GALAXIES

BRYN JONES
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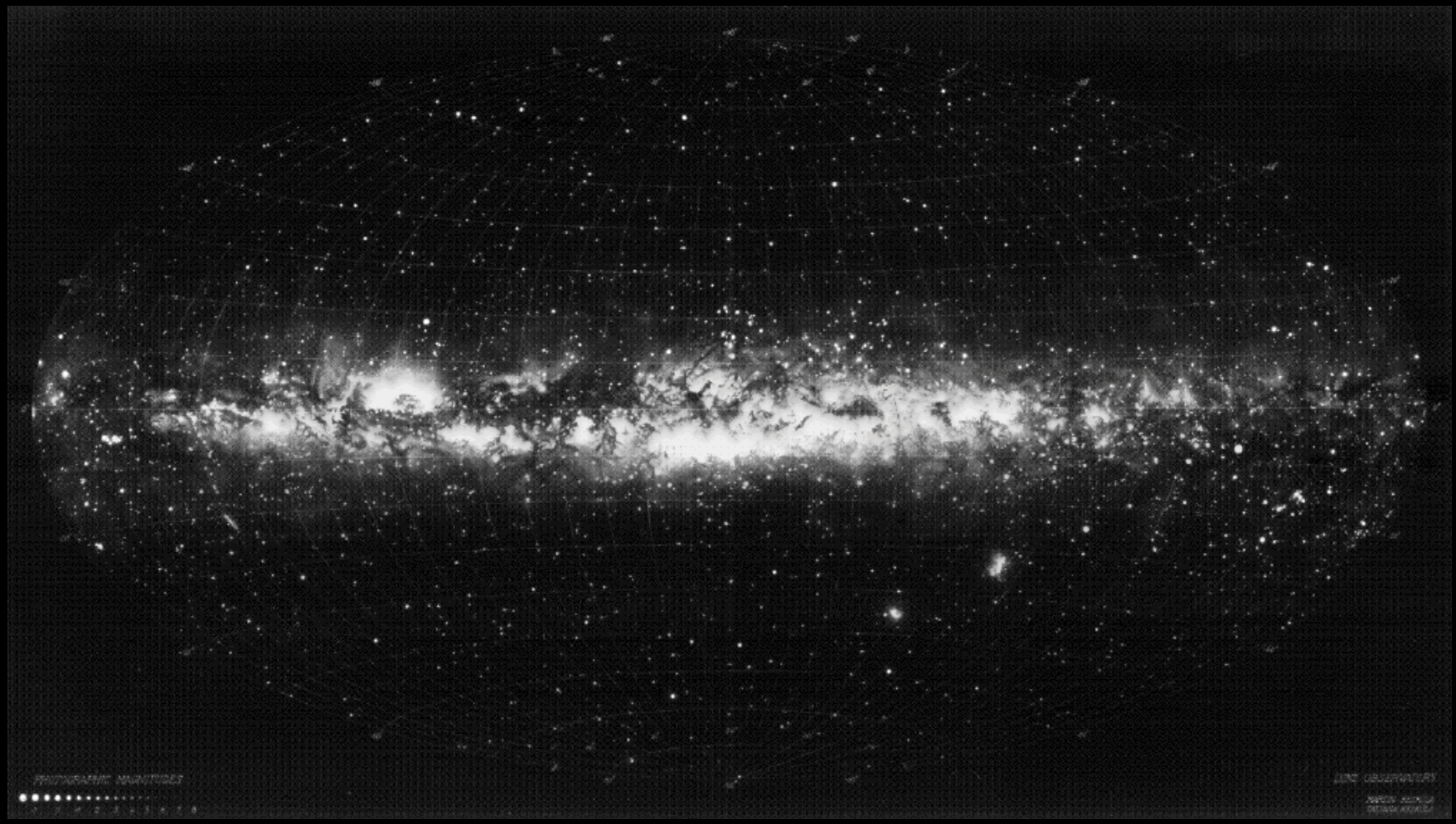
The Milky Way

Picture by
Fred Espenak

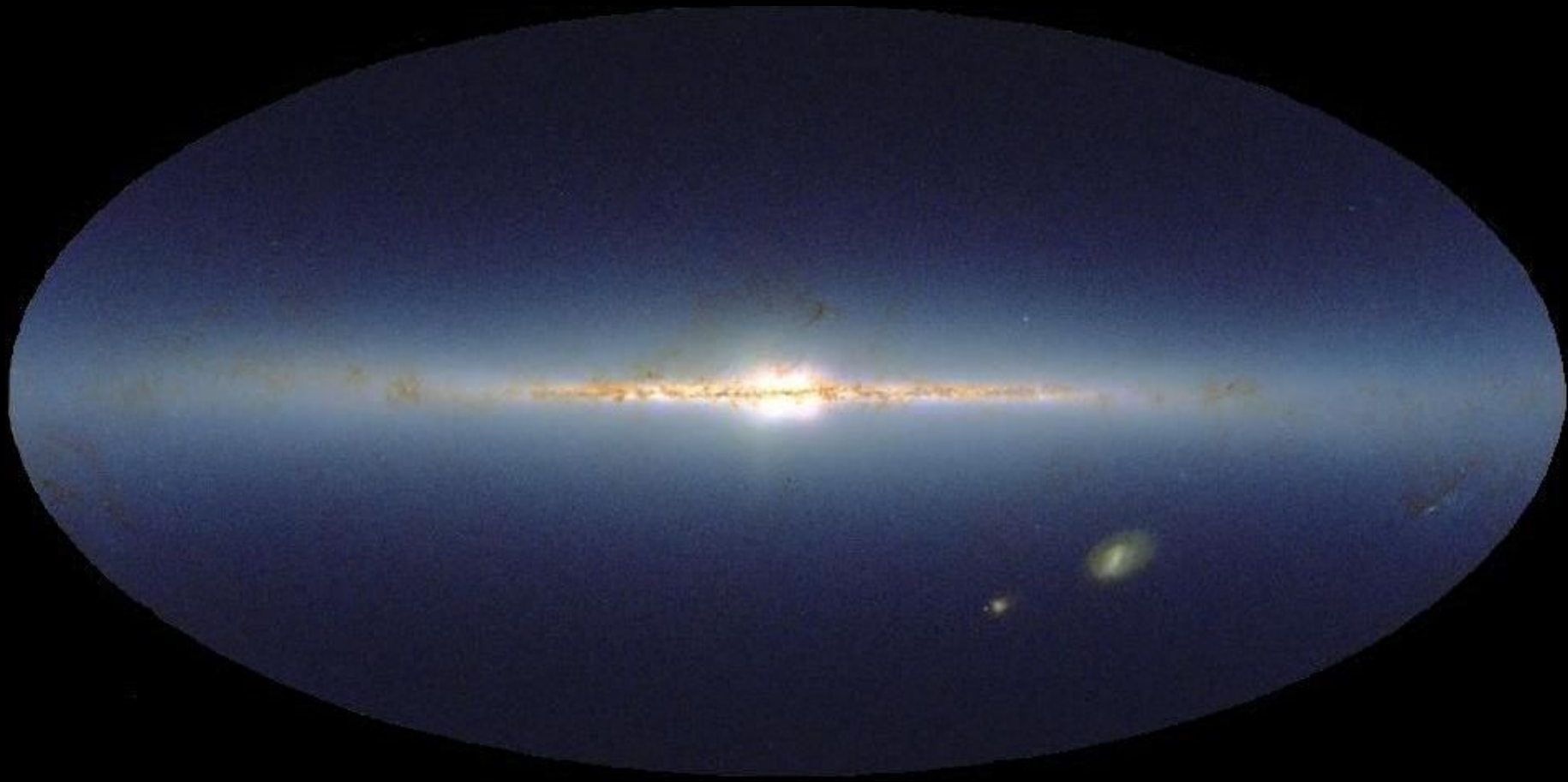
The Milky Way

All-sky picture by Knut Lundmark (1940s)



The Milky Way

2MASS infrared survey of 250 million stars



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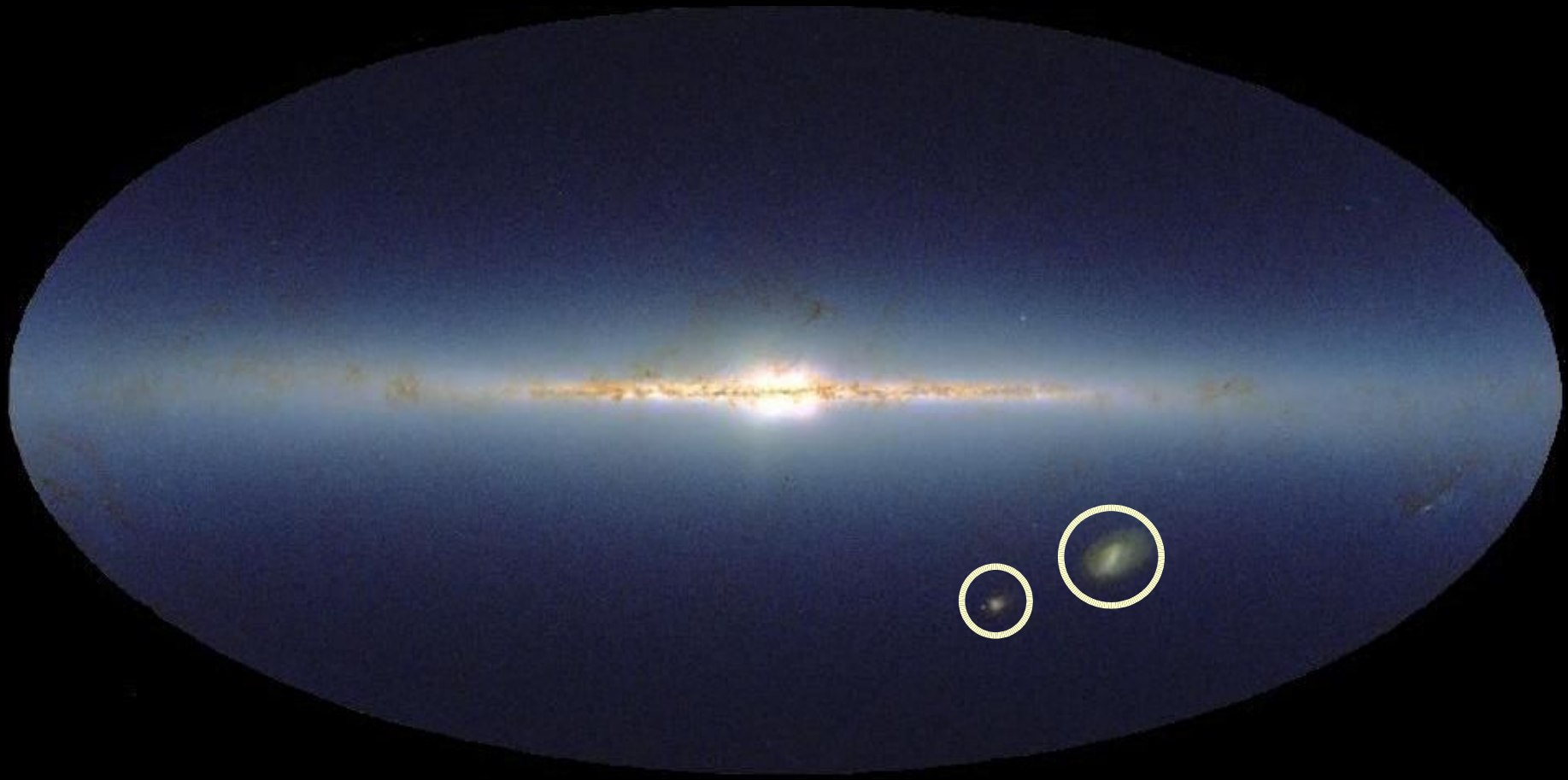


The Large Magellanic Cloud

The Small Magellanic Cloud

Andromeda Galaxy, M31

Burrell Schmidt photographs
NOAO / AURA / NSF

Galaxy morphological types

Normal galaxies are found to come in distinct types :

- elliptical
- S0 (lenticular)
- spiral - barred and unbarred
- irregular

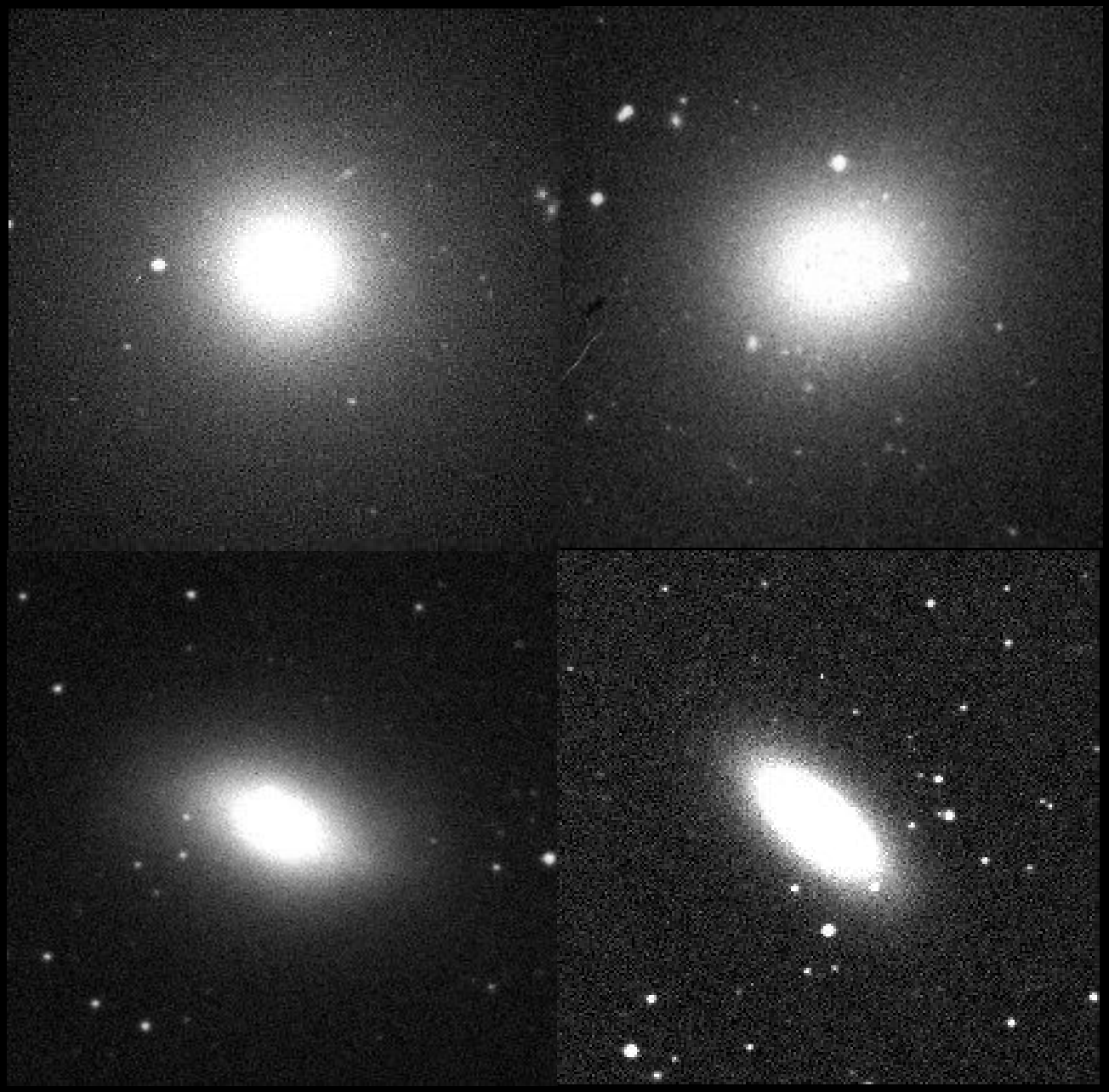
Some have peculiar morphologies

Active galaxies

- have active nucleus, powerful energy source
  e.g. radio galaxies, Seyfert galaxies, quasars

Elliptical galaxies

SuperCOSMOS Sky Survey
UKST data from the ROE



NGC 1407
E0

NGC 1395
E2

NGC 584
E4

NGC 4033
E6

Elliptical galaxies

M87 in Virgo Cluster

Elliptical galaxies

Smooth, mostly featureless appearance

Spectra show the combined light of old stars

Light is red - indicating old stars

Motions of stars - orbits are elongated and randomly orientated

Very little gas or dust - no stars currently being formed

Spiral galaxies

Normal spirals (without bars)

ESO286-G10
Sa

NGC 3223
Sb

M74
Sc

UKST and POSS-II data from the SuperCOSMOS Sky Survey at the ROE
Photographic images through a blue filter

Spiral galaxies

Normal spirals (without bars)

NGC 300
Sd

NGC 4395
Sm

UKST and POSS-II data from the SuperCOSMOS Sky Survey at the ROE
Photographic images through a blue filter

Spiral galaxies

Barred spirals

NGC 4440
SBa

NGC 1097
SBb

NGC 1073
SBc

UKST and POSS-II data from the SuperCOSMOS Sky Survey at the ROE
Photographic images through a blue filter

Spiral galaxies

Barred spirals

NGC 1313
SBd

NGC 4597
SBm

UKST and POSS-II data from the SuperCOSMOS Sky Survey at the ROE
Photographic images through a blue filter

Spiral galaxies

Spiral galaxies

NGC 3370 HST

2.2-metre Telescope, La Silla, Chile NGC 300

Spiral galaxies

Sombrero Galaxy M104 VLT

Spiral galaxies

NGC 4013
HST

Spiral galaxies

M83 barred spiral galaxy AAT

Spiral galaxies

Contain a flattened disc

Disc is rotating - stars and gas on near-circular orbits in the disc

Discs have spiral arms with luminous blue stars

Spectra - light from stars and gas - absorption lines from the stars, emission lines from the gas

Gas is confined to the plane of the disc
Gas contains dust

Spiral galaxies

Gas is forming stars - mix of stars with a range of ages

Spheroidally distributed halo of old stars in elongated orbits, random orientations

Central bulge of old stars

Some spirals have central bars, some do not

Spheroidally distributed globular clusters

Spiral galaxies: spiral arms

NGC 2997 through blue, red and infrared filters

Blue

Red

Infrared

UKST / SuperCOSMOS Sky Survey

Irregular galaxies

NGC 1569

NGC 4214

NGC 4449

NGC 7292

UKST and POSS-II data from the SuperCOSMOS Sky Survey at the ROE
Photographic images through a blue filter

Irregular galaxies

Irregular morphologies

Large fraction of gas

Gas is forming stars

Many young blue stars

Overall colours are very blue

Spectra show prominent emission lines from the gas and absorption spectra from the stars

Irregular galaxies

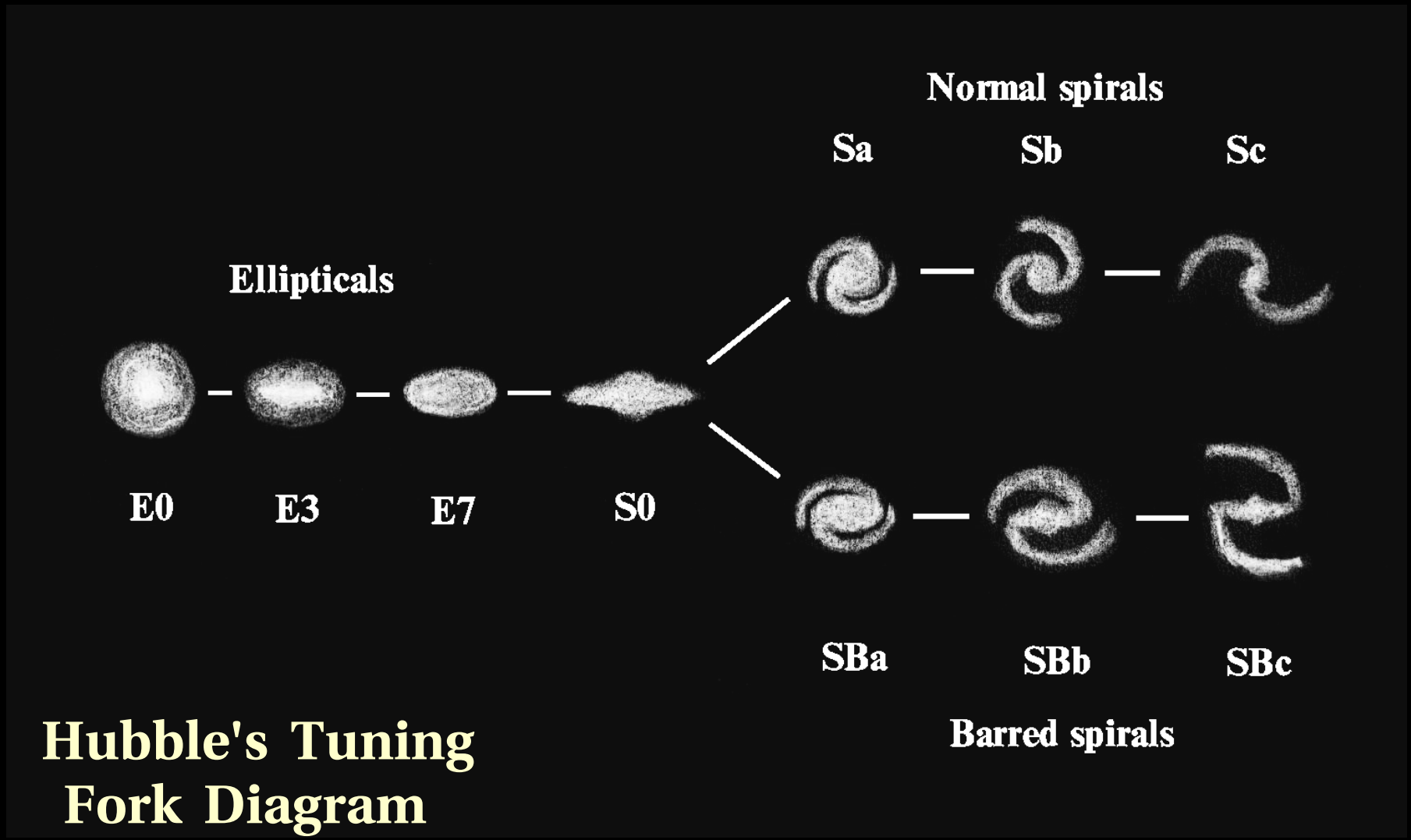
NGC 6822
Local Group
galaxy

1.6 Mly distant

4m Blanco
Telescope

Local Group
Galaxies Survey
Team/NOAO/
AURA/NSF

Galaxy morphological types



Hubble's Tuning Fork Diagram

Galaxy morphological types

Galaxy properties vary in a sequence

E S0 Sa Sb Sc Sd Irr

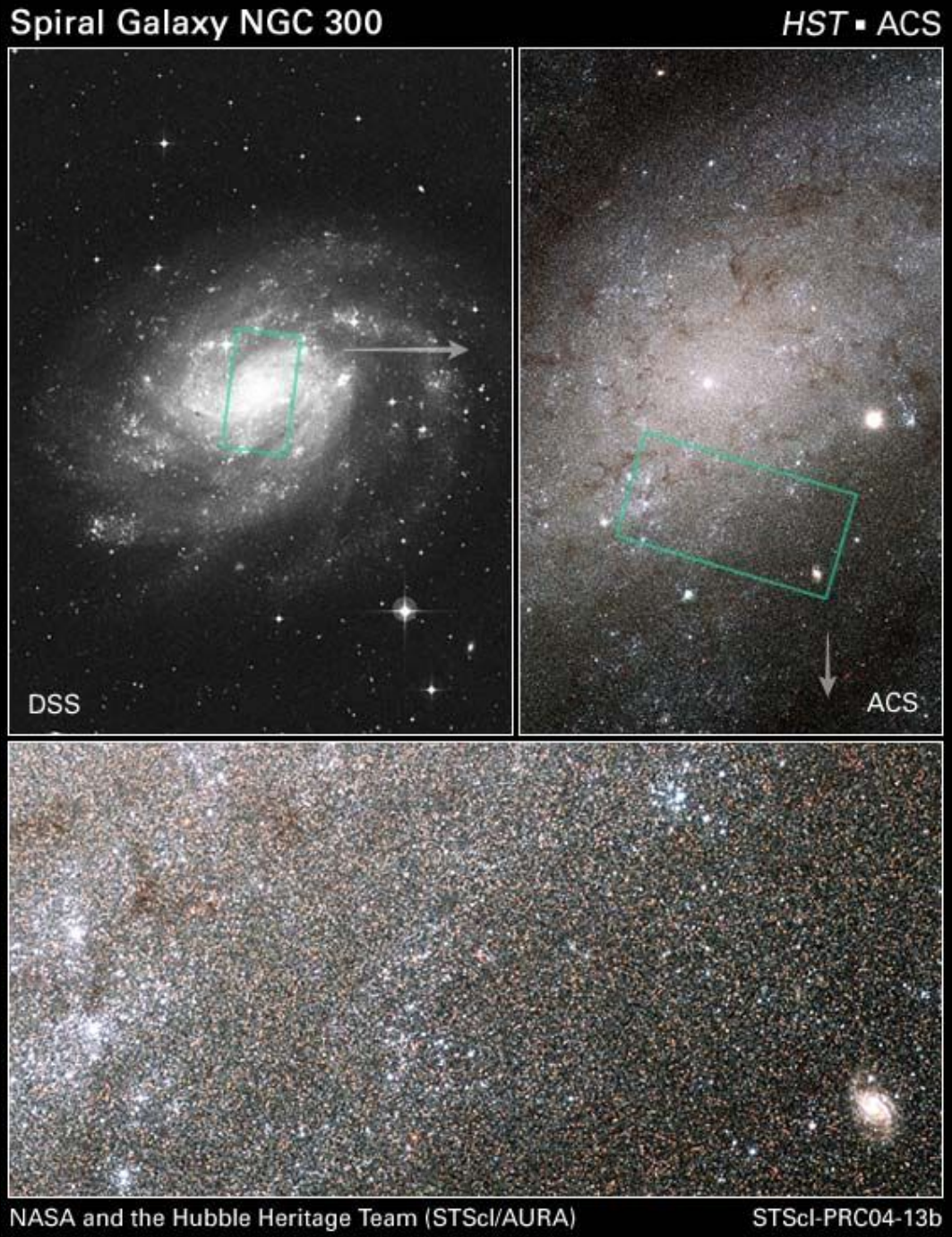
Early type Late type

Old stars	Young stars
Red colour	Blue colour
Gas poor	Gas rich
Absorption-line spectra	Strong emission lines in spectra

Some evolution along this sequence from late to early

Stars in nearby galaxies

Can resolve individual stars in relatively nearby galaxies



Stars in nearby galaxies

Can compare properties of stars in nearby galaxies with stars in our Galaxy of known distance

e.g. main sequence fitting

 distance of galaxy

Distance indicators can work to greater distances

e.g. variable stars - Cepheids, RR Lyrae

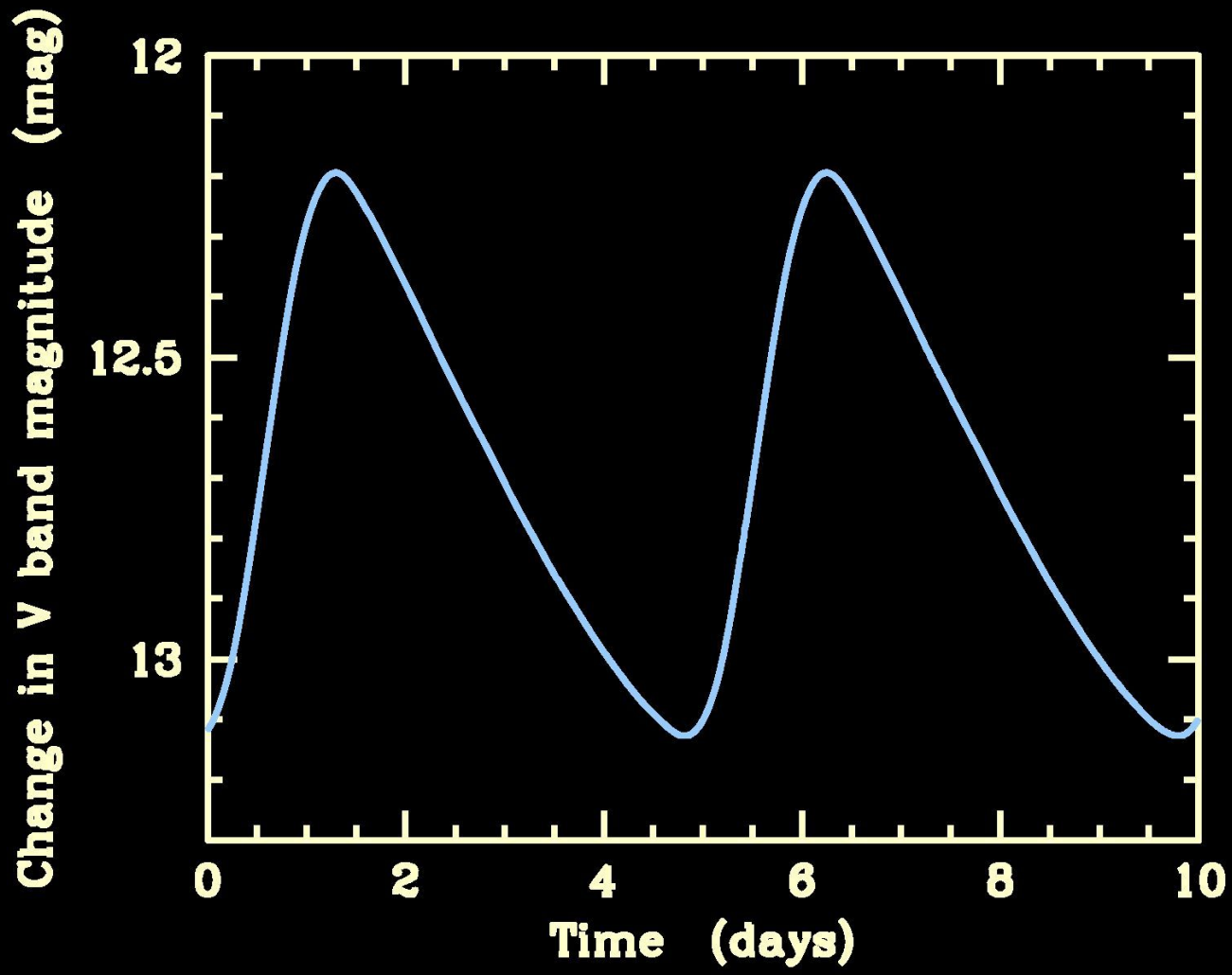
planetary nebulae

most luminous stars

supernovae - Type Ia

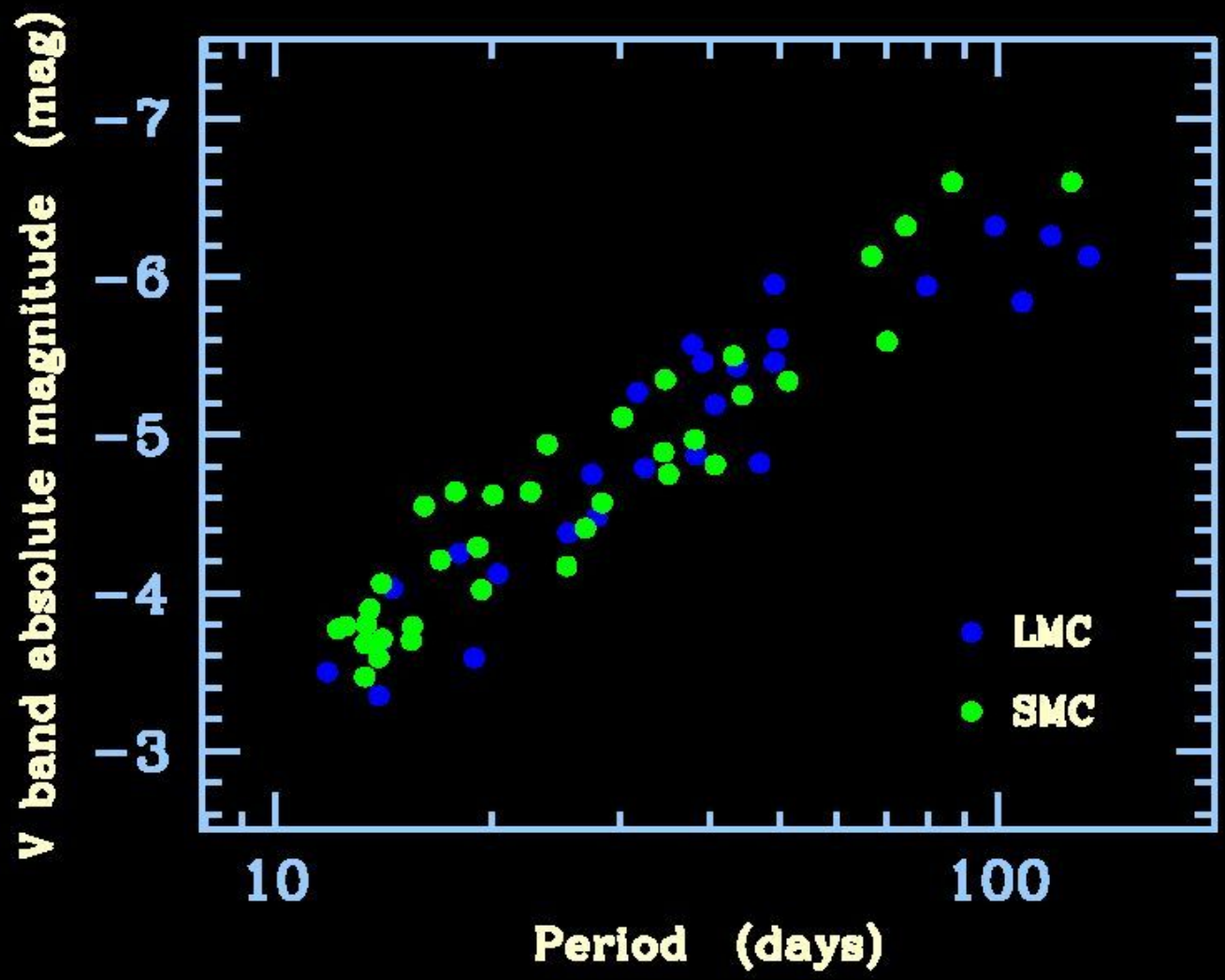
Stars in nearby galaxies : Cepheid variable stars

Characteristic change in brightness



Stars in nearby galaxies : Cepheid variable stars

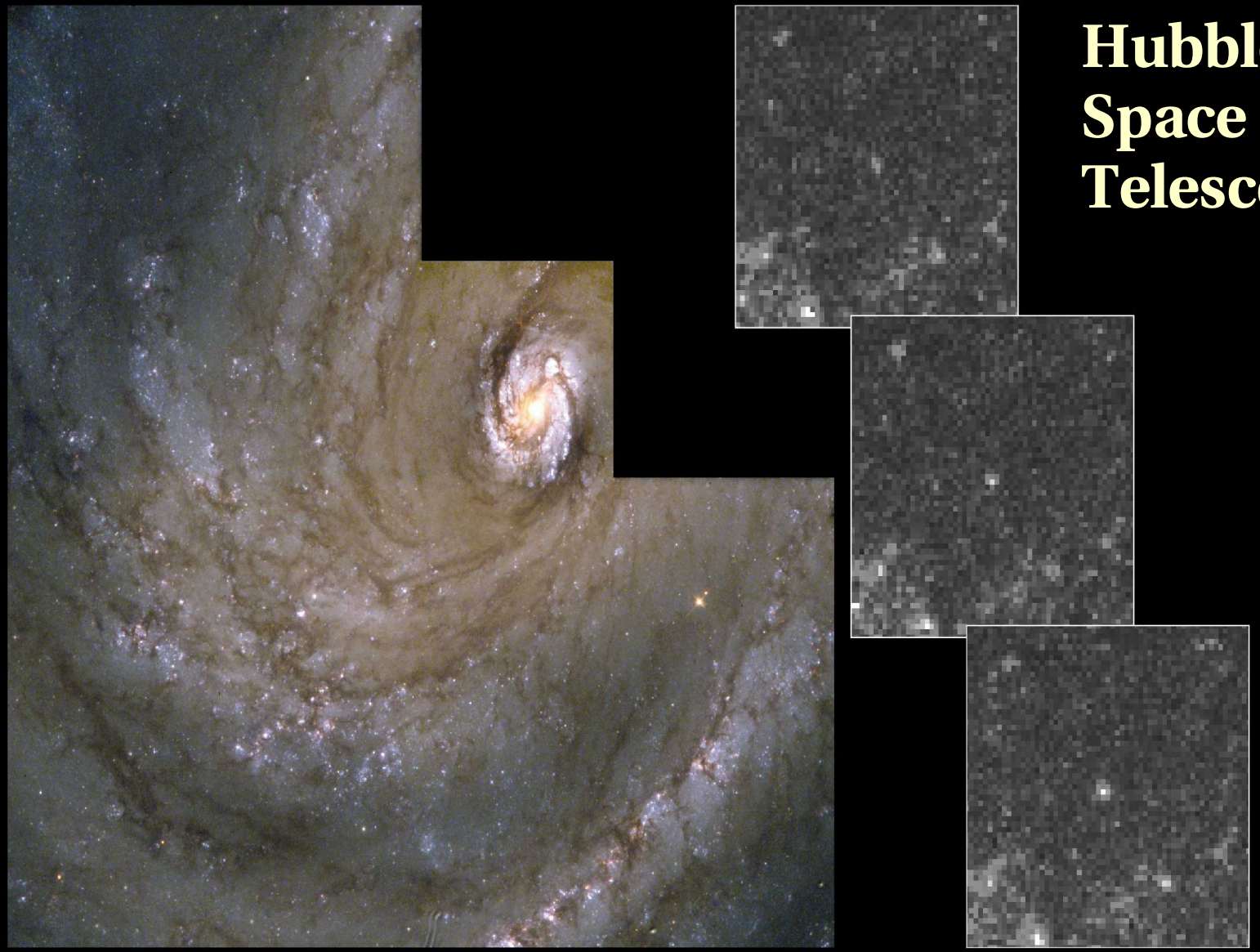
Period – luminosity relation



Madore & Freedman, PASP, 103, 933, 1991

Stars in nearby galaxies

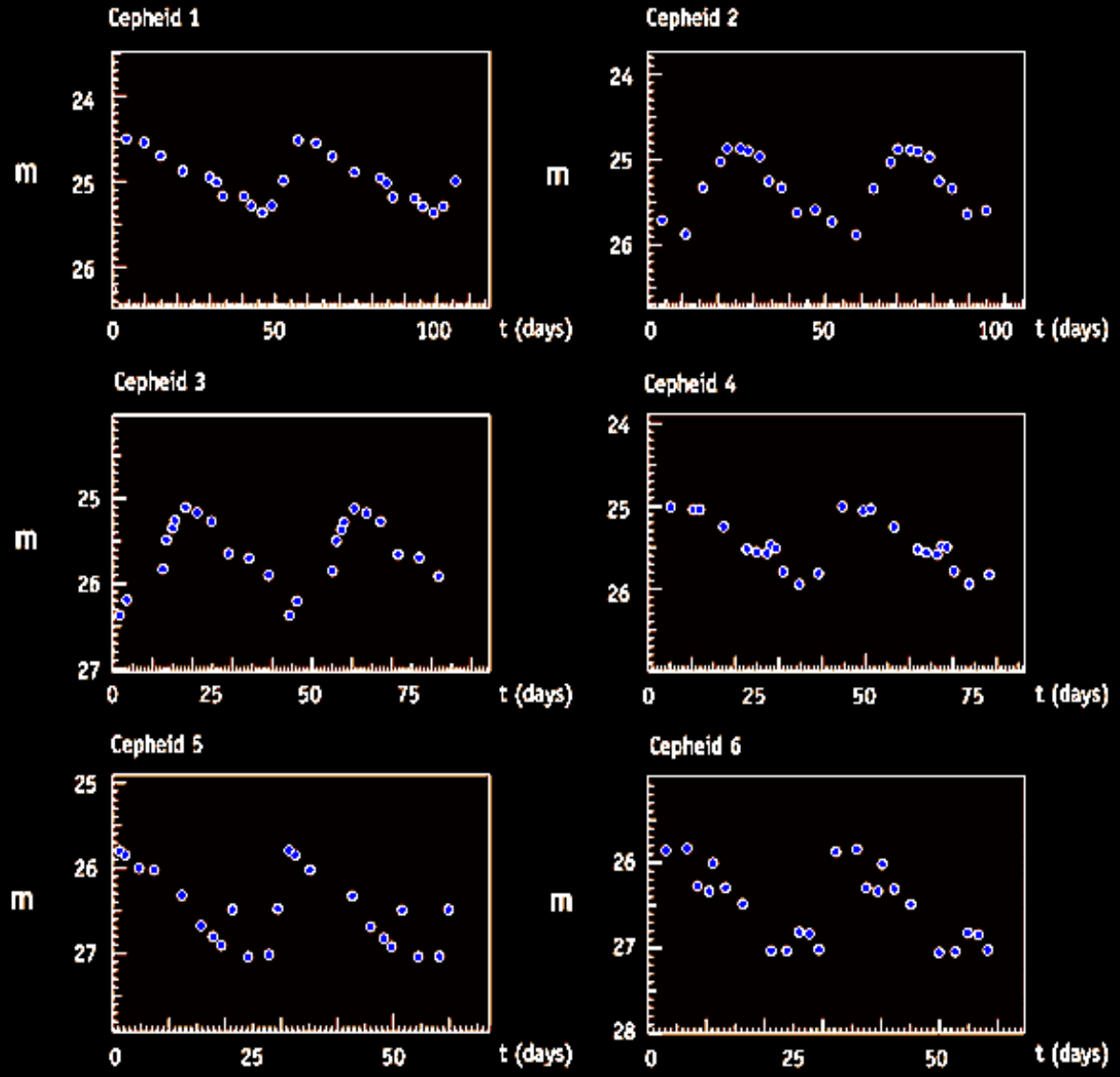
Cepheid variables in M100 in the Virgo Cluster of galaxies



Hubble Space Telescope

Stars in nearby galaxies

Cepheid variables in M100 in the Virgo Cluster of galaxies



Hubble Space Telescope

Use of distances

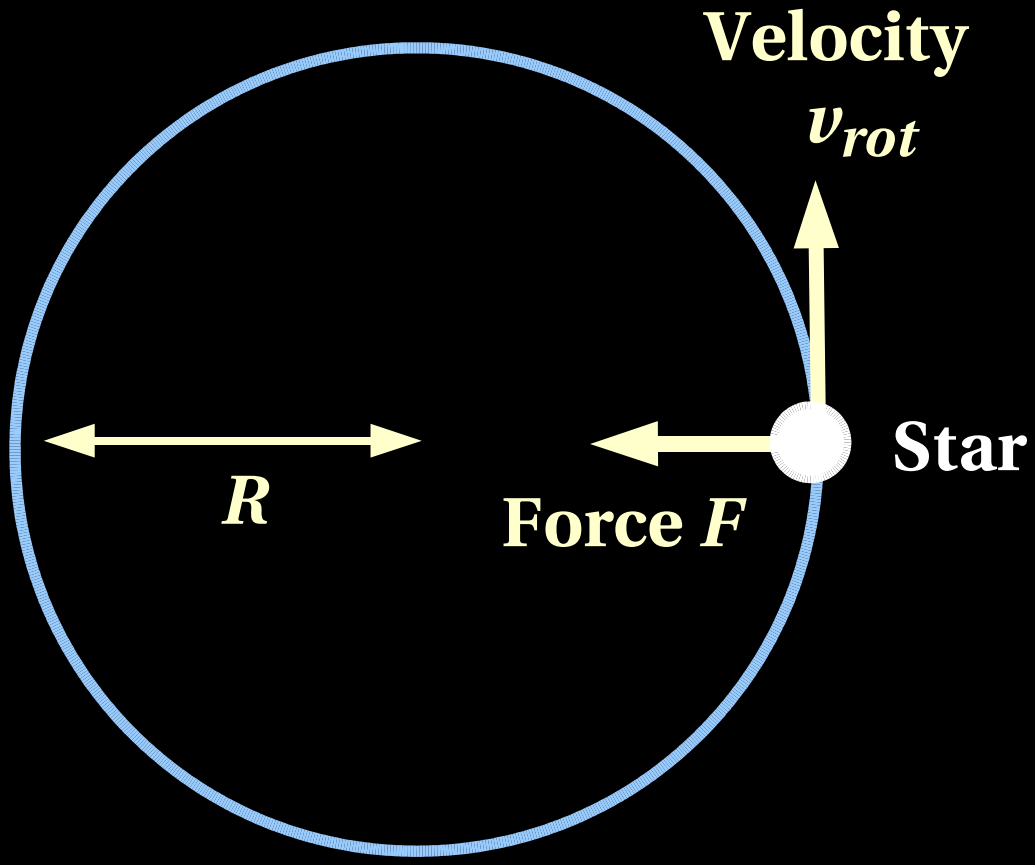
Once distances are known:

Observed brightness → **total energy emitted per unit time** *luminosity*

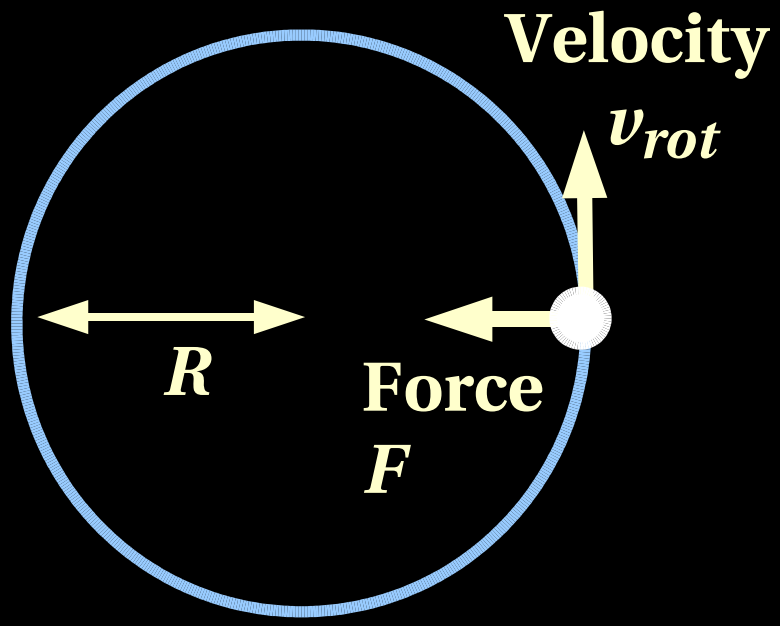
Angular size on sky → **physical size**

Rotation velocity

Consider a star of mass m in circular motion about the centre of a galaxy at a distance R from the centre



Rotation velocity



For a spherically symmetric mass distribution,

$$\text{Force } F = \frac{G\, M_{int}\, m}{R^2}$$

where $M_{int}(R)$ is the mass interior to radius R

Using $F = m\,a$ and $a = v_{rot}^2 / R$,

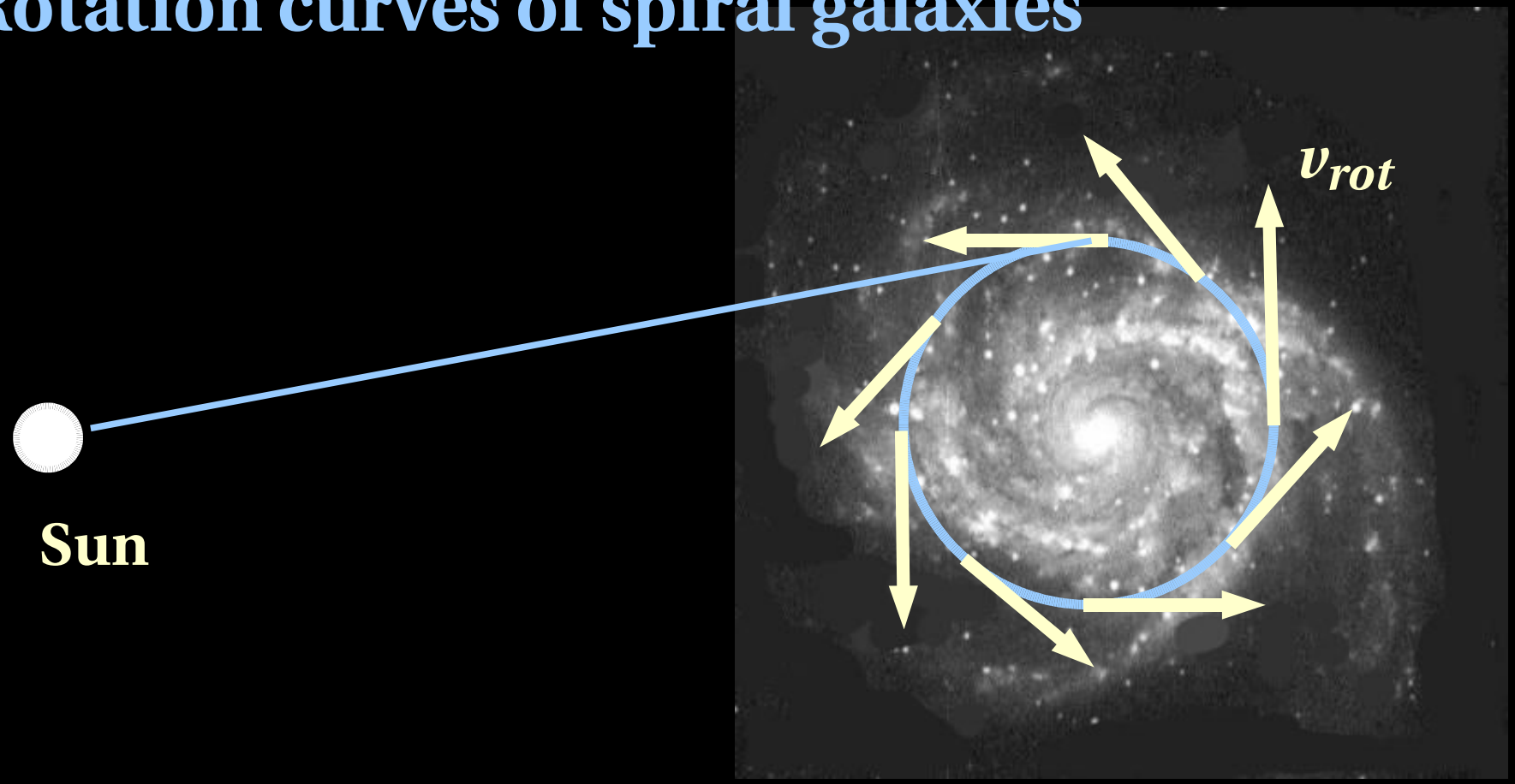
$$v_{rot} = \sqrt{\frac{G M_{int}(R)}{R}}$$

Rotation velocity of spiral galaxies

Can measure the rotation of spiral galaxies from the spectrum of the material in the galaxy using the Doppler shift

- from the combined spectrum of the stars
- from the emission lines from excited gas
- from the 21cm radio emission from cold neutral hydrogen

Rotation curves of spiral galaxies



Measure rotation velocity as function of distance from centre of galaxy - *rotation curve*

Rotation curves of spiral galaxies

Can calculate mass interior to a point as a function of radius from v_{rot}

$$M_{int(R)} = \frac{R\ v_{rot}^2}{G}$$

v_{rot} increases rapidly with radius R near the centre

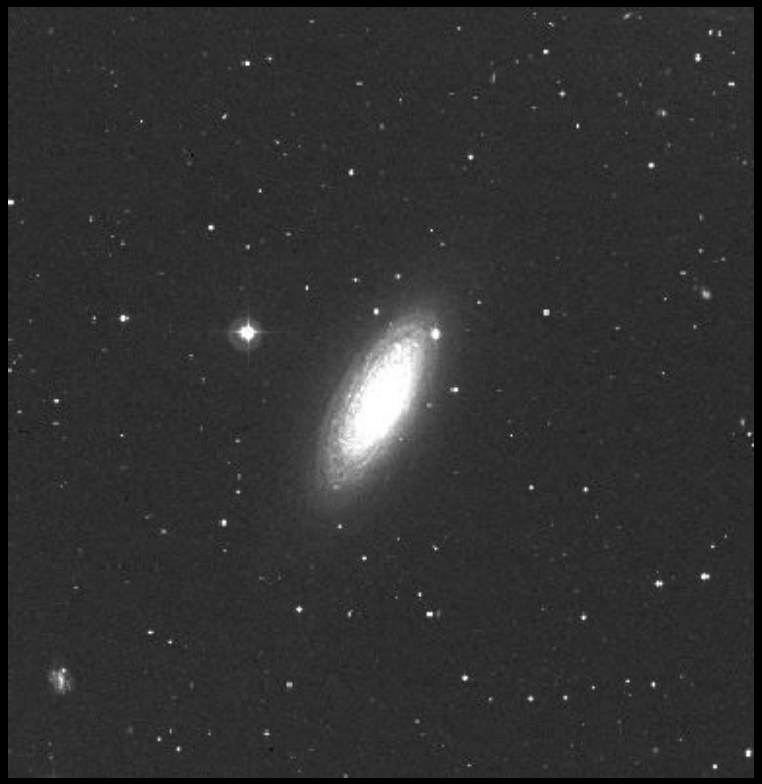
- then remains nearly constant for almost all observable radii

Indicates a large amount of unseen matter

- *dark matter*

Rotation curves of spiral galaxies

Rotation curve of NGC 2841 from radio observations



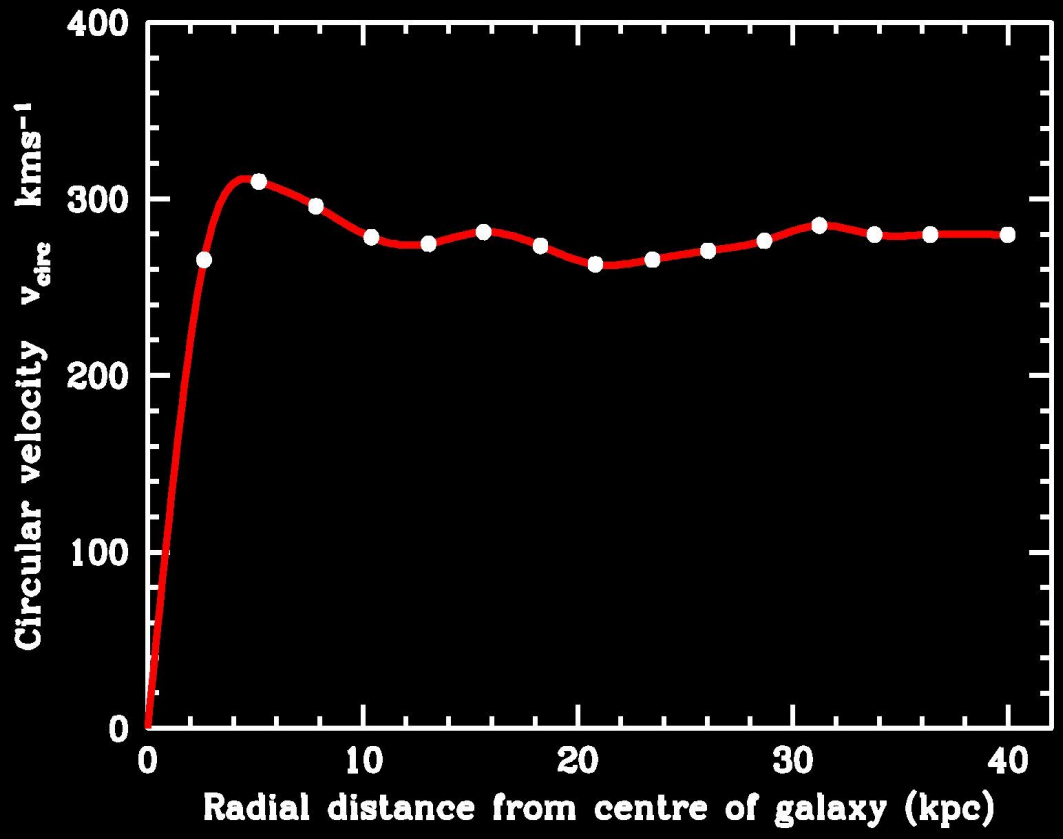


Image from the Digitized Sky Survey
Rotation curve data by S. M. Kent from A. Bosma, AJ, 93, 816, 1987

The spiral structure of spiral galaxies

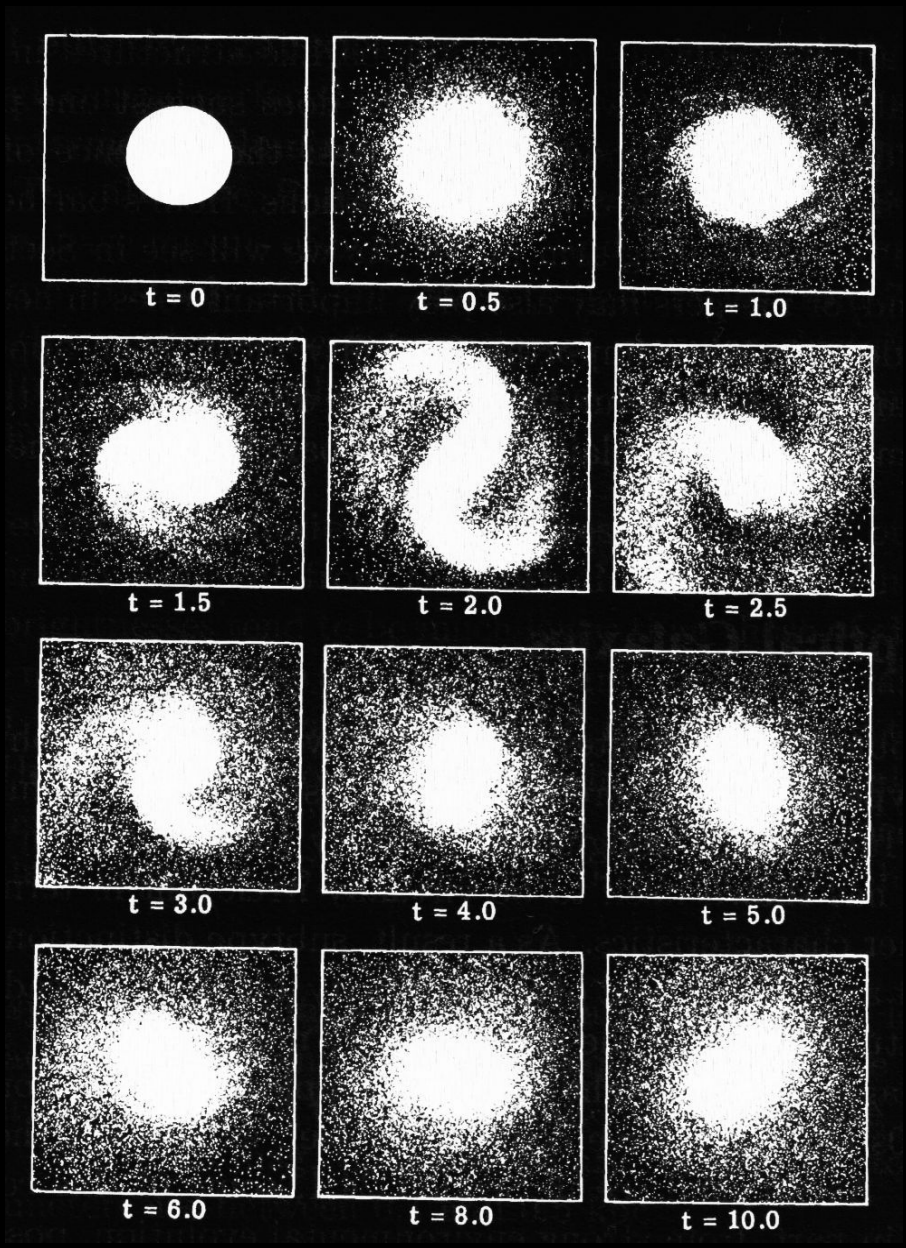
Spiral arms mark the regions of recent active star formation

Arms are the regions of greatest gas density

Spiral density patterns arise naturally particularly when stimulated by tides of nearby galaxies

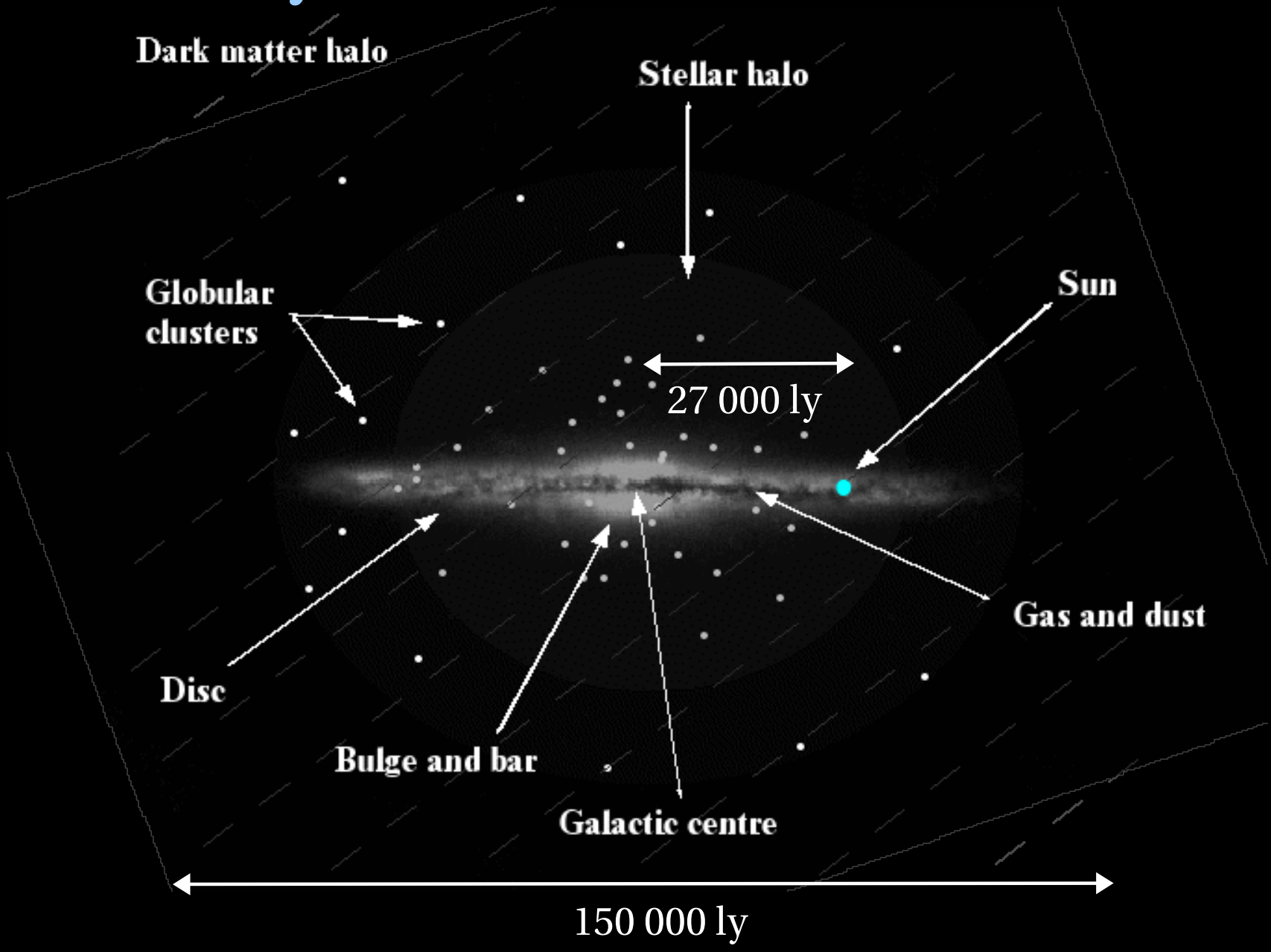
The spiral structure of spiral galaxies

Simulation of formation of spiral pattern



Hohl, ApJ, 168, 343, 1971

Our Galaxy


Dark matter halo
Stellar halo
Globular clusters
Sun
27 000 ly
Gas and dust
Disc
Bulge and bar
Galactic centre
150 000 ly

Evolution of galaxies

Galaxies can change over time

New stars can be formed if they contain gas

Evolved stars can return gas into the interstellar medium, containing heavy elements

As galaxies age, stars evolve - without new stars being formed, galaxy will become redder and slightly fainter

Gas can be removed from galaxies, through forming stars, being removed by pressure of gas in clusters

Interacting galaxies

NGC 2207 and IC 2163 HST

Interacting galaxies

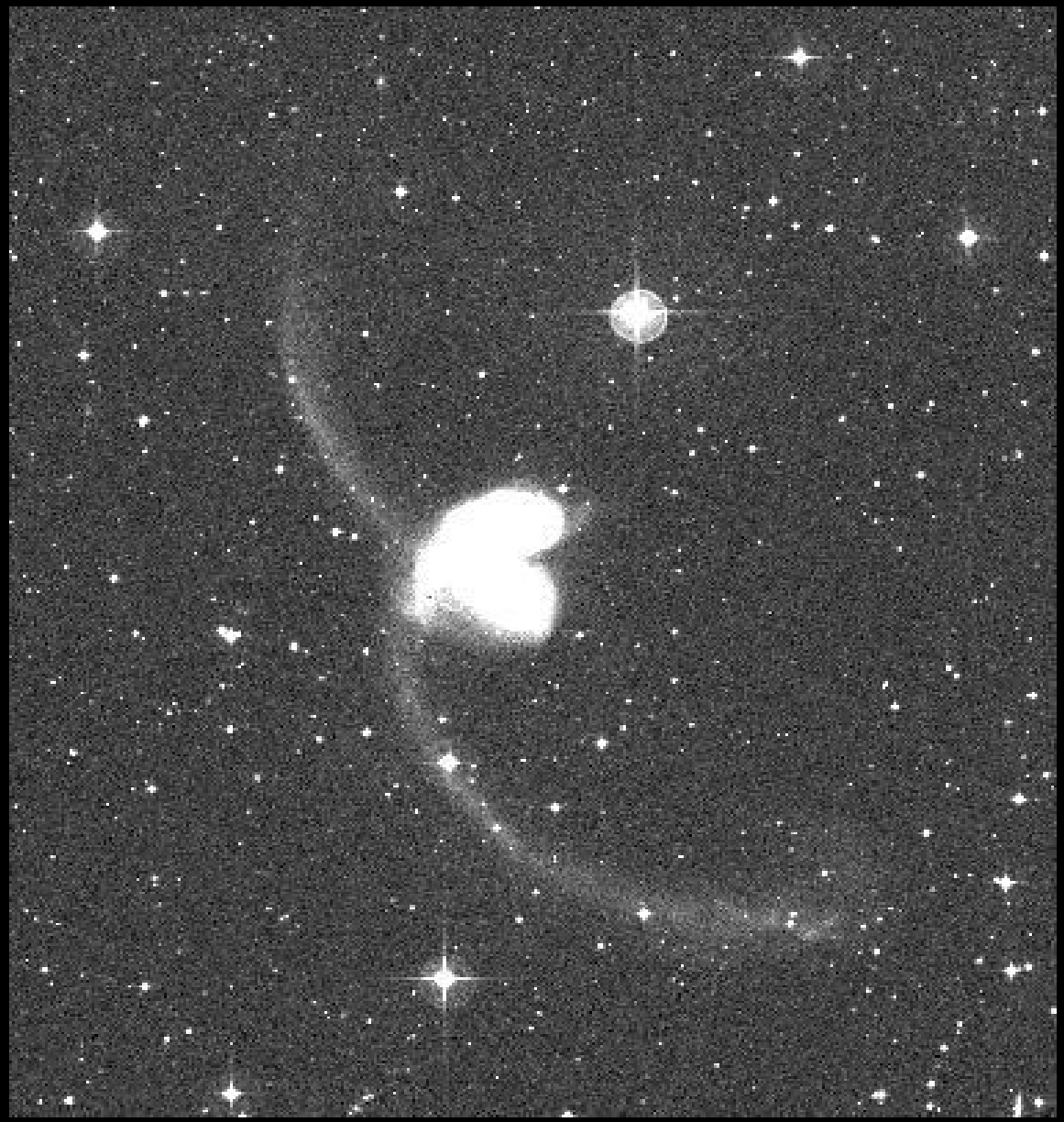
Interactions cause star formation
- gas is compressed and shocked

Some gas is used up in star formation

The Tadpole Galaxy UGC 10214 HST ACS

Merging galaxies

The Antennae: wide-angle view



UKST blue data from the SuperCOSMOS Sky Survey at the ROE

Merging galaxies

The core of The Antennae

Merging galaxies

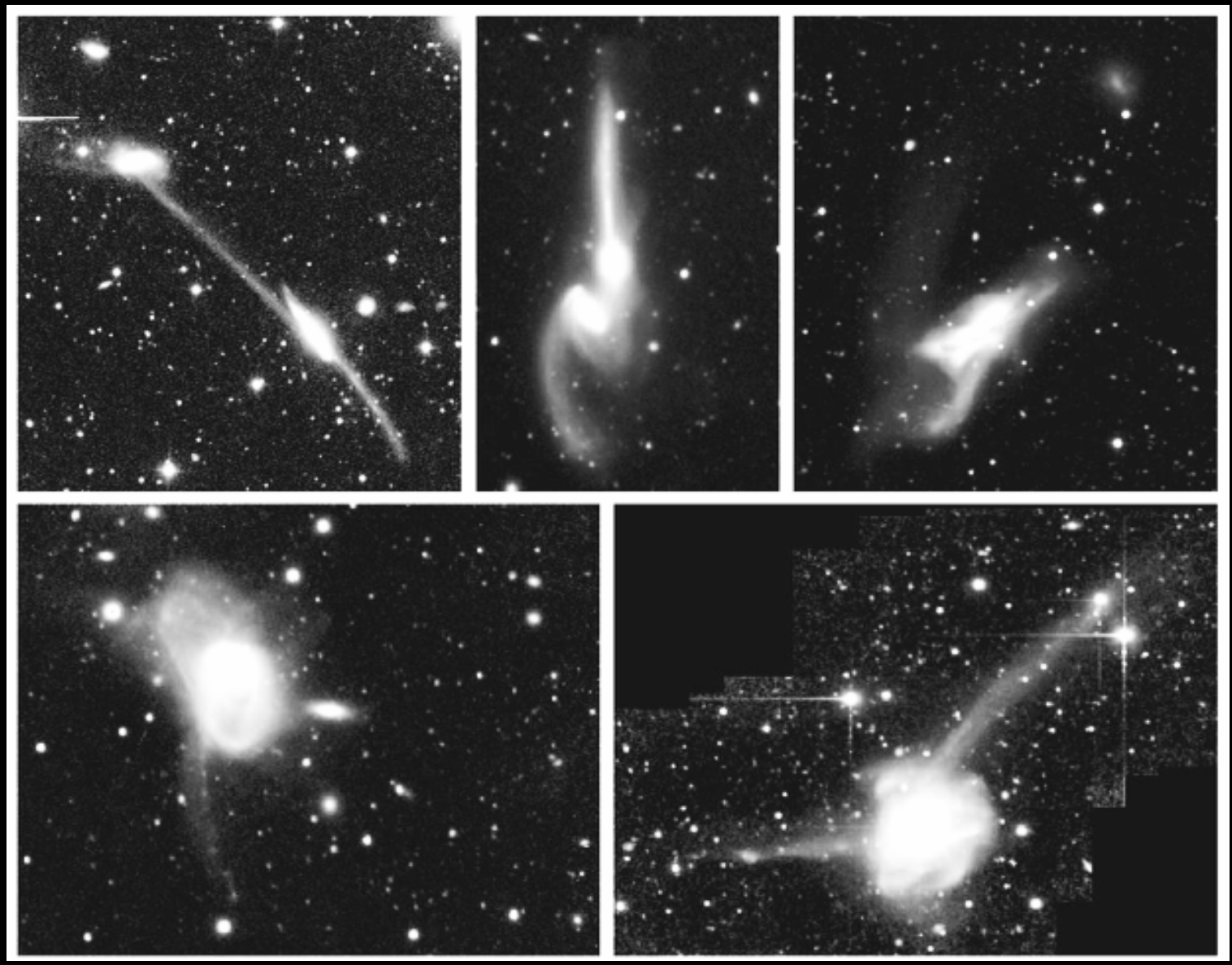
Gas is compressed and shocked
- intense star formation

Gas is used up in star formation

Mergers can form ellipticals

Merging galaxies

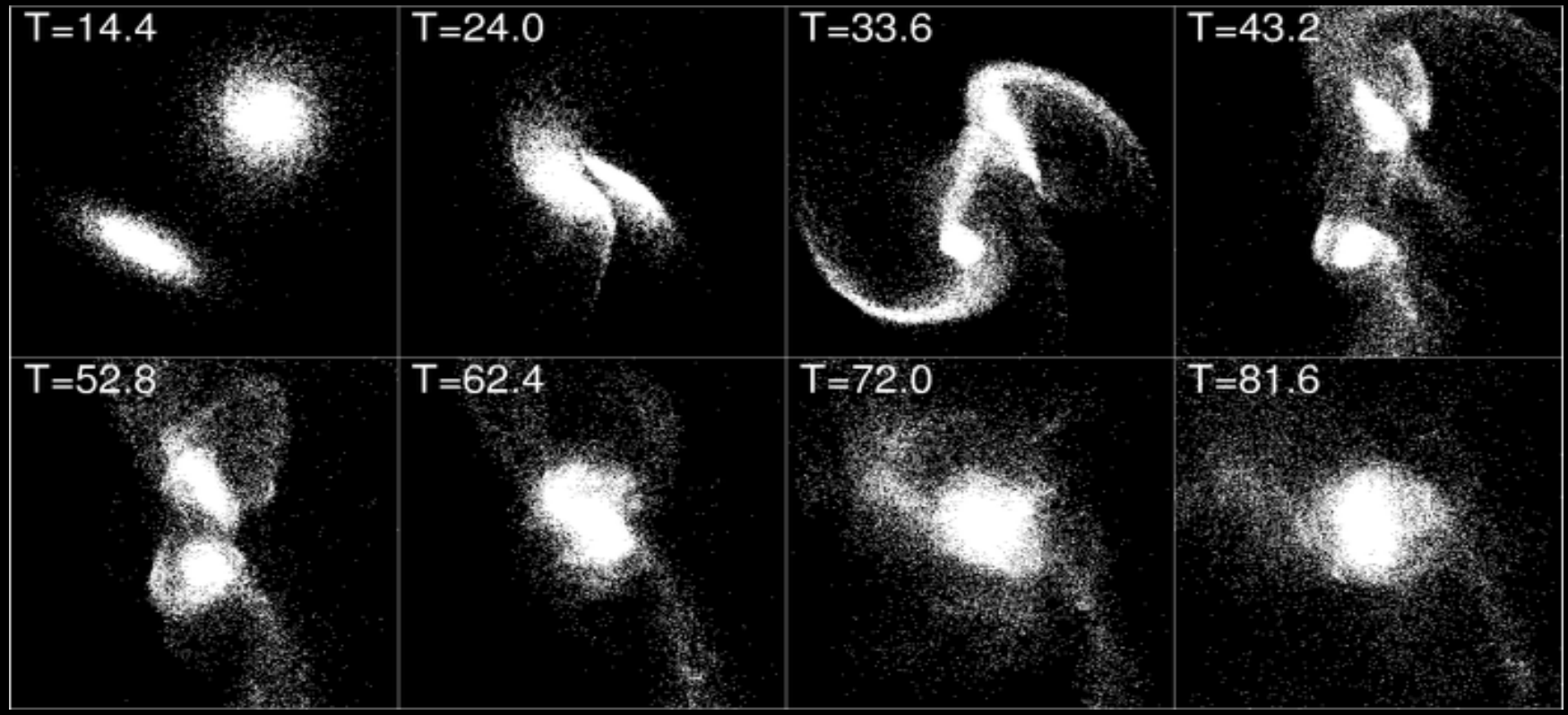
Observed examples



Hibbard & van Gorkum, AJ, 111, 655,1996

Merging galaxies

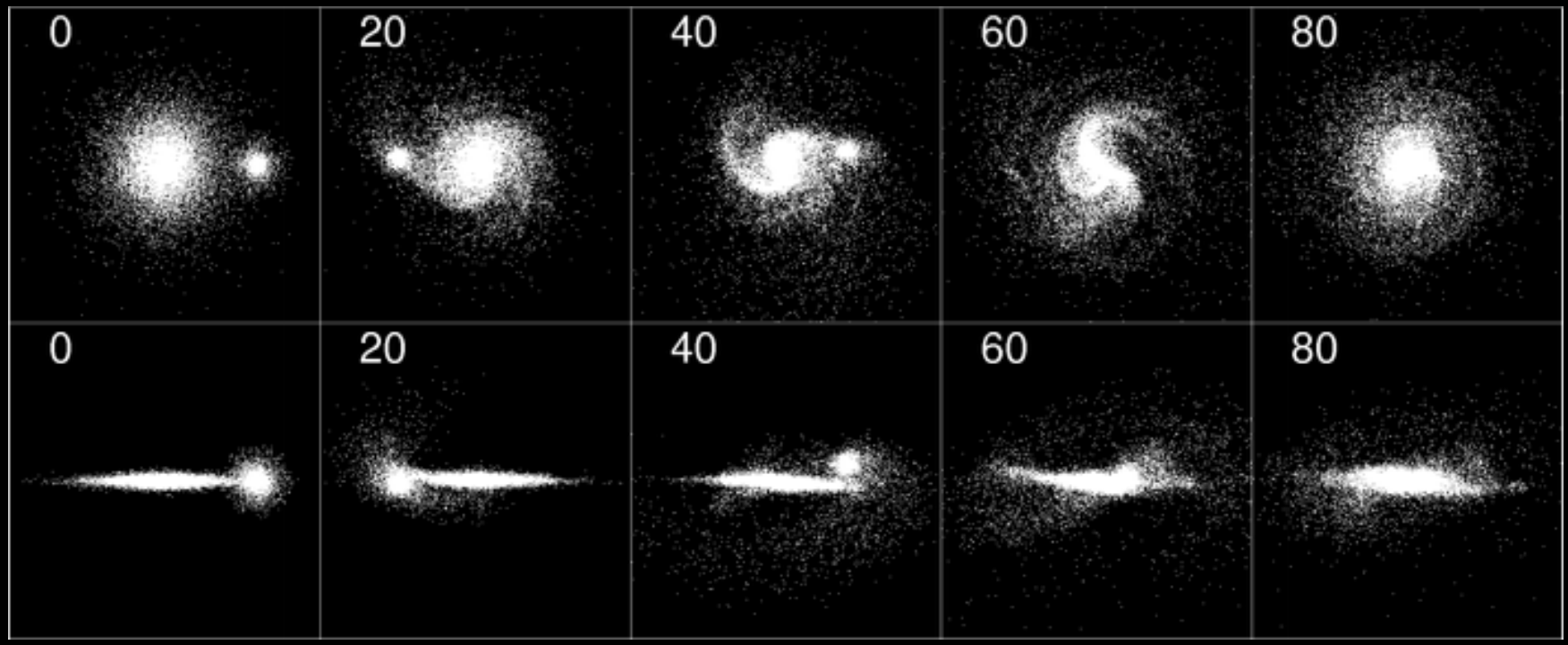
Simulation of merger of two spiral galaxies



Mihos & Hernquist, ApJ, 464, 662, 1996

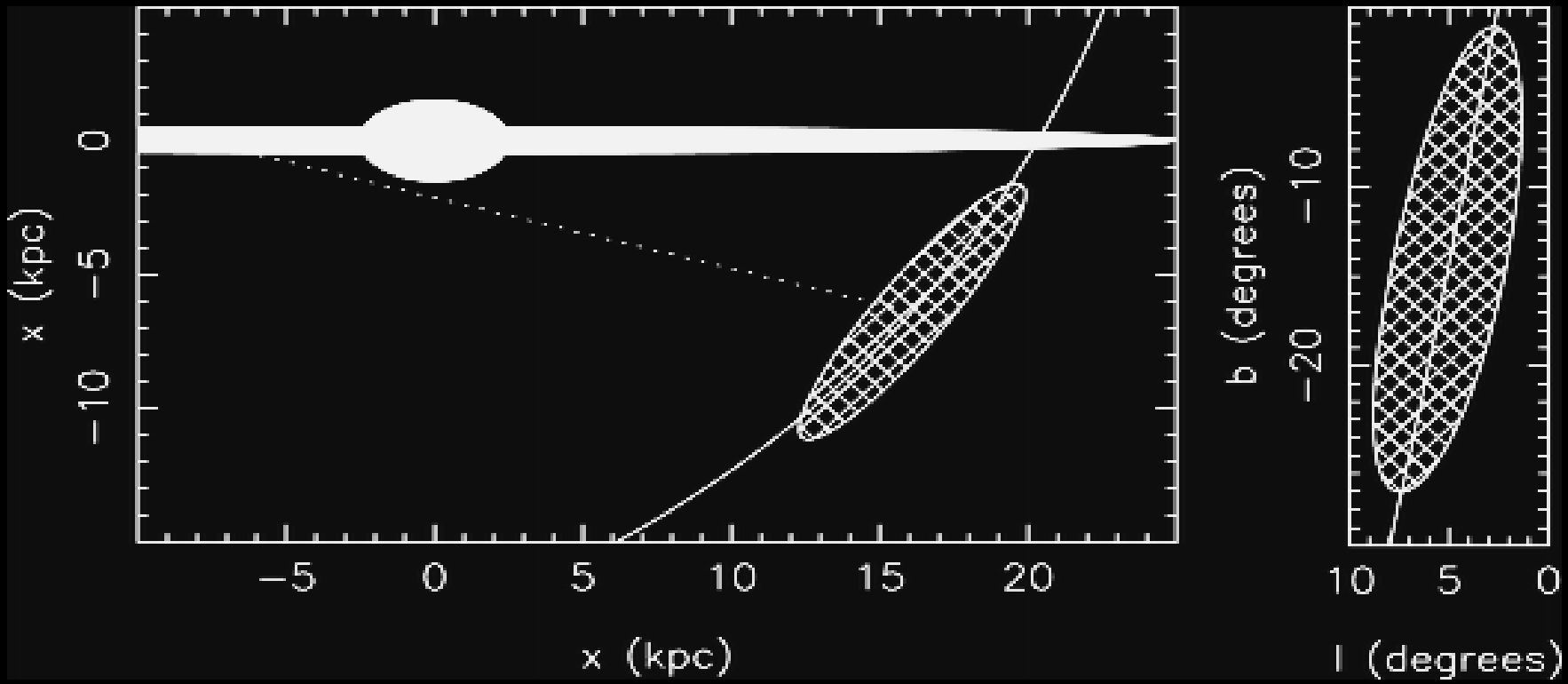
Merging galaxies

Simulation of merger of a spiral and a dwarf galaxy



Hernquist & Mihos, ApJ, 448, 41, 1995

Merging galaxies : our Galaxy and the Sagittarius Dwarf Galaxy



Where galaxies live

Our Galaxy lies in a collection of 40 – 50 galaxies called the *Local Group*

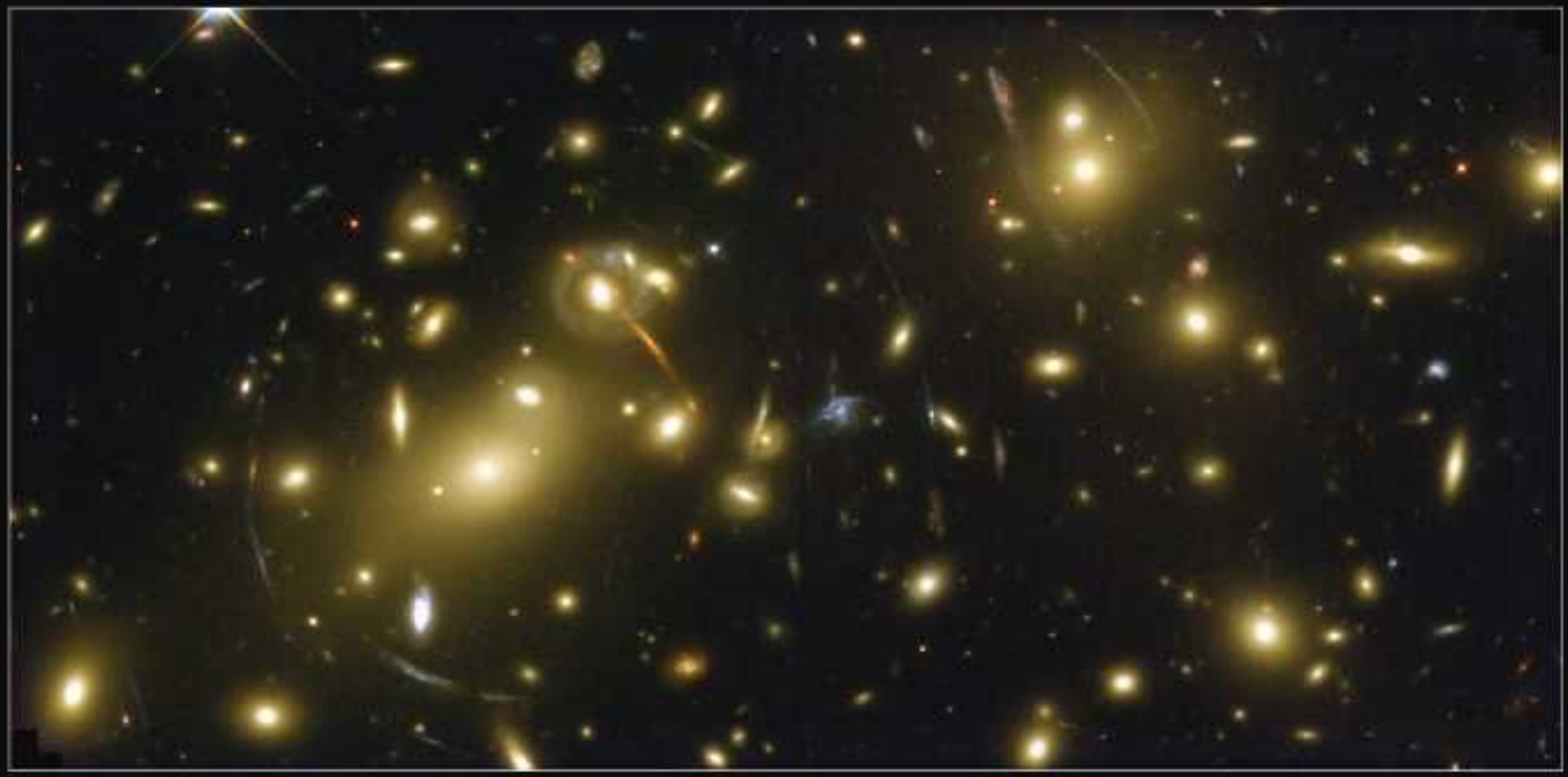
Some galaxies are isolated

Some exist in groups - few to few hundred galaxies

Some lie in clusters of galaxies - hundreds or thousands of galaxies
Some clusters are dense

Clusters of galaxies

Abell 2218 HST



Galaxy type vs. environment

Elliptical galaxies are plentiful in clusters
but rare in the field

Spirals and irregulars are plentiful in the field
but less so in clusters

Interactions, mergers and stripping of gas has
ended much of the star formation in clusters

Other types of galaxy

Dwarf galaxies

Low luminosity galaxies

Plentiful e.g. most galaxies in the Local Group are dwarfs

Main types

- dwarf irregulars
- dwarf ellipticals
- dwarf spheroidals

Dwarf galaxies

NGC 1705 dwarf irregular

HST

Dwarf galaxies

NGC 205 / M110

Local Group, companion to M31

2.2 Mly distant

0.9m telescope Kitt Peak National Observatory

Dwarf galaxies

Tucana dwarf spheroidal galaxy

UKST / SuperCOSMOS Sky Survey
blue plate

Local Group

2.9 Mly
distant

Dwarf galaxies

Leo I dwarf spheroidal galaxy

Local Group, 800 000 ly

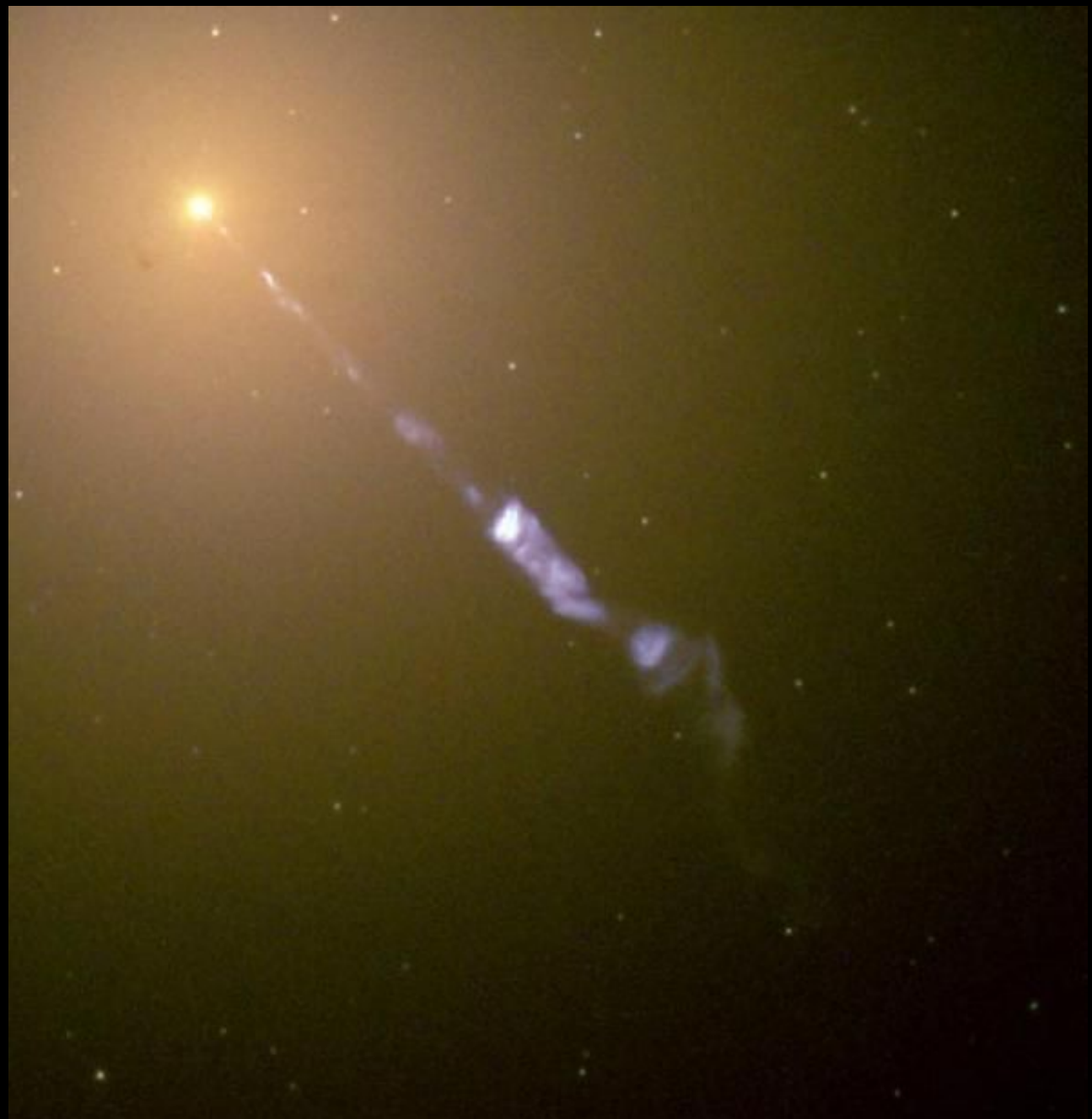
Anglo-Australian Telescope

Active galaxies

Extremely powerful energy source in a compact nucleus

Probably accretion on to a black hole

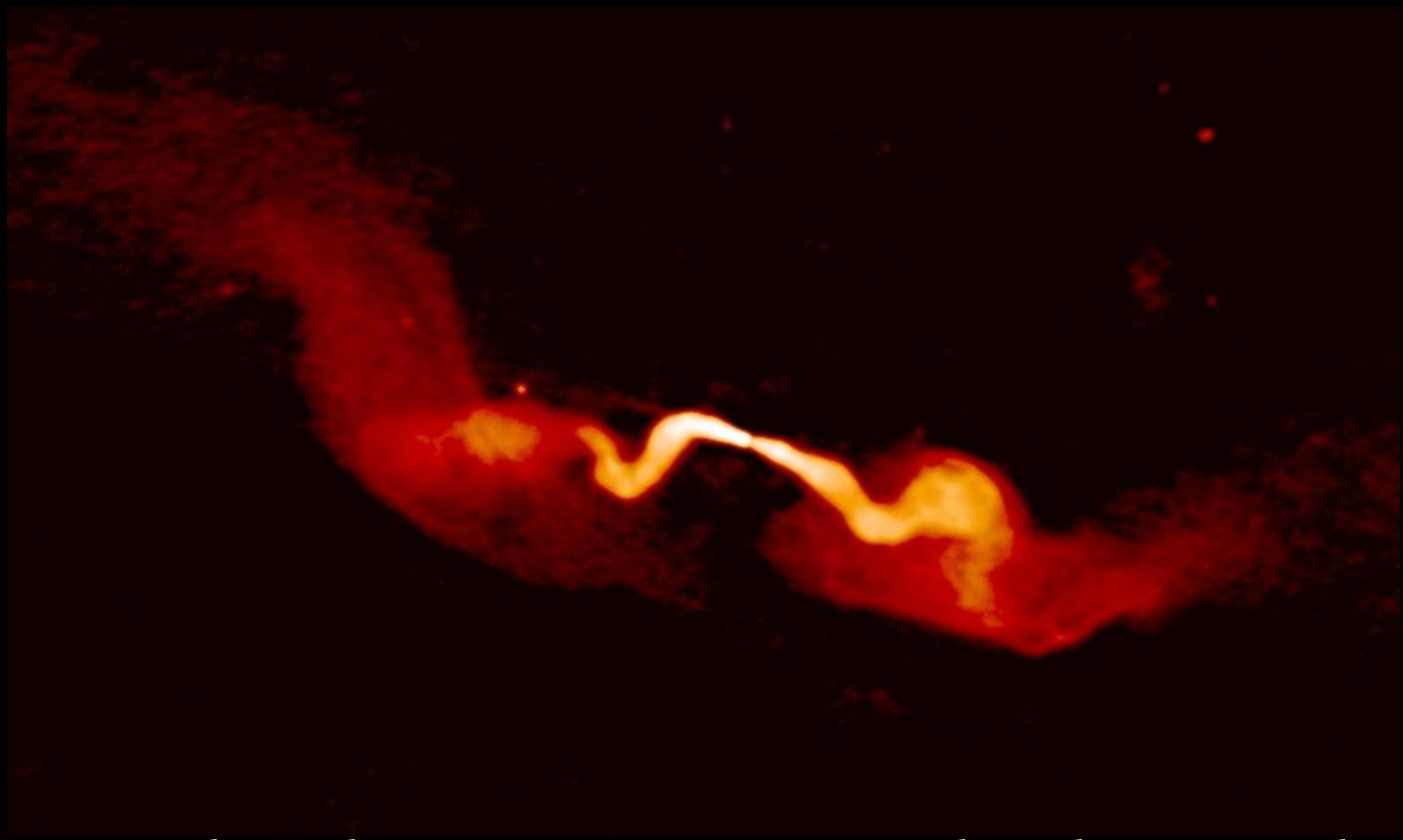
Active galaxies



M87 jet

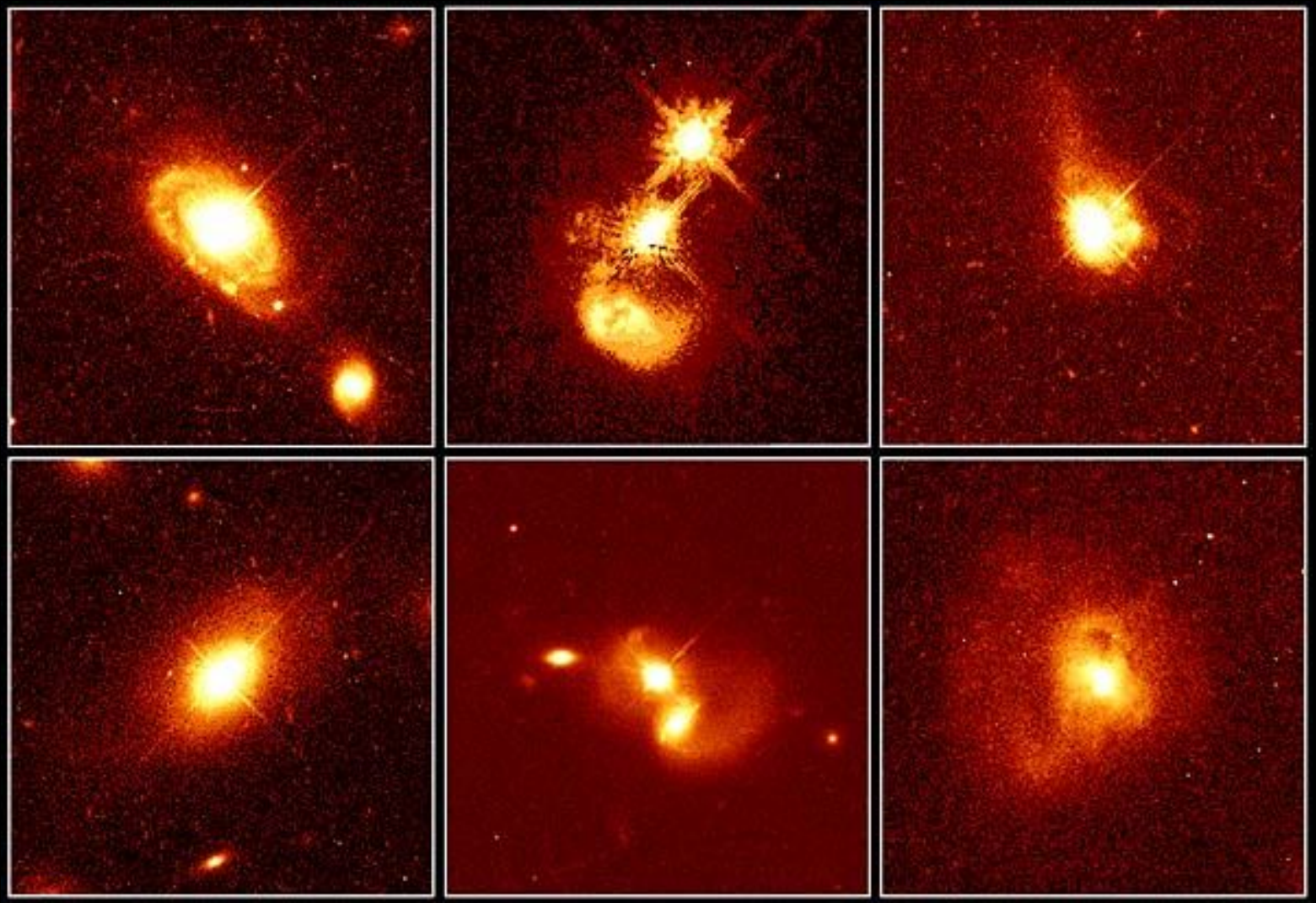
HST

Radio galaxies



Radio galaxy 3C31 (NGC383) with radio jets and lobes. Observed with the Very Large Array.

Quasars


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

Galaxy formation

How did galaxies form ?

Once it was believed that a single large cloud collapsed to form a galaxy

Clouds with little angular momentum formed ellipticals

Clouds with substantial angular momentum formed spirals

Galaxy formation

How did galaxies form ?

Numerical simulations show that dark matter in the early Universe formed many small clumps
- **also contained gas**

The clumps merged to form larger units, producing galaxies

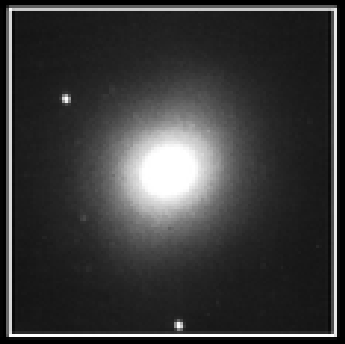
Age of the Universe

Today: 14 Billion Years

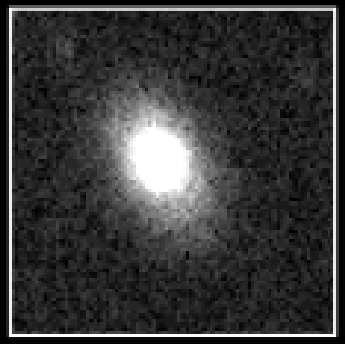
9 Billion Years

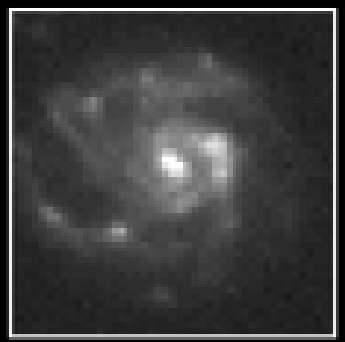
5 Billion Years

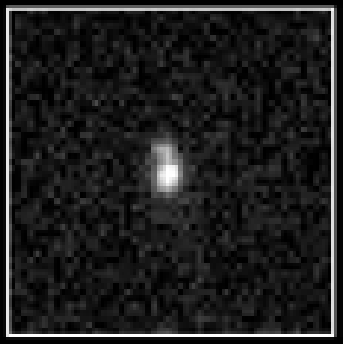
2 Billion Years



Elliptical







Spiral

In Summary

The Universe is populated with galaxies

Vast systems of 10^6 to 10^{12} stars

Spirals, ellipticals, irregulars, peculiars, dwarfs, active galaxies

Contain stars, many contain gas, but dark matter dominates

Spirals and irregulars plentiful in the field, ellipticals plentiful in clusters of galaxies

In Summary

Evolution determined by conversion of gas into stars, interactions, mergers, passage through diffuse gas in clusters

Formation probably by merging of small galaxies and sub-galactic units early in the Universe

Curious object

NGC 2997

Red

Infrared

UKST / SuperCOSMOS Sky Survey