clusters

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 ~**100x** greater than visible **stellar mass**



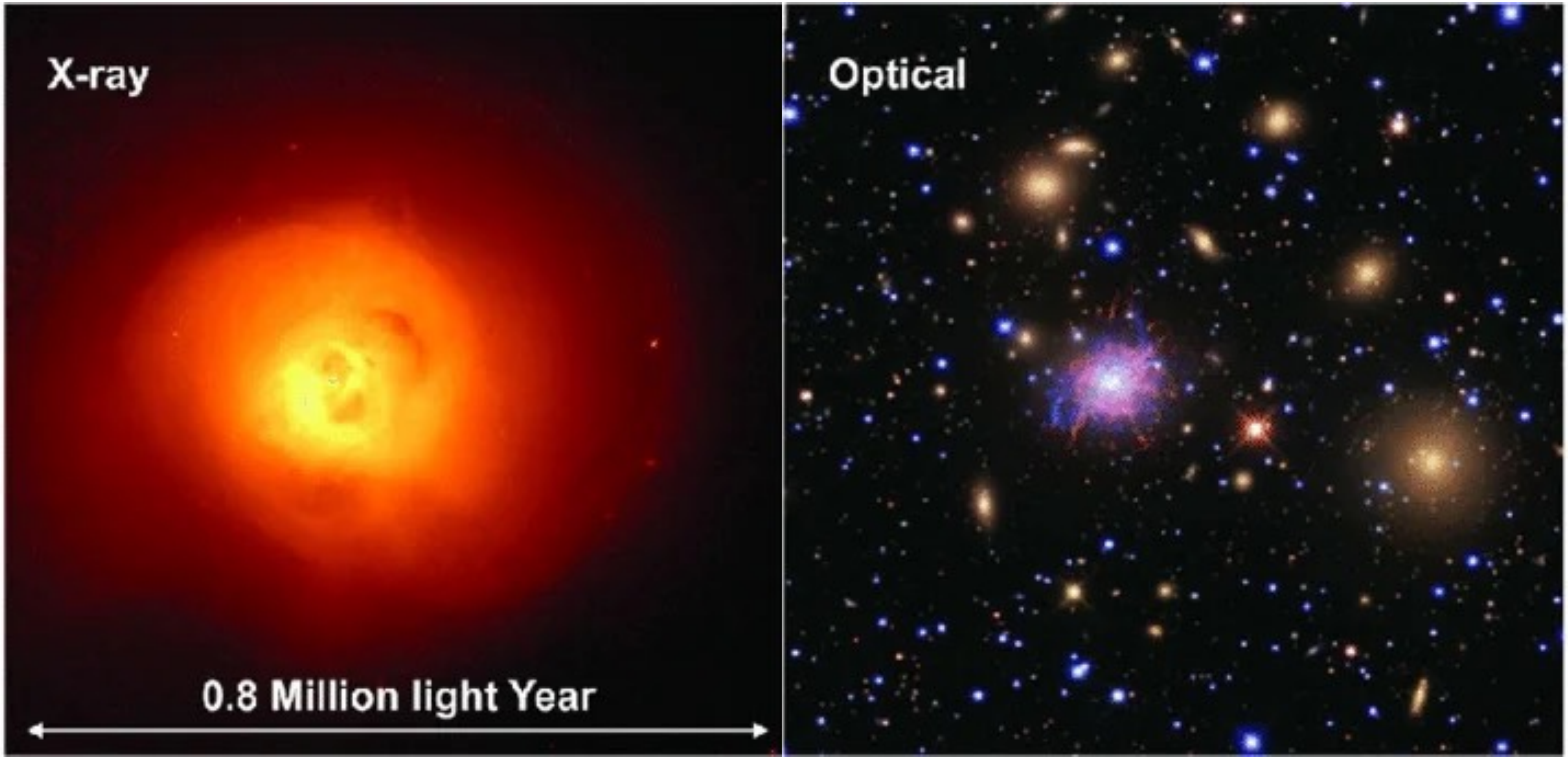
Gaussian Probability Density Function

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

where σ is the standard deviation and μ the mean

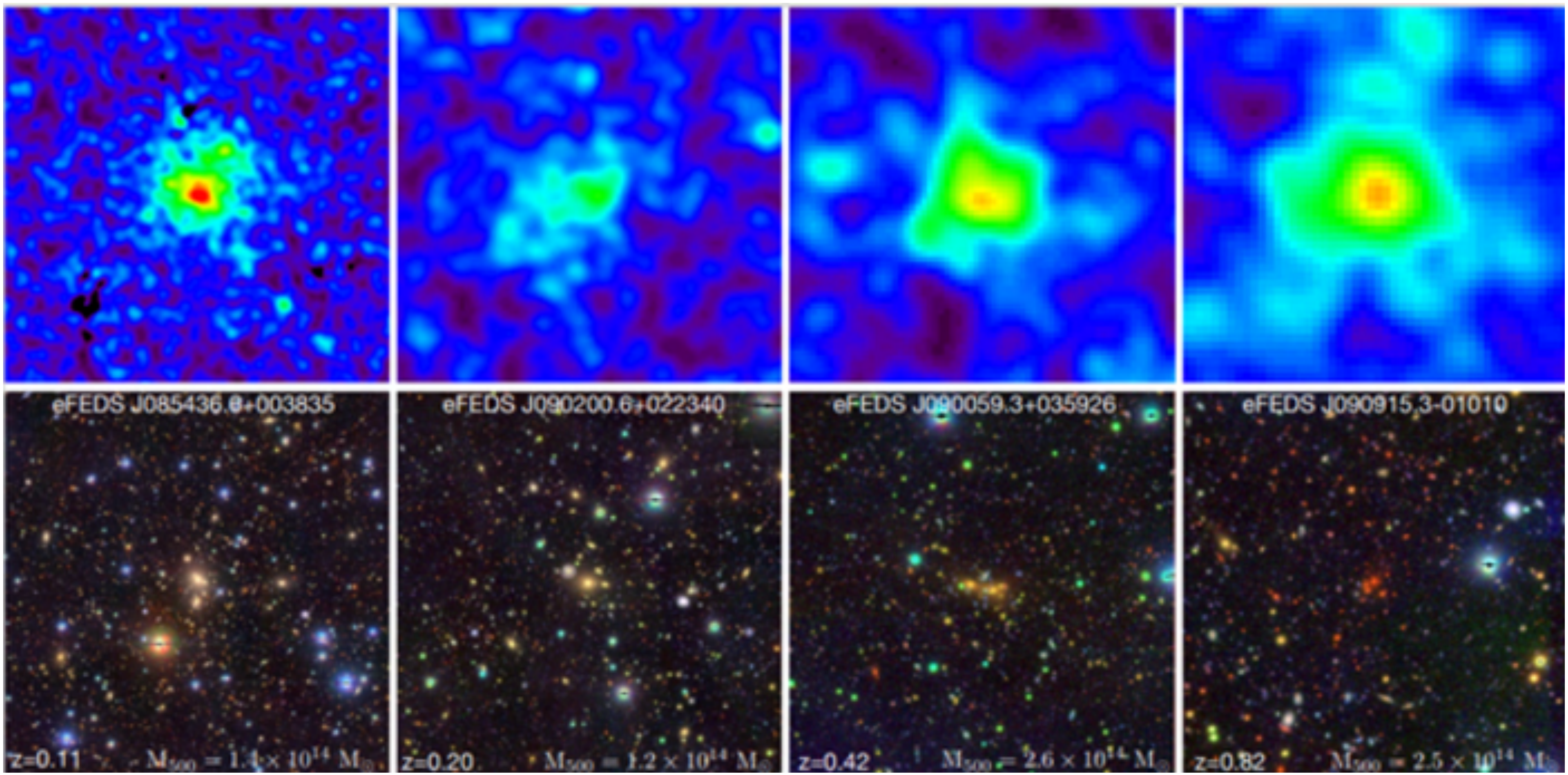
But, Zwicky didn't know about this:

- Most of the normal matter (baryons: nucleons) are not in stars, instead, they are in diffuse, hot X-ray-emitting gas called the intra-cluster medium (ICM).

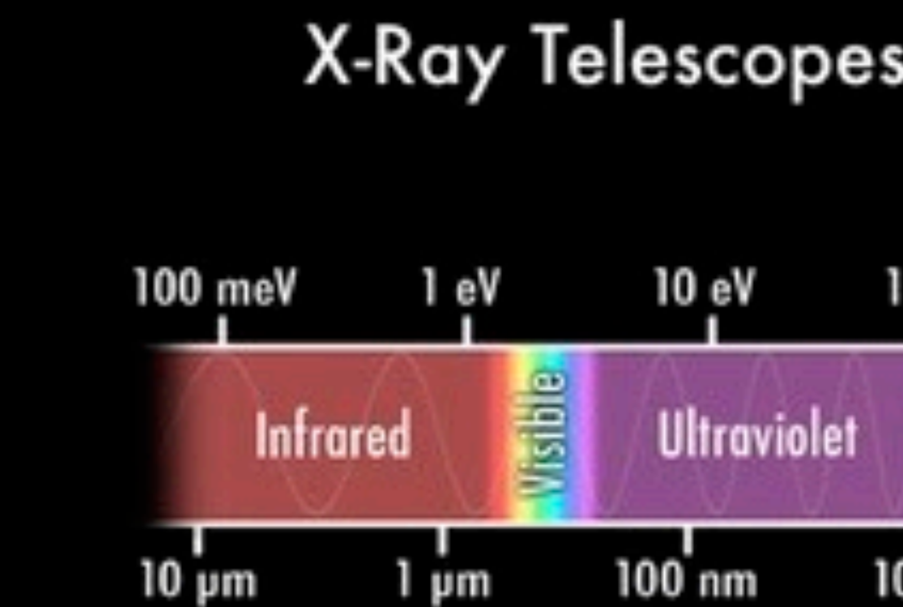


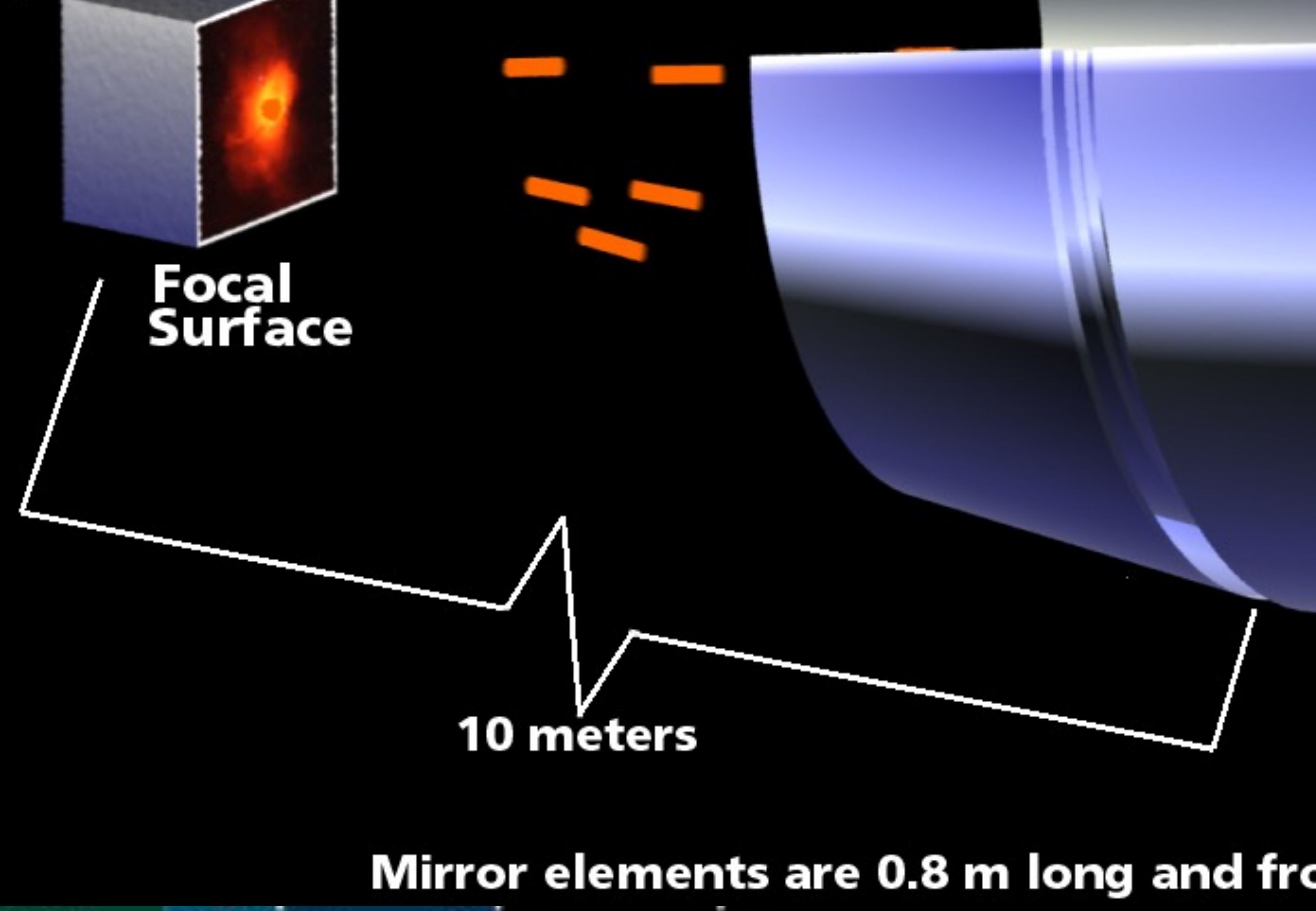
“Hidden” Normal Matter in Galaxy Clusters

- Most of the normal matter (baryons: nucleons) are not in stars (*bottom row*); instead, they are in diffuse, hot X-ray-emitting gas called the intra-cluster medium (ICM) (*top row*). **M_{ICM} is ~10x greater than M_{star}.**
- So Zwicky (1933) ***overestimated*** the Dark Matter to Normal Matter ratio.



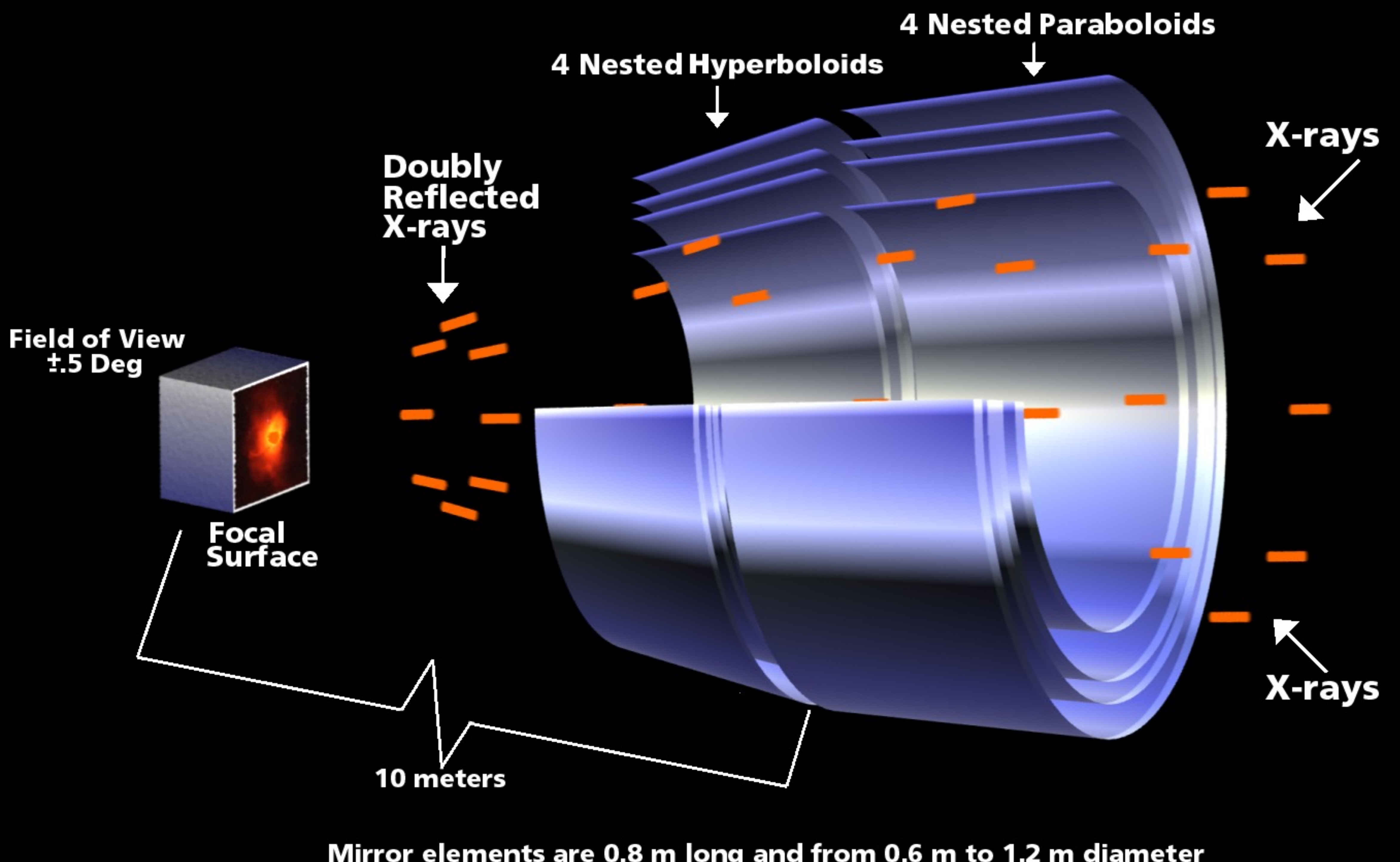
X-ray Telescopes (all





X-ray Telescope Optical Design

X-ray telescopes use **grazing reflection** (shallow, skipping angles), because high-energy X-ray photons penetrate normal, perpendicular mirrors.



Method 4: Weak Gravitational Lensing

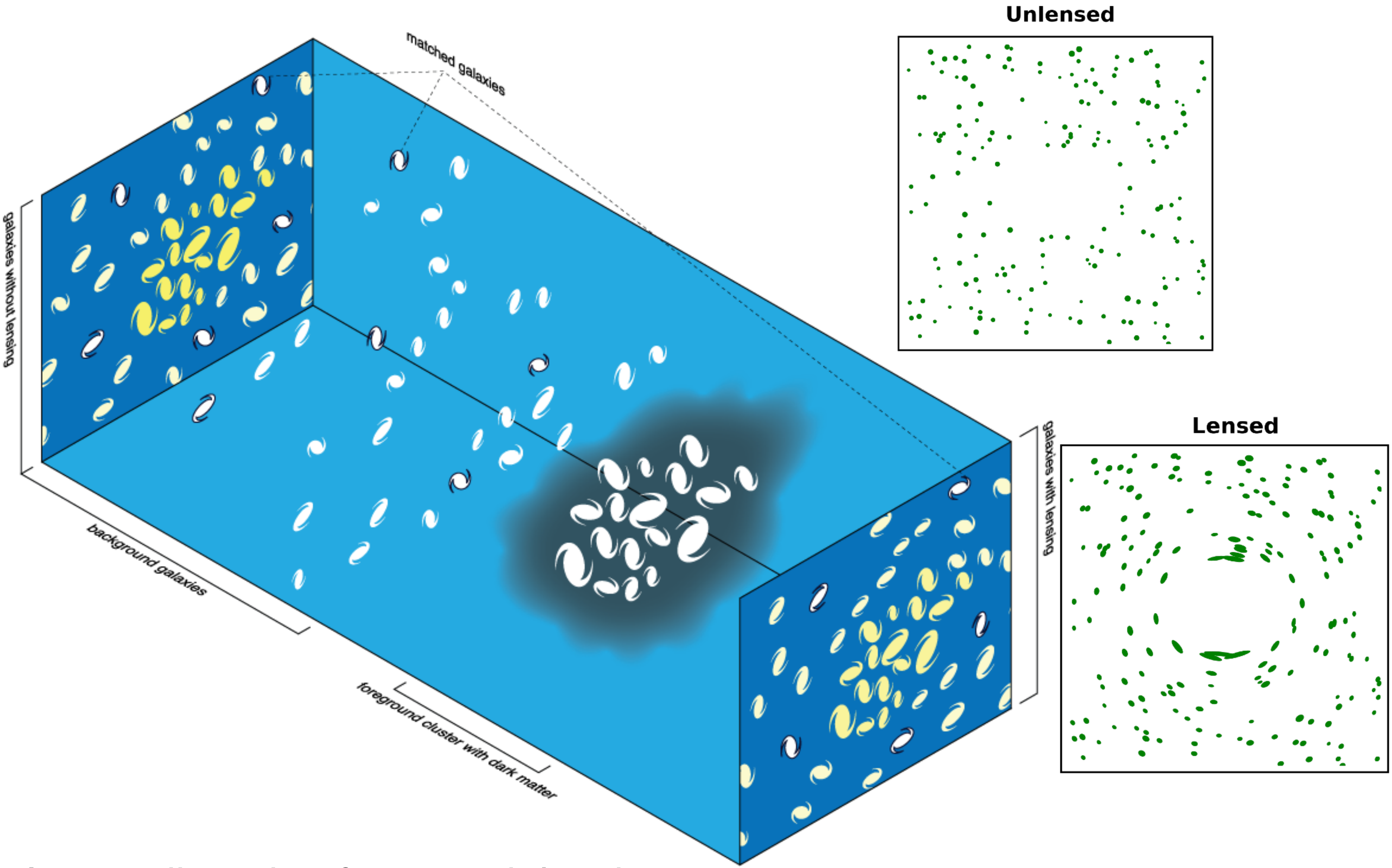
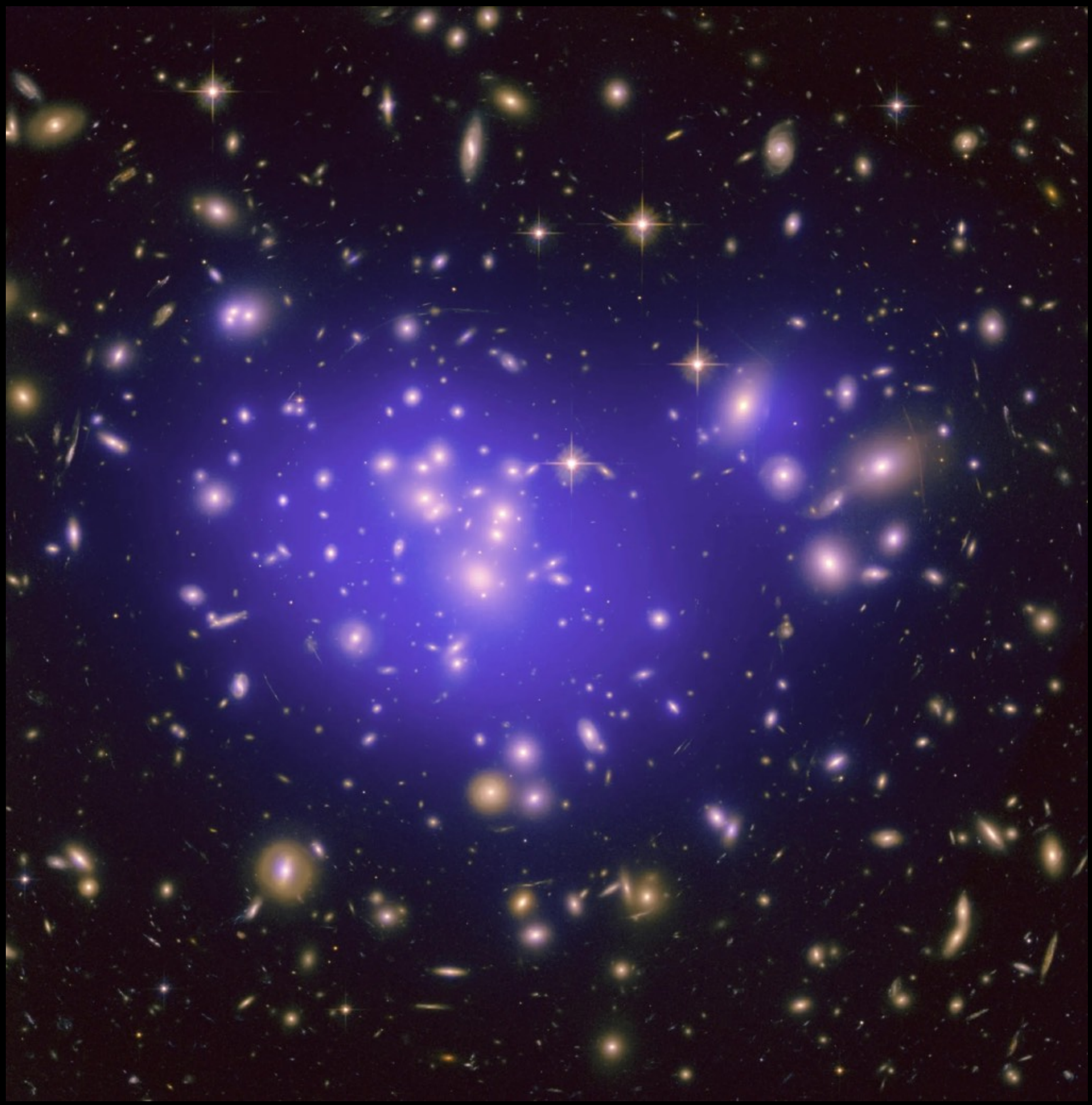


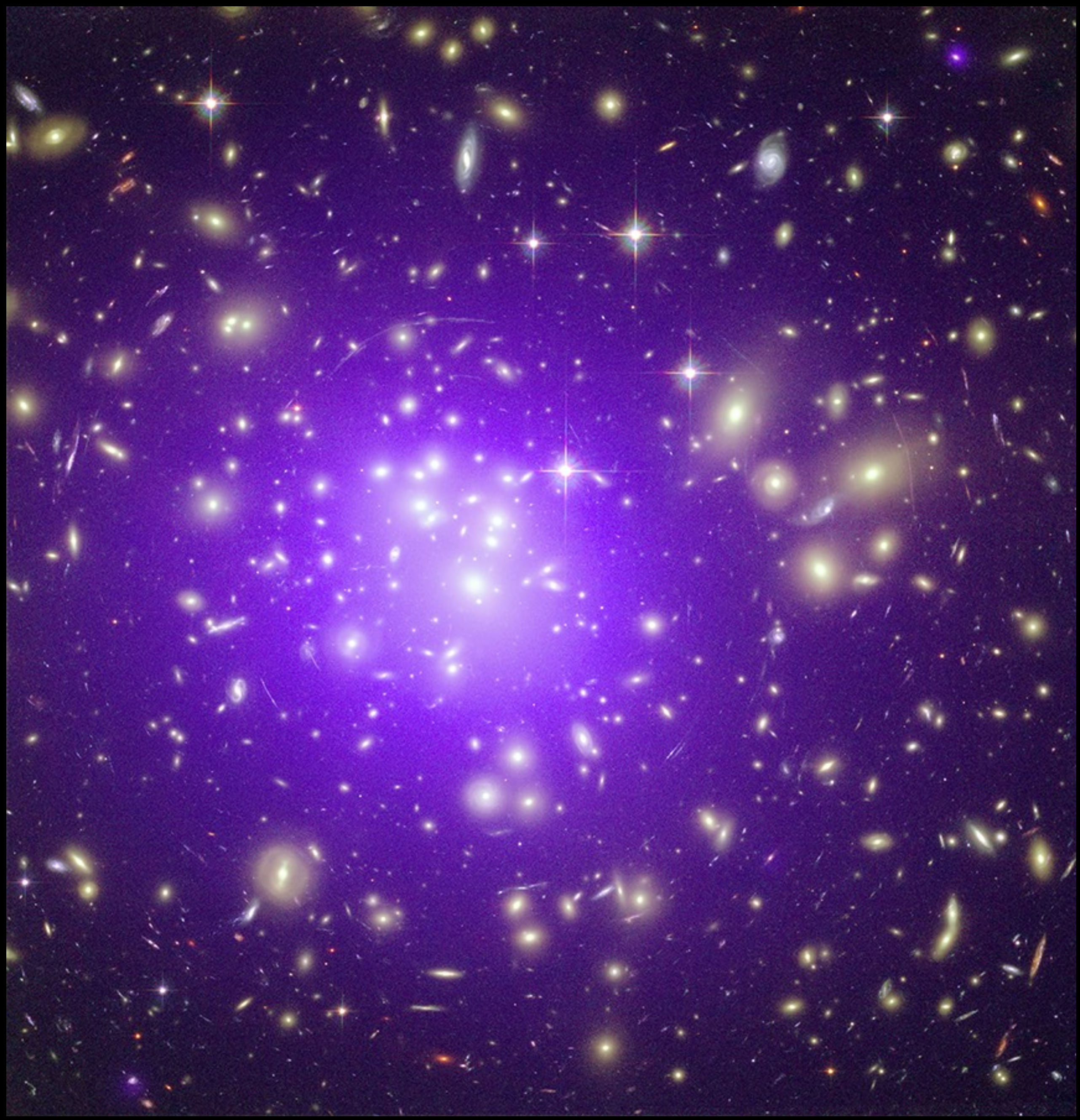
Image distortion from weak lensing

Total mass distribution of a galaxy cluster from weak lensing

Abell 1689 Weak Lensing vs. Optical



Abell 1689 X-ray vs. Optical



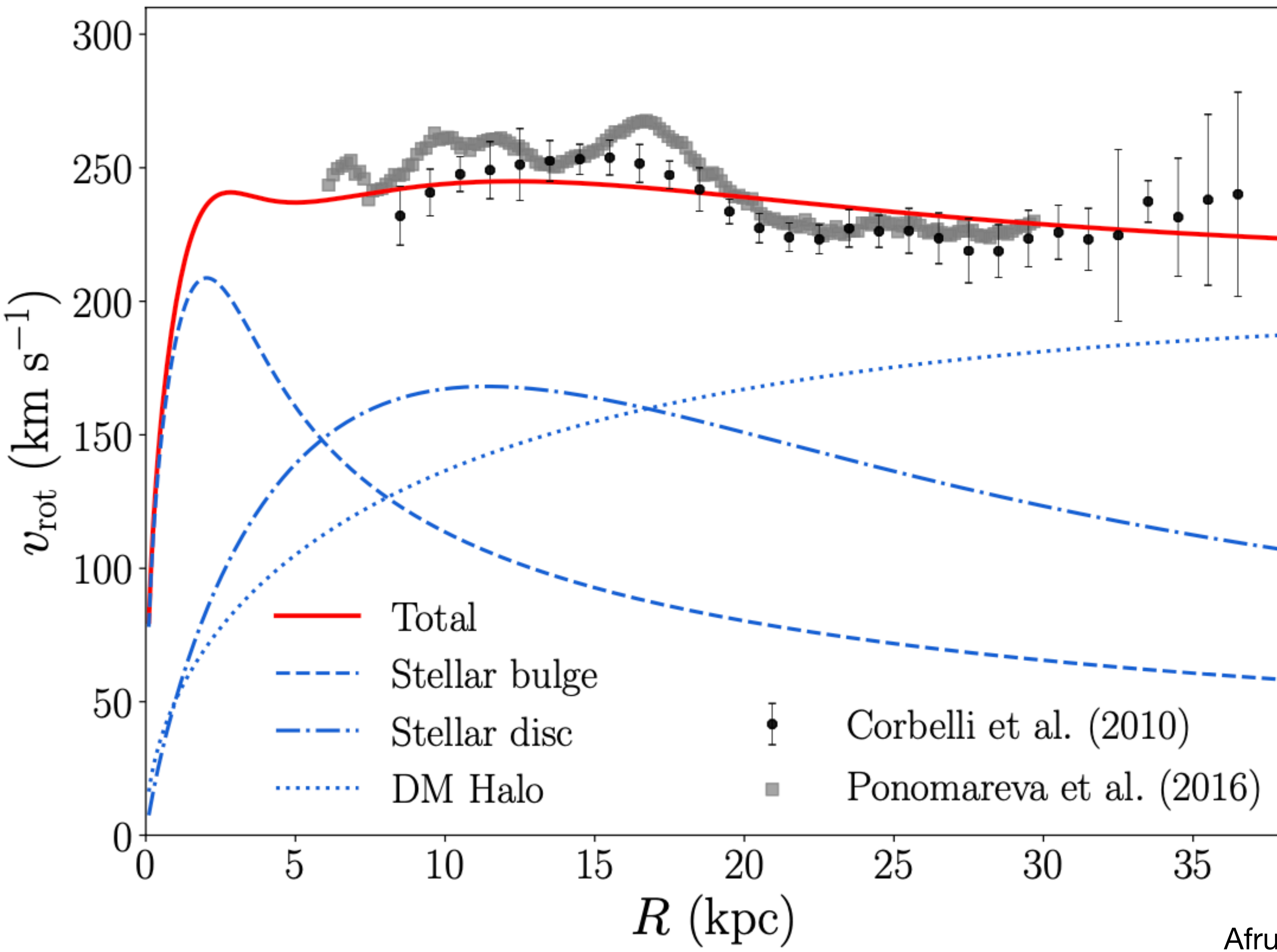
In galaxy clusters, the mass of the X-ray-emitting plasma in the ICM is ~10x more massive than the stars in the galaxies

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

IDCS J1426.5+3508

Dark Matter vs. Modified Newtonian Dynamics (MOND)

Modeling Rotation Curves with Dark Matter Halo



Afruni+2021

Modified Newtonian Dynamics (MOND) Can Explain Flat Rotation Curves without Involving Dark Matter

Flat rotation problem

$$\left.\begin{aligned} a &= \frac{v^2}{r} \\ a_N &= \frac{GM}{r^2} \end{aligned}\right\} \Rightarrow v = \sqrt{\frac{GM}{r}} \propto \sqrt{\frac{1}{r}}$$

but $v =$ const.

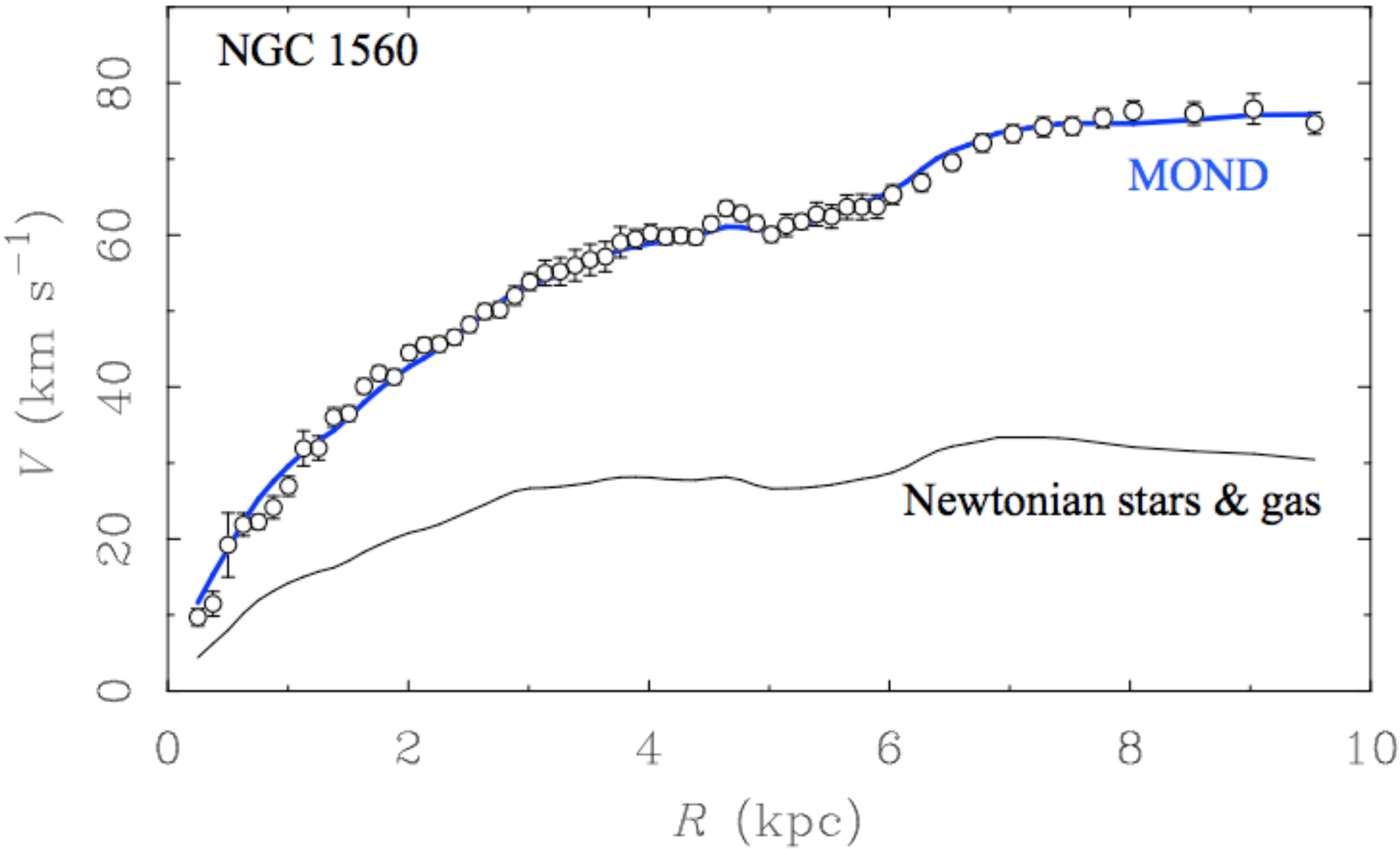
so we need $M \neq$ const

$M \propto r$

MOND or $a_M = \sqrt{a_N \cdot a_0}$

Solar system acceleration: $\frac{v^2}{r} = \frac{(220\ km/s)^2}{8\ kpc} = 1\ \text{Å}/s^2$

MOND uses interpolation to model the full rotation curve



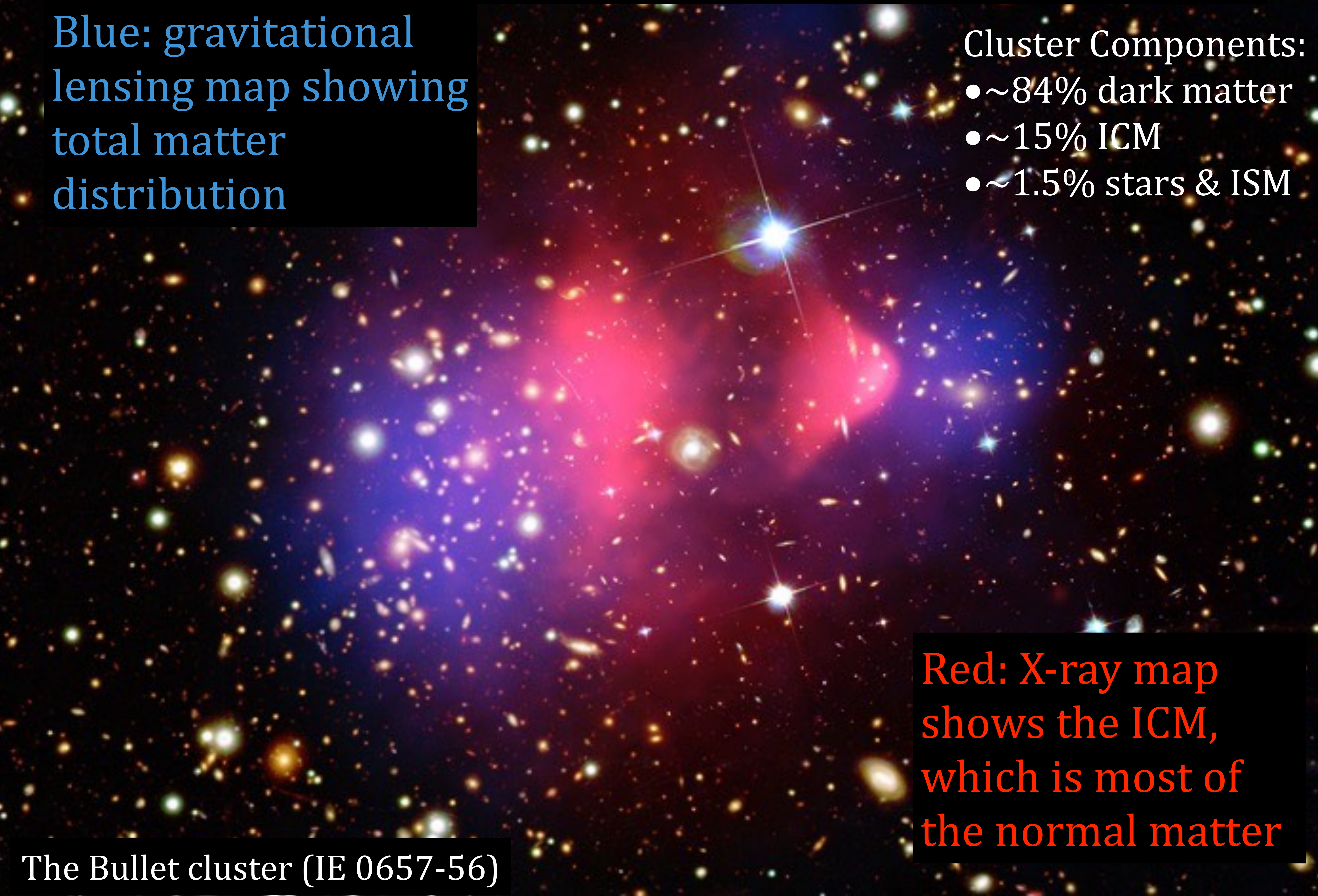
The rotation curve of NGC 1560 (Begeman et al. 1991; Gentile et al. 2010). The black line shows the expected contribution of stars and gas ($f_g = 3/4$). The blue line is the MOND fit.

Stacy McGaugh (2011)

DM vs MOND in Galaxy Clusters

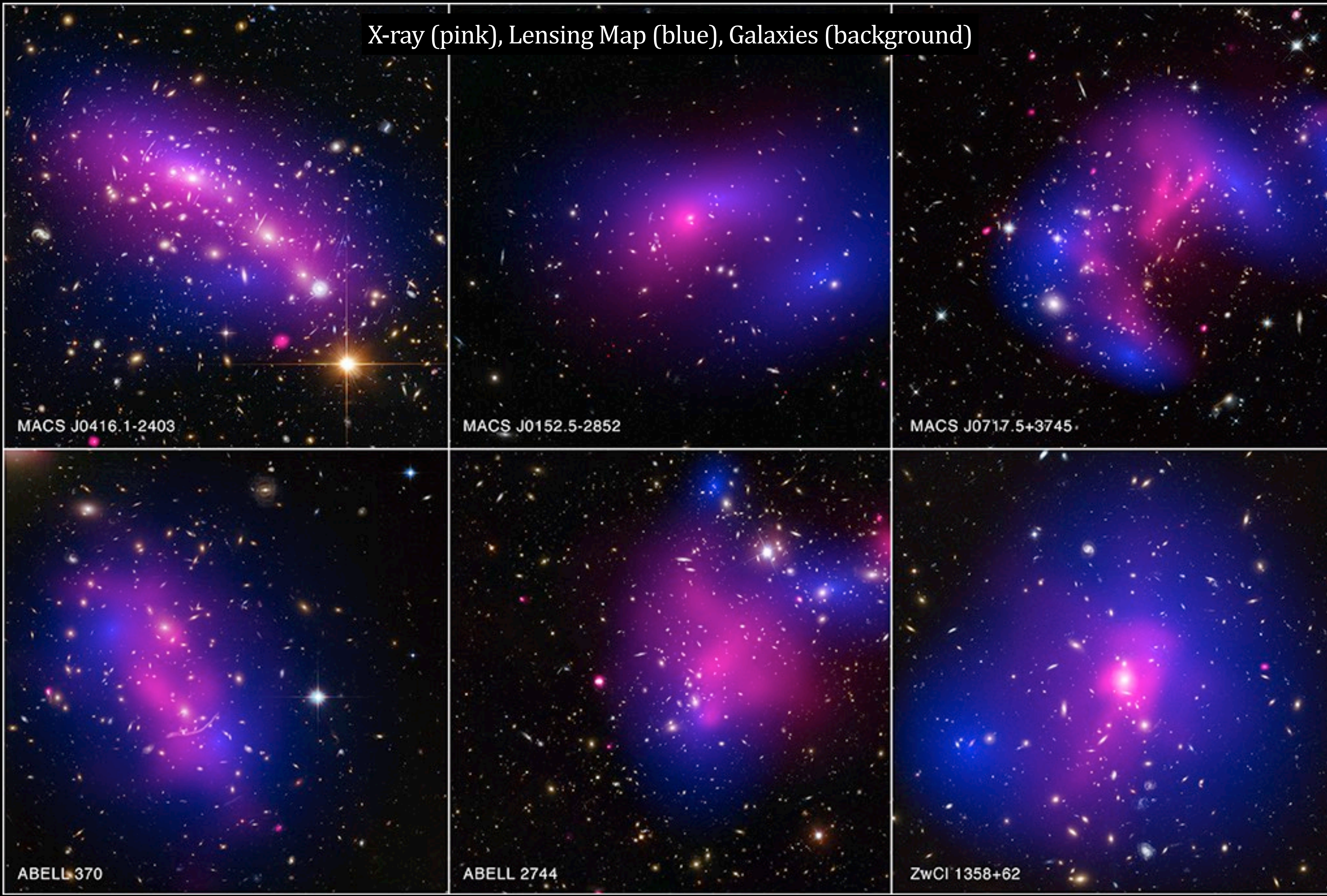
If dark matter and normal matter are distinctly separated in a galaxy cluster, we would expect the mass distribution from lensing to be completely different from the X-ray gas distribution

Cluster collision separates normal matter from dark matter



The Bullet cluster (IE 0657-56)

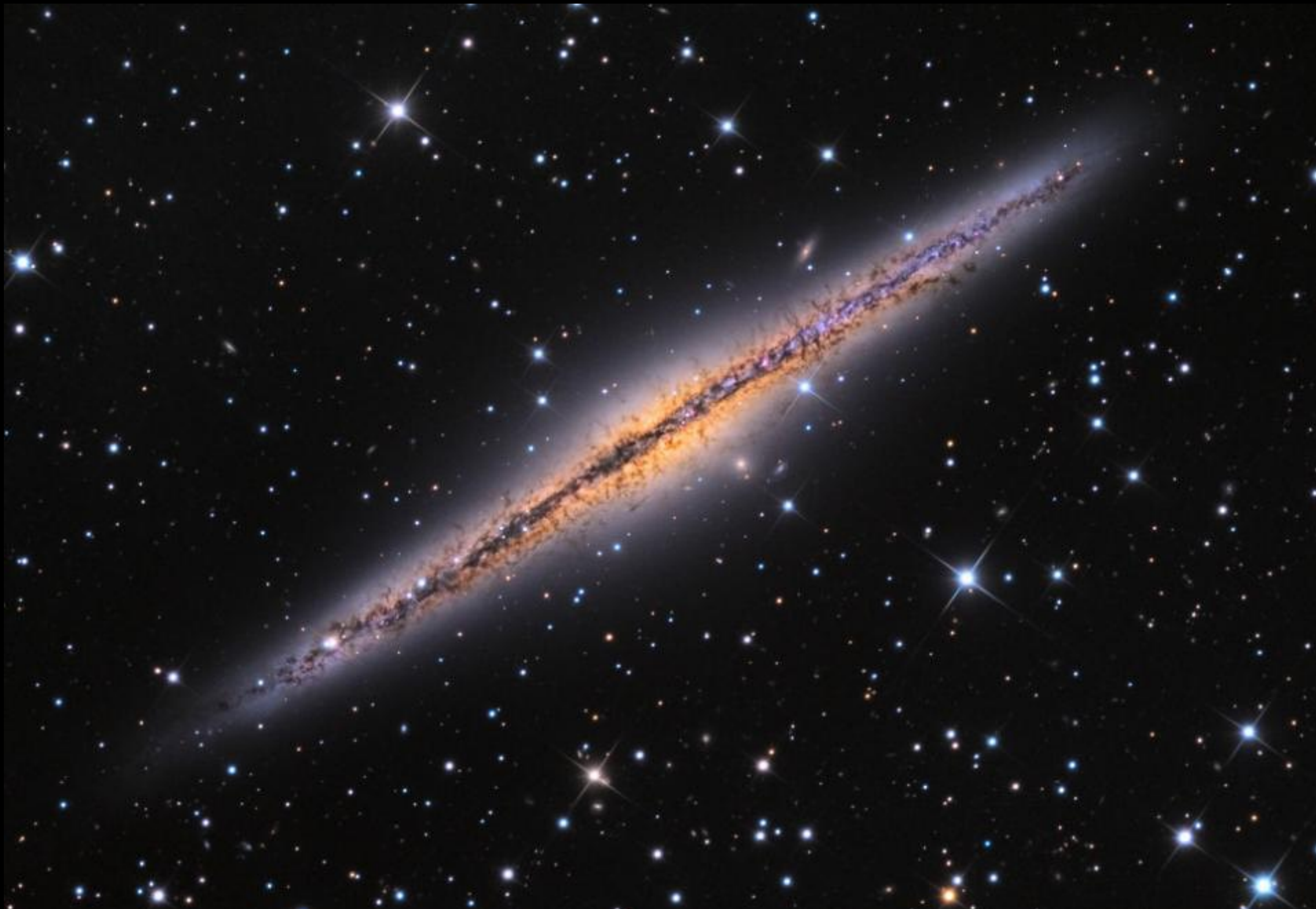
When clusters collide, the ICM could be separated from the dark matter



The Milky Way:
Viewing a Large Spiral Galaxy from Inside -

The Milky Way & Devils Tower, Wyoming

NGC 891 - an edge-on spiral galaxy

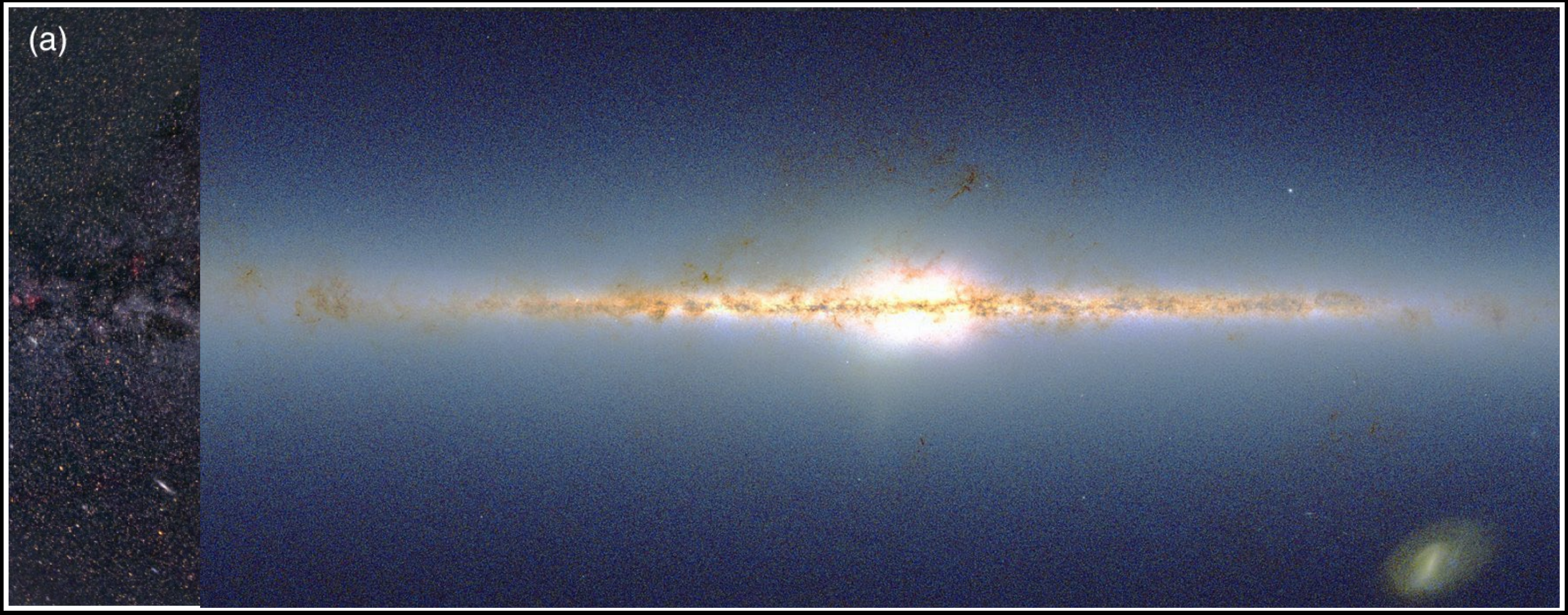


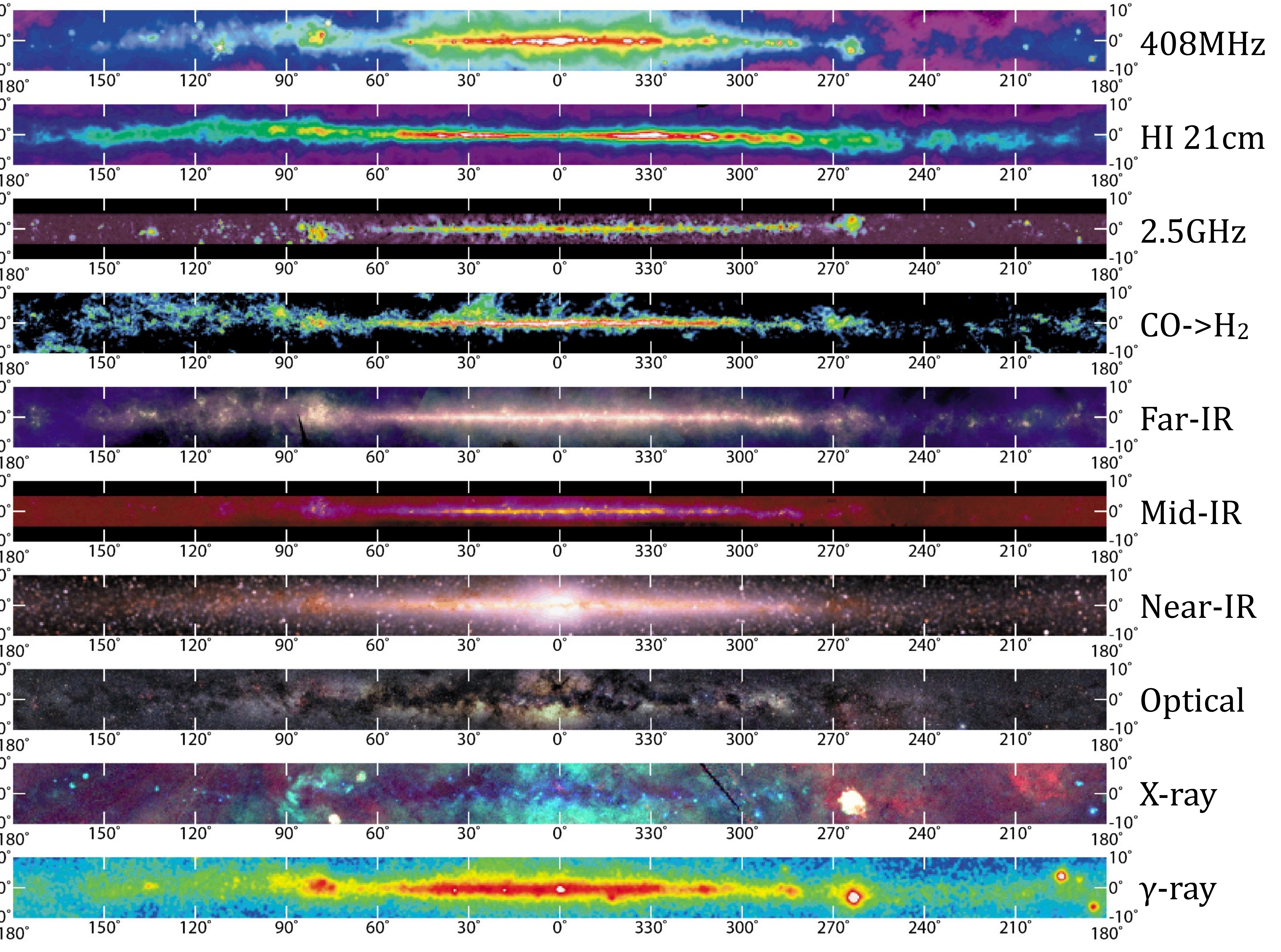
Milky Way compared to NGC 891 (an edge-on Spiral galaxy)

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

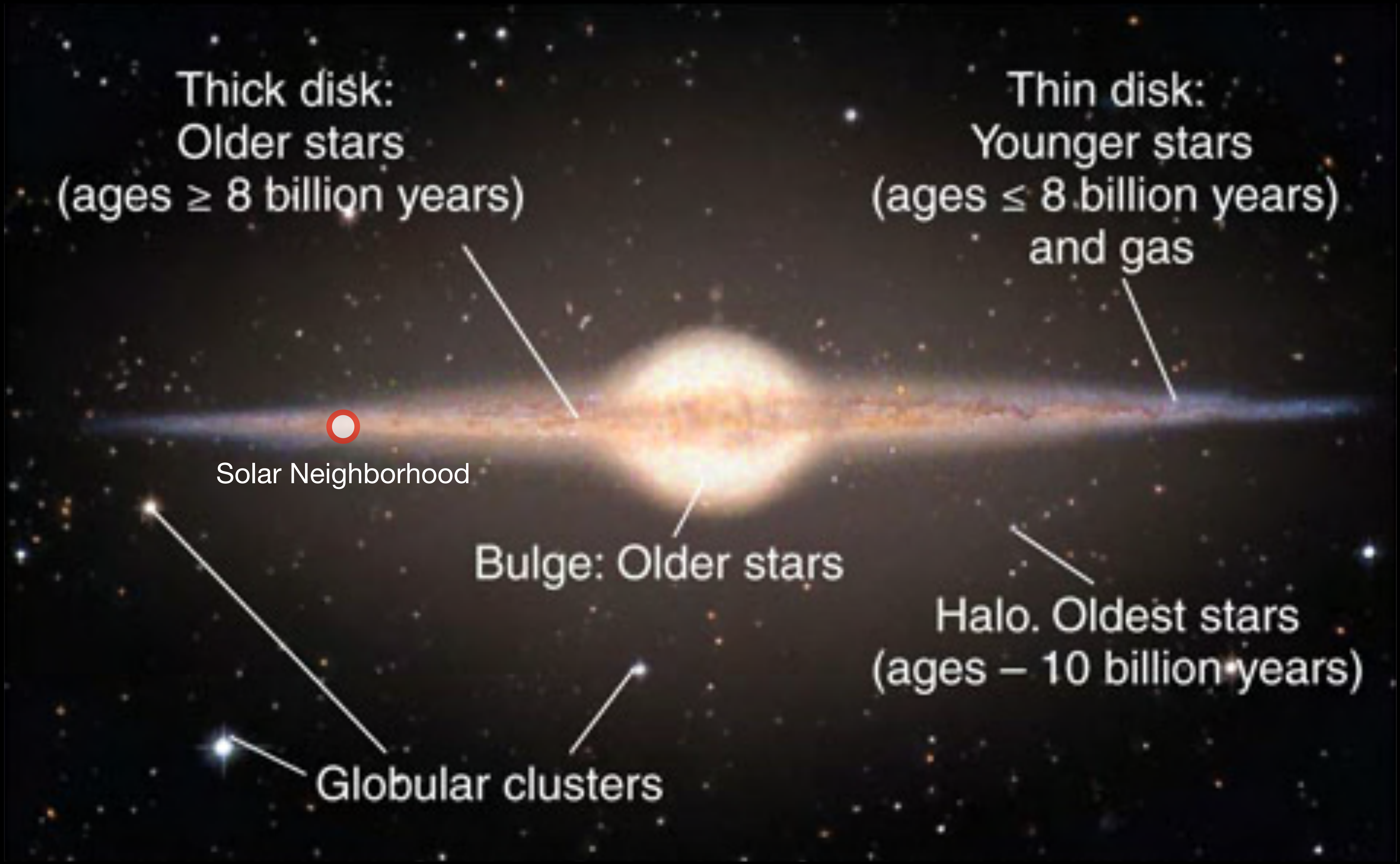



408MHz
HI 21cm
2.5GHz
CO->H2
Far-IR
Mid-IR
Near-IR
Optical
X-ray
γ-ray
10°
0°
-10°
180°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180°

Complex Stellar Populations

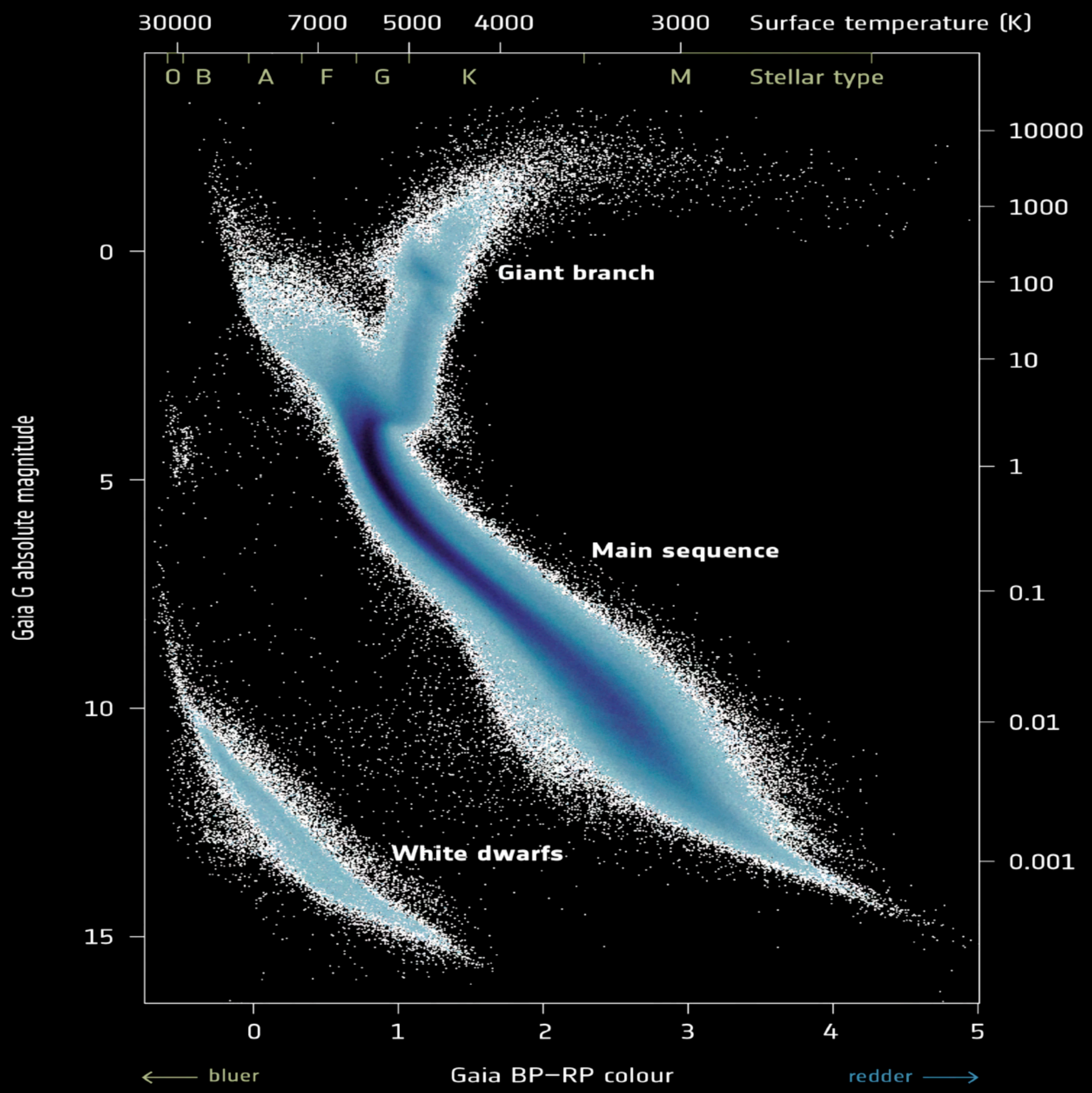
Solar neighborhood stars' H-R diagram

Stars in the Solar Neighborhood (d < 500 pc)?

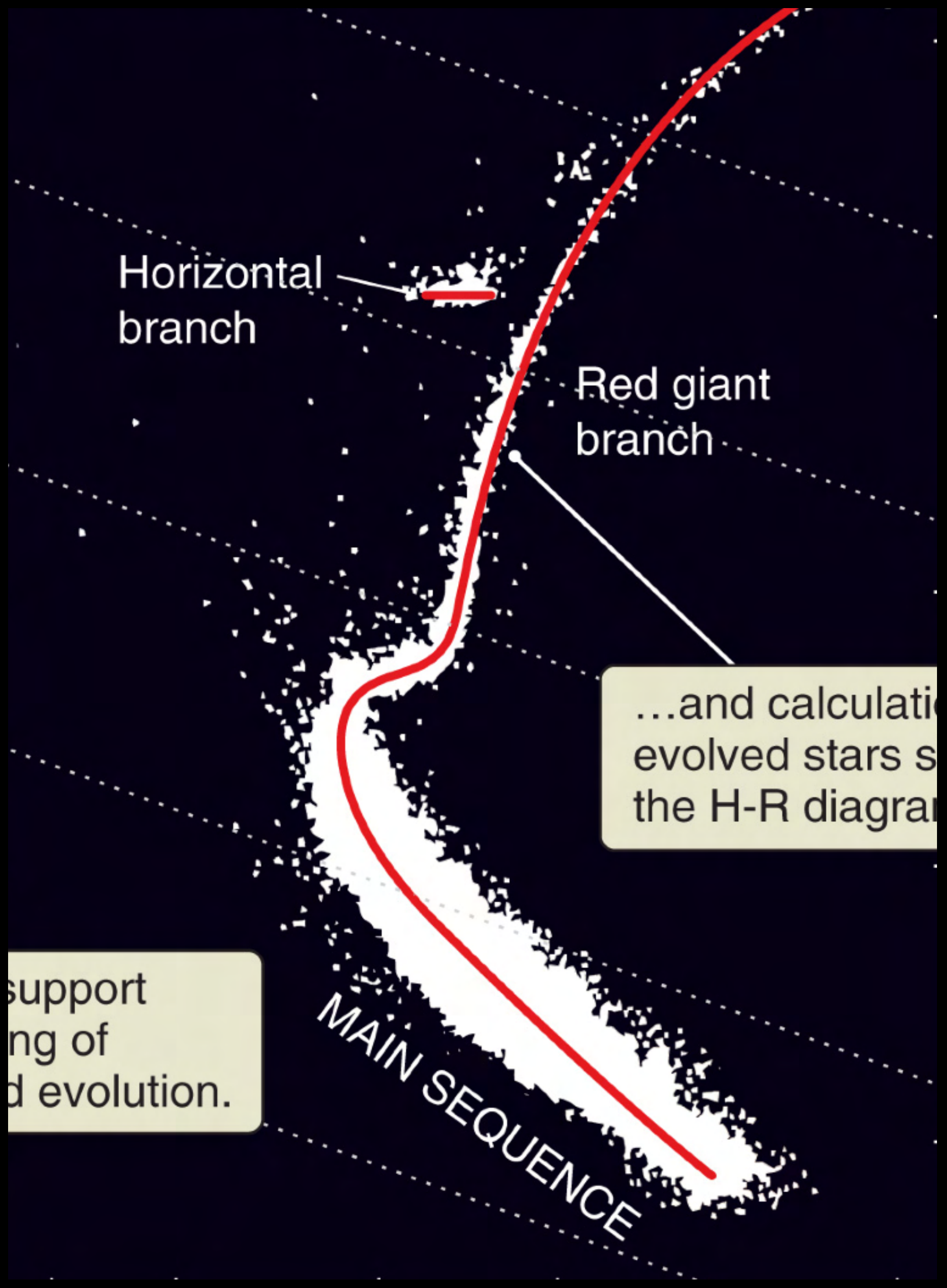


Why the HR diagram of Solar Neighbors looks so different?

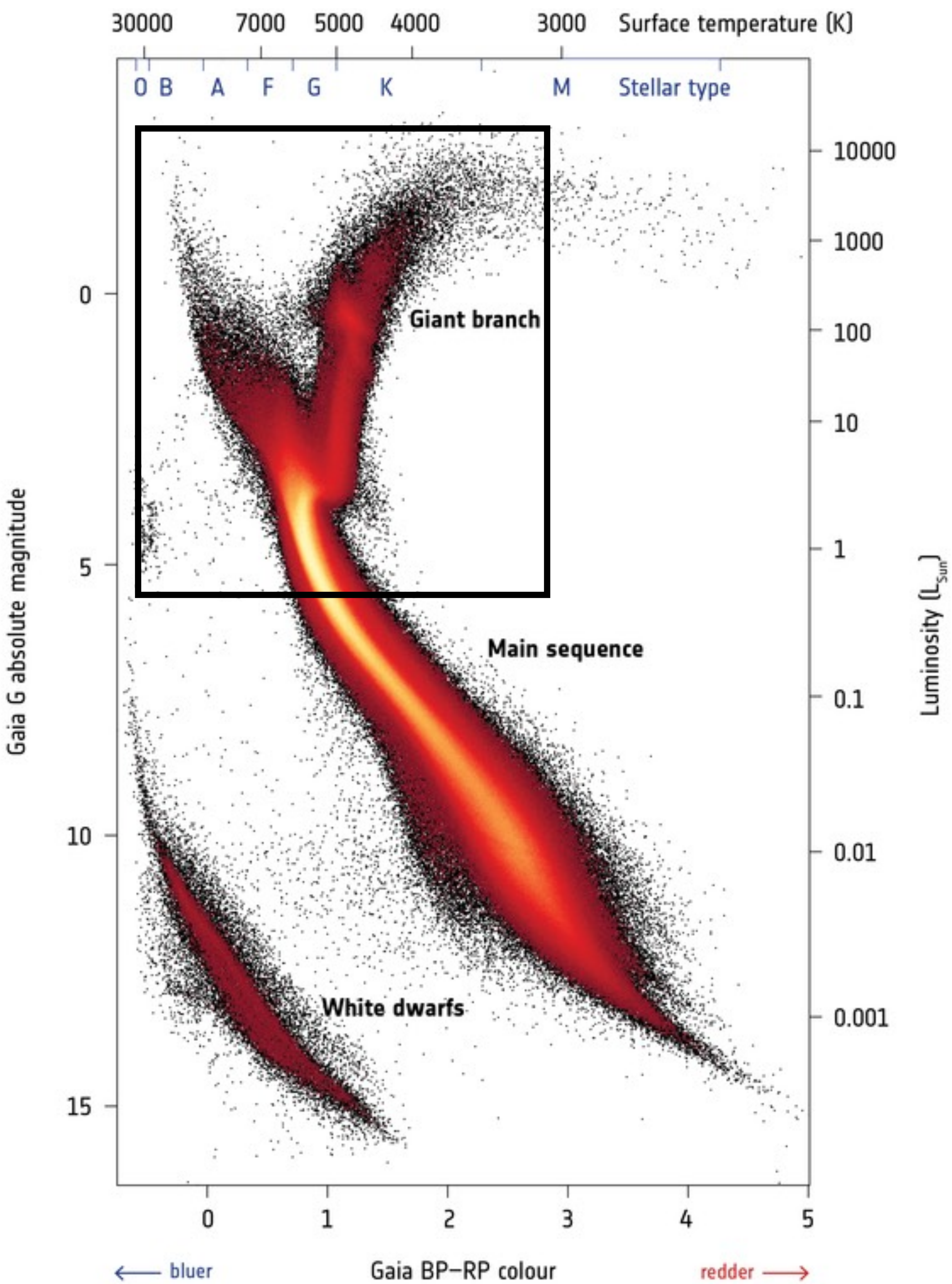
Solar neighborhood HR diagram

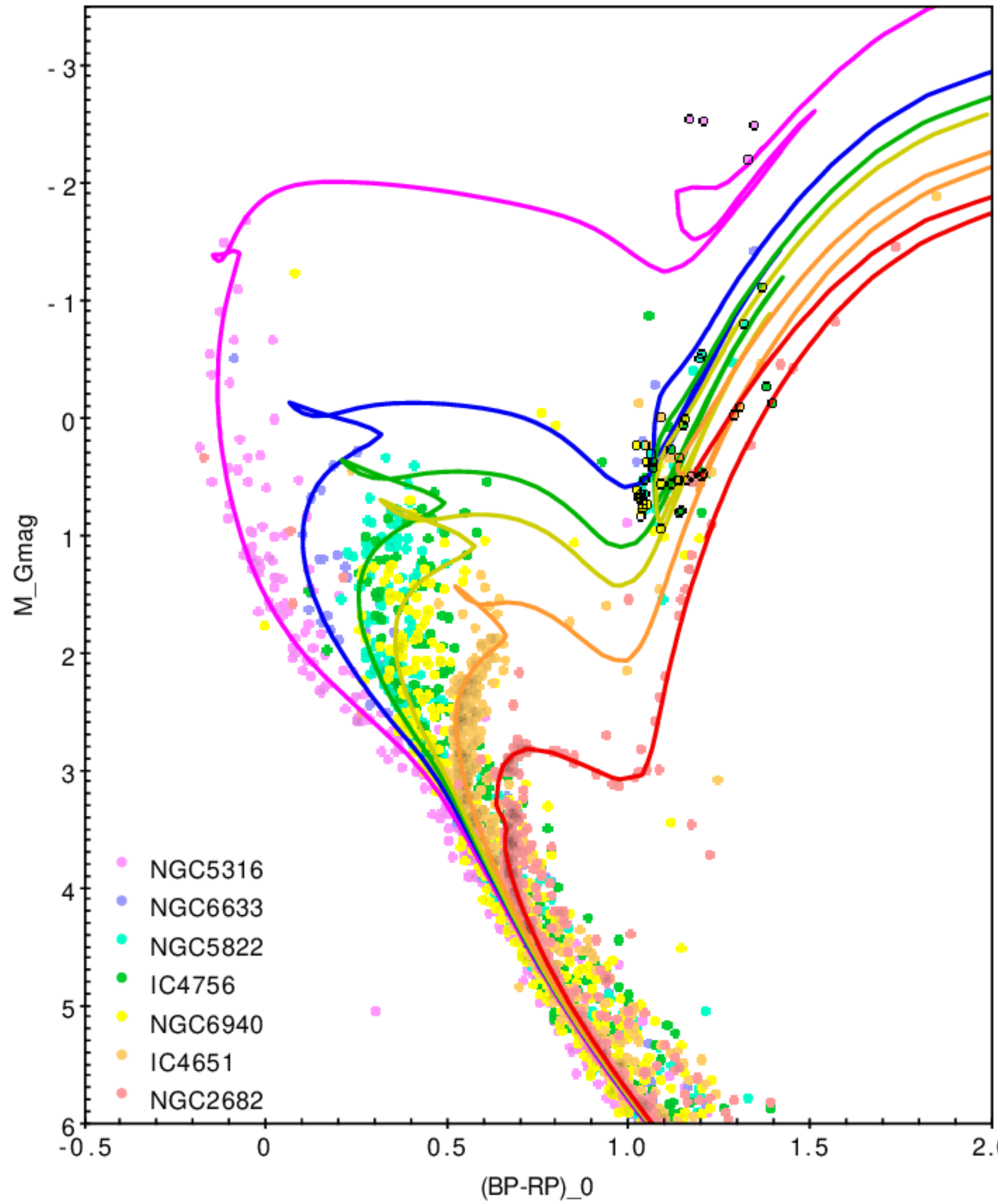


Cluster HR diagram

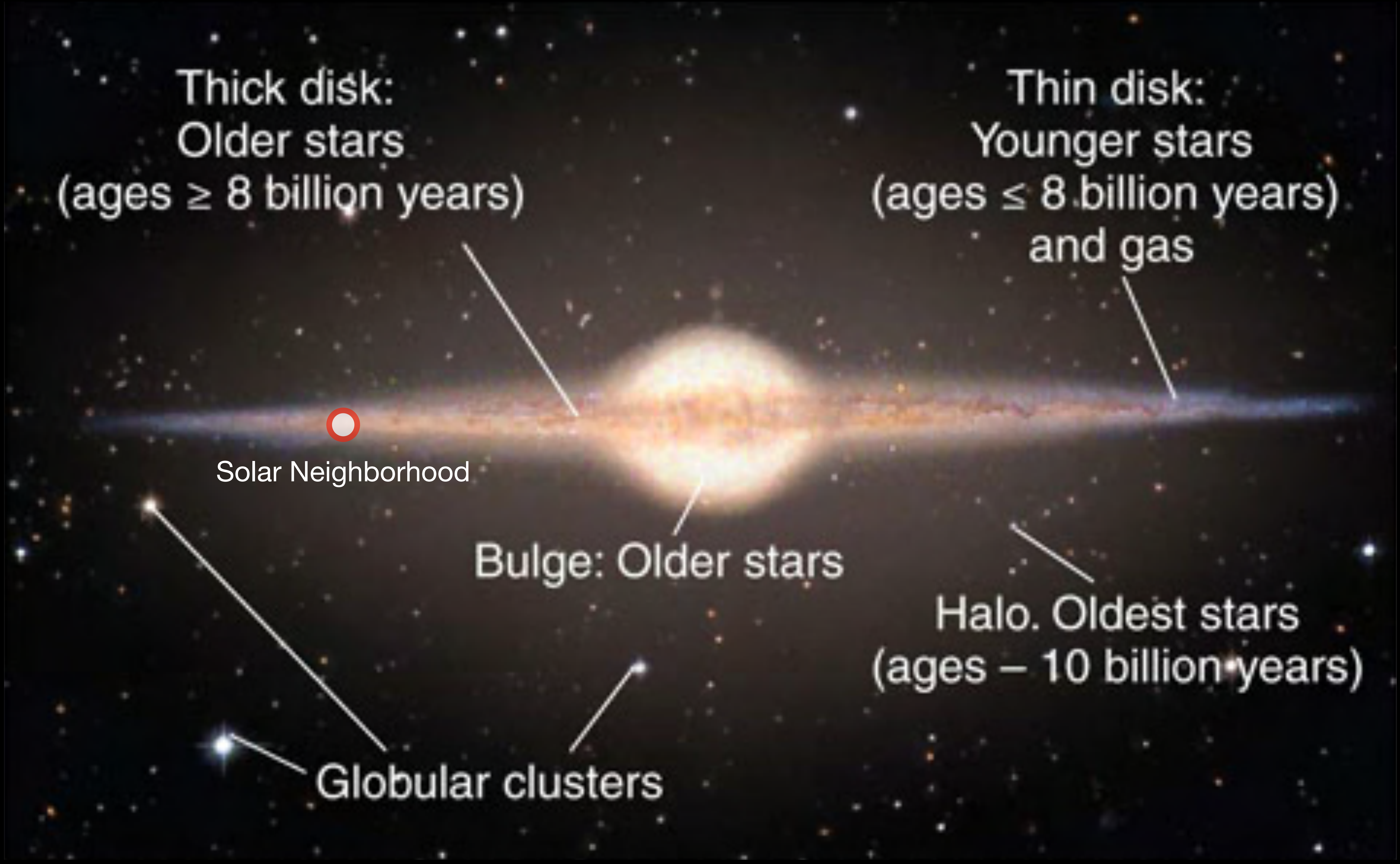


The Solar neighborhood stars are a mixed stellar population, and its HR diagram can be understood as a combination of multiple isochrones



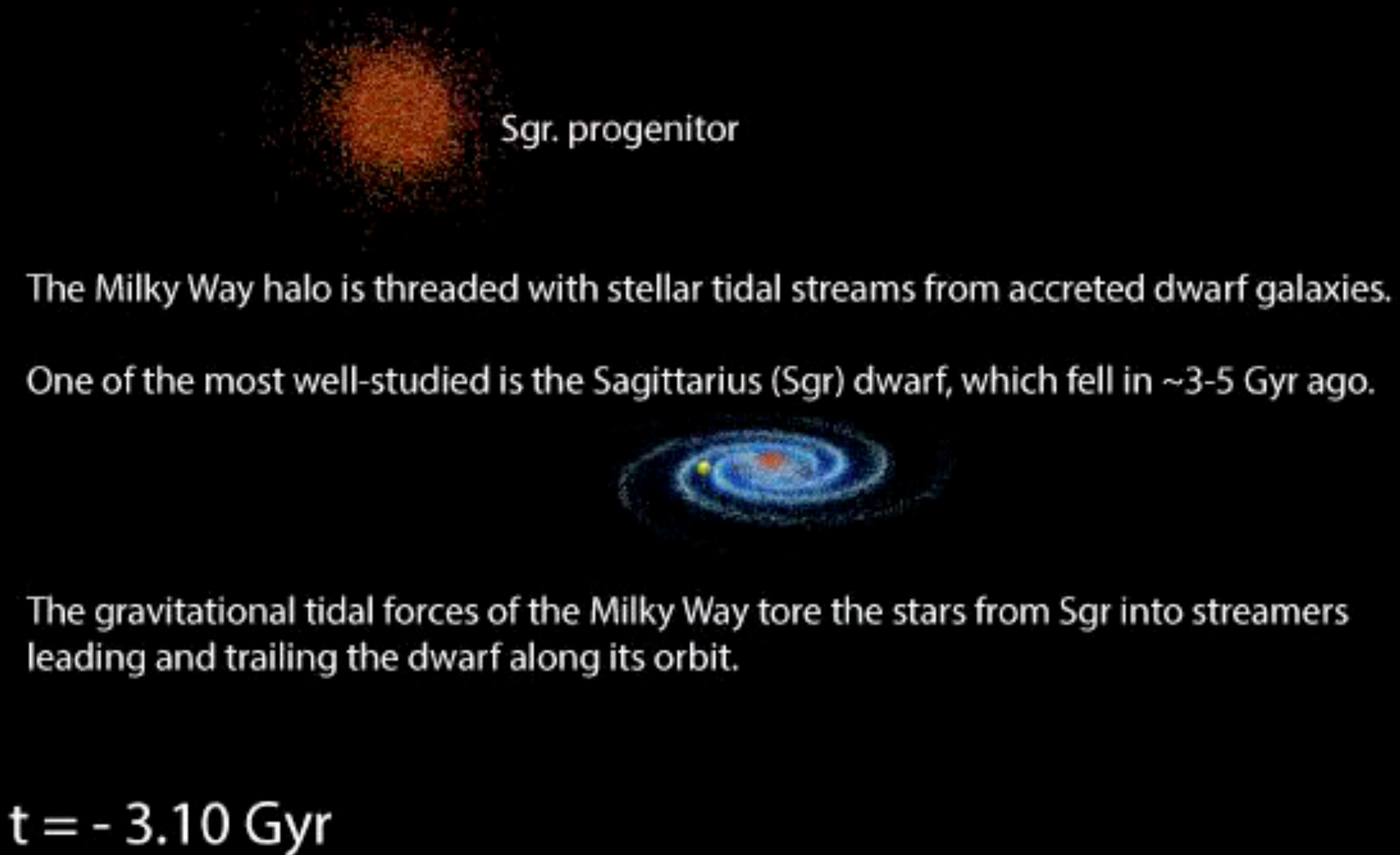


The study of Solar neighbors' HR diagram made us realize that ``Rome wasn't built in a day''

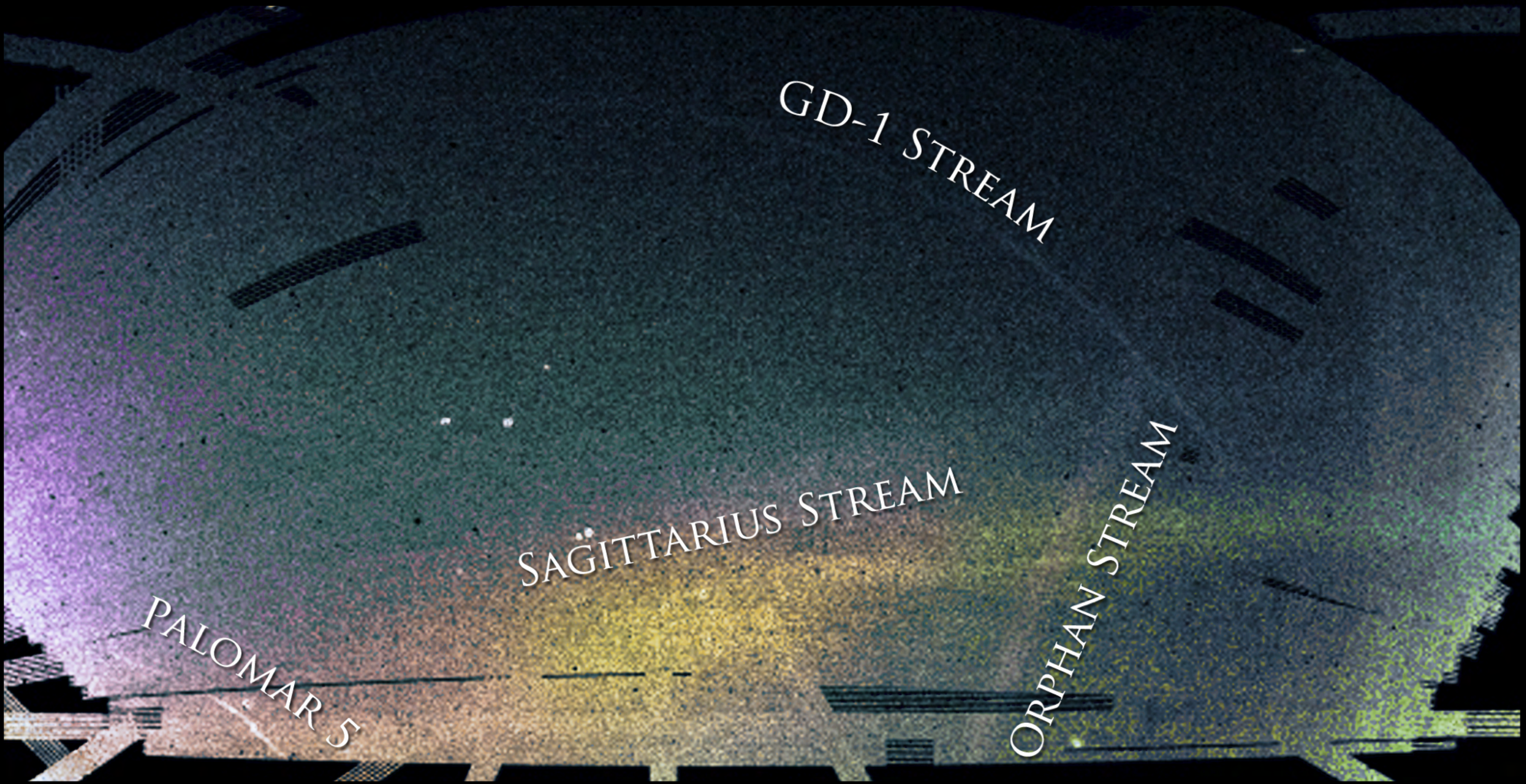


A large fraction of stars in the Milky Way formed in other galaxies before they were accreted by the Galaxy

Small galaxies get shredded by large galaxies

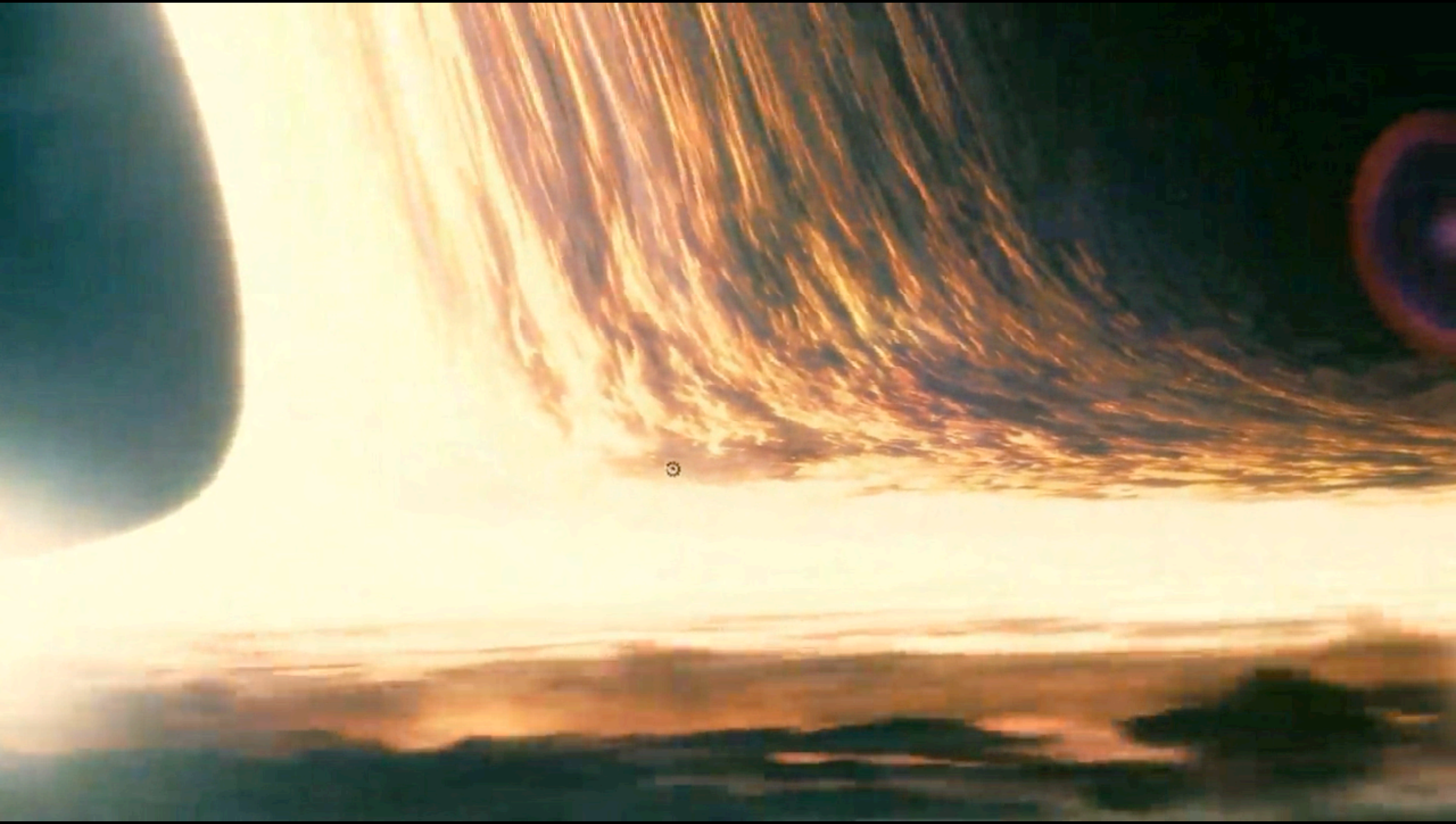


Inside the Milky Way's Halo: Tidally Stripped Stars from Dwarf Galaxies



Southern Sky

Interstellar (2014)



Hunting for SMBHs in Galaxies
methodology

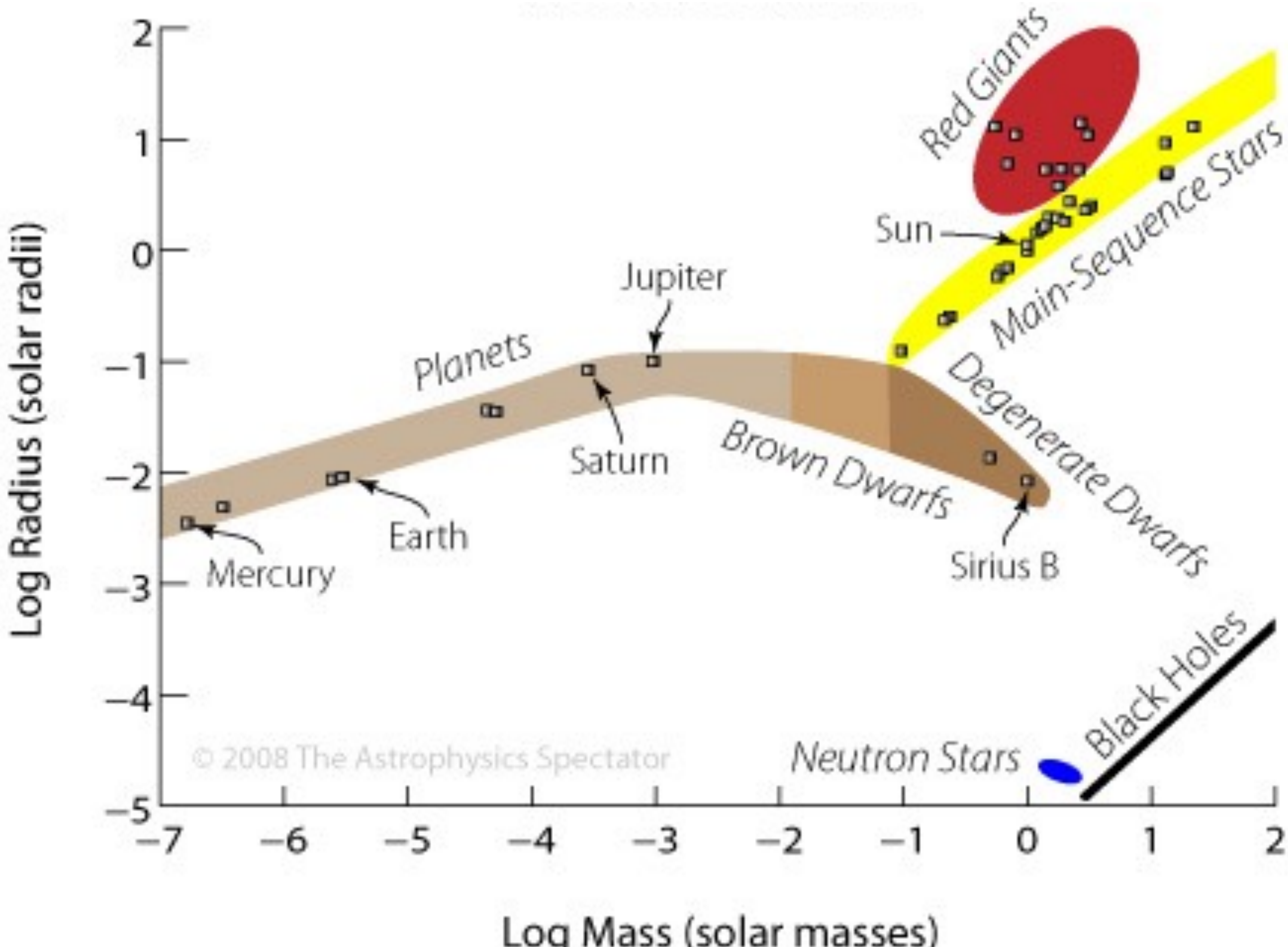
Method 1: Resolving the Event Horizon (Schwarzschild Radius)

- 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:

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

- For M87:

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

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

Resolving the Event Horizon is Very Difficult, even for SuperMassive BHs

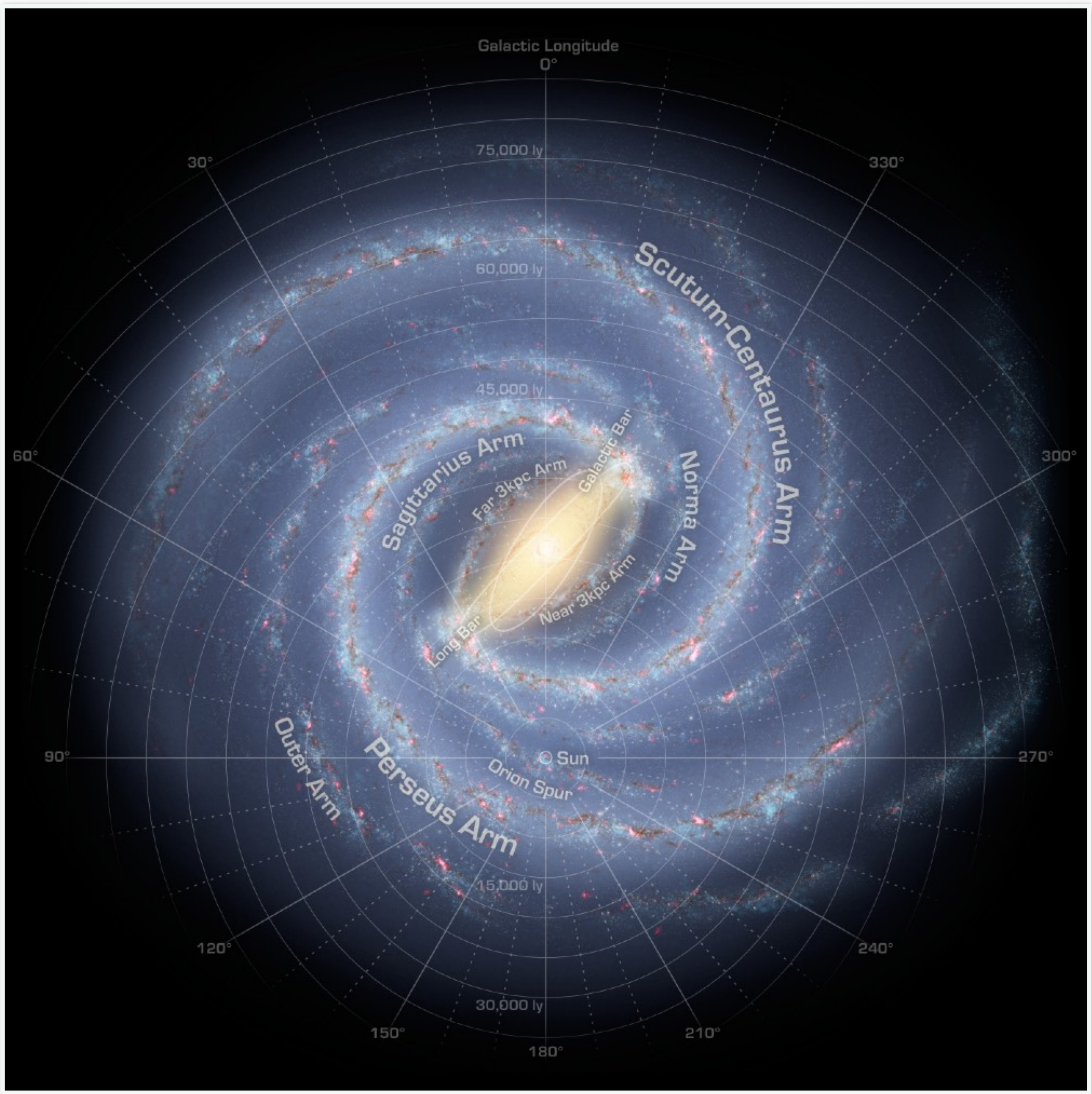
- **Schwarzschild (1916) radius**. $\mathbf{r_s}$ defines the **event horizon** of a non-rotating black hole:

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

- ***This is a billion times smaller than the size of a galaxy:***
  10 kilo parsec = 2062650000 AU = 2e8 AU

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?

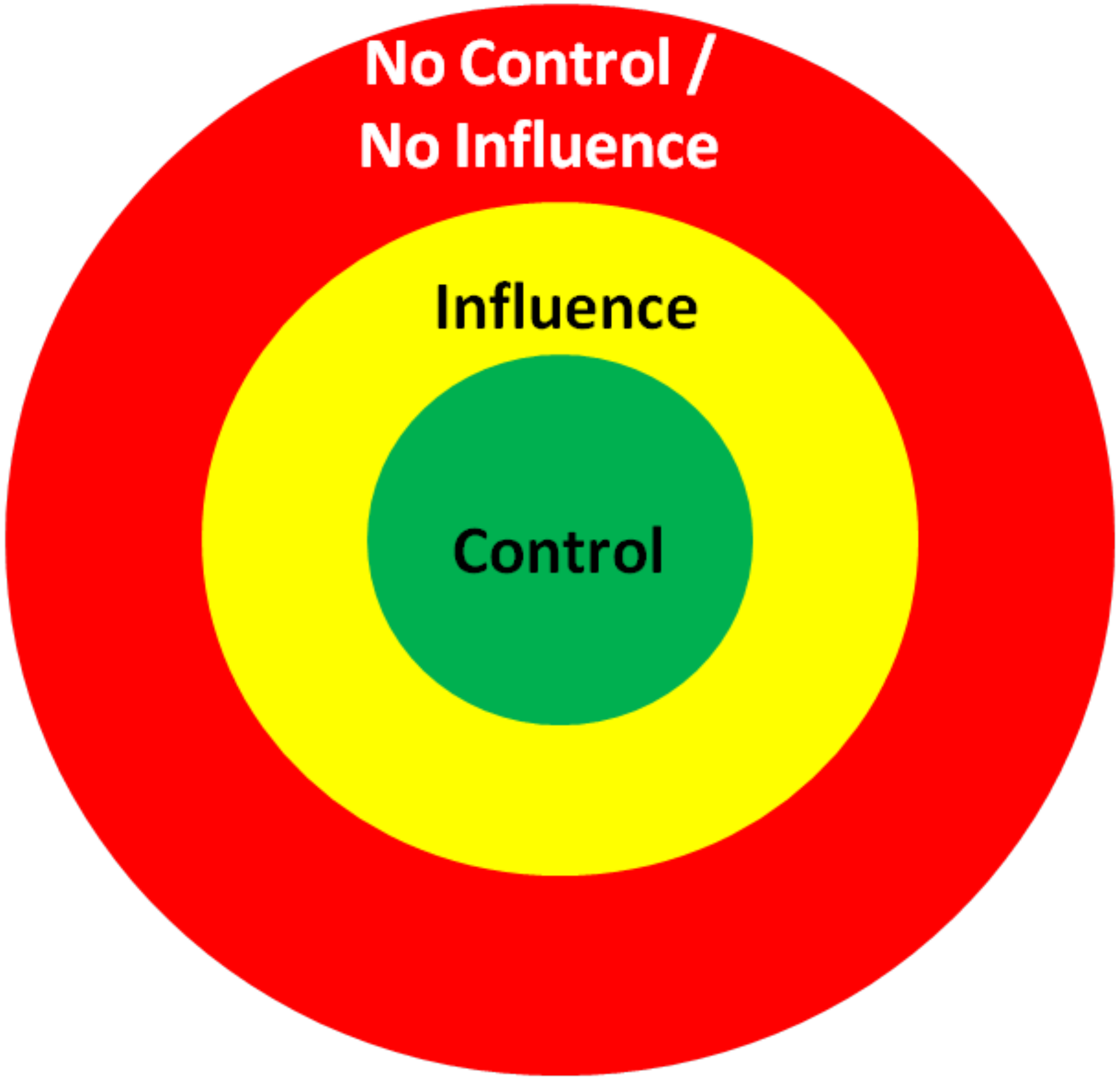


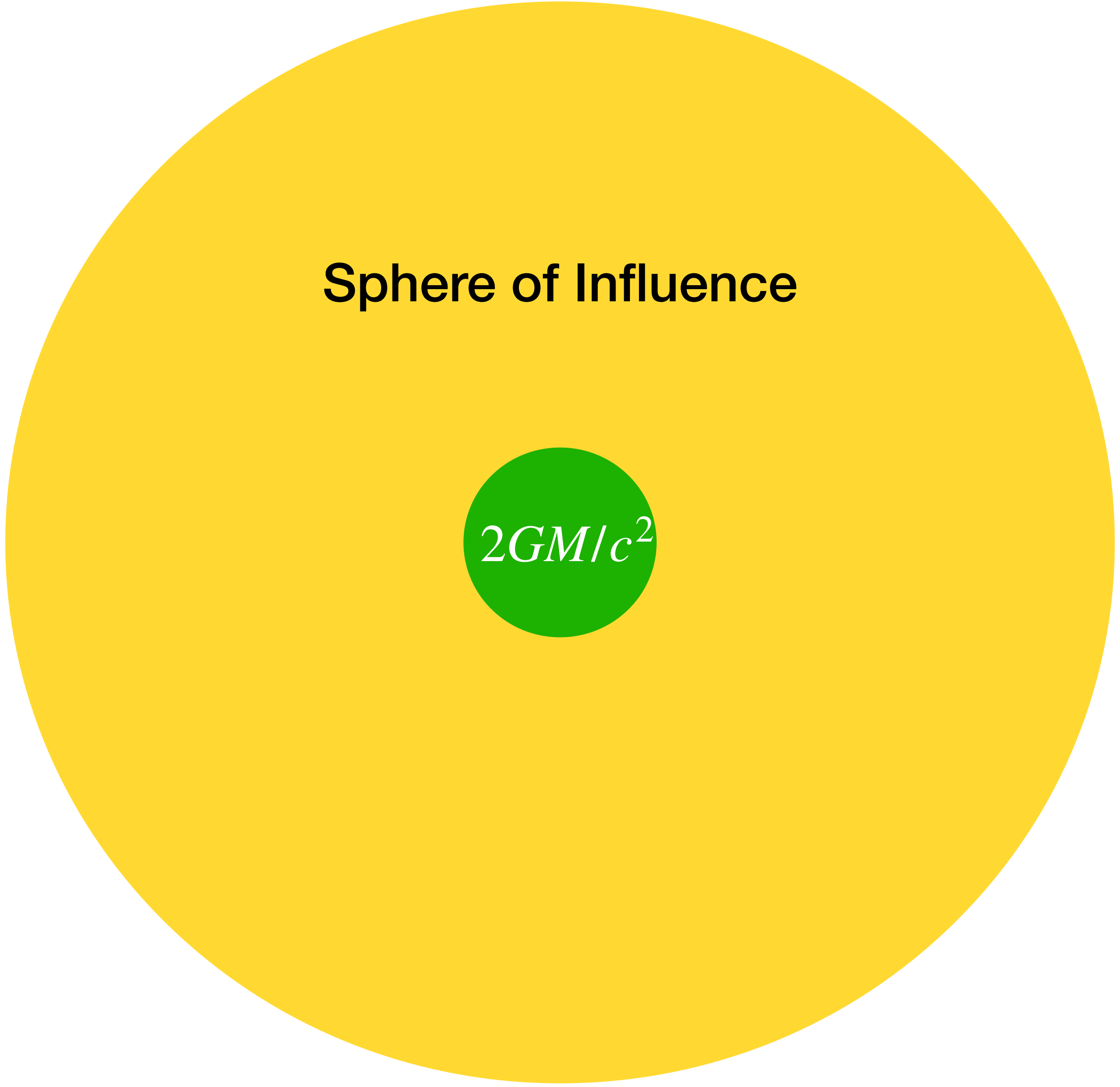
1 AU at 1 pc = 1 arcsec
1 AU at 1 kpc = 1 mas
2 AU at 8 kpc = 0.25 mas
= 250 micro-arcsec

Hubble Space Telescope's diffraction limit:
wavelength/diameter
~ 52 mas

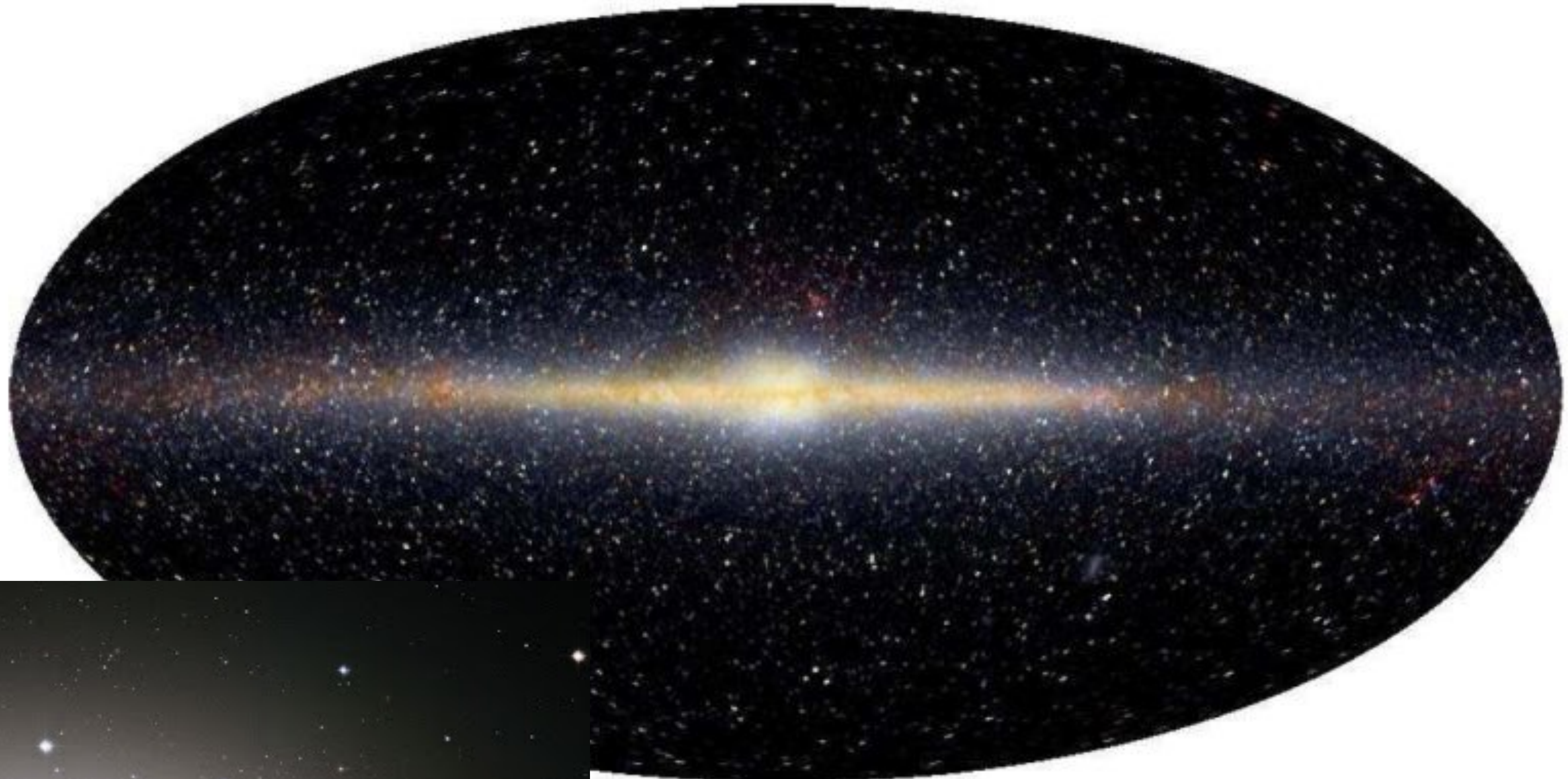
Method 2: Resolve the Sphere of Influence (not event horizon)

The **Sphere of Influence** of an entity is usually larger than the size of the entity Itself (see demo in class)





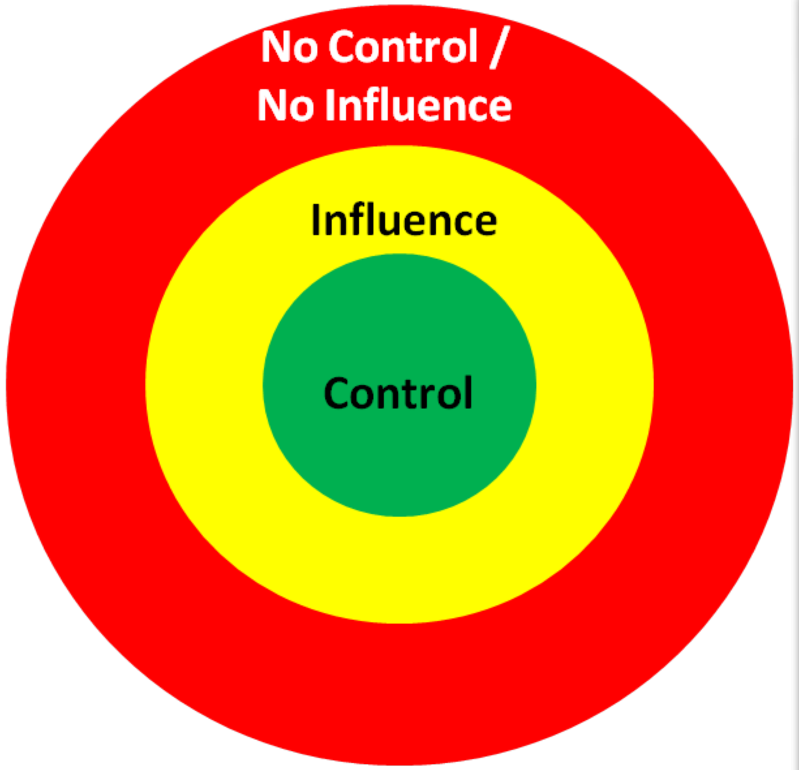
But, SMBHs live inside stellar bulges that is much more massive than the SMBH itself



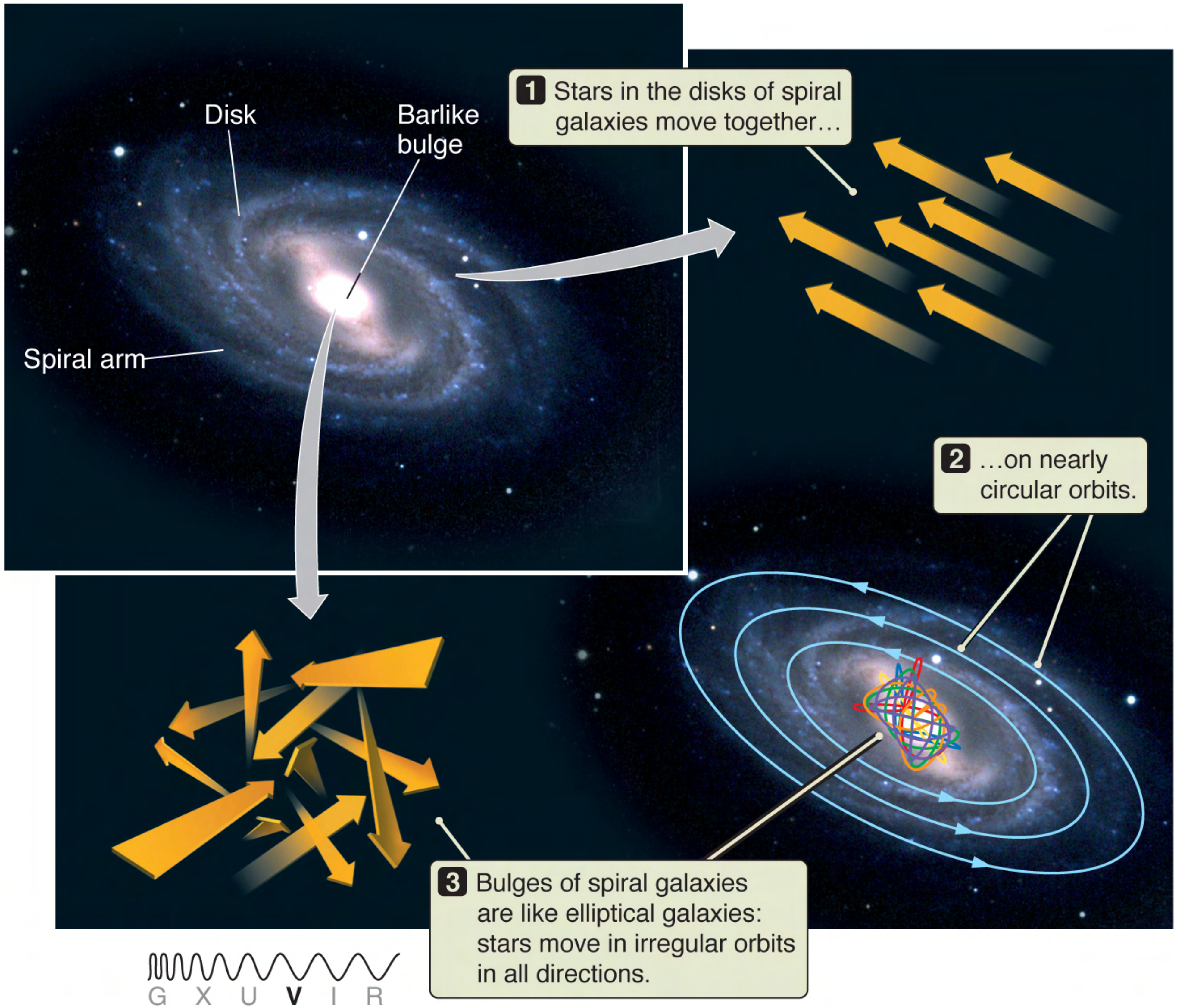
The Milky Way Galaxy

The Sombrero Galaxy

Example: Inside the Sphere of Influence of Napoleon I (1799-1821 CE), cities were controlled by aristocrats other than Napoleon himself!



Regular Circular Orbits of Disk Stars vs. Irregular Orbits of Bulge stars

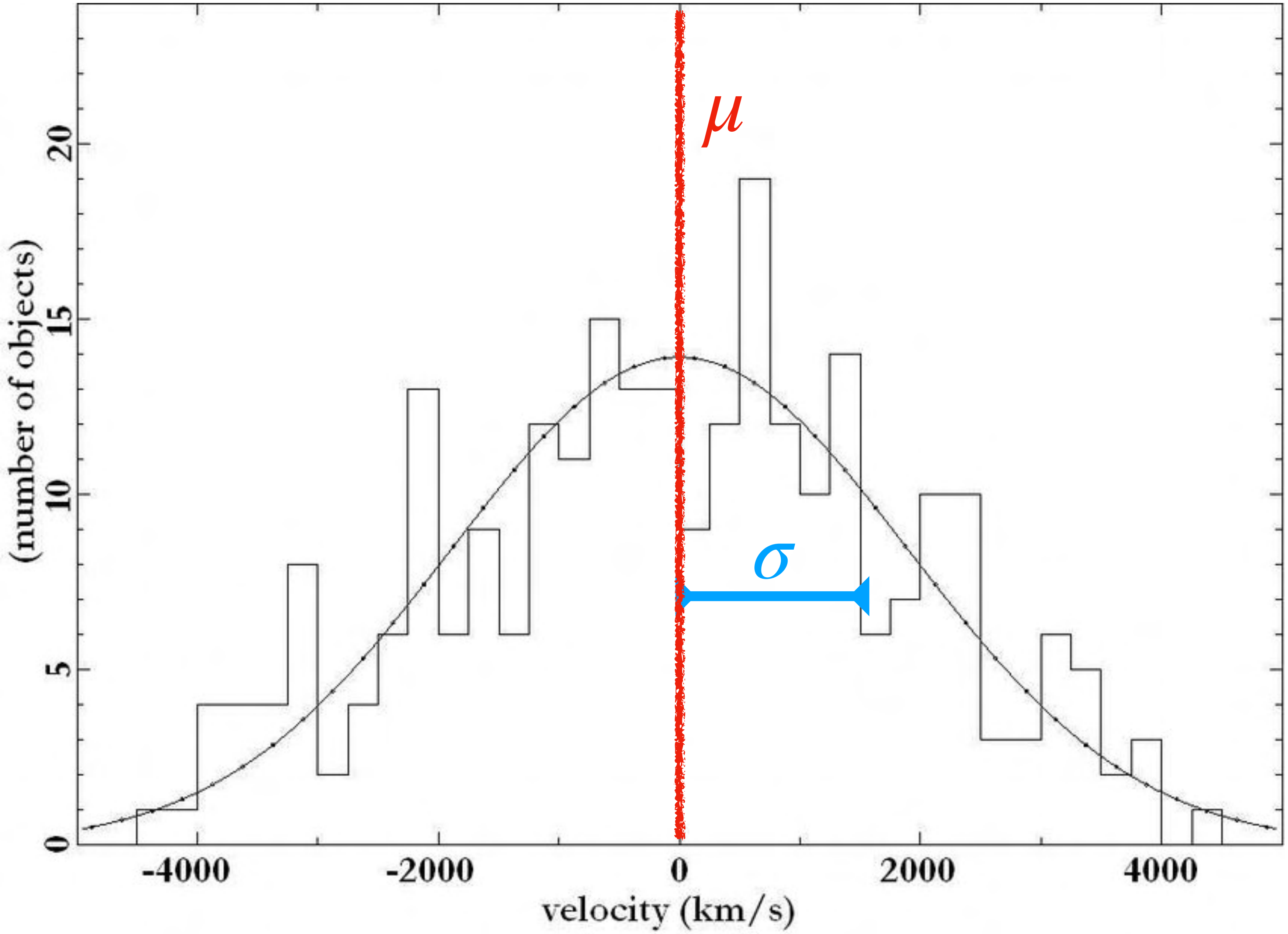


Velocity Dispersion of Stars in Galactic Bulge

Gaussian Distribution:

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

where σ is the standard deviation and μ the mean



Estimate the Size of the Sphere of Influence of a SMBH

- The **mass profile** and **enclosed mass** of the stellar **bulge** is:

$$\rho(r) = \frac{\sigma_*^2}{2\pi G r^2} \quad \text{and} \quad M(r) = \int_0^r \rho(r) 4\pi r^2 dr = \frac{\sigma_*^2 r}{G}$$

- The **sphere of influence** of the **SMBH** is the region *where the enclosed stellar mass is less than the BH mass*:

$$M(r) = \frac{\sigma_*^2 r}{G} < M_{\rm BH}$$

which gives the size of ***the sphere of influence:***

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

The Sphere of Influence is much larger than the Event Horizon

- The **Schwarzschild radius** defines the **event horizon** of a 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** defines its gravitational territory:

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

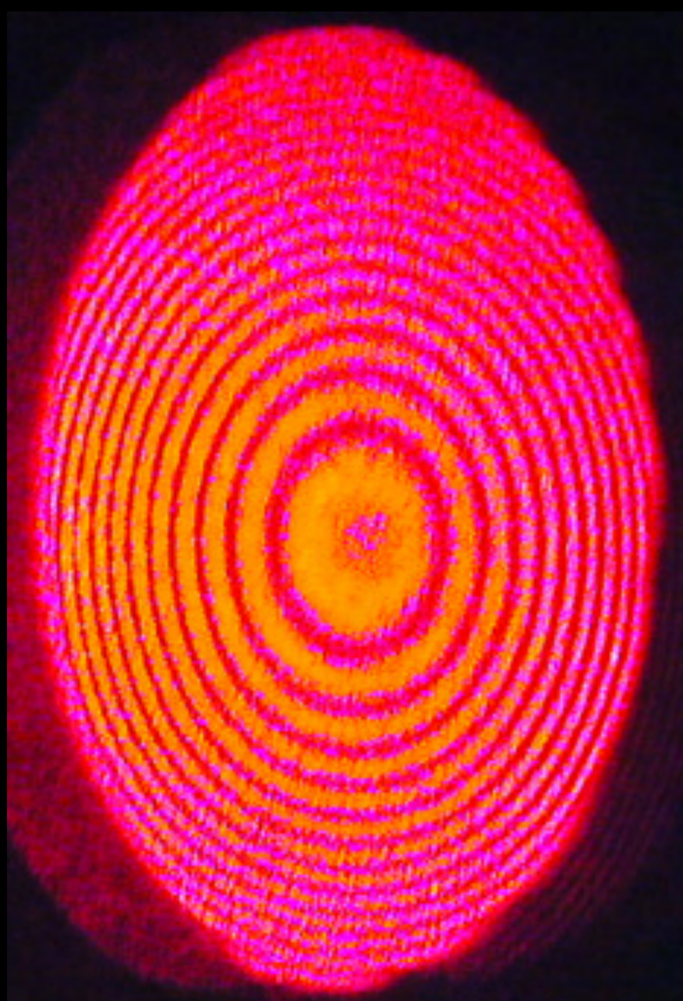
- For a 10^8 M_{sun} BH inside a stellar bulge that has a velocity dispersion σ_* of 200 km/s, the radius of **the sphere of influence** is ***a million times*** greater than the radius of **the event horizon**.

- **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.**

Evidence of SMBHs in the Nearest Massive Galaxies

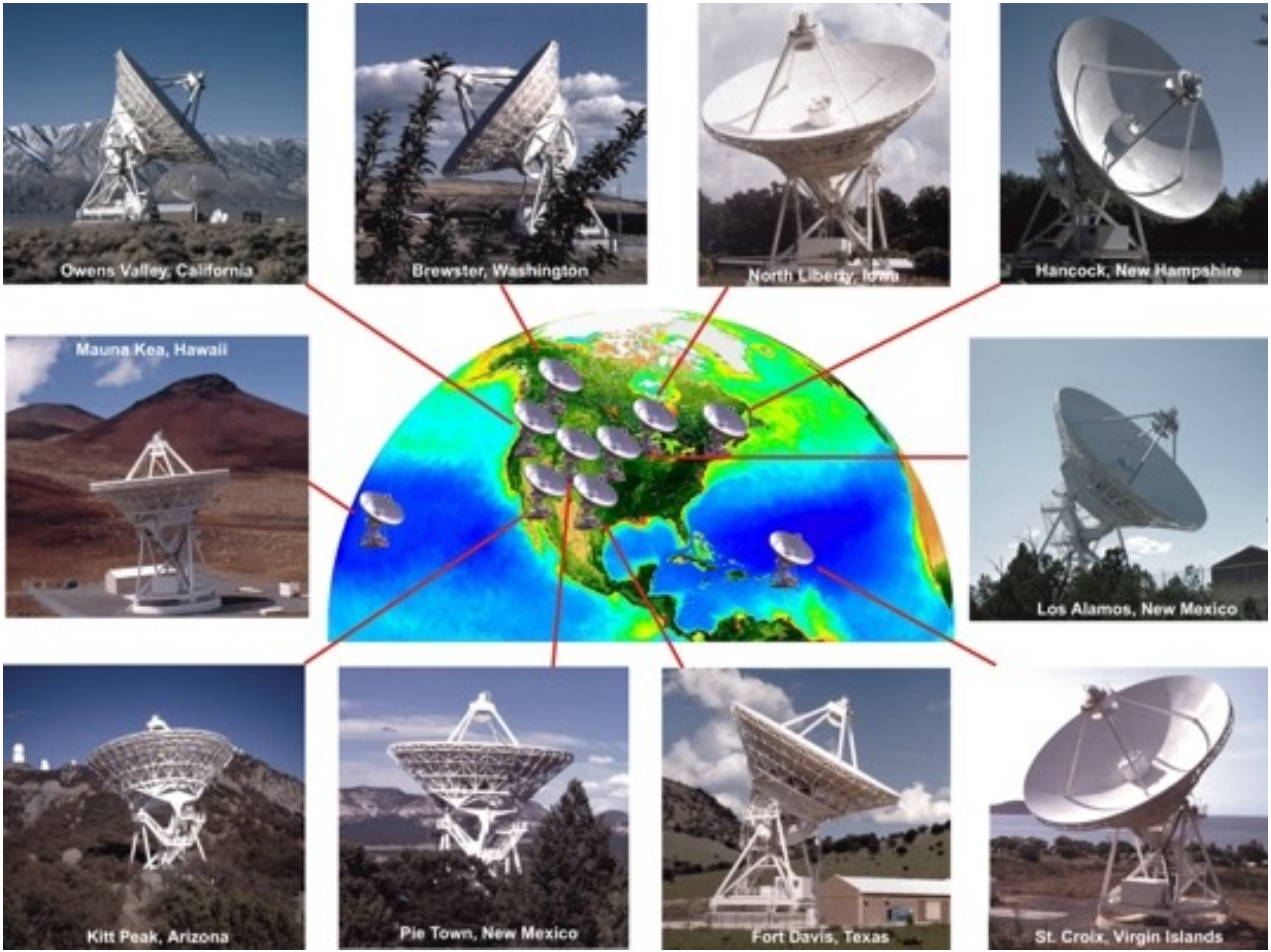
Resolving the event horizon

Michelson interferometer (demo)



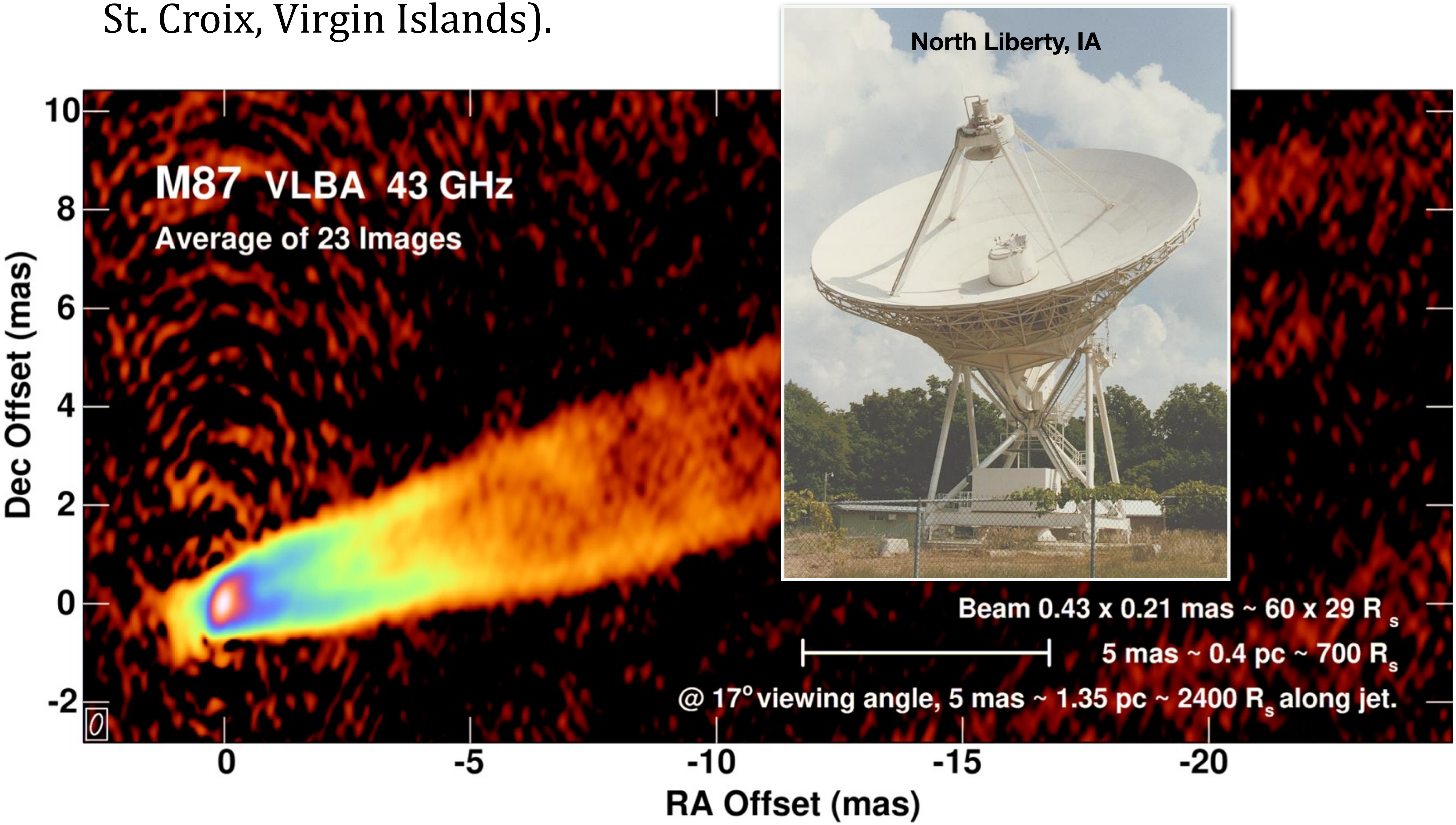
The Very Large Array (VLA) in New Mexico

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).

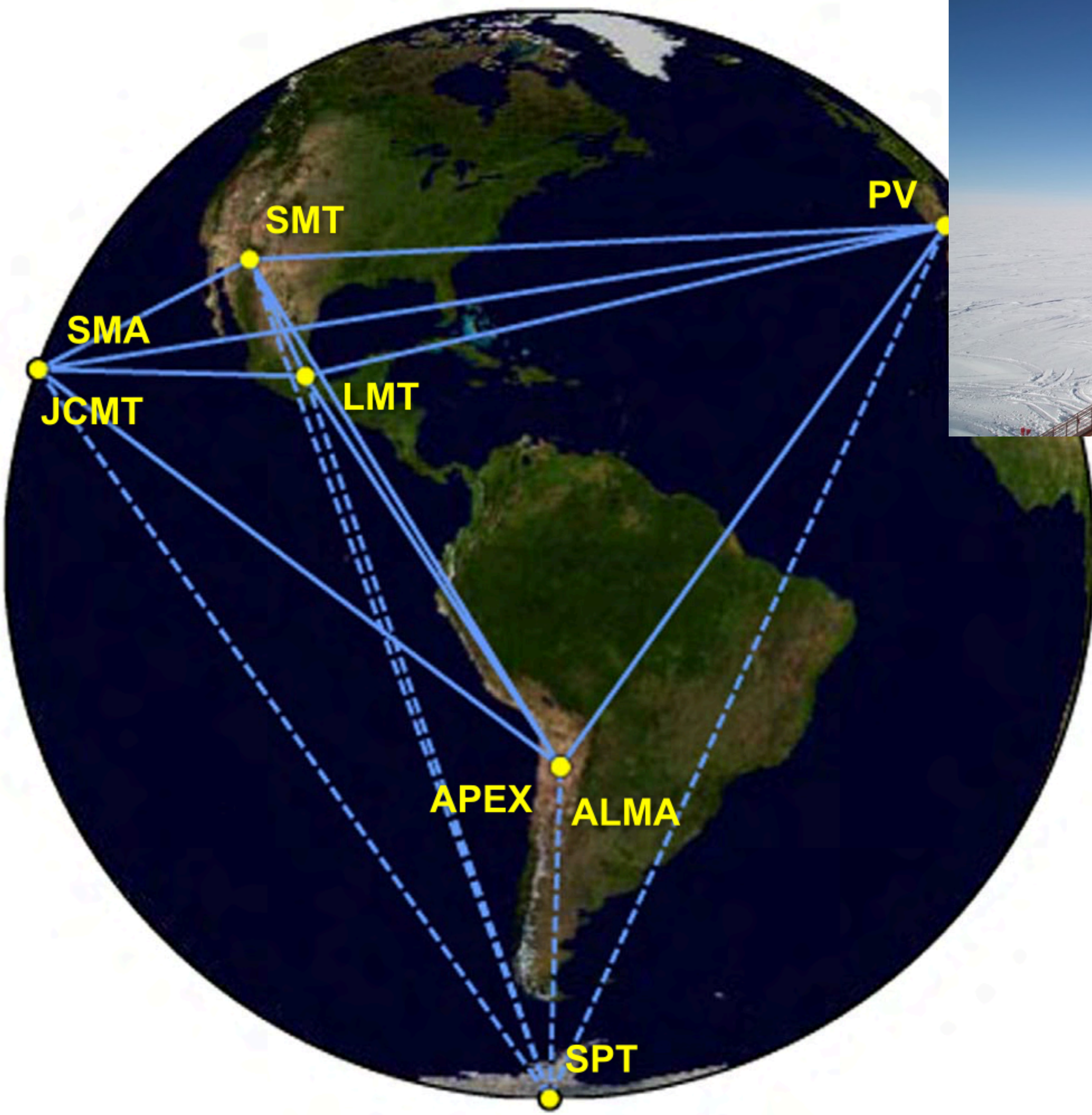


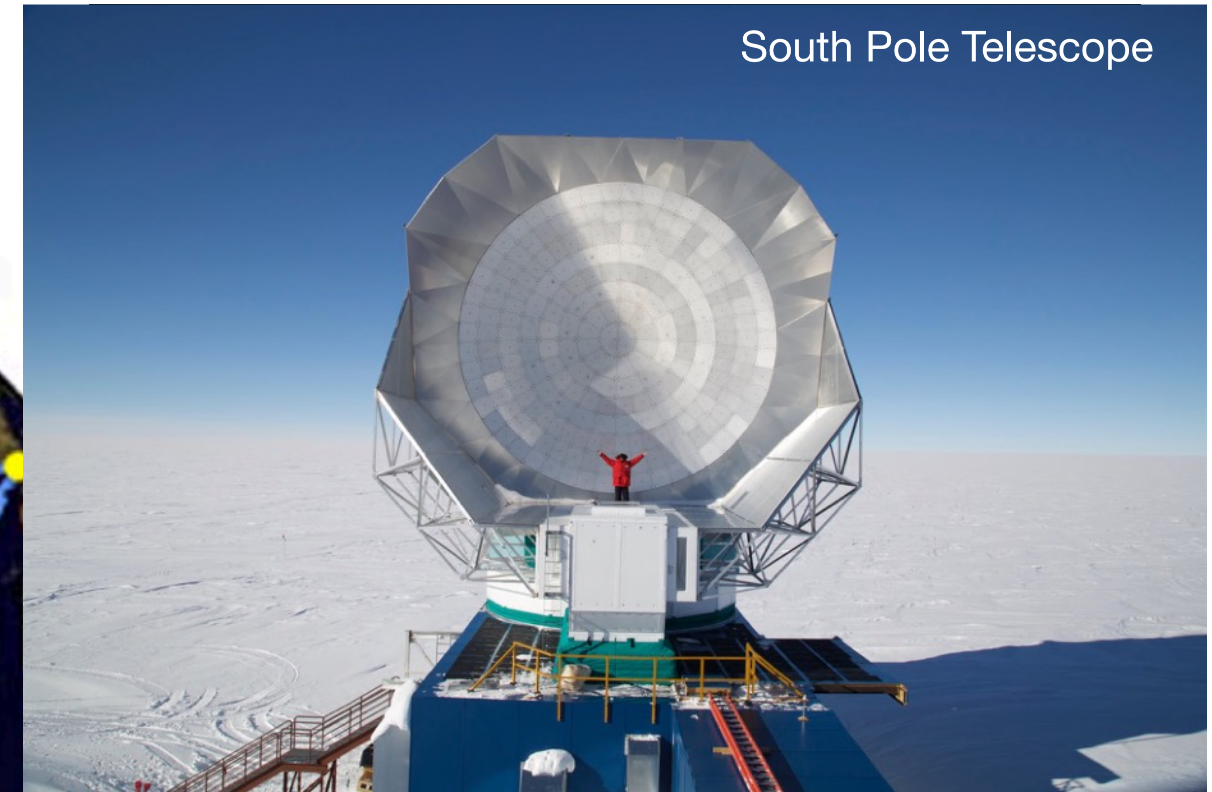
The Univ. of Iowa North Liberty Radio Observatory in 1973


Mehaffey Bridge Rd NE
VLBA North Liberty Station

What's the angular resolution required to resolve the event horizon of M87*

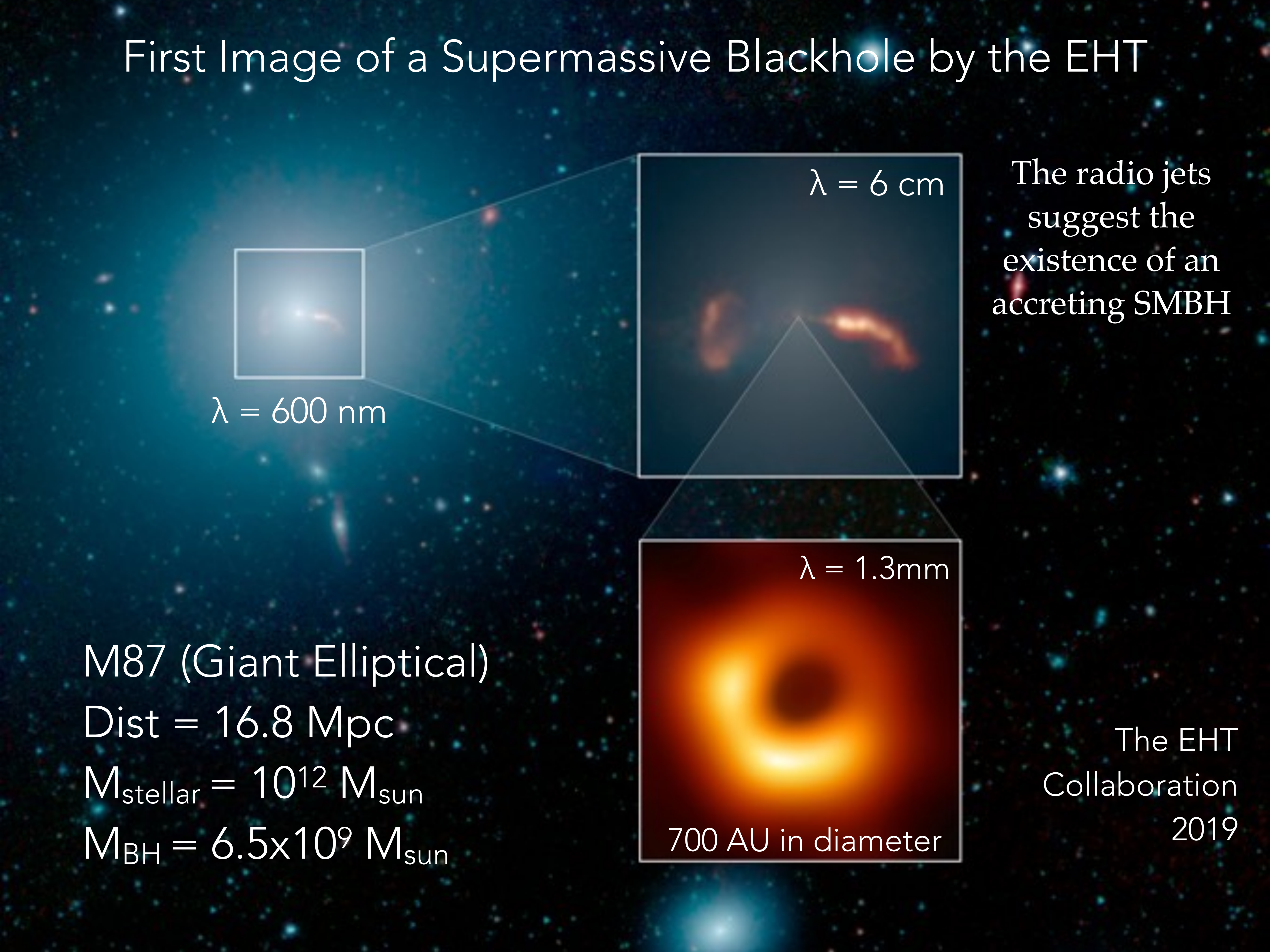
The Event Horizon Telescope



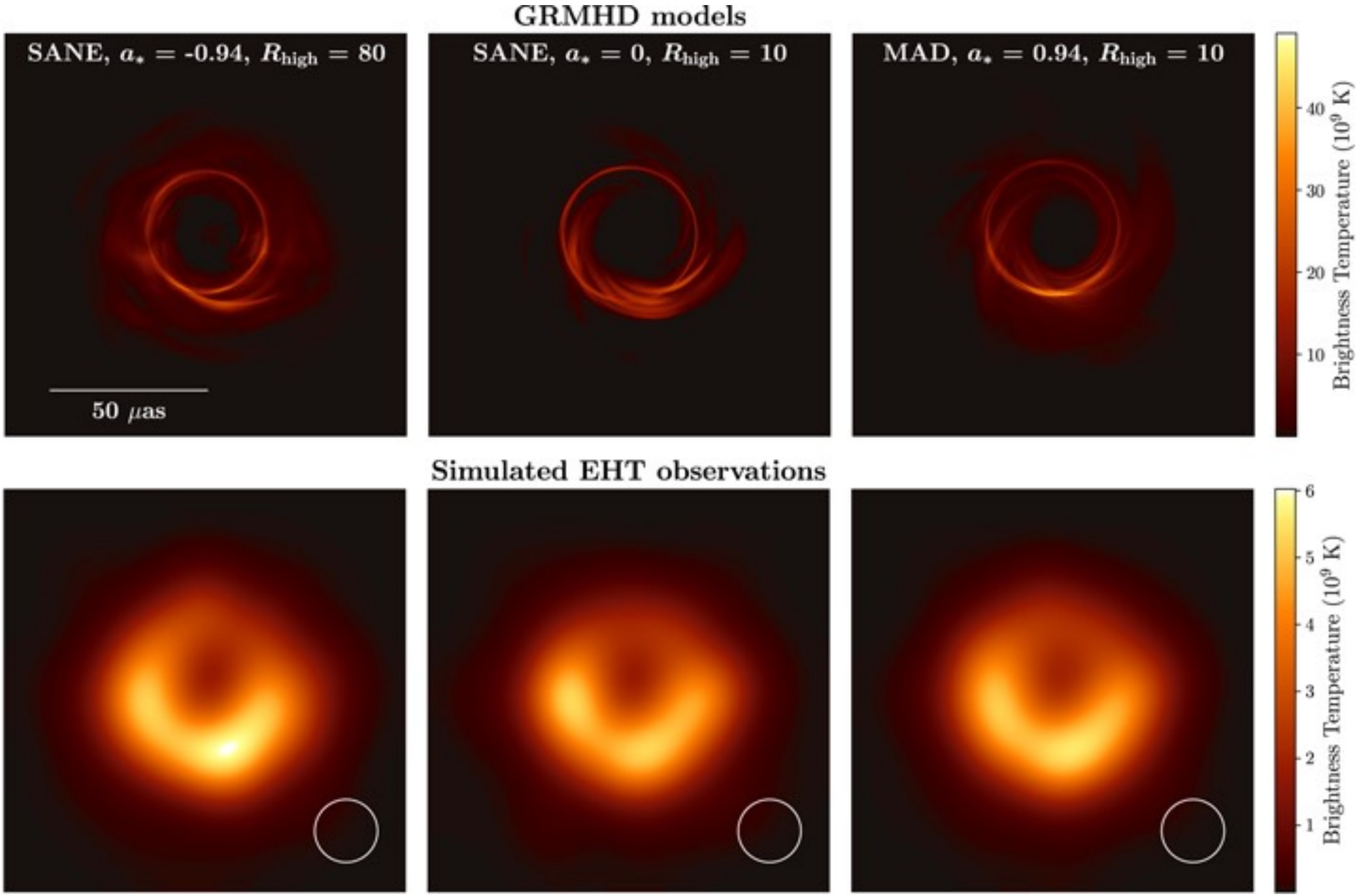


Wavelength: 1.3 mm
Frequency: 231 GHz
Theoretical diffraction limit: 25 microarcsec

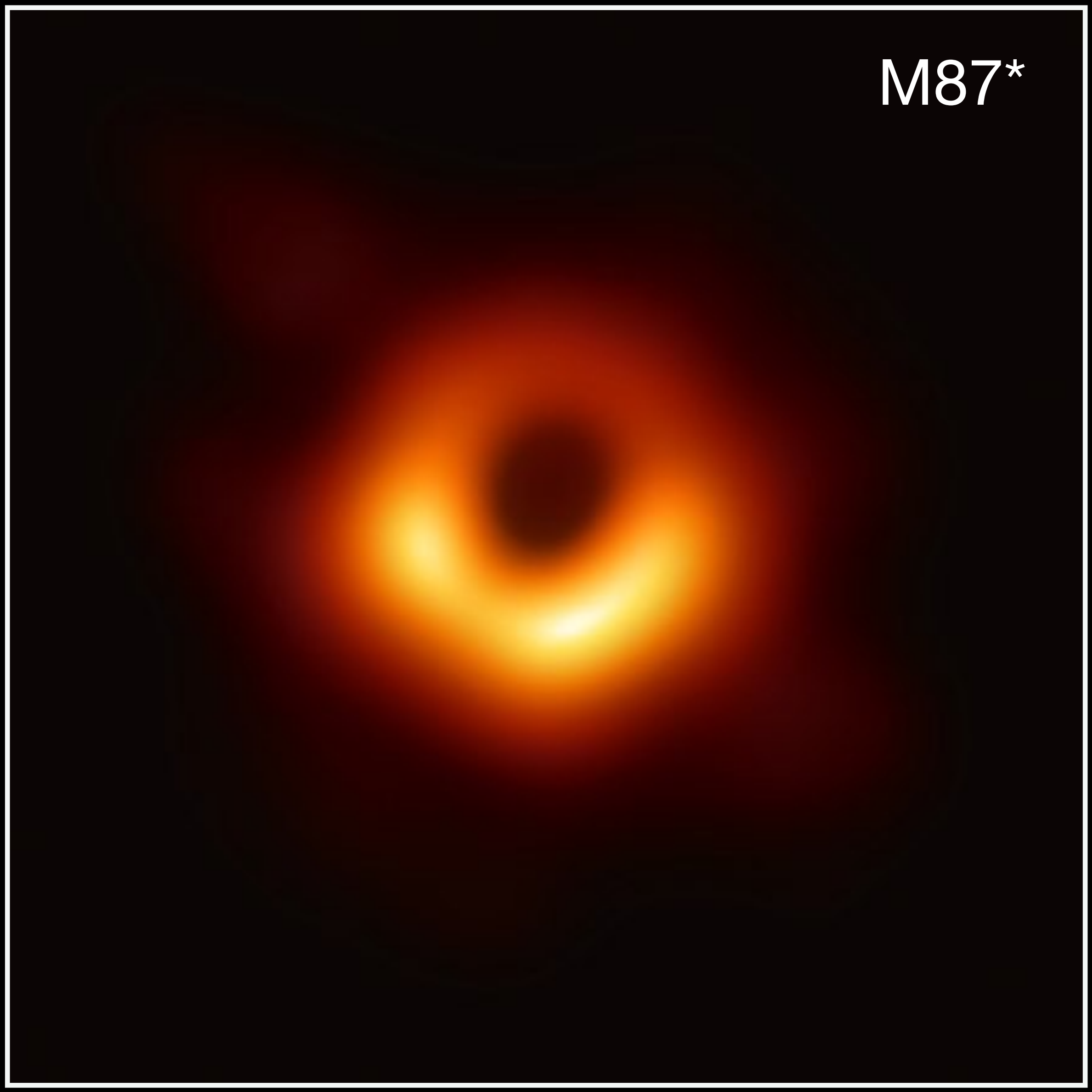
https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT

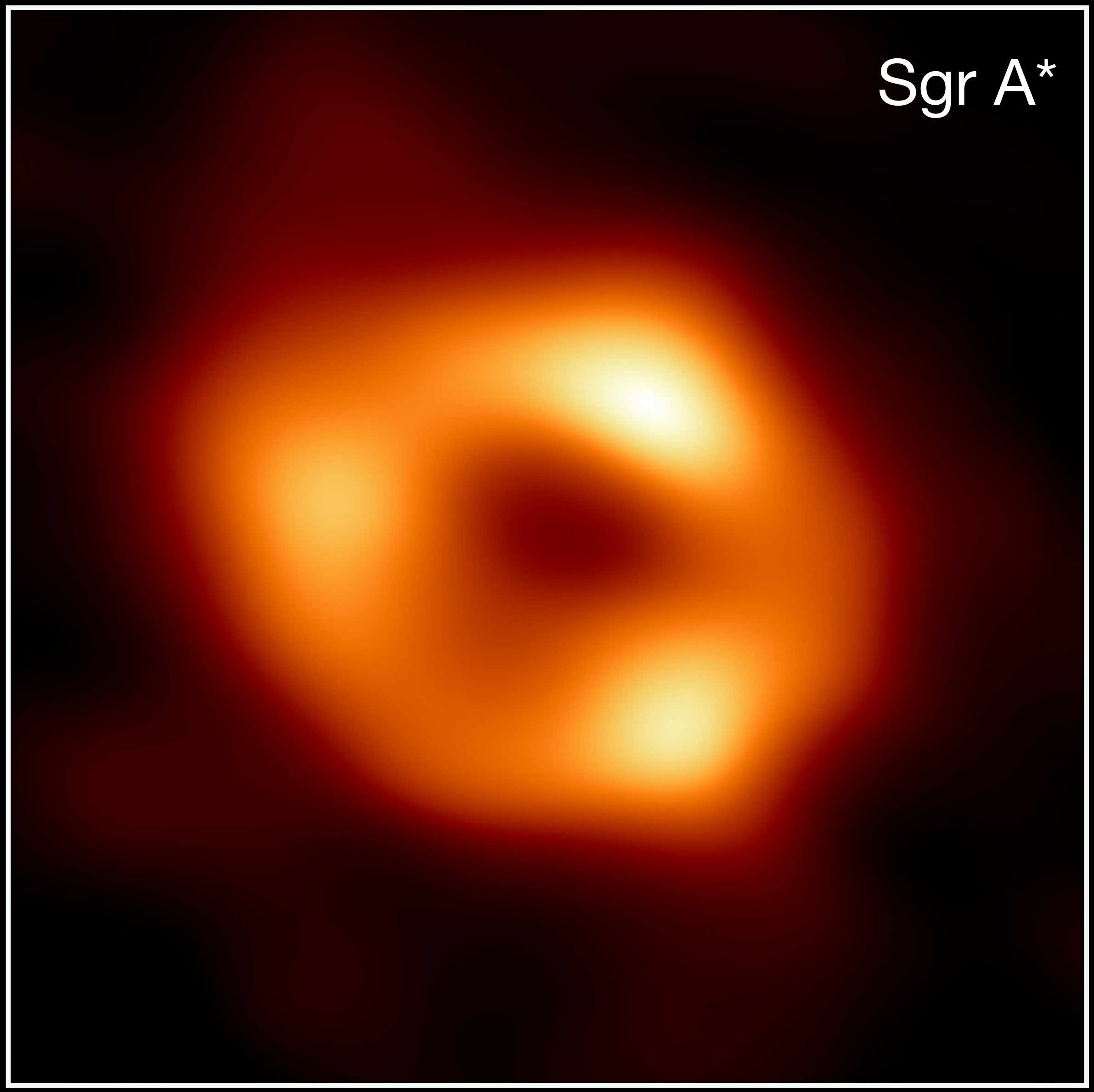

First Image of a Supermassive Blackhole by the EHT
λ = 600 nm
λ = 6 cm
The radio jets suggest the existence of an accreting SMBH
λ = 1.3mm
700 AU in diameter
M87 (Giant Elliptical)
Dist = 16.8 Mpc
$M_{stellar} = 10^{12}\ M_{sun}$
$M_{BH} = 6.5 \times 10^{9}\ M_{sun}$
The EHT Collaboration 2019

GRMHD simulations of different spin parameters and accretion flows



Directly Imaging the Event Horizon of SMBHs

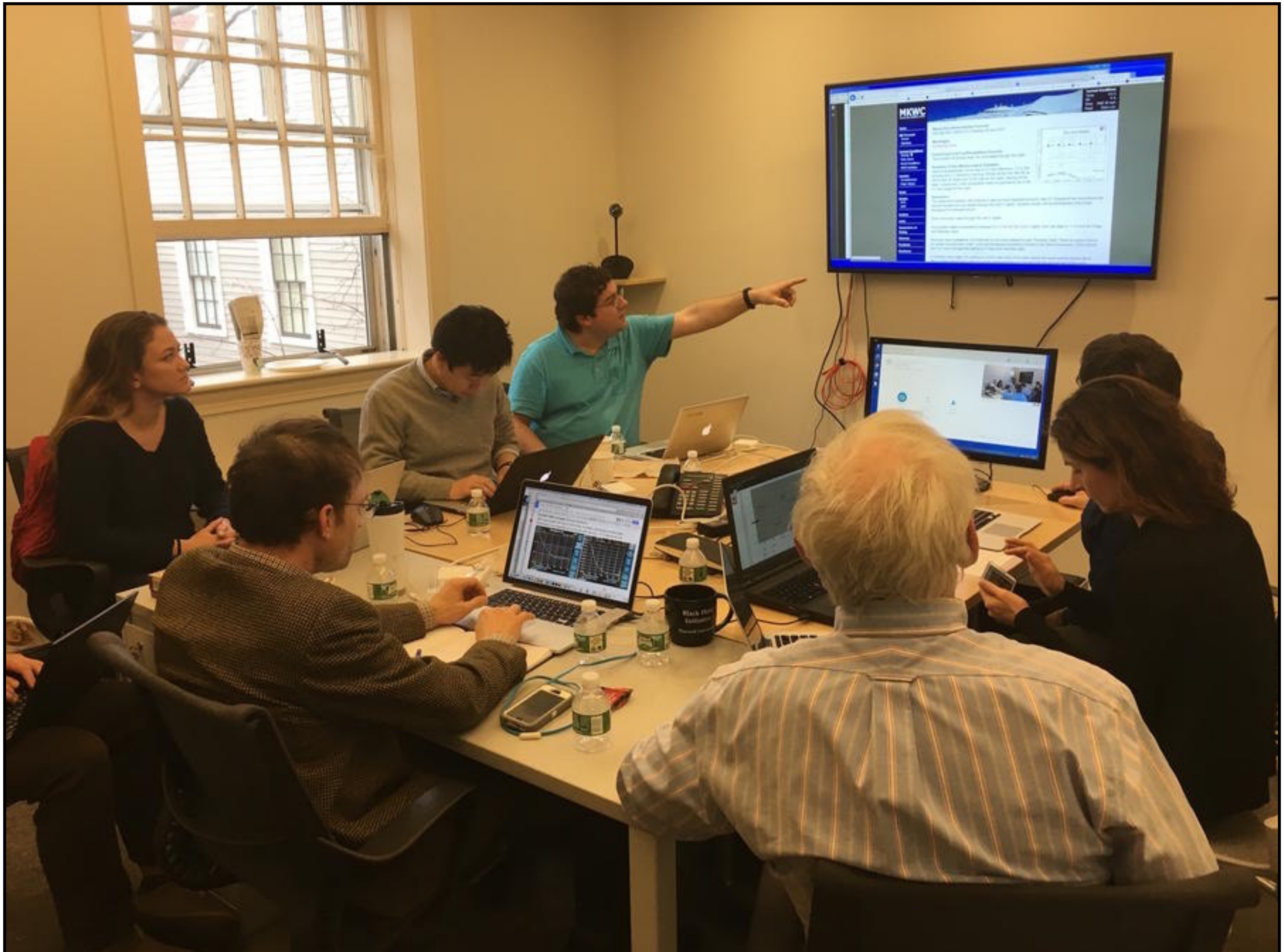




Event Horizon Telescope


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.

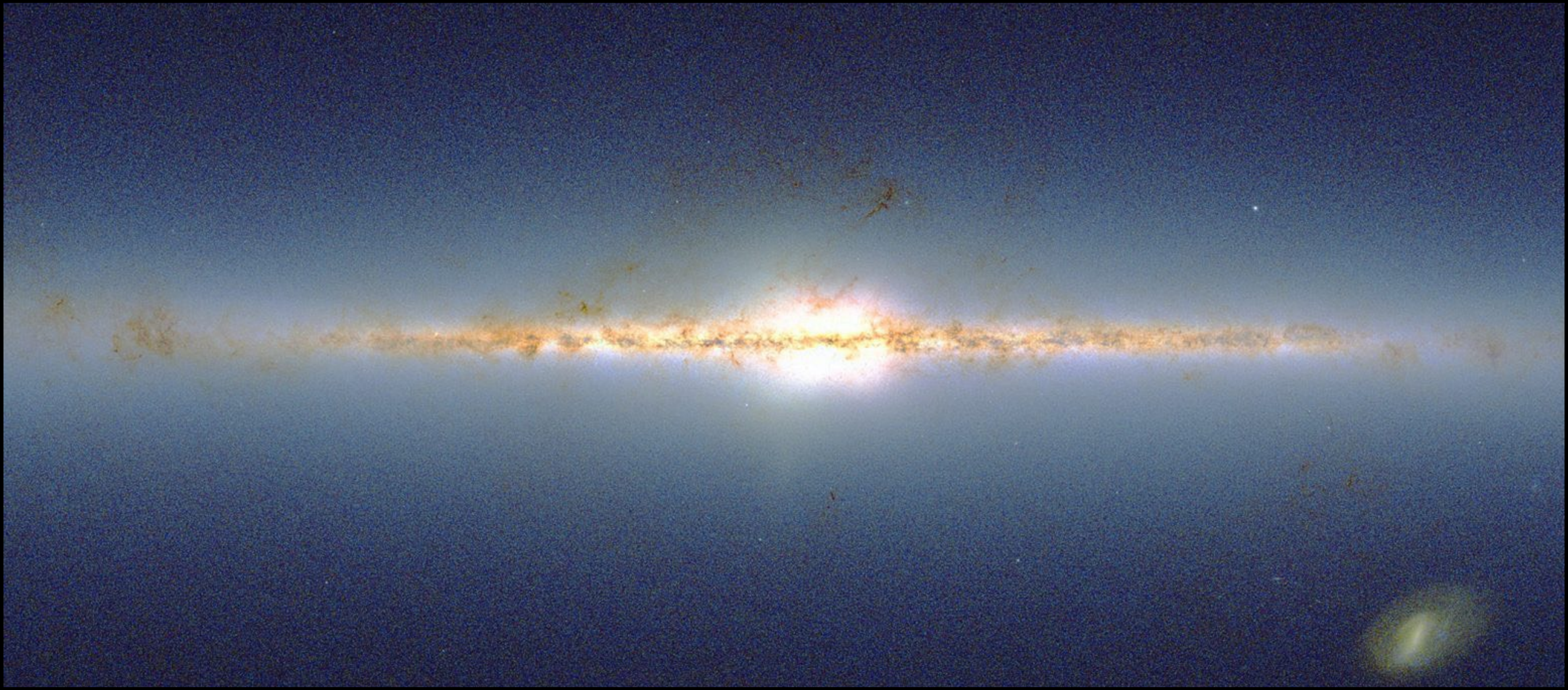
Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: individual (M87) – galaxies: jets – gravitation

Weighing the SMBH in the Milky Way

individual star's kinematics in the sphere of influence

Near Infrared Map of the Milky Way Galaxy

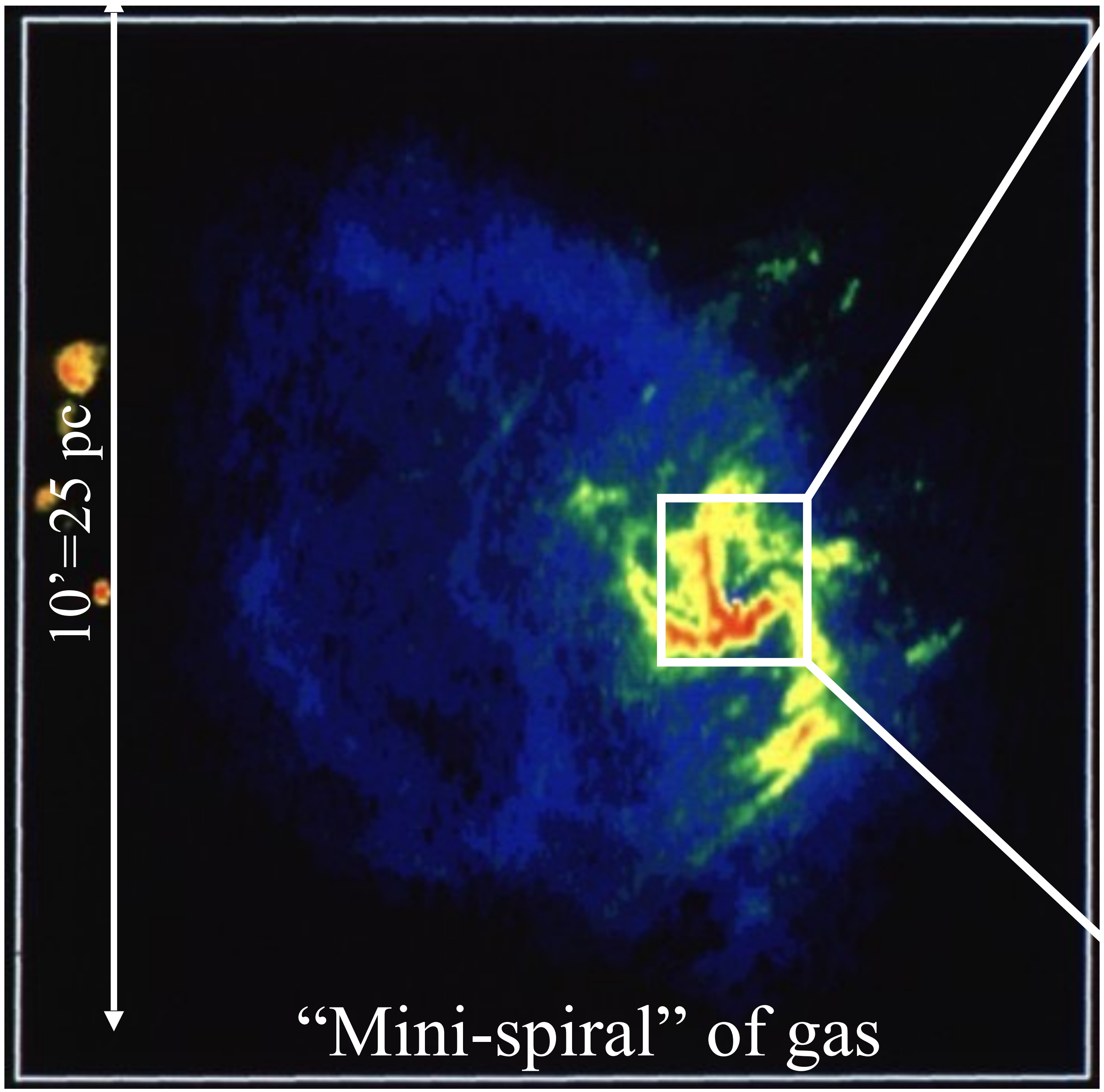
- The IR light is less attenuated by dust, revealing the central stellar bulge that is barely visible in optical.
- The map gives us a rough direction to the Galactic center

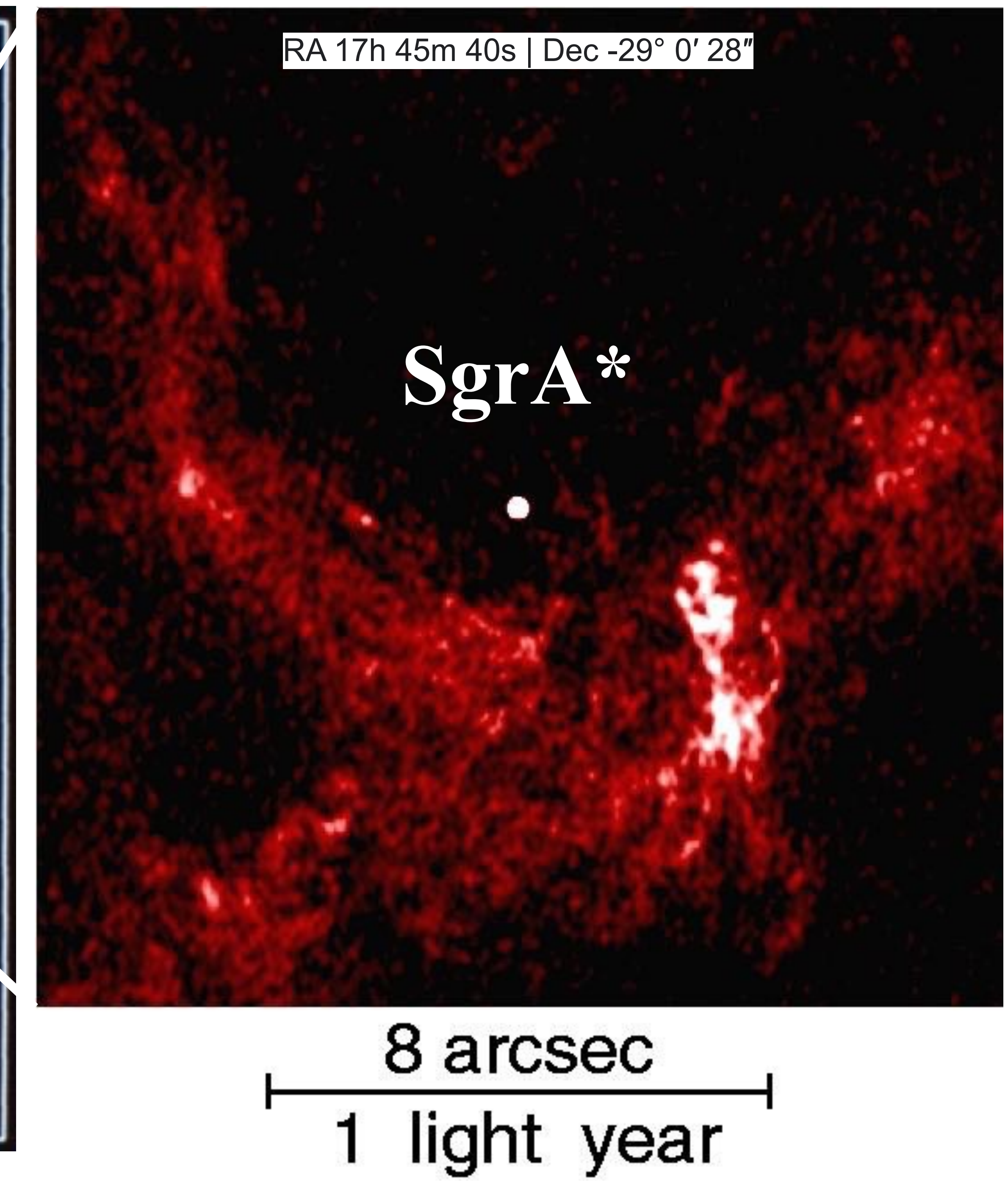


Pinpoint the Galactic Center:

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

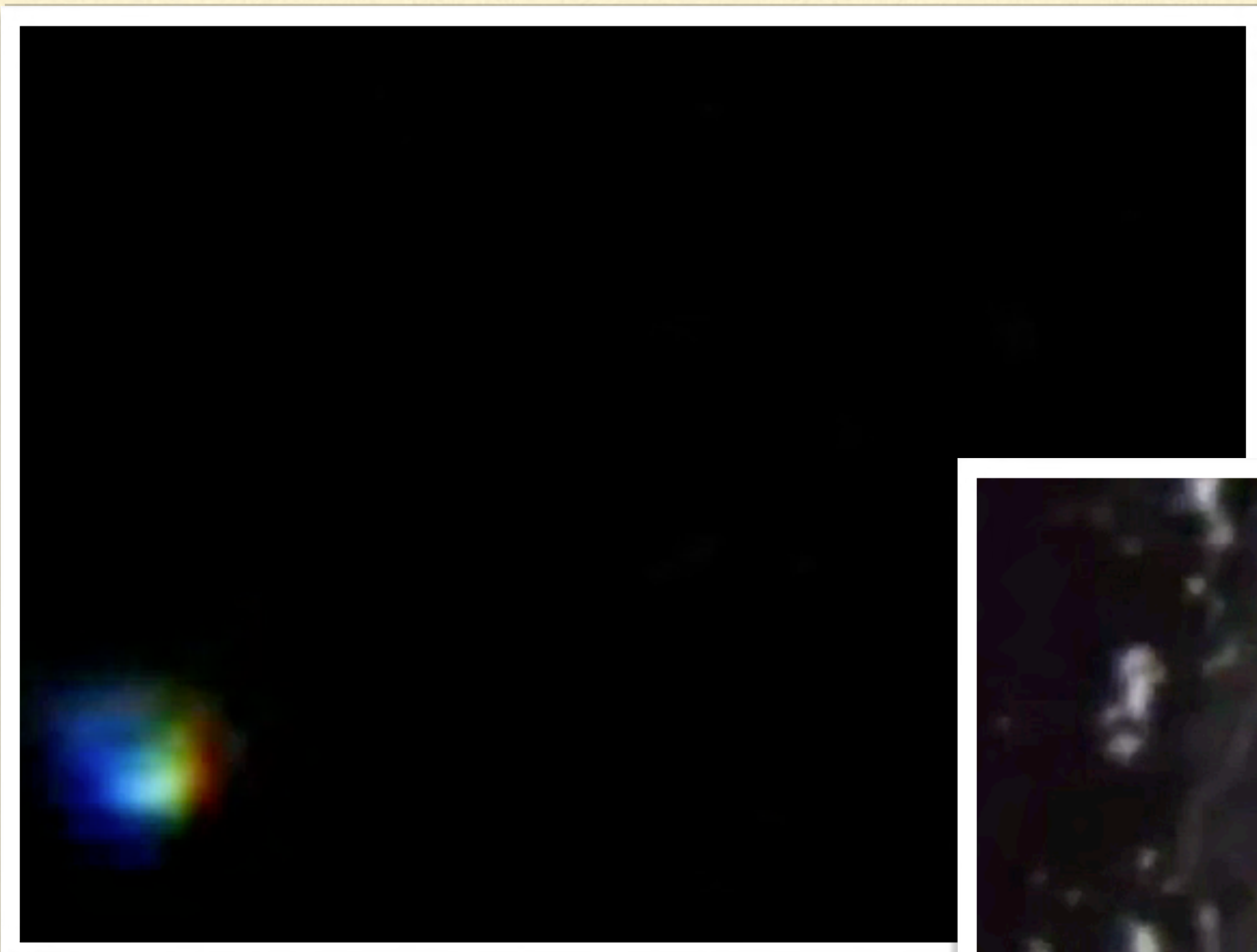
But stars are invisible in the radio, whose kinematics trace r_*



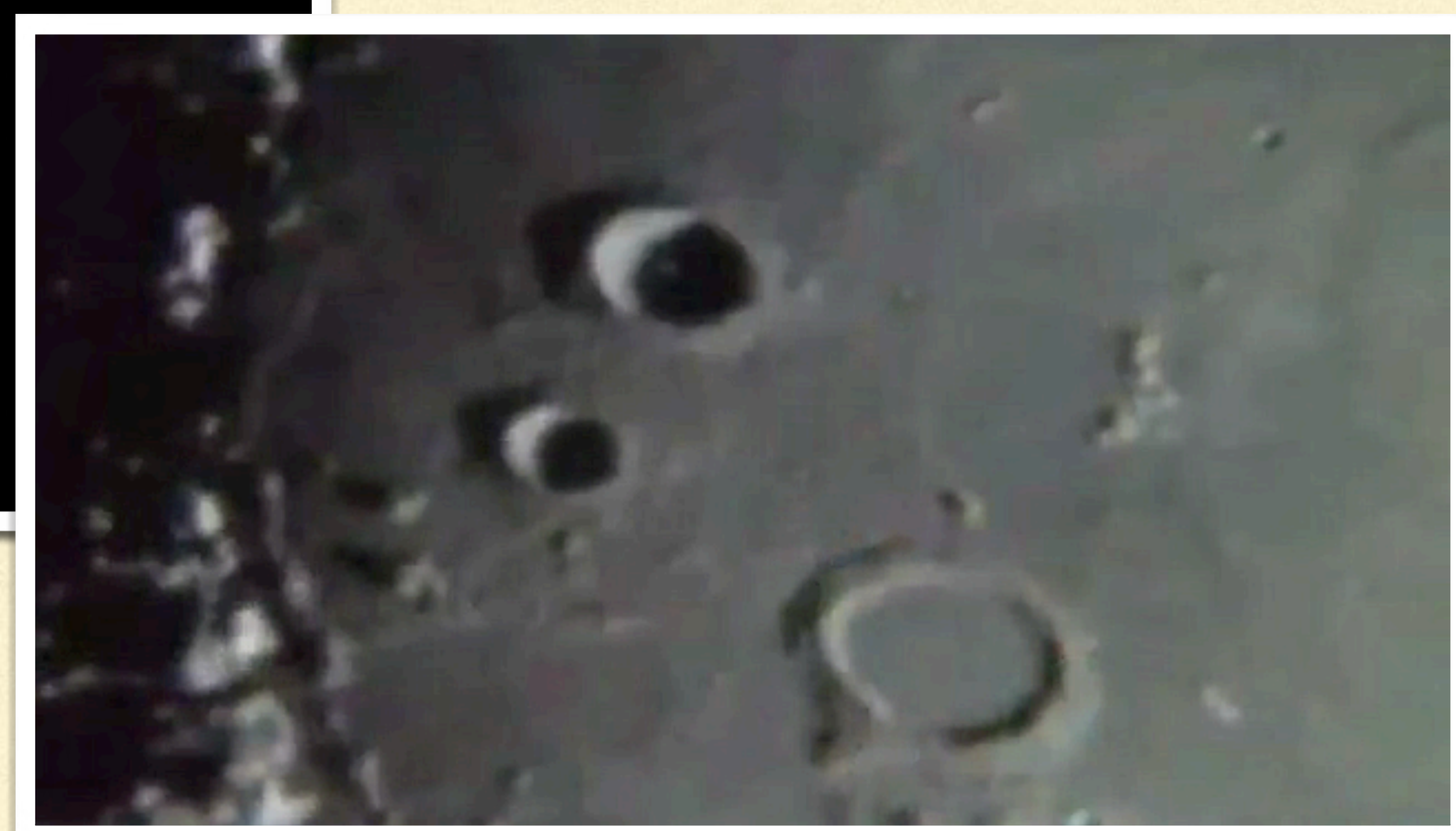


6 cm VLA image (Ekers et al. 1983)

GROUND-BASED OPTICAL AND INFRARED OBSERVATIONS ARE LIMITED BY **ATMOSPHERIC TURBULENCE (SEEING)**



Twinkling of stars and the moon caused by pockets of air at different densities



Seeing quantifies the amount of aberrations from atmosphere turbulence

- Large-scale T gradients trigger subsonic turbulences. The T differences between **turbulent eddies** then cause variations of density and refractive index
- Most of the turbulence that blurs your image originate from the lowest and most massive atmosphere layer: the **troposphere** at altitudes < 15 km
- Typical seeing blurs the **Airy** pattern to a **Gaussian** with a FWHM of ~**1 arcsec**

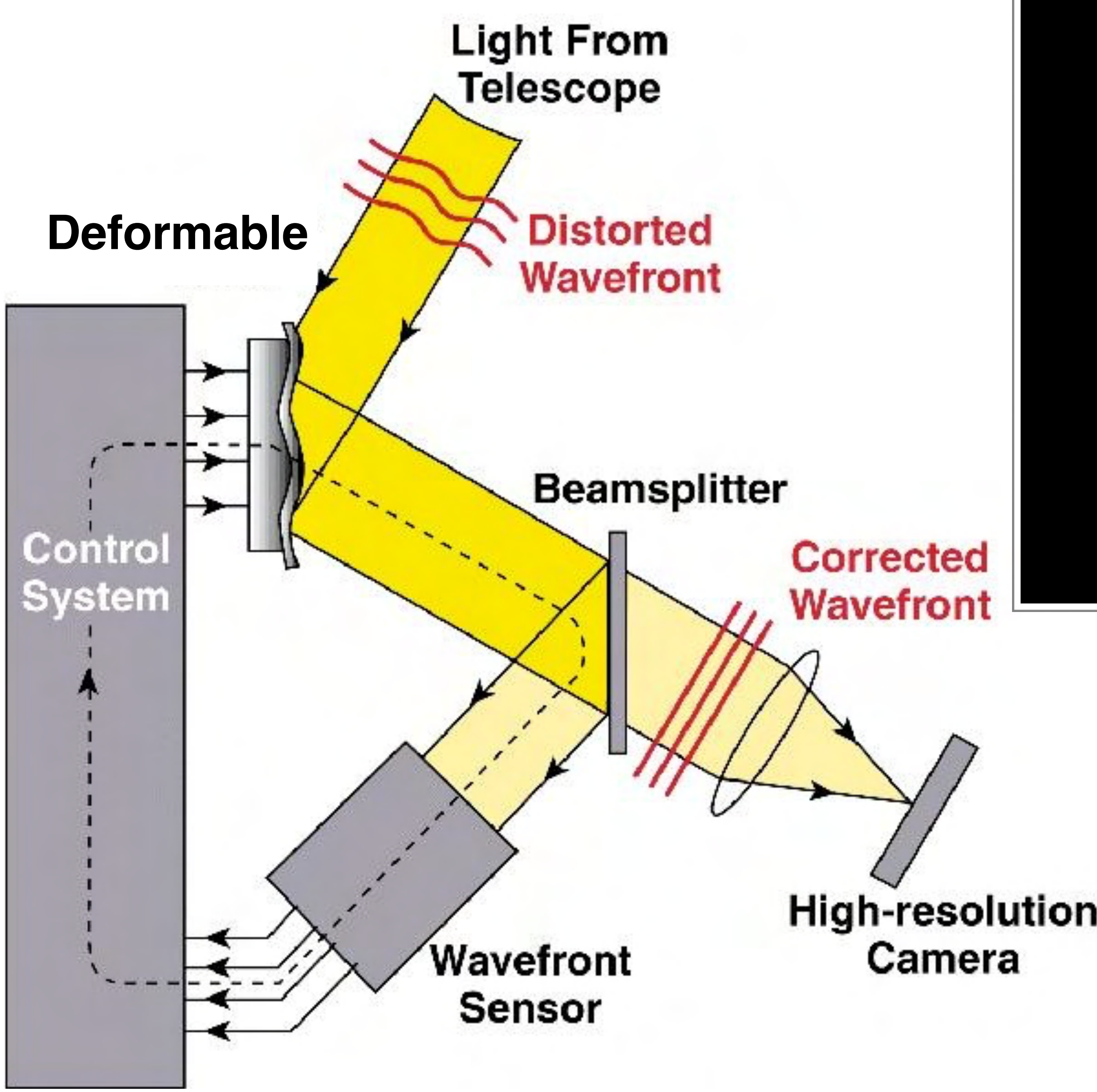
THE GOAL OF OPTICAL ASTRONOMERS: **REACHING DIFFRACTION LIMIT ON THE GROUND**

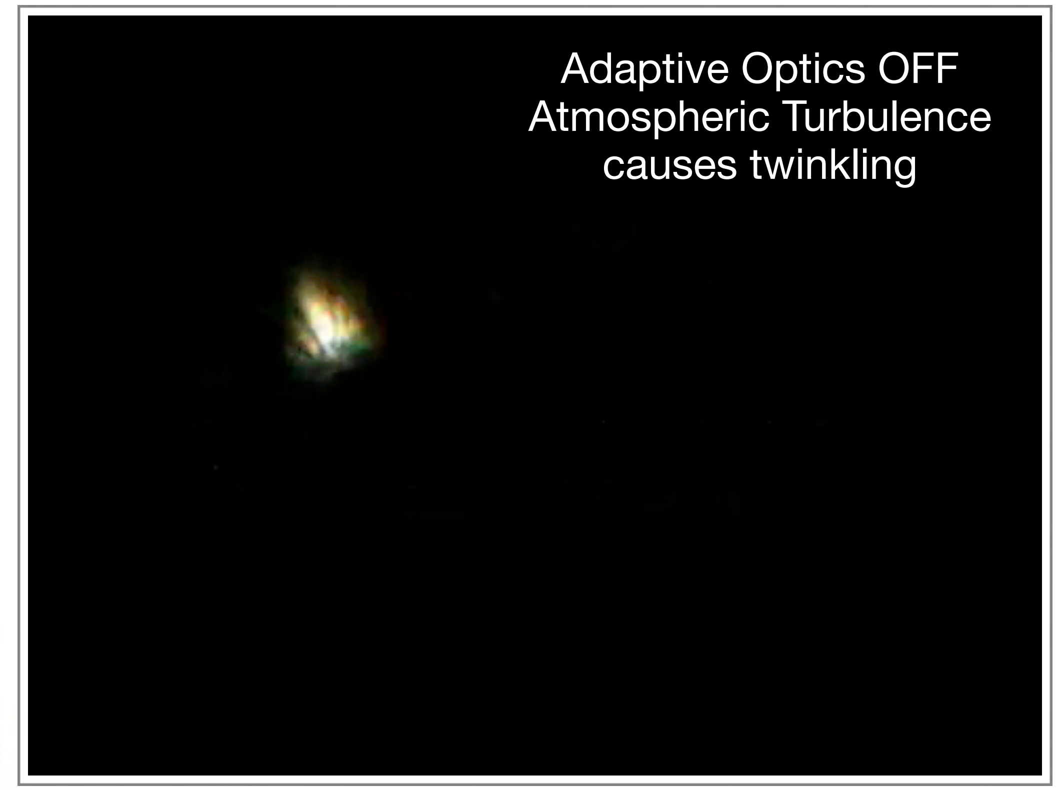
THE VISION: 1953

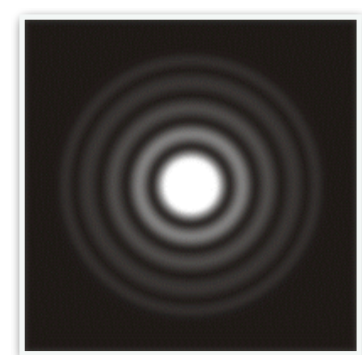
- "If we had the means of continually **measuring** the deviation of rays from all parts of the mirror, and of amplifying and **feeding back** this information so as to correct locally the figure of the mirror in response to the schlieren pattern, we could expect to **compensate both for the seeing and for any inherent imperfection of the optical figure**"

  (**Horace Babcock 1953 PASP**)

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

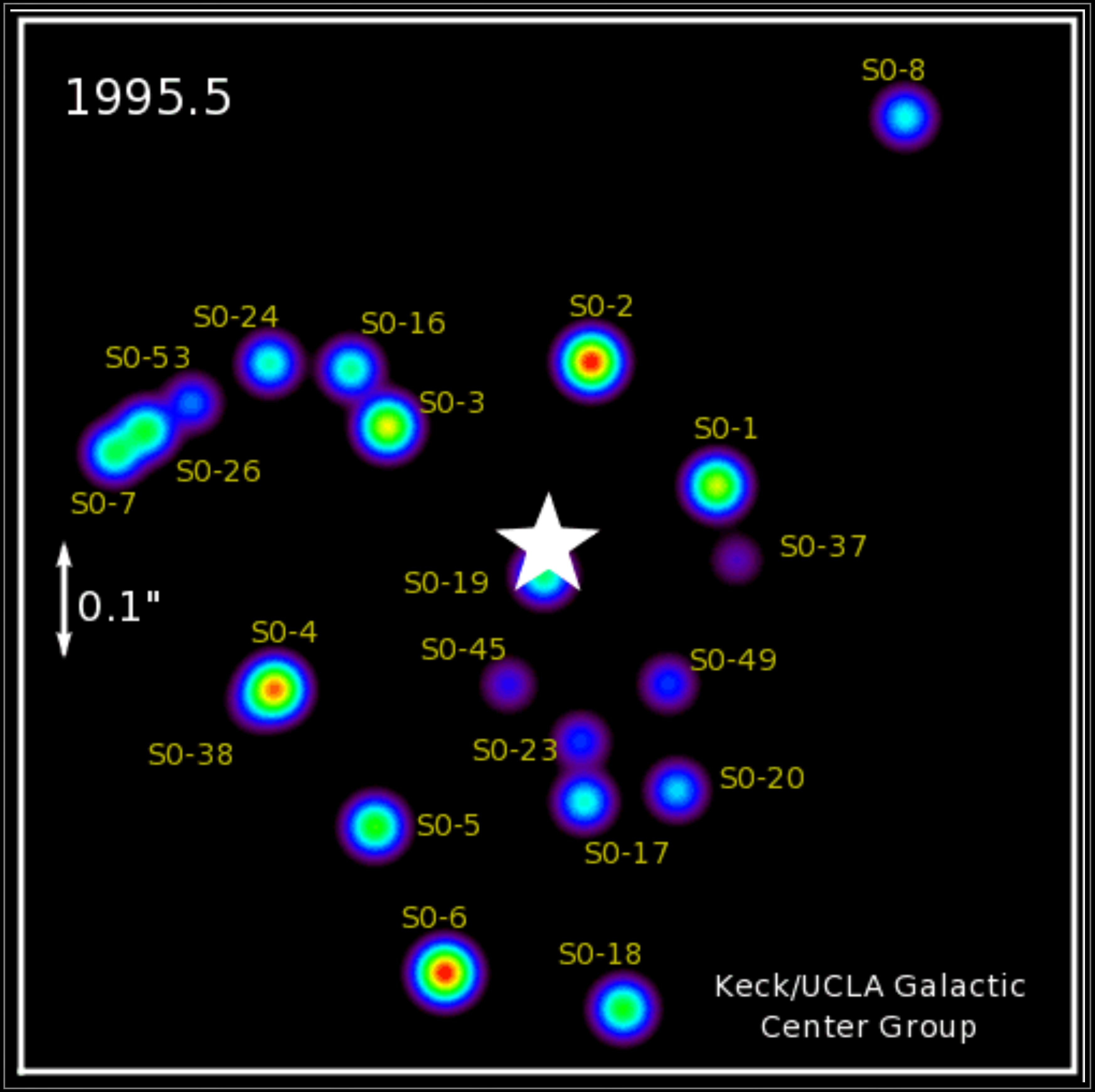




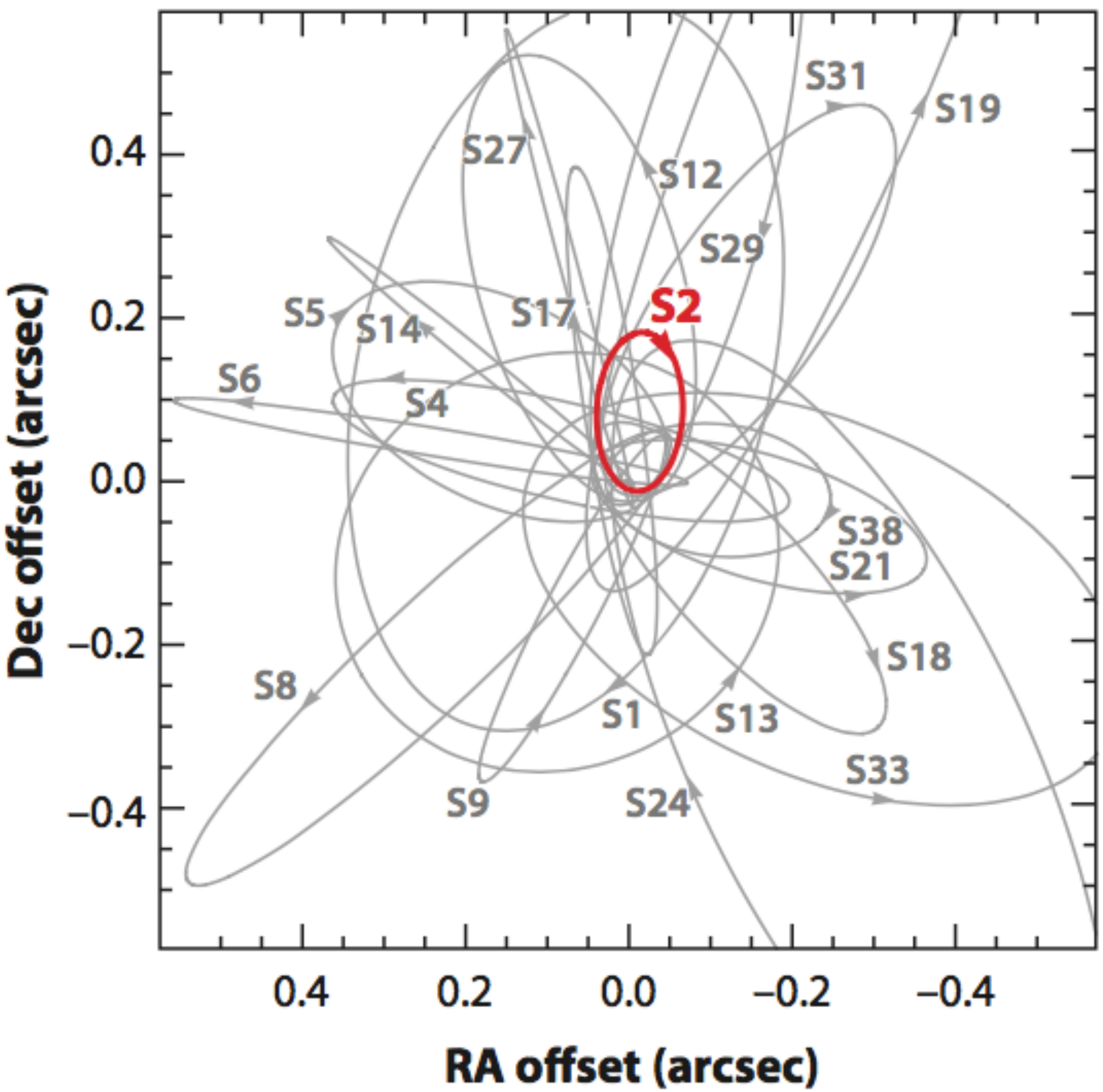


Adaptive Optics ON reaching diffraction limit

Resolving individual stars near Sgr A* with IR Adaptive Optics



Mass and distance of the SMBH in the Milky Way Galaxy

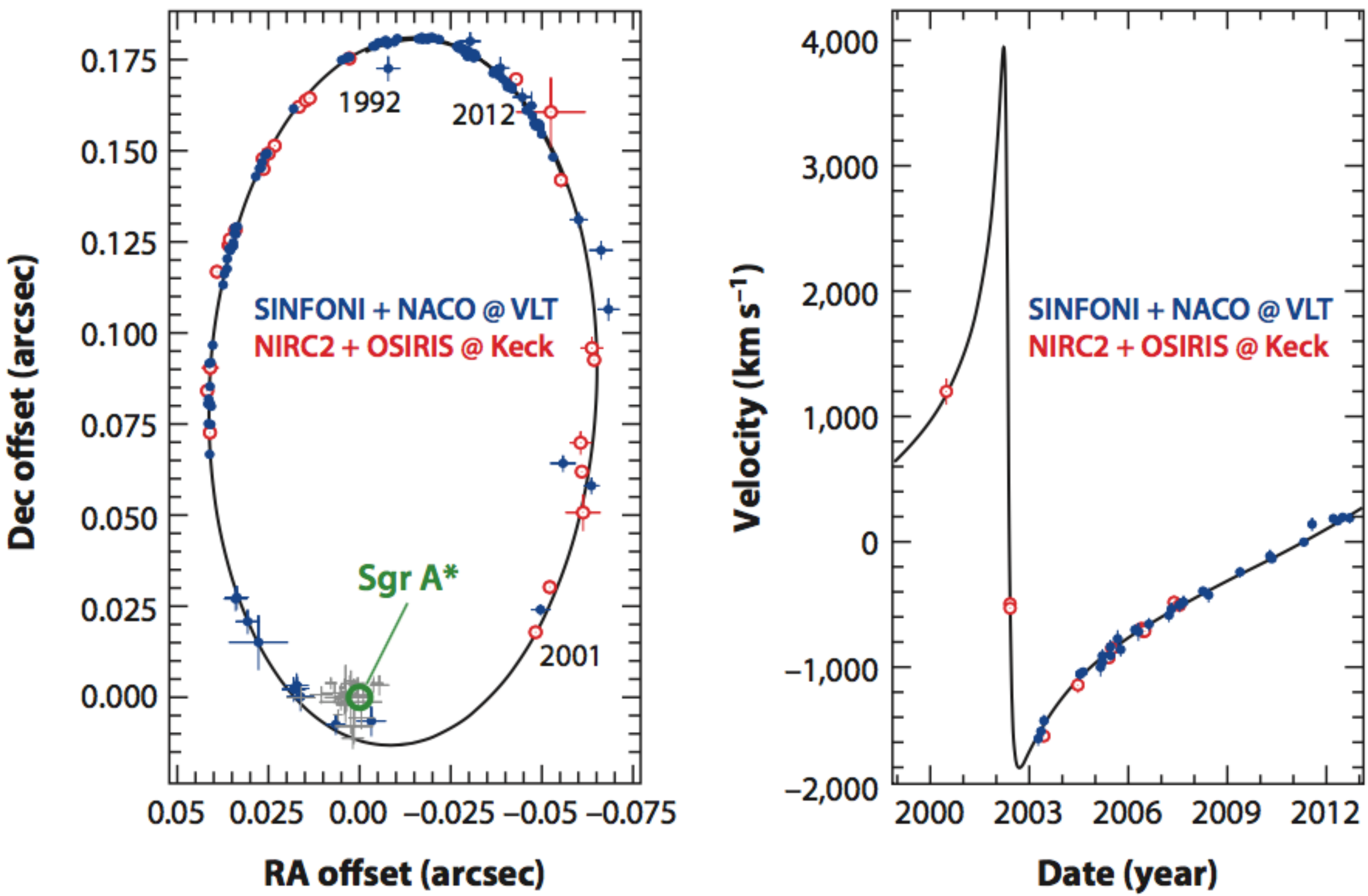


By **monitoring individual star's positions over 20 years and their velocities,** we can measure both the mass and the distance of the SMBH:

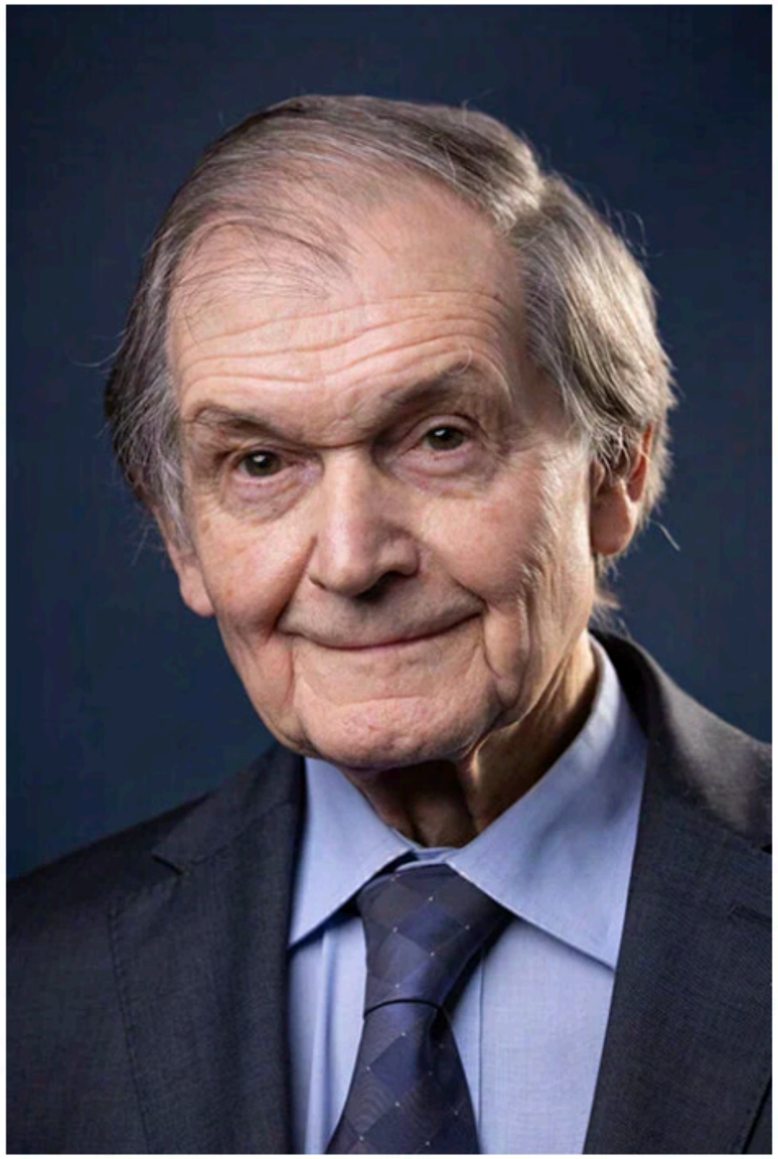
Mass: 4 million M_{sun}
Distance: 8.3 kpc

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

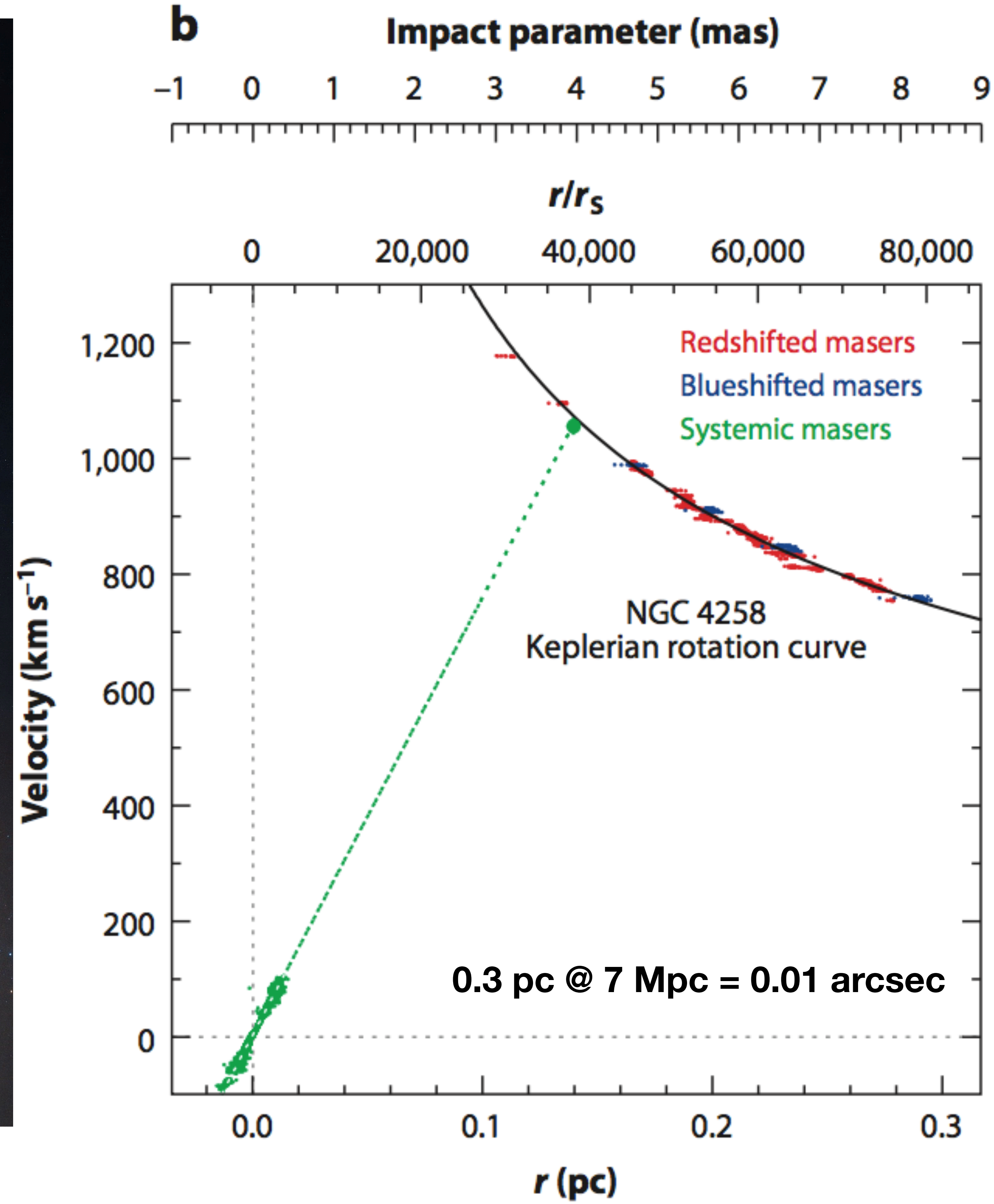
Prize share: 1/4

Weighing SMBHs in Other Galaxies

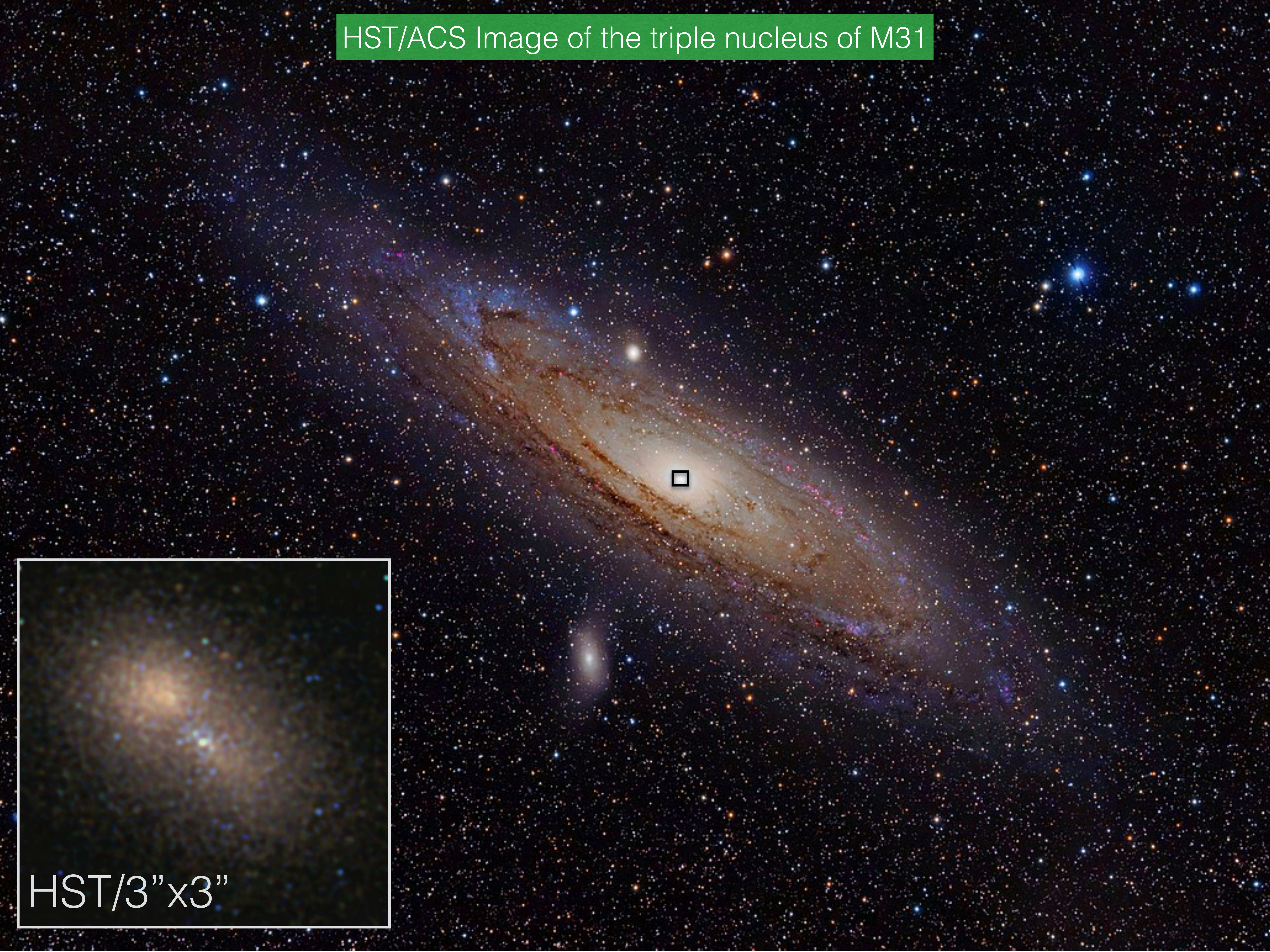
Collective stellar or gaseous kinematics in sphere of influence


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

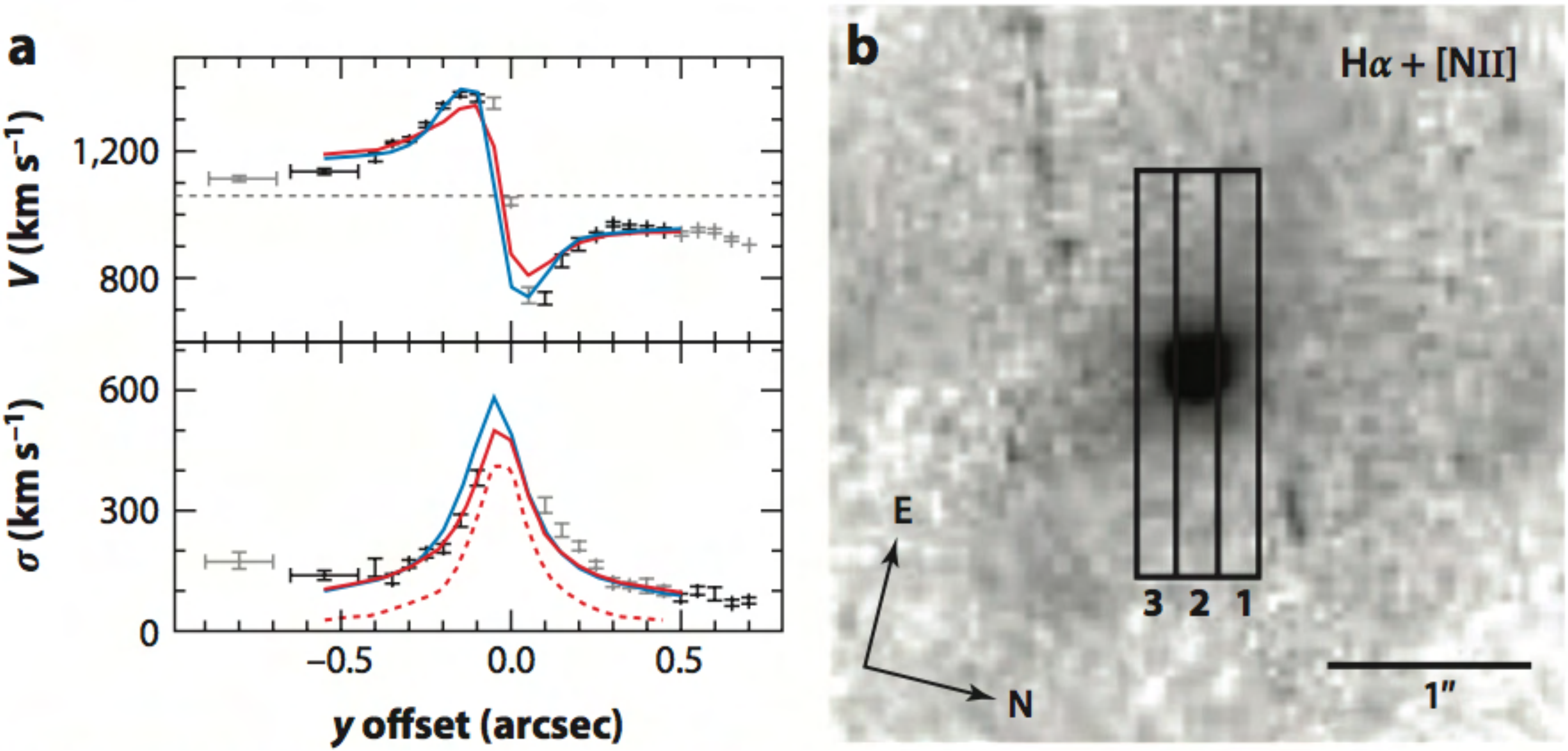
NGC 4258: Keplerian Disk of H_2O Masers w/i the central pc



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

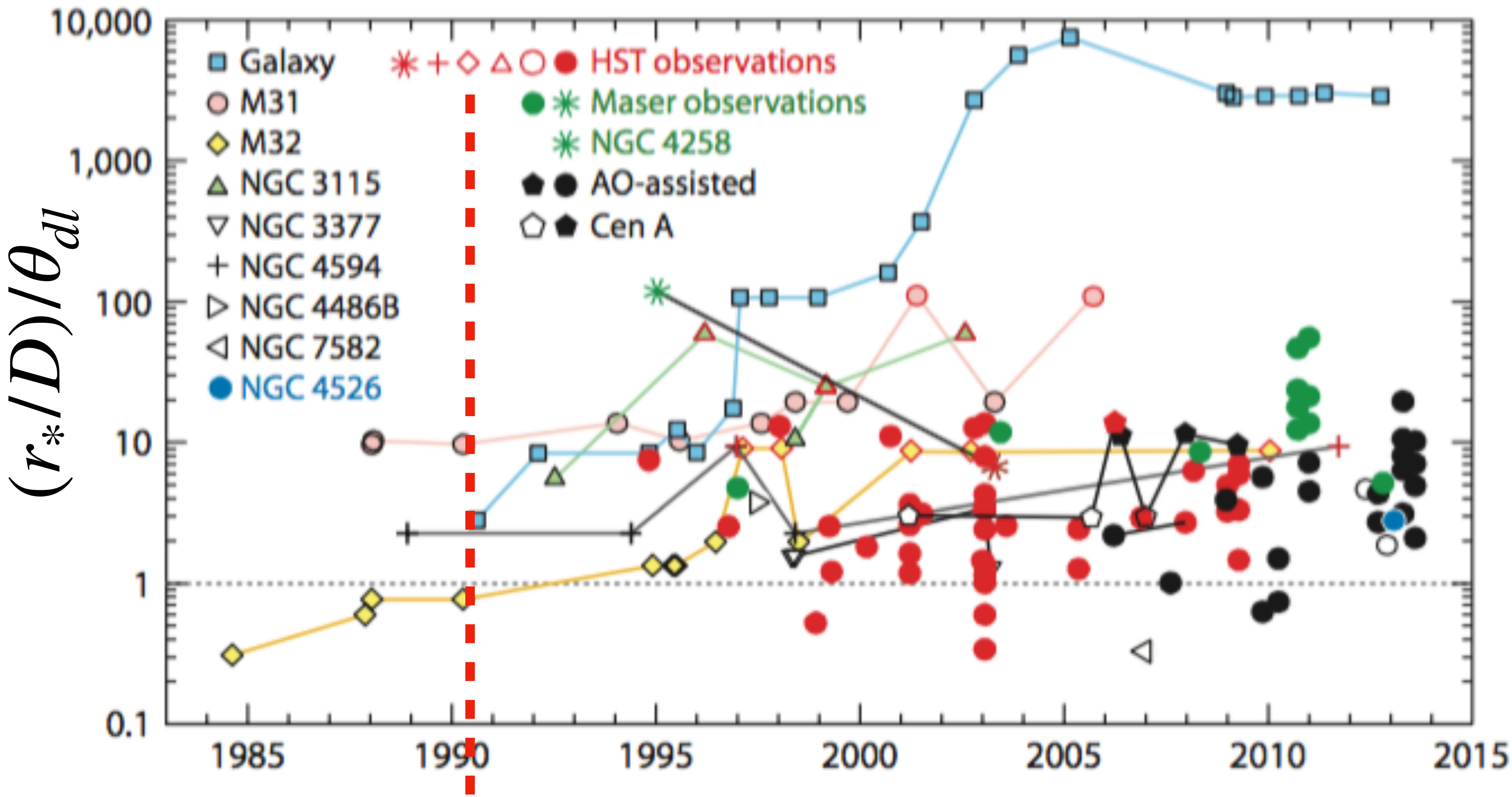

HST/ACS Image of the triple nucleus of M31
HST/3”x3”

Elevated Gas Velocity Dispersion in the Sphere of Influence



NGC 4374, HST/STIS, Walsh+2010

Making Progress in Resolving the Sphere of Influence



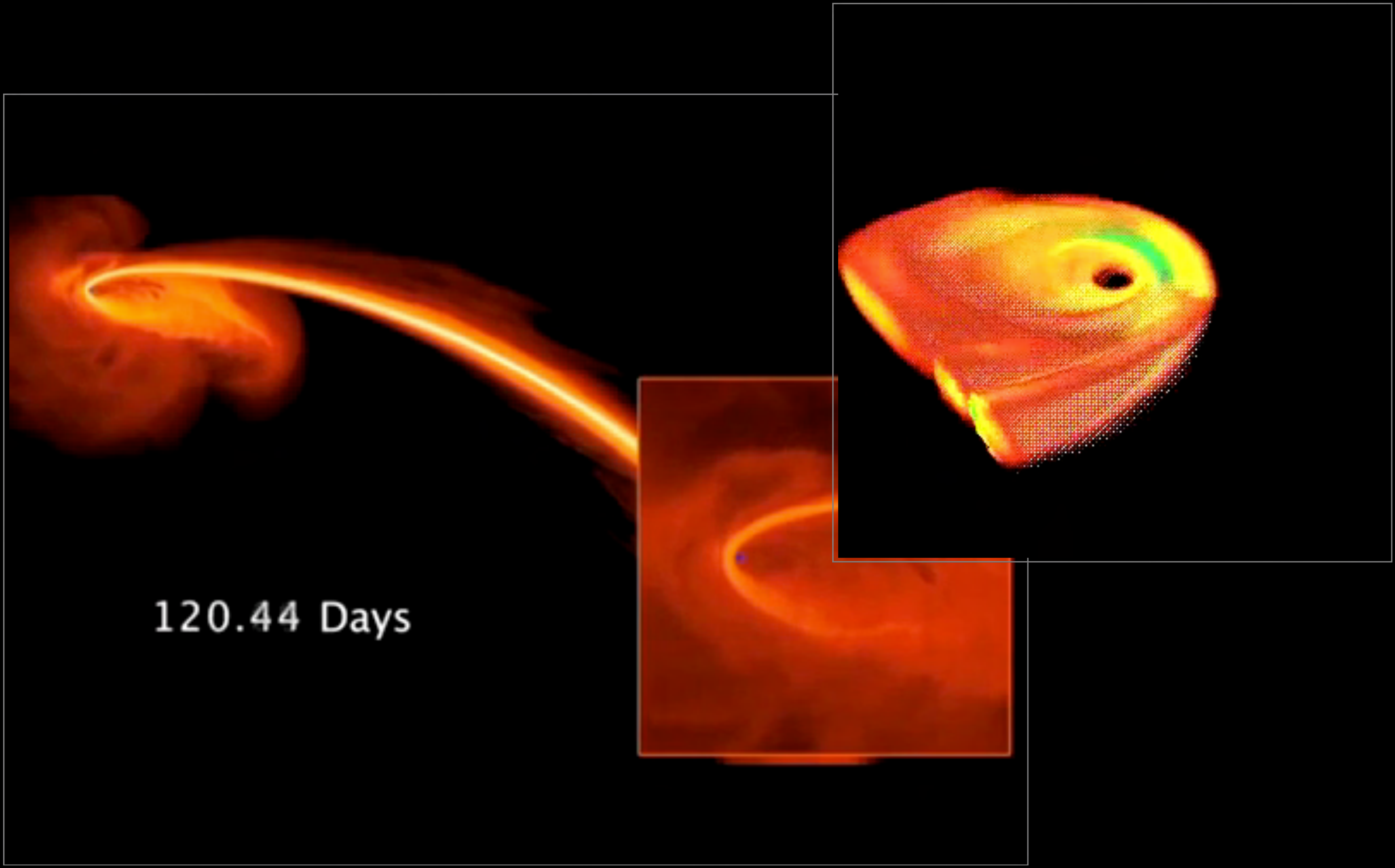
Thanks to Hubble & Adaptive Optics

Kormendy & Ho 2013

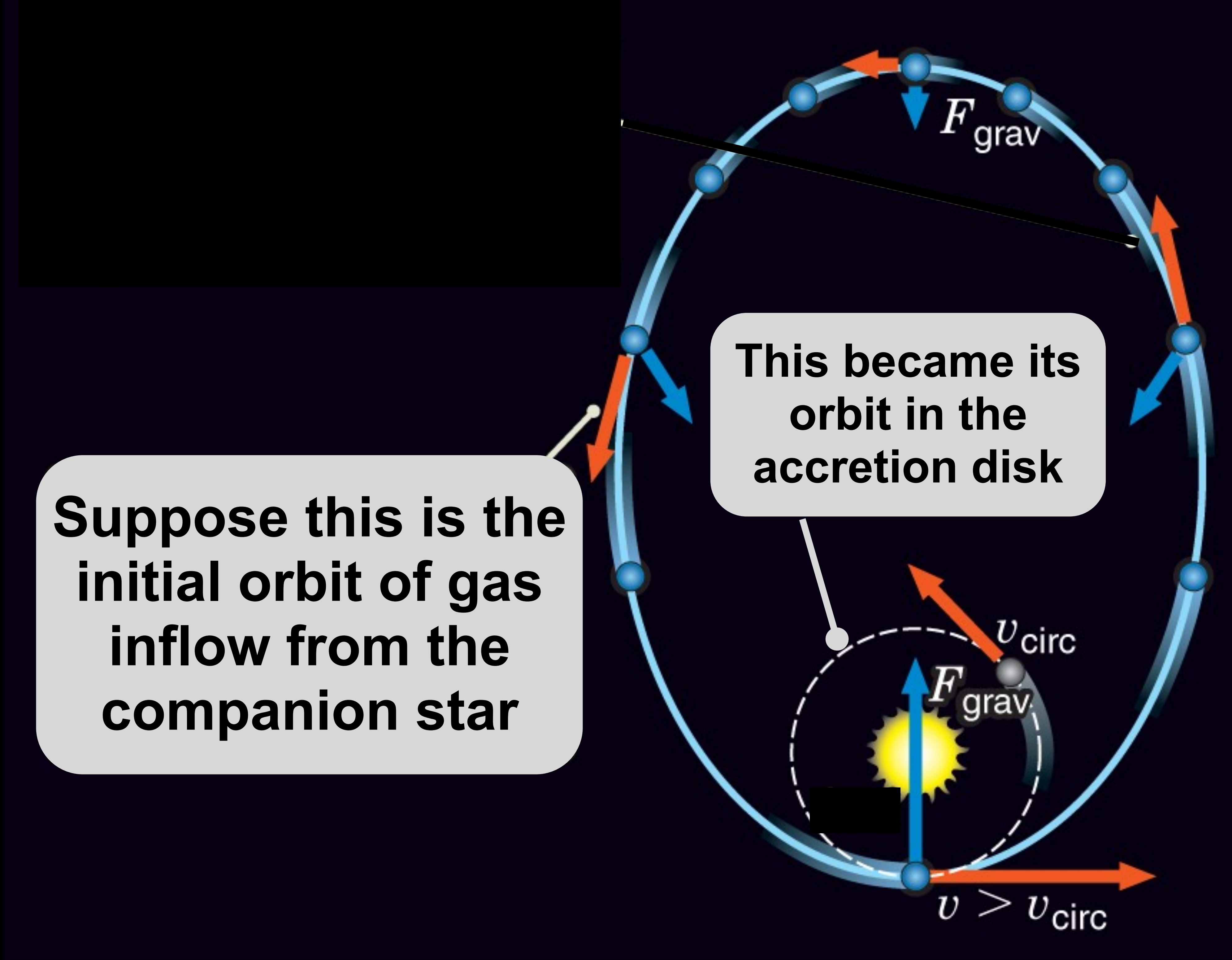
Hunting for SMBHs in Galaxies

Method III:
Detecting gravitational accretion power

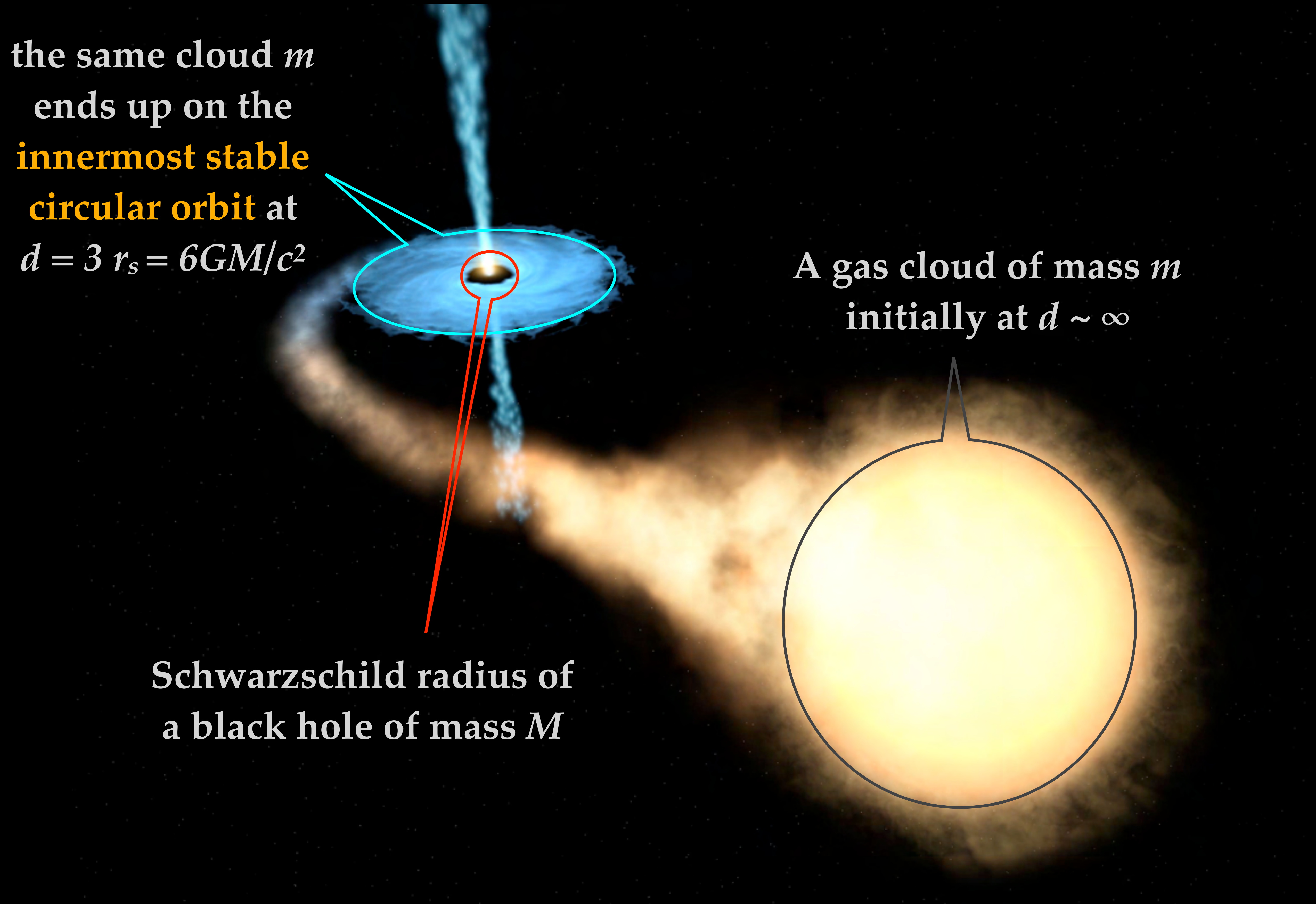
Simulation of the formation of an accretion disk



How gravitational accretion produces energy?



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

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

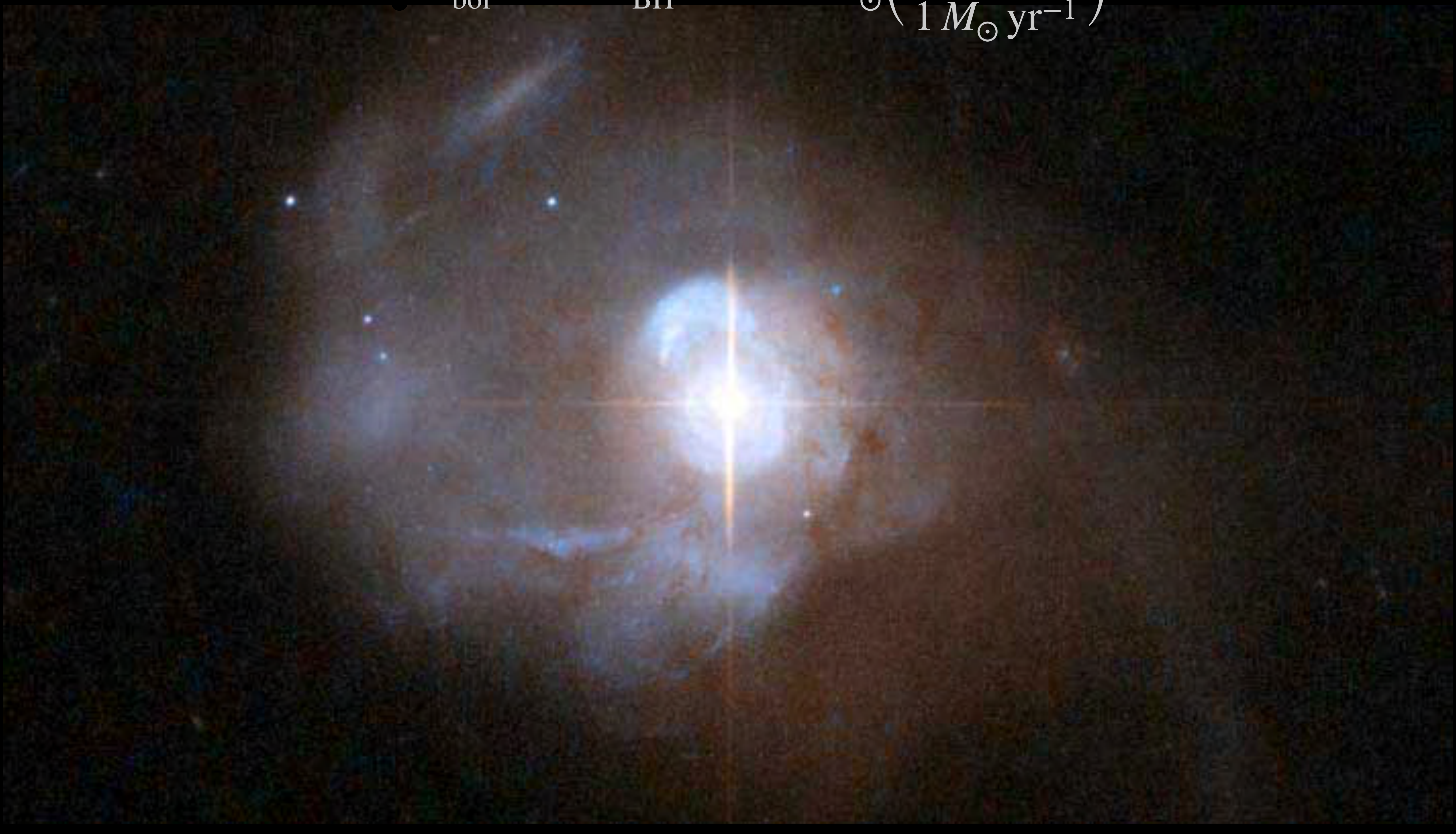
- The difference between the initial energy and the final energy must be released to allow accretion to occur. So the amount of energy released is $mc^2/12$ during the accretion of mass m.

- This shows that roughly **10%** (~1/12) of the **rest mass energy (mc^2)** of the accreted material 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!

Active Galactic Nuclei (AGN), which include Quasars

Powered by accreting supermassive black holes

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



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

Würzburg radar

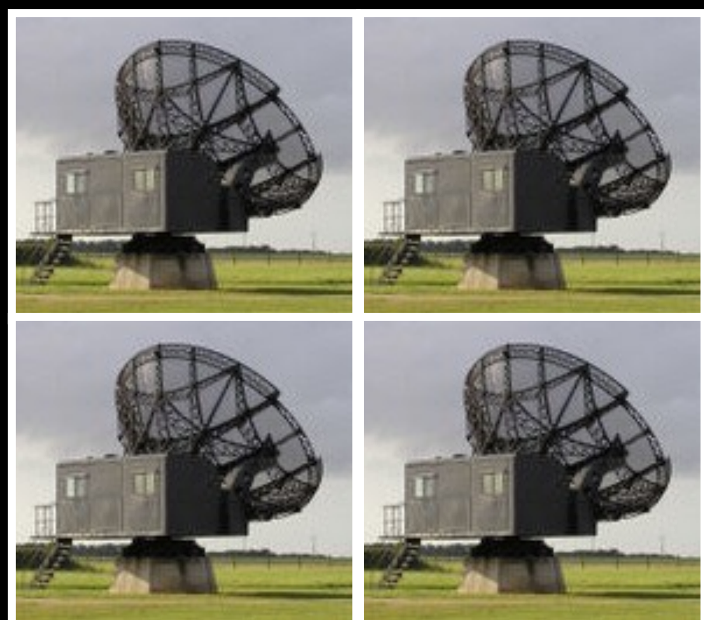
Article Talk

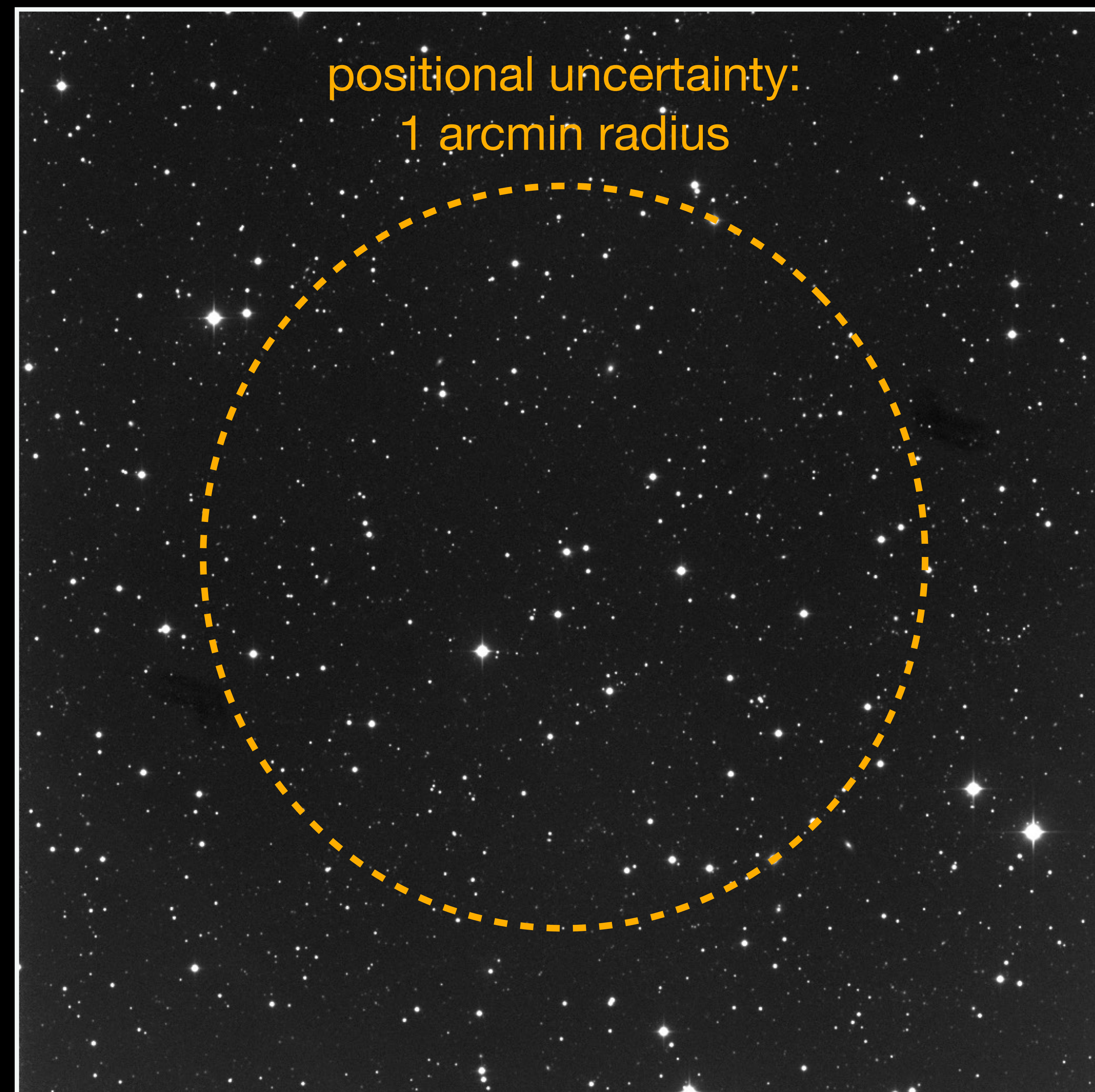
From Wikipedia, the free encyclopedia

The low-UHF band **Würzburg radar** was the primary ground-based tracking radar for the Wehrmacht's Luftwaffe and Kriegsmarine (German Navy) during World War II. Initial development took place before the war and the apparatus entered service in 1940. Eventually, over 4,000 Würzburgs of various models were produced. It took its name from the city of Würzburg in Bavaria.

Discovery of 3C 273: the First Quasar

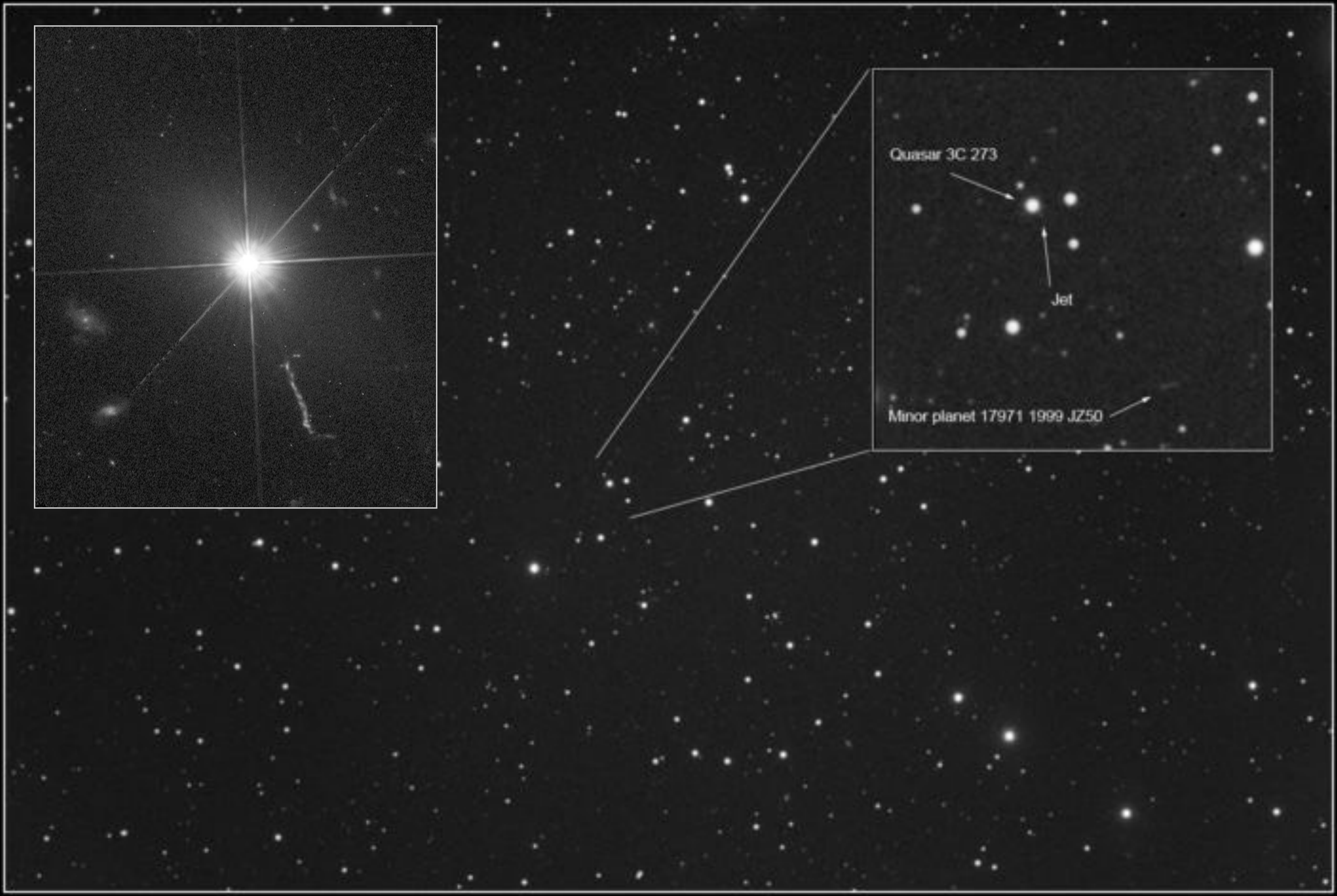
Edge *et al* (1959) - 1′





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

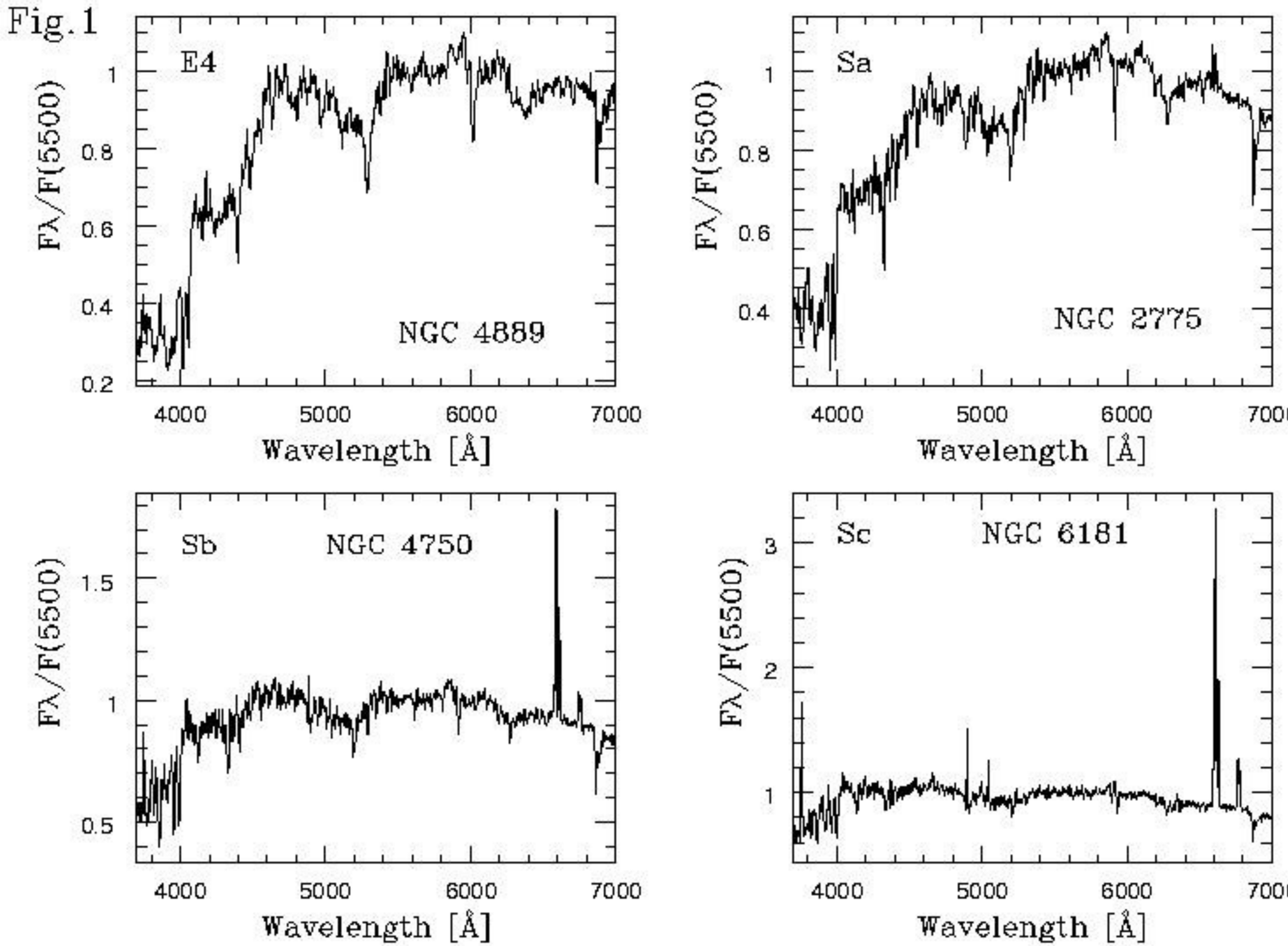
Optical Counterpart of 3C273



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

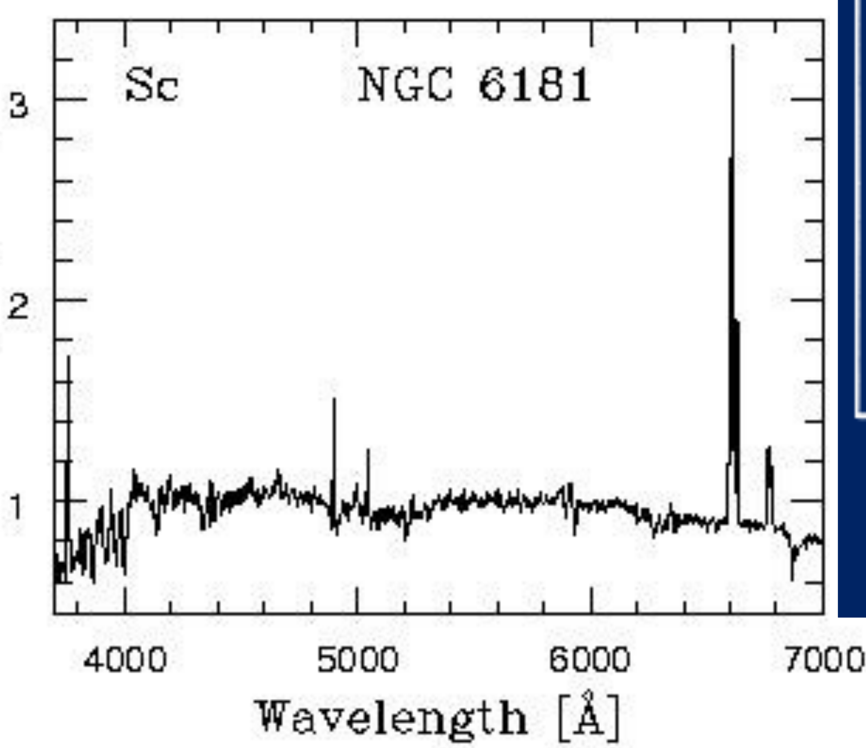
Time for spectroscopy: Expected Spectra

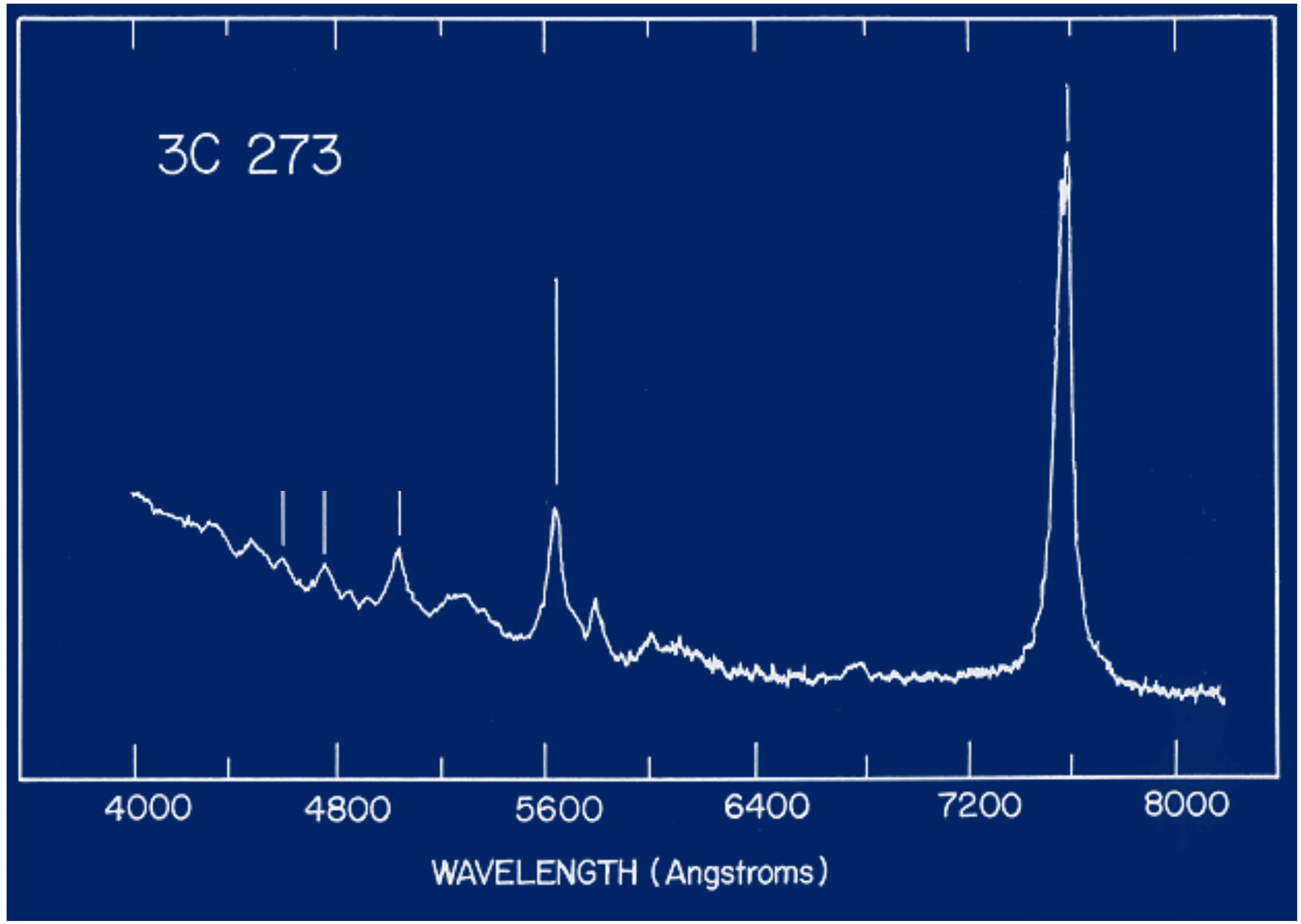
- Typical spectra from galaxies: they look very similar to stellar spectra, with absorption lines that are often seen in stellar atmosphere. Sometimes they show emission lines from ionized gas in nebulae



The Optical Spectrum of 3C273

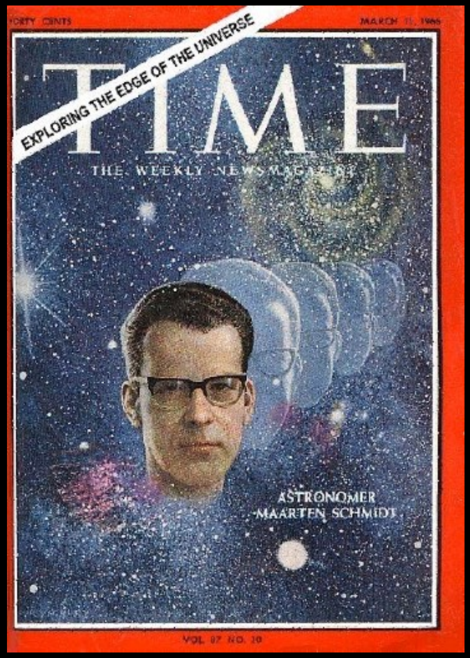
- **Blue continuum** and very **broad emission features** that were never seen before.

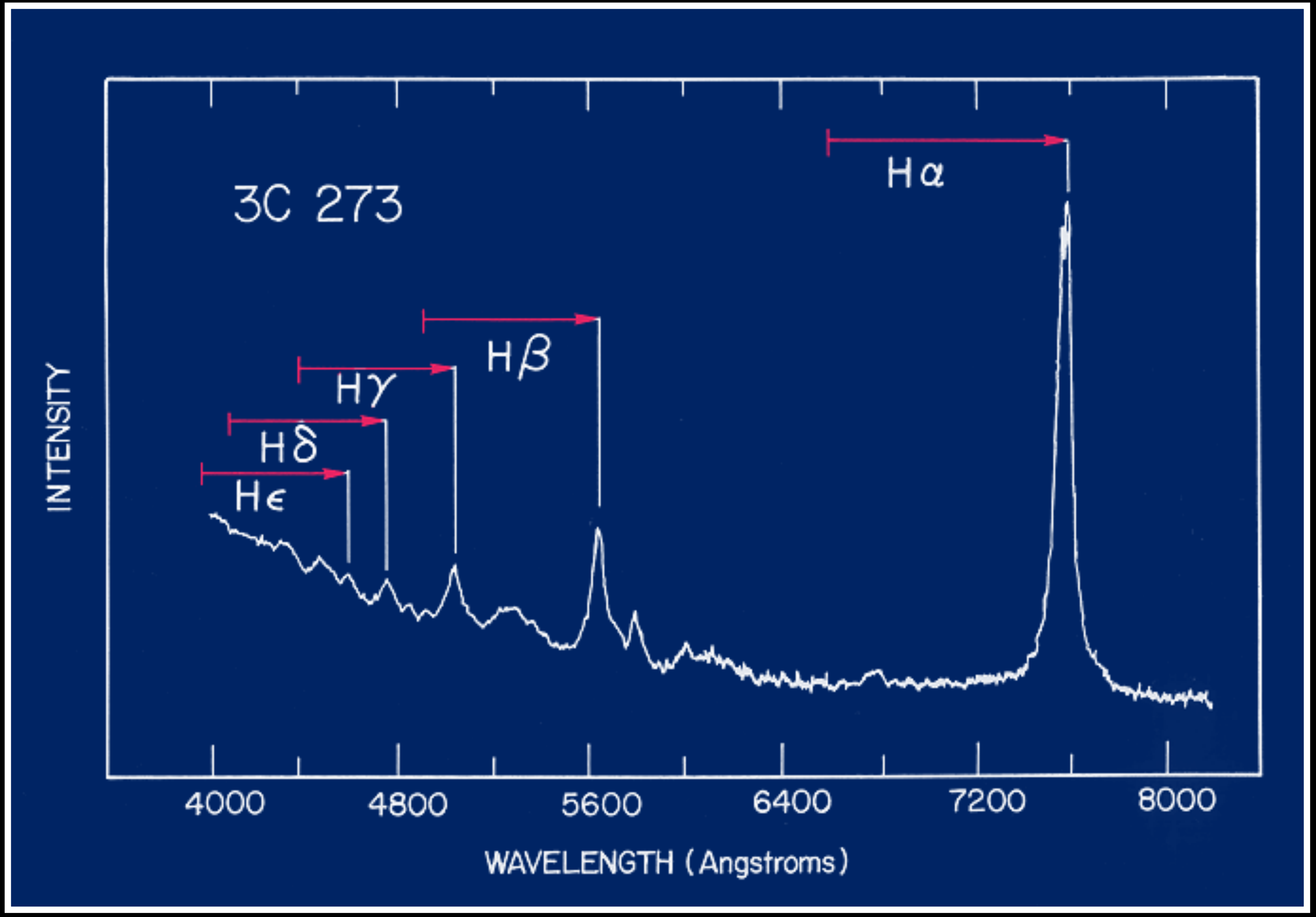




Schmidt (1963) identified the broad lines as Hydrogen Balmer Series, establishing a new class of luminous objects at cosmological distances:

Quasars (Quasi-Stellar Radio Sources)



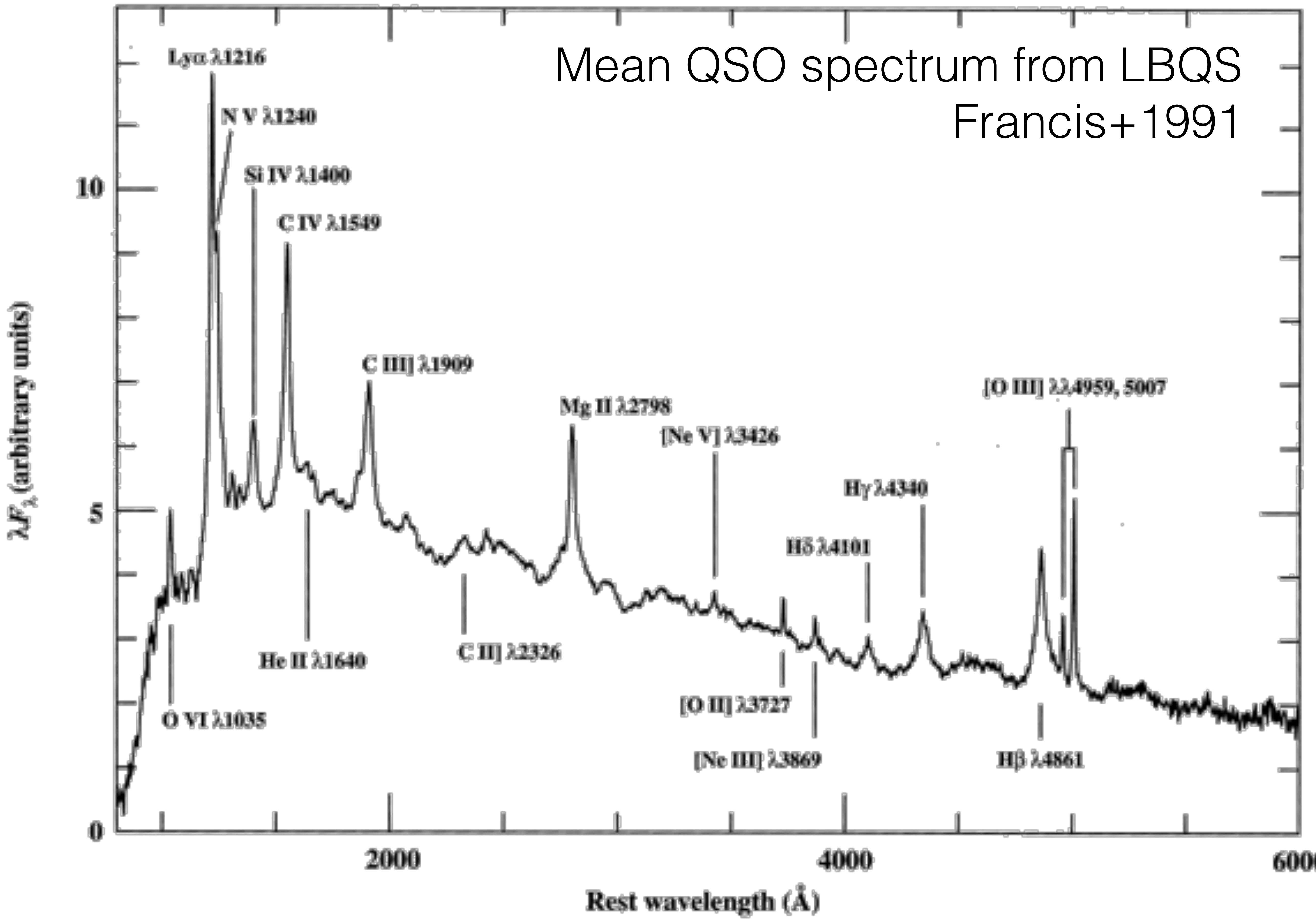


$z = 0.158$ (*760 Mpc*)

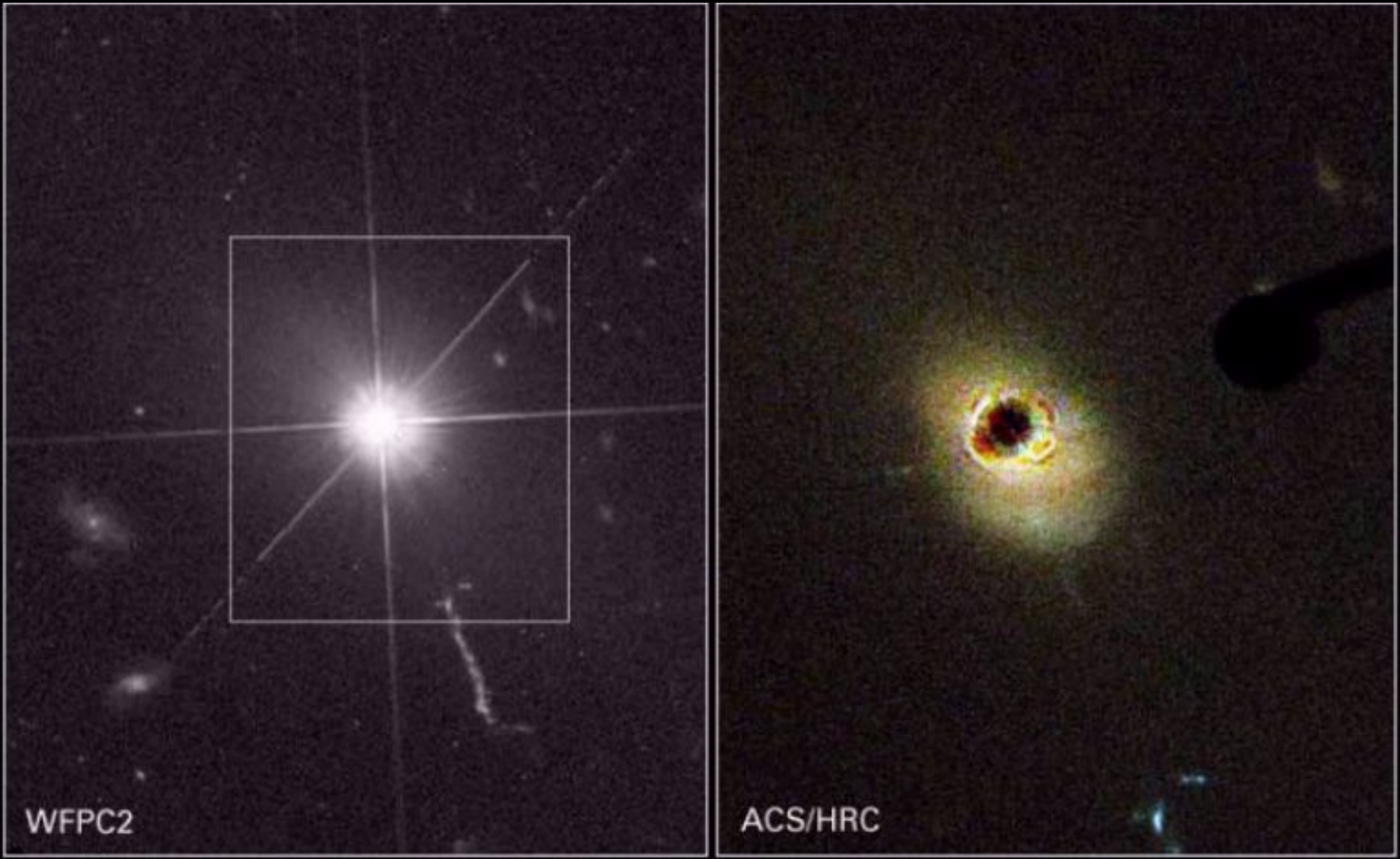
Schmidt (1963)

H Balmer Series:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{2^2} - \frac{1}{n^2} \right)$$


Mean QSO spectrum from LBQS
Francis+1991
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
10
5
0
2000
4000
6000
Rest wavelength (Å)
λF_λ (arbitrary units)

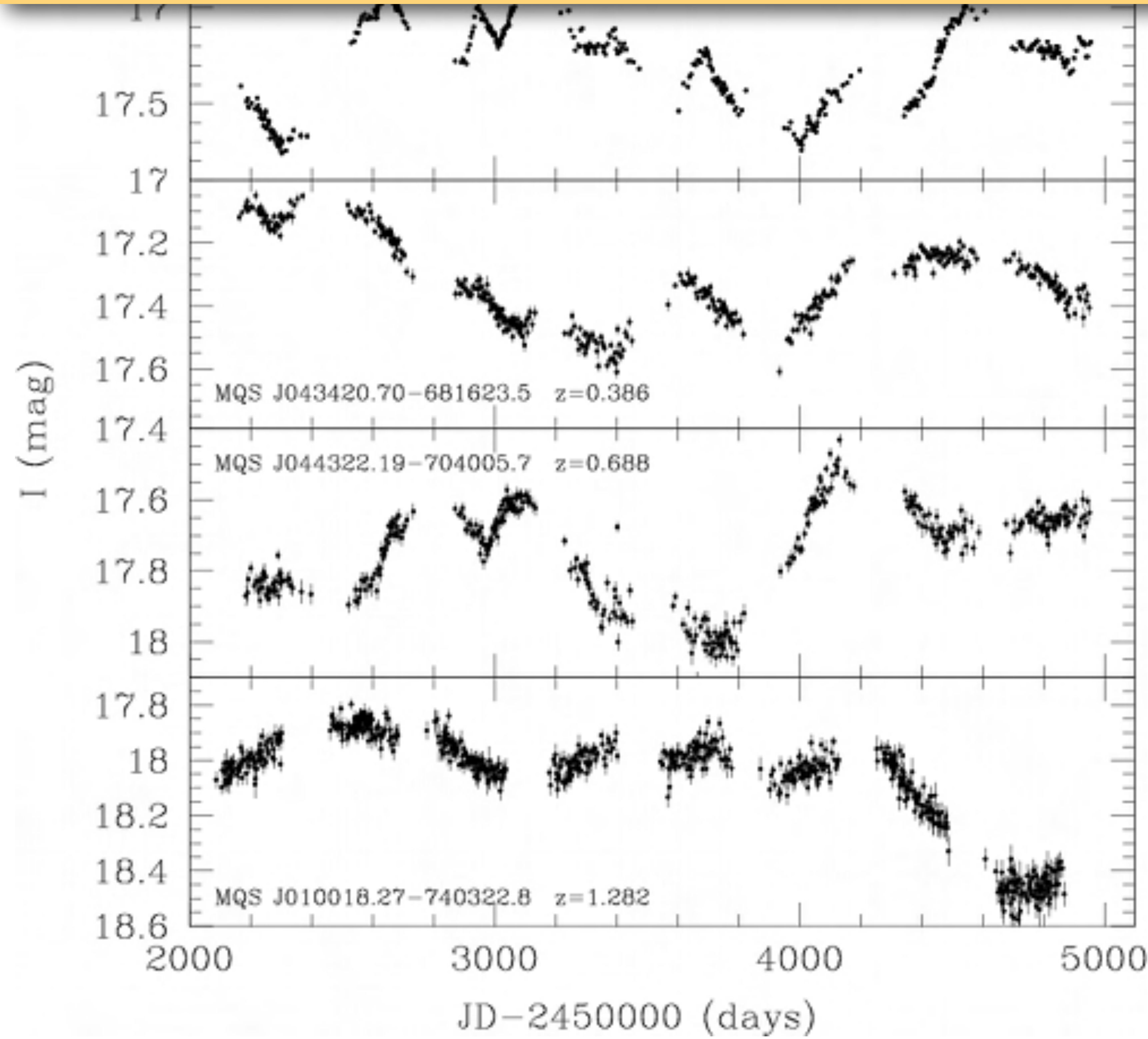
HST coronagraphic image reveals the host galaxy of 3C273



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

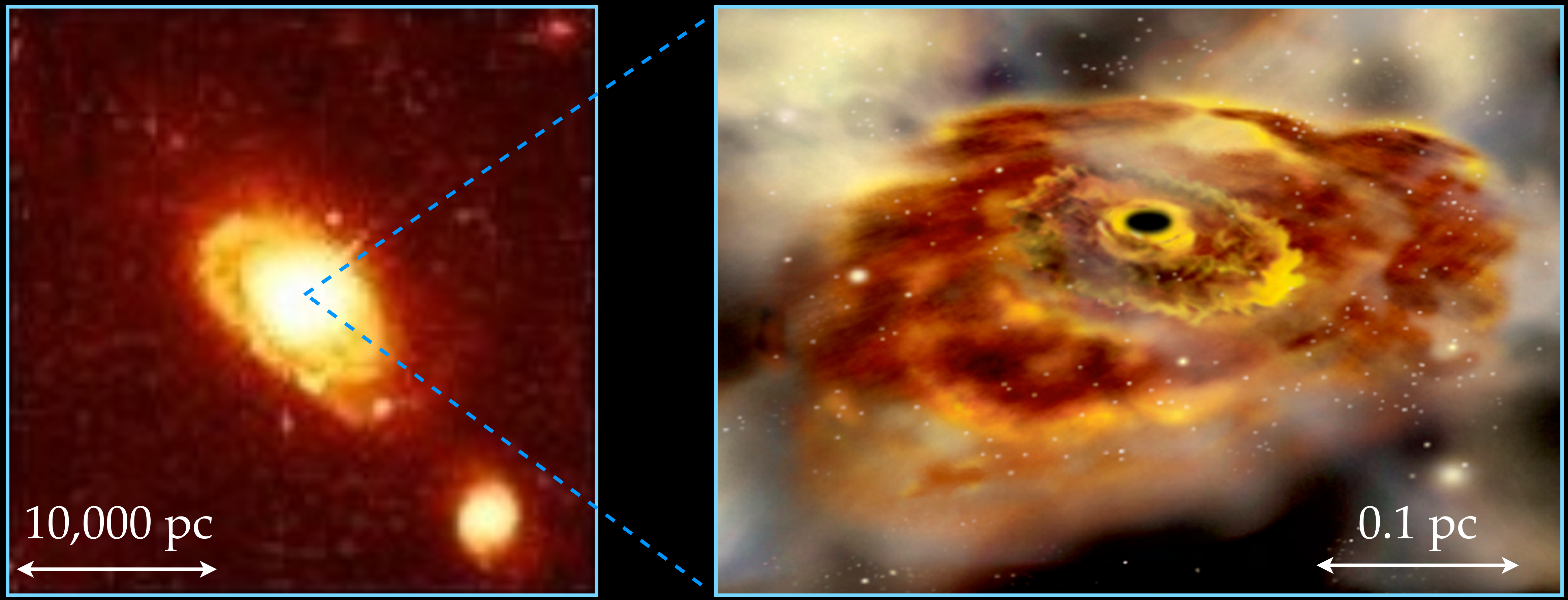
Quasars Show Rapid Variations in Brightness

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



What Could Power Quasars?

Accreting supermassive black holes



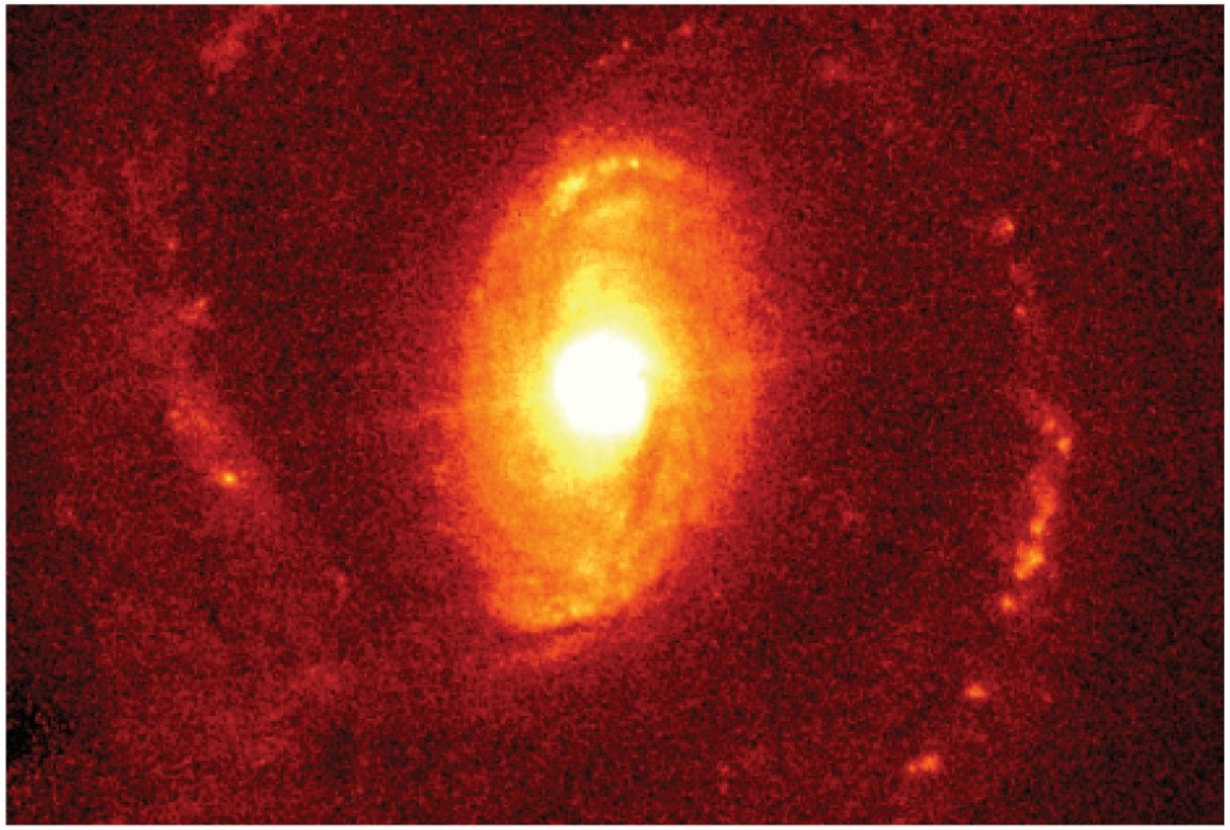
Hoyle et al (1964), Lynden-Bell (1969)

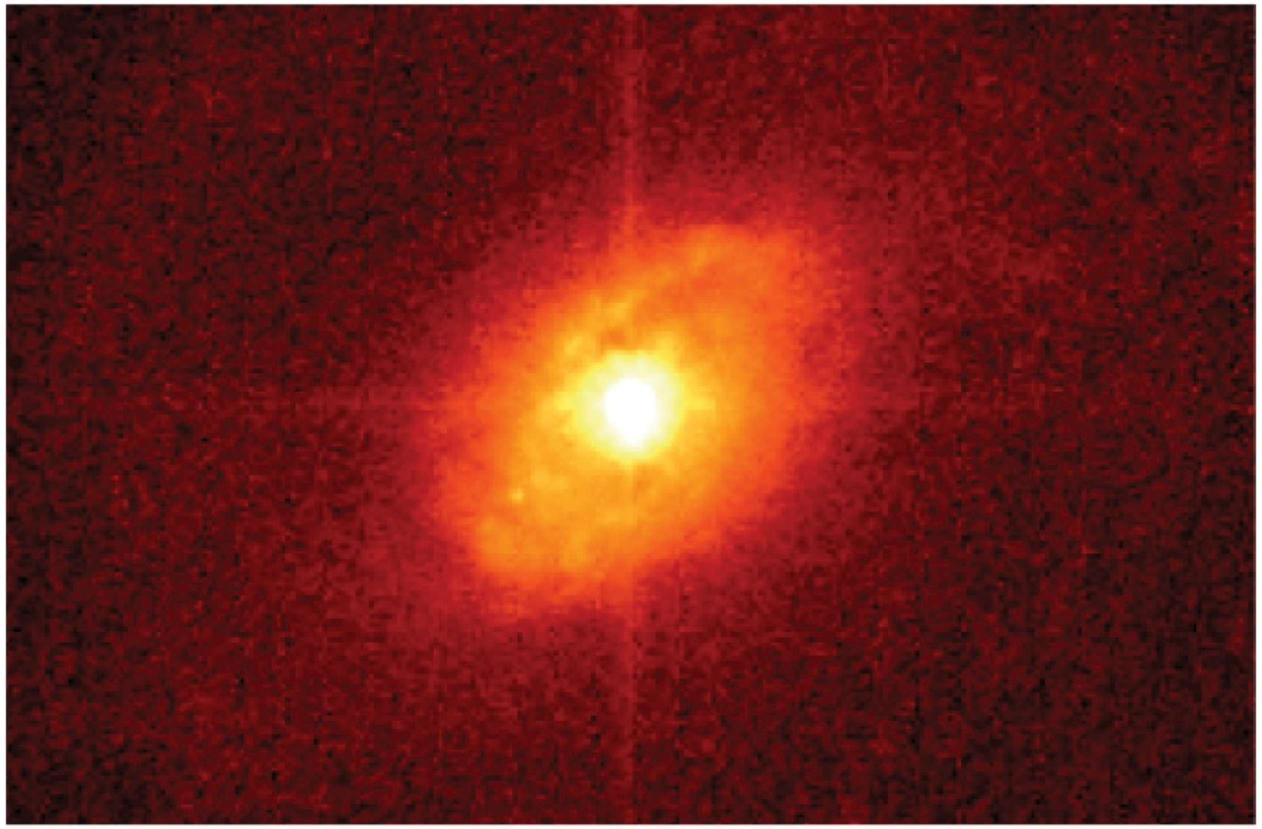
Active Galactic Nuclei (AGN) include Quasars and Seyferts

- All **AGN** are powered by **accreting supermassive black holes**:

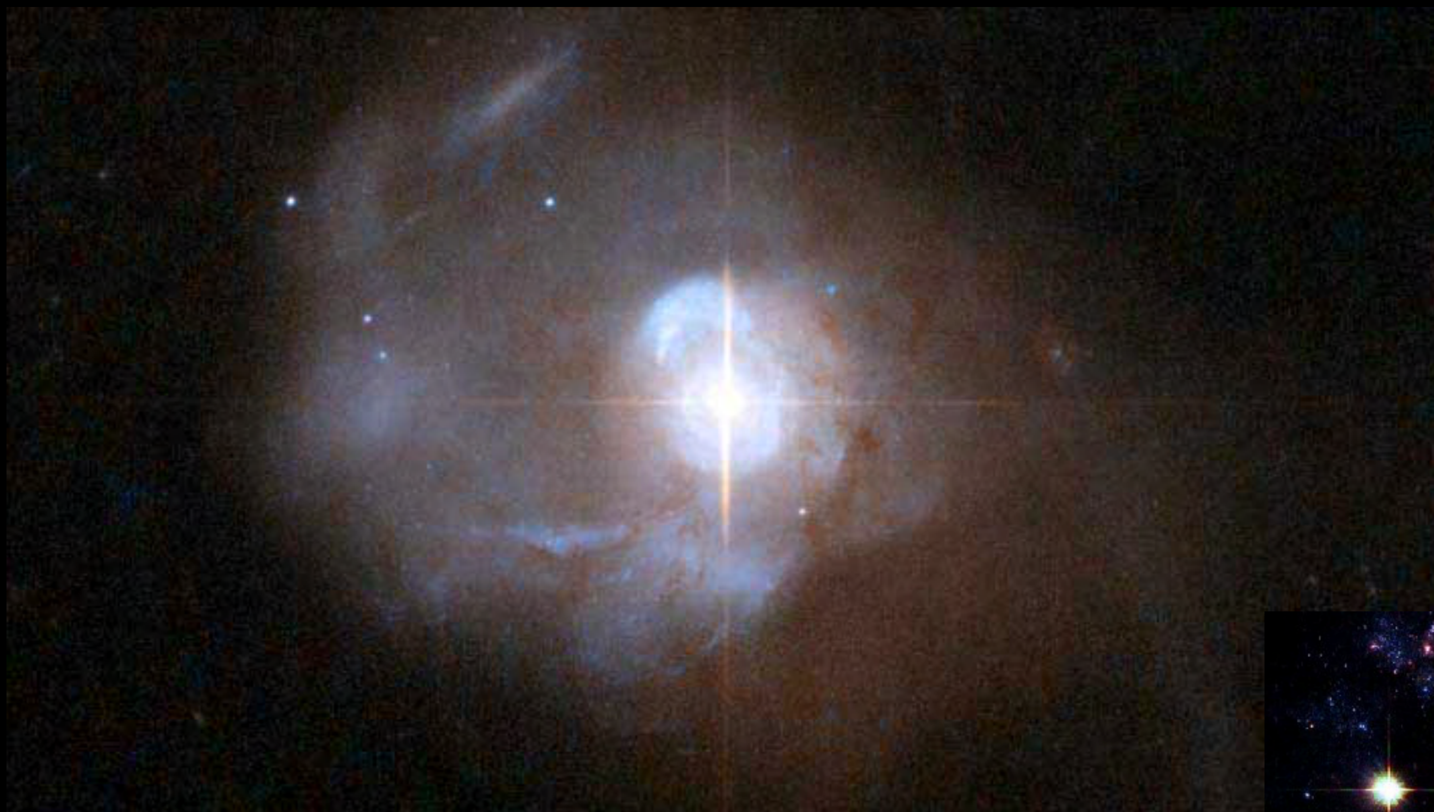
$$L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,{\rm yr}^{-1}}\right)$$

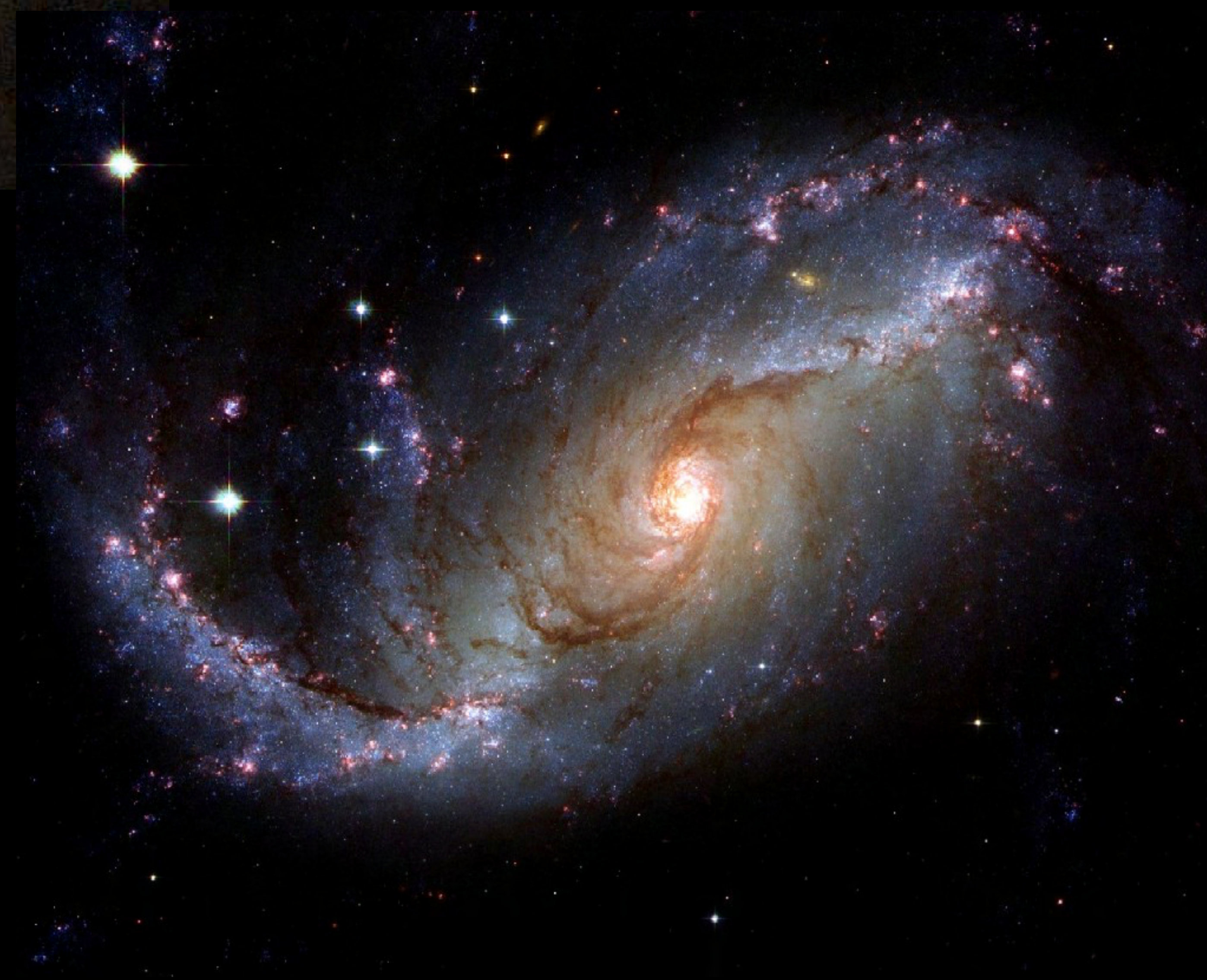
- The most luminous **AGN** are called **Quasars or QSOs**, the less luminous AGN are called **Seyferts** (named after Carl K. Seyfert who first identified this class in **1943**).



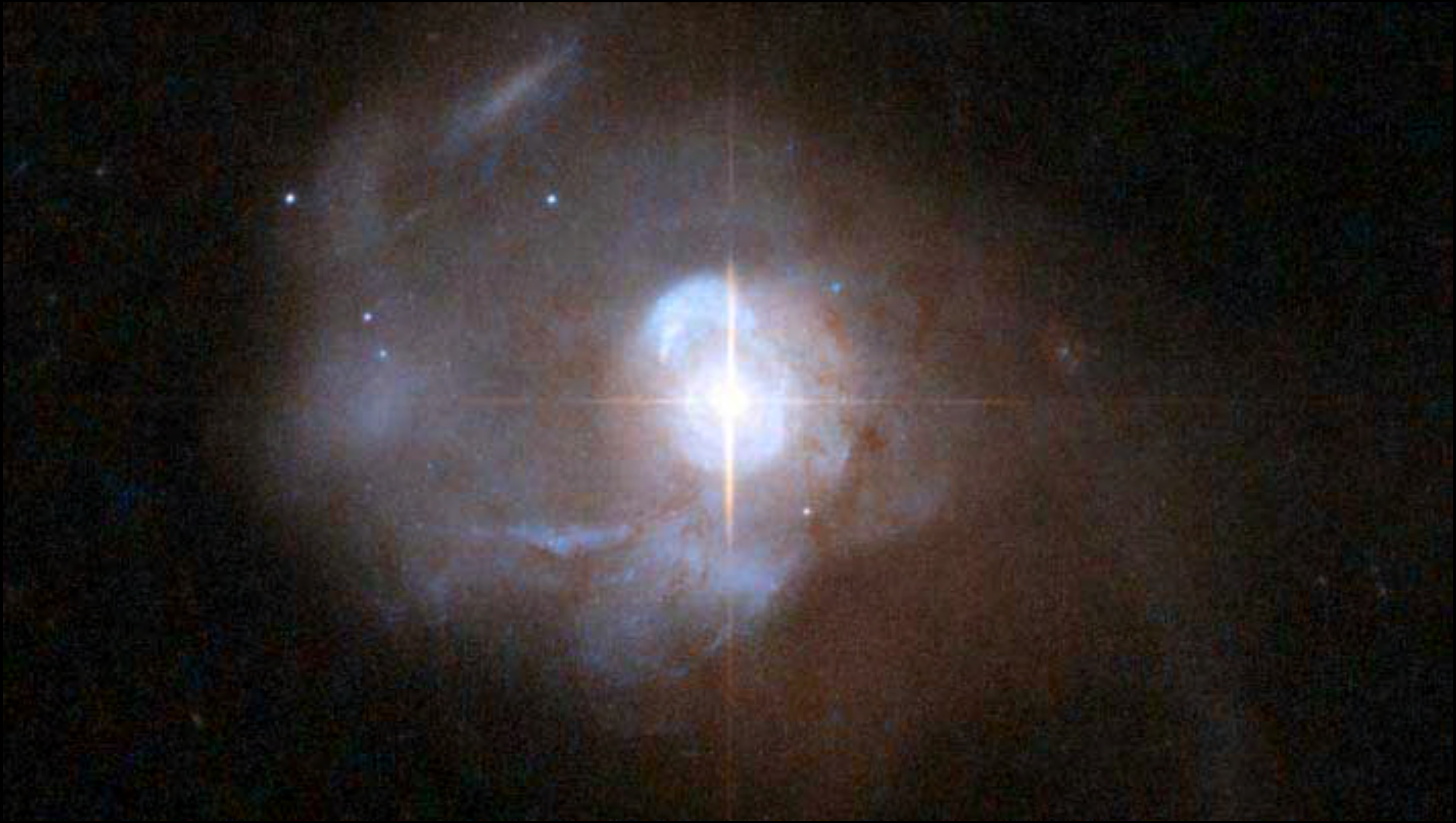


Geometric Effects on Appearance: Type I vs. Type II AGN



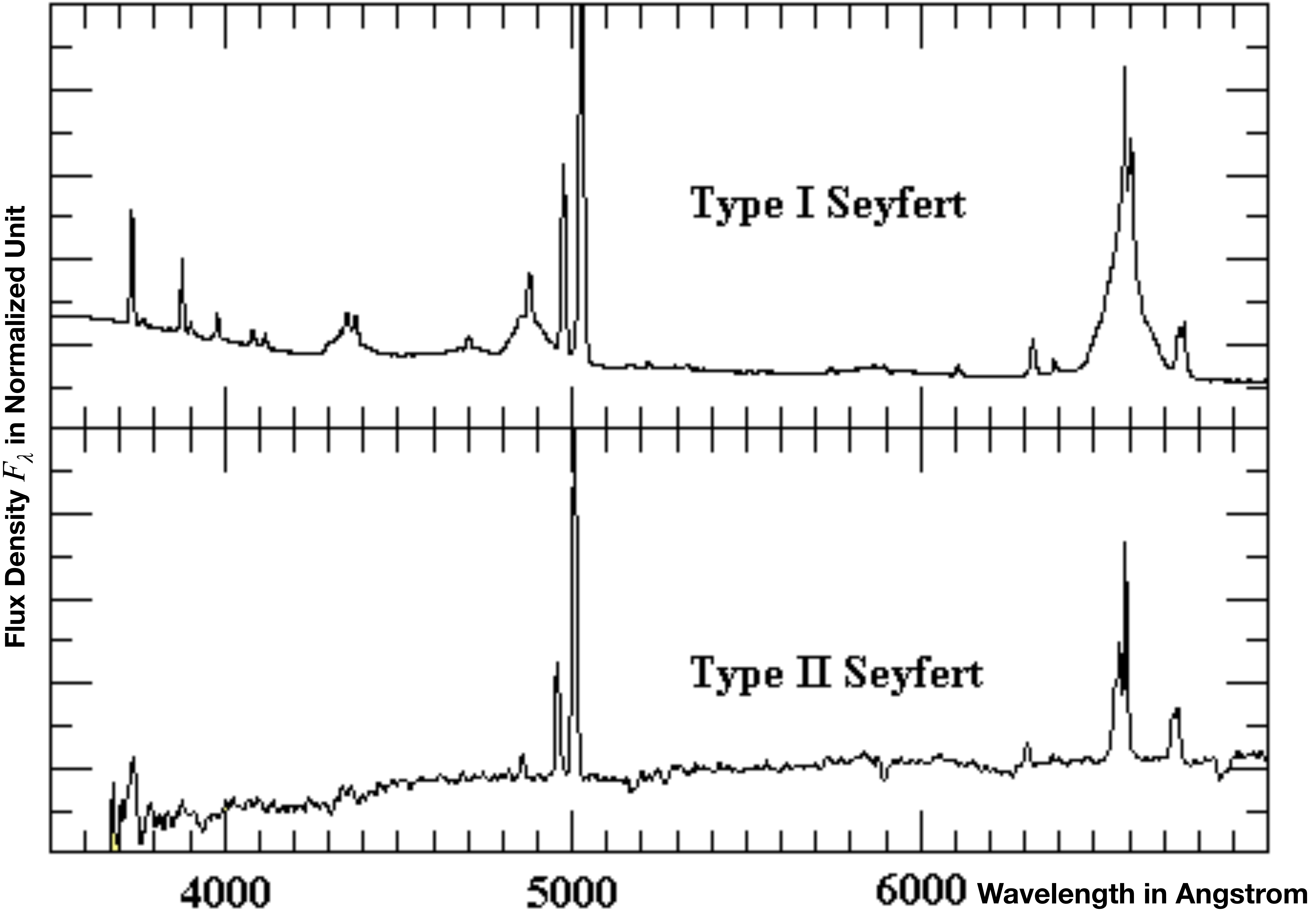


Mrk 231: a Type 1 Seyfert



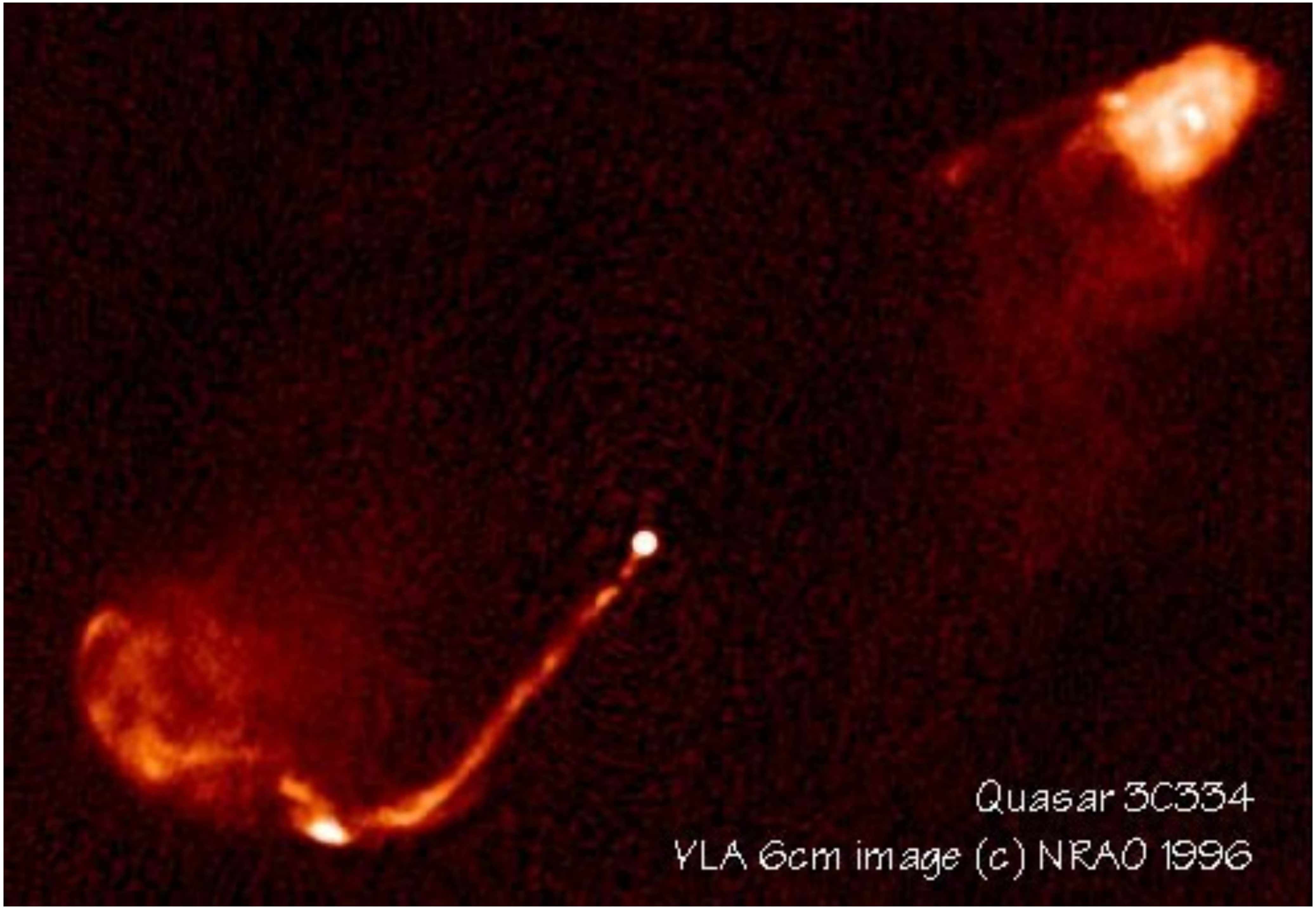
NGC 1672: a Type 2 Seyfert

Spectroscopic differences between Type I and Type II AGN



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

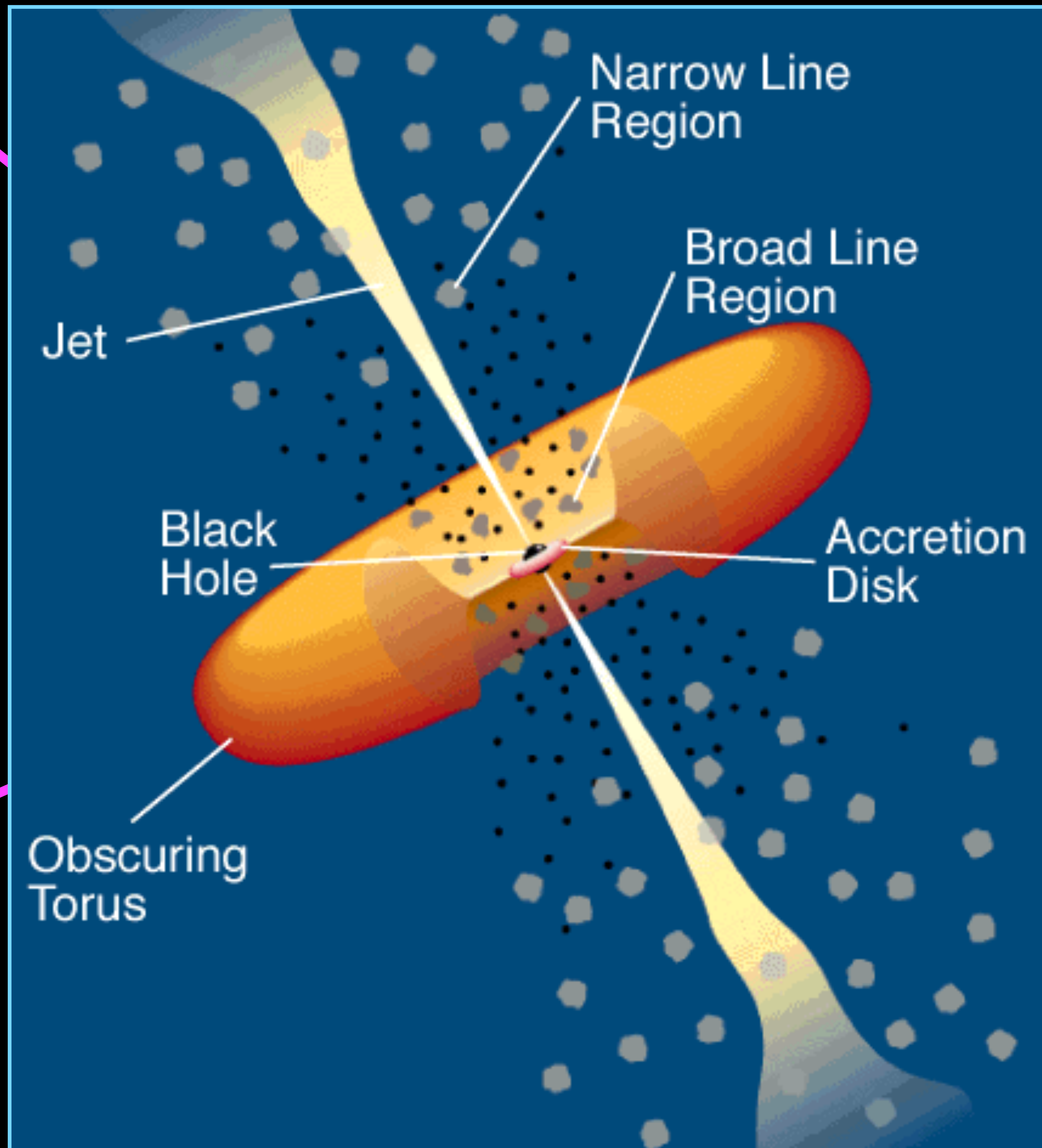
- **Radio galaxies** are ***elliptical galaxies*** that have large jets and lobes of radio emission, powered by the central engine.
- Their radio properties are similar to **radio-loud quasars** but they **do NOT** show the central brilliant point source

Centaurus A (distance 3.4 Mpc)

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



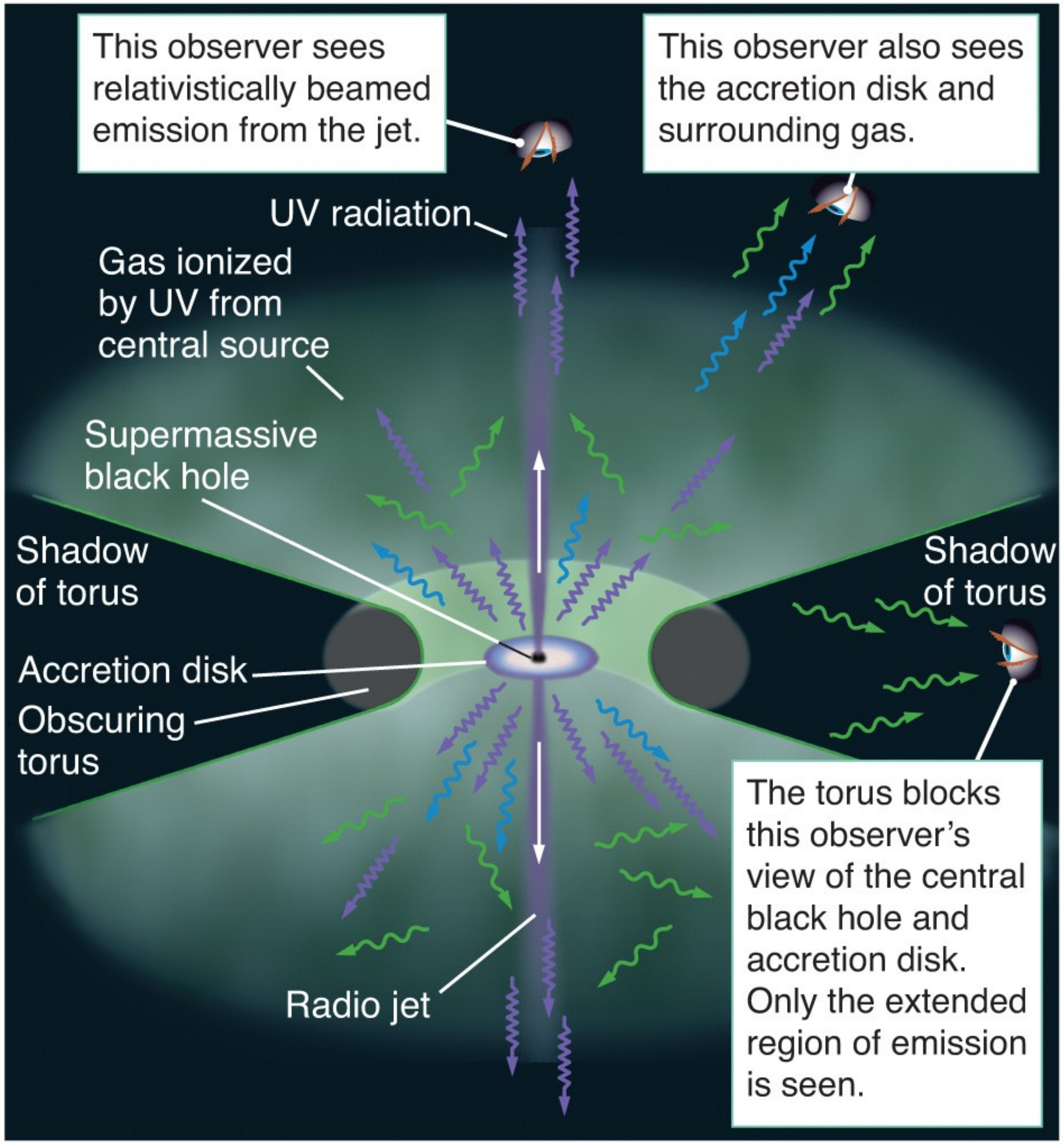
Seyfert 2s
Radio
Galaxies

Torus Size
~ 10 pc

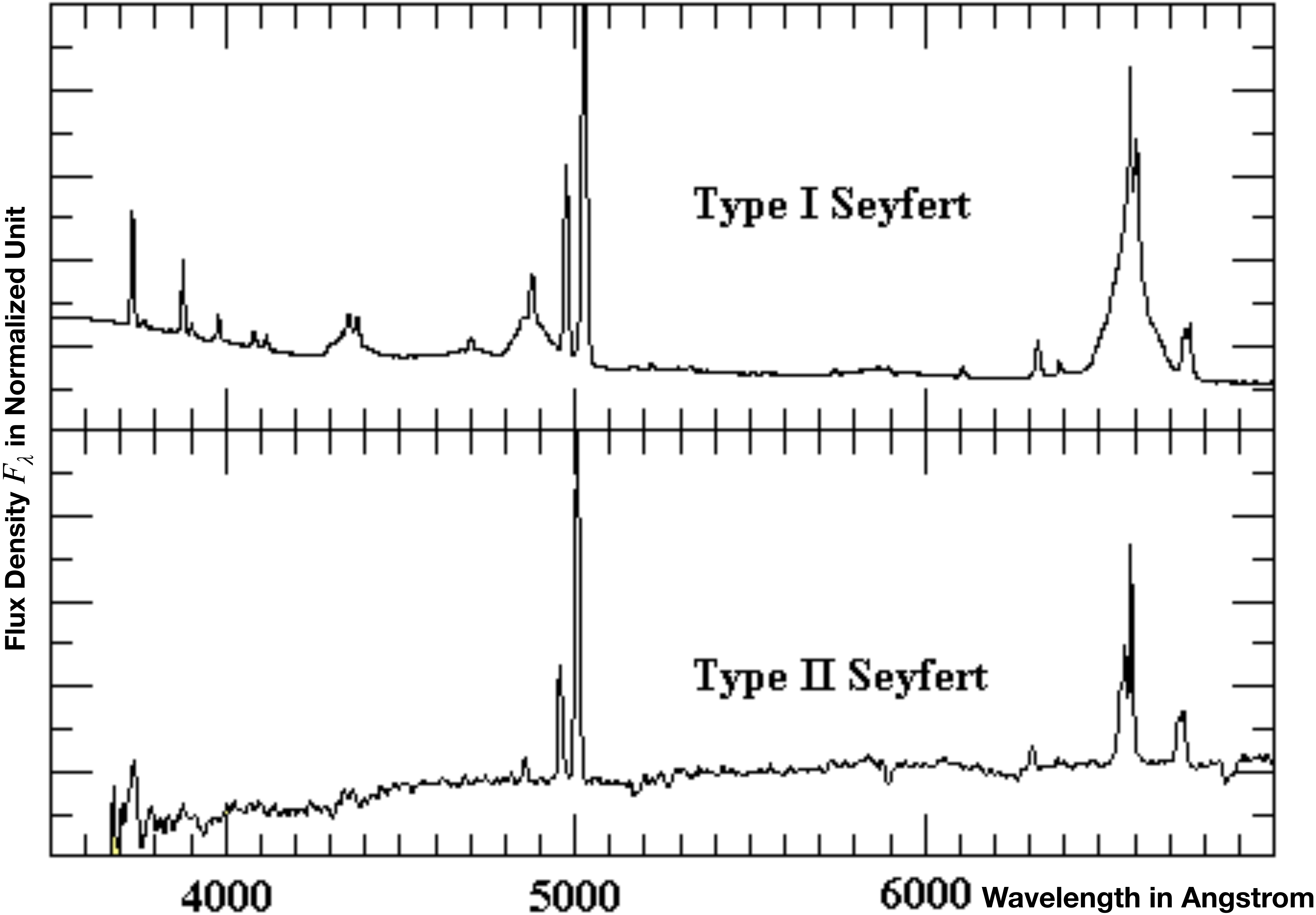
Urry & Padovani 1995

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.
  - **Face on**: unobscured emission from the accretion disk **(blue continuum)** and photoionized gas in the sphere of influence that emits broad lines (**Broad line region**)
  - **Edge on**: emission from broad-line region and accretion disk is obscured by a 10-pc-scale torus
  - Photoionized gas on more extended (kpc) scale show narrower emission lines, so the torus cannot obscure the **narrow-line region**

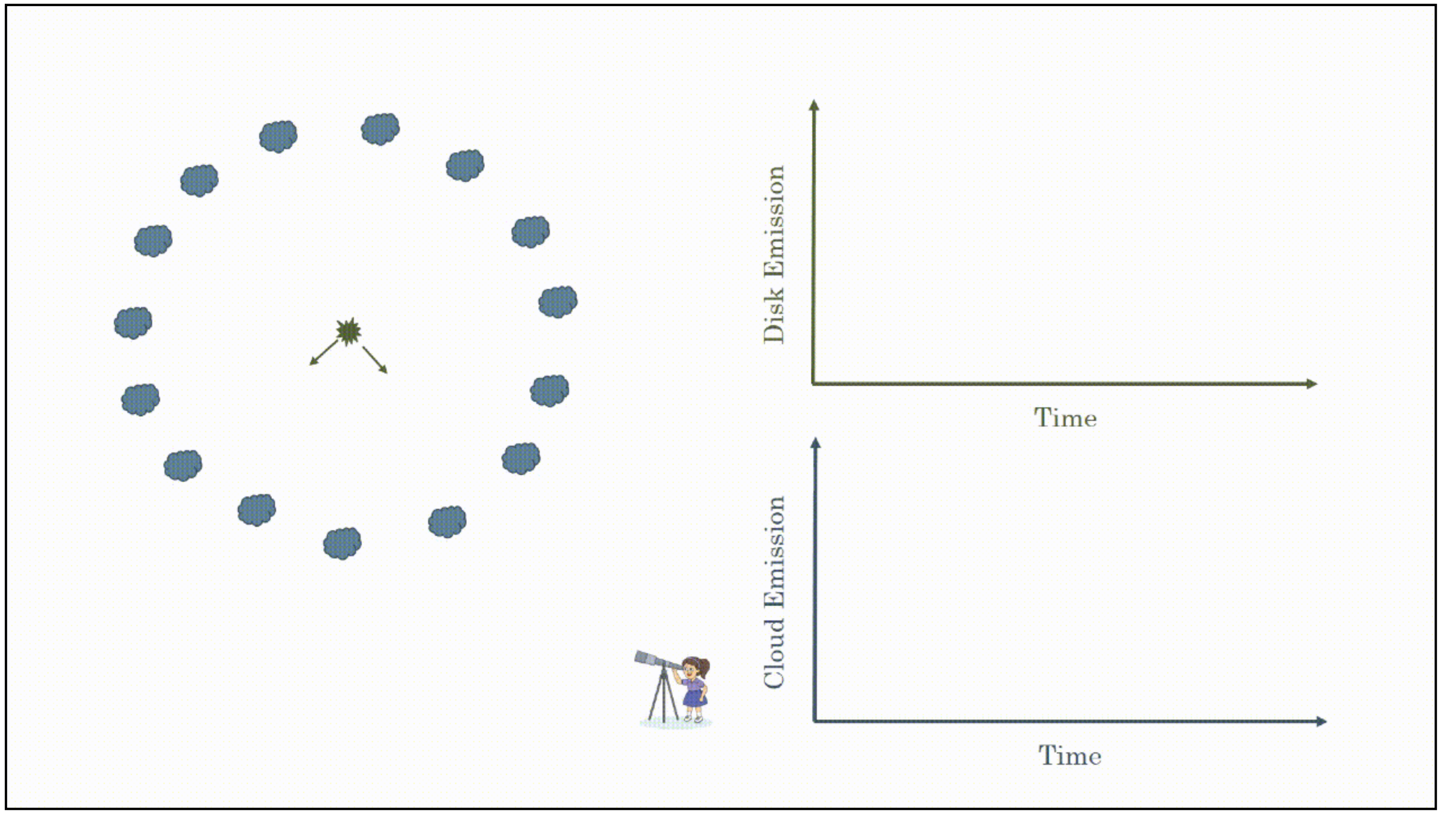


Spectroscopic differences between Type I and Type II AGN

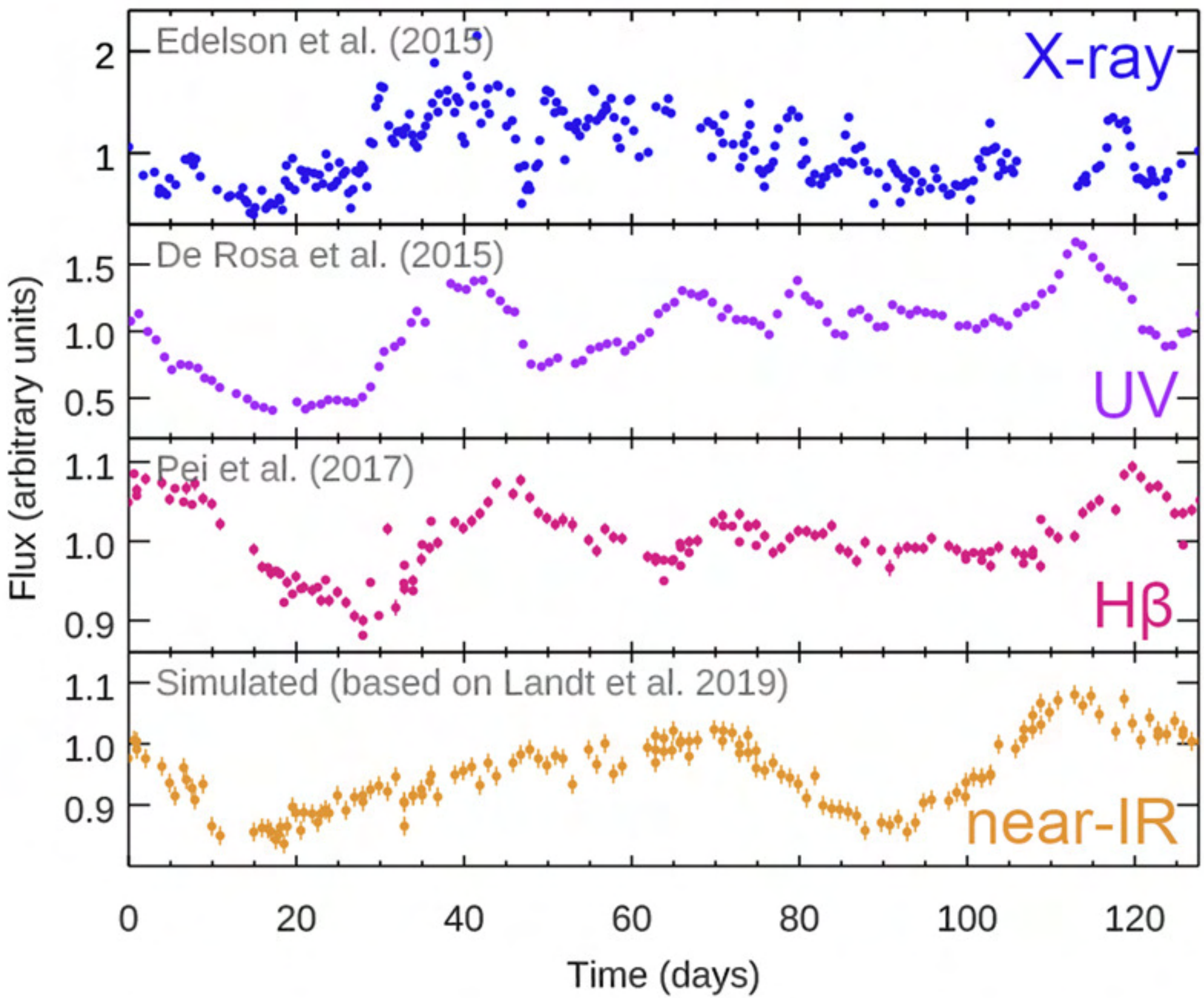


Estimating AGN Black Hole Mass w/ Reverberation Mapping

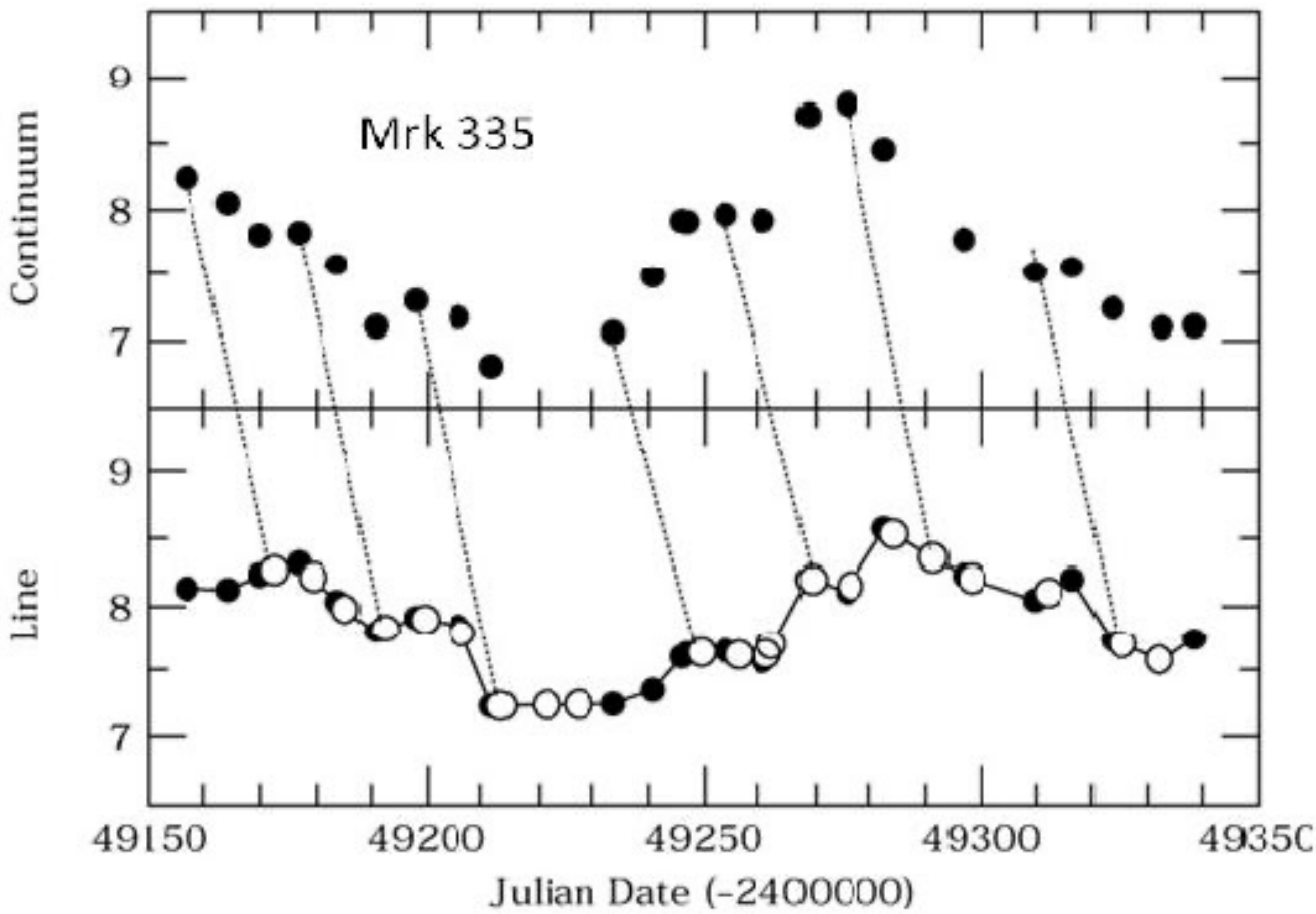
- **Virial Theorem** (applicable to any self-gravitating systems):
$$2K + U = 0 \Rightarrow \bar{v}^2 - GM_{\rm vir}/R = 0 \Rightarrow M_{\rm vir} = \bar{v}^2 R/G$$
- Typical velocity of the gas clouds in the broad line region is proportional to the width of the emission lines:
$$\bar{v} \propto \frac{\Delta\lambda}{\lambda} c$$
this is called **Doppler broadening** of the lines
- The size of the broad line region can be estimated from the time lag between light curves of the accretion disk and the broad emission lines. The technique is called **reverberation** (light echo) **mapping** as illustrated below.



Reverberation Mapping: Time Delay in Light Curves



Reverberation Mapping: Time Delay in Light Curves



Given the rarity of AGN, how important could they be?

- In a galaxy, there are two main sources of kinetic energy that could disrupt the ISM gas and thus affect the future evolution of the galaxy:
  - Total energy from supernovae explosions (E_{SN})
    - **10^{44} Joules** in kinetic energy per type II SN (EM energy is 100x less, Neutrino energy is 100x more but impossible to harness)
    - Roughly there will be 1 type II SN for every **100 M_{sun}** of stars formed
    - Therefore, total kinetic energy from a stellar population of mass M*: **~10^{42} Joules M^*/M_{sun}**
  - Total energy from SMBH accretion (E_{SMBH}) [Note: this is not luminosity]
    - Accretion Energy: **$0.1\, M_{BH}\, c^2 = 1.8\times10^{46}$ Joules M_{BH}/M_{sun}**
- Let's compare the contribution from the two sources of energy:

$$\frac{E_{\mathrm{SMBH}}}{E_{\mathrm{SN}}} = \frac{1.8\times10^{46}\, J\,(M_{BH}/M_{\odot})}{10^{42}\, J\,(M^*/M_{\odot})} = 18000\frac{M_{BH}}{M^*} \approx 20$$

  where we had used the observational result that on average, the SMBH mass is ~1000x less than the stellar mass in a galaxy.
- **Conclusion**: Even if only **5%** of the accretion energy is deposited into the surrounding ISM as kinetic energy, the total kinetic energy output from SMBH accretion would be equal to that from all type II SNe.

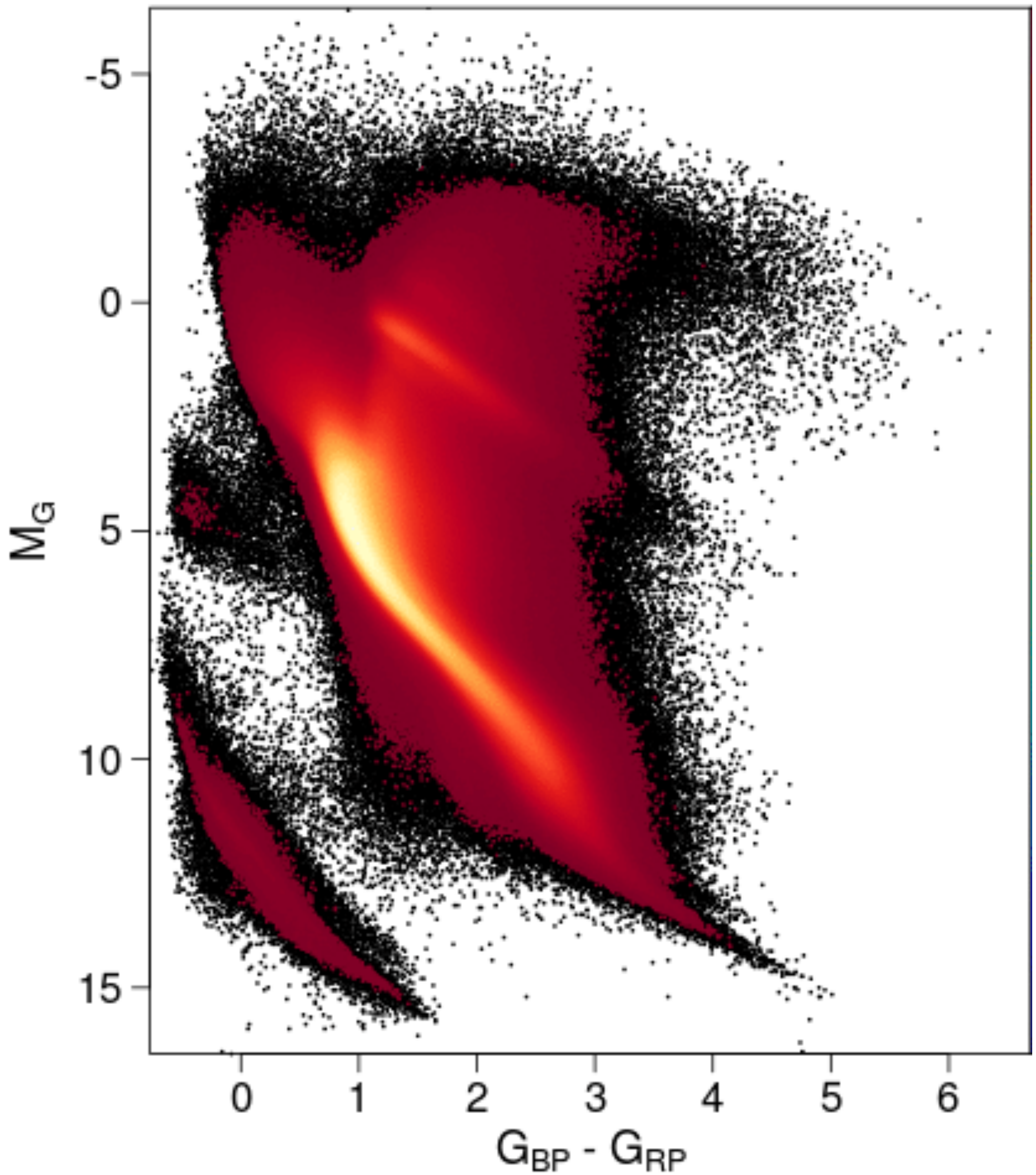
Summary: Tools for detecting supermassive black holes

- **Resolve the event horizon**
  - $$r_s = \frac{2GM_{\rm BH}}{c^2} = 3\,{\rm km}\left(\frac{M_{\rm BH}}{1M_\odot}\right) = 2\,{\rm AU}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$$
  - Aperture synthesis with a network of mm-wave telescopes
  - Minimizing the diffraction limit: $\theta = \lambda/D$
- **Resolve the sphere of influence**
  - $$r_* = \frac{GM_{\rm BH}}{\sigma_*^2} = 11\,{\rm parsec}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{200\,{\rm km/s}}{\sigma_*}\right)^2$$
  - stellar and gas kinematics near galactic center
  - Adaptive Optics or Space Telescopes like HST/JWST
- **Detect the incredible accretion energy**
  - $$L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,{\rm yr}^{-1}}\right)$$
  - Active Galactic Nuclei (AGN), ~1% of all galaxies

The “HR Diagram” of Galaxies:

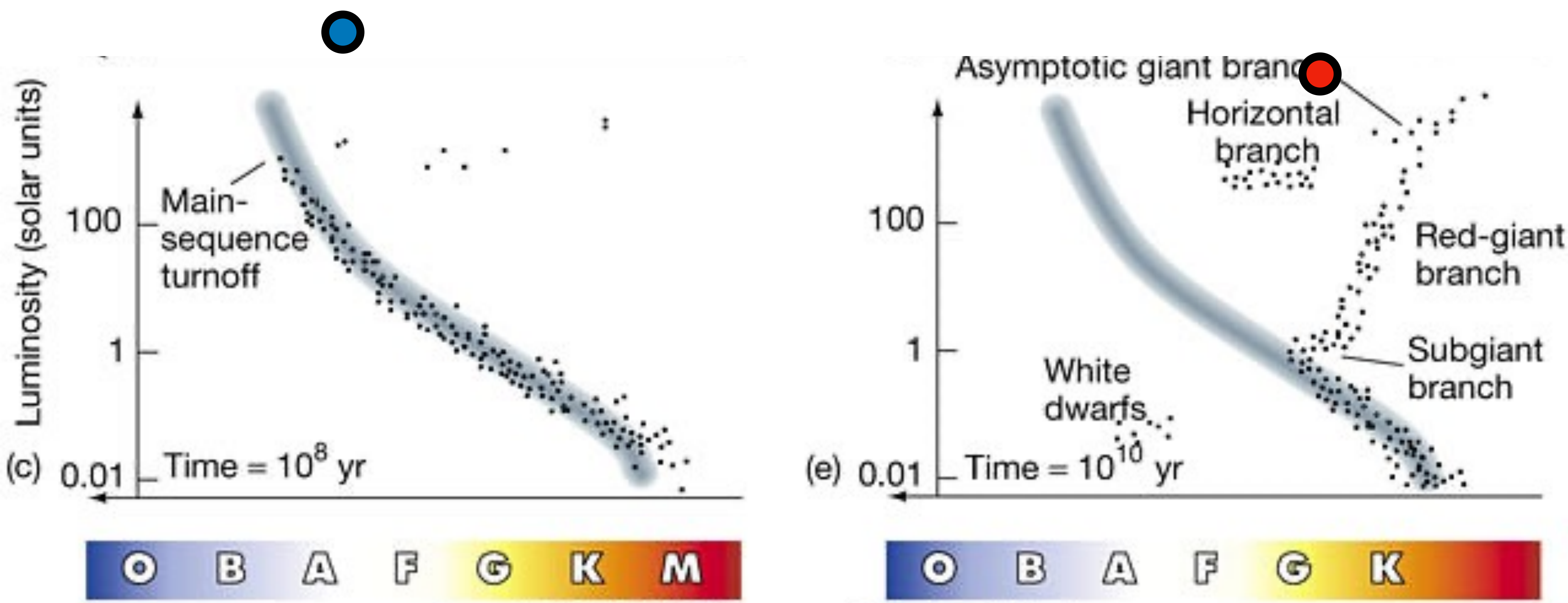
the Color-Magnitude Diagram

HR Diagram is a Color-Magnitude Diagram of Stars

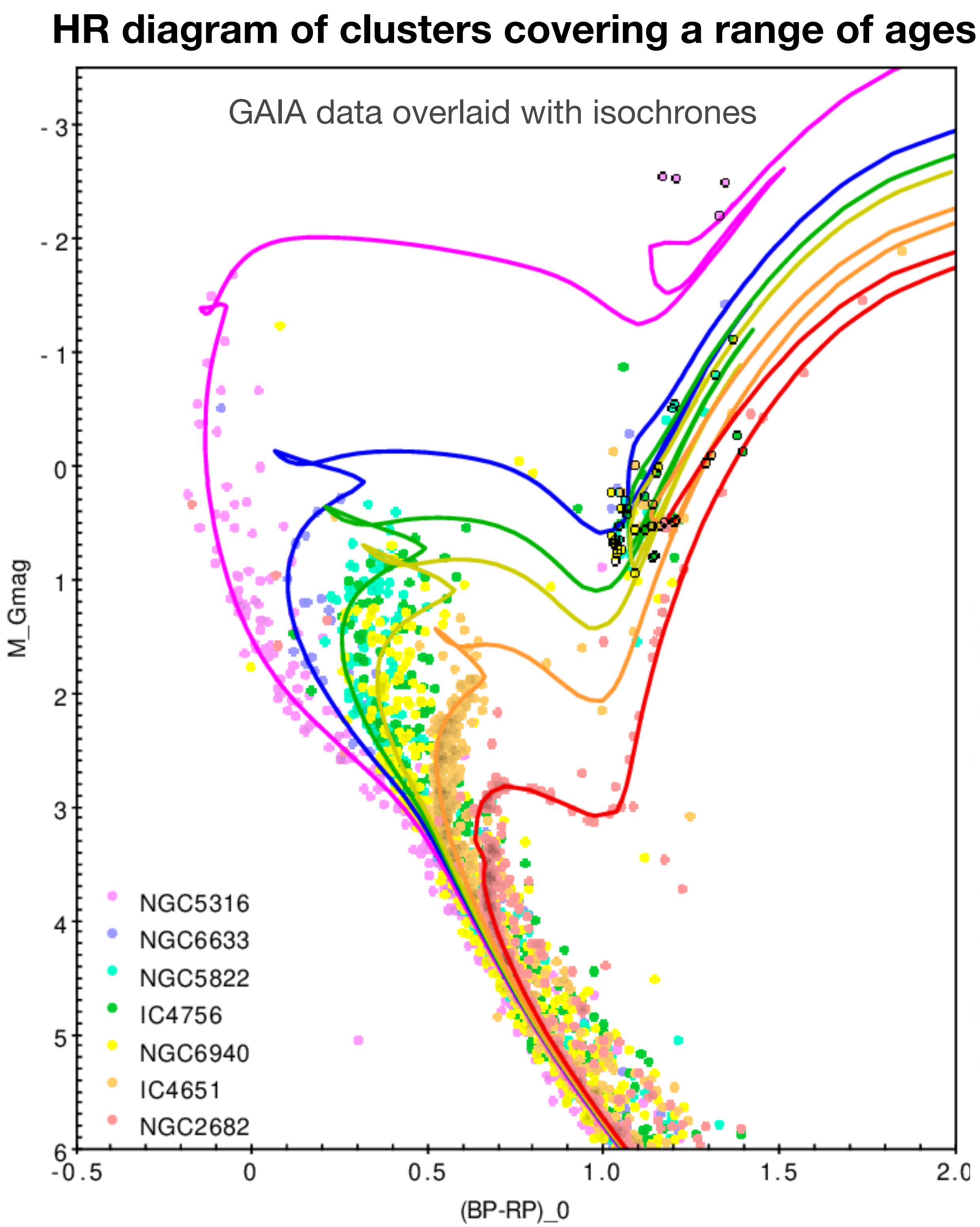


Integrated color and luminosity of simple stellar populations

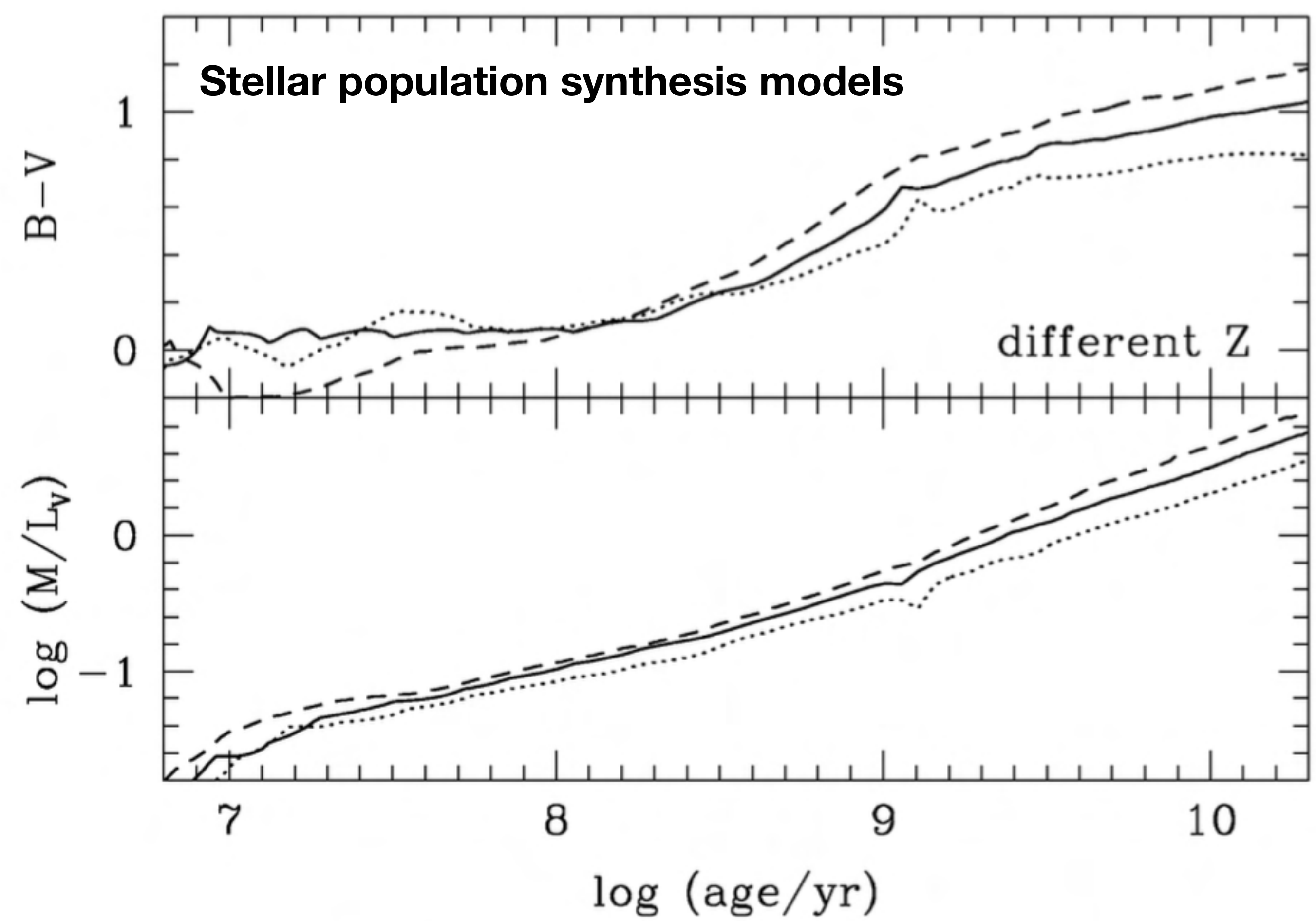
- Because individual stars are usually unresolved in galaxies, we can only measure the **integrated color** and the **total luminosity** from billions of stars in the same galaxy.
- We can illustrate this process with the HR diagram of star clusters, which represent **simple stellar populations**.
-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



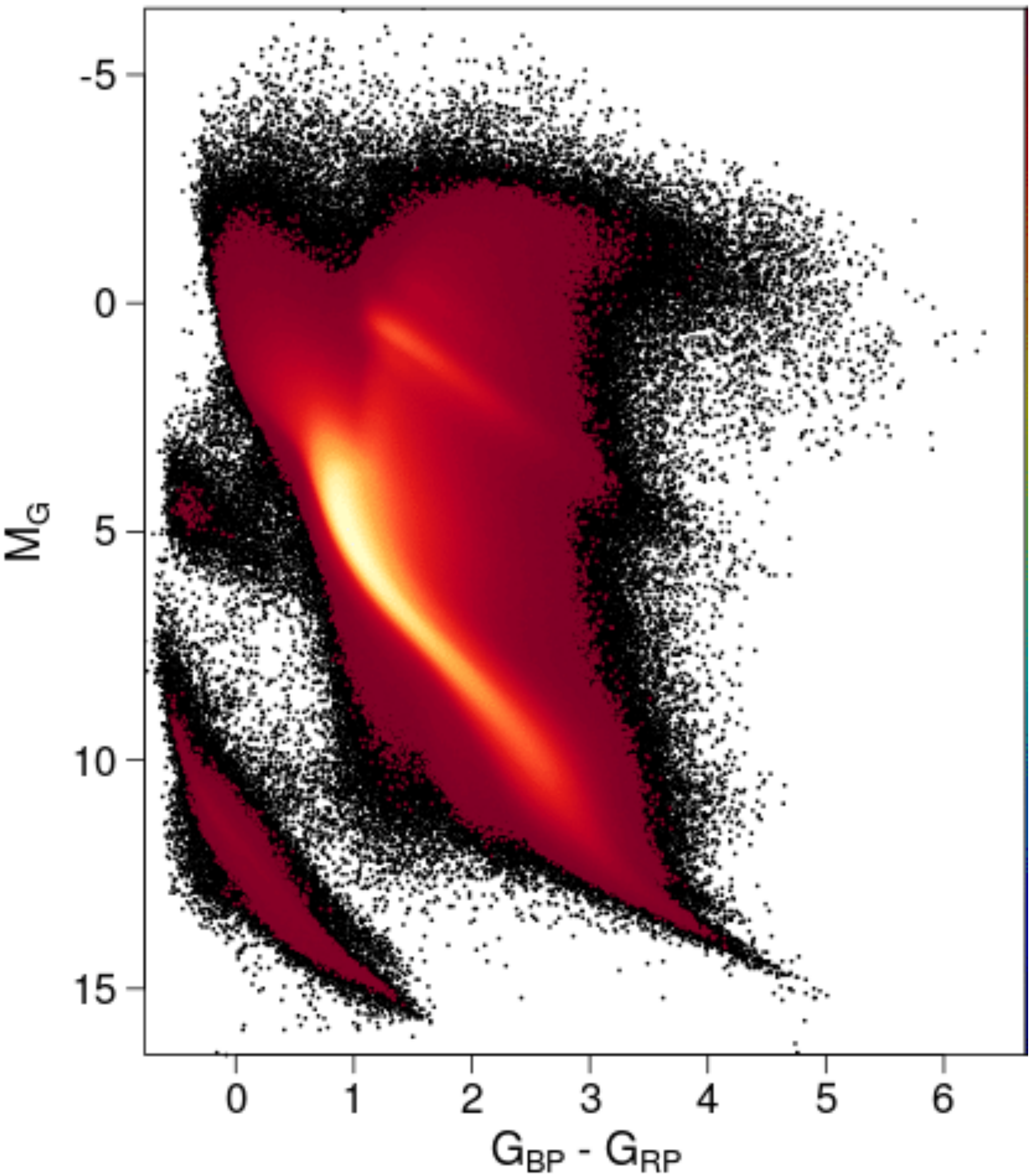
As a stellar population ages, it becomes redder and fainter

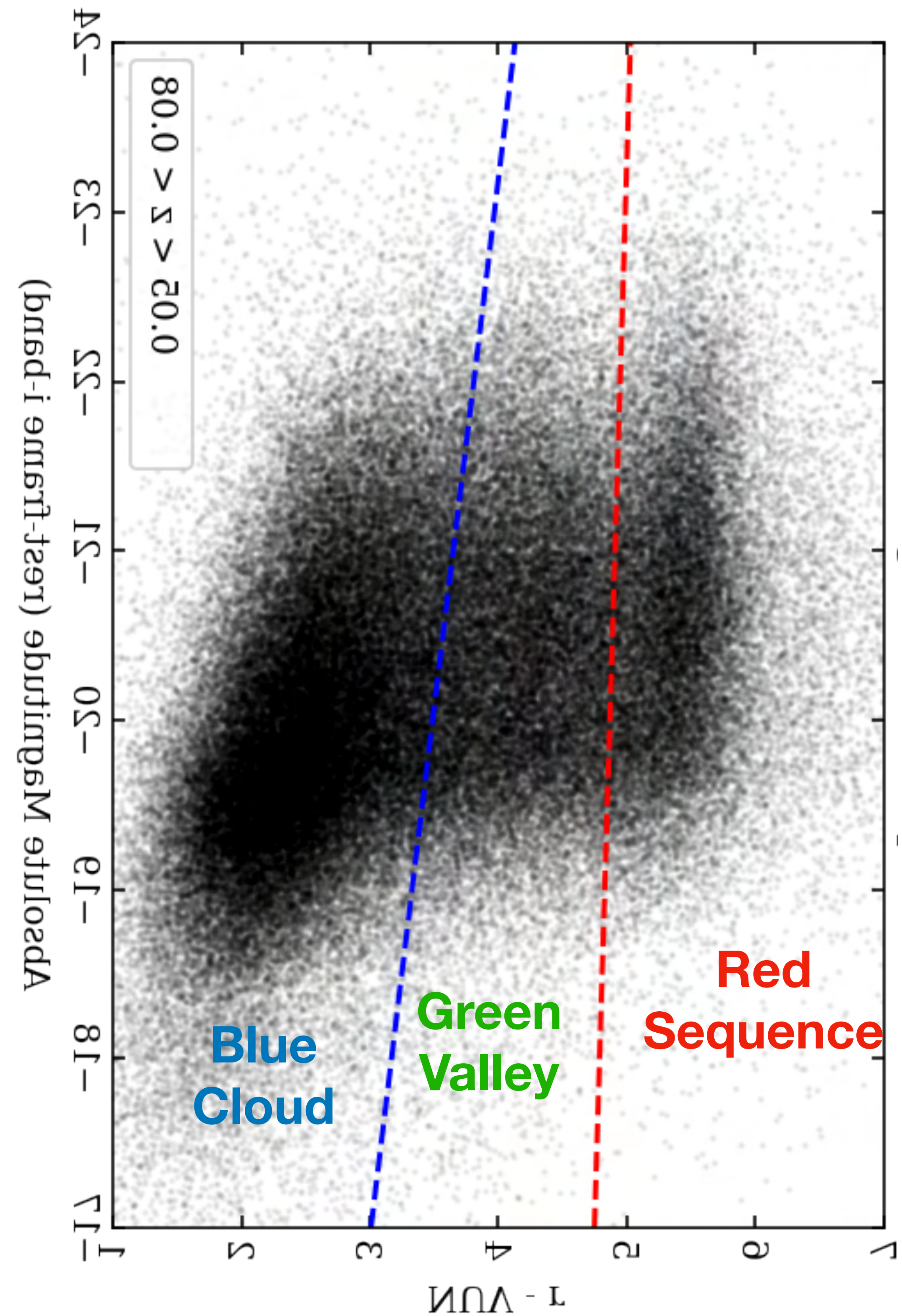


- Stellar population synthesis models follow the **isochrone evolution** of stellar populations and predict the **integrated color** and the **total luminosity** as a function of age.
- The **mass-to-light ratio (M/L)** increases because luminosity decreases faster than mass loss.

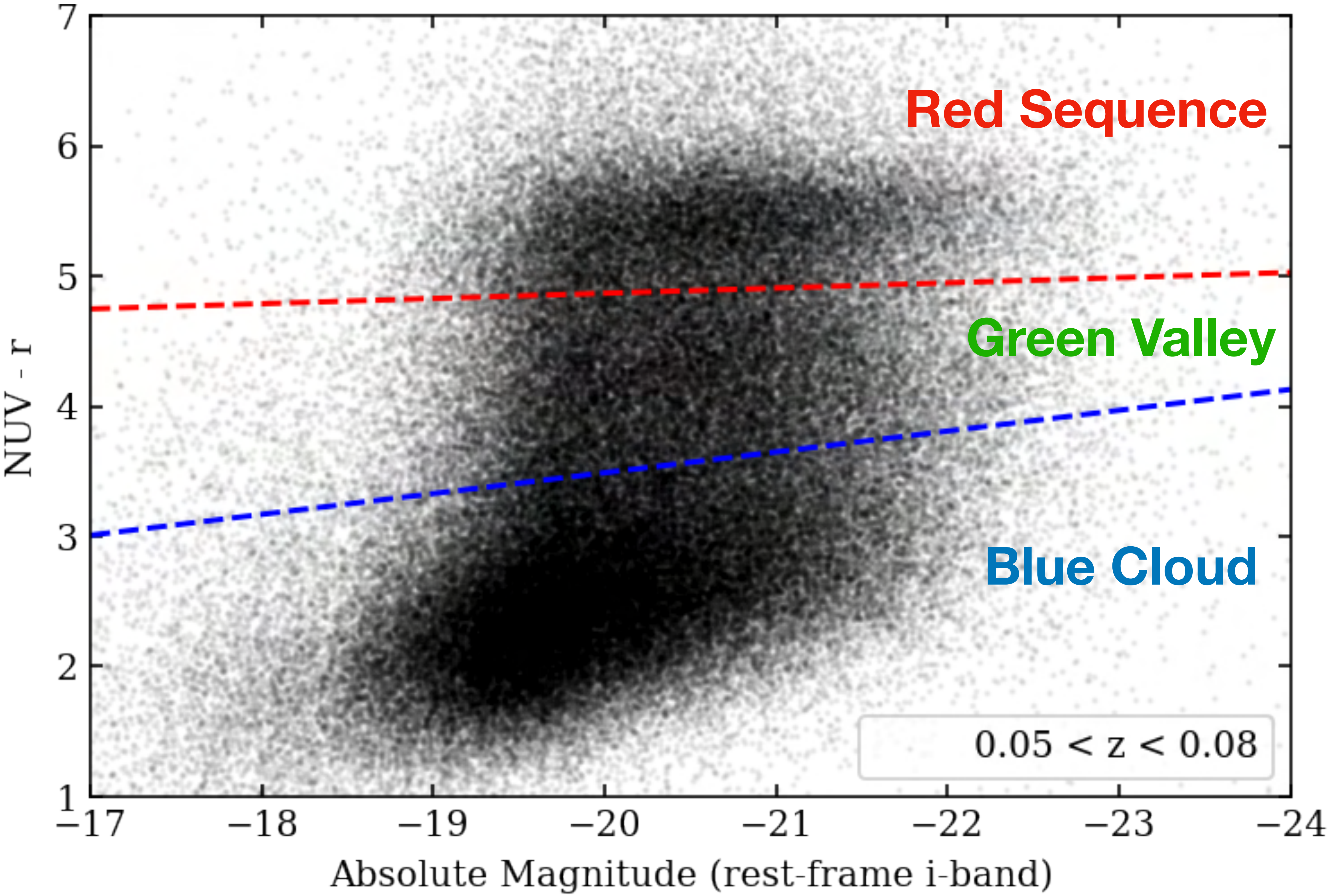


HR Diagram of Stars vs. CM Diagram of Galaxies





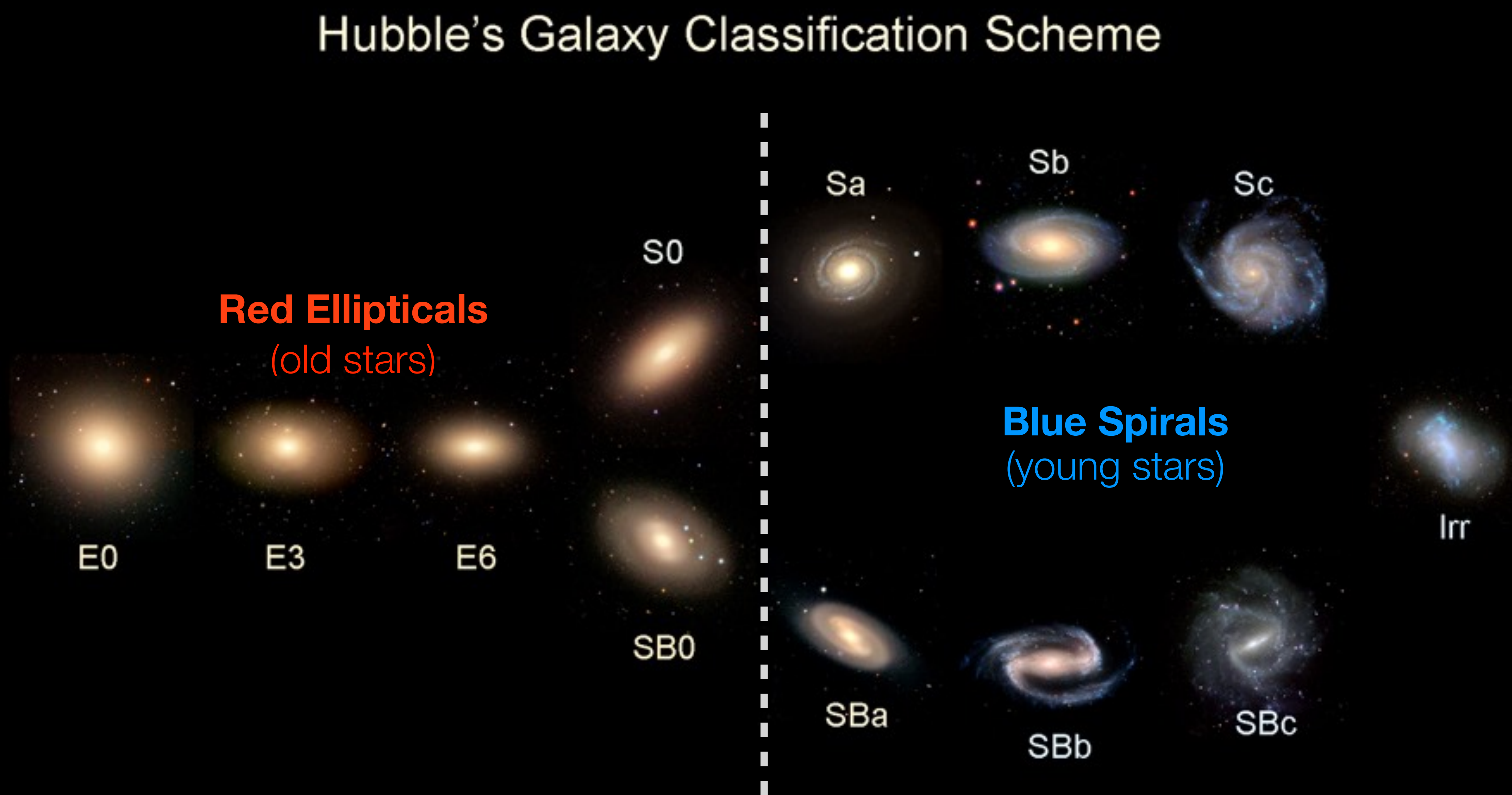
Color-Magnitude Diagram of Galaxies



Integrated Color Naturally Separates Spirals and Ellipticals

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

Galaxies are either blue spirals or red ellipticals



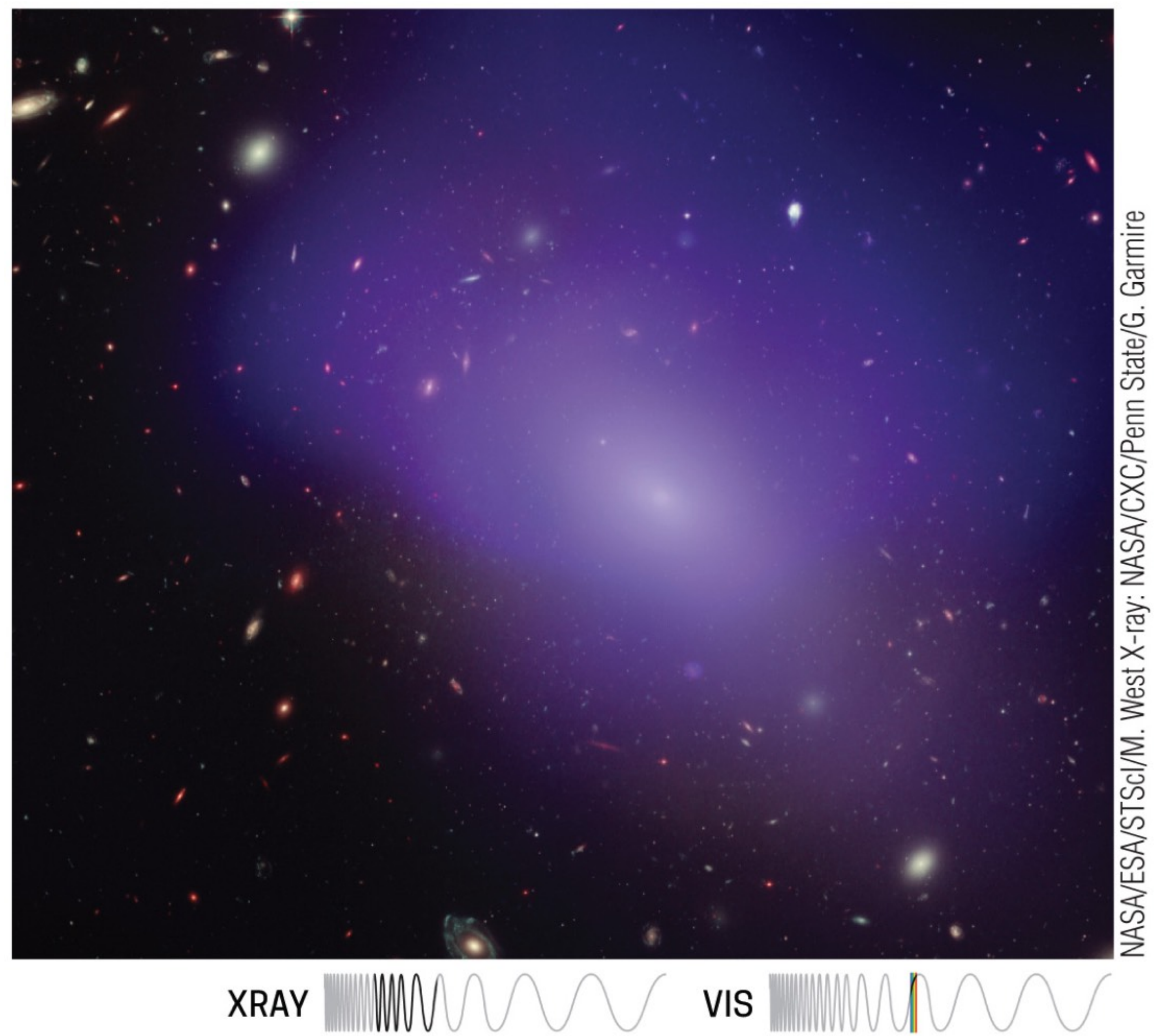
Galaxies in the Current Universe

Spiral Galaxies: Ongoing Star Formation in Spiral Arms

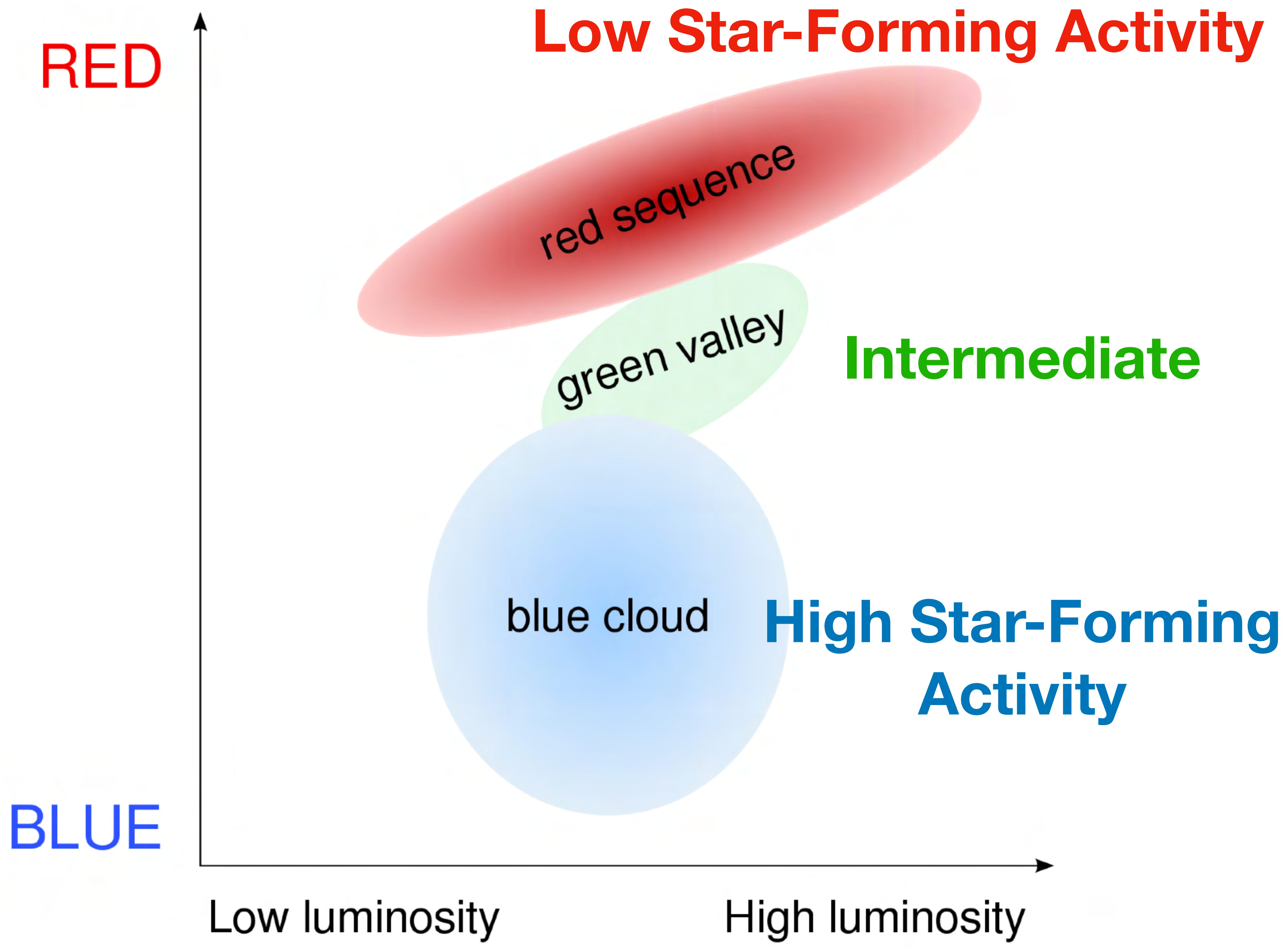
- Spiral arms contain cold gas and dust that get compressed into clouds.
  - Cold gas can form into molecular clouds, out of which stars form.
- Star formation occurs in the spiral arms and produces a blue color.
  - Blue light comes only from young stars.

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?



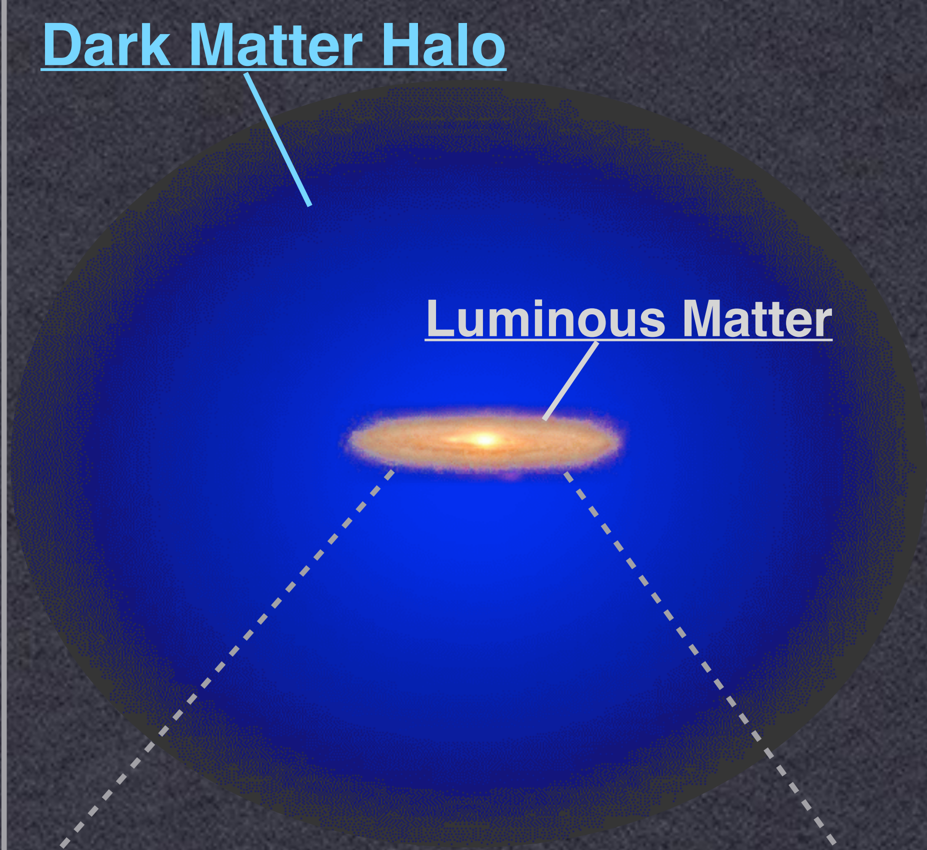
Color-Magnitude Diagram of Galaxies



Chap 5: Galaxies and Active Galactic Nuclei

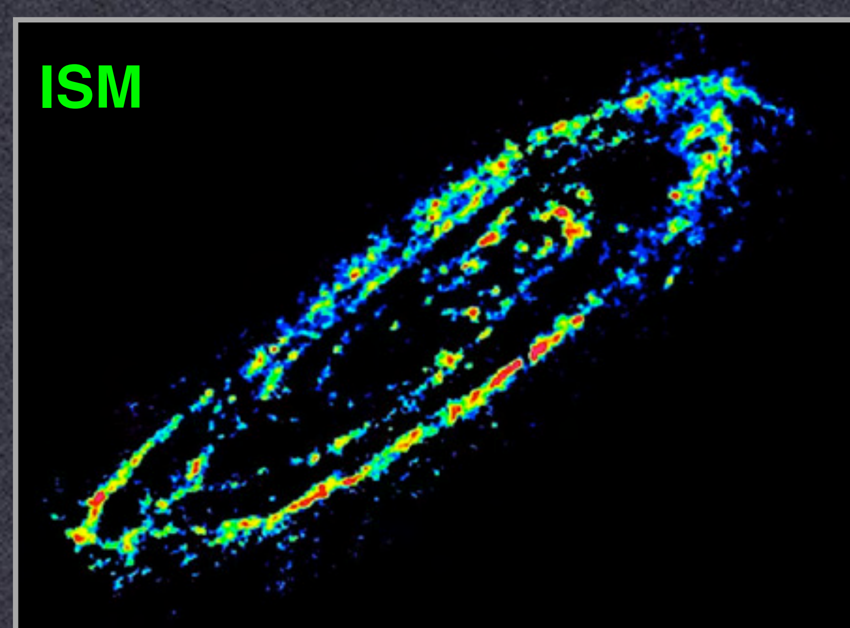
- Astronomers' distance ladders to reach beyond 100 Mpc
- Evidence of dark matter in galaxies and clusters
- Complex stellar population in galaxies (MW as example)
- Evidence of supermassive black holes at the centers of massive galaxies
- The color-magnitude diagram
- How morphology is related to the stellar population?

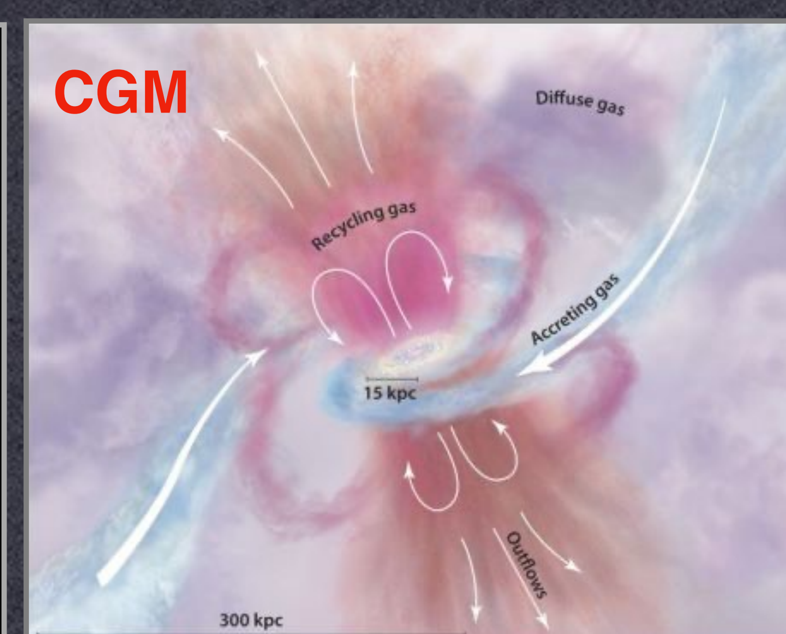
M31: a massive disk galaxy today



- Total Dynamical Mass: $1.2 \times 10^{12}\ M_{\odot}$
- Supermassive Black Hole: $\sim 10^{8}\ M_{\odot}$
- Dark Matter (~84% or 5/6): $\sim 10^{12}\ M_{\odot}$
- 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





Summary: Tools for detecting supermassive black holes

- **Resolve the event horizon**
  - $r_s = \frac{2GM_{\rm BH}}{c^2} = 3\,{\rm km}\,\left(\frac{M_{\rm BH}}{1M_\odot}\right) = 2\,{\rm AU}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$
  - Aperture synthesis with a network of mm-wave telescopes
  - Minimizing the diffraction limit: $\theta = \lambda/D$
- **Resolve the sphere of influence**
  - $r_* = \frac{GM_{\rm BH}}{\sigma_*^2} = 11\,{\rm parsec}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{200\,{\rm km/s}}{\sigma_*}\right)^2$
  - stellar and gas kinematics near galactic center
  - Adaptive Optics or Space Telescopes like HST/JWST
- **Detect the incredible accretion energy**
  - $L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,{\rm yr}^{-1}}\right)$
  - Active Galactic Nuclei (AGN), ~1% of all galaxies

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**:**

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