Dark Matter: Evidence and Properties

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Contents

Standard Model of Cosmology

Big Bang Model $\Rightarrow$ Age of universe $\simeq$ 15 billion years.

Can explain : CMB, abundance of elements, large scale structure ...

But it is clear that new physics is required to explain everything!

Beyond Standard Model

Standard Model cannot explain:

- Gravity,
- Neutrino Masses and Oscillations,
- Matter-Antimatter asymmetry,
- Dark Matter - Dark Energy.

Definition of Dark Matter

"Dark Matter (DM) is intoduced to explain the difference between how objects in the sky ought to move, according to some preconceived notion, and how they are actually observed to move."

In this sense the first to introduce DM where the... ancient Greeks! Eudoxus of Cnidus $\Rightarrow$ Sun and stars move in "stellar" sphere around Earth.

These spheres are not dark but transparent! But still unseen! So "dark" according to the definition!

Early History

The first to introduce the modern term dark matter was *Fritz Zwicky* in 1933 after observing the velocity distribution in the Coma cluster of galaxies.
The velocities too big $\Rightarrow$

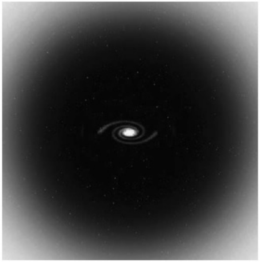
- the cluster would disperse,
- more unseen dark matter.

Using Newtonian dynamics and since the cluster is there, he found: $M_c = 3 \cdot 10^{14} M_\odot$. But $M_v = 10^{12} M_\bigodot$.
The mass-to-light (M/L) ratio was big!

"Should this turn out to be true, the surprising result would follow that *dark matter* is present in a much higher density than radiating matter"

Fritz Zwicky

In 1960's Miller, Prendergast, Hohl and later Ostriker proposed that a for a spiral galaxy to be stable a dark halo is needed.



This came out from computer experiments and showed that the mass of the halo should be at least equal to the galaxy disk mass.

Rotation Curves

1970s radio telescopes observing 21-cm line of Hydrogen.
H observation revealed: H gas distribution beyond visible image of galaxy $\Rightarrow$ gas disk larger than luminous stellar disk.

We can draw *extended rotation curves* i.e. graph between $v_{rot}(km/s)$ and $r(kpc)$ from the center of galaxy.

Hydrogen gas:

- $m_H \ll M_{lsg}$ $\quad \text{lsg} = \text{luminous spiral galaxy}$
- extended well beyond lsg

So very good *tracer* for gravitational force law beyond galaxy, like Solar System.

Assuming Newtonian gravitational force:

$$g_n = V_{rot}^2 / r. \quad (1)$$

But we know:

$$g_n = GM/r^2. \quad (2)$$

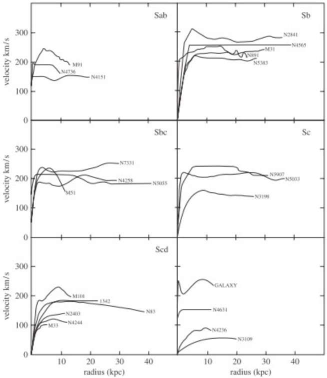
So

$$M = V_{rot}^2 r / G \quad (3)$$

or

$$V_{rot} = \sqrt{GM/r}. \quad (4)$$

In 1975 M. Roberts and R. Whitehurst measured the ERC of M31.
It was flat beyond bright galaxy!
Certainly not in a Keplerian fashion!



What does it mean?

Looking at (4), G =const. so we replace $M = M(r)$.

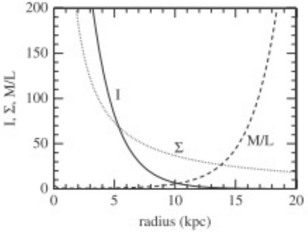
$V \rightarrow$ const. means that $M(r) \propto r$.

In 1970 Freeman:

$$I = I_0 e^{-r/h} \tag{5}$$

for the surface luminosity.

So dramatic increase of M/L in the outer region.



Spiral galaxies are becoming darker and darker in outer regions!
In 1972 Rogstad and Shostak confirmed the flat ERC for 5 spiral galaxies and concluded "*the requirement for low-luminosity material in the outer regions of these galaxies*".

$\Rightarrow$ Dark Halo! (again)

Introduction

In 1979 Faber and Gallagher set $M/L = \mathrm{O}(100)$ as originally estimated by Zwicky.

What is the dark matter distribution?
Trying to answer this question some missing mass found.

Hot gas

In 1960s started the X-ray detection. Low sensitivity and angular resolution.

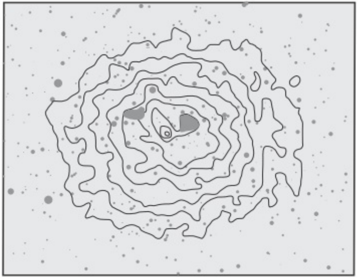
In 1970 "Uhuru satellite" in Kenya observed that clusters of galaxies are the most common extragalactic X-ray sources having large luminosities.

In 1978 NASA launched the Einstein Observatory with higher angular resolution and sensitivity.

Assuming "hydrostatic equilibrium" we get:

$$M(r) \approx \frac{kT}{\mu m_p} \frac{r}{G} \frac{\Delta\rho}{\rho}. \tag{6}$$

So we can actually calculate the distribution of gravitating mass.



Equal X-ray Intensity

Jones and Forman in 1984 using "Einstein" found:

Corellation between $T_{\rm hot\ gas}$ and V dispersion of galaxies,

$M_{\rm hot\ gas} \sim 10^{13} - 10^{14} M_{\odot} \simeq 3 - 4 M_{\rm stars}$ in galaxies.
$\Rightarrow$ Hot gas dominates the $M_{\rm galaxies}$.

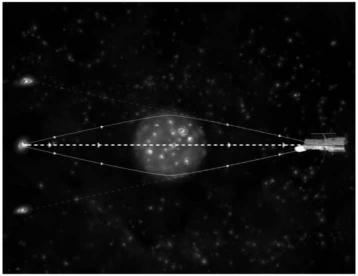
This implies that $M_{\rm dyn} \simeq 10^{15} M_{\odot}$, i.e. $M/L \sim 6$ from 100.

Some fraction of dark matter found!

Gravitational lensing (GL)

In 1979 Walsh, Carswell and Weymann first discovered an example of GL! New tool to estimate the mass distribution in galaxies.

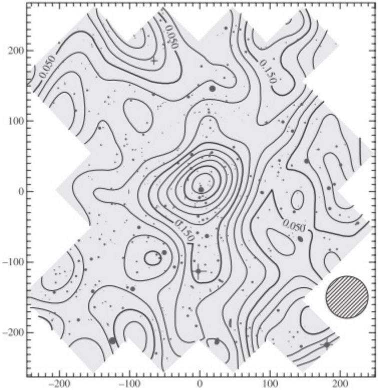
"Principle of equivalence" $\Rightarrow$ Rocket example $\Rightarrow$ light bending!



Can have both strong and weak GL. E.g. Abel 2218

Abel 2218 by Hubble telescope

In 1998 Hoekstra, Franx, Kuijken and Squires using Hubble mapped the matter, primarily DM, distribution.



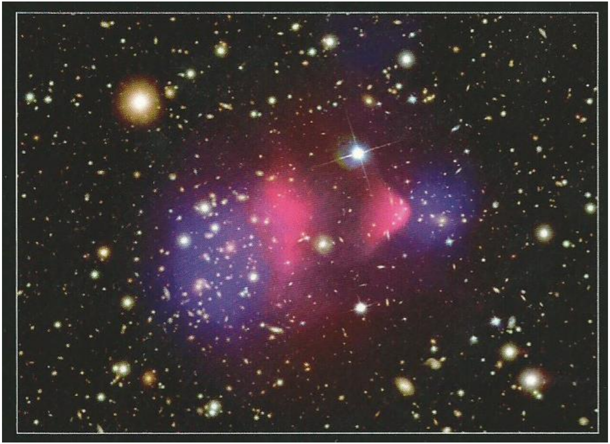
DM surface-density distribution in cluster 1358+62

GL provides a true map of the DM distribution, assume only that GR is true.
X-ray emmiting gas technics assume hydrostatic equilibrium, e.g. not true for colliding clusters!
But for clusters with a relaxed appearance $\Rightarrow$ similar results!

- GL: $M \sim 4.4 \cdot 10^{14} M_{\odot}$
- X-ray: $M \sim 4.2 \cdot 10^{14} M_{\odot}$

for 1358+62 cluster. In both cases the discrepancy between Bar M and Det M is of the same order.

The Bullet



Clusters in collision.
Combination of three technics:

- optical observation,
- X-ray observations and mapping of the Hot gas,
- GL and DM mapping.

X-Ray observations showed that gases collide. The red part of the image.
The galaxies are collisionless.
DM coincides with galaxies not Hot gas! The blue part.
So DM also collisionless ⇒ non-baryonic particles. This direct detection is proof of that.

Brief Thermal History of the Universe
The Standard Model of Cosmology

- $T \sim 10^{16}$GeV. GUT breaks into SM. Little Known.
- $T \sim 10^{2}$GeV. SM breaks into $SU(3)_C \otimes U(1)_Q$. Electroweak SB.
- $T \sim 0.3$GeV. QCD phase transition. Quarks and Gluons $\Rightarrow$ Hadrons.
- $T \sim 1$MeV. Neutrons decouple and freeze out. ν decouple.
- $T \sim 0.5$MeV $\simeq m_e$. $e^- - e^+$ annihilation. Reheating.
- $T \sim 100$KeV. Big Bang nucleosynthesis (BBN).
- $T \sim 0.4 - 1$eV. $\rho_m \simeq \rho_r$. Recombination $\Rightarrow$ CMB.
- $T \sim 2.7$K$\sim 10^{-4}$eV. Today.

By 1970 physicists had realized that relic neutrinos are present in the universe $\approx$ photons in CMB.

Around 1970 missing solar neutrinos $\Rightarrow$ neutrino oscillations, i.e. neutrinos have mass.

Neutrinos could be the missing mass, could be dark matter!

Neutrinos would need mass $\approx$ 17.5 eV to "close" the universe.

About 1978 realized that a relic particle has a major impact for structure formation and CMB.

Why ν can NOT be the DM we need?

1st Problem.

Low mass $\approx$ 0.05 - 2 eV. But not such a big problem.

ν decouple at $\approx$ 2MeV $\Rightarrow$ highly relativistic, "hot dark matter" (HDM).

All fluctuations are washed out $\Rightarrow$ top bottom formation. Not like that due to observations and computer simulations.

2nd Problem.

In 1979 Tremaine and Gunn: limit in how much ν's can put in a dark halo.

The density of ν's can never exceed their original value.

ν density in halo $\sim$ mass and velocity. Bigger mass and velocity disperssion means more ν density in halo.

With values known ν could not comprise the halos of low-mass galaxies.

Cold Dark Matter (CDM)

CDM is particles that are non-relativistic when decouple from photons. Need it to explain the structure formation.

Physical size of density fluctuation $\lambda_f \propto \sqrt{t}$.

Horizon $l_h \approx ct$ so eventually fluctuations will "enter the horizon", all before recombination.

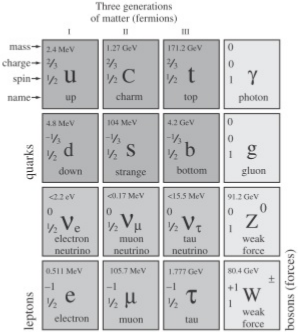
After entering the horizon they don't grow but oscillate maintaining the same amplitude ($\approx 10^{-5}$), agree with observations of CMB.

So we have a "bottom-up" structure formation.

What particles consist CDM?

CDM properties:

- massive,
- not charged,
- stable,
- "cold"



No SM particle!

Dark Matter Candidates

- Sterile ν
- Axion
- Light scalar DM
- Kaluza Klein states
- Neutralinos
- Sneutrinos
- Gravitinos
- Axinos

And many many more!

Strong CP Problem

Non-Abelian structure of QCD.

Many vacua, quantum travelling between them:

$$|\theta\rangle = \sum_n e^{-in\theta}|n\rangle \tag{7}$$

Full quantum theory, including quark masses, invariant:

$$q_i \rightarrow e^{i\alpha_i\gamma_5/2}q_i \tag{8}$$

$$m_i \rightarrow e^{-i\alpha_i}m_i \tag{9}$$

$$\theta \rightarrow \theta - \sum_{i=1}^{N}\alpha_i. \tag{10}$$

Not a symmetry of QCD due to (10).

But

$$\bar{\theta} \equiv \theta - \arg(m_1 m_2 \ldots m_N) \tag{11}$$

is invariant and thus observable unlike θ.

In presence of θ QCD violates P and CP. However CP violation is not observed.

θ results in a neutron dipole moment:

$$|d_n| \sim 10^{-16}\bar{\theta} \quad \mathrm{e\ cm} \tag{12}$$

Observations show:

$$|d_n| < 6.3 \times 10^{-26} \quad \mathrm{e\ cm.} \tag{13}$$

The Peccei-Quinn solution.

In the PQ solution $\bar{\theta}$ is promoted to a field.

A global $U(1)_{PQ}$ is introduced which possesses a colour anomaly.

SSB is resulting in the pseudo-Nambu-Goldstone boson a, the axion.

Initially massles but non-perturbative effects result in a potential for the axion.

Axion relaxes to the CP conserving minimum of the potential and acquires mass.

Although the PQ axion has been ruled out by observations there are other "invisible" axion models that are viable.

In these models the PQ symmetry is decoupled from EW scale and is SB at higher T, decreasing axion mass.

Two models exist:

- Kim-Shifman-Vainshtein-Zakharov (KSVZ)
- Dine-Fischler-Srednicki-Zhitnitsky (DFSZ)

Axion as DM particle.

Axion is:

- stable,
- effectively collisionless, interact only gravitationally ,
- low-mass but still "cold",

and could enough to provide the missing mass needed.

There are three mechanisms to produce the axions:

- vacuum realignment,
- string decay,
- domain wall decay.

Which dominates depends on whether T_{PQ}, the temperature at which the PQ symmetry breaks, is greater or not than the inflationary reheating temperature T_R.

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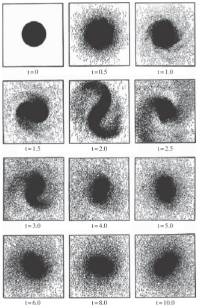
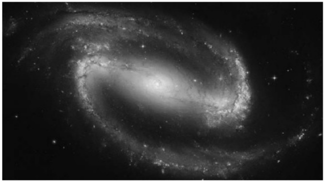
Galaxy Stability

In 1960's Miller, Prendergast and Hohl considered the *Newtonian N-body problem*.

N-body system for flat-disk galaxies.

Results: galaxies should be unstable!





NGC 1300

They tried to fix it cooling it (colliding gas loses energy). $\Rightarrow$ Spiral galaxies, but after turning it off the instabilities grew again.

Dark Halos

Ostriker, student of Chandrasekhar:
For a system in equilibrium:

$$2T + U = 0. \tag{14}$$

T consists of $T = T_{rot} + T_{ran}$ so:

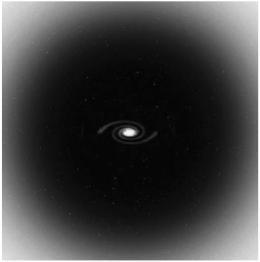
$$t + r = 1/2, \tag{15}$$

where $t = T_{rot}/(-U)$ and $r = T_{rot}/(-U)$. t in a sense measures the temperature and low t means "hot".

From classical rotating spheroids we know that $t > 0.14$ i.e. 28% of the T is T_{ran} $\Rightarrow$ instability!
For our galaxy $t \approx 0.49$! Our Galaxy should be violently unstable!

Solution: Dark Halos!

Additional spheroidal hot component with low M/L extending far above the galaxy plane would decrease $t = T_{rot}/(-U)$ and stabilize the galaxy!

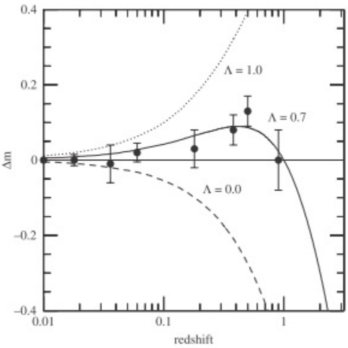


Ostriker and Peedles's (1973) computer experiments showed that the halo mass should be at least equal to the galaxy disk mass for the galaxy to be stable.

CMB and Dark Energy.

Supernovas of type I have about the same luminosity and decay rate.

"Standard candles". Their luminosity decrease depends upon the geometry of space-time.



Supernovae about 20% fainter than in an empty universe!

Universe is expanding accelerating!

Concordance model of Universe requires 72% Dark Energy, 23% CDM, 4.6% Matter.

(2007) WMAP data give:

$$H_0 = 72.4 \quad km/s/Mpc, \tag{16}$$

$$t_0 = 13.69 \quad \text{billion years}, \tag{17}$$

$$\Omega_{\text{total}} = 1.099 \pm 0.1. \tag{18}$$

Hot gas emission mechanism has two possibilities:

- thermal emission or Bremsstrahlung (e^- acceleration)
  $I \propto \exp(-hv/kT)$,
- non-thermal (low energy γ scattering in X-ray energies)
  $I \propto v^{-\alpha}$.

By 1975 more propable thermal emission in $T \sim 10^7 - 10^8$ degrees.
Now we know $\Rightarrow$ thermal emission.

CDM is non-relativistic particles means that they do not erase density fluctuations.

No lower limit on the mass of objects that can first gravitationally collapse.

CDM fluid fluctuations continue to grow after they become smaller than the horizon.

So we have a "bottom-up" structure formation.