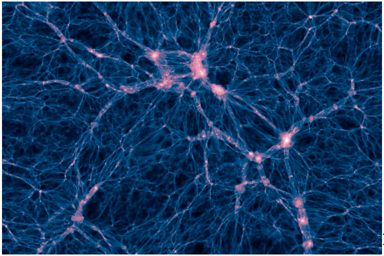
The Evidence for Dark Matter

Albert Zhou

June 3, 2019

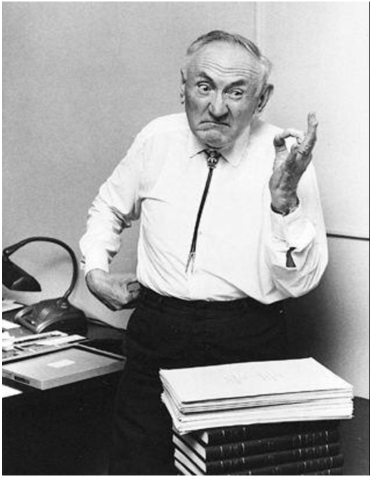
[1]

[1] http://www.ung.si/en/research/cac/ReserachTopics/darkmatter/

The Birth of Dark Matter

The Birth of Dark Matter

- Dark matter predicted by Fritz Zwicky in 1933 [Helv. Phys. Acta **6**, 110127 (1933)].



The Birth of Dark Matter

- Dark matter predicted by Fritz Zwicky in 1933 [Helv. Phys. Acta **6**, 110127 (1933)].
- Zwicky looked at the Coma cluster of galaxies.

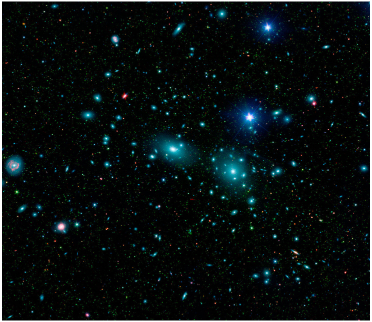


Figure: NASA / JPL-Caltech / L. Jenkins (GSFC)

The Birth of Dark Matter

- Dark matter predicted by Fritz Zwicky in 1933 [Helv. Phys. Acta **6**, 110127 (1933)].
- Zwicky looked at the Coma cluster of galaxies.

Figure: NASA/ESA/Hubble Heritage Team (STScI/AURA)

The Birth of Dark Matter

- Dark matter predicted by Fritz Zwicky in 1933 [Helv. Phys. Acta **6**, 110127 (1933)].
- Zwicky looked at the Coma cluster of galaxies.
- The Coma cluster as a whole obeys Hubble's law ($v \sim 7500\,\mathrm{km}/\mathrm{s}$), but individual galaxies have a peculiar velocity.

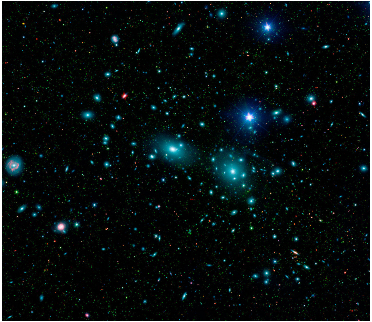


Figure: NASA / JPL-Caltech / L. Jenkins (GSFC)

The Birth of Dark Matter

- Dark matter predicted by Fritz Zwicky in 1933 [Helv. Phys. Acta **6**, 110127 (1933)].
- Zwicky looked at the Coma cluster of galaxies.
- The Coma cluster as a whole obeys Hubble's law ($v \sim 7500\,\mathrm{km/s}$), but individual galaxies have a peculiar velocity.
- From 8 galaxies, Zwicky observed a relative velocity between galaxies $\sim 1000\,\mathrm{km/s}$ (agrees with modern value).

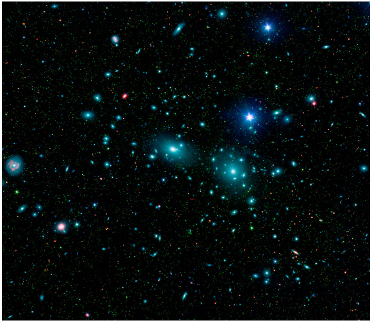


Figure: NASA / JPL-Caltech / L. Jenkins (GSFC)

The Virial Theorem (recap)

- To relate the mass to velocity, Zwicky used the Virial theorem.

The Virial Theorem (recap)

- To relate the mass to velocity, Zwicky used the Virial theorem.
- Recall the moment of inertia (sum over galaxies)

$$I = \sum_i M_i r_i^2, \quad G \equiv \frac{dI}{dt}.$$

The Virial Theorem (recap)

- To relate the mass to velocity, Zwicky used the Virial theorem.
- Recall the moment of inertia (sum over galaxies)

$$I = \sum_i M_i r_i^2, \quad G \equiv \frac{dI}{dt}.$$

- Take second time derivative

$$\frac{d^2 I}{dt^2} \equiv \frac{dG}{dt} = 2T + V_{\rm TOT}, \quad V_{\rm TOT} = \sum_{j<k} V(r_{jk}).$$

The Virial Theorem (recap)

- To relate the mass to velocity, Zwicky used the Virial theorem.
- Recall the moment of inertia (sum over galaxies)

$$I = \sum_i M_i r_i^2, \quad G \equiv \frac{dI}{dt}.$$

- Take second time derivative

$$\frac{d^2 I}{dt^2} \equiv \frac{dG}{dt} = 2T + V_{\mathrm{TOT}}, \quad V_{\mathrm{TOT}} = \sum_{j<k} V(r_{jk}).$$

- For a stable, bound system, the time average of a derivative is zero,

$$\left\langle \frac{dG}{dt} \right\rangle = 0 = 2\left\langle T \right\rangle + \left\langle V_{\mathrm{TOT}} \right\rangle.$$

The Virial Theorem (recap)

- To relate the mass to velocity, Zwicky used the Virial theorem.
- Recall the moment of inertia (sum over galaxies)

$$I = \sum_i M_i r_i^2, \quad G \equiv \frac{dI}{dt}.$$

- Take second time derivative

$$\frac{d^2 I}{dt^2} \equiv \frac{dG}{dt} = 2T + V_{\mathrm{TOT}}, \quad V_{\mathrm{TOT}} = \sum_{j<k} V(r_{jk}).$$

- For a stable, bound system, the time average of a derivative is zero,

$$\left\langle \frac{dG}{dt} \right\rangle = 0 = 2\langle T \rangle + \langle V_{\mathrm{TOT}} \rangle .$$

- The coma cluster is roughly spherical: model it as a homogeneous sphere. Then,

$$V_{\mathrm{TOT}} = -\frac{3G}{5}\frac{M_{\mathrm{TOT}}^2}{R^2}.$$

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\mathrm{TOT}}\sigma_v^2 = V_{\mathrm{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\mathrm{TOT}}}{R^2}.$$

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\mathrm{TOT}}\sigma_v^2 = V_{\mathrm{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\mathrm{TOT}}}{R^2}.$$

- Since astronomers only observe light, need to convert luminosity to mass.

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\text{TOT}}\sigma_v^2 = V_{\text{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\text{TOT}}}{R^2}.$$

- Since astronomers only observe light, need to convert luminosity to mass.
- If most stars are like our sun, then $M_\odot/L_\odot = 1$ (mass-to-light ratio).

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\text{TOT}}\sigma_v^2 = V_{\text{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\text{TOT}}}{R^2}.$$

- Since astronomers only observe light, need to convert luminosity to mass.
- If most stars are like our sun, then $M_\odot / L_\odot = 1$ (mass-to-light ratio).
- Zwicky obtained a mass-to-light ratio of 400 (actual value is 50 due to incorrect Hubble constant).

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\text{TOT}}\sigma_v^2 = V_{\text{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\text{TOT}}}{R^2}.$$

- Since astronomers only observe light, need to convert luminosity to mass.
- If most stars are like our sun, then $M_\odot / L_\odot = 1$ (mass-to-light ratio).
- Zwicky obtained a mass-to-light ratio of 400 (actual value is 50 due to incorrect Hubble constant).
- Assuming the average star is like our sun (good approx.), luminous matter only accounts for $\sim 2\%$ of matter!

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\mathrm{TOT}}\sigma_v^2 = V_{\mathrm{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\mathrm{TOT}}}{R^2}.$$

- Since astronomers only observe light, need to convert luminosity to mass.
- If most stars are like our sun, then $M_\odot / L_\odot = 1$ (mass-to-light ratio).
- Zwicky obtained a mass-to-light ratio of 400 (actual value is 50 due to incorrect Hubble constant).
- Assuming the average star is like our sun (good approx.), luminous matter only accounts for $\sim 2\%$ of matter!
- Zwicky concluded there must be non-luminous *dunkle Materie*.

Light traces matter

- Relate velocity and total mass via virial theorem:

$$2T = M_{\mathrm{TOT}}\sigma_v^2 = V_{\mathrm{TOT}} \implies \sigma_v^2 = \frac{3G}{5}\frac{M_{\mathrm{TOT}}}{R^2}.$$

- Since astronomers only observe light, need to convert luminosity to mass.
- If most stars are like our sun, then $M_\odot/L_\odot = 1$ (mass-to-light ratio).
- Zwicky obtained a mass-to-light ratio of 400 (actual value is 50 due to incorrect Hubble constant).
- Assuming the average star is like our sun (good approx.), luminous matter only accounts for $\sim 2\%$ of matter!
- Zwicky concluded there must be non-luminous *dunkle Materie*.
- This result confirmed by Smith (1936) with the Virgo cluster (however the result is not as rigorous, as Virgo is not spherical).

What are our assumptions?

What are our assumptions?

- We assumed $M/L \sim 1$. Coma galaxy has $O(10^3)$ galaxies, each with $O(10^9)$ stars. True?

What are our assumptions?

- We assumed $M/L \sim 1$. Coma galaxy has $O(10^3)$ galaxies, each with $O(10^9)$ stars. True?
- If false, we'd have a whole cluster of galaxies ($O(10^{12})$ stars) with abnormally massive stars. Unlikely. (Even if $M/L \sim 10$, luminous matter could only contribute $\sim 20\%$.)

What are our assumptions?

- We assumed $M/L \sim 1$. Coma galaxy has $O(10^3)$ galaxies, each with $O(10^9)$ stars. True?
- If false, we'd have a whole cluster of galaxies ($O(10^{12})$ stars) with abnormally massive stars. Unlikely. (Even if $M/L \sim 10$, luminous matter could only contribute $\sim 20\%$.)
- We neglected the intracluster medium (still not enough – only accounts for 10% of total mass; NB this is 5 times the mass of the stars). Even theoretically impossible, due to thermal expansion (cooling time $< 10^6$ yrs).

What are our assumptions?

- We assumed $M/L \sim 1$. Coma galaxy has $O(10^3)$ galaxies, each with $O(10^9)$ stars. True?
- If false, we'd have a whole cluster of galaxies ($O(10^{12})$ stars) with abnormally massive stars. Unlikely. (Even if $M/L \sim 10$, luminous matter could only contribute $\sim 20\%$.)
- We neglected the intracluster medium (still not enough – only accounts for 10% of total mass; NB this is 5 times the mass of the stars). Even theoretically impossible, due to thermal expansion (cooling time $< 10^6$ yrs).
- No absorption of the entire optical spectrum (no evidence contrary).

What are our assumptions?

- We assumed $M/L \sim 1$. Coma galaxy has $O(10^3)$ galaxies, each with $O(10^9)$ stars. True?
- If false, we'd have a whole cluster of galaxies ($O(10^{12})$ stars) with abnormally massive stars. Unlikely. (Even if $M/L \sim 10$, luminous matter could only contribute $\sim 20\%$.)
- We neglected the intracluster medium (still not enough – only accounts for 10% of total mass; NB this is 5 times the mass of the stars). Even theoretically impossible, due to thermal expansion (cooling time $< 10^6$ yrs).
- No absorption of the entire optical spectrum (no evidence contrary).
- Galactic clusters are stable (Zwicky argued this is true, as we have never seen isolated galaxies with peculiar velocities $\sim 1000\,\mathrm{km}\,/\,\mathrm{s}$). The existence of long-lived dense clusters attests to this [van den Bergh, S.; Astron. J. **66** 566 (1961)].

What are our assumptions?

- We assumed $M/L \sim 1$. Coma galaxy has $O(10^3)$ galaxies, each with $O(10^9)$ stars. True?
- If false, we'd have a whole cluster of galaxies ($O(10^{12})$ stars) with abnormally massive stars. Unlikely. (Even if $M/L \sim 10$, luminous matter could only contribute $\sim 20\%$.)
- We neglected the intracluster medium (still not enough – only accounts for 10% of total mass; NB this is 5 times the mass of the stars). Even theoretically impossible, due to thermal expansion (cooling time $< 10^6$ yrs).
- No absorption of the entire optical spectrum (no evidence contrary).
- Galactic clusters are stable (Zwicky argued this is true, as we have never seen isolated galaxies with peculiar velocities $\sim 1000\,\mathrm{km}/\mathrm{s}$). The existence of long-lived dense clusters attests to this [van den Bergh, S.; Astron. J. **66** 566 (1961)].
- We understand galactic dynamics. (The contrary position was default after Zwicky's paper [arXiv:1703.00013]). *Cf.* modified gravity.

Introducing: the Andromeda Galaxy a.k.a. M31

Figure: Credit: Adam Evans

Introducing: the Andromeda Galaxy a.k.a. M31

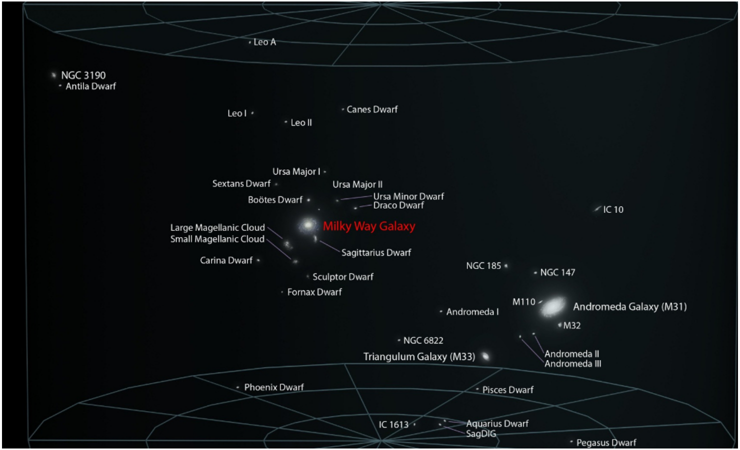


Figure: Credit: `www.sun.org`

Blue shift of M31

Blue shift of M31

- (Historical aside) Babcock (1939) found (pseudo-)anomalous rotation curves of M31. He (erroneously) concluded there must be strong absorption or modified gravity, but did not consider dark matter. (More on rotation curves later).

Blue shift of M31

- (Historical aside) Babcock (1939) found (pseudo-)anomalous rotation curves of M31. He (erroneously) concluded there must be strong absorption or modified gravity, but did not consider dark matter. (More on rotation curves later).
- Based on then-recent measurements, Kahn & Woltjer (1959) [ApJ, **130**, 705] noticed M31 was moving towards the Milky Way at 125 km / s (contrary to Hubble's law).

Blue shift of M31

- (Historical aside) Babcock (1939) found (pseudo-)anomalous rotation curves of M31. He (erroneously) concluded there must be strong absorption or modified gravity, but did not consider dark matter. (More on rotation curves later).
- Based on then-recent measurements, Kahn & Woltjer (1959) [ApJ, **130**, 705] noticed M31 was moving towards the Milky Way at 125 km / s (contrary to Hubble's law).
- Assuming the galaxies in the Local group formed in the Local group, this implies the galaxies must be orbiting.

Blue shift of M31

- (Historical aside) Babcock (1939) found (pseudo-)anomalous rotation curves of M31. He (erroneously) concluded there must be strong absorption or modified gravity, but did not consider dark matter. (More on rotation curves later).
- Based on then-recent measurements, Kahn & Woltjer (1959) [ApJ, **130**, 705] noticed M31 was moving towards the Milky Way at 125 km / s (contrary to Hubble's law).
- Assuming the galaxies in the Local group formed in the Local group, this implies the galaxies must be orbiting.
- Using Kepler's third law, they find a reduced mass 20 times larger than the reduced mass due to stars alone.

Blue shift of M31

- (Historical aside) Babcock (1939) found (pseudo-)anomalous rotation curves of M31. He (erroneously) concluded there must be strong absorption or modified gravity, but did not consider dark matter. (More on rotation curves later).
- Based on then-recent measurements, Kahn & Woltjer (1959) [ApJ, **130**, 705] noticed M31 was moving towards the Milky Way at 125 km / s (contrary to Hubble's law).
- Assuming the galaxies in the Local group formed in the Local group, this implies the galaxies must be orbiting.
- Using Kepler's third law, they find a reduced mass 20 times larger than the reduced mass due to stars alone.
- They suggest the extra mass is due to gas within Local Group (since disproved).

The Bullet Cluster (1E 0657-558)

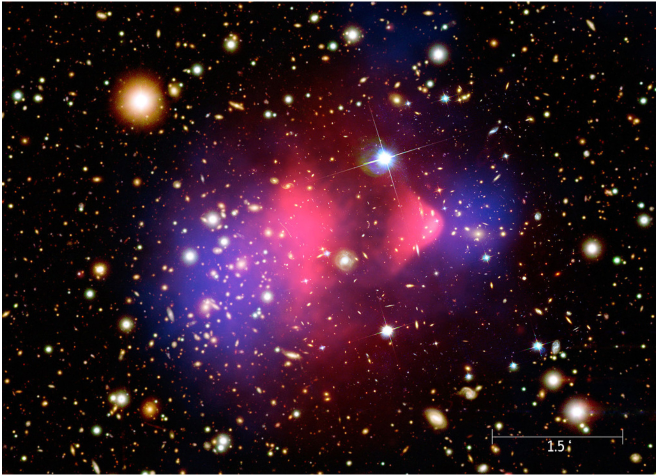


Figure: Credit: NASA/CXC/M. Weiss, Chandra X-Ray Observatory

The Bullet: What does it mean?

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.
- MoND (Modified Newtonian Dynamics) was initially proposed as an alternative to dark matter to explain rotation curves (more on that later).

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.
- MoND (Modified Newtonian Dynamics) was initially proposed as an alternative to dark matter to explain rotation curves (more on that later).
- It has a relativistic generalisation called Tensor-Vector-Scalar theory (TeVeS).

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.
- MoND (Modified Newtonian Dynamics) was initially proposed as an alternative to dark matter to explain rotation curves (more on that later).
- It has a relativistic generalisation called Tensor-Vector-Scalar theory (TeVeS).
- The tensor is the metric; the scalar incorporates MoND (for rotation curves); the vector was introduced to modify gravitational lensing.

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.
- MoND (Modified Newtonian Dynamics) was initially proposed as an alternative to dark matter to explain rotation curves (more on that later).
- It has a relativistic generalisation called Tensor-Vector-Scalar theory (TeVeS).
- The tensor is the metric; the scalar incorporates MoND (for rotation curves); the vector was introduced to modify gravitational lensing.
- The crux of the Bullet is the gravitational lensing map. TeVeS can explain the Bullet Clutser [arXiV:astro-ph/0702146] by modified gravitational lensing.

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.
- MoND (Modified Newtonian Dynamics) was initially proposed as an alternative to dark matter to explain rotation curves (more on that later).
- It has a relativistic generalisation called Tensor-Vector-Scalar theory (TeVeS).
- The tensor is the metric; the scalar incorporates MoND (for rotation curves); the vector was introduced to modify gravitational lensing.
- The crux of the Bullet is the gravitational lensing map. TeVeS can explain the Bullet Clutser [arXiV:astro-ph/0702146] by modified gravitational lensing.
- Trainwreck Cluster (Abell 520) – conflicting results.

The Bullet: What does it mean?

- If there is dark matter, it must be collisionless, like the galaxies.
- Death of modified gravity? Not quite.
- MoND (Modified Newtonian Dynamics) was initially proposed as an alternative to dark matter to explain rotation curves (more on that later).
- It has a relativistic generalisation called Tensor-Vector-Scalar theory (TeVeS).
- The tensor is the metric; the scalar incorporates MoND (for rotation curves); the vector was introduced to modify gravitational lensing.
- The crux of the Bullet is the gravitational lensing map. TeVeS can explain the Bullet Clutser [arXiV:astro-ph/0702146] by modified gravitational lensing.
- Trainwreck Cluster (Abell 520) – conflicting results.
- Striking astrophysical system with rich dynamics. Significance to the problem of dark matter overstated in popular media. (Hype.) No conclusion can be made from a single system alone.

Galactic Stability

Figure: An example of a bar galaxy (courtesy of NASA, ESA, and The Hubble Heritage Team STScI/AURA)

Galactic Stability

- Spiral galaxies like NGC1300 and the Milky way are rotating at $\sim 100 - 300\,\mathrm{km}\,/\,\mathrm{s}$ with peculiar velocities $\sim 30 - 40\,\mathrm{km}\,/\,\mathrm{s}$. Are such configurations stable?

Galactic Stability

- Spiral galaxies like NGC1300 and the Milky way are rotating at $\sim 100 - 300\,\mathrm{km}\,/\,\mathrm{s}$ with peculiar velocities $\sim 30 - 40\,\mathrm{km}\,/\,\mathrm{s}$. Are such configurations stable?
- This is different to the rotation curves (later) and Zwicky's analysis, which assume spherical symmetry.

Galactic Stability

- Spiral galaxies like NGC1300 and the Milky way are rotating at $\sim 100 - 300\,\mathrm{km}/\mathrm{s}$ with peculiar velocities $\sim 30 - 40\,\mathrm{km}/\mathrm{s}$. Are such configurations stable?
- This is different to the rotation curves (later) and Zwicky's analysis, which assume spherical symmetry.
- Investigated by Hohl, F. (1971) [Ap. J. **168** 343].

Unstable numerical galaxies

- Result: a rotationally supported disc of stars (galaxy) initially at equilibrium, at the same scale as a real galaxy, is stable *assuming* circular symmetry (*i.e.* the gravitational field was assumed to be *purely* radial).

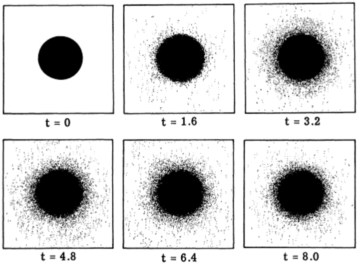


FIG. 1.—Axisymmetric evolution of an initially balanced, uniformly rotating disk of 100000 stars. The stars have an initial velocity dispersion given by Toomre's criterion, and they move under a purely radial gravitational field. Time in this and all subsequent figures is given in units of the rotational period of the cold balanced disk.

Figure: From Hohl, F. (1971) [Ap. J. **168** 343]

Unstable numerical galaxies

- Result: a rotationally supported disc of stars (galaxy) initially at equilibrium, at the same scale as a real galaxy, is stable *assuming* circular symmetry (*i.e.* the gravitational field was assumed to be *purely* radial).
- Result: the same situation as above, but dropping the assumption of circular symmetry yields *instability*. A bar-like galaxy evolves – but is not long-lived!

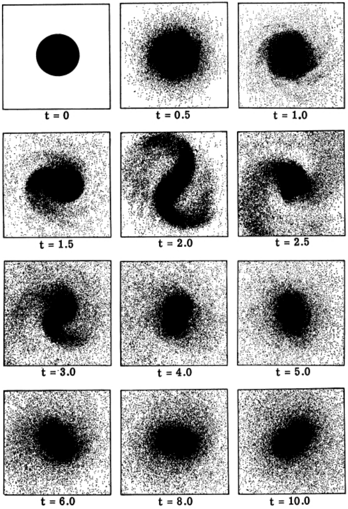


Fig. 4.—Unconstrained evolution of the initially balanced uniformly rotating disk of 100000 stars. The stars have an initial velocity dispersion given by Toomre's criterion.

Figure: From Hohl, F. (1971)

Unstable numerical galaxies

- Result: a rotationally supported disc of stars (galaxy) initially at equilibrium, at the same scale as a real galaxy, is stable *assuming* circular symmetry (*i.e.* the gravitational field was assumed to be *purely* radial).
- Result: the same situation as above, but dropping the assumption of circular symmetry yields *instability*. A bar-like galaxy evolves – but is not long-lived!
- Time in units of orbital period: 150 million yrs.

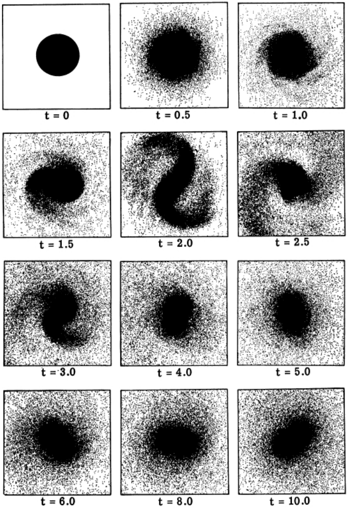


FIG. 4.—Unconstrained evolution of the initially balanced uniformly rotating disk of 100000 stars. The stars have an initial velocity dispersion given by Toomre's criterion.

Figure: From Hohl, F. (1971)

Ostriker's hypothesis: dark halo

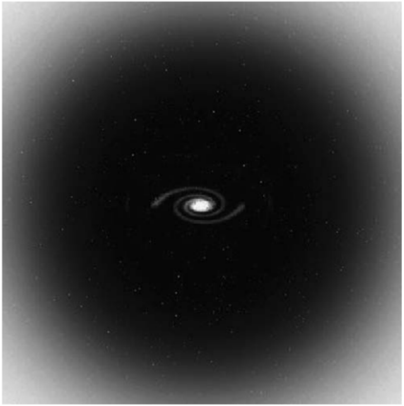


Fig. 3.4. The Ostriker–Peebles–Yahil (1974) view of spiral galaxies. The galaxy disk is embedded in a more extensive dark pressure-supported system – a dark halo with a total mass larger than that of the visible object.

Figure: From Sanders, R. H. (2010)

Ostriker's hypothesis: dark halo

- Recall Virial theorem $2T + V = 0$. Split kinetic energy into rotational and peculiar (random) component

$$T = T_{\mathrm{rot}} + T_{\mathrm{rand}}.$$

Ostriker's hypothesis: dark halo

- Recall Virial theorem $2T + V = 0$. Split kinetic energy into rotational and peculiar (random) component

$$T = T_{\rm rot} + T_{\rm rand}.$$

- Define $t = T_{\rm rot}/(-V)$ and $r = T_{\rm rand}/(-V)$; then,

$$t + r = \frac{1}{2}.$$

Ostriker's hypothesis: dark halo

- Recall Virial theorem $2T + V = 0$. Split kinetic energy into rotational and peculiar (random) component

$$T = T_{\text{rot}} + T_{\text{rand}}.$$

- Define $t = T_{\text{rot}}/(-V)$ and $r = T_{\text{rand}}/(-V)$; then,

$$t + r = \frac{1}{2}.$$

- Low t means system is supported against gravity mostly by random motion ("hot").

Ostriker's hypothesis: dark halo

- Recall Virial theorem $2T + V = 0$. Split kinetic energy into rotational and peculiar (random) component

$$T = T_{\rm rot} + T_{\rm rand}.$$

- Define $t = T_{\rm rot}/(-V)$ and $r = T_{\rm rand}/(-V)$; then,

$$t + r = \frac{1}{2}.$$

- Low t means system is supported against gravity mostly by random motion ("hot").
- As $t \to 1/2$, system is supported mostly by rotation ("cold").

Ostriker's hypothesis: dark halo

- Recall Virial theorem $2T + V = 0$. Split kinetic energy into rotational and peculiar (random) component

$$T = T_{\mathrm{rot}} + T_{\mathrm{rand}}.$$

- Define $t = T_{\mathrm{rot}}/(-V)$ and $r = T_{\mathrm{rand}}/(-V)$; then,

$$t + r = \frac{1}{2}.$$

- Low t means system is supported against gravity mostly by random motion ("hot").
- As $t \to 1/2$, system is supported mostly by rotation ("cold").
- Ostriker knew from his research that quasi-spherical systems are only stable at $t \sim 0.14$. But our Galaxy has $t \approx 0.49$. Does this mean the Galaxy is unstable? (Yes.)

Evidence for dark halos: numerics

- Ostriker and Peebles (1973) numerically modelled a galaxy with a dark halo (only gravitational interactions).

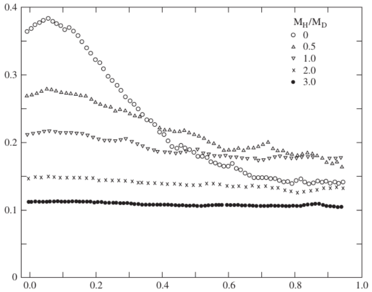


Figure: A plot of $t = T_{\rm rot}/(-V)$ vs. time τ (in units or orbital period). From Ostriker & Peebles (1973) [Ap. J. **186** 467]

Evidence for dark halos: numerics

- Ostriker and Peebles (1973) numerically modelled a galaxy with a dark halo (only gravitational interactions).
- A galaxy with no halo will have parameter $t \to 0.14$. A galaxy with halo comparable to galaxy mass has relatively constant t parameter.

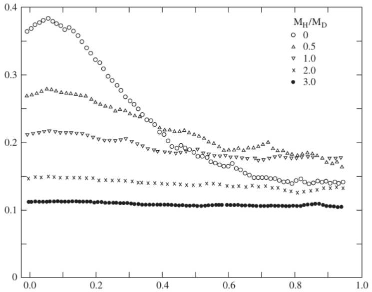


Figure: A plot of $t = T_{\rm rot}/(-V)$ vs. time τ (in units or orbital period). From Ostriker & Peebles (1973) [Ap. J. **186** 467]

Evidence for dark halos: numerics

- Ostriker and Peebles (1973) numerically modelled a galaxy with a dark halo (only gravitational interactions).
- A galaxy with no halo will have parameter $t \to 0.14$. A galaxy with halo comparable to galaxy mass has relatively constant t parameter.
- Numerics quite involved. *E.g.* a cutoff for the Newtonian potential has to be introduced to avoid the $1/r$ singularity.

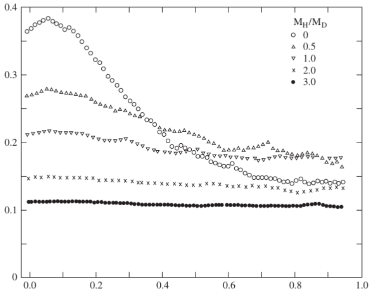


Figure: A plot of $t = T_{\rm rot}/(-V)$ vs. time τ (in units or orbital period). From Ostriker & Peebles (1973) [Ap. J. **186** 467]

Caveats

- Further work (by Lia Athanassoula and Jerry Sellwood, 1986) demonstrates the mass of dark halo can be reduced, but some sort of halo is needed (see Sanders, 2010 for more detail).

Caveats

- Further work (by Lia Athanassoula and Jerry Sellwood, 1986) demonstrates the mass of dark halo can be reduced, but some sort of halo is needed (see Sanders, 2010 for more detail).
- MoND can provide alternative explanation (see Sanders, 2010).

Observational evidence for dark halos

- If galaxies needed dark halos to be stable, larger galaxies should have more massive dark halos.

Observational evidence for dark halos

- If galaxies needed dark halos to be stable, larger galaxies should have more massive dark halos.
- Ostriker, Peebles & Yahil (1974) [Ap. J. **193** L1] analysed the relationship between the size of various galaxies, to their dynamical mass (mass as determined from dynamics like rotation/blue-shift) – determined by various methods.

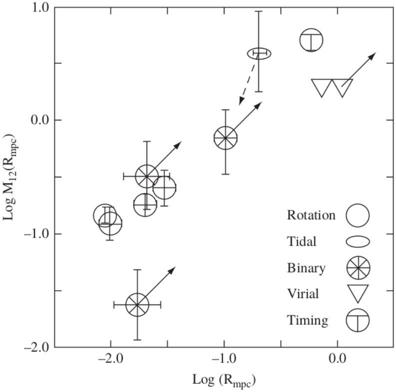


Figure: Log-log plot of mass in units of $10^{12} M_{\odot}$ vs. size in units of Mpc. From Ap. J. **193** L1 (1974)

Observational evidence for dark halos

- If galaxies needed dark halos to be stable, larger galaxies should have more massive dark halos.
- Ostriker, Peebles & Yahil (1974) [Ap. J. **193** L1] analysed the relationship between the size of various galaxies, to their dynamical mass (mass as determined from dynamics like rotation/blue-shift) – determined by various methods.
- Observations consistent with hypothesis.

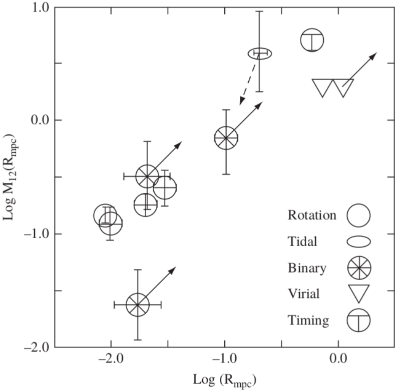


Figure: Log-log plot of mass in units of $10^{12} M_\odot$ vs. size in units of Mpc. From Ap. J. **193** L1 (1974)

Rotation Curves (the classic anomaly)

- Galactic (in)stability developed simultaneously with the rotation-curve anomaly.

Rotation Curves (the classic anomaly)

- Galactic (in)stability developed simultaneously with the rotation-curve anomaly.
- Point masses have a Keplerian decline in its rotation curve.

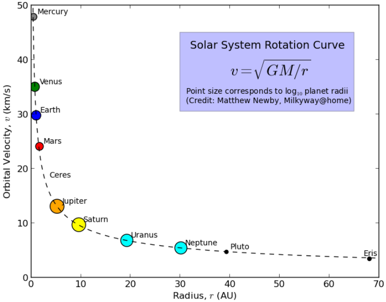


Figure: Source: Matthew Newby, Milkyway@home

Rotation Curves (the classic anomaly)

- Galactic (in)stability developed simultaneously with the rotation-curve anomaly.
- Point masses have a Keplerian decline in its rotation curve.
- Galaxies have exponential decline of brightness. The outer edge of galaxies should have a Keplerian decline, assuming light traces mass.

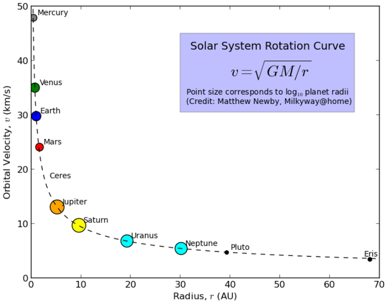


Figure: Source: Matthew Newby, Milkyway@home

Rotation Curves (the classic anomaly)

- Galactic (in)stability developed simultaneously with the rotation-curve anomaly.
- Point masses have a Keplerian decline in its rotation curve.
- Galaxies have exponential decline of brightness. The outer edge of galaxies should have a Keplerian decline, assuming light traces mass.
- The opposite is observed! Rotation curve is asymptotically flat. Work first done by Roberts & Whitehurst, as well as Rogstad & Shostak.

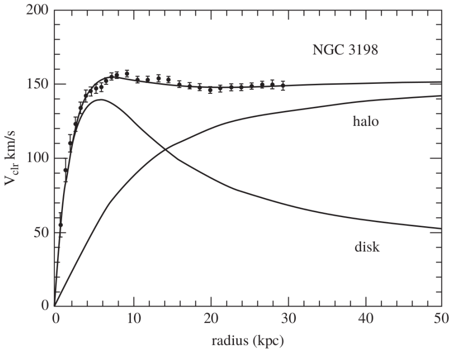


Figure: Source: van Albada *et al.* (1985) [Ap. J. **295** 305]

Caveats

- Kalnjas (1983) demonstrated that using the observed luminosity (as a function of radius) as a tracer for mass, he could reproduce the *optical* rotation curves, with $M/L \leq 6.5$.

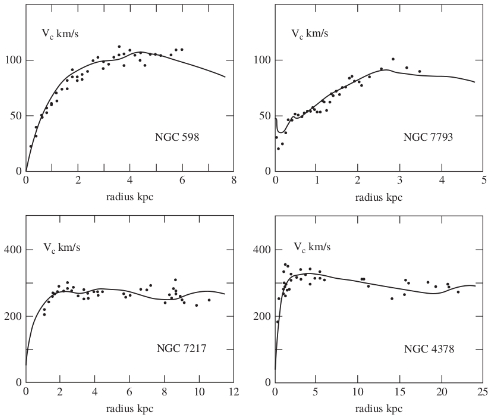


Fig. 5.2. The rotation curves (solid curves) of four spiral galaxies calculated by Kalnajs assuming that the light exactly traces the mass distribution and that the mass is in a thin disk. The points show rotation curves determined from observations of optical emission lines; thus, the measured rotation curves do not extend beyond the visible disk. The adopted M/L values for the stellar disks are 5.0, 2.9, 4.2 and 6.5. From Kalnajs (1983).

Figure: Source: Sanders, 2010

Caveats

- Kalnjas (1983) demonstrated that using the observed luminosity (as a function of radius) as a tracer for mass, he could reproduce the *optical* rotation curves, with $M/L \leq 6.5$.
- Only outside the optical edge of a galaxy, does the anomaly present itself. (This is very significant.)

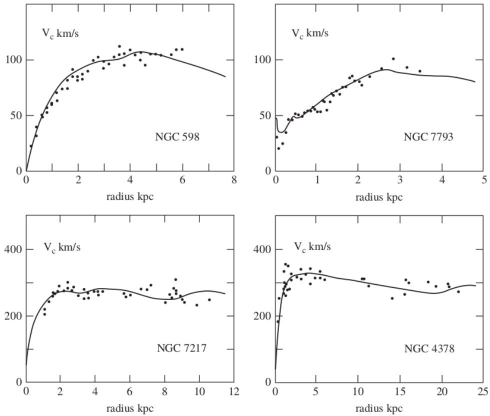


Fig. 5.2. The rotation curves (solid curves) of four spiral galaxies calculated by Kalnajs assuming that the light exactly traces the mass distribution and that the mass is in a thin disk. The points show rotation curves determined from observations of optical emission lines; thus, the measured rotation curves do not extend beyond the visible disk. The adopted M/L values for the stellar disks are 5.0, 2.9, 4.2 and 6.5. From Kalnajs (1983).

Figure: Source: Sanders, 2010

An Aside: 21cm spin-flip radiation (HI line)

- The coupling of nuclear and electronic spin produces the hyperfine splitting of the two spin states in a hydrogen atom.

An Aside: 21cm spin-flip radiation (HI line)

- The coupling of nuclear and electronic spin produces the hyperfine splitting of the two spin states in a hydrogen atom.
- The two hyperfine levels of the hydrogen 1s ground state have an energy difference of $\approx 5.8\mu\,$eV. The wavelength of the emitted photon is 21cm.

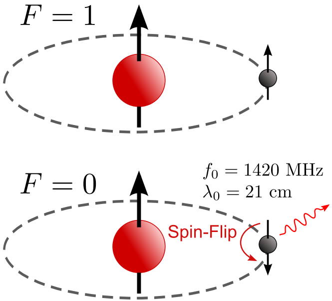


Figure: Courtesy of User Tiltec, Wikipedia

An Aside: 21cm spin-flip radiation (HI line)

- The coupling of nuclear and electronic spin produces the hyperfine splitting of the two spin states in a hydrogen atom.
- The two hyperfine levels of the hydrogen 1s ground state have an energy difference of $\approx 5.8\mu\,$eV. The wavelength of the emitted photon is 21cm.
- The lifetime of the excited state is 10 million years!

An Aside: 21cm spin-flip radiation (HI line)

- The coupling of nuclear and electronic spin produces the hyperfine splitting of the two spin states in a hydrogen atom.
- The two hyperfine levels of the hydrogen 1s ground state have an energy difference of $\approx 5.8\mu\,$eV. The wavelength of the emitted photon is 21cm.
- The lifetime of the excited state is 10 million years!
- Despite this, the redshift of spin-flip radiation is used to measure the velocity of neutral hydrogen gas beyond the optical edge of the galaxy. [Only occurs in spiral galaxies (not elliptical).]

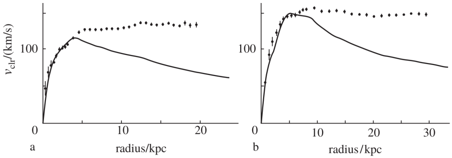


Figure: 21cm data of highly symmetric galaxies with rotation curved calculated from observed luminosity with $M/L = 1.9$ (left) and $M/L = 4.0$ (right); by van Albada and Sancisi (1986) [Phil. Trans. R. Soc. Lond. A. **320** 447]

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.

Further Developments

- No natural explanation for flat rotation curves with CDM.
  Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.
- Soon discovered that galaxies have an upper limit for surface-brightness. Such high-surface-brightness (HSB) galaxies were selected for in early rotation-curve studies, as they were easier to observe.

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.
- Soon discovered that galaxies have an upper limit for surface-brightness. Such high-surface-brightness (HSB) galaxies were selected for in early rotation-curve studies, as they were easier to observe.
- HSB galaxies all have flat rotation curves.

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.
- Soon discovered that galaxies have an upper limit for surface-brightness. Such high-surface-brightness (HSB) galaxies were selected for in early rotation-curve studies, as they were easier to observe.
- HSB galaxies all have flat rotation curves.
- By 1990, low-surface-brightness (LSB) galaxies were studied.

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.
- Soon discovered that galaxies have an upper limit for surface-brightness. Such high-surface-brightness (HSB) galaxies were selected for in early rotation-curve studies, as they were easier to observe.
- HSB galaxies all have flat rotation curves.
- By 1990, low-surface-brightness (LSB) galaxies were studied.
- LSB galaxies have *asymptotically increasing* rotation curves.

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.
- Soon discovered that galaxies have an upper limit for surface-brightness. Such high-surface-brightness (HSB) galaxies were selected for in early rotation-curve studies, as they were easier to observe.
- HSB galaxies all have flat rotation curves.
- By 1990, low-surface-brightness (LSB) galaxies were studied.
- LSB galaxies have *asymptotically increasing* rotation curves.
- LSB galaxies have an anomaly in the optical region (contrary to HSB *cf.* Kalnjas).

Further Developments

- No natural explanation for flat rotation curves with CDM. Fine-tuning problem: *disc-halo conspiracy*.
- Rotation curves of *fake* galaxies can be fitted! Fitting rotation curves is not good evidence for CDM. Also, no unique fit (degeneracy).
- Milgrom (1980) proposed MoND as a natural explanation for flatness. Only one free parameter: M/L.
- Soon discovered that galaxies have an upper limit for surface-brightness. Such high-surface-brightness (HSB) galaxies were selected for in early rotation-curve studies, as they were easier to observe.
- HSB galaxies all have flat rotation curves.
- By 1990, low-surface-brightness (LSB) galaxies were studied.
- LSB galaxies have *asymptotically increasing* rotation curves.
- LSB galaxies have an anomaly in the optical region (contrary to HSB *cf.* Kalnjas).
- MoND is extremely successful as a theory to describe rotation curves (more later). It also has serious deficiencies.

Galaxy formation in CDM (core-cusp problem)

- Fitting halo densities to rotation curves is not good! Not evidence. How to make prediction?

Galaxy formation in CDM (core-cusp problem)

- Fitting halo densities to rotation curves is not good! Not evidence. How to make prediction?
- With better computing power, gravitational N-body simulations demonstrated a universal halo density profile, named after its discoverers: Navarro, Frenk & White (NFW).

Galaxy formation in CDM (core-cusp problem)

- Fitting halo densities to rotation curves is not good! Not evidence. How to make prediction?
- With better computing power, gravitational N-body simulations demonstrated a universal halo density profile, named after its discoverers: Navarro, Frenk & White (NFW).
- With the advent of precision cosmology, ΛCDM could be used to constrain one of the parameters of NFW. (More on ΛCDM later). $3 \to 2$ parameters. Previous halos used the *isothermal sphere*, with 3 parameters.

Galaxy formation in CDM (core-cusp problem)

- Fitting halo densities to rotation curves is not good! Not evidence. How to make prediction?
- With better computing power, gravitational N-body simulations demonstrated a universal halo density profile, named after its discoverers: Navarro, Frenk & White (NFW).
- With the advent of precision cosmology, ΛCDM could be used to constrain one of the parameters of NFW. (More on ΛCDM later). $3 \to 2$ parameters. Previous halos used the *isothermal sphere*, with 3 parameters.
- *But*, NFW profiles *cannot* describe low-mass LSB galaxies. This is due to a sharp increase (cusp) in the core of the dark halo, which does not exist in the isothermal sphere: *Cusp-core problem* [arXiv:0910.3538].

Possible resolutions

Three possible scenarios [arXiv:astro-ph/0210641]:

1. ΛCDM is wrong [I think unlikely – particularly given DES result].

Possible resolutions

Three possible scenarios [arXiv:astro-ph/0210641]:

1. ΛCDM is wrong [I think unlikely – particularly given DES result].
2. Feedback from baryonic matter changes the NFW profile (which only includes DM-DM gravitational interaction) [I think likely] *or* DM is not cold (self-interacting or warm) *or* something else we don't understand about DM.

Possible resolutions

Three possible scenarios [arXiv:astro-ph/0210641]:

1. ΛCDM is wrong [I think unlikely – particularly given DES result].
2. Feedback from baryonic matter changes the NFW profile (which only includes DM-DM gravitational interaction) [I think likely] *or* DM is not cold (self-interacting or warm) *or* something else we don't understand about DM.
3. The N-body simulations yielding the NFW profile are wrong.

Possible resolutions

Three possible scenarios [arXiv:astro-ph/0210641]:

1. ΛCDM is wrong [I think unlikely – particularly given DES result].
2. Feedback from baryonic matter changes the NFW profile (which only includes DM-DM gravitational interaction) [I think likely] *or* DM is not cold (self-interacting or warm) *or* something else we don't understand about DM.
3. The N-body simulations yielding the NFW profile are wrong.
4. Of course, one may also consider modified gravity.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.

Figure: (Caption from Sanders, 2010) The halo which forms in an N-body simulation of a CDM universe. The central object has a mass comparable to that of the Milky Way and it is seen to be surrounded by numerous companions – sub-halos which have failed to merge with the more general structure. There are far more such objects than observed dwarf satellites of the Galaxy. Courtesy of Volker Springel.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.
- Prediction: many dwarf galaxies around normal galaxies.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.
- Prediction: many dwarf galaxies around normal galaxies.
- Original problem: the Milky Way originally had only 11 dwarf galaxies. Increased to 50 by SDSS and DES.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.
- Prediction: many dwarf galaxies around normal galaxies.
- Original problem: the Milky Way originally had only 11 dwarf galaxies. Increased to 50 by SDSS and DES.
- Those near the Milky Way get eaten up (dissipation from gas). New expected number: 30.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.
- Prediction: many dwarf galaxies around normal galaxies.
- Original problem: the Milky Way originally had only 11 dwarf galaxies. Increased to 50 by SDSS and DES.
- Those near the Milky Way get eaten up (dissipation from gas). New expected number: 30.
- Some argue [arXiv:1711.06267] that there are always galaxies too faint to observe, so observing 50 ultra-faint dwarf galaxies means there are actually thousands, by detection statistics.

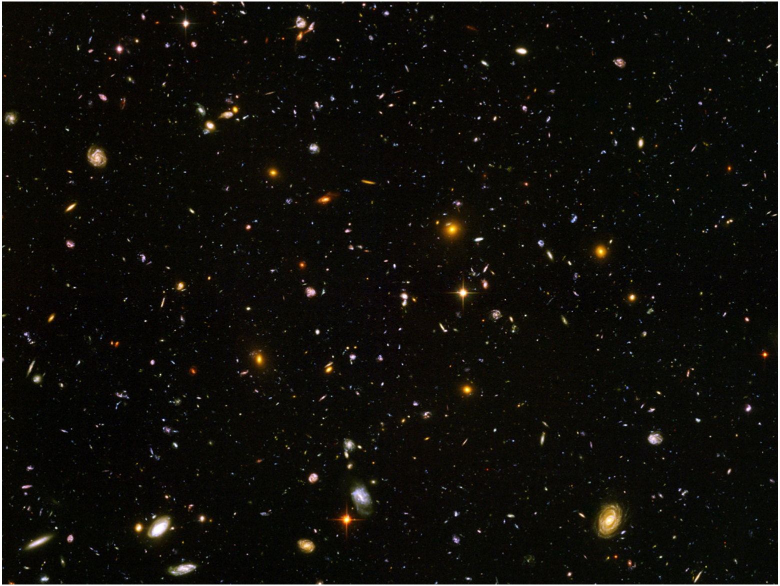
Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.
- Prediction: many dwarf galaxies around normal galaxies.
- Original problem: the Milky Way originally had only 11 dwarf galaxies. Increased to 50 by SDSS and DES.
- Those near the Milky Way get eaten up (dissipation from gas). New expected number: 30.
- Some argue [arXiv:1711.06267] that there are always galaxies too faint to observe, so observing 50 ultra-faint dwarf galaxies means there are actually thousands, by detection statistics.
- *Too many* instead of missing satellites. Still early days. If true, would be difficult for warm DM.

Dwarf galaxy problem (missing satellites problem or too many?)

- Structure formation is hierarchical: small structures form first and then condense into large structures.
- From simulation, we expect many (~ 100) small DM halos surrounding a massive galactic halo.
- Prediction: many dwarf galaxies around normal galaxies.
- Original problem: the Milky Way originally had only 11 dwarf galaxies. Increased to 50 by SDSS and DES.
- Those near the Milky Way get eaten up (dissipation from gas). New expected number: 30.
- Some argue [arXiv:1711.06267] that there are always galaxies too faint to observe, so observing 50 ultra-faint dwarf galaxies means there are actually thousands, by detection statistics.
- *Too many* instead of missing satellites. Still early days. If true, would be difficult for warm DM.
- CDM mini-halos could form dwarf galaxies (assumed impossible before). See recent popular article and references within.

Hubble Ultra Deep Field



The ICM as a probe of DM distribution

- Recall intracluster medium (ICM): hot gas emitting X-rays in clusters like Coma.

The ICM as a probe of DM distribution

- Recall intracluster medium (ICM): hot gas emitting X-rays in clusters like Coma.
- Assuming hydrostatic equilibrium (thermal pressure balanced by gravity), measuring the ICM probes DM distribution.

The ICM as a probe of DM distribution

- Recall intracluster medium (ICM): hot gas emitting X-rays in clusters like Coma.
- Assuming hydrostatic equilibrium (thermal pressure balanced by gravity), measuring the ICM probes DM distribution.
- Can only be done for (quasi-)spherically symmetric systems (like Coma).

The ICM as a probe of DM distribution

- Recall intracluster medium (ICM): hot gas emitting X-rays in clusters like Coma.
- Assuming hydrostatic equilibrium (thermal pressure balanced by gravity), measuring the ICM probes DM distribution.
- Can only be done for (quasi-)spherically symmetric systems (like Coma).
- Mass of cluster can also be measured via lensing (like the Bullet) – two methods consistent.

The ICM as a probe of DM distribution

- Recall intracluster medium (ICM): hot gas emitting X-rays in clusters like Coma.
- Assuming hydrostatic equilibrium (thermal pressure balanced by gravity), measuring the ICM probes DM distribution.
- Can only be done for (quasi-)spherically symmetric systems (like Coma).
- Mass of cluster can also be measured via lensing (like the Bullet) – two methods consistent.
- Sanders (2010) claims that baryon fraction in clusters is inconsistent with cosmology [his source: White *et al.* Nature **366**, 429 (1993)].

The ICM as a probe of DM distribution

- Recall intracluster medium (ICM): hot gas emitting X-rays in clusters like Coma.
- Assuming hydrostatic equilibrium (thermal pressure balanced by gravity), measuring the ICM probes DM distribution.
- Can only be done for (quasi-)spherically symmetric systems (like Coma).
- Mass of cluster can also be measured via lensing (like the Bullet) – two methods consistent.
- Sanders (2010) claims that baryon fraction in clusters is inconsistent with cosmology [his source: White *et al.* Nature **366**, 429 (1993)].
- I cannot find more current literature sources; indeed it seems the opposite is the case [arXiv:1103.4829].

The ICM as a probe of ΛCDM

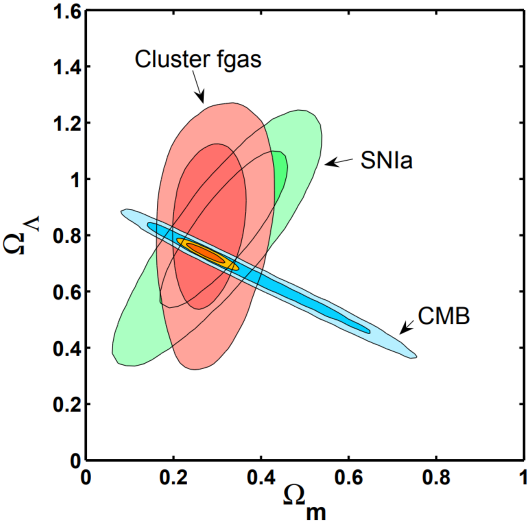


Figure: From Allen *et al.* (2011) [arXiv:1103.4829].

Modified Newtonian Dynamics (MoND)

- CDM cannot explain rotation curves (*cf.* core-cusp problem). The problem is there is no theory of galaxy-halo formation.

Modified Newtonian Dynamics (MoND)

- CDM cannot explain rotation curves (*cf.* core-cusp problem). The problem is there is no theory of galaxy-halo formation.
- MoND was proposed as a natural explanation for flat rotation curves.

Modified Newtonian Dynamics (MoND)

- CDM cannot explain rotation curves (*cf.* core-cusp problem). The problem is there is no theory of galaxy-halo formation.
- MoND was proposed as a natural explanation for flat rotation curves.
- Hypothesis: Newton's law is invalid in the limit of *small* acceleration.

Modified Newtonian Dynamics (MoND)

- CDM cannot explain rotation curves (*cf.* core-cusp problem). The problem is there is no theory of galaxy-halo formation.
- MoND was proposed as a natural explanation for flat rotation curves.
- Hypothesis: Newton's law is invalid in the limit of *small* acceleration.
- How small? For $a < a_0 \sim 1.2 \times 10^{-10}$. Propose new force law:

$$F = ma \times \mu(a/a_0), \quad \mu(x) \to 1 \text{ as } x \to \infty, \quad \mu(x) \to x \text{ as } x \to 0.$$

Modified Newtonian Dynamics (MoND)

- CDM cannot explain rotation curves (*cf.* core-cusp problem). The problem is there is no theory of galaxy-halo formation.
- MoND was proposed as a natural explanation for flat rotation curves.
- Hypothesis: Newton's law is invalid in the limit of *small* acceleration.
- How small? For $a < a_0 \sim 1.2 \times 10^{-10}$. Propose new force law:

$$F = ma \times \mu(a/a_0), \quad \mu(x) \to 1 \text{ as } x \to \infty, \quad \mu(x) \to x \text{ as } x \to 0.$$

- Precise form of μ not important; standard choice:

$$\mu(x) = \frac{x}{\sqrt{1 - x^2}.}$$

Modified Newtonian Dynamics (MoND)

- CDM cannot explain rotation curves (*cf.* core-cusp problem). The problem is there is no theory of galaxy-halo formation.
- MoND was proposed as a natural explanation for flat rotation curves.
- Hypothesis: Newton's law is invalid in the limit of *small* acceleration.
- How small? For $a < a_0 \sim 1.2 \times 10^{-10}$. Propose new force law:

$$F = ma \times \mu(a/a_0), \quad \mu(x) \to 1 \text{ as } x \to \infty, \quad \mu(x) \to x \text{ as } x \to 0.$$

- Precise form of μ not important; standard choice:

$$\mu(x) = \frac{x}{\sqrt{1 - x^2}.}$$

- Note that a_0 is a fundamental constant. When fitting rotation curves, the only free parameter is M/L. No fine-tuning!

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,
- LSB rotation curves (CDM has difficulties),

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,
- LSB rotation curves (CDM has difficulties),
- the Tully-Fisher relation for spiral galaxies (CDM *cannot*)

$$M_{\text{baryon}} = (Ga_0)v^4_{\text{asympt.}},$$

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,
- LSB rotation curves (CDM has difficulties),
- the Tully-Fisher relation for spiral galaxies (CDM *cannot*)

$$M_{\text{baryon}} = (Ga_0)v^4_{\text{asympt.}},$$

- the Faber-Jackson relation for elliptic galaxies , globular star clusters and galactic clusters (CDM *cannot*)

$$L \propto \sigma_v^4.$$

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,
- LSB rotation curves (CDM has difficulties),
- the Tully-Fisher relation for spiral galaxies (CDM *cannot*)

$$M_{\mathrm{baryon}} = (Ga_0)v^4_{\mathrm{asympt.}},$$

- the Faber-Jackson relation for elliptic galaxies , globular star clusters and galactic clusters (CDM *cannot*)

$$L \propto \sigma_v^4.$$

- MoND is extremely successful at explaining galactic phenomena. Because of modified gravity, or is it just a useful parameterisation, reflecting a hidden universal theory of galaxy-halo formation?

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,
- LSB rotation curves (CDM has difficulties),
- the Tully-Fisher relation for spiral galaxies (CDM *cannot*)

$$M_{\text{baryon}} = (Ga_0)v^4_{\text{asympt.}},$$

- the Faber-Jackson relation for elliptic galaxies , globular star clusters and galactic clusters (CDM *cannot*)

$$L \propto \sigma^4_v.$$

- MoND is extremely successful at explaining galactic phenomena. Because of modified gravity, or is it just a useful parameterisation, reflecting a hidden universal theory of galaxy-halo formation?
- Problem: MoND *cannot* explain high peculiar velocities of clusters like Coma (back to Zwicky), *the cluster problem*. An analysis of many clusters demonstrates that MoND generally needs 2-3 times the observed baryonic mass (mostly ICM).

Successes and problems of MoND

- MoND can naturally explain: asymptotically flat rotation curves,
- LSB rotation curves (CDM has difficulties),
- the Tully-Fisher relation for spiral galaxies (CDM *cannot*)

$$M_{\text{baryon}} = (Ga_0)v^4_{\text{asympt.}},$$

- the Faber-Jackson relation for elliptic galaxies , globular star clusters and galactic clusters (CDM *cannot*)

$$L \propto \sigma_v^4.$$

- MoND is extremely successful at explaining galactic phenomena. Because of modified gravity, or is it just a useful parameterisation, reflecting a hidden universal theory of galaxy-halo formation?
- Problem: MoND *cannot* explain high peculiar velocities of clusters like Coma (back to Zwicky), *the cluster problem*. An analysis of many clusters demonstrates that MoND generally needs 2-3 times the observed baryonic mass (mostly ICM).
- Problem: cosmology (next section).

The Cluster Problem

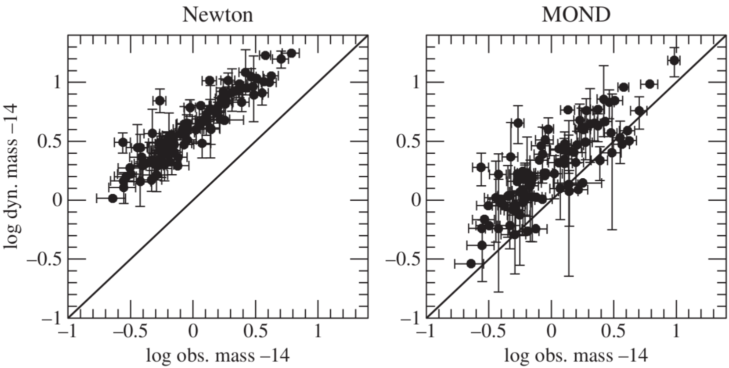


Fig. 10.6. The panel on the left is a log–log plot of the Newtonian dynamical mass against the directly observed baryonic mass (mostly in the form of hot gas). The units are 10^{14} $M_{\odot}$. The panel on the right is the same for the MOND dynamical mass. Note that MOND reduces the discrepancy but does not remove it.

Figure: From Sanders, 2010.

What DM isnt: MaCHOs

- Could DM be faint low-mass stars or (primordial) black holes? (Generically a massive compact halo object or MaCHO – size of a star rather than galaxy.)

What DM isnt: MaCHOs

- Could DM be faint low-mass stars or (primordial) black holes? (Generically a massive compact halo object or MaCHO – size of a star rather than galaxy.)
- When such an object passes in front of a source, it would cause a microlensing event. A microlensing curve depends only on a single time parameter $\hat{t}$.

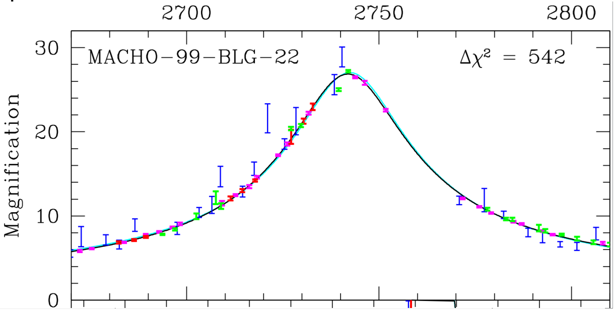


Figure: From [arXiv:astro-ph/0207006]; x-axis is time.

What DM isnt: MaCHOs

- Could DM be faint low-mass stars or (primordial) black holes? (Generically a massive compact halo object or MaCHO – size of a star rather than galaxy.)
- When such an object passes in front of a source, it would cause a microlensing event. A microlensing curve depends only on a single time parameter $\hat{t}$.
- Griest (1991) calculated $m = (t/130\,\text{days})^2 M_\odot$.

What DM isnt: MaCHOs

- Could DM be faint low-mass stars or (primordial) black holes? (Generically a massive compact halo object or MaCHO – size of a star rather than galaxy.)
- When such an object passes in front of a source, it would cause a microlensing event. A microlensing curve depends only on a single time parameter $\hat{t}$.
- Griest (1991) calculated $m = (t/130\,\text{days})^2 M_\odot$.
- MACHO project aimed to observe such events, with the Large Magellanic Cloud as the source (in our Local Group).

What DM isnt: MaCHOs

- Could DM be faint low-mass stars or (primordial) black holes? (Generically a massive compact halo object or MaCHO – size of a star rather than galaxy.)
- When such an object passes in front of a source, it would cause a microlensing event. A microlensing curve depends only on a single time parameter $\hat{t}$.
- Griest (1991) calculated $m = (t/130\,\text{days})^2 M_\odot$.
- MACHO project aimed to observe such events, with the Large Magellanic Cloud as the source (in our Local Group).
- Can calculated expected number of events as a function of MaCHO mass. (How?)

What DM isnt: MaCHOs

- Could DM be faint low-mass stars or (primordial) black holes? (Generically a massive compact halo object or MaCHO – size of a star rather than galaxy.)
- When such an object passes in front of a source, it would cause a microlensing event. A microlensing curve depends only on a single time parameter $\hat{t}$.
- Griest (1991) calculated $m = (t/130\,\text{days})^2 M_\odot$.
- MACHO project aimed to observe such events, with the Large Magellanic Cloud as the source (in our Local Group).
- Can calculated expected number of events as a function of MaCHO mass. (How?)
- Alcock (2001) [ApJL **550** L169] observed 13 events, and were able to rule out some parameter space.

MACHO results

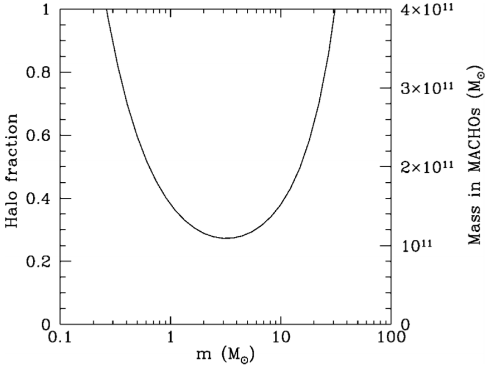


FIG. 3.—Limit on MACHO contribution to the Galactic halo as a function of lens mass for model S. The region above the line is ruled out at a 95% CL. The left axis shows the MACHO halo fraction, while the right axis shows the more model-independent constraint on total mass in MACHOs within 50 kpc.

Figure: From Alcock (2001) [ApJL **550** L169].

Gravitational lens – near complete Einstein ring

Figure: Courtesy of ESA/Hubble & NASA.

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.
- However, pressure can "push back" (via sound waves). The response time given by l/c_s where c_s is speed of sound.

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.
- However, pressure can "push back" (via sound waves). The response time given by l/c_s where c_s is speed of sound.
- If pressure cannot respond fast enough, a perturbation will grow, until non-linear theory is applicable (condensation).

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.
- However, pressure can "push back" (via sound waves). The response time given by l/c_s where c_s is speed of sound.
- If pressure cannot respond fast enough, a perturbation will grow, until non-linear theory is applicable (condensation).
- Only perturbations larger than the Jean's *critical length* will grow, given by

$$l_c = c_s t_c = \frac{c_s}{\sqrt{G\rho}}.$$

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.
- However, pressure can "push back" (via sound waves). The response time given by l/c_s where c_s is speed of sound.
- If pressure cannot respond fast enough, a perturbation will grow, until non-linear theory is applicable (condensation).
- Only perturbations larger than the Jean's *critical length* will grow, given by

$$l_c = c_s t_c = \frac{c_s}{\sqrt{G\rho}}.$$

- For large l_c, structure formation is "top-down" – large structures ($l > l_c$) form first.

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.
- However, pressure can "push back" (via sound waves). The response time given by l/c_s where c_s is speed of sound.
- If pressure cannot respond fast enough, a perturbation will grow, until non-linear theory is applicable (condensation).
- Only perturbations larger than the Jean's *critical length* will grow, given by

$$l_c = c_s t_c = \frac{c_s}{\sqrt{G\rho}}.$$

- For large l_c, structure formation is "top-down" – large structures ($l > l_c$) form first.
- Before (photon) decoupling, baryons were relativistic. The Jean's length was comparable to a causally connected region, thus no gravitational collapse in radiation-dominated era.

Jean's length

- Consider a self-gravitating gas, initially homogeneous of density ρ.
- Ignoring pressure, a perturbation $\delta\rho/\rho$ grows like e^{t/t_c} where $t_c = (G\rho)^{-1/2}$, due to gravity.
- However, pressure can "push back" (via sound waves). The response time given by l/c_s where c_s is speed of sound.
- If pressure cannot respond fast enough, a perturbation will grow, until non-linear theory is applicable (condensation).
- Only perturbations larger than the Jean's *critical length* will grow, given by

$$l_c = c_s t_c = \frac{c_s}{\sqrt{G\rho}}.$$

- For large l_c, structure formation is "top-down" – large structures ($l > l_c$) form first.
- Before (photon) decoupling, baryons were relativistic. The Jean's length was comparable to a causally connected region, thus no gravitational collapse in radiation-dominated era.
- See Mukhanov, 2005, §6 for consistent treatment, as well as Sanders, 2010 §6.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\rm bar}/\rho_{\rm bar} \sim 10^{-3}$.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\mathrm{bar}}/\rho_{\mathrm{bar}} \sim 10^{-3}$.
- Such perturbations of baryon density should be observable in CMB spectrum (photons and baryons tightly coupled).

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\mathrm{bar}}/\rho_{\mathrm{bar}} \sim 10^{-3}$.
- Such perturbations of baryon density should be observable in CMB spectrum (photons and baryons tightly coupled).
- Observed perturbations are $\delta\rho/\rho \sim \delta T/T_0 \sim 10^{-5}$.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\text{bar}}/\rho_{\text{bar}} \sim 10^{-3}$.
- Such perturbations of baryon density should be observable in CMB spectrum (photons and baryons tightly coupled).
- Observed perturbations are $\delta\rho/\rho \sim \delta T/T_0 \sim 10^{-5}$.
- With only baryons and standard GR, there shouldn't be any galaxies today!

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\rm bar}/\rho_{\rm bar} \sim 10^{-3}$.
- Such perturbations of baryon density should be observable in CMB spectrum (photons and baryons tightly coupled).
- Observed perturbations are $\delta\rho/\rho \sim \delta T/T_0 \sim 10^{-5}$.
- With only baryons and standard GR, there shouldn't be any galaxies today!
- We need an additional type of matter, which is *not* coupled to the relativistic plasma before decoupling: cold dark matter (CDM). The effect is on anisotropy is much smaller at radiation-dominated era.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\mathrm{bar}}/\rho_{\mathrm{bar}} \sim 10^{-3}$.
- Such perturbations of baryon density should be observable in CMB spectrum (photons and baryons tightly coupled).
- Observed perturbations are $\delta\rho/\rho \sim \delta T/T_0 \sim 10^{-5}$.
- With only baryons and standard GR, there shouldn't be any galaxies today!
- We need an additional type of matter, which is *not* coupled to the relativistic plasma before decoupling: cold dark matter (CDM). The effect is on anisotropy is much smaller at radiation-dominated era.
- CDM perturbations grow logarithmically in the radiation-era.

A conundrum

- In an expanding universe, perturbations do not grow exponentially, but like a power law.
- In the matter-dominated era (after decoupling), perturbations grow like $t^{2/3}$.
- If we want $\delta\rho/\rho \gtrsim 1$ (non-linear structure) today, then at decoupling ($z \sim 1000$) we need $\delta\rho_{\text{bar}}/\rho_{\text{bar}} \sim 10^{-3}$.
- Such perturbations of baryon density should be observable in CMB spectrum (photons and baryons tightly coupled).
- Observed perturbations are $\delta\rho/\rho \sim \delta T/T_0 \sim 10^{-5}$.
- With only baryons and standard GR, there shouldn't be any galaxies today!
- We need an additional type of matter, which is *not* coupled to the relativistic plasma before decoupling: cold dark matter (CDM). The effect is on anisotropy is much smaller at radiation-dominated era.
- CDM perturbations grow logarithmically in the radiation-era.
- See Mukhanov, 2005, §6 and Sanders, 2005, §A8.

CDM Hypothesis: Numerical Results

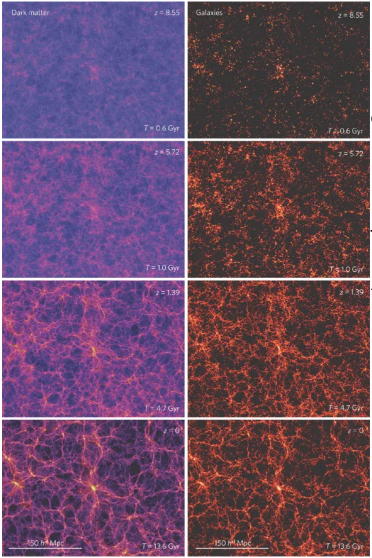


Figure: From Springel *et al.* [Nature **440** 1137 (2006)]. Left: dark matter distribution at (top to bottom) 600 million, 1 billion, 4.7 billion and 13.6 billion years after the Big Bang, from the Millennium N-body simulation. The colour from blue to red encodes the local velocity dispersion; the brightness is a logarithmic measure of the density. Right: predicted distribution of galaxies in the same region and times (semi-analytic techniques used for galaxy formation). Colour encodes stellar mass. The dark matter evolves from a smooth, nearly uniform distribution into a highly clustered state, quite unlike the galaxies, which are strongly clustered from the start.

What we actually observe

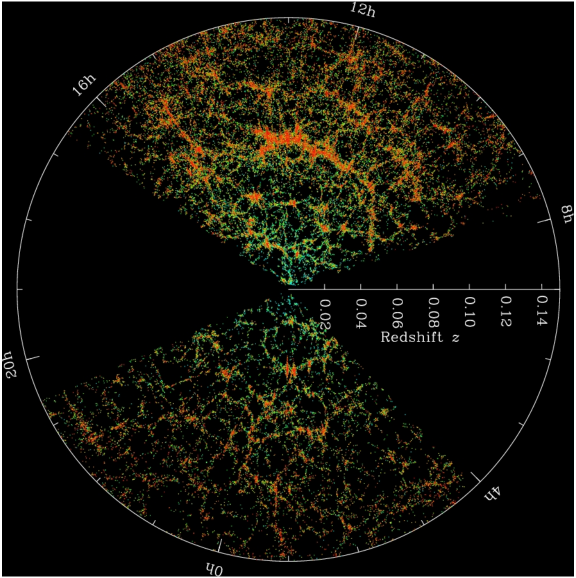


Figure: Earth at centre. Each point is a galaxy. Galaxies coloured according to age of their stars: redder is older. Outer circle is 2 bil lyrs. Empty region not mapped as dust in our own Galaxy obscures the view. Credit: M. Blanton and the Sloan Digital Sky Survey.

Comparison

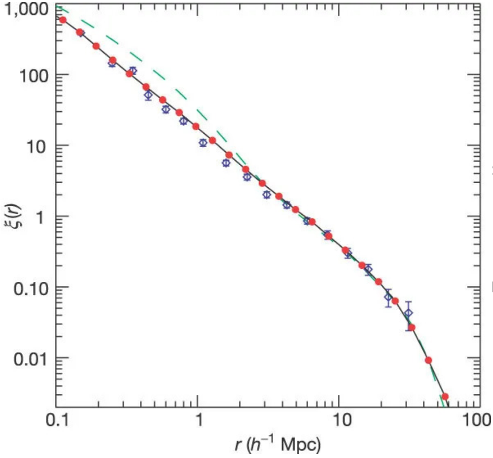


Figure: Galaxy two-point correlation function, $\xi(r)$, at $t =$ now as a function of separation r. Black line is from simulation, dashed green line is simulated dark matter. Red symbols (with vanishingly small Poisson error bars) are from model galaxies brighter than $M_K = -23$, where M_K is the magnitude in the K-band. Data from 2dFGRS are shown as blue diamonds together with their 1σ error bars. The SDSS and APM surveys give similar results. Springel *et al.* [Nature **435**, 629 (2005)]

How does it compare to MoND/TeVeS?

- There is no theory of large-scale structure formation for MoND/modified gravity.

How does it compare to MoND/TeVeS?

- There is no theory of large-scale structure formation for MoND/modified gravity.
- Just doing cosmology is hard and there are fine-tuning and stability issues.

How does it compare to MoND/TeVeS?

- There is no theory of large-scale structure formation for MoND/modified gravity.
- Just doing cosmology is hard and there are fine-tuning and stability issues.
- Even getting non-linear structure $\delta\rho/\rho > 1$ contradicts observations of baryon acoustic oscillations [arXiV:1112.1320, Fig. 1].

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].
- Hubble controversy (Riess) probably due to age bias (see Rigault).

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].
- Hubble controversy (Riess) probably due to age bias (see Rigault).
- Observations: SNe1a, BAO, CMB anisotropies, clusters.

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].
- Hubble controversy (Riess) probably due to age bias (see Rigault).
- Observations: SNe1a, BAO, CMB anisotropies, clusters.
- No one knows why SNe1a are standard candles.

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].
- Hubble controversy (Riess) probably due to age bias (see Rigault).
- Observations: SNe1a, BAO, CMB anisotropies, clusters.
- No one knows why SNe1a are standard candles.
- Theory of CMB anisotropy *very* involved. (Acoustic peaks). See [Mukhanov, 2005, §9], [arXiv:astro-ph/9512161].

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].
- Hubble controversy (Riess) probably due to age bias (see Rigault).
- Observations: SNe1a, BAO, CMB anisotropies, clusters.
- No one knows why SNe1a are standard candles.
- Theory of CMB anisotropy *very* involved. (Acoustic peaks). See [Mukhanov, 2005, §9], [arXiv:astro-ph/9512161].
- Minimal ΛCDM has 10 parameters, 6 non-trivial. Not predictive.

ΛCDM

- Cosmic inventory: dark energy $w = -1$, matter (CDM & SM) $w = 0$, radiation $w = 1/3$.
- After decoupling, can ignore radiation.
- Is dark energy dynamical? DES constrains this for $z < 1$.
- Larger redshifts: open question. Quasar Hubble diagram has 4σ anomaly for $z > 1.4$ [arXiv:1811.02590].
- Hubble controversy (Riess) probably due to age bias (see Rigault).
- Observations: SNe1a, BAO, CMB anisotropies, clusters.
- No one knows why SNe1a are standard candles.
- Theory of CMB anisotropy *very* involved. (Acoustic peaks). See [Mukhanov, 2005, §9], [arXiv:astro-ph/9512161].
- Minimal ΛCDM has 10 parameters, 6 non-trivial. Not predictive.
- Many different measurements agree (three lines do not meet coincidentally): 'concordance' model.

CMB Anisotropies

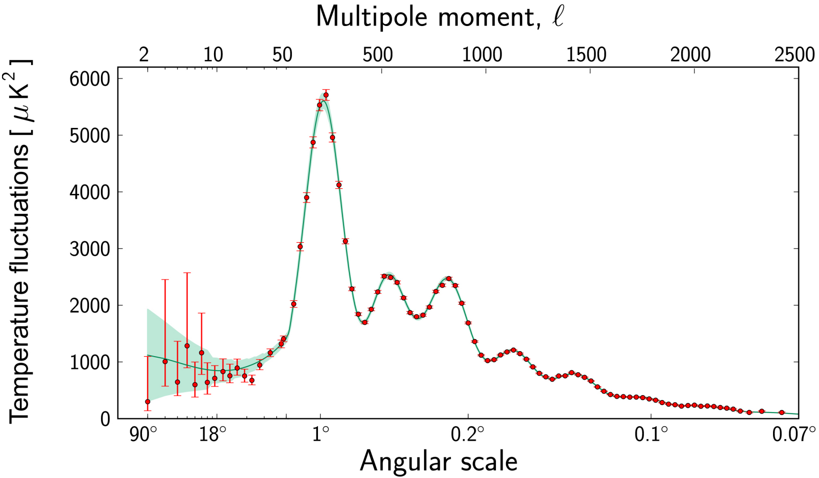


Figure: ESA and the Planck Collaboration

BAO

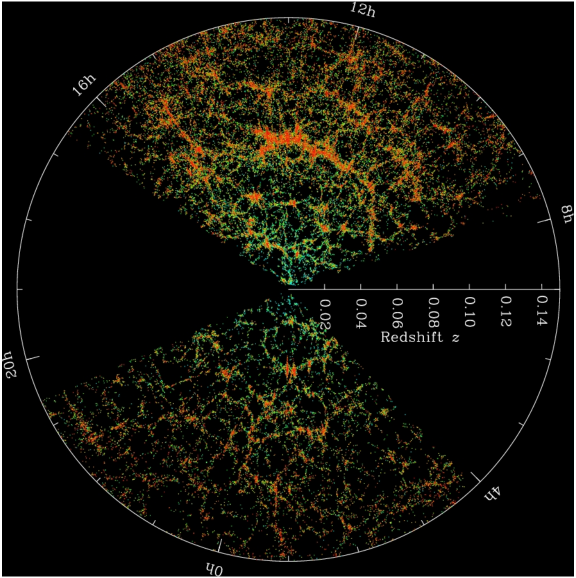
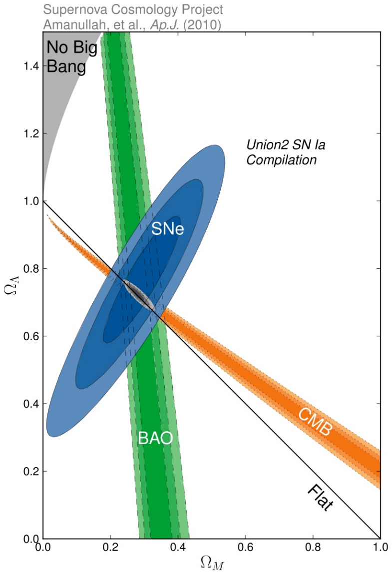


Figure: Earth at centre. Each point is a galaxy. Galaxies coloured according to age of their stars: redder is older. Outer circle is 2 bil lyrs. Empty region not mapped as dust in our own Galaxy obscures the view. Credit: M. Blanton and the Sloan Digital Sky Survey.

Concordance: three lines don't coincidentally meet



References

- Sanders, R. H. – The Dark Matter Problem: A Historical Perspective (2010) [Warning: it's presentation of MoND is lightly biased in favour, due to the author's connection with its early inception. But it is unbiased regarding CDM, in my humble opinion.]
- Mukhanov, V. E. – Physical Foundations of Cosmology (2005) [Purely theoretical textbook.]