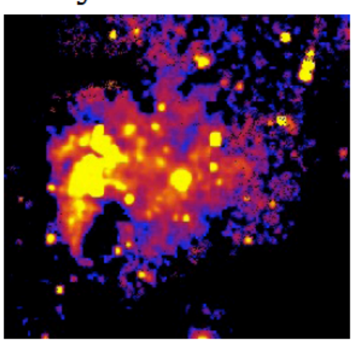
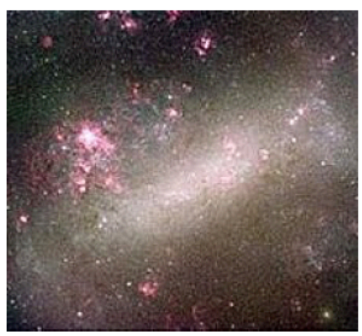
The LMC

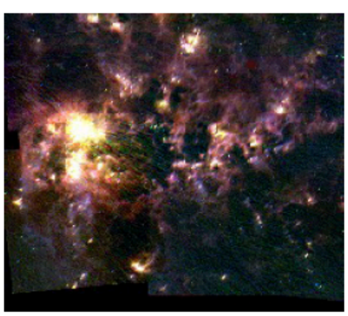
- Distance 50kpc
- Dwarf Irregular
  - Type Sm
- Tarantula Nebula
  - active star forming region
- Barred galaxy
- $L \approx 1.7 \text{x} 10^9 L_\odot$

Xray: ROSAT

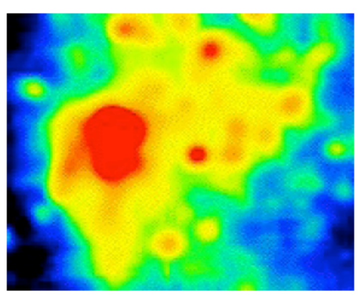


AAO optical 3 color





IRAS (Jason Surace)

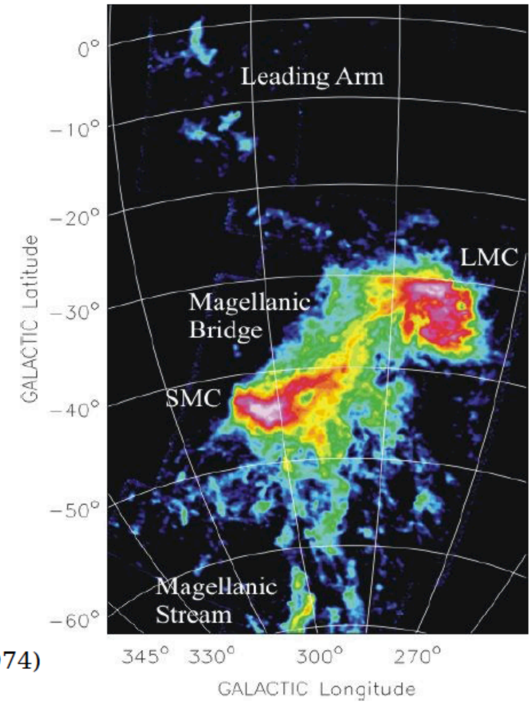


Radio (RAIUB/MPIFR Bonn

Each image is about 4°.5 on a side (9x moon's diameter)

- Clues to the MC's dynamics
  - Common HI envelope
  - Stream of gas “following” the MC's

Magellanic Bridge (Hindman 1961)
Magellanic Stream (Mathewson et al. 1974)
Leading Arm (Putman et al. 1998)

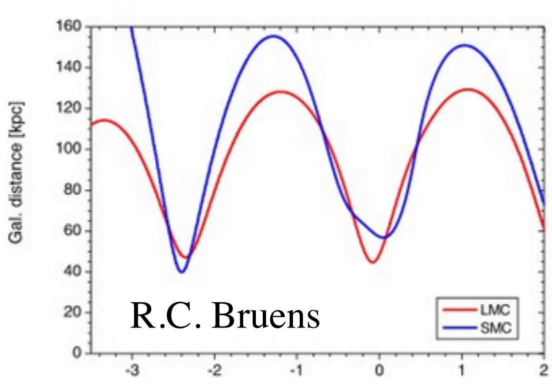


(RAIUB/MPIFR Bonn) Brüns et al 2004 A&A

Magellanic Clouds

- Satellites of the MW: potentially dynamics of SMC and LMC and the Magellanic stream can allow detailed measurement of mass of the MW.
- LMC D~50kpc $M_{gas} \sim 0.6 \times 10^9 M_\odot$ (~10% of Milky Way)Supernova rate ~0.2 of Milky Way

  Position of LMC and SMC over time- in full up dynamical model; no merger with MW in 2 Gyrs



Magellanic stream
-tidally removed gas??

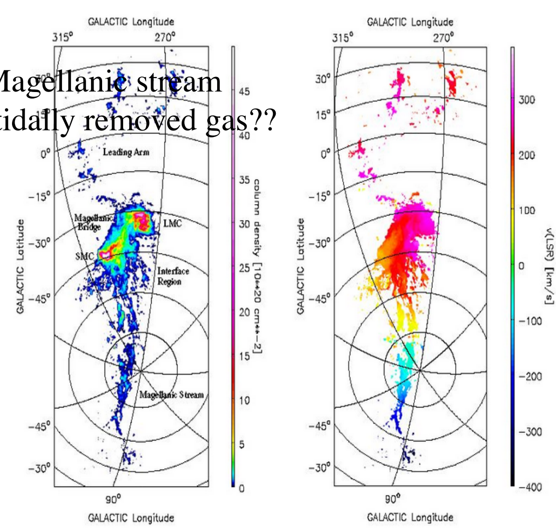
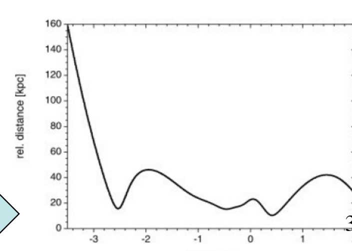


Figure 2: Single-dish observations of HI gas (Brüns et al. 2004).
Left: HI column density map of the entire Magellanic System. ***Right:*** Mean velocity v(LSR), map of the entire Magellanic System.



Analytic Estimate How Fast Will Local Group Merge?

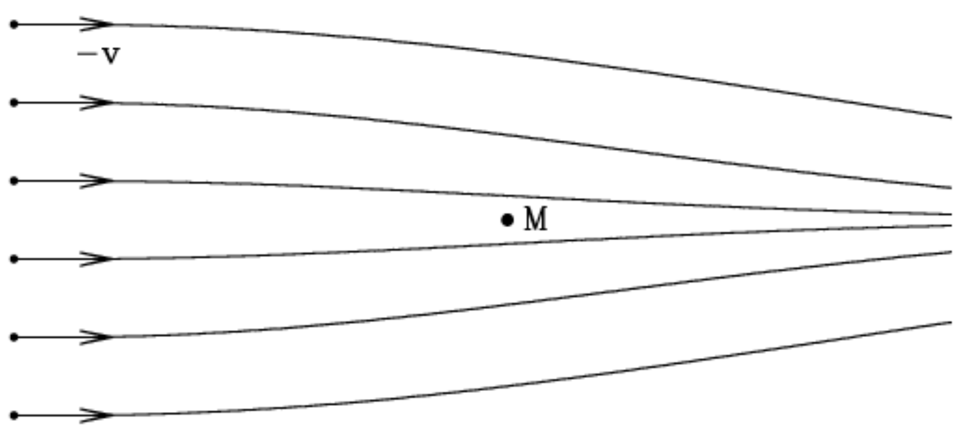
- Dynamical friction (S+G 7.1.1.MBW sec 12.3, sec 8.1 MBW)-occurs when an object has a relative velocity wrt to a stationary set of masses. The moving stars are deflected slightly, producing a higher density 'downstream'- producing a net drag on the moving particles
- Net force $=Mdv/dt \sim C\, G^2M^2\rho/V^2$ for particles of equal mass -so time to 'lose' significant energy-timescale for dynamical friction-slower galaxy moves larger its deacceleration

Analytic Estimate How Fast Will Local Group Merge?

- $t_{friction} \sim V/(dv/dt) \sim V^3/4\pi G^2 M m \rho \ln\Lambda$

$M \sim 10^{10}\ M_\odot$; $m=1M_\odot$; $\rho \sim 3\times10^{-4}\ M/pc^3$ Galactic density at distance of LMC (problem 7.6)

putting in typical values **$t_{friction} \sim 3$Gyrs**



- Accurate estimates of the effects of dynamical friction and the timescale for an orbiting satellite to lose its energy and angular momentum to merge with a host are essential for many astrophysical problems.
- the growth of galaxies depends on their dynamical evolution within larger dark matter halos.

- dynamical friction provides a critical link between dark matter halo mergers and the galaxy mergers that determine, e.g., stellar masses, supermassive black hole masses, galaxy colors, and galaxy morphologies. (Boylan-Kolchin et al 2007)

Dynamical Friction Derivation pg 285 S&G

- As M moves past it gets a change in velocity in the perdicular direction

$\delta V = 2Gm/bV$ (in the limit that $b >> 2G(M+m)/V^2$

momentum is conserved so change in kinetic energy in the perpendicular direction is

$\delta(KE) = (M/2)(2Gm/bV)^2 + (m/2)(2GM/bV)^2 =$

$2G^2 mM(M+m)/b^2V^2$ (eq 7.5 S&G)notice that the smaller object acquires the most energy which can only come from the forward motion of galaxy M

$\delta V \sim [2G^2 m(M+m)/b^2V^3]$

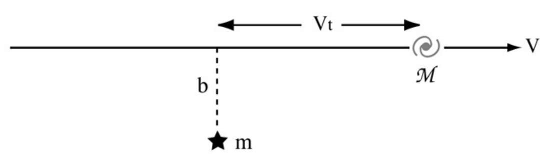


Fig 7.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

and if the intruding galaxy flies thru the more massive galaxy which has n stars per unit volume of mass m

$dV/dt \sim 4\pi G^2[(M+m)/V^2] nm \ln\Lambda$

slower the galaxy moves the faster it slows down.

Dynamical Friction-cont

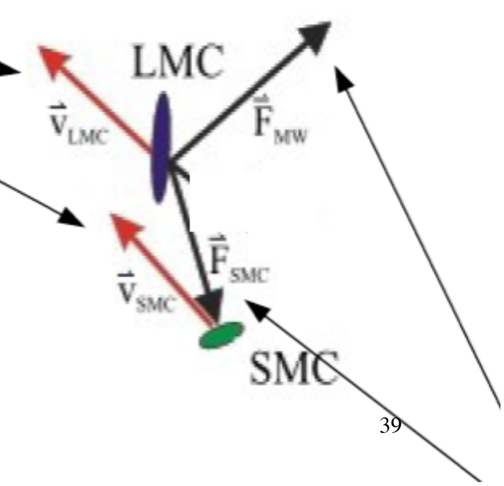
- basically this process allows the exchange of energy between a smaller 'incoming' mass and the larger host galaxy
- The smaller object acquires more energy
- -removes energy from the directed motion small particles (e.g. stars) and transfers it to random motion (heat) - incoming galaxy 'bloats' and it loses stars.
- It is not identical to hydrodynamic drag- in the low velocity limit the force is ~velocity, while in the high limit is goes as v^{-2}
- It is also independent of the mass of the particles but depends on their total density- e.g. massive satellite slowed more quickly than a small one

Need distance to convert angular coord
to physical units

Forces on the Magellanic Clouds

Dynamical friction vector
depend on shape and size

Space Velocity



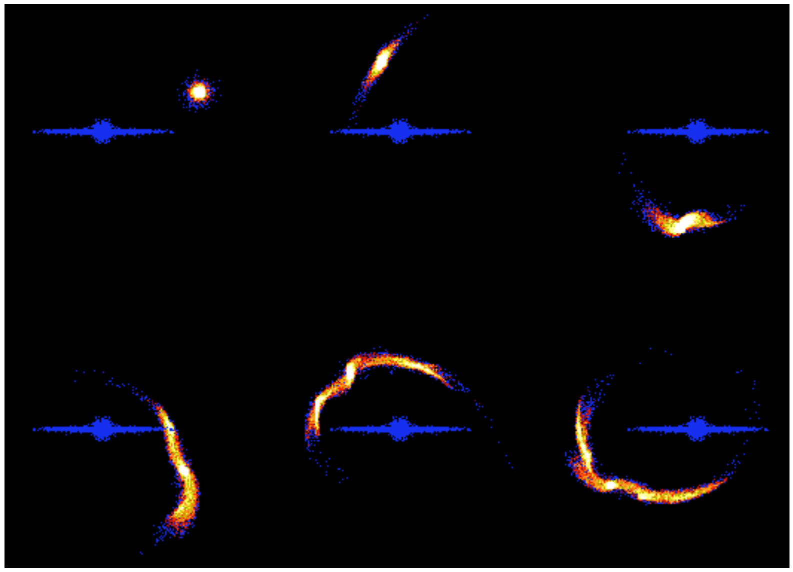
To get orbit to MCs need all 6 quantitates (x,y,z) and v_x,v_y,v_z
measure position and radial velocity easy
tangent velocity is hard
recent results differ a lo
v_x,v_y,v_z[km/s] 41±44, -200±31, 169±37

LMC Merger??

- Depends sensitively on LMC orbit and model of MW potential-

At the Clouds' present-day position, a large fraction of their observed line of sight and proper motion speeds are due to the Sun's motion around the Galactic center!

- The origin of the Magellanic Clouds is still an enigma as they are the only blue, gas-rich irregulars in the local group.



K. Johnston

Please read

Beasts of the Southern Wild : Discovery of nine Ultra Faint satellites in the vicinity of the Magellanic Clouds.

Koposov, Sergey E.; Belokurov, Vasily; Torrealba, Gabriel; Evans, N. Wyn 2015ApJ...805..130K

(skip section 2, sec 4.2)

OR

2010ApJ...721L..97B

Besla, G.; Kallivayalil, N.; Hernquist, L.; van der Marel, R. P.; Cox, T. J.; Kereš, D.

Simulations of the Magellanic Stream in a First Infall Scenario

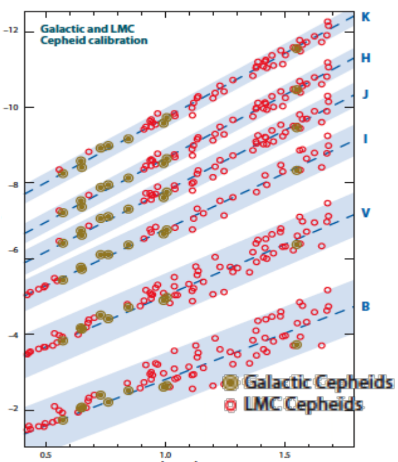
Distance to LMC

- LMC is unique in that many Cepheids can be detected in a galaxy with rather different metallicity with no effect of crowding

distance modulus, μ,   (log d=1+μ/5) pc

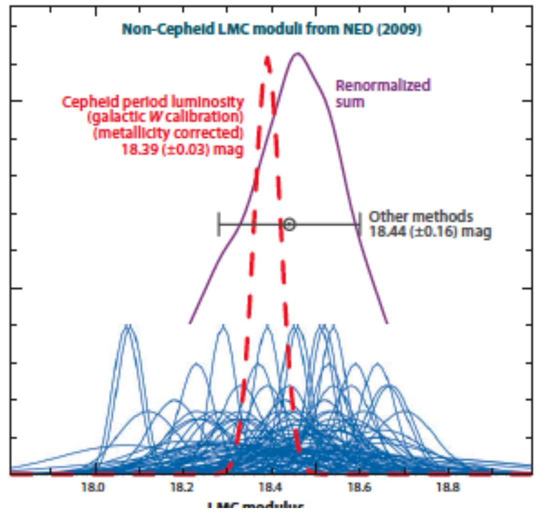
LMC μ= 18.48 ± 0.04 mag; (49.65 Kpc)

absolute mag in each band



log Period (days)

Relative probability



LMC Distance Modulus

This sets the distance scale for comparison with Cepheids in nearby galaxies (Freedman+Madore 2010)

High energy γ-ray emission from the LMC

total signal | point source subtracted

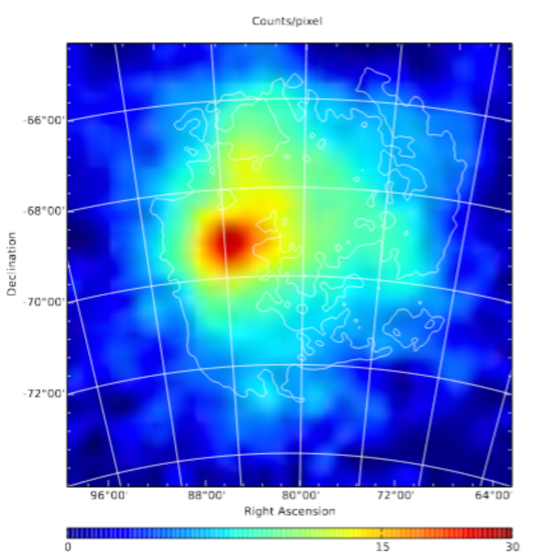
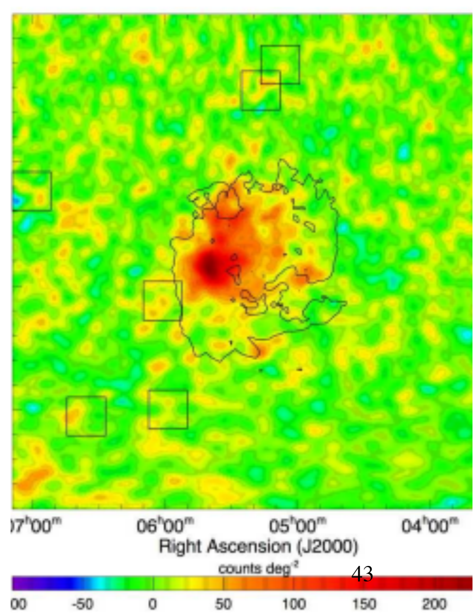
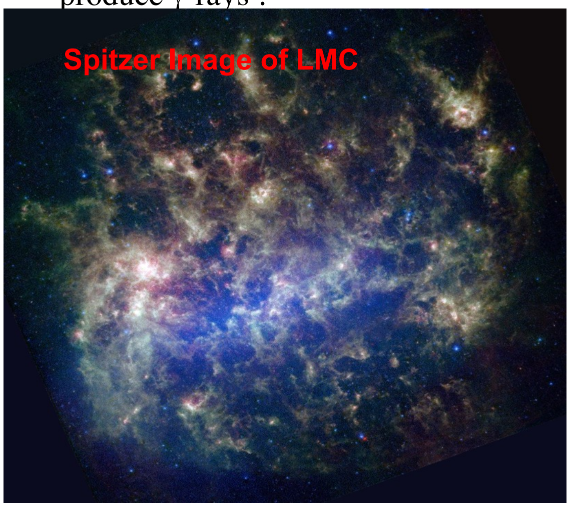


Fig. 1. Total counts map in the 0.2–100 GeV band and residual

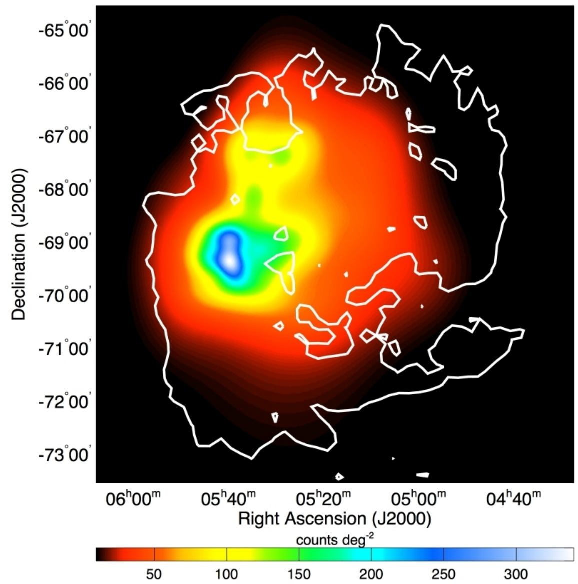


Cosmic Rays and γ-rays

- LMC and SMC are only galaxies, other than MW, for which γ-ray images exist.
- Look for correlations with sites of CR acceleration and/or for dense gas which the CRs interact with to produce γ-rays .



γ-ray Map of LMC

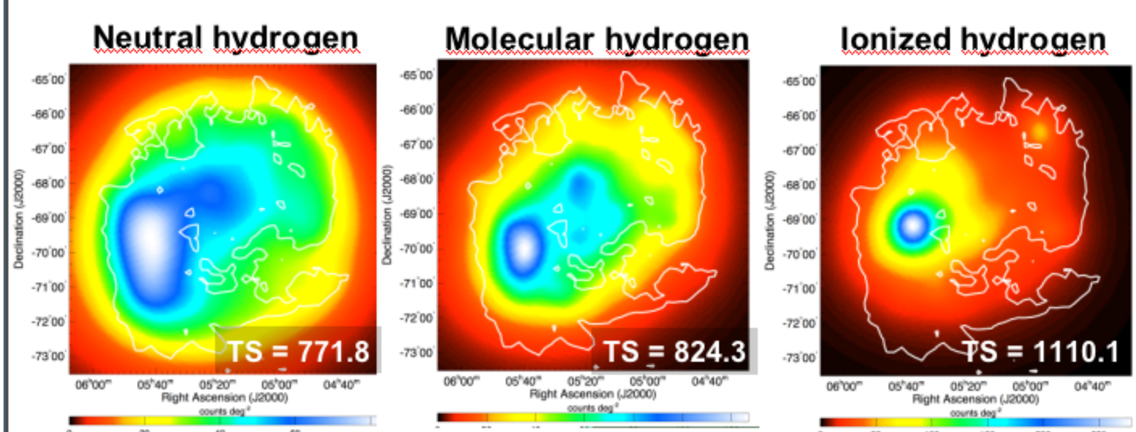


γ-ray intensity scale

LMC Cosmic Rays and γ-rays

γ-ray emission correlates with massive star forming regions and not with the gas distribution (simulated images if the γ-ray emission was distributed like the source)

- Compactness of emission regions suggests little CR diffusion
- 30 Doradus star forming region is a bright source of γ−rays and very likely a cosmic-ray accelerator



- **Neutral & molecular hydrogen templates poorly fit the data**
- **Ionized hydrogen template provides best fit**

Dermer 2011

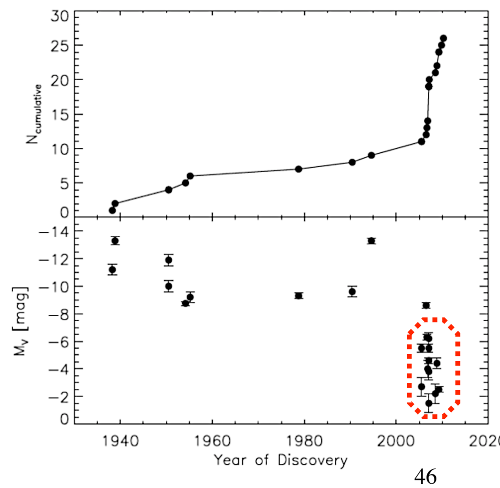
γ-ray emission poorly correlated with dense gas (!)

Dwarf Galaxies

- As we will discuss later one of the main problems with the present cold dark matter (CDM) paradigm for galaxy formation is the *relative absence of small, low mass galaxies*
- It is only in the local group that such systems can be discovered and studied
- they are the most dark matter dominated of all objects- and the smallest and least luminous galaxies known.
- very faint and very low surface brightness, very hard to find (Walker 2012).
- Many people believe that some dwarf spheroidals are 'relics' of the early universe

TABLE 1
GALACTIC DWARF SPHEROIDAL GALAXIES WITH LARGE M/L

Name	L ($10^5 L_\odot$)	d (kpc)	r_k (pc)	M/L ($M_\odot/L_\odot$)
Carina...	2.4 ± 1.0	85 ± 5	581 ± 86	59 ± 47
Draco...	1.8 ± 0.8	72 ± 3	498 ± 47	245 ± 155
Ursa Minor...	2.0 ± 0.9	64 ± 5	628 ± 74	95 ± 43
Sextans...	4.1 ± 1.9	83 ± 9	3102 ± 1028	107 ± 72

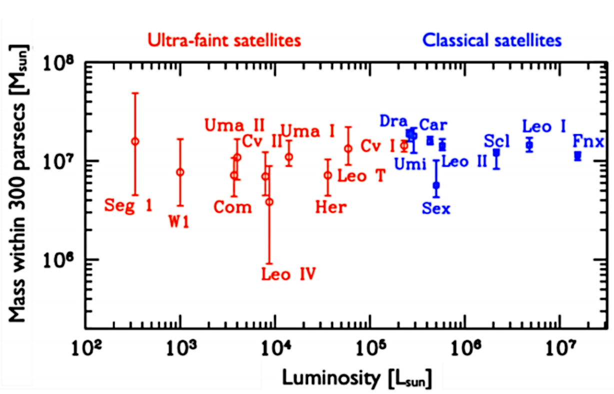


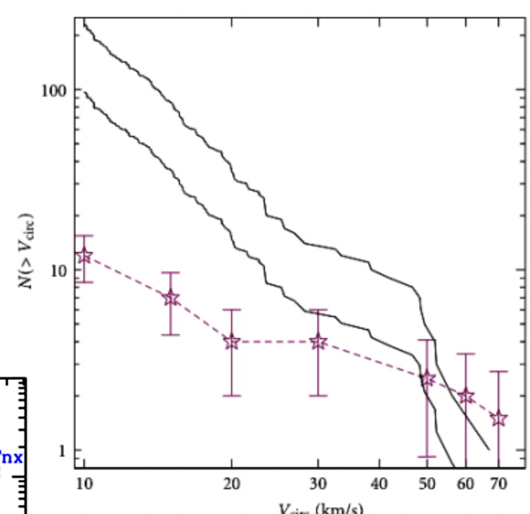
Number of Satellites around MW- Observed vs Theoretical

- Number of satellites vs their circular velocity: theory - between black lines

  red points observed objects (Klypin 2010)-order of magnitude discrepancy at low masses?

Absence of correlation between luminosity and dynamical mass

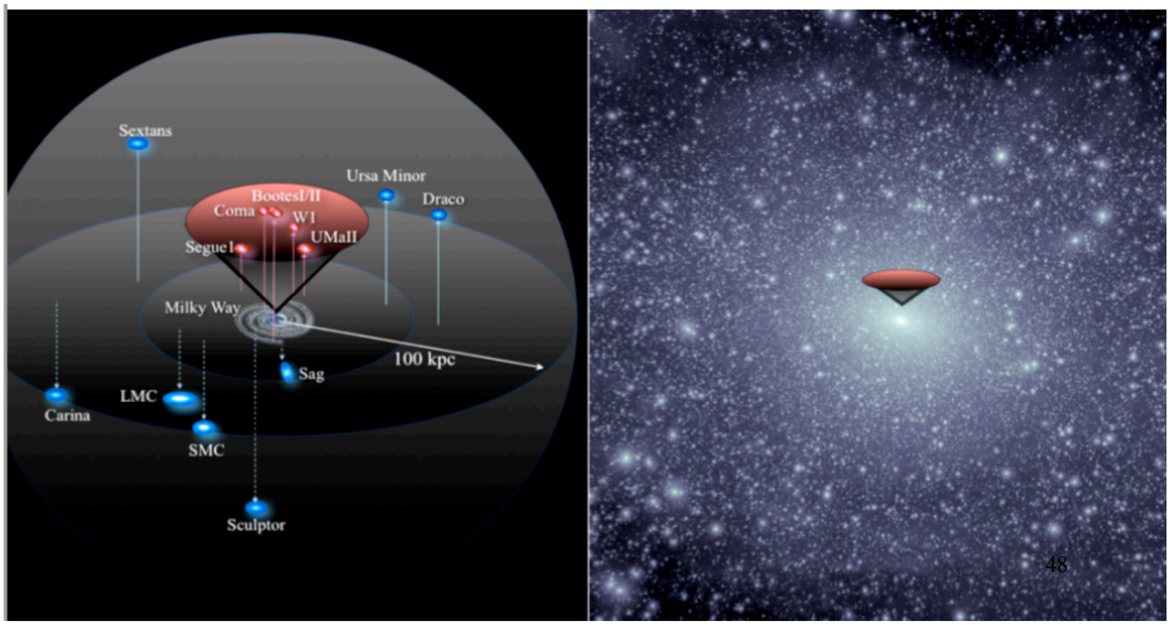




Odd property that satellites all have *same mass, but 10^5 range in luminosity*

Where are the Satellites of MW-Bullock 2010

- Know satellites of MW within 100kpc-left
- Right- CDM simulation of LG/ MW halo- cones show where sample of dwarfs is complete-SDSS data, only in the north



Dwarf galaxies as laboratories for fundamental physics: missing satellites, cusps & cores, & "too big to fail"

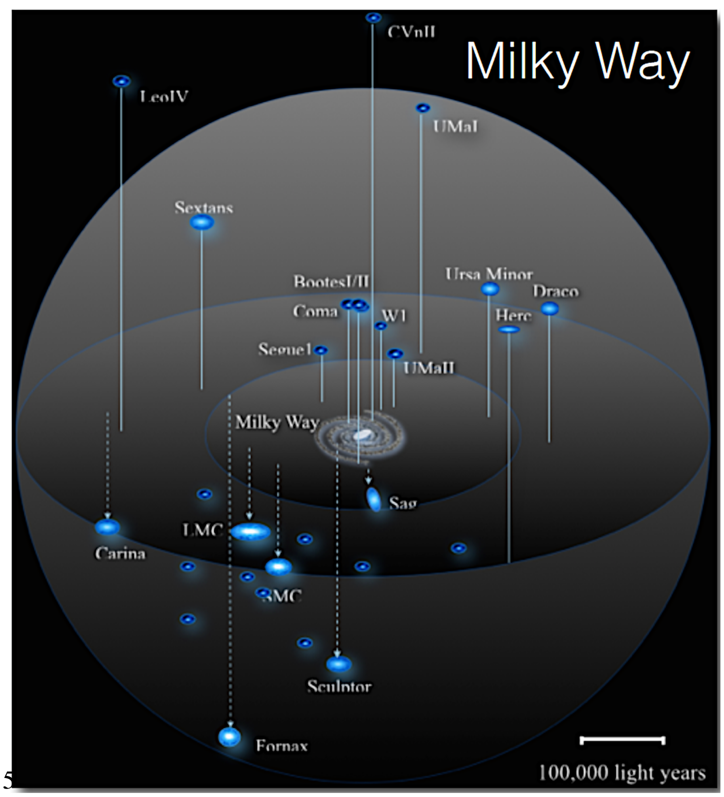
discovery of new "ultrafaint" dwarf galaxies in the Local Group (satellite count has tripled in past decade; SDSS/Segue/DES/ DECam/LSST)

-very high M/L

-pure ancient stellar pop

-fossils of reionization ?

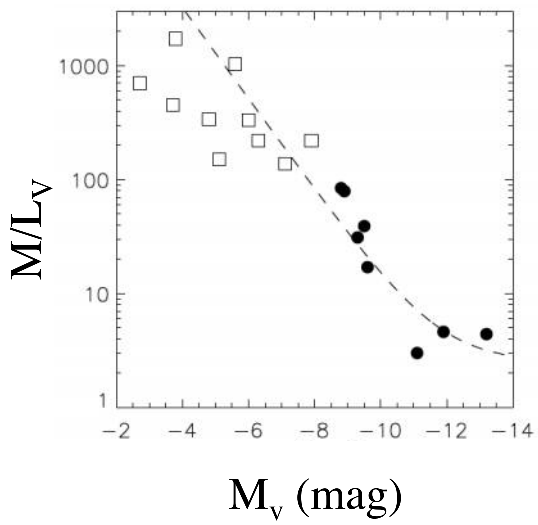
Willman et al. 2005; Zucker et al. 2006
Belokurov et al. 2007; Koposov et al. 2015
Bechtol et al. 2015; Kim et al. 2015

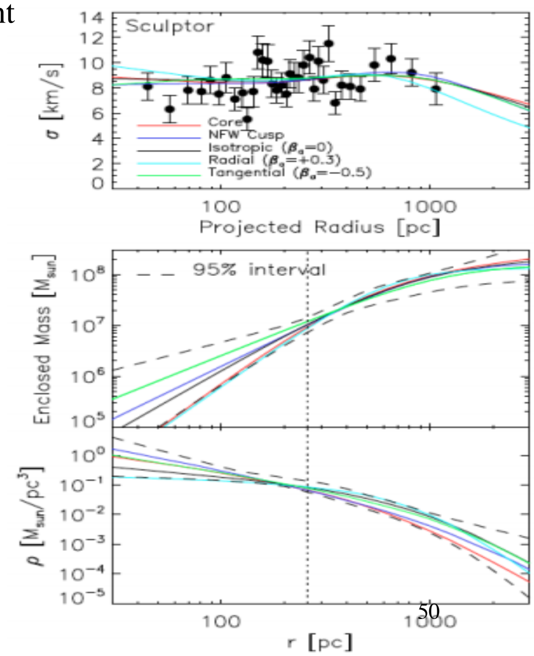


slide credit: J. Bullock

Dwarfs

- Have VERY low internal velocity dispersion~10km/sec, r_{scale}~50-1000pc
- IF mass follows light- very dark matter dominated- but precise mass is not well determined even with ~3000 stars individually measured (!)
- - using Jeans method: all solutions (different shapes of the potential or orbital distributions) are ok

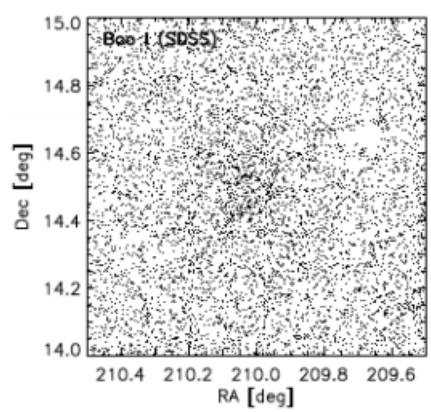




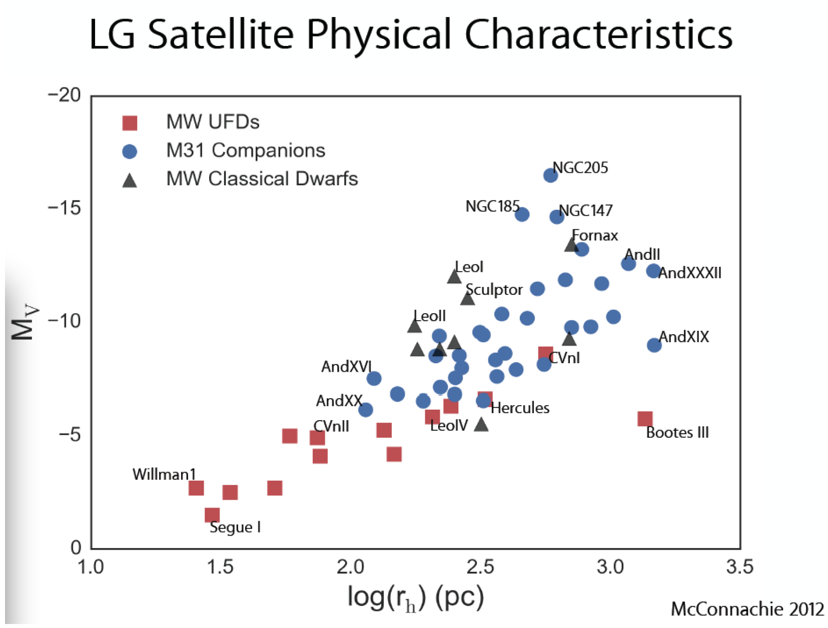
Dwarfs

- They are detected as overdensities of intrinsically bright red giant stars which detectable as point sources with m_V<21 mag out to distances of ~0.5 Mpc- (modern large telescopes can reach 4 mags fainter; - since red giants have a 'unique' luminosity can use them as distance selector)
- the ‘ultrafaint’ satellites discovered with SDSS data are not apparent to the eye, even in deep images- detected by correlating spatial overdensities with overdensities in color-magnitude space
- the low surface densities of dSphs imply internal relaxation timescales of >10^3 Hubble times

Image of Boo I

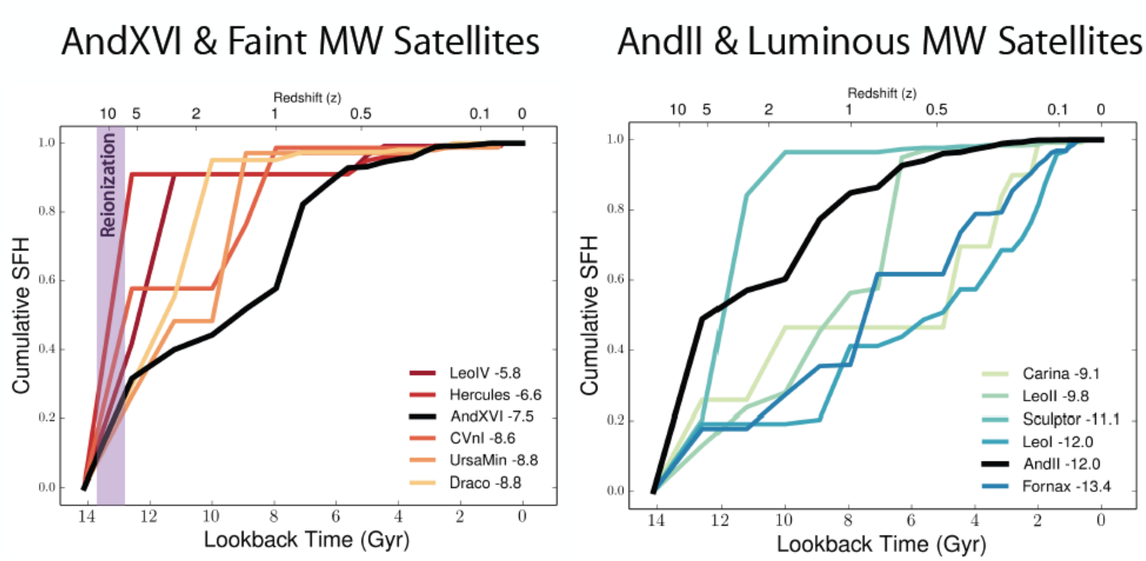


- With HST can study dwarfs around M31 also (UFD= ultra-faint dwarfs)



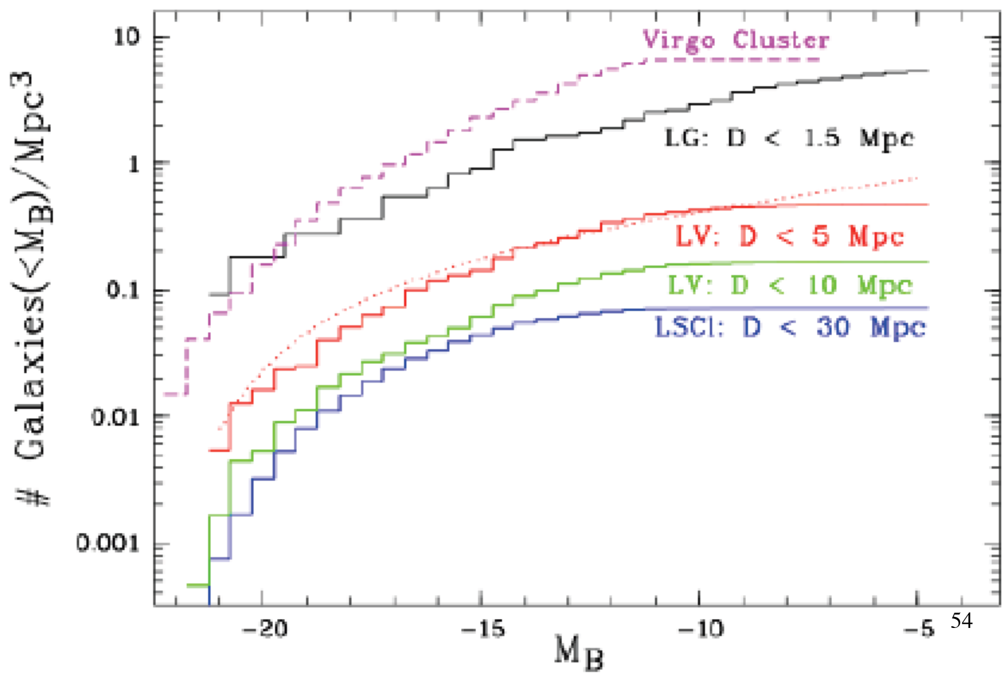
Relics of the Early Universe??

- Dan Weisz University of Washington KITP meeting 2015
- See article in web page 'Precious Fossils of the Early Universe'



Overdensity of the Local Group

Drozdovsky+2008

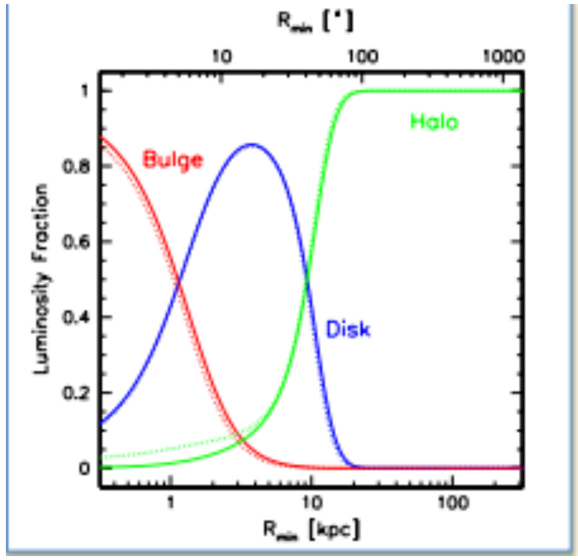


Local Group Summary

- What is important
  - local group enables detailed studies of objects which might be representative of the rest of the universe (e.g CMDs of individual stars to get SF history, spectra of stars to get metallicity, origin of cosmic rays etc)
  - wide variety of objects -2 giant spirals, lots of dwarfs
  - chemical composition of other galaxies in local group (focused on dwarfs and satellites of the MW) similar in gross terms, different in detail; indications of non-gravitational effects (winds); went thru 'closed box' approximation allowed analytic estimate of chemical abundance
  - dynamics of satellites of MW (Magellanic clouds) clues to their formation, history and amount of dark matter
  - dwarfs are the most dark matter dominated galaxies we know of- closeness allows detailed analysis.
  - dwarf galaxy 'problem' are there enough low mass dwarfs around MW??- lead to discussion later in class about galaxy formation and Cold dark matter models

M31 and the MW

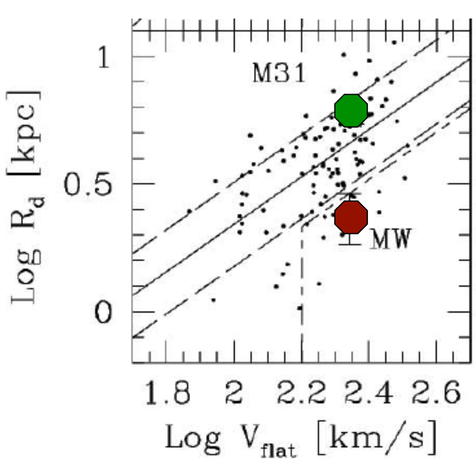
- the Milky Way and M31 have different properties
- M31 shows a lower star formation rate (SFR) than the Milky Way
- M31 appears to be a more typical spiral galaxy than the Milky Way (Hammer et al. 2007).
- M31 shows evidence for a formation and evolution history affected by merging and/or accretion events, including substructures in its halo- MW does not
- M31 scale length of 6kpc is 3x that of the MW 2.3 kpc but similar rotation curve.
- stellar mass M_{star} ~10.3 x $10^{10} M_\odot$ for M31; disk 7.2x $10^{10} M_\odot$ and bulge 3.1x 10^{10} $M_\odot$

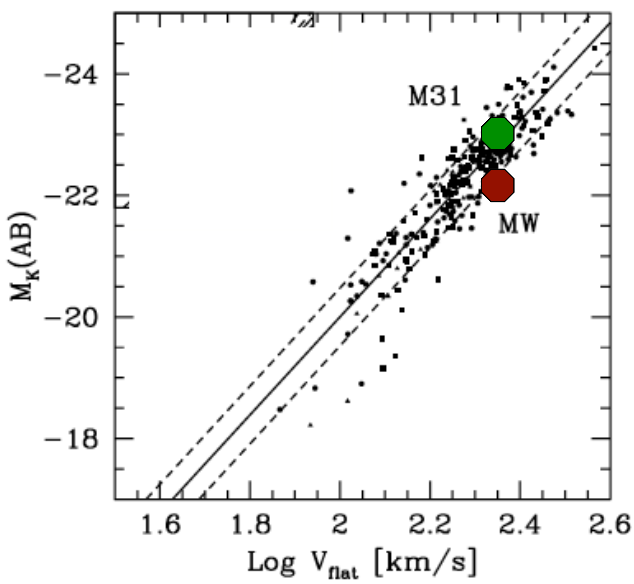


Mass decomposition of M31
Courteau 2012

Tully Fisher Relation

- The relationship of luminosity to rotation speed for spirals- also relation of scale length to rotation velocity
- M31 and MW have similar v_{rot} but factor of 2 different luminosities+scale lengths - MW is more discrepant

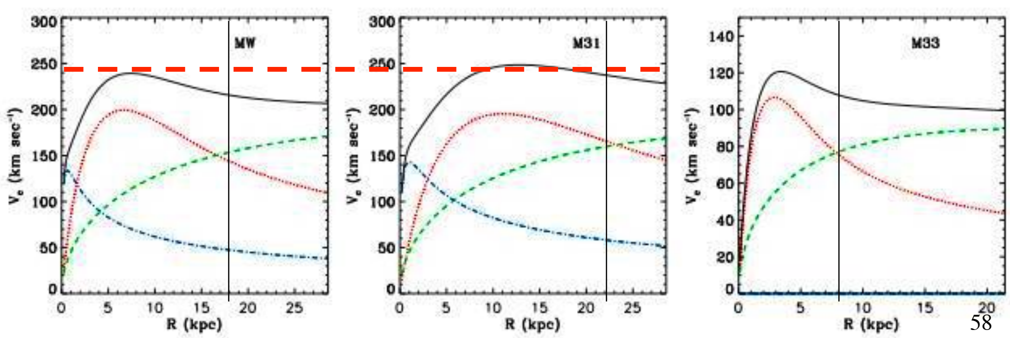




M31, compared to the Milky Way, has 2 x more stellar mass and 2.5 x more specific angular momentum
Hammer 2007

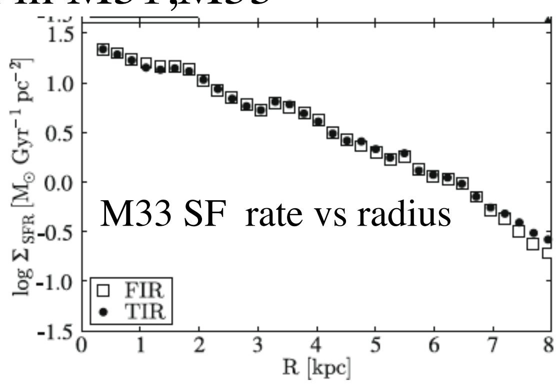
Comparison of Rotation Curve for MW, M31,M33

- Black is total curve
- blue is bulge (notice no bulge in M33), green is DM and red is disk (data from van der Maerl 2012)
- observed maximum circular velocity for each galaxy: $V_c \approx 239$ kms at
- the solar radius for the MW, $V_c \approx 250$km/s for M31 $V_c \approx 120$ kms M33
- S+G says that M31 has a higher rotation velocity, latest data on MW has changed that ! Notice where DM becomes dominant- 22 kpc for M31, 18kpc for MW, 8kpc for M33
- Virial mass of M33=$2.2 \times 10^{11} M_\odot$

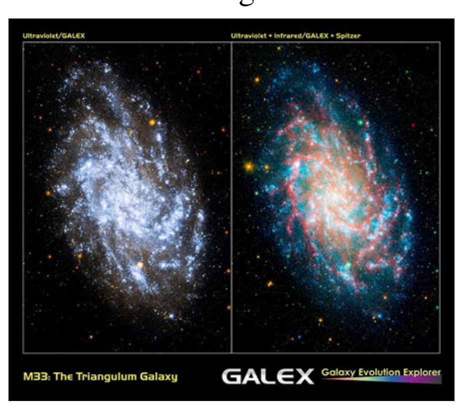


Star Formation in M31,M33

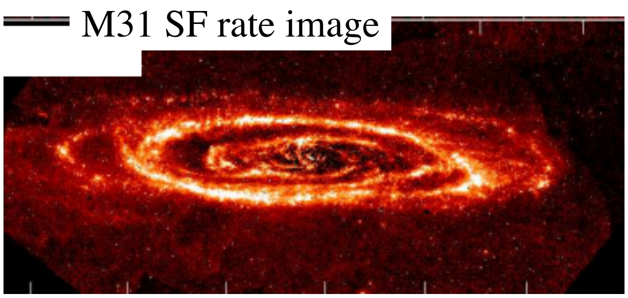
- the specific star formation rate in M31 is less than in the MW with a present rate of ~0.6M/yr.
- the SF is concentrated in a ring 10kpc out
- M33 on the other hand is vigorously forming stars 0.45M/yr all over (why??)



M33 UV and IR images



M31 SF rate image



M33

- M33 is almost unique in having very tight constraints placed on the presence of a supermassive black hole in its nucleus.
- It is probably tidally involved with M31-220kpc away

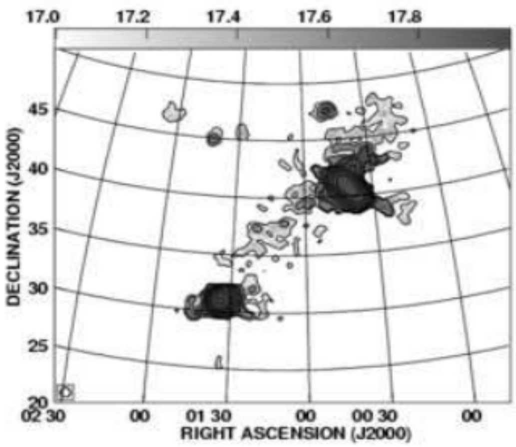
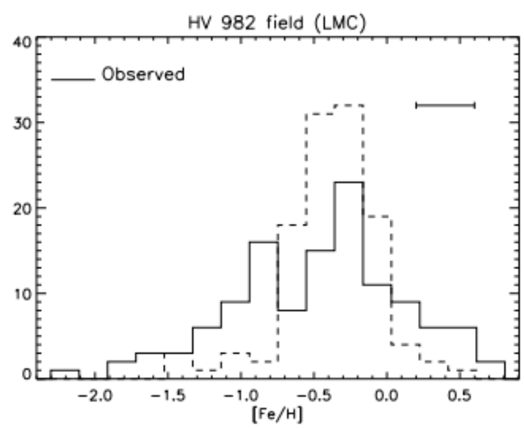


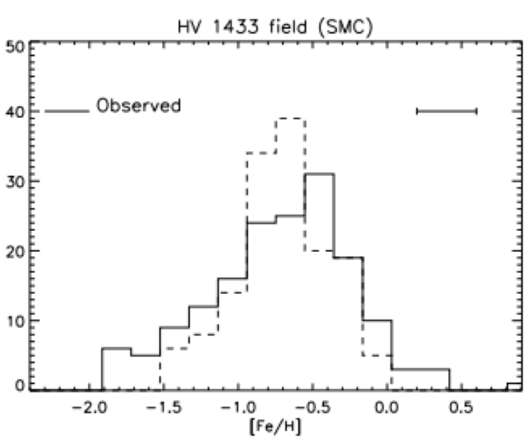
Fig. 9. Integrated H I emission from the subset of detected features apparently associated with M31 and M33. The grey-scale

$M_{disk,stellar}$~$3.8x10^9 M_\odot$
$M_{bulgek,stellar}$~$1x10^8 M_\odot$
M_{virial}~$2.2x10^{11} M_\odot$

Chemical Evolution

- The one zone no infall or outgo model while analytic (S&G eq 4.13-4.16) does not really represent what has happened
- LMC and SMC are more 'metal poor' than the MW or M31; [Fe/H]~-0.35 and -0.6 respectively - but with considerable variation from place to





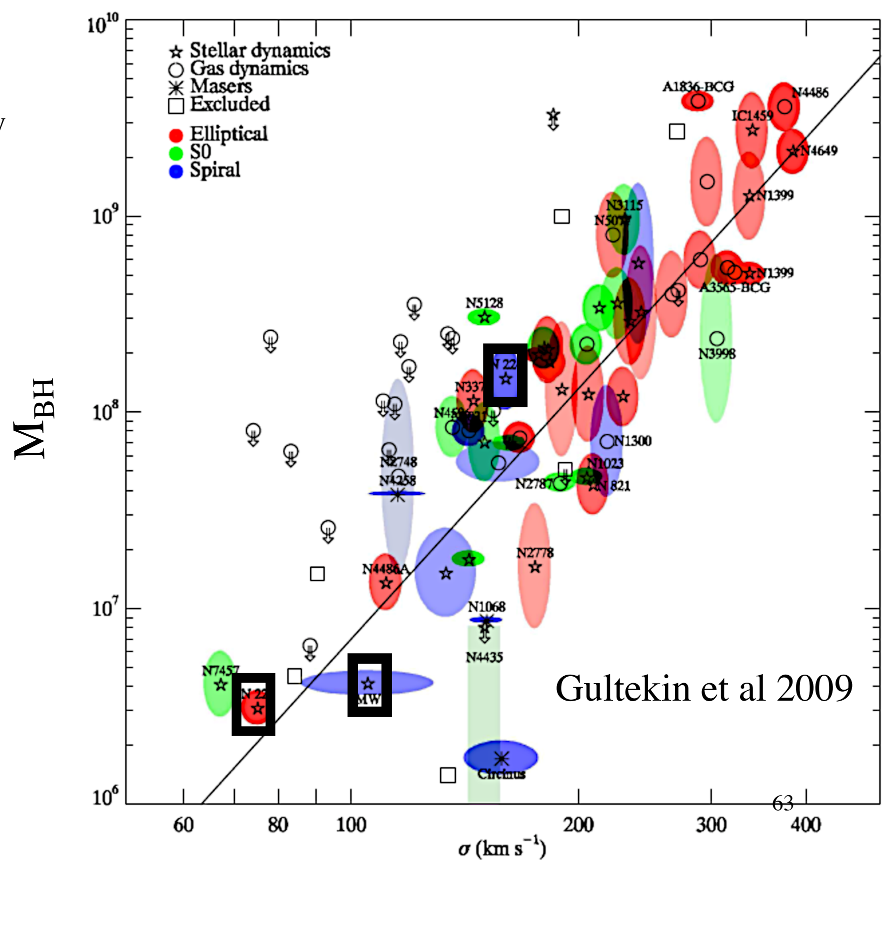
In general line of trend for less massive galaxies to be more metal poor (but large scatter)

Black Holes

- It is now believed that 'all' massive galaxies have super massive black holes in their nuclei whose mass scales with the bulge properties of the galaxies
- What about the smaller galaxies in the local group?
- Search for BHs 2 ways
  - dynamics
  - presence of an AGN (active galactic nucleus)
- None of the Local group galaxies host an AGN (today)
- Of the small galaxies only M32 shows dynamical evidence for a black hole (van der Maerl 2009) of M_{BH}~$2.5x10^6 M_\odot$ for a galaxy of luminosity -16.83 compared to -21.8 for M31 (100x less luminous) **which has a similar mass BH**- M32 is spheroidal (all bulge)

		$M_{BH}(M_\odot)$	$M_{bulge} M_\odot$
M33	Scd	< 3 x 10^3	1.5 x 10^8
NGC205	E	< 2.4x10^4	2.7 x 10^8
M32	E	~2.5x10^6	~2.5x 10^8

- Black hole mass vs bulge velocity dispersion
- Local group galaxies



Local Group timing argument-Kahn and Woltjer (1959).

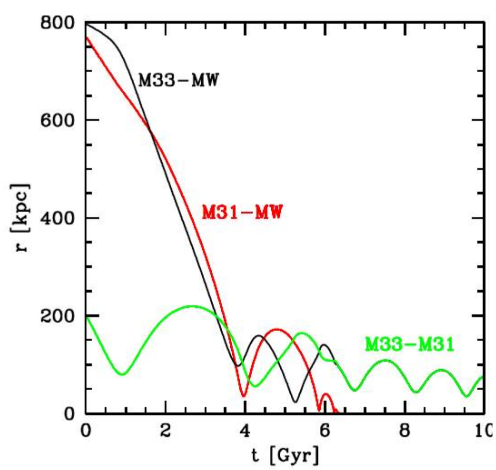
Use dynamics of M31 and the MW to estimate the total mass in the LG.

- the radial velocity of M31 with respect to the MW ~-120km//sec e.g. towards MW presumably because their mutual gravitational attraction has halted, and eventually reversed their initial velocities from the Hubble flow.
- neglect other galaxies in LC, and treat the two galaxies as an isolated system of two point masses.
- assume orbits are radial, then Newton's law gives $dr^2/dt^2=GM_{total}/r$
- Period of orbit less than age of the universe:
  - Kepler's Law $P^2=4\pi a^3/GM$; $P<3x10^{33}$sec
- Assume purely radial orbits (no ang Mom) so $GM_*/2a=(GM_*//d)-E_k$; d=distance to center of mass and E is KE/unit mass

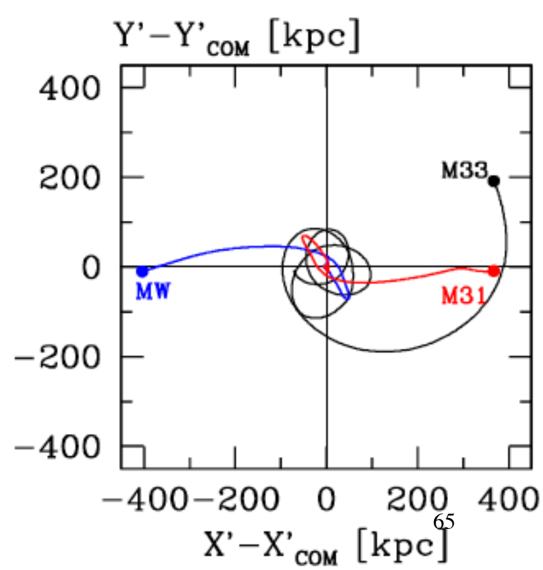
derive total $M>1.8x10^{12}M_\odot$; much larger than stellar mass of MW/ M31

The future of the local group (S+G 4.5)

- It seems clear that M31 has had a much more active merger history than the MW- so beware of close by objects
- given what we know about the mass of M31, M33 and MW they will all merge in ~ 6 Gyrs (van den Maerl 2012)



separations in the MW-M31-M33 system as function



Local Group timing argument Details

M_{total} is the sum of the 2 masses Initially, take r=0 at t=0
(see https://ned.ipac.caltech.edu/level5/March01/Battaner/node16.html)

- solution of the form $r=(R_{max}/2)*(1-\cos\theta)$ and $t[=(R^3_{max}/8M_{total}G)^{1/2}](\theta-\sin\theta)$
- θ is the 'eccentric anomaly'-angular parameter that defines the position of a body that is moving along an elliptic Kepler orbit. https://en.wikipedia.org/wiki/Eccentric_anomaly

- The distance increases from 0 (for $\theta=0$) to some maximum value R_{max} (for $\theta=\pi$), and then decreases again. The relative velocity is
- $v=dr/dt=(dr/d\theta)/(d\theta/dt) =(2GM_{total}/R_{max})^{1/2}(\sin\theta/(1-\cos\theta))$
- The last three equations can be combined to eliminate R_{max}, and M_{tota} , to give
- $vt/r=\sin\theta*(\theta-\sin\theta)/(1-\cos\theta)^{1/2}$

v can be measured from Doppler shifts, and r from Cepheid variables. For t take the age of the Universe, 13.8Gyrs.

Local Group timing argument

solve the previous equation (numerically) to find $\theta=4.32$radians, assuming M31 is on its first approach to the MW

- $M_{total}=3.66\times10^{12}\ M_\odot$and mass MW ~1/3 of total
- the estimate of is increased if the orbit is not radial, or M31 and the MW have already had one (or more) pericenter passages since the Big Bang.

- So the very large mass inferred from the LG dynamics strongly corroborates the evidence from rotation curves and Oort's constants, that most of the mass in the MW (and presumably also in M31) is dark.

- estimate the extent of such a putative dark halo. If V^2_c is circular velocity out to R_{halo}, then $R_{halo} =GM_{MW}/V^2_c =G*10^{12}/(220km/s)^2 =90kpc$
- If, the rotation speed drops at large R, then R_{halo} is even bigger.
- Hence the extent of the dark matter halo around the MW and M31 is very large. the size of the stellar disk is of order 20kpc or so, and 780kpc is the distance to M31 . So the dark matter haloes of the MW and M31 may almost overlap

timing argument

- M_{total}=3.66x10^{12} $M_{\odot}$ and mass MW ~1/3 of total
- R_{halo} =GM_{MW}/V^2_c =G*10^{12}/(220km/s)^2 =90kpc
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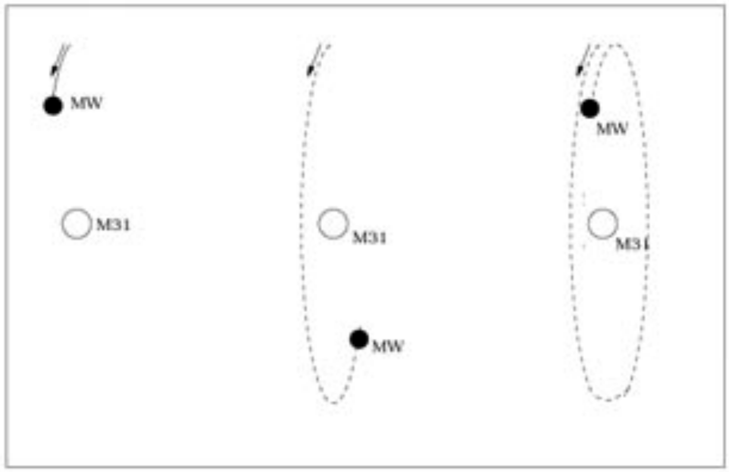
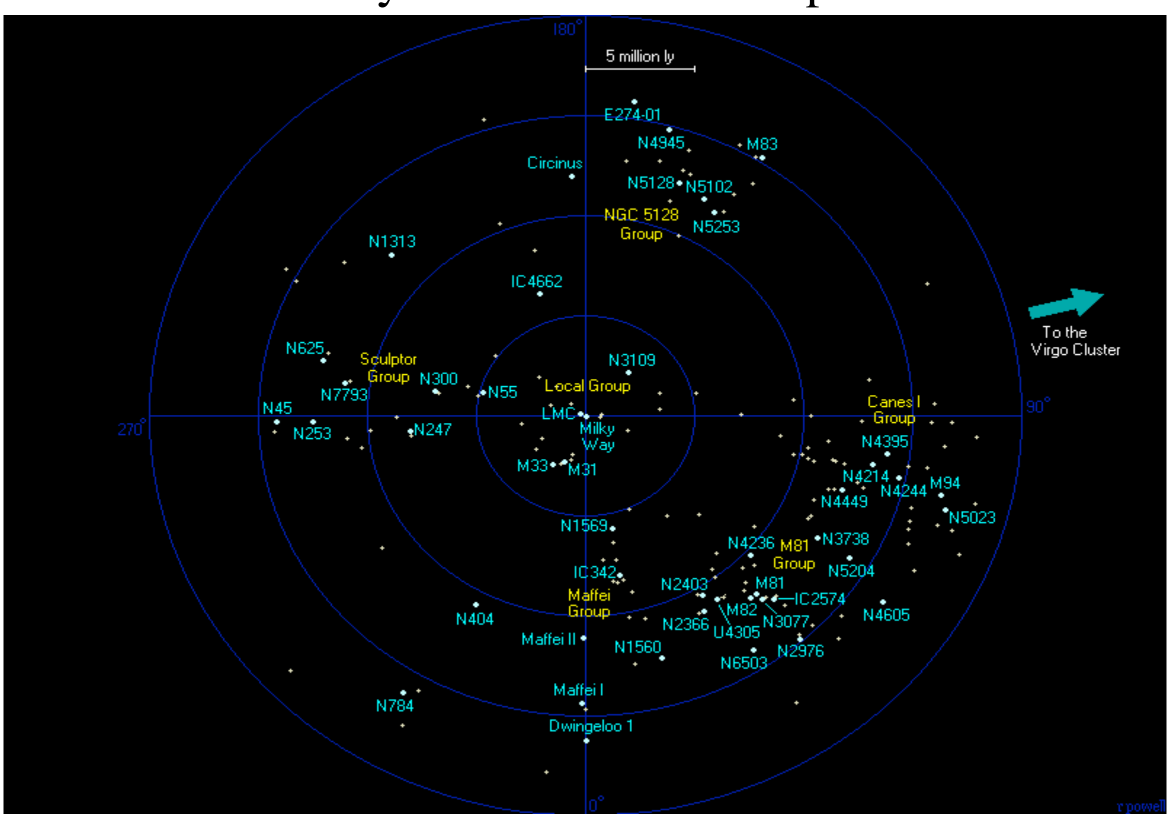


Beyond the Local Group



Local Volume of Space

As indicated by CDM simulations the universe is lumpy

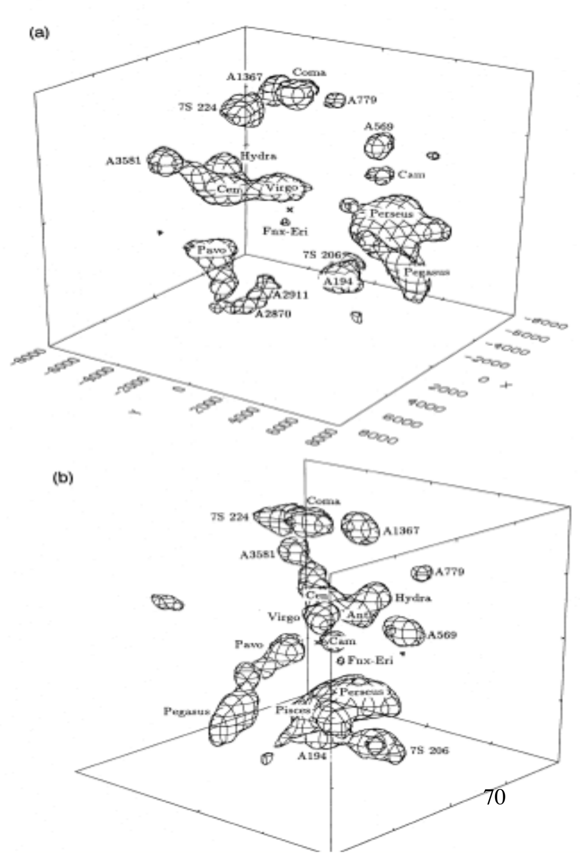
Here is a 'map' (Hudson 1994) of the nearby universe

Objects labled 'A' are rich clusters

other massive clusters are labeled Virgo Coma, Cen, Perseus

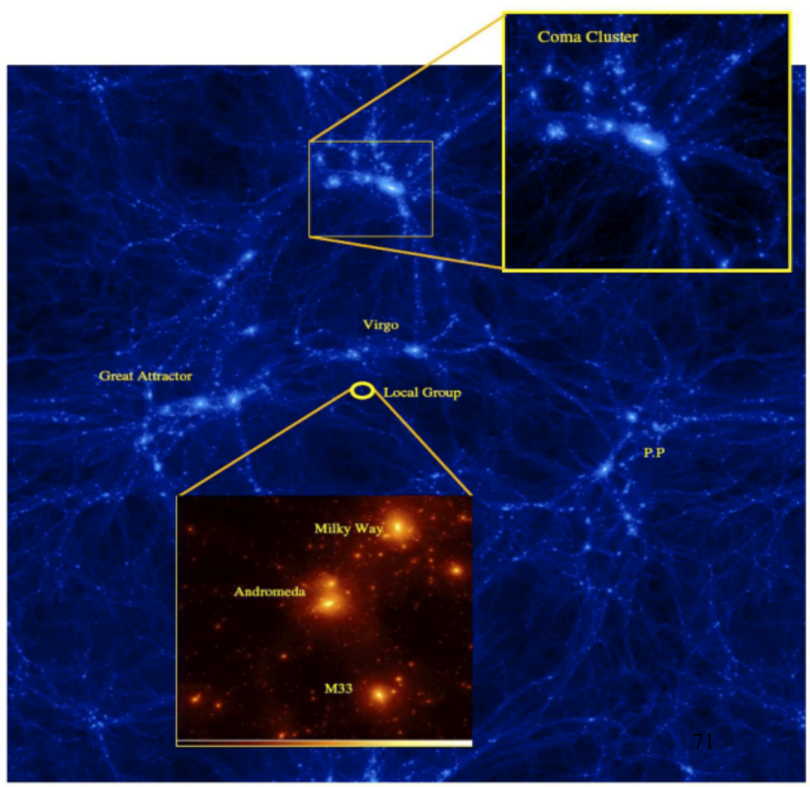
of galaxies from Abells catalog - axis are labeled in velocity units (km/sec)

Notice filamentary structure.



Constrained Realization

- In order for numerical galaxy formation models to 'work' properly need to sample a large volume of space.
- Constrained to have properties of Local group



Where is the Local Group

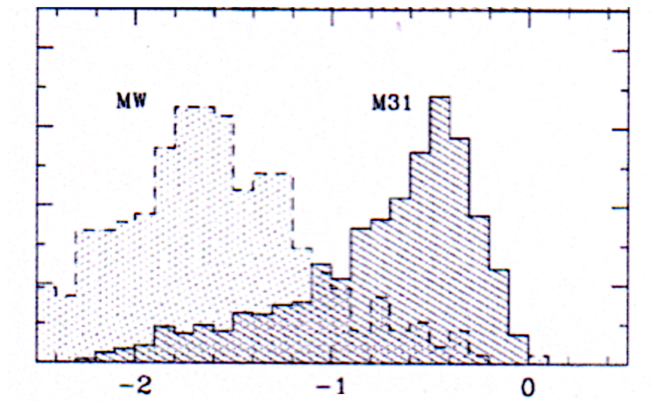
- This visualization shows our "Local Universe", as simulated in the constrained realization project.
- The Local Group is in the centre of the sphere. In the initial orientation of the sphere, the Great Attractor is on the left, and the Cetus Wall on the lower right.
- Credit: Volker Springel
- Simulation code: Gadget

Summary of Today Lecture Local Group

- Introduction of Tully-Fisher scaling relation- how to compare galaxies- much more in discussion of spirals next week.
- Discussion of detailed properties of M31, M33 comparison to MW; differences in how they formed; MW very few 'major mergers' M31 more; not all galaxies **even those close to each other do not have the same history.**
- Dynamics of local group allow prediction that M31 and MW (and presumably the Magellanic clouds) will merge in ~6 gyr
- A supermassive black hole exists in the centers of 'all' *massive* galaxies- properties of BH are related to the bulge and not the disk of the galaxy
- Use 'timing argument' to estimate the mass of the local group (idea is that this is the first time MW and M31 are approaching each other and the orbit is radial) use 'simple' mechanics to get mass
- Local group is part of a larger set of structures- the 'cosmic web' galaxies do not exist in isolation

Comparison of Metallicity of Halo Stars in M31 and MW

- The vastly different chemical compositions of the halo of MW and M31 indicate different formation histories or processes EVEN in the Local Group
- Chemical composition of stars in the dwarfs differs subtly from stars in globular clusters or MW halo.
- Comparison of observed metallicities to theoretical yields from a closed box approx (S+G 4.13-4.16) indicates outflow of enriched material (or according to S+G inflow of material enriched to 0.15 solar)



- Halo of M31 = Andromeda (Durrell et al. 2001)
- Halo of the Milky Way (Ryan & Norris 1991)

Mass Models For M31

- Several different potential forms give reasonable fits to velocity data; differ in 'total' mass by <50%
- the merging history of a galaxy, together with its star formation history, and mass re-arrangement (such as gas flows or stellar radial migration) is written in its structure, stellar ages, kinematic and chemical-elemental abundance distribution functions.

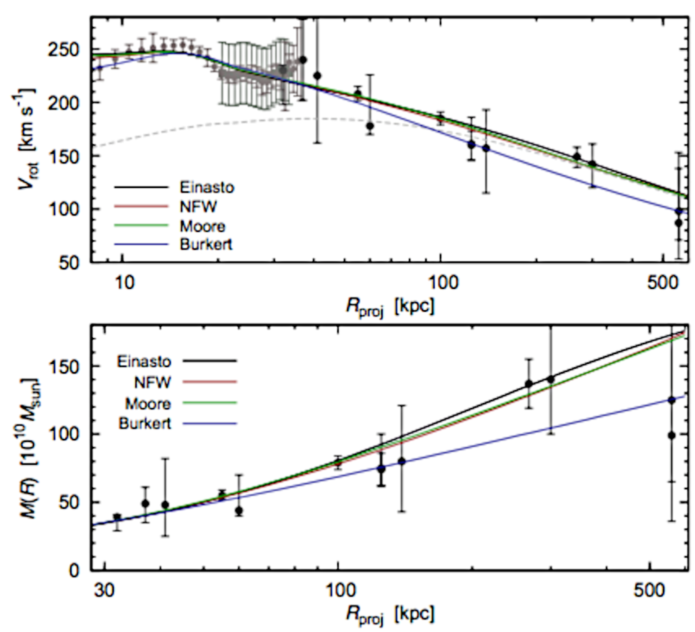


Fig. 6. Outer rotation curve observations and models (*upper*