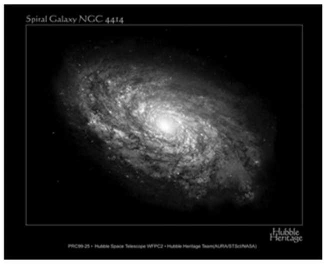
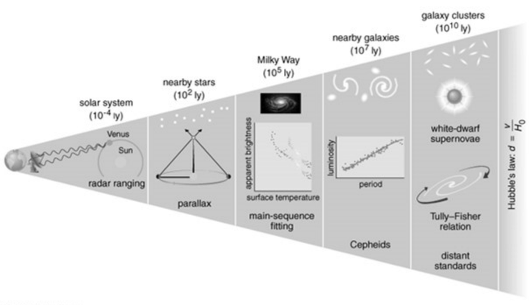
Physics of Galaxies 2020
10 credits
Lecture 2: The Milky Way and Local Group



Outline

- The Extragalactic Distance Scale
- The Milky Way Galaxy
- The Local Galaxy Group

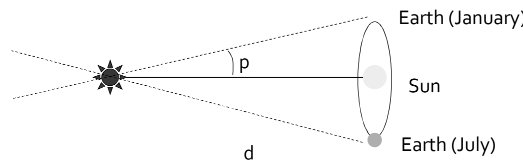
The Extragalactic Distance Ladder



Note: Outdated range estimates…

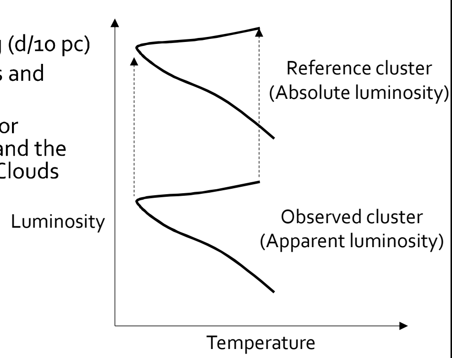
The Extragalactic Distance Ladder: Trigonometric Parallax

- d (pc) = 1 / p (arcsec)
- Currently applicable out to ~ 500 pc (closest stars)
- Satellites (e.g. Gaia) → Applicable out to 10000 pc



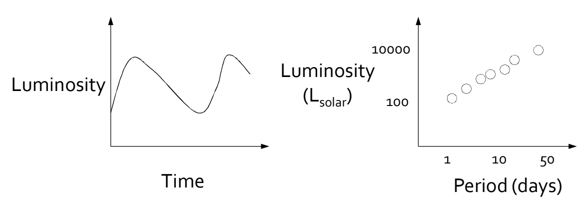
The Extragalactic Distance Ladder: Main-Sequence Fitting

- M = m - 5log (d/10 pc)
- Star clusters and Galaxies
- Applicable for Milky Way and the Magellanic Clouds



The Extragalactic Distance Ladder: Cepheid Variables

- Period → Luminosity (Absolute Magnitude) → Distance
- Applicable out to ~ 30 Mpc (slightly beyond the Virgo galaxy cluster)

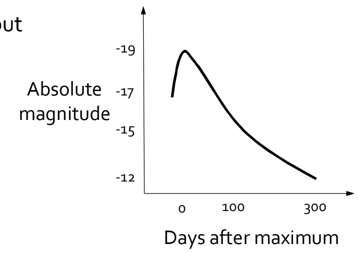


The Extragalactic Distance Ladder: Tully-Fisher / Faber-Jackson

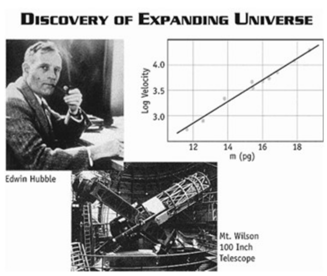
- Tully-Fisher: $L \propto v_{max}^4$ (for disk galaxies)
- Faber-Jackson: $L \propto \sigma_v^4$ (for elliptical galaxies)
- Applicable out to ~ 100 Mpc (the Coma galaxy cluster)

The Extragalactic Distance Ladder: SN Type Ia

- Applicable at least out to $z \approx 2$ (≈ 3000 Mpc)
- Formed in binary system in which matter from a red giant falls onto a white dwarf

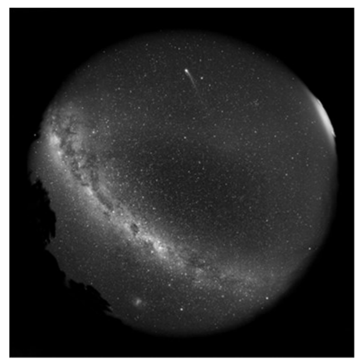


The Extragalactic Distance Ladder: Hubble's Law



- $v = H_0 d$
- Note! Not a real velocity!
- Peculiar motions irrelevant at high distances
- $z \ll 1 \rightarrow v/c \approx z$
- Higher-order terms required at high redshifts

The Milky Way Galaxy



The Milky Way Galaxy

- Disk (Thin & Thick)
- Bulge
- Stellar Halo
- Dark Halo
- Nucleus (Supermassive Black Hole)

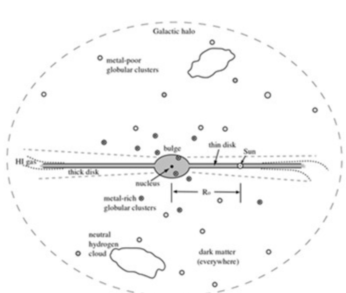
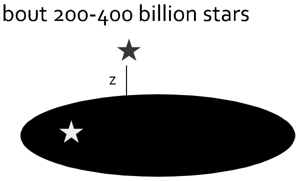


Fig 1.8 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The Milky Way Galaxy

- Spiral galaxy of type Sb/Sbc or SABbc
- Contains about 200-400 billion stars



Galactic coordinates

$$n(R, z, S) = n(0,0,S)\exp[-R/h_R(s)]\exp[-|z|/h_z(s)]$$

h_R: Scale length, h_z: Scale height
S: Stellar type

The Milky Way Galaxy

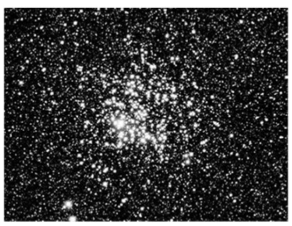
- The concept of populations:
  - Three types with increasing age: population I, II & III. Pop III stars are the first to form in the universe.
  - No strict dividing line between the types
  - Less used today, except pop III which is a hot topic in the high-redshift Universe
- Correlation between age and metallicity (amount of heavy elements) $\rightarrow$ can obtain information both about when and where the stars formed

The Milky Way Stellar Disk I

- Radius of the disk: > 15 kpc
- Scalelength h_r of the disk: 2—4 kpc
- Disk luminosity: 15—20 $\times 10^9$ L_{solar}
- Stellar Disk mass: 6 $\times 10^{10}$ M_{solar}
- Thin disk:
  - Scaleheight h_z : 300—400 pc
  - Contains 95% of all disk stars & all the young ones
  - High metallicity
- Thick disk:
  - Scaleheight: 1000—1500 pc
  - Lower metallicity

The Milky Way Stellar Disk II

- Stars form in clusters and associations
- Open clusters:
  - Few hundred stars at most
  - Luminosity 100-30000 L_{solar}
  - Core radius ~ few pc
  - Young (Only ~5% more than 1 Gyr old)
  - More bound than associations, but most dissolve over a few hundred Myr



Messier 11 – the Wild Duck Cluster: An open cluster in the Milky Way

The Milky Way Stellar Disk III

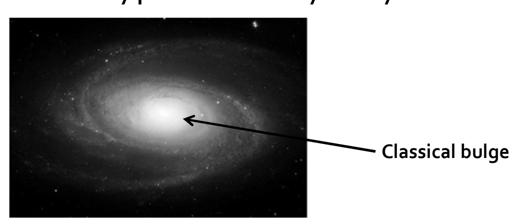
- Associations:
  - Not gravitationally bound
  - Forms temporary systems

An OB association in the Large Magellanic Cloud

The Milky Way Bulge

- Flattened (a/b $\approx$ 0.6), radius ~ 1 kpc
- Possibly contains bar (2—3 kpc long)
- Rotates in same direction as disk stars, but slower ($\approx$ 100 km/s)
- Contributes 20% of the MW luminosity
- Stars several Gyr old, but younger than in halo
- Average stellar metallicity $\approx 0.5\ Z_{solar}$

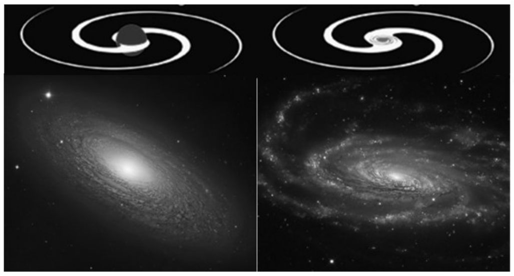
Bulge and pseudobulge – unclear which type the Milky Way has



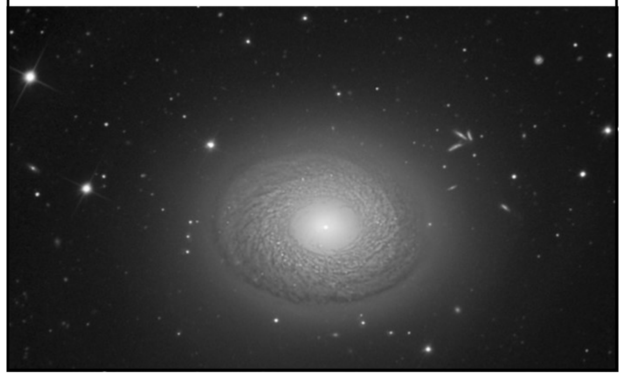
Classical bulge: Resembling a small elliptical galaxy, formed through mergers

Pseudobulge: Disk-like properties, formed internally (so-called "secular evolution"). No mergers required.

Classical bulge   Pseudobulge

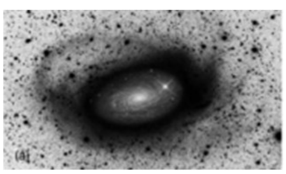


Intermission: bulge or pseudobulge?



The Milky Way Stellar Halo I

- Somewhat flattened, but rounder than bulge
- Radius ≈ 50 kpc
- Stellar density $\propto r^{-3.5}$
- Total mass in halo stars: ~ 10^9 Solar masses
- 1/1000 of all local stars belong to halo
- Eccentric orbits, sometimes retrograde

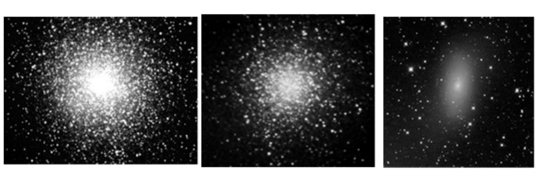


Highly processed image, showing the stellar halo (black) around the galaxy M63

The Milky Way Stellar Halo II

- Globular clusters
  - Up to 1 million stars
  - Total mass ~ 10^5 Msolar
  - No dark matter (at least not anymore)
  - Core radius < 1 pc
  - Tidal / truncation radius 20-30 pc
  - About 150 objects known, ages 10—14 Gyr (oldest objects in the Galaxy)
  - Typically very metal-poor

Intermission: Which of these is *not* a globular cluster?



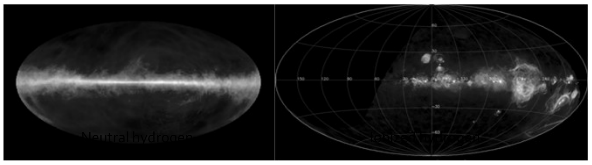
The Milky Way Dark Halo

- Radius > 100 kpc
- Contributes ~ 90% of the mass inside 100 kpc
- Content unknown
- Standard assumption: Weakly Interacting Massive Particles (WIMPs)

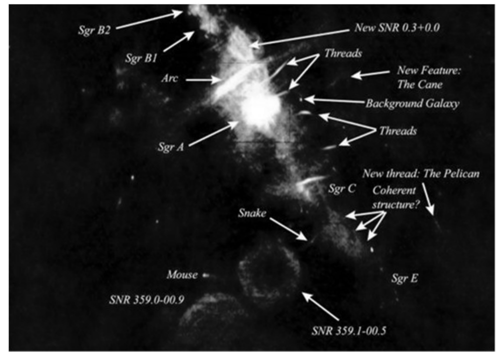
Dark matter halo from the Aquarius simulation

The Milky Way Gaseous Disk

- 4—8 × 10^9 solar masses HI
- 2—4 × 10^9 solar masses H_2 (but uncertain)
- Dust ~ 1 % of HI mass



The Milky Way Centre



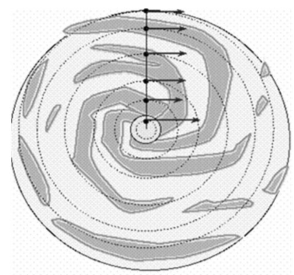
1 m Radio observations

The Milky Way Centre

- **Infrared light shows a dense star cluster which peaks at the center, near Sagittarius A*.**
- **The high velocities of the stars require a mass of ~2 x 10^6 M_{solar} within 1 pc**
- **Stars are only 1000 AU apart**
- **Collisions every ≈ 10^6 years!**
- **The centre of the star cluster likely hosts a Supermassive Black Hole (although somewhat lightweight)**

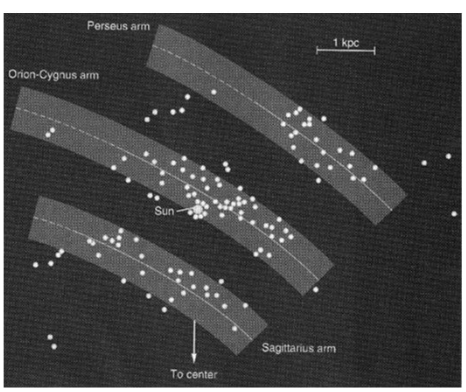
Galactic Rotation

- Differential rotation
- Neutral hydrogen: 21 cm line
- Distance Sun-centre: 8 kpc
- Sun's Velocity around the centre 220 km/s
- One revolution in 250 Myr

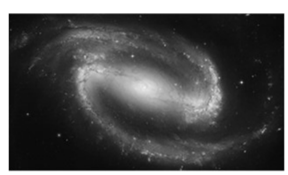


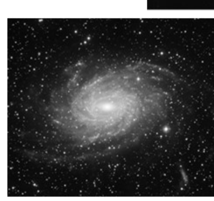
The mass inside an orbit can be found using the size of the orbit and the orbital speed. The arrows show the speeds for certain points on the **rotation curve** for this galaxy.

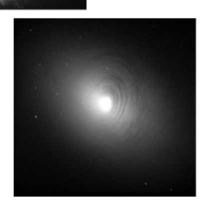
Galactic Rotation



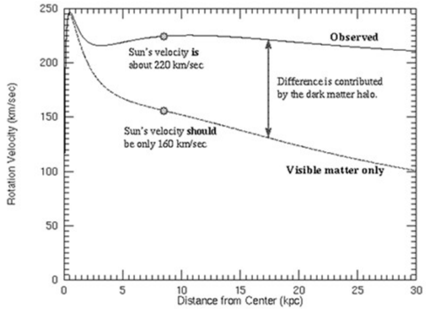
Intermission: Which of these is most similar to the Milky Way?







Galactic Rotation

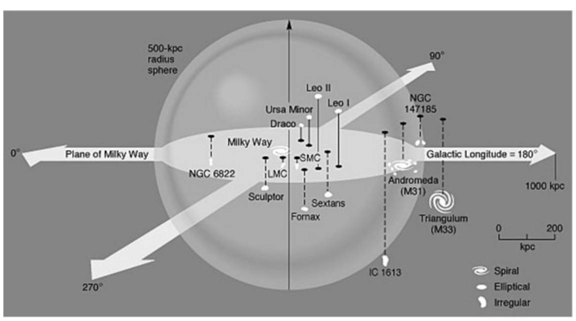


The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo**.

The Local Group

- The Local Galaxy Group
  - Local Group "Geography" & Inventory
  - The Large and Small Magellanic Clouds
  - The Magellanic Stream
  - Satellites of the Milky Way
  - The Andromeda Galaxy & M33

Local Group "Geography"



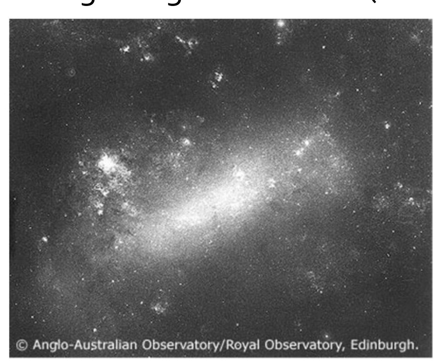
The Local Group Inventory

- Radius ~1.2 Mpc
- Held together by gravity (decoupled from the "Hubble flow")
- Contains at least 80 galaxies
- Three spirals: Milky Way, M31, and M33
- Two more massive galaxies:
  - Large Magellanic Cloud (Irregular)
  - Small (dwarf) elliptical galaxy M32
- The rest are dwarf galaxies (dI, dE, dSph) with $M_V > -18$

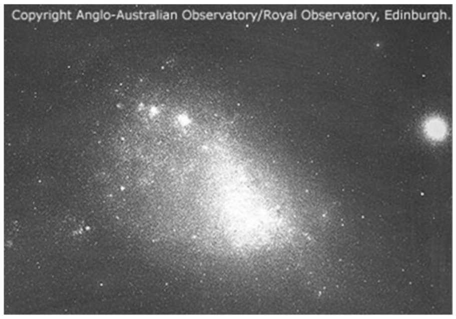
The Local Group Inventory

- The Local Group does not contain:
  - Blue compact dwarf galaxies
  - Dwarf spirals
  - Massive ellipticals
  - Active galaxies

The Large Magellanic Cloud (LMC)



The Small Magellanic Cloud (SMC)

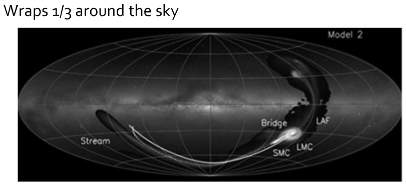


The Magellanic Clouds

	LMC	SMC
Diameter	24 deg.	7 deg.
Distance	50 kpc	63 kpc
Total mass	6×10^9 s.m.	2×10^9 s.m.
Luminosity	~10% of MW	~1% of MW
HI mass	7×10^8 s.m.	6.5×10^8 s.m.
Z	0.70 solar	0.25 solar
M(HI)/M(total)	0.09	0.32

The Magellanic Stream & Bridge

- Magellanic Bridge:
  - HI bridge between LMC and SMC
  - Size ≈ 20 kpc
  - Mass: 2×10^8 solar masses HI
  - Contains stars formed 10—25 Myr ago
  - Could have formed 200 Myr ago when LMC and SMC where the closest
- Magellanic Stream:
  - Gas trailing behind LMC and SMC
  - Wraps 1/3 around the sky



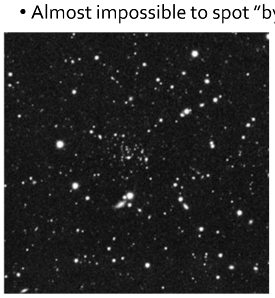
The 11 "Classical" Satellites of the Milky Way

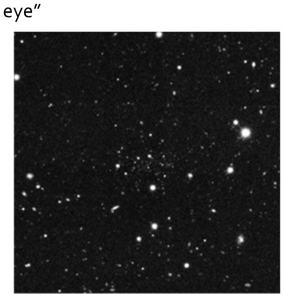
- LMC
- SMC
- Fornax
- Sagittarius
- Leo I (DDO 74)
- Sculptor
- Leo II (DDO 93)
- Sextans
- Carina
- Ursa Minor
- Draco (DDO 216)

But dark matter theory suggests a factor of ~ 10 more → "The missing satellite problem" Lots of so-called ultrafaint dwarfs detected in the past decade – still unclear if this is the solution

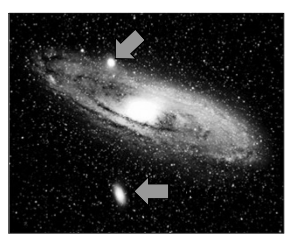
Ultrafaint dwarf galaxies

- Some of the most dark matter-dominated systems known
- More than 40 ultrafaint Milky Way satellite galaxies known
- Almost impossible to spot "by eye"





The Andromeda Galaxy & M33



M31 (Andromeda)

M33 (Triangulum)

Andromeda, Milky Way, Triangulum
- The Big Spirals of the Local Group-

- Luminosity: 1.5 × MW, 1 × MW, 0.35 × MW
- Andromeda & The Milky Way have warped disks, probably caused by interaction with M32 and Magellanic Clouds
- Milky Way & Andromeda may collide in ~ 5 Gyrs