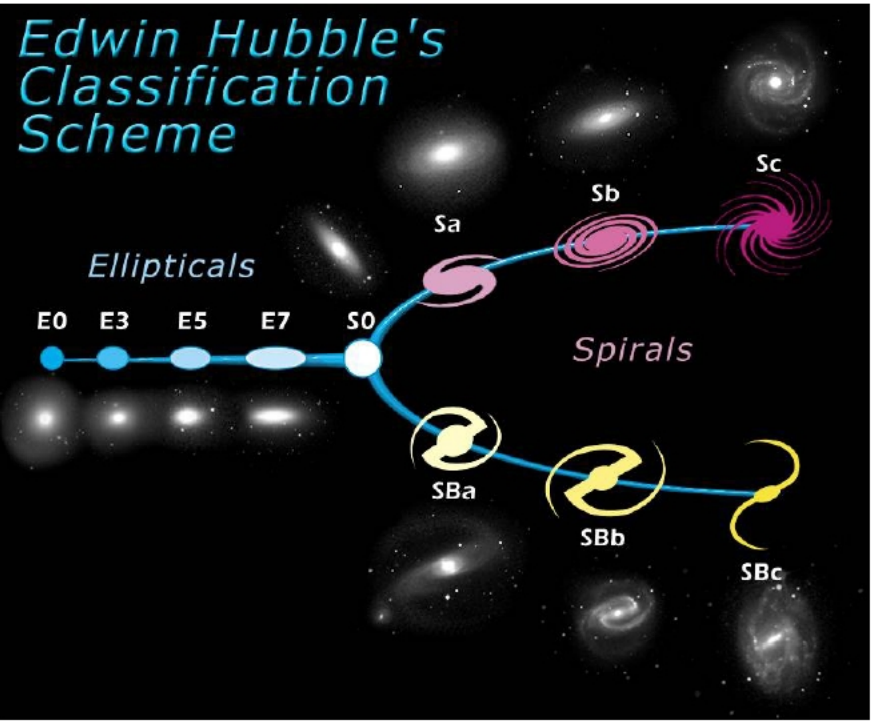
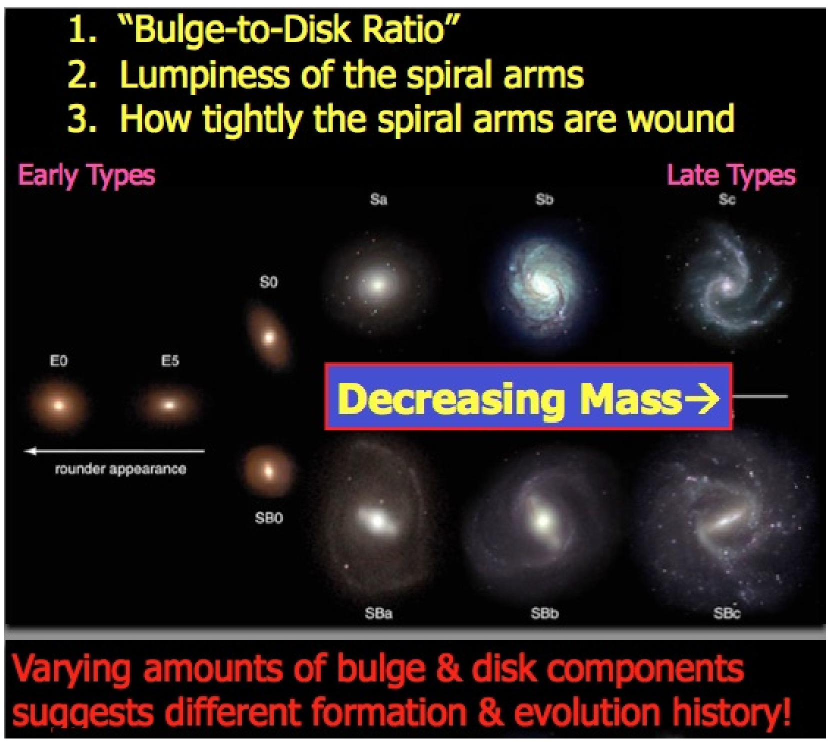
Astr 102: Introduction to Astronomy

Fall Quarter 2009, University of Washington, Željko Ivezić

Lecture 11:

Lives of Galaxies



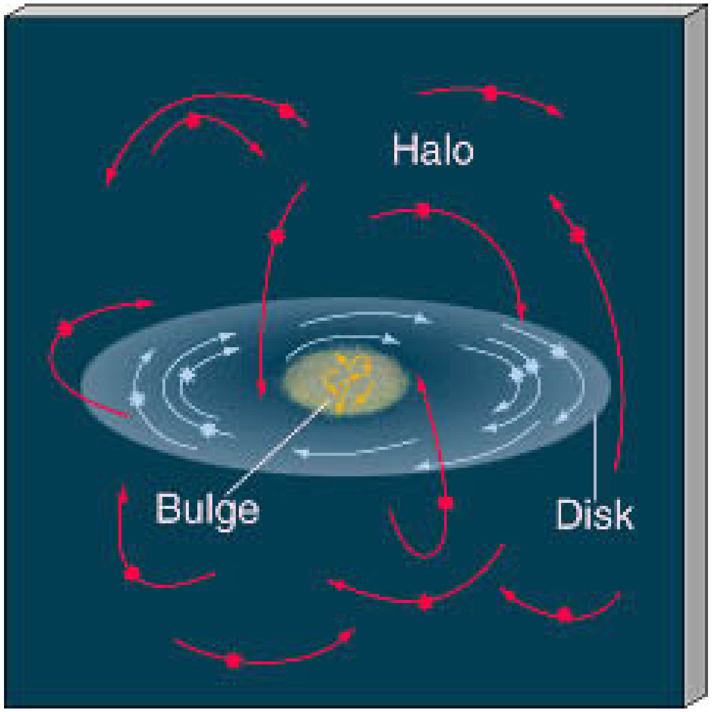


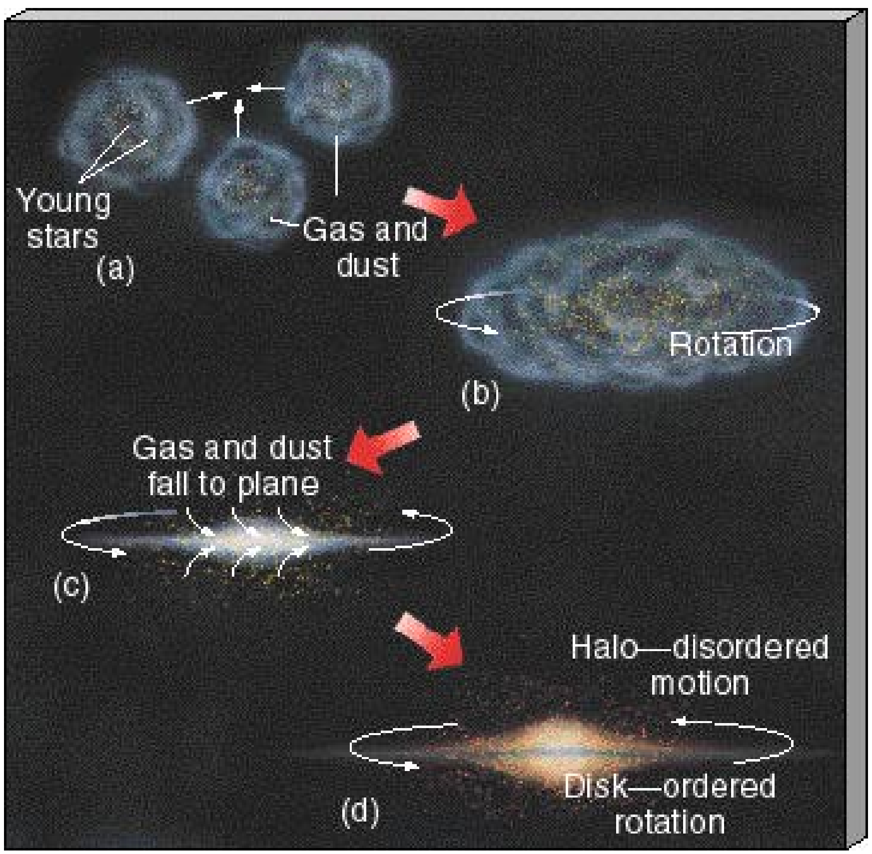
Galaxy Zoo: A Diverse Bunch!

- Galaxies differ in many properties: mass, luminosity, age (colors of stellar populations), the amount of interstellar medium (gas and dust), angular momentum, detailed structure (spiral arms, bars, star-forming regions)
- Galaxy formation: how and when were galaxies assembled?
- Galaxy evolution: how did properties of galaxies change with time? What happens when galaxies collide and merge?
- Three main tools to study galaxy formation and evolution:
  1. Studies of galaxies at different redshifts: **a time machine!**
  2. Computer simulations
  3. Detailed studies of the Milky Way and other nearby galaxies

Galaxy Formation

- The Monolithic Collapse Model (top-down)
- The Merger Model (bottom-up)
- Galaxy Interactions





Basic Ideas

- Stars move in a gravitational potential
- Two types of motion: disk stars **rotate** around the center, while halo stars are on randomly distributed elliptical orbits
- The motion of stars was set during the formation period
- The details are governed by the laws of physics: conservation of energy and conservation of angular momentum!
- As the cloud collapses, its rotation speed must increase. As it spins faster, it must flatten.
- **A key question:** is all the action over "quickly", or do galaxies evolve througout their lifetime (billions of years)?

The ELS Monolithic Collapse Model

- The ELS model (Eggen, Lynden-Bell and Sandage, 1962): the Milky Way formed from the rapid collapse of a large proto-galactic nebula: top-down approach
  - the oldest halo stars formed early, while still on nearly radial trajectories and with low metalicity
  - then disk formed because of angular momentum conservation, and disk stars are thus younger and more metal-rich
  - the ongoing star formation is confined to distances of $\sim$100 pc from the midplane, at a typical rate of a few $M_\odot$ per year

The ELS Monolithic Collapse Model

How fast do the galaxies form?

The free-fall time (comes from basic mechanics) is

$$t_{ff} = \sqrt{\frac{3\pi}{32}\frac{1}{G\rho_o}}, \tag{1}$$

where ρ_o is the mean density:

$$\rho_o = \frac{3M}{4\pi r^3}. \tag{2}$$

For $M = 6 \times 10^{11}\ M_\odot$ and $r = 100$ kpc, $t_{ff} = 7 \times 10^8$ yr ~ 1 Gyr (upper limit, centrally peaked clouds collapse somewhat faster)

NB the lifetime of most massive stars is ~ 1 Myr: many stellar generations lead to chemical enrichment

Problems with the monolythic collapse scenario:

- Why are half the halo stars in retrograde orbits? We would expect that most stars would be moving in roughly the same direction (on highly elliptical orbits) because of the initial rotation of the proto-Galactic cloud.

- Why there is an age spread of ~ 3 Gyr among globular clusters (GCs)? We would expect < 1 Gyr spread (free-fall time).

Some important questions that are left without robust answers:

- Why GCs become more metal-poor with the distance from the center?

- Detailed calculations of chemical enrichment predict about 10 times too many metal-poor stars in the solar neighborhood (the G-dwarf problem), why?

An alternative model for galaxy formation

- A bottom-up scenario: galaxies are built up from merging smaller fragments (similar but not the same as hypothesis that giant ellipticals formed from merging spiral galaxies)

- by observing galaxies at large redshifts (beyond 1), we are probing the epoch of galaxy formation – indeed, galaxies at large redshifts have very different morphologies, and the fraction of spirals in galaxy clusters is greater than today. Also, the volume density of galaxies was larger in the past: consistent with the merger hypothesis

- We have some important evidence for galaxy merging in our own backyard: detailed Milky Way structure (next time)

Star formation and starbursts

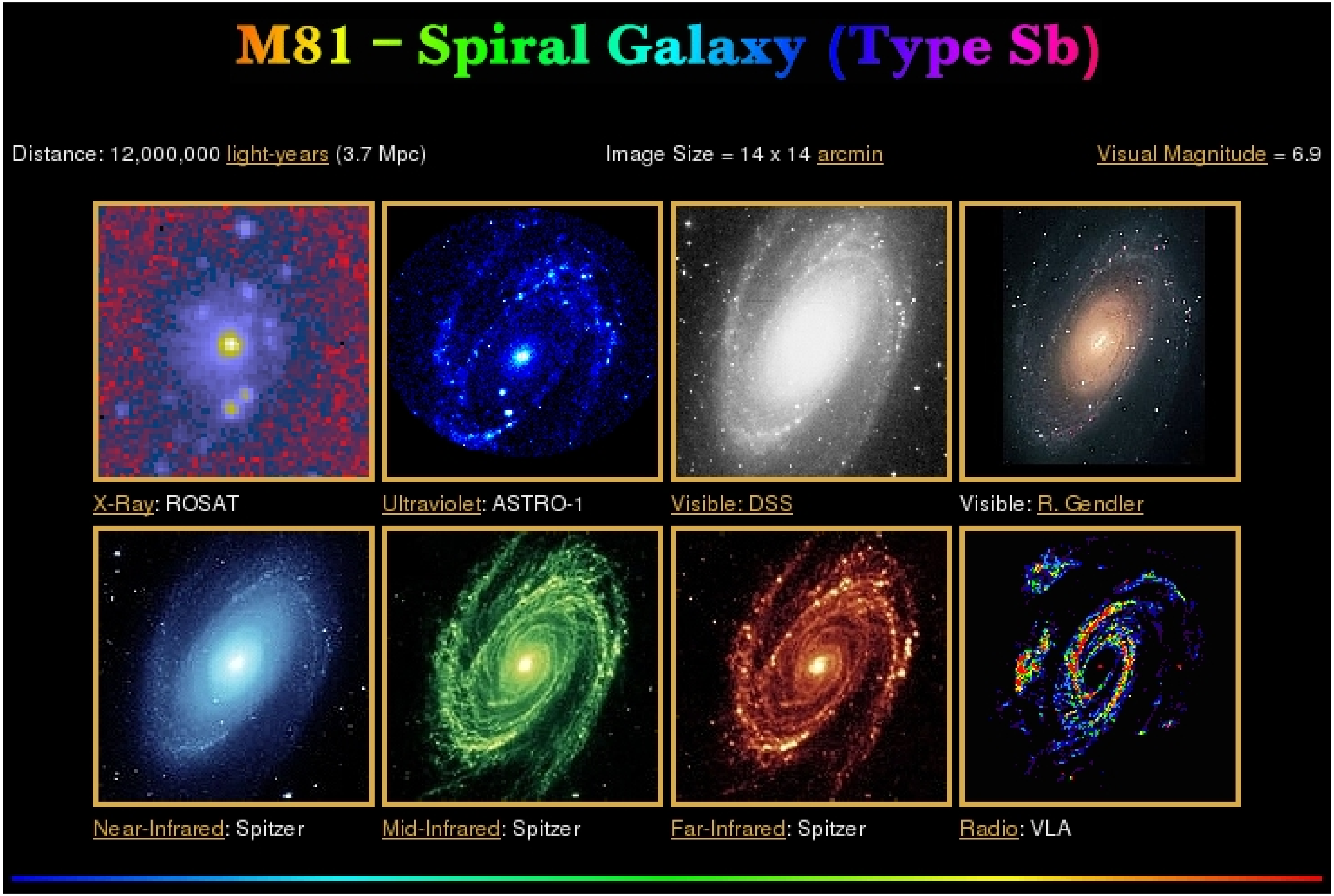
- The hottest stars, which have the shortest lifetimes, can be present only if there is an ongoing star formation; hence, the strong UV radiation is a sign of ongoing star formation (however, note that AGN spectrum is similar so one needs to be careful: spatially resolved observations, X-ray and radio observations, etc)

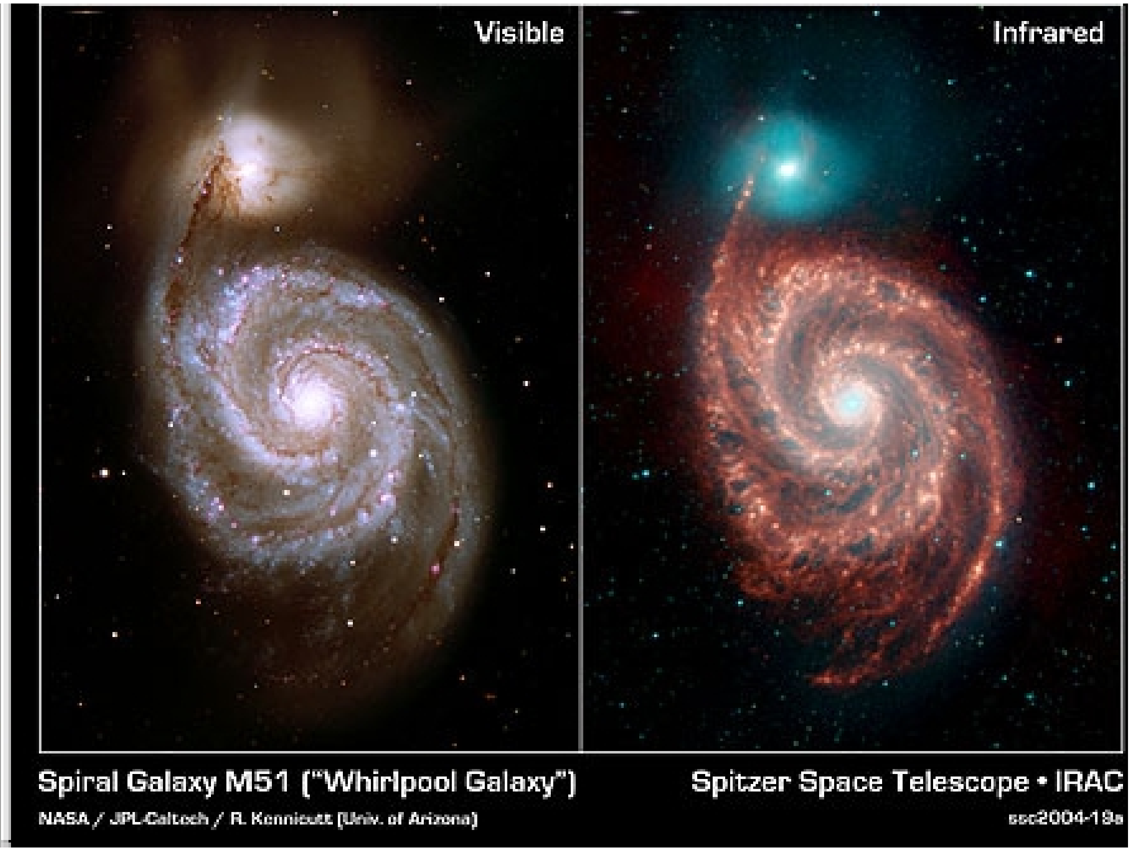
- Strong IR emission from circumstellar and diffuse dust is also a good sign of ongoing star formation (although here too confusion with AGN is possible, more details in lecture on AGNs/quasars)

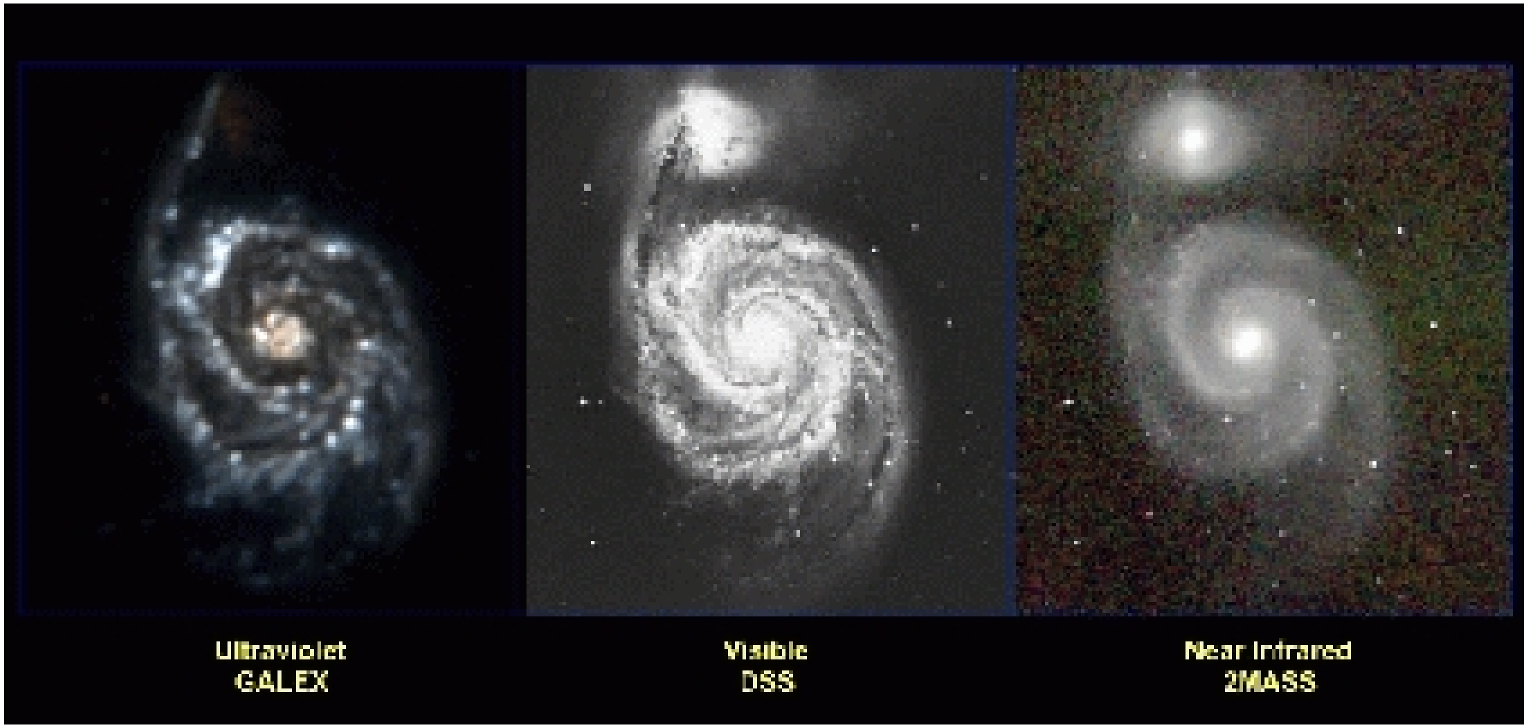
- Another indicator of star formation is $H\alpha$ line

Andromeda Galaxy
GALEX

Andromeda Galaxy
Visible light image (John Gleason)


M81 – Spiral Galaxy (Type Sb)
Distance: 12,000,000 light-years (3.7 Mpc)
Image Size = 14 x 14 arcmin
Visual Magnitude = 6.9
X-Ray: ROSAT
Ultraviolet: ASTRO-1
Visible: DSS
Visible: R. Gendler
Near-Infrared: Spitzer
Mid-Infrared: Spitzer
Far-Infrared: Spitzer
Radio: VLA


Visible
Infrared
Spiral Galaxy M51 ("Whirlpool Galaxy")
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)
ssc2004-19a



Note that the smaller galaxy (NGC 5195) is not visible in GALEX image (left): the burst of star formation is only in M51!

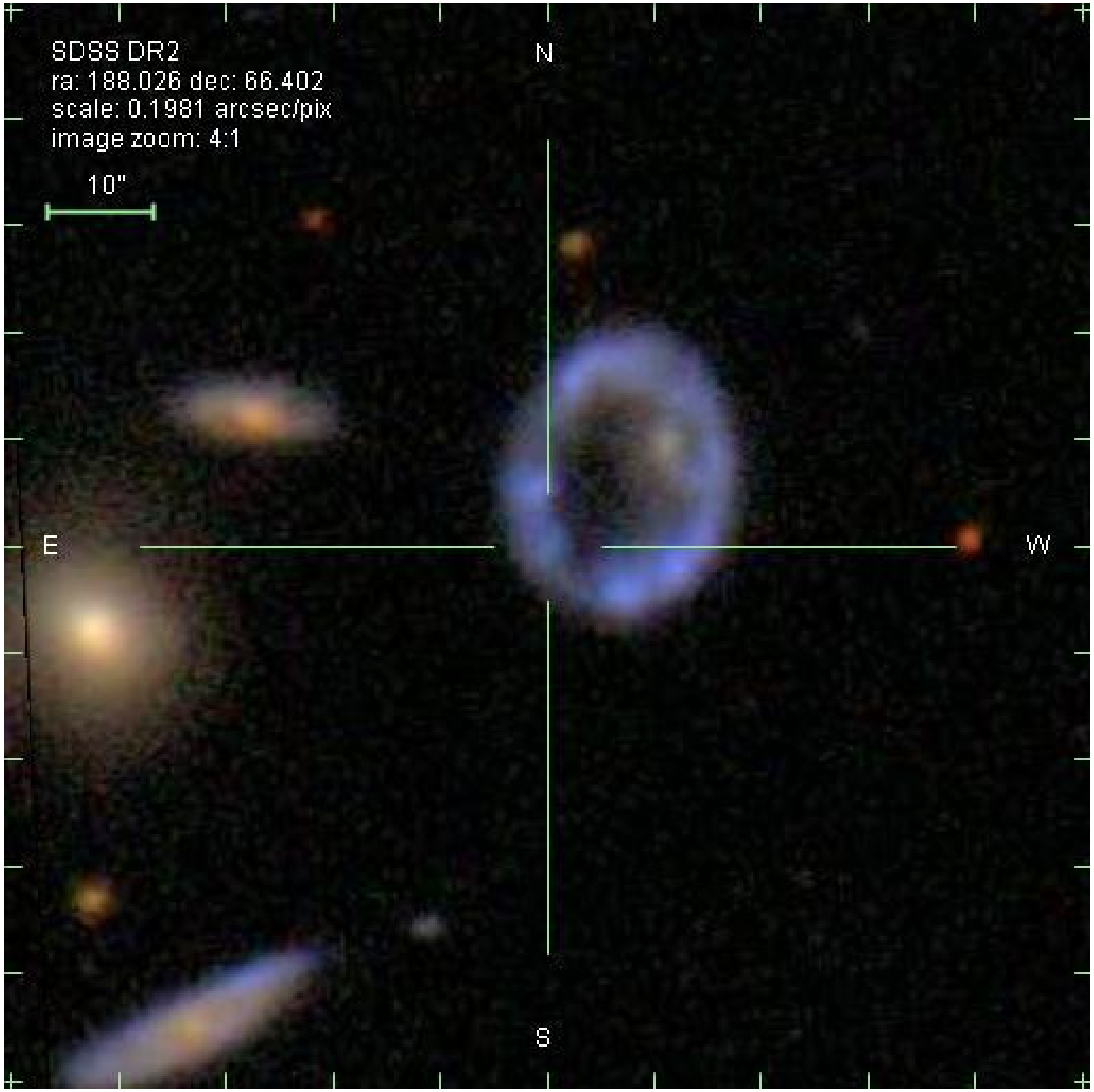
Star formation and starbursts

- After the end of star formation phase, galaxies become redder with time (in optical), $H\alpha$ becomes weaker, and IR emission disappears

- **Passive (or anemic) spirals:** galaxies caught right after the end of star formation will still have spiral structure, but no strong UV flux, nor $H\alpha$ line

Passive spirals in SDSS

Goto et al. (2003)



Interactions can results in various shapes and forms!

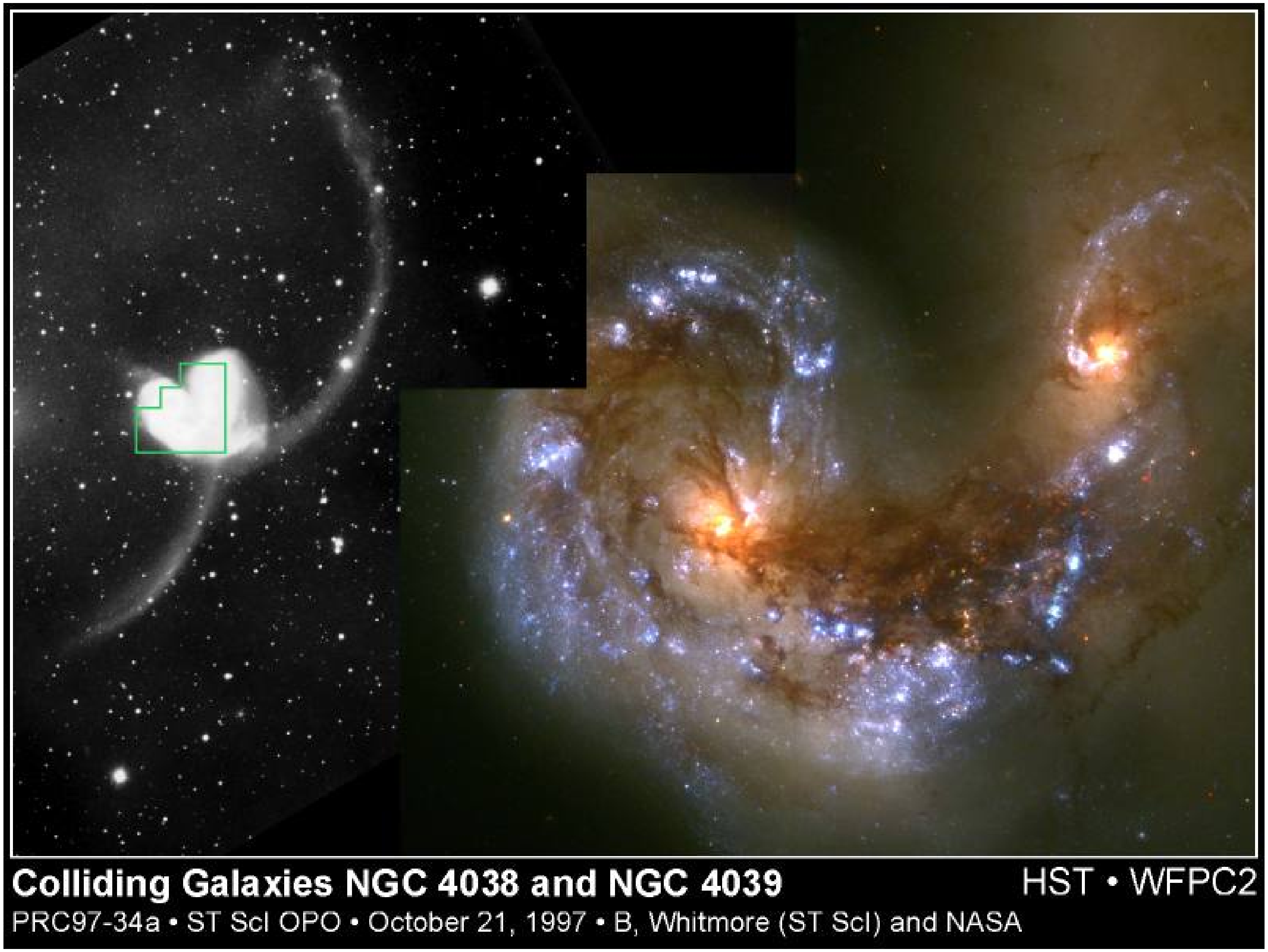
Galaxy Interactions: basic considerations

It is much more likely for two galaxies to interact/collide than for two stars becomes typical distance between two galaxies (say $\sim$ 1 Mpc) is only about 10-100 times larger than the size of a typical galaxy. For stars, typical distance (say 1 pc) is about 10^8 times larger than typical stellar size!

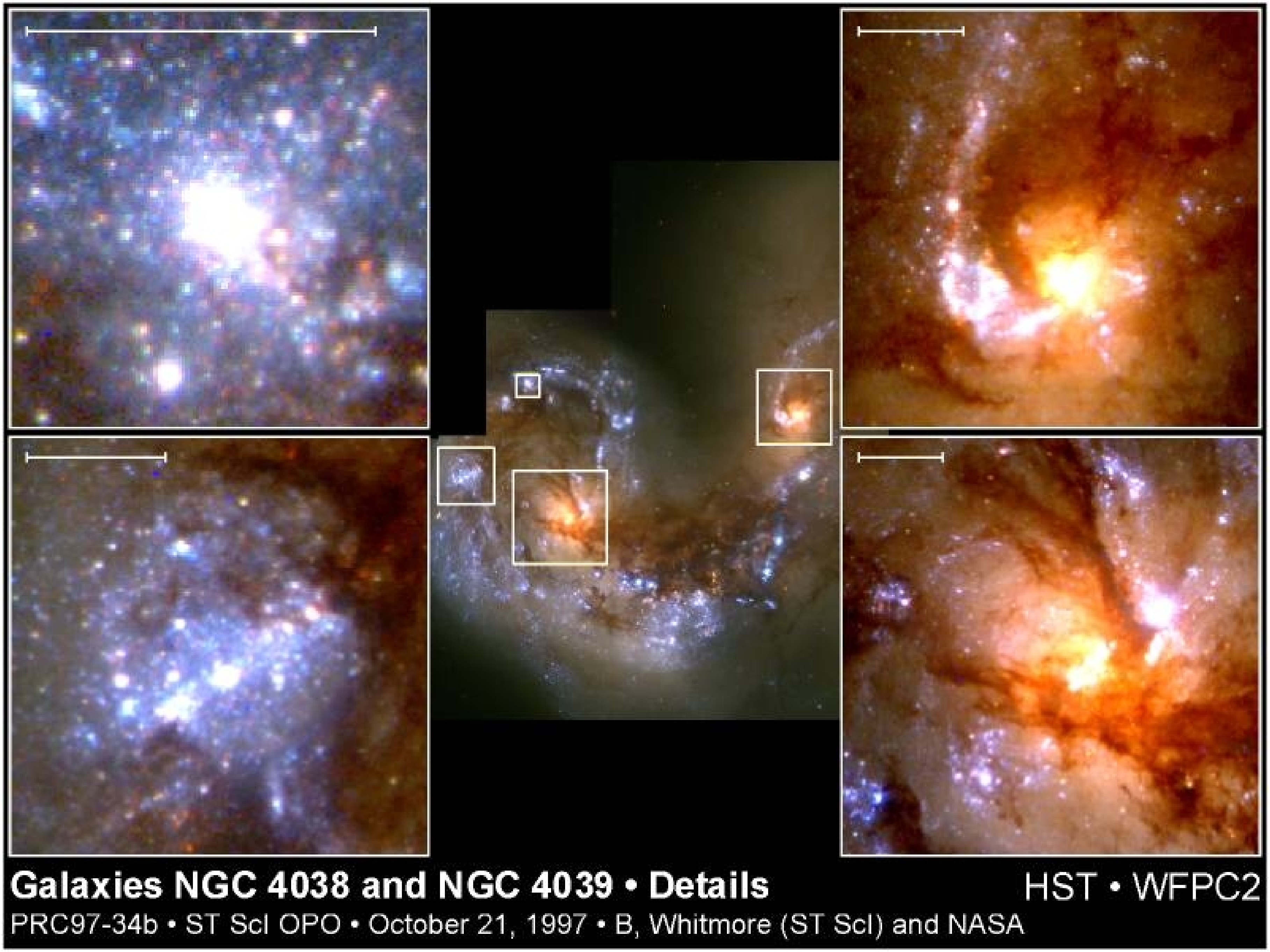
E.g. Andromeda is coming overhere at 100 km/s – expect fireworks 6 Gyr from now!

Fraction of the Milky Way's disk that is covered by stars: 10^{-14}! Even if another galaxy, such as Andromeda with 10^{11}–10^{12} stars, would score a direct hit, the probability of a direct stellar collision is still negligible.

The main effect of a galaxy collision is on interstellar gas, which is shocked and heated. The compressed gas cools off rapidly and fragments into new stars. A collision usually triggers a burst of star formation!

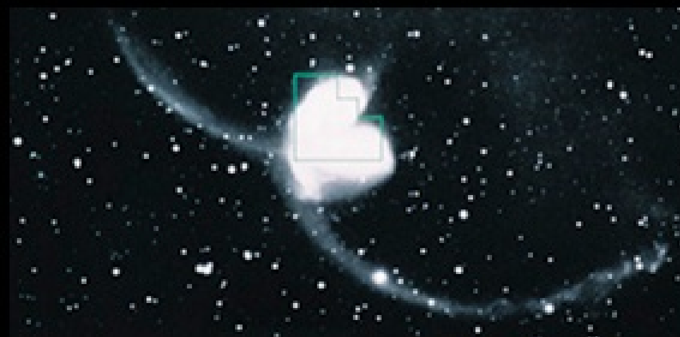


An example: Antennae Galaxy


Galaxies NGC 4038 and NGC 4039 • Details
HST • WFPC2
PRC97-34b • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Galaxies are evolving....

Can we see this process in motion?



- Directly, over our lifetime, no.

  We live for less than 100 years, or 0.000001% of the age of the universe, or 0.01% of the age of the shortest lived O-stars.

The Universe is a Time Machine!

- Speed of light not infinite!
- **Distant = Younger!**

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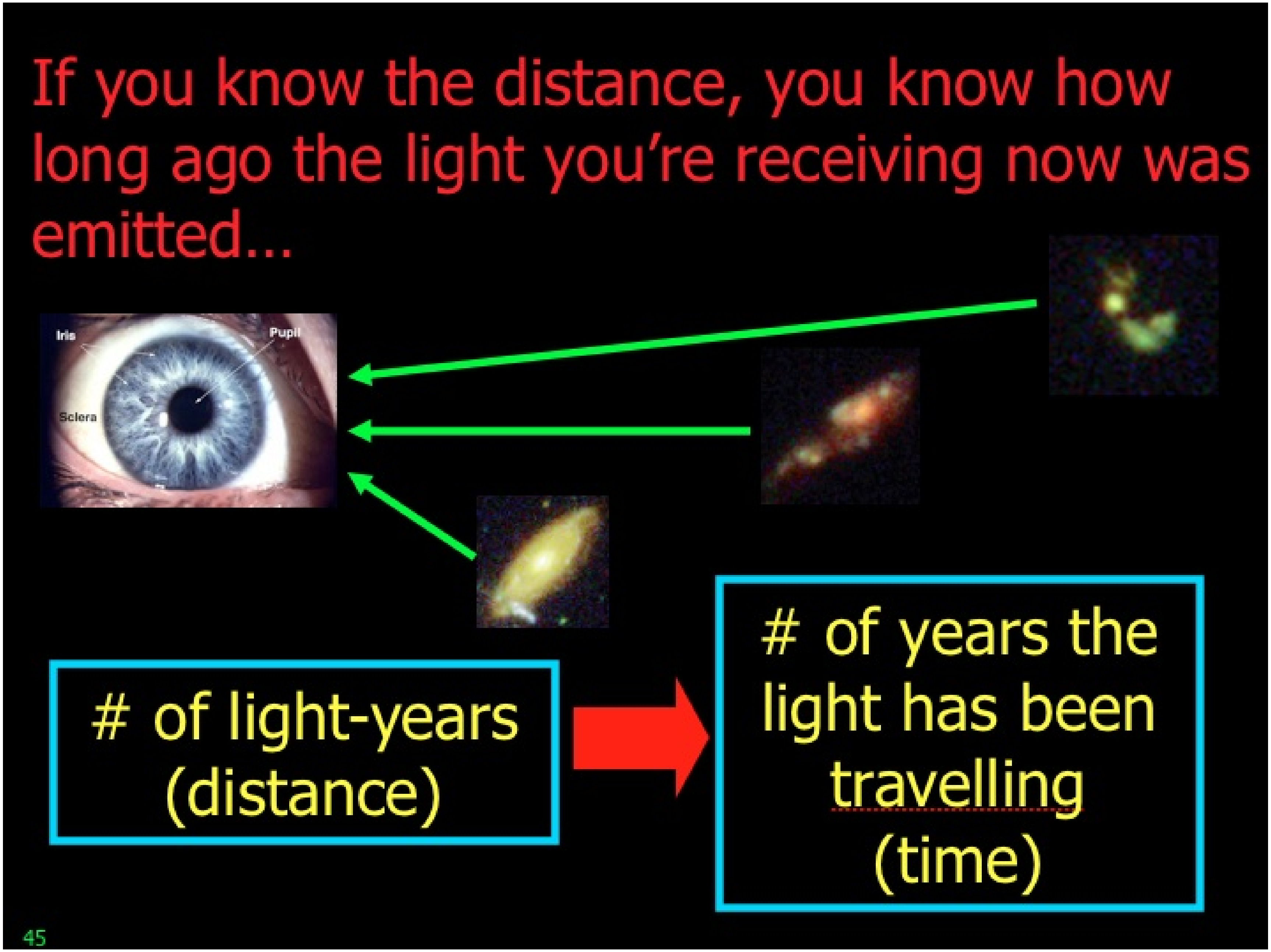
If you know the distance, you know how long ago the light you're receiving now was emitted…
Iris
Pupil
Sclera
# of light-years (distance)
# of years the light has been travelling (time)
45

We can piece together the history of the universe by observing it at different distances! **BUT…**

- Can't see the **same** galaxy at different distances.
- Distant galaxies appear fainter, so harder to detect.
- Distant galaxies appear smaller (angularly), so harder to resolve features.

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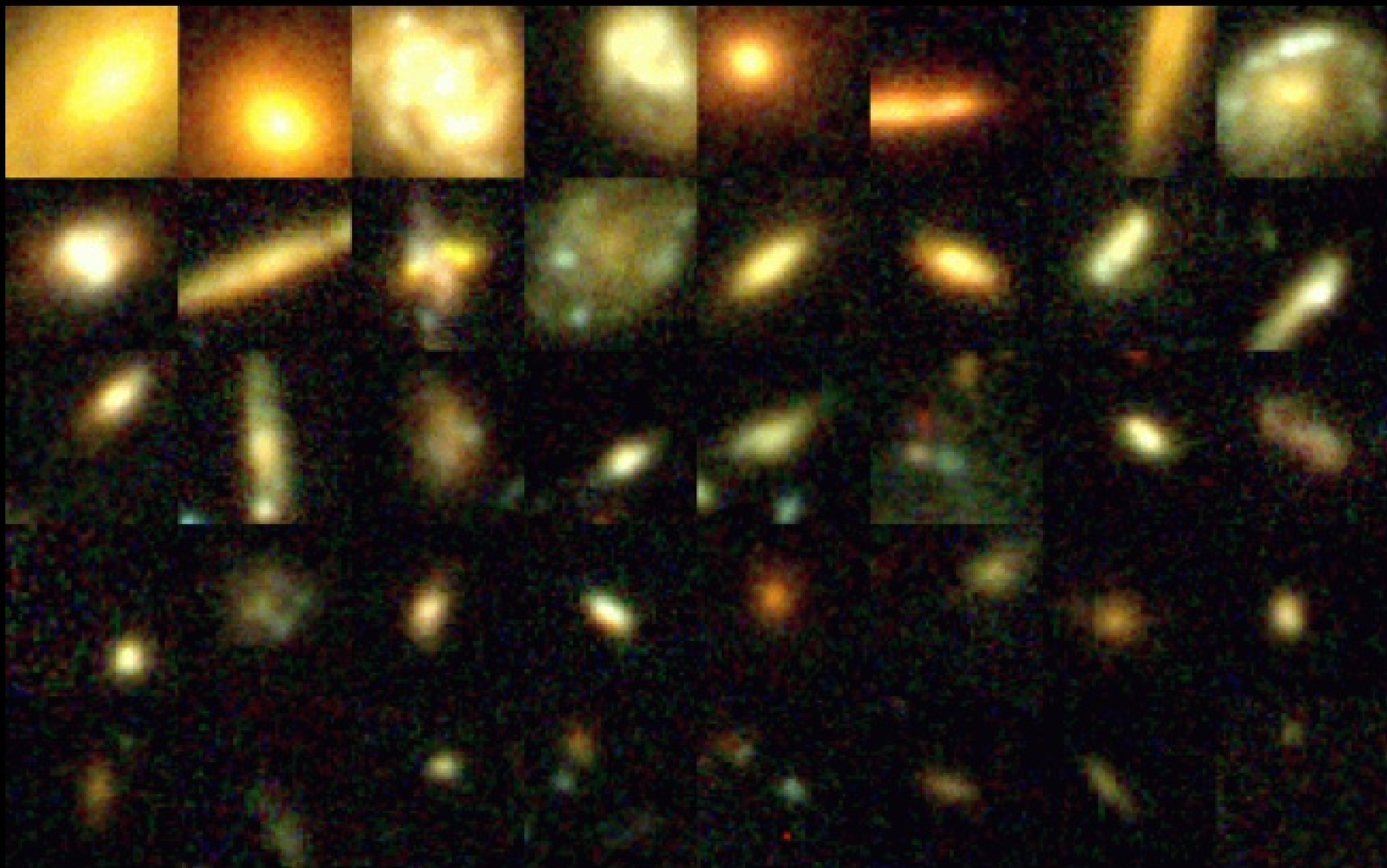
Close...

Further (younger)...



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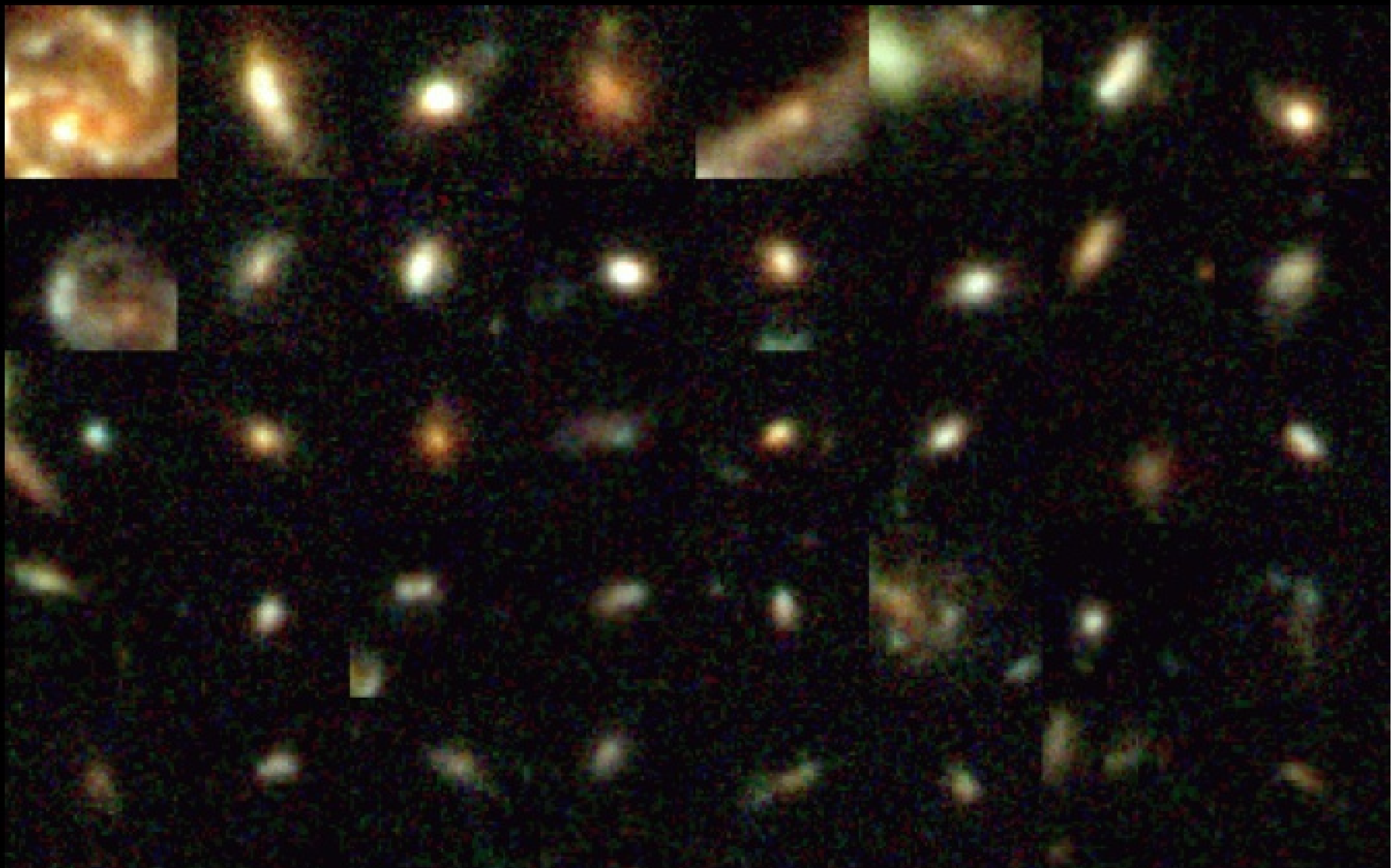
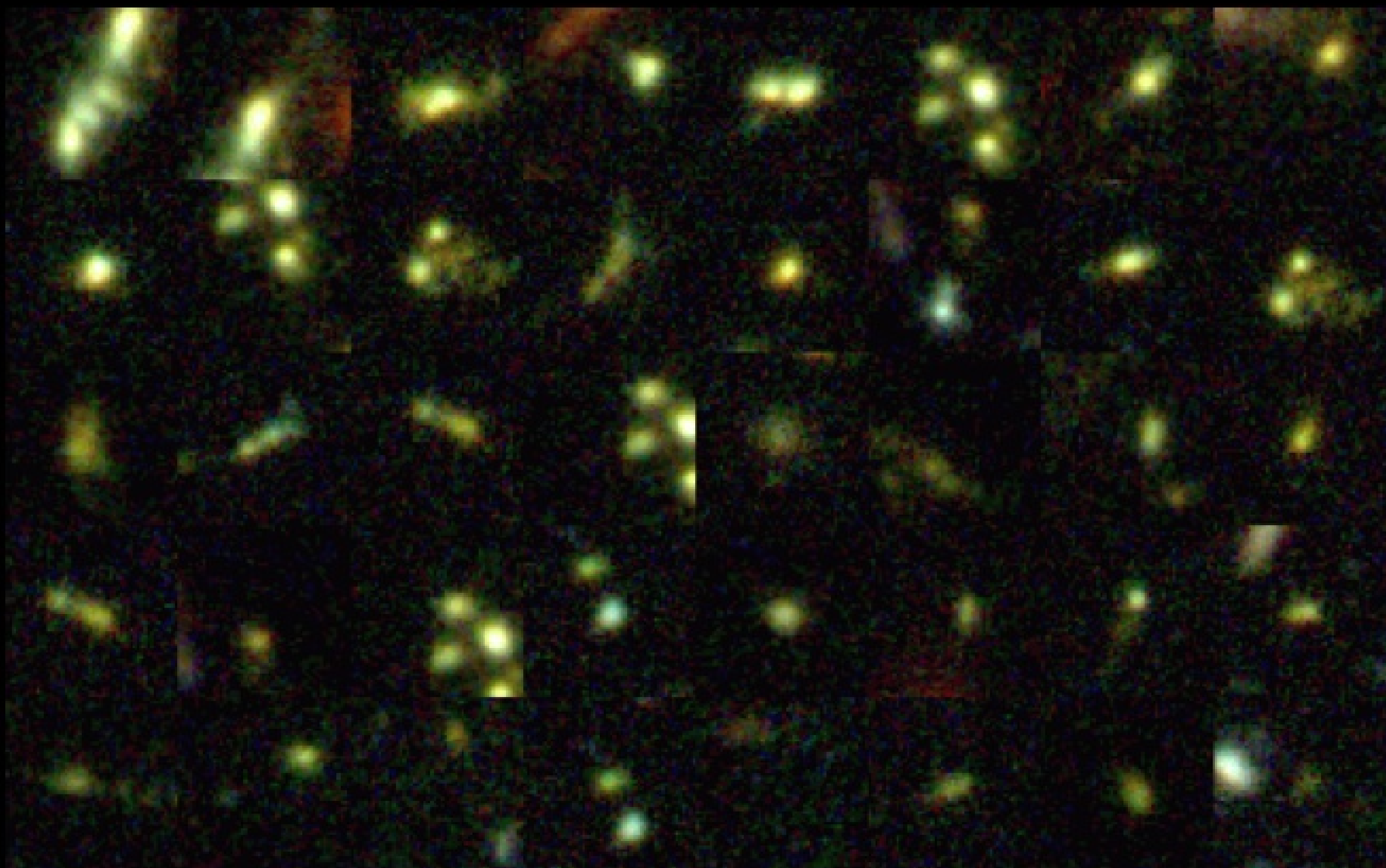
Even Further (even younger)...



And younger and further still…



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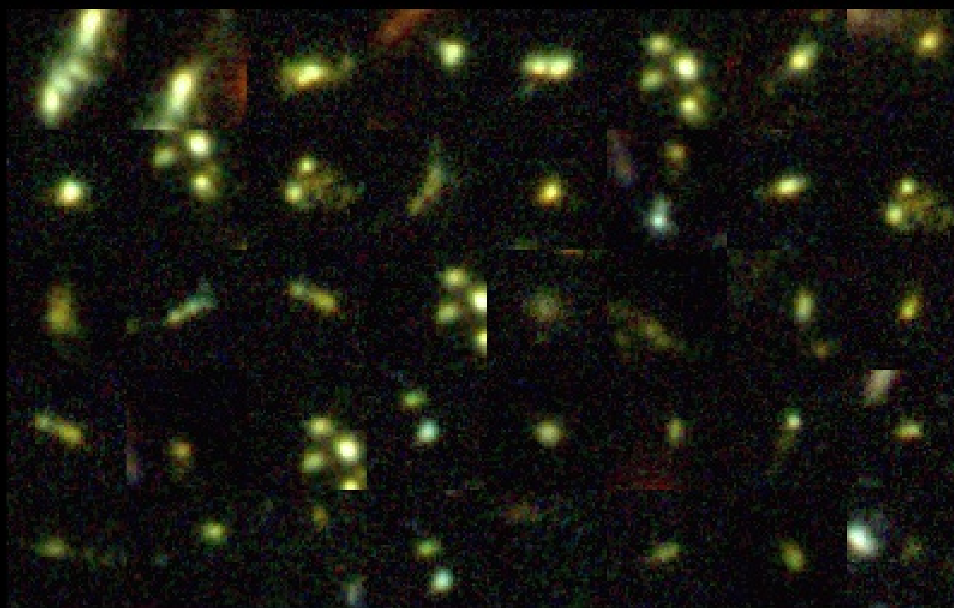
Galaxies do seem to be forming "hierarchically" (i.e., bigger things



- Lots-o-lumps
- No galaxies that look like massive normal galaxies today.

Good support for "cold dark matter"!

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A ``grand-design''spiral seen face-on.

A flocculent spiral with ragged spiral arms.

More on spiral arms: In addition to Hubble's classification, there are different types of spiral structure: grand design spirals, with clearly outlined and well organised globally correlated spiral structure, and flocculent (fluffy) spirals with many small short globally uncorrelated spiral arms

Theories of Spiral Structure

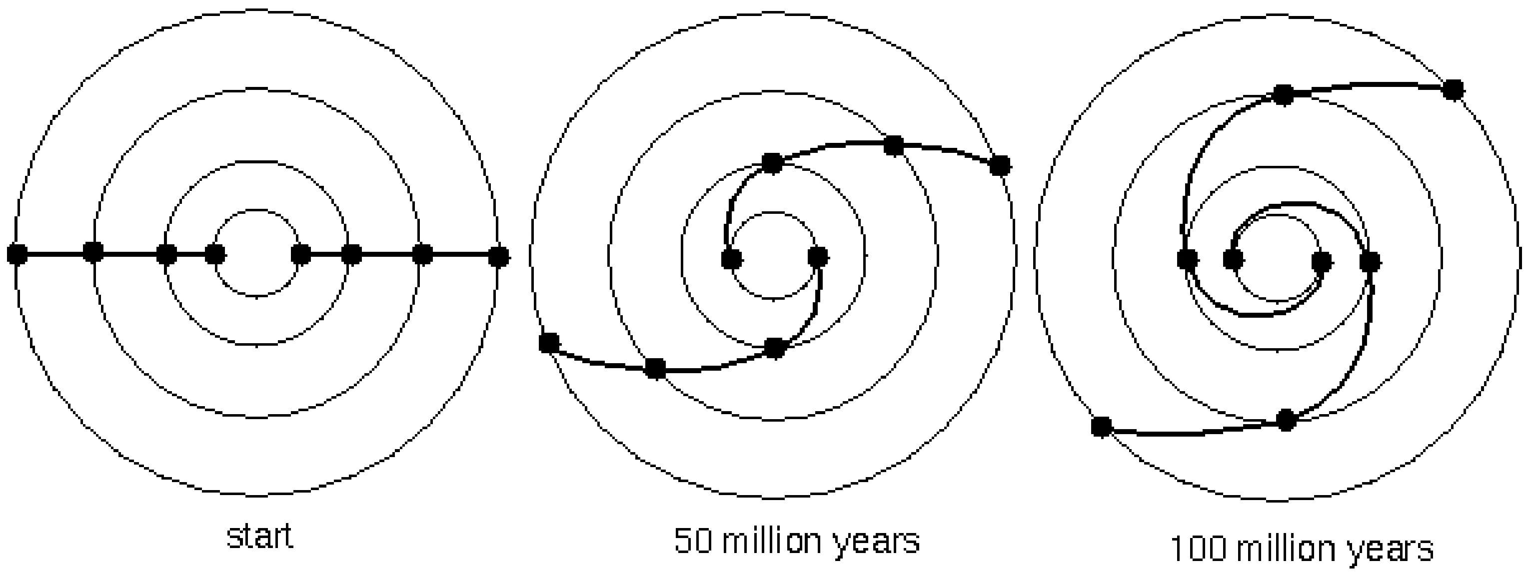
A little "secret": Despite 50 years of work, spirals are not very well understood. It seems clear now that the spiral structure of galaxies is a complex problem without any unique and tidy answer.

Differential rotation clearly plays a central role, as well as global instabilities, stochastic spirals, and the shocks patterns that can arise in shearing gas disks when forced by bars.

There are (at least) two popular theories, one of which is more commonly used to explain grand design spirals, the other for flocculent spirals.

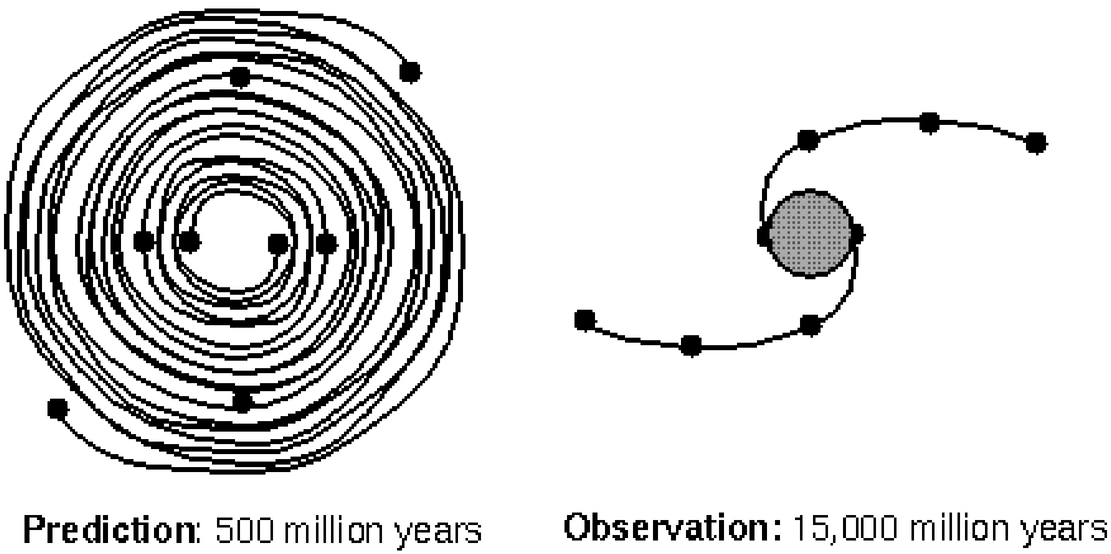
But before proceeding: **winding problem** (Lindblad)

Winding problem



Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

Winding problem

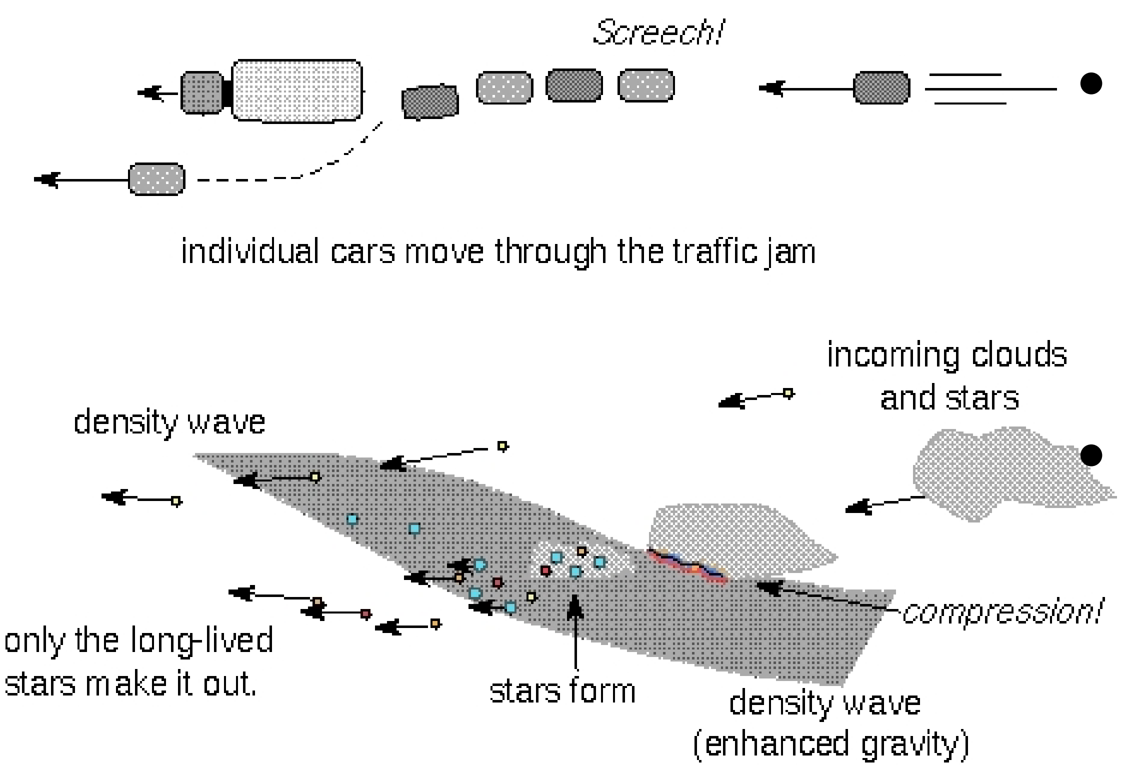


The problem: most spiral galaxies would be tightly wound by now, which is inconsistent with observations.

Spiral arms cannot be a static structure (i.e. at different times, arms must be made of different stars)

Density Wave theory

C.C. Lin & F. Shu (1964-66)



Spiral density waves are like traffic jams. Clouds and stars speed up to the density wave (are accelerated toward it) and are tugged backward as they leave, so they accumulate in the density wave (like cars bunching up behind a slower-moving vehicle). Clouds compress and form stars in the density wave, but only the fainter stars live long enough to make it out of the wave.

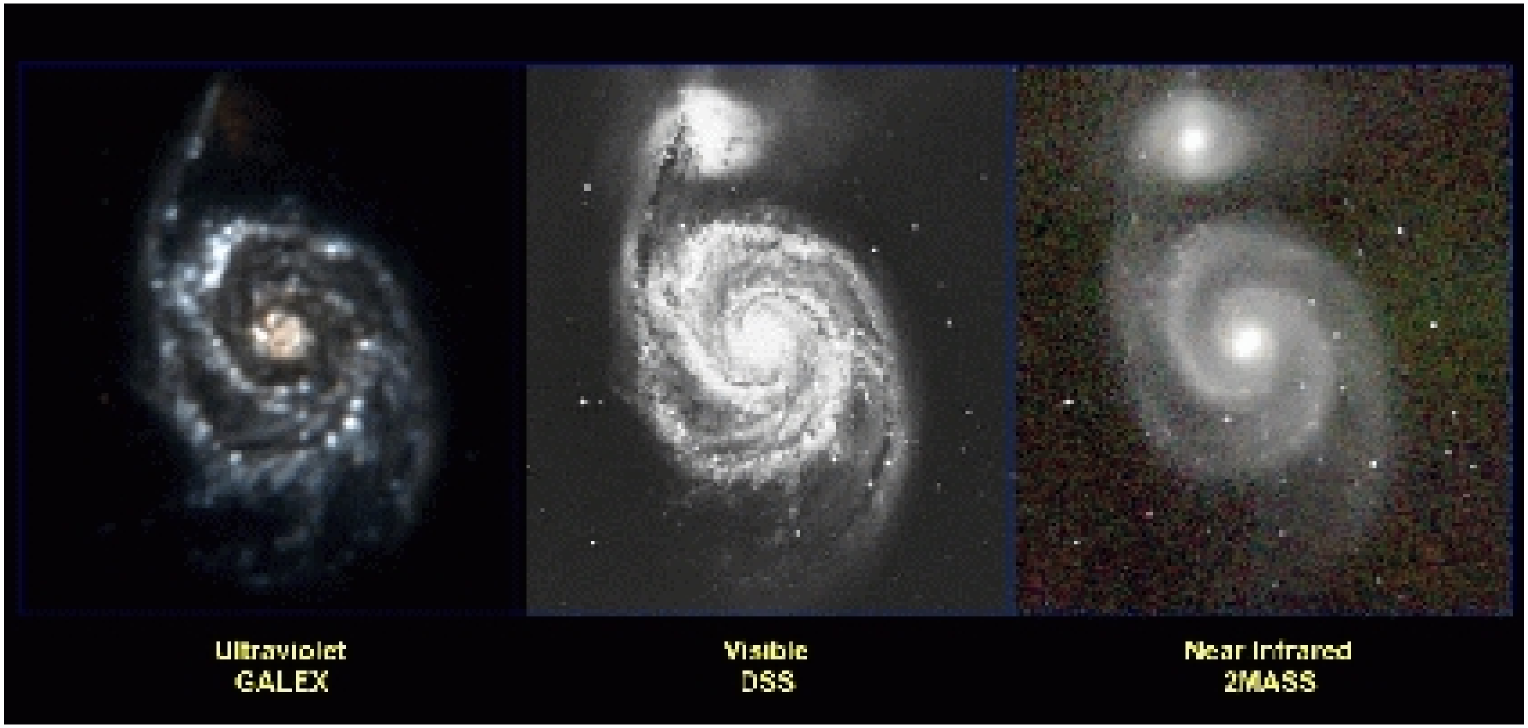
- This is the preferred model for grand design spirals.
- The spiral arms are over-dense regions which move around at a different speed than star: stars thus move in and out of the spiral arm
- How these density waves are set up is unclear, but it may have to do with interactions. Once they are set up, they must last for a long enough time to be consistent with the observed number of spiral galaxies

Stochastic Self-Propagative Star Formation

- This model probably cannot explain grand design sprials, but it may account for flocculent spiral structure.

- Ongoing star formation triggers star formation in areas adjacent to it. As the galaxy rotates, differential rotation leads to the appearance of a spiral pattern.

Spiral arms are made of short-lived massive blue stars!



Note that the smaller galaxy (NGC 5195) is not visible in GALEX image (left, compare to figs. 6-1 and 6-4 from the textbook)

The spiral structure is associated with (short-lived) hot stars.

The Sombrero Galaxy (VLT ANTU + FORS1)

ESO PR Photo 07a/00 (22 February 2000)

Disks contain a lot of dust! Spiral arms are almost exclusively seen in disks with a lot of gas and dust, unlike bars which are often seen in galaxies without ISM. Bars are not a wave of star formation – they are orbital features.

To remember:

- Spiral arms are not static structure (winding problem)
- Not all spirals are alike: more than one pattern
- Not clear if spiral arms are transient or quasy-steady phenomenon
- The appearance dominated by young luminous blue stars, but the overall density of *all* stars is elevated by 10-20% in spiral arms