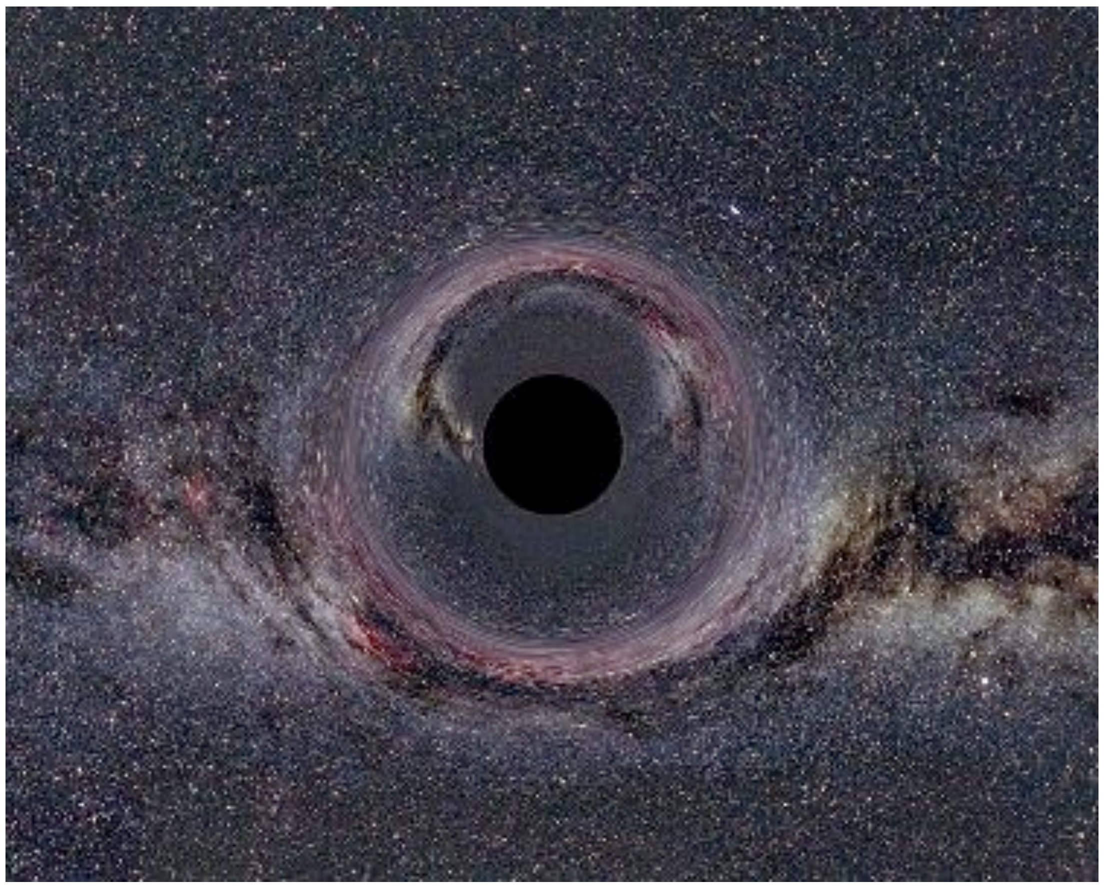
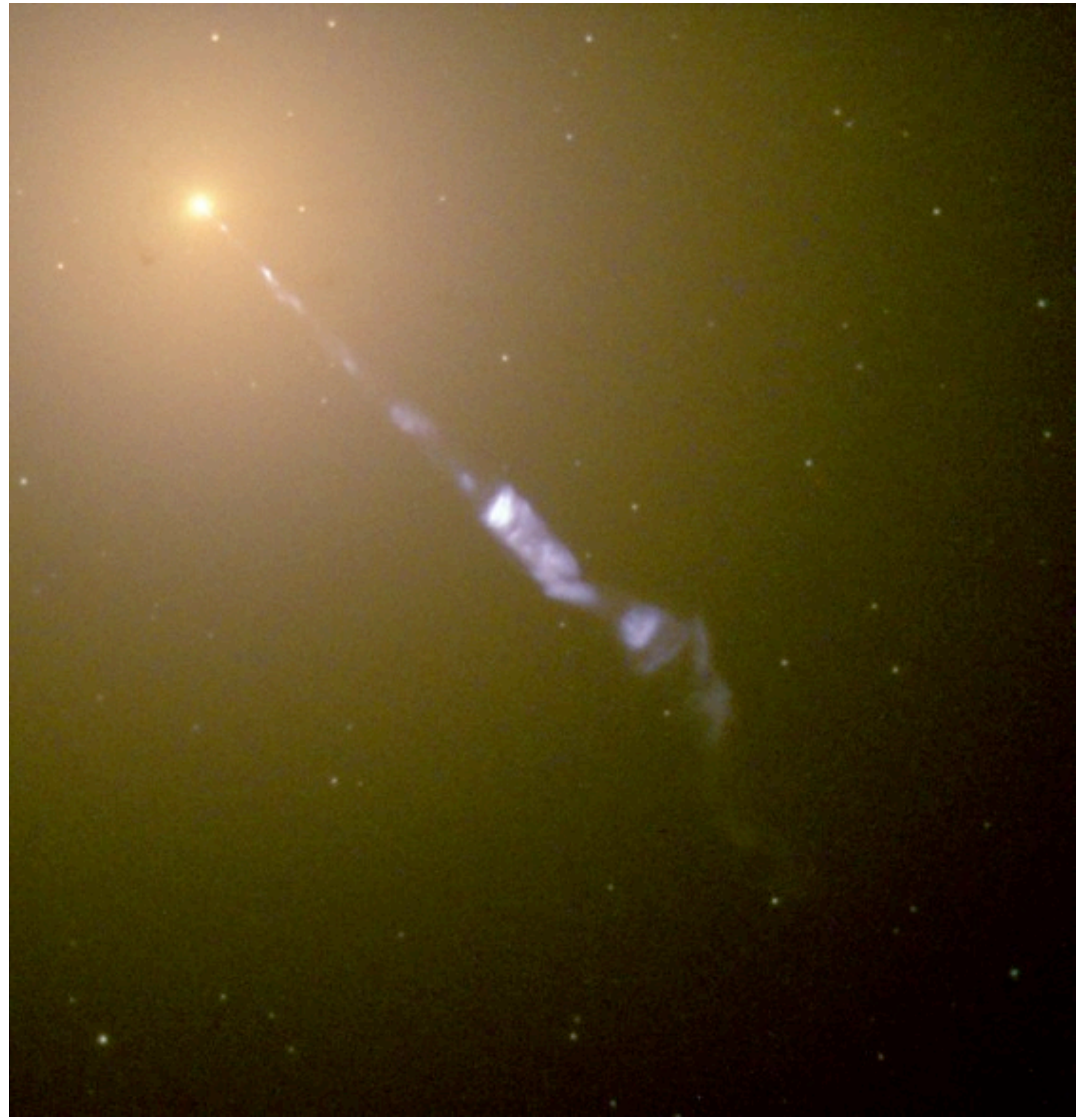
Black Holes





General Relativity Intro

We try to explain the black hole phenomenon by using the concept of escape velocity, the speed to clear the gravitational field of an object. According to Newtonian mechanics, if something is sufficiently massive its escape velocity will exceed the speed of light and as this is impossible nothing will escape from it. This is not a satisfactory explanation. Two concepts introduced by Albert Einstein are needed to explain this phenomenon.

General Relativity Intro

Time and space are not two independent entities, but are different aspects of the same entity, spacetime. An object is not free to move around spacetime at will; it cannot change its position in space faster than the speed of light. This is the main result of the theory of special relativity.

The second concept is the base of general relativity; mass deforms the structure of spacetime and as a result, masses appear attracted to other masses. This is referred to as gravity. This deformation effect becomes more pronounced as the distance to the mass becomes smaller. At some point close to the mass, the distortion becomes so strong that all the possible paths an object can take lead towards the mass. This implies that any object that crosses this point can no longer get further away from the mass. This point is called the event horizon.

A Black Hole is a region of space containing, at its center, matter squeezed into a point of infinite density, called a SINGULARITY

Within a spherical region around the singularity, the gravitational pull is so great that nothing, not even light can escape. Hence its name BLACK HOLE.

Dormant Black holes can detected from the behaviour of material around them, from the gravitational effects they induce.

Most if not all galaxies have black holes with the mass of many millions of Suns, known as super-massive black holes, at their centre

Most such black holes are dormant

This means that material has long since settled into a stable orbit around it. The black hole no longer has any material to accrete.

What is a Black Hole ????

Einstein and Mercury

Mercury's perihelion (closest point to the Sun) moves which each orbit, it precesses. Newtonian mechanics couldn't account for the amount by which the orbit shifts.

Careful observations of Mercury showed that the actual value of the precession disagreed with that calculated from Newton's theory by 43 seconds of arc per century.

In the 19th century it was proposed that a planet called Vulcan! existed inside Mercury's orbit and produced this effect.

However General Relativity explained away the problems with Mercury's orbit. Orbits in general relativity are not quite periodic, but precess. The precession effect for calculated for Mercury's orbit agreed with observations.

Mercury Precession

$$\frac{d^2u}{d\theta^2} + u = \frac{GM}{L^2} \quad \Rightarrow \quad u = \frac{GM}{L^2}(1 + e\cos\theta)$$

$$\frac{d^2u}{d\theta^2} + u = \frac{GM}{L^2} + \frac{3GMu^2}{c^2}$$

$$\Rightarrow \quad u = \frac{GM}{L^2}\left(1 + e\cos[\theta(1-\alpha)]\right)$$

$$\alpha = \frac{3(GM)^2}{(Lc)^2}$$

Some History

The idea of an object with gravity strong enough to prevent light escaping dates from the 1700's. Black holes as they are currently understood originate as a result of the General Theory of Relativity (first published by Albert Einstein in 1916)

General Relativity predicts that when a large enough amount of mass is present in a sufficiently small region of space, all paths through space are warped inwards towards the center of the volume, preventing all matter and radiation within it from escaping. Karl Schwarzschild first described mathematically how the concept of a black hole originates from general relativity

Karl Schwarzschild (October 9, 1873 – May 11, 1916) was a German Jewish physicist.

He is best known for providing the first exact solution to the Einstein field equations of general relativity, for the limited case of a single spherical non-rotating mass, which he accomplished in 1915, the same year that Einstein first introduced general relativity. The Schwarzschild solution, which makes use of Schwarzschild coordinates and the Schwarzschild metric, leads to the well-known Schwarzschild radius, which is the size of the event horizon of a non-rotating black hole.

Schwarzschild accomplished this triumph while serving in the German army during World War I.

Today when we talk about Black Holes we are talking about Schwarzschild Black Holes

Schwarzschild Radius

In astrophysics, the radius of the event horizon surrounding a black hole is called the Schwarzschild radius.

For a black hole of mass M_b the Schwarzschild radius is given by

$R_s = 2Gm/c^2$

Neutron Stars

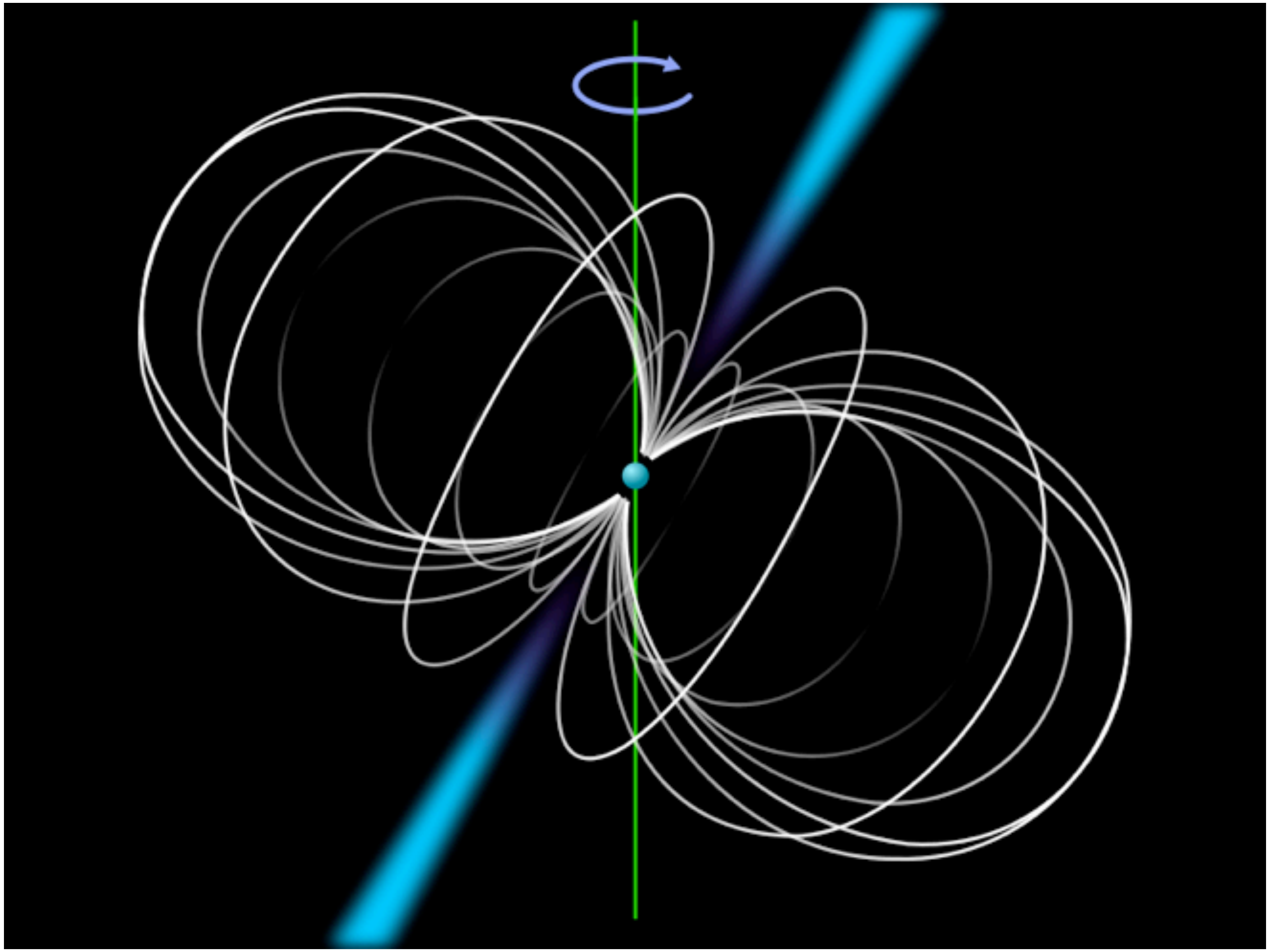
Neutron stars are one of the by-products of Type II supernova explosions. During a supernova the outer layers of the star are blown off, leaving an extremely dense compact star comprising mostly of neutrons or a Neutron Star.

Neutron stars have a mass between 0.1 and 3 solar masses. Above this mass there is no mechanism which can stop the star collapsing and a black hole forms.

As the neutron star forms, the magnetic field of the parent star becomes concentrated and grows in strength. In addition the rotation of the star increases in speed with collapse.

Neutron stars are characterised by their strong magnetic fields and rapid rotation.

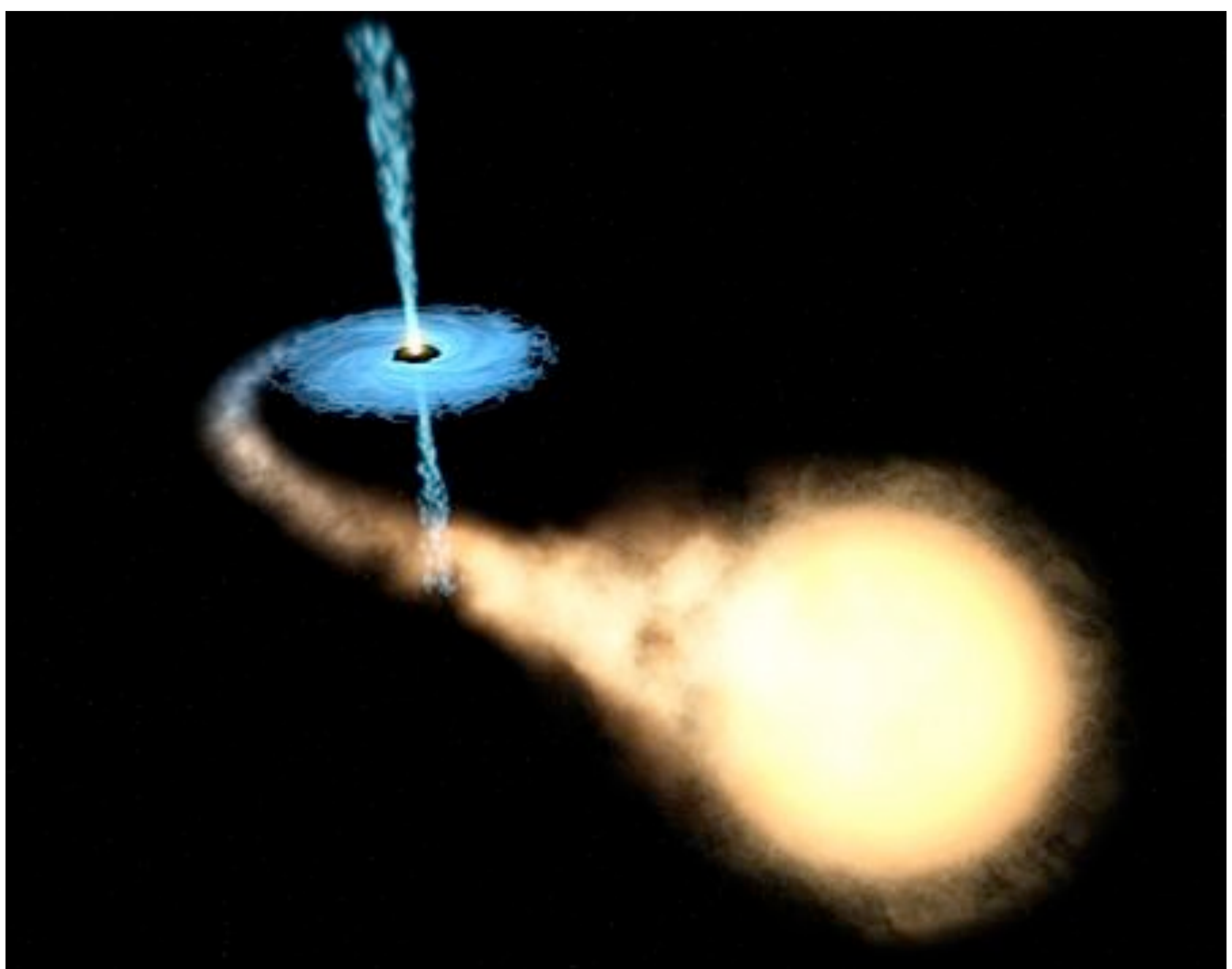
Neutron stars that emit directed pulses of radiation at regular intervals are known as pulsars.



Schematic view of a pulsar. The sphere in the middle represents the neutron star, the curves indicate the magnetic field lines and the protruding cones represent the emission beams.

If the remnant of a supernova explosion is greater than about three solar masses, there is no mechanism that can stop it collapsing. It becomes so small and dense that its resulting gravitational pull is great enough to stop even radiation, including visible light from escaping. Such objects are known as stellar mass black holes.

Black Holes Candidates (BHCs) can only be detected by the effect they have on mass around them so we tend to see them in binaries. In particular x-ray binaries



As a black hole is rotating matter is not pulled directly into the black hole but forms a disk around it. Matter impacts onto the disk creating hot spots that can be detected by the radiation they emit. Also as matter in the disk gradually spirals
into the black hole, radiation is emitted, predominantly in x-rays.

We tend to see stellar mass black holes as x-ray binaries

Super Massive Black Holes

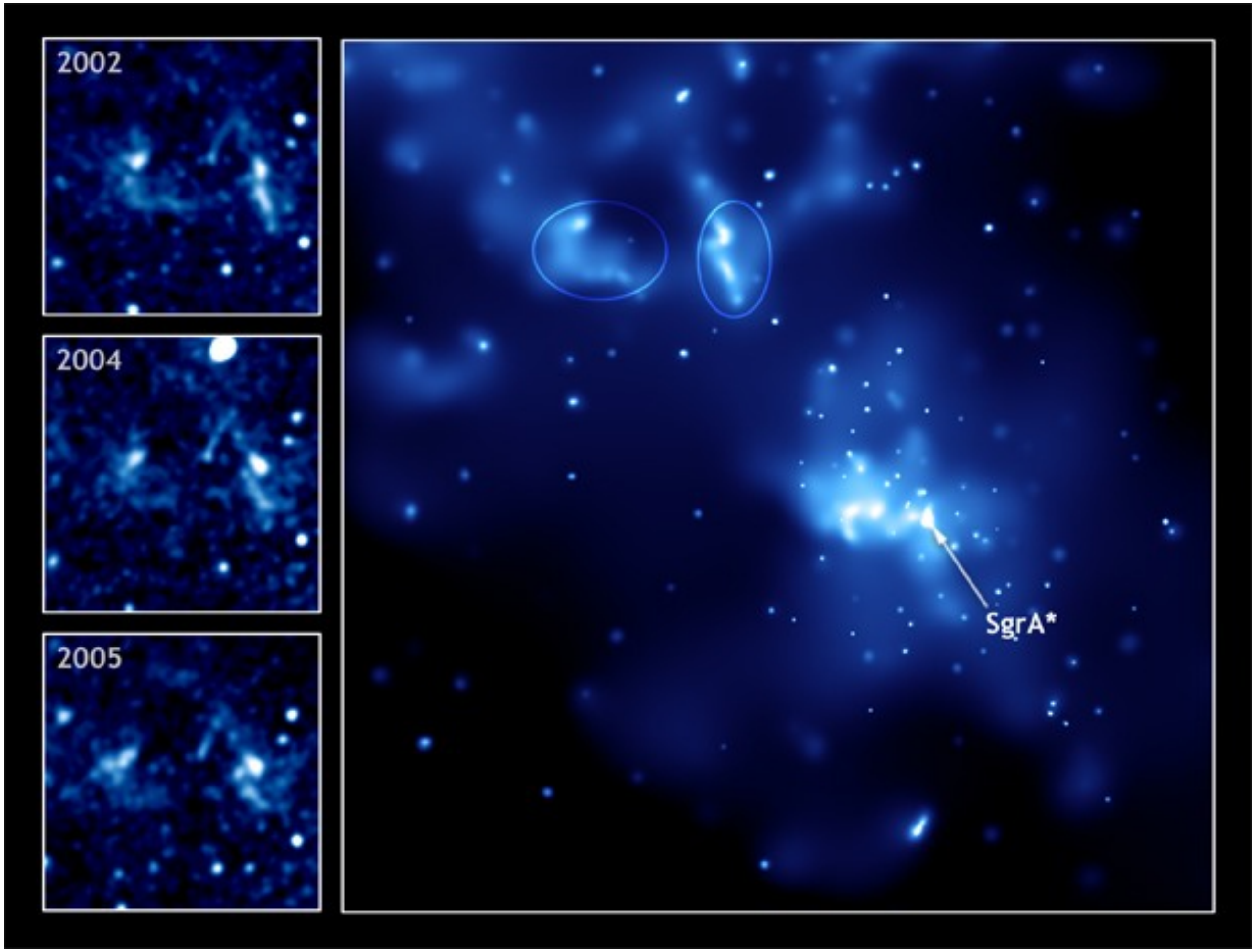
A super-massive black hole is a black holes which lies at the centre of a galaxy.

Every galaxy is expected to have a black hole at the centre with the mass of the galaxy proportional to the mass of the black hole. We know of the existence of these black holes due to fast orbits of the stars at galactic nuclei.
Their orbits suggest an enormous concentration of mass in a tiny volume. This can only point to a black hole.

In most cases the black hole is dormant! In other words matter has settled into a stable orbit around the black hole and matter is no longer pulled in.

Some galaxies do exhibit unusual properties. These are called Active Galactic Nuclei or AGN

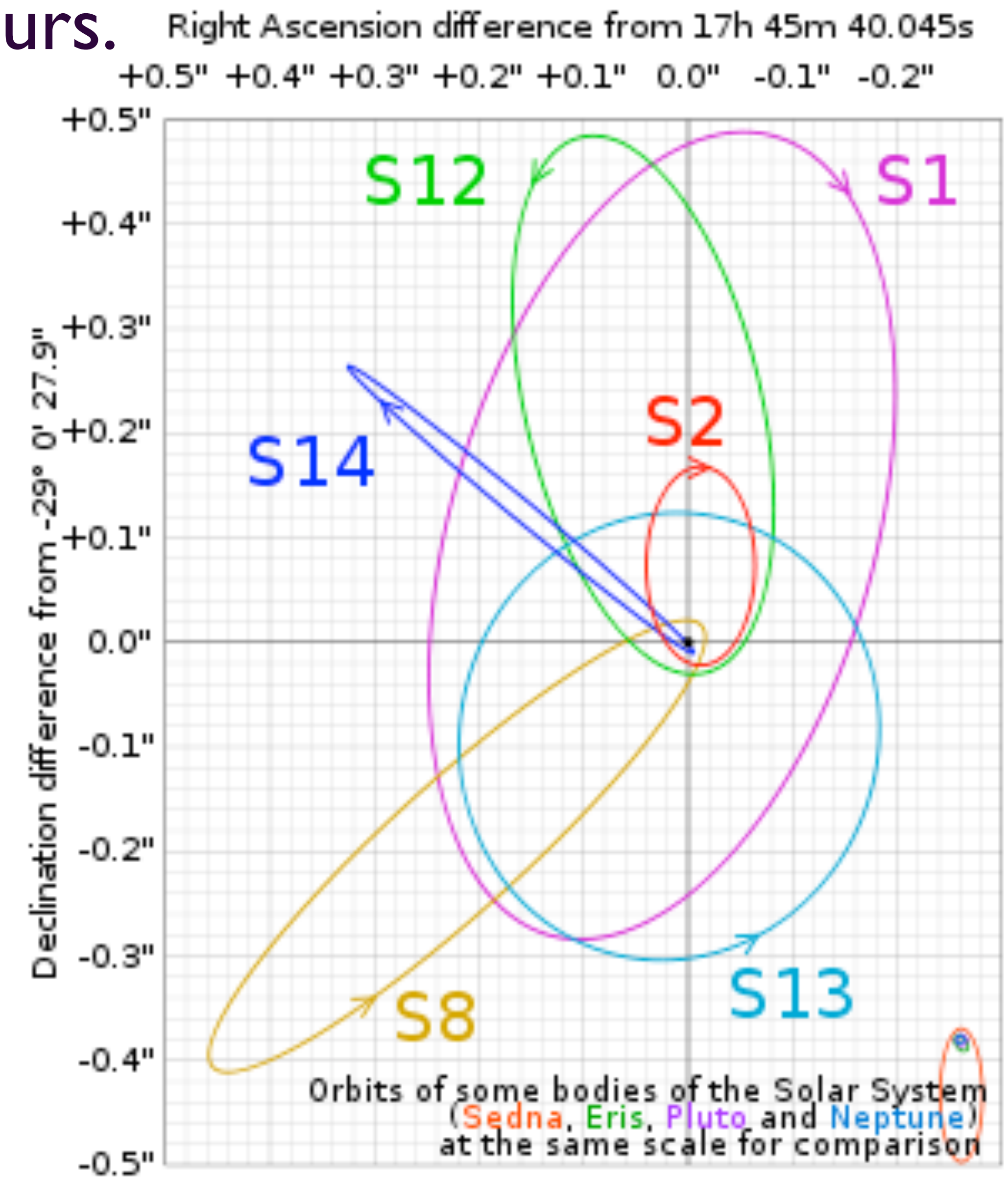
Center of Our Galaxy?



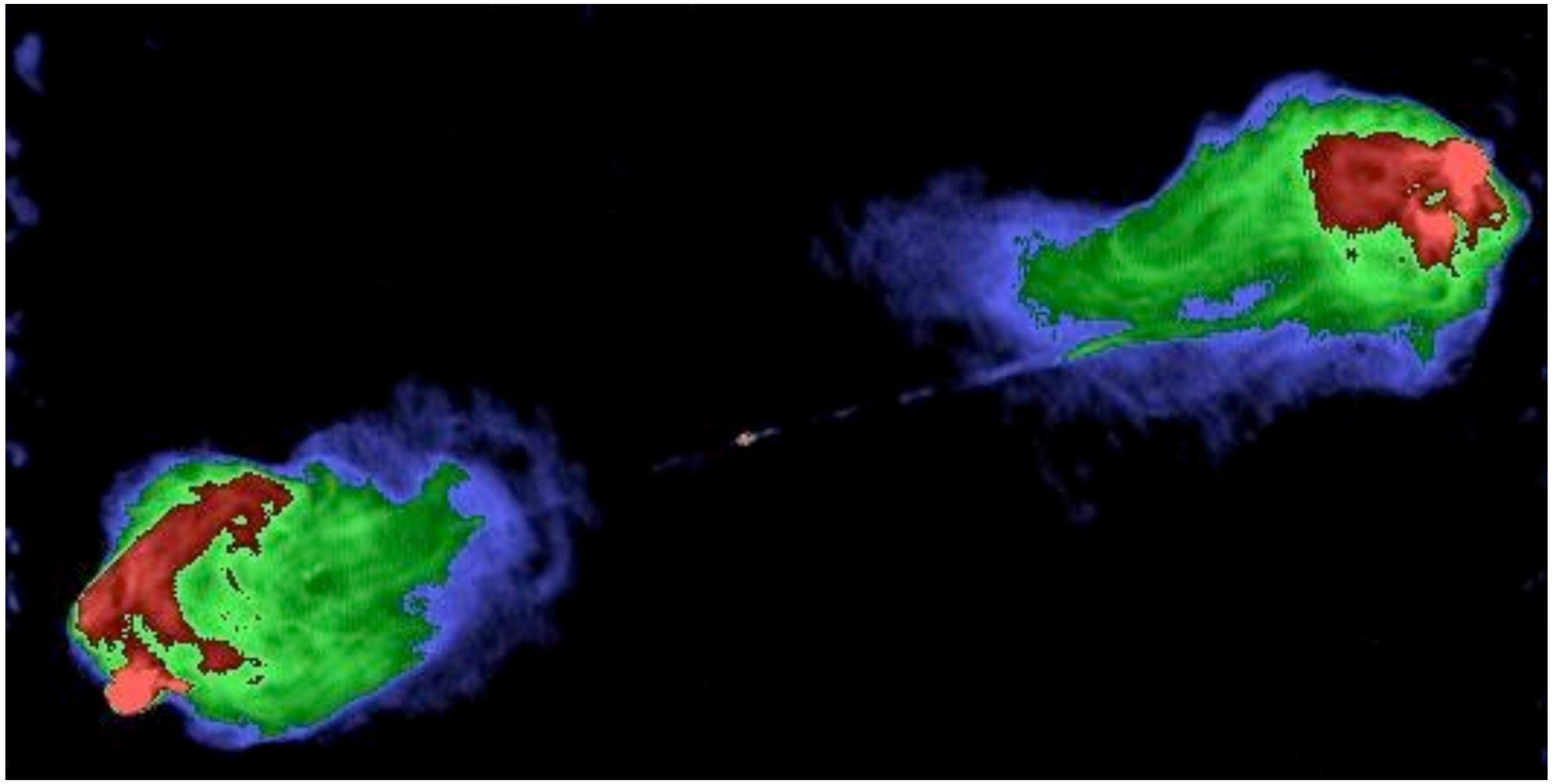
Sagittarius A*

Astronomers believe that our own Milky Way galaxy has a supermassive black hole at its center, in a region called Sagittarius A*:

- A star called S2 (star) follows an elliptical orbit with a period of 15.2 years and a pericenter (closest) distance of 17 light hours from the central object.
- The first estimates indicated that the central object contains 4 million solar masses and has a radius of less than 17 light hours.



AGN- Active Galactic Nuclei



An active galactic nucleus (AGN) is a compact region at the centre of a galaxy which has a much higher than normal luminosity over some or all of the electromagnetic spectrum (in the radio, infrared, optical, ultra-violet, X-ray and/or gamma ray wavebands).

A galaxy hosting an AGN is called an active galaxy. The radiation from AGN is believed to be a result of accretion of mass by the supermassive black hole at the centre of the host galaxy. AGN are the most luminous persistent sources of electromagnetic radiation in the universe, and as such can be used as a means of discovering distant objects

Micro Black Holes?

There is theoretically no smallest size for a black hole. Once created, it has the properties of a black hole. Stephen Hawking theorized that primordial black holes could evaporate and become even tinier, i.e. micro black holes. Searches for evaporating primordial black holes are proposed for the Fermi Gamma-ray Space Telescope, which was launched on June 11, 2008.

Lecture Problems

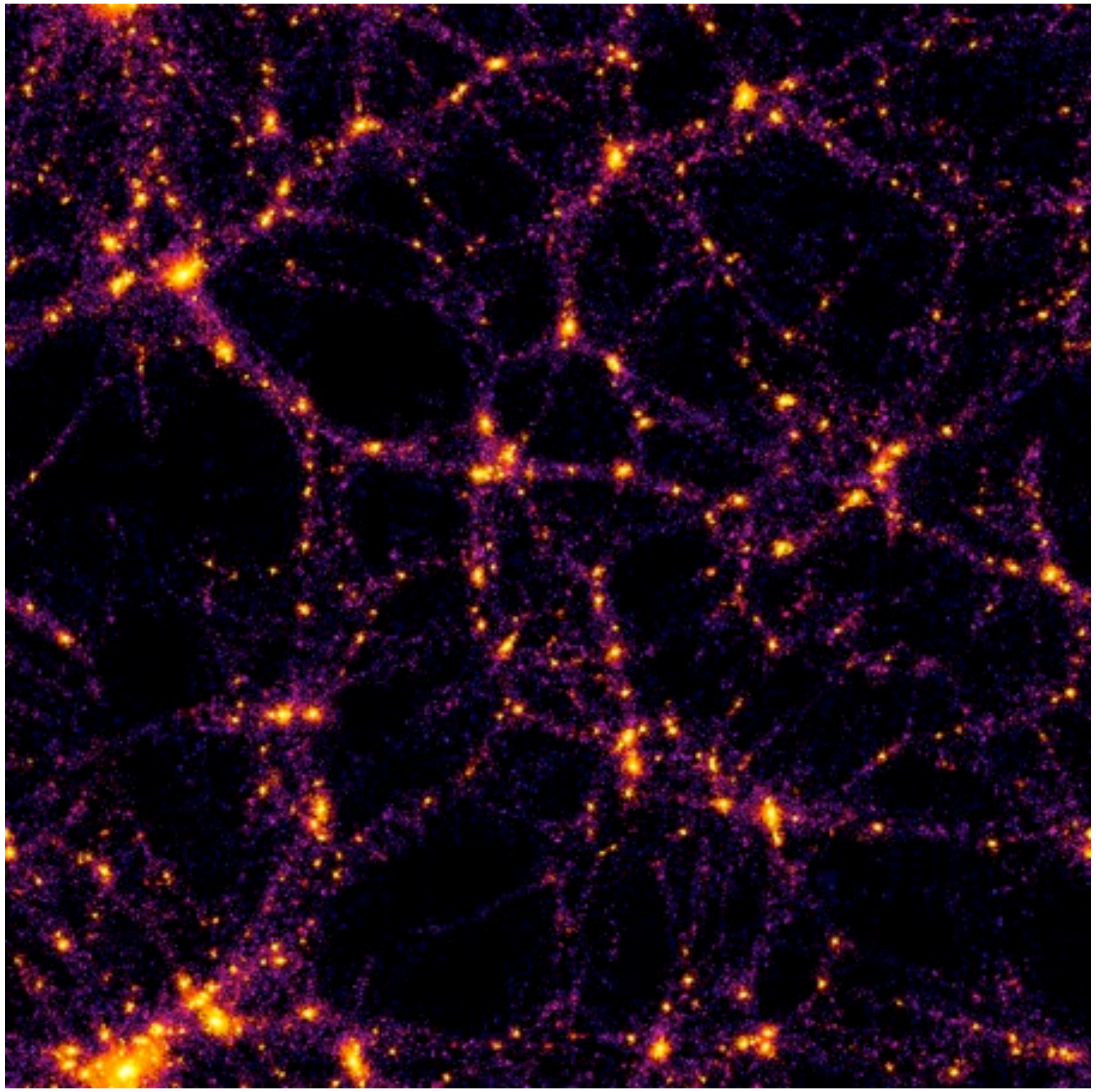
In Jules Verne's novel "From the Earth to the Moon", an attempt is made to launch a rocket from the Earth's surface with sufficient velocity to escape its gravitational field (the escape velocity). In terms of the gravitational constant G, the Earth's mass, M_{Earth} and the Earth's radius, R_{Earth}, what was the rocket's required velocity?

What is this velocity? (km s^{-1})

If the mass of the Earth, M_{Earth}, were forced into a radius of 2 cm, what would be the escape velocity from its surface?

Dark Matter

The Missing Mass Problem



Dark Matter is matter of unknown composition that cannot be observed directly, but whose presence can be inferred from gravitational effects on visible matter. According to present observations of structure larger than galaxy-sized as well as Big Bang Cosmology, dark matter accounts for the vast majority of mass in the observable universe

Coma cluster of galaxies

The Missing Mass Problem

In 1933, Fritz Zwicky analysed the orbits of the Coma cluster of galaxies, and found that they were moving so fast that they ought to have been flung apart. The gravity of the visible galaxies in the cluster would be far too small for such fast orbits so something extra was required. This is known as the missing mass problem and based on these conclusions, Zwicky inferred the existence of DARK MATTER.

Scientists now know that DARK MATTER forms a halo around galaxies but still not sure about what dark matter is??

Evidence for the Existence of Dark Matter

1. Galactic Rotation Curves

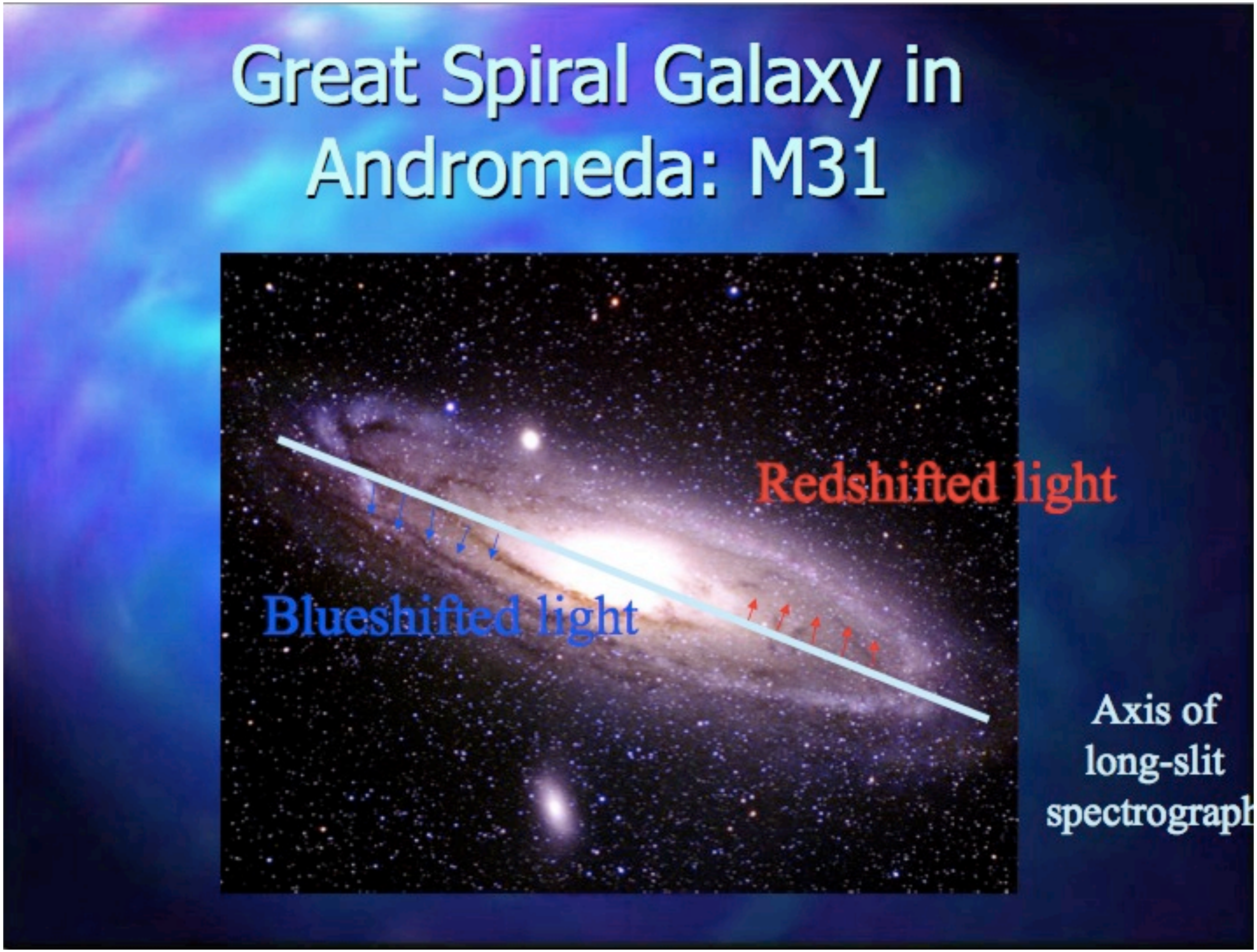
2. Galaxy Cluster Velocity Dispersions

3. Galaxy Cluster X-ray Emission

4. Gravitational Lensing

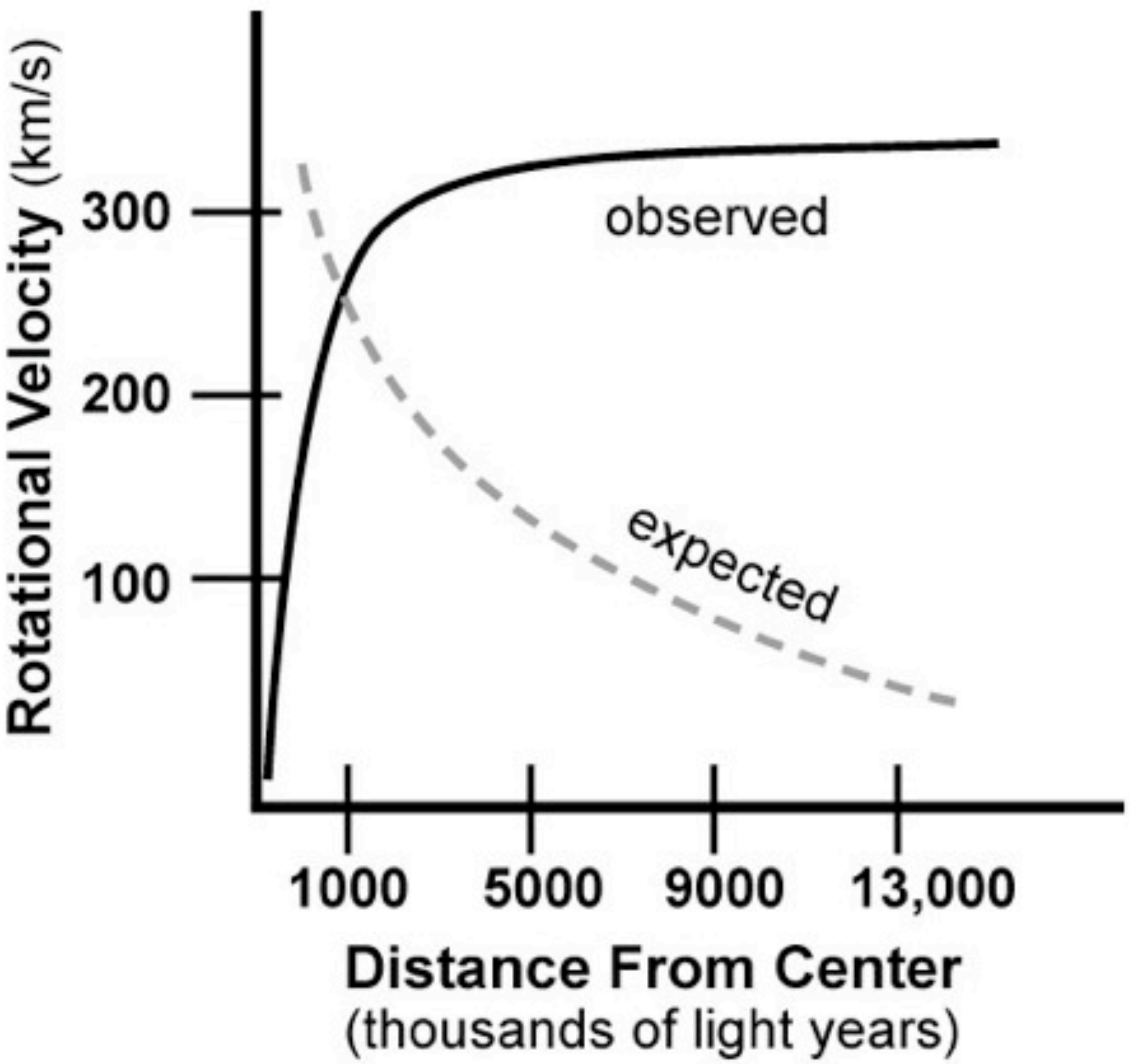
5. Cosmic Microwave Background Radiation

Galactic Rotation Curves

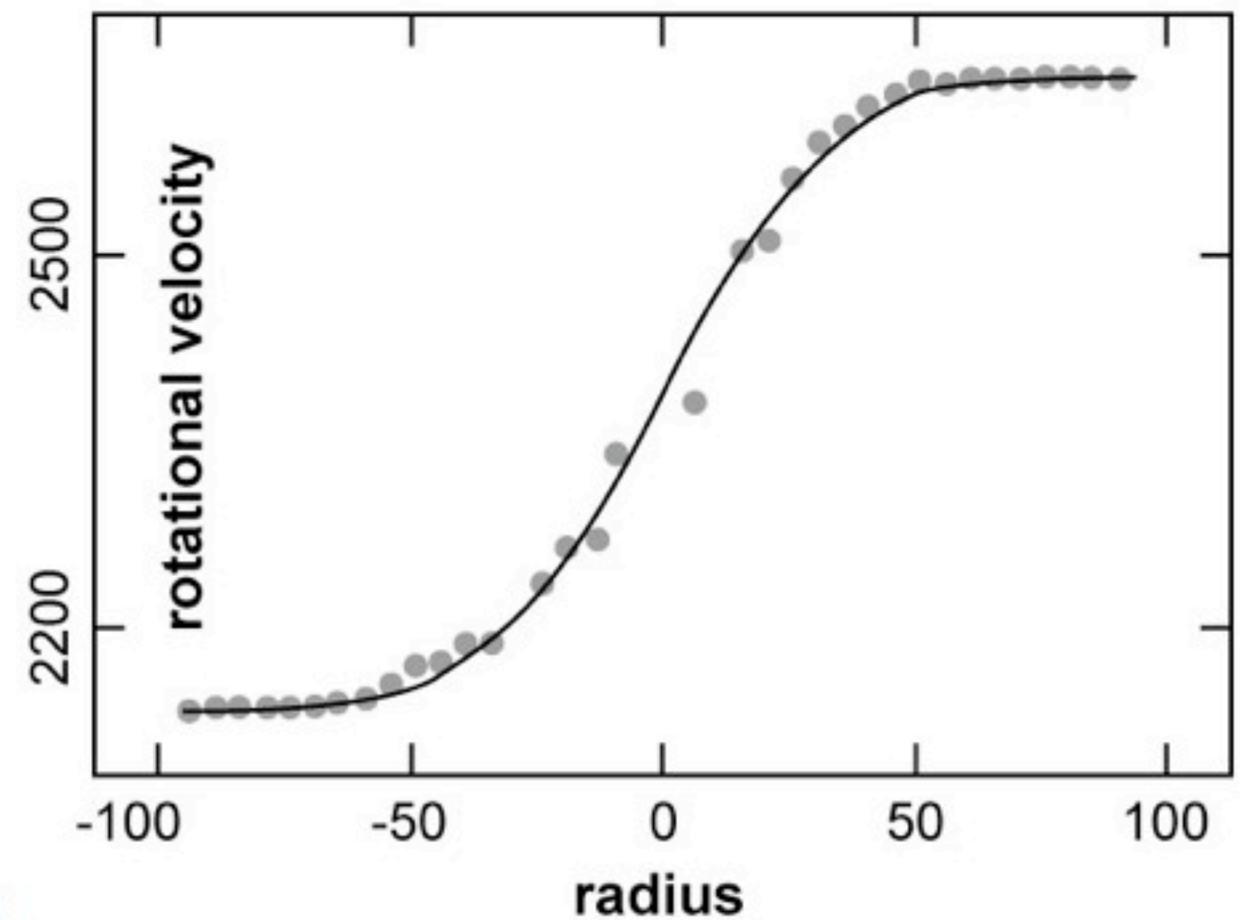


Rotation did not drop off but levelled off at a constant value

What we expected:

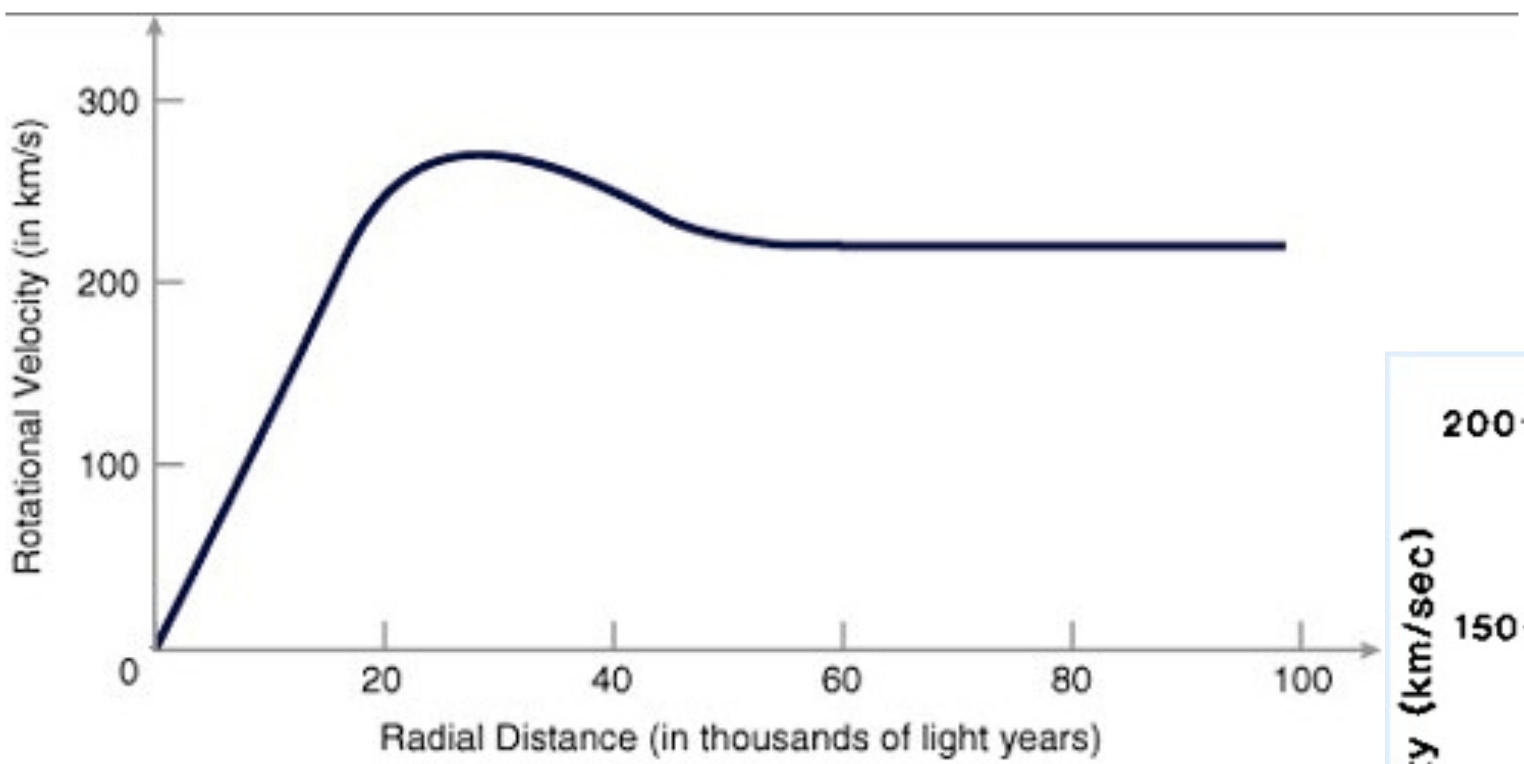


What we really observe:

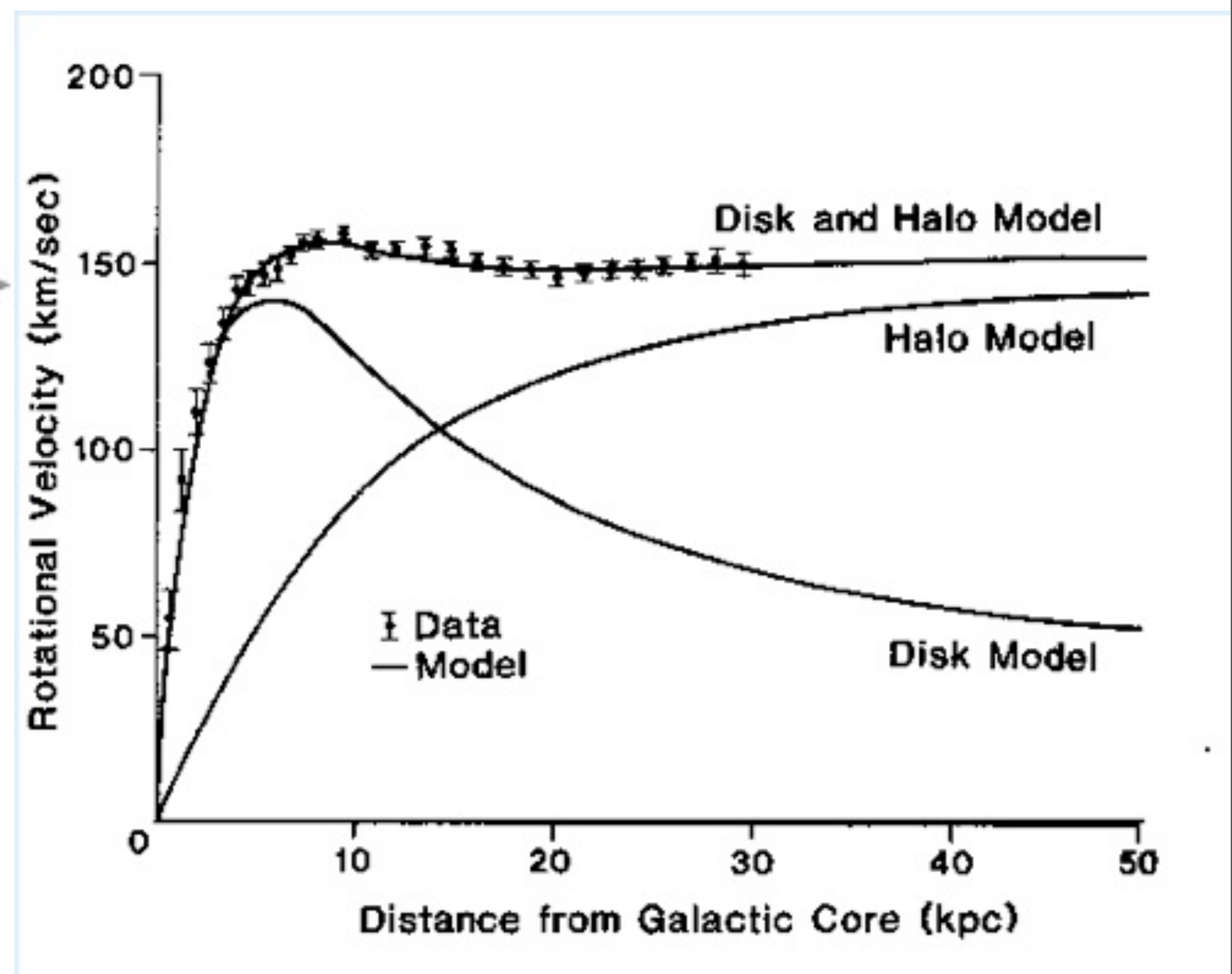


Why Astronomers Believe that there is a halo of Dark Matter Surrounding Spiral Galaxies

Rotation Curve of the Andromeda Galaxy

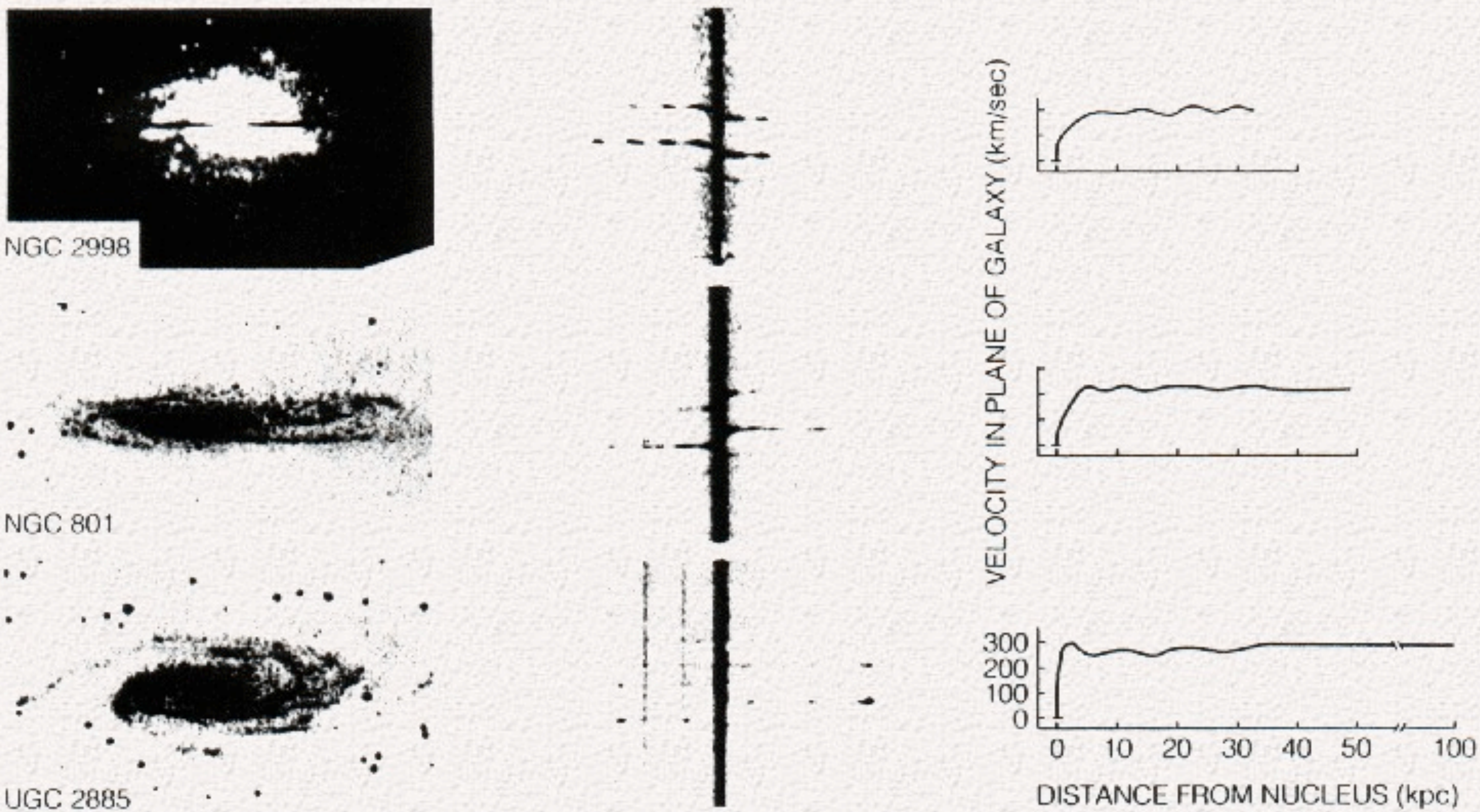


Model Curves for different theories of where DM is located. Halo matches best



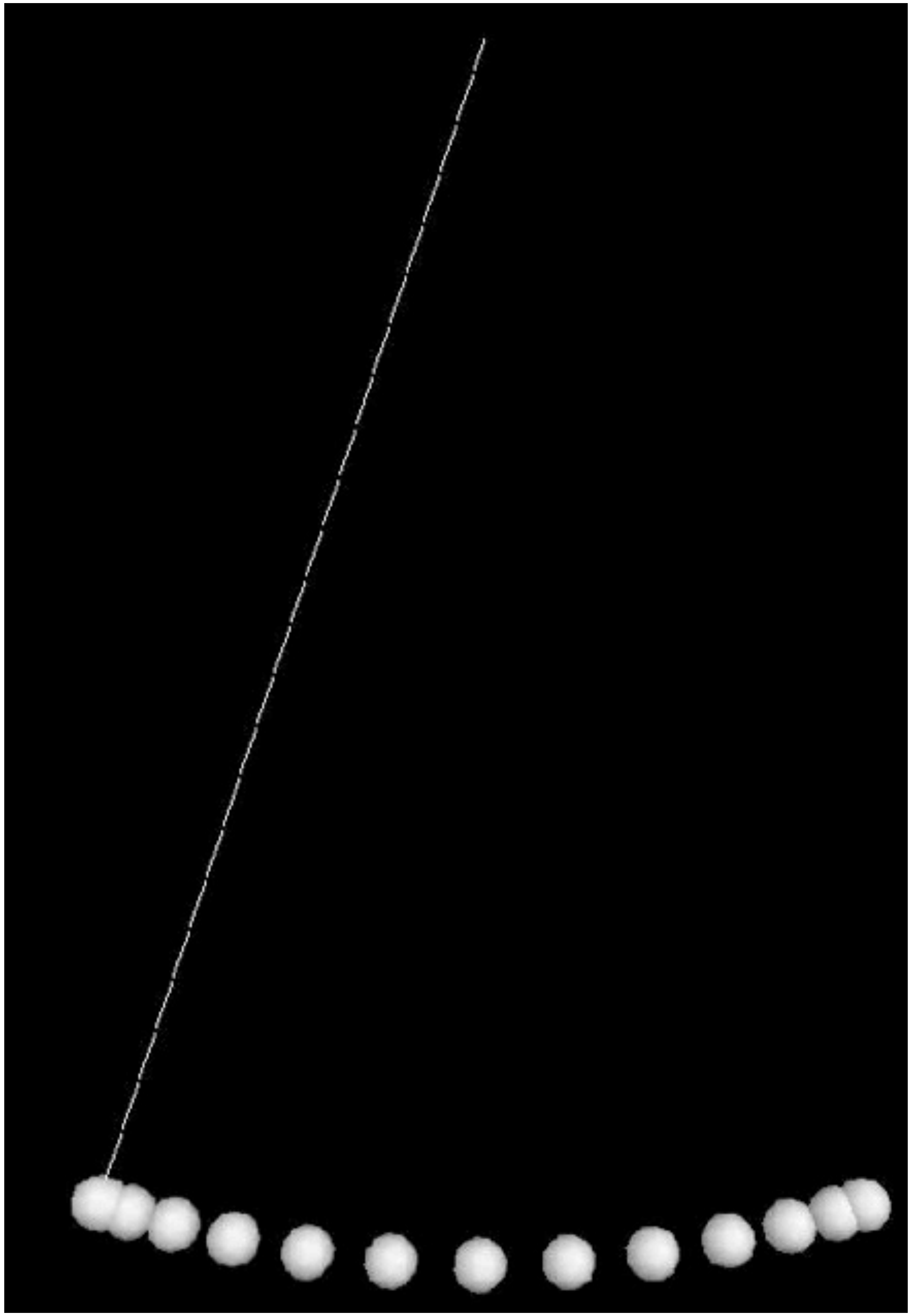
$V \propto R^{-1/2}$ expected

More Rotation Curves



Rotation Curves for 3 Spiral Galaxies - Galaxy Image(left), Spectrum (center - photographic negative), & Plot (right).

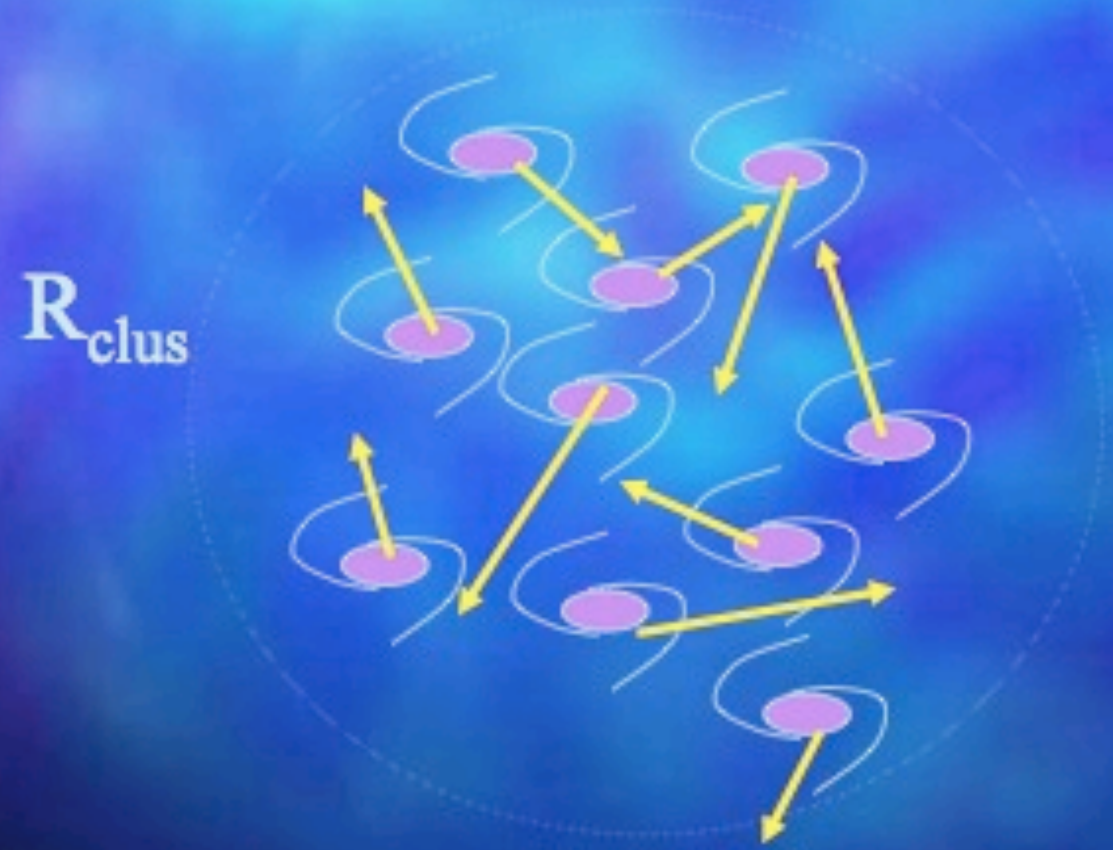
Virial Theorem



pendulum ball spends more time with its energy stored gravitationally than stored kinetically

Galaxy Cluster Velocity Dispersions

- Assume cluster is gravitationally bound and in equilibrium



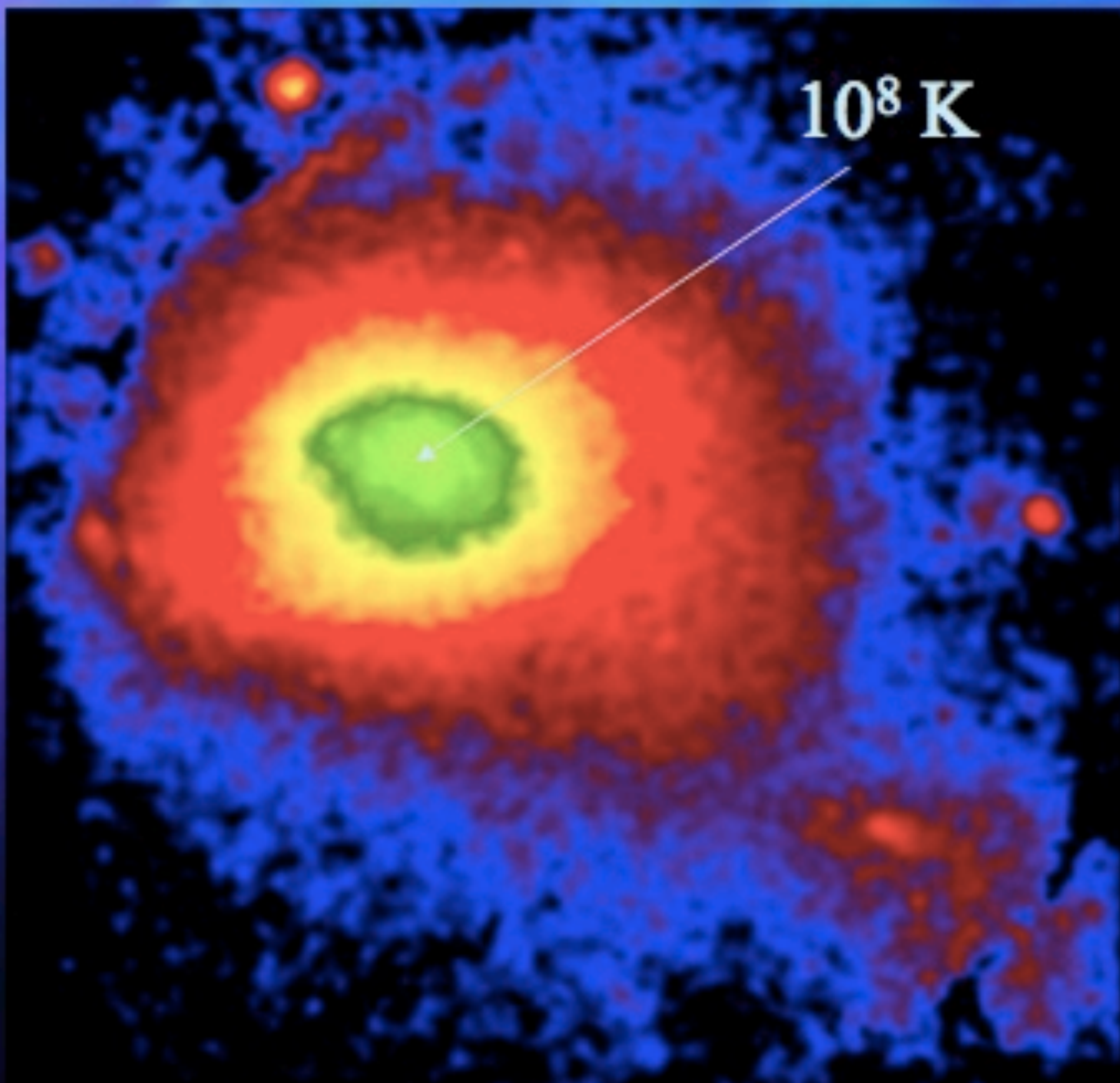
$$2E_{kin} + E_{grav} = 0$$

$$2\cdot\frac{3}{2}\left\langle V_x^2\right\rangle - \frac{GM_{clus}}{R_{clus}} = 0$$

$$\Rightarrow M_{clus} = 3\left\langle V_x^2\right\rangle R_{clus} / G$$

Analysis shows M_{clus}=10-20 times the total galaxy masses

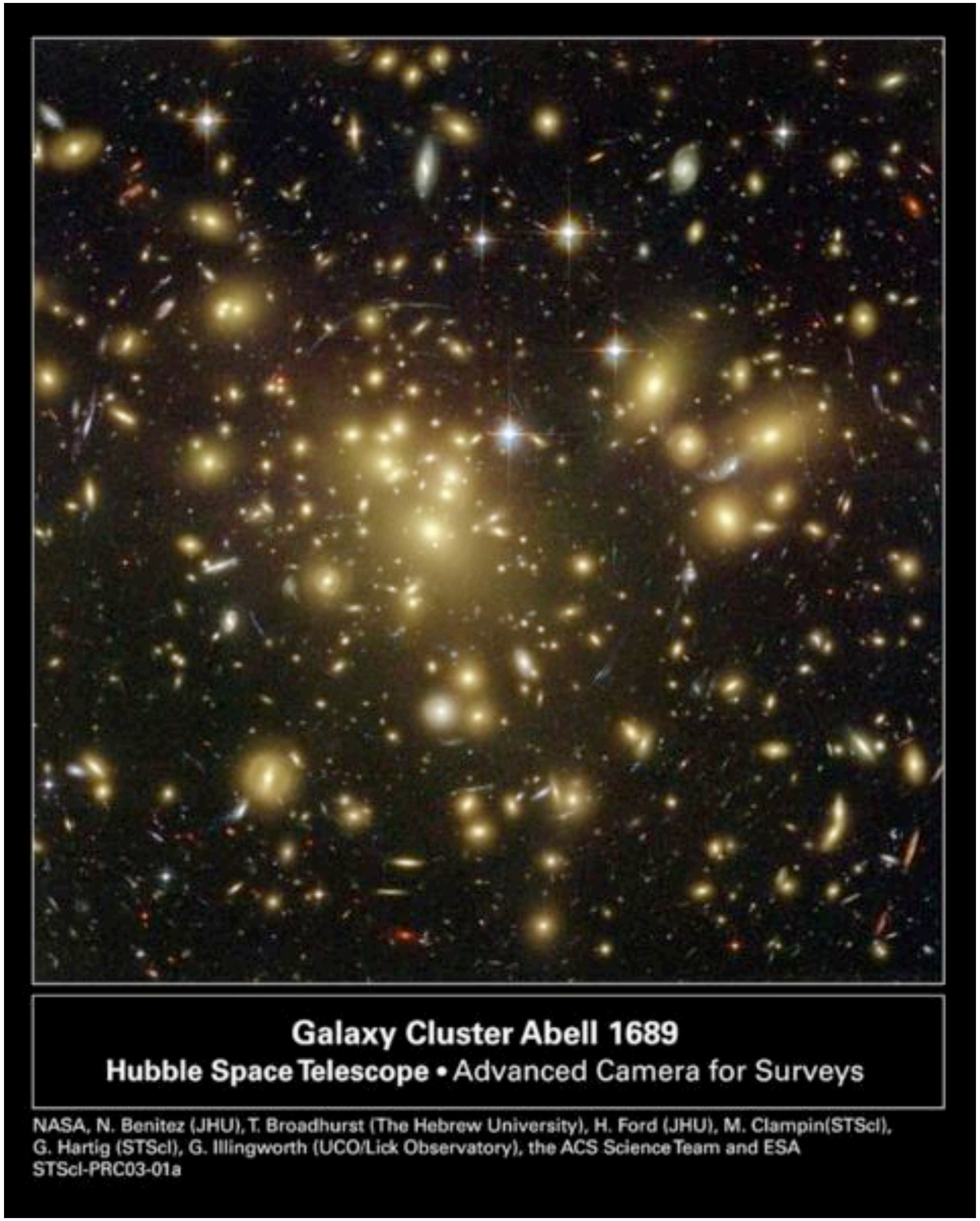
Galaxy Cluster X-ray Emission



Coma cluster seen in X-rays

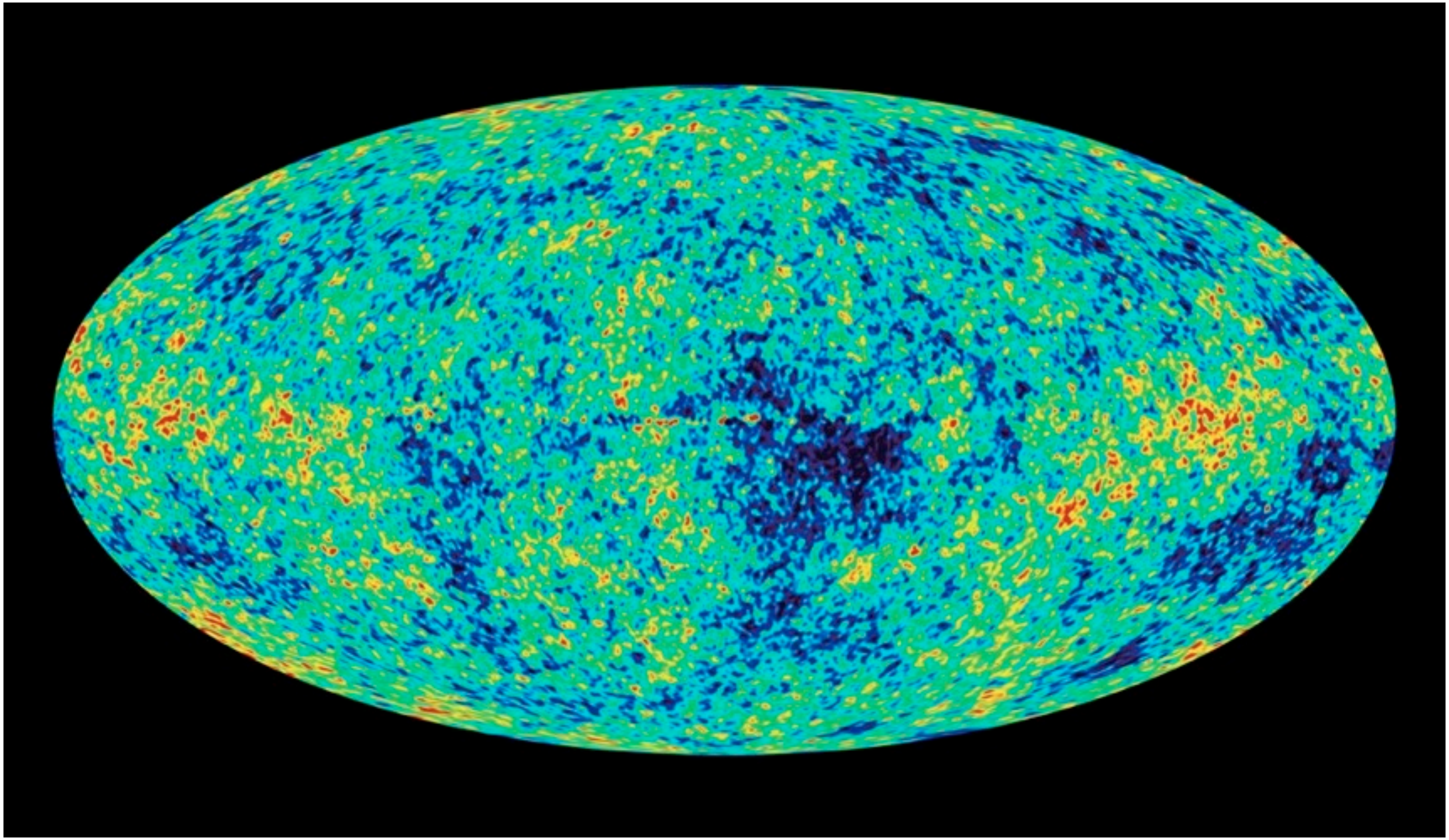
- Can measure the density and temperature of the X-ray emitting gas, and hence compute its pressure
- In order to confine gas to cluster, M_{clus}=10-20 M_{gal}

Gravitational Lensing

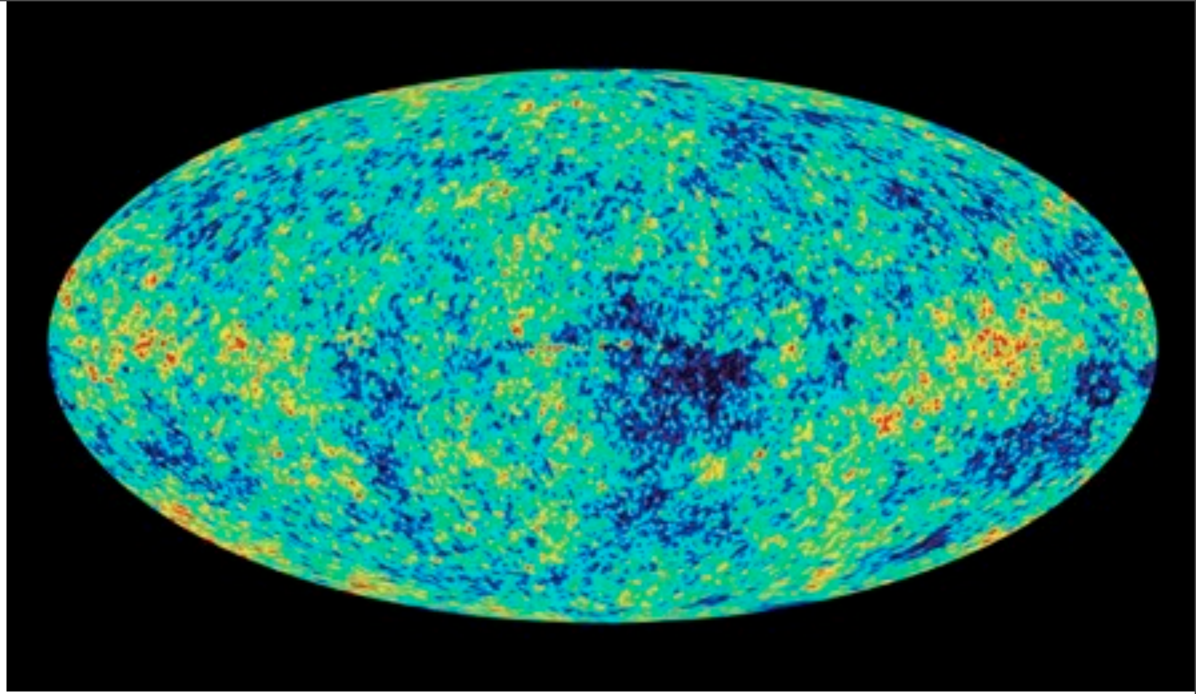


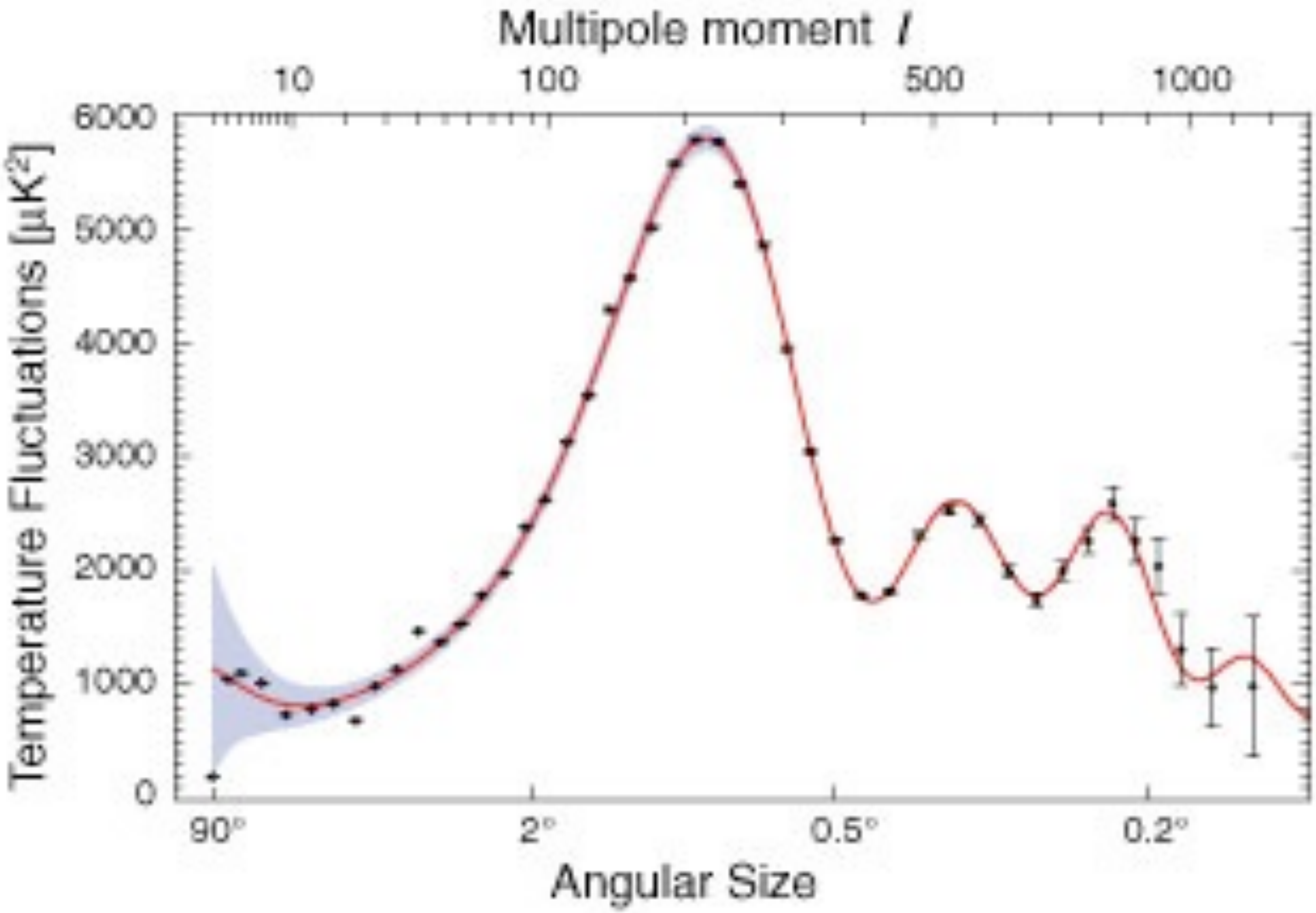
The galaxy cluster Abell 2029 is composed of thousands of galaxies enveloped in a cloud of hot gas, and an amount of dark matter equivalent to more than 10^{14} Suns. At the center of this cluster is an enormous, elliptically shaped galaxy that is thought to have been formed from the mergers of many smaller galaxies. Gravitational lensing the observed distortion of background galaxies into arcs when the light passes through a gravitational lens relies on the effects of general relativity to predict masses without relying on dynamics, and so is a completely independent means of measuring the dark matter. By measuring the distortion geometry, the mass of the cluster causing the phenomena can be obtained. In the dozens of cases where this has been done, the mass-to-light ratios obtained correspond to the dynamical dark matter measurements of clusters

Cosmic Microwave Background Radiation



CMB Radiation





Universe Expansion Rate

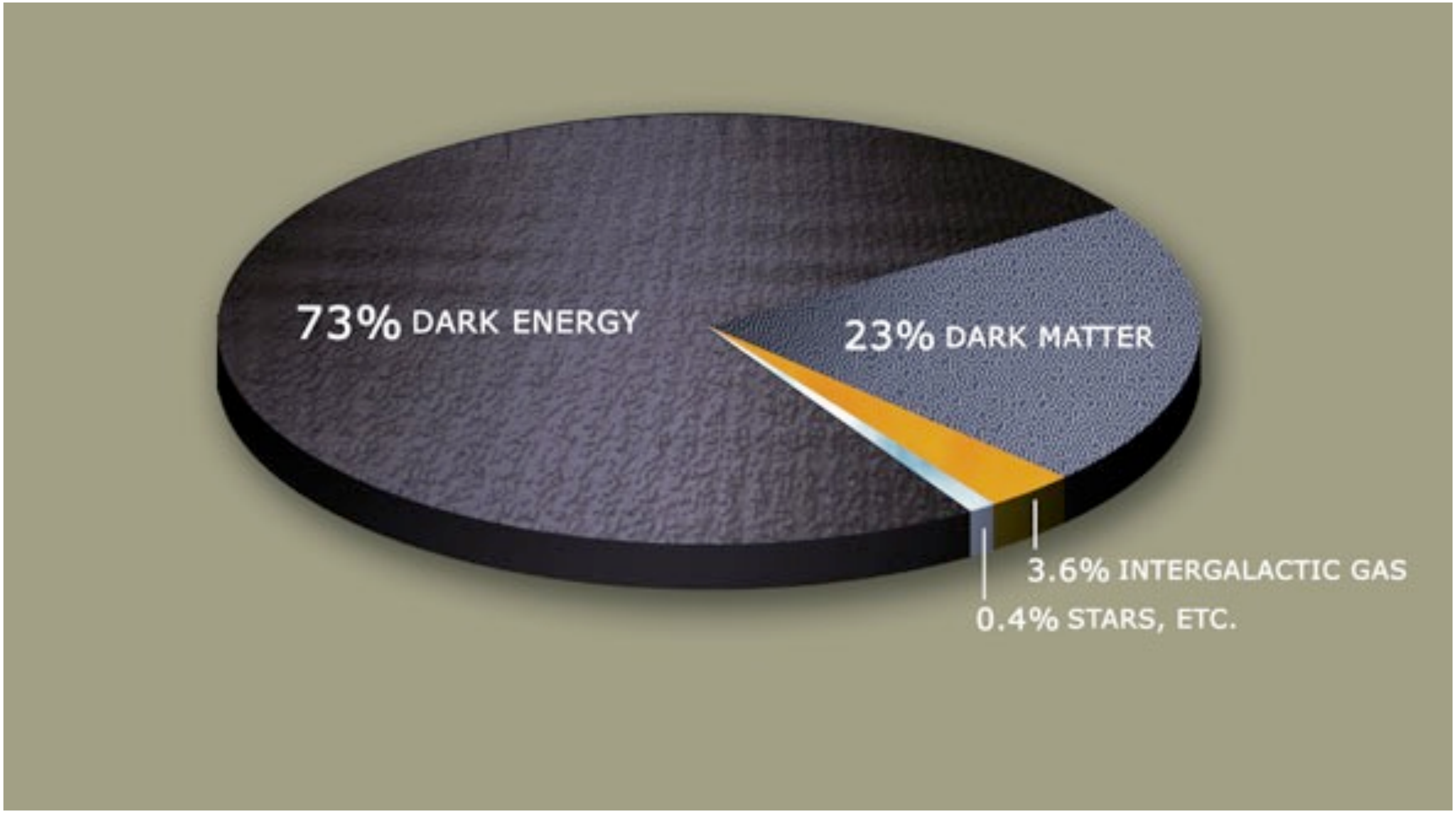
radiation energy density | vacuum energy density

$$H^2 = H_0^2 \left[\frac{\Omega_\gamma}{a^4} + \frac{\Omega_M}{a^3} + \Omega_\Lambda \right]$$

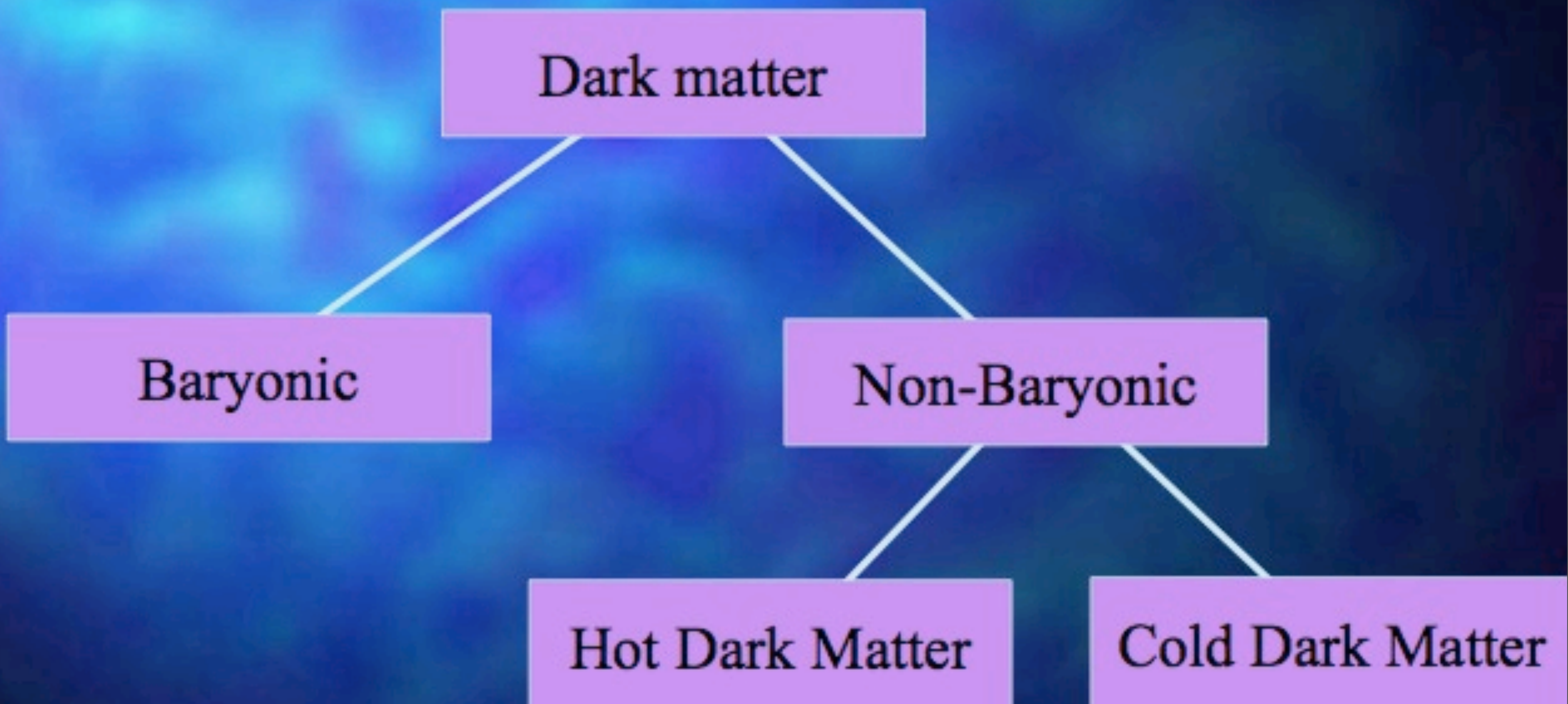
matter energy density

Where $H = \frac{1}{a}\frac{da}{dt}$ and $a = \frac{1}{1+z}$

CMB measurements suggest $\Omega_\gamma + \Omega_M + \Omega_\Lambda = 1$


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Types of Dark Matter



Baryonic Dark Matter

- Big Bang nucleosynthesis (amount of He/H, etc) predicts $\Omega_b \sim 0.05$
- Yet we only observe $\Omega_{stars} \sim 0.005$

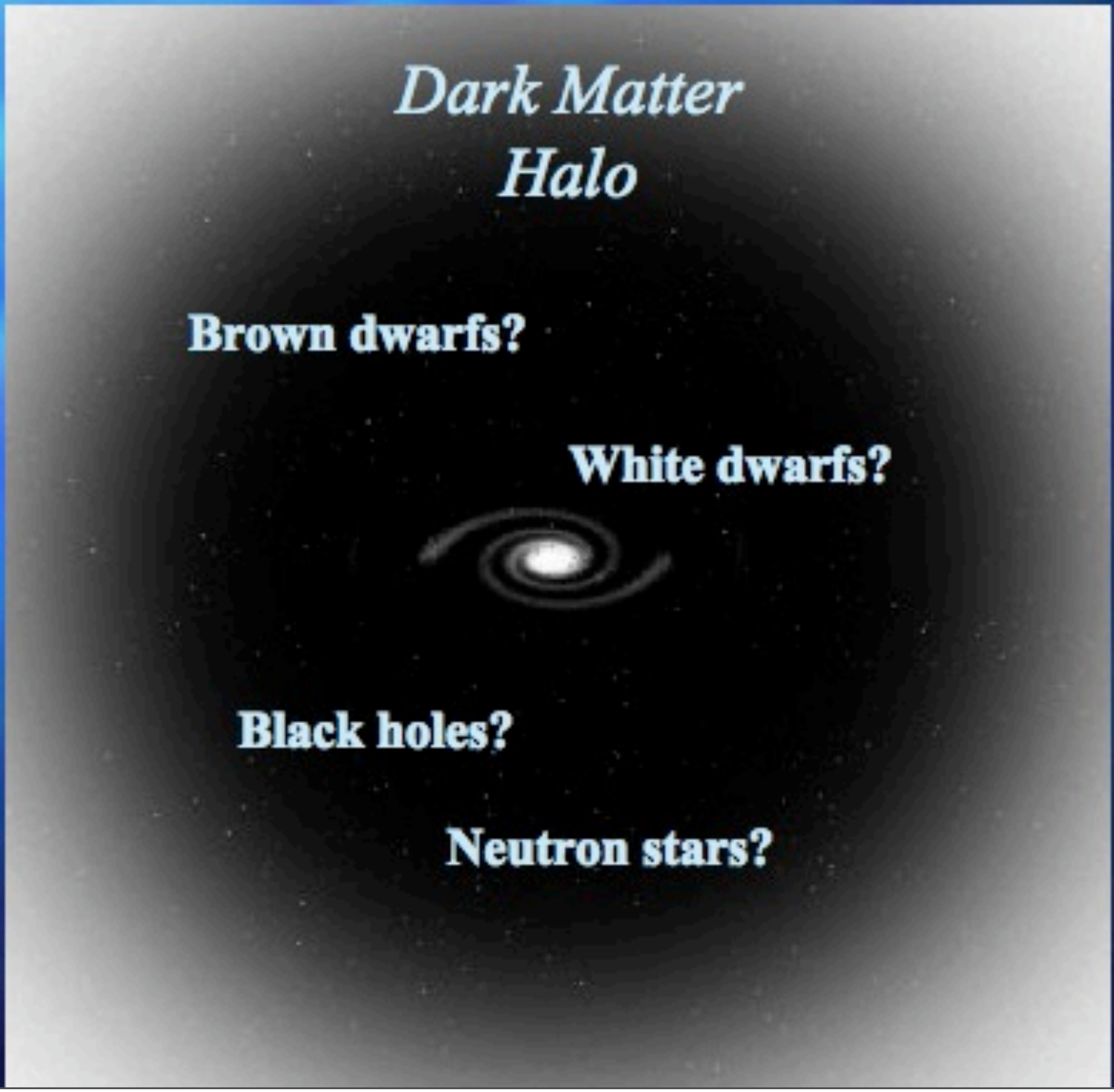
Where are all the missing baryons?

Baryonic Dark Matter Candidates

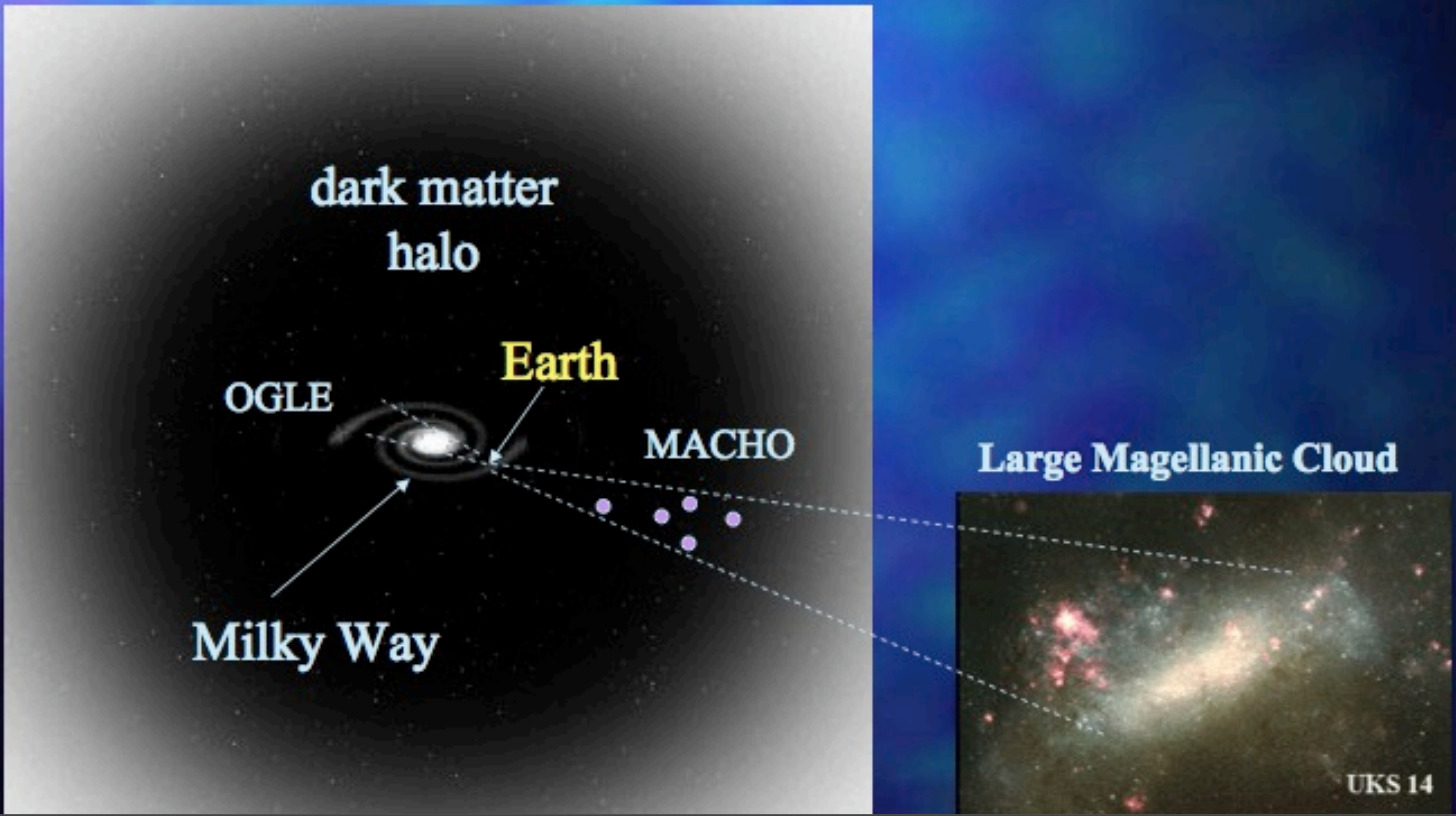
- Brown dwarfs – objects too small to ignite normal nuclear fusion and become stars
- Stellar remnants
  - white dwarfs
  - neutron stars
  - stellar black holes
- Primordial black holes
  - black holes formed in early universe

MACHOS:

Massive Astrophysical Compact Halo Objects



MACHO Searches



OGLE project

OGLE-II

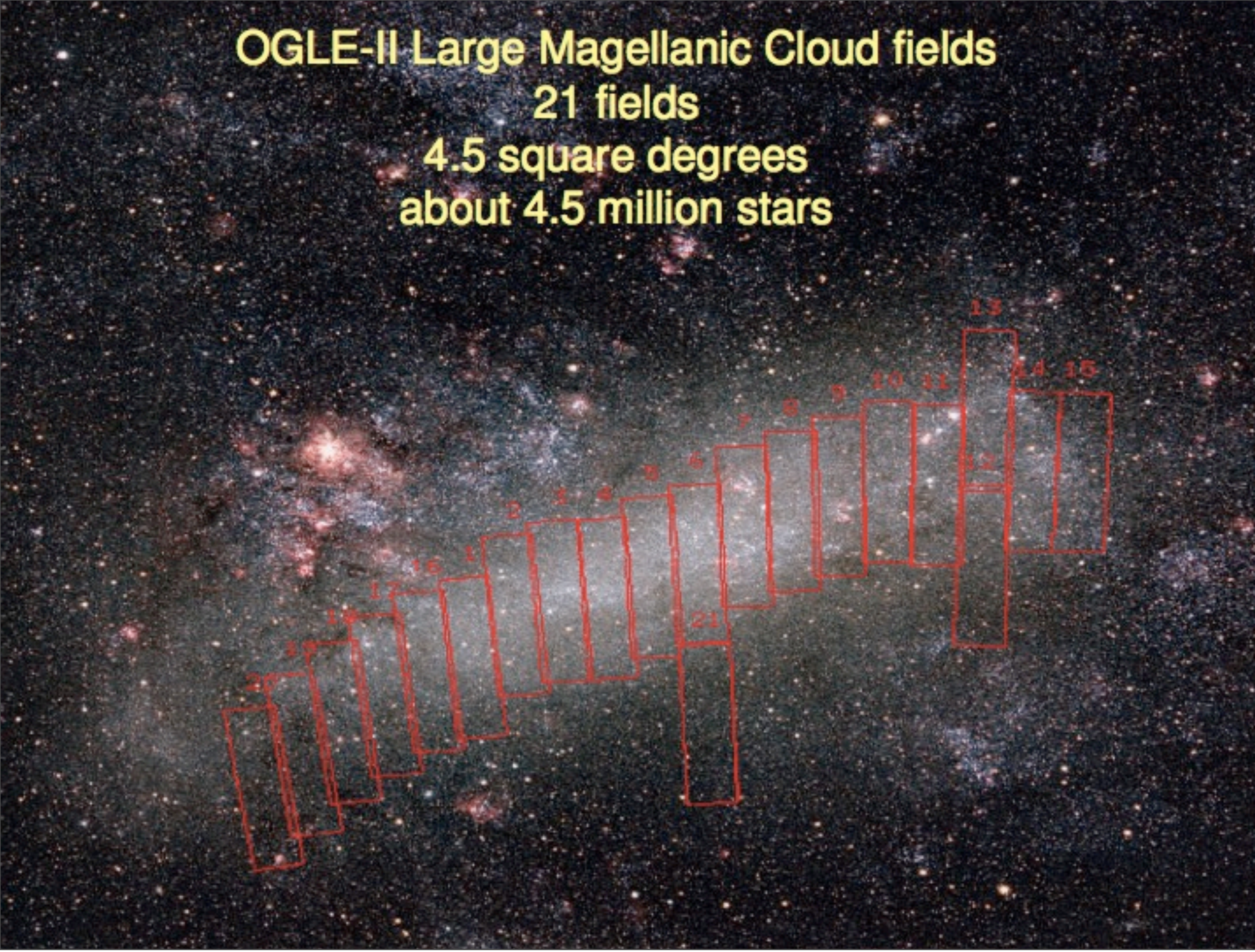
- 1996 – 2000
- 2k x 2k single CCD
- driftscan observing mode
- ld's fov: 14 x 54 arcmin (0.21 sq deg)

OGLE-III

- 2001 – ...
- 8 chip mosaic camera
- 2k x 4k each CCD
- field's fov: 35 x 35 arcmin (0.34 sq deg

1.3 m Warsaw telescope

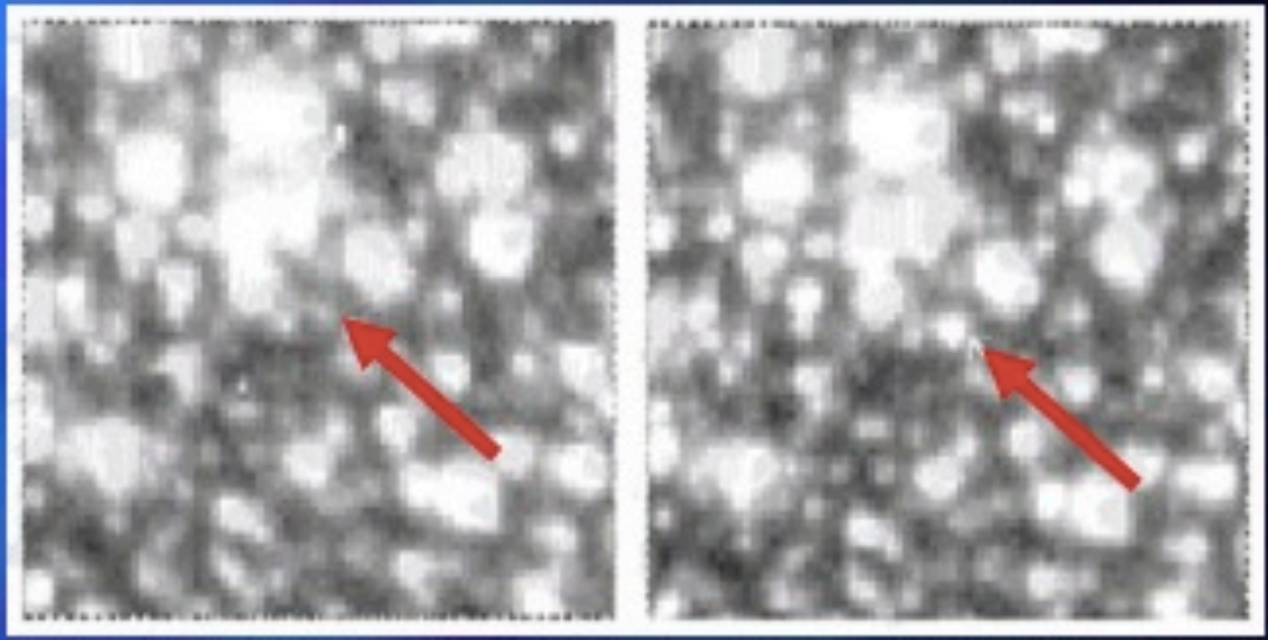
Las Campanas Observatory, Chile


OGLE-II Large Magellanic Cloud fields
21 fields
4.5 square degrees
about 4.5 million stars

Search procedure

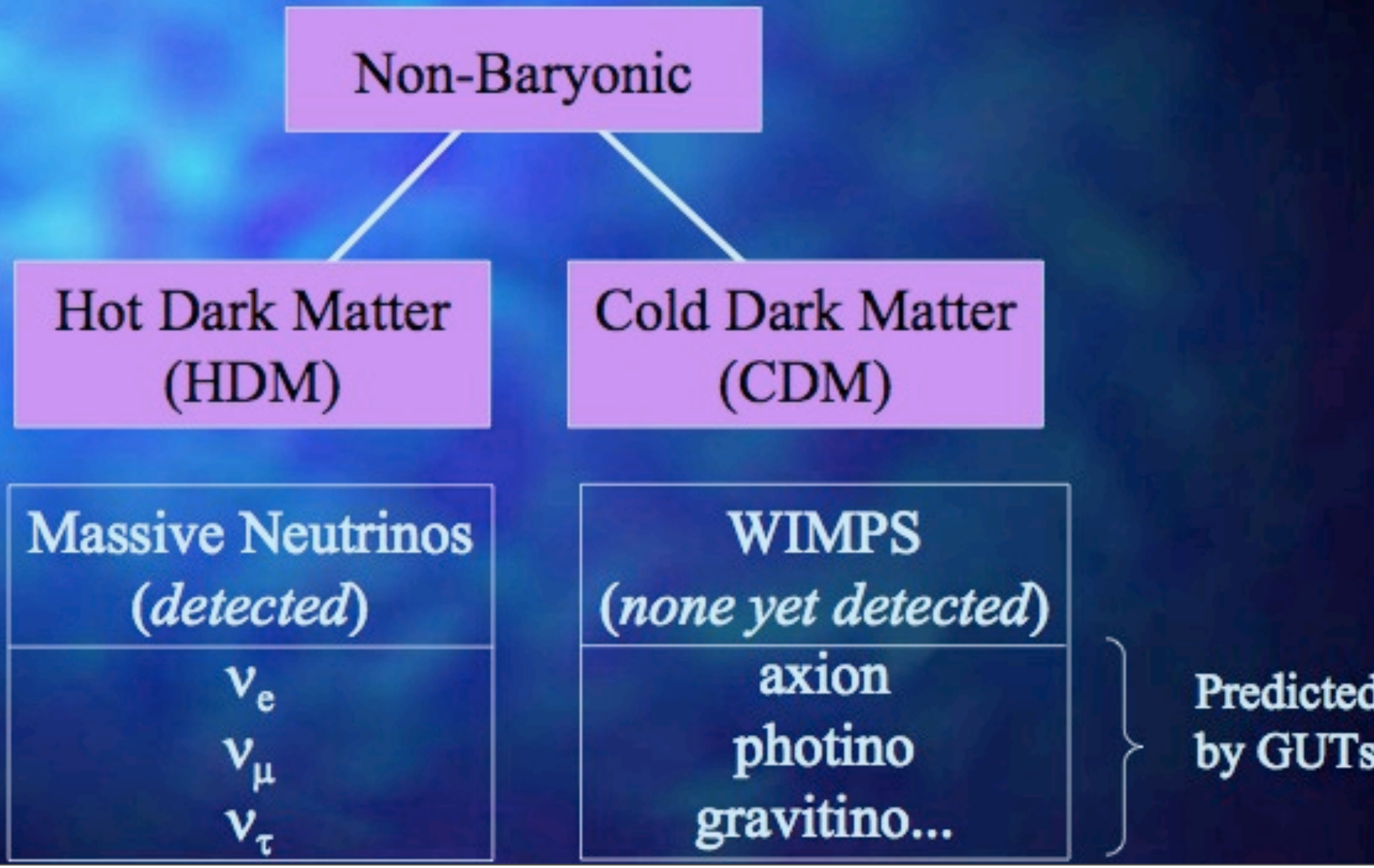
MACHO Search Results

- Dozens of micro-lensing events observed
- $M_{macho} \sim 0.5\text{-}1.0\ M_{sun}$
- Event rate too low by factor of 10 to account for dark halo mass



OGLE Project

Non-Baryonic Dark Matter: Exotic Particles



Neutrinos as Dark Matter

- Until recently, neutrinos thought to be *massless*, contributing nothing to Ω
- New evidence suggests that neutrino types *oscillate*, implying they are *not massless*

$$\nu_e \Rightarrow \nu_\mu \Rightarrow \nu_\tau \Rightarrow \nu_e$$

Lecture Problems

Pick the observational motivation for the existence of dark matter you find the most convincing, and summarise the argument for the existence of dark matter from this observation.

List all the assumed physics that this argument rests upon.

Astrophysics Lectures

Dr Andrew Taylor

Course Books:

"High Energy Astrophysics" Vol. 1+ 2
by Malcolm Longair