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DARK MATTER IN THE UNIVERSE: OBSERVATIONS AND THEORY

What is dark matter?

- What we actually see is **excess gravity**, not matter per se
- **Zwicky (1933):**
  - Applied virial theorem to Coma cluster
  - 90% of mass is invisible! M/L ~ few hundred
- **Rubin (1970's):** Rotation curve of Andromeda
  - Made DM a mainstream idea
- Alternative explanations exist
  - Modified Newtonian Dynamics (MOND)

Where do we see dark matter?

- Galaxies
  - Rotation curves (stars, HI gas, …)
  - Velocity dispersion (elliptical galaxies)
- Galaxy clusters and groups
  - Galaxy motions and interactions (e.g. Zwicky)
  - Hot X-ray gas
  - Gravitational lensing
- Indirectly: Large Scale Structure, CMB fluctuations

I. Spiral Galaxies

- Primary tool: **Rotation curves**
- Probably the best-studied example of dark matter
- Dominated by visible matter inside (solid-body rotation), dark matter outside (flat rotation curve/differential rotation)
- M/L ~ 3 to 25 (3 for Milky Way)
- In general, fainter spirals have higher M/L

II. Elliptical Galaxies

- Primary tool: **Velocity dispersion σ**
- Thought to form from spiral mergers -> should contain DM
- Found to contain **little or no dark matter,** posing a challenge to the merger theory
- But more careful analysis could overturn this (Dekel et al., 2005)

III. Dwarf galaxies

- Highest DM content of any type of galaxy (M/L ~ 200)
- Dominated by dark matter at ALL locations within the galaxy

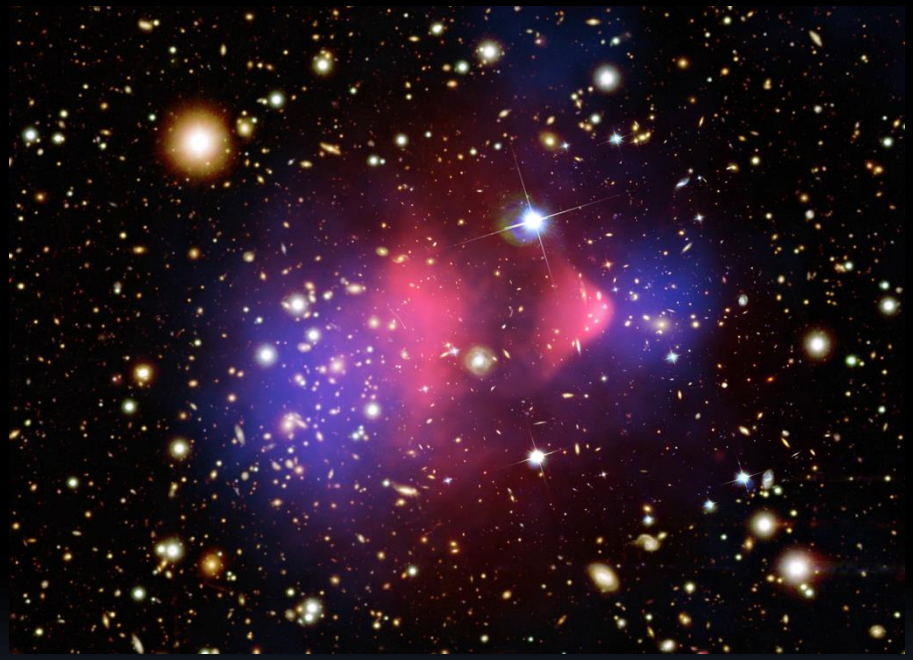
IV. Galaxy clusters and groups

- Very DM dominated; M/L ~ a few hundred (60-90% DM by mass)
- Galaxy Interactions -> Stripped gas/truncated rotation curves (evidence for stripping of DM halos)
- Evidence that much of the DM is evenly distributed throughout cluster, not associated with individual galaxies

Dark matter on smaller scales

- **Globular clusters**: Little or no dark matter (supports theoretical expectation), based on observations of clusters in MW Halo
- **Our Solar System:** Little or no dark matter, from detailed observations of planets and spacecraft. Implications unclear

Case Study: The Bullet Cluster



- Dark matter (blue) offset from x-ray gas (red), stars (optical)
- Evidence against MOND
- Mostly consistent with ΛCDM

The Nature of Dark Matter

- Does not interact through electromagnetic or strong forces
- Generally thought to be **nonbaryonic** (from flatness $\Omega = 1$)
  - *Alternative*: Baryonic DM -> MACHOs -> Brown dwarfs or black holes. But none seen in MW halo.
- Galaxies are enshrouded in roughly spherical **DM haloes** much larger than the visible galaxy

Cold vs. Hot Dark Matter

Hot DM:

- Higher thermal velocity -> Larger free-streaming length -> Supercluster-sized clouds form first, then galaxies (False!)

Cold DM (ΛCDM):

- Galaxies form before clusters (true)
- Currently favored over hot DM
- But encounters problems on scale of galaxies and intragalactic structure

Unsolved problems in ΛCDM
(not exhaustive!)

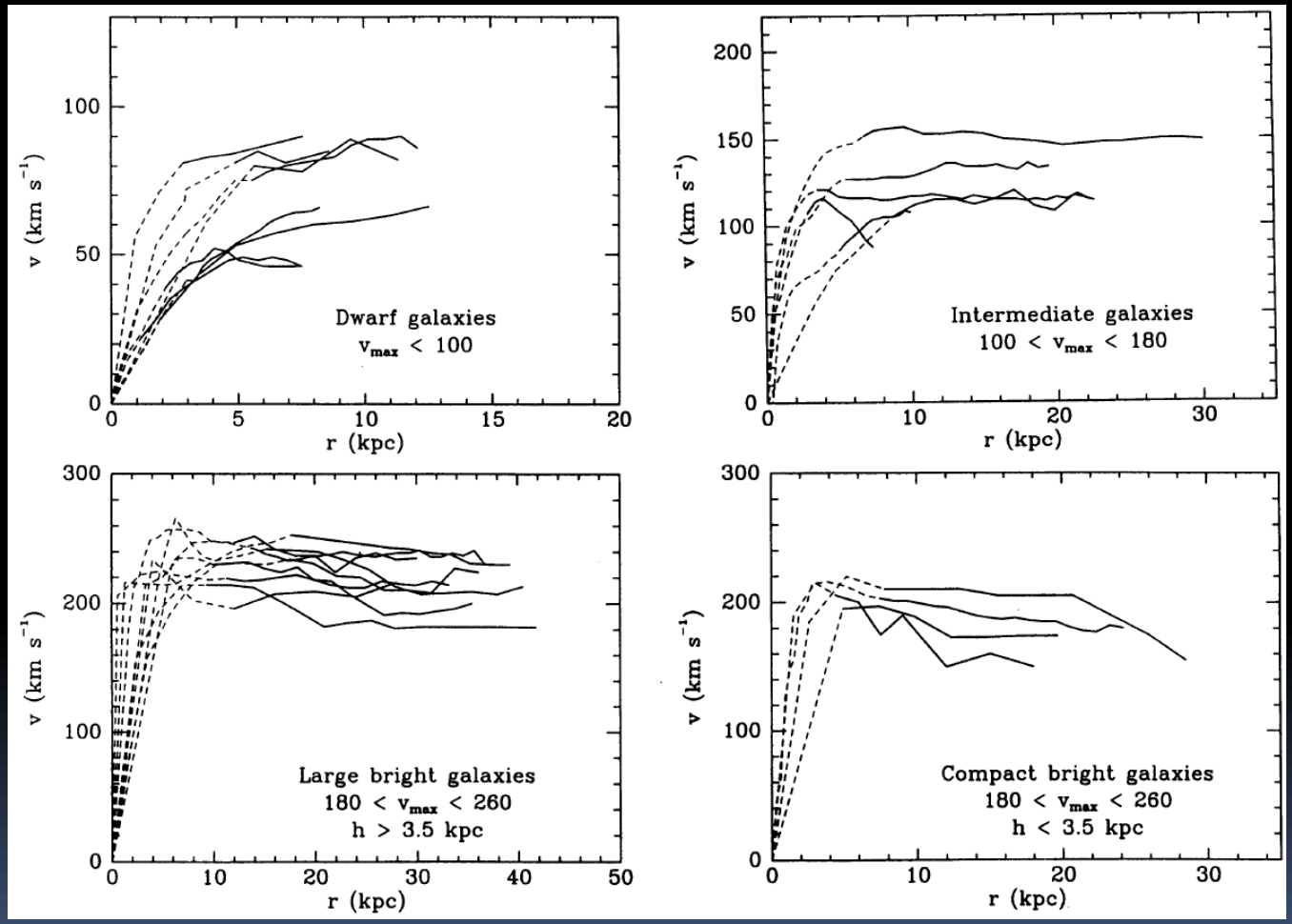
- No DM in elliptical galaxies
- No DM in disk of Milky Way
- The cusp-core problem*
- The disk-halo conspiracy*

I. The Disk-Halo Conspiracy

- Rotation curves of spiral galaxies are dominated by visible matter inside (solid-body rotation), DM outside (flat rotation curve)
- Generally, no unusual rotation curve features in the 'transition' zone between visible and DM dominated regions
- Does this require fine-tuned balance between DM halo and visible matter (a 'conspiracy')?

I. The Disk-Halo Conspiracy

Actually, maybe the tuning is not too fine:



Note that rotation curves of dwarves continue to rise, while those of bright spirals flatten or fall. (Source: Ashman (1992))

II. The cusp-core problem

- **ΛCDM** predicts DM halos are isothermal -> have **'cuspy' central densities** (density increases sharply towards the center)
- But observations (especially of dwarf and late-type galaxies) show that the DM density is uniform over the central region (a central 'core', not a cusp)
- Possible explanations:
  - Warm DM
  - Supernova or AGN feedback -> less contraction of dark halo
  - Noncircular orbits

Summary

- Excess gravity/dark matter is seen on large scales almost everywhere in the universe
- Different structures (e.g. types of galaxies) have different amounts and distributions of DM
- Currently DM is thought to be nonbaryonic, invisible, cold (**ΛCDM);** reproduces many cosmological observations
- But many challenges remain for ΛCDM, especially within galaxies