Understanding Dark Matter:
Clues from the Formation of Structure

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the big questions:

• How much stuff is there in the Universe?
• What kind of stuff is it?
• How does it interact and evolve?
simplest way to determine how much stuff you have:

count up what you see
another way to determine how much stuff you have:

determine how it moves
light doesn’t always trace mass
The Coma Cluster

Dark Matter in Galaxy Clusters
“Missing Mass” in Galaxy Clusters

- Fritz Zwicky measured velocities for \( \sim 1000 \) galaxies in the Coma Cluster.
- Expect \( v = \sqrt{\frac{M}{r}} \)

More mass than light, by a large factor!

Combining (33) and (34), we find

\[ M > 9 \times 10^4 \text{ gr}. \] (35)

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

\[ \overline{M} > 9 \times 10^4 \text{ gr} = 4.5 \times 10^5 M_\odot. \] (36)

somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about \( 8.5 \times 10^7 \) suns. According to (36), the conversion factor \( \gamma \) from luminosity to mass for nebulae in the Coma cluster would be of the order

\[ \gamma = 500, \] (37)

as compared with about \( \gamma' = 3 \) for the local Kapteyn stellar system.
“Missing Mass” in Spiral Galaxies

- In mid 1960’s, Vera Rubin measured the rotation curve of the Andromeda galaxy.
- It was close to flat, not decreasing at large radii.
- Subsequent measurements on other galaxies showed the same feature.
- Same basic problem: indicates substantially more matter around galaxies than is seen.
What could explain this?

- extra matter around every galaxy and galaxy cluster
- ~spherical distribution of dark matter surrounding each galaxy or galaxy cluster
What do we mean by Dark?

dark matter

not dark matter
What is it?

baryonic

• golf balls?
• red matter?
• brown dwarfs?

non-baryonic

• neutrinos
• WIMPS
• axions
We can also measure the mass of the whole Universe

- The idea is similar to galaxies and clusters: measure the dynamics.
- There are actually two ways to do this:
  - measure the expansion rate
  - measure the “growth of structure” i.e., the clumping rate
The expansion rate is like a scale

- If the Universe is expanding away at a given rate, what will matter do to it?
- Slow it down (the more you have, the more rapidly gravity will slow it down).
- If you can measure the how the expansion rate changes with time, you can measure the Universe slowing down, and infer the total amount of matter.
Total amount of normal matter

- “Baryons”: matter made up from protons and neutrons
- Not all in stars -- some remains in primordial gas (mostly hydrogen, both cold and hot) that has not yet formed stars.
- We can measure the total amount of baryons using our understanding of nuclear physics and the expansion of the early universe
  \[ \Omega_b = 0.019h^{-2} \]
  \[ \approx 0.04 \]
- BBN prediction is
- In good agreement with several other constraints
“Missing Mass” in the whole Universe

- Dark matter: 85%
- Non-visible baryons: 13%
- Stars: 2%
But gravity doesn’t just act on the Universe as a whole...

Primordial ripples evolve into large scale structure
CMB gives initial conditions for structure formation

density fluctuations are $1/100,000$ (380,000 years after the big bang)
How does this structure evolve?
Simulating the Universe

- Gravity is the strongest force on large scales
- Dark matter dominates the mass, so to first order we can ignore the baryons when trying to understand the effect of gravity on structure formation
- When the fluctuations are small, we can do these calculations analytically. As they grow, it becomes a non-linear problem best solved by large computers.
Pretty good problem: we know the initial conditions and we know the physics

small density perturbations evolve under the influence of gravity soon becomes a non-linear problem: use a big computer

state of the art simulations have ~ 10 billion particles
The first N-body simulation

ON THE CLUSTERING TENDENCIES AMONG THE NEBULAE

II. A STUDY OF ENCOUNTERS BETWEEN LABORATORY MODELS OF STELLAR SYSTEMS BY A NEW INTEGRATION PROCEDURE

ERIK HOLMBERG

ABSTRACT

In a previous paper, the writer discussed the possibility of explaining the observed clustering effects among extragalactic nebulae as a result of captures. The present investigation deals with the important problem of whether the loss of energy resulting from the tidal disturbances at a close encounter between two nebulae is large enough to effect a capture. The tidal deformations of two models of stellar systems, passing each other at a small distance, are studied by reconstructing, piece by piece, the orbits described by the individual mass elements. The difficulty of integrating the total gravitational force acting upon a certain element at a certain point of time is solved by replacing gravitation by light. The mass elements are represented by light-bulbs, the candle power being proportional to mass, and the total light is measured by a photocell (Fig. 1). The nebulae are assumed to have a flattened shape, and each is represented by 37 light-bulbs. It is found that the tidal deformations cause an increase in the attraction between the two objects, the increase reaching its maximum value when the nebulae are separating, i.e., after the passage. The resulting loss of energy (Fig. 6) is comparatively large and may, in favorable cases, effect a capture. The spiral arms developing during the encounter (Figs. 4) represent an interesting by-product of the investigation. The direction of the arms depends on the direction of rotation of the nebulae with respect to the direction of their space motions.


Fig. 4a.—Tidal deformations corresponding to parabolic motions, clockwise rotations, and a distance of closest approach equal to the diameters of the nebulae. The spiral arms point in the direction of the rotation.

Fig. 4b.—Same as above, with the exception of counterclockwise rotations. The spiral arms point in the direction opposite to the rotation.
$z = 6$
$z = 1.5$
$z=0$
still challenging to simulate the necessary range of scales

Lasdamas: LArgeSuite of DArk MAter Simulations

10 billion light years

Bolshoi

800 million light years

10 billion particles

7 million cpu hours for 200 simulations with 1-3 billion particles each

7 million cpu hours on Pleides
Structure formation depends on:

• The initial density fluctuations
• The total amount of matter
• The type of matter (baryons, cold DM, warm DM, hot DM)
• The expansion rate
So how do we know if we have the correct model?

- Compare to the distribution of galaxies
- Try to measure the evolution of the matter distribution directly (gravitational lensing)
if each sufficiently massive dark matter clump is identified with a galaxy with $L_{\text{galaxy}} = f(M_{\text{DM}})$, the statistics match
Gravitational Lensing

Illustration by Martin Kornmesser & Lars Lindberg Christensen, ST-ECF
a cluster lens

statistical lensing

8 billion light years

COSMOS survey

Galaxy Cluster Abell 1689
Bottom Line:

- virtually all current measurements are consistent with a model in which 85% of the matter in the Universe is dark: about 1-5% neutrinos, and the rest pure cold dark matter (e.g. a WIMP)

- hot dark matter is strongly ruled out -- would produce completely different structure. can use this to measure the mass of the neutrino!

- dark matter is required for structure formation: hard to form galaxies without it!
Galaxies & Dark Matter

- all dark matter clumps above a given mass host a galaxy. But how much light they have depends on their mass.

- small galaxies (and massive clusters) have more dark matter (proportionally).
• spherical dark matter “halo” surrounding each galaxy

• but dark matter structure is close to self similar...
Peebles 1970

Simulation progress

18. [18] Springel et al. (2005)
Small scales are particularly interesting

• “hot” dark matter is already ruled out, but dark matter could be a little bit “warm”

• this would show up on small scales: less substructure
our Milky Way’s observed galaxies
but remember...light doesn’t always trace mass
Small scales are particularly interesting... and challenging

- number of observed galaxies depends on:
  - dark matter properties, which determine how many substructures there are
  - physics of gas cooling and star formation in small clumps, which determine which of them light up
12 new galaxies detected in last 5 years!

should be many more to come!
Small galaxies are also particularly interesting for detecting cold dark matter.

Newly detected galaxies have very few stars... even more mass per unit light. They are also very dense.

Means less background and more signal!
• What does “dark matter” mean?
  • doesn’t emit or absorb light, doesn’t interact with you.

• Does it really exist?
  • extremely compelling evidence
  • including formation of structure and galaxies!

• How much is there?
  • 85% of the mass in the universe

• Where is it?
  • everywhere!

• How does it behave?
  • very clumpy! small things form first, then merge and grow

• What is it?
  • A (mostly?) “cold” particle. Stay tuned for detection!

• Who cares?
  • Galaxies couldn’t form without it!
Next up: Hints for Dark Matter?!