

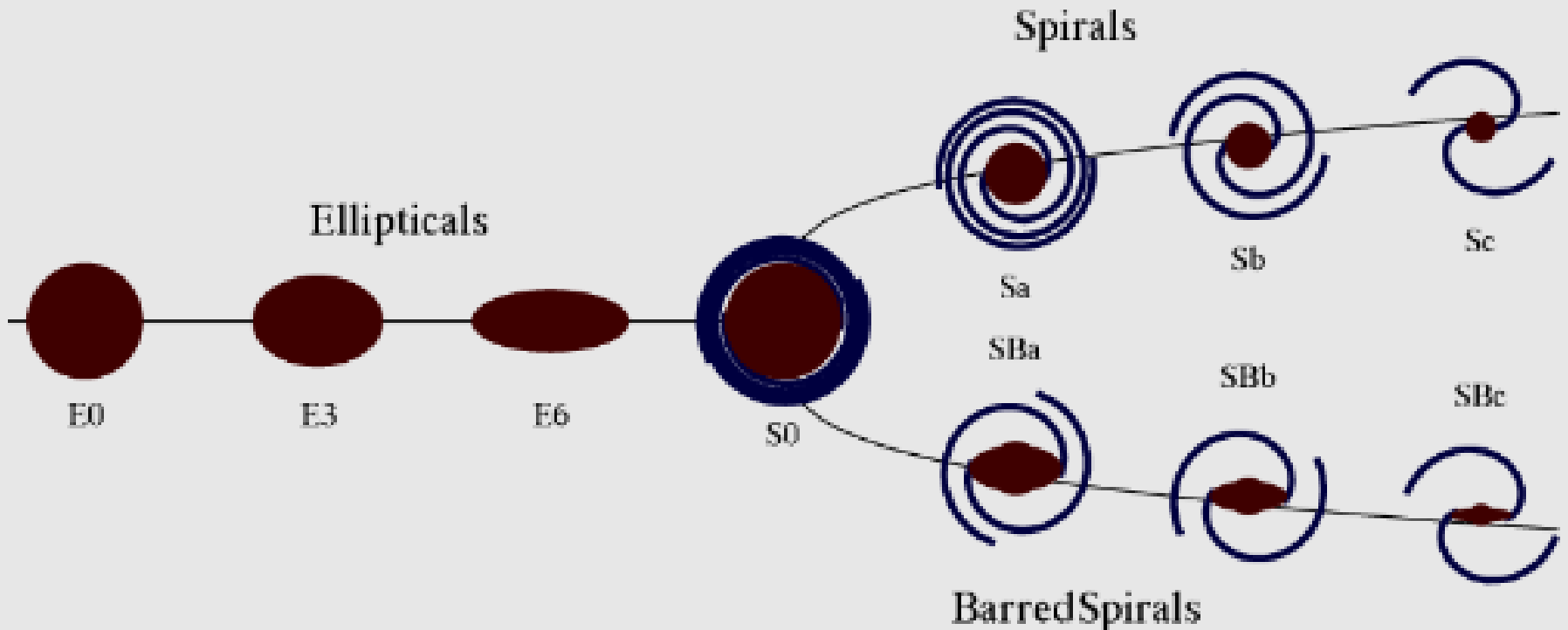
Chap 20,21: Galaxies – Classifications, Evolution

Here's the Story We'll Unfold for You...

- Hubble's galaxy classifications: Spirals, ellipticals, irregulars.
- Structural parts of galaxies: disk, halo, nucleus, bulge
- Spiral arms – tracers of star formation
- Globular clusters, relics of galaxy collisions
- Elliptical Galaxies, clues to their structure and formation
- Galaxy mergers
- Giant Black Holes in Galaxies: Quasars, Seyferts, Radio Galaxies
- Dwarf's the most common galaxy, starbursts early on blew away their gas and shut off further star formation

The Hubble Sequence of Galaxy Types.

From left to right, the gas+dust fraction goes up, the current star formation rate goes up, and the disk/bulge ratio goes up



Hubble's Classification

Ellipticals: like amped-up globular clusters, and looking a bit squashed as projected onto the sky.

S0's: Bulge + disk, but the disk is faint and has no spiral arms or star formation going on.

Spirals: Bulge + disk. Disk has spiral arms and is where the new star formation is happening.

Barred Spirals: Same, but additionally have a straight “bar” of stars centered on the center of the galaxy. Milky Way is a barred spiral

Irregular: Messy looking galaxies, now known mostly to be galaxies undergoing mergers

**A Classic Spiral Galaxy – Andromeda. Blue Pop I Disk,
Reddish Pop II Central Bulge**





The Closest Elliptical Galaxy NGC 205 (lower left); Andromeda's Neighbor

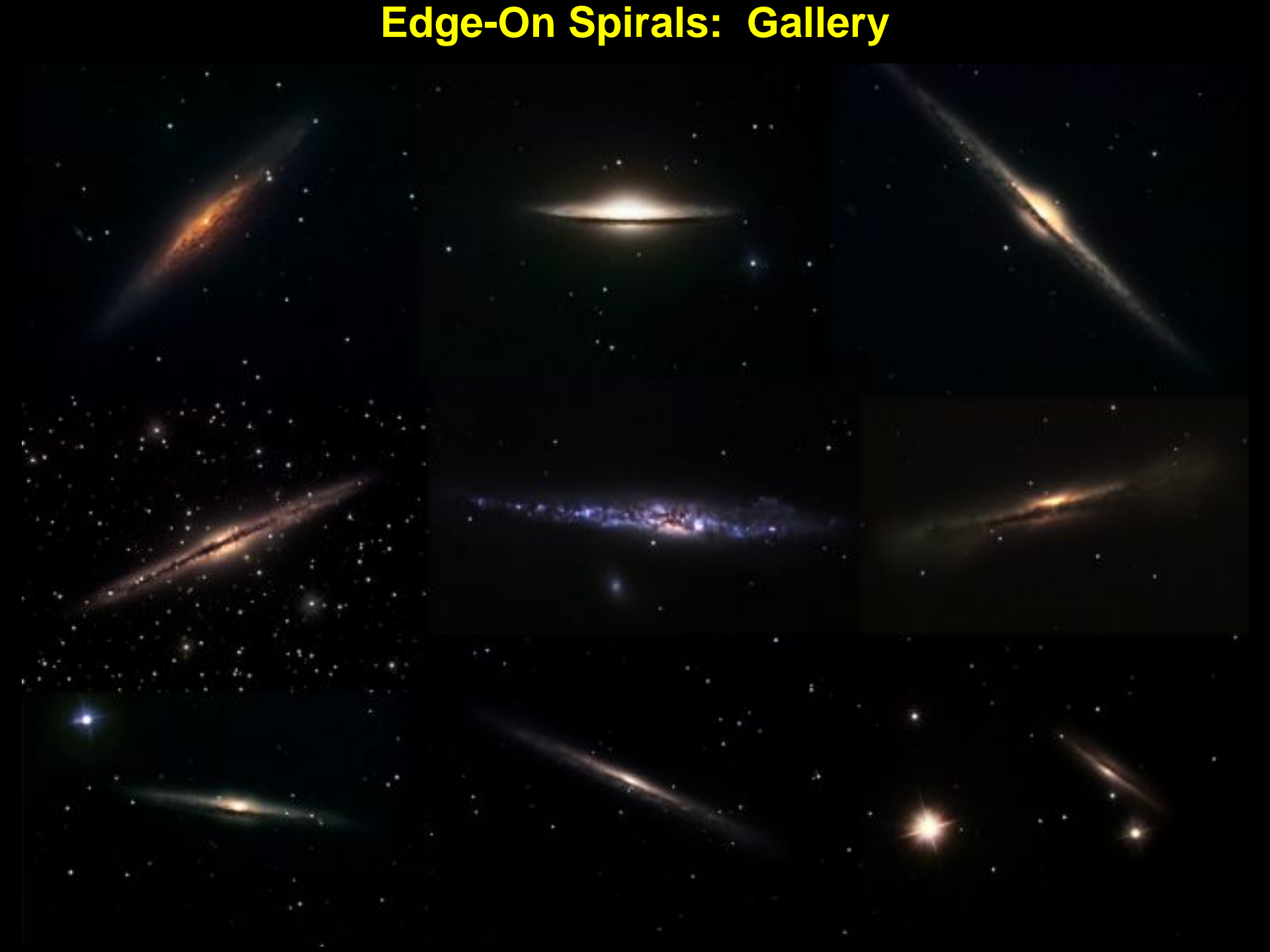


Edge-On Galaxy NGC 4013



Dust settles
into thin disk,
star orbits
gradually
fatten into
thicker disk,
scattering
sometimes
vertically off
of each other
and giant
molecular
clouds

Edge-On Spirals: Gallery



A Classic Sa Galaxy – Bright, Massive Stellar Halo

Sombrero Galaxy • M104



Spiral Galaxy NGC 4622



An Sa/Sb
Galaxy:
Weaker
bulge,
more star
formation
in disk

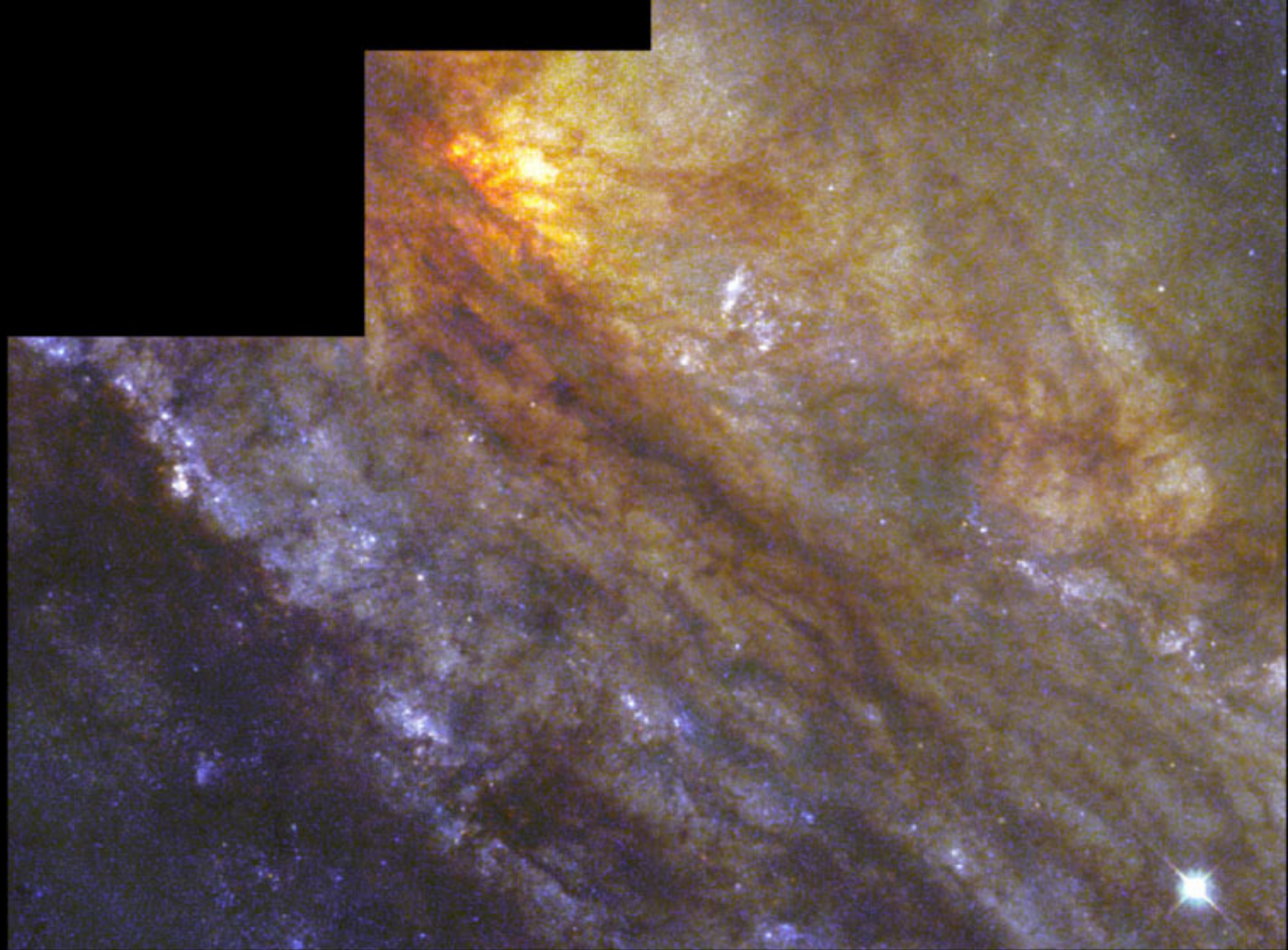
**An Sc Spiral. Very weak central bulge,
strong star formation in the spiral arms**



NGC 3949 – an Sc Spiral

Spiral Galaxy NGC 3949





Galaxy NGC 253

Hubble
Heritage

Galaxy Colors: Clue to Stellar Populations

- **The bulge is reddish** – made up of Pop II stars: old stars whose hot massive members have already died, leaving the cooler red giants or lower mass main sequence stars.
- **The disk is bluish** – made up of Pop I stars and lit up especially by those few, young stellar “superstars” that shine hot and bright and blue.

Spiral arms are bluish from hot young stars. Central bulge is reddish from old Pop II red giants. NGC 3370 is an Sc Spiral

Spiral Galaxy NGC 3370

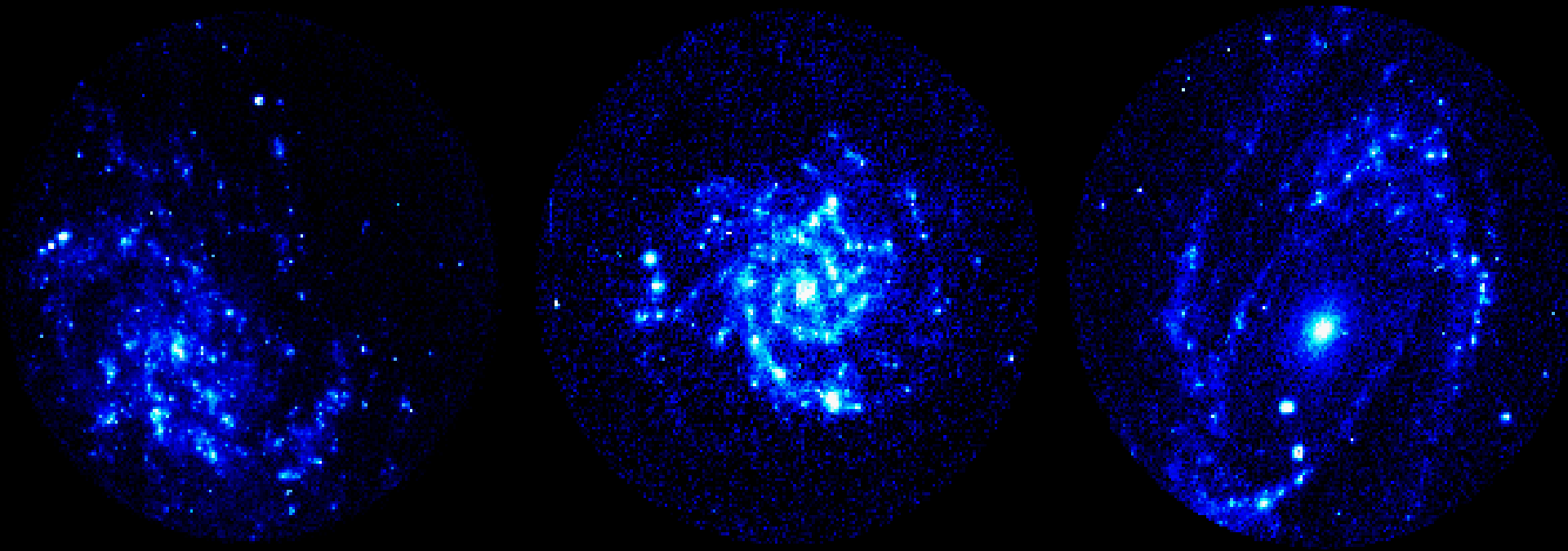




The Whirlpool Galaxy: An Sc Spiral.

Bright spiral arms with Vigorous Star Formation, Weak Bulge

Spirals. UltraViolet light from hot young massive stars in the spiral arms





Galaxy NGC 2787



Spiral Galaxy NGC 4414



A Barred Spiral; type SBc



Barred Spiral: SBb, we think very much like our Milky Way



Another Barred Spiral (and Seyfert Galaxy at upper right in background)

NGC 4319 and Markarian 205



A Milky Way companion – the Large Magellanic Cloud; a tidally stripped dwarf barred spiral? More usually classified as an Irregular



The Small Magellanic Cloud (and 2 MW globular clusters)



Dwarf Spheroidal galaxy companions to the Milky Way

- Dwarf spheroidals are small, low mass dark-matter dominated galaxies.
- The escape velocity from these low-mass systems is low enough to be a problem...
- They have few stars because the initial star burst produced supernovae which blew the gas right out of the galaxy, shutting off further star formation.
- Dwarf galaxies, whether they are spheroidals or irregulars are the most common type of galaxy in the universe

But Dwarf Spheroidals are Dim

- So photographs, which of course can only see down to a given brightness, miss most of them.
- For BRIGHT galaxies, the most common (i.e. the ones you'll mostly see on survey photographs covering the whole sky) are Spirals.
- There's roughly equal numbers of normal spirals and barred spirals. Together, they're the most common bright galaxies

**The Leo I dwarf spheroidal galaxy.
Stars are sparse. No gas or dust**



The Fornax Dwarf Spheroidal



The Sculptor Dwarf; a bit richer than average

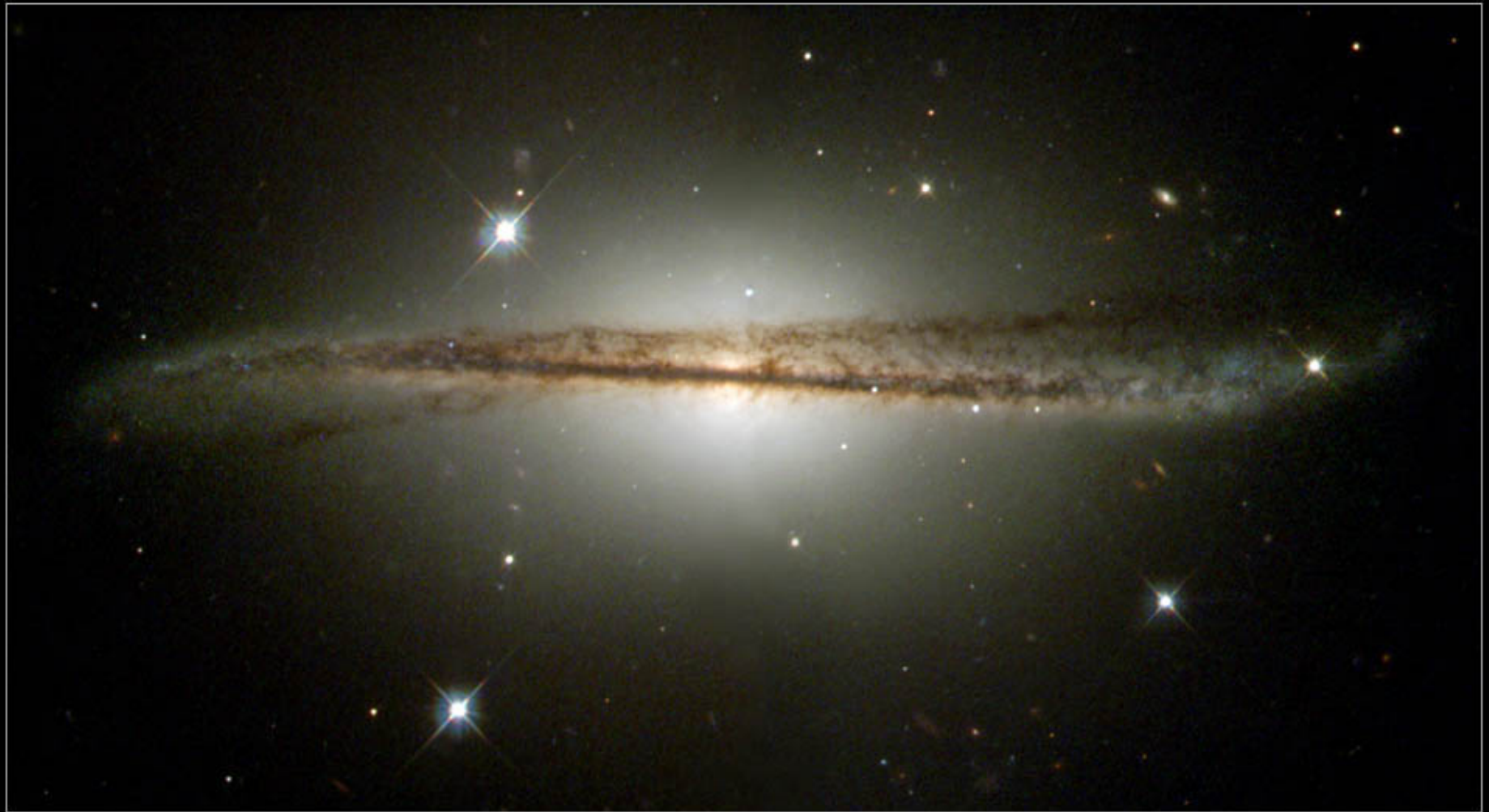


Galaxies are fragile. Especially those floppy disks!

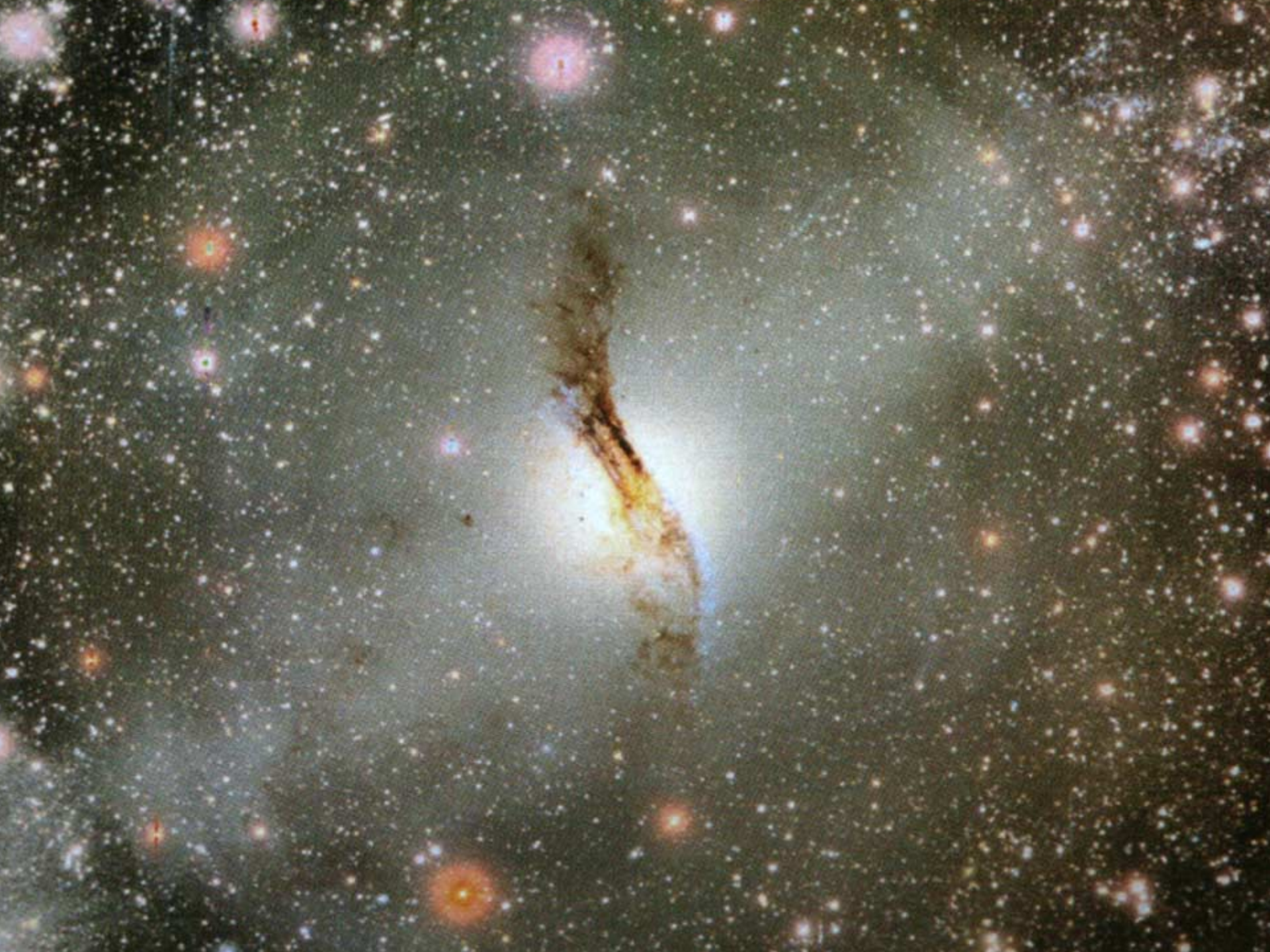
- And it's a dense environment out there. Smash-ups do happen. It's not uncommon.
- Near – misses or encounters with dwarfs may just warp your disk...
- See lots of slightly disturbed, to badly mangled spiral galaxies in collision in the following slides....



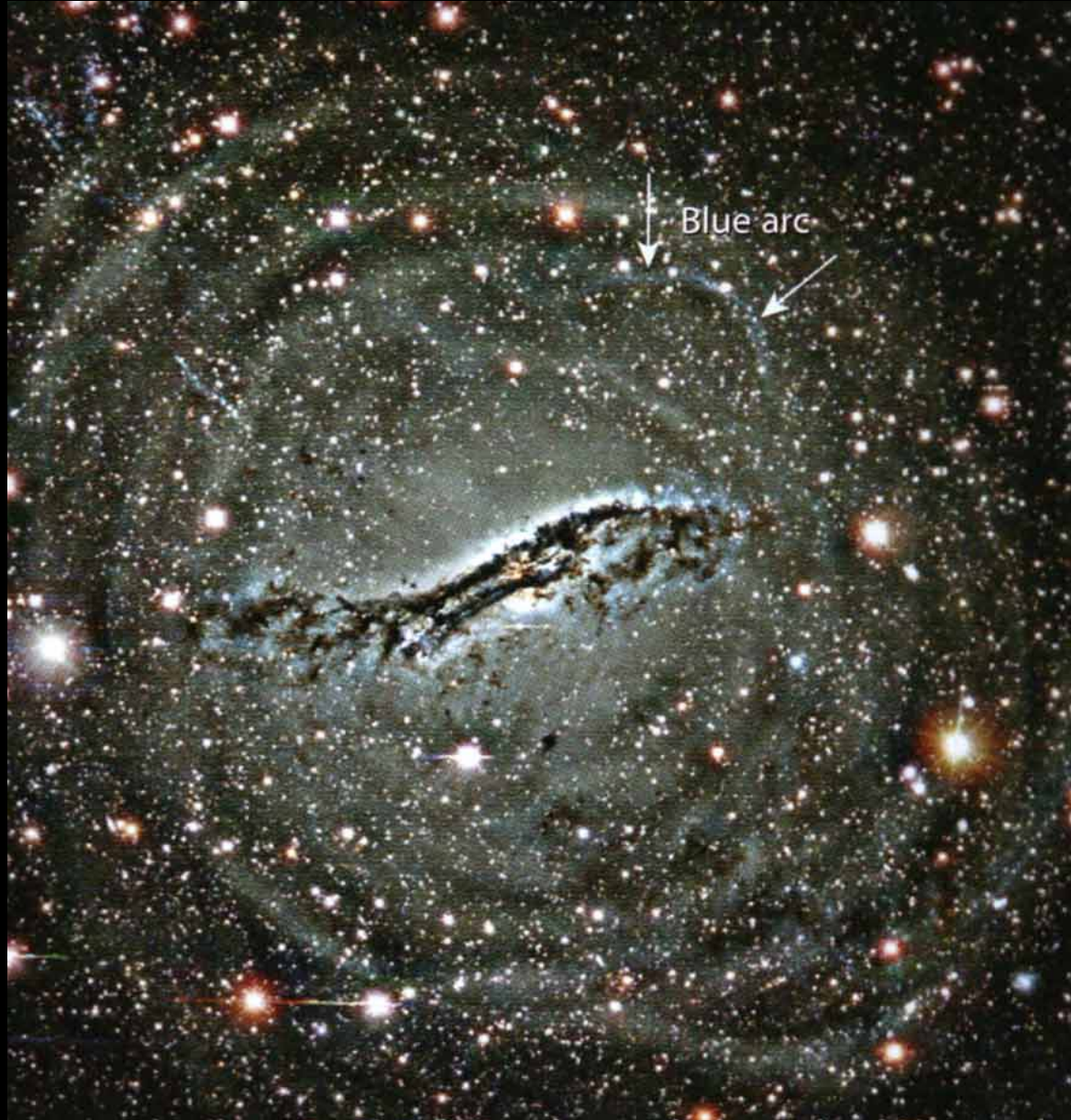
Galaxy ESO 510-G13



Hubble
Heritage



Arcs are sign of past collision. Radial Orbiting Stars Pause at Farthest Point, Creating Arcs



Messy Collision: Hot X-ray Gas (purple) and stars, dust in optical light





**A compact
group of
galaxies.
Before the
demolition
derby
really gets
going**

Are These Galaxies in Collision?

Galaxies NGC 2207 and IC 2163



How about these? In collision?

Spiral Galaxy Pair NGC 3314



No. These Were Not (yet) in Collision.

- The “tell” is that the galaxies, fragile though they are, are clearly not “disturbed” in structure, yet.
- Instead, they’re separated by at least several diameters, and one is directly in front of the other.
- Can you tell who’s in front?

Hit-and-Run Spirals: Tidal Tails of stars, gas, dust



Interacting Galaxy System NGC 6745



Hard collisions of gas will compress it, initiate star bursts. Some new stars are massive, brilliant, blue



Ring Galaxies

- If a small galaxy has a central collision with a larger spiral galaxy, the gravitational pulse can compress gas/dust and make a star formation burst in a ring.
- Collision energy added to the central bulge can stretch it out into a very non-spherical shape.





Hubble

Polar-Ring
Galaxy
NGC 4650A



PRC99-16
Space Telescope
Science Institute
Hubble Heritage Team
(AURA/STScI/NASA)

Hubble
Heritage

The Formation of Elliptical Galaxies



After these Messy Collisions Gravitationally Settle Down...

- ...all the detailed delicate structure of the former galaxies has been blender'ed away
- It is a blob of stars, more concentrated in the center, but otherwise pretty featureless

They can be non-round. Can you guess what astronomers 40 years ago thought as to why?



E0

E2

E3

E4

E5



E⁺0

E⁺2

E⁺3

E⁺4

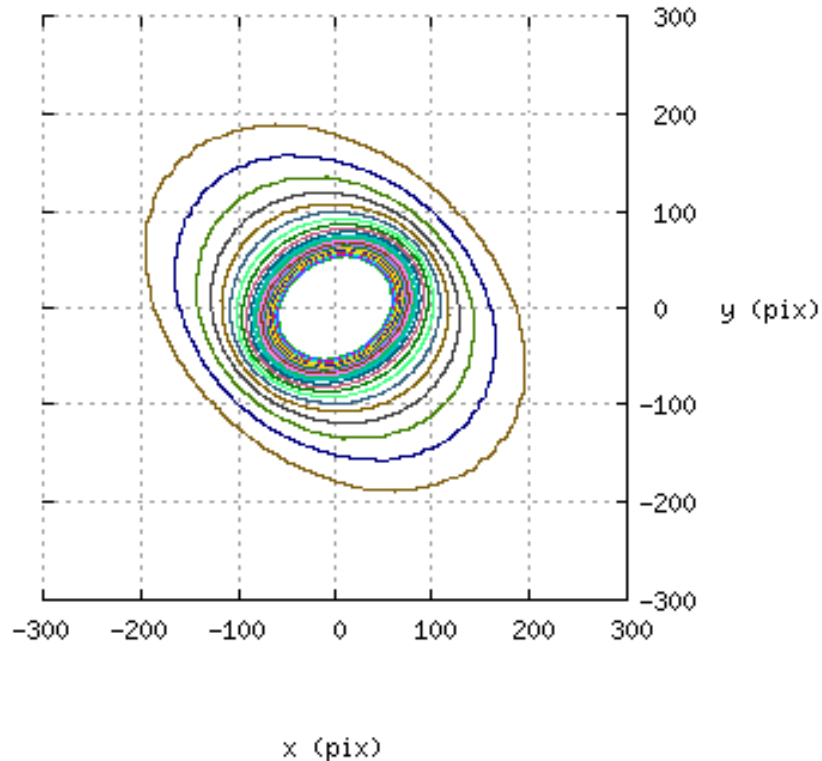
E⁺7

They figured they were just rotationally flattened objects, like spiral disks but “fatter” in thickness

- But we figured out an interesting test to see if this was true.
- First, consider that we only see the full 3-dimensional shape of these galaxies as it projects onto the 2-dimensional sky.
- What are the 3 possible types of shapes that E galaxies can have and the elliptical shapes shown on photographs?

- They could be Oblate: Like “hamburger buns”. Oblate objects have two equal axes and a shorter axis
- They could be Prolate: Like “hot dogs”. Prolate objects have two equal axes and a longer axis
- They could be Tri-axial: 3 different length axes
- Which were Ellipticals? Before the 1970’s, we didn’t have the technology to tell, and we guessed they were oblate, rotating spheroids
- Wrong guess!

We Noticed Something Interesting on Photographs...



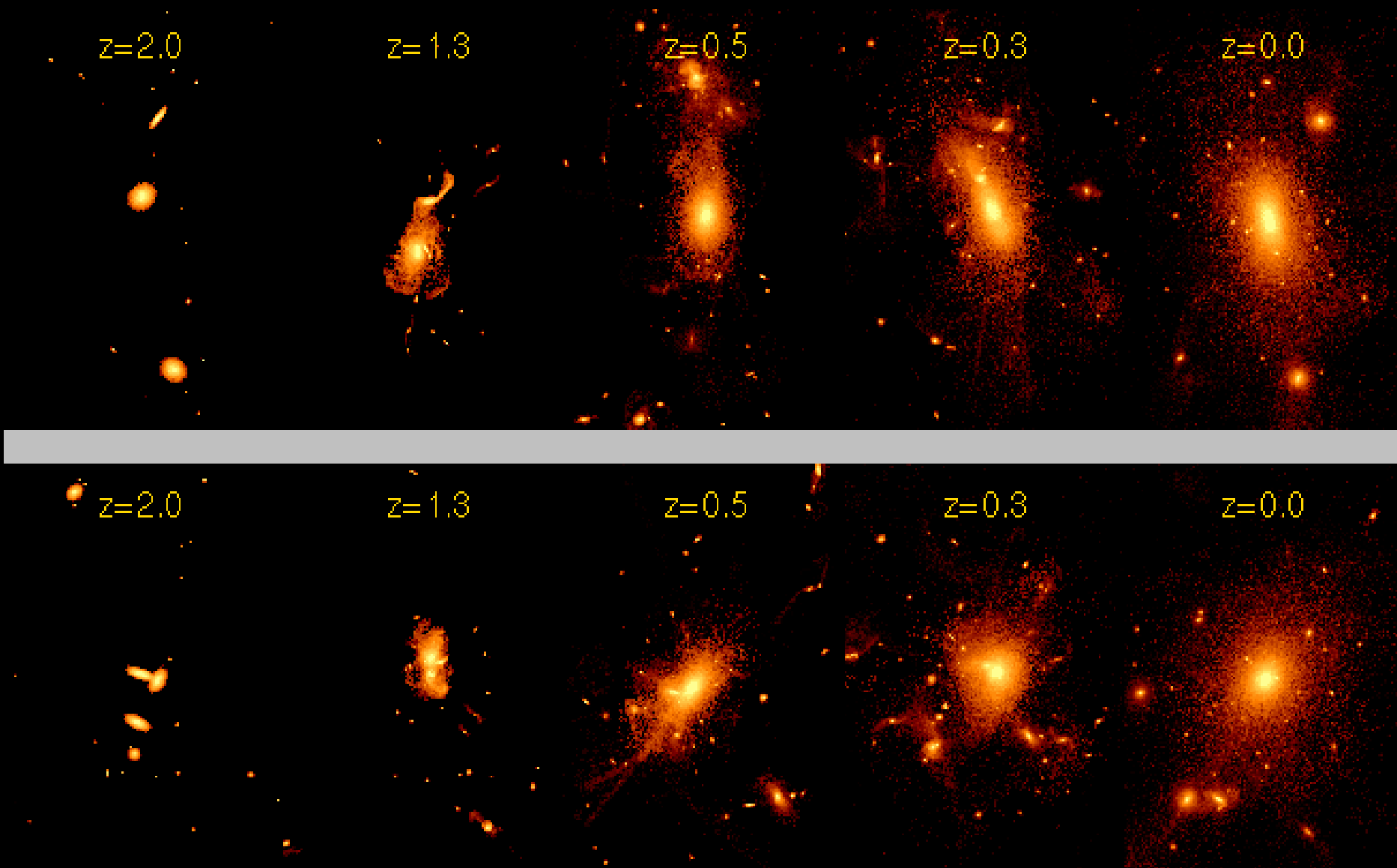
Twisted Isophotes!

- By creating oblate objects and prolate objects in a computer and “observing” them projected as they would be on the sky, astronomers determined that ...
- Oblate and Prolate objects both do NOT show Twisted Isophotes
- Triaxial objects did! Ergo – ellipticals were triaxial in general
- Remember this: **Elliptical galaxies are triaxial ellipsoids**

If they aren't rotationally flattened oblate spheroids, what process made them?

- When computers got big and fast enough to do realistic numerical simulations of their evolution, we found that ...
- Galaxy Collisions make a mess (an irregular galaxy), which settles down to become a triaxial ellipsoid (an elliptical galaxy) as the star orbits randomize by feeling their mutual gravity
- Galaxy collisions are not uncommon. Galaxies in a group or cluster may be only a few dozen galaxy diameters apart (vs. 10 million star diameters apart for stars in a given galaxy, so which ~never collide)

Simulation Galaxy Collisions In Rich Clusters Producing a Single Giant Elliptical Galaxy



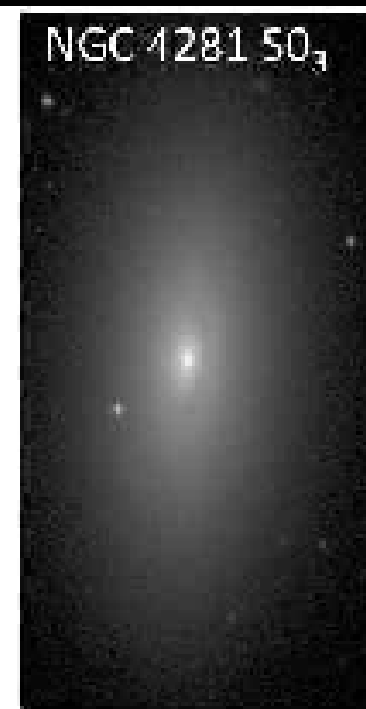
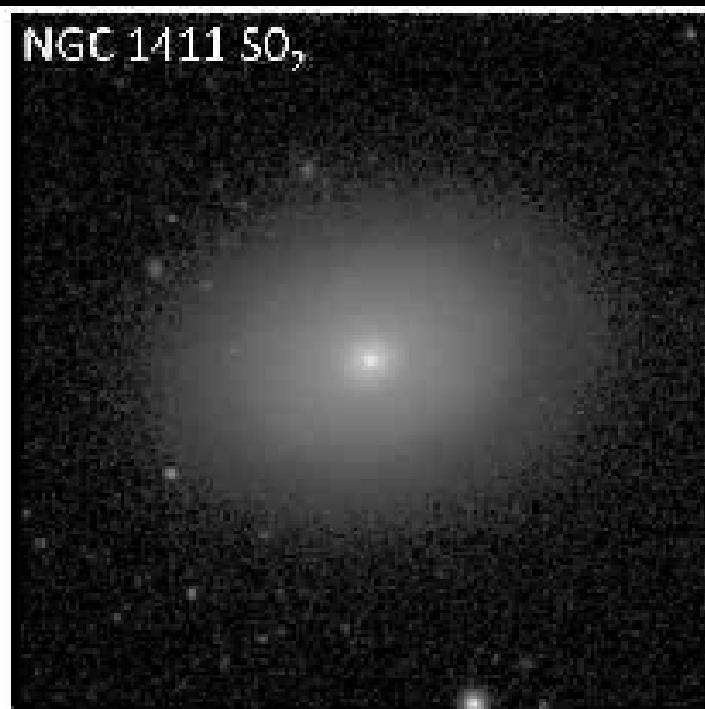
A Compact Group which will become an irregular galaxy, and eventually a single large elliptical



Stephan's Quintet: Classic compact group. Mergers underway. in a few hundred million years will be a single Irregular galaxy, and a billion years later, an elliptical.



S0 galaxies: How did THEY form?



A Spiral, moving through the intergalactic medium inside a rich cluster...

- ...has its own gas stripped out by ram pressure
- A good analogy; smoke inside a convertible rolling down the freeway, after you drop the top. Ram pressure blows the smoke right out of the car

**With No Gas, Star Formation Shuts Off, and the Spiral Arms
Soon Fade, Lit Up as they are by Massive Stars which die
young. The Rest of the Disk will Fade as well**



**How would you look for
evidence, beyond this
sensible theory, that this is
in fact true?**

- Think about it....
- Then I'll tell you.

The Galaxy Type – Density Relations

- We would therefore expect that **irregular galaxies would be more common when the universe was younger** and denser – and this is indeed what we see
- We would also expect **elliptical galaxies to be more common in rich galaxy clusters**, since such tri-axial structures should form by collisions. And this too is what we see in real data.
- And, we'd expect **S0 galaxies to be more common in rich clusters as well** – and this is also what we see.

How a Galaxy's Color Evolves

- When a galaxy has a lot of gas and dust, it has the raw materials for lots of star formation. When stars form, the most massive ones have FAR more luminosity and dominate the total light of the galaxy or at least the area.
- And massive stars are HOT and therefore BLUE
- So, gas-rich galaxies are blue, especially the disk, where most star formation happens

When the Gas Supply Runs Low

- Star formation shuts down, and since the massive stars die young, the galaxy's stellar population ages.
- **Older** stellar populations are **Redder**, because the young hot blue stars are gone, leaving red giants and low mass main sequence stars to dominate the light

Galaxy Collisions Lead to...

- Very blue Irregulars, as they use up their gas/dust quickly in “star formation bursts” (or “star bursts”)
- These settle down to become ellipticals, which have almost no gas or dust left (it’s either turned into stars, or blown away in the star bursts), and therefore no young blue stars, and their older stellar population means they are redder.

The Active Galaxies Story...

- In 1940's Carl Seyfert identified a class of spiral galaxies – with bright star-like cores.
- In 1960's with the first radio telescopes, these also often showed strong radio emission
- Now called “Seyfert Galaxies”
- Similar elliptical's with bright star-like cores were called “BL Lac” objects

A bright, nearby Seyfert Galaxy

Galaxy NGC 7742





Quasi-Stellar Radio Sources

- In 1960's, we found “stars” with strong radio emission
- Spectra contained few lines, and the lines couldn't be identified
- Spectra showed both absorption and emission lines. But stars rarely have emission lines
- They looks like stars, so we assumed initially that they WERE stars, and therefore in our own Galaxy, and did not have large Doppler shifts, so that the lines should be easy to identify with known transitions in known chemical elements
- Hmmm. Bizarre!

How far away were these things?

- Spectral lines eventually identified, and all QSO's showed strong redshifts; like 30%-90% of the speed of light!
- What could that mean?!
- We have to look at the distance ladder and introduce our first bit of cosmology to consider this...

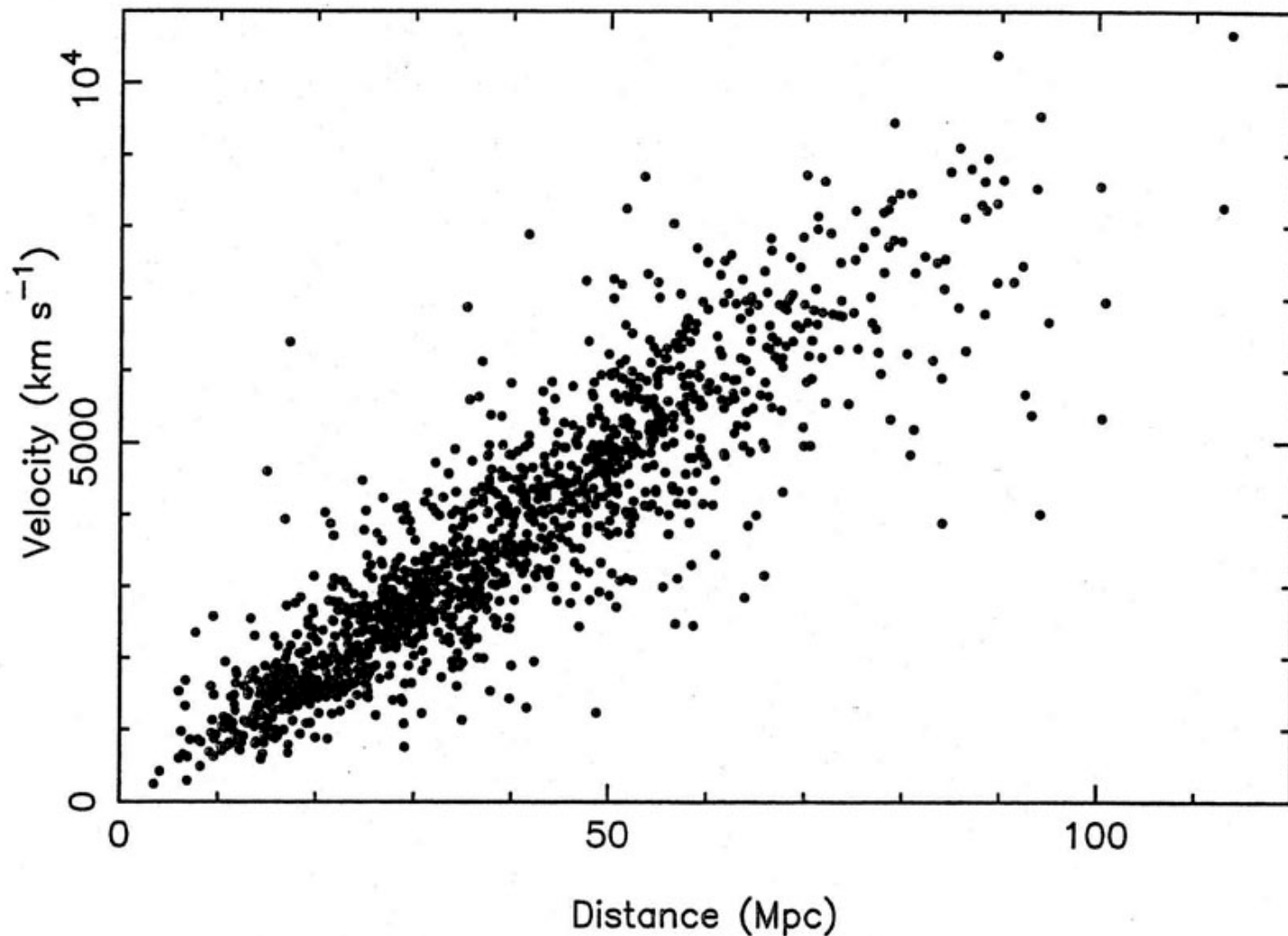


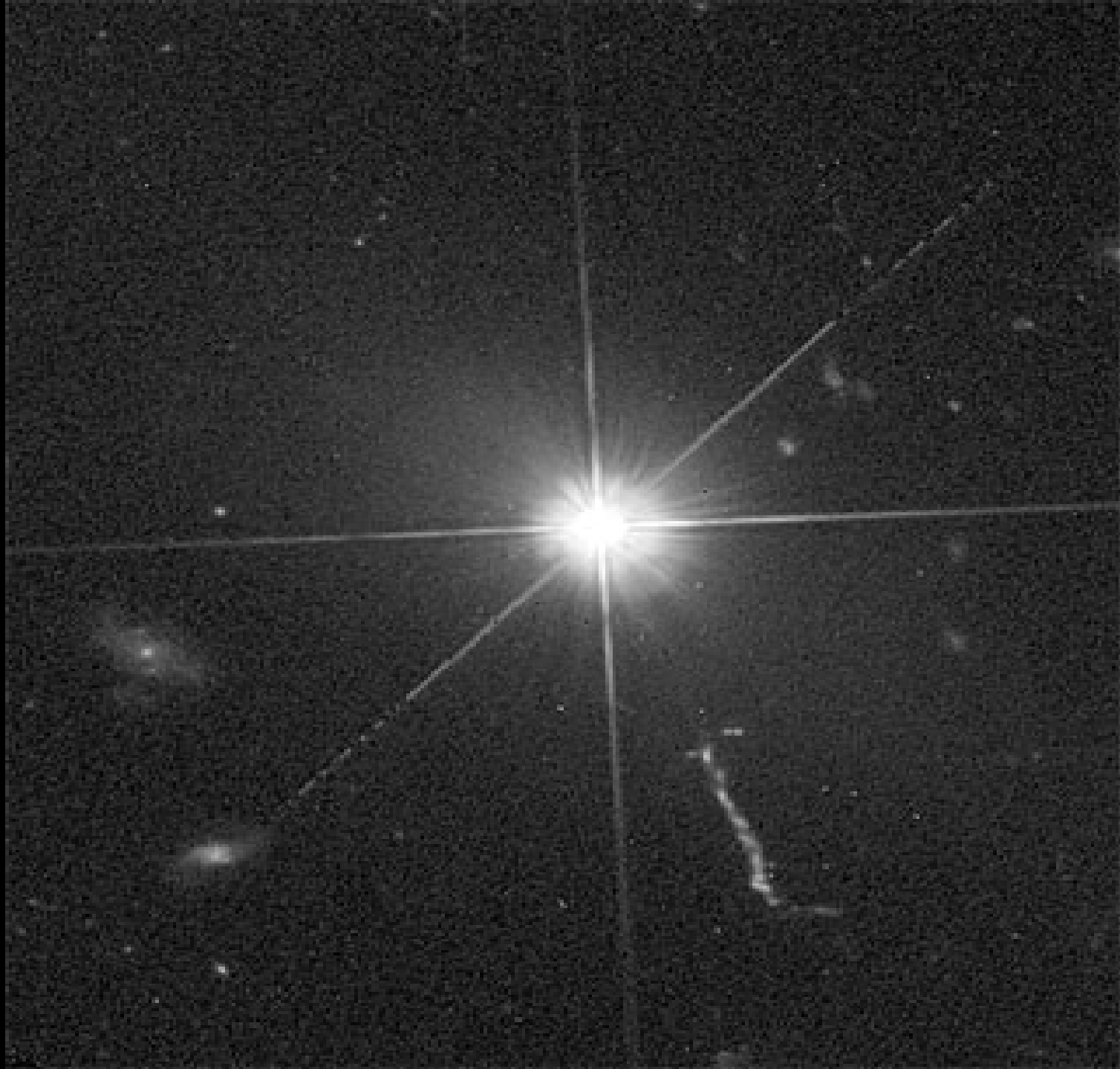
Figure 2.5 A plot of velocity versus estimated distance for a set of 1355 galaxies. A straight-line relation implies Hubble's law. The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law. [The x -axis scale assumes a particular value of H_0 .]

Hubble Discovered the Universe is Expanding

- Velocity V of a galaxy away from us was seen to be proportional to its distance D from us
- $V=HD$ **Hubble's Law**
- H = Hubble parameter; it's the slope of the line in the graph on the blackboard
- H = one of the Holy Grail's of astronomy! It's now been measured accurately. It's $H = 70$ km/sec for every additional megaparsec further out you look
- **Now we have our final rung in the Distance Ladder: Solve for D and get $D=V/H$**

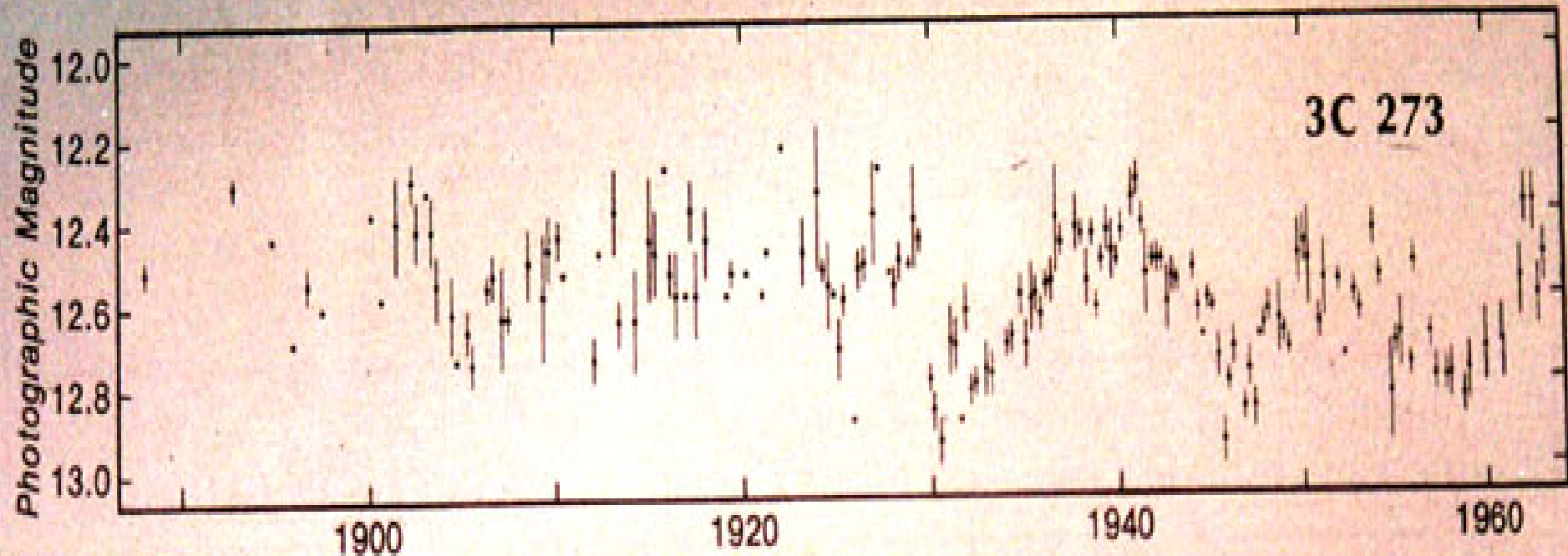
Use this on QSO's and get...

- They're BILLIONS of light years away!
- Yeah, they're faint, but at that distance their luminosity still turns out to be pretty big. Like up to 1000 times the luminosity of our Milky Way Galaxy!
- Yow!!! But the story gets even more bizarre...



70 years of old photos showed this quasar varied in brightness

Below: This light curve, prepared by H. Smith and D. Hoffleit in 1963, revealed for the first time optical variability of an object akin in size to the nucleus of a galaxy.



June, 1980, SKY AND TELESCOPE 503

Careful brightness measurements night after night showed these things could vary by a lot in as little as One Day!

- So, therefore.... What's the maximum size that the light emitting region could possibly be? Remember the physics we've learned.

1 Light-day!!!!

- 1 light day! Yikes! That's only the size of the solar system. How can you possibly get 1000 galaxies worth of luminosity out of something only as big as our solar system?
- Only one mechanism can do it – a massive black hole with an accretion disk of infalling matter being heated to millions of degrees and giving off a ton of radiation at all wavelengths.

~10-100 million solar masses is the sweet spot for getting the maximum amount of radiated escaping light.

- Bigger than this, and some of the bright disk is inside the Event Horizon and doesn't escape.
- Much smaller, and the gravity-power necessary to heat the disk starts to affect the luminosity

The closest we have to a Quasar Nearby, is M87

- M87 is the central dominant (cD) “cannibal” galaxy at the heart of the Virgo Cluster of galaxies
- A cD galaxy is a merger product of several galaxies in a rich cluster, and which sinks to the bottom of the gravitational field
- Infall into the centers of such a galaxy can be relatively large

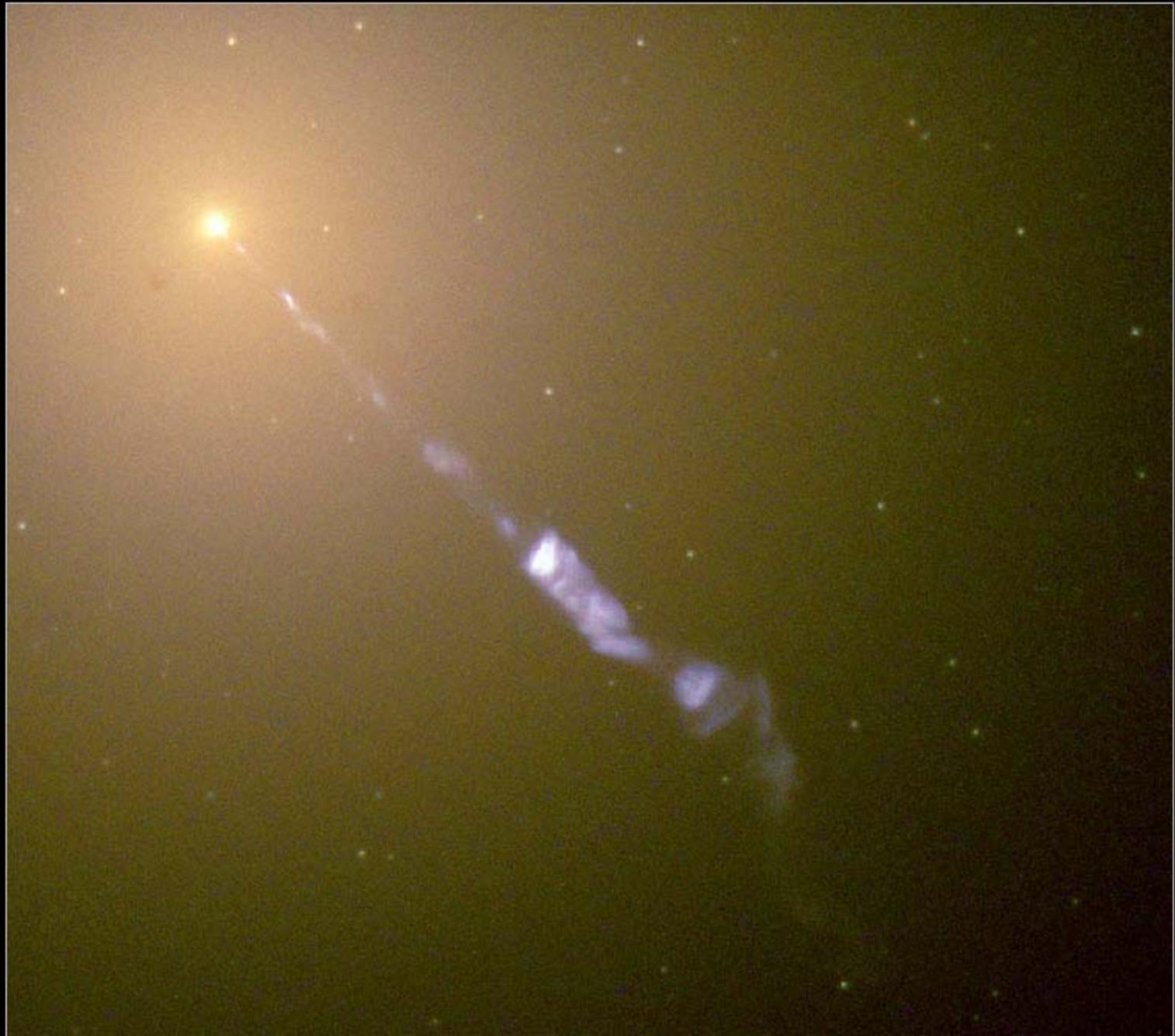
M87; “Cannibal Galaxy” core of the Virgo Cluster

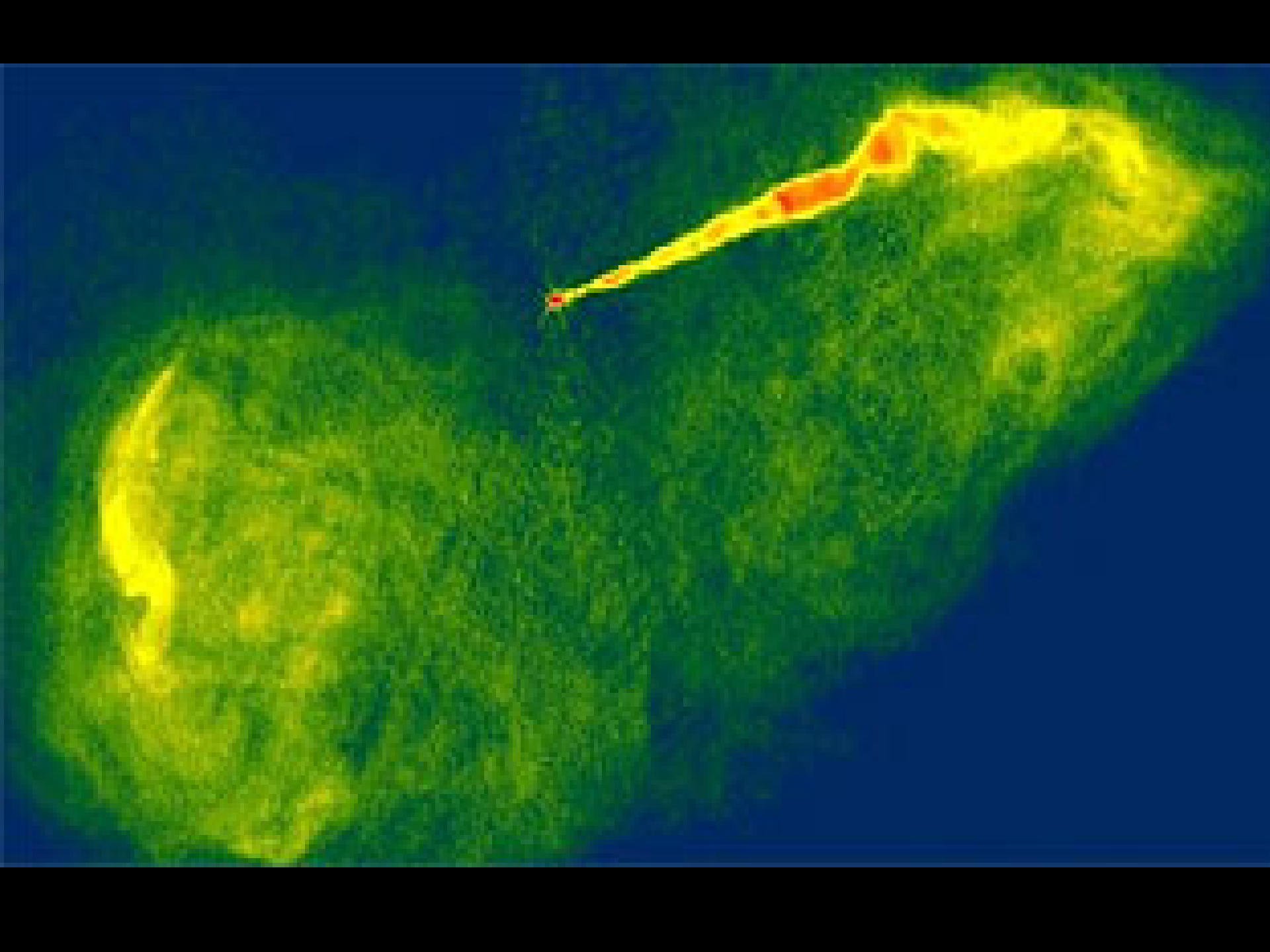


Jets from the Cores of These Active Galaxies

- Hot spinning accretion disks are ionized, and the spinning charges create a magnetic field, with poles perpendicular to the spinning disk
- Electrons captured by this field are flung outward along the magnetic axis, emitting radio waves as they spiral around the field lines
- Radio images (sometimes even optical images) will show this emission

The M87 Jet

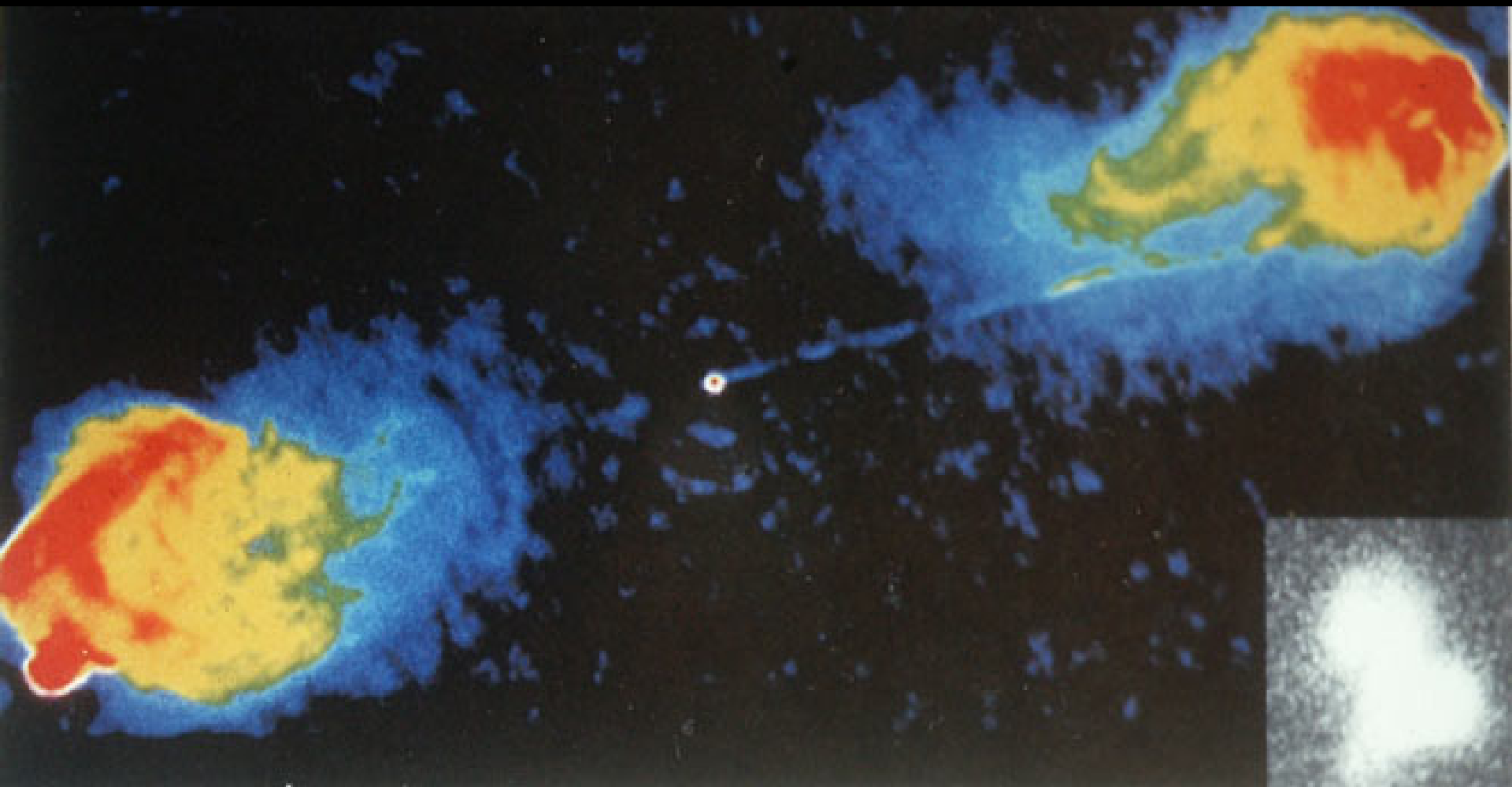


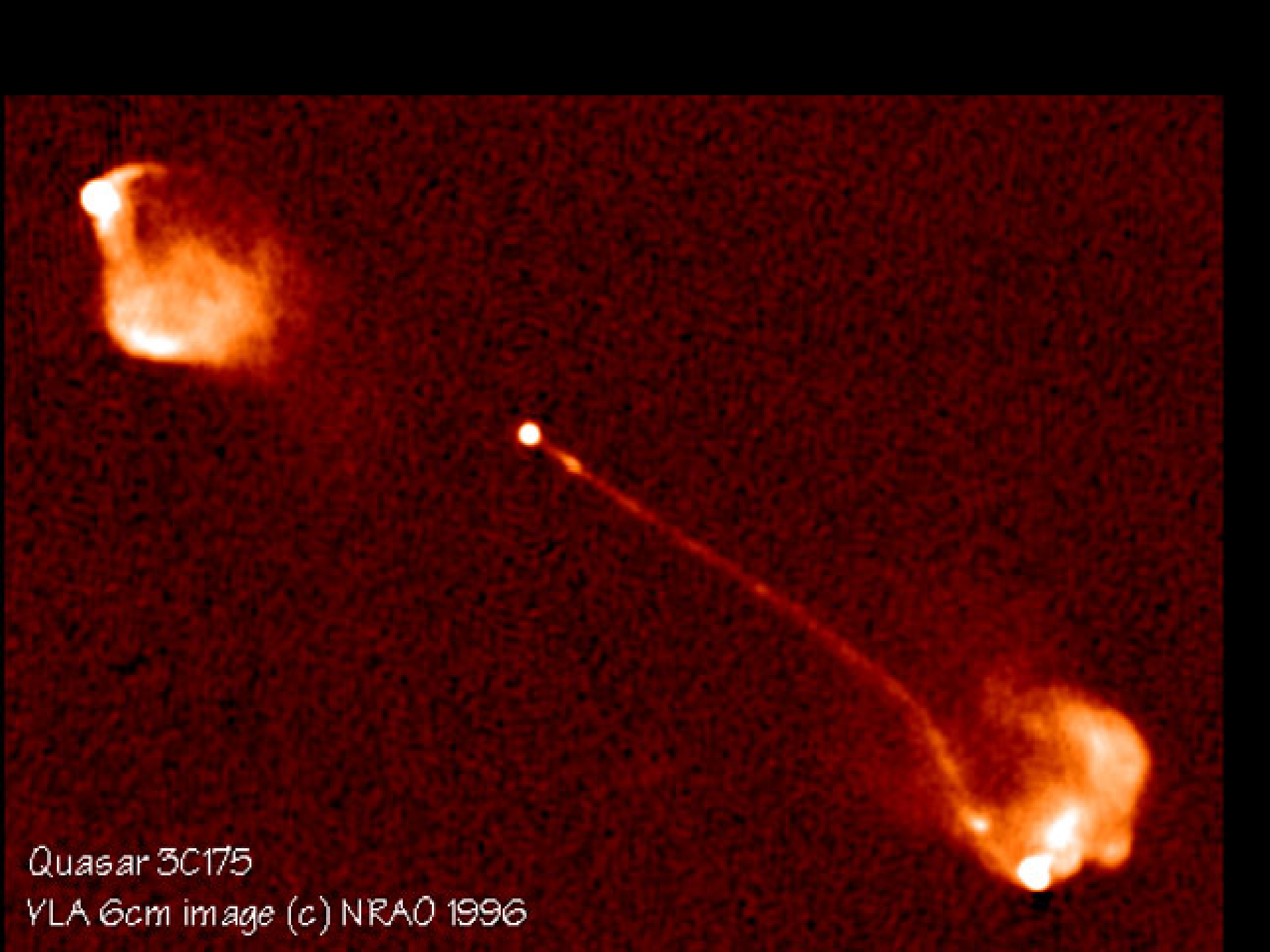


Radio Lobes (in Fornax A), caused by electron beams from the central supermassive black Hole at core of the galaxy



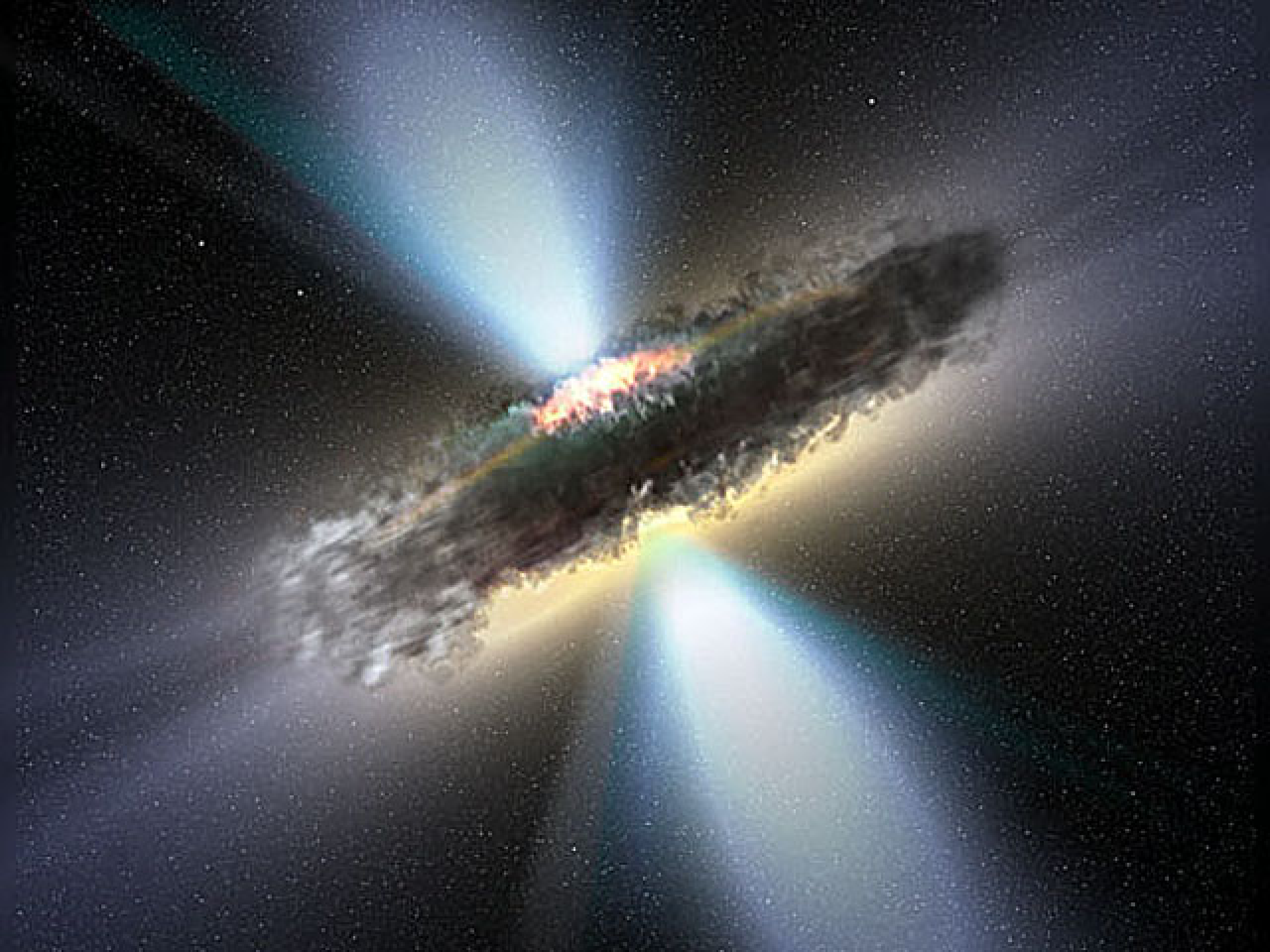


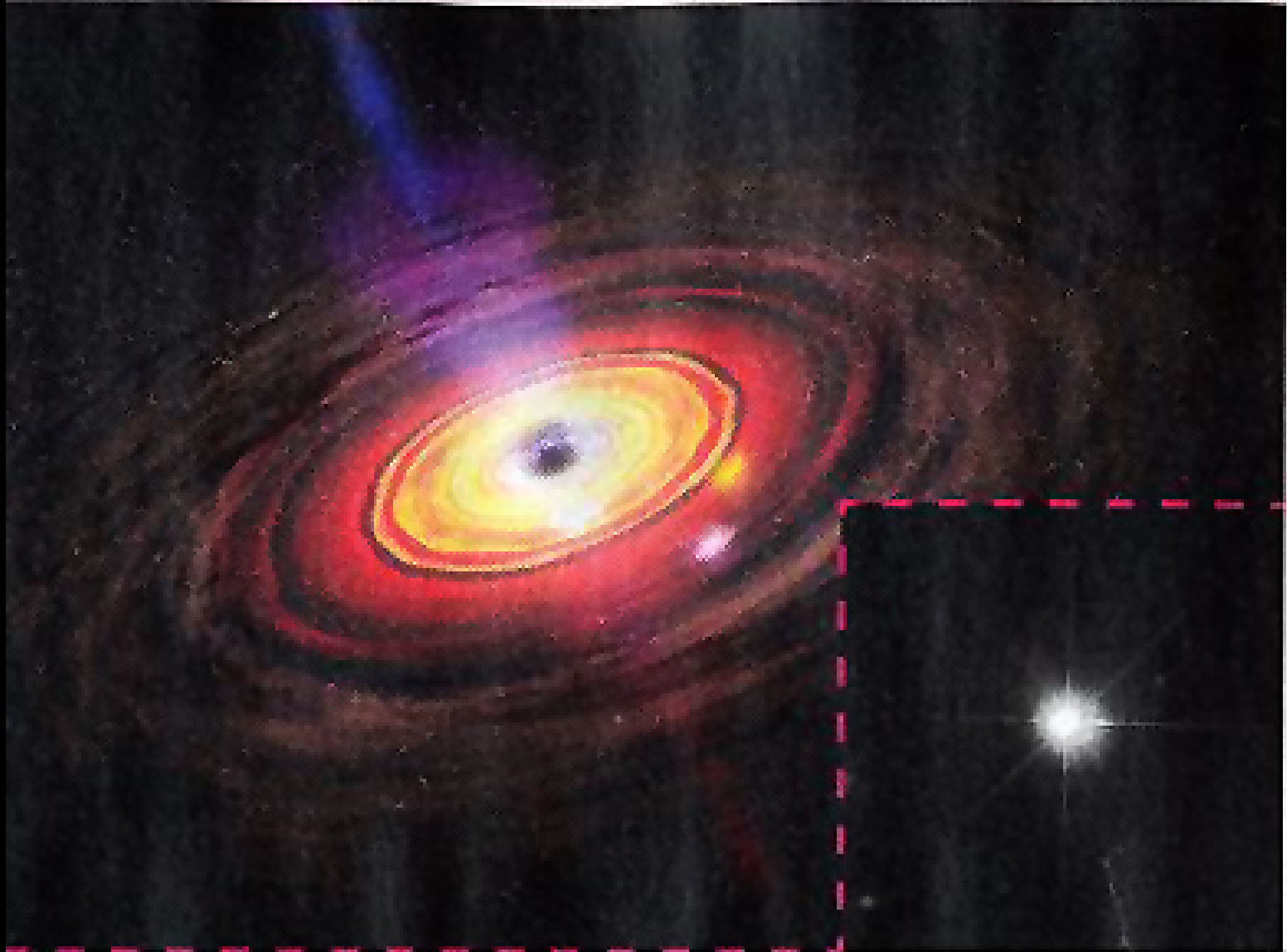




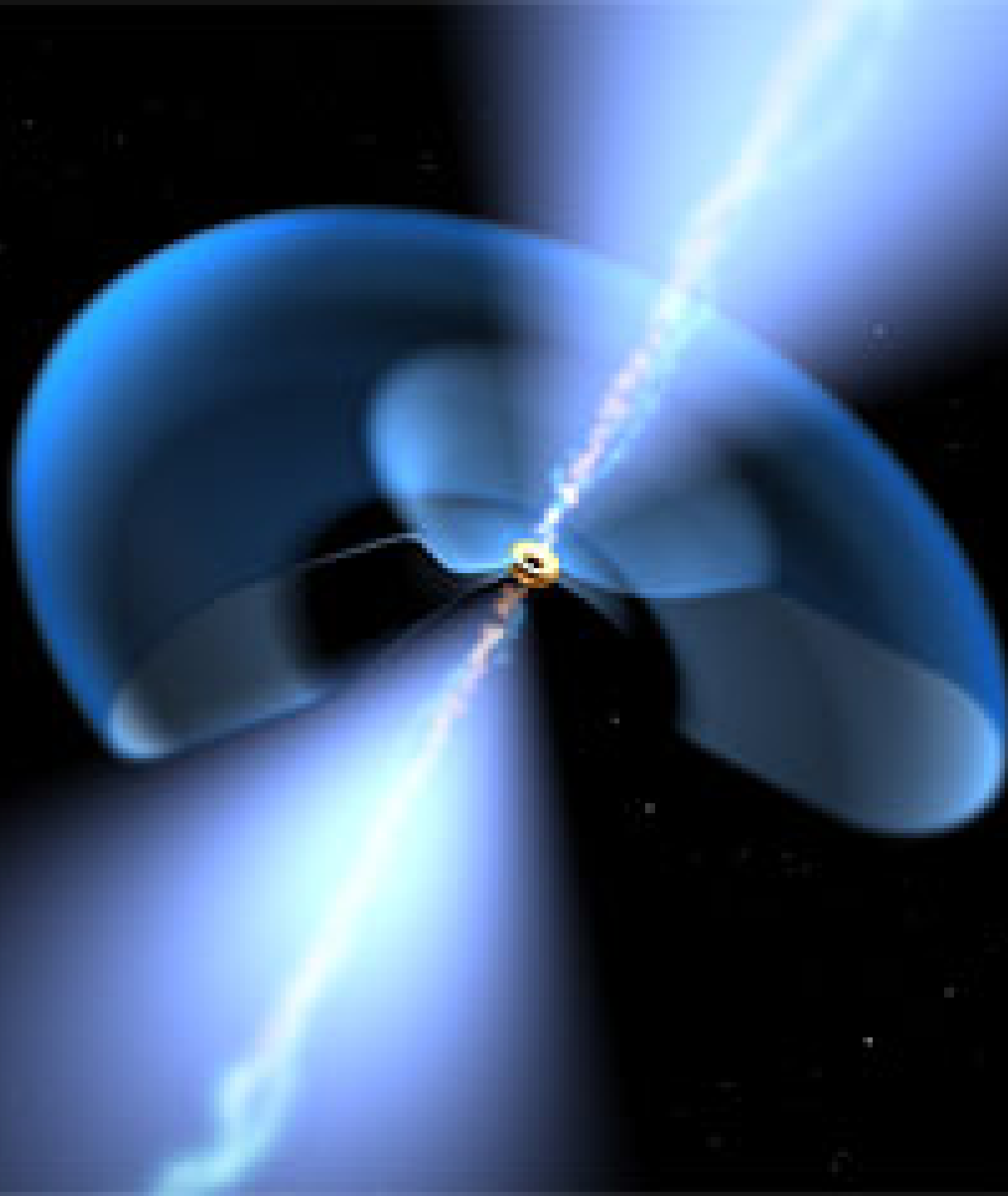
Quasar 3C175

YLA 6cm image (c) NRAO 1996

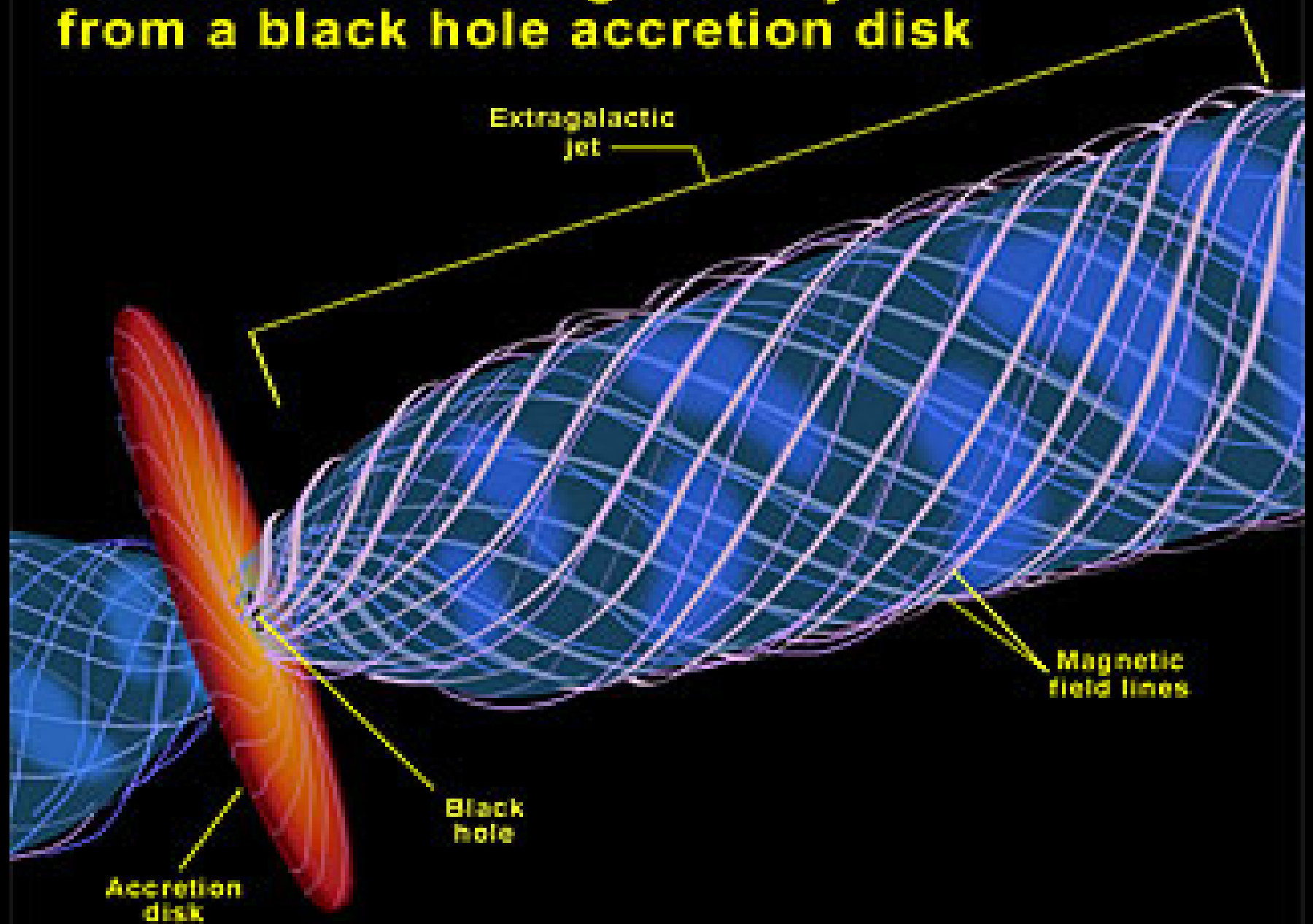




HIDDEN POWERHOUSE The supermassive black holes at the cores of galaxies whip up matter to the point that the resulting radiation spews out in powerful jets. If aimed right at Earth, we see it as a blazar (*inset*).



Formation of extragalactic jets from a black hole accretion disk



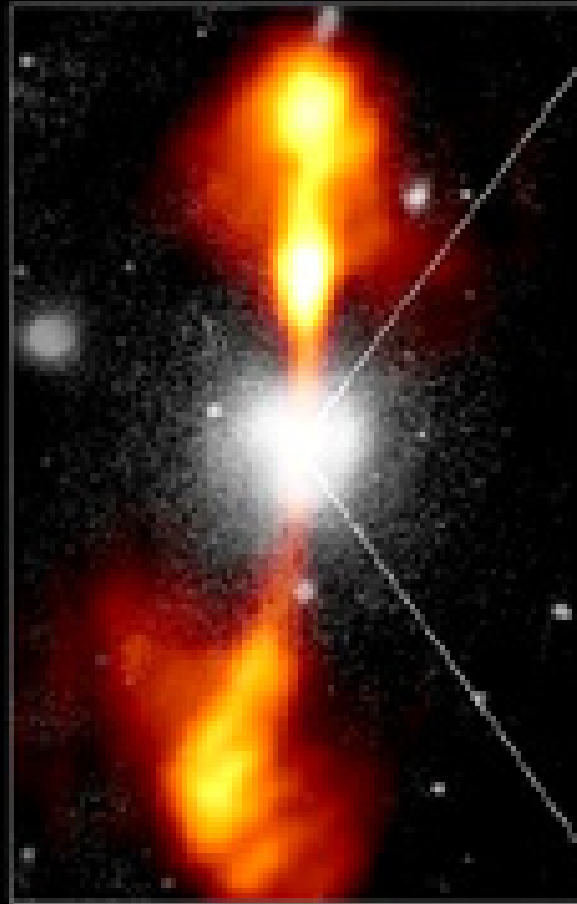


Core of Galaxy NGC 4261

Hubble Space Telescope

Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

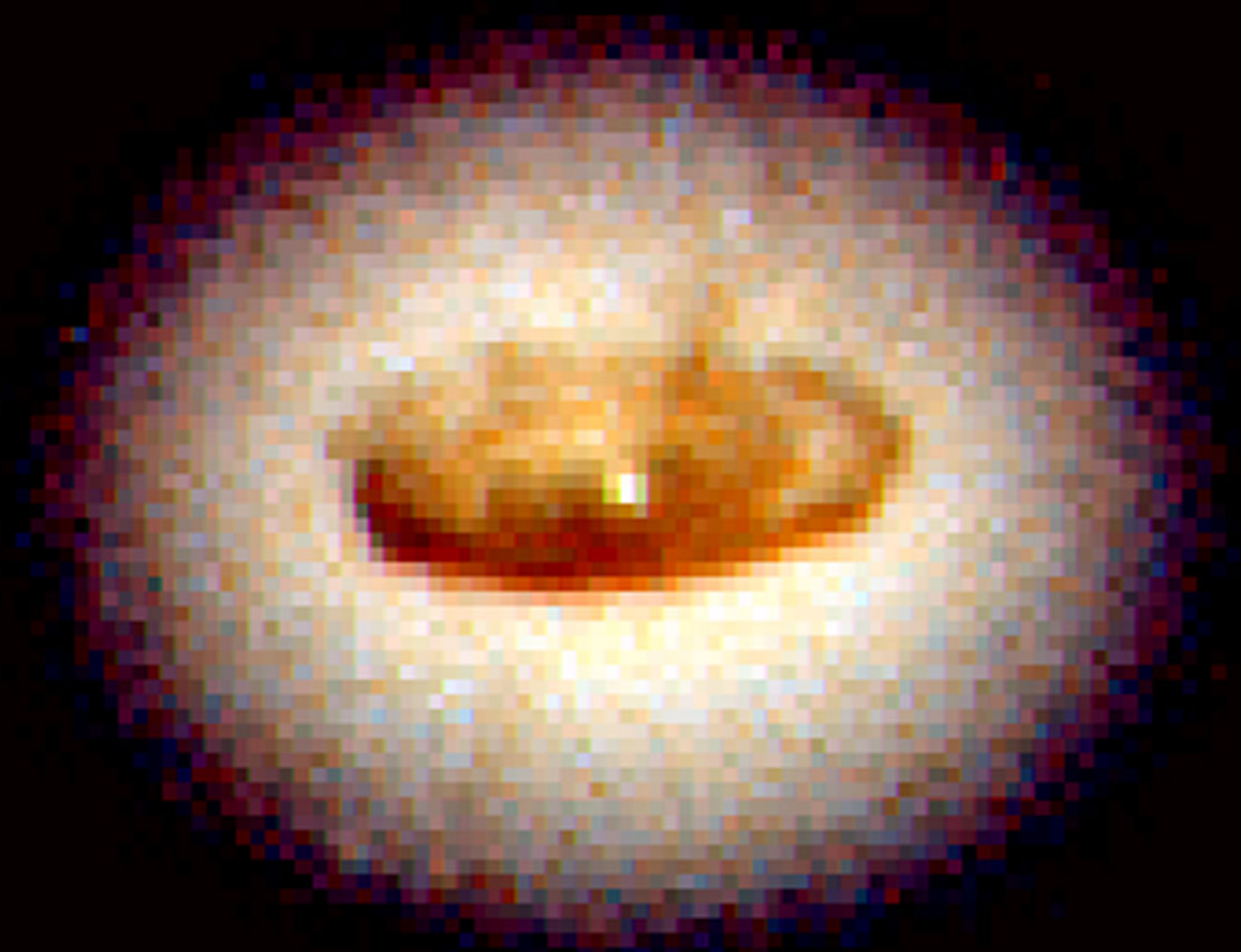


360 Arc Seconds
88,000 LIGHTYEARS

HST Image of a Gas and Dust Disk



17 Arc Seconds
400 LIGHTYEARS



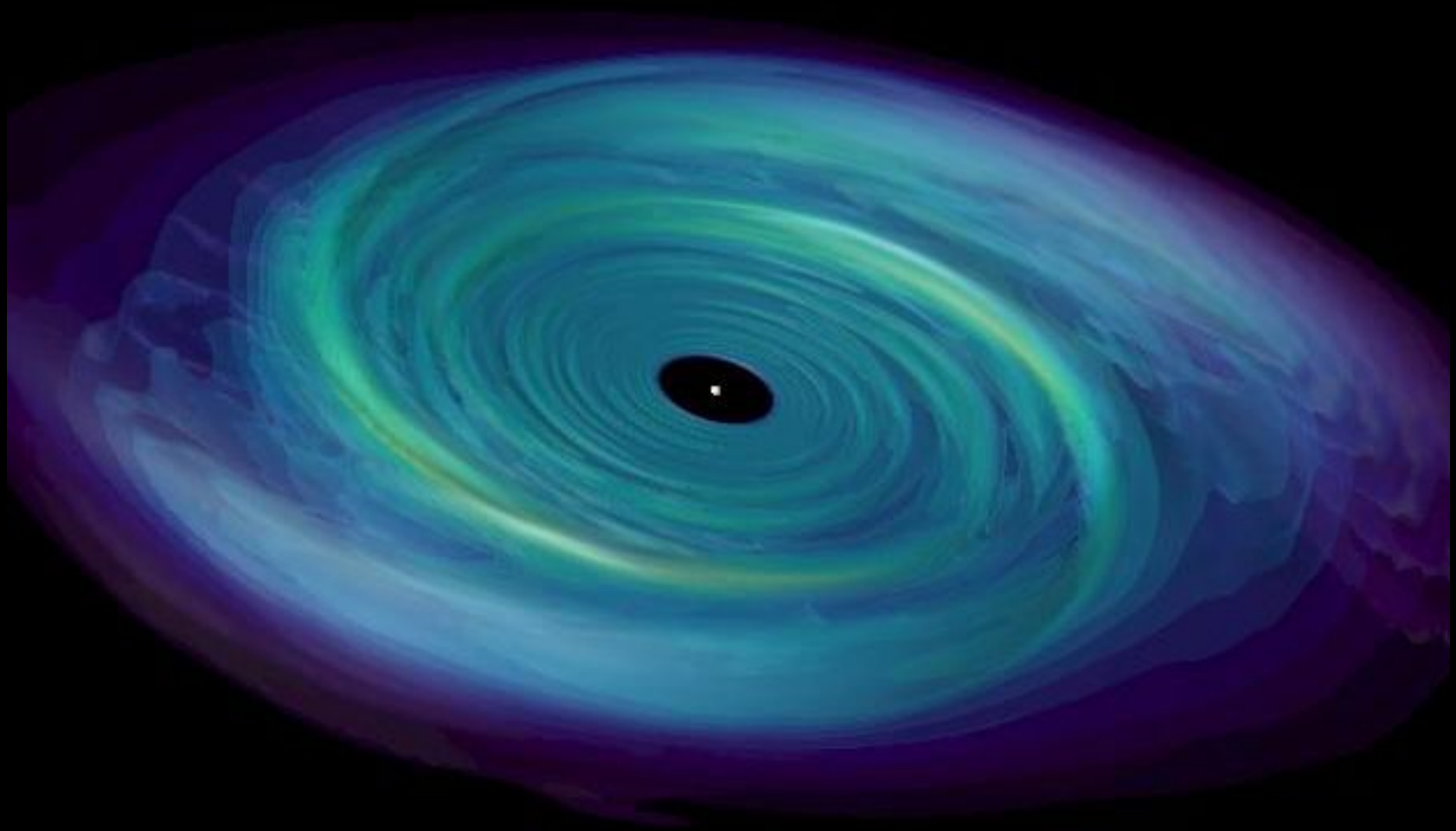
Active Galaxy NGC 1275

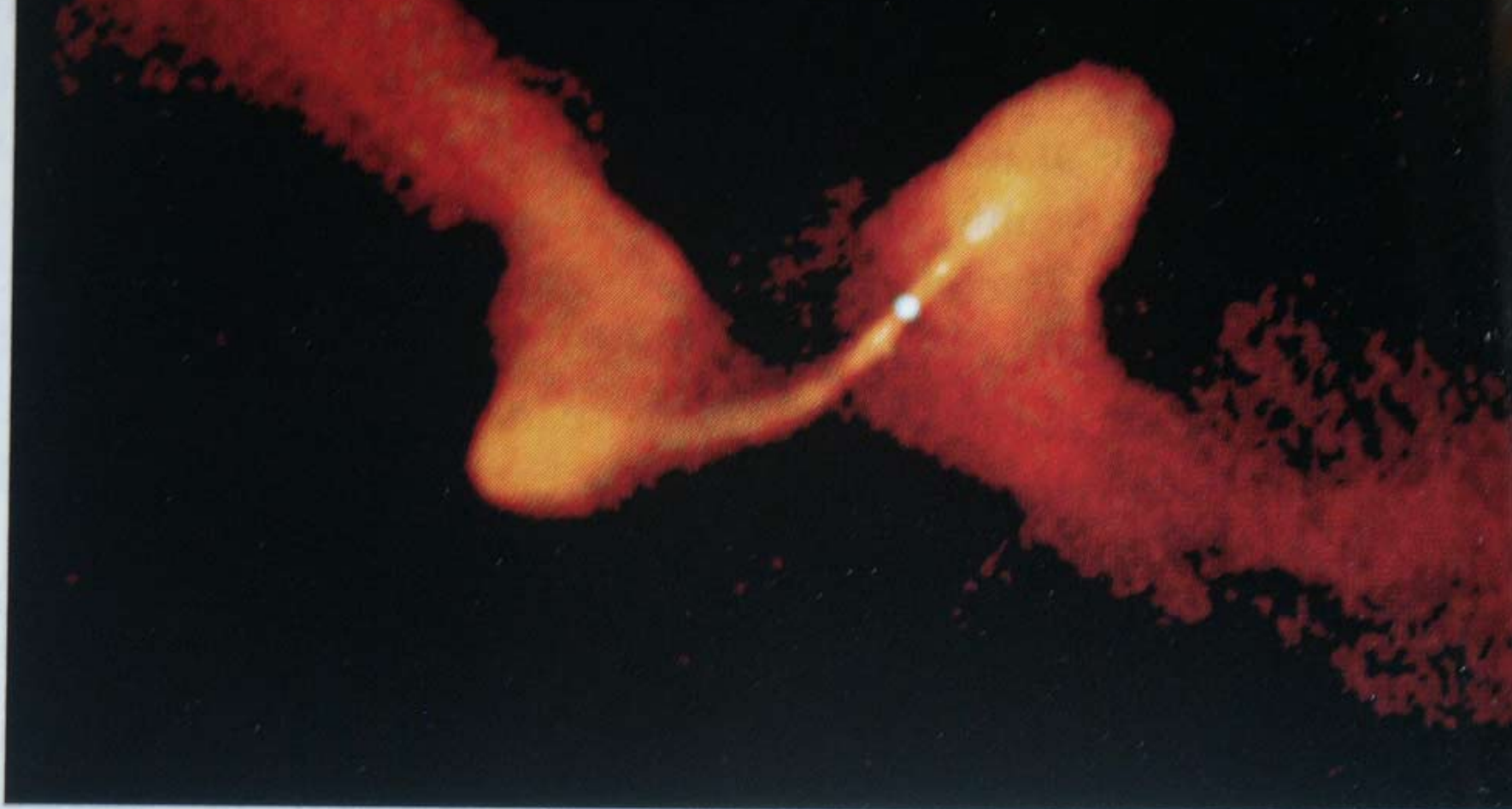












A sign that two supermassive black holes have melded into one? A new study notes that a jet-spewing black hole at the center of an active galaxy will abruptly tilt when joined by a second black hole. The kinked lobes of plasma in this 4-arcminute-wide radio image of NGC 326 in Pisces suggest just such an event.

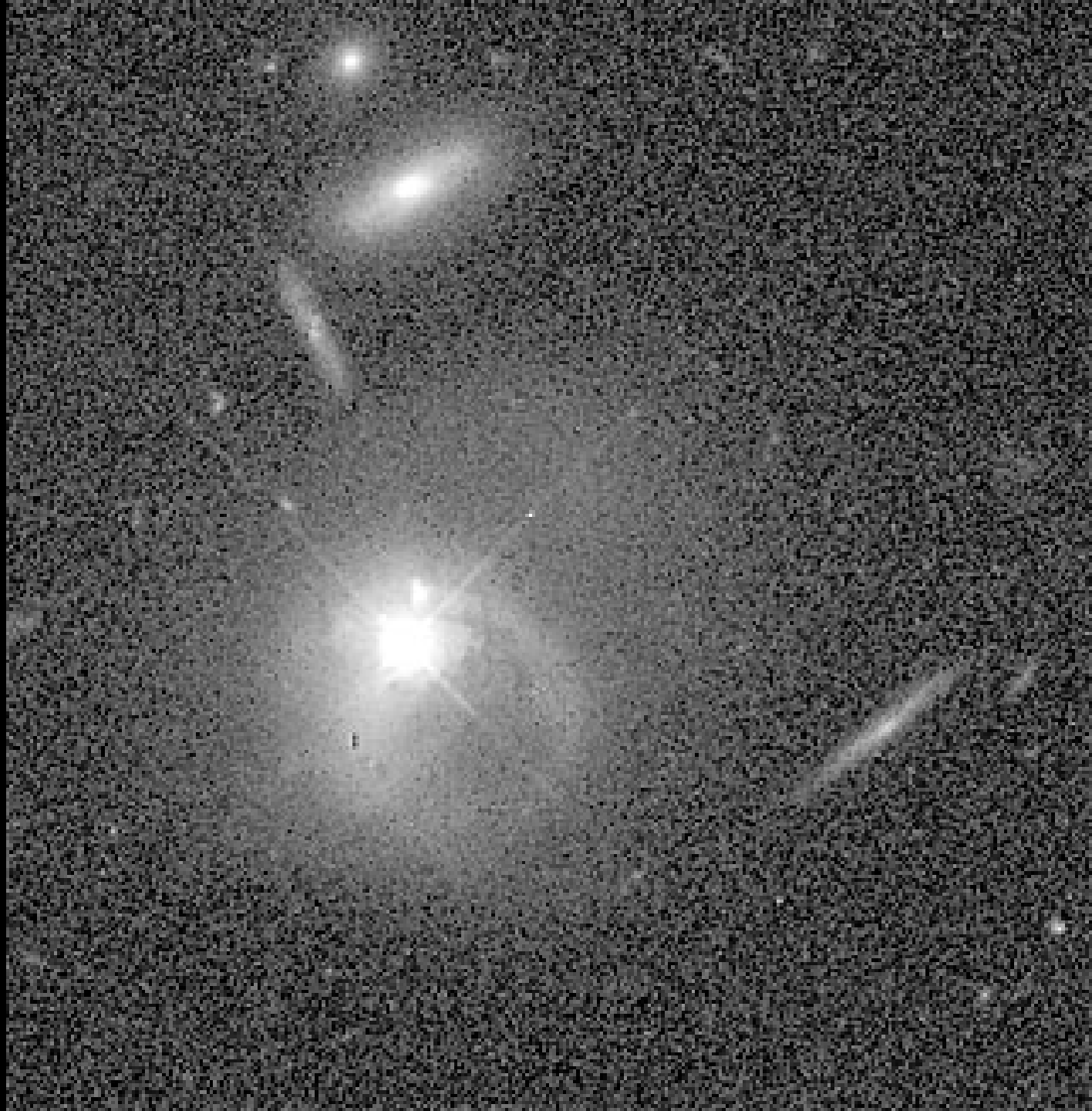


Quasar Host Galaxies

HST • WFPC2


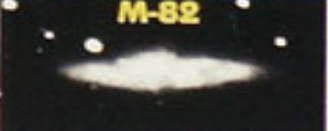



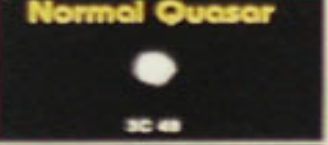

PRC96-35a • ST ScI OPO • November 19, 1996

J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA



The Active Galaxy Energy League

In this table we're making a comparison between the energy output of active galaxies at various wavelengths and that of a typical normal spiral at the same wavelengths. The figures don't reflect the relative importance of energy output in the different spectral regions. Normal spirals, for instance, give off vastly more energy at optical wavelengths than they do in the radio region. N-galaxies and quasars, on the other hand, are especially active in the infrared, and by comparison their optical emission is insignificant.

	Radio	Infrared	Optical	X-ray
Normal Spiral  <small>NGC-1090</small>	1	1	1	1
M-82 	6	70	?	?
M-87 	1,800	1.5	2.5	5,000
Radio Galaxy  <small>NGC-1275</small>	2,000 - 2,000,000	0.5 - 1.5	2.5	100 - 5,000
N-Galaxy/Seyfert  <small>NGC-4151</small>	20 - 2,000,000	10,000	1.5	300 - 70,000
Normal Quasar  <small>3C 48</small>	200,000 - 2,000,000	300 - 50,000	?	?
Very Bright Quasar  <small>3C 273</small>	6,000,000	300,000	250	2,500,000

So here is the active galaxy evolutionary story...

- In the early universe, gravity pulls together a galaxy, and a certain small fraction falls straight to the center and becomes a massive black hole
- The infall of matter early on can be large, enough to power an accretion disk at a rate of ~ 1 star per year – enough to make a Quasar, which is so bright it outshines the galaxy it is in

The Active Galaxy Evolutionary Process

- **Supermassive Black Holes** are born as a natural by-product of galaxy formation. About 1/10,000 of the total mass ends up in the center as a black hole. A million solar masses or more!
- Mass infall is high when galaxy is young, so bright accretion disk can overwhelm the light from the rest of the galaxy and a **Quasar** may even result. Up to 1 solar mass/year infall.
- Later, as the galaxy ages, the stuff that CAN fall in, pretty much HAS fallen in, and fueling rate drops. The core fades and instead of looking like a quasar it looks like a **Seyfert** or similar type active galaxy. Maybe 1/1000 of a solar mass per year typical. You can still see radio jets and lobes, and a starlike core
- Finally, when fueling fades to only a ~millionth of a solar mass per year, it just looks like a **normal galaxy**. Like ours! And we still have the black hole in our core.
- Waiting... lurking.... Hungry...

Today, Galaxy Collisions can Re-populate those straight-in orbits and re-fuel the black hole (but not up to full-on quasar strength)

- Collisions are most common in **OLD** galaxy clusters that are *rich* in galaxies. Lots of opportunities for collisions.
- Mergers will move slower, sink to the center of the cluster. If they're big enough to identify as having eaten several galaxies, we call them "central dominant" or "**cannibal galaxies**" ...

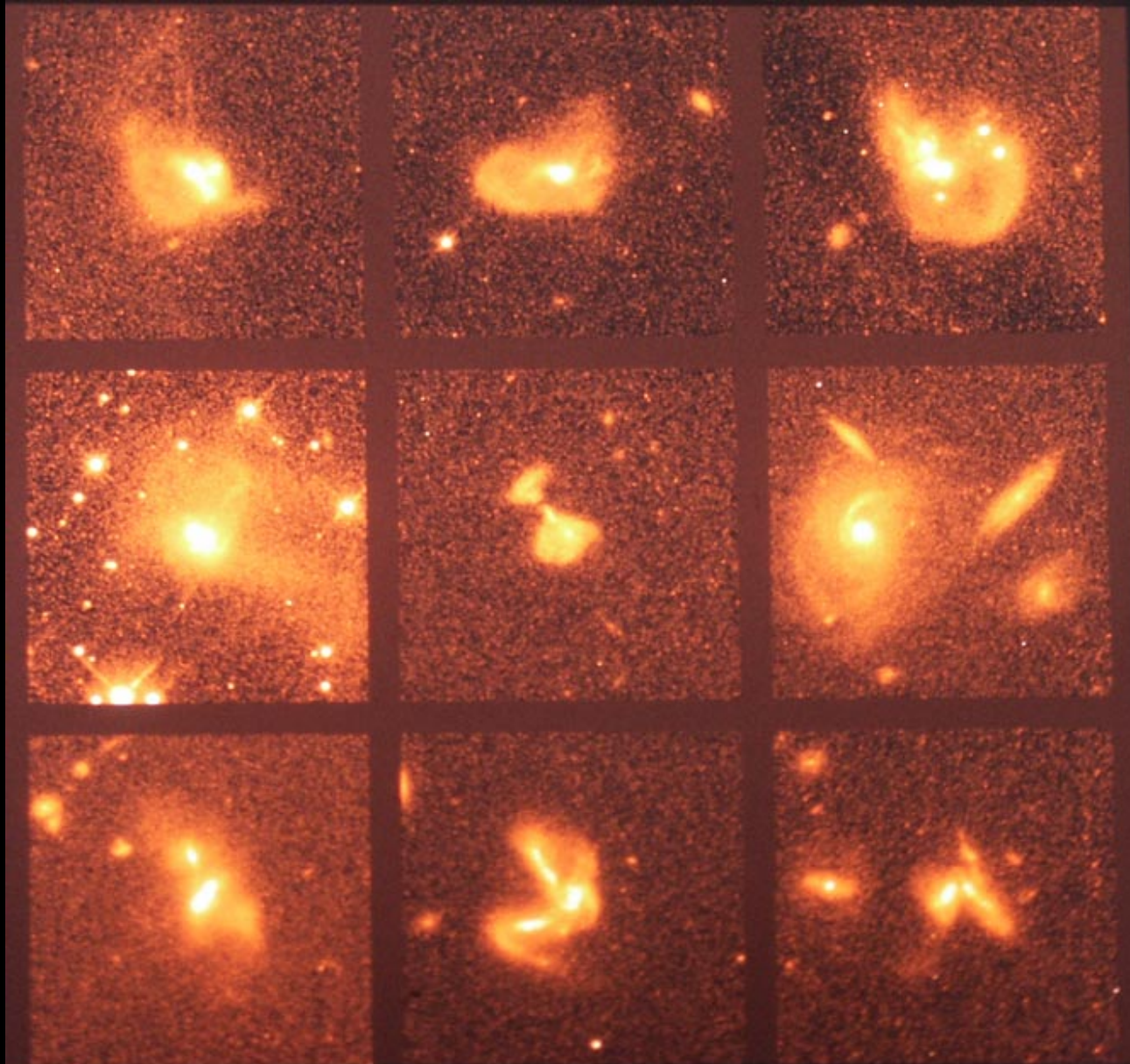




Galaxy Formation Summary

- Galaxies form from collisions of proto-galactic clumps in the first billion years or so after the Big Bang
- Many have later infalling matter which has been pulled on by nearby other proto-galaxies and thus doesn't fall straight in. It settles itself into a flat, roughly circularly orbiting plane of material
- This material gradually condenses enough to initiate star formation. Then supernovae and spiral density waves can further initiate on-going star formation, continuing right up to today.
- Major collisions convert galaxies of any type into **Elliptical Galaxies**, with an intermediate period of being **Irregular Galaxies**.

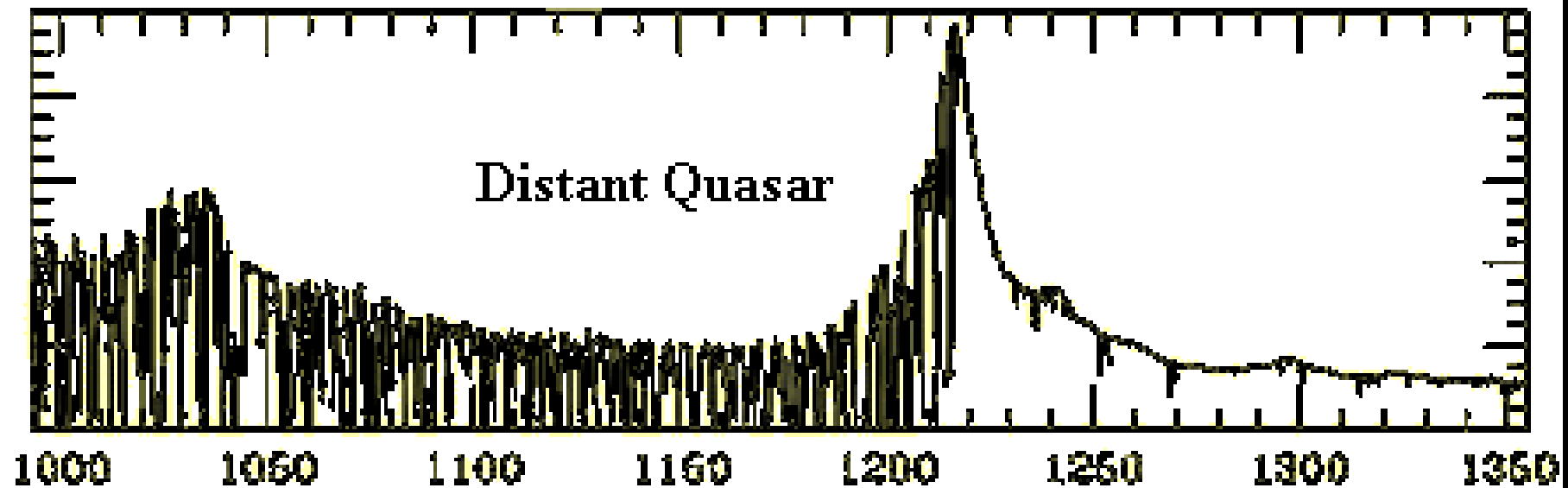
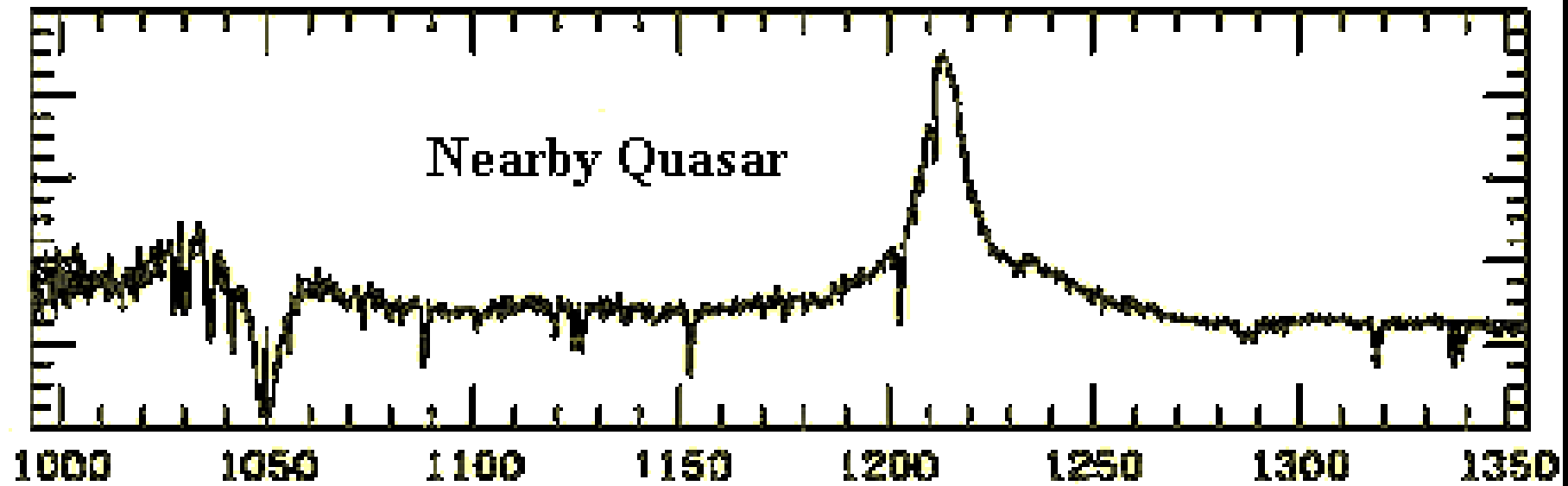
Distant galaxies, seen when the universe was only a few billion years old, and galaxy collisions, and hence irregular galaxies, were more common



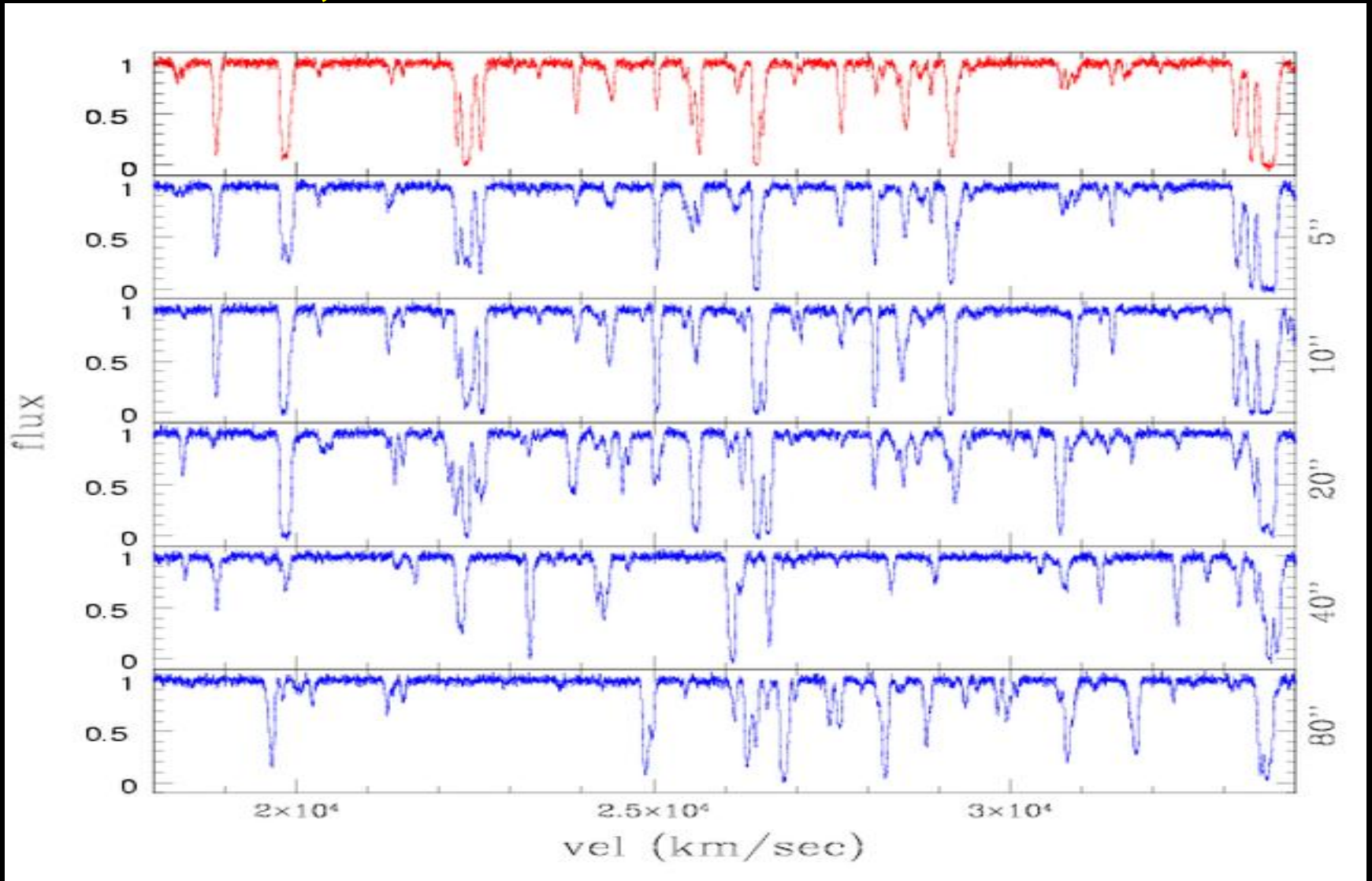
These collisions likely produced the present-day central bulges and early beginnings of the disks of modern spirals

- Disks formed from later infall of further out gas which felt the gravity of competing new galaxies and hence fell in with some angular momentum
- The resulting material formed a disk as gas dissipates its vertical motion by compressing against other gas, heating, radiating away the energy and settling into a thinner disk

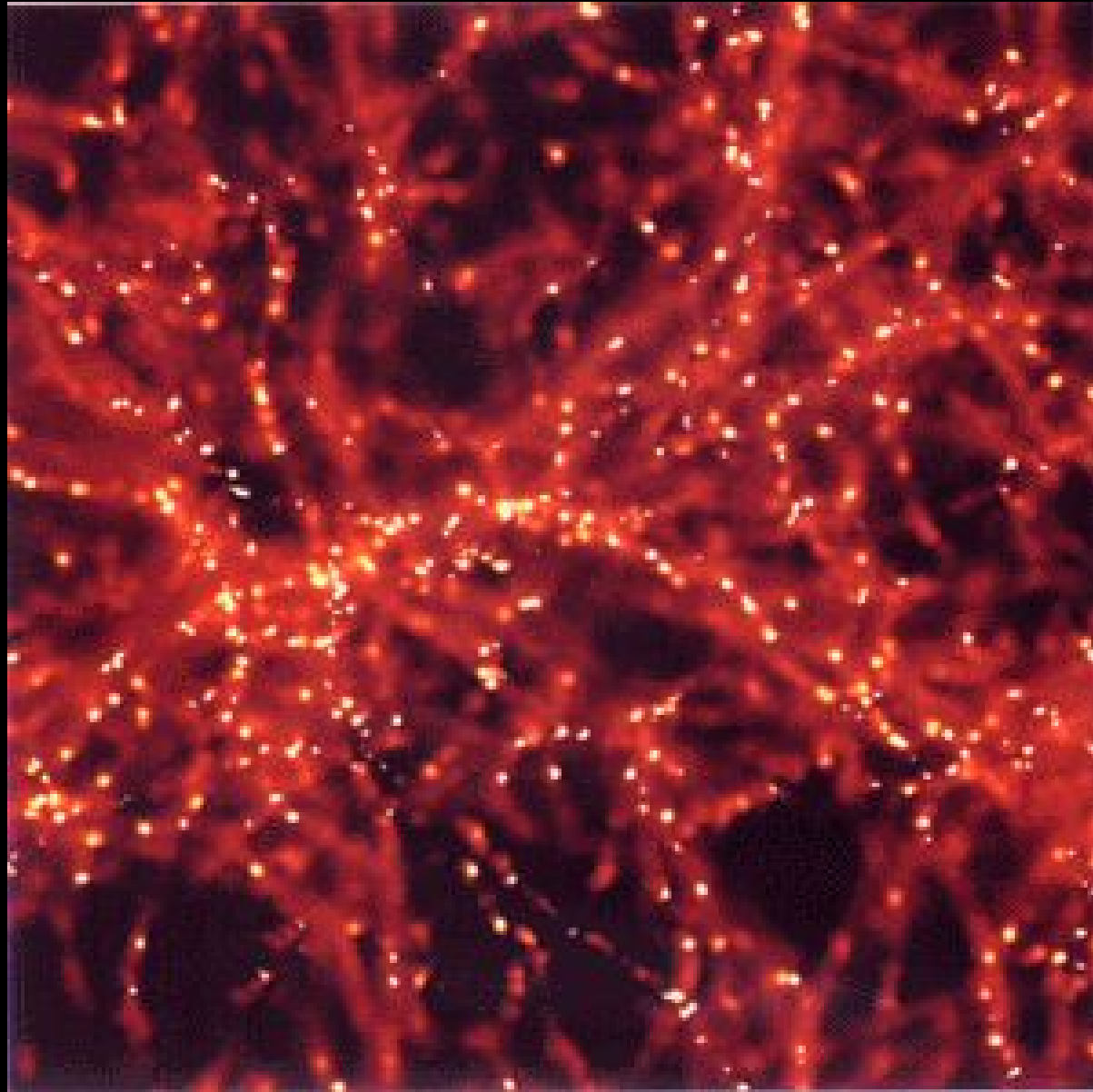
The Lyman Alpha Forest



Lyman Alpha Lines: Clustering tells how cold hydrogen is clustering in the universe, and comparing to later galaxy clusters tells us the clustering history of matter in our Universe, and constrains the nature of Dark Matter



Filamentary clustering of hydrogen in a numerical simulation. Looking through these intermediate distance filaments to distant quasars, produces the Lyman Alpha Forest, because nearer filaments are less red-shifted



Key Points: Chapter 20-21: Galaxies and Active Galaxies

- Galaxies formed by gravitational infall of proto-galactic clumps which were already forming stars by the time they came together, forming spheroid, and bulge
- Disk formed from later infalling gas of higher angular momentum, which dissipates against itself to settle into a thin disk
- A Galaxy's color evolves from bluer, towards redder as stellar population ages, young blue stars die out
- Galaxy collisions common because they're usually only 100 or fewer galaxy diameters apart
- Collisions between galaxies produce irregulars which settle into ellipticals
- More **massive ellipticals have broader spectral lines** – this is how we measure their mass
- SO's formed in clusters of galaxies, by ram pressure stripping their gas out, shutting off later star formation
- Active galaxies: all galaxies have millions to billions of solar masses sized black holes in their core.
- Accretion rate onto the black hole drops with time, causing Quasar to become a Seyfert (spiral) or BL Lac (E) galaxy, later to be a normal galaxy as accretion rate approaches zero
- Quasars all show huge redshifts and rapid luminosity changes, showing they are very distant, very luminous, very tiny, and a phenomenon of the early universe, not today's universe.
- Most galaxies are dwarfs, but most LUMINOUS galaxies are spirals (around 80%)
- E's and SO's more common in rich clusters, where collisions and gas medium are more common
- The "Lyman Alpha Forest" tells us about the clustering of cold hydrogen clouds which are settling down onto galaxies or forming into galaxies