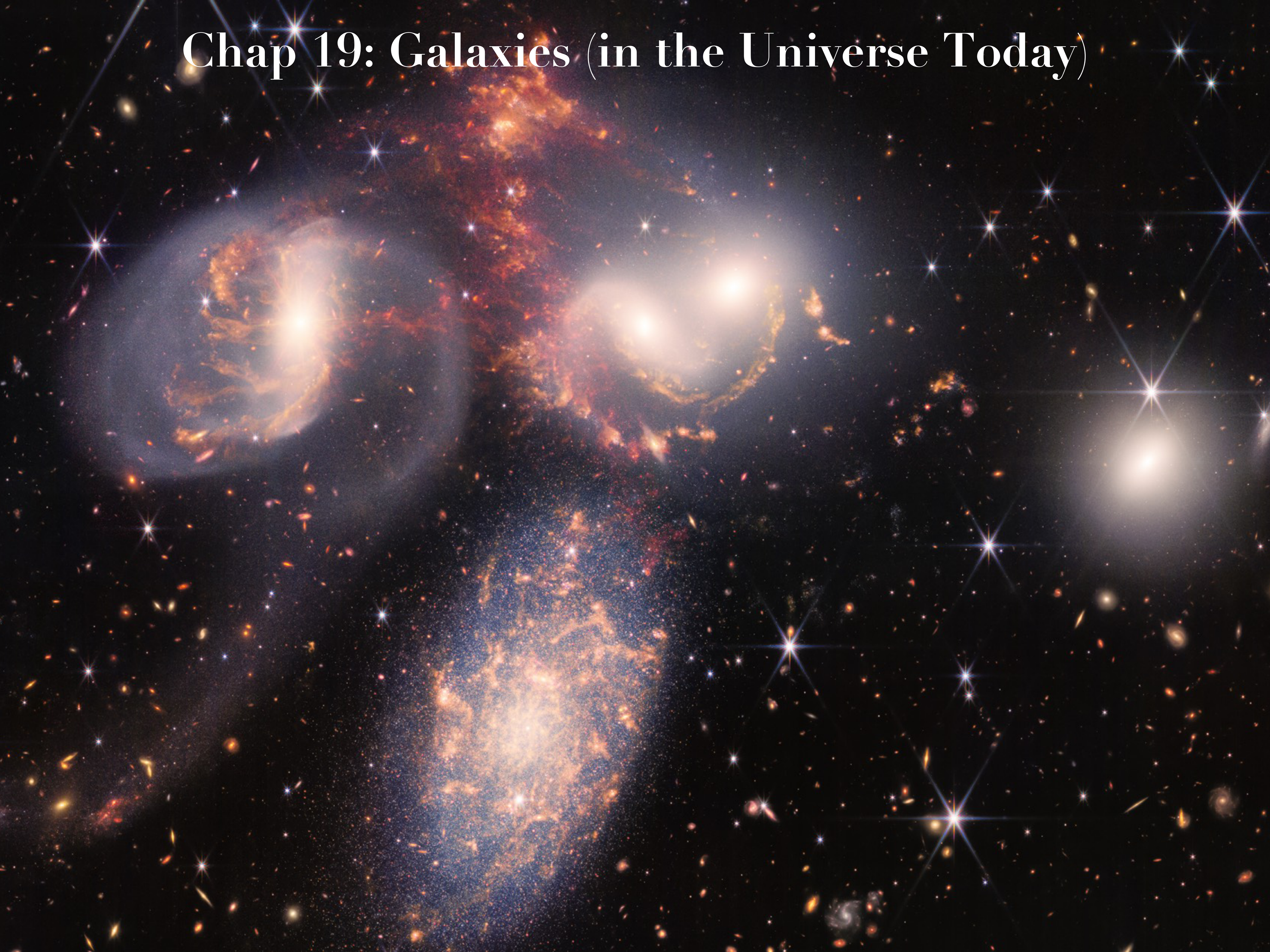
Chap 19: Galaxies (in the Universe Today)



Chap 19: Galaxies

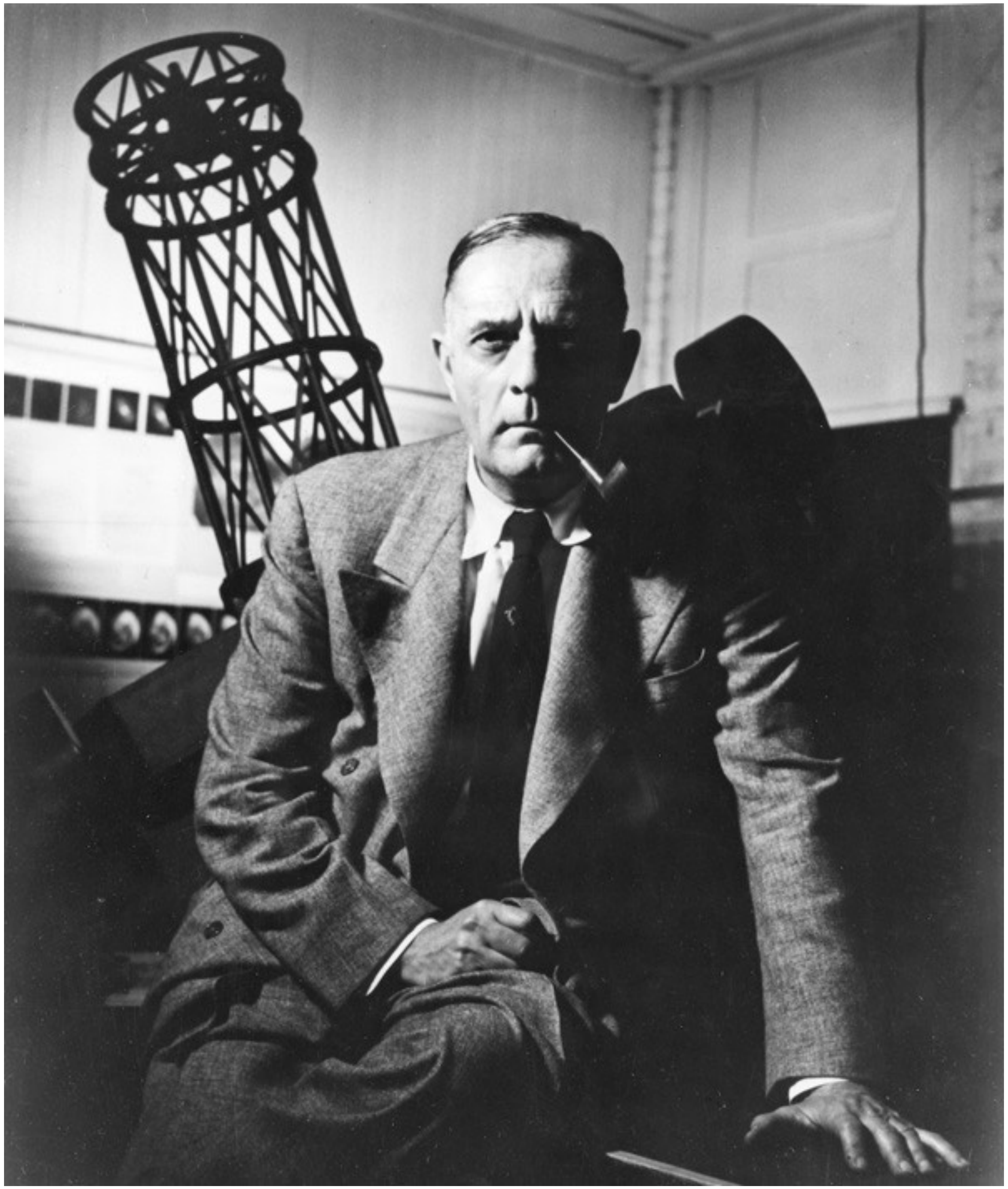
- How to determine distances to galaxies? What is the distance ladder?
- What are the morphologies of galaxies today?
- How morphology is related to the stellar population?
- How orbits of stars and galaxy morphology are intertwined?
- Evidence of dark matter
- Evidence of supermassive black holes &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

Nebulae or Island Universes?

Are They “Nebulae” or “Island Universes”?

- Charles **Messier** and William and Caroline **Herschel** identified thousands of **fuzzy “nebulae”** in 18th century.
- 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** had calculated the Milky Way to be three times larger than previous estimates. 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**.

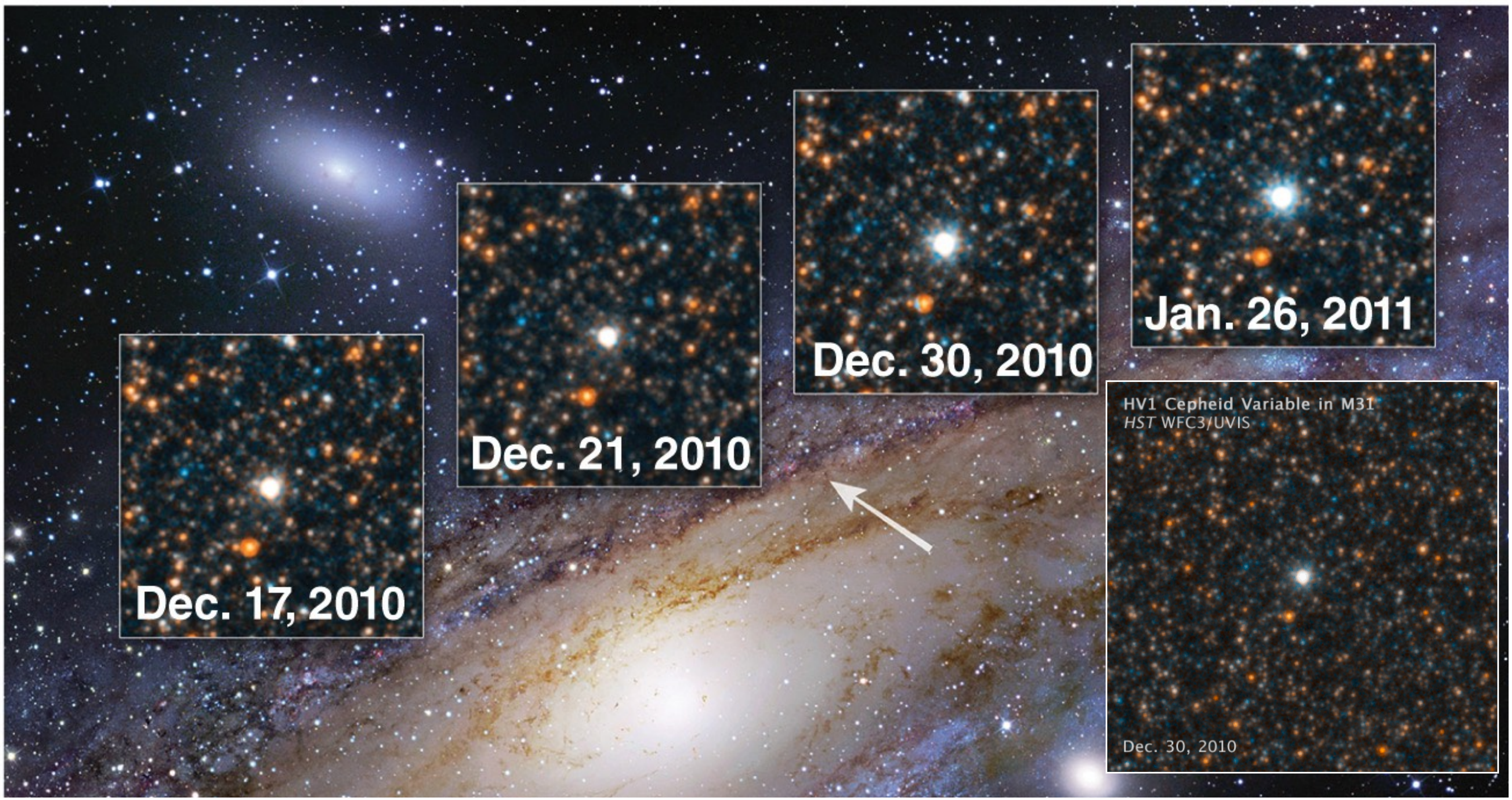
Edwin Hubble (1889-1953)



- Born in **Marshfield, Missouri**
- B.S. & Ph.D. from University of Chicago
- Key accomplishments:
  - M31's distance: 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.

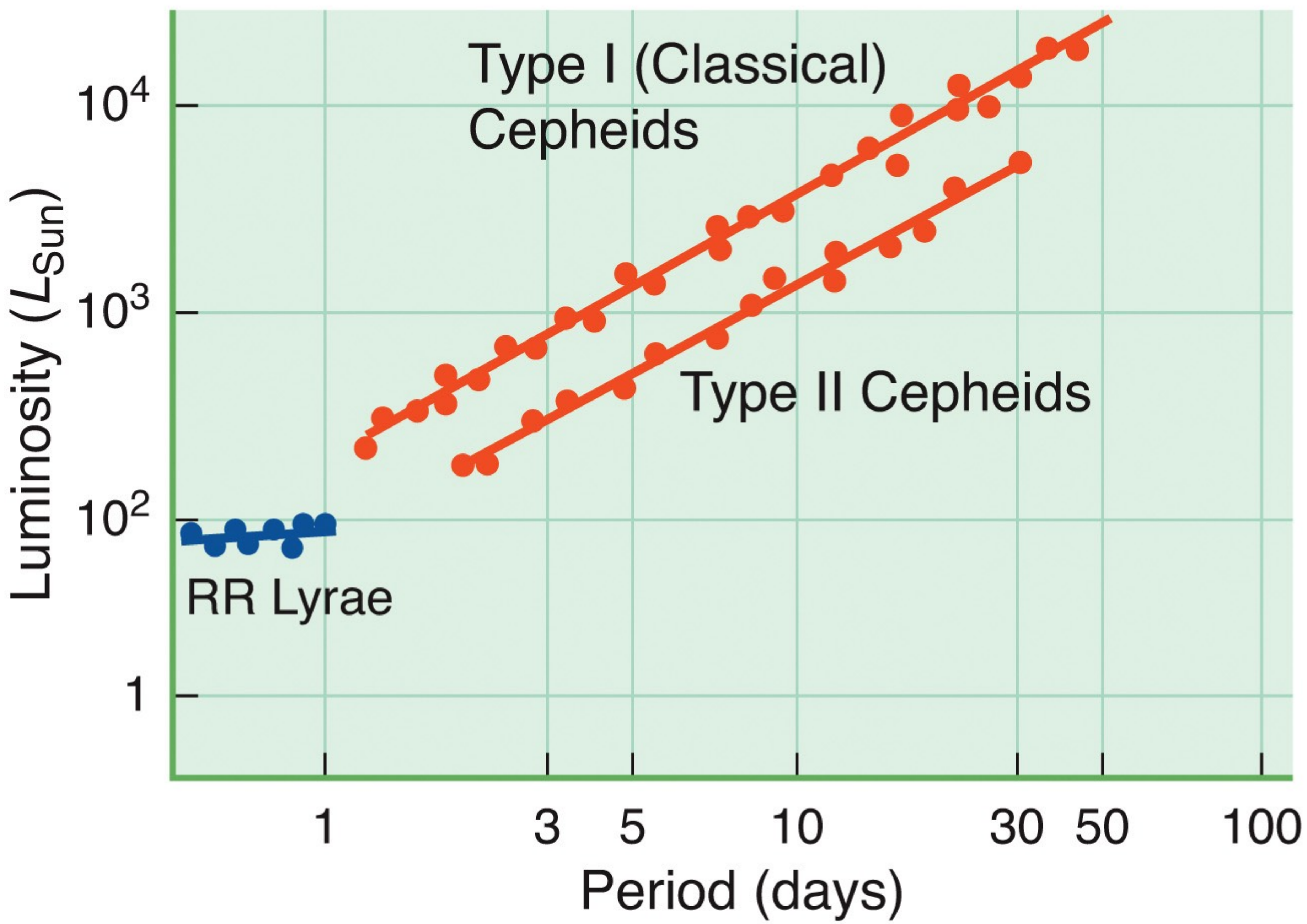
The debate was resolved by observations

- 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.



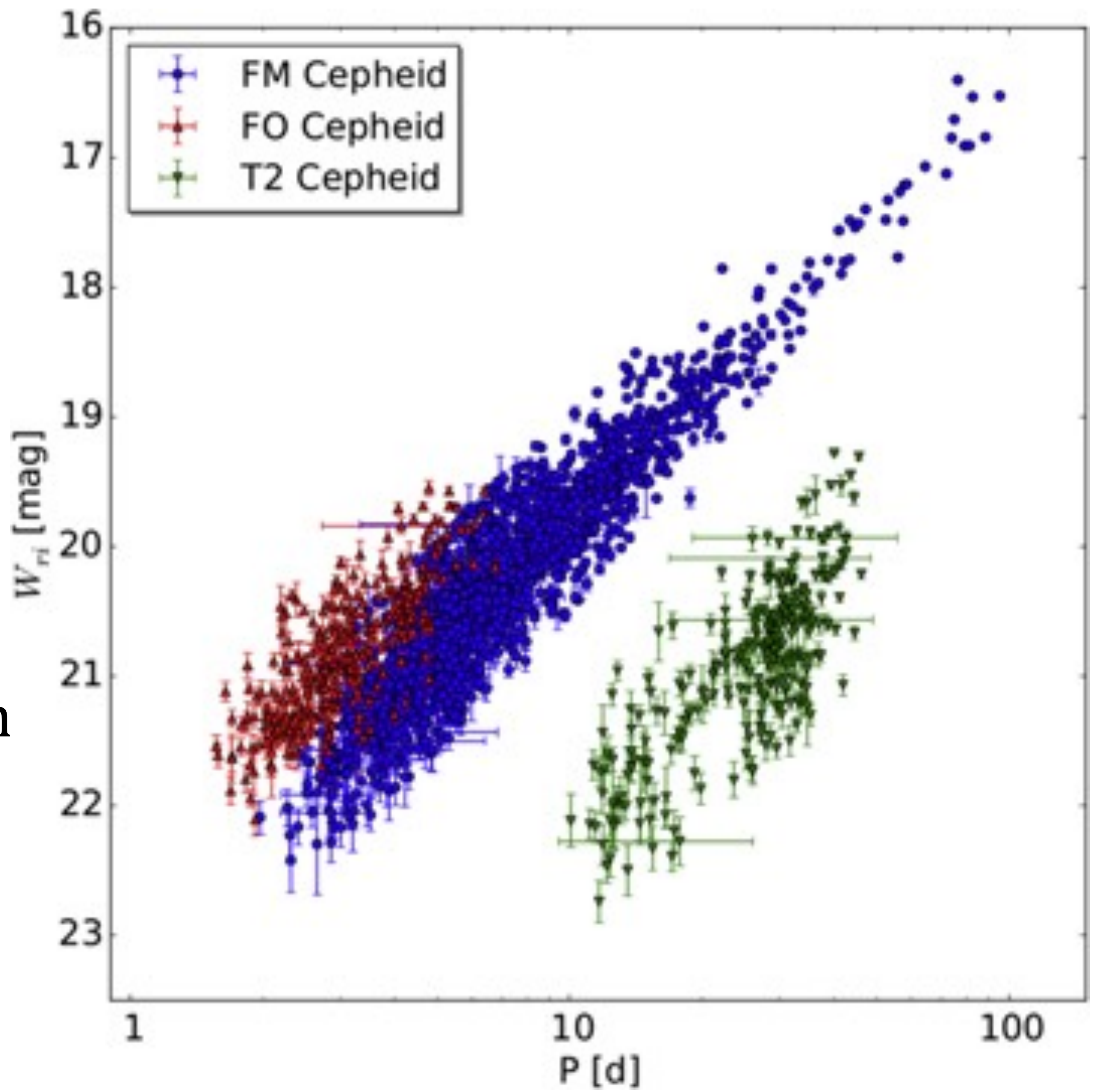
Period-Luminosity Relations (Leavitt 1912)

- $M_V = -2.43\log(P_{\text{day}}) - 1.62$ (Classical Cepheids, Benedict et al. 2007)
- This period-luminosity relationship is important for determining distances to other galaxies: *Measuring period gives luminosity (absolute magnitude), which combined with apparent magnitude, gives the distance modulus (thus distance):* $m - M = 5\log(d_{\text{pc}}) - 5$



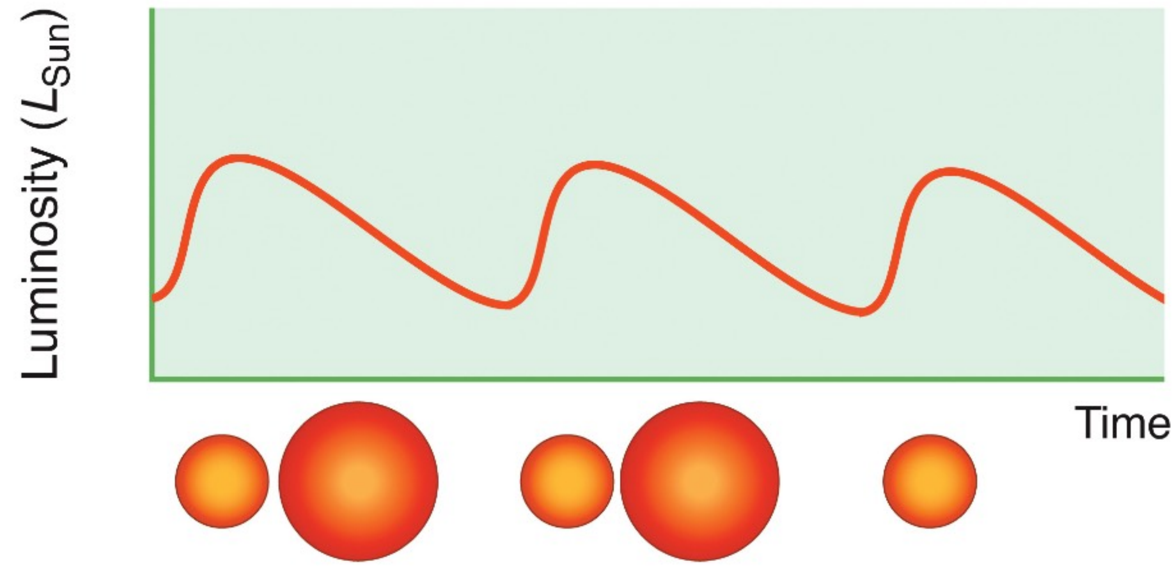
Period-Luminosity Relation of Different Types of Cepheids

- Based on the shape of the light curve, astronomers have classified three main types of Cepheids:
  - FM - Fundamental Mode
  - FO - First Overtone
  - T2 - Type II
- The P-L relations of the three types differ from each other, as illustrated on the diagram using ~2000 Cepheids in M31 (Kodric+2018; Fig 10).

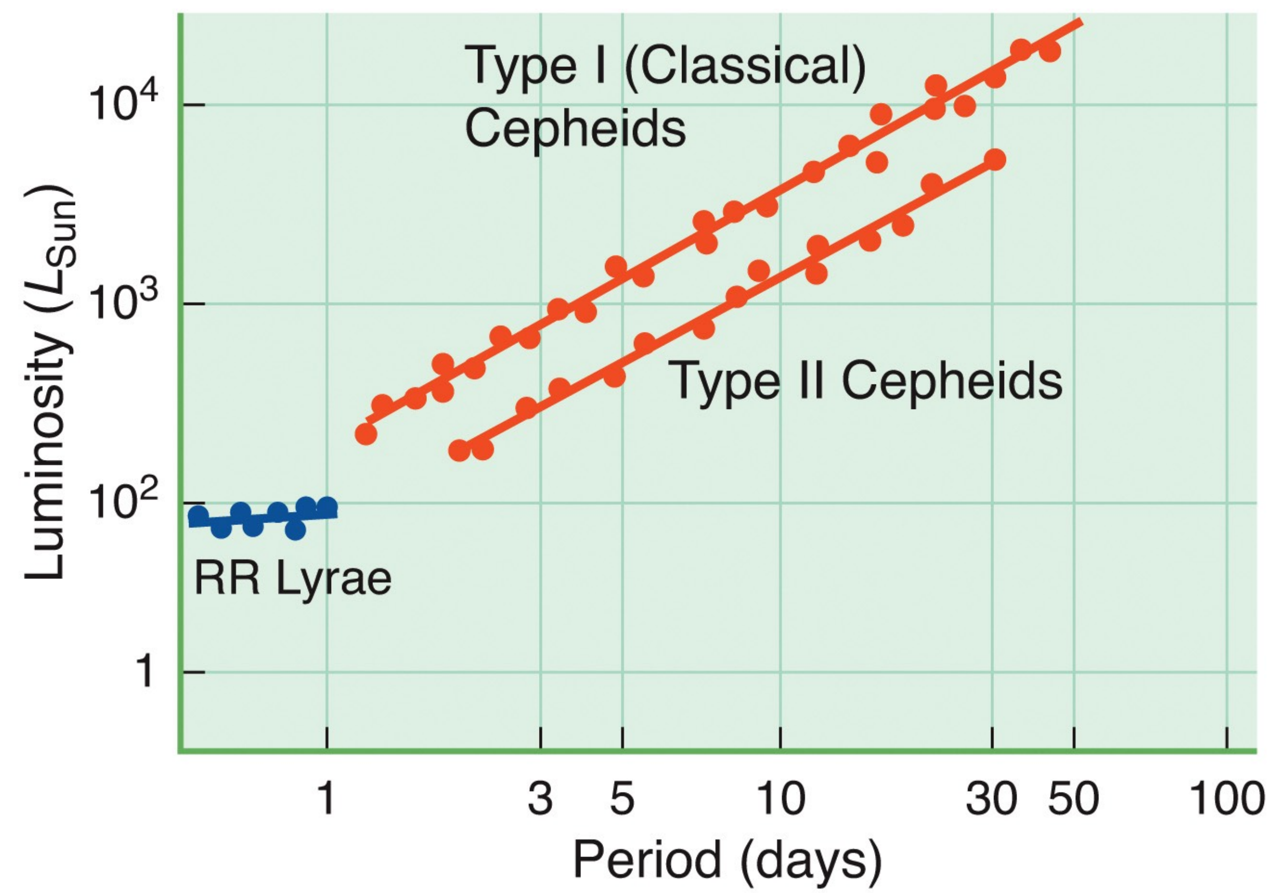


How to Tell Apart the Different Types of Pulsating Variable Stars?

- **Type I Cepheid variables**
  - Cepheid variables are high-mass stars becoming supergiants.
  - They have periods from 1 to 100 days.
  - More luminous stars have longer periods.
- **RR Lyrae variables and Type II Cepheid variables**
  - These are low-mass stars on the horizontal branch.
  - They are less luminous than Cepheid variables.



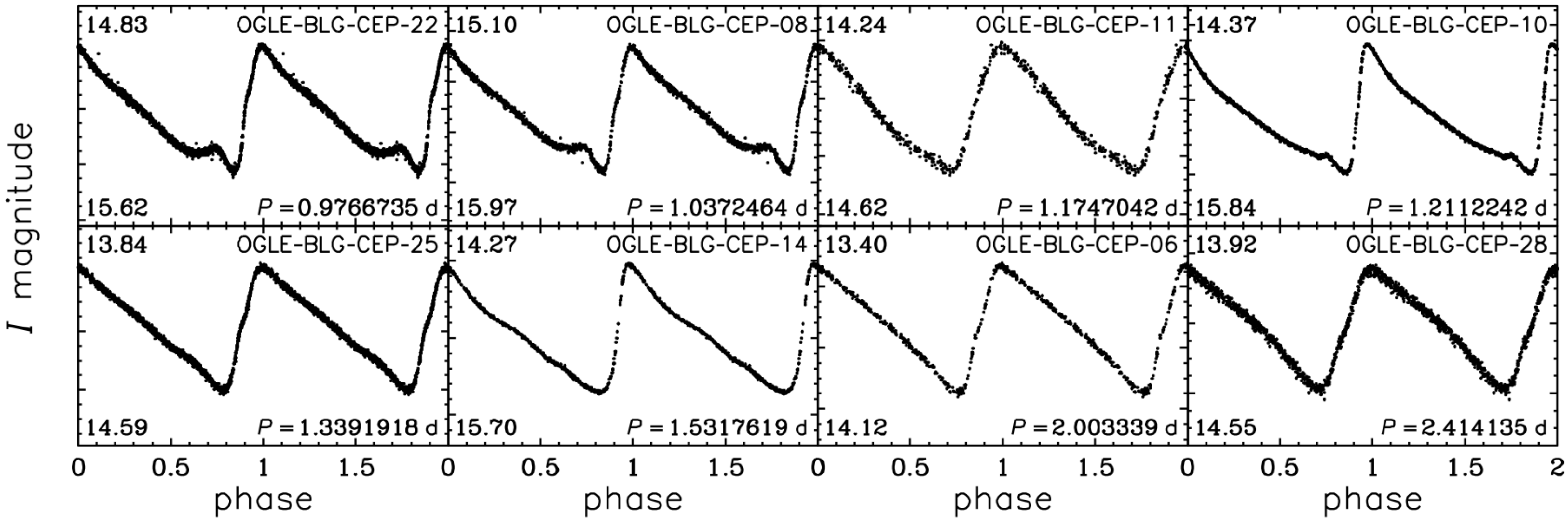
Luminosity vs. time



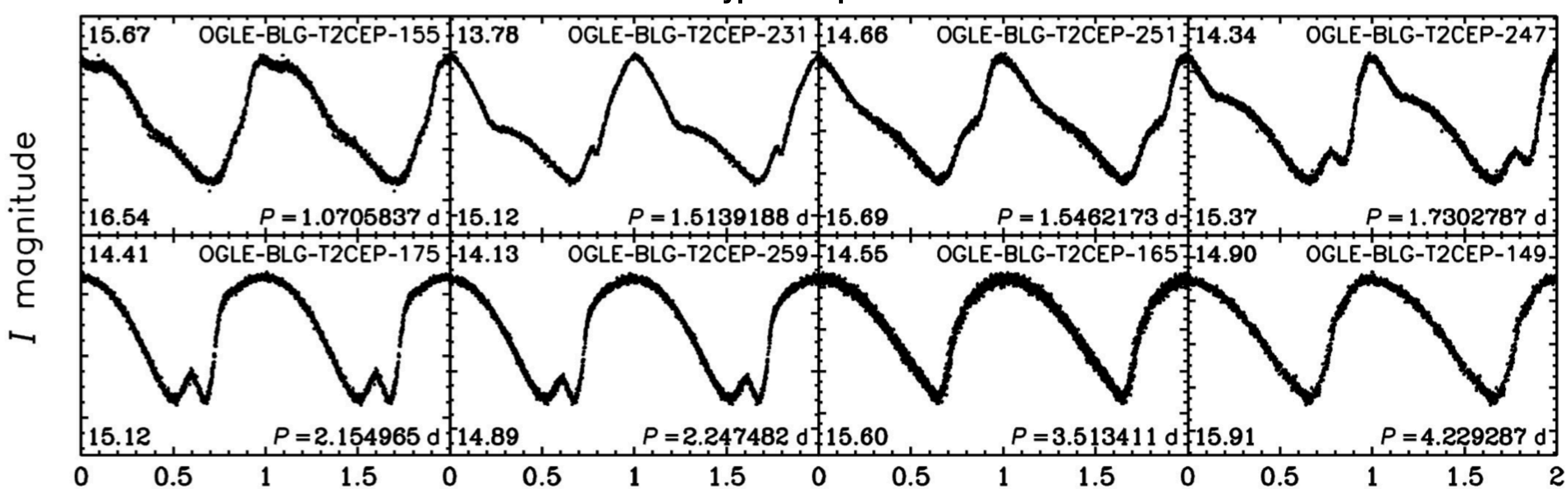
Period-luminosity relationship

Cepheids Light Curves - Type I vs. Type II Cepheids

Classical (or Type I) Cepheids



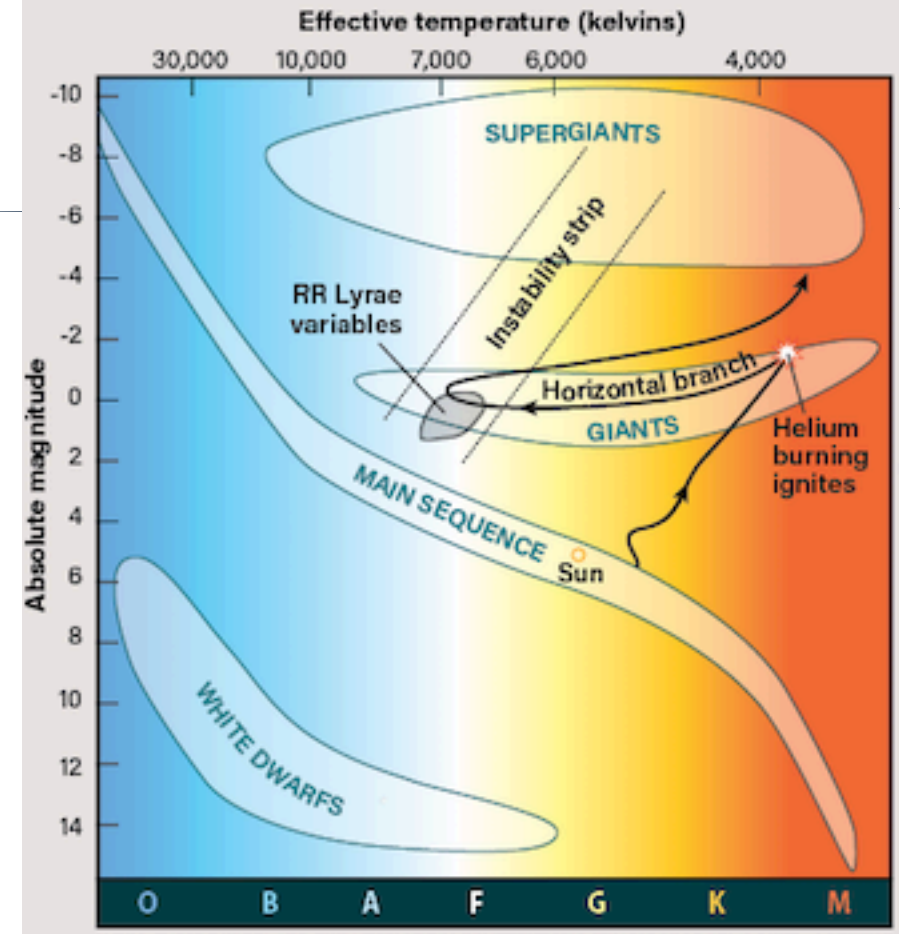
Type II Cepheids



https://arxiv.org/abs/1112.1406

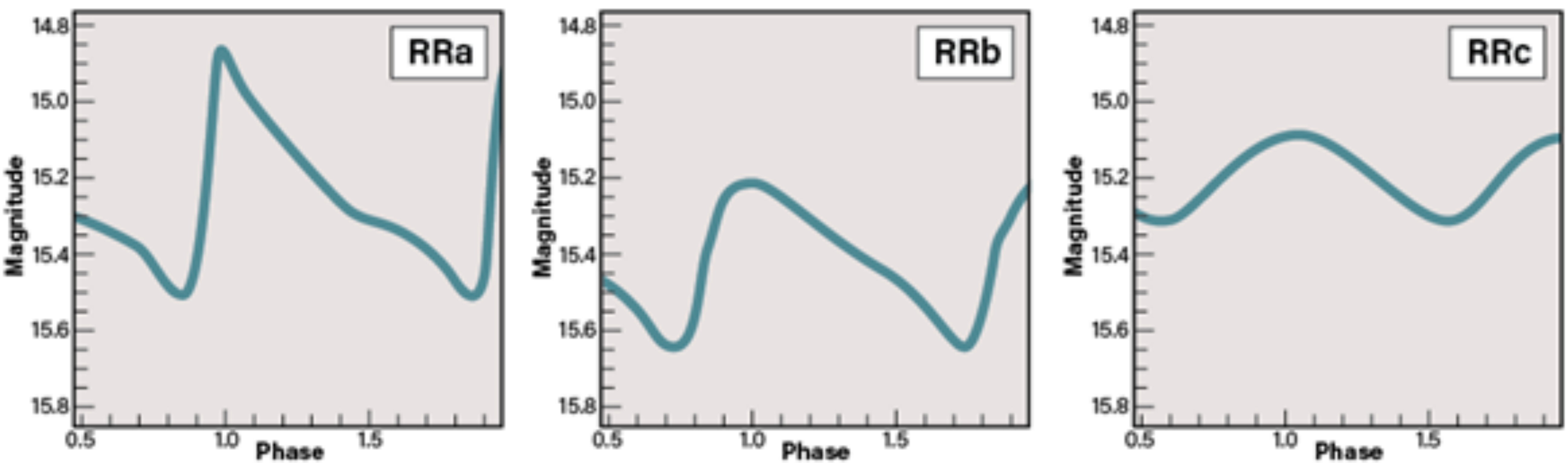
RR Lyrae - Shorter Periods

- RR Lyrae variables have periods shorter than one day.
- Like Cepheids, their light curves show a variety shapes.
- They are low-mass stars in the horizontal branch phase.



RR LYRAE LIGHT CURVES

There are two major classes of RR Lyrae stars, based on the shape of their light curve, which measures a star's brightness over time: RRab- (left, middle) and RRc-type stars. ASTRONOMY: ROEN KELLY



https://astronomy.com/magazine/news/2020/07/how-pulsating-stars-unlock-our-universe

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.

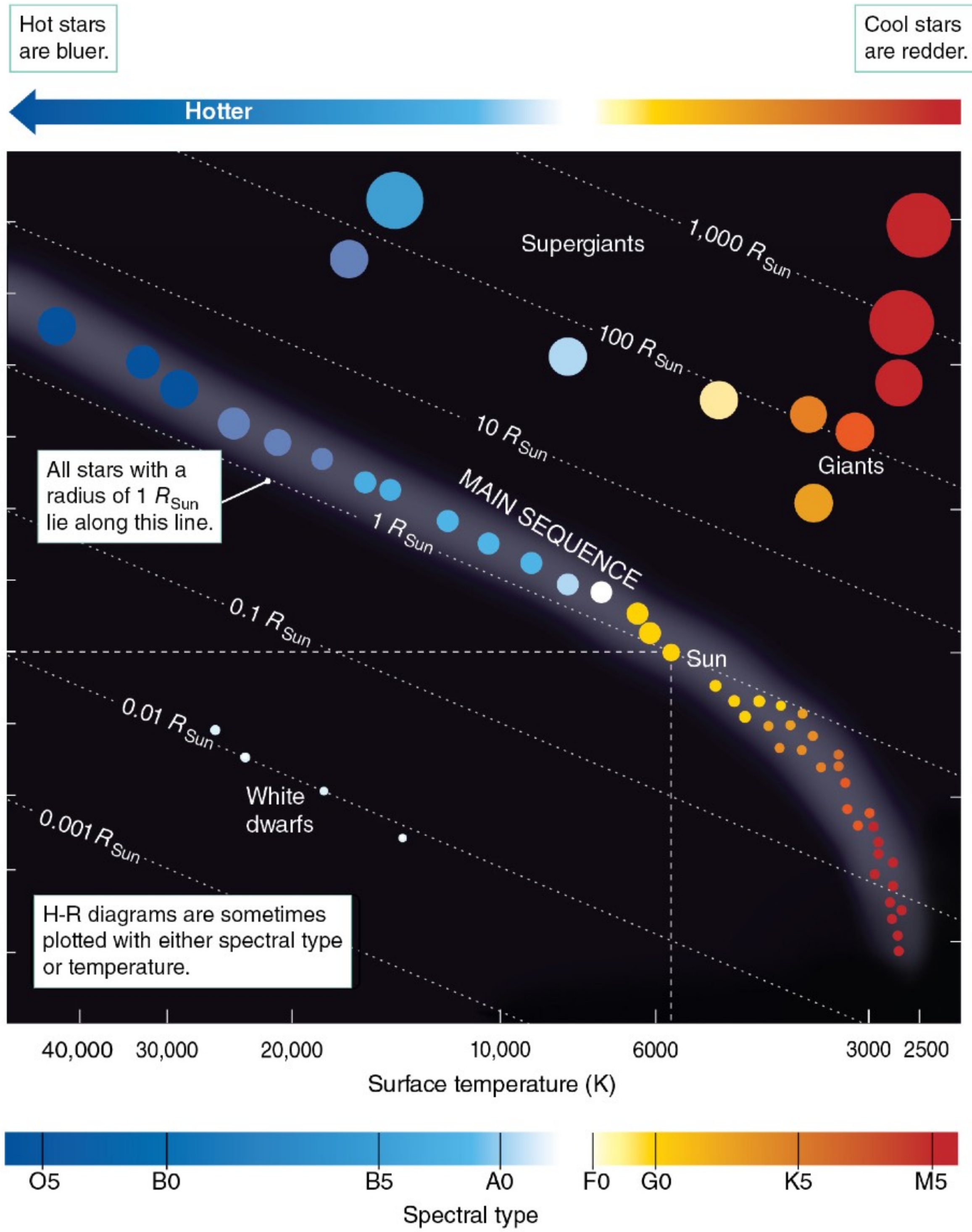
- **Parallax** uses geometry to measure the distances to stars.
- **Standard candles** are objects with a luminosity inferred from other properties, so that their brightness and luminosity can be combined to calculate a distance.
  - **Spectroscopic "parallax"** uses the luminosity-spectral type relation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

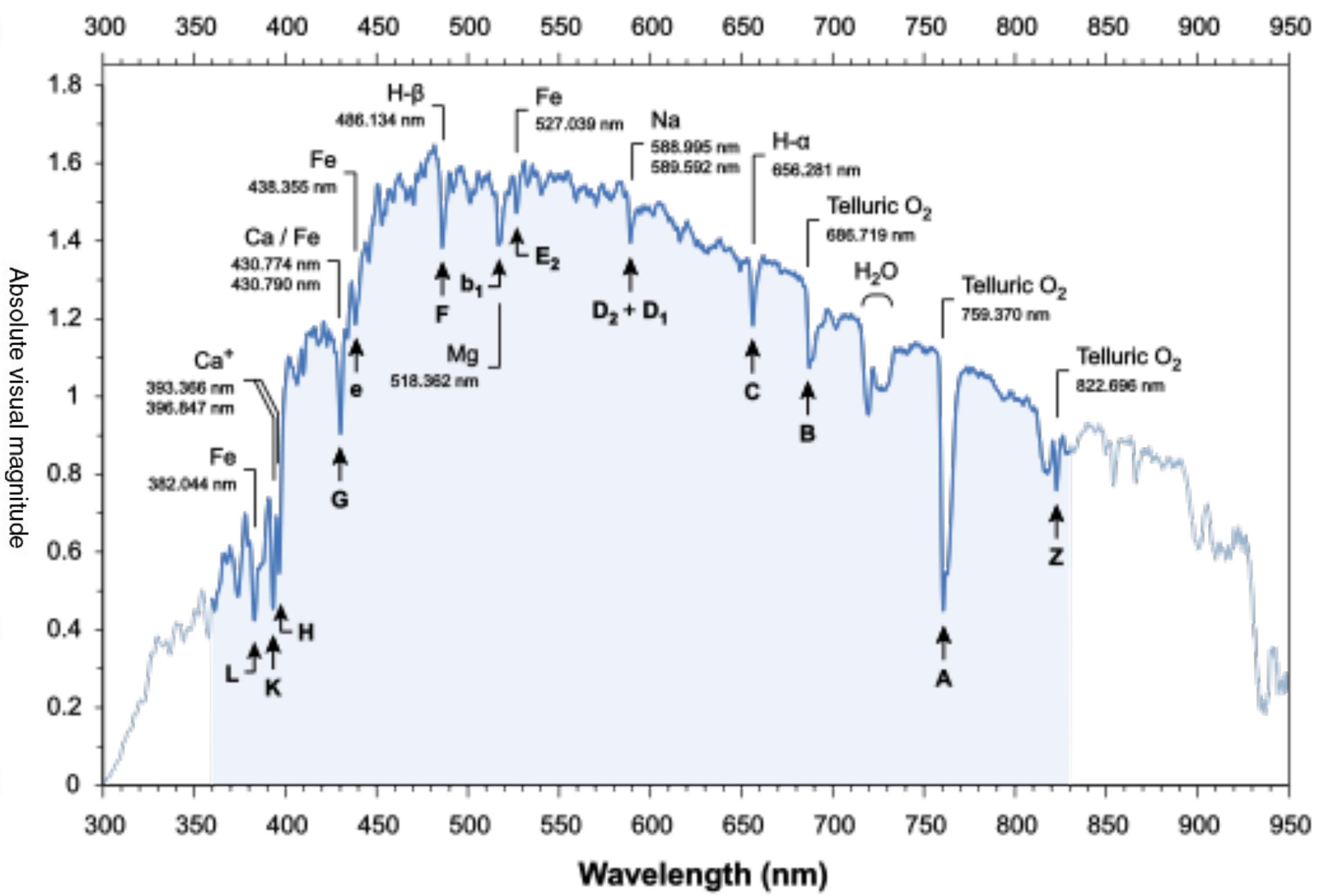
The Standard Candle Methods

- 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:

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

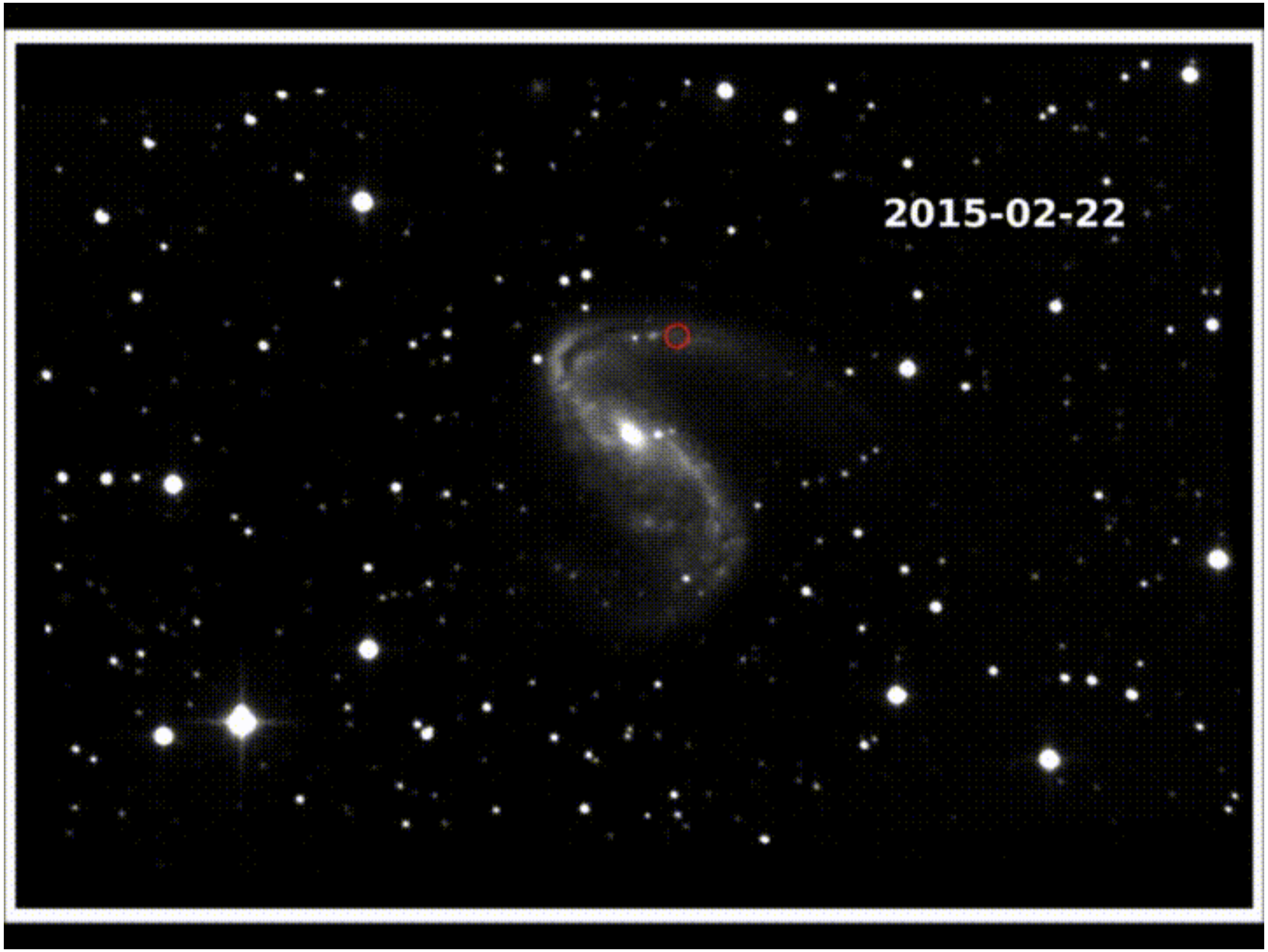
Standard Candle Method 1 — Spectroscopic "Parallax"



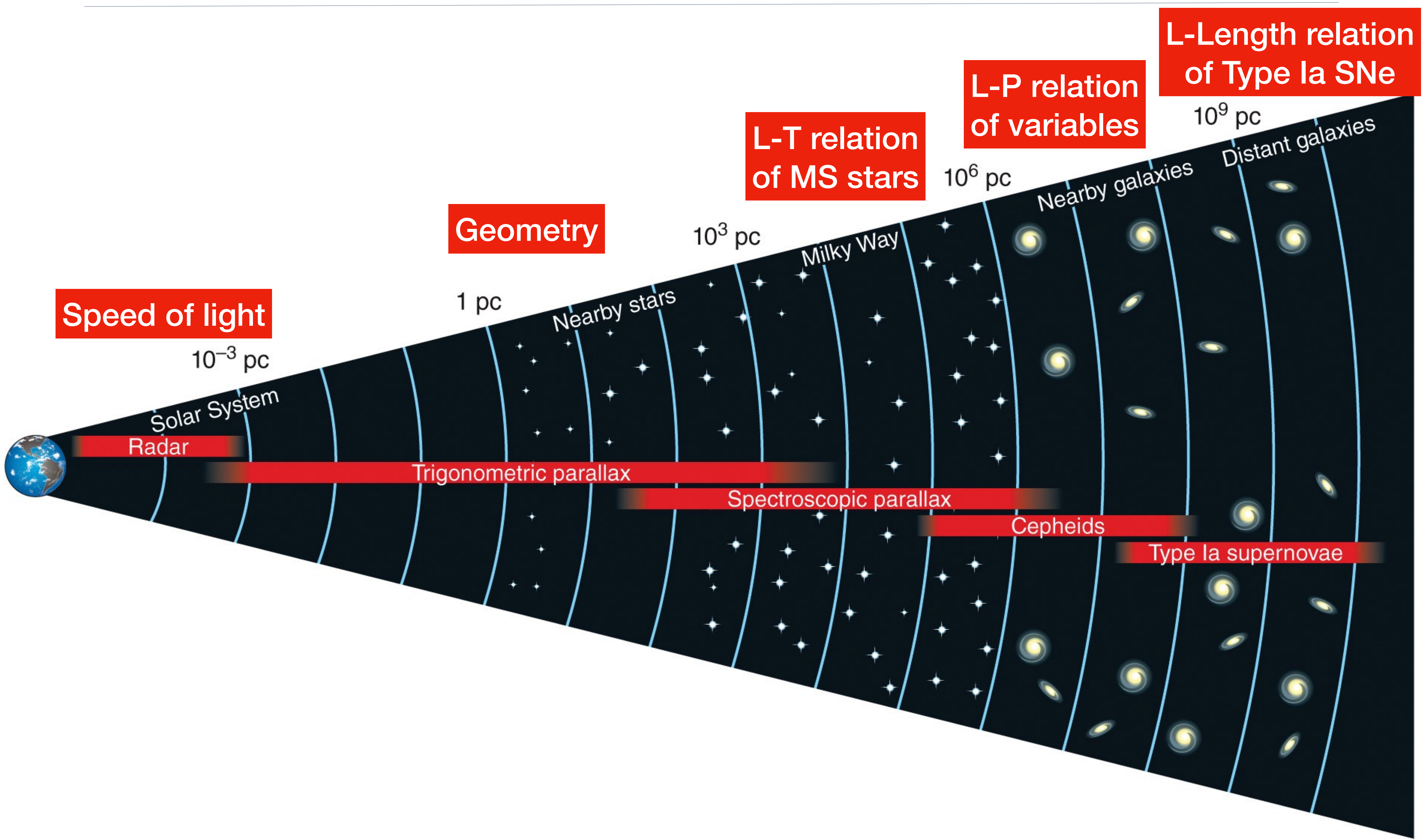


The Standard Candle Method 2 — Type Ia SNe

- 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 (the Chandrasekhar mass) to trigger the thermonuclear explosion, reaching a peak absolute magnitude of $\mathbf{M_V = -19}$.



The Distance Ladder from Solar System to Galaxies



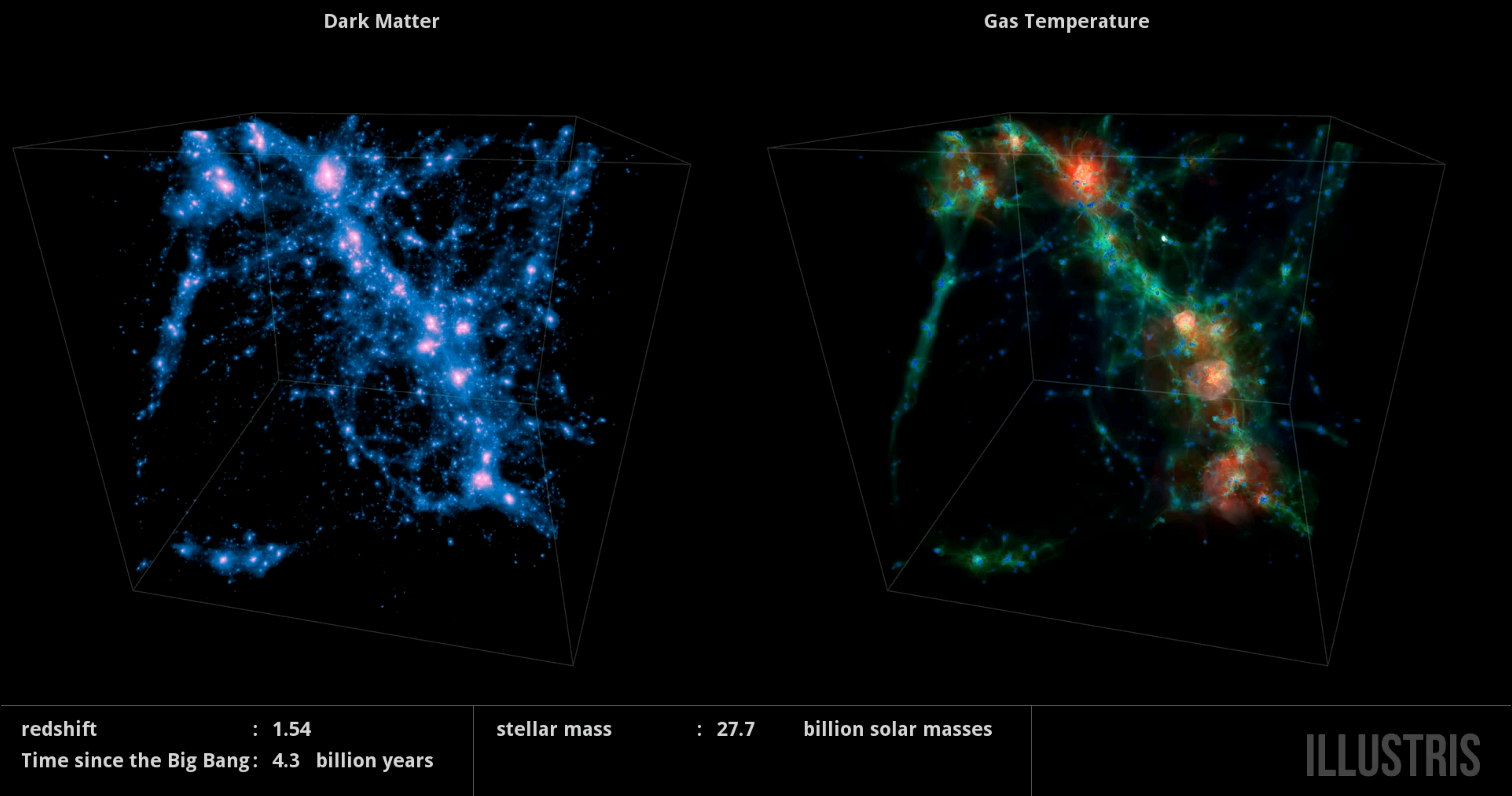
A Universe of Galaxies

- 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.

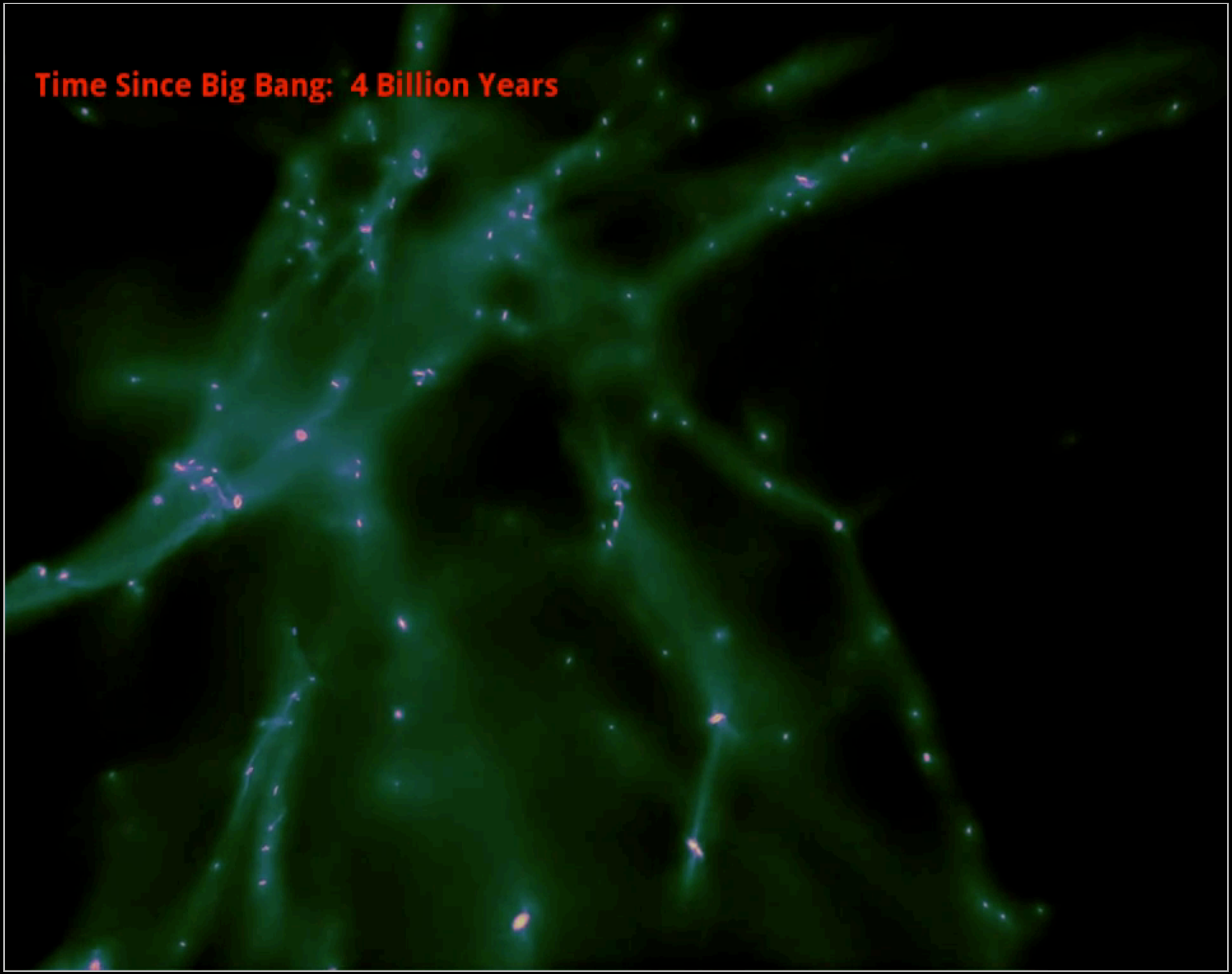

JWST

Galaxies evolve over time

Simulation of a Cube 30 Million Light Year Across



Simulation: showing only baryonic components



Galaxy evolution highly depends on environment

Massive Galaxies Today:

Spirals and Ellipticals

Spiral Galaxies

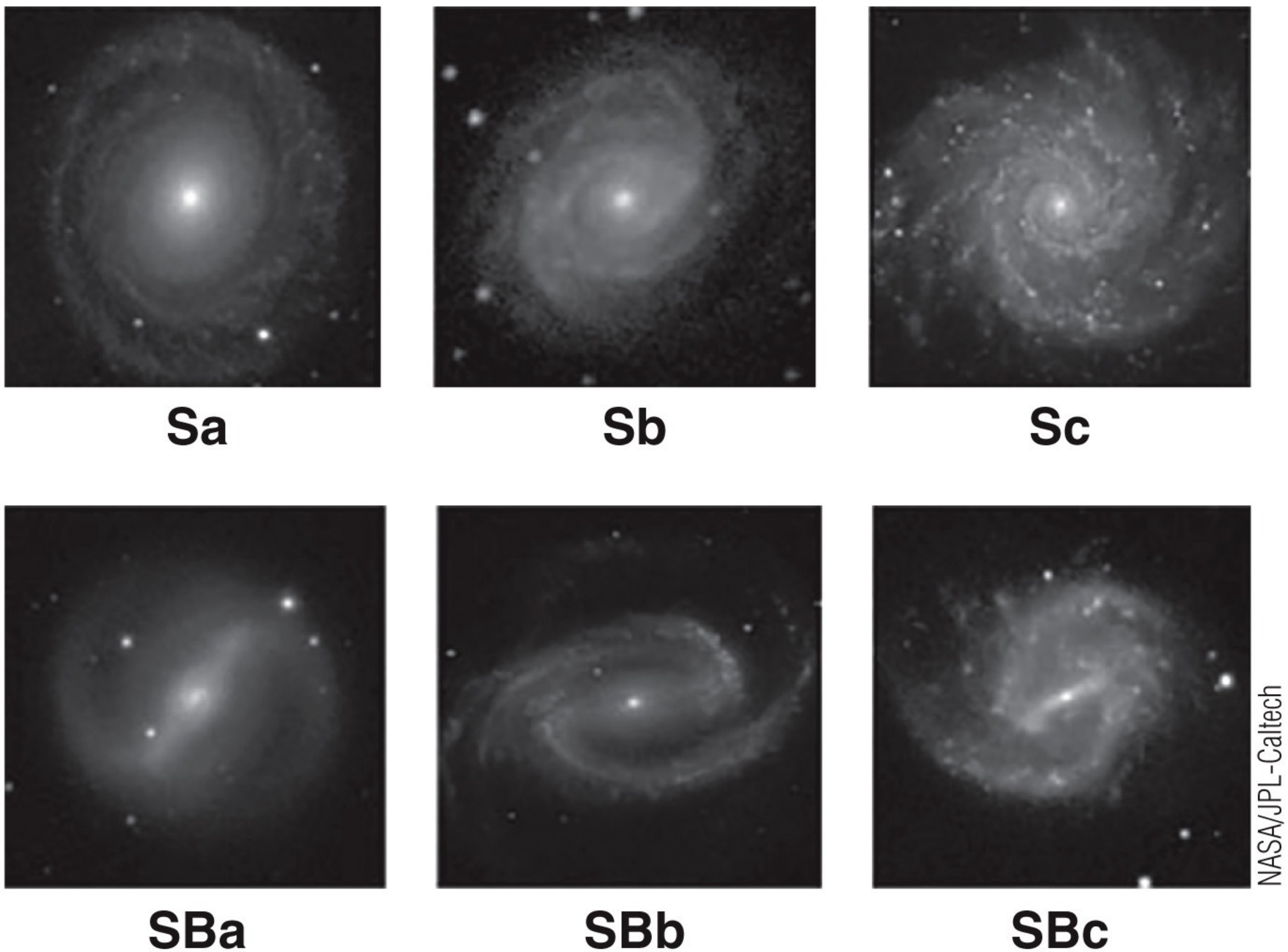
- **Spiral galaxies** have arms that lie in a flat disk and a central bulge that extends above and below the disk.
- There are two types of spirals: **regular** and **barred**.

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



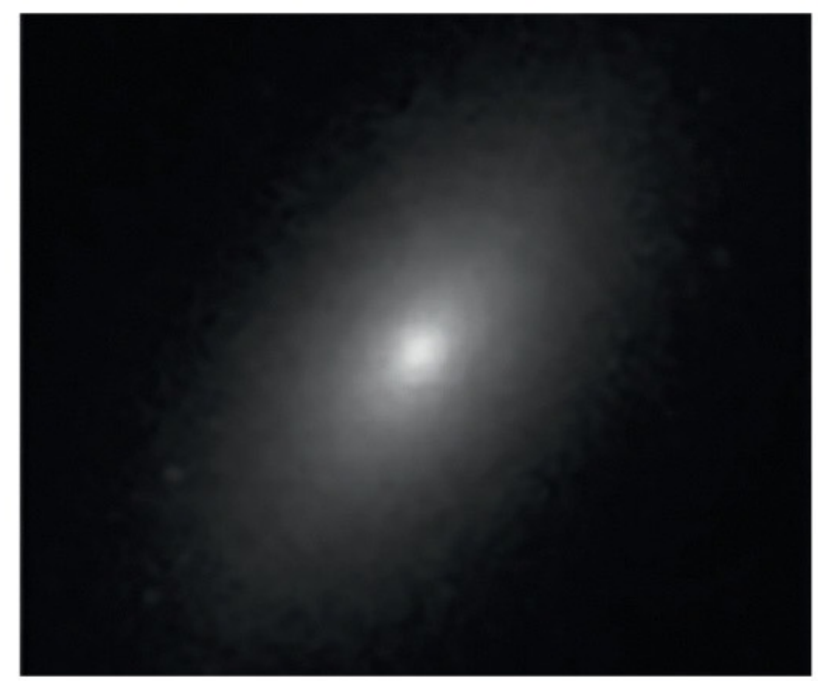
Elliptical Galaxies: e.g., Central Cluster Galaxy in Abell S740

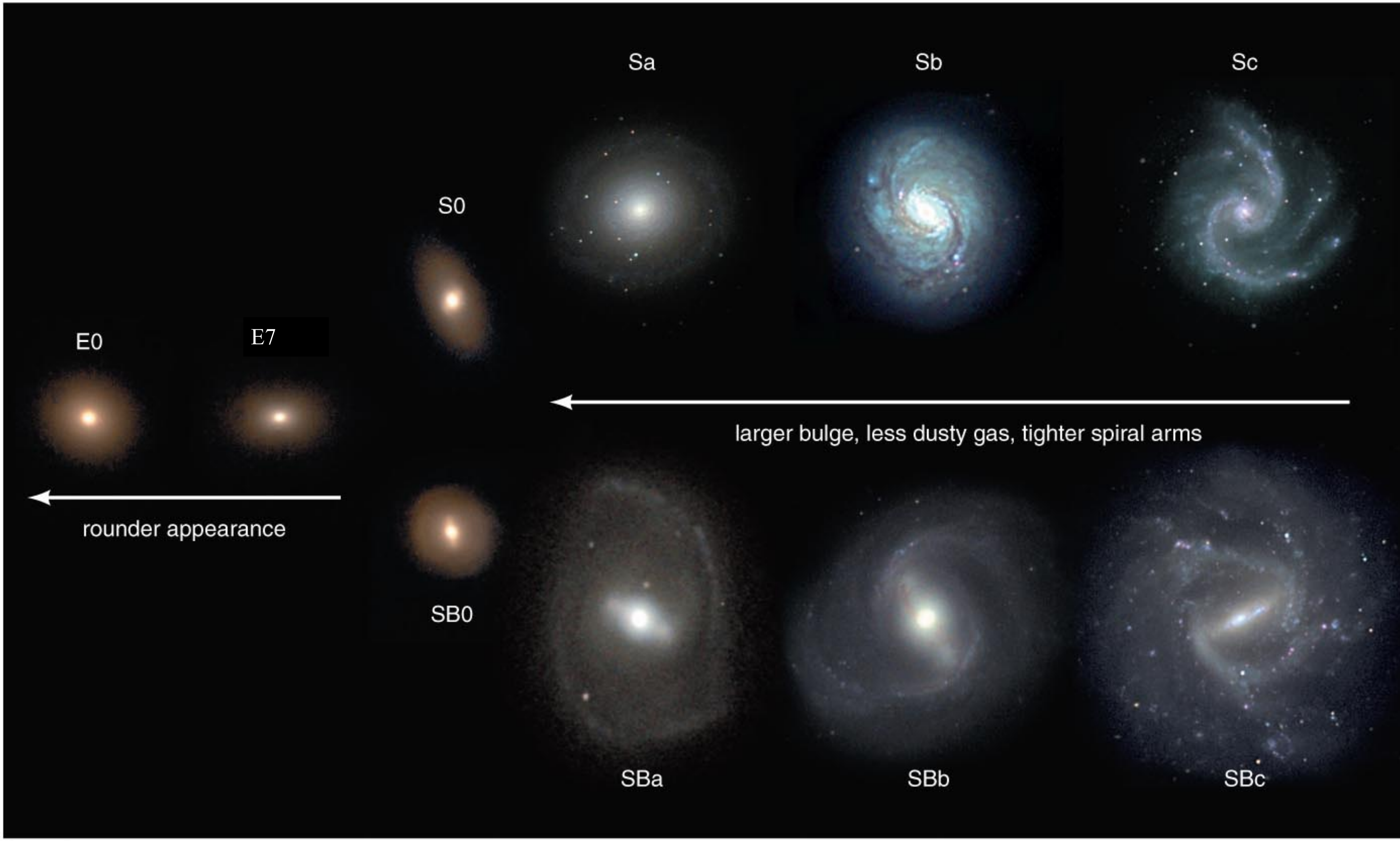
Elliptical Galaxy Classification

- **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

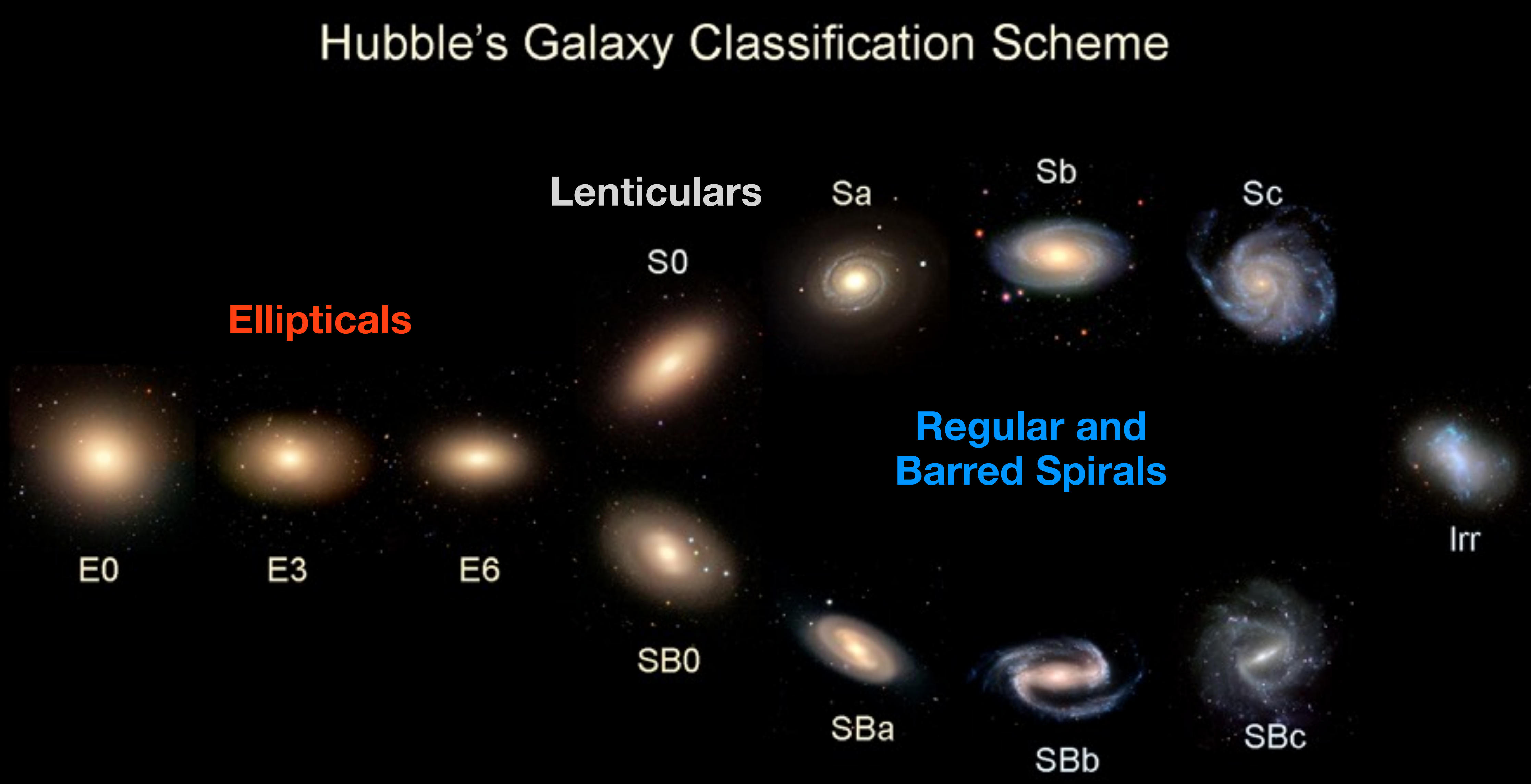
Caveat: geometrical effects

Two spiral galaxies: why they look so different?

Inclination Angles Change the Appearance of Disk Galaxies

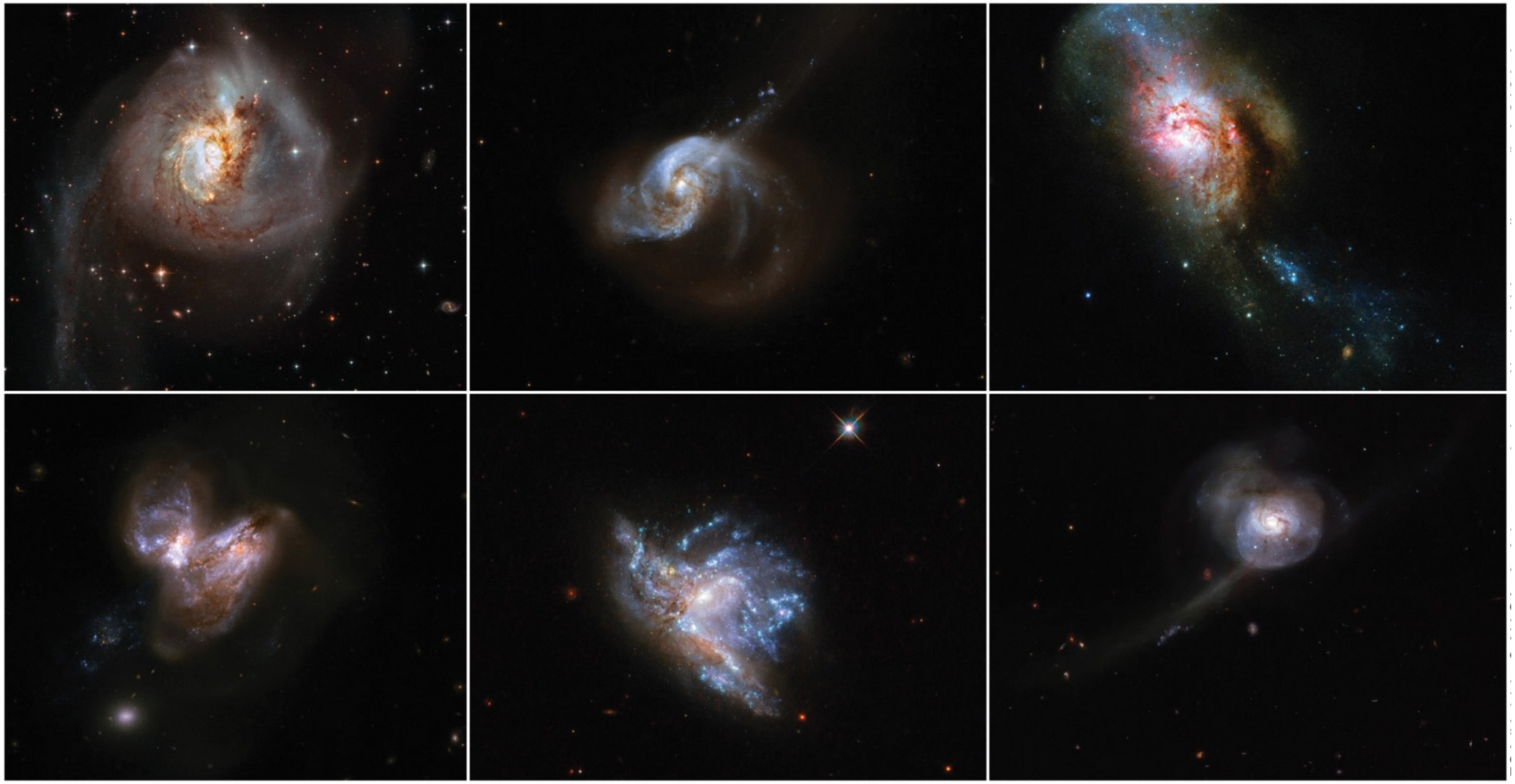
Irregular and Dwarf Galaxies

Hubble's Tuning Fork



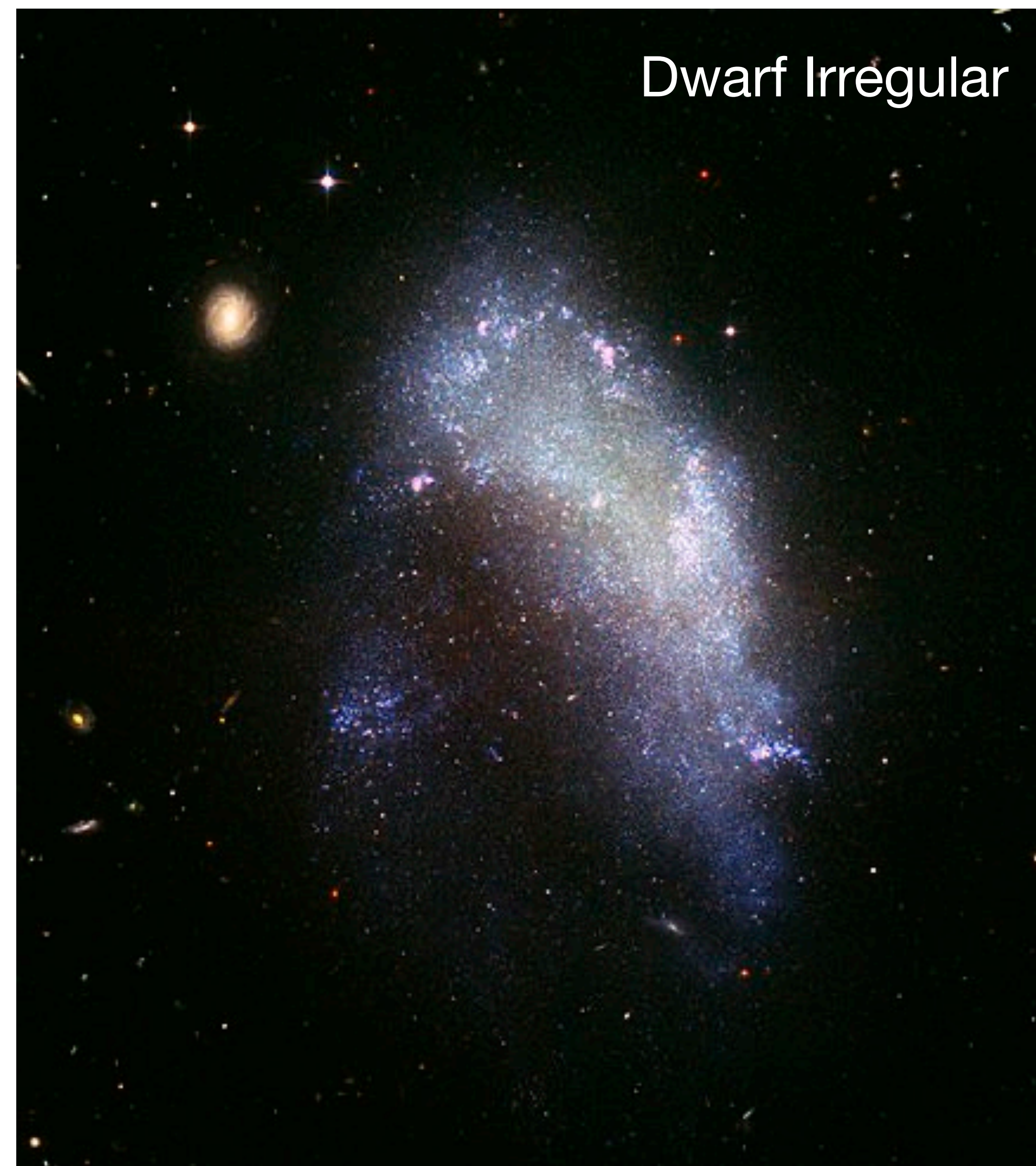
Massive Irregular Galaxies

- **Irregular galaxies** have no defined shape.
  - They are likely the product of a gravitational interaction between two galaxies.
- They are often blue in color, indicating significant star formation.
  - Many are forming stars at such a high rate that they are classified as starburst galaxies.

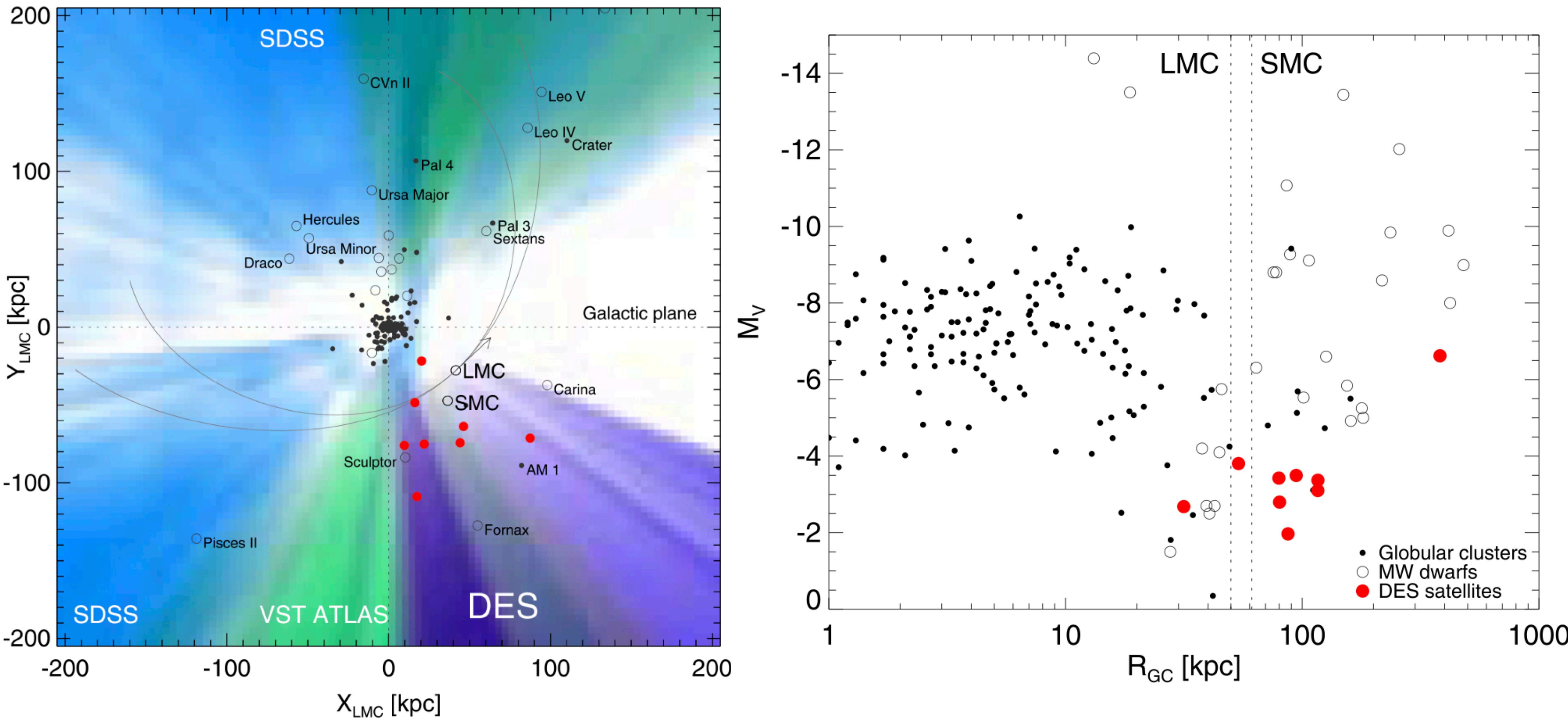


Dwarf Galaxies vs. Massive Galaxies

- **Dwarf galaxies** have **<10% the stellar mass** of the **Milky Way**.
- The largest dwarf galaxies are tens of thousands times more massive than the smallest dwarf galaxies.
- The surface brightness of dwarf galaxies is low, so hard to observe.



The Distribution of Dwarf Galaxies around the Milky Way



Koposov et al. 2015

Dwarf Galaxies: A Diverse Population

Bright dwarfs:

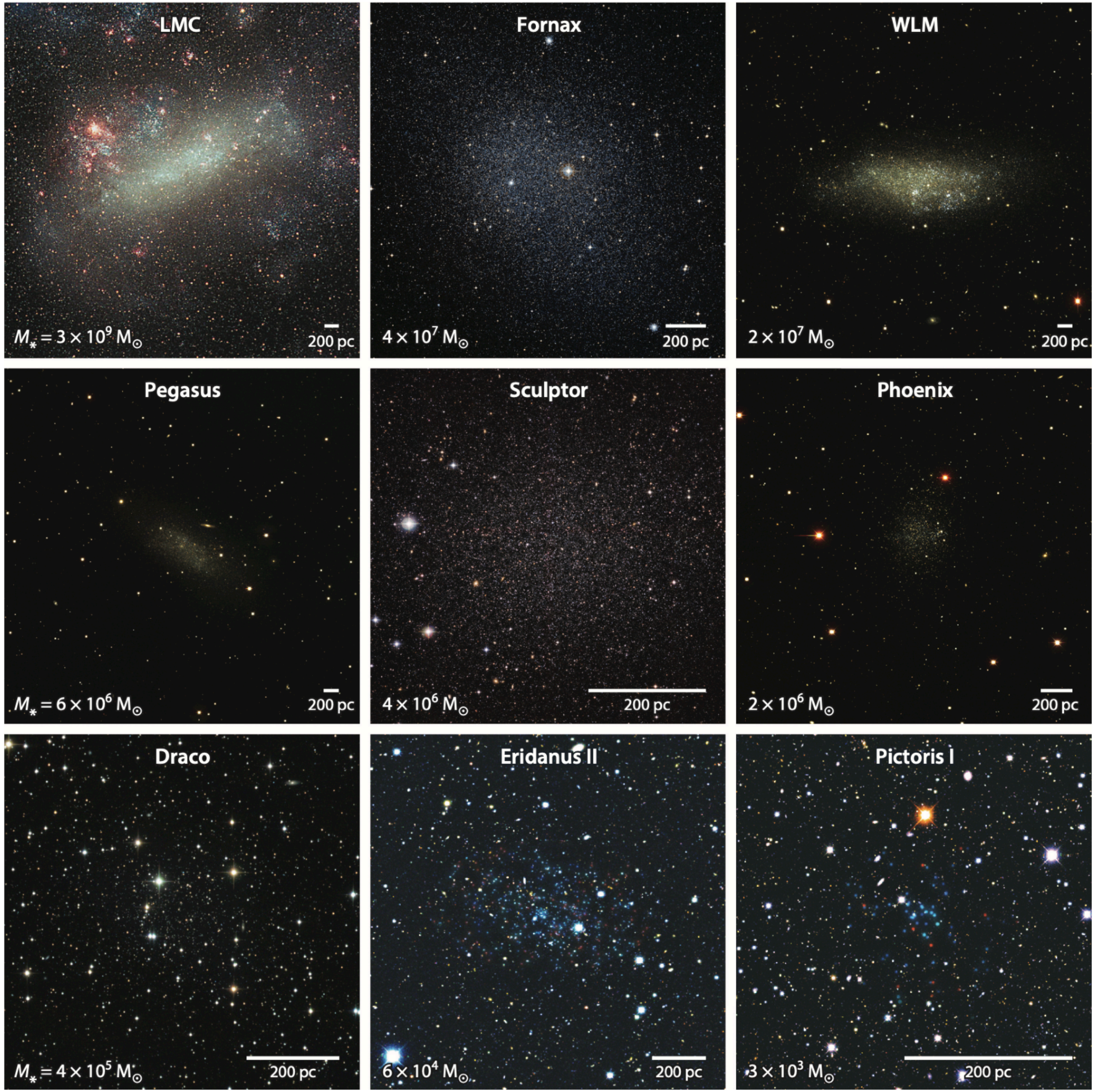
$M_\star \approx 10^8\ \mathrm{M}_\odot$,
$M_{\mathrm{vir}} \approx 10^{11}\ \mathrm{M}_\odot$,
$M_\star/M_{\mathrm{vir}} \approx 10^{-3}$

Classical dwarfs:

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

Ultra-faint dwarfs:

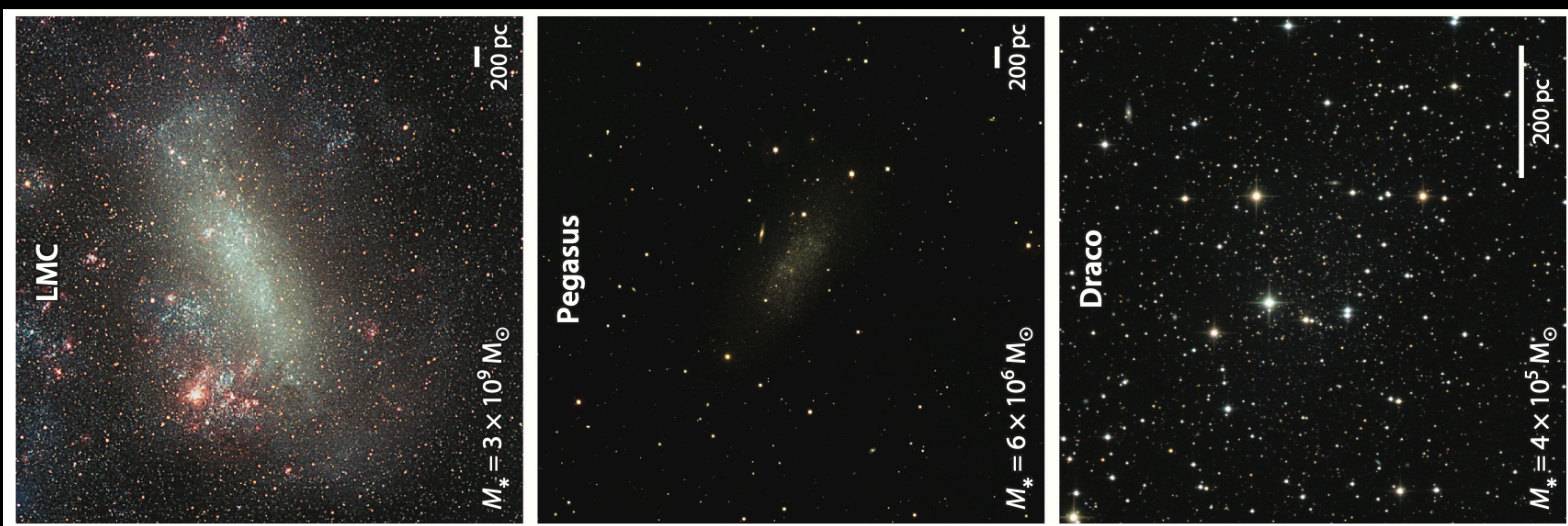
$M_\star \approx 10^4\ \mathrm{M}_\odot$,
$M_{\mathrm{vir}} \approx 10^9\ \mathrm{M}_\odot$,
$M_\star/M_{\mathrm{vir}} \approx 10^{-5}$



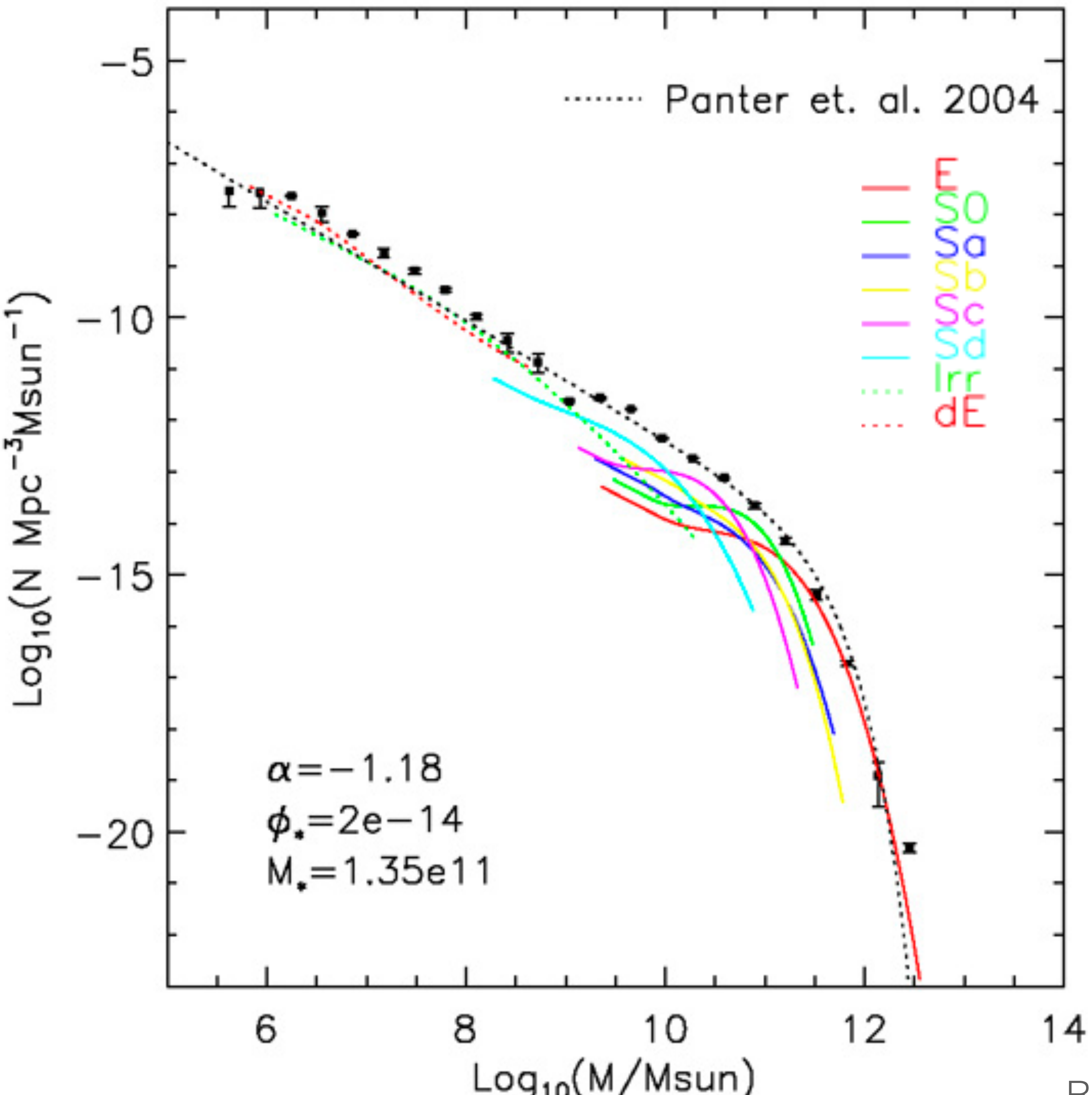
Bullock & Boylan-Kolchin 2017

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



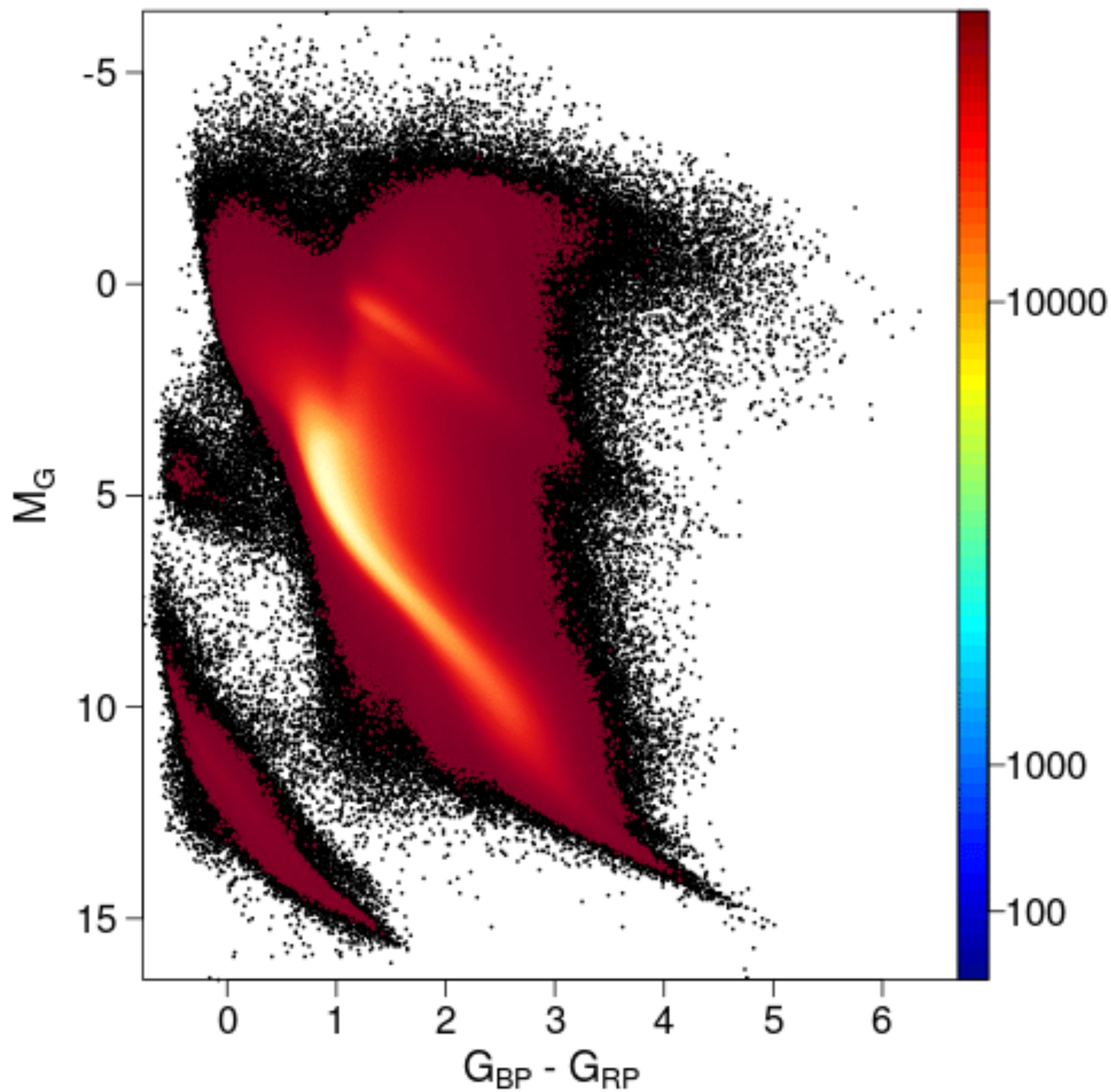
The Mass (Distribution) Function of Galaxies Today



Read & Trentham 2005

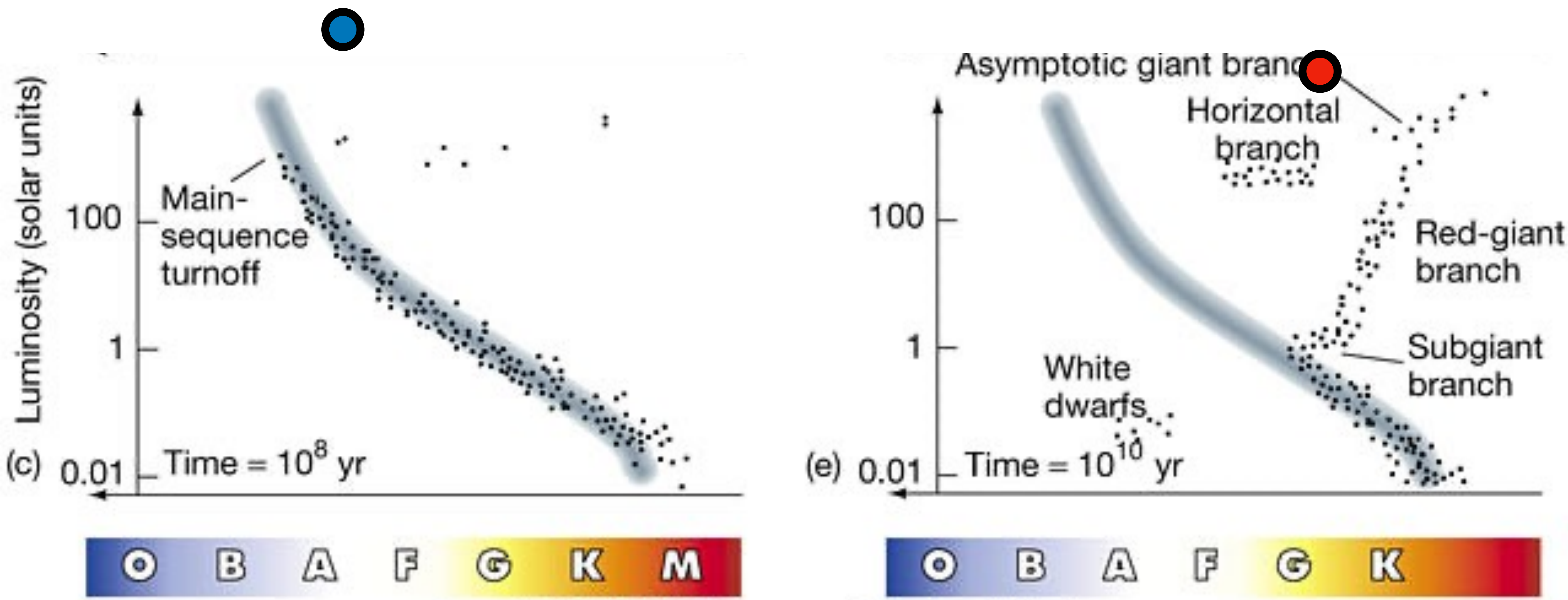
The HR Diagram of Galaxies

HR Diagram is a Color-Magnitude Diagram of Stars



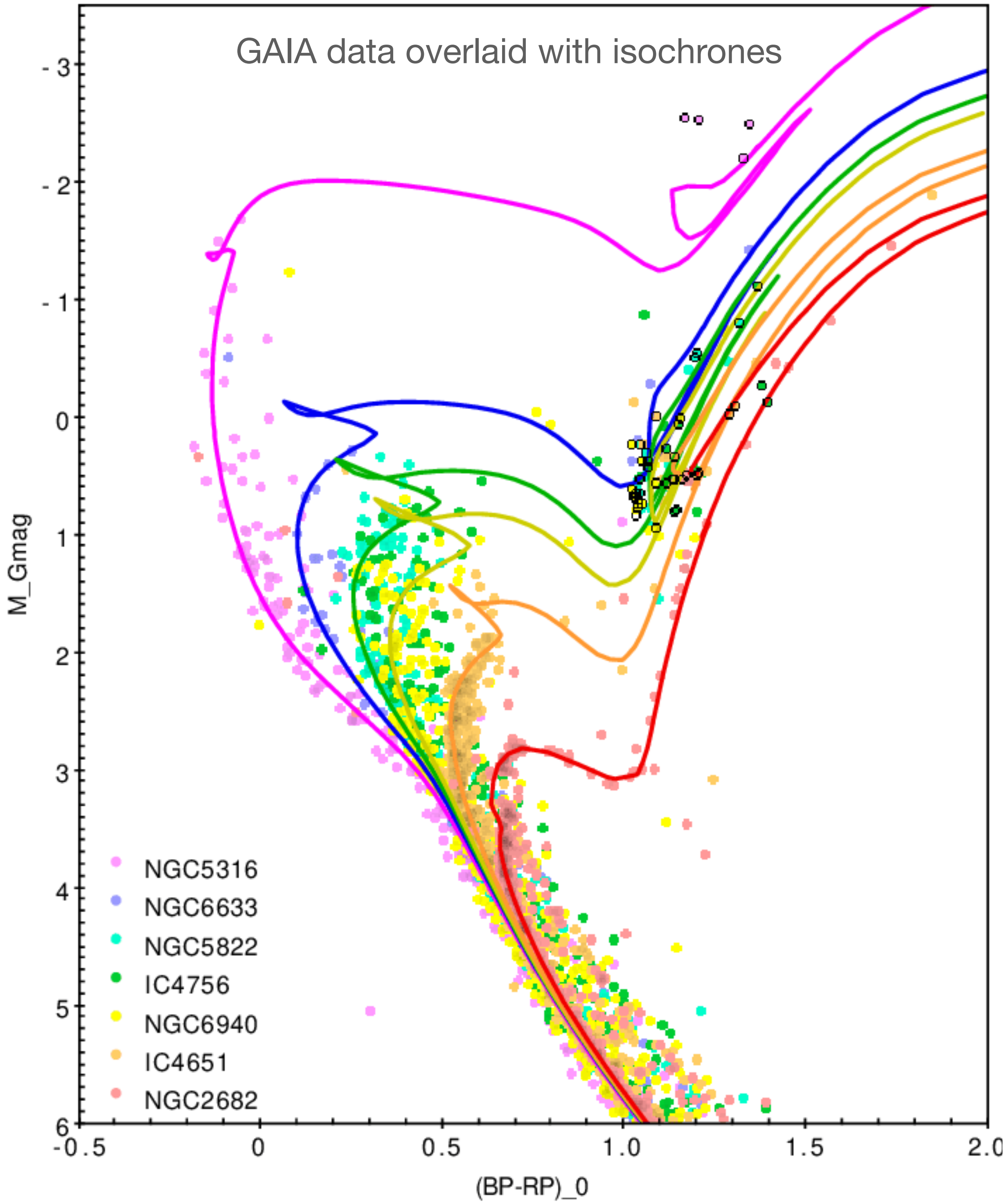
Adding stars in a cluster to get integrated color and total luminosity

- 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.
- If you sum up all of the stars in the two clusters below, what would be the resulting **integrated color** and **total luminosity**?

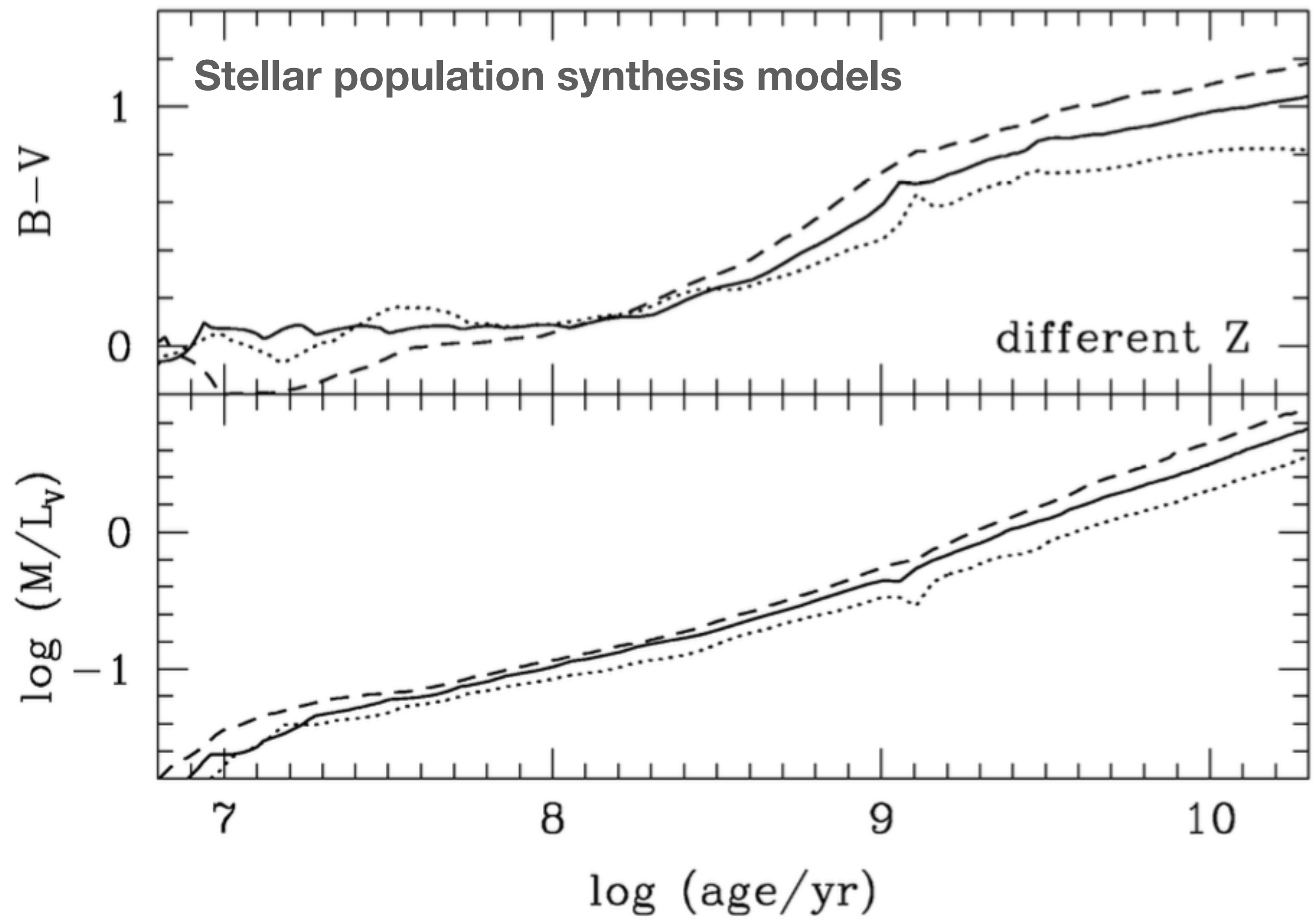


As a cluster ages, it becomes redder and fainter

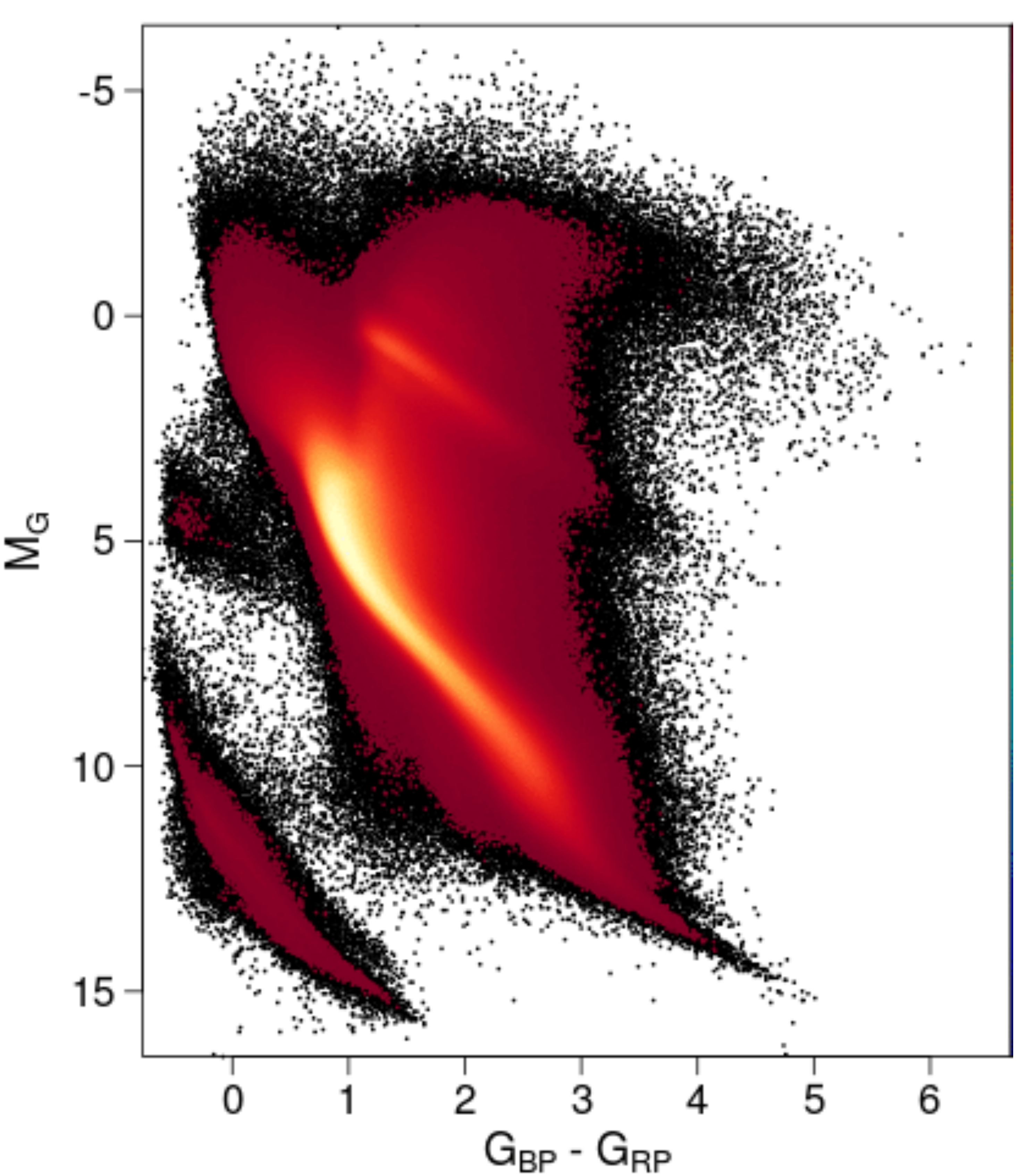
HR diagram of clusters covering a range of ages

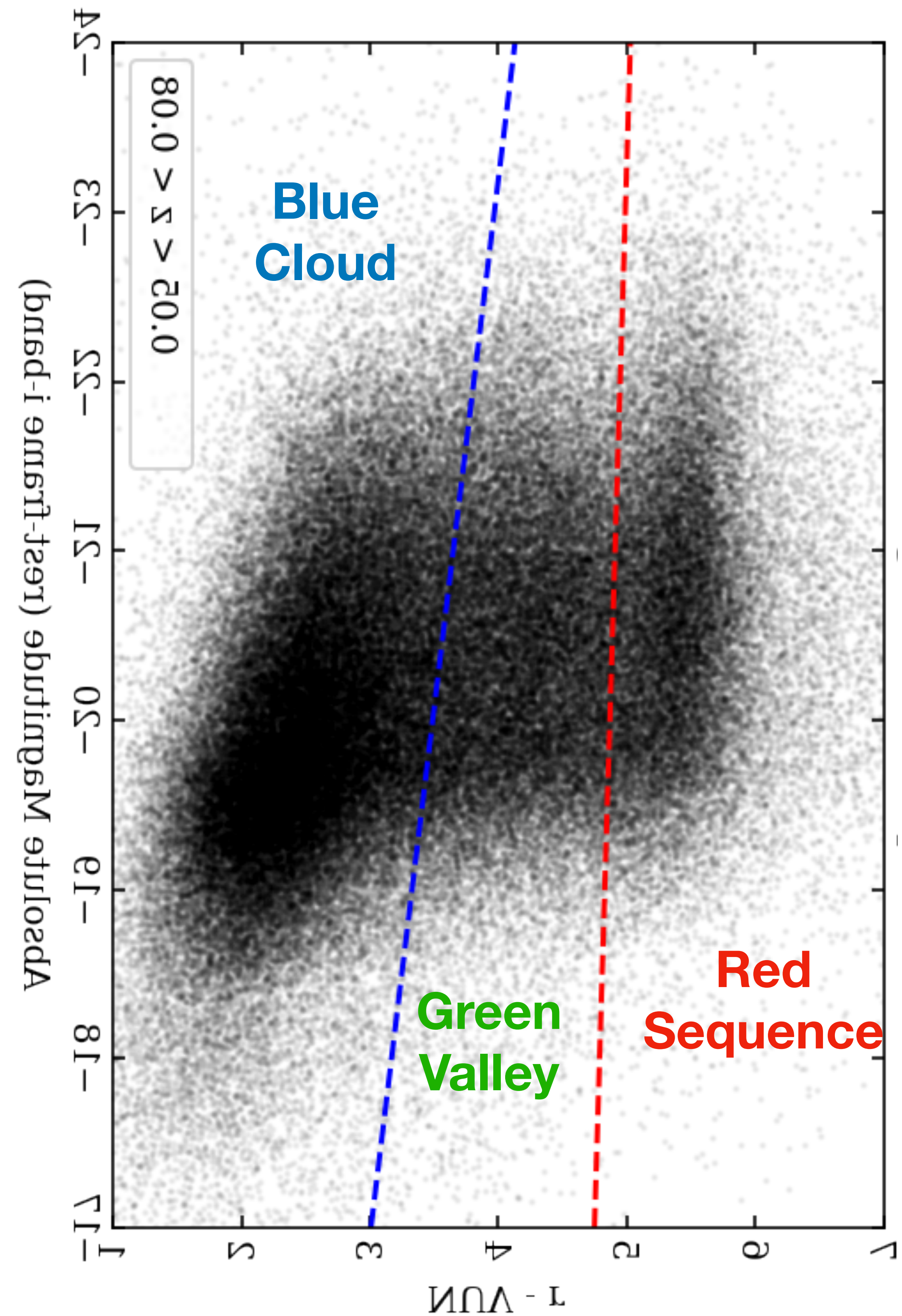


- Stellar population synthesis models follow the **isochrone evolution** of stellar populations and predict the **integrated color** and the **total luminosity** as a function of age.
- The **mass-to-light ratio (M/L)** increases because luminosity decreases faster than mass loss.

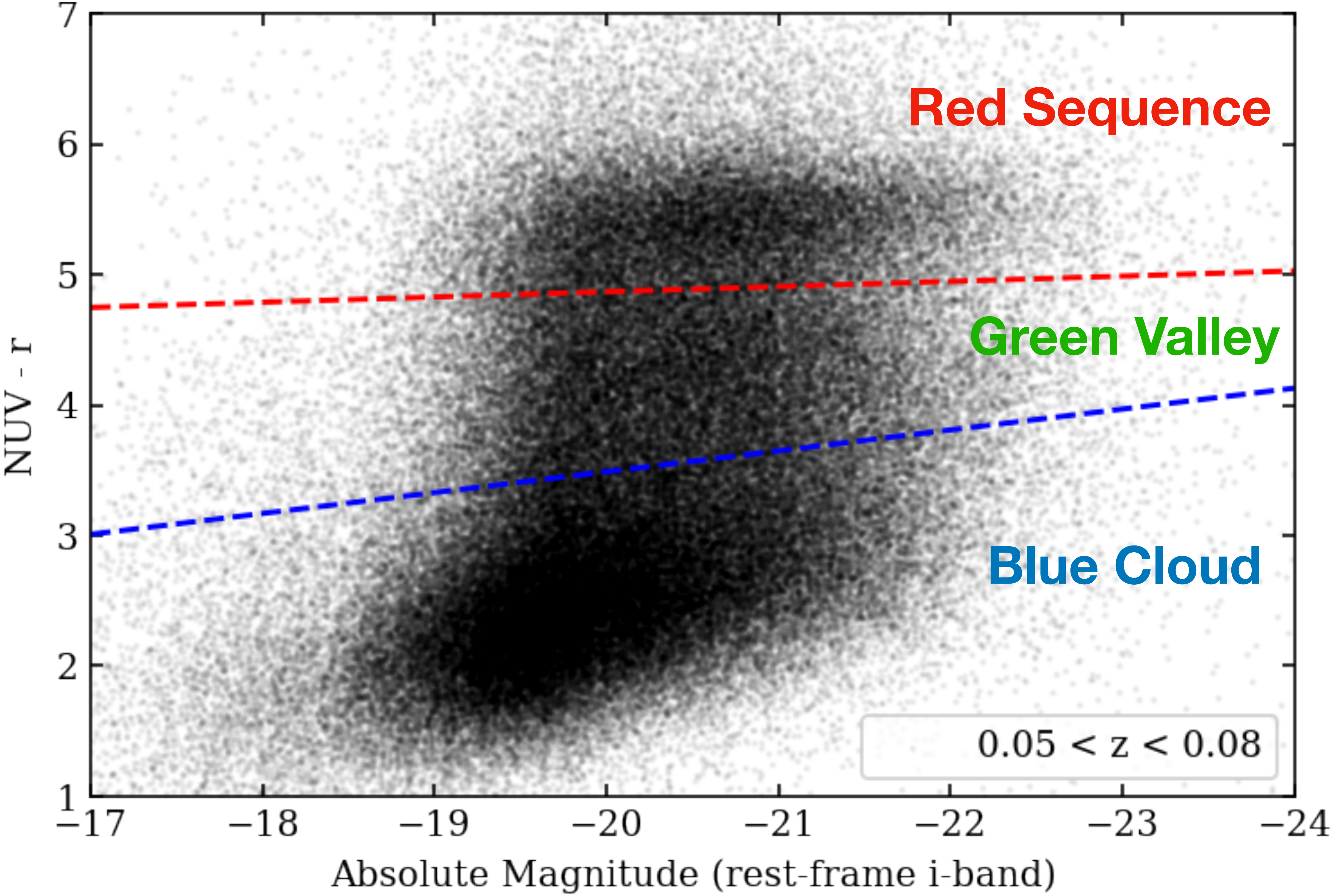


HR Diagram of Stars vs. CM Diagram of Galaxies

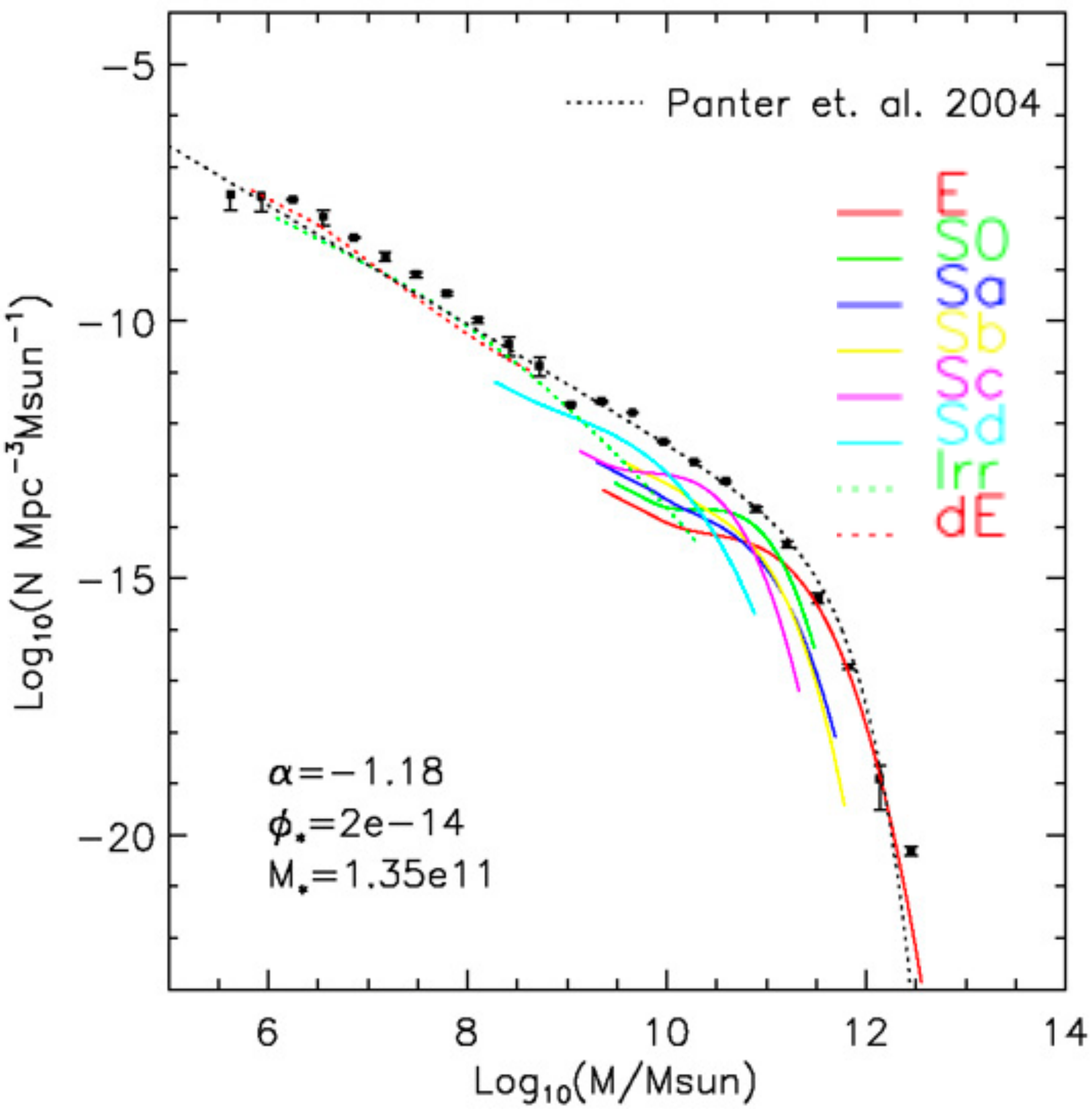




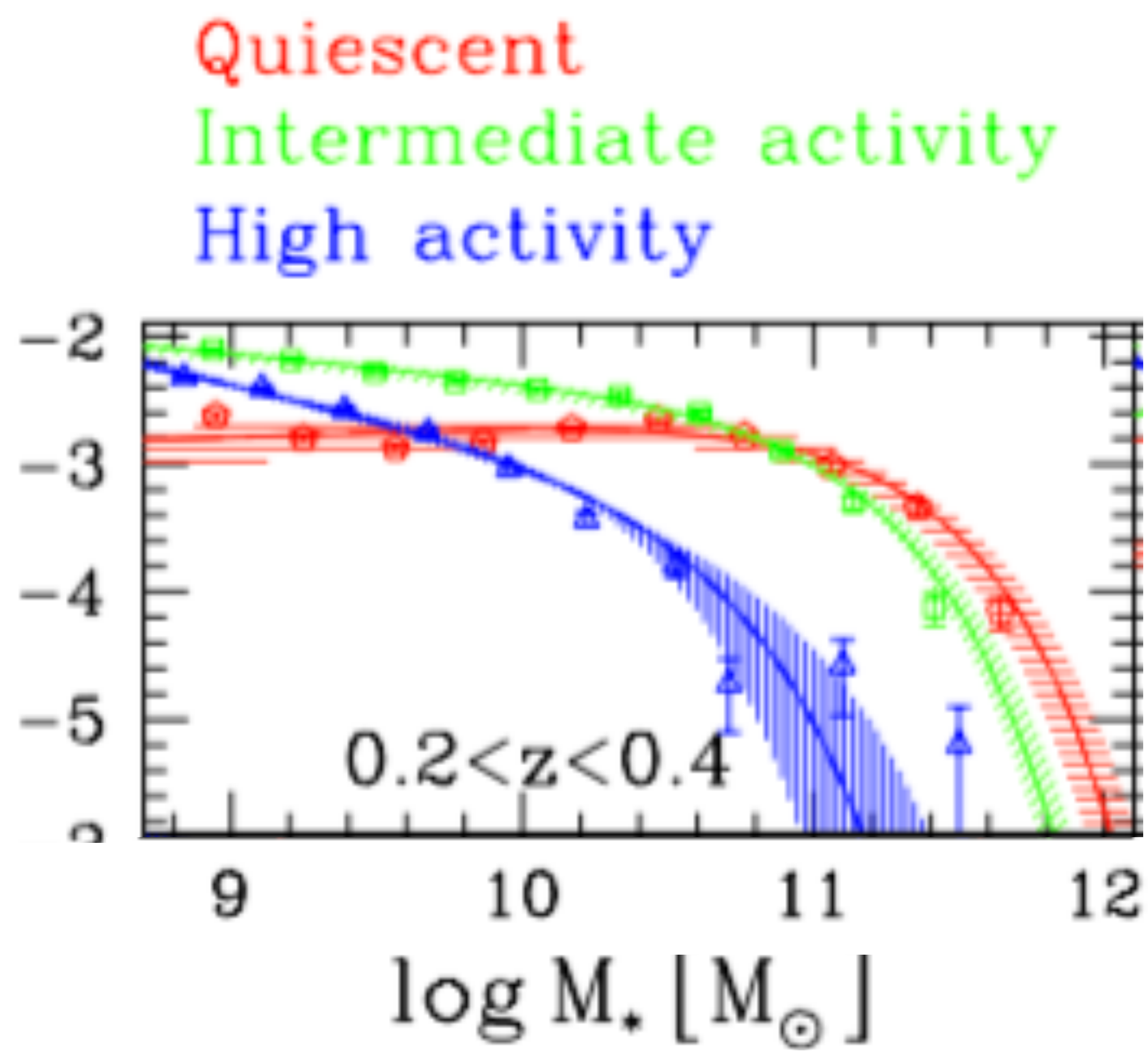
Color-Magnitude Diagram of Galaxies



Mass Function of Galaxies divided by Star Formation Activity Level



Read & Trentham 2005
y-axis unit: log(# Mpc^{-3} M_{sun}^{-1})



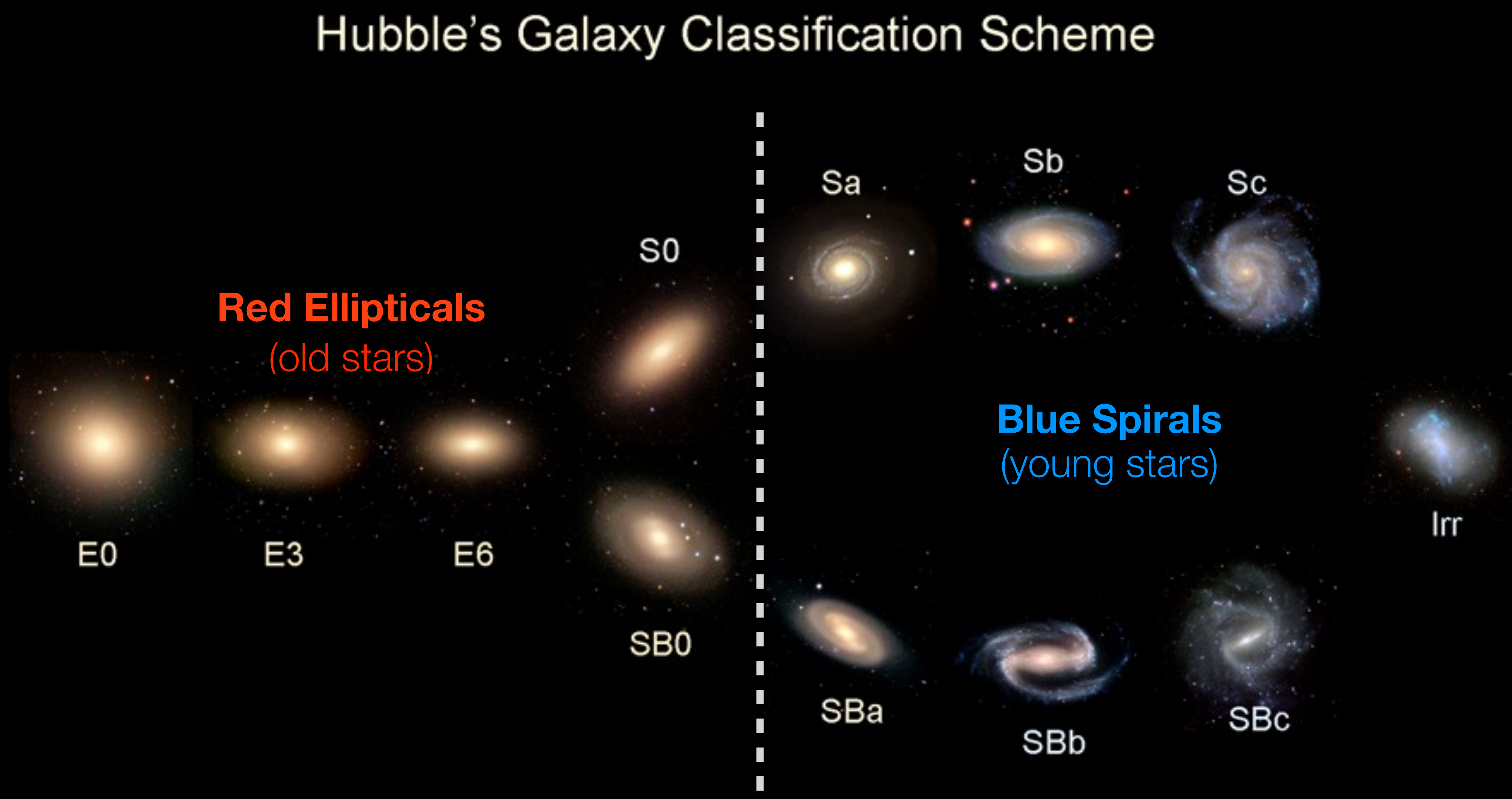
Ilbert+2010;
y-axis unit: log(# Mpc^{-3} dex^{-1})

Morphology correlates with color or star formation

Morphology-Color Correlation on the CMD

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

Galaxies are either blue spirals or red ellipticals



Galaxies in the Current universe

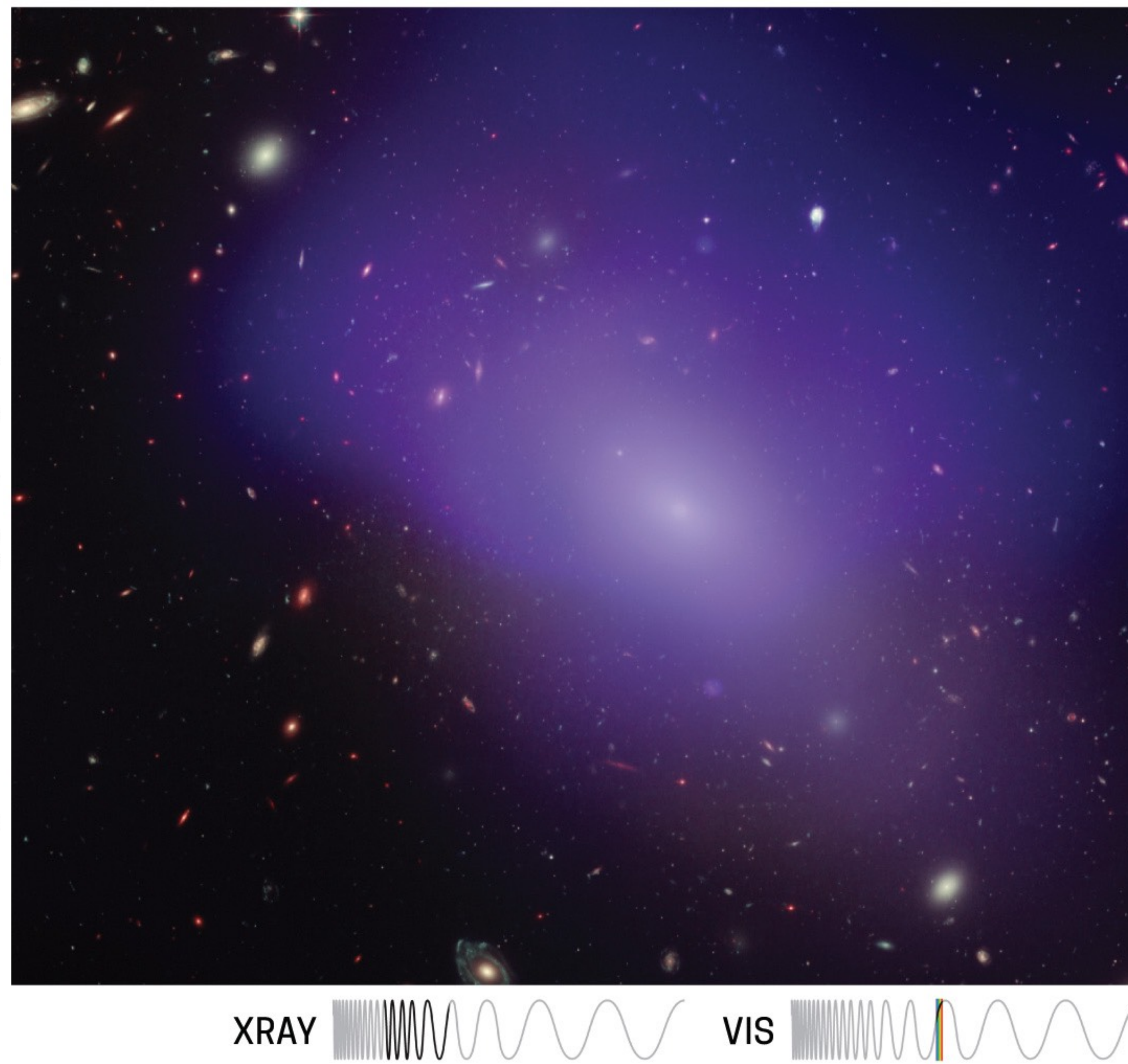
Spiral Galaxies: Star Formation

- 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: Star Formation

- Gas in ellipticals is mostly hot and only visible at X-ray wavelengths.
- Hot diffuse gas cannot collapse to form stars (recall "Jeans mass").
- No star formation occurs in elliptical galaxies.
- There is also very little dust in elliptical galaxies.

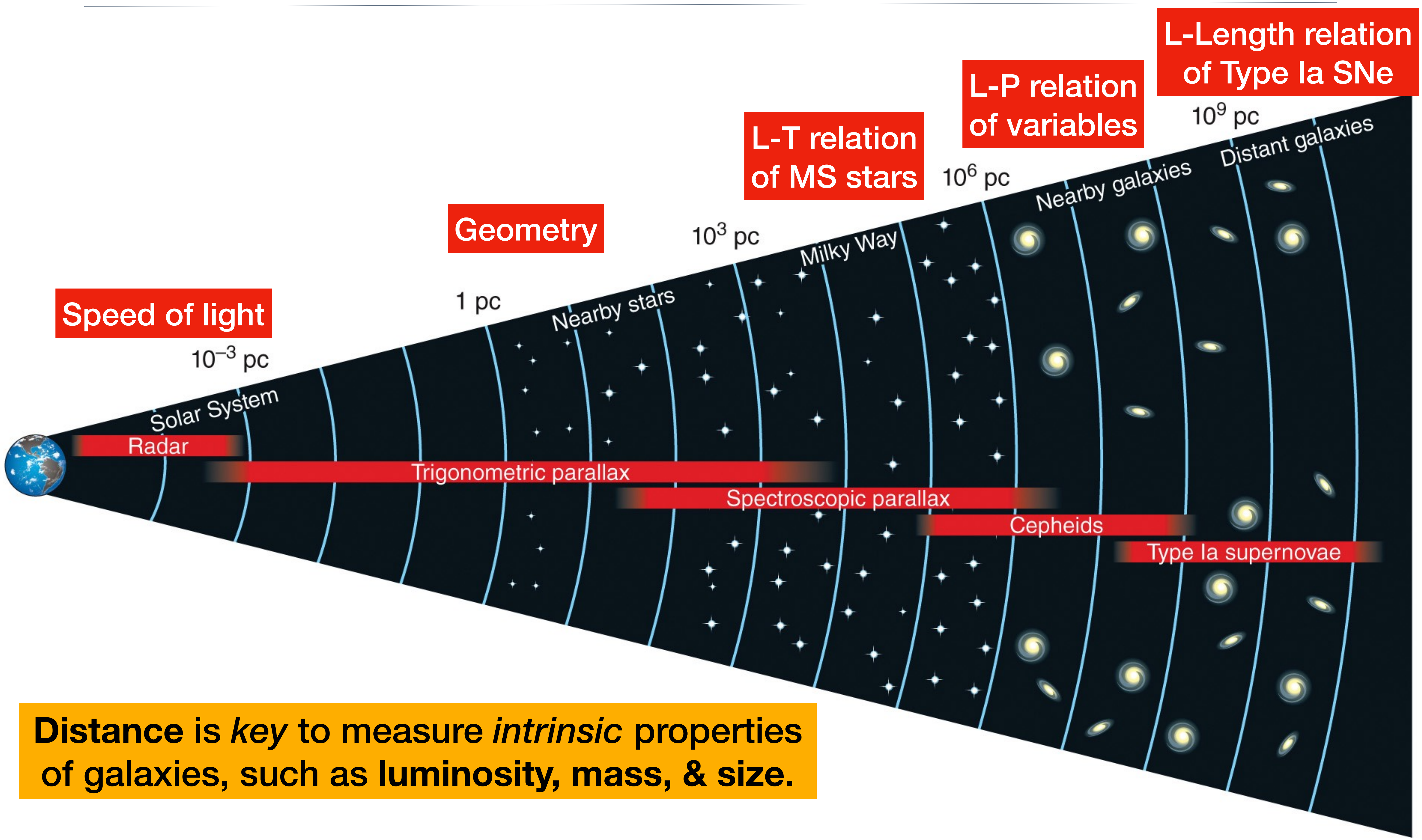
NASA, ESA and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration



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

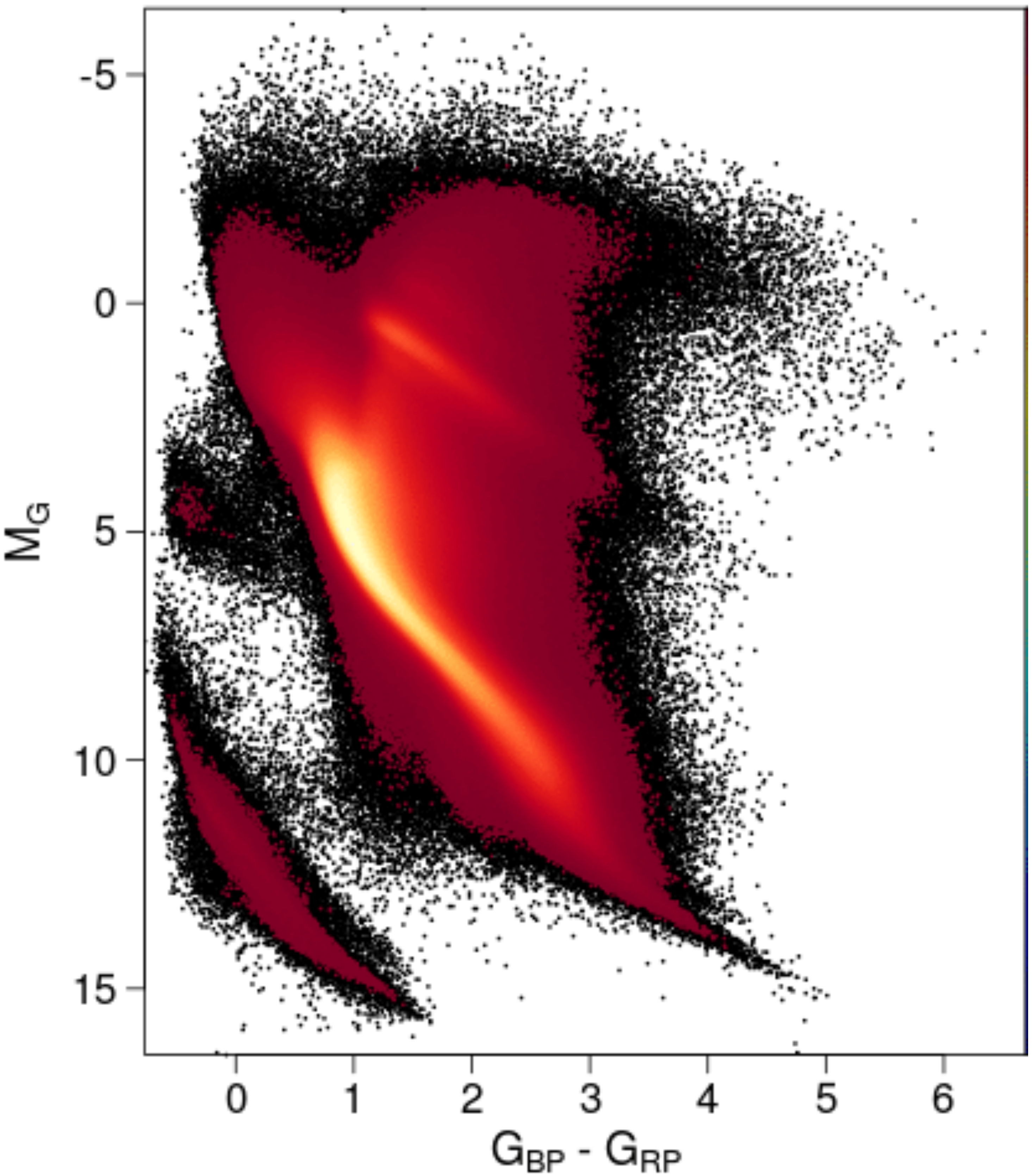
A quick recap of the two previous lectures

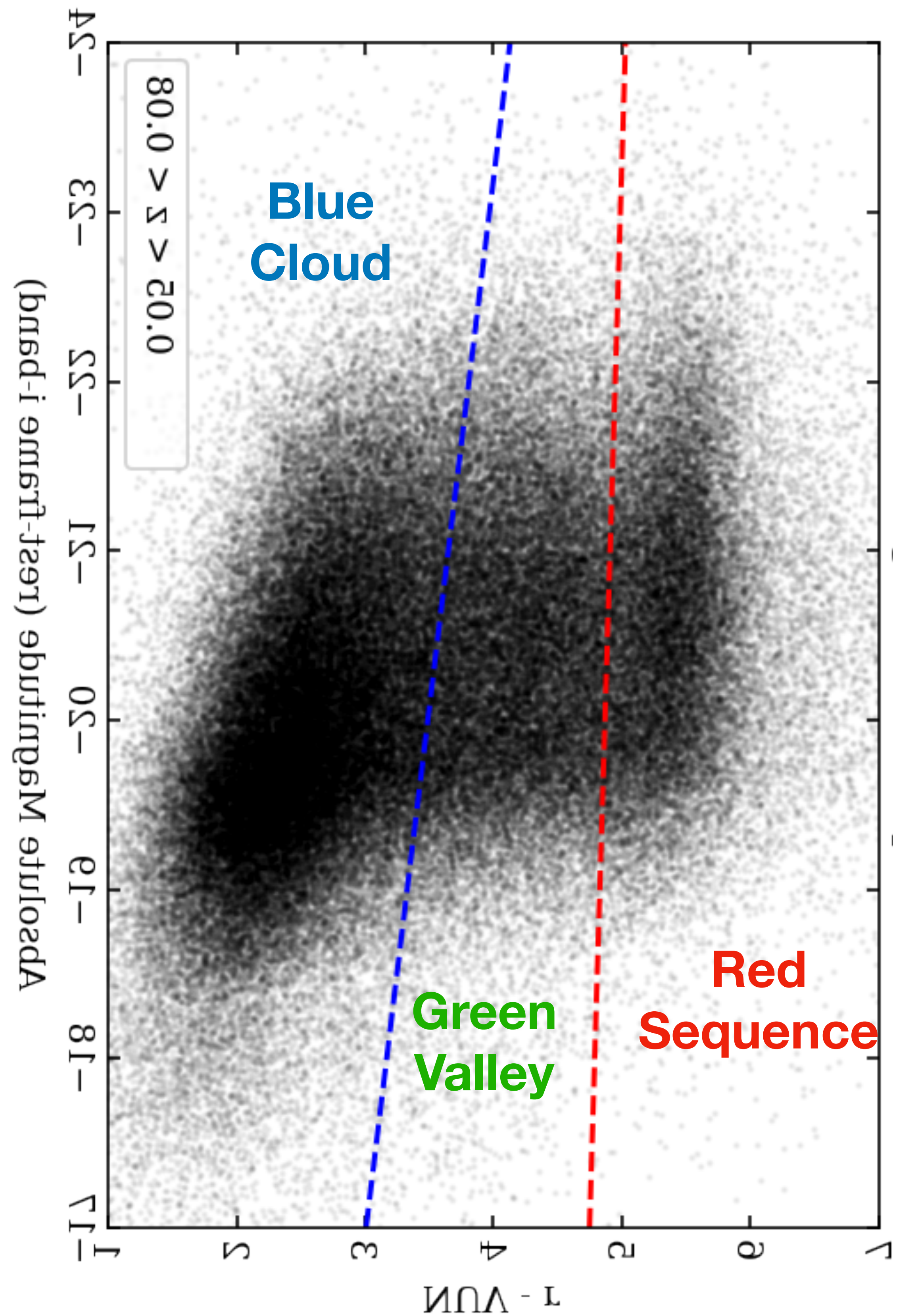
The Distance Ladder from Solar System to Galaxies



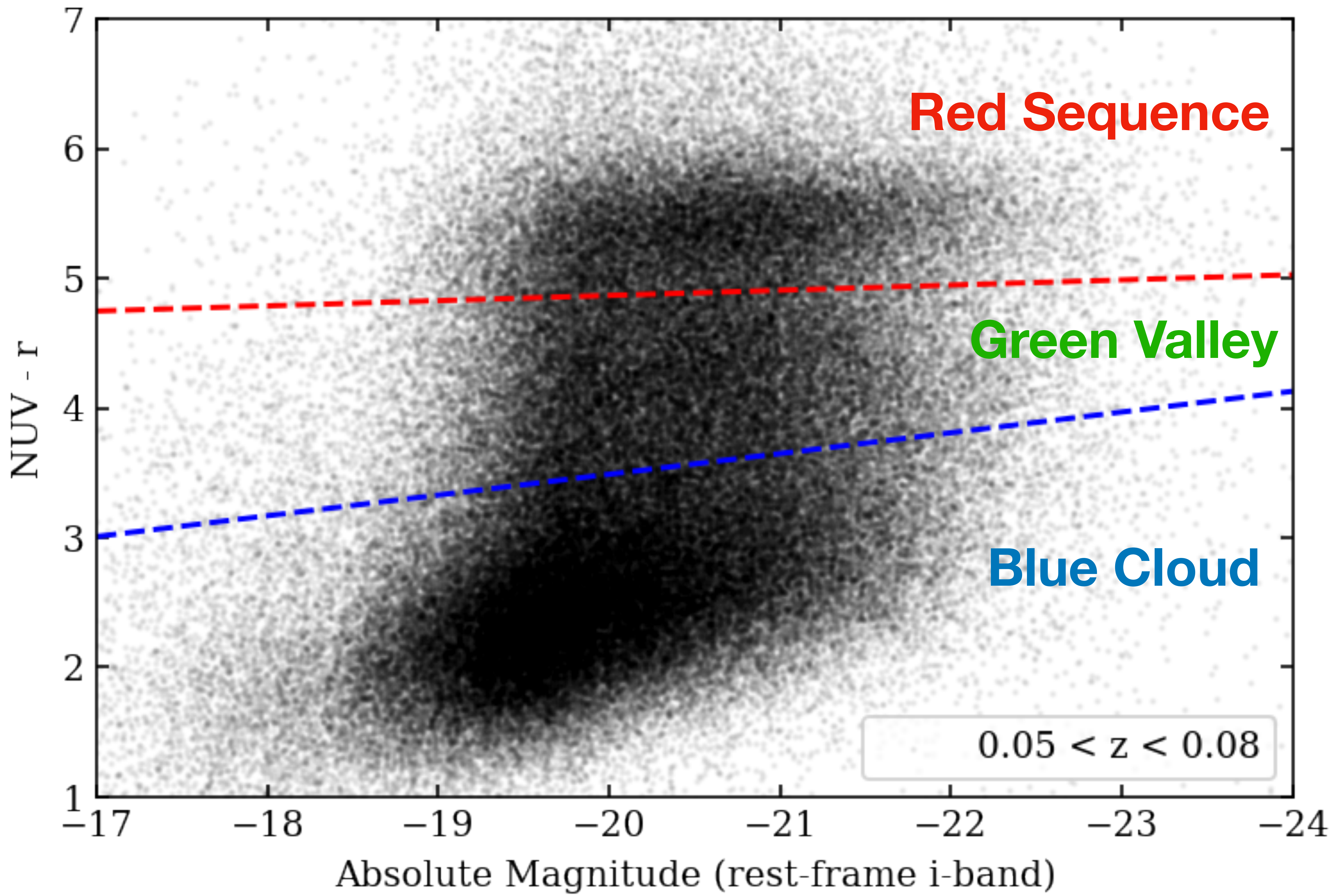
Distance is *key* to measure *intrinsic* properties of galaxies, such as **luminosity, mass, & size.**

HR Diagram of Stars vs. CM Diagram of Galaxies



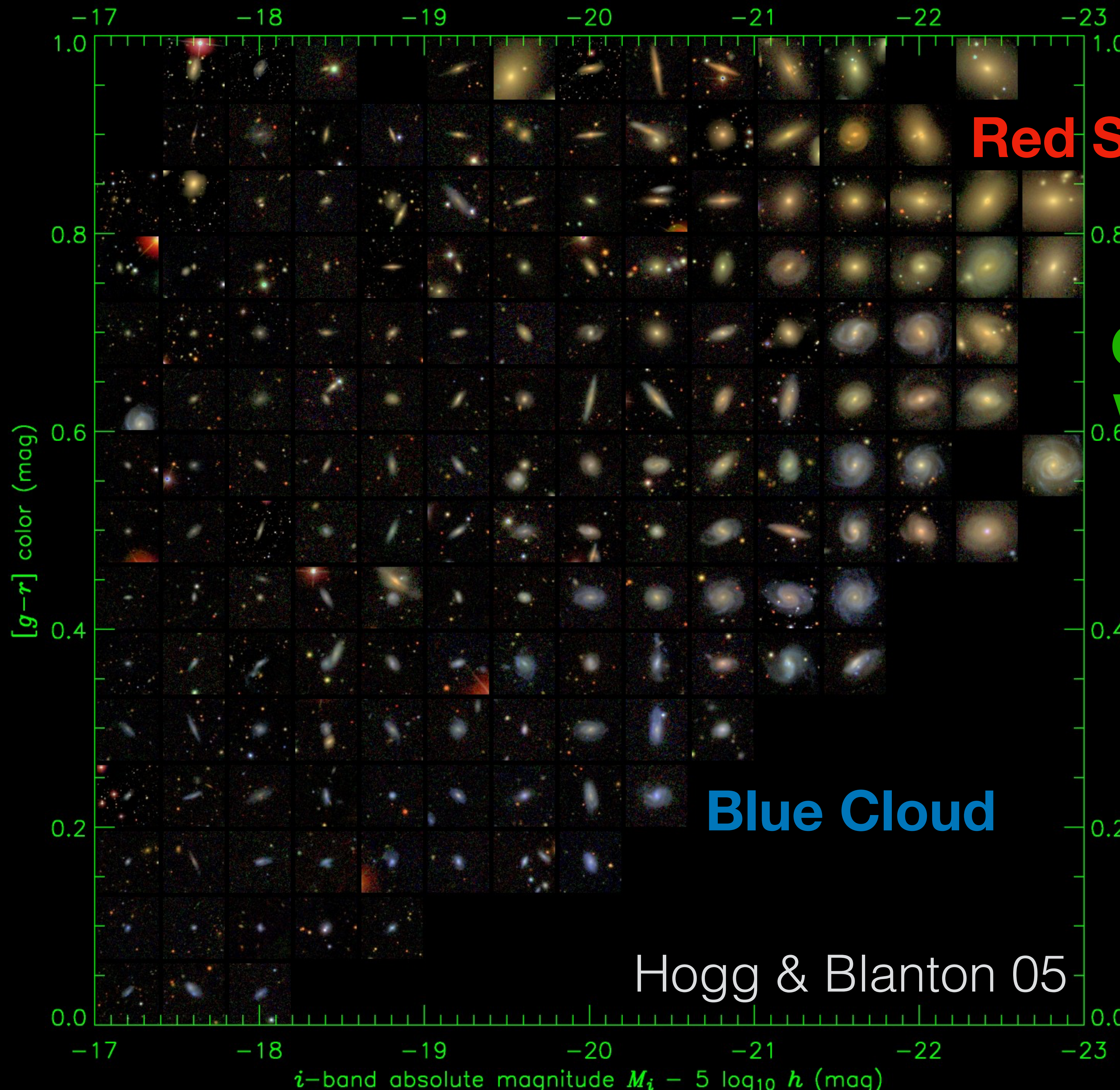


Color-Magnitude Diagram of Galaxies



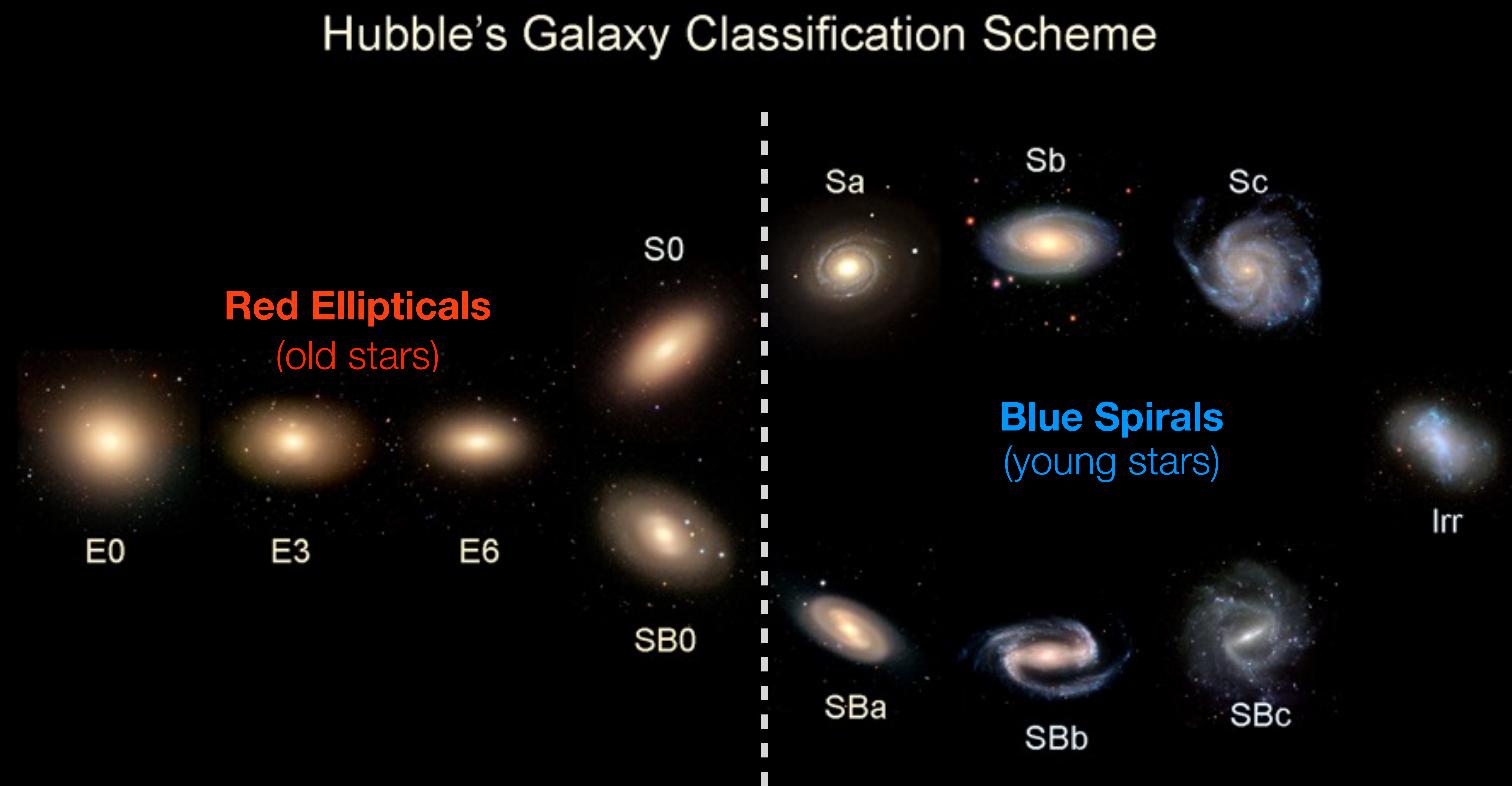
SDSS NSA catalog, H. Fu

Morphology-Color Correlation on the CMD



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

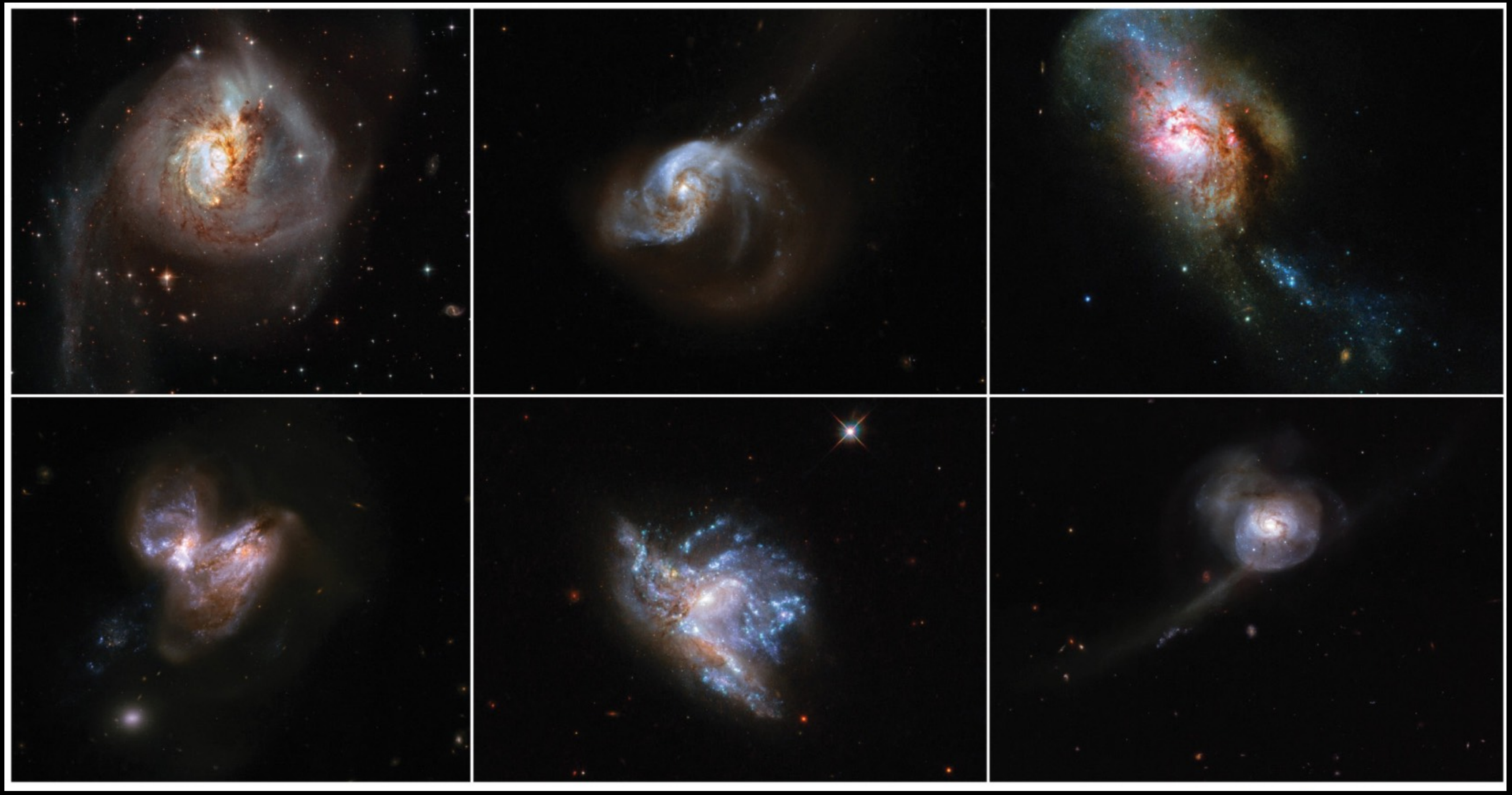
Galaxies are either blue spirals or red ellipticals



Galaxies in today's universe

Chap 19: Galaxies

- How to determine distances to galaxies with the distance ladder?
- What are the morphologies of galaxies today?
- What are dwarf galaxies?
- The HR diagram of galaxies
- The morphology-color correlation
- What is the evidence of dark matter in galaxies and galaxy clusters?
- How orbits of stars and galaxy morphology are intertwined?
- What is the evidence of supermassive black holes?
- How efficient is an accretion disk in generating energy?

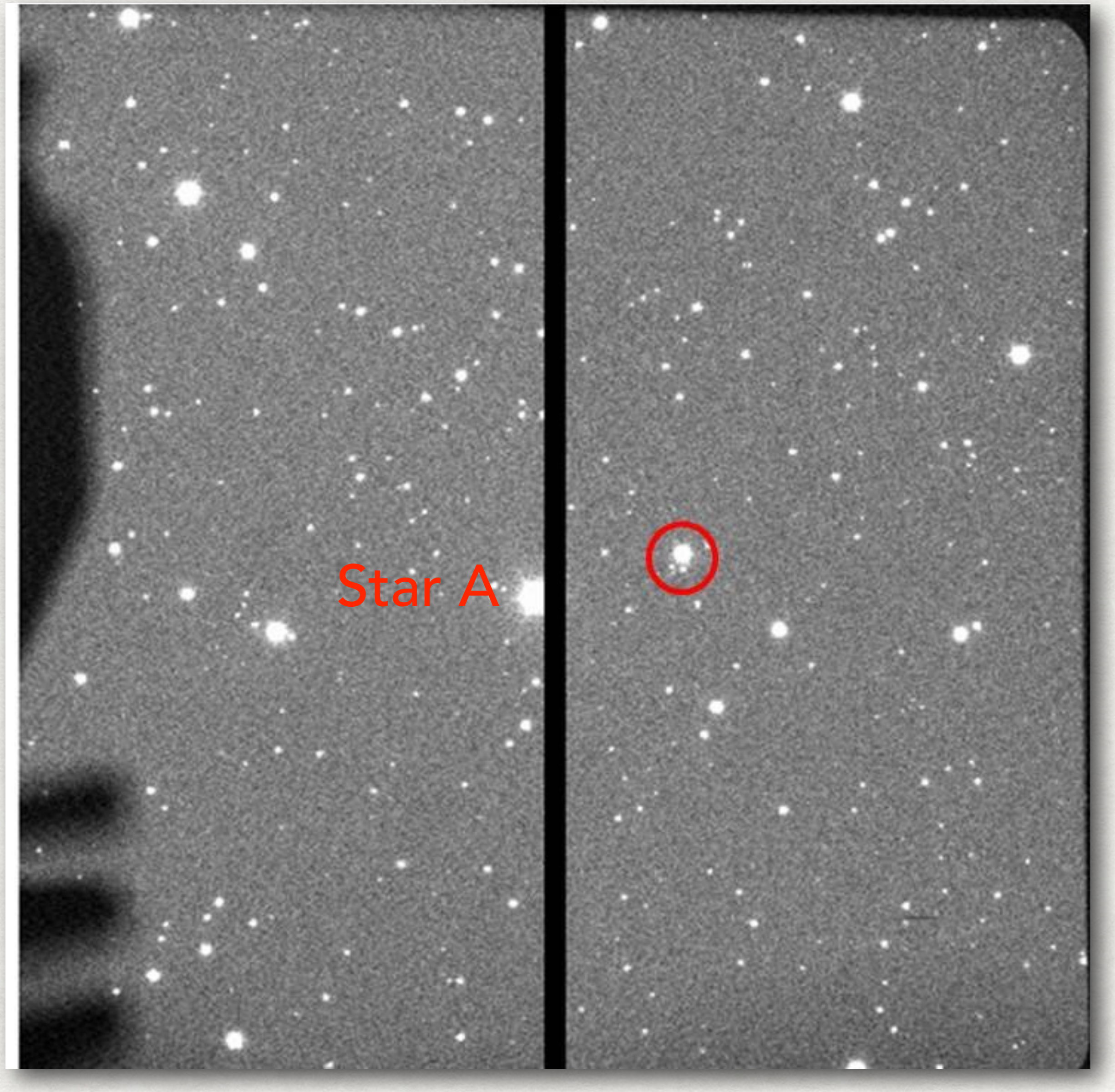


Stellar and Gas Kinematics from Spectroscopy

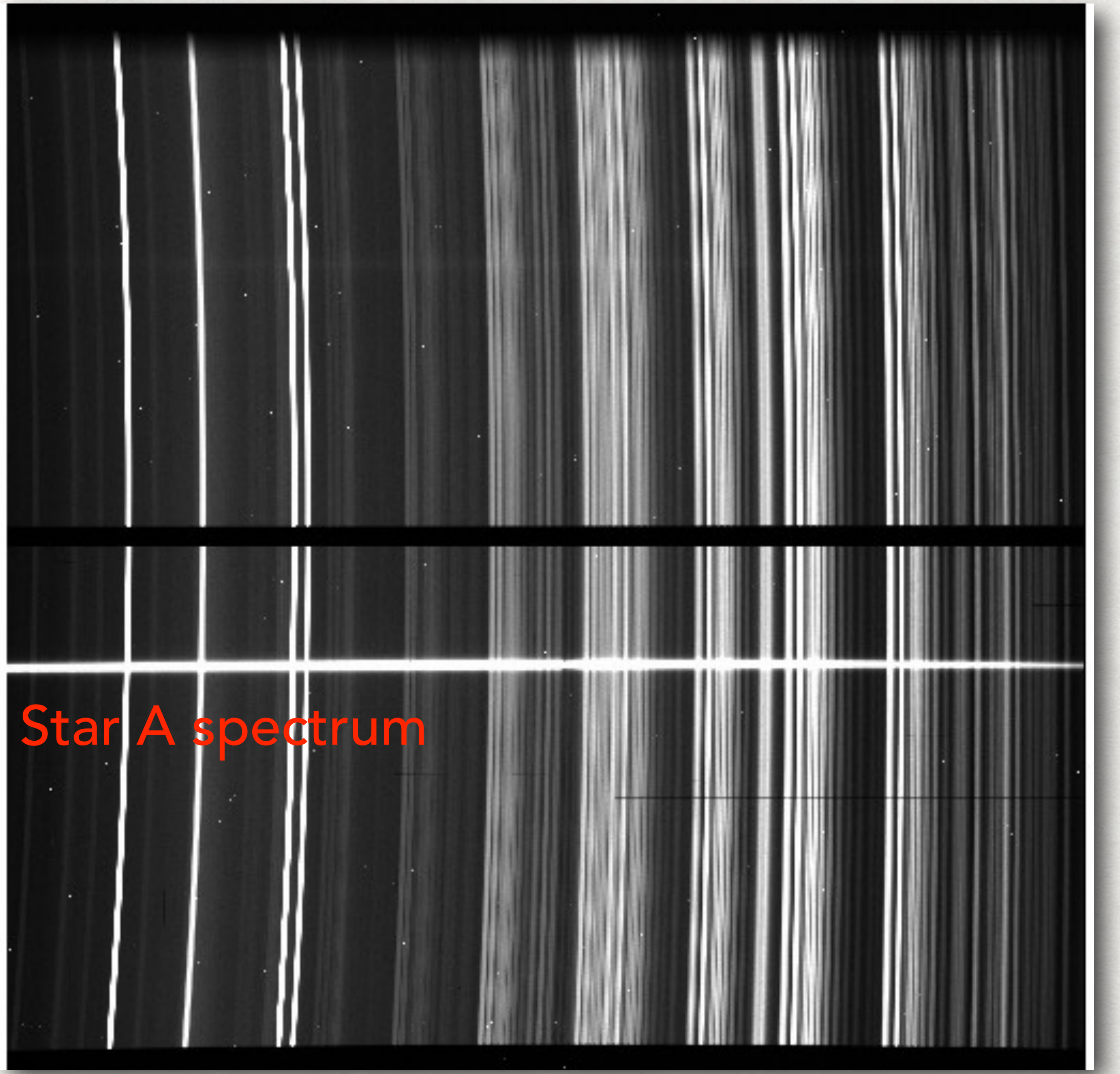
LONG SLITS PLACED AT THE FOCAL PLANE

LONGSLIT SPECTROSCOPY

Slit-viewing camera for target acquisition
the central gap is the slit,
the rest of the focal plane is reflective

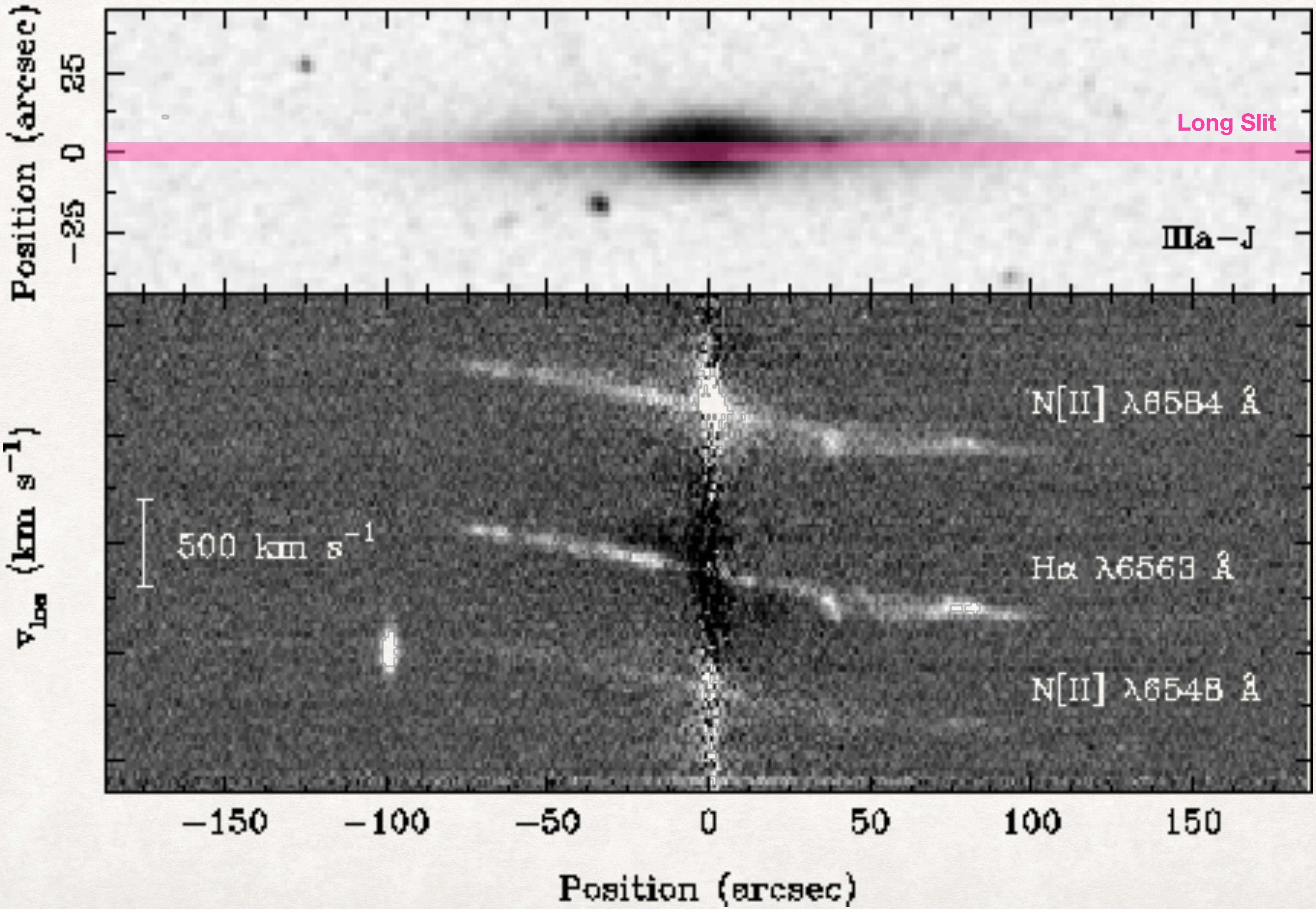


Resulting image of the spectrum:
the central gap is the gap between two CCDs
Vertical lines are emission lines from the atmosphere

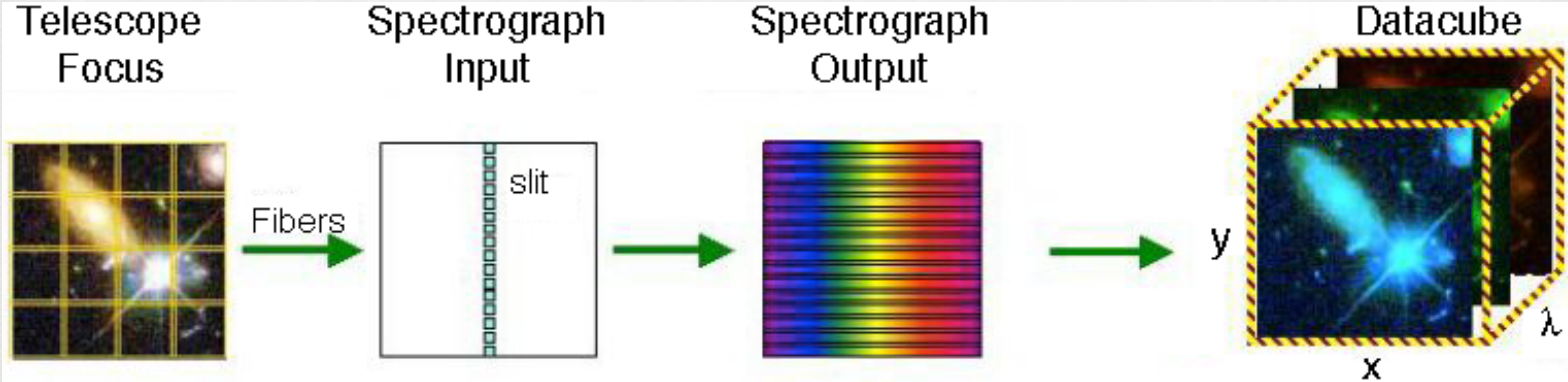


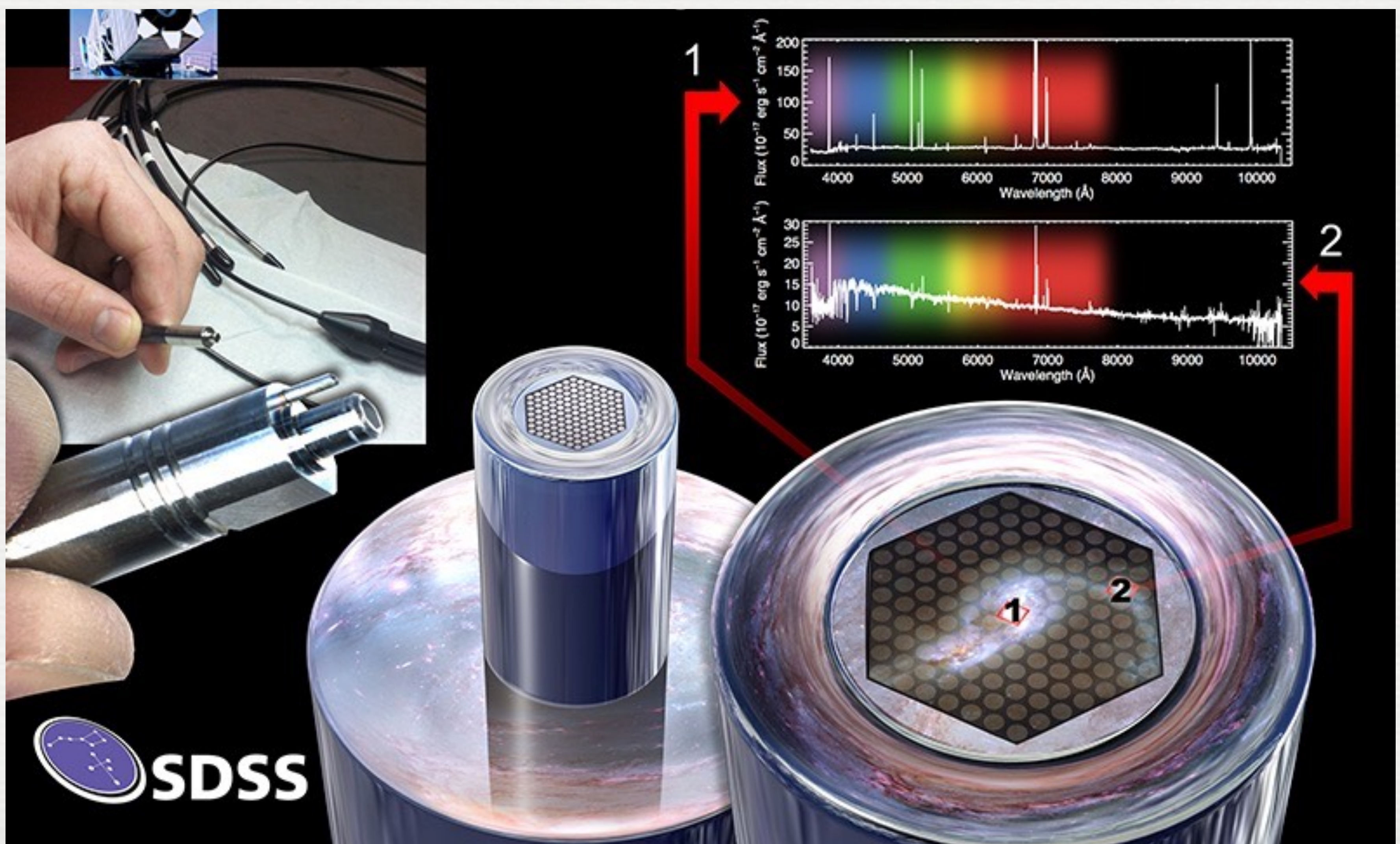
Advantages: (1) blocking sky background, (2) avoiding overlaps of spectral from different objects
Disadvantages: (1) limited sources can be observed at the same time, (2) lengthy target acquisition

A LONGSLIT PLACED ALONG A GALAXY'S MAJOR AXIS

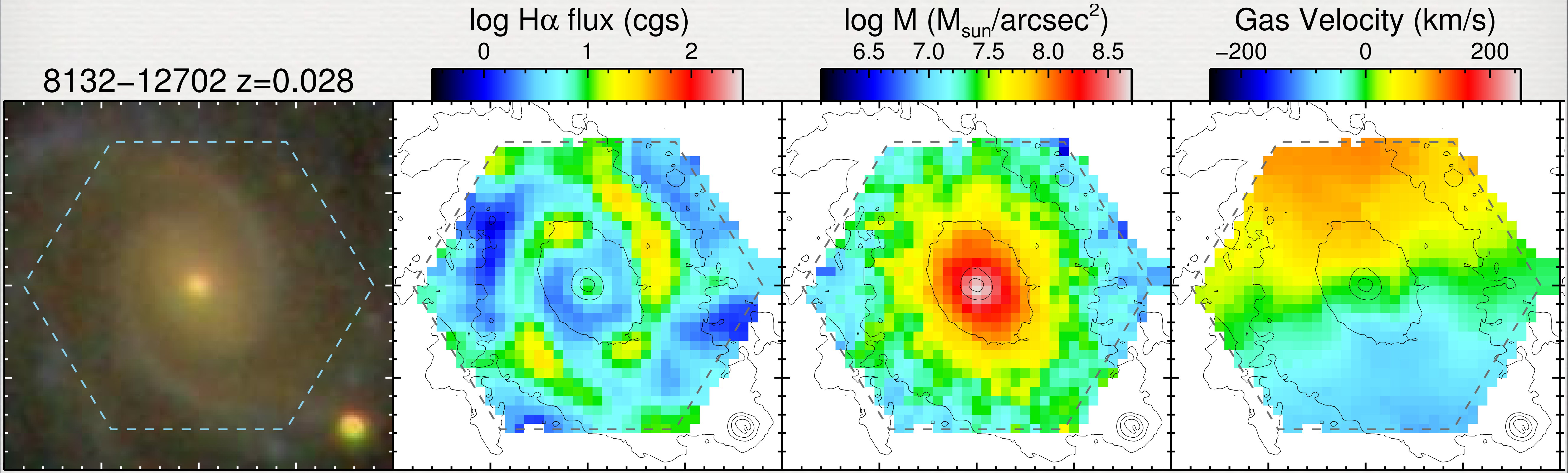


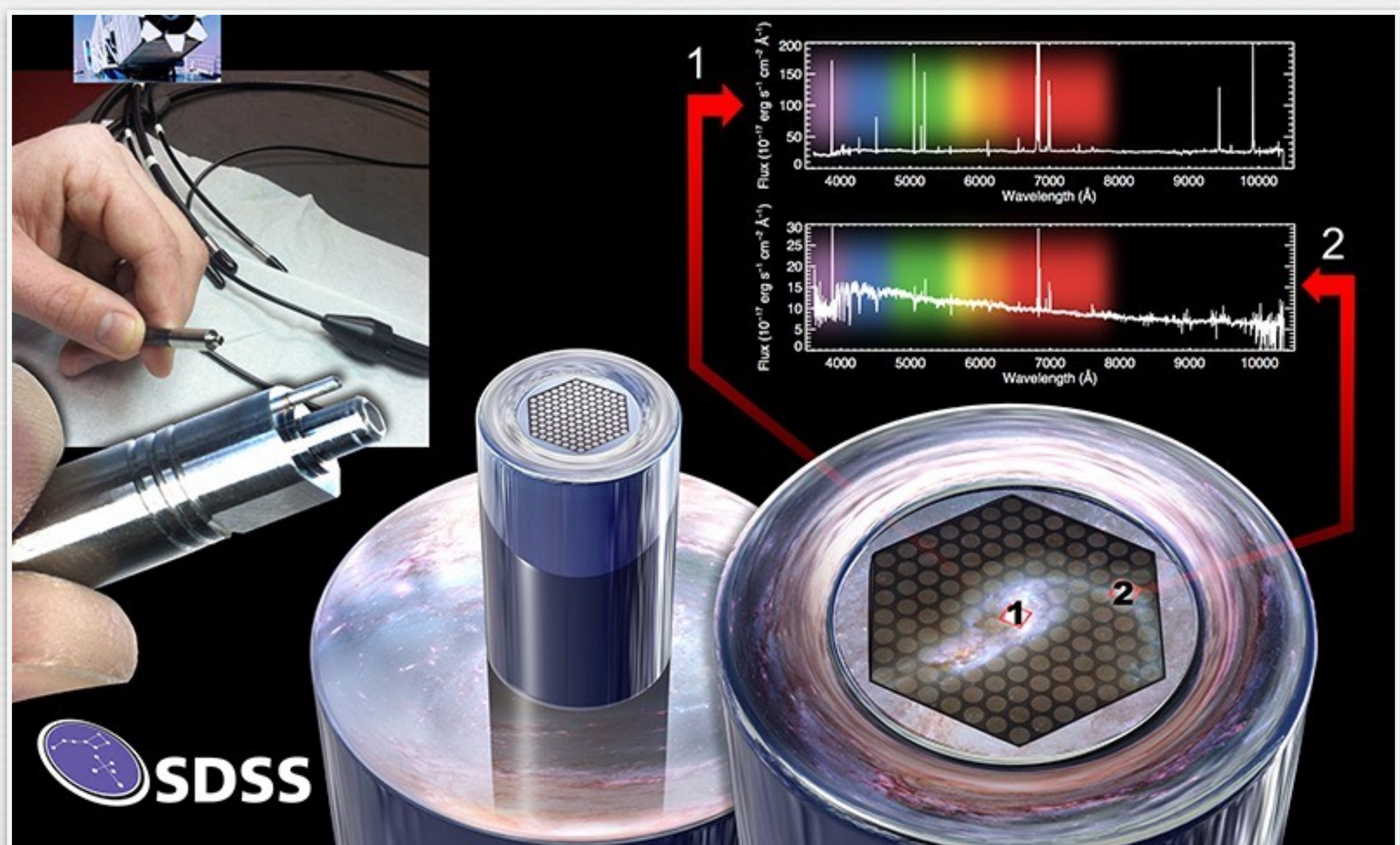
Integral-Field Spectroscopy





Integral-Field Spectroscopy: MaNGA





Data from SDSS IV/ MaNGA Survey, Figure made by H. Fu

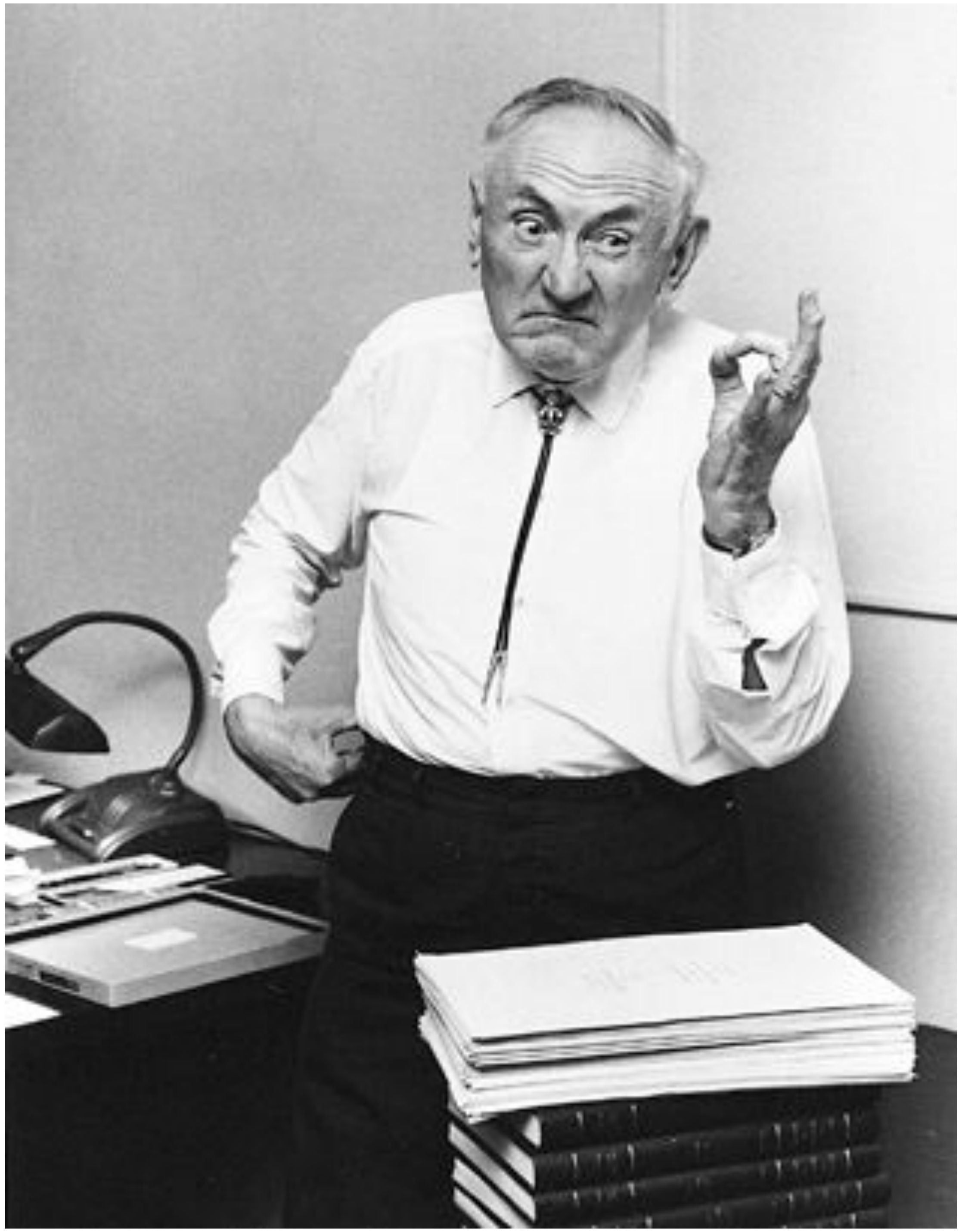
Evidence of Dark Matter

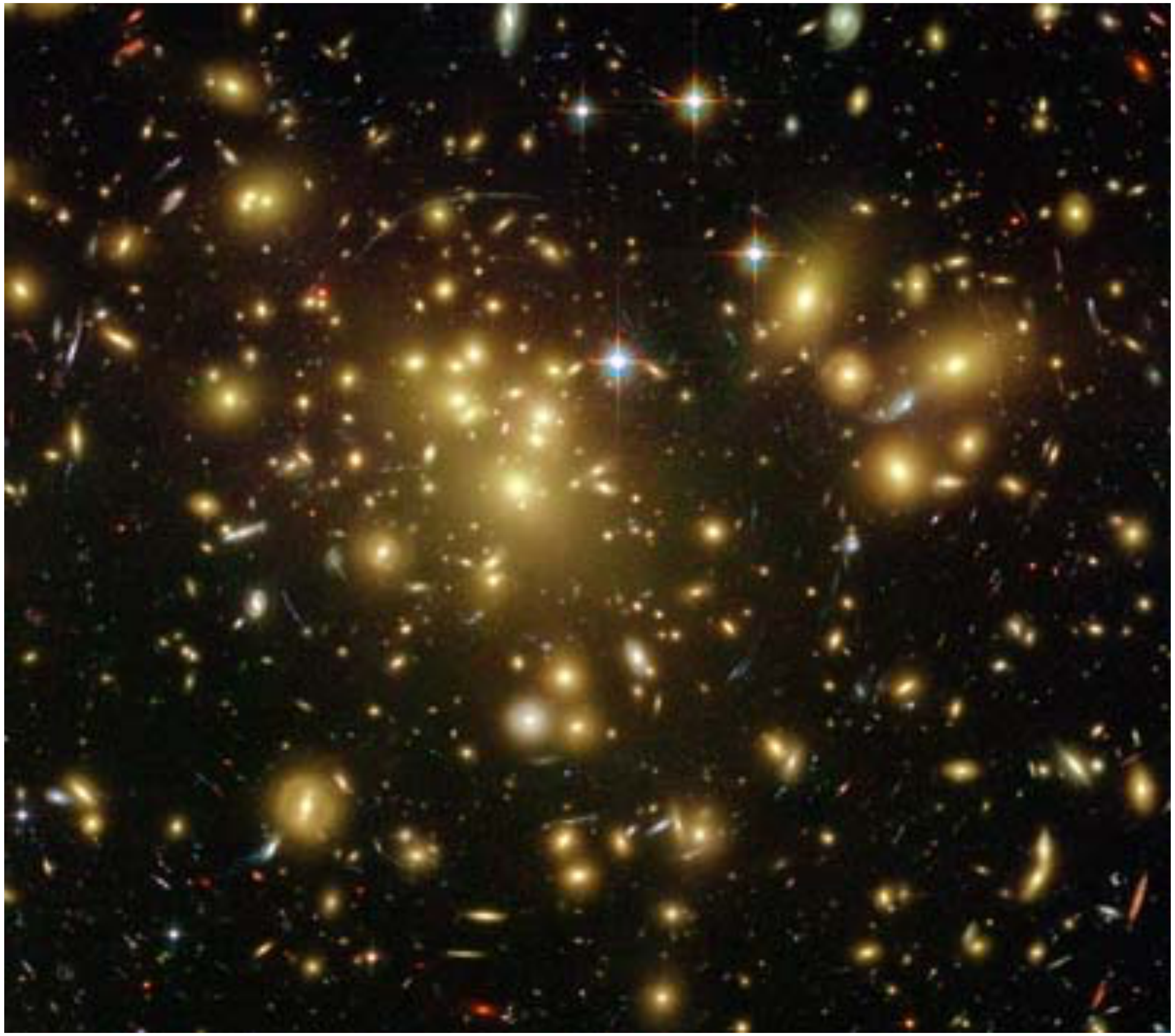
The First Observational Evidence of Dark Matter

Zwicky 1933: velocity dispersion of galaxies in the Coma Cluster

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

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





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

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12}\ \mathrm{cm}^2/\mathrm{s}^2 \tag{7}$$

and furthermore

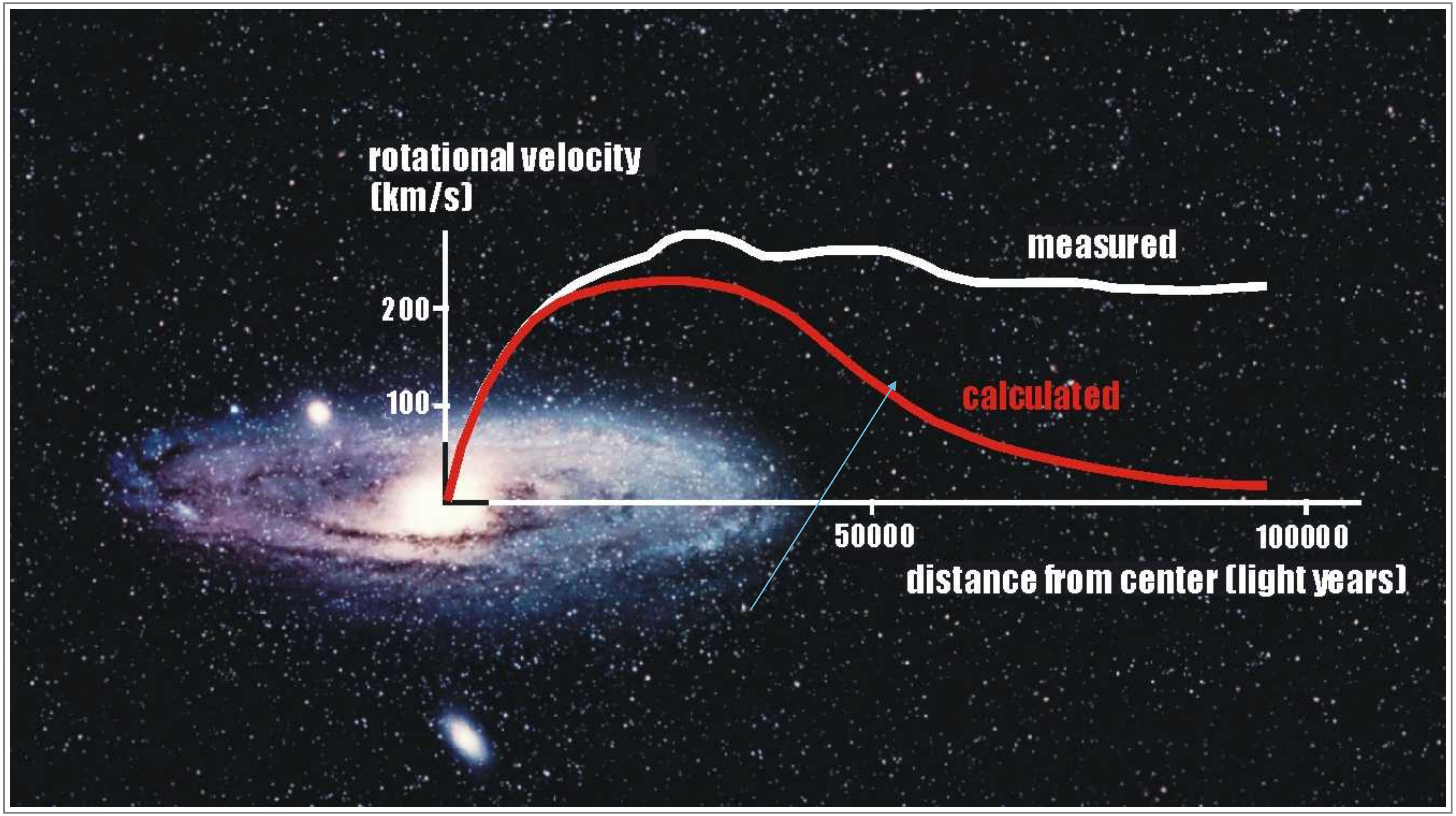
$$\varepsilon_k = \overline{v^2}/2 = -\varepsilon_p/2 = 32 \times 10^{12}\ \mathrm{cm}^2/\mathrm{s}^2 \qquad (\overline{v^2})^{1/2} = 80\ \mathrm{km/s}. \tag{8}$$

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.

Evidence of Dark Matter in Disk Galaxies

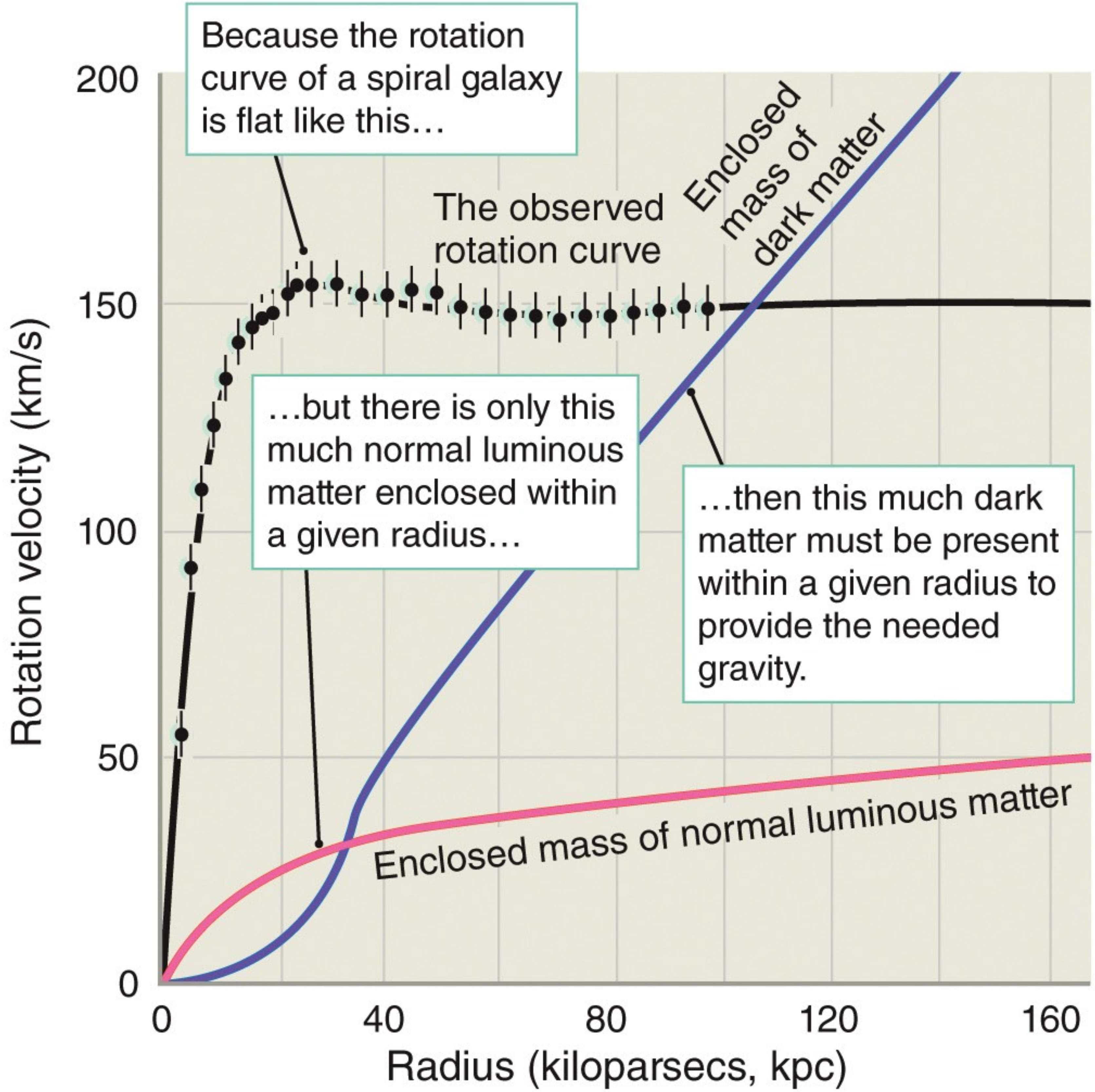
Newton's laws: $GM(r)/r^2 = v^2/r$

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

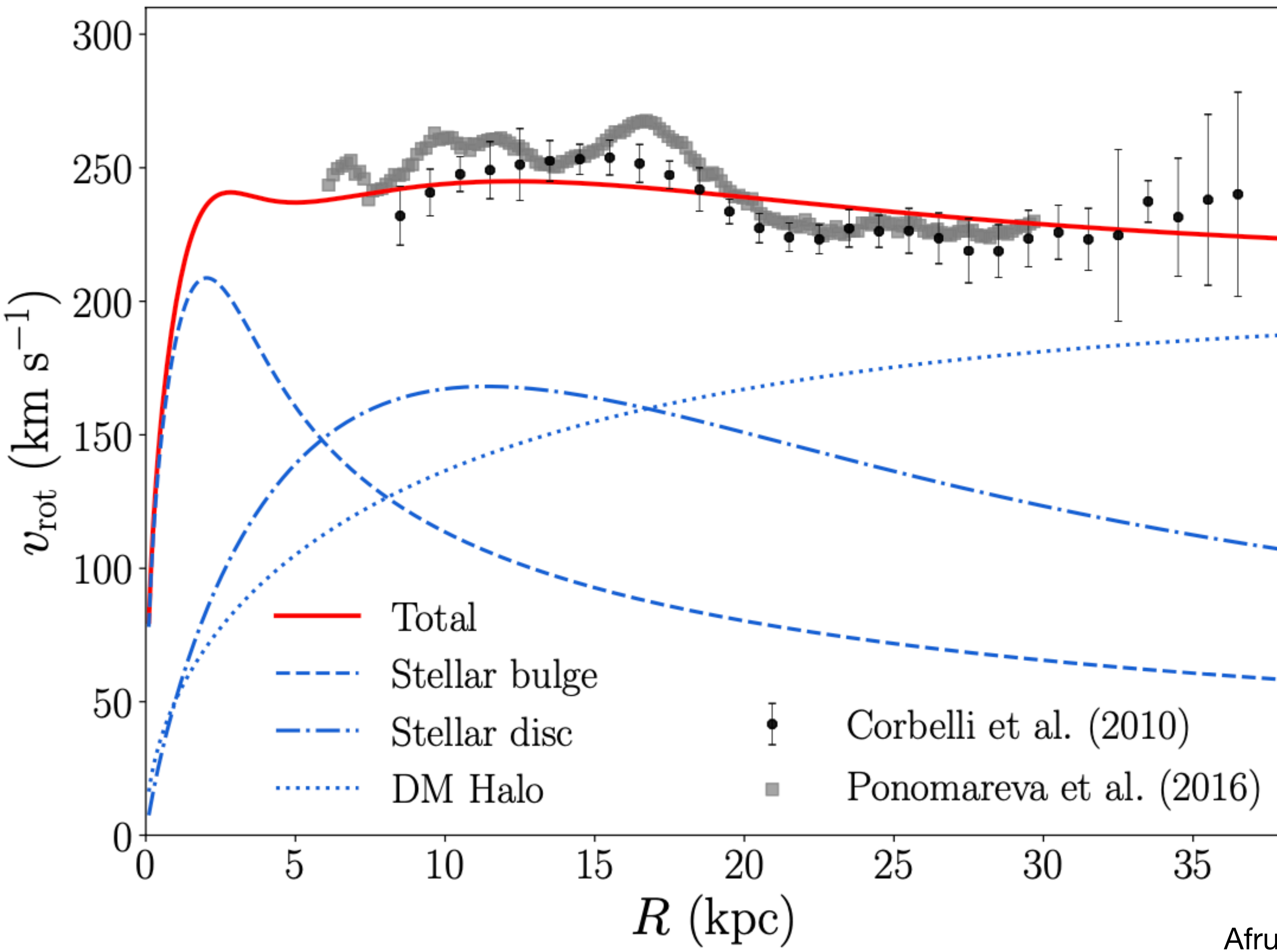


Flat Rotation Curves Provide Evidence for Dark Matter

- 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!**).



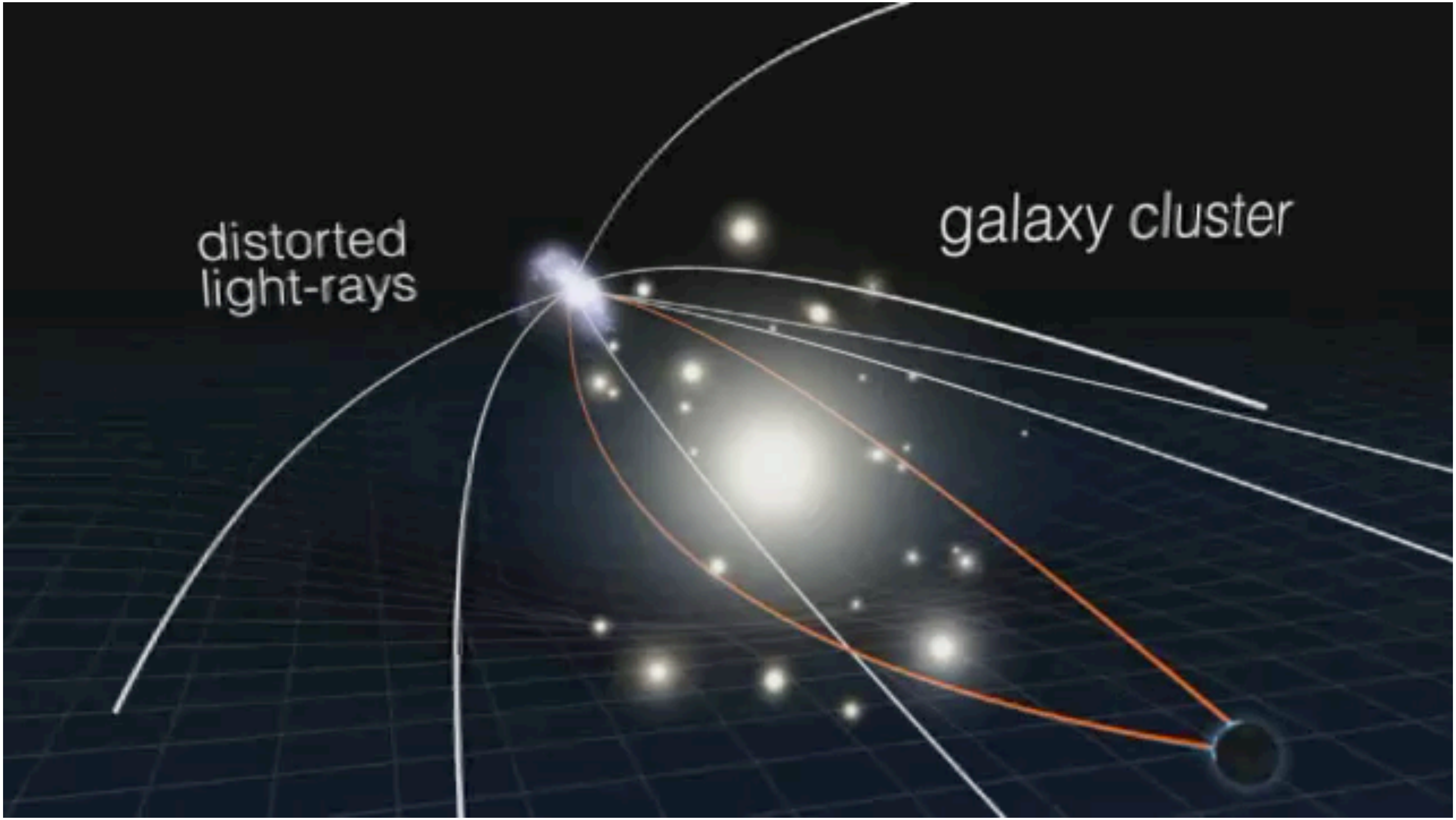
Rotation Curve Decomposition of M31 (Andromeda Galaxy)



Afruni+2021

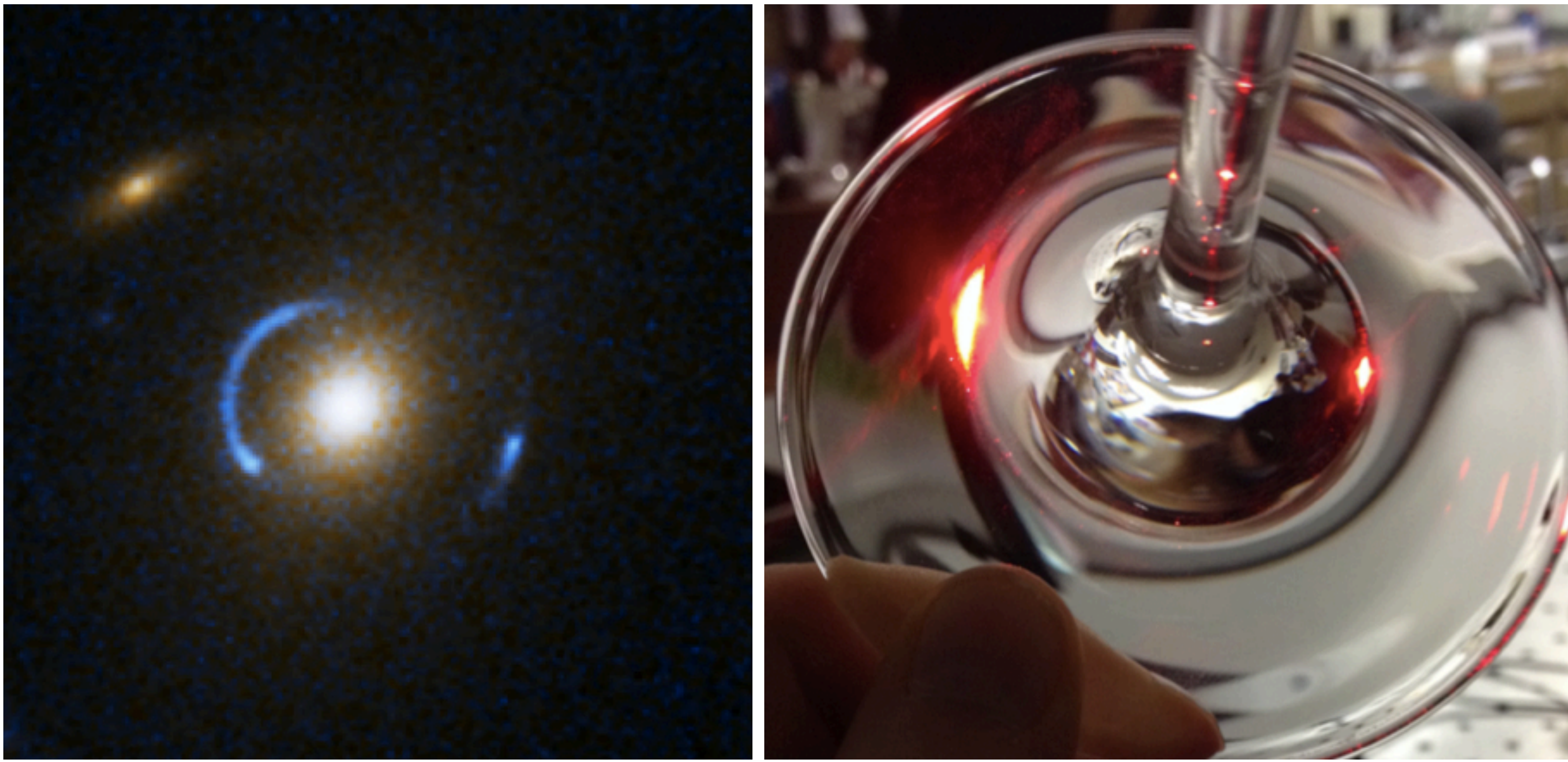
Non-Dynamical Evidence for Dark Matter: Gravitational Lensing

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



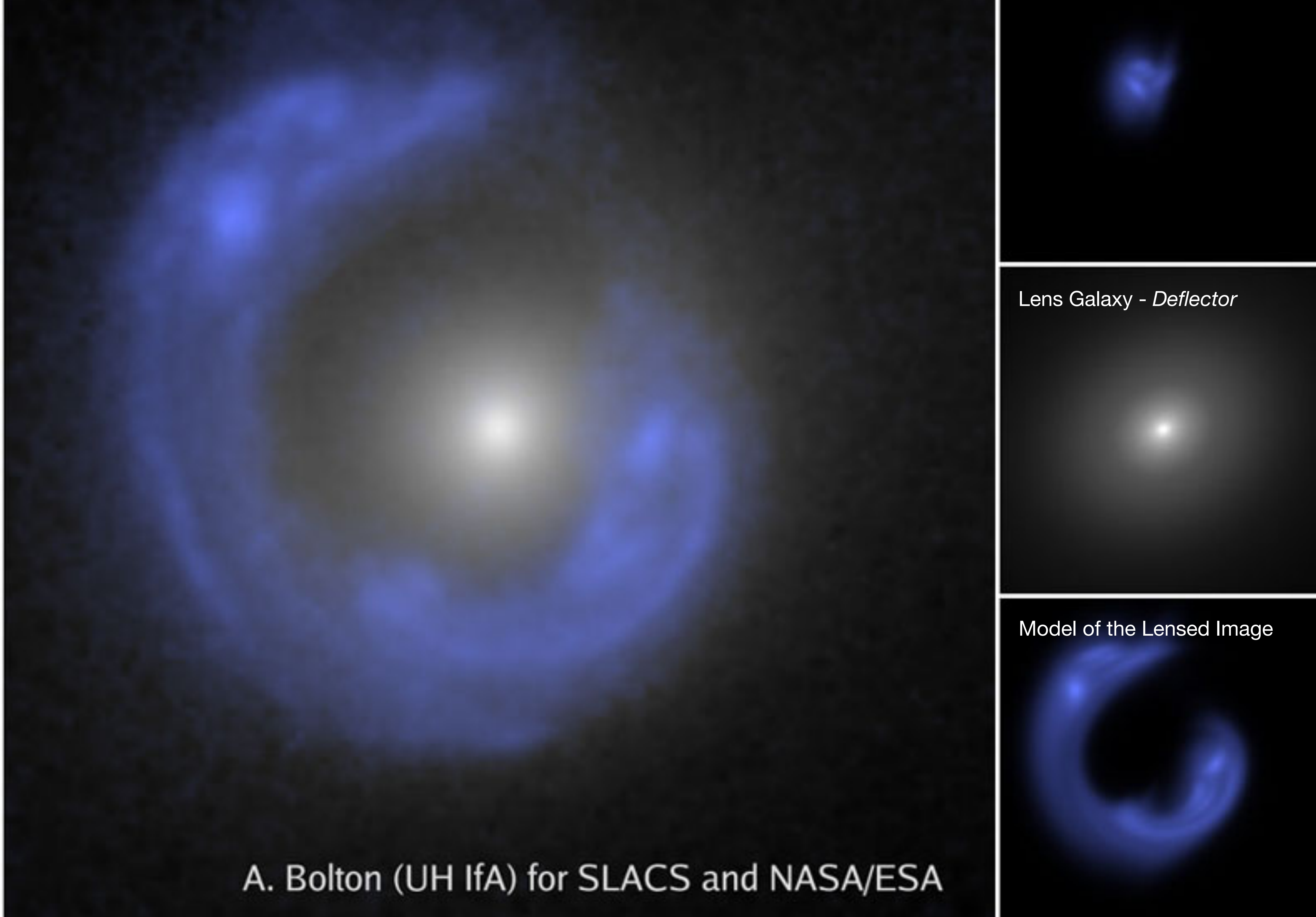
Gravitational Lensing

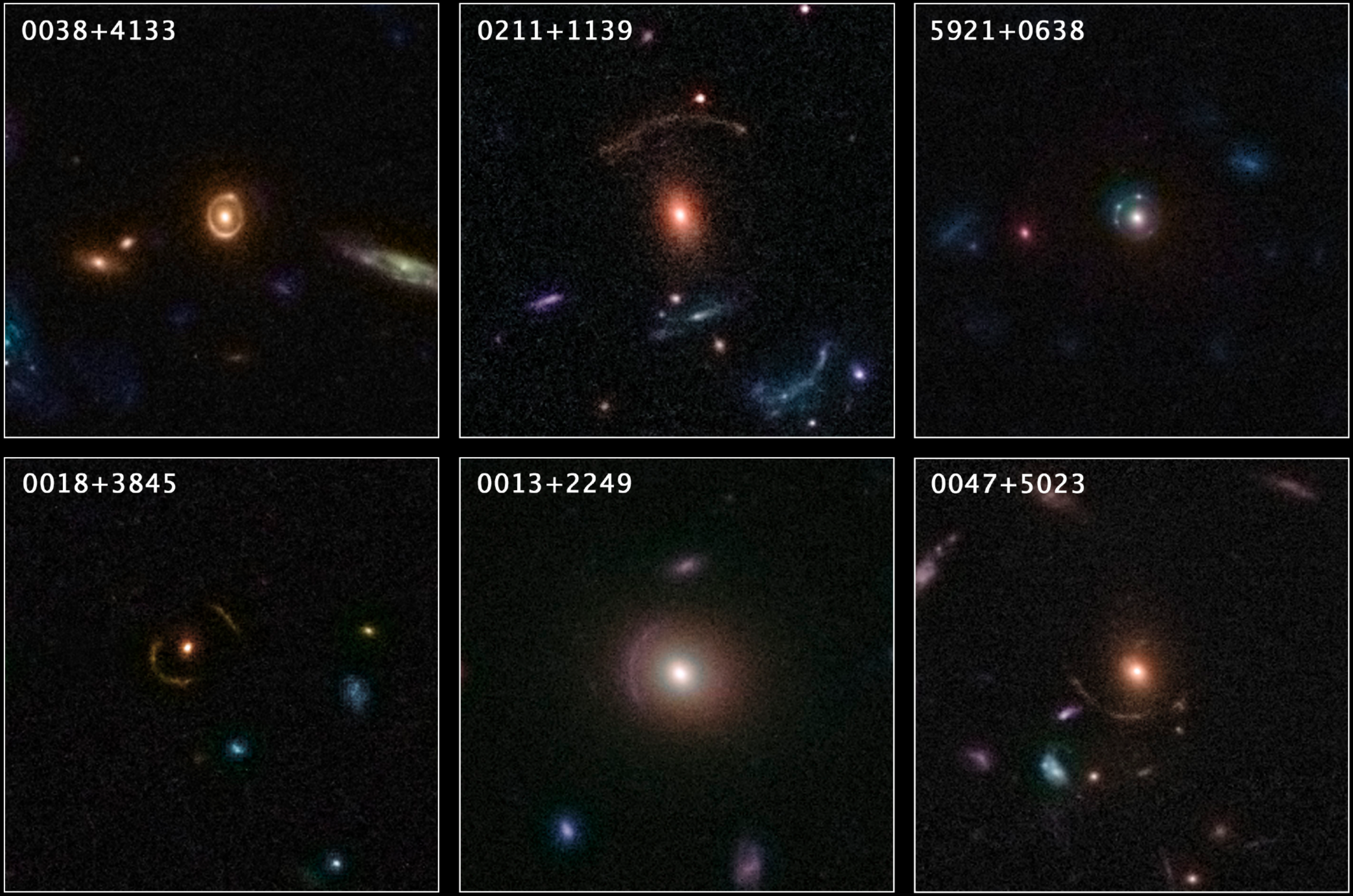
Galaxy-galaxy lensing reproduced with a wine glass and a light source



Various lensing configurations reproduced by a wine glass

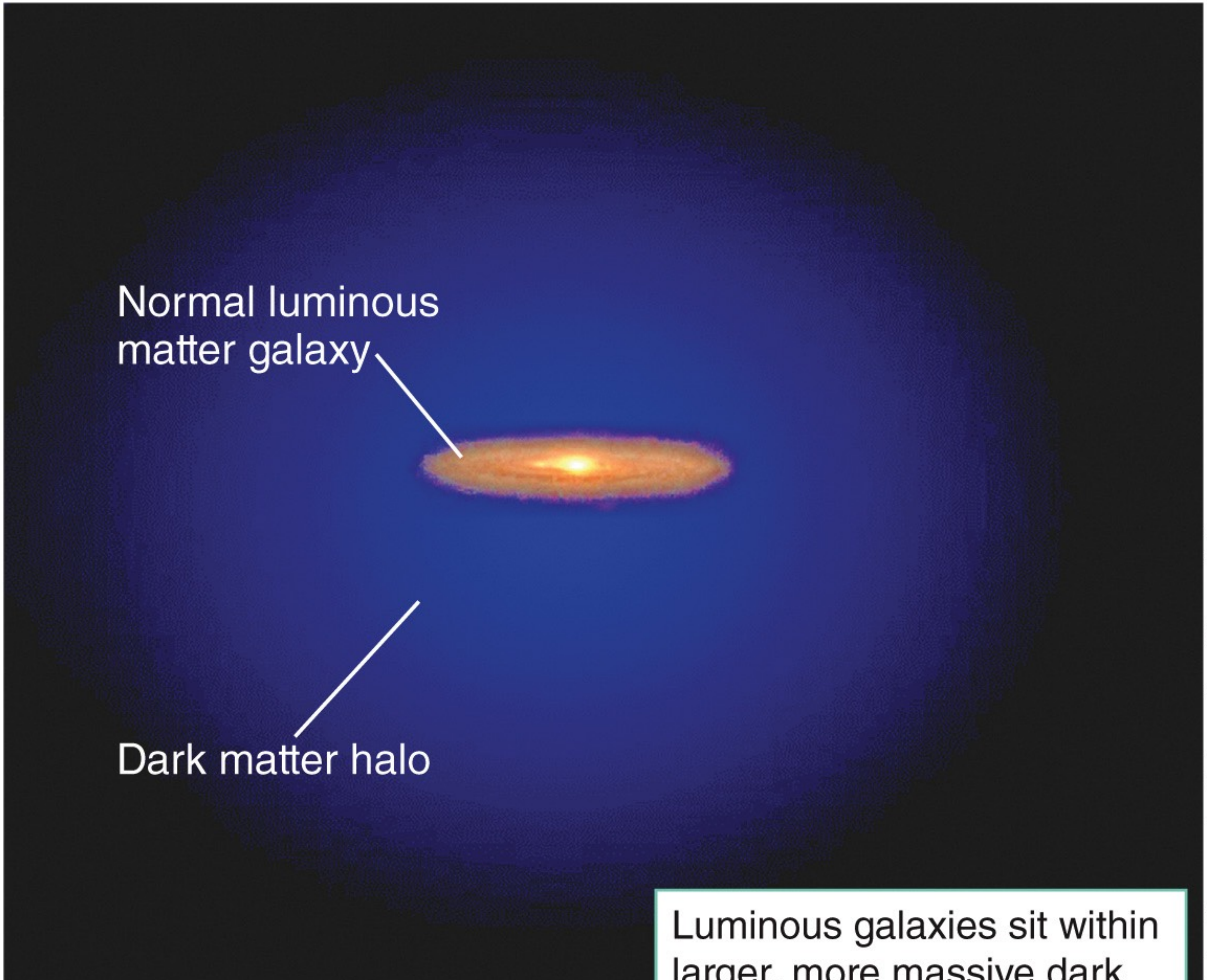
Modeling Strong Gravitational Lensing





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

Rotation Curve & Strong Lensing: “Galaxies Are Mostly Dark Matter”

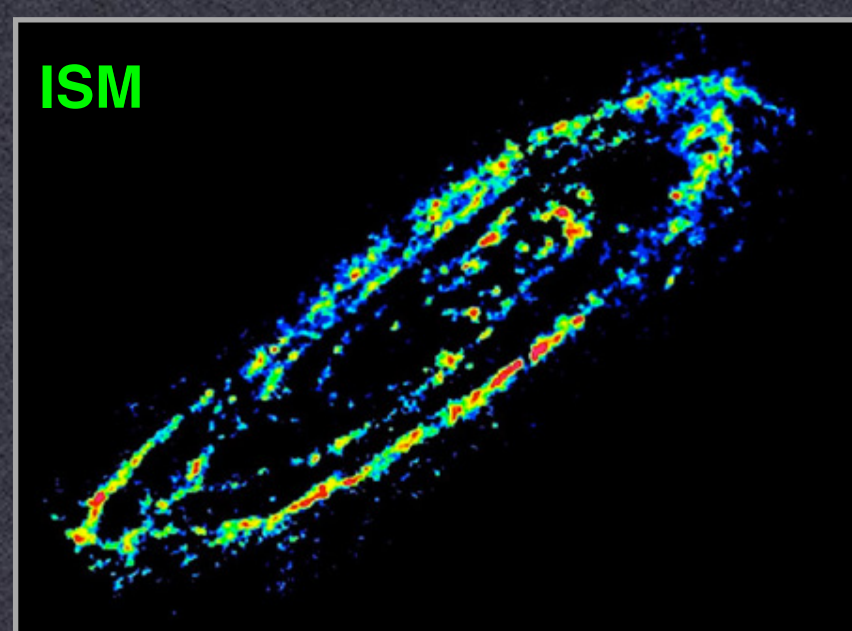


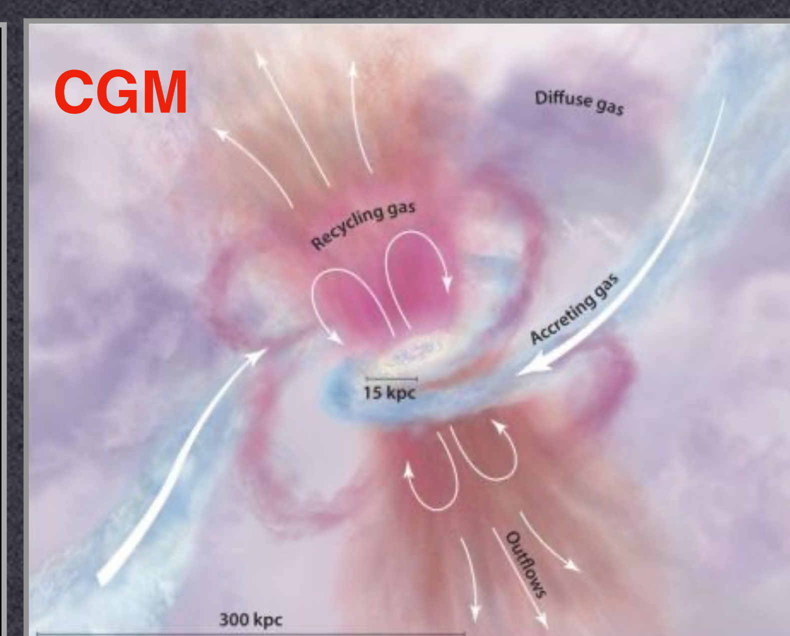
John Kormendy, University of Texas Astronomy

Luminous galaxies sit within larger, more massive dark matter halos.

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: $\sim 10^{12}\ M_\odot$



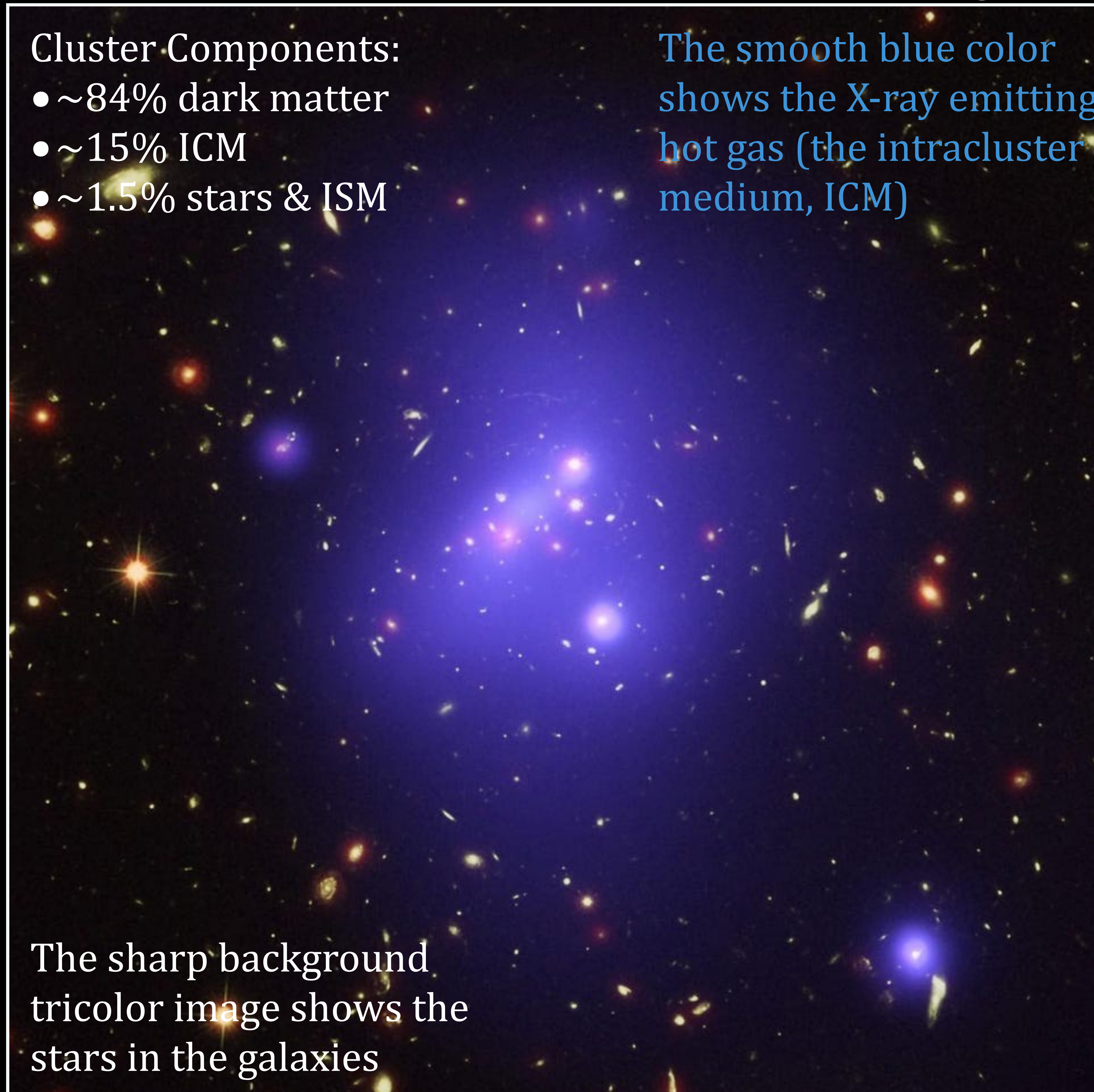


references: Corbelli+2010, Nieten+2005, Lehner+2015

The mass of normal matter is inferred from luminosities of stars and gas, so it depends on the mass-to-light ratio, the value of which could be quite uncertain

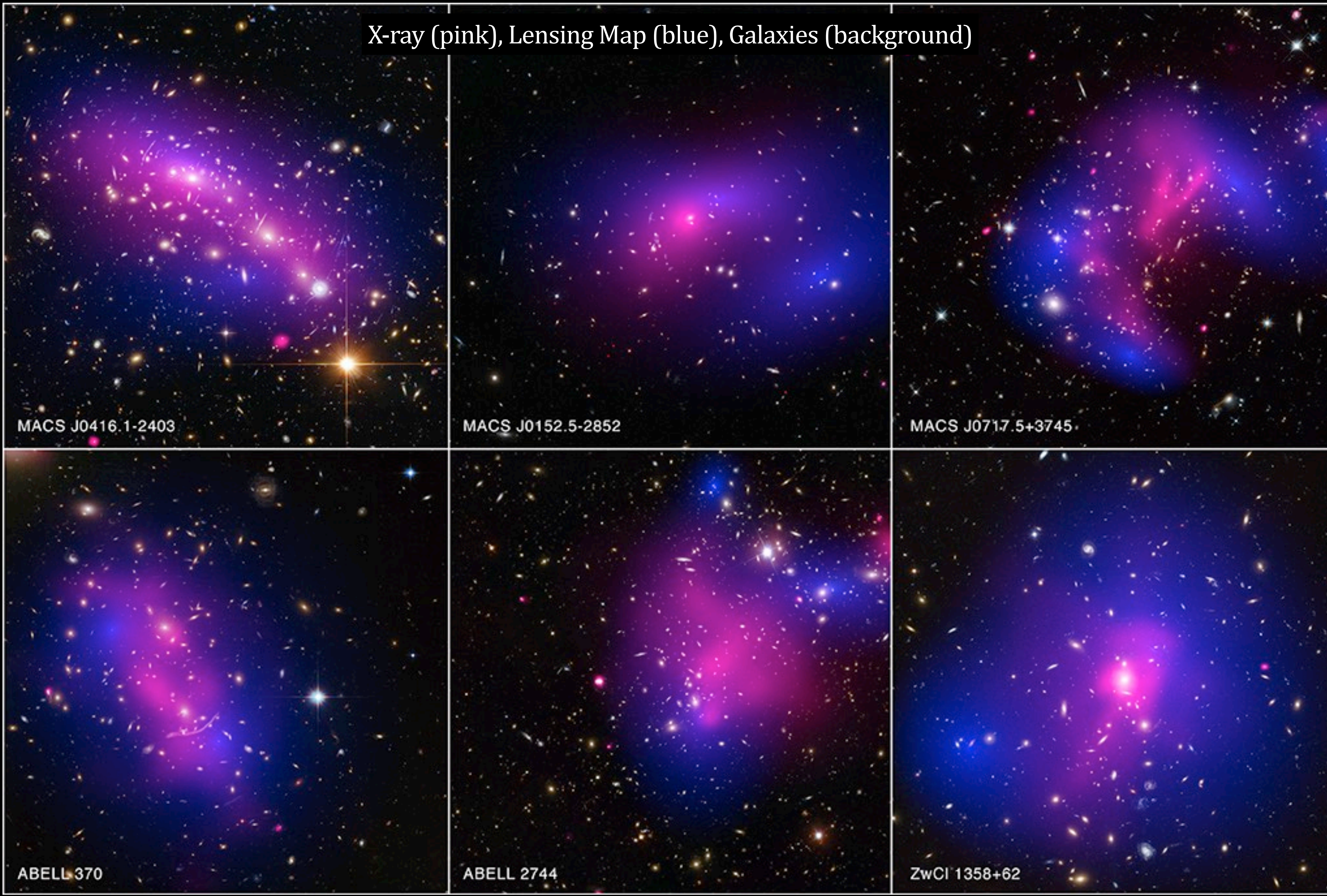
But if DM and NM are spatially separated in an astrophysical object, we would expect the mass distribution that is completely different from the light distribution, and the detection of DM would not depend on the mass-to-light ratio

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



IDCS J1426.5+3508

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



Cluster collision separates normal matter from dark matter

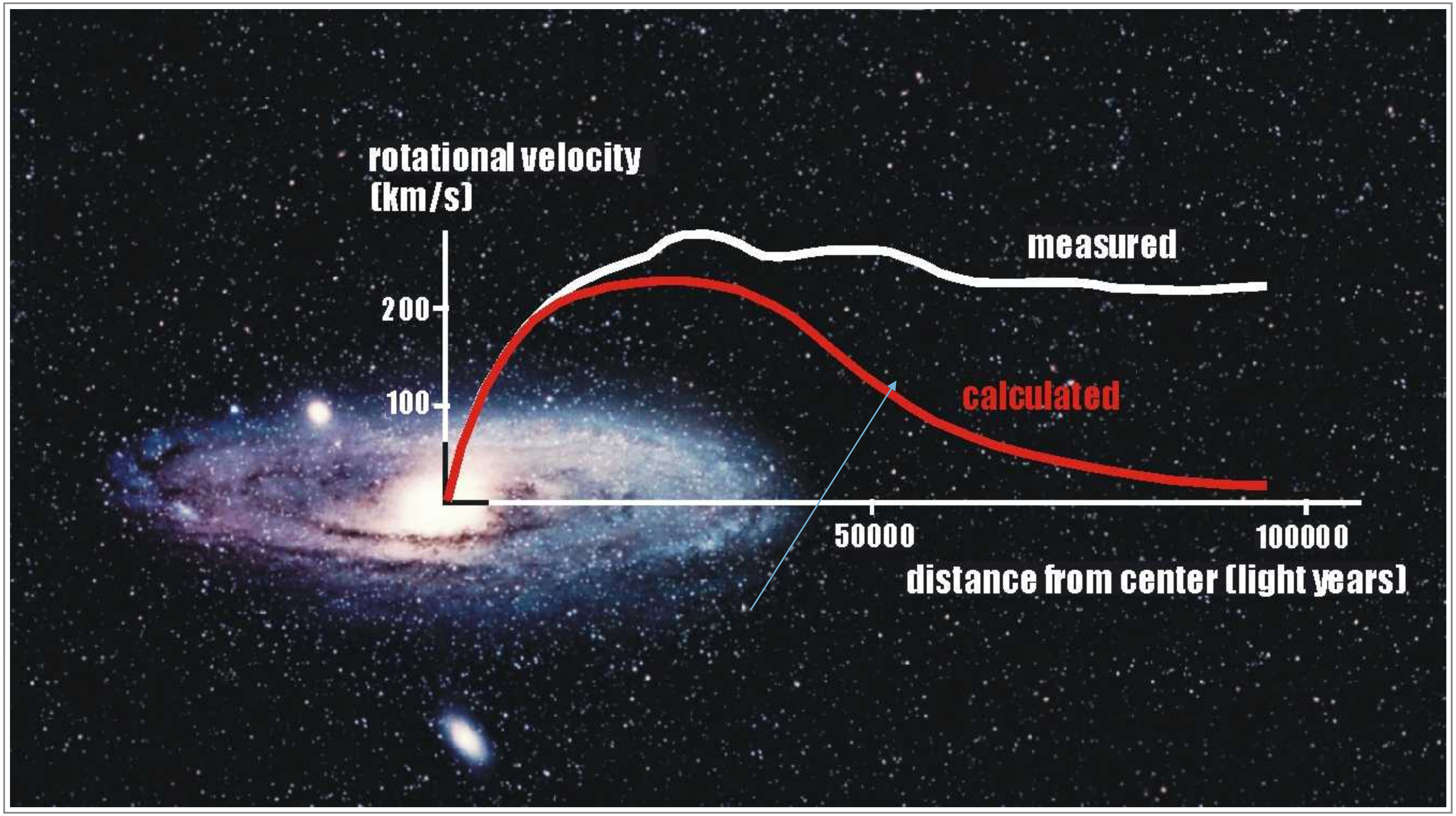
The Bullet cluster (IE 0657-56)

How to measure rotation velocity at large galactocentric distances?

Evidence of Dark Matter in Disk Galaxies

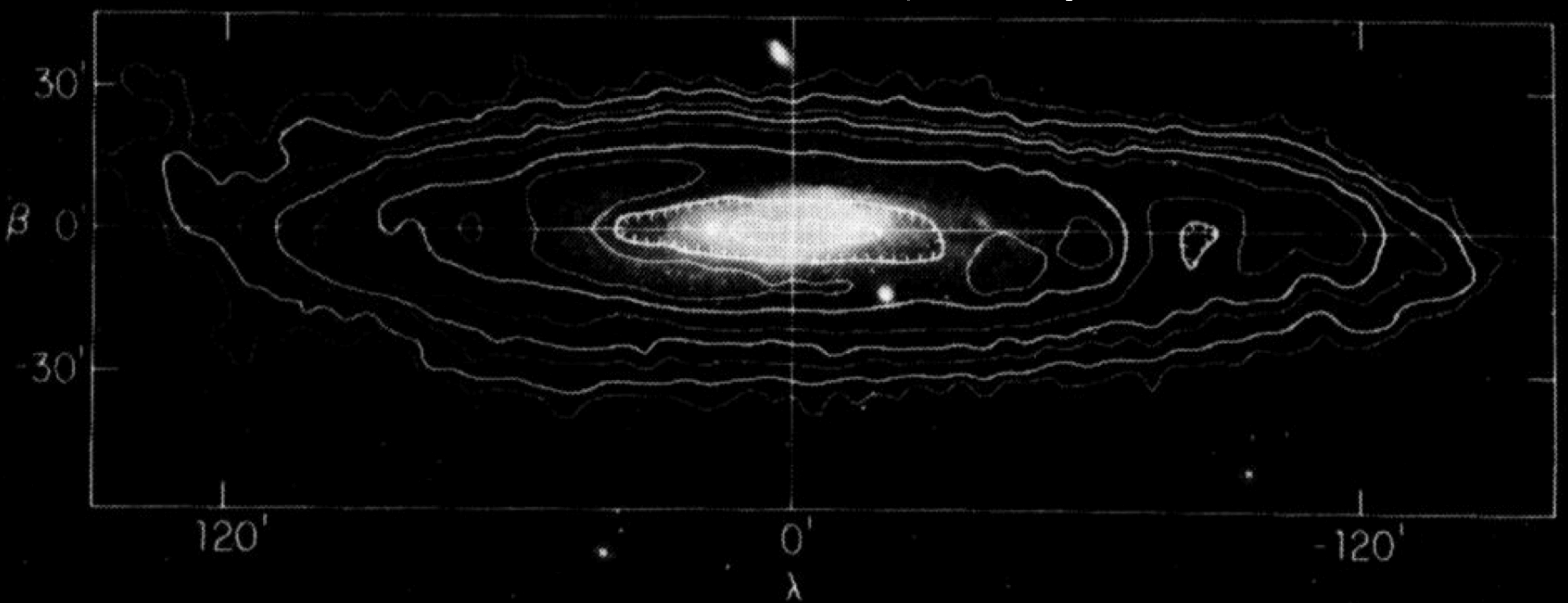
Newton's laws: $GM(r)/r^2 = v^2/r$

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



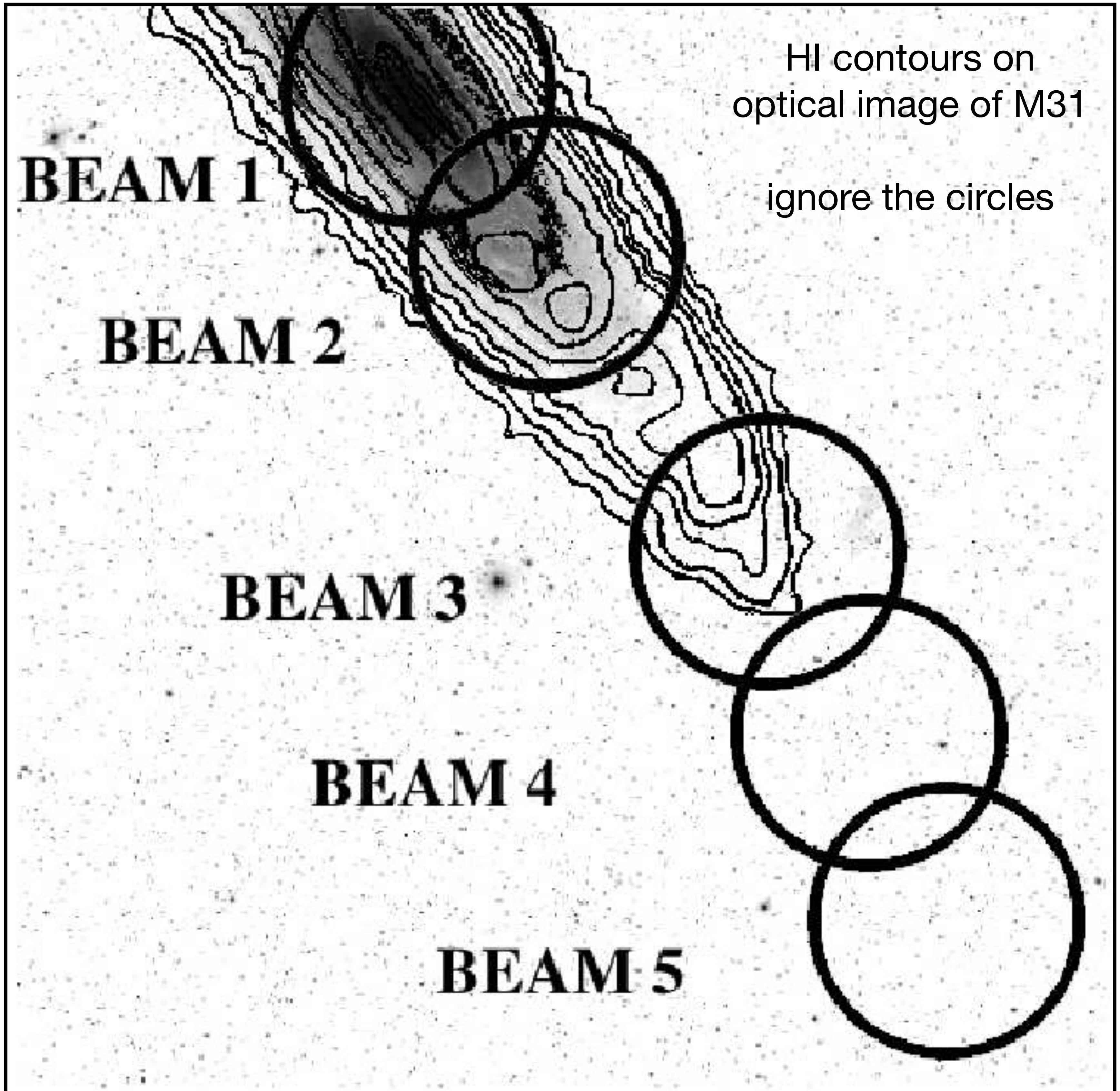
Neutral Hydrogen disk is much more extended than the optical stellar disk

Radio HI contours on optical image



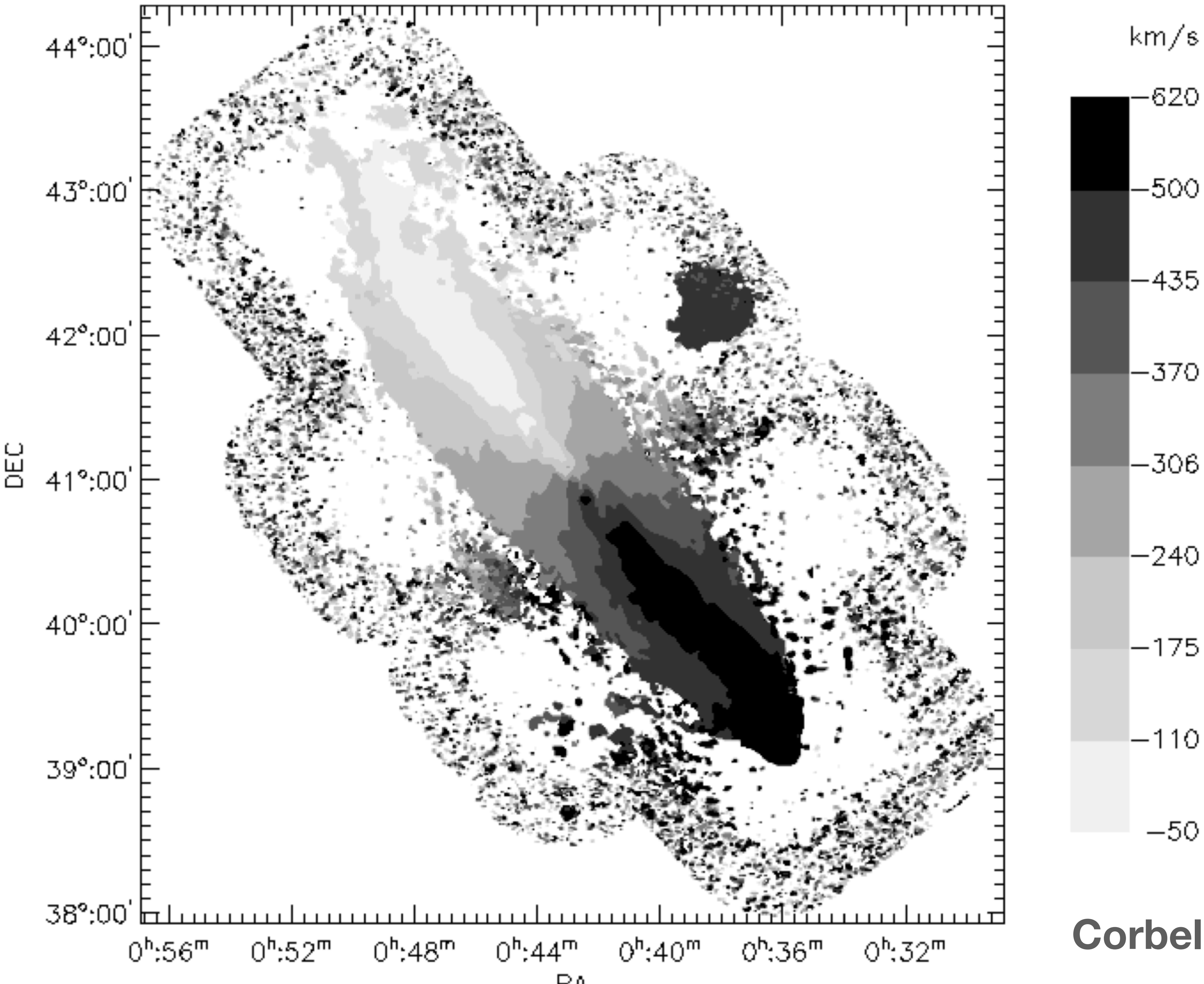
Cram+1980

Neutral Hydrogen disk extends farther out than the optical stellar disk



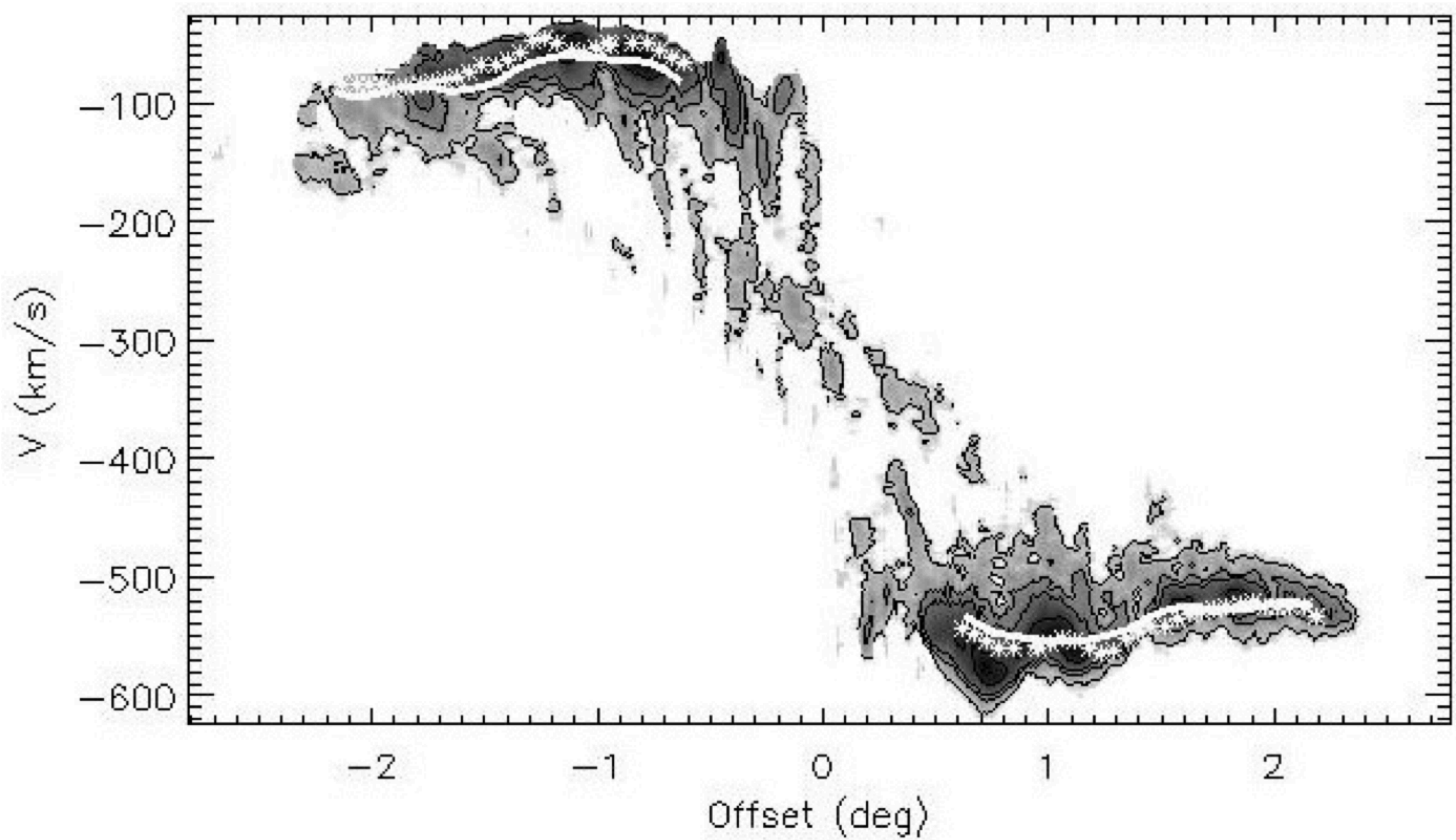
Madson+2001

Rotation of the extended HI Disk Revealed by the 21cm Line



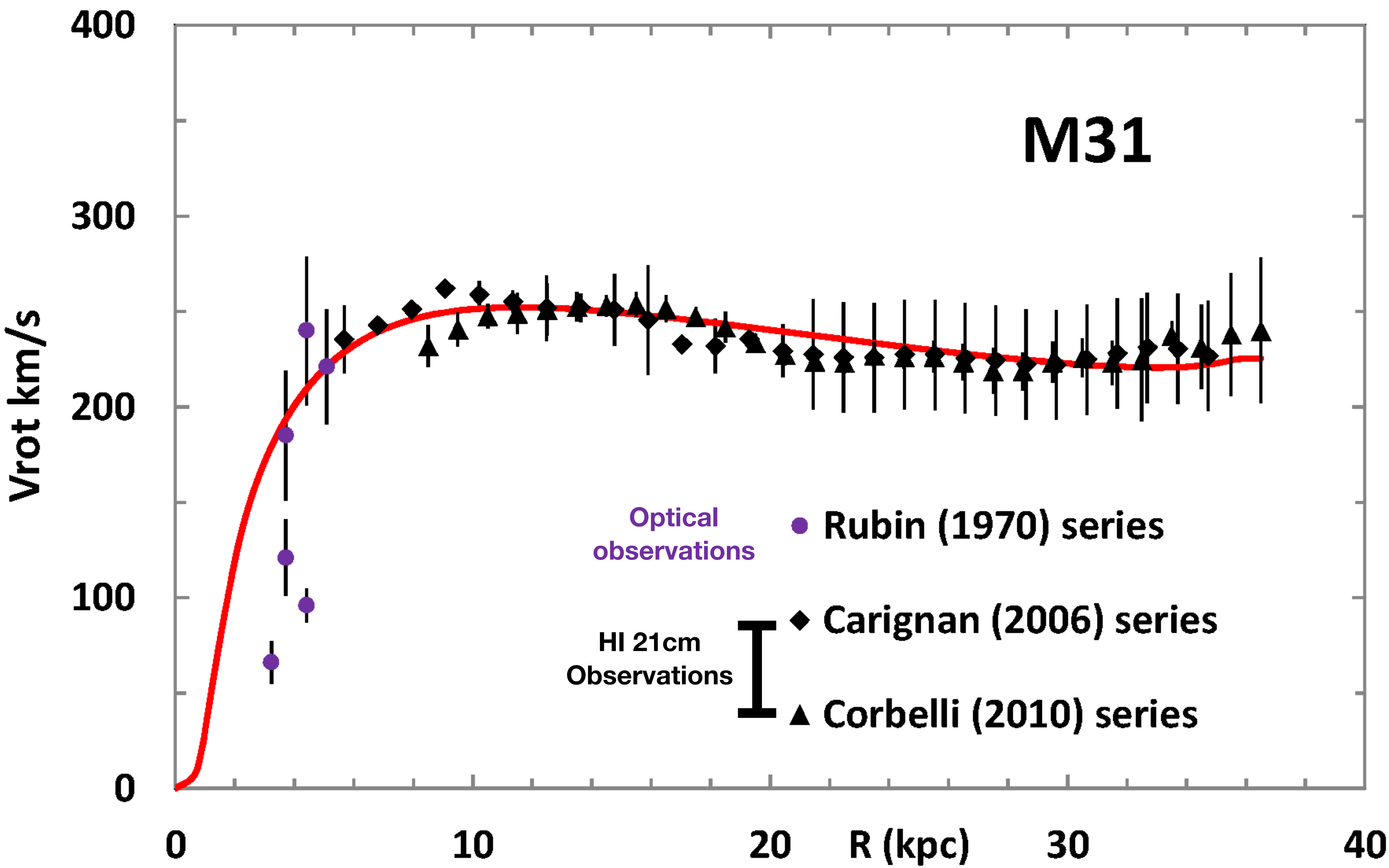
Corbelli+2010

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



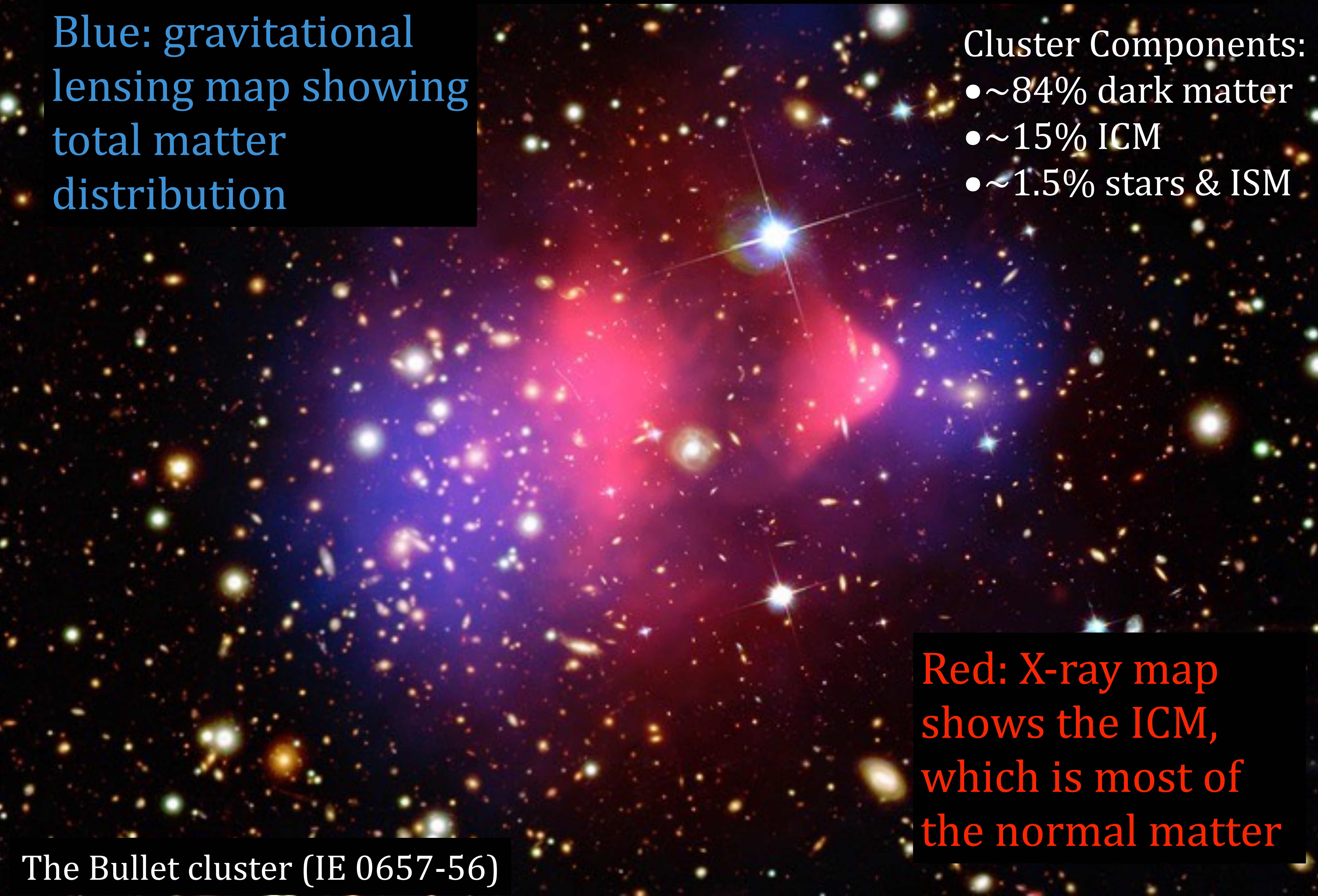
Corbelli+2010

M31's Full Rotation Curve: Original Data Sources



What is Dark Matter?

Cluster collision separates normal matter from dark matter



Blue: gravitational lensing map showing total matter distribution

Cluster Components:

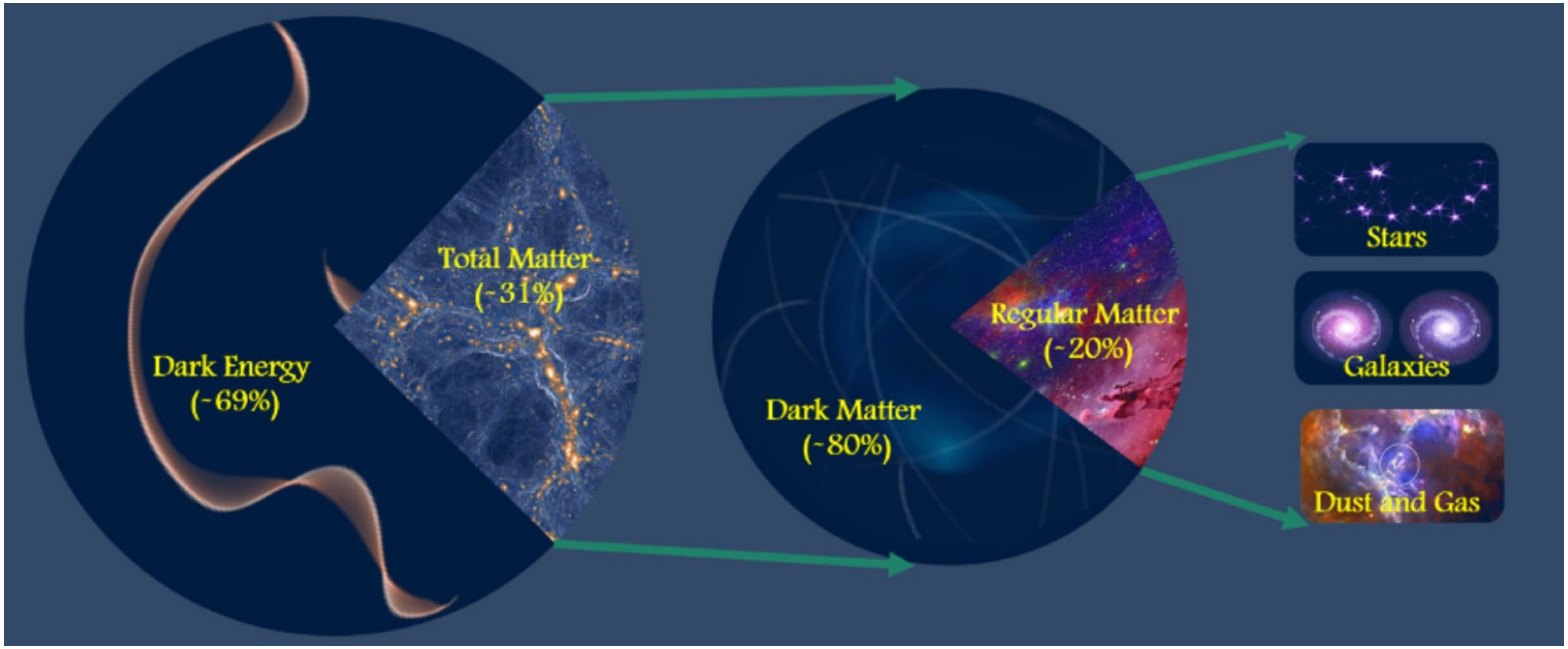
- ~84% dark matter
- ~15% ICM
- ~1.5% stars & ISM

Red: X-ray map shows the ICM, which is most of the normal matter

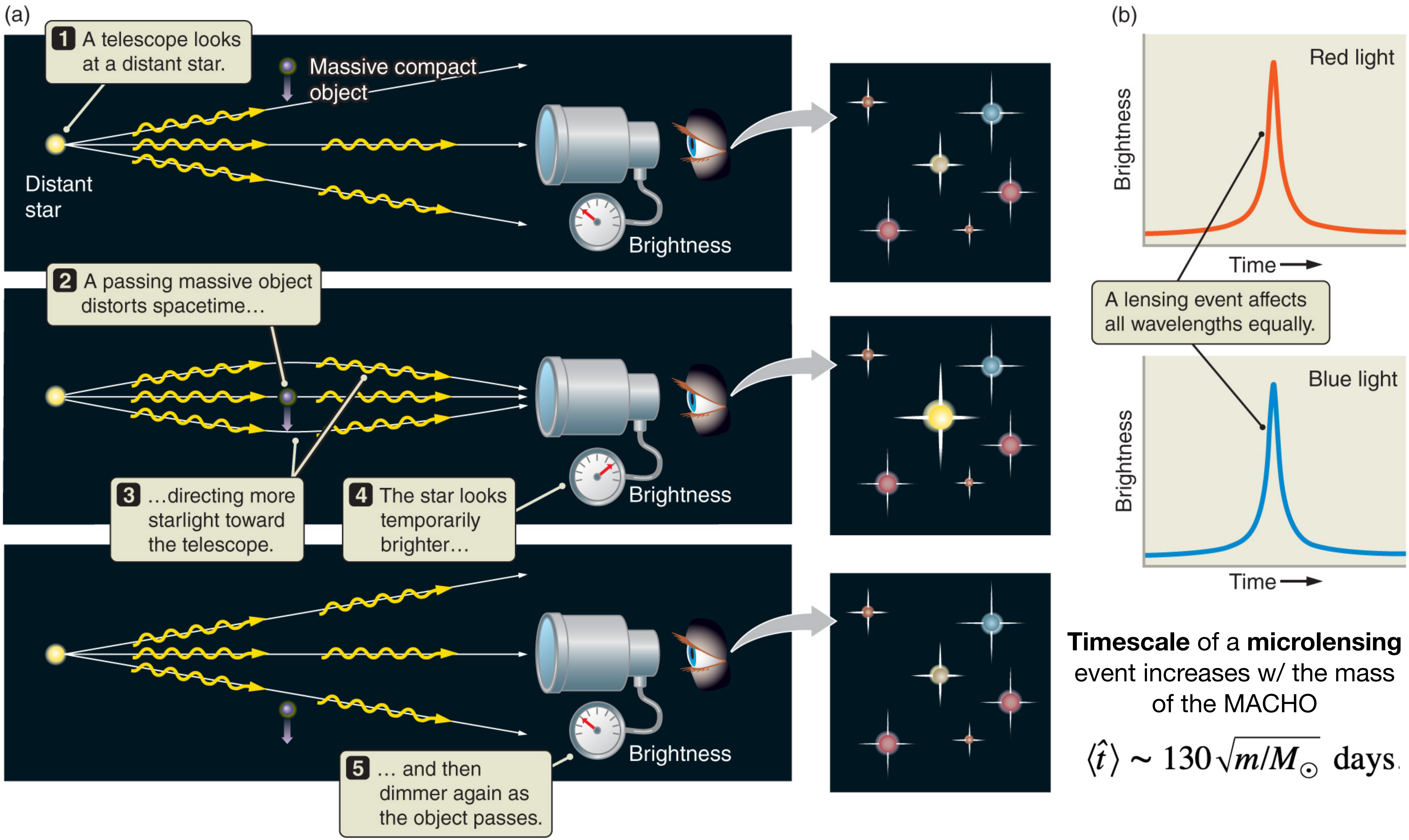
The Bullet cluster (IE 0657-56)

What Is Dark Matter?

- No direct detection of dark matter has been made, but there are two broad categories of candidates:
  - **MACHOs** — massive compact halo objects with masses larger than 10^{-8} M_{sun}, such as planets, stars, white dwarfs, neutron stars, or stellar-mass black holes
  - **WIMPs** — weakly interacting massive particles; some fundamental particles like neutrinos but much more massive. Details of WIMP particles are unknown.



Detecting MACHOs with gravitational micro-lensing



Timescale of a **microlensing** event increases w/ the mass of the MACHO

$$\langle \hat{t} \rangle \sim 130\sqrt{m/M_{\odot}}\ \text{days}$$

Microlensing surveys place strict upper limits on the MACHO fraction

- Two years of data on 9 million stars in LMC found 0 microlensing event.
- Even **planet-mass MACHOs** contribute **less than 10%** of halo mass
- These results make **WIMPs** the currently favored DM candidate.

EROS AND MACHO COMBINED LIMITS ON PLANETARY-MASS DARK MATTER IN THE GALACTIC HALO

C. Alcock,[1,2] R. A. Allsman,[3] D. Alves,[1,4] R. Ansari,[5] É. Aubourg,[6] T. S. Axelrod,[7] P. Bareyre,[6,8] J.-Ph. Beaulieu,[9,10] A. C. Becker,[2,11] D. P. Bennett,[1,2,12] S. Brehin,[6] F. Cavalier,[5] S. Char,[13] K. H. Cook,[1,2] R. Ferlet,[9] J. Fernandez,[13] K. C. Freeman,[7] K. Griest,[2,14] Ph. Grison,[9] M. Gros,[6] C. Gry,[15] J. Guibert,[16] M. Lachièze-Rey,[6] B. Laurent,[6] M. J. Lehner,[17] É. Lesquoy,[6] C. Magneville,[6] S. L. Marshall,[1,2] É. Maurice,[18] A. Milsztajn,[6] D. Minniti,[1] M. Moniez,[5] O. Moreau,[16] L. Moscoso,[6] N. Palanque-Delabrouille,[6] B. A. Peterson,[7] M. R. Pratt,[19] L. Prévôt,[18] F. Queinnec,[6] P. J. Quinn,[20] C. Renault,[6,21] J. Rich,[6] M. Spiro,[6] C. W. Stubbs,[2,7,11] W. Sutherland,[22] A. Tomaney,[2,11] T. Vandehei,[2,14] A. Vidal-Madjar,[9] L. Vigroux,[6] and S. Zylberajch[6]

Received 1998 March 9; accepted 1998 March 19; published 1998 May 4

ABSTRACT

The EROS and MACHO collaborations have each published upper limits on the amount of planetary-mass dark matter in the Galactic halo obtained from gravitational microlensing searches. In this Letter, the two limits are combined to give a much stronger constraint on the abundance of low-mass MACHOs. Specifically, objects with masses $10^{-7}\ M_\odot \lesssim m \lesssim 10^{-3}\ M_\odot$ make up less than 25% of the halo dark matter for most models considered, and less than 10% of a standard spherical halo is made of MACHOs in the $3.5 \times 10^{-7}\ M_\odot < m < 4.5 \times 10^{-5}\ M_\odot$ mass range.

Subject headings: dark matter — gravitational lensing — stars: low-mass, brown dwarfs

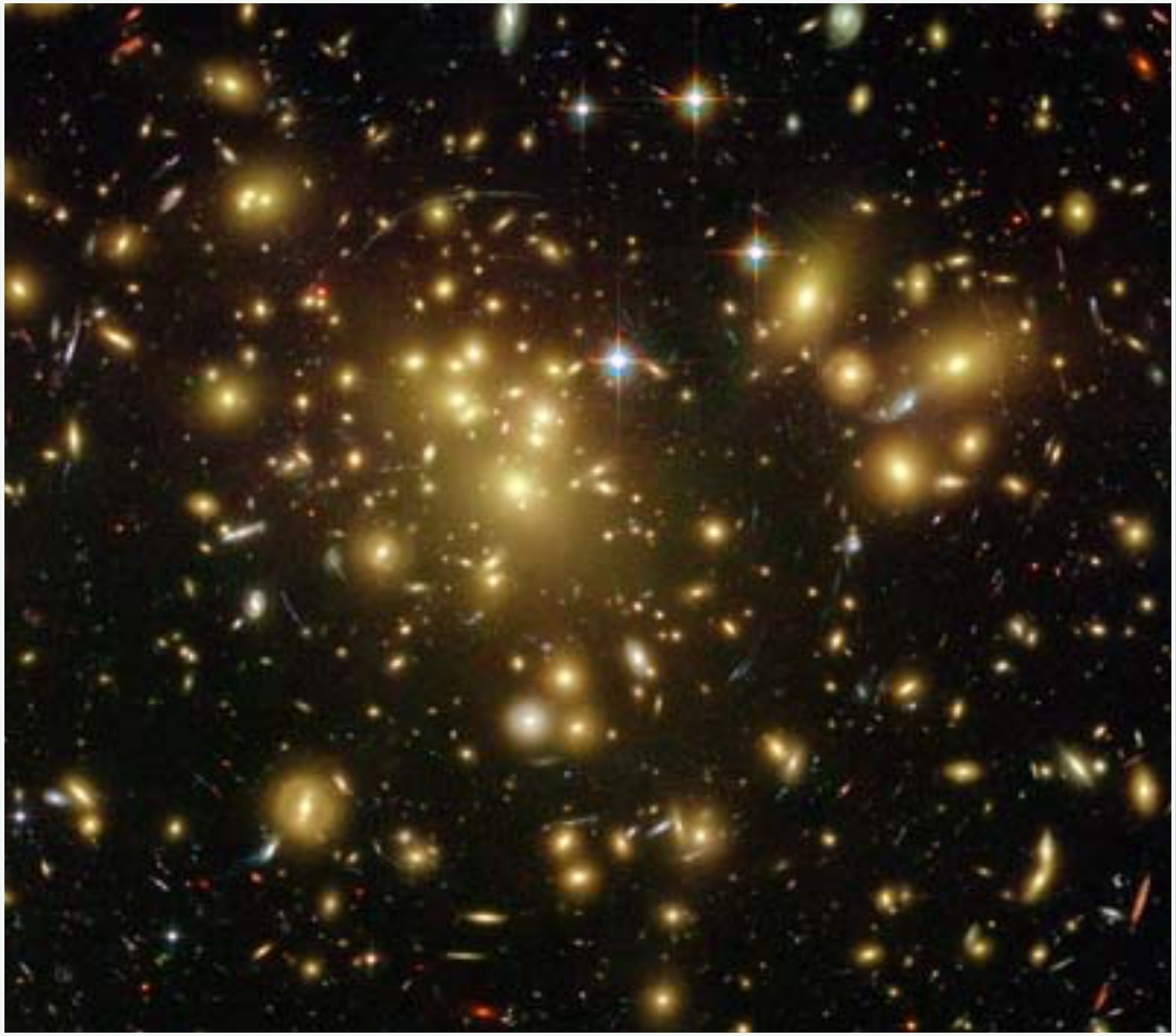
How orbits of stars and galaxy morphologies are intertwined?

All self-gravitating systems in equilibrium follow the Virial theorem, but they can have very different appearances

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

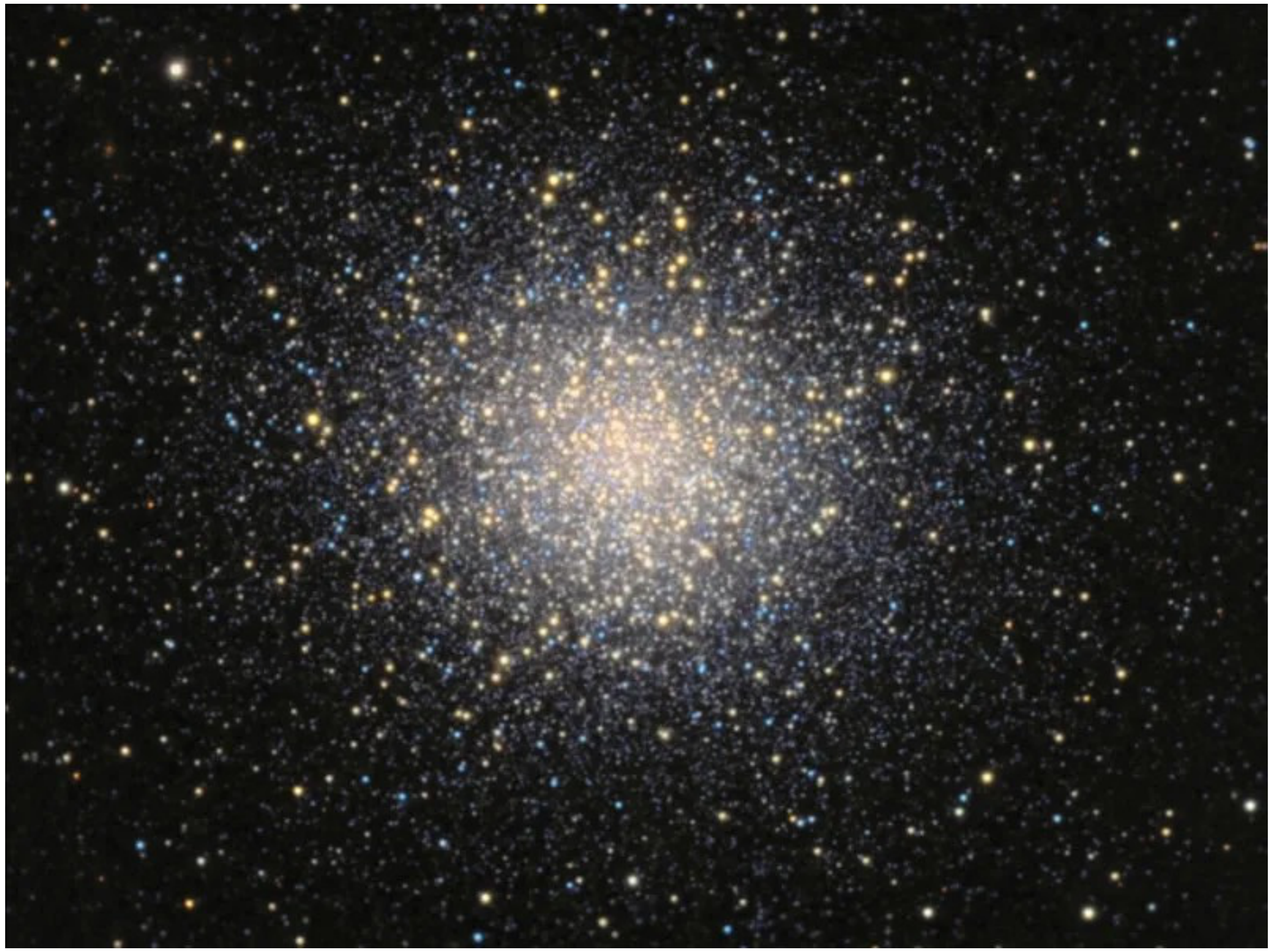
This applies to all self-gravitating systems:

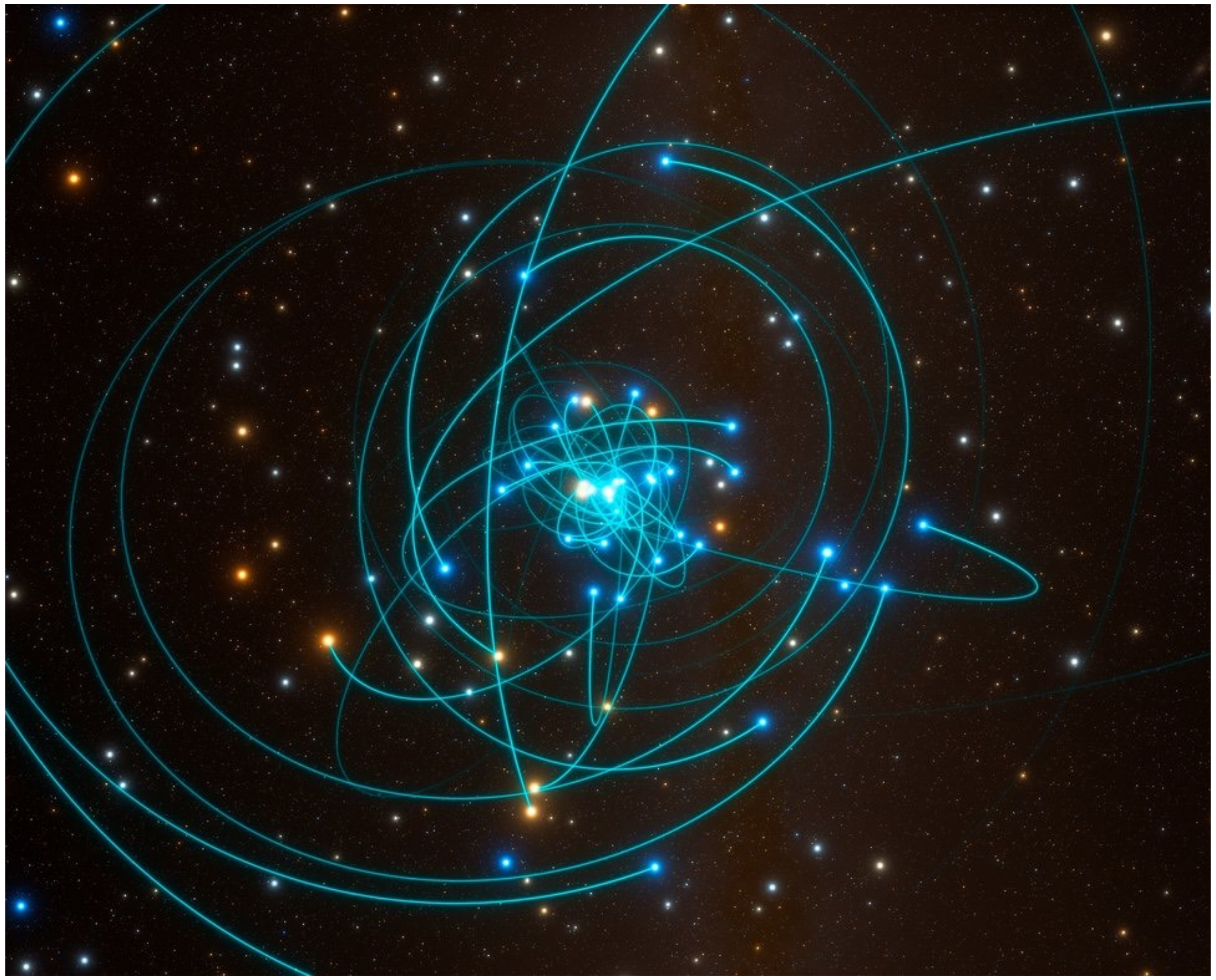
planetary systems, molecular clouds, stars, star clusters, galaxies, galaxy clusters



Galaxies are self-gravitating systems in dynamical equilibrium

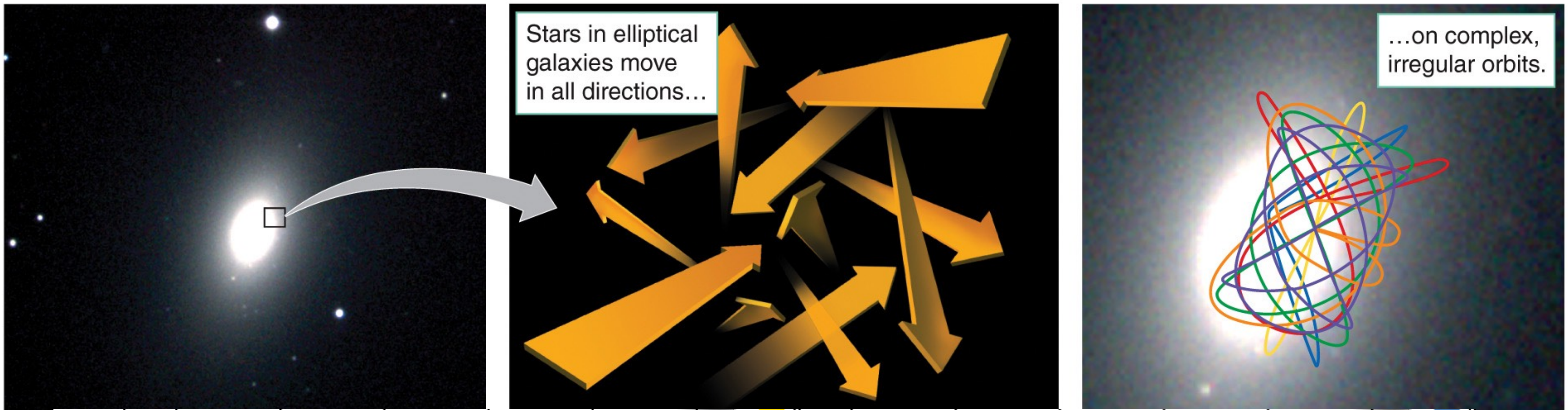
- *For simplicity, imagine an E0 galaxy similar to a* ***globular cluster*** *(ignoring dark matter); Unlike the Solar system, there is no dominating mass at the center.*
- The **distribution of stars** determine its mass distribution
- The mass distribution determines its gravitational potential
- The gravitational potential determines the orbits of the stars
- The orbits of stars determine the **distribution of stars**, and the loop continues

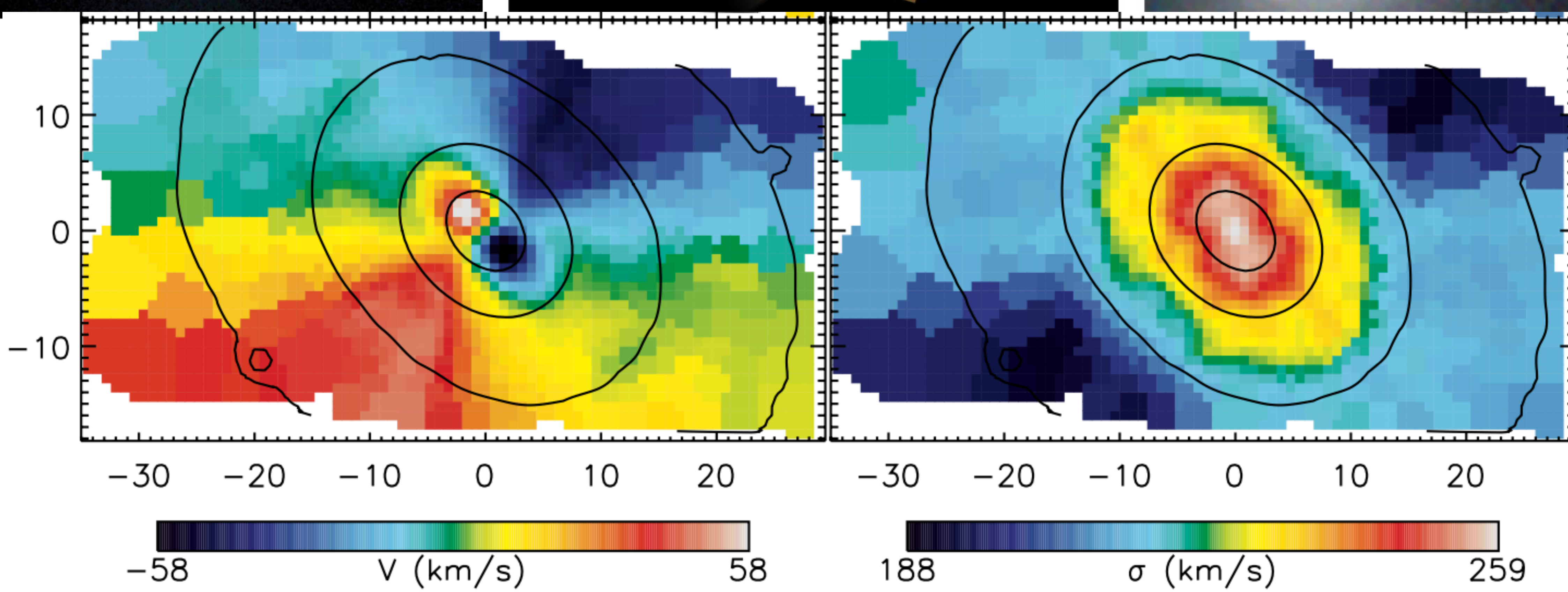




Elliptical Galaxies: Irregular Orbits of Stars

In ellipticals and in bulges of spiral galaxies, stars orbit in many different directions and move on irregular orbits. The velocity dispersion (*random motion*) dominates over the rotation velocity (*ordered motion*)

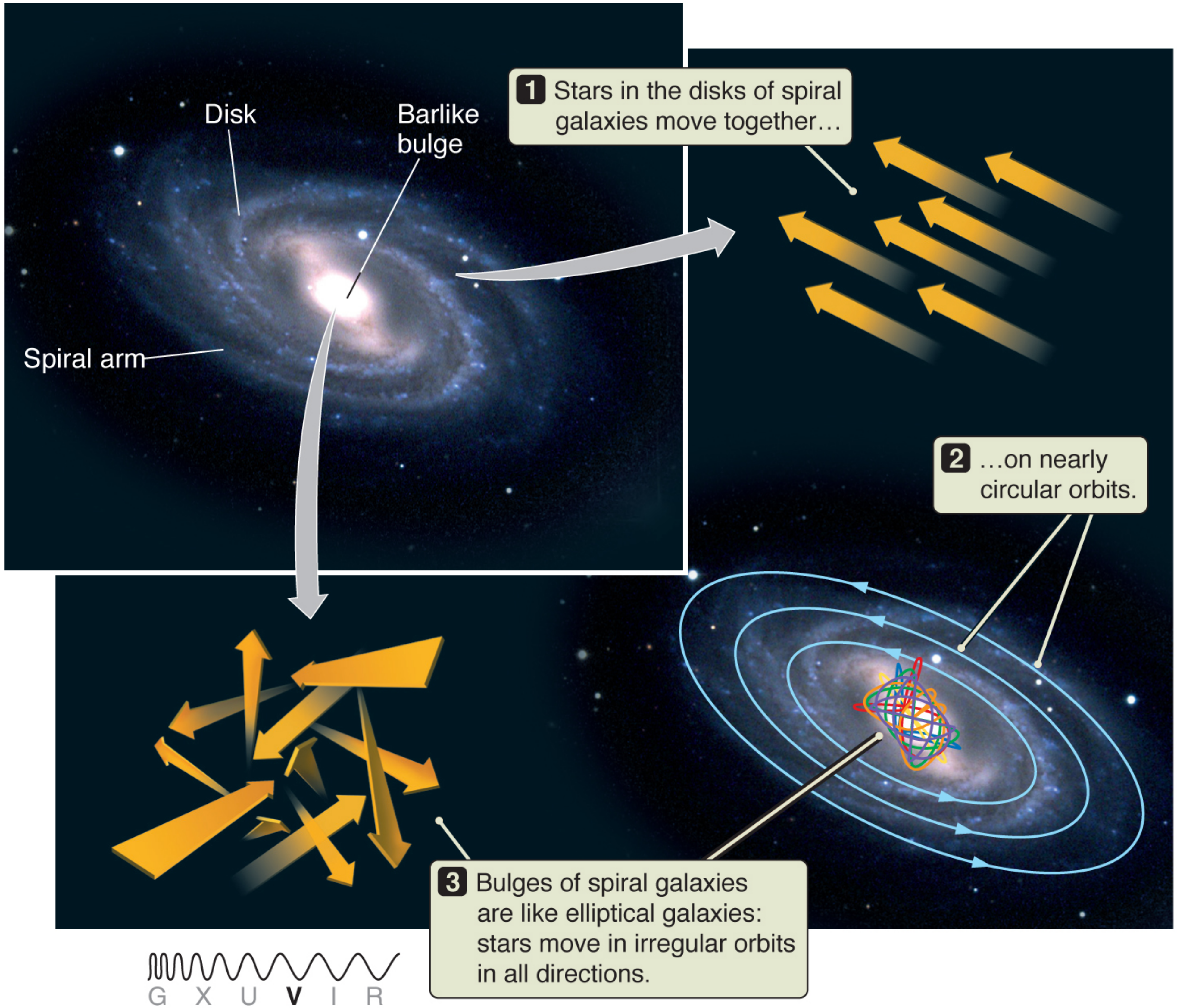




NGC4365

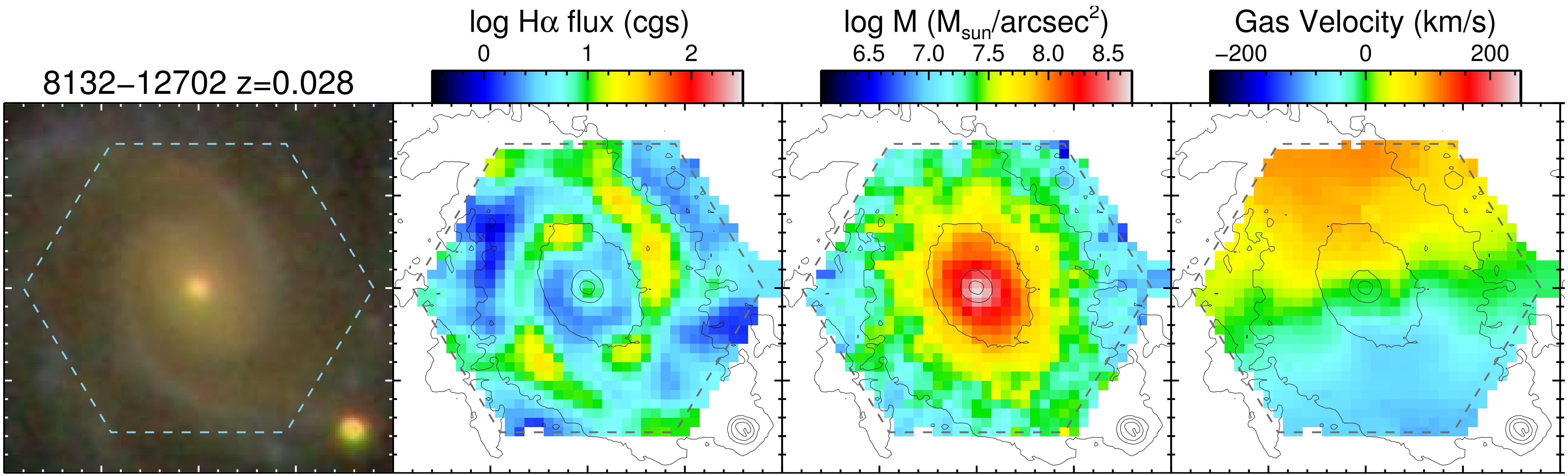
van den Bosch+ 2008

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



Imaging and spectroscopy provide useful 2D measurement, but to infer the full 3D information requires dynamical modeling

- Imaging observations provide maps of the light distribution of stars and gas in the galaxy, which can be used to infer the 2D projected mass distribution
- Integral-field spectroscopic observations provide a map of Doppler shift, which then gives us the line-of-sight velocities.
- But even perfect observations provide **incomplete information** of the galaxy**:**
  - only the surface density *projected* along the line-of-sight is measured
  - only the velocity component along the line-of-sight is measured

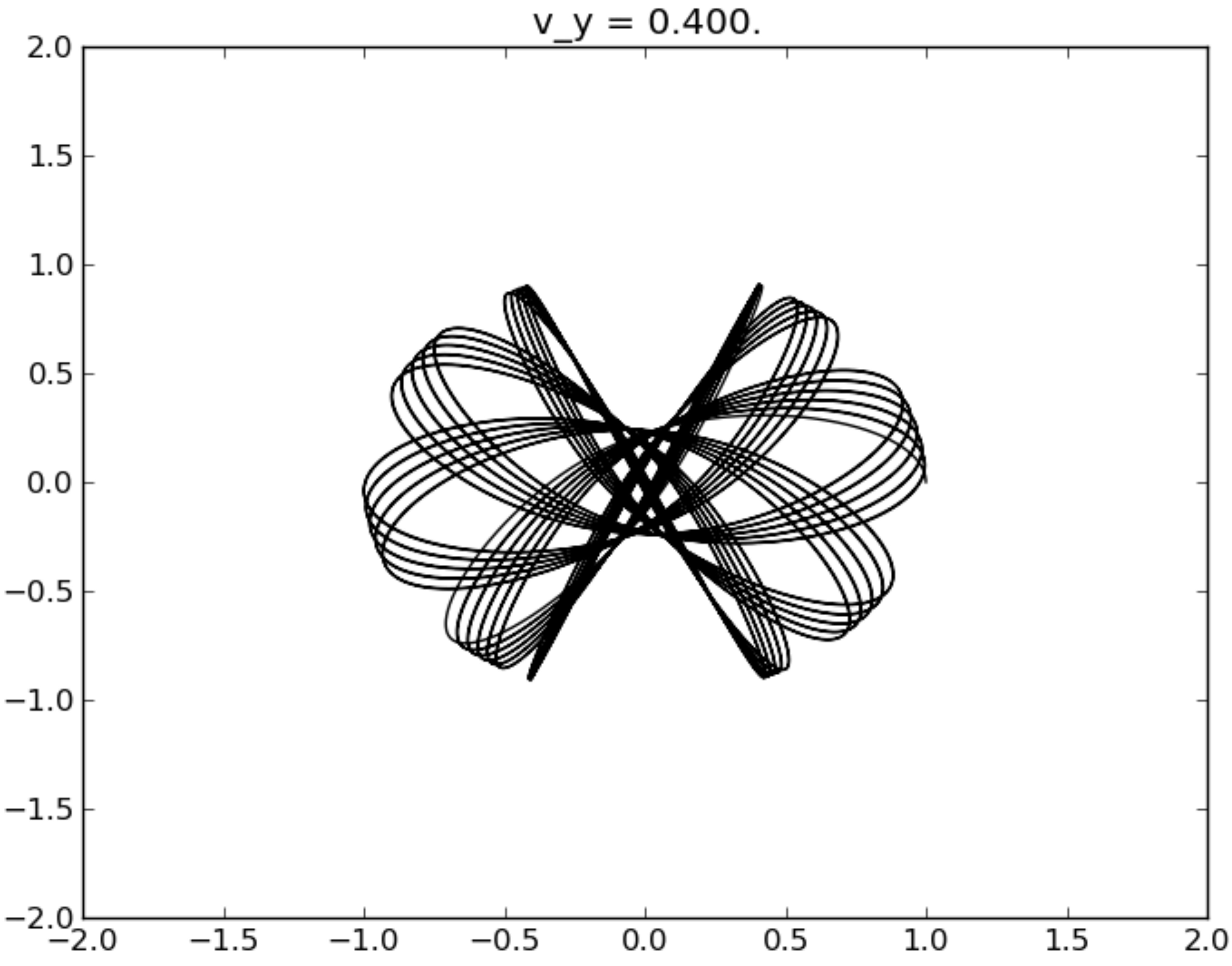


Data from SDSS IV/MaNGA Survey, Figure made by Hai Fu

How to find a dynamical model that is consistent with observations?

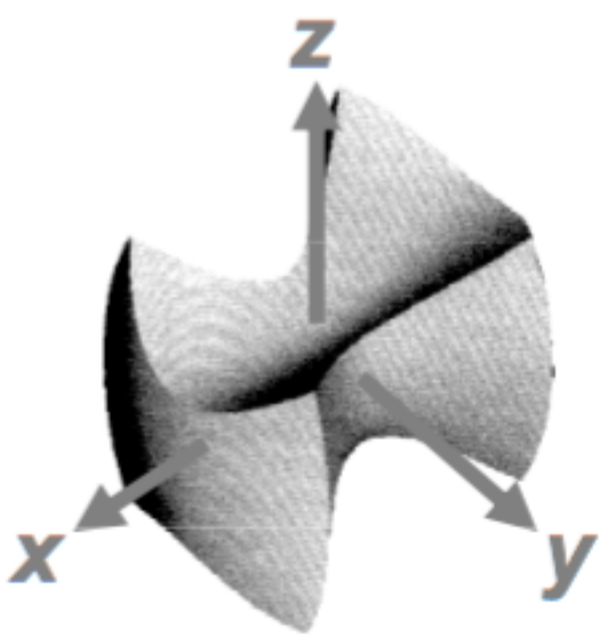
- The orbit-superposition approach by **Martin Schwarzschild (1979)**.
- Specify a ***M/L*** and a geometric model to *deproject* the observed surface light distribution $\Sigma(\alpha, \delta)$ to obtain the 3D density distribution $\rho(\vec{x})$
- Find the corresponding gravitational potential by solving the Poisson Equation: $\nabla^2\Phi(\vec{x}) = 4\pi G\rho(\vec{x})$
- Construct a grid of ***K* cells** in position space
- Choose initial positions and velocities for a set of ***N* orbits,** for each one
  - integrate the equation of motion for many orbital periods $\vec{g}(\vec{x}) = -\nabla\Phi(\vec{x})$
  - keep track of the time the orbit spends in each of the **K cells;** this is proportional to how much mass the orbit contributes to each cell.
- Determine **non-negative weights** for each orbit such that the summed mass in each cell is equal to the mass implied by the original $\rho(\vec{x})$.
- Use the model to predict the line-of-sight velocity distribution and compare it with the **observed stellar kinematics**, modify $\rho(\vec{x})$ if necessary and repeat until the process converges.

What do these orbits look like?

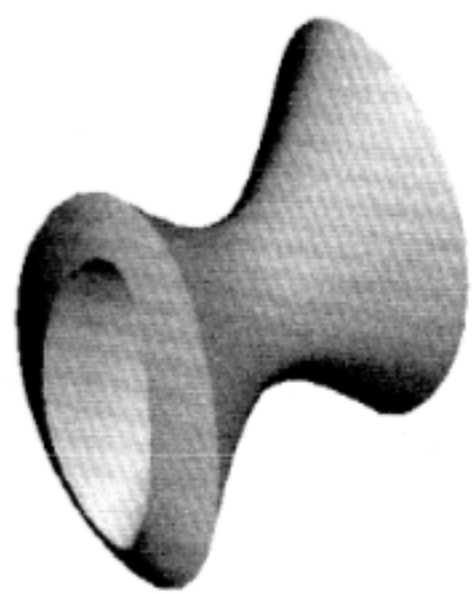


Elliptical Galaxies and Bulges: Irregular Orbit Families

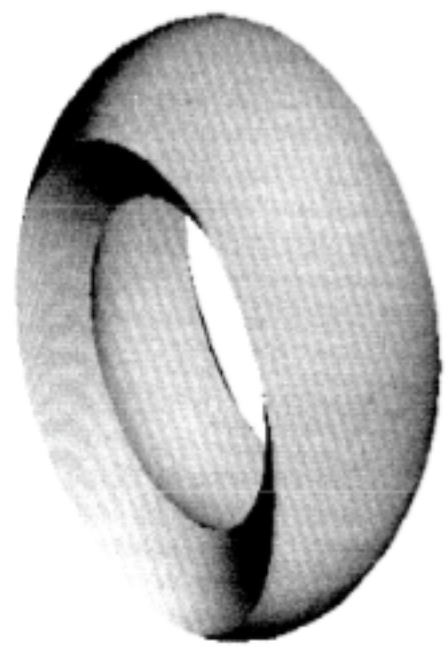
- In elliptical galaxies and bulges of spiral galaxies, stars orbit in many different directions and move on irregular orbits.
- There are four main orbit families in the triaxial gravitational potential of elliptical galaxies.



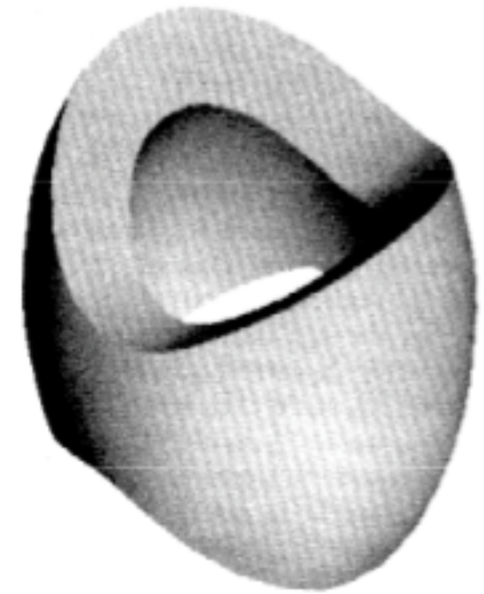
Box



Inner long-axis tube



Outer long-axis tube



Short-axis tube

Projected Views of a Box and a Minor-Axis Tube Orbit

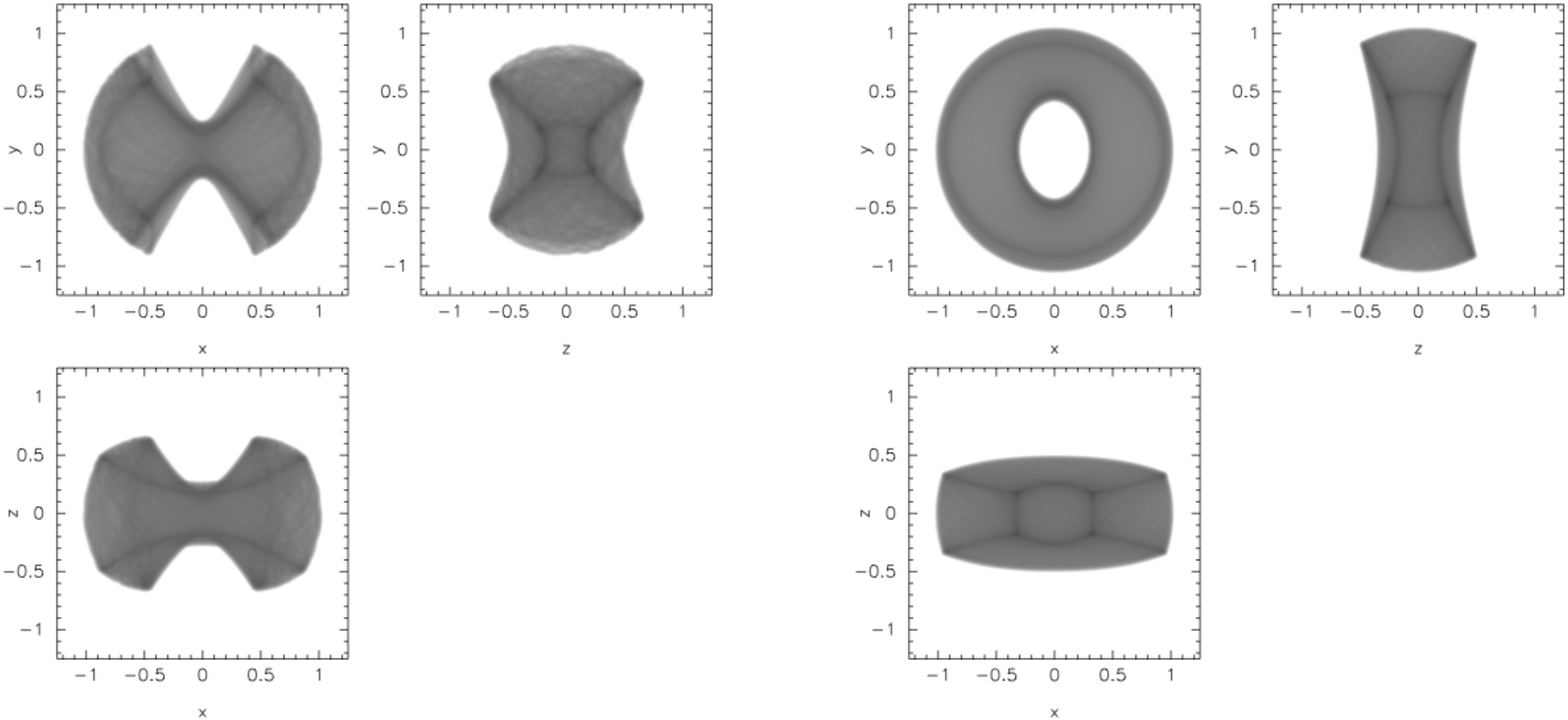
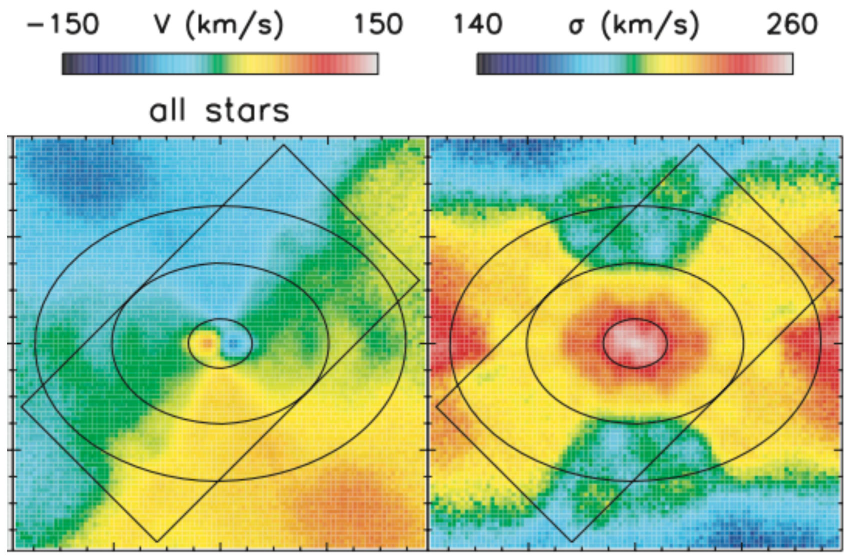


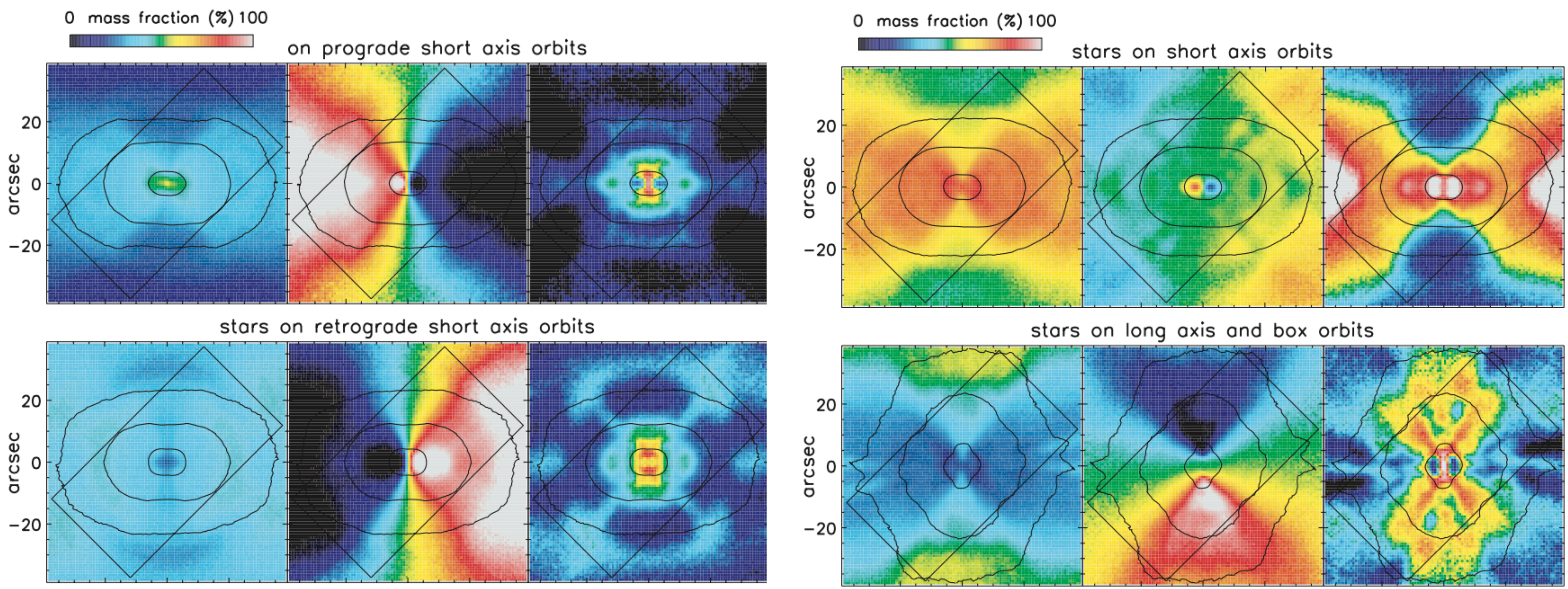
Figure 10.1: Time-averaged orbits in a triaxial logarithmic potential (7.20) with $b = 0.9$, $c = 0.8$, and $R_c = 0.2$. Left: a box orbit generated by starting at position $(x, y, z) = (1, 0, 0)$ with velocity $(v_x, v_y, v_z) = (0, 0.3, 0, 4)$. Right: a minor-axis tube orbit generated by starting at position $(x, y, z) = (1, 0, 0)$ with velocity $(v_x, v_y, v_z) = (0, 0.6, 0.4)$.

Separating the contribution from stars in the four orbit families



NGC4365

van den Bosch+ 2008



Hunting for SMBHs in Galaxies

methodology

Method 1: The Size of 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 ***$r = r_s = 2GM/c^2$*** , and ***r_s*** is called the **Schwarzschild radius**. **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: $r_s \propto M$

Working It Out 19.3: 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:

$$R_S = \frac{2GM_{\text{BH}}}{c^2}$$

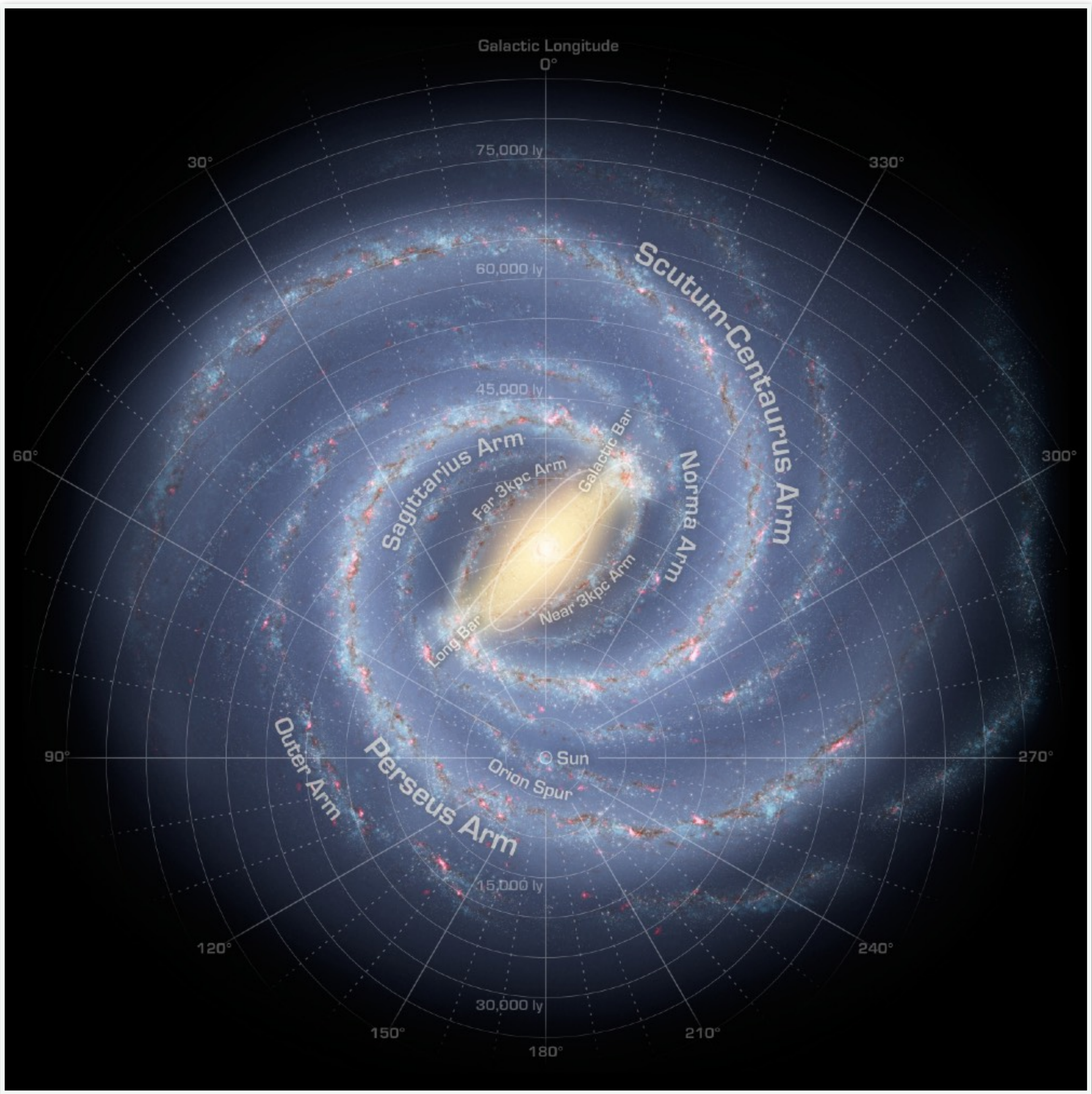
- For M87:

$$R_S = 1.9 \times 10^{10} \text{ km} \text{ (130 AU)}$$

- This is just about 4 times the radius of Neptune's orbit!

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

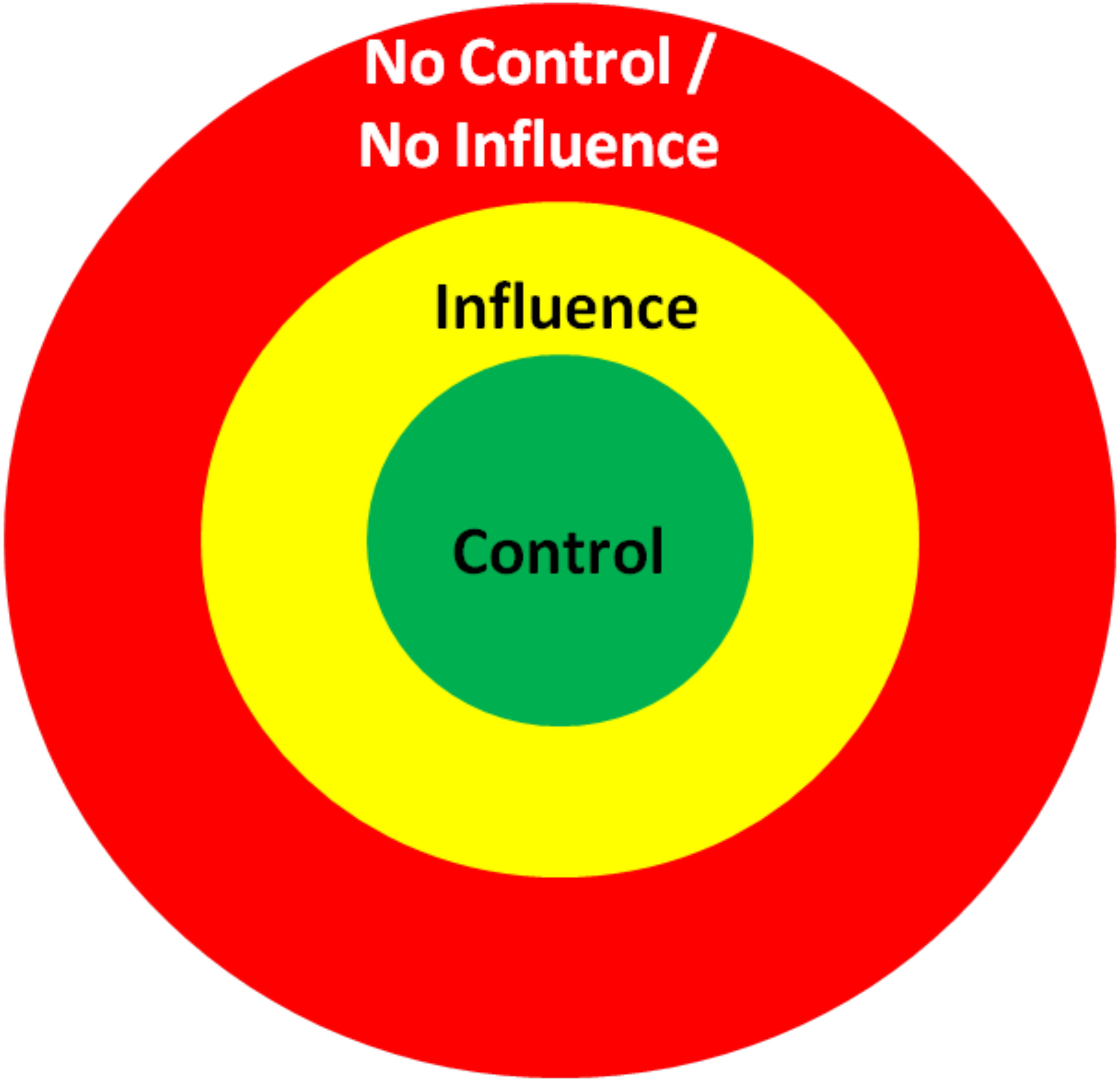
- Our distance to our Milky Way's center is 8 kpc.
- Suppose the SMBH at the center of MW is 1e8 M_{sun}(*much larger than actual mass*), its event horizon would have a radius of 2 AU.
- At this distance, what's the ***angular radius*** of the event horizon?



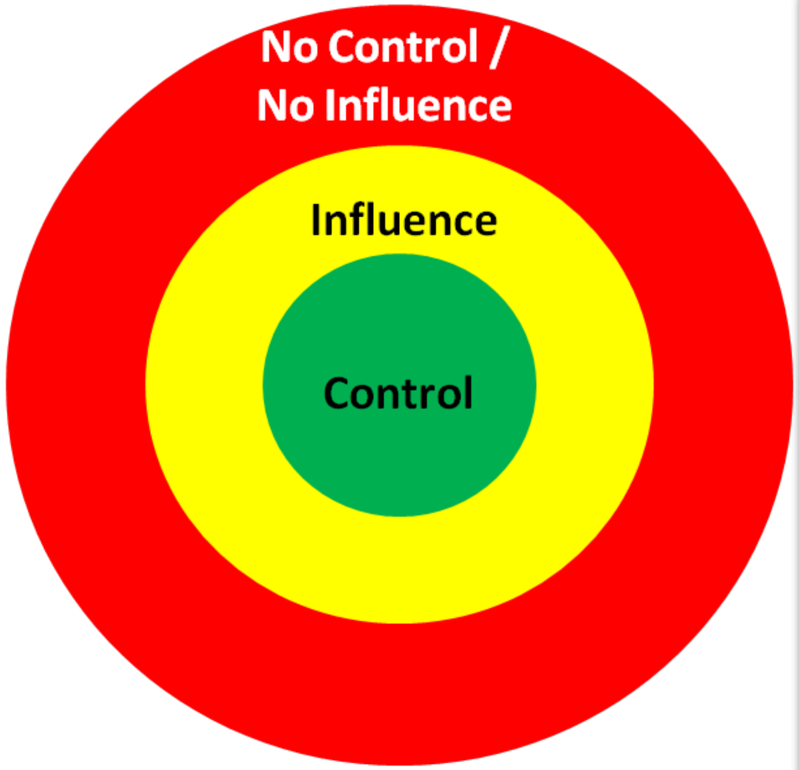
1 AU at 1 pc = 1 arcsec
1 AU at 1 kpc = 1 mas
2 AU at 8 kpc = 0.25 mas
= 250 micro-arcsec

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: France during Napoleon I (1799-1821 CE)



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 blackhole defines the region around the BH where the BH's gravity strongly affect the kinematics of stars:

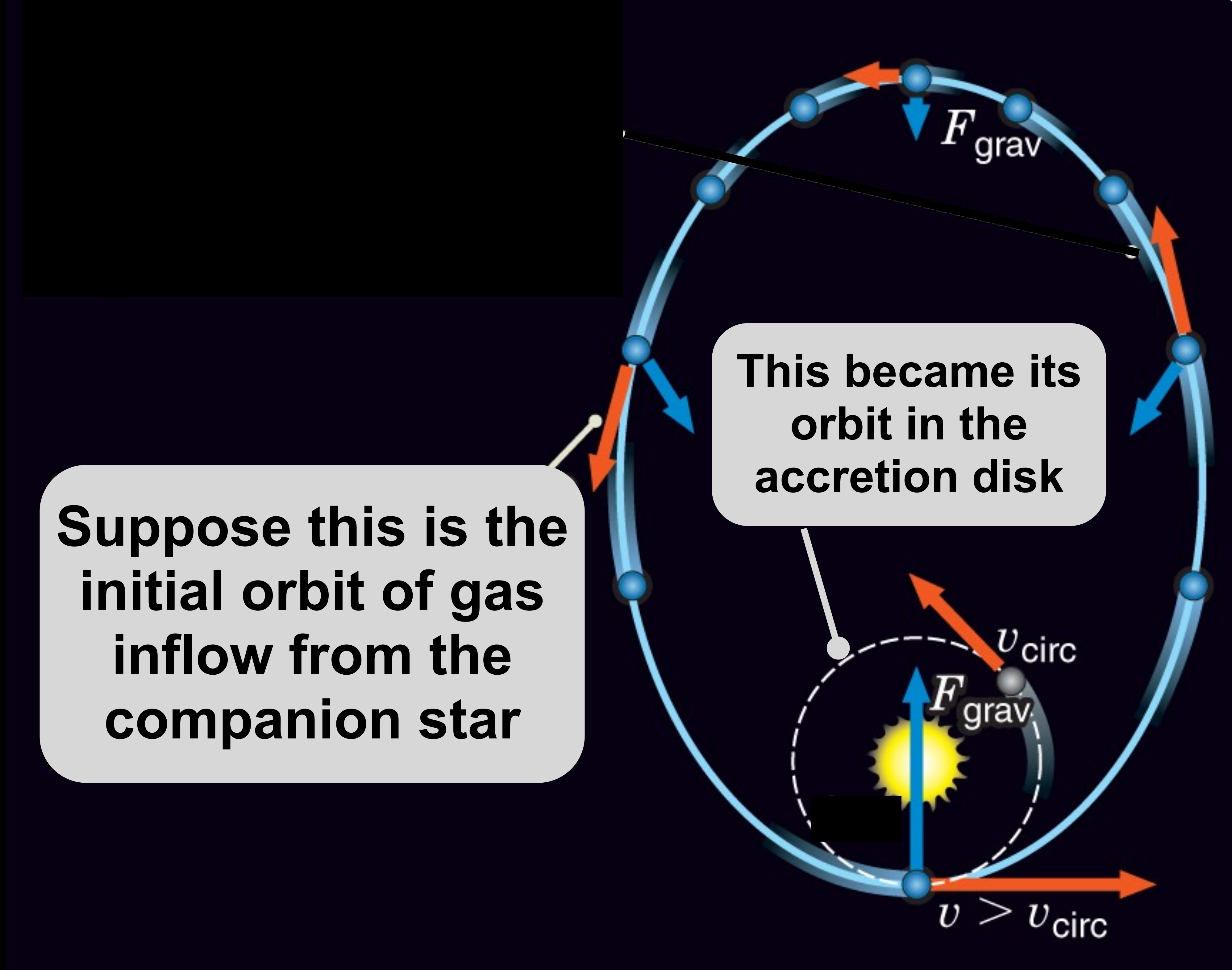
$$\frac{GM_{\rm BH}}{r^2} \geq \frac{\sigma_*^2}{r} \Rightarrow$$

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

- For a 10^8 M_{sun} BH, the radius of **the sphere of influence** is ***a million times*** greater than the radius of **the event horizon**.

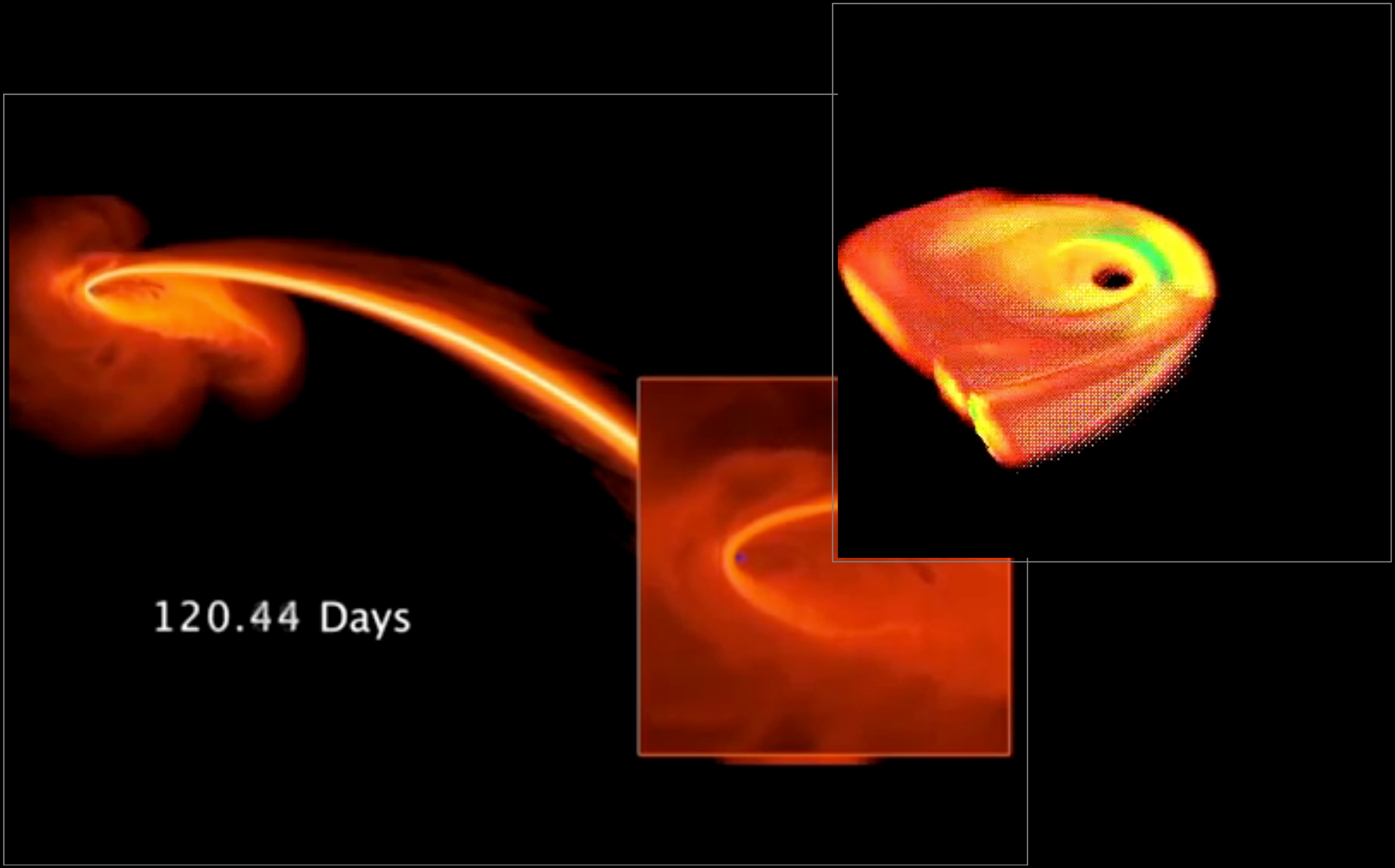
- **But note that the sphere of influence is still *tiny* compared to the size of the galaxy, which is at least ~10 kpc in radius (1000x larger), depending on how you define its boundary.**

Method 3: Detect Enormous Accretion Energy

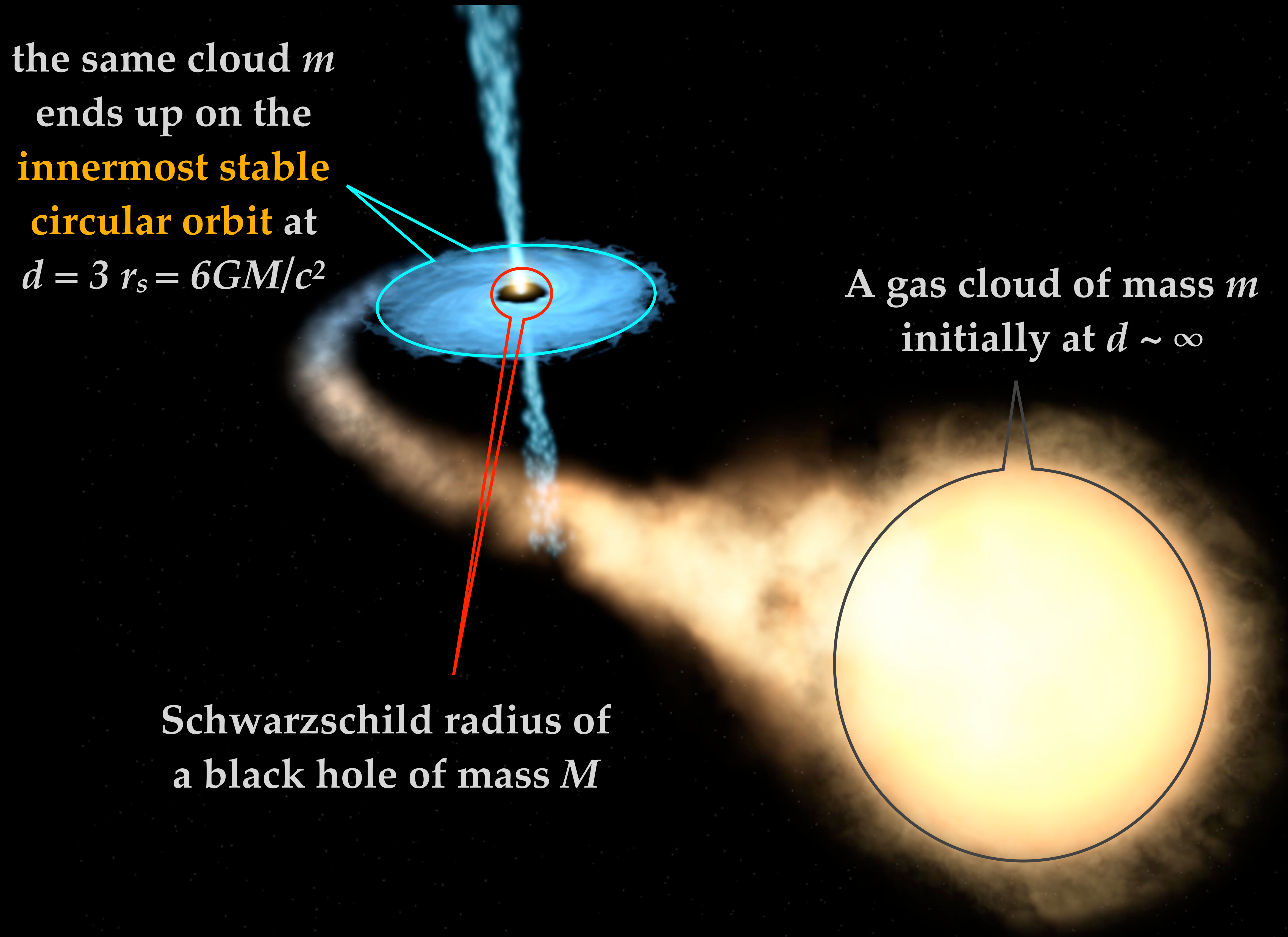


How gravitational accretion produces energy?

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!

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 radio observatories
  - Minimizing the diffraction limit: $\theta = \lambda/D$
- **Resolve the sphere of influence**
  - $r_* = \frac{GM_{\rm BH}}{\sigma_*^2} = 11\,{\rm parsec}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{200\,{\rm km/s}}{\sigma_*}\right)^2$
  - Studies of Stellar and Gas Kinematics
  - Adaptive Optics or Space Telescopes like HST
- **Detect the incredible energy generation from accretion**
  - Studies of Active Galactic Nuclei
- **Detect the gravitational wave generated from BH mergers**
  - Gravitational wave detectors like the Pulsar Timing Array


With the appropriate equipment, we are now ready to hunt the dragons!

Evidence of SMBHs in the Nearest Massive Galaxies

Resolving the event horizon

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

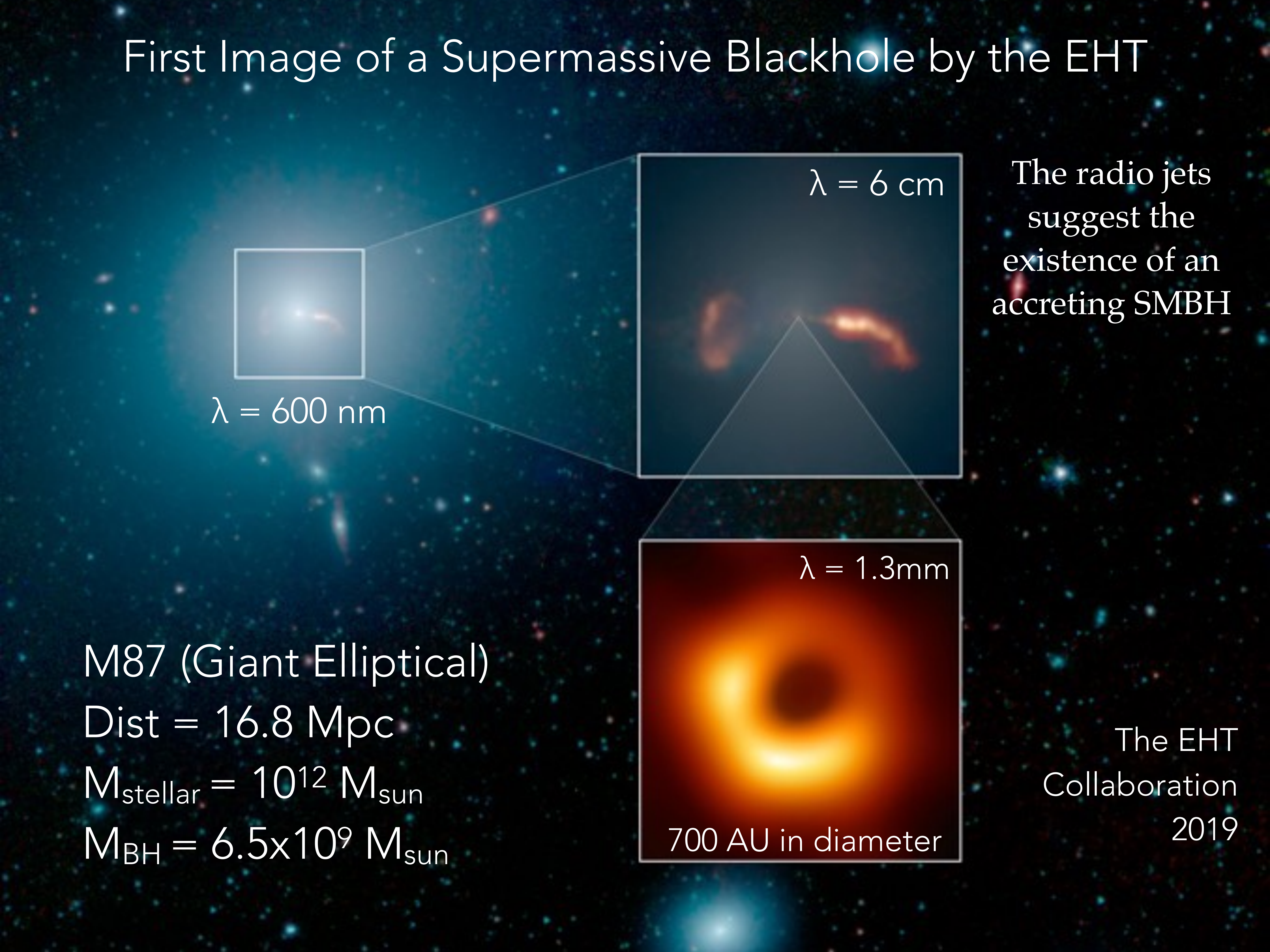
First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

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

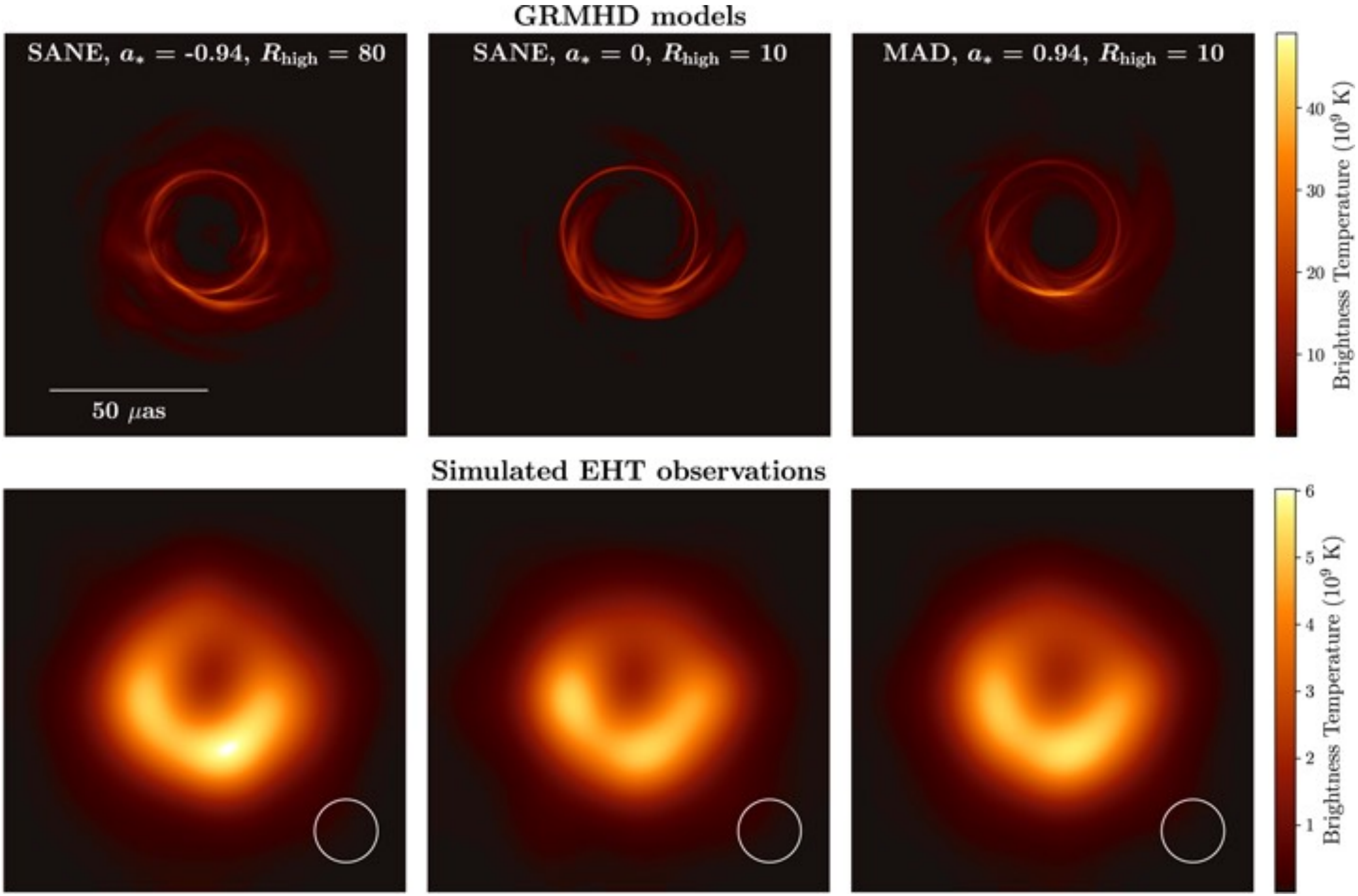
Abstract

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.

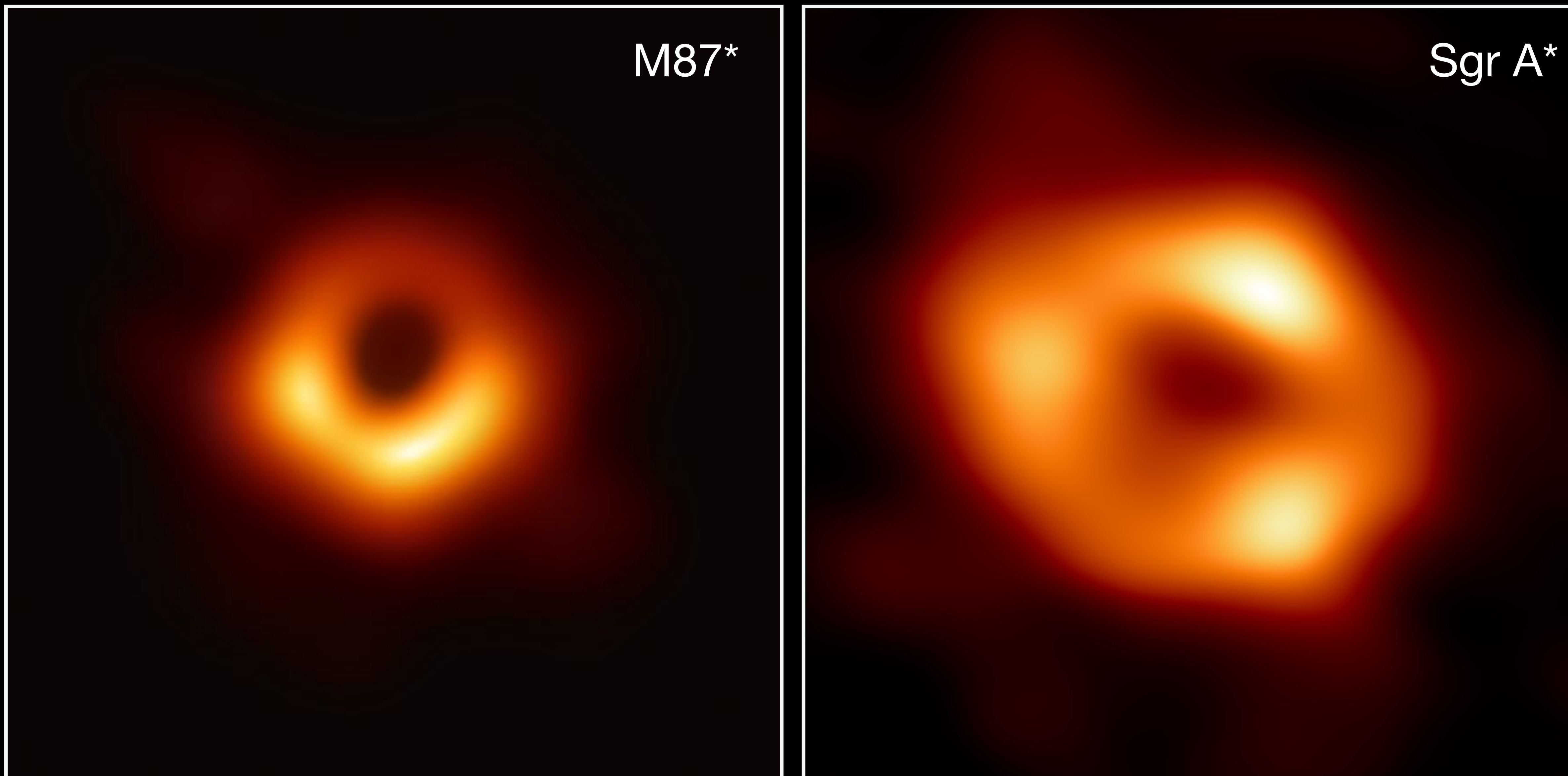
Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: individual (M87) – galaxies: jets – gravitation


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

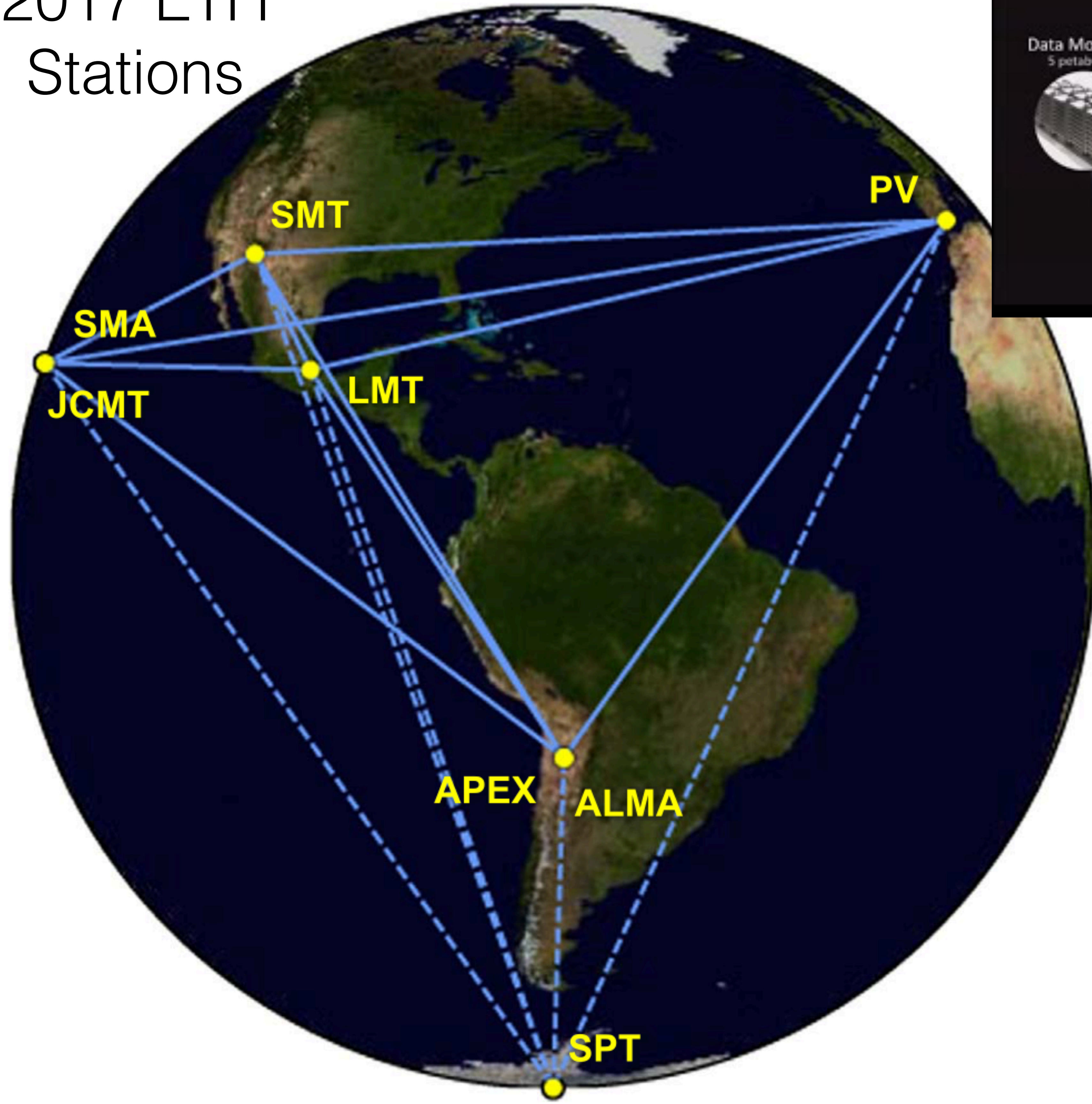


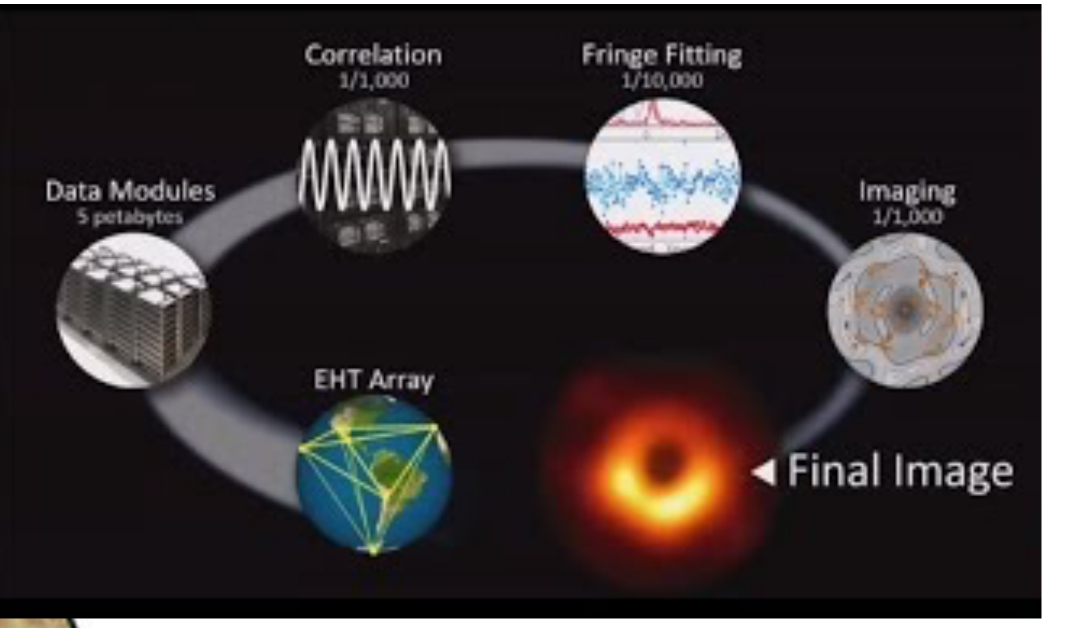
Event Horizon Telescope

Angular magnification required to resolve the event horizon

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

2017 ETH Stations

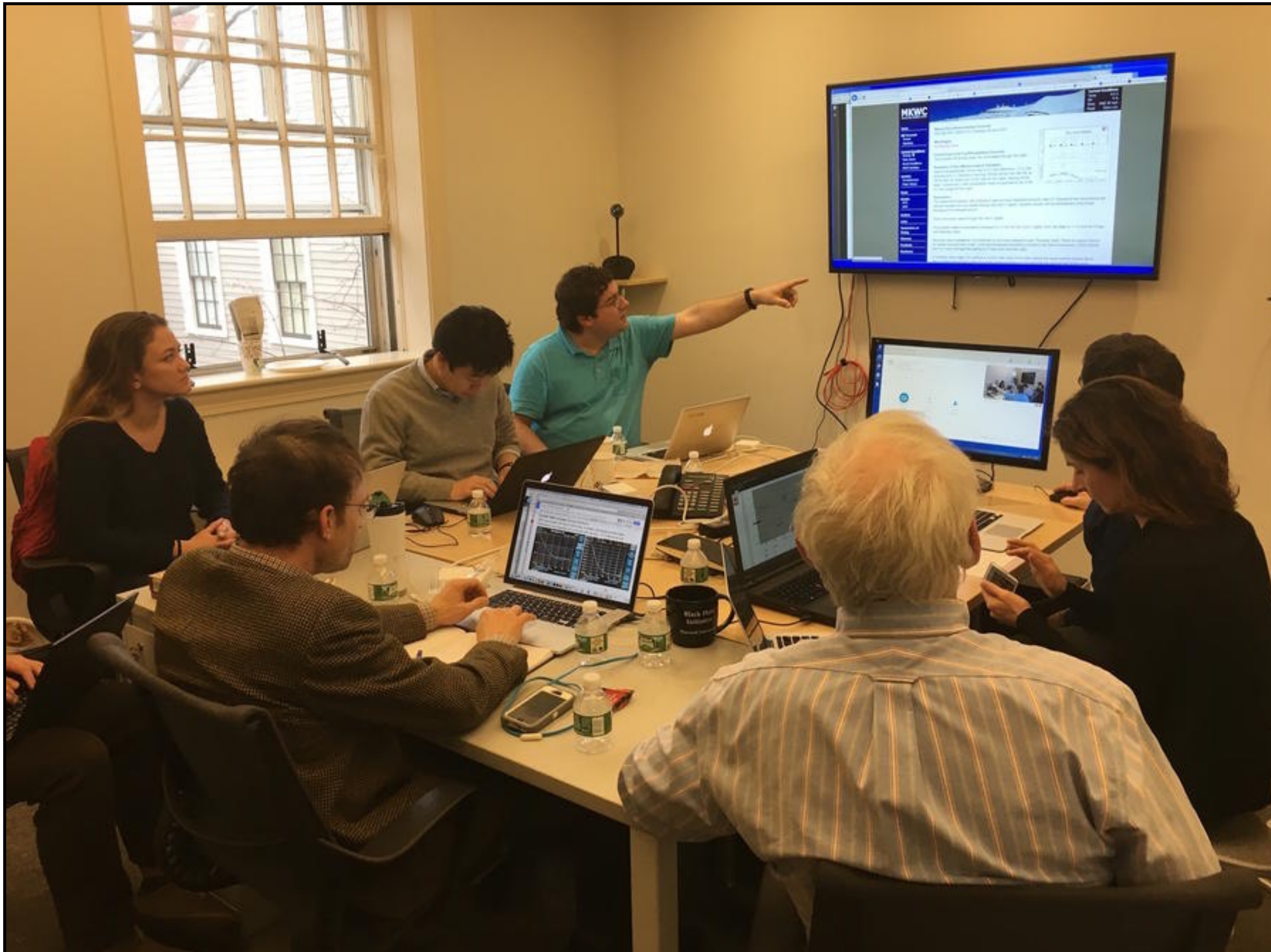




https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT


5 petabytes (PB) of data

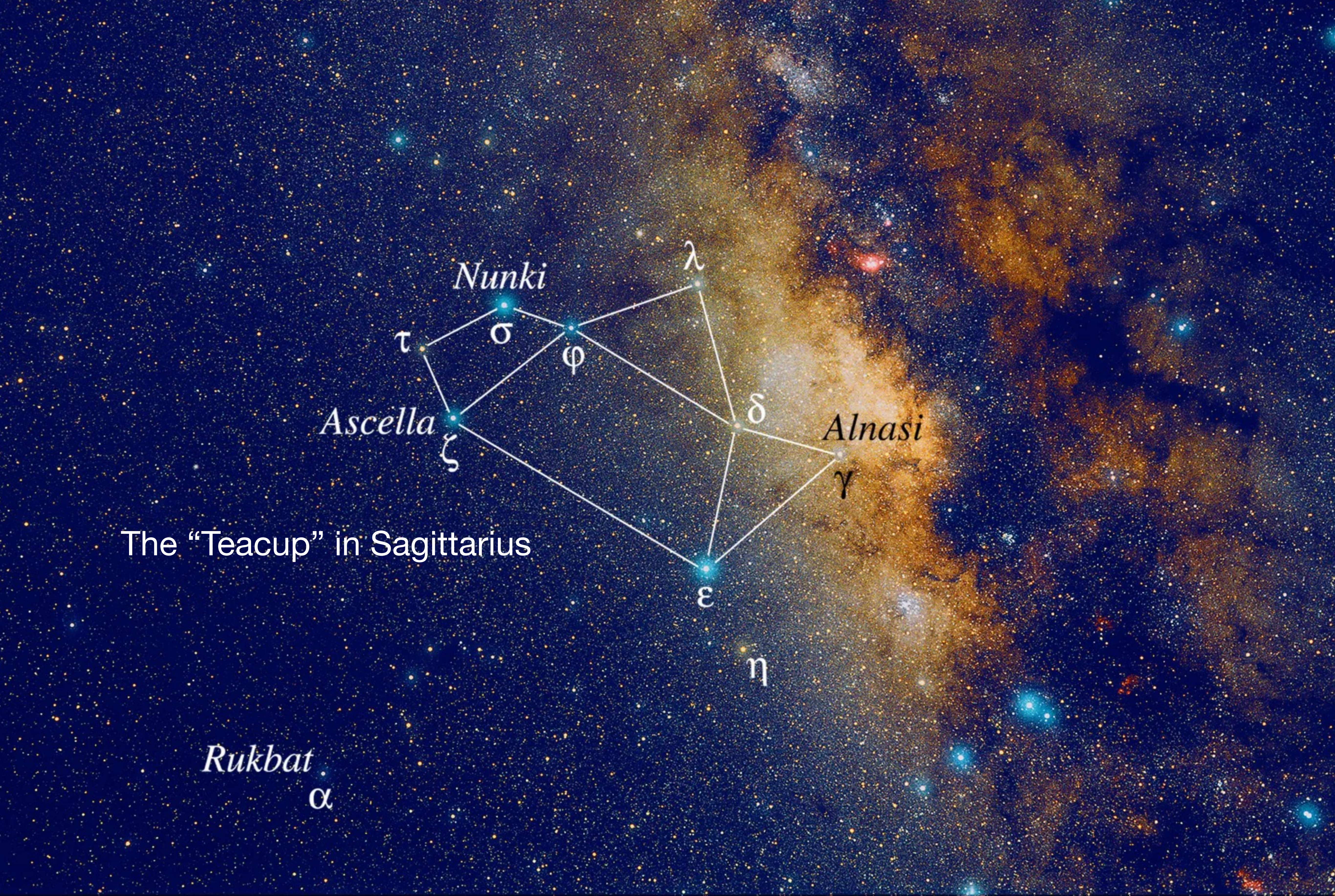
"More than **200 members from 59 institutes in 20 countries and regions** have devoted years to the effort, all unified by a common scientific vision."



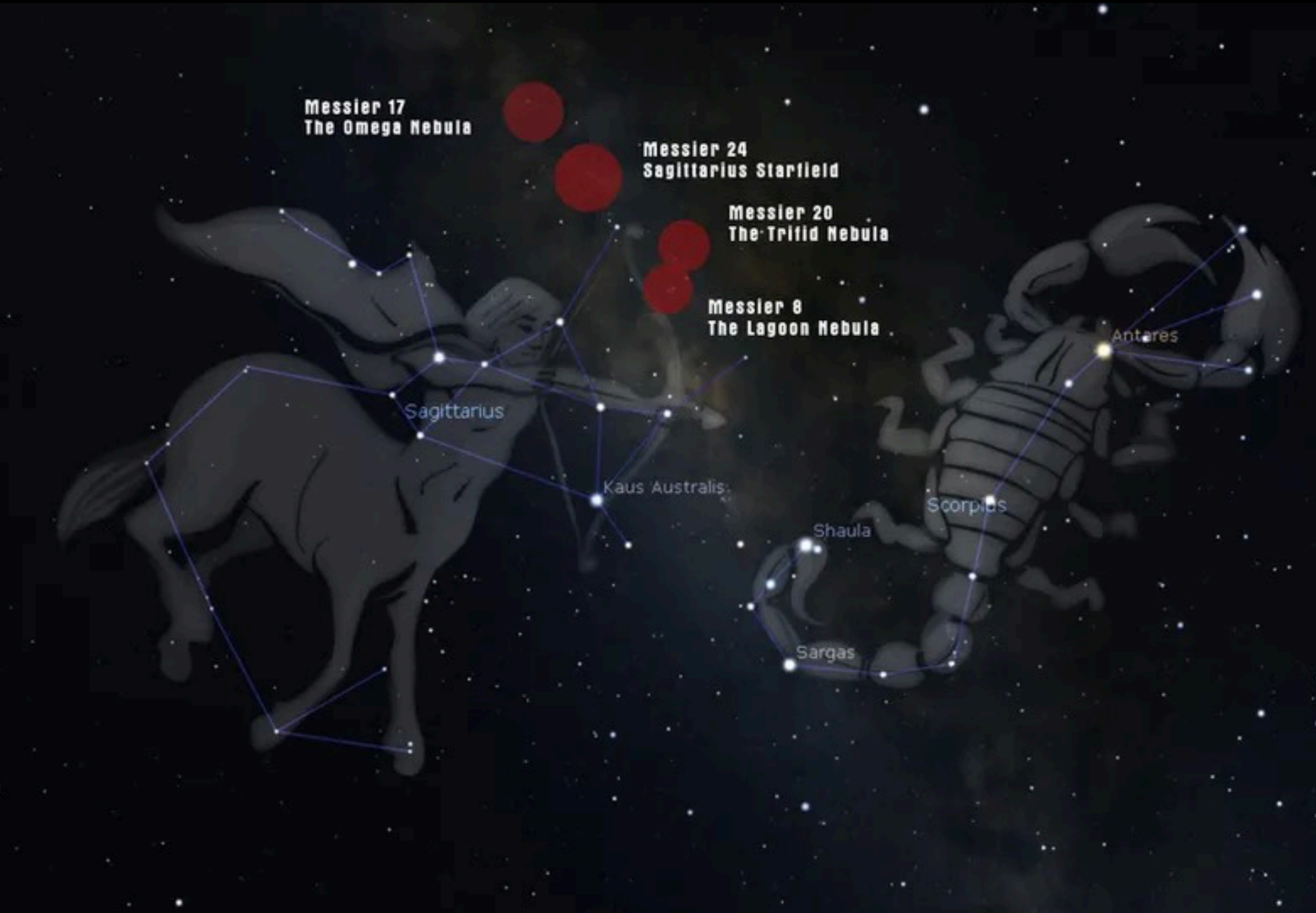
Weighing the SMBH in the Milky Way

resolving the sphere of influence

Where is the Galactic Center?



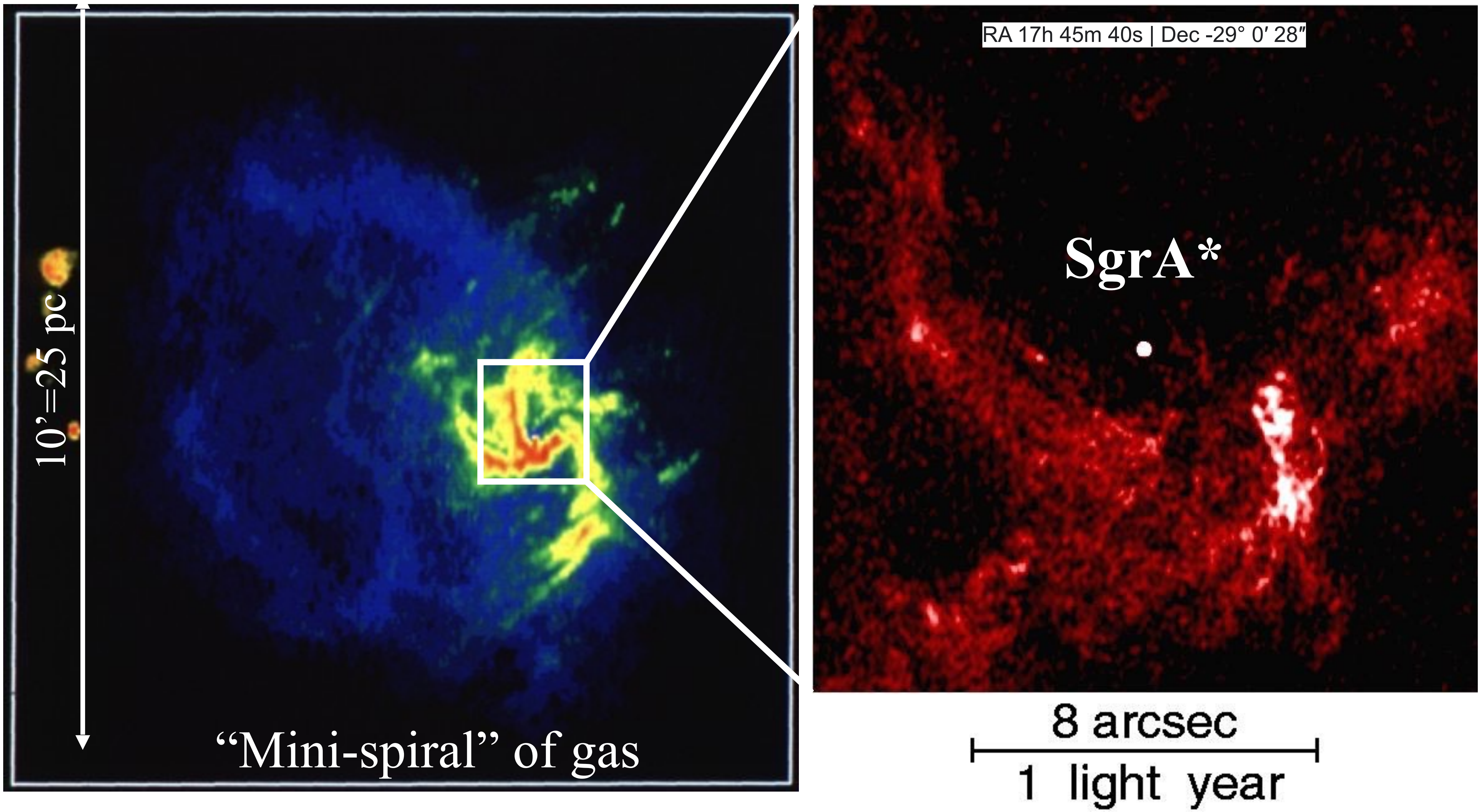
Where is the Galactic Center?



Pinpoint the Galactic Center:

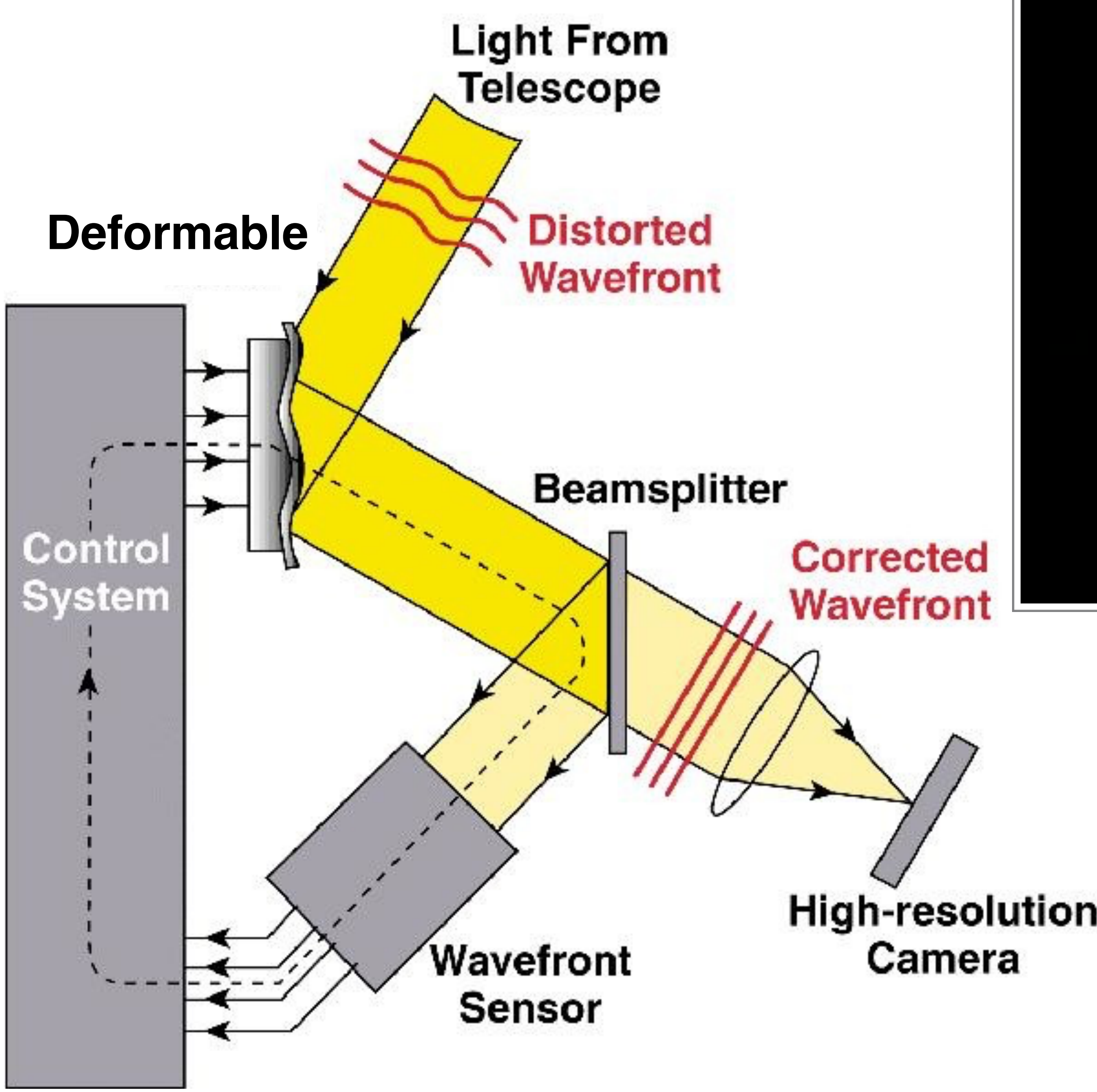
Radio images of the Galactic central region shows an unusually bright single point source surrounded by extended spirals.

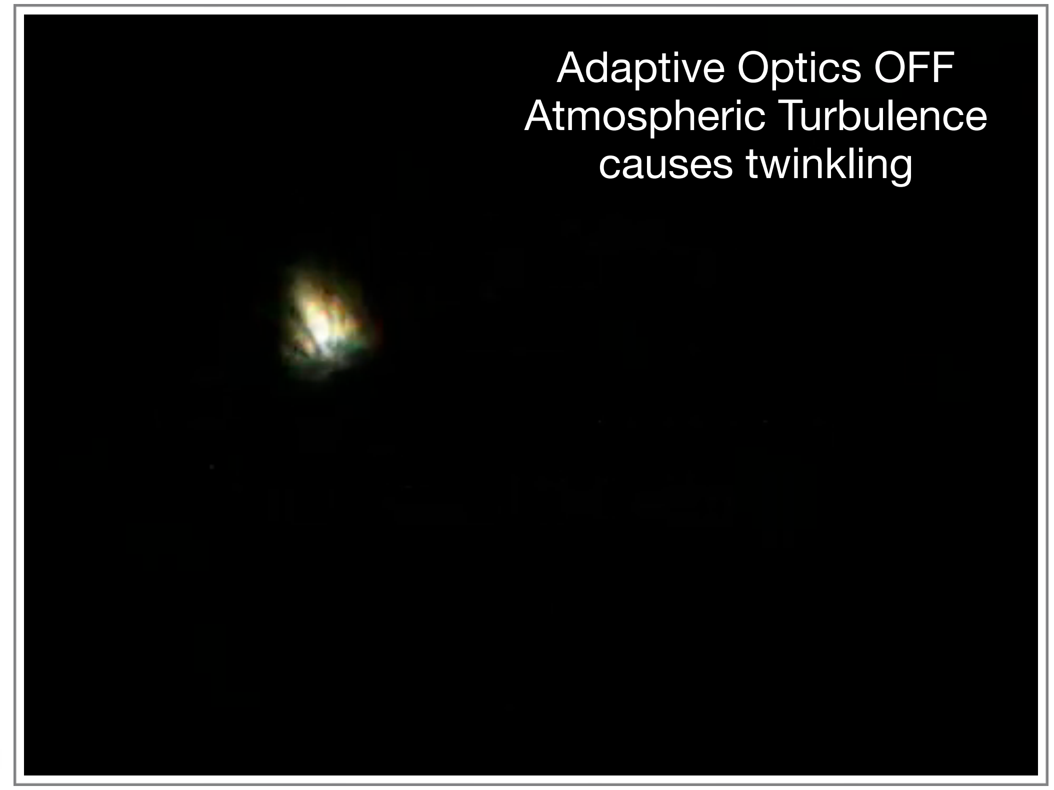
Think about why do we need radio observations?

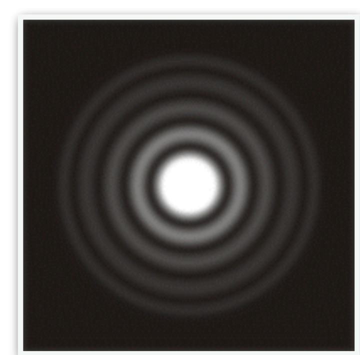


6 cm VLA image (Ekers et al. 1983)

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

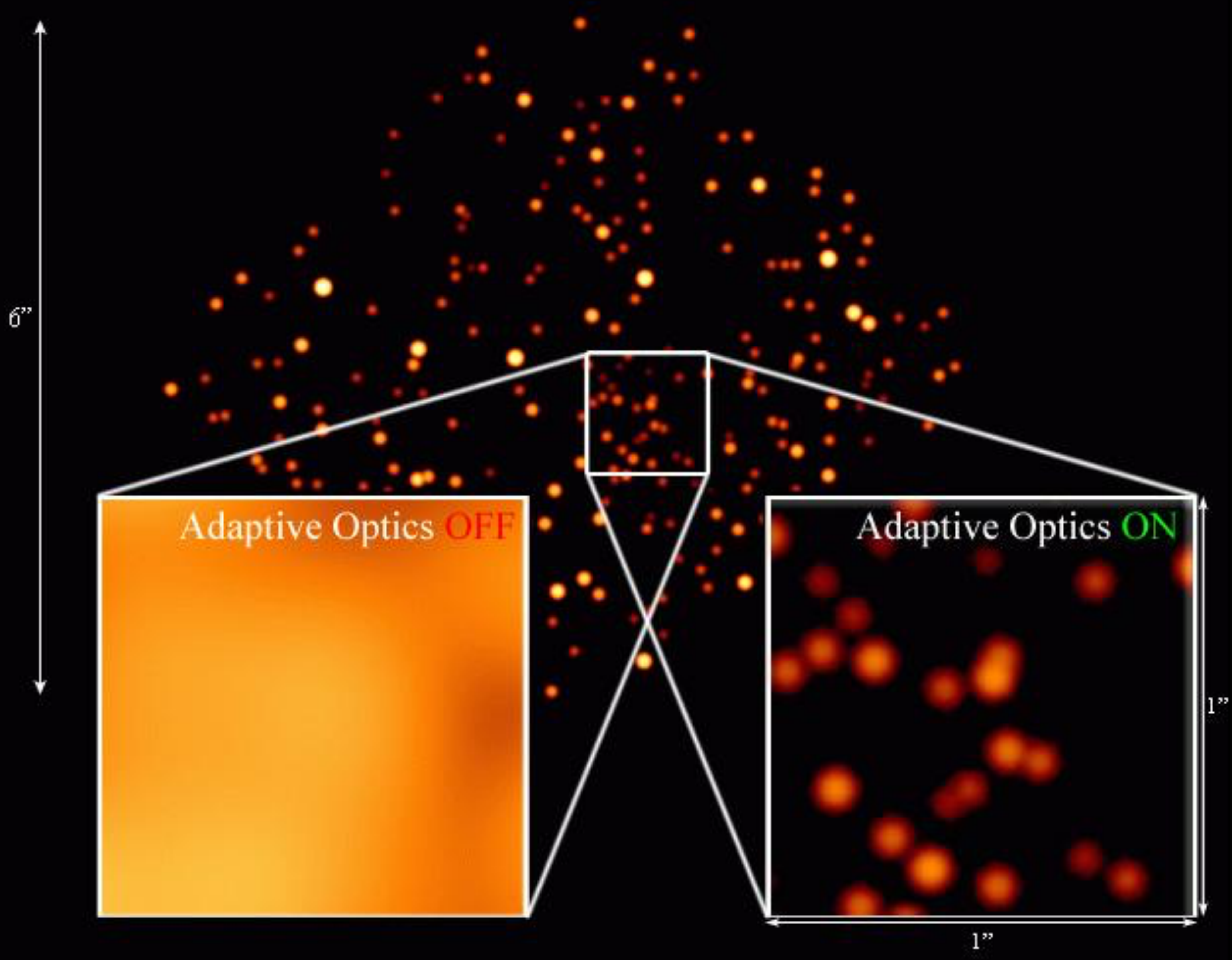




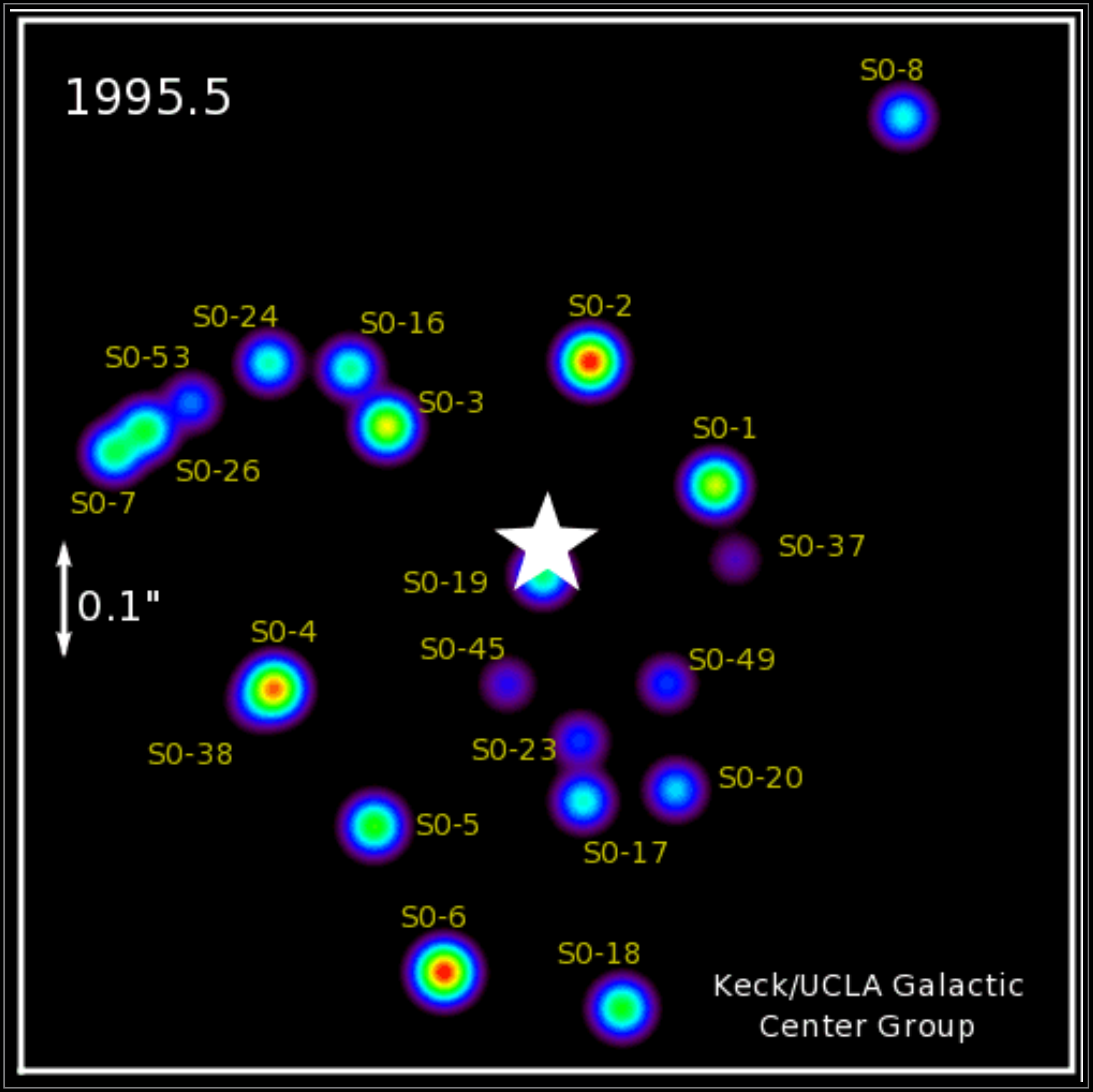


Adaptive Optics ON reaching diffraction limit

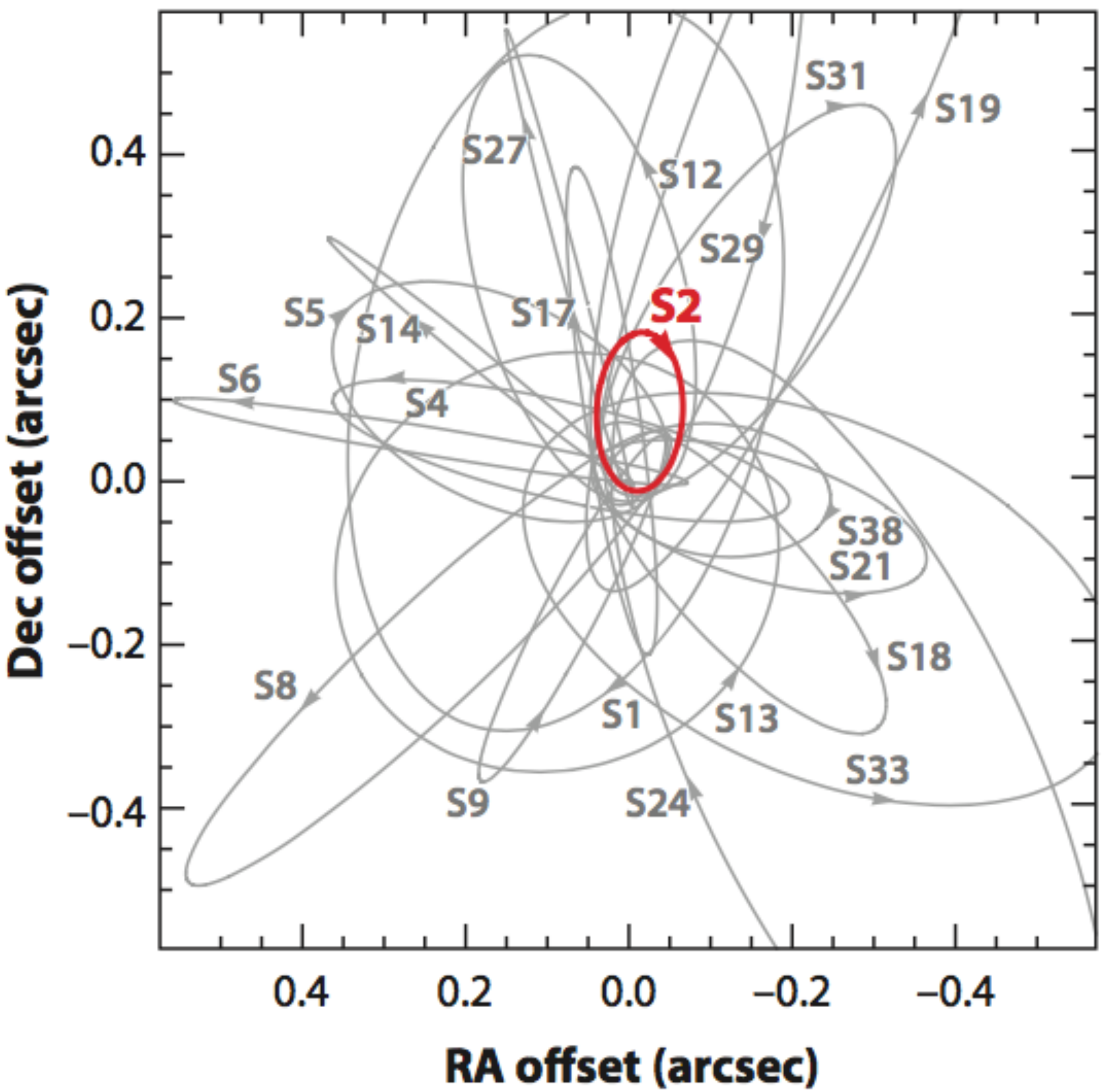
The Galactic Center at 2.2 microns



Resolving individual stars near Sgr A* with IR Adaptive Optics



Mass and distance of the SMBH in the Milky Way Galaxy

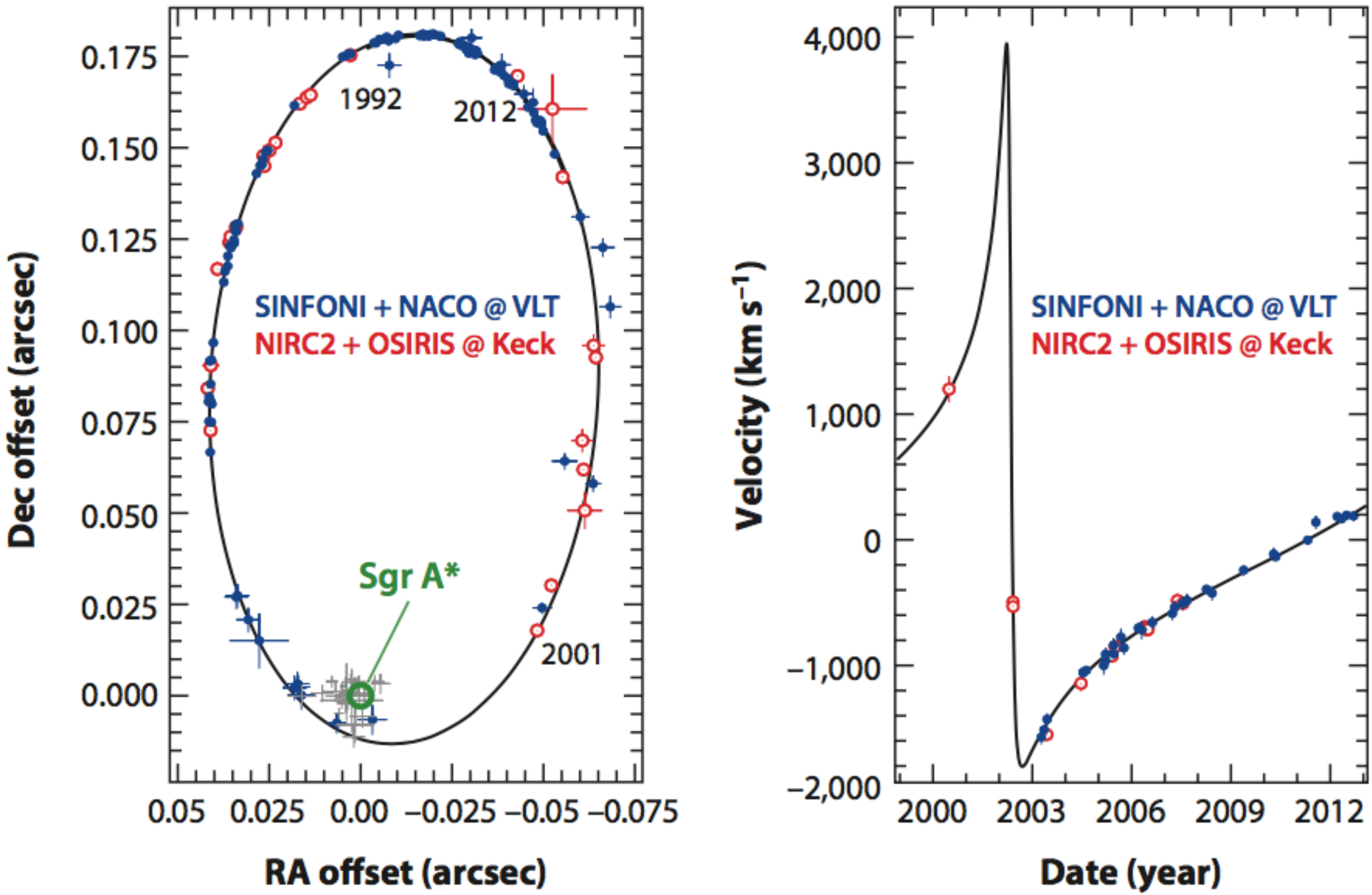


By monitoring **individual star's orbits and their velocities,** we can measure both the mass and the distance of the SMBH:

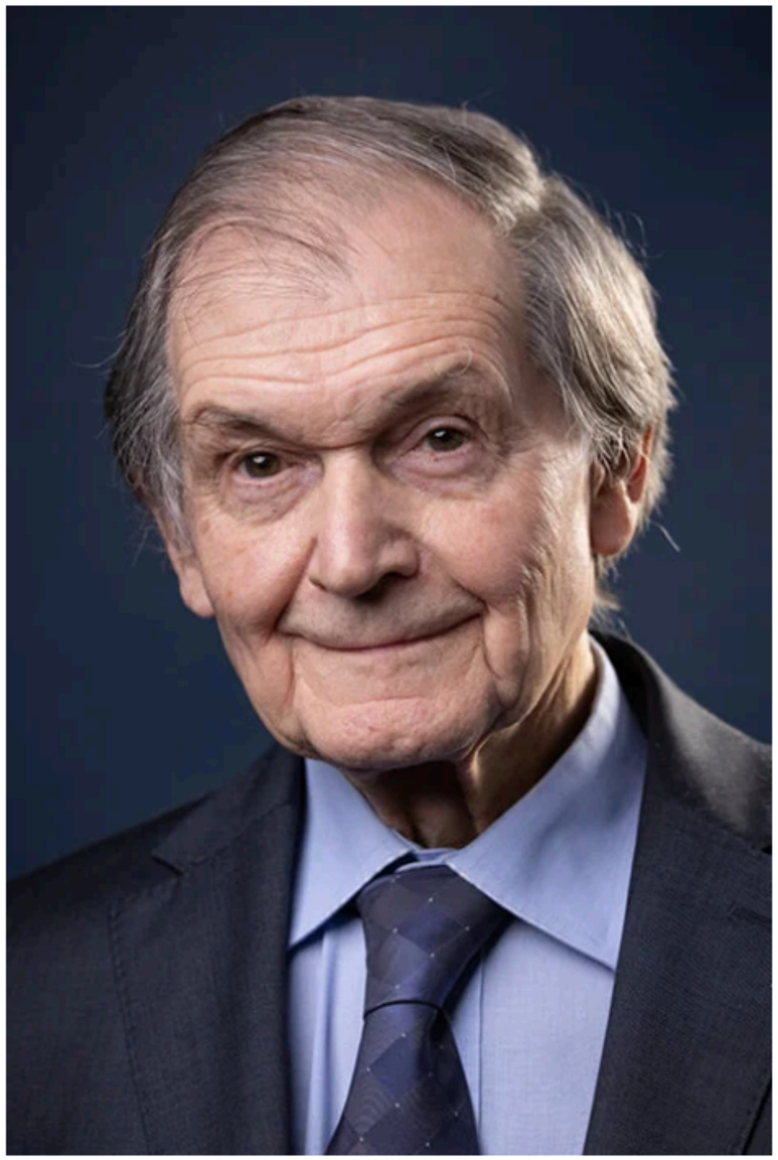
Mass: 4 million M_{sun}
Distance: 8.3 kpc

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

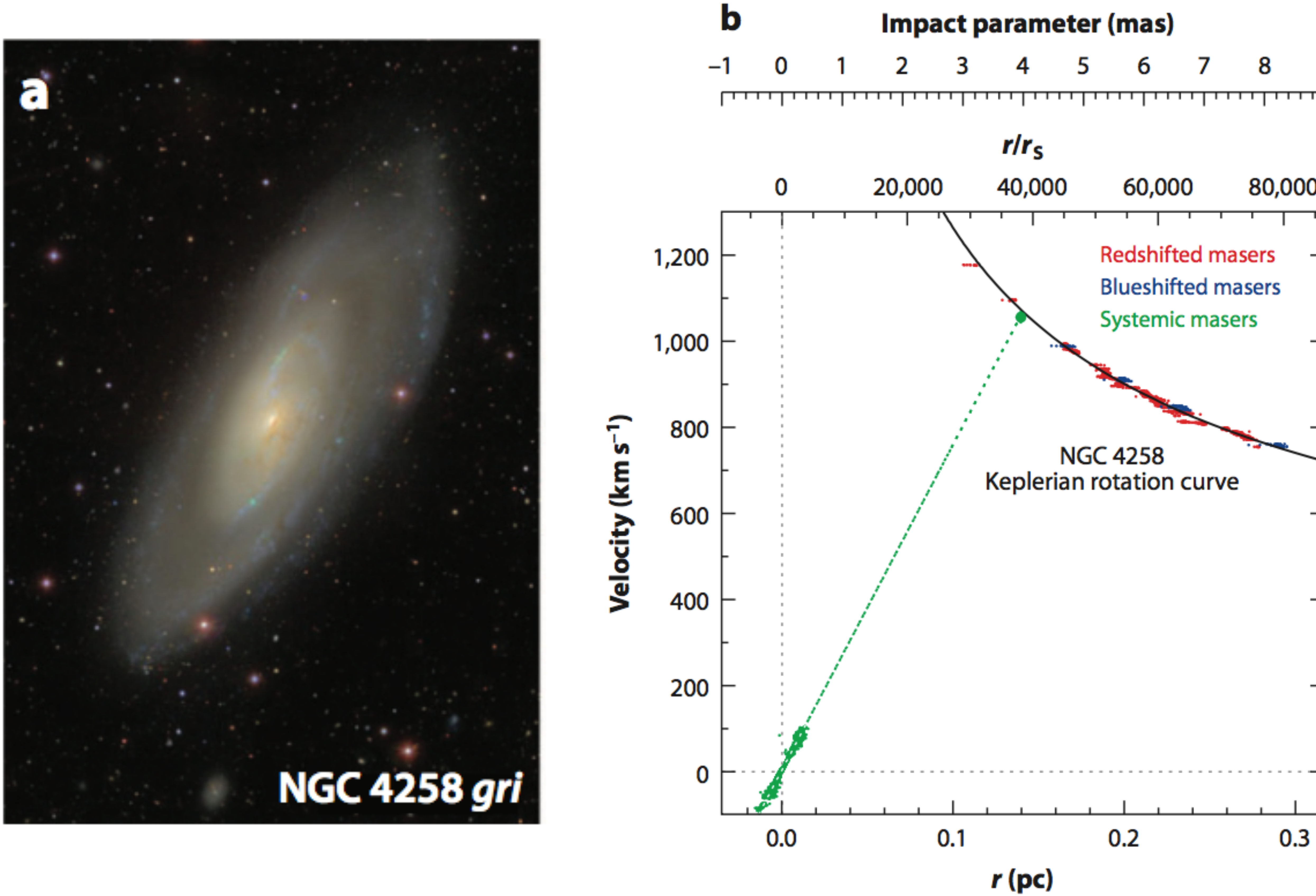
Andrea Ghez

Prize share: 1/4

Weighing SMBHs in Other Galaxies

resolving the sphere of influence

M106/NGC 4258: Keplerian Rotating Disk of H_2O Masers



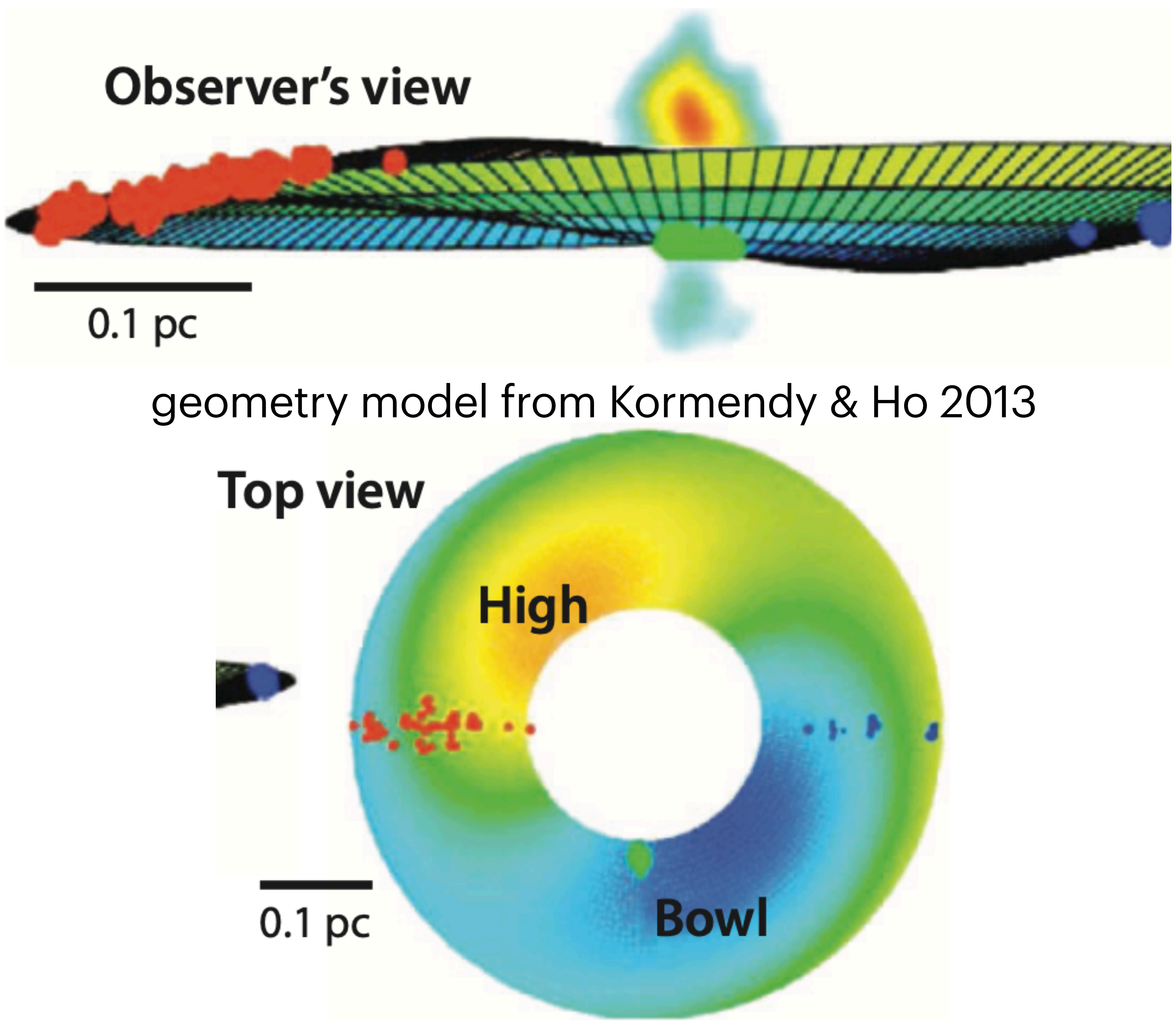
Kormendy & Ho 2013, with data from Argon+07, Moran 08

Distance and BH mass of NGC 4258 (Humphreys+13)

to determine distance. Essentially, the rotation curve of the high-velocity maser emission constrains $\mathcal{M}^{1/2} \sin i_r$ where $\mathcal{M} = (M_{\rm bh}/D)$ and the accelerations of the systemic maser features provide distance via $D = (-G\mathcal{M}/r^2 a_{\rm los,model}) \sin i_r \sin\phi$.

The component of centripetal acceleration in the LOS is given by

$$a_{\rm los,model} = \frac{-GM_{\rm bh}}{(rD)^2} \sin i_r \sin\phi, \qquad (2)$$



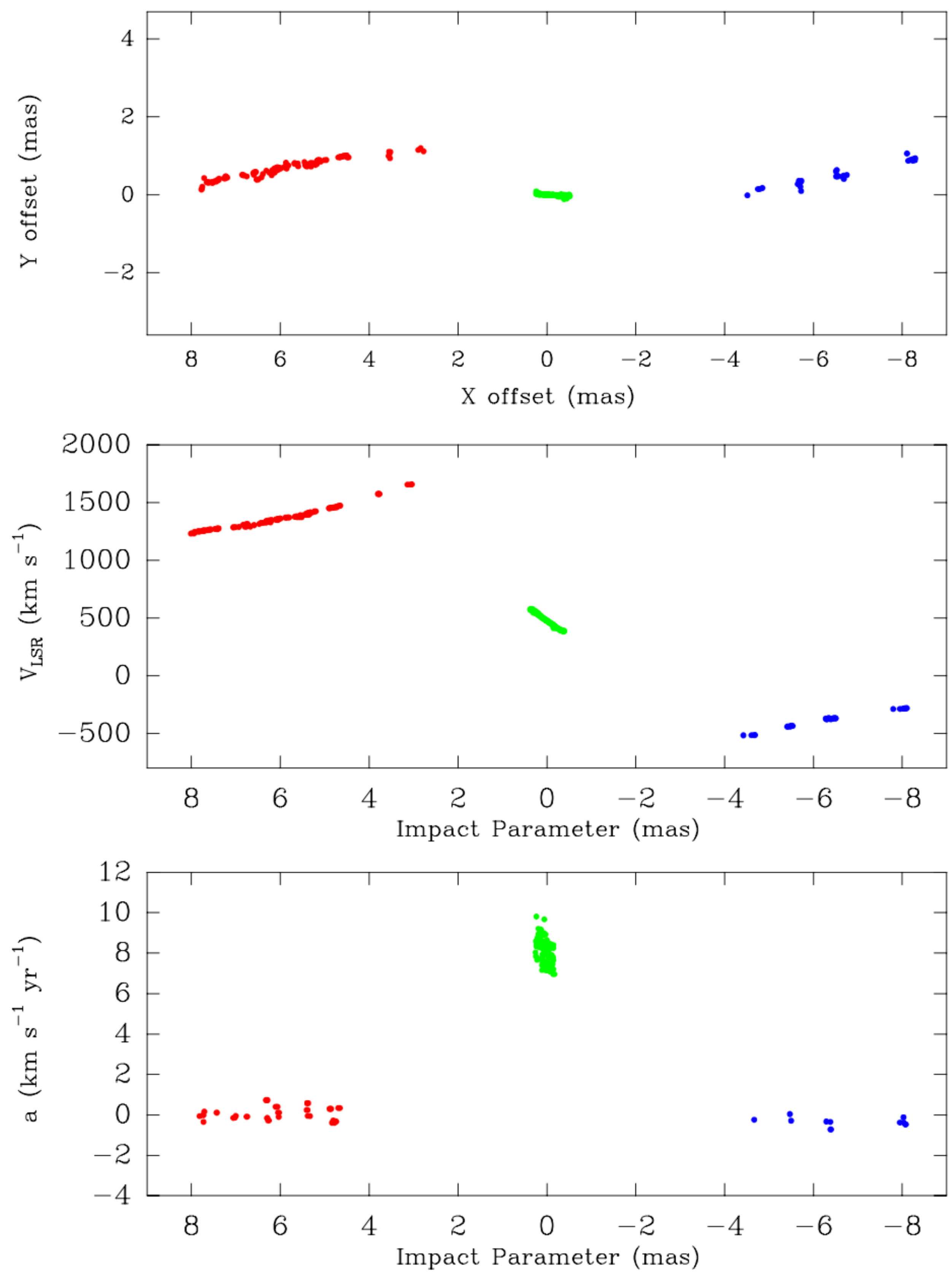
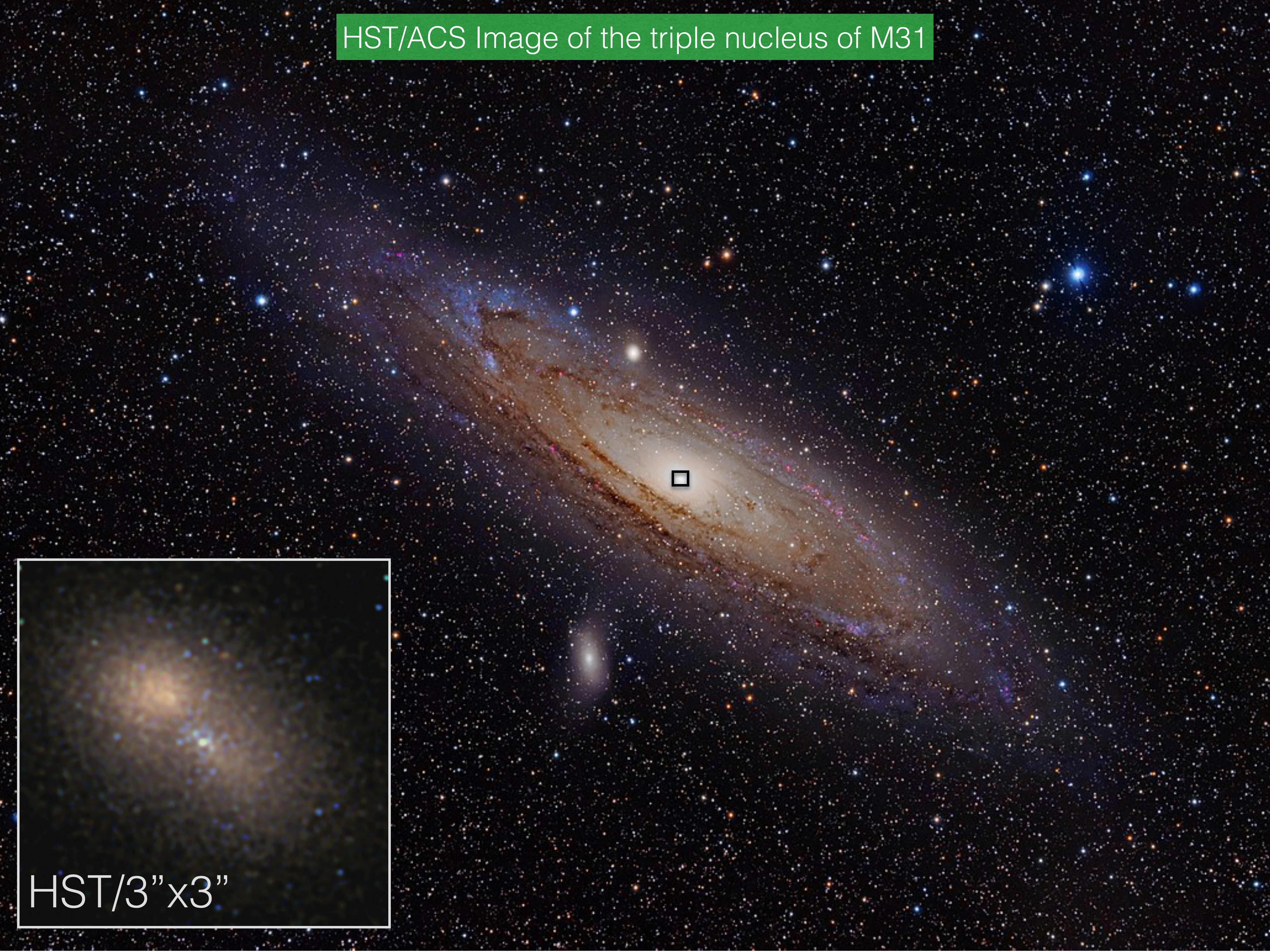
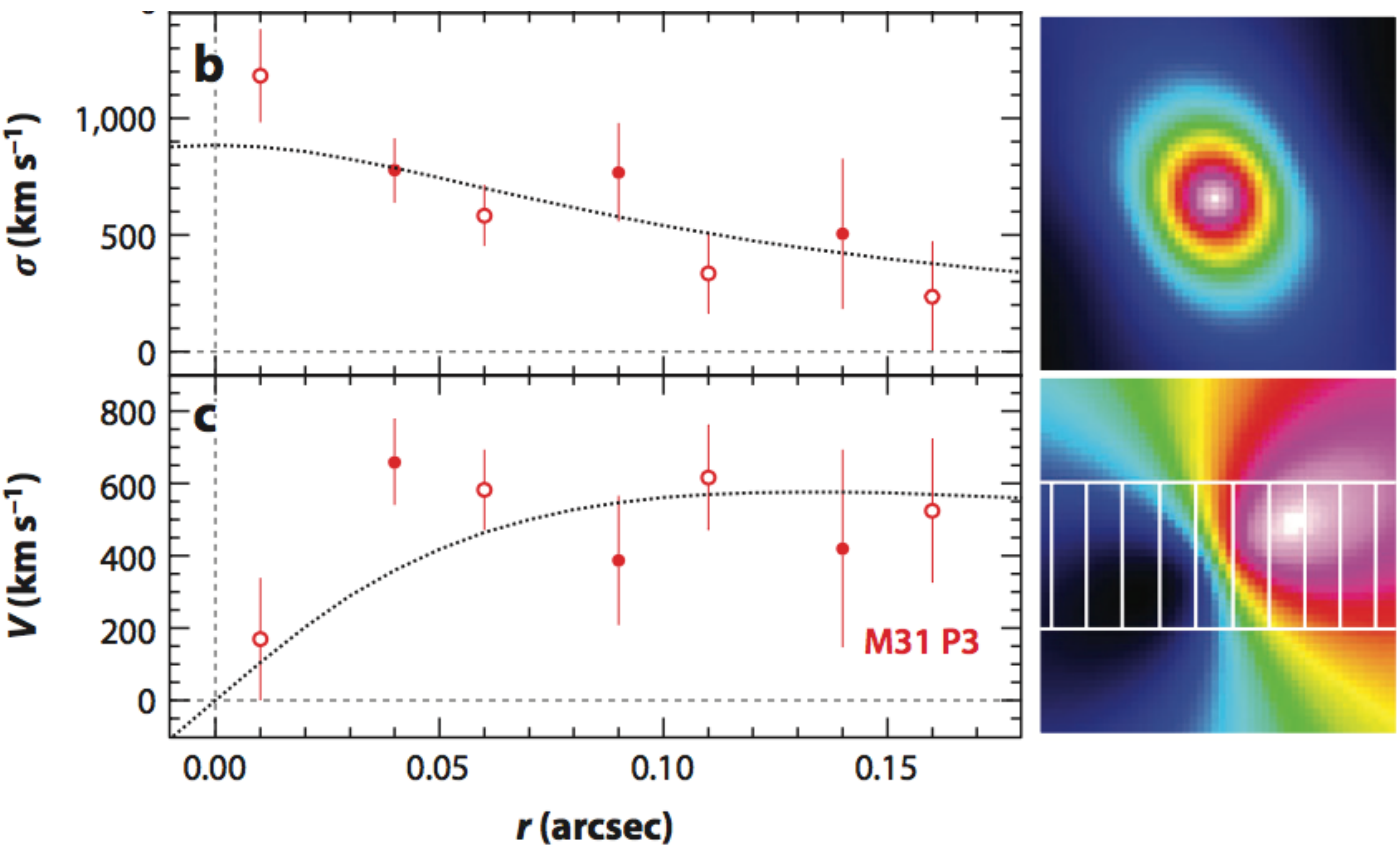


Figure 2. Input data to the model: maser sky positions (top), *P–V* diagram (middle), and accelerations (bottom).

HST/ACS Image of the triple nucleus of M31

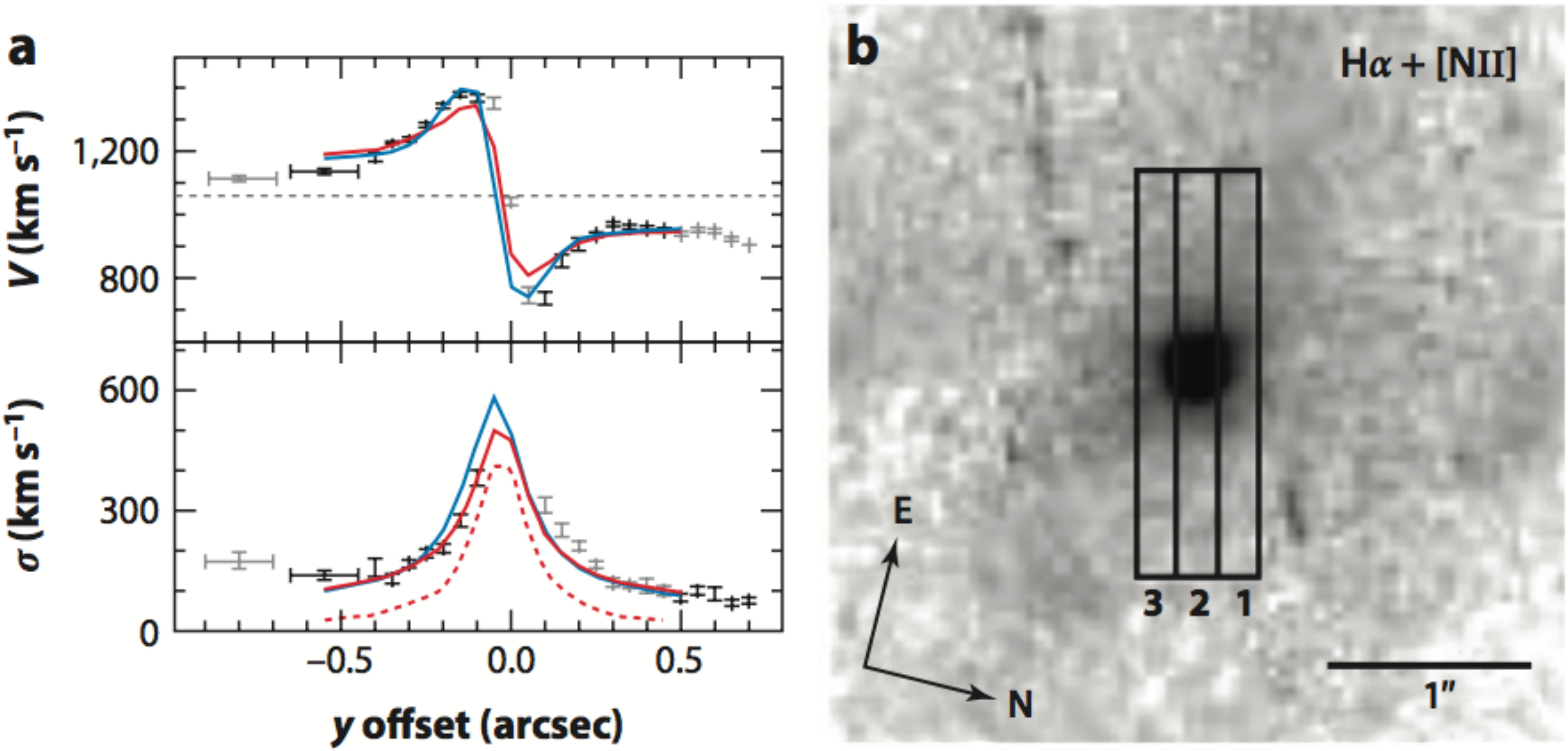


Elevated Stellar Velocity Dispersion in the Sphere of Influence



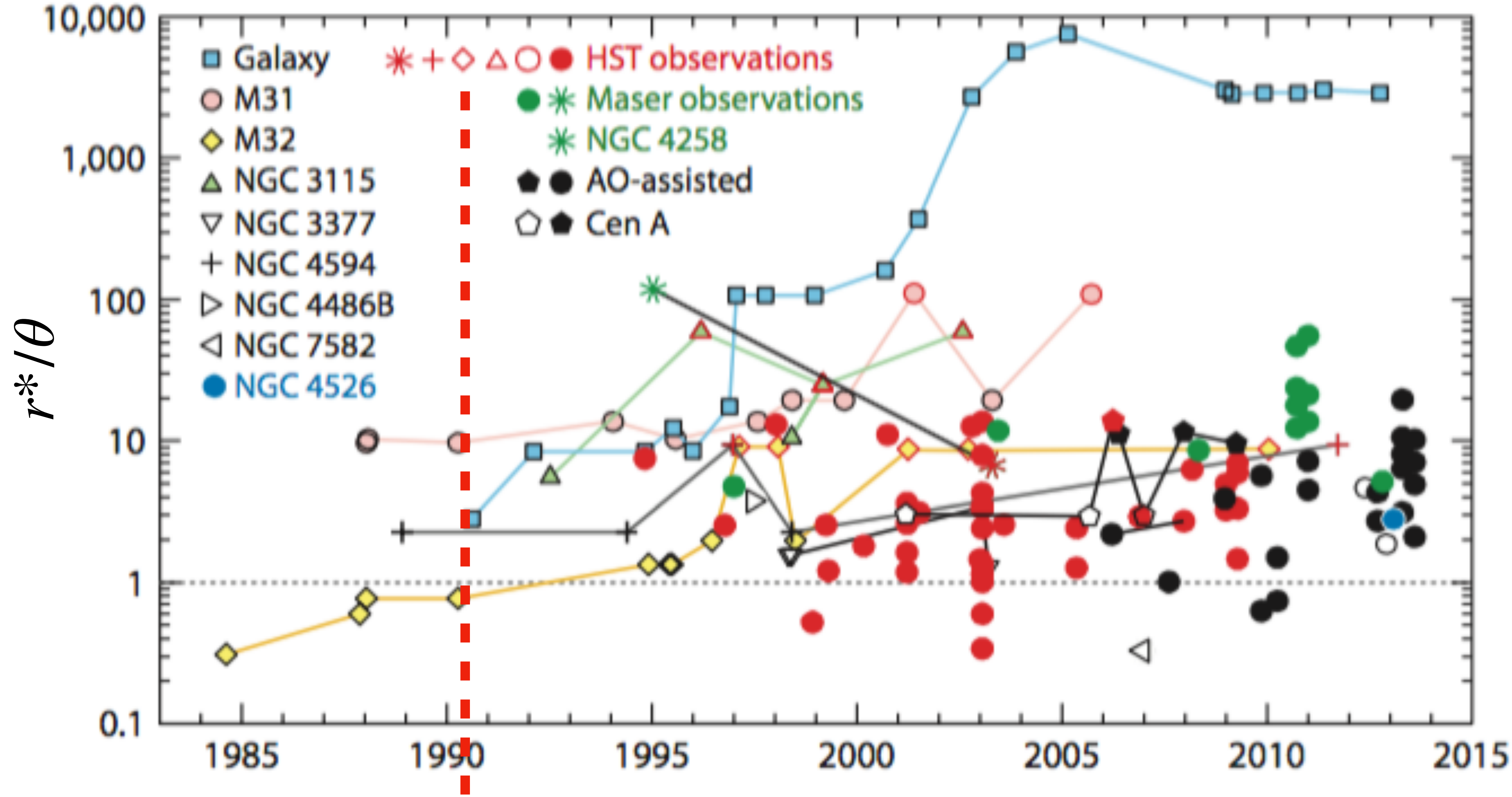
Bender+05

Elevated Gas Velocity Dispersion in the Sphere of Influence



NGC 4374, HST/STIS, Walsh+2010

Making Progress in Resolving the Sphere of Influence



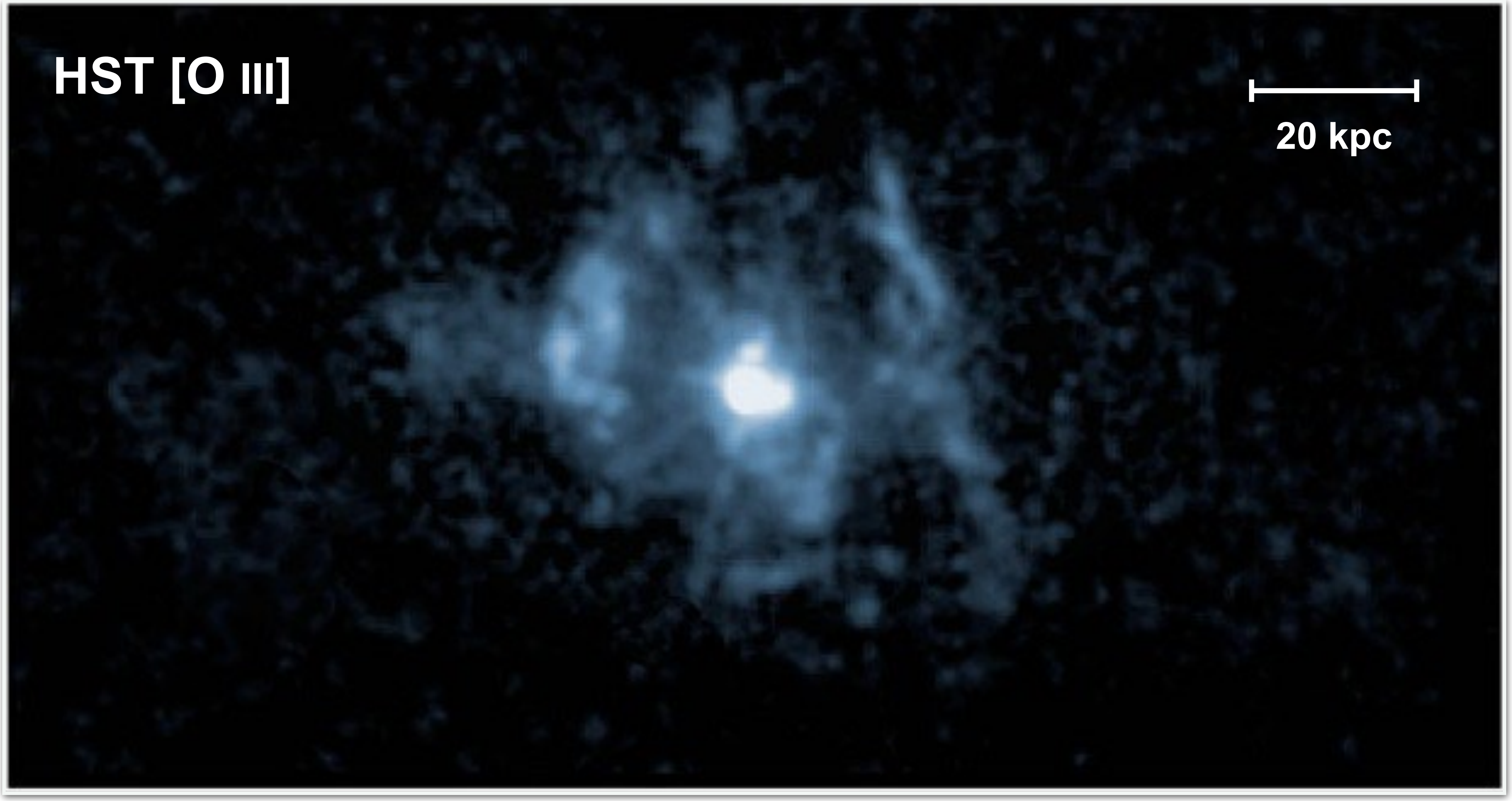
Thanks to Hubble & Adaptive Optics

Kormendy & Ho 2013

Evidence of SMBHs in Active Galaxies

Detecting gravitational accretion power

Extended Nebulae around ~25% of Quasars (My PhD Thesis)



Institute of Physics
https://iopscience.iop.org › article

EXTENDED EMISSION-LINE REGIONS - IOPscience

by H Fu · 2008 · Cited by 116 — These "**extended emission-line regions**" (EELRs; following Stockton & MacKenty 1983) are clearly physically associated with the quasars: the ionized gas…

Discovery of Quasars: the Cambridge Interferometer

Radio astronomers (**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 interferometer

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

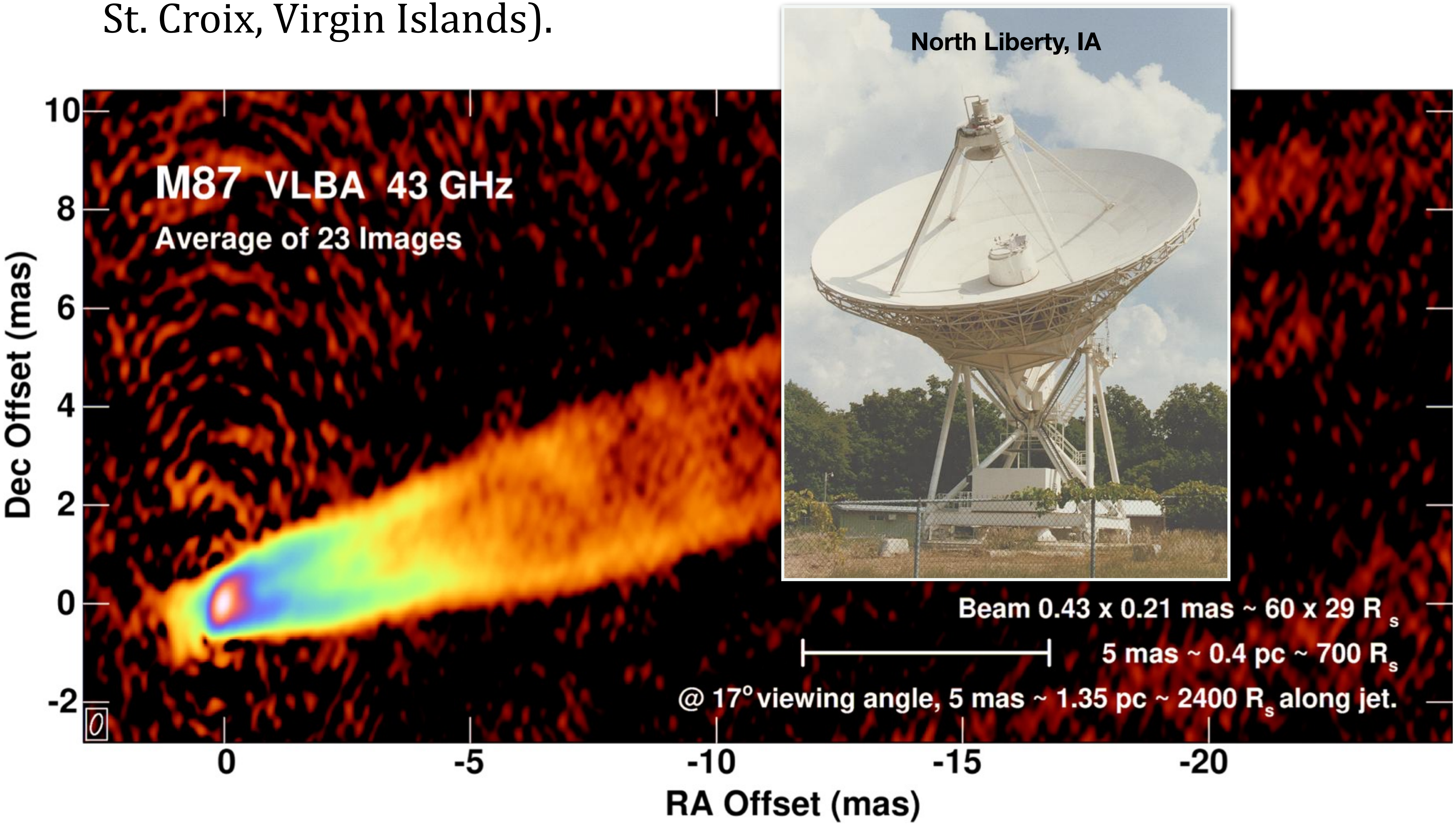
Speaking about surplus radio antennae …

- The University of Iowa’s Astronomy program started from a surplus radio antenna that tracks spacecrafts and receives spacecraft data.

The Univ. of Iowa North Liberty Radio Observatory in 1973

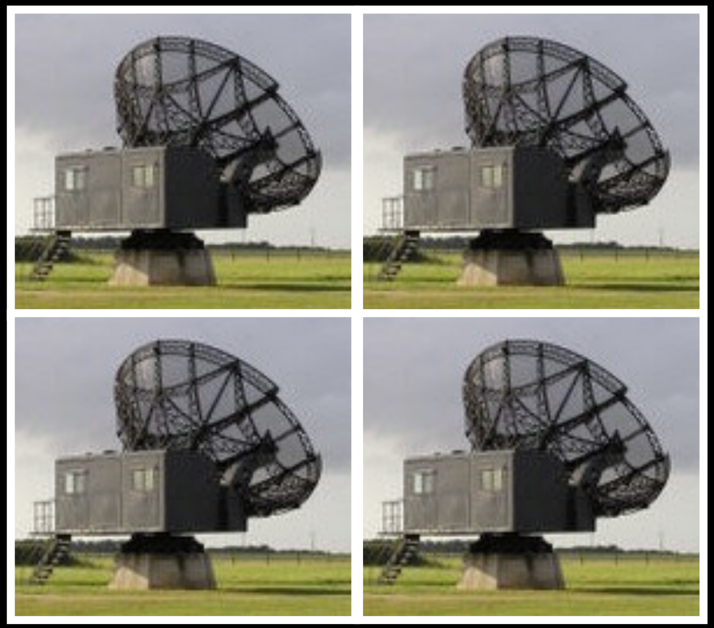
Now the North Liberty Station of the Very Long Baseline Array

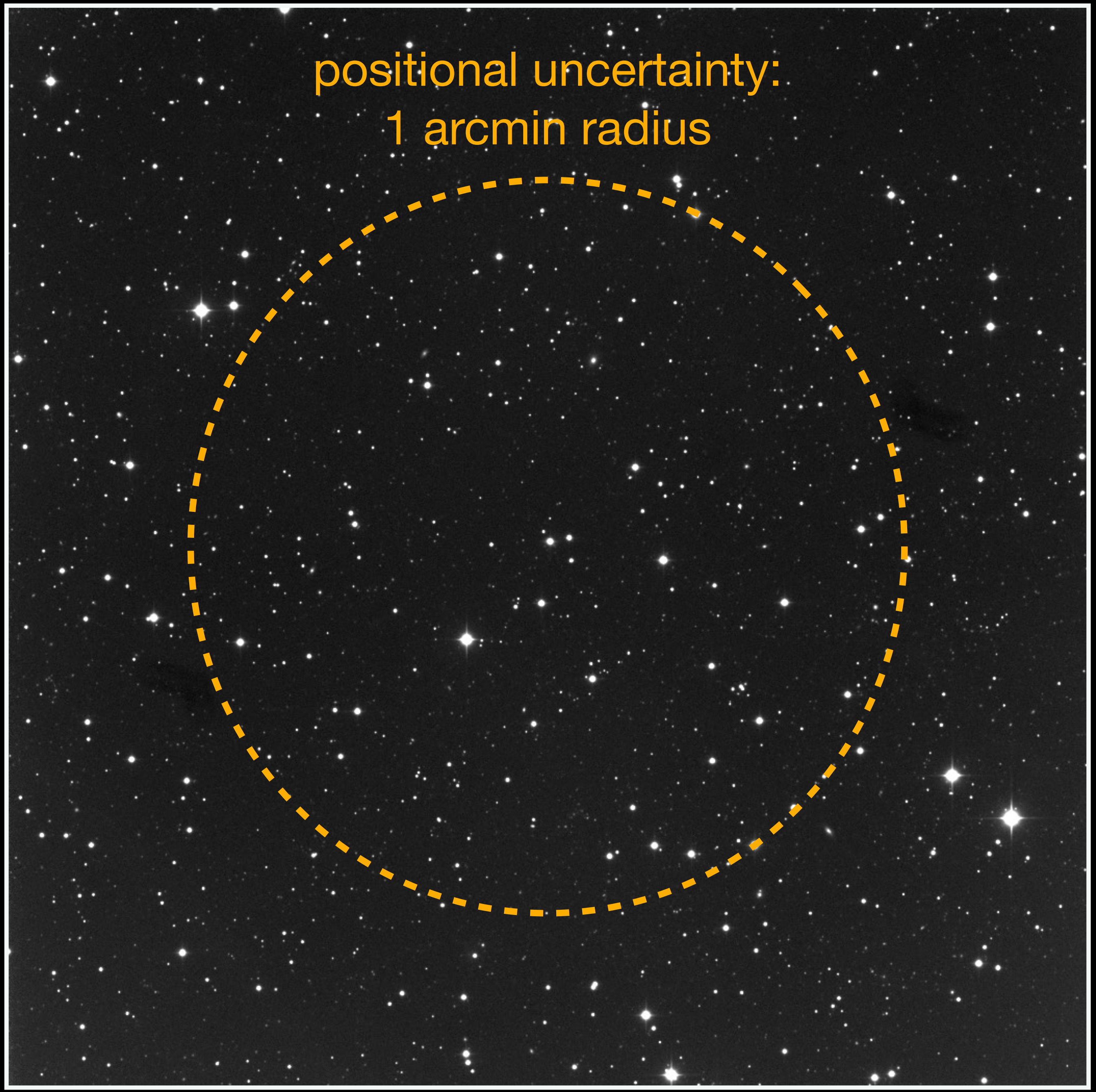
- The VLBA is an interferometer consisting of 10 identical 25-meter antennas, separated by distances from 200km to transcontinental 8600 km (with the longest baseline between Mauna Kea, Hawaii and St. Croix, Virgin Islands).



Discovery of 3C 273: the First Quasar

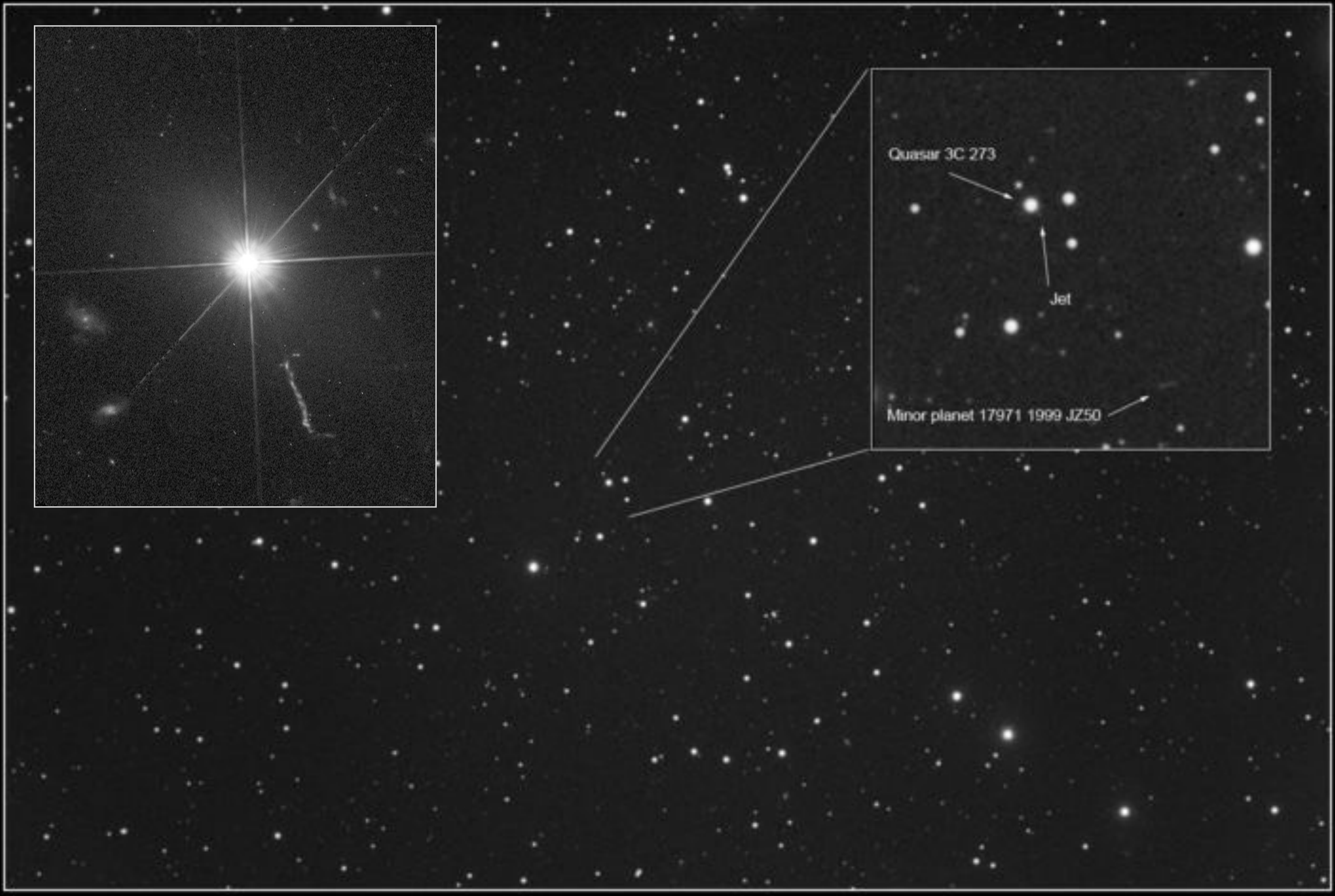
Edge *et al* (1959) - **1′**





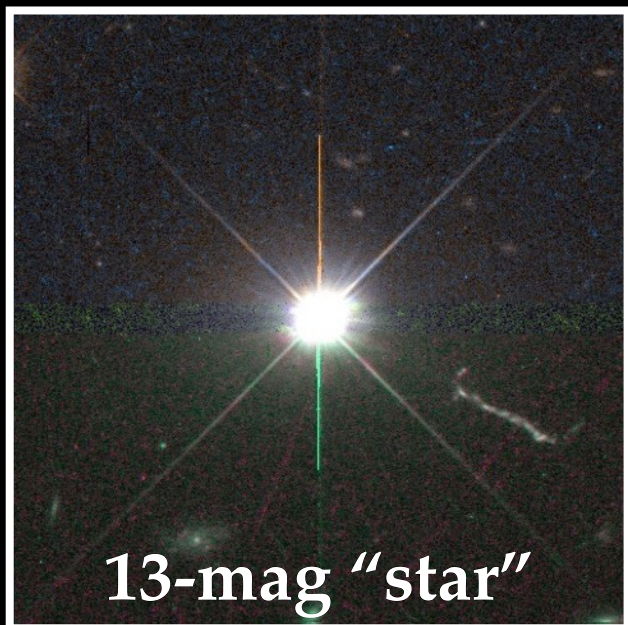
Hazard *et al* (1963) - lunar occultation, **1″**

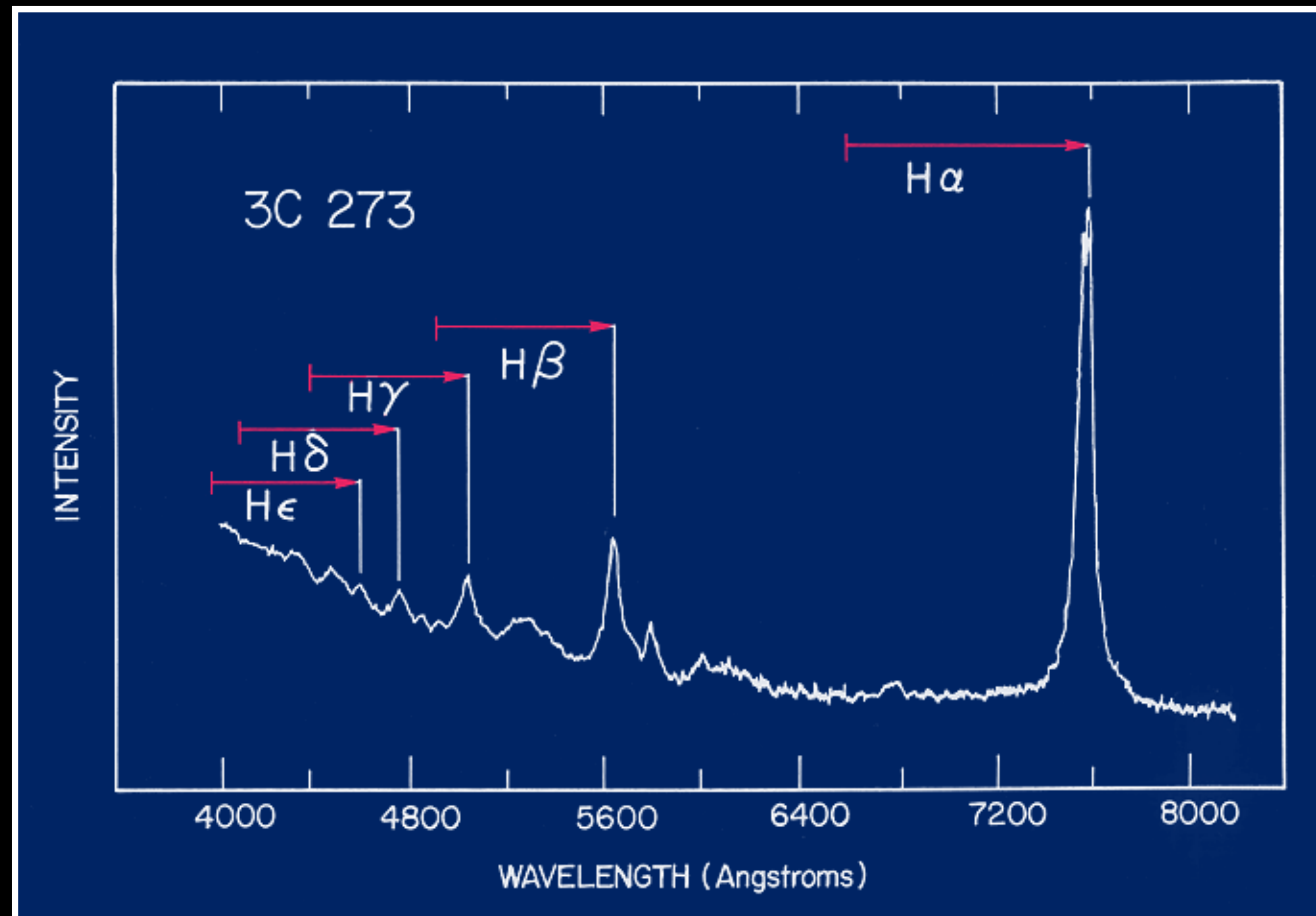
Optical Counterpart of 3C273

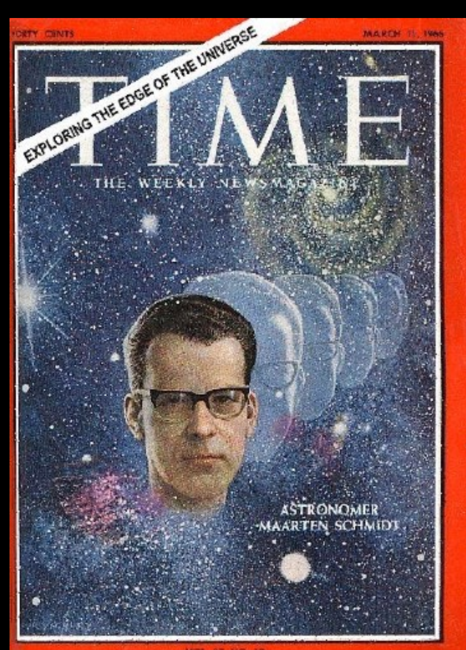


Quasar 3C 273 w/Jet & MP 17971 1999 JZ50

Discovery of 3C 273: the First Quasar



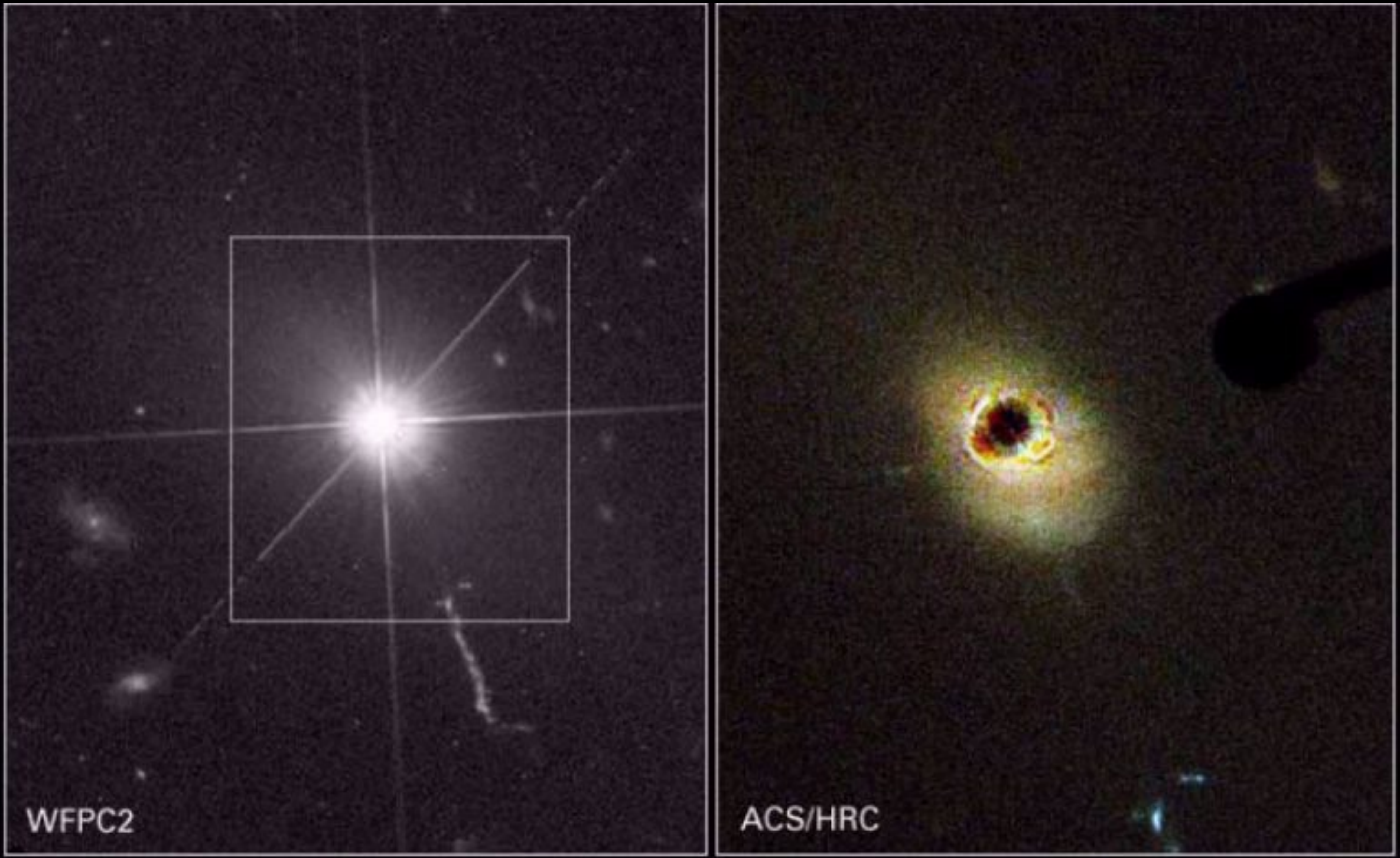




z = 0.158 (760 Mpc)

Schmidt (1963)

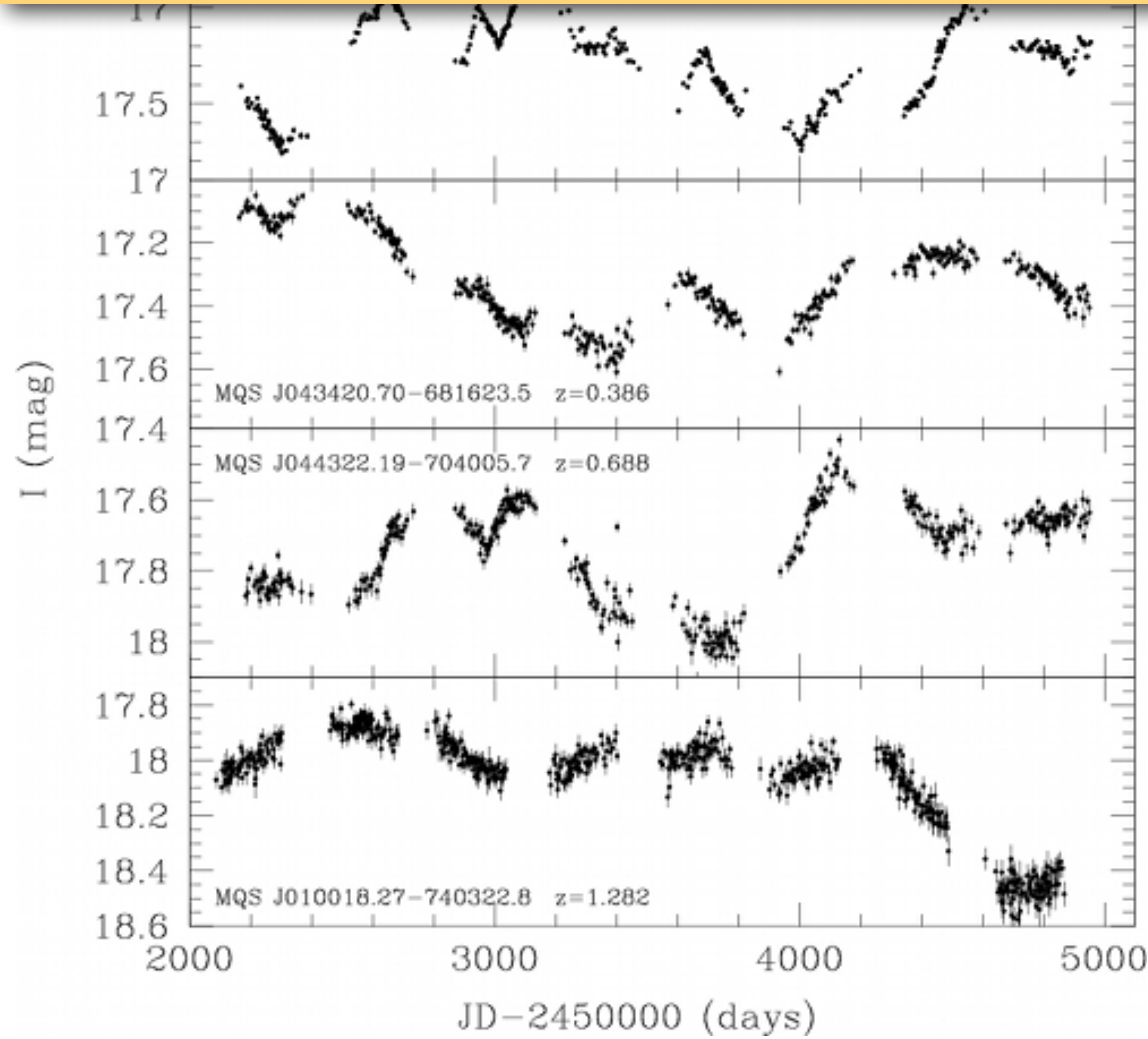
HST coronagraphic image reveals the host galaxy of 3C273



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

Quasars Show Rapid Variations in Brightness

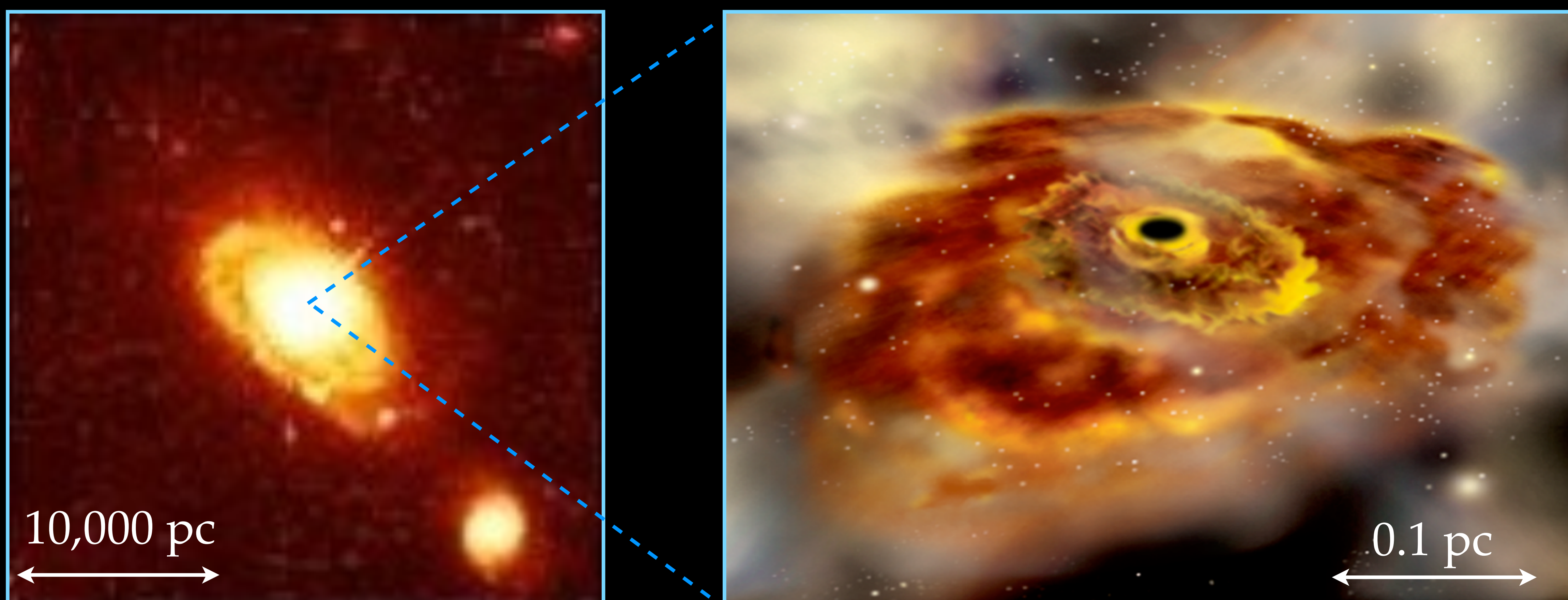
$c \times 1$ week = 0.006 pc = 1212 AU



What Could Power Quasars?

Accreting supermassive black holes

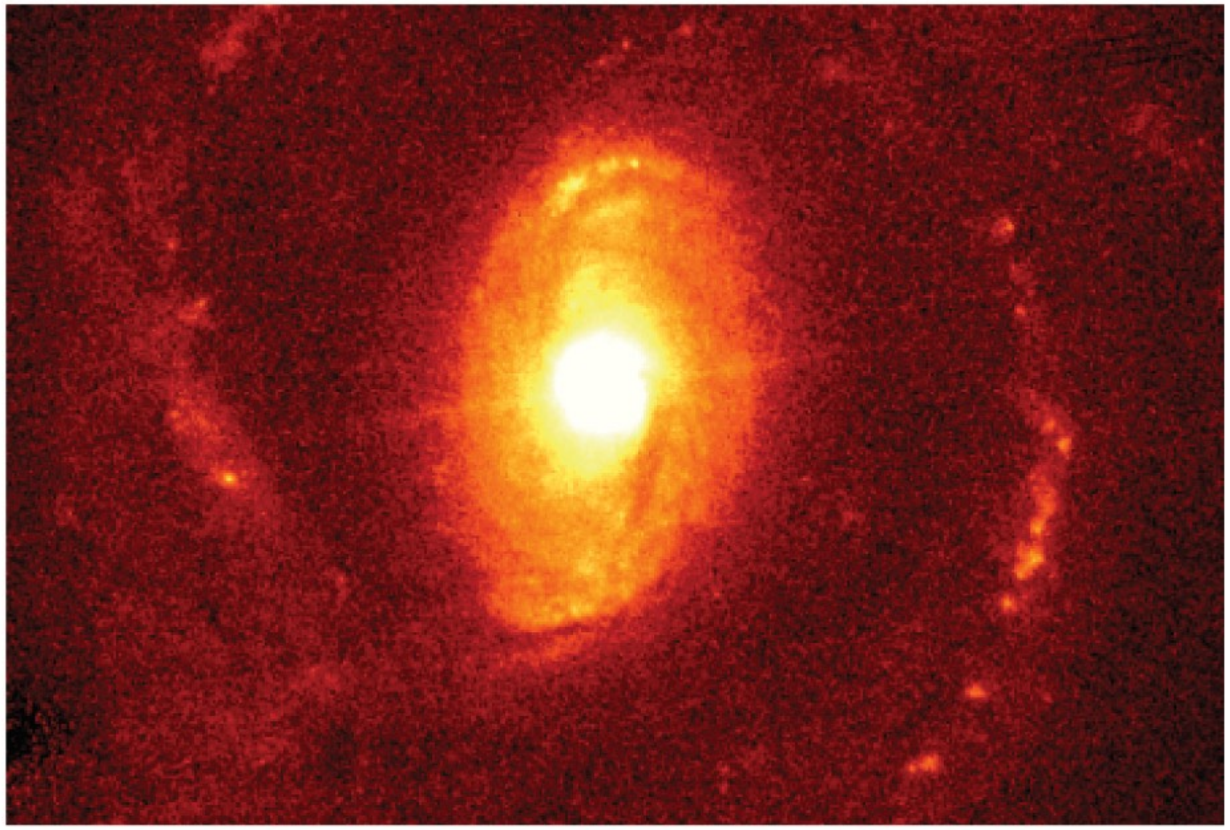
$$L_{\rm bol} = 0.1\dot{M}_{\rm BH}c^2 = 10^{12}L_\odot\left(\frac{\dot{M}_{\rm BH}}{1\,M_\odot\,{\rm yr}^{-1}}\right)$$

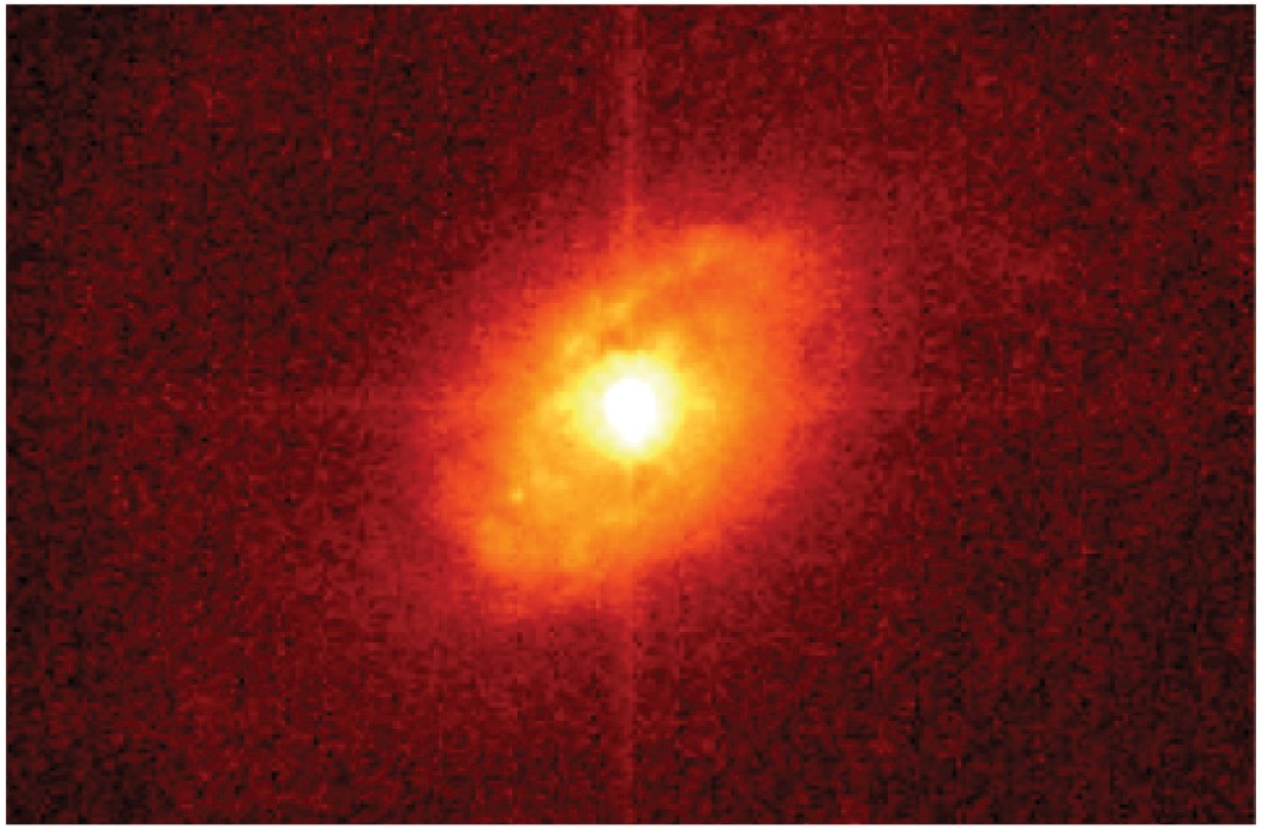


Hoyle et al (1964), Lynden-Bell (1969)

Active Galactic Nuclei: a Rare but Important Class of Galaxies

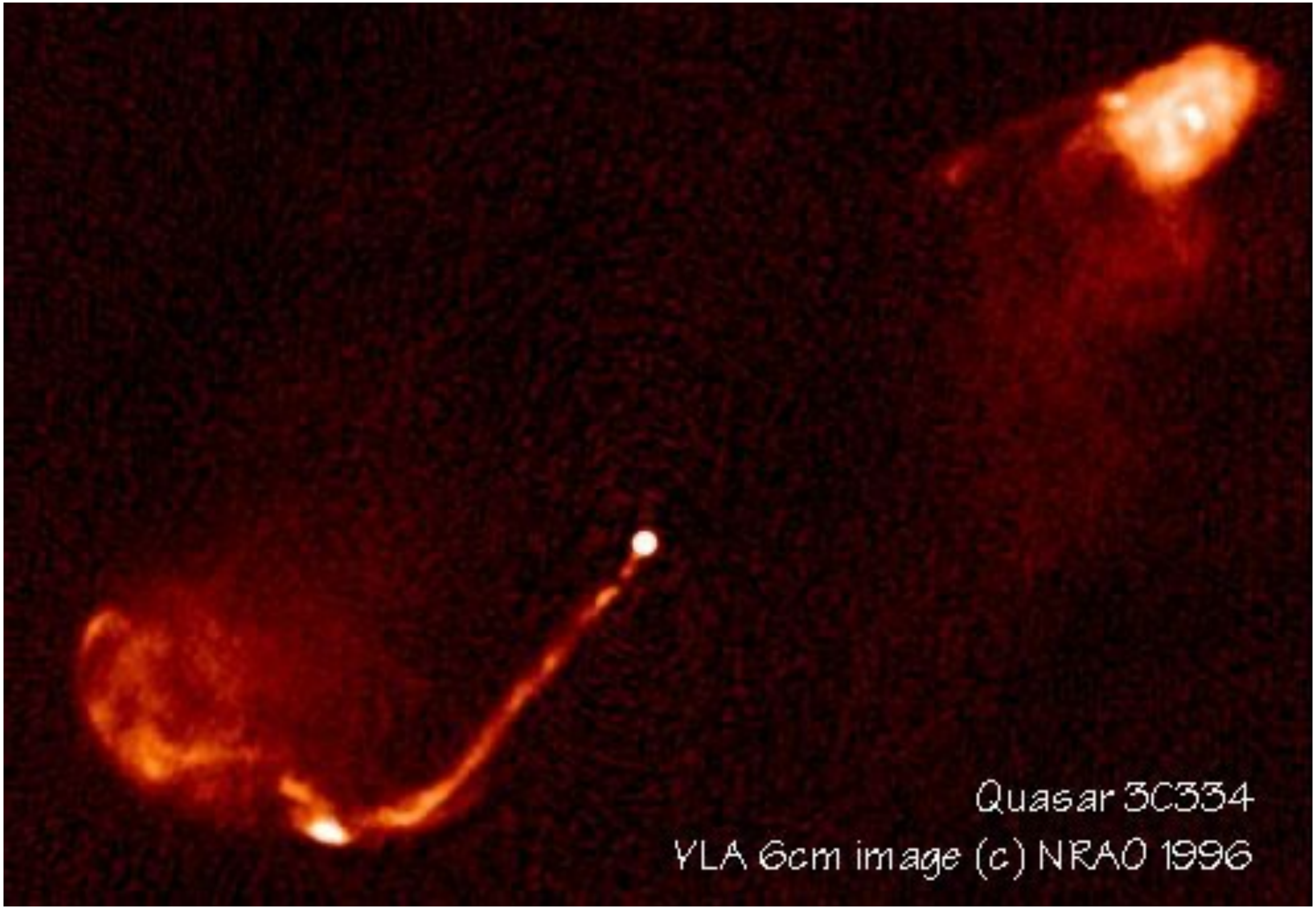
- **Quasars** are only one type of **active galactic nuclei (AGN)**.
  - The luminosity of a quasar can be as large as the rest of the galaxy.
  - The most luminous AGN are called **quasars**, the less luminous AGN are called **Seyferts**.
- All **AGN** are powered by central **supermassive black holes** with accretion disks. "**supermassive**" means at least **10^3** solar masses





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

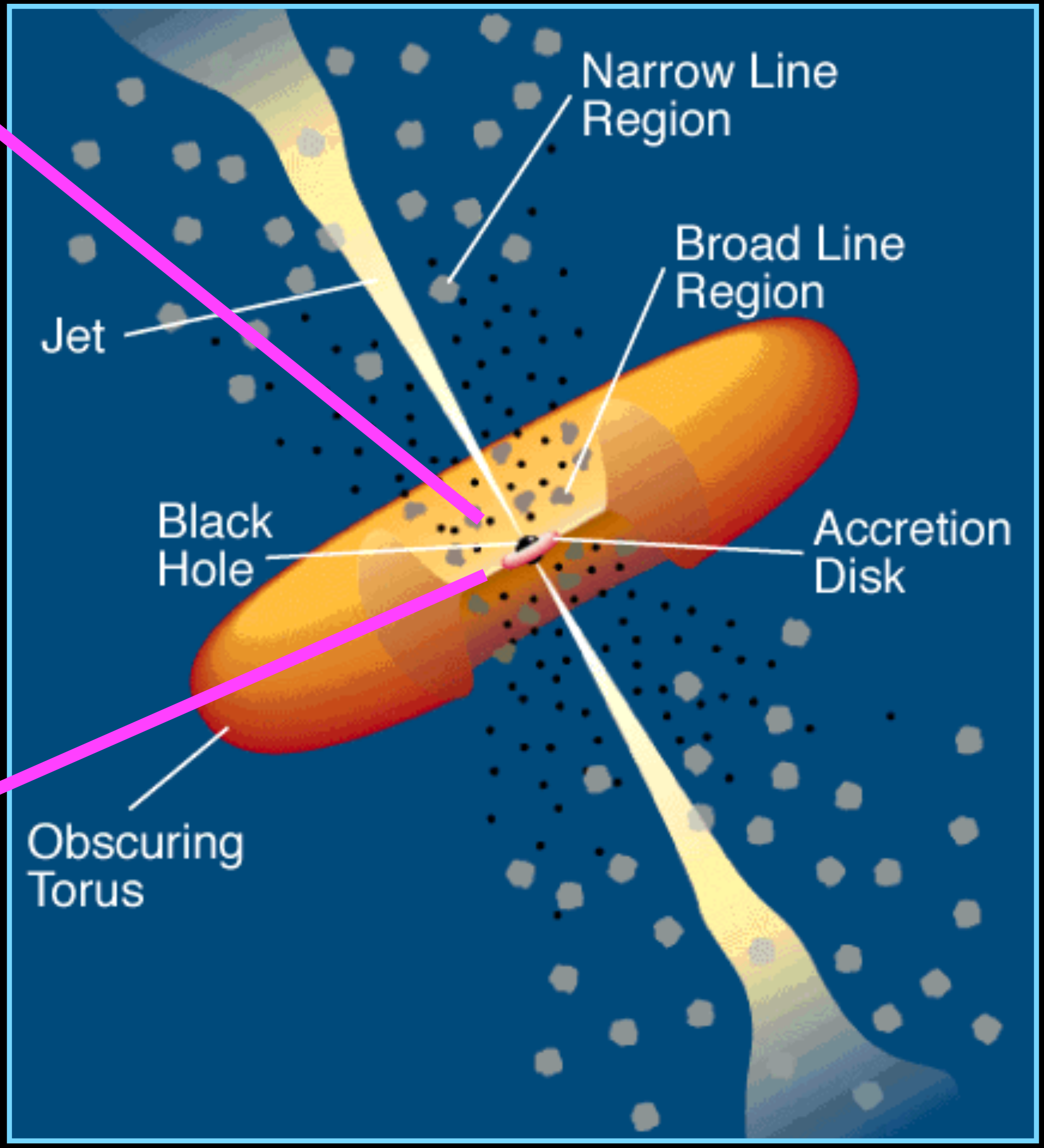
- **Radio galaxies** are ***elliptical galaxies*** that have large jets and lobes of radio emission, powered by the central engine.
- Their radio properties are similar to radio-loud quasars but they don't show the central brilliant point source

Centaurus A (distance 3.4 Mpc)

Could Radio Galaxies and Quasars be the Same Type of Objects?

Different Viewing Angles w.r.t. Obscuring Torus

Type 1



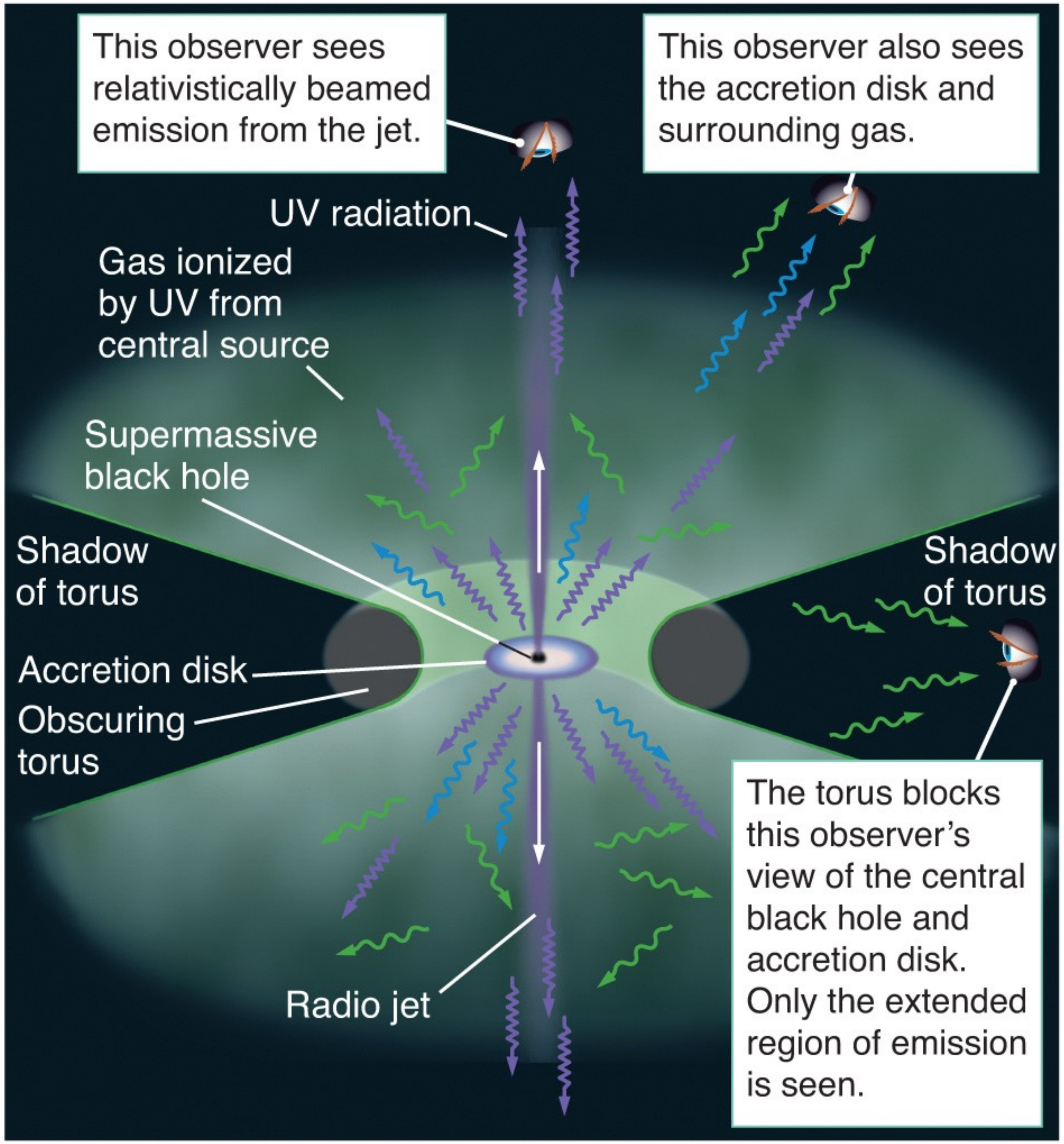
Type 2

Torus Size ~ 5 pc

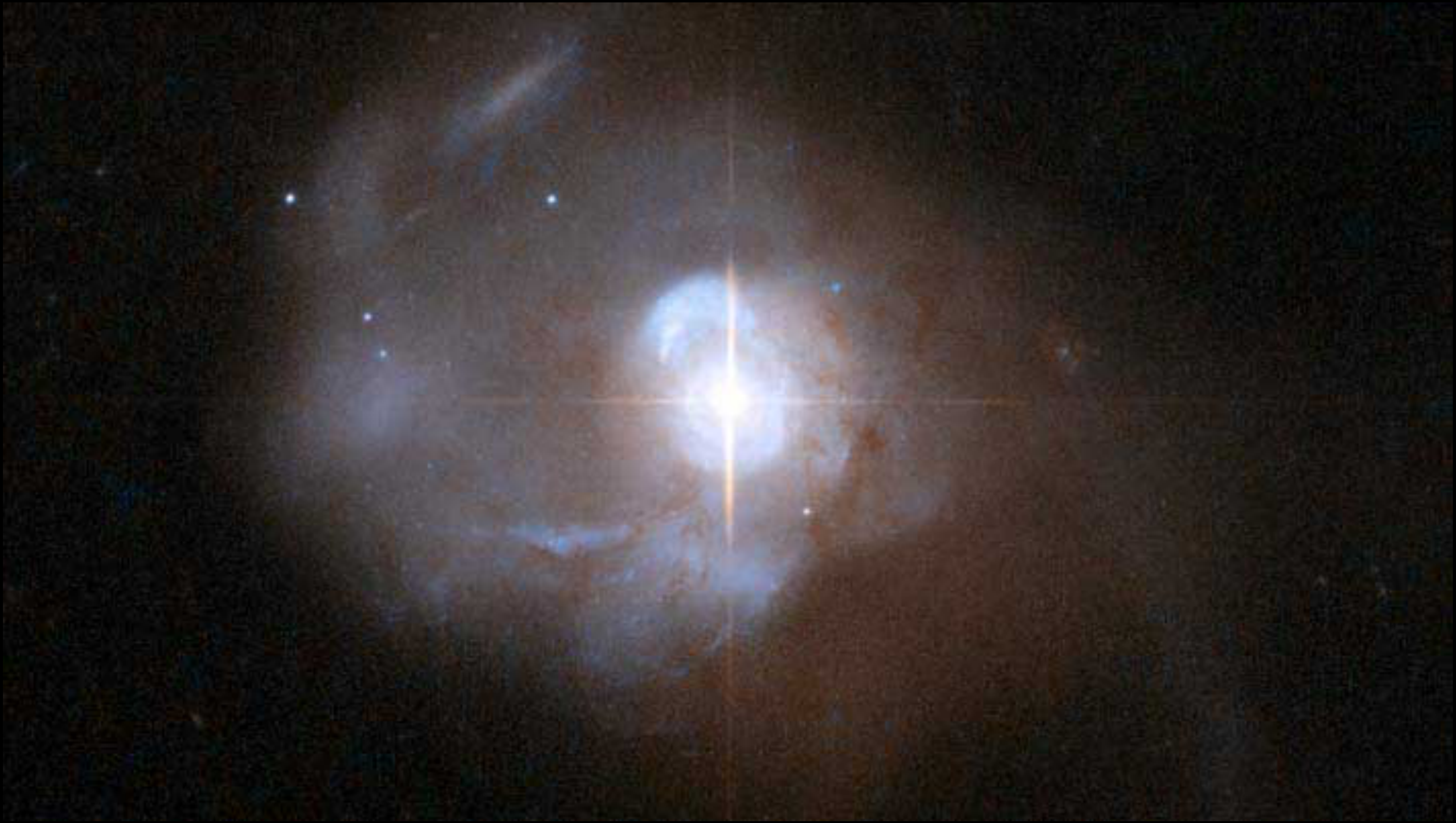
Urry & Padovani 1995

Unified Model of AGN: applicable to both Seyferts and Quasars

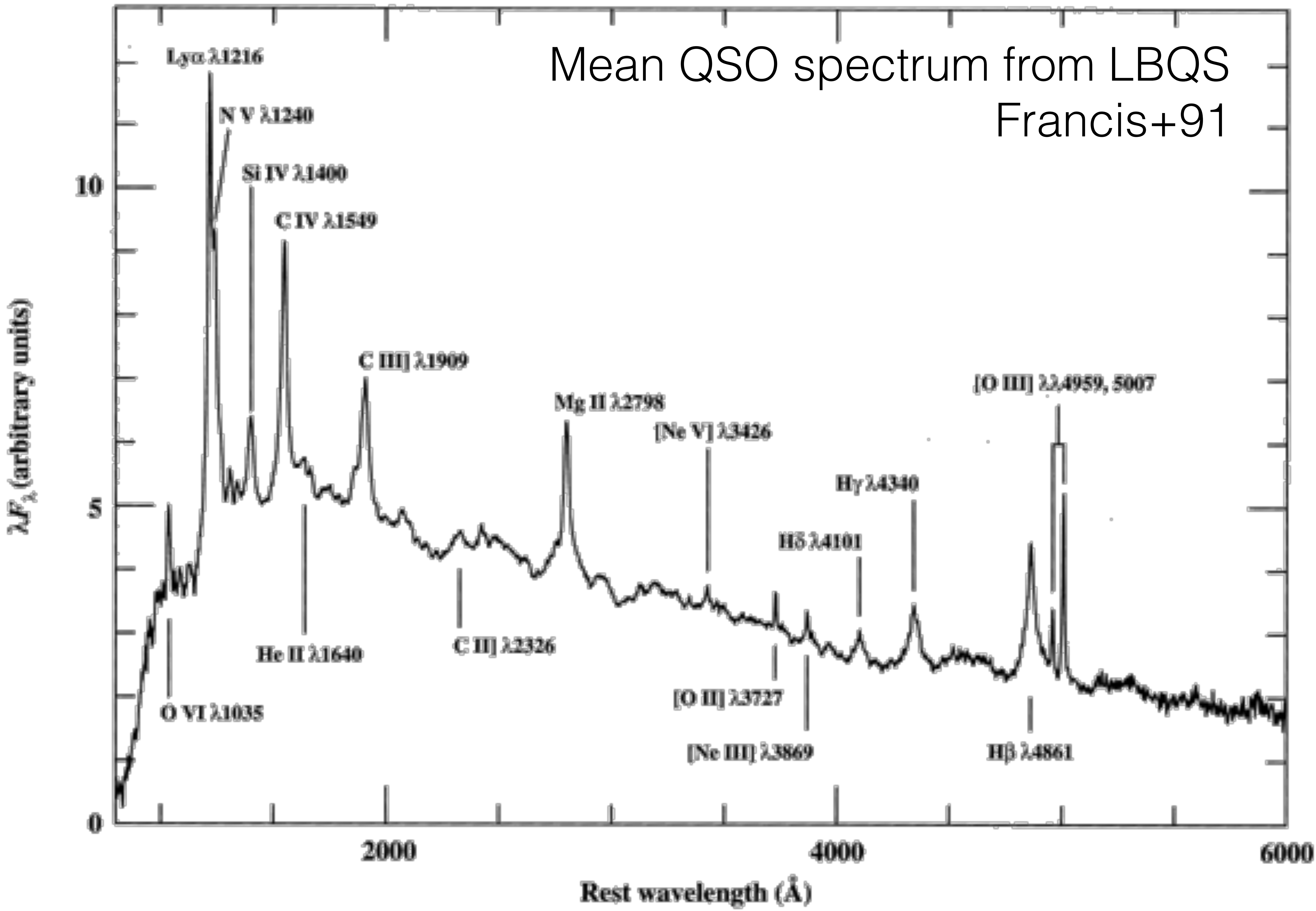
- The **unified model of AGN** attempts to explain the different types of AGN.
- What we see depends on our viewing angle of the AGN.
  - **Edge on**: viewing emission from the torus
  - **Face on**: viewing emission from the accretion disk and jet
  - ***Blazar*** when viewing straight down the jet

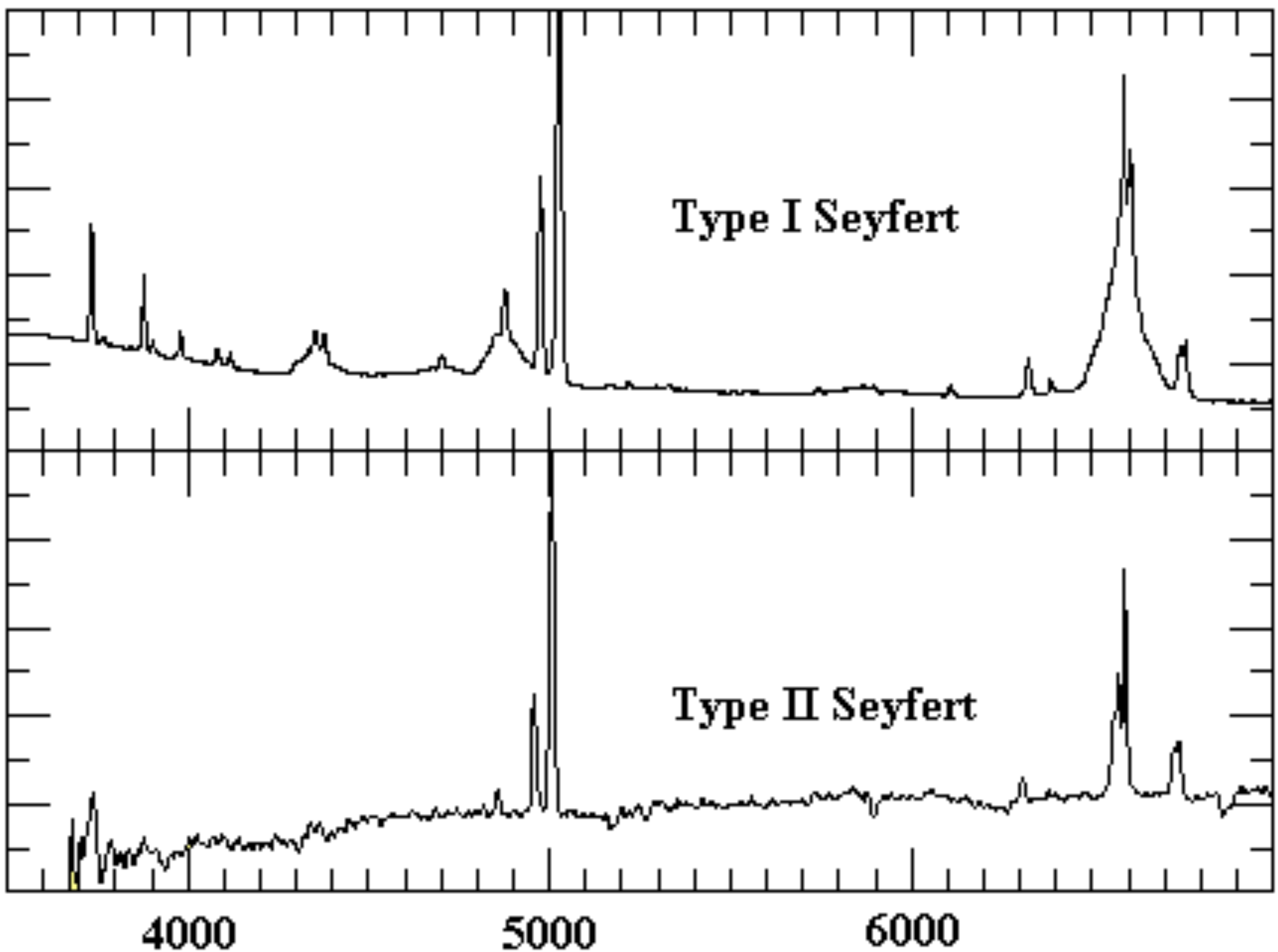


Mrk 231: a Type 1 Seyfert

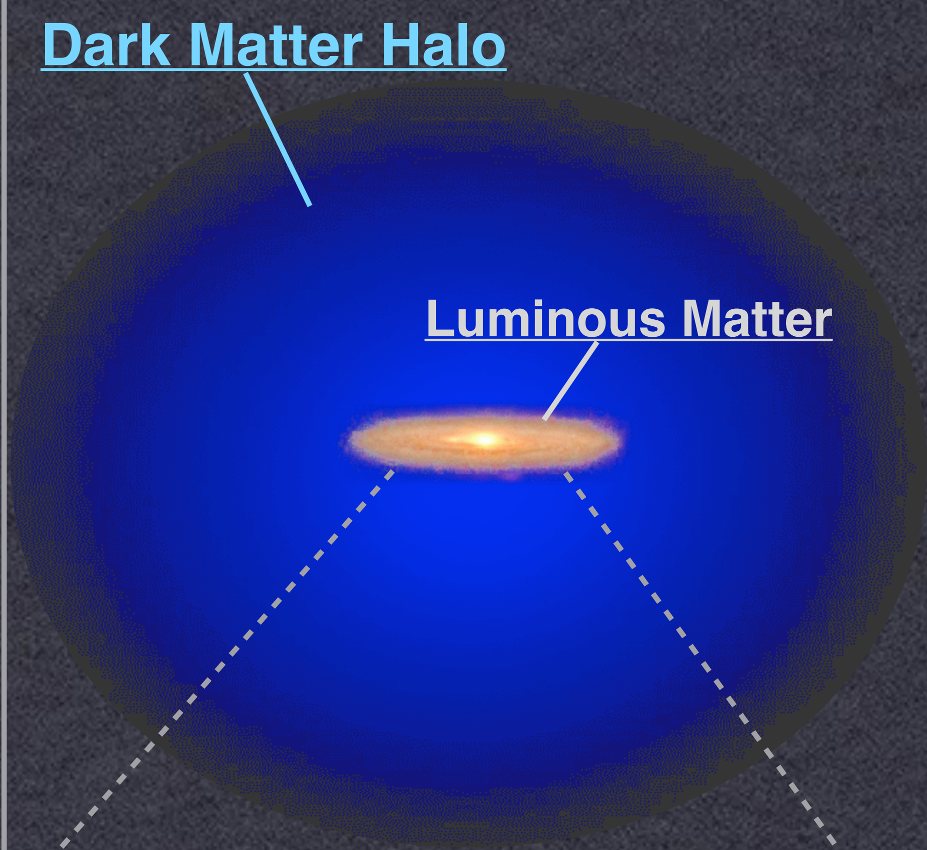


NGC 1672: a Type 2 Seyfert

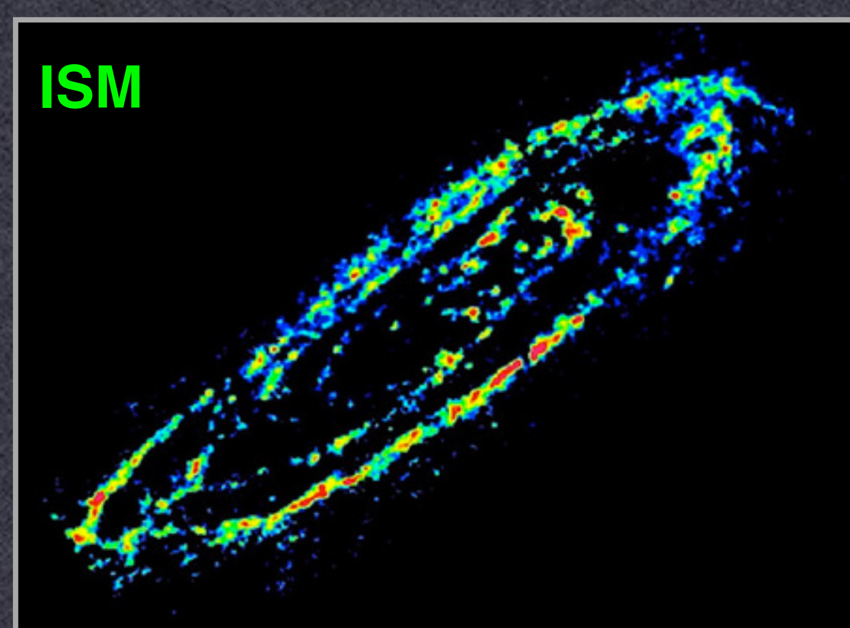

Mean QSO spectrum from LBQS
Francis+91
Lyα λ1216
N V λ1240
Si IV λ1400
C IV λ1549
C III] λ1909
Mg II λ2798
[Ne V] λ3426
[O III] λλ4959, 5007
Hγ λ4340
Hδ λ4101
He II λ1640
C II] λ2326
[O II] λ3727
[Ne III] λ3869
Hβ λ4861
O VI λ1035
10
5
0
2000
4000
6000
Rest wavelength (Å)
λF_λ (arbitrary units)

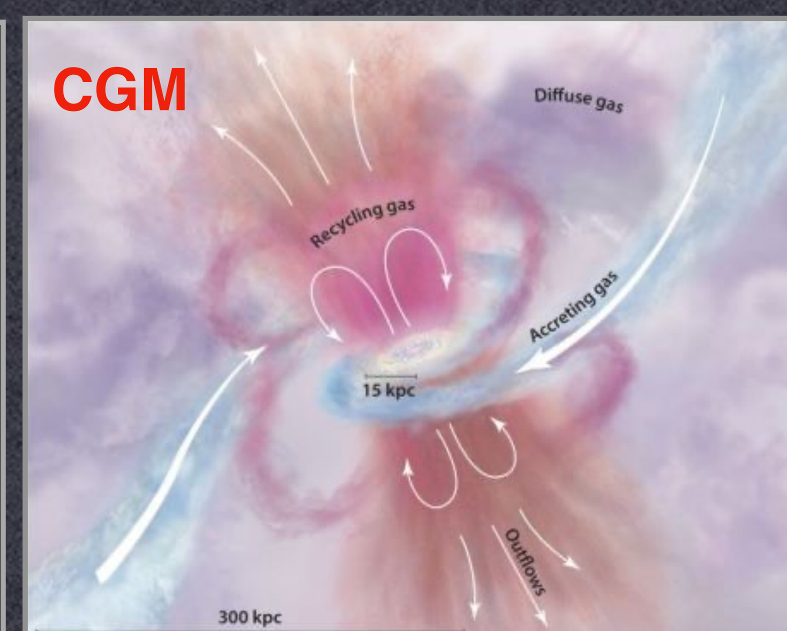

Type I Seyfert
Type II Seyfert
4000
5000
6000

Summary: Components of M31



- Total Dynamical Mass: $1.2\text{x}10^{12}\ M_\odot$
- 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 19: 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 19: Key Equations

- **Period-Luminosity relation** of Cepheids: $M_V = -2.43\log(P_{\rm day}) - 1.62$
- **Distance modulus**: $m - M = 5\ (\log d_{\rm pc} - 1) \Rightarrow d_{\rm pc} = 10^{1+0.2(m-M)}$
- **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**:**

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