The fifth element: astronomical evidence for black holes, dark matter, and dark energy

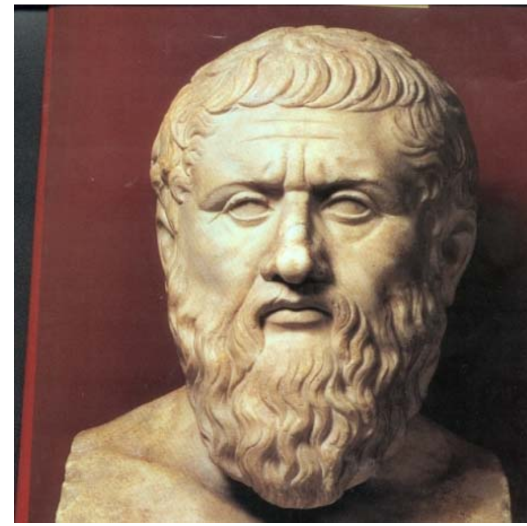
A brief history of astrophysics

- Greek philosophy contained five "classical" elements:
  - earth
  - air
  - fire
  - water

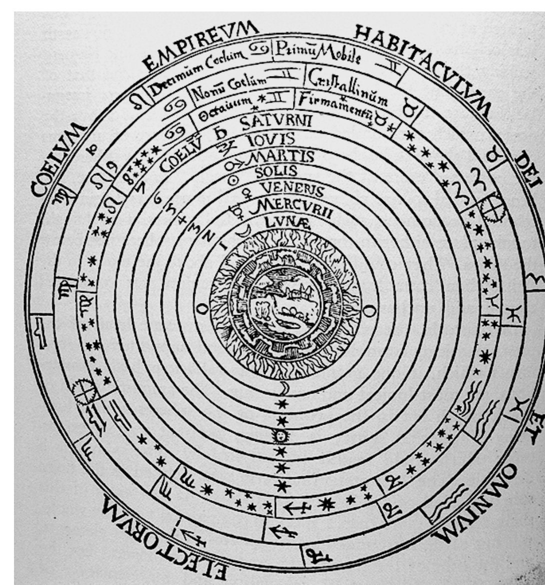
  terrestrial; subject to change

  - ether

  heavenly; unchangeable



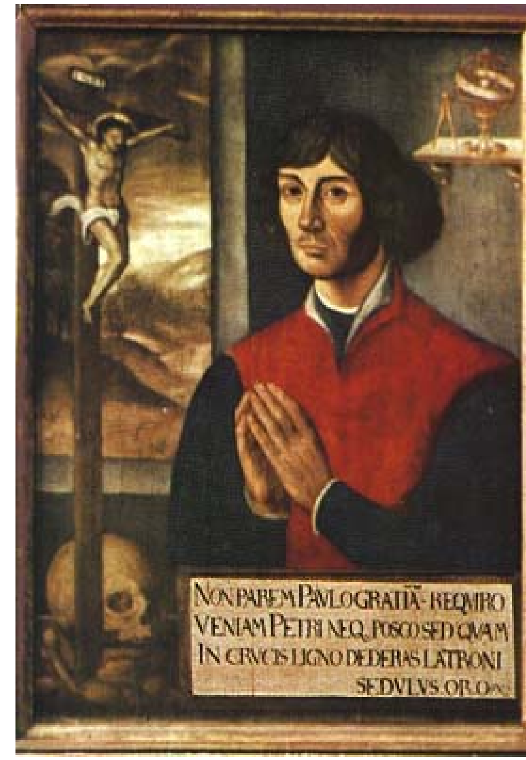
- in Greek astronomy, the universe was geocentric and contained eight spheres, seven holding the known planets and the eighth the stars



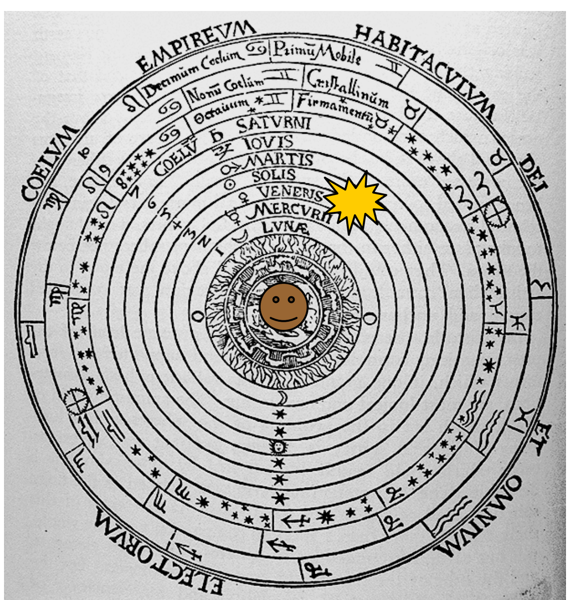
A brief history of astrophysics

- Nicolaus Copernicus (1473 – 1543)
- argued that the Sun, not the Earth, was the center of the solar system
- the Copernican Principle:

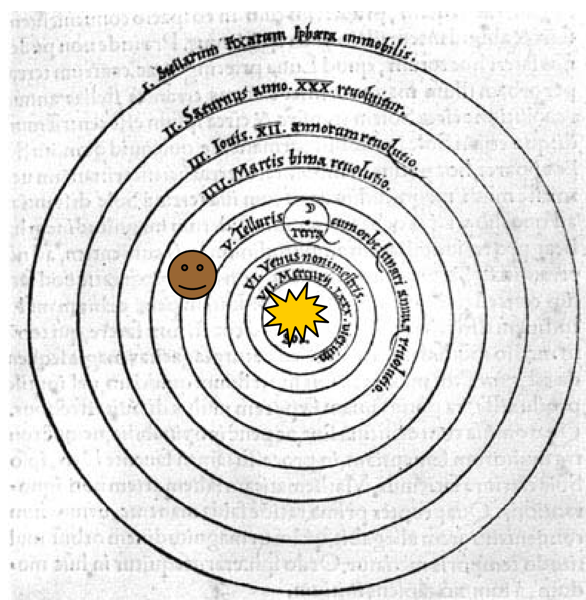
  We are not located at a special place in the Universe, or at a special time in the history of the Universe



Greeks



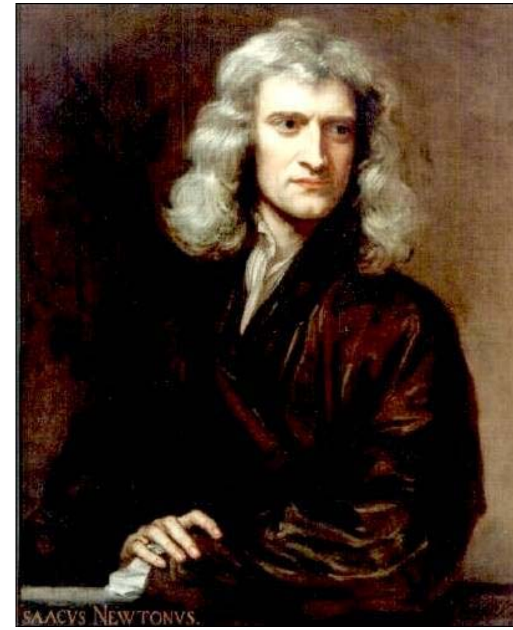
Copernicus

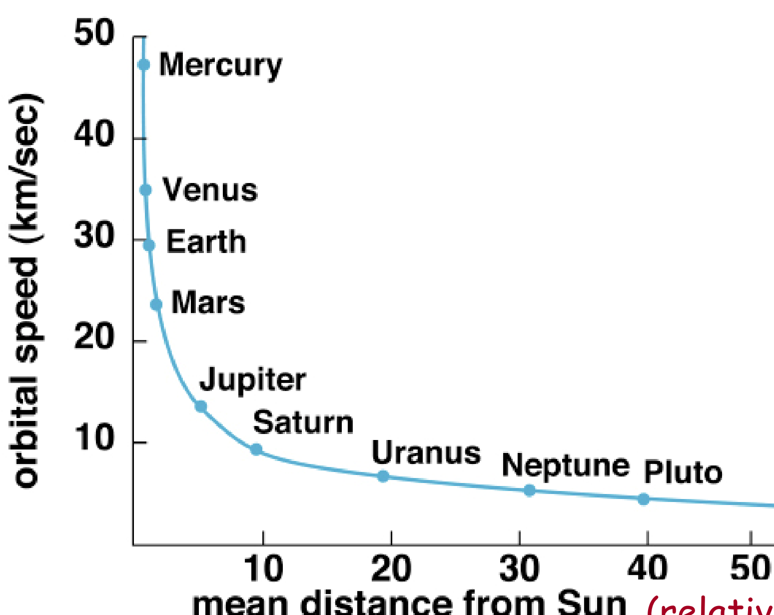


A brief history of astrophysics

- Isaac Newton (1642-1747)
- the law of gravity that makes apples fall to Earth also governs the motions of the Moon and planets (the law of universal gravitation)
  - thus the square of the speed of a planet in its orbit varies inversely with its radius

⇒ ***the laws of physics that can be investigated in the lab also govern the behavior of stars and planets***



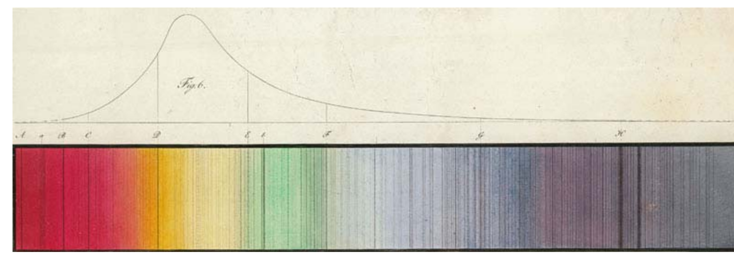


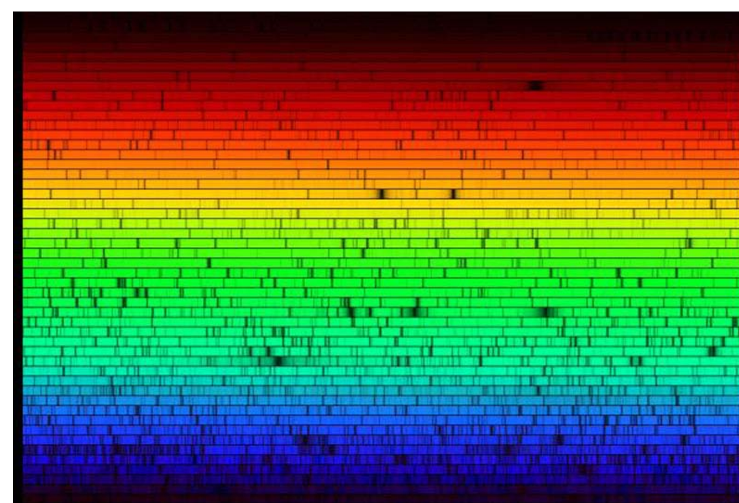
(relative to Earth)

A brief history of astrophysics

- Joseph von Fraunhofer (1787-1826)
- discovered narrow dark features in the spectrum of the Sun
- realized these arise in the Sun, not the Earth's atmosphere
- saw some of the same lines in the spectrum of a flame in his lab
- each chemical element is associated with a set of spectral lines, and the dark lines in the solar spectrum were caused by absorption by those elements in the upper layers of the sun

⇒ ***the Sun is made of the same elements as the Earth***



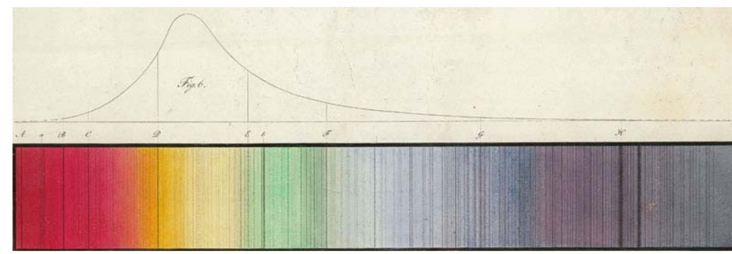


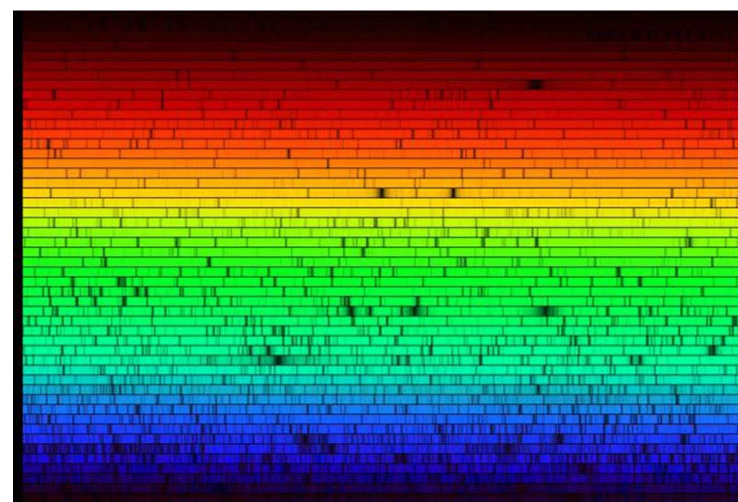
A brief history of astrophysics

⇒ ***the Sun is made of the same elements as the Earth***

- in 1868 Fraunhofer lines not associated with any known element were found: *"a very decided bright line...but hitherto not identified with any terrestrial flame. It seems to indicate a new substance, which we propose to call Helium"*
- helium was only isolated on Earth in 1895

⇒ ***astronomy can teach us new physics***





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⇒ ***the Sun is made of the same elements as the Earth***

- however, the mix of elements in the Sun is not the same as Earth:
    - 75% hydrogen
    - 23% helium
    - all other elements only 2%

⇒ ***hydrogen and helium are the main constituents of the universe, in about a 3:1 ratio***

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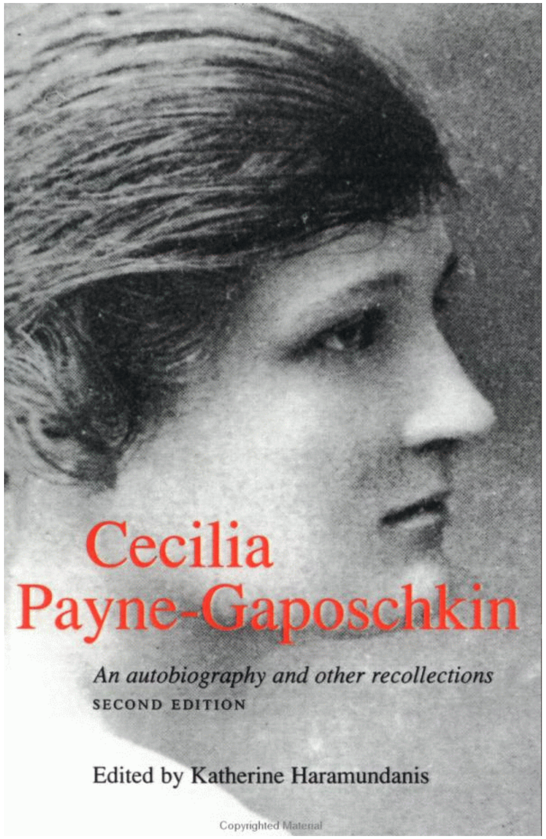


Cecilia Payne-Gaposchkin (1900-1979)

• first Ph.D. in astronomy from Harvard

• first woman promoted to tenured professor at Harvard (1956)

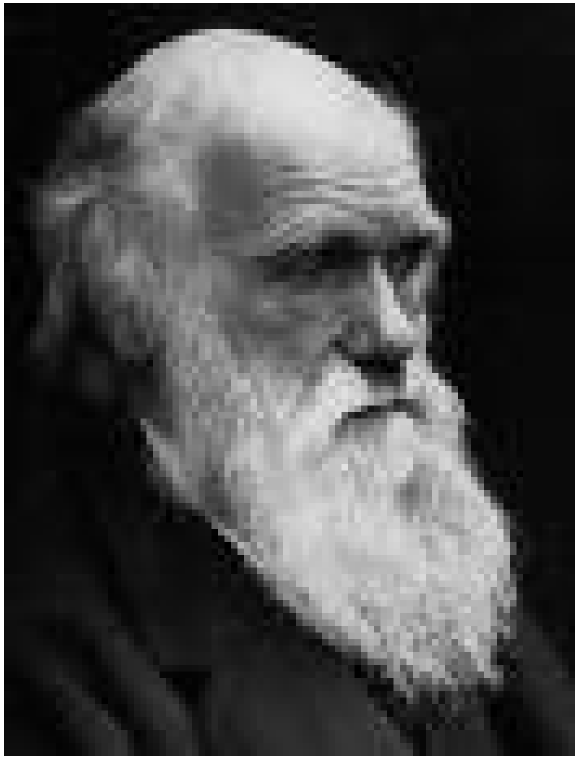
• first woman to head a department at Harvard

A brief history of astrophysics

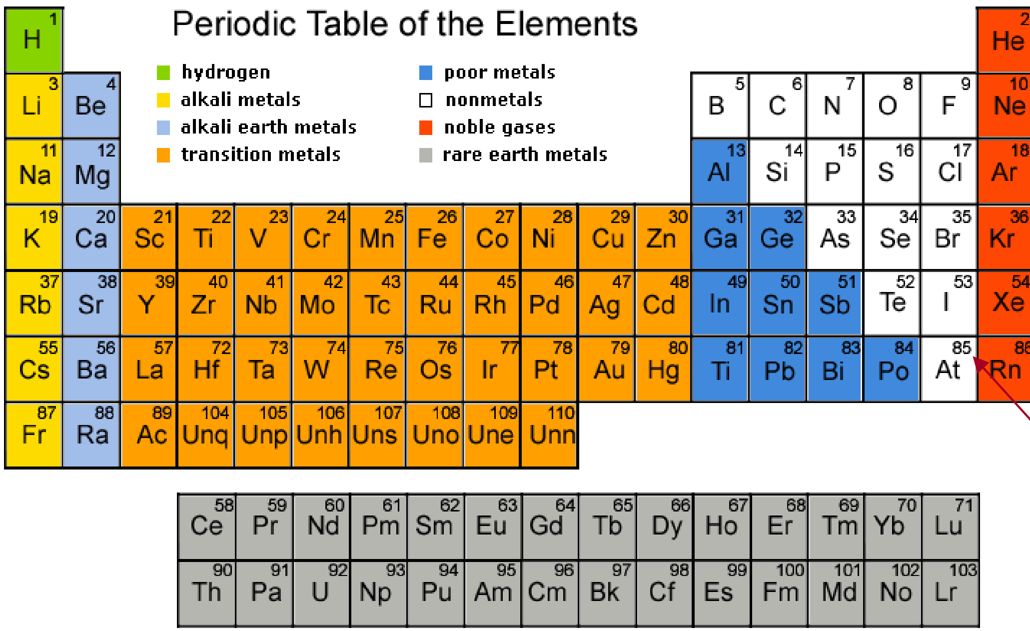
- once astronomers knew what elements the stars were composed of, they began to think about the origin of these elements

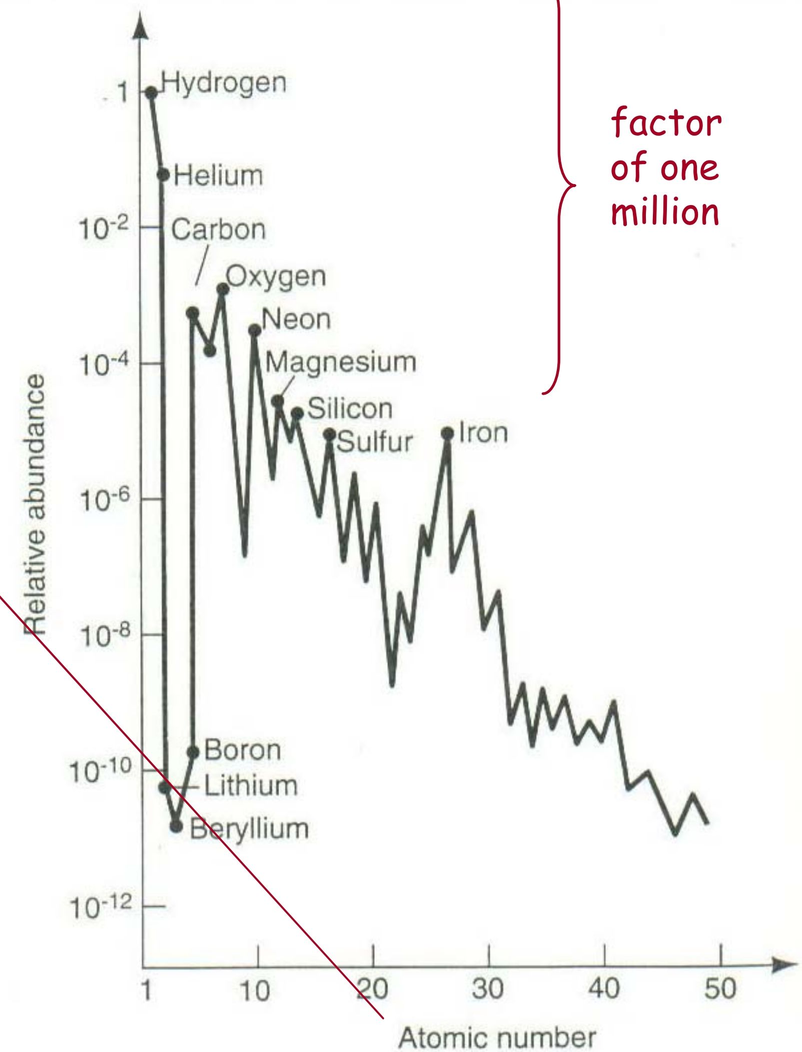
"It is mere rubbish thinking, at present, of origin of life; one might as well think of origin of matter."

(letter from Charles Darwin, March 29, 1863)



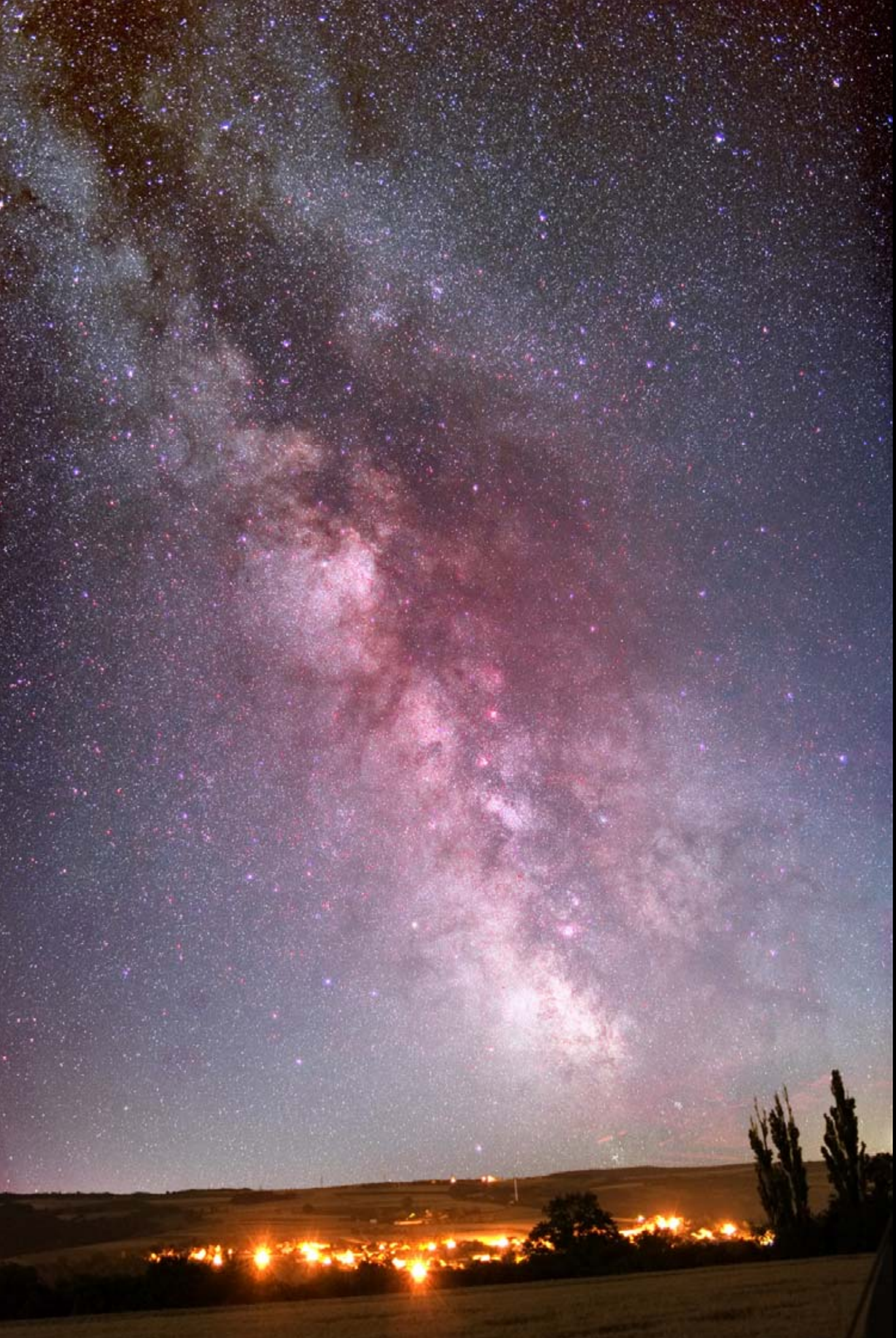
- about 150 years after Darwin, we know much more about the origin of matter than about the origin of life

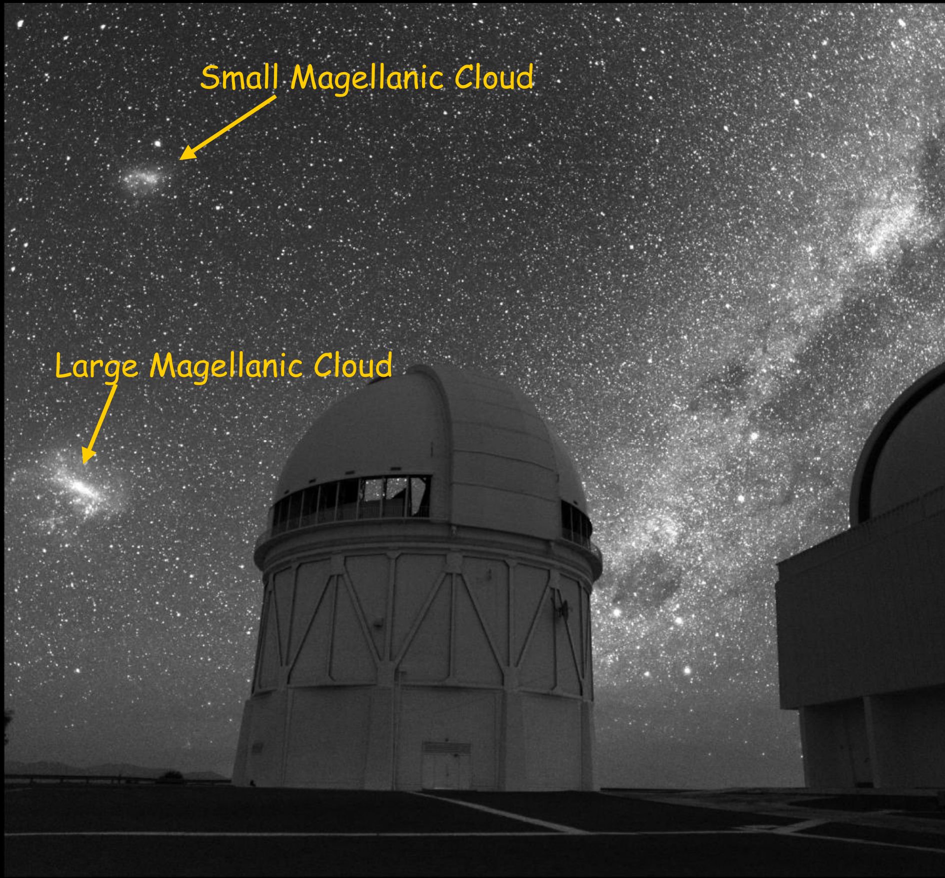


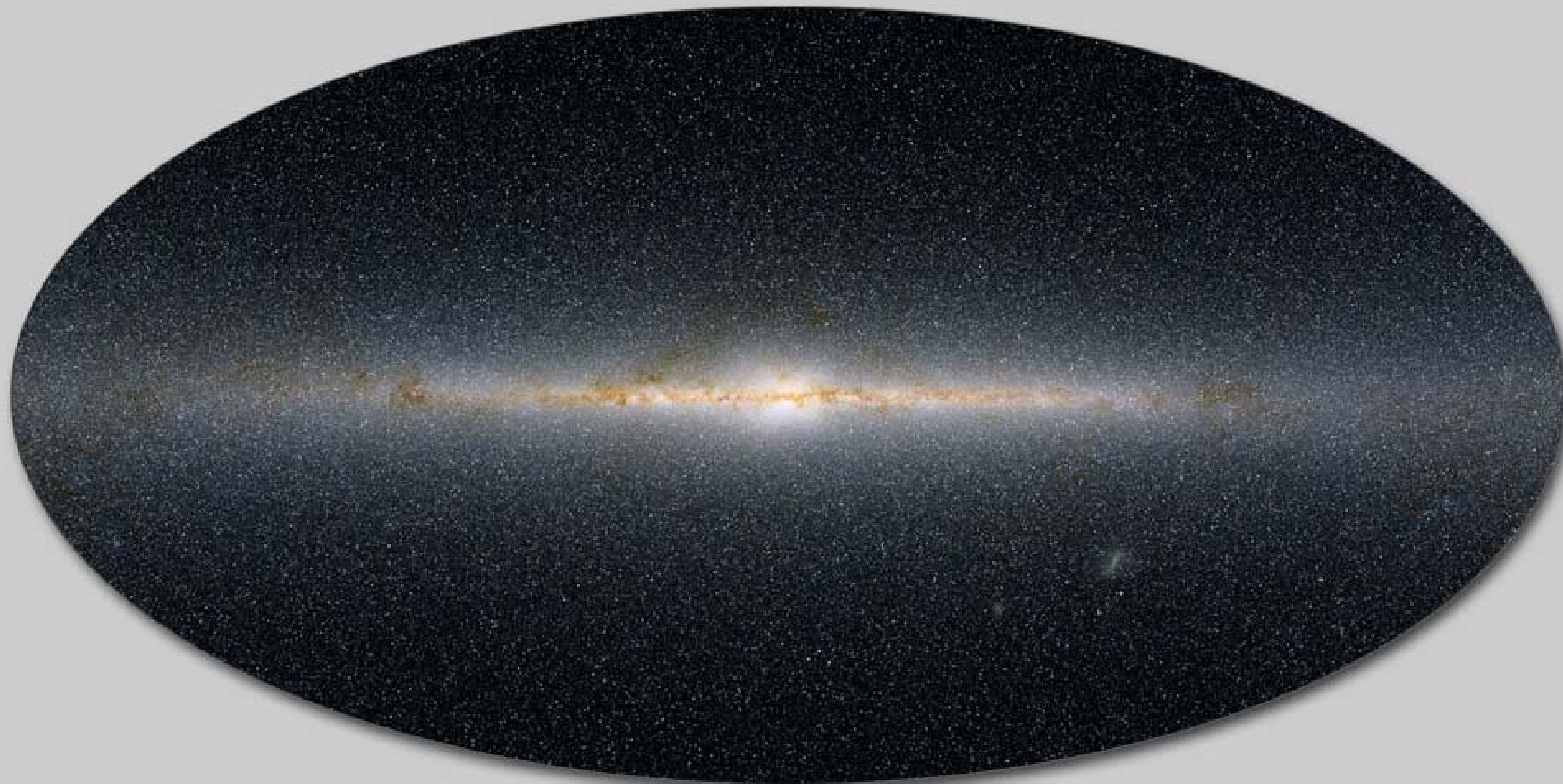


factor of one million

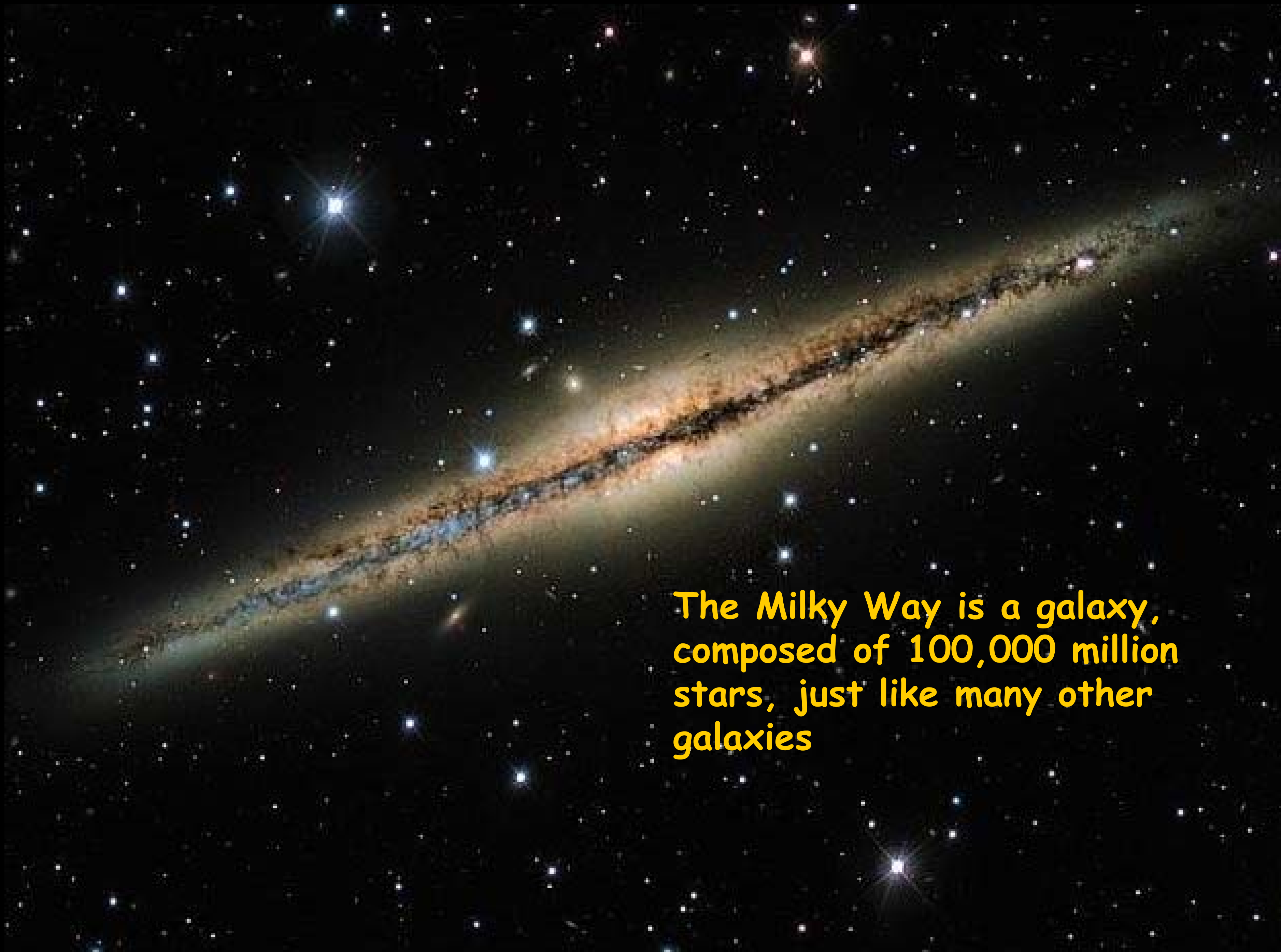
The Milky Way is a galaxy, composed of 100,000 million stars...







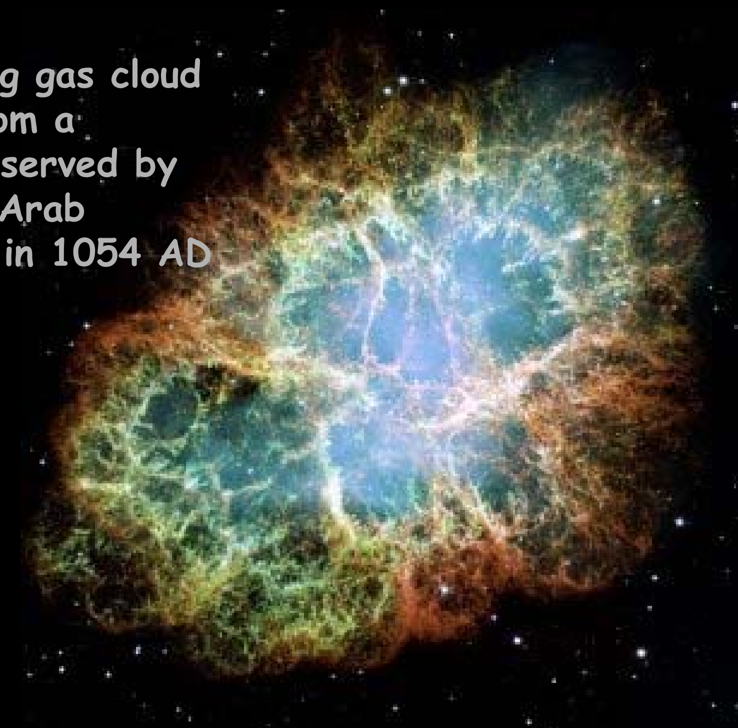
The Milky Way is a galaxy, composed of 100,000 million stars...


The Milky Way is a galaxy, composed of 100,000 million stars, just like many other galaxies

Galaxies like the Milky Way contain stars and gas; the gas is slowly but steadily turned into new stars...

before and after images of a supernova in a distant galaxy

before and after images of the 1987 supernova in the Large Magellanic Cloud

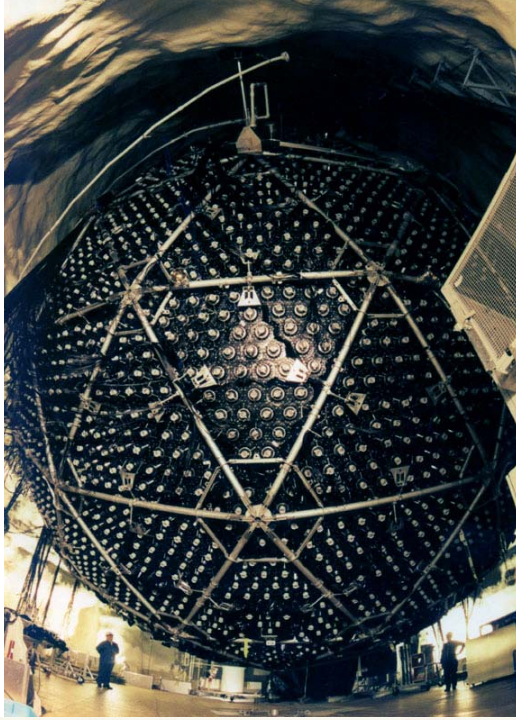


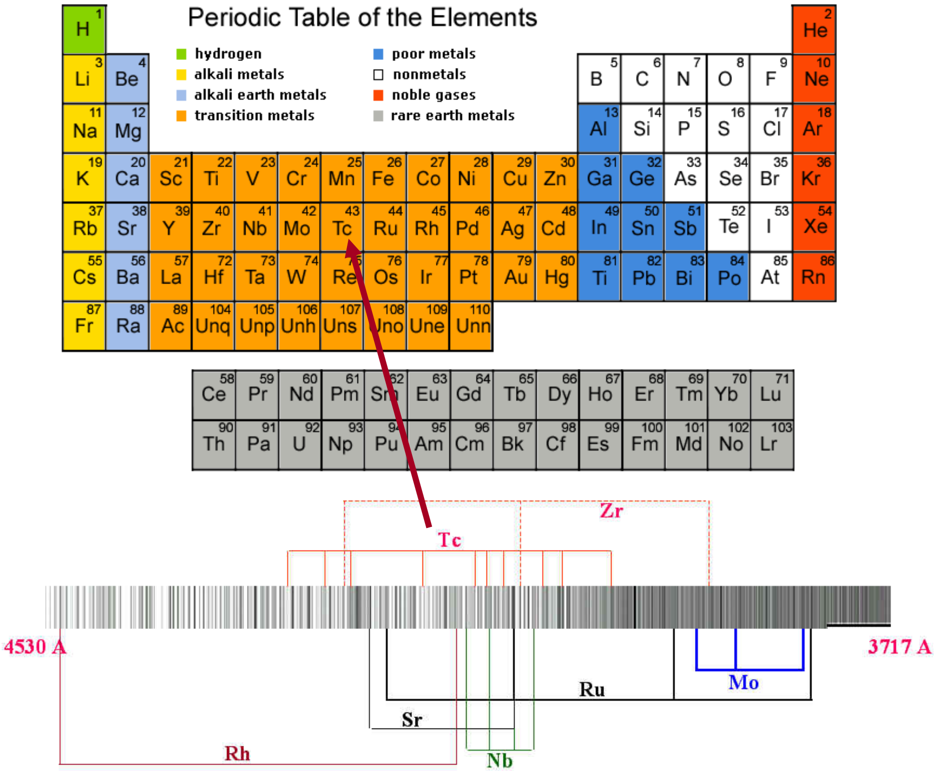
the expanding gas cloud remaining from a supernova observed by Chinese and Arab astronomers in 1054 AD

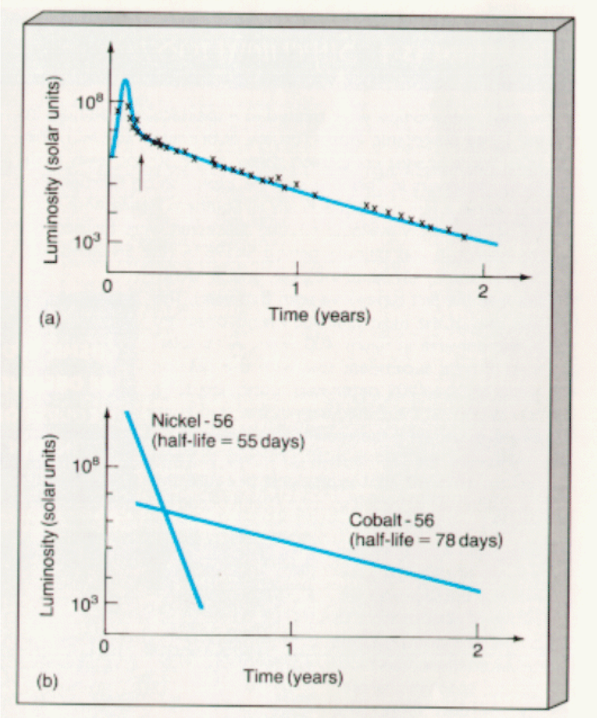
Galaxies like the Milky Way contain stars and gas; the gas is slowly but steadily turned into new stars; in turn, some stars explode at the end of their lives, producing brilliant supernovae and returning their material to the interstellar gas

all stars, including the Sun, are powered by nuclear reactions:

- neutrinos produced by nuclear reactions deep in the Sun's interior are detected in underground labs
- the decay of supernova brightness is determined by the radioactive decay of nickel and cobalt produced in the explosion
- some stars show Fraunhofer lines of technetium, which is a short-lived nucleus (half-life 2 million years) so must have been made recently

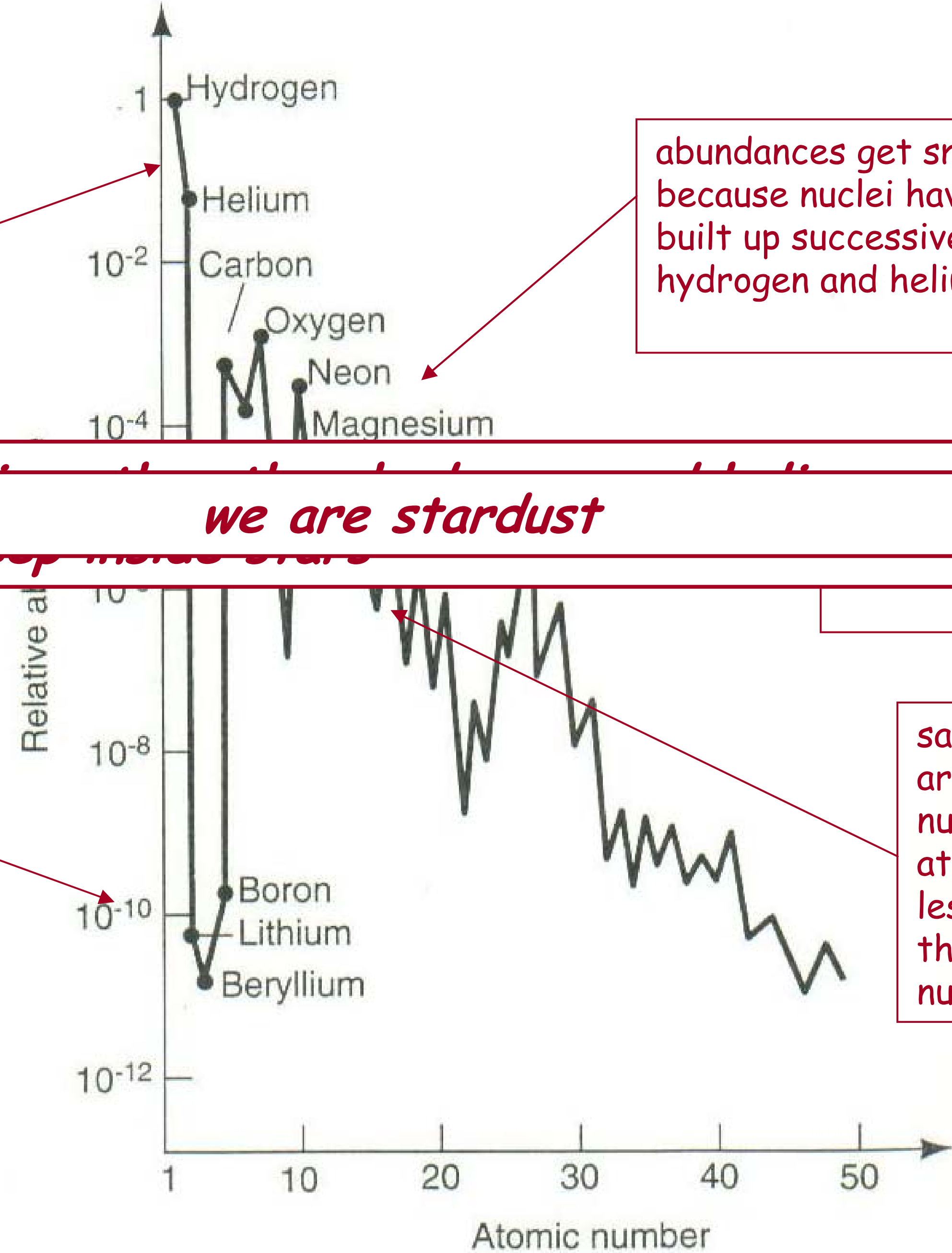






initially the star is composed of only hydrogen and helium

abundances get smaller because nuclei have to be built up successively from hydrogen and helium



we are stardust

made deep inside stars

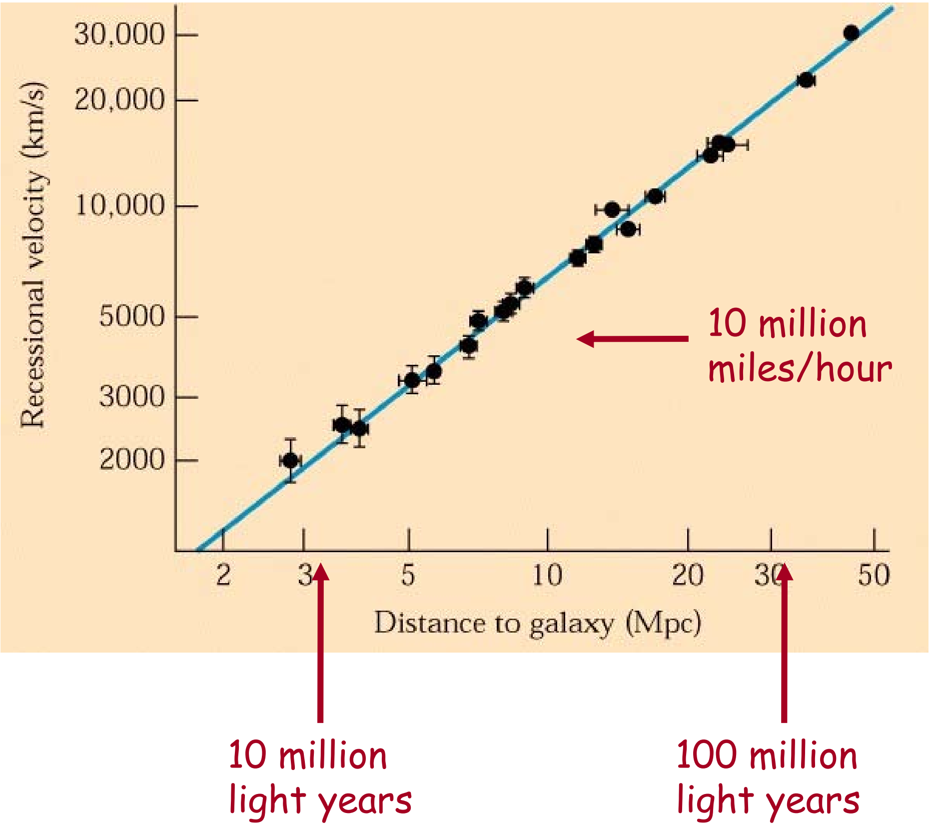
e nucleus –
on "ash" from
ning in stars

these elements are destroyed by nuclear reactions in stars

sawtooth pattern arises because nuclei with odd atomic number are less stable than those with even number

Where did the hydrogen and helium come from?

- the universe is expanding
- extrapolating backward in time, we find that it emerged from a singularity (the Big Bang) 13.7 billion years ago
- Einstein's theory tells us that the geometry of the universe is determined by its average matter content:
    - if the average density at present is less than the critical density, the universe is infinite
    - if the average density exceeds the critical density, the universe is finite
    - critical density = 1.0 X 10^{-26} kg/cubic meter or about 1 atom per cubic meter



Where did the hydrogen and helium come from?

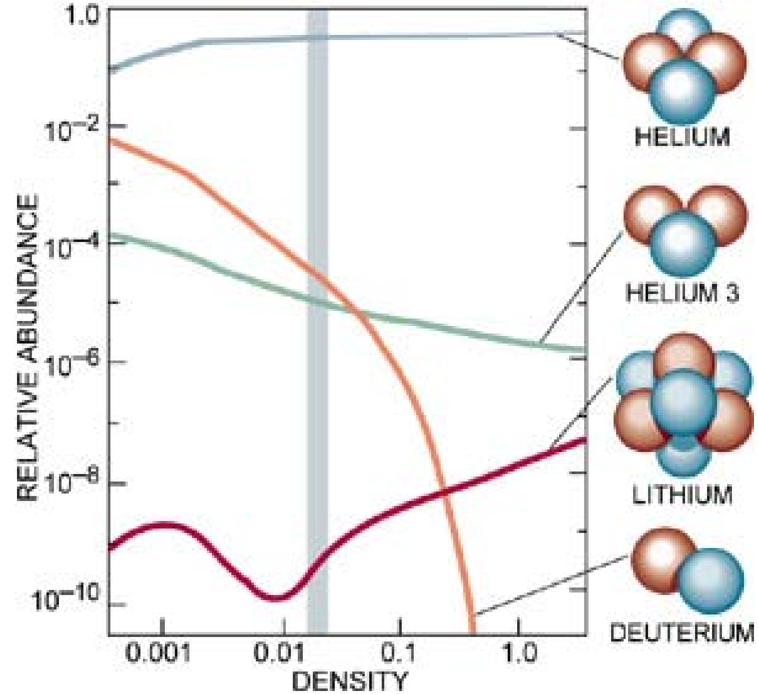
• the universe is expanding

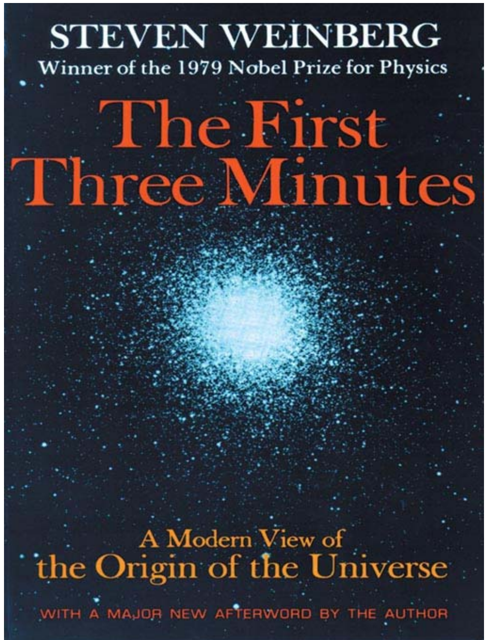
• extrapolating backward in time, we find that it emerged from a singularity (the Big Bang) 13.7 billion years ago

• at earlier times the universe was hotter and denser

• hydrogen and helium were created in the first three minutes after the Big Bang, along with trace amounts of other light elements (deuterium, lithium, etc.)

• the correct relative amounts (e.g., 23% helium, as in the Sun) are obtained ***only*** if the density of matter is 4.0% of the critical density

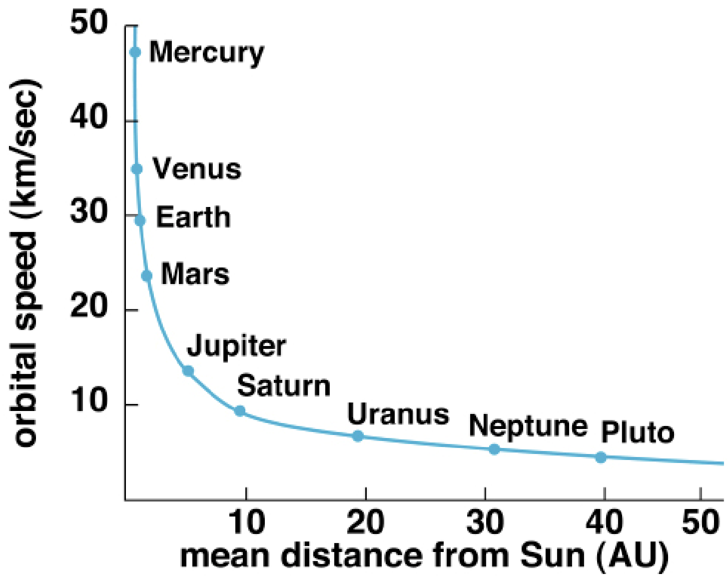


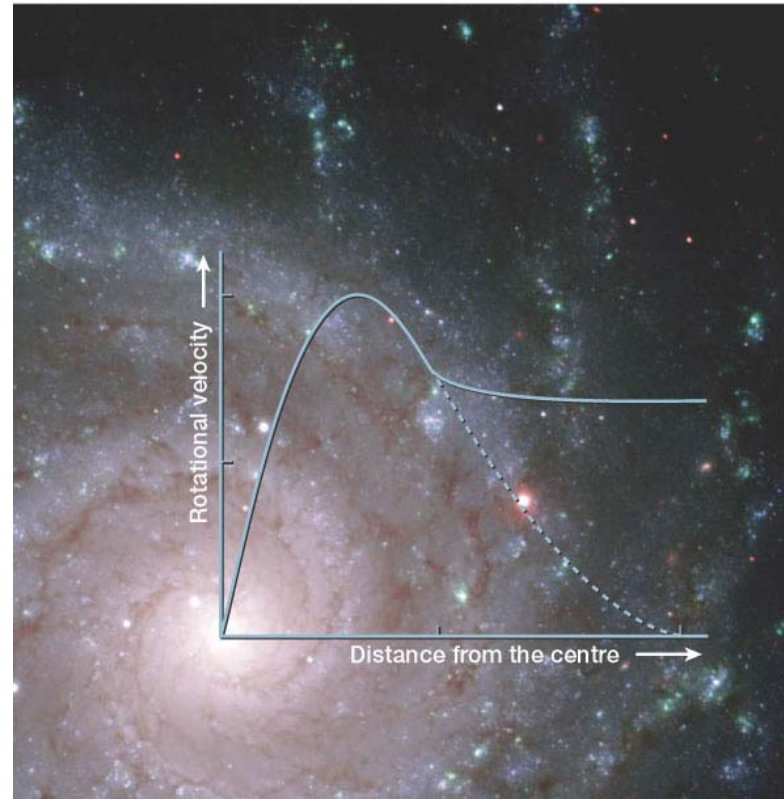


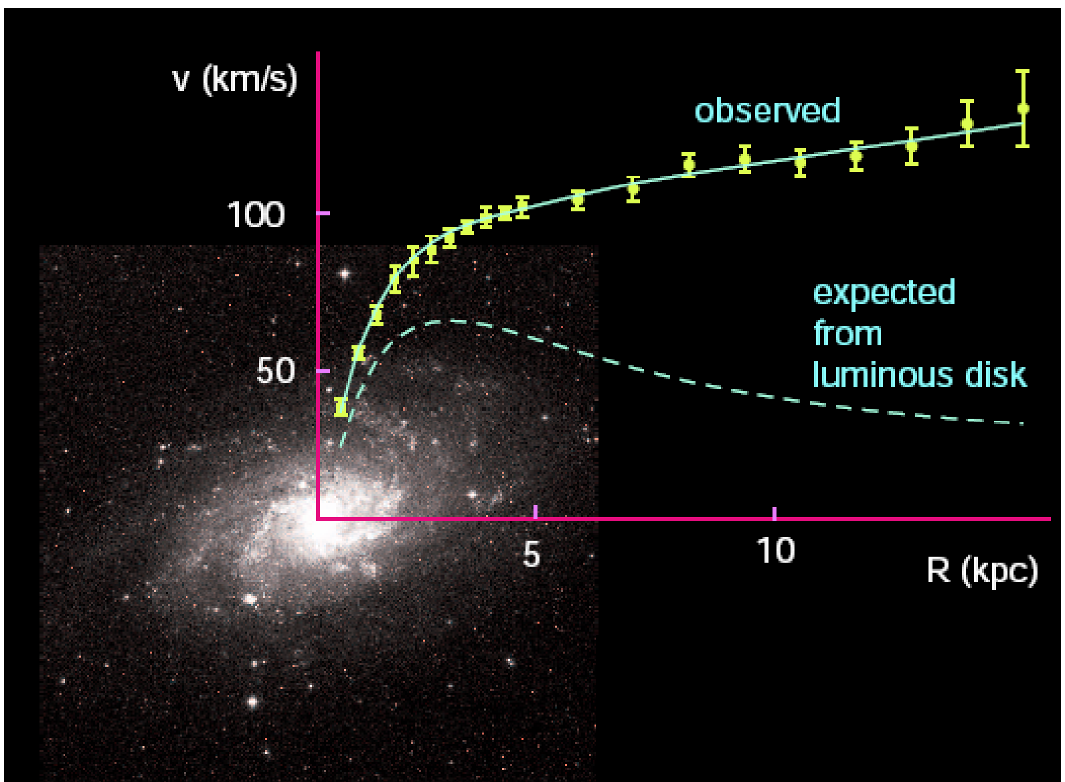
the principles of twentieth-century astrophysics

- we are not located at a special place in the Universe, or at a special time in the history of the Universe (the Copernican principle)
- the laws of physics that we investigate in the lab also govern the behavior of astronomical objects
- the study of astronomical objects can reveal new laws of physics
- the Sun and stars are made of the same elements as the Earth
- these elements were made in the Big Bang (hydrogen and helium) and in the centers of stars (everything else)

astronomy + physics = astrophysics



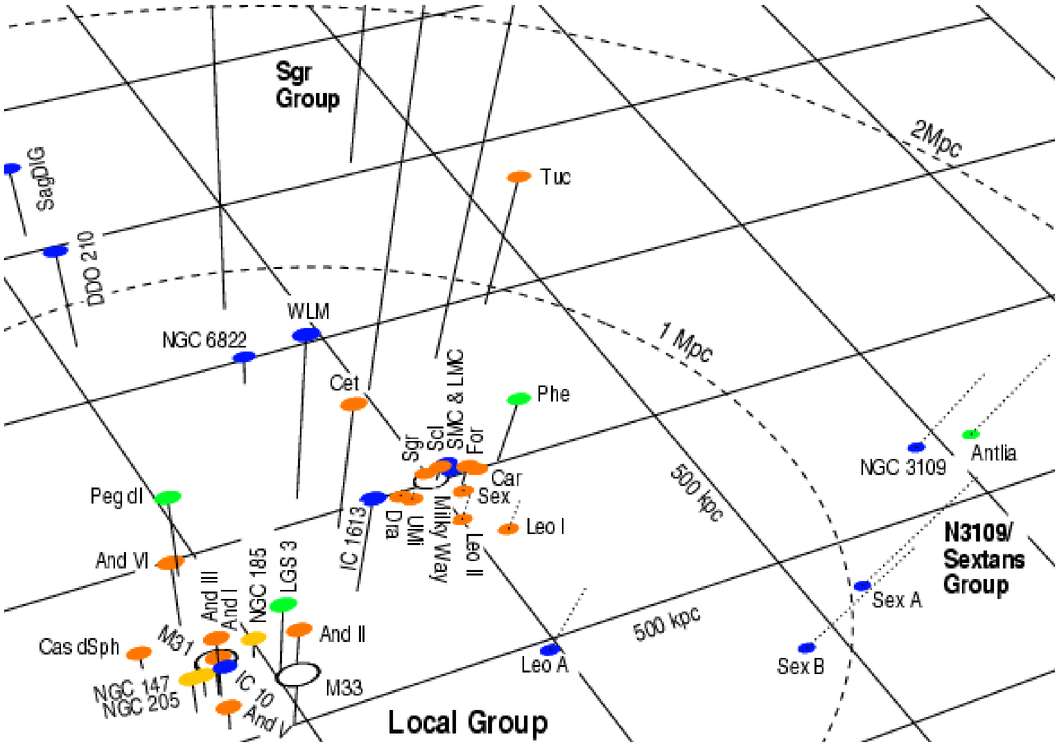


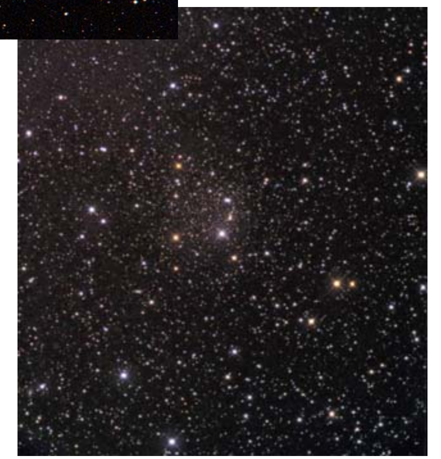


Either

• Newton's law of gravity doesn't work for galaxies, or

• galaxies must have large amounts of matter in some unseen form in their outer parts (***at least*** 2-3 times as much as in stars and gas)





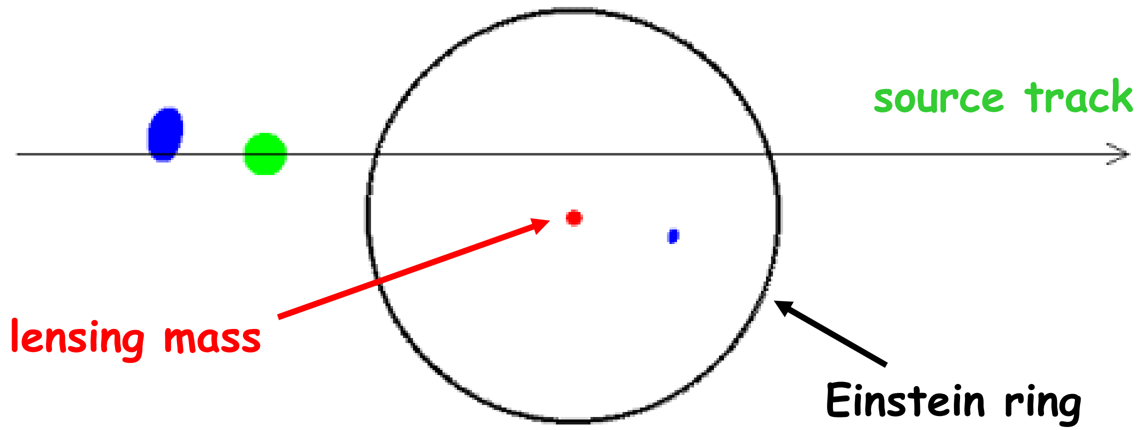
dwarf galaxies near the Milky Way have up to 100 X more mass in dark matter than they do in stars

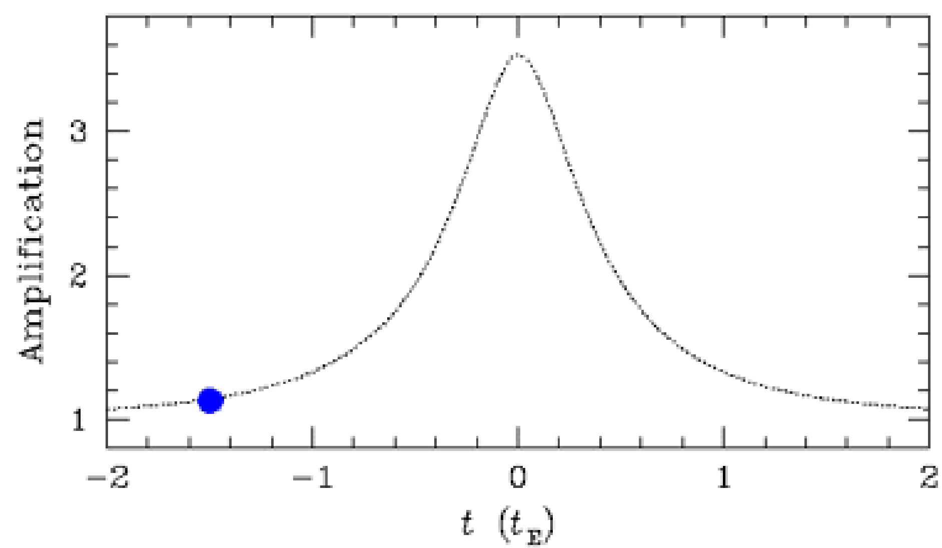
The masses of clusters of galaxies such as this one are five times as large as the mass in stars and gas

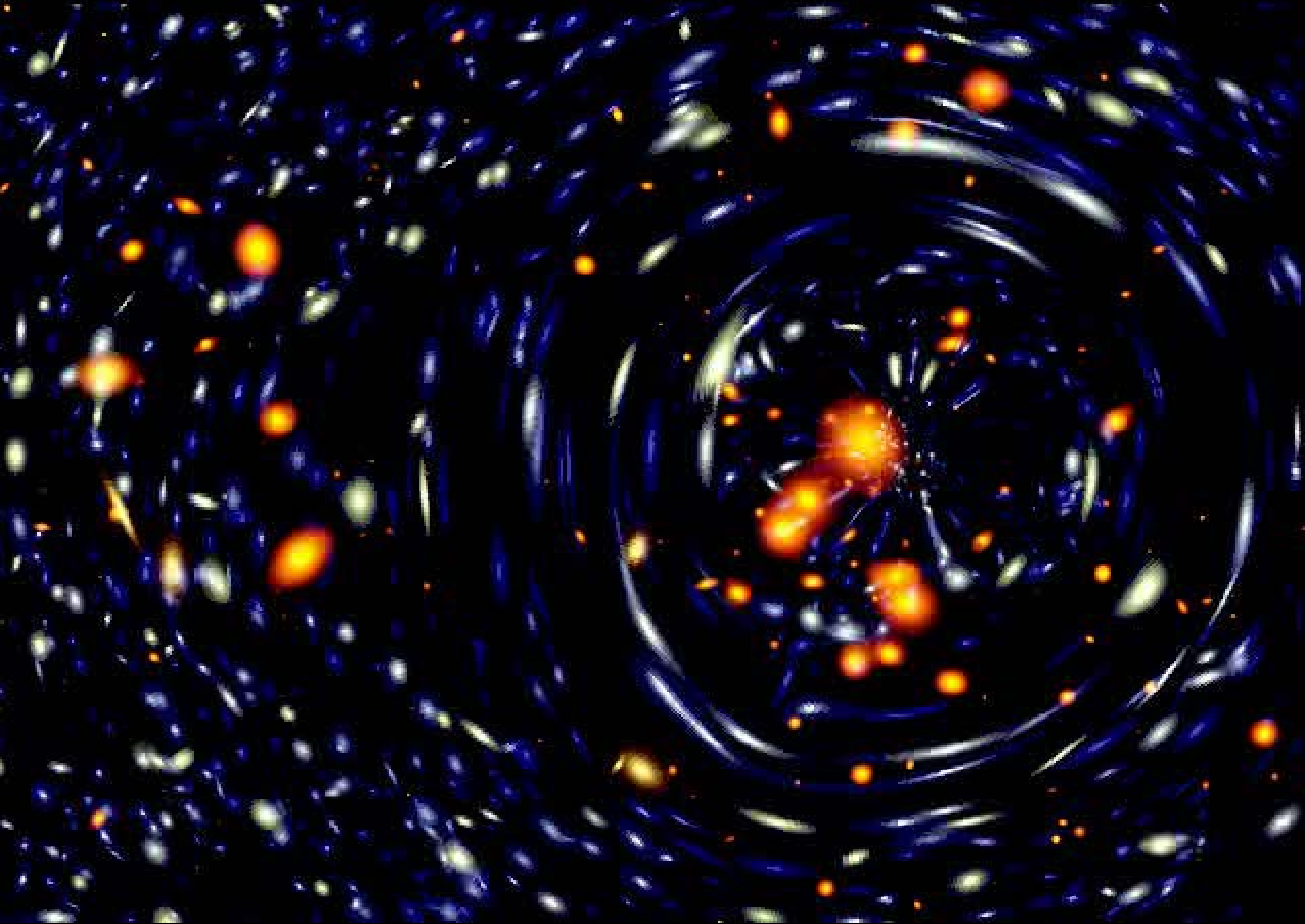
Gravitational lensing

the gravitational field from the intervening mass bends light and therefore:

- splits image into two
- magnifies one image and demagnifies the other
- if source, lens and observer are exactly in line the image appears as an "Einstein ring"







• mass determinations from gravitational lensing confirm mass determinations from Newton's law of gravity

• the masses of clusters of galaxies such as this one are five times as large as the mass in stars and gas

- *all* measurements of galaxies and galaxy clusters on large scales (more than 300,000 light years) show that the mass in stars and gas is only 1/5 of the total mass
- the vast majority of the matter in the universe must therefore be in some unknown and invisible form
- what is it?
    - rocks?
    - very faint stars?
    - planets?
    - black holes?

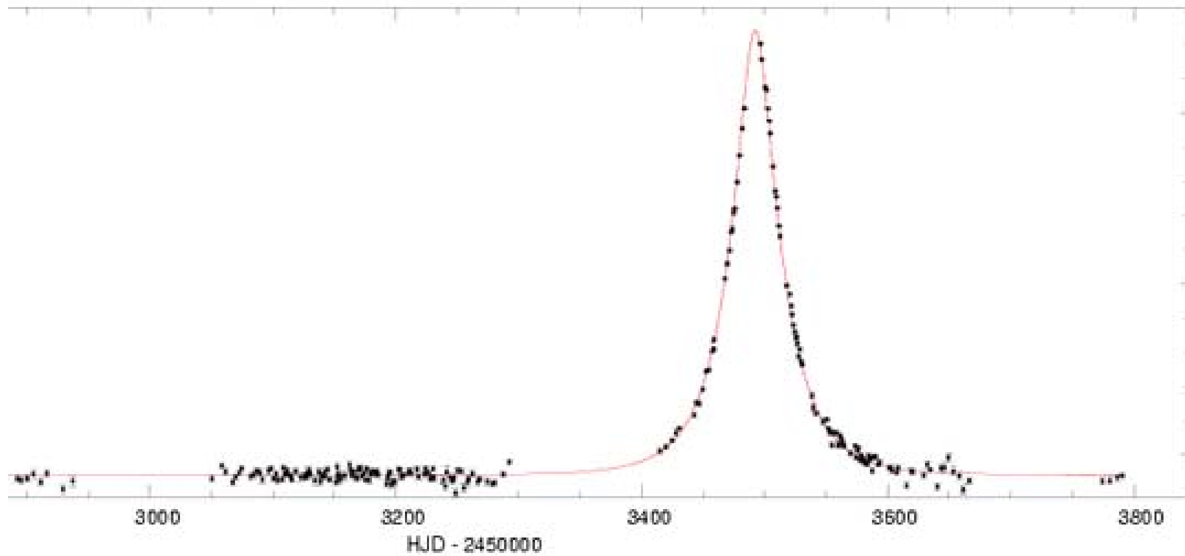
Gravitational lensing

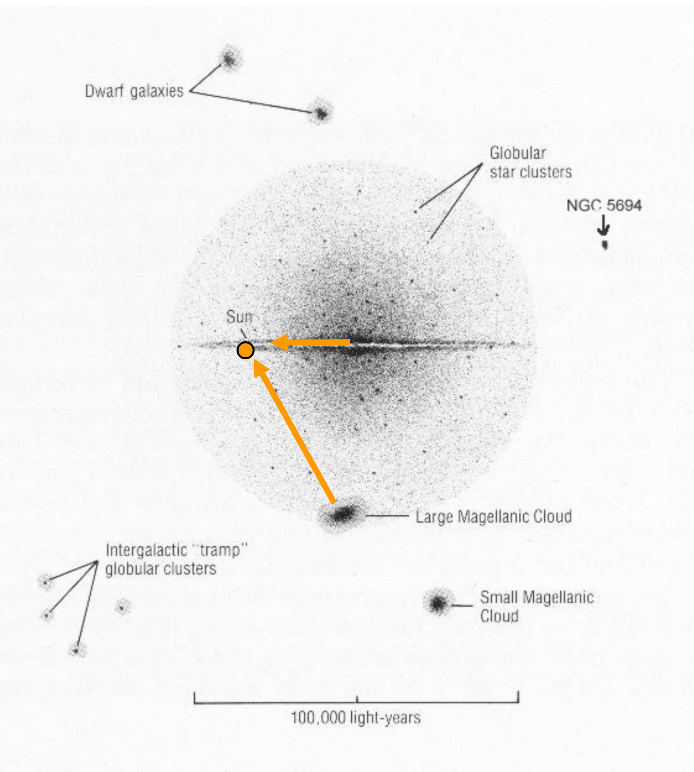
stars can also be gravitationally lensed
- image splitting is too small to see but magnification can be detected over a few months of monitoring
- stare at dense fields of stars and look for flares in the brightness of individual stars due to passing planets, black holes, faint stars, etc.

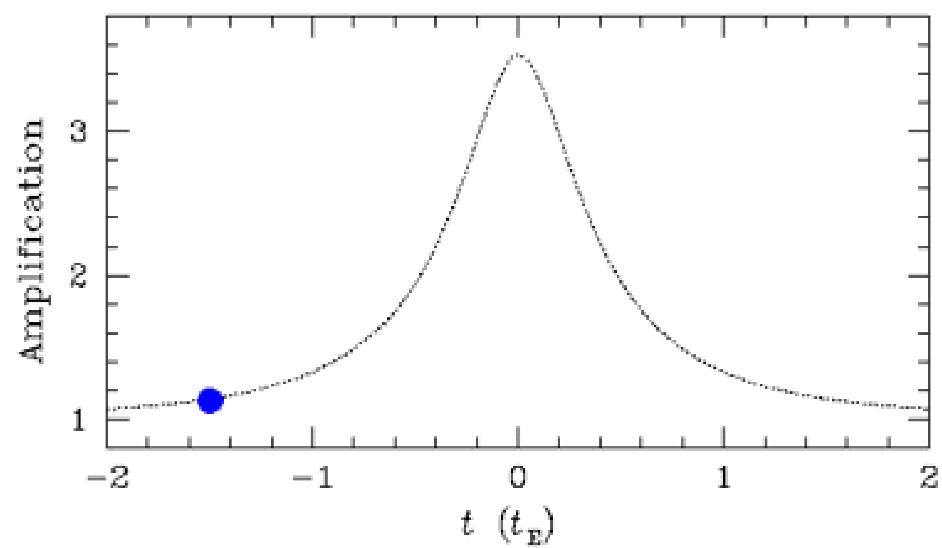
Gravitational lensing

- stars near the center of the Milky Way are lensed by intervening stars

- stars in the Large Magellanic Cloud ***should*** be lensed by intervening black holes, planets, faint stars, etc. but are not







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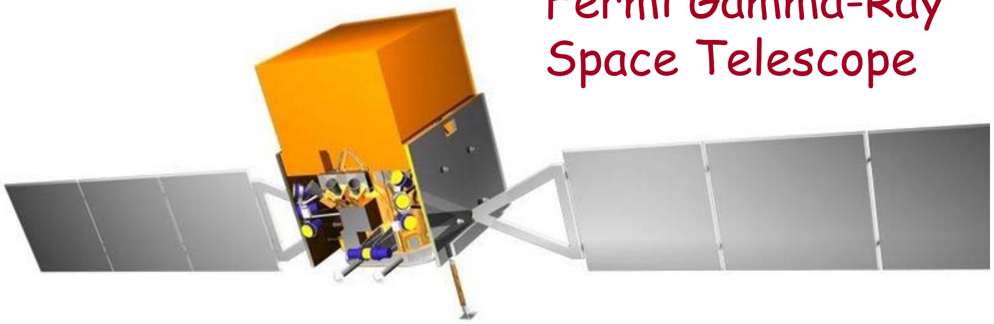
- what is it?
    - ~~rocks?~~
    - ~~very faint stars?~~
    - ~~planets?~~
    - ~~black holes?~~

1. No gravitational lensing is detected from the dark matter in the Milky Way

2. The right amount of helium is created in the Big Bang ***only*** if the density of "ordinary" matter is 4% of the critical density, but the average density of dark matter is 5 X larger, or 20% of the critical density

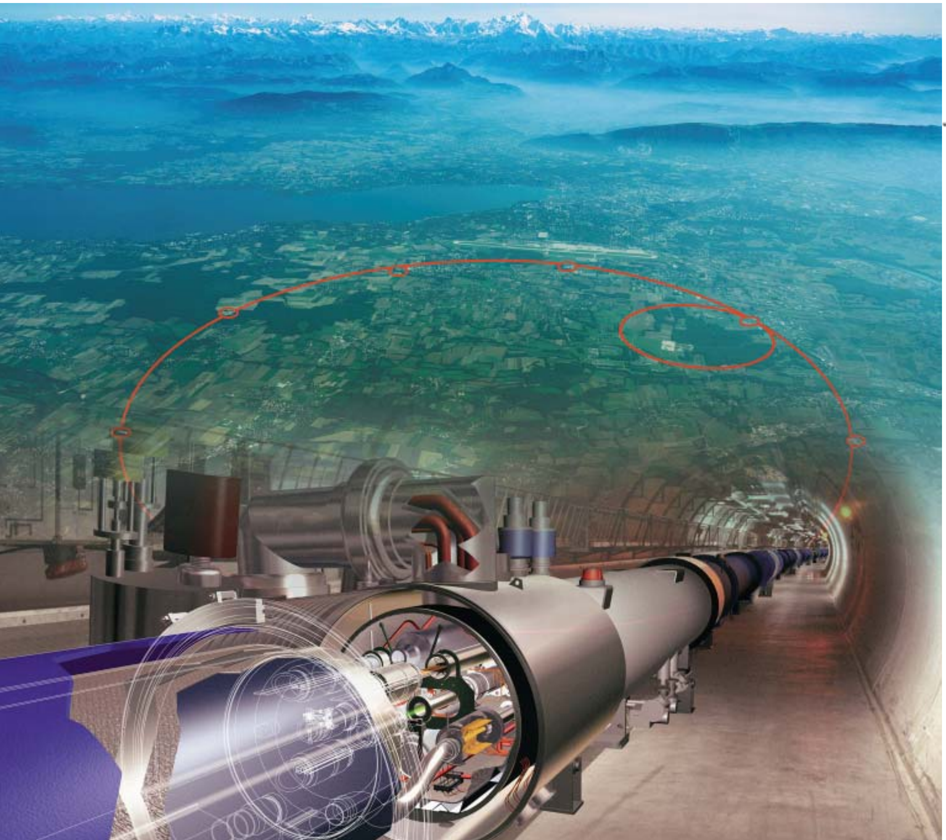
- *all* measurements of galaxies and galaxy clusters on large scales (more than 300,000 light years) show that the mass in stars and gas is only 1/5 of the total mass
- the vast majority of the matter in the universe must therefore be in some unknown and invisible form
- the dark matter must be some exotic form of matter never found on Earth, in the stars, in laboratory experiments, etc.
- most likely the dark matter is some unknown elementary particle that was produced in huge amounts in the Big Bang



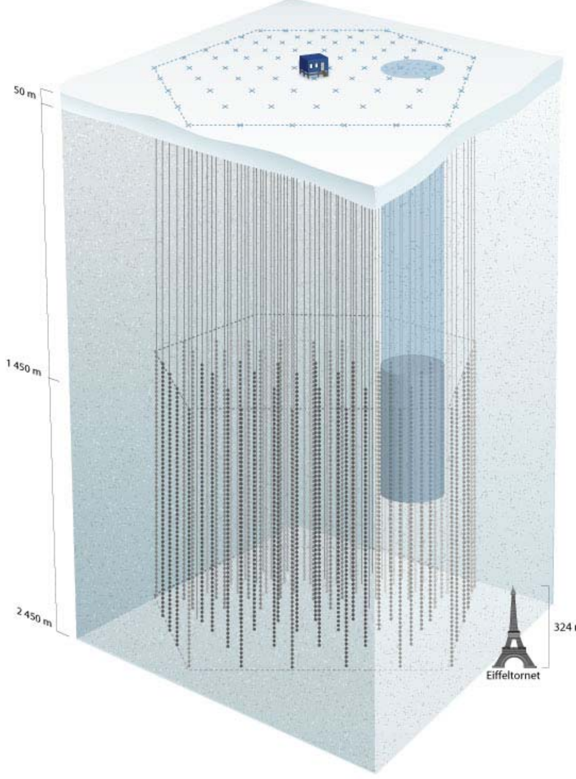
Fermi Gamma-Ray Space Telescope

Cryogenic Dark Matter Search

Large Hadron Collider

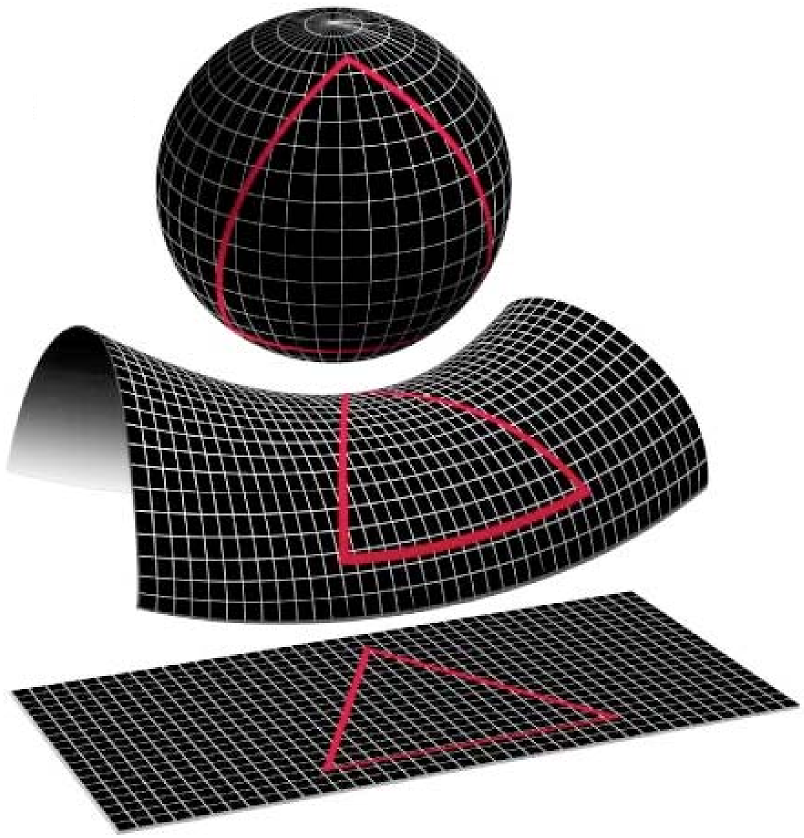


Ice Cube



The history and geometry of the universe

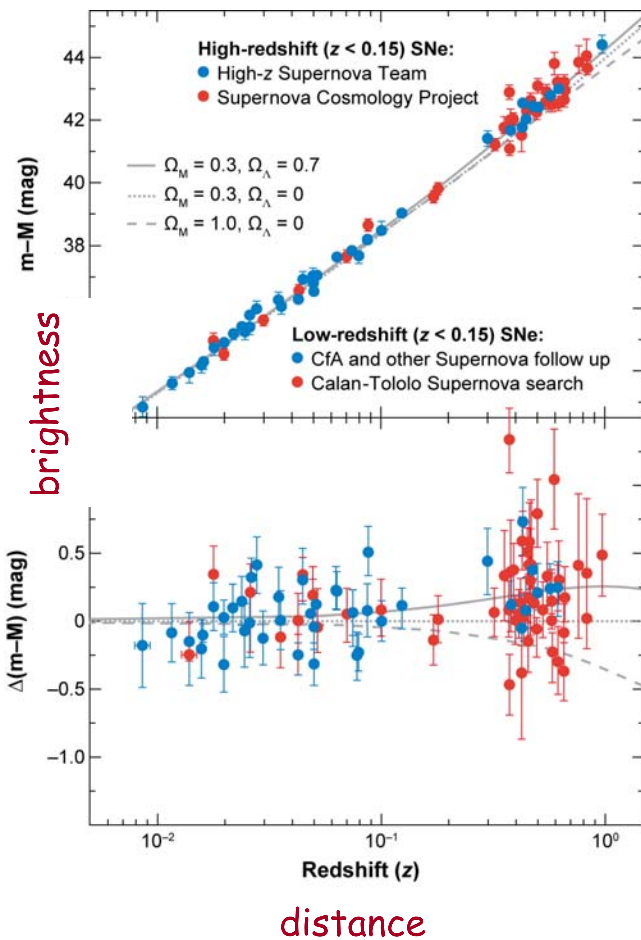
- the total density of ordinary matter (stars and gas) and exotic matter is 25% of the critical density
- Einstein's theory tells us that the geometry of the universe is determined by its average matter content:
    - if the average density exceeds the **critical density**, the universe is finite, and space is curved like the surface of the globe
    - if the average density at present is less than the critical density, the universe is infinite and space is curved like a saddle
    - if the average density equals the critical density, the universe is infinite and space is flat
    - critical density = 1.0 X 10^{-26} kg/cubic meter or about 1 atom per cubic meter
- since the total amount of matter is conserved, we can also deduce the expansion history of the universe

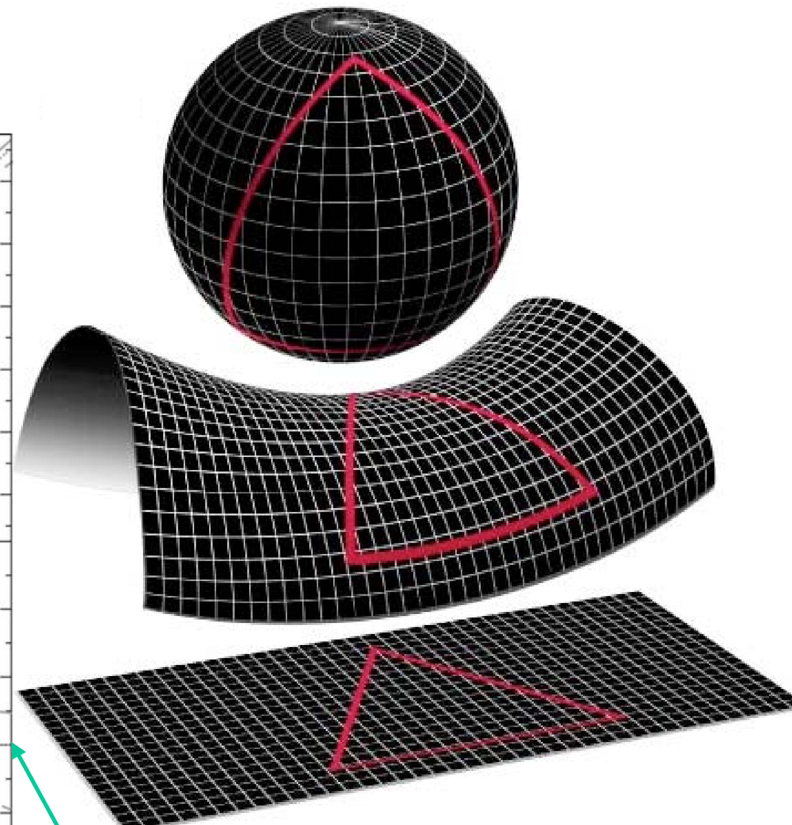


The history and geometry of the universe

We can measure the history and geometry of the universe in several ways:

• relation between distance and brightness of supernovae



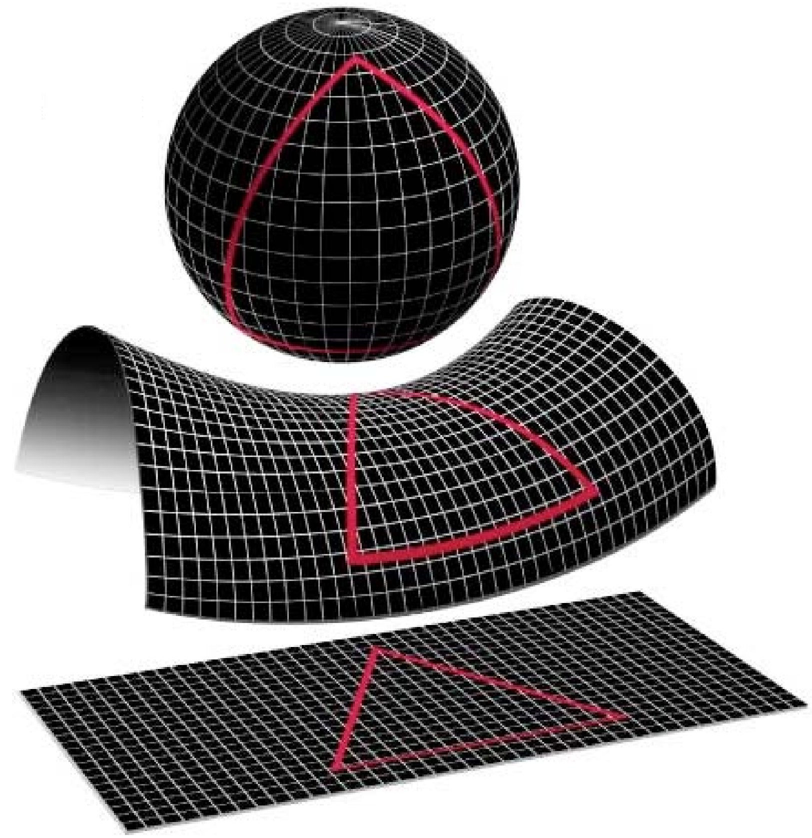


25% of critical density

The history and geometry of the universe

We can measure the history geometry of the universe in several ways:

- relation between distance and brightness of supernovae
- large-scale distribution of galaxies



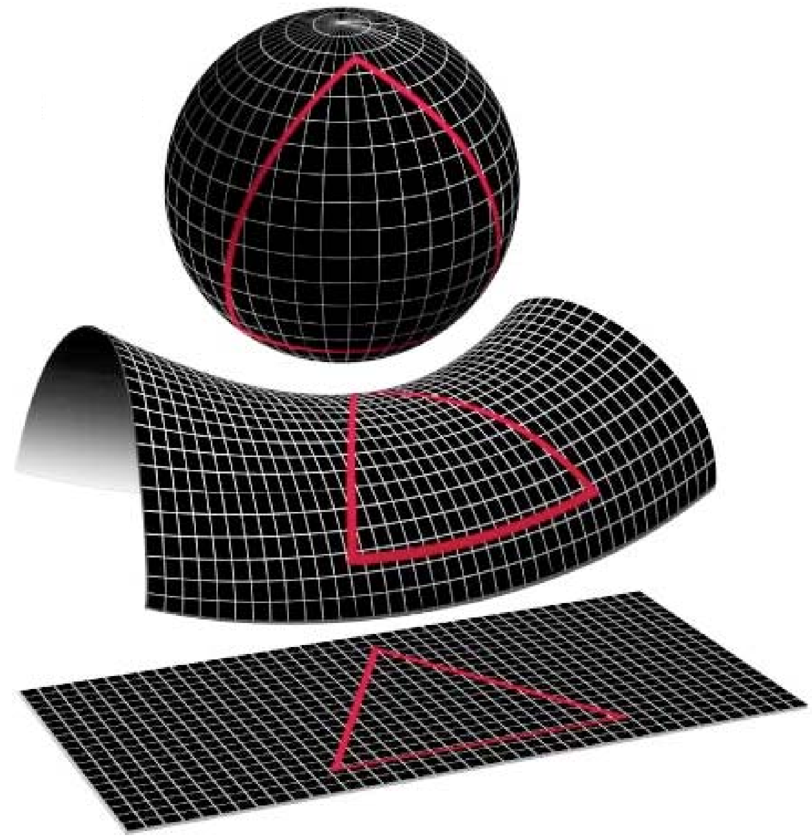
The history and geometry of the universe

We can measure the history and geometry of the universe in several ways:

• relation between distance and brightness of supernovae

• large-scale distribution of galaxies

• the age of the universe (deduced from the oldest stars)



The history and geometry of the universe

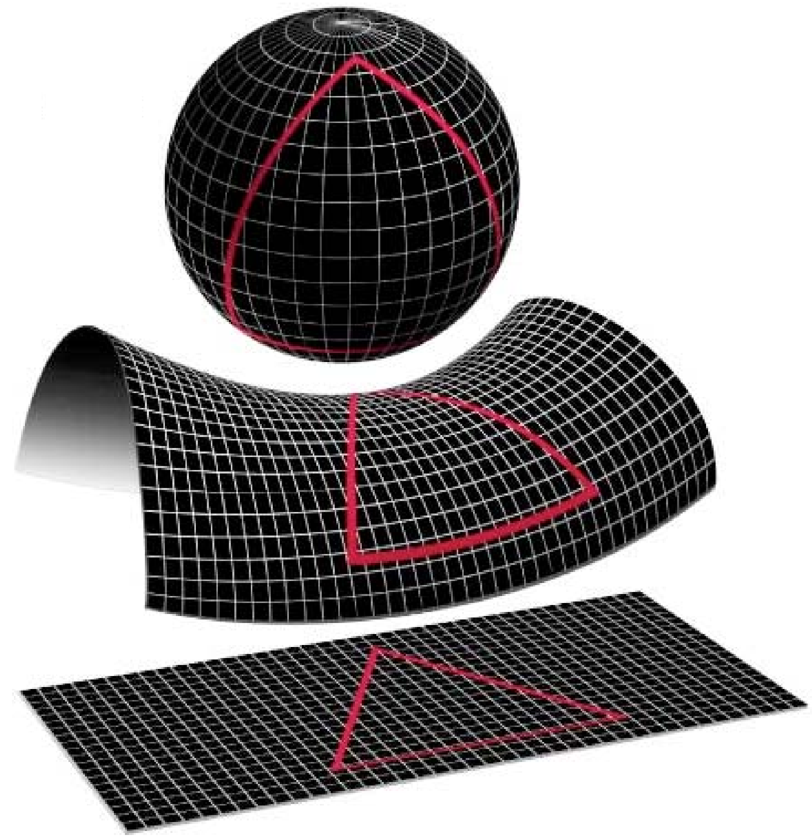
We can measure the history and geometry of the universe in several ways:

• relation between distance and brightness of supernovae

• large-scale distribution of galaxies

• the age of the universe

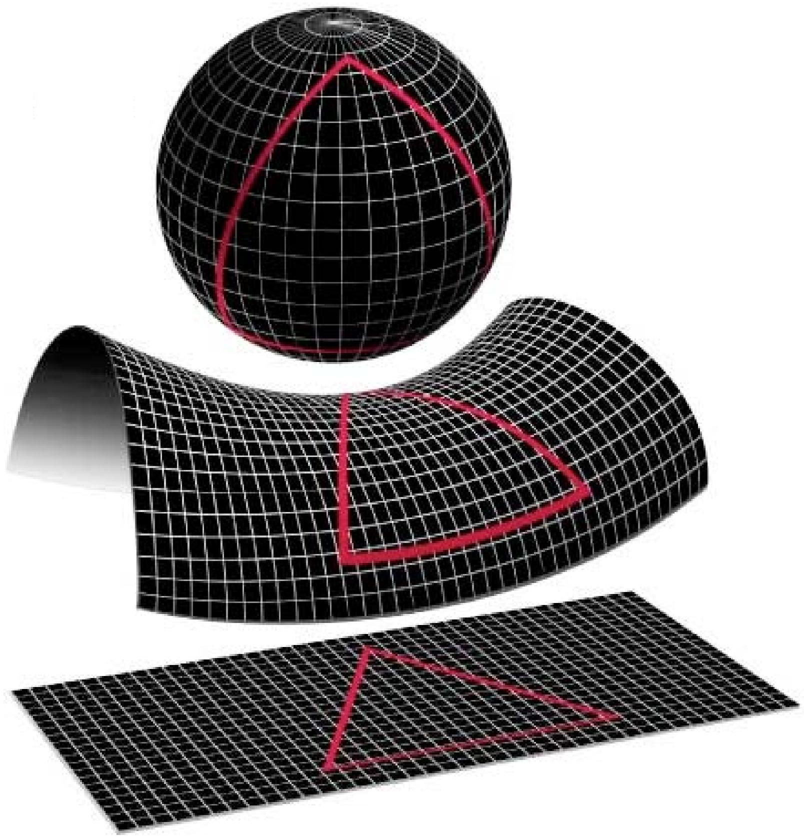
• small irregularities in the background radiation left over from the Big Bang



The history and geometry of the universe

We can measure the history and geometry of the universe in several ways:

- relation between distance and brightness of supernovae
- large-scale distribution of galaxies
- the age of the universe
- small irregularities in the background radiation left over from the Big Bang



All these estimates agree that the universe is flat, not curved.

Einstein's theory then says that the total density must equal the critical density:

ordinary matter: 4%

exotic matter: 20%

??? : 76%

total : 100% of critical density

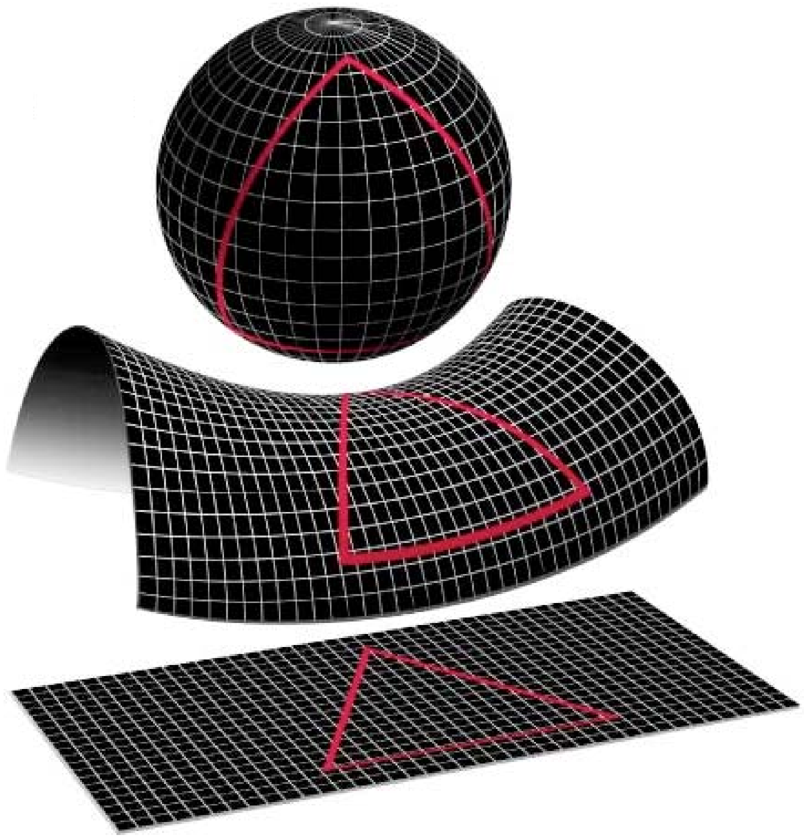
The geometry of the universe

All these estimates agree that the universe is flat, not curved.

Einstein's theory then says that the total density must equal the critical density:

ordinary matter	:	4%
exotic matter	:	20%
???	:	76%
total	:	100% of critical density

The remaining 76% is variously known as dark energy, the cosmological constant, or vacuum energy (energy of empty space)

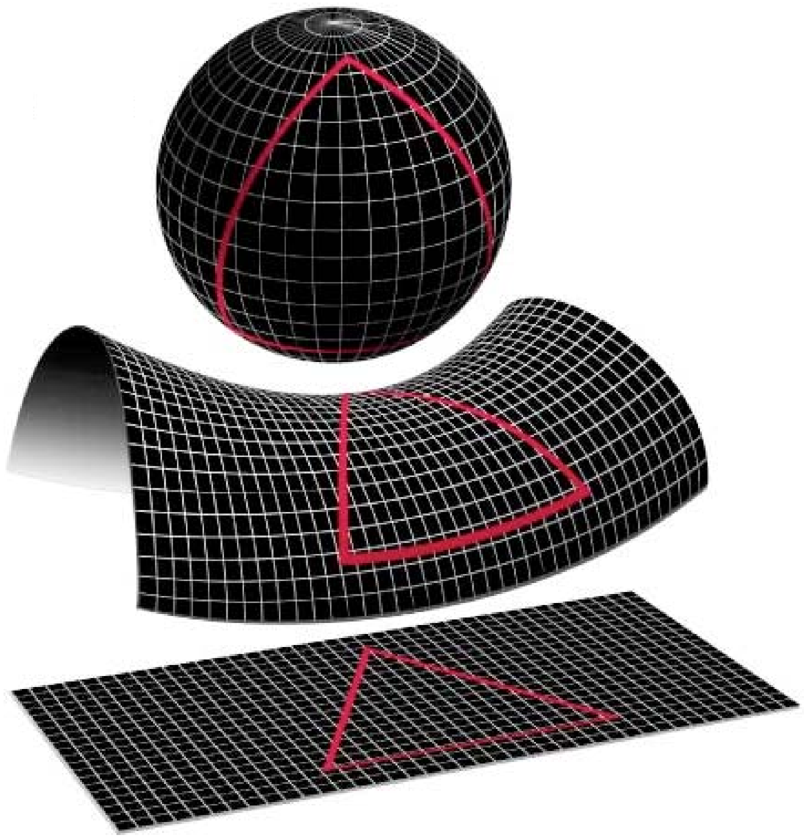


Dark energy

• first introduced by Einstein in 1917 as an ad hoc addition to general relativity to permit static cosmological models ("my biggest blunder")

• dark energy exerts negative gravitational force so the expansion of the universe is now accelerating

• theoretical estimates imply that either the dark energy should be exactly zero or 60-100 orders of magnitude larger than what we observe



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu}$$

The history and geometry of the universe

ordinary matter: 4%

exotic matter: 20%

dark energy : 76%

total : 100% of critical density

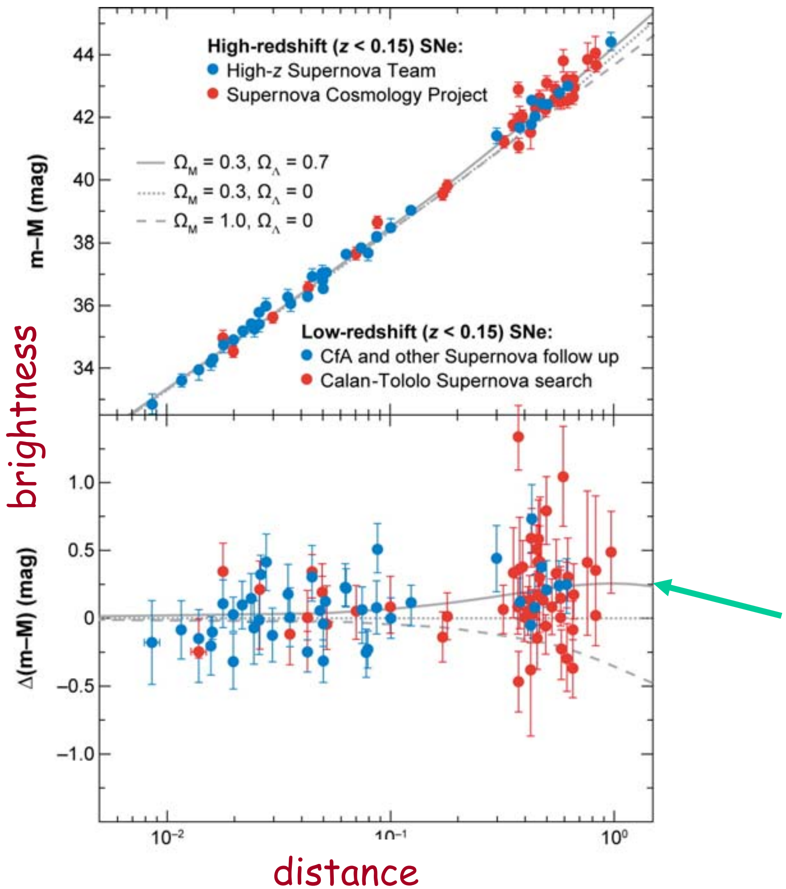
Although we don't understand the properties of exotic matter or dark energy, a model of the universe with these properties does a remarkably good job of fitting the data:

• relation between distance and brightness of supernovae

• large-scale distribution of galaxies

• the age of the universe

• small irregularities in the background radiation left over from the Big Bang



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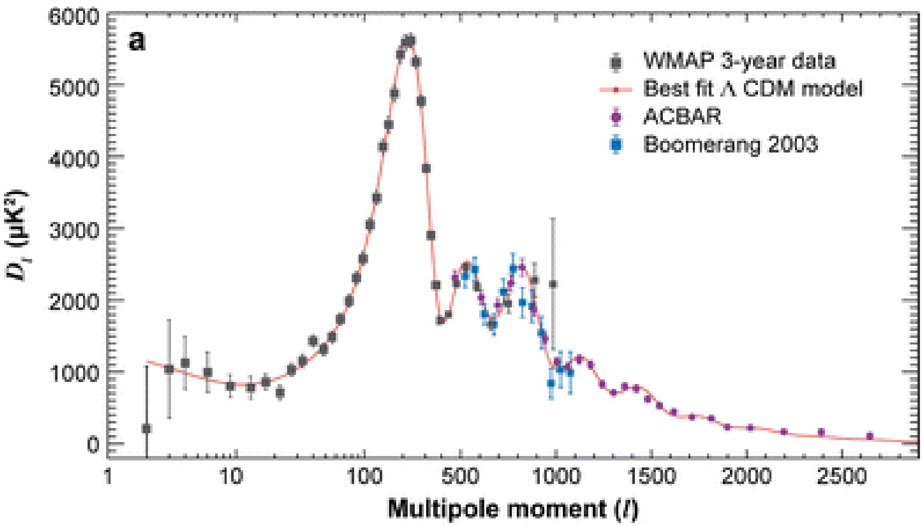

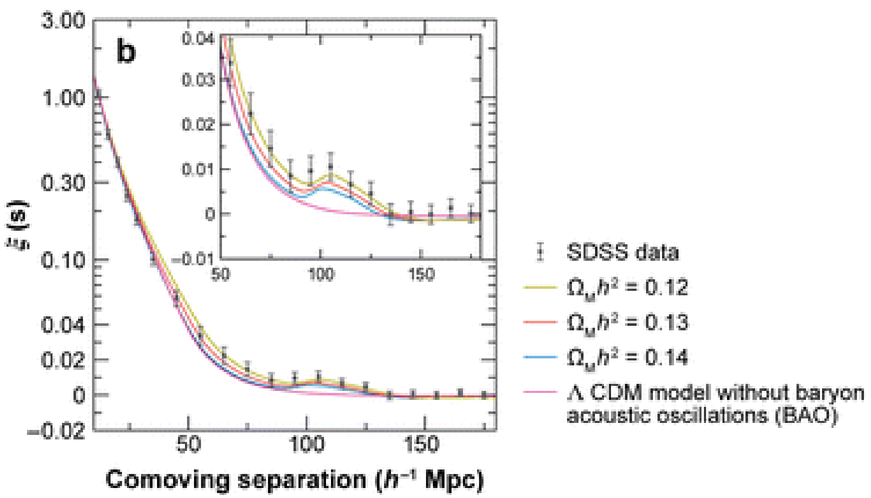

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• average density is equal to the critical density to within 1%, so the geometry of the universe is very nearly flat

• age of the universe is 13.7 billion years to within a few %

• density of ordinary matter is 4.2% of critical with an uncertainty of 0.2%

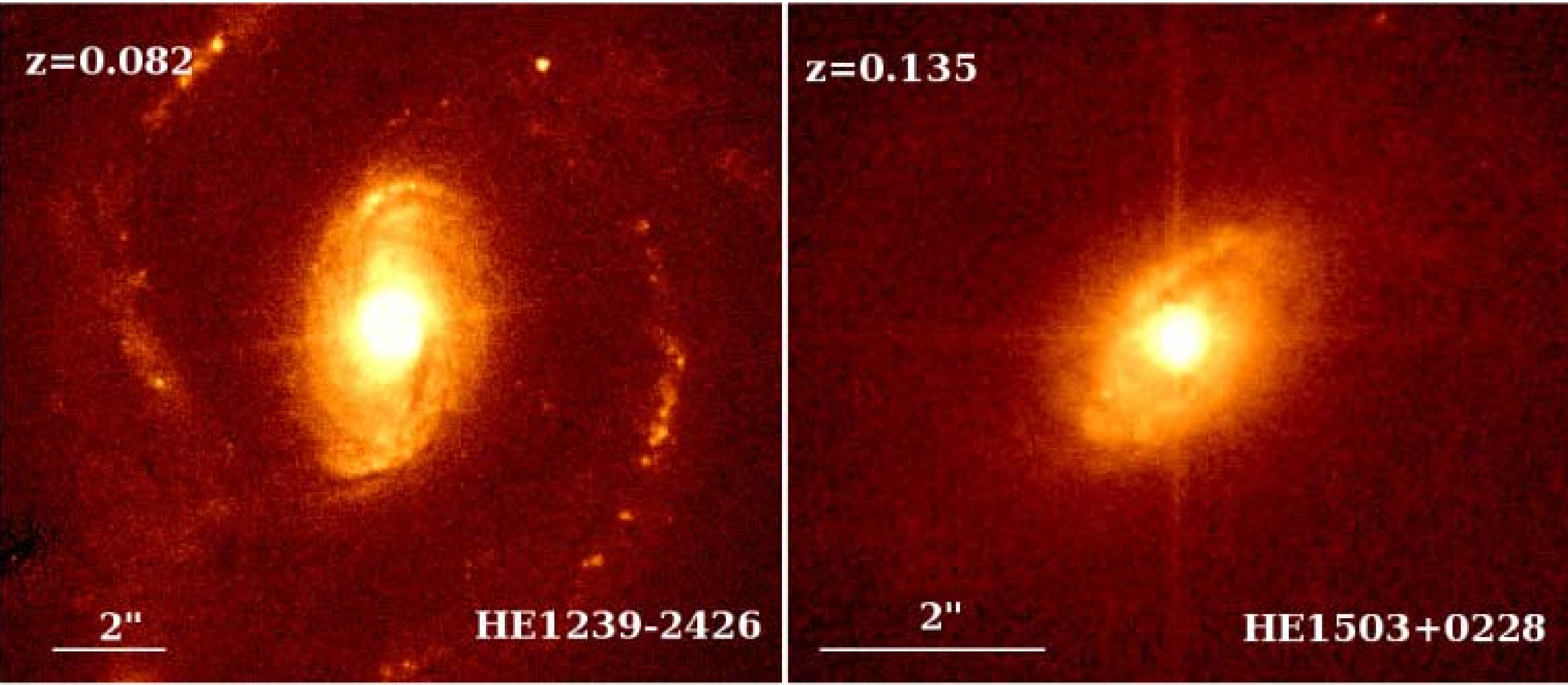
• on the largest scales, the universe is isotropic (the same in all directions) to within about 10 parts per million

Black holes

- a region of space in which the gravitational field is so strong that even light cannot escape
- first suggested by John Michell in 1783
- consistent description was only possible through general relativity
- interior of a black hole (inside the event horizon) is invisible, but the black hole may reveal its presence through its actions on nearby matter:
  - gravitational lensing
  - orbits of nearby stars
  - heating gas orbiting the black hole to very high temperature
- black holes are ***very*** small, e.g., event horizon for a black hole with the mass of the Sun is only 3 kilometers

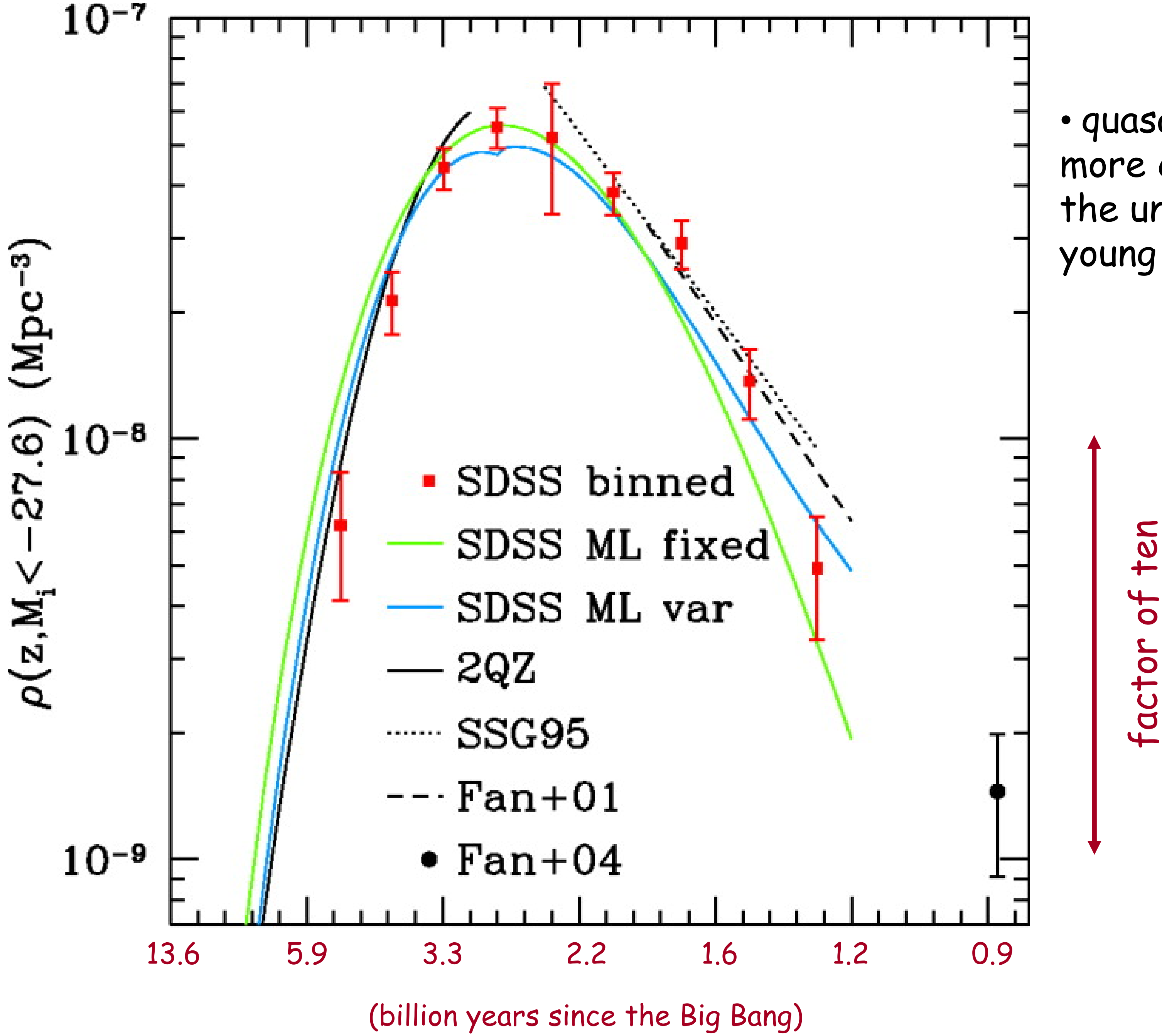
Quasars

- some strong astronomical radio sources are galaxies; others are star-like (quasi-stellar objects)
- quasars were first thought to be unusual stars in the Milky Way but were discovered to be 100 million times further away
- quasars turn out to be intense sources of radiation located in the centers of galaxies
  - usually far brighter than the galaxy itself so they mask the light from the galaxy
  - up to 10 billion times the energy output of the Sun
- quasars are the strongest steady power sources in the universe



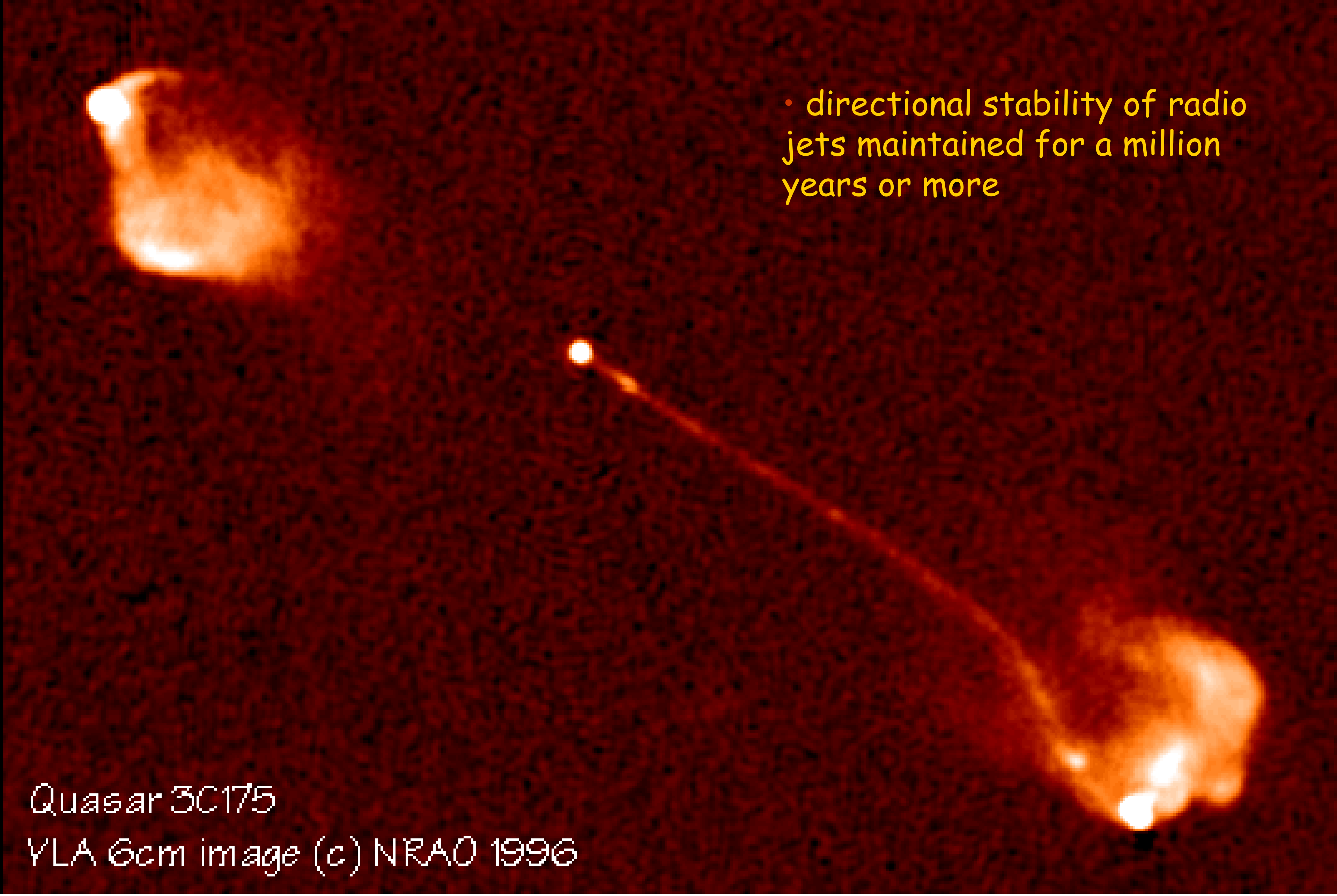
Two Quasars with Their Host Galaxy
(HST)

ESO PR Photo 28a/05 (September 14, 2005)

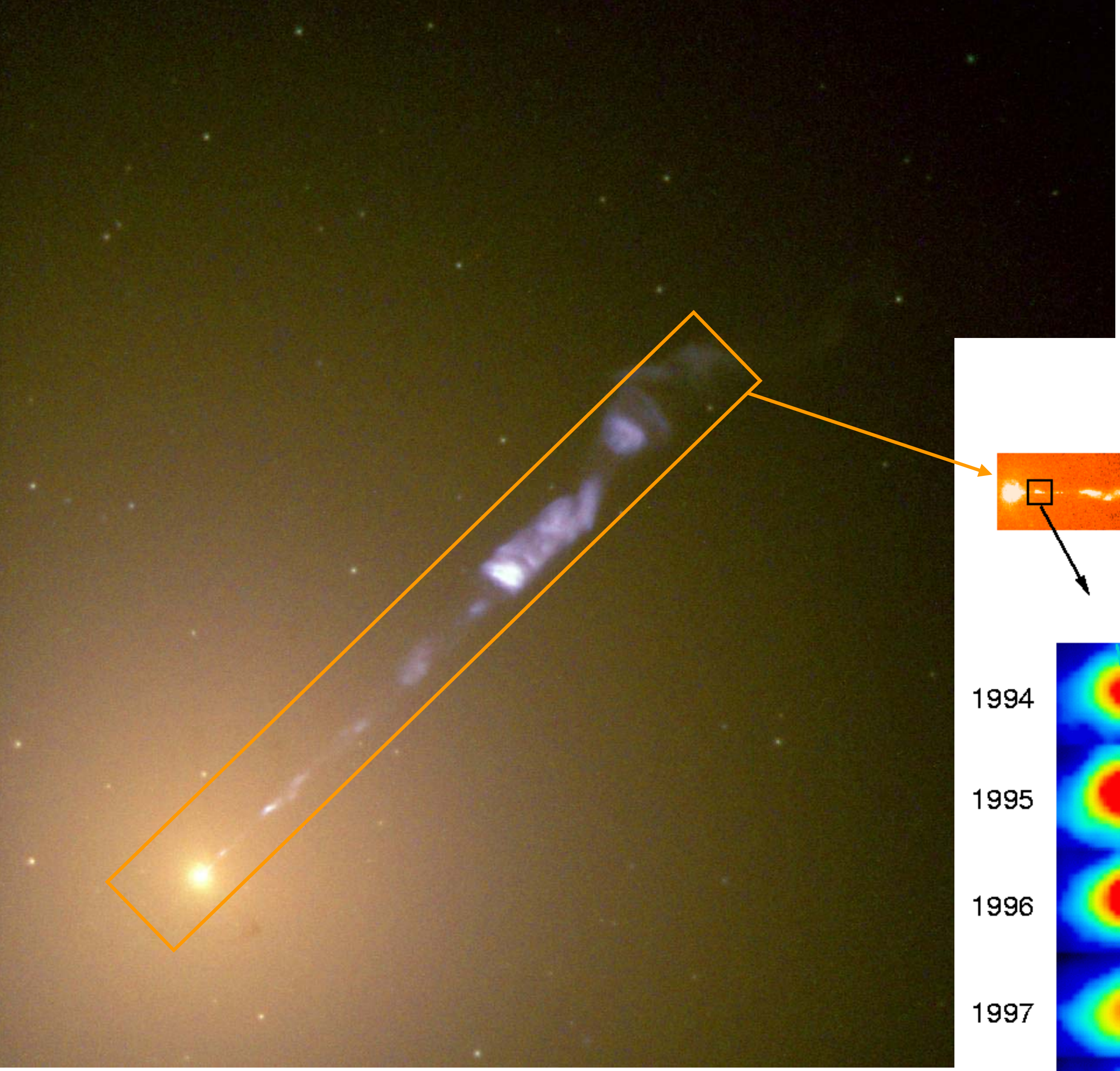


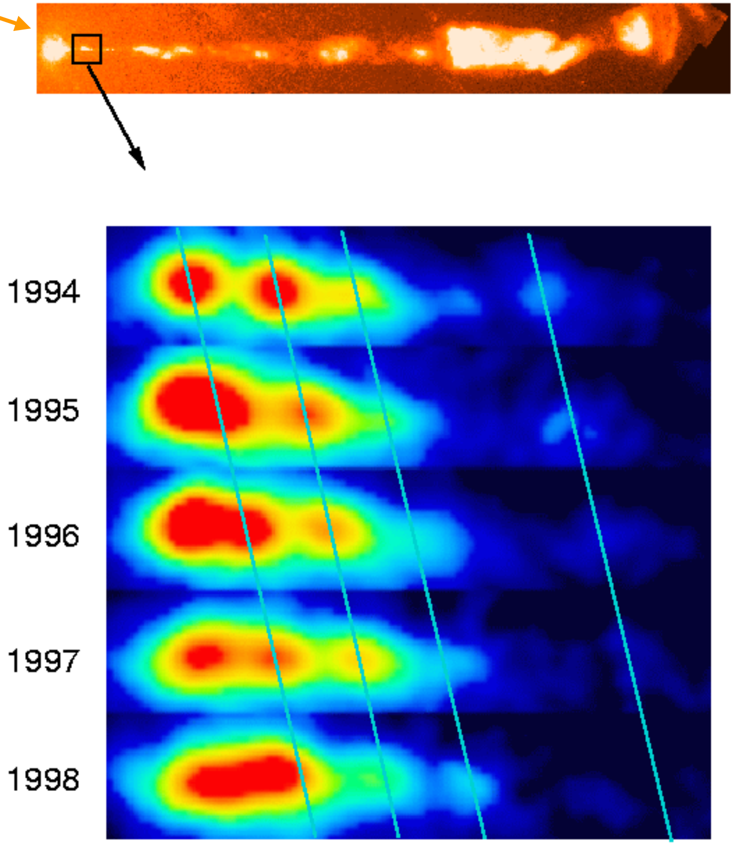
- quasars were much more common when the universe was young quasars are black holes with masses of one million to one billion times the mass of the Sun, shining from super-heated gas that is slowly spiraling into the black hole and making it grow...

- directional stability of radio jets maintained for a million years or more



- velocities in radio jets are close to the speed of light





- quasars vary on timescales of months
    - implies size less than the distance light can travel in a month, or about 100 X the size of the solar system
    - tighter constraint is about equal to the size of the solar system (distance to outermost planets)

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  - tighter constraint is about equal to the size of the solar system (distance to outermost planets)
- efficiency
  - $E=Mc^2$ if mass is converted entirely to energy; efficiency of any engine is E/Mc^2
    - gasoline 0.0000000003
    - nuclear reactors 0.001
    - black holes 0.1 – 0.3
  - all U.S. energy needs could be met with a fuel supply of 100 pounds per day

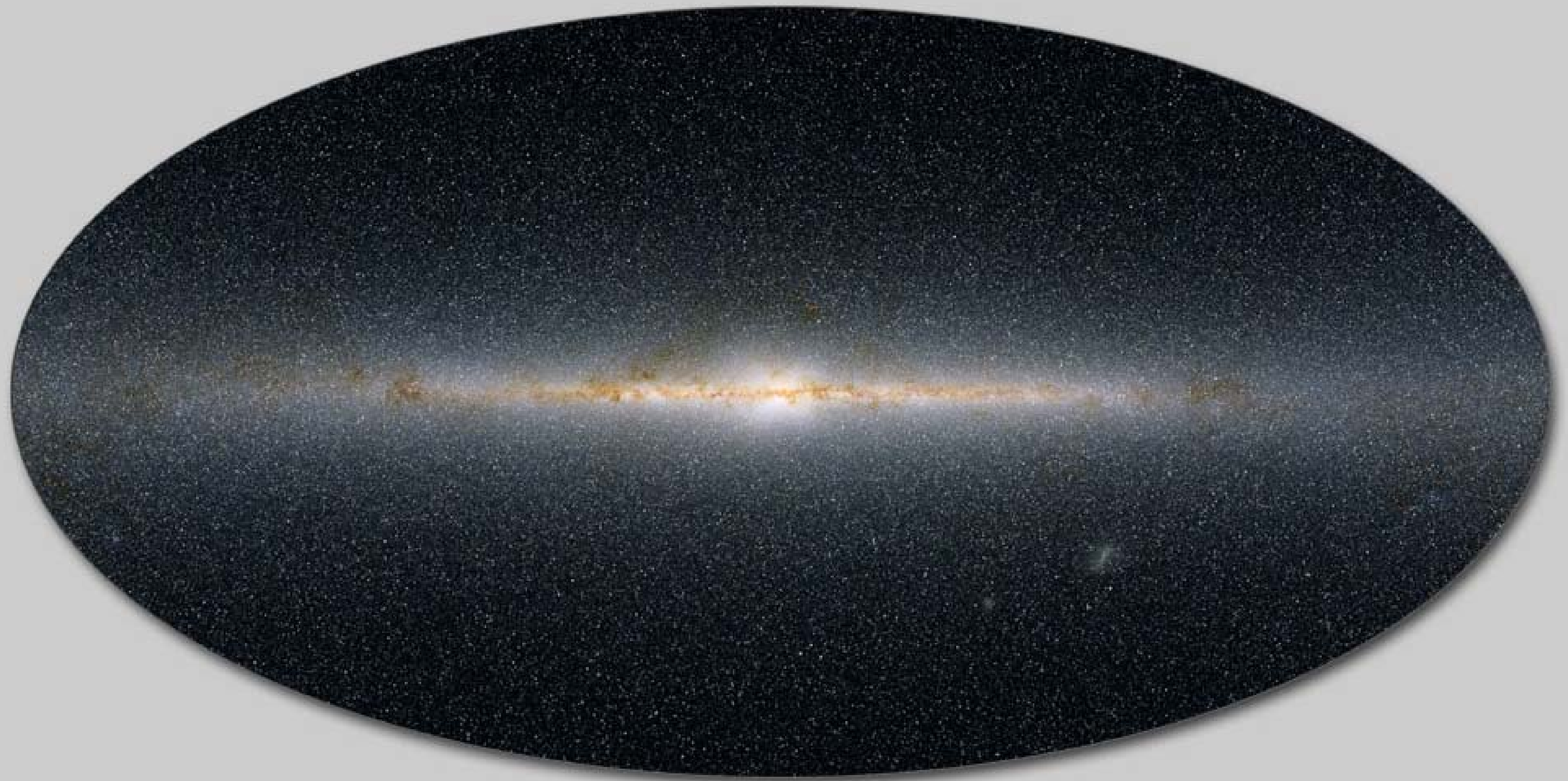
if

- black holes are the power source for quasars
- the present abundance of quasars is much less than the abundance early in the history of the universe
- quasars are found in the centers of galaxies

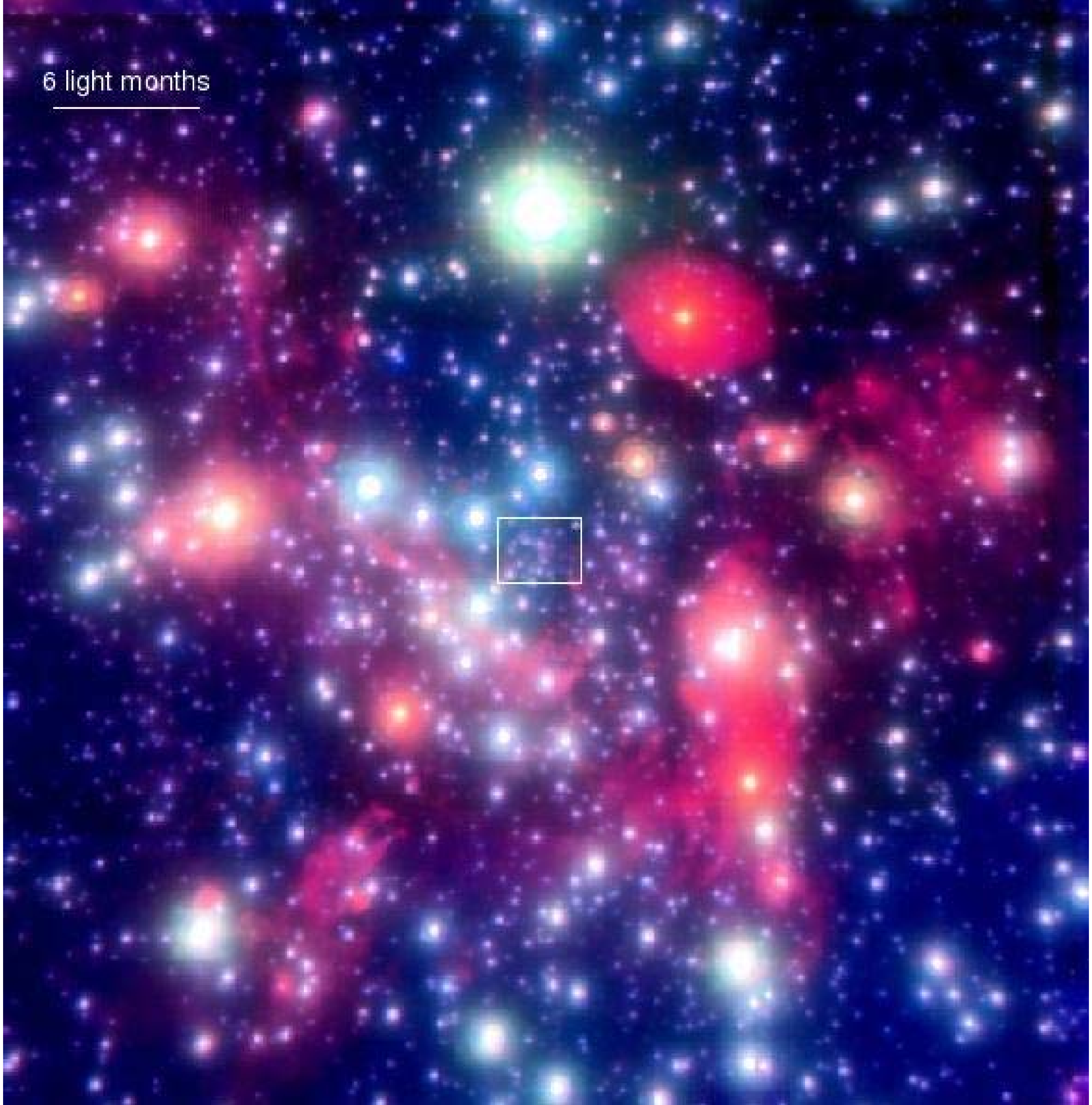
then

many nearby galaxies must contain black holes (dead quasars) at their centers

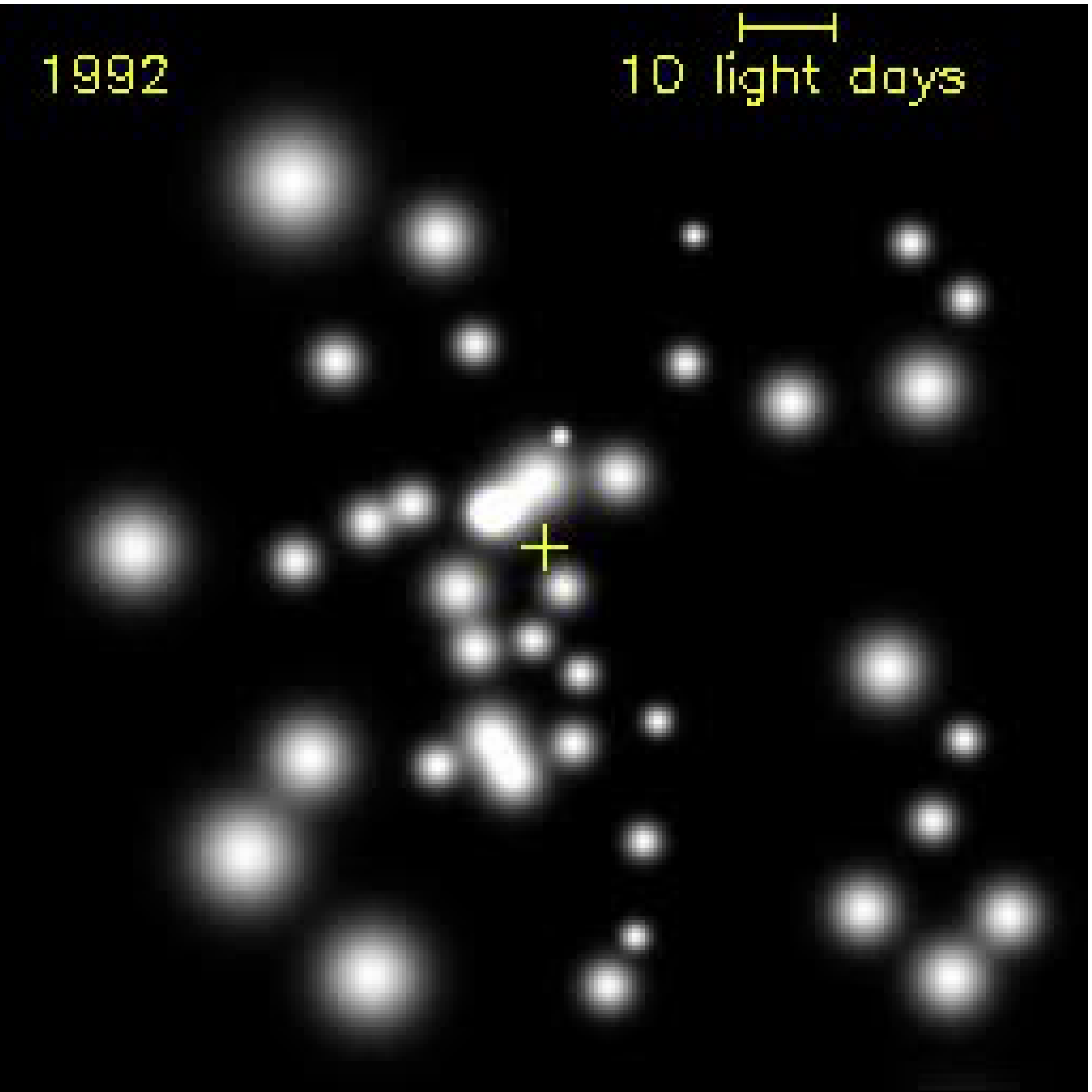
The Milky Way



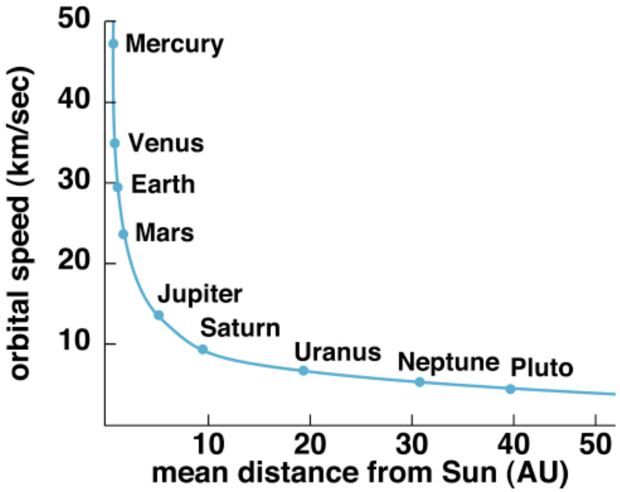
1000 light years

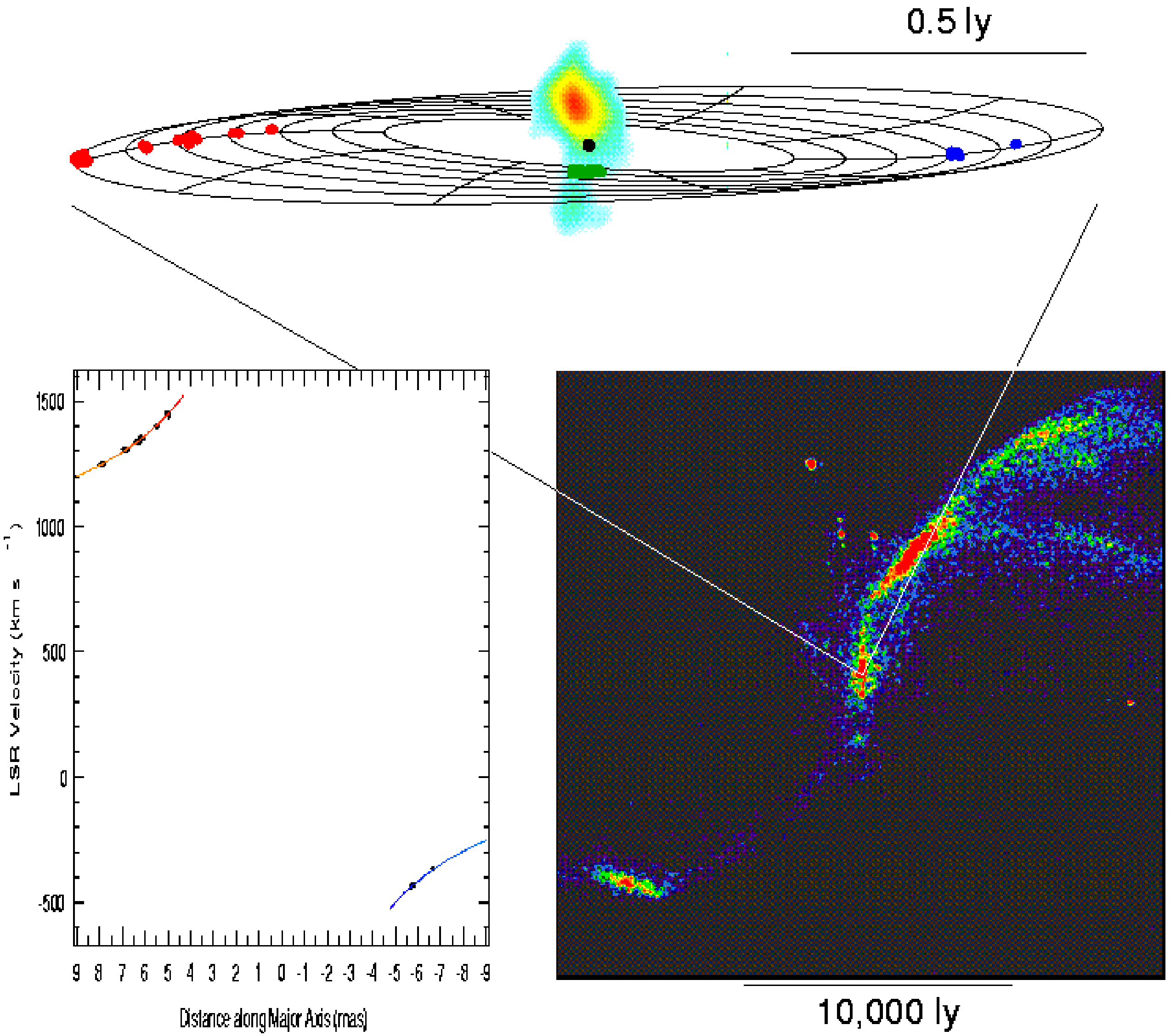

6 light months

The Milky Way



- the stars must be orbiting an object of mass 4 million times the mass of the Sun, of size less than the distance from the Earth to Pluto
- no known astronomical object other than a black hole has these properties
- if this object is a black hole, its event horizon is about 10% of the Earth-Sun distance





- mass of central object is 40 million solar masses with an uncertainty of only 2%
- no known object other than a black hole could be so massive and so small

total mass of ash that must be left over from all the quasars in the past history of the universe, if efficiency is 0.1 Mc^2:

5,000 – 10,000 solar masses in a box of a million light-years on a side

total mass of black holes found in the centers of nearby galaxies:

8,000 – 14,000 solar masses in a box of a million light-years on a side

Summary

- we are not located at a special place in the Universe, or at a special time in the history of the Universe (the Copernican principle)
- the laws of physics that we investigate in the lab also govern the behavior of astronomical objects
- the study of astronomical objects can reveal new laws of physics
- the Sun and stars are made of the same elements as the Earth

Summary

- we are not located at a special place in the Universe, or at a special time in the history of the Universe (the Copernican principle)
    - nor are we made of a special material – everything we have ever seen or felt comprises only 4% of the mass and energy in the universe
- the laws of physics that we investigate in the lab also govern the behavior of astronomical objects
- the study of astronomical objects can reveal new laws of physics
- the Sun and stars are made of the same elements as the Earth

Summary

- we are not located at a special place in the Universe, or at a special time in the history of the Universe (the Copernican principle)
- the laws of physics that we investigate in the lab also govern the behavior of astronomical objects
  - there is now indisputable evidence that black holes exist, of masses as large as a billion solar masses
  - the question for the next decade is whether they behave according to Einstein's theory
  - one of the most remarkable predictions of theoretical physics – black holes – is confirmed by one of the most dramatic discoveries of observational astronomy – quasars
- the study of astronomical objects can reveal new laws of physics
- the Sun and stars are made of the same elements as the Earth

Summary

- we are not located at a special place in the Universe, or at a special time in the history of the Universe (the Copernican principle)
- the laws of physics that we investigate in the lab also govern the behavior of astronomical objects
- the study of astronomical objects can reveal new laws of physics
    - and may well be the most powerful method we have to discover new physics in the twenty-first century
- the Sun and stars are made of the same elements as the Earth

Summary

- we are not located at a special place in the Universe, or at a special time in the history of the Universe (the Copernican principle)
- the laws of physics that we investigate in the lab also govern the behavior of astronomical objects
- the study of astronomical objects can reveal new laws of physics
- the Sun and stars are made of the same elements as the Earth
    - but most of the universe is not
    - Plato's immutable, unchangeable fifth element comprises 75% of the mass and energy of the universe, and its nature is one of the central problems for twenty-first century physics