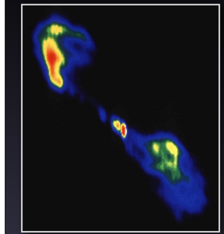
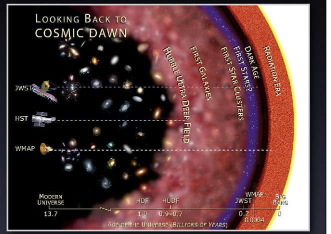
Active Galaxies & Cosmology





Koupelis :- chapters 17 & 18
Openstax : chapters 27, 28 & 29

Our Sun is located

at the very outer edge of the Galaxy. 0%

far from the center of the Galaxy, but not at the outer edge. 0%

near the center of the Galaxy, but not right at the center. 0%

at the center of the Galaxy. 0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

Why is observation of distant parts of the Milky Way limited in the visible region?

Interstellar dust blocks visible light. 0%

The redshift of the distant stars makes them difficult to detect. 0%

Opacity of our atmosphere blocks visible light. 0%

Relative motion of the spiral arms makes them difficult to detect. 0%

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A calculation of the mass of the inner part of a galaxy can be made based on

observations of nebulae in the spiral arm. 0%

Kepler's laws. 0%

distances to Cepheid variables. 0%

star counts. 0%

Cepheid variables are important in calculating

the composition of the interstellar medium. 0%

the temperature of stars. 0%

the ages of galaxies. 0%

the distance to galaxies. 0%

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The Local Group consists of

about 100 nearby stars. 0%

about 30 nearby stars. 0%

about 30 nearby galaxies. 0%

about 100 nearby galaxies. 0%

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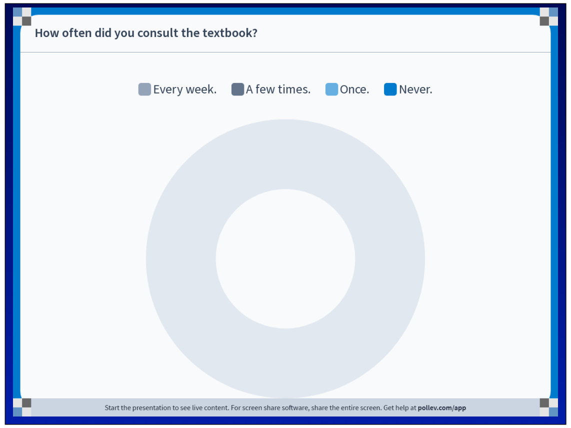
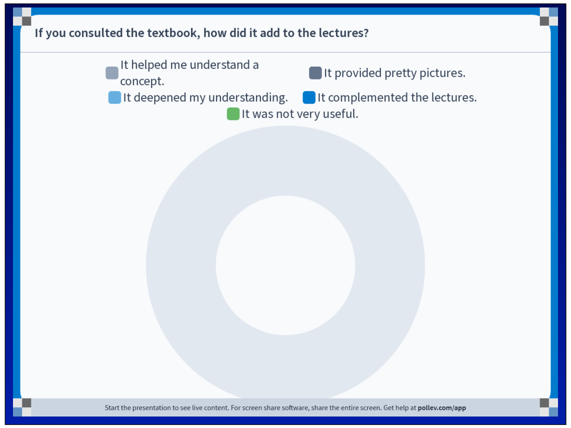

How often did you consult the textbook?
Every week.
A few times.
Once.
Never.
Start the presentation to see live content. For screen share software, share the entire screen. Get help at pollev.com/app


If you consulted the textbook, how did it add to the lectures?
It helped me understand a concept.
It provided pretty pictures.
It deepened my understanding.
It complemented the lectures.
It was not very useful.
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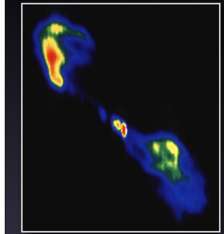
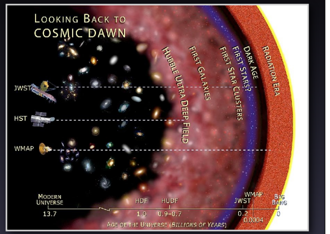
Active Galaxies & Cosmology





Koupelis :- chapters 17 & 18
Openstax : chapters 27, 28 & 29

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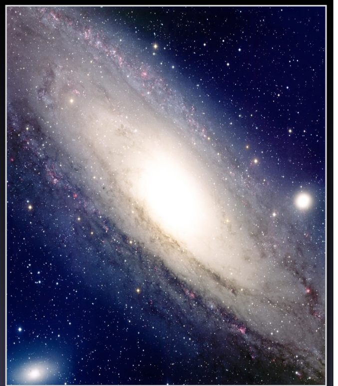
until 1950:

A quiescent Universe...



The first indications for a 'restless' Universe:

Messier 87:
'flames' or 'jet streams' emanate from the core

(Fath, 1908)

Further indications for highly energetic processes:

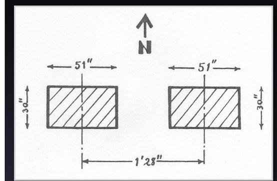
UV-bright cores and
emission lines from extremely hot gas

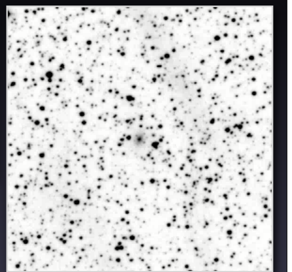
(Seyfert 1943)

Then, radio astronomy develops...

Grote Reber (1911-2002)

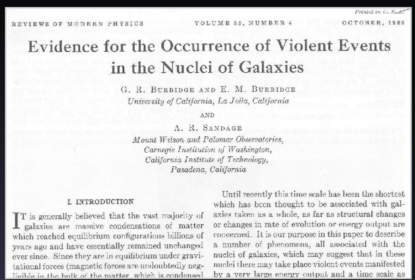
…and giant radio clouds are discovered near galaxies!





1954: Cygnus A

The discovery of 'radio galaxies' is a strong motivation to develop radio-interferometry techniques.



Printed in U. S. A.

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Evidence for the Occurrence of Violent Events in the Nuclei of Galaxies

G. R. BURBIDGE AND E. M. BURBIDGE
University of California, La Jolla, California

AND

A. R. SANDAGE
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

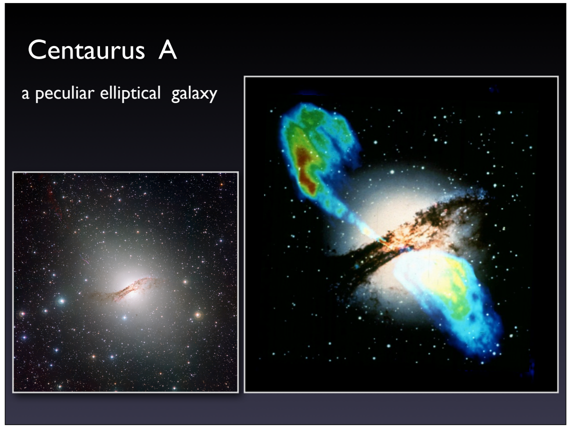
I. INTRODUCTION

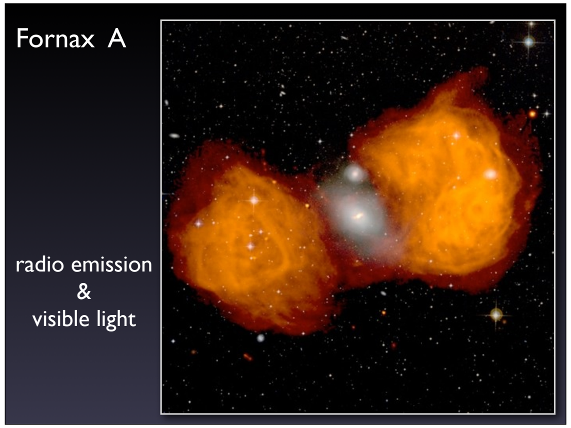
IT is generally believed that the vast majority of galaxies are massive condensations of matter which reached equilibrium configurations billions of years ago and have essentially remained unchanged ever since. Since they are in equilibrium under gravitational forces (magnetic forces are undoubtedly negligible in the bulk of the matter, which is condensed

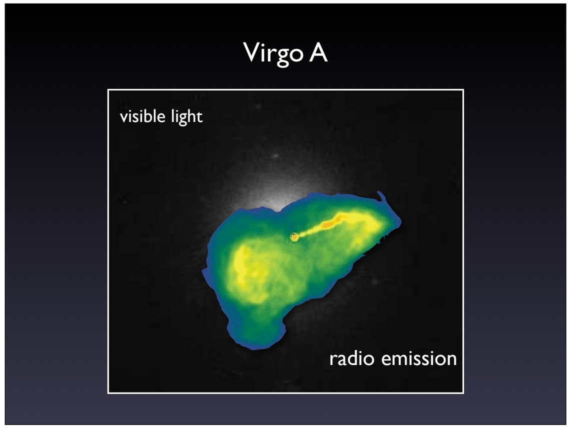
Until recently this time scale has been the shortest which has been thought to be associated with galaxies taken as a whole, as far as structural changes or changes in rate of evolution or energy output are concerned. It is our purpose in this paper to describe a number of phenomena, all associated with the nuclei of galaxies, which may suggest that in these nuclei there may take place violent events manifested by a very large energy output and a time scale as

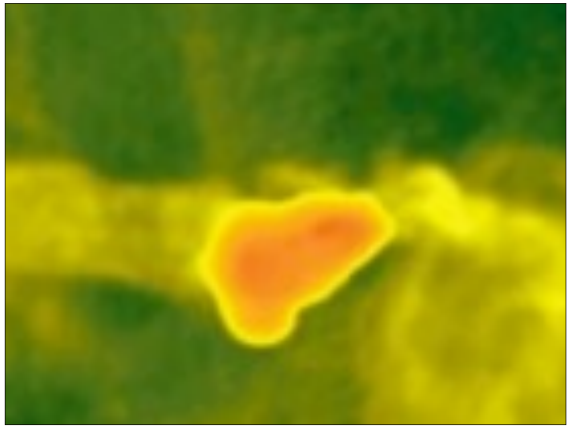
(1963)

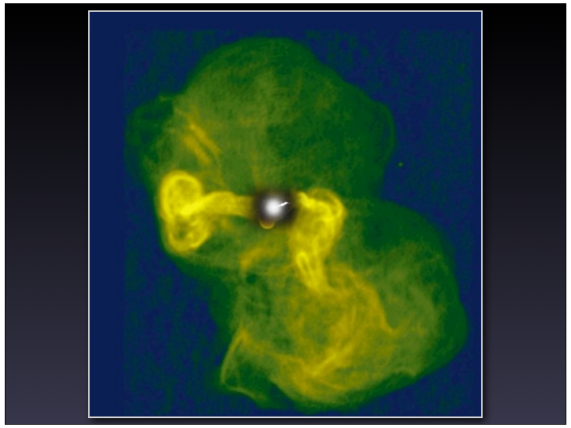
This allows the detailed mapping of radio emission from galaxies.


Centaurus A
a peculiar elliptical galaxy

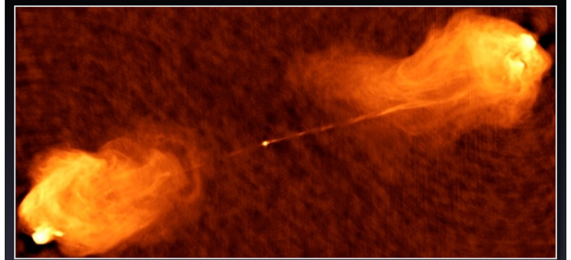

Fornax A
radio emission
&
visible light


Virgo A
visible light
radio emission



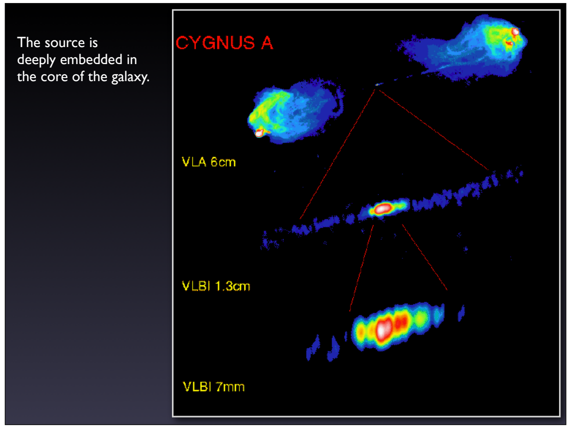


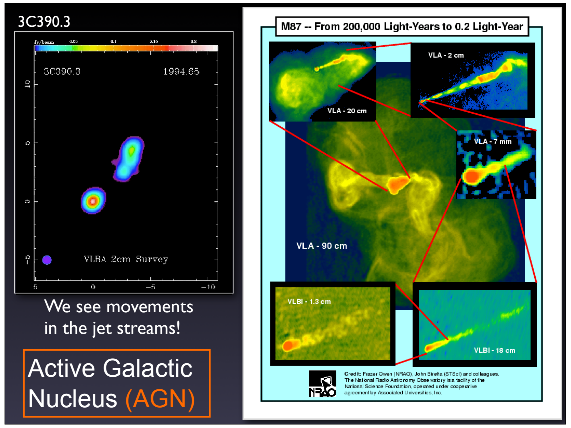
Cygnus A

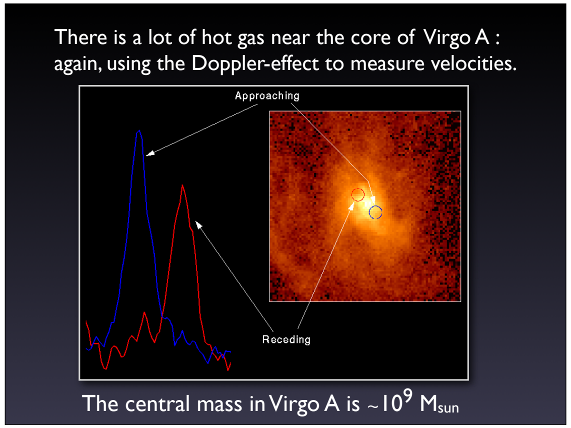


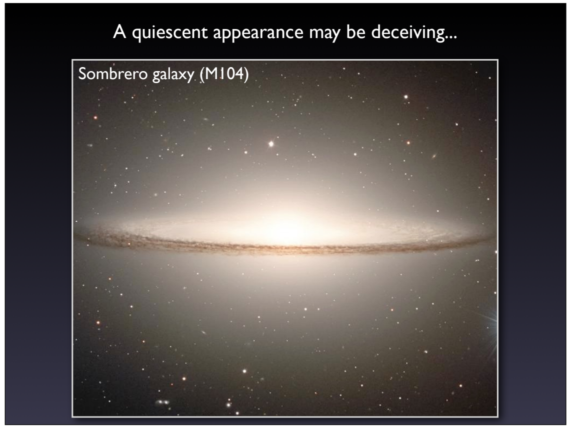
Radio power amounts to ~10^{40} Watt

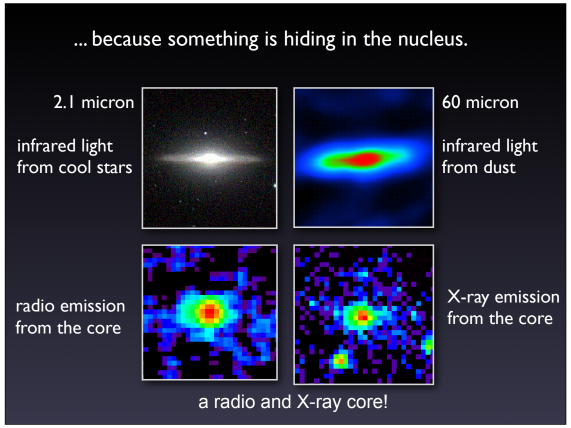
→ millions of times more radio emission compared to the Milky Way.

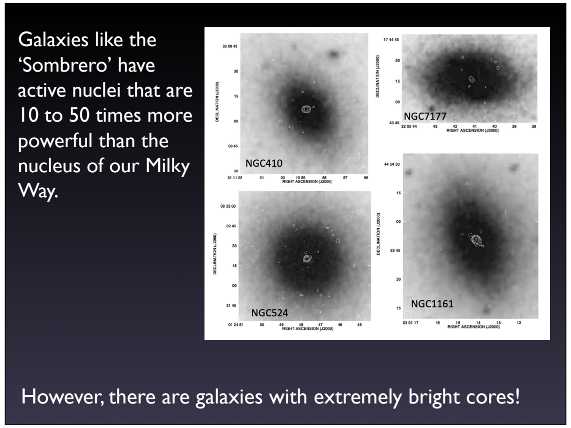

The source is deeply embedded in the core of the galaxy.
CYGNUS A
VLA 6cm
VLBI 1.3cm
VLBI 7mm


3C390.3
3C390.3
1994.65
VLBA 2cm Survey
We see movements in the jet streams!
Active Galactic Nucleus (AGN)
M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 20 cm
VLA - 2 cm
VLA - 7 mm
VLA - 90 cm
VLBI - 1.3 cm
VLBI - 18 cm

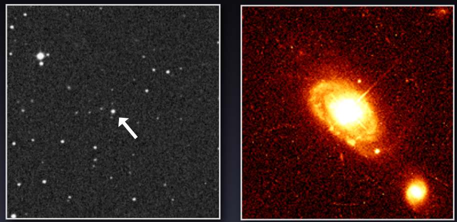

There is a lot of hot gas near the core of Virgo A : again, using the Doppler-effect to measure velocities.
Approaching
Receding
The central mass in Virgo A is ~10^9 M_{sun}


A quiescent appearance may be deceiving...
Sombrero galaxy (M104)


... because something is hiding in the nucleus.
2.1 micron
infrared light
from cool stars
60 micron
infrared light
from dust
radio emission
from the core
X-ray emission
from the core
a radio and X-ray core!


Galaxies like the 'Sombrero' have active nuclei that are 10 to 50 times more powerful than the nucleus of our Milky Way.
NGC410
NGC7177
NGC524
NGC1161
However, there are galaxies with extremely bright cores!

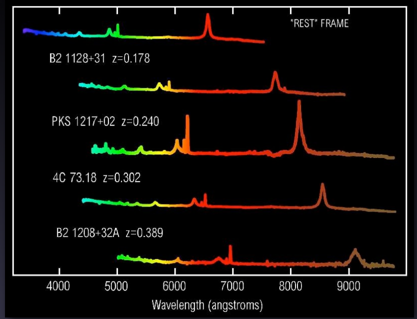
Quasars (Quasi-Stellar Objects) - discovered in 1963.
Although discovered as radio sources,
some 90% of the Quasars are not 'radio bright'.



Quasars are quasi-stellar because the extremely bright cores outshine the entire galaxy → visible at very large distances.

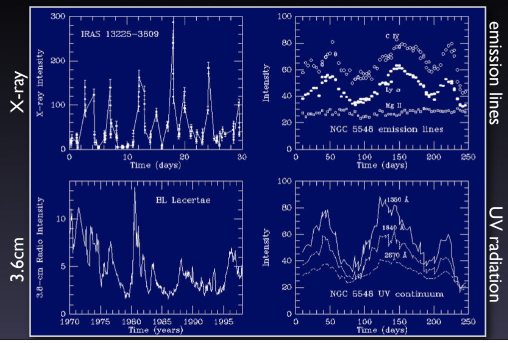
These are extremely 'active' galaxies.

The emission lines in Quasar-spectra show huge redshifts…
This made it difficult to identify their nature.



→ They are at enormous distances (Hubble law).

Since the '60s we discovered that active galaxies are also bright sources of energetic X-ray and gamma-ray radiation, and sometimes highly variable!



Properties of active galaxies:

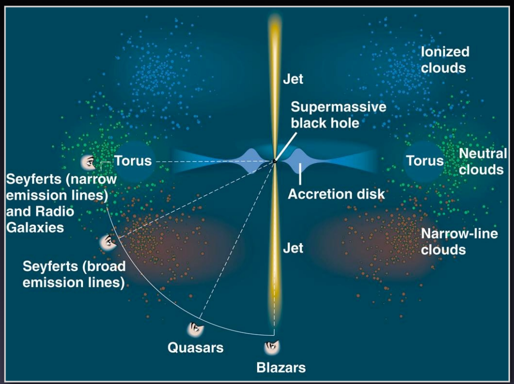
- UV-bright core, sometimes variable
- very hot gas,
  spread over thousands of light years
- often radio emission, usually in 'jets' that are light days to millions of light years in length.
- a lot of infrared radiation
- X-ray and gamma-ray radiation,
  usually variable on short time scales

⇒ biased search makes it easy to find them

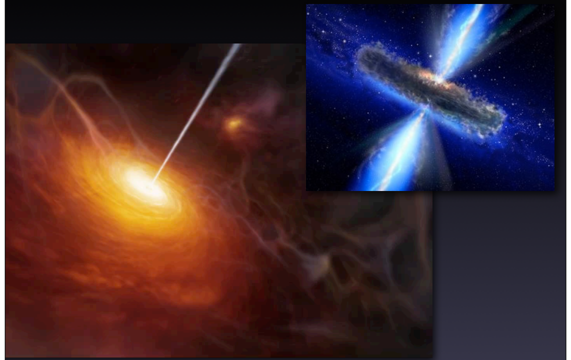
We distinguish the following AGN classes, depending on their luminosities, variability, and radiation properties:

- Seyfert galaxies (typically spirals)
  Type I : narrow emission lines
  Type II: broad emission lines
- Radio galaxies (typically ellipticals)
  Type I : narrow jets, bright radio clouds
  Type II : broad jets, no radio clouds
- Quasars
  radio-bright and radio-faint
- BL Lac objects
  highly variable

a unifying geometric model to explain AGNs



a general geometric model to explain AGNs



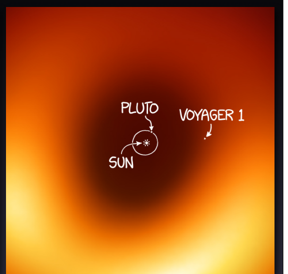
First image of a Super-Massive Black Hole

A Zoom to the Black Hole in M87

Visualization: F. Summers, STScI
Music: "First Day of Spring", David Hilowitz, CC BY-NC

Messier 87 : a giant elliptical galaxy in the Virgo cluster of galaxies at a distance of ~17 Mpc

First image of a Super-Massive Black Hole

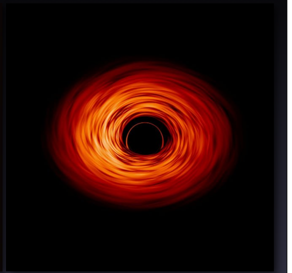


500 AU

Event Horizon Telescope:
Seven telescopes performing
global Very-Long-Baseline-Interferometry
at mm-wavelengths.

First image of a Super-Massive Black Hole

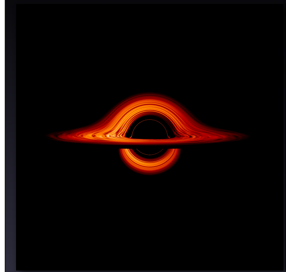
6.5 billion solar masses

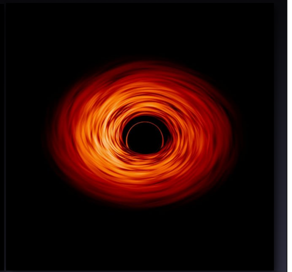


Event Horizon Telescope:
Seven telescopes performing
global Very-Long-Baseline-Interferometry
at mm-wavelengths.

Computer animation

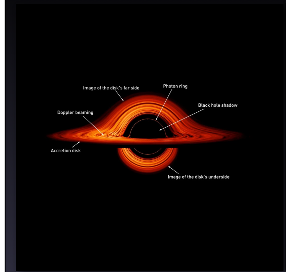
First image of a Super-Massive Black Hole

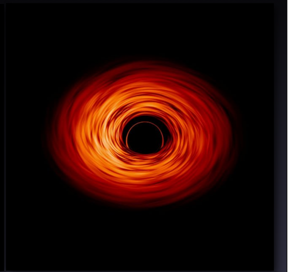




Computer animation

First image of a Super-Massive Black Hole



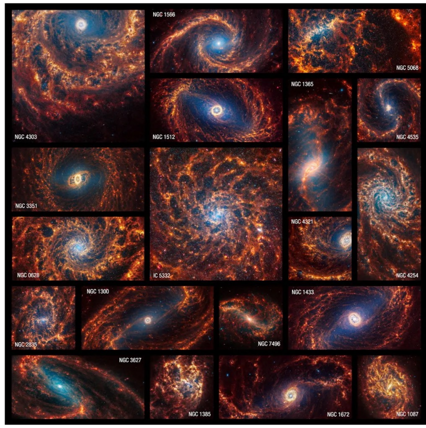


Computer animation

What's known today:

- galaxies with an AGN are relatively common
- a large variety of properties and appearances
- extremely radio-bright objects are usually found in elliptical galaxies
- the number of AGNs evolves over cosmic time
- all galaxies host a super-massive, central black hole.

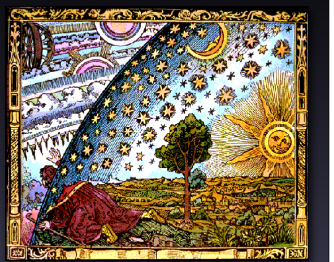
What is not known:
How do these massive black holes form?
What causes their activity?



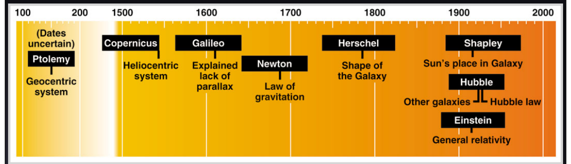
Break

Cosmology : the formation of our world view, the study of the Universe as a whole

- What ?
- Why ?
- How ?
- What is our place in the Universe ?



An evolution of insights : 'what' and 'why'.

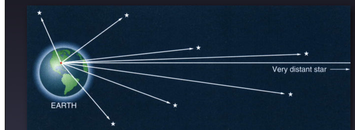


A long journey of discovery,
from a Geo- (or ego-)centric
to a relativistic Cosmology.

Olbers' Paradox :
Why is the night sky dark?

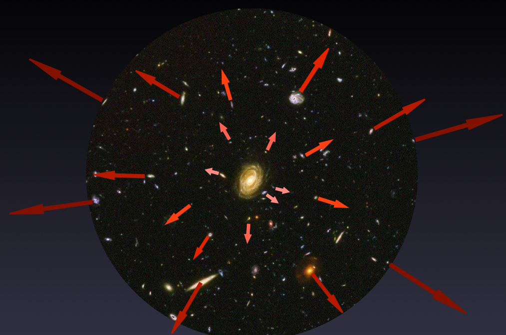
A simple question with huge implications.

In an infinitely large and old Universe, you would see the photosphere of a star in <u>any</u> direction.



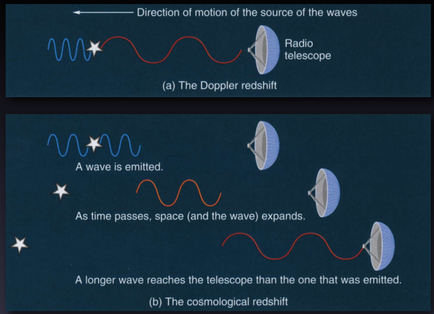
Conclusion: the Universe expands and therefore had a beginning!

<u>Fact</u> : the Universe expands at ~70 km s^{-1} Mpc^{-1}



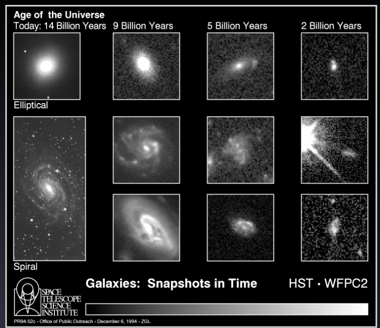
<u>Consequence</u> : more distant objects move away at higher speeds
→ very large redshifts!

Doppler versus Cosmological redshifts



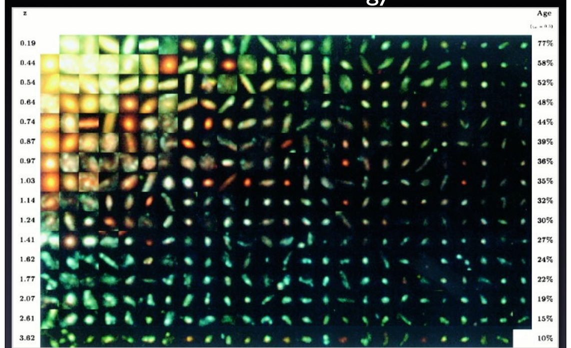
Galaxies do not move through space,
but *space itself* is expanding!

Fact : the speed of light is finite   C = 299.793 km/s



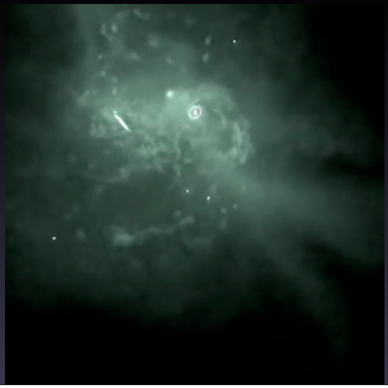
Consequence : objects at larger distances,
are seen further back in time.

Cosmic archeology:

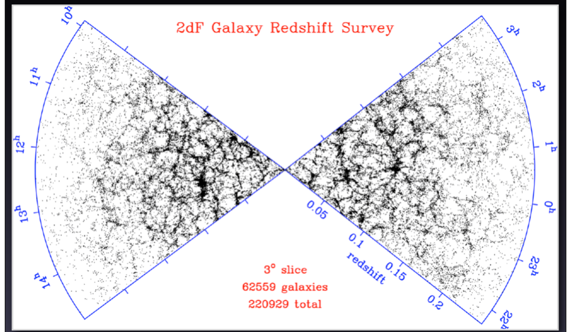


→ there were more and smaller galaxies in the past.

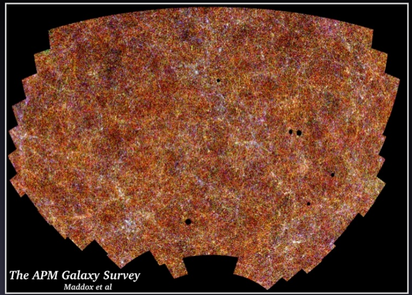
computer simulation of galaxy formation



Fact : galaxies are distributed in a web-like structure along walls, filaments and clusters ...



... but at the largest scale, the Universe is homogeneous and isotropic: the Cosmological Principle

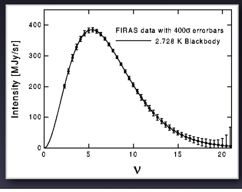


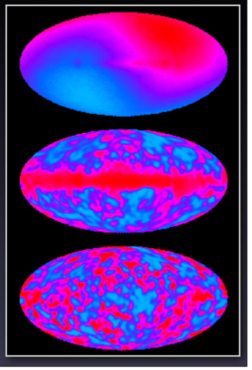
The Perfect Cosmological Principle demands constancy in time (Steady State)

Fact : over the entire sky we measure a glow of millimetre radiation: Cosmic Microwave Background (CMB)

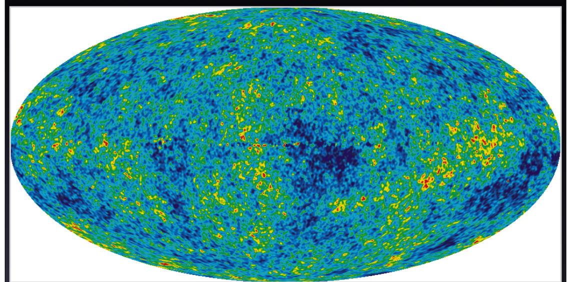
Discovered in 1964.
accurately measured in 1992
with the COBE satellite:

→ a nearly perfect Planck curve (2.73 K) with tiny temperature fluctuations of 1 : 100.000





A more detailed map of the CMB by the WMAP satellite :



Consequences & Questions:

Expansion: - the Universe was smaller and hotter in the past
- Doppler-effect indicates very high redshifts

Will the Universe expand forever?

Speed of light : - we're looking back in time

Can we see the moment of the Big Bang?

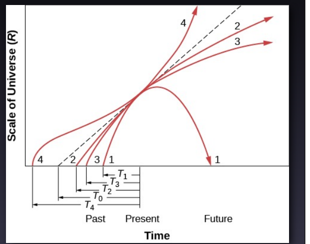
Structure : - not all structures expand at the same speed: in dense regions there is more gravity that slows down the expansion locally

How did the web-like structure emerge from tiny fluctuations?

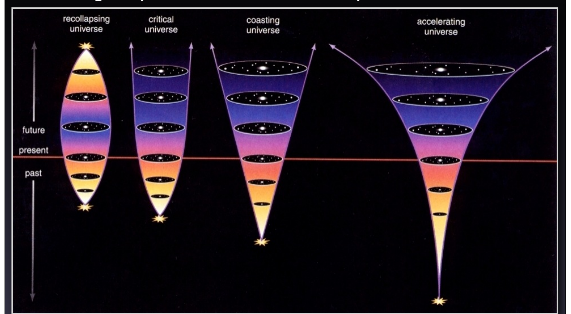
The Universe expands homogeneously:
there must have been a beginning - the Big Bang

However:
The measured Hubble-constant H=70 (km/s/Mpc) describes the *current* expansion rate.

The value of H must have been larger in the past: H = H(t)

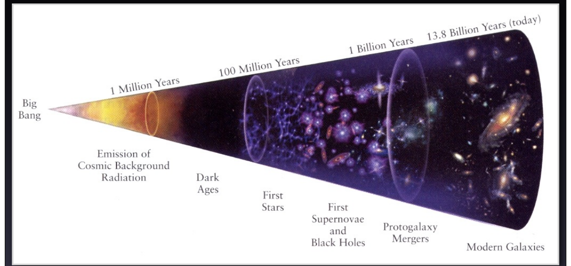


The future of the Universe depends on the amount of matter, and thus gravity, that slows down the expansion.

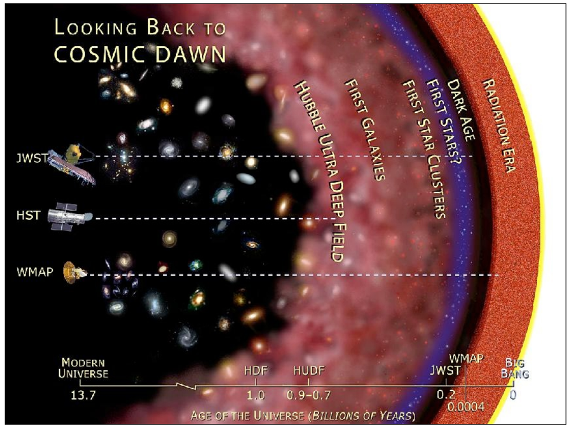


Note: the age of the Universe depends on the rate of expansion in the past, and its future depends on amount of matter to slow/revert expansion.

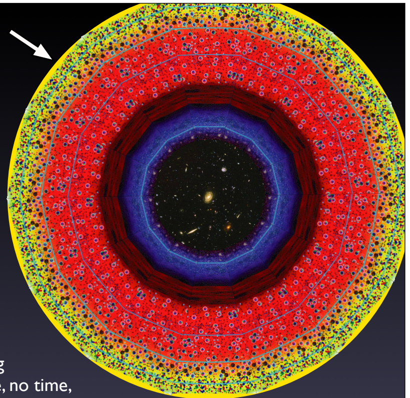
Looking back in time : we distinguish different epochs.



Cosmological Principle:
we see this cosmic history in <u>all directions on the sky</u>!



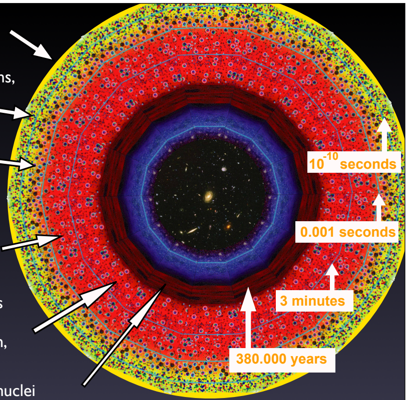
Big Bang



space,
time and
forces
originate...

Before the Big Bang
there was no space, no time,
no matter, no gravity, no electromagnetic radiation,...

Big Bang



quarks, (anti-)electrons, and the fundamental forces of nature

quarks combine to (anti-)protons and (anti-)neutrons

anti-matter and matter annihilate ➥ anti-matter disappears

protons and neutrons form the nuclei of Hydrogen, Deuterium, Helium and Lithium

loose electrons and nuclei combine to atoms ➝ the Universe becomes transparent to radiation

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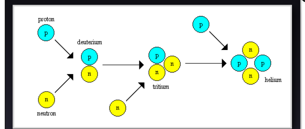
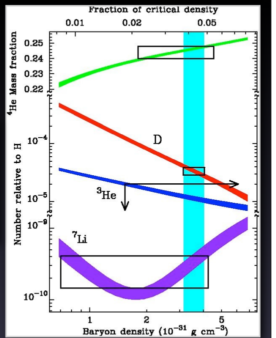
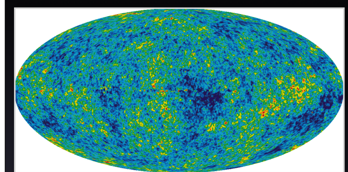
Nucleosynthesis of the light-weight elements in the first 3 minutes:





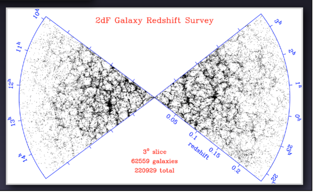
The observed concentrations of Deuterium, Helium and Lithium agree with theoretical predictions according to the Big Bang model !

How do galaxies, stars, planets and humans form out of these tiny density fluctuations?



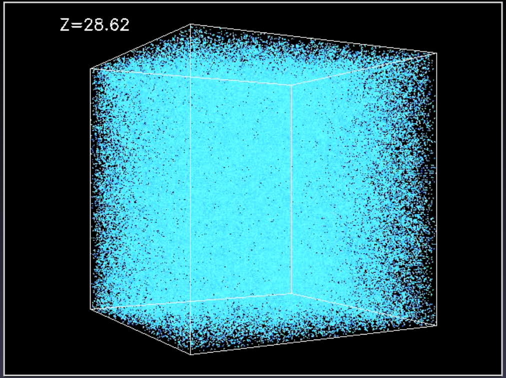
A nearly uniform distribution of only gas and dark matter, 380.000 years after Big Bang.

?



A filamentary cosmic web outlined by a diversity of galaxies, 13.7 billion years after Big Bang.

computer simulation of large-scale structure formation



The basic formula for the state of the Universe:

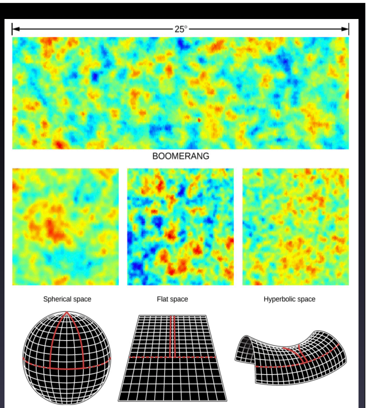
$$\boxed{\Omega_M + \Omega_K + \Omega_\Lambda = 1}$$

Ω_M = fractional contribution of all matter
(visible and dark matter, radiation)
to the total density of the Universe: $\Omega_M = 0.27$

Ω_K = contribution by the curvature of space
<0 : closed Universe
0 : flat Universe
>0 : open Universe

Ω_Λ = contribution by the Cosmological Constant
mathematically allowed by the theory of General Relativity but physical meaning is unknown.
Also known as 'Dark Energy'

WMAP measured the curvature of space by analysing the fluctuations in the CMB.

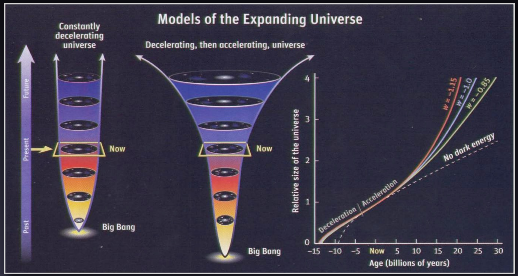


Conclusion: $\Omega_K = 0$
(flat Universe)

Therefore:
$\Omega_\Lambda = 1 - \Omega_K - \Omega_M$
$= 1 - 0 - 0.27$
$= 0.73$!

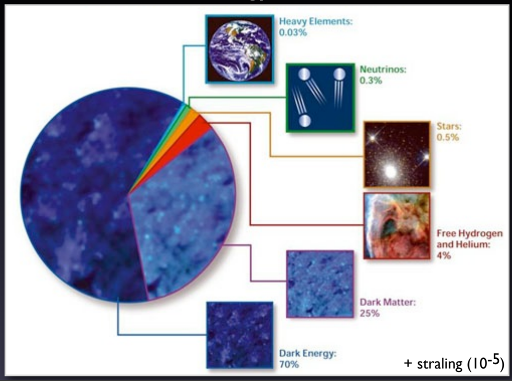
A combination of various observations indicates an age of the Universe of 13.7 billion years.

A Λ-dominated flat Universe is older!



Eventually the Universe will fly apart: the Big Rip

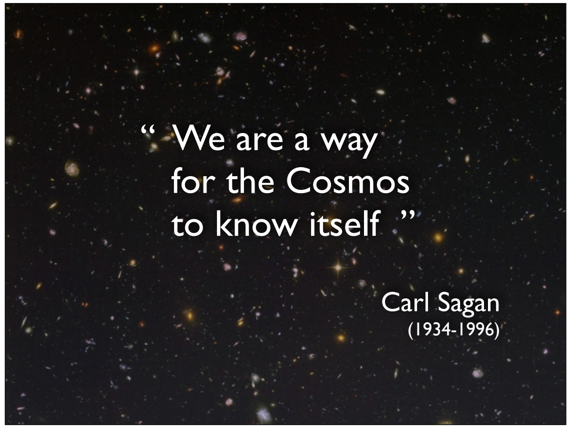
Matter and Energy in the Universe



+ straling (10^{-5})

Important (partially) open questions:

1. What is the exact composition of the flat Universe?
2. What is the origin of the primordial density fluctuations?
3. How does large-scale structure form and evolve?
4. uniformity of the CMB ➙ How did super-massive black holes form?
5. What is the nature of the Dark Matter?
6. What is the nature of the Dark Energy Λ?
7. ‘First Light’: How and when did the first stars form?
8. What are the global parameters of the Universe:
   What is the exact fate of the evolving Universe?


“ We are a way
for the Cosmos
to know itself ”
Carl Sagan
(1934-1996)