Masses

If molecular clouds are gravitationally bound and in equilibrium, the Virial Theorem states:

$$-2 < KE > = < PE >$$

Per molecule: $KE \sim \frac{1}{2} m_{H_2} v_{rms}^2$ $\qquad PE \sim -\frac{GMm_{H_2}}{R}$

Then $M = M_{vir} \sim \frac{Rv_{rms}^2}{G}$

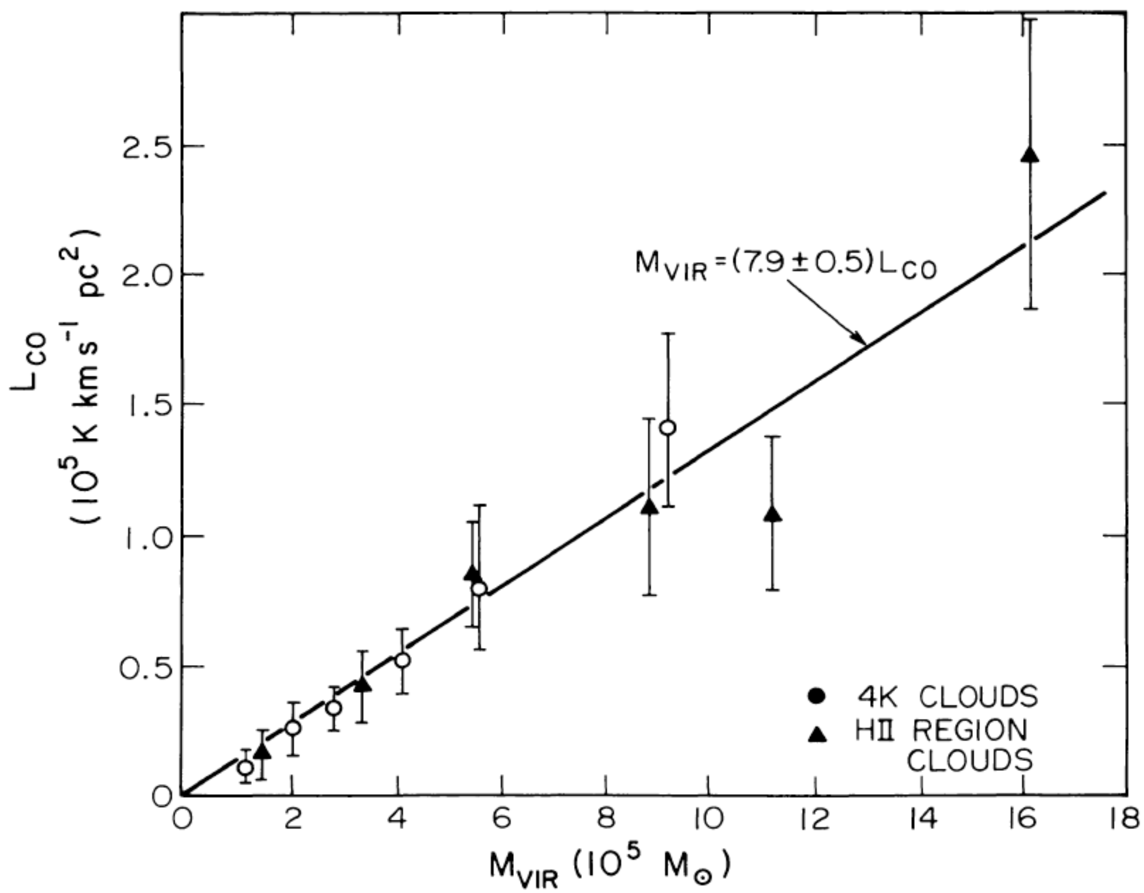
If spectral line is broadened by motion of molecules, get v_{rms} from linewidth.

We get R from mapping the extent of the cloud (must know its distance). From this we will find the virial mass M_{vir}.

Observation: $L_{CO} \propto M_{vir}$

Thus, if clouds are virial, L_{CO} is a good tracer of H_2 mass.

From this we derive conversion factor X from CO to H_2 mass



Scoville et al 1987

The CO-to-H_2 Conversion Factor

CO

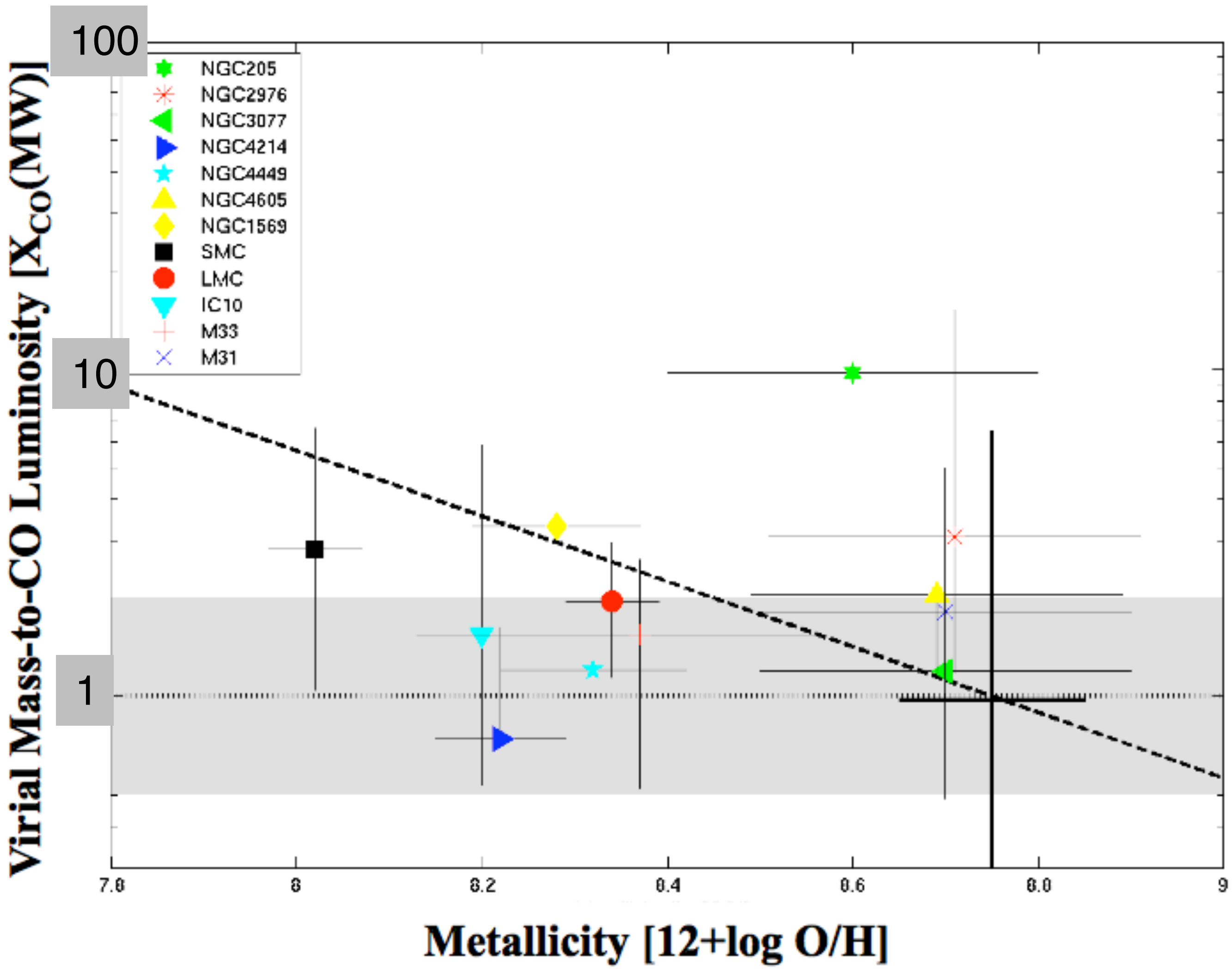
Ratio of virial mass to CO luminosity vs. metallicity.

- X_{CO} for virialized clouds.

No strong trend.

SMC completely compatible with MW clouds and Solomon (0.8) slope…

- i.e., $M_{vir}/L_{CO} \sim L_{CO}^{-0.2}$



Bolatto et al. 2008

Luminosity-Virial Mass Relation

CO

(one version of other independent Larson's Law)

We find $M_{vir} \sim L_{CO}$ ...

- Solomon (MW): $M_{vir} \sim L_{CO}^{0.8}$

CO-to-H2 factor roughly as MW if GMCs are virialized...

SMC falls on Galactic line.

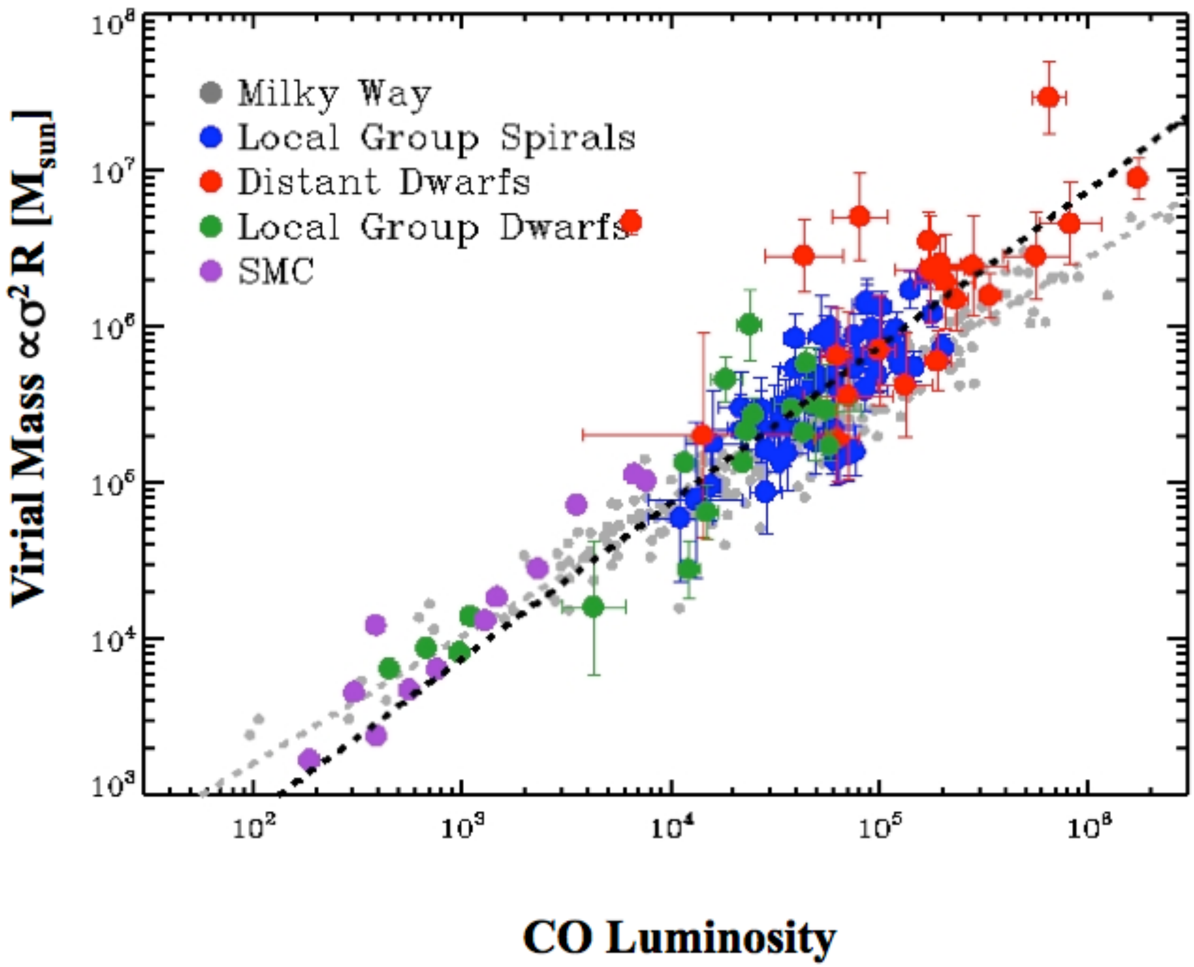
Other scaling relations:

L_{CO} *vs.* R

L_{CO} *vs.* σ

M_{vir} *vs.* R

follow from these two.



Bolatto et al. 2008

Results:

Most molecular gas is in *Giant Molecular Clouds (GMCs)*:

- A few hundred known in the Milky Way
- $M \sim 10^3$-10^7 $M_\odot$
- sizes 5-100 pc.

Associated with the spiral arms of the Milky Way (more on this later).

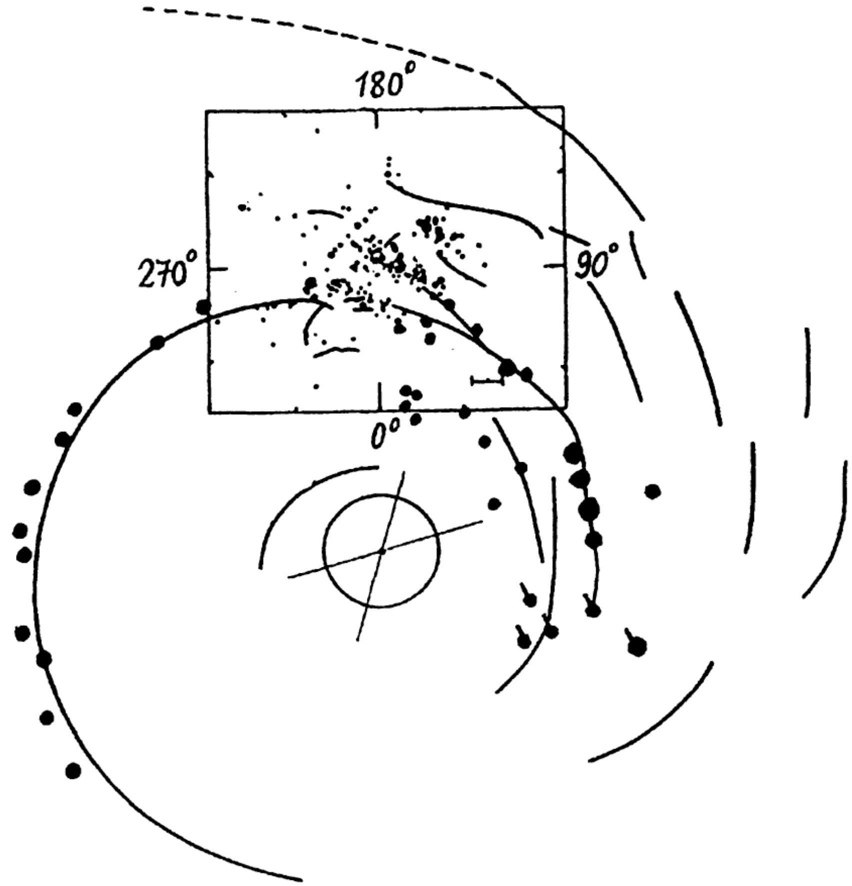
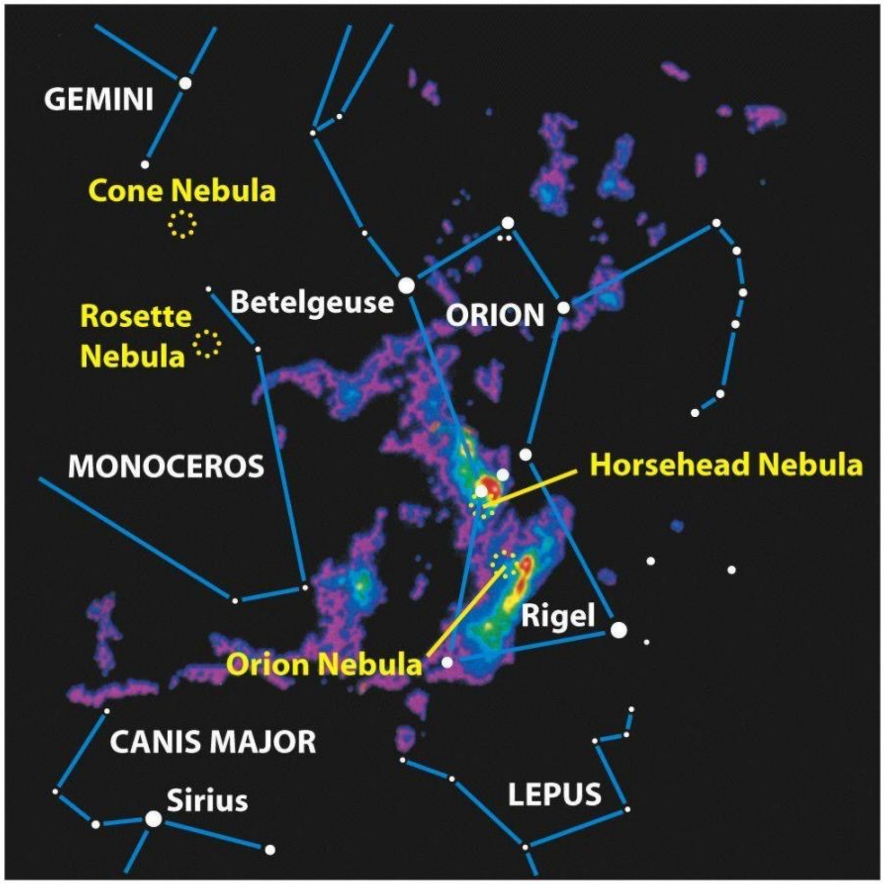
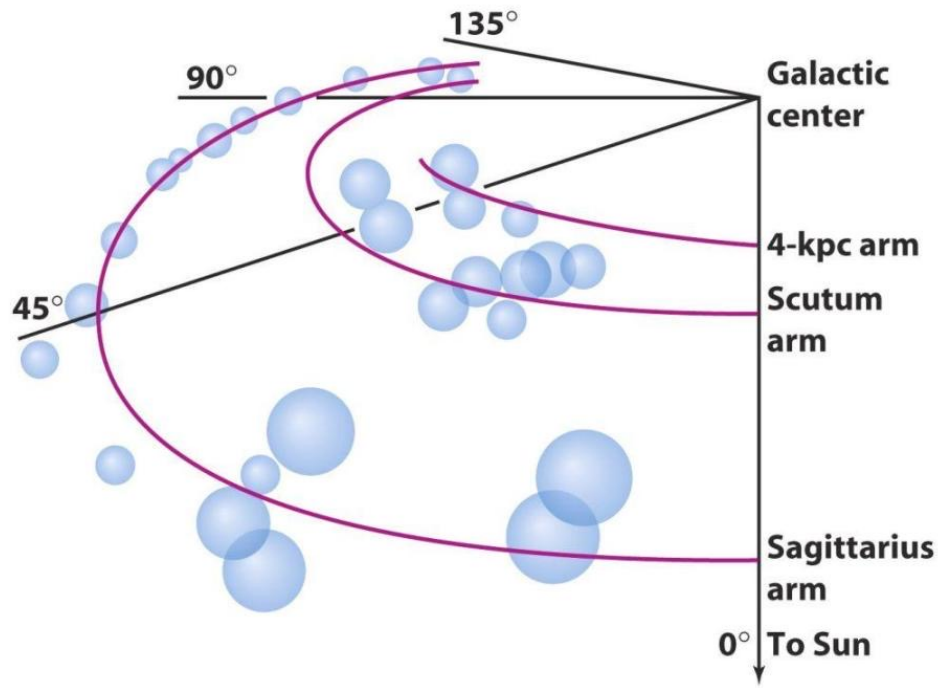


Figure 1 Positions of superclouds in the I quadrant (sizes are proportional to masses) and within the Car arm in the IV quadrant (sizes are arbitrary), superimposed on the H I ridges and the local distribution of young clusters and associations (after Weaver, 1970). Two extreme possible positions for the bar are also shown. Within the I quadrant the superclouds for which the distance may be uncertain (far distances being adopted) are marked with a tick.

Efremov 1988

From *Universe* (Freedman & Kaufman)





Finally: The Mass Function

Whenever you have a large number of objects with various masses, useful to describe the number as a function of mass, N(M), or size, N(R). Constrains theories of their origin. Useful for Kuiper Belt, asteroids, impact craters, Saturn's ring particles, stars, gas clouds, galaxies.

Often have many small objects and a few large ones, which we can try to describe with a "power law" mass function:

$$N(M) \propto M^{-\beta}$$

Gives relative importance of large and small objects

For KBOs, can measure reflectivity of Solar radiation. Know distance from Sun by measuring orbit. From this and assumed albedo, can get radius of each. Find

$$N(R) \propto R^{-4}$$

If they all have the same density then M/R^3 = constant, so $M \propto R^3$, so $R^{-4} \propto M^{-4/3}$, and

$$N(M) \propto M^{-4/3}$$

Now can ask, for example, how many are there of mass M_1 vs. $10xM_1$?

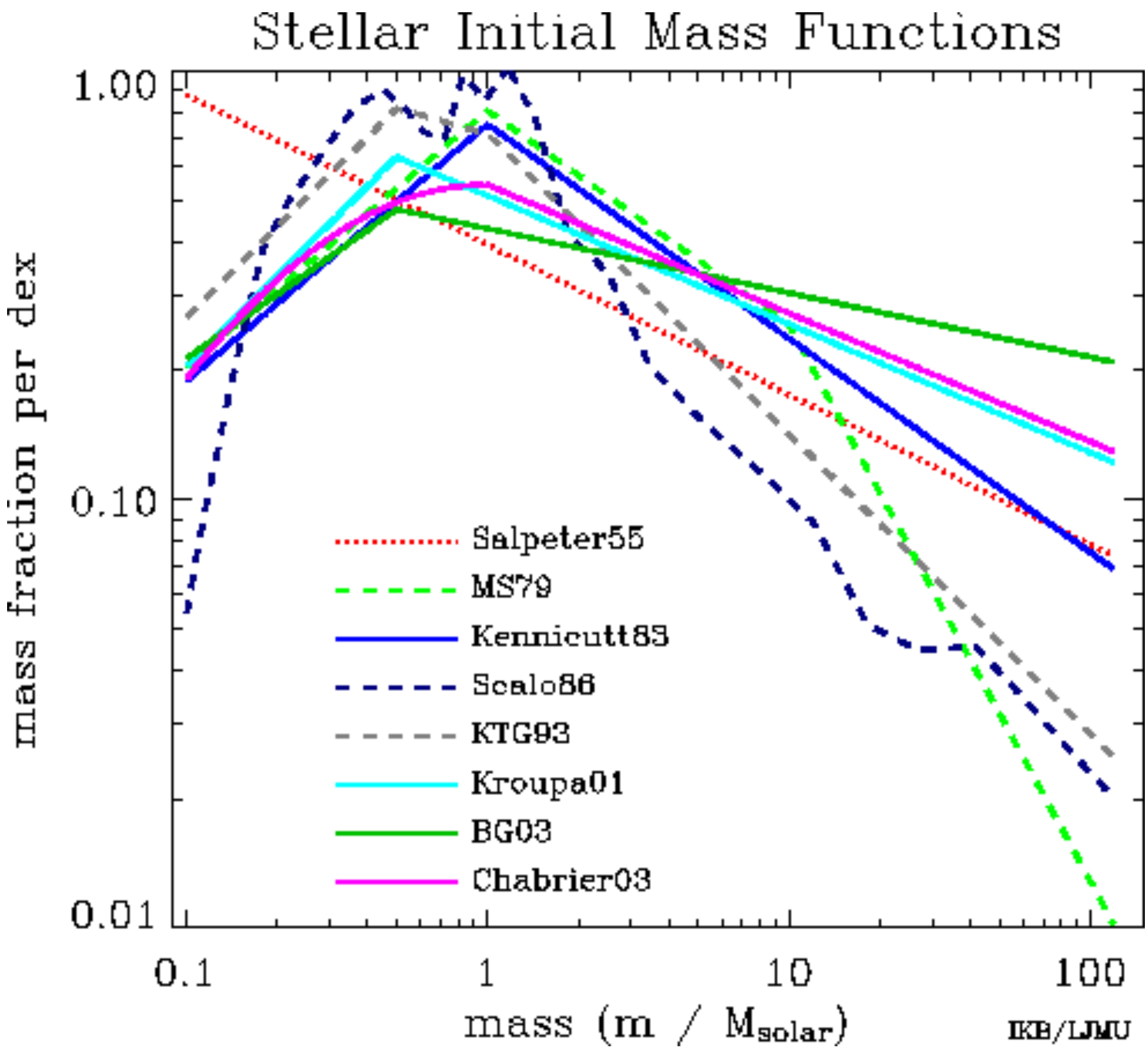
$$N(M_1)/N(10xM_1) = M_1^{-4/3}/(10xM_1)^{-4/3} = 10^{4/3} = 21.5$$

Can also ask: is most of the mass in larger KBOs or smaller ones? For example, how much mass in objects of mass M_1 vs. objects of mass $10xM_1$?

If you have N objects of mass M, the total mass is MxN. So for N=N(M), total mass is MxN(M) α $MxM^{-4/3}$ or $M^{-1/3}$. So relative mass is

$$M_1^{-1/3}/(10xM_1)^{-1/3} = 10^{1/3} = 2.2$$

So more mass in lower mass objects. Recall β was -4/3. Note if $\beta < -1$, more mass in higher mass objects.


Stellar Initial Mass Functions
1.00
0.10
0.01
mass fraction per dex
0.1
1
10
100
mass (m / M solar)
IKB/LJMU
Salpeter55
MS79
Kennicutt83
Scalo86
KTG93
Kroupa01
BG03
Chabrier03

Initial Mass Function for Stars

By observing the relative numbers of various masses of stars, we can deduce something about the cloud fragmentation process.

The *initial mass function* (IMF) describes the relative numbers of each stellar mass. Defined for stars in the Solar neighborhood by Salpeter (1955):

$$\xi(M) = \xi_0 M^{-2.35}$$

M = mass in solar units.

Thus, the number of stars that form with masses between *M* and *ΔM:*

$$\xi(M)\Delta M$$

Total number of stars formed with masses M_1 and M_2:

$$N = \int_{M_1}^{M_2} \xi(M) dM = \xi_0 \int_{M_1}^{M_2} M^{-2.35} dM = \frac{\xi_0}{1.35}\left[M_1^{-1.35} - M_2^{-1.35}\right]$$

Similarly, we can work out the total mass in stars born within that given mass range:

$$M_{tot} = \int_{M_1}^{M_2} M\xi(M)dM$$

Properties of the Salpeter IMF:

- most of the stars, by number, are low mass stars
- most of the mass in stars reside in low mass stars
- following a burst of star formation, most of the luminosity comes from high mass stars.

The Salpeter IMF fails at low masses, since extrapolating to very low masses means total mass $\rightarrow \infty$

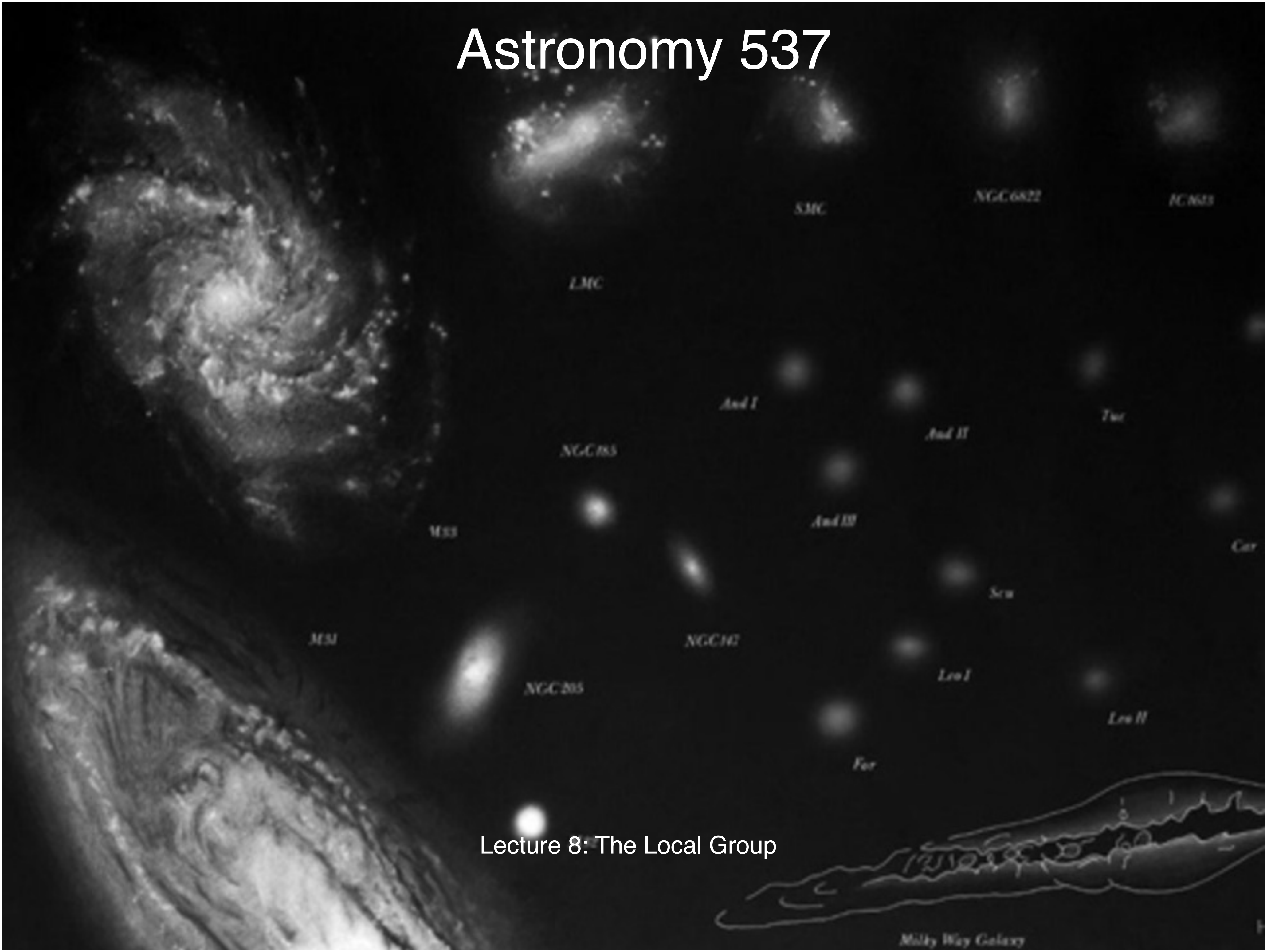
Observations implies Salpeter IMF valid for $M > 0.5$ $M_{\odot}$, and that it flattens at lower masses.

Worksheet:

Consider a cloud with a total mass of $1000M_\odot$.

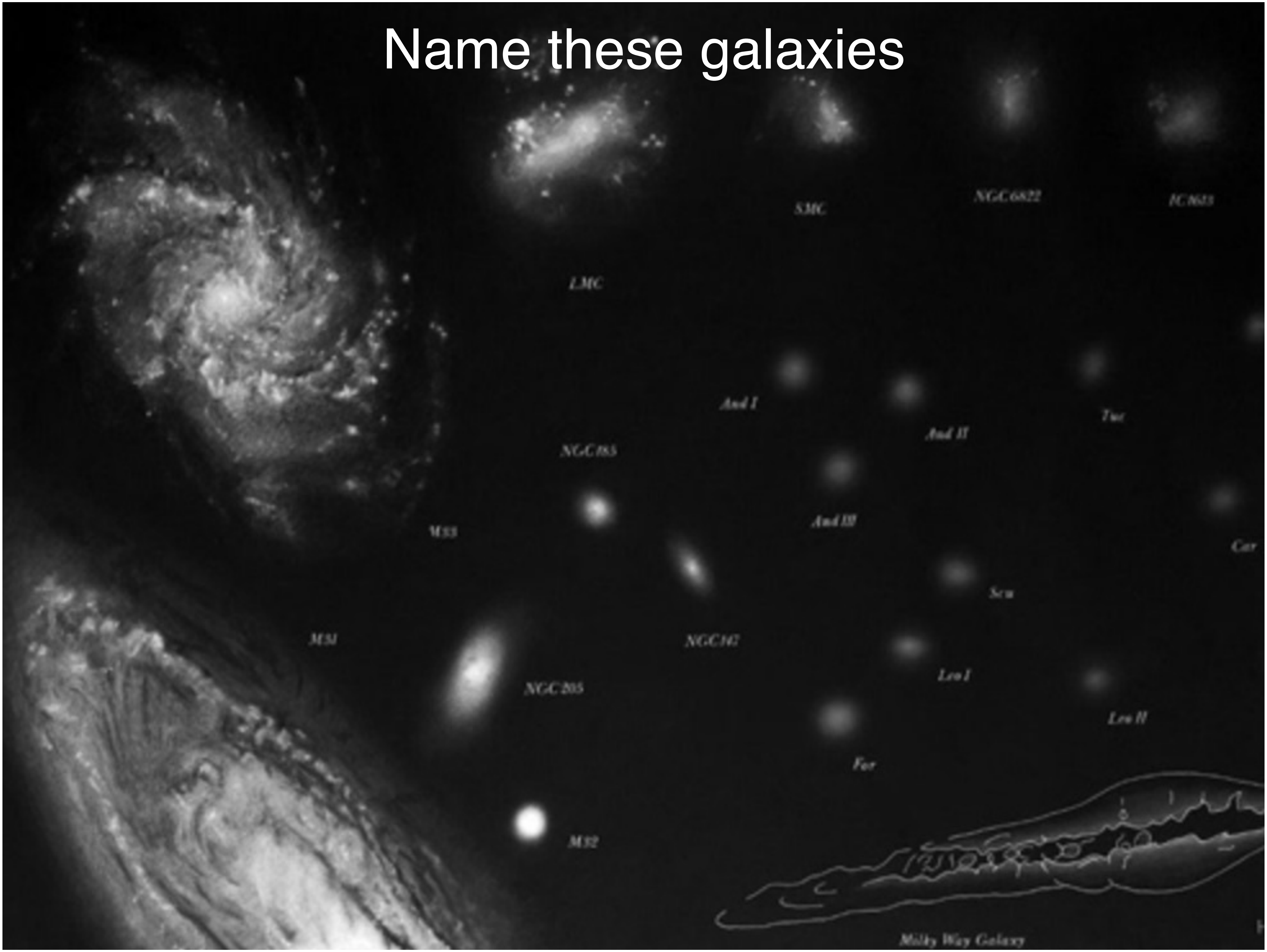
How many $10M_\odot$ stars are formed if it follows the Salpeter IMF and forms stars over a range from 1 to $50M_\odot$?

Astronomy 537



Lecture 8: The Local Group

Name these galaxies



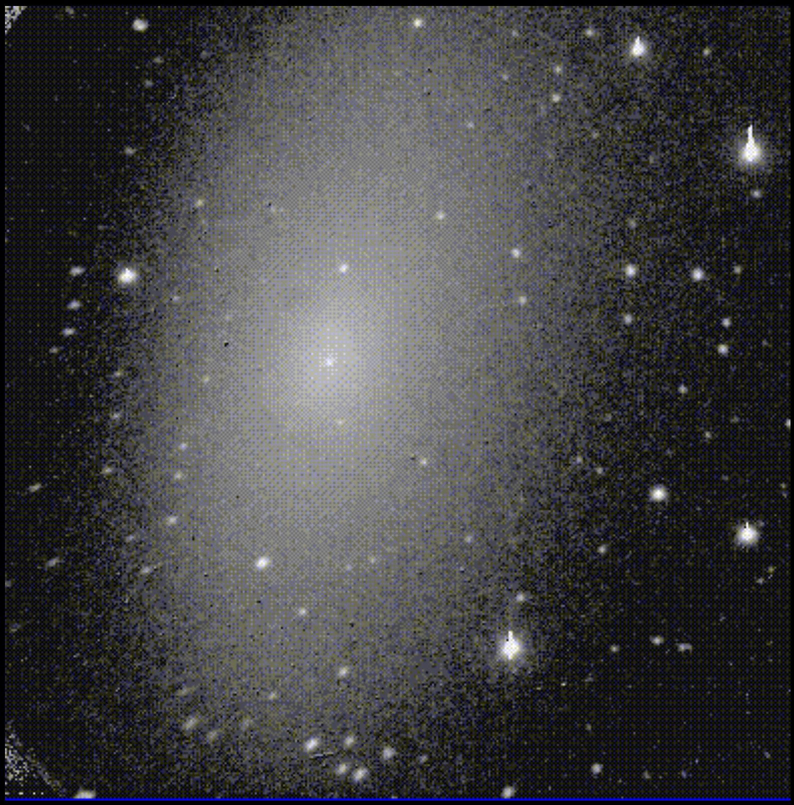
Key concepts:

- Local Group
- Physical properties
- Star formation

Leo I - Dwarf spheroidal galaxy

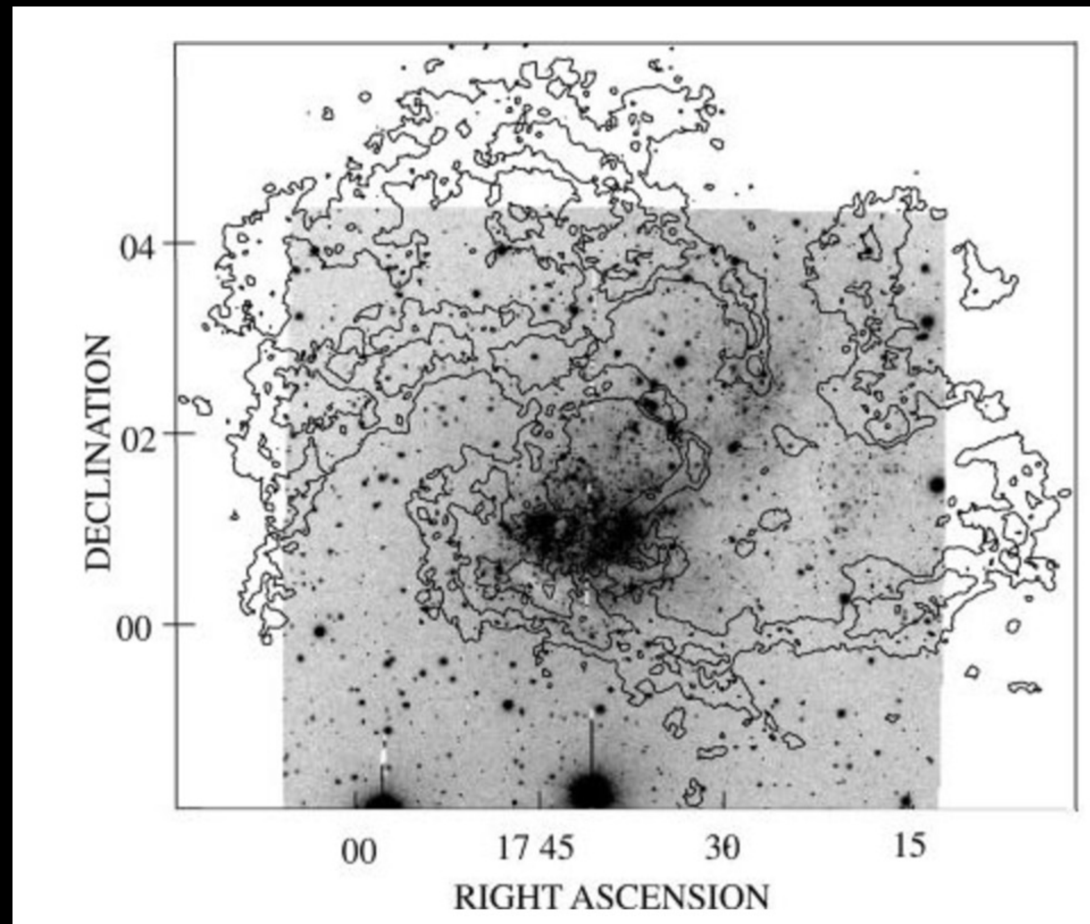

Fornax dwarf - Dwarf spheroidal galaxy

NGC205: Dwarf elliptical



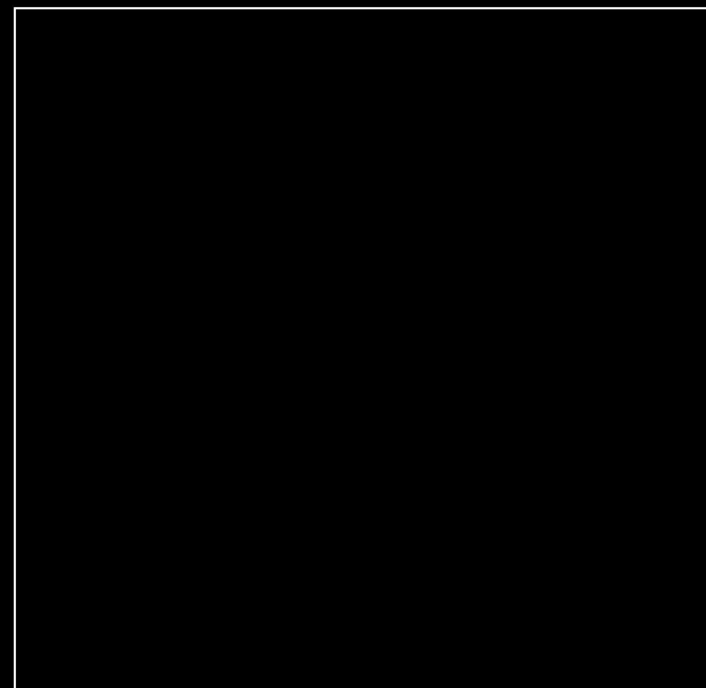
IC10: Dwarf irregular

IC10: Dwarf irregular

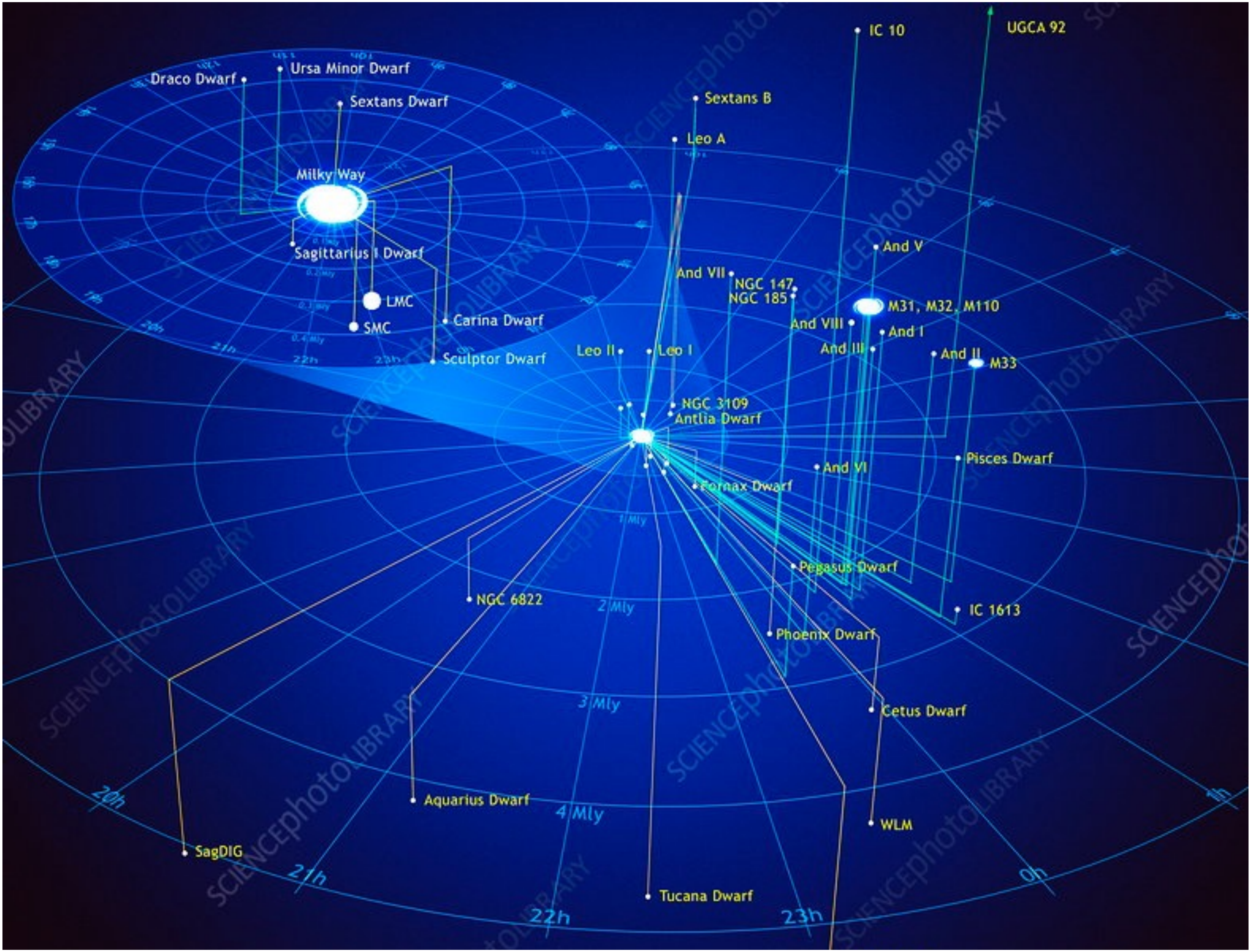


Neutral H in IC10 ~ 44 million M_sun

UGCA285: Low surface brightness galaxy



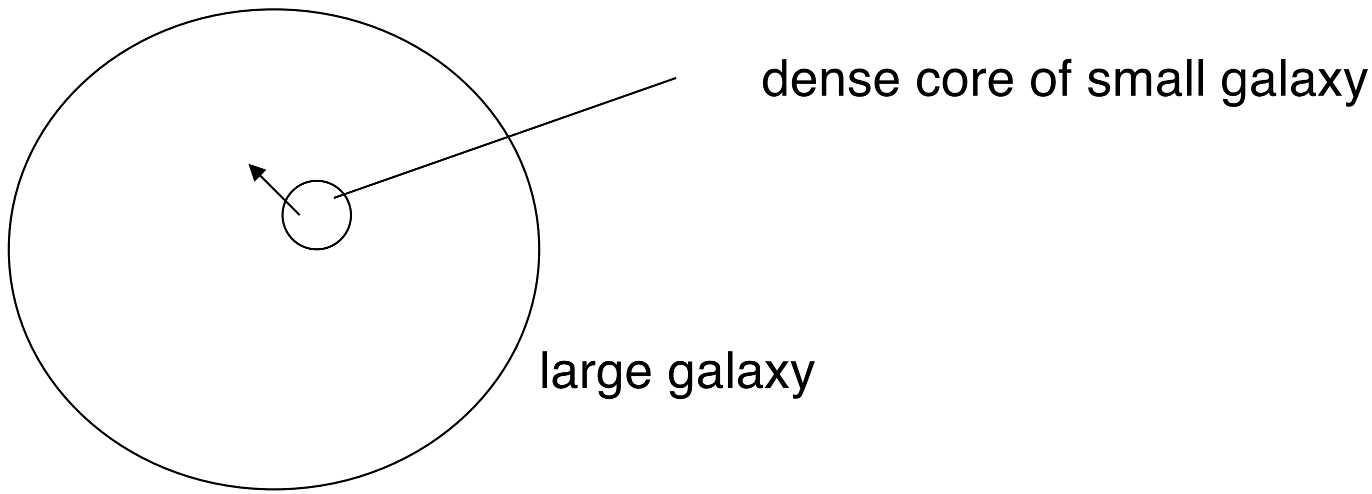
UGCNAN: Ultra Low surface brightness galaxy



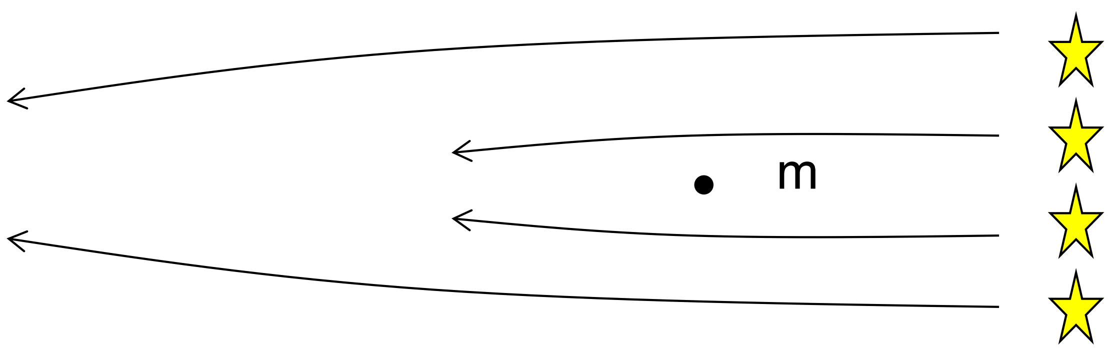
Draco Dwarf
Ursa Minor Dwarf
Sextans Dwarf
Milky Way
Sagittarius I Dwarf
LMC
SMC
Carina Dwarf
Sculptor Dwarf
IC 10
UGCA 92
Sextans B
Leo A
And V
And VII
NGC 147
NGC 185
M31, M32, M110
And VIII
And I
And III
And II
M33
Leo II
Leo I
NGC 3109
Antlia Dwarf
Pisces Dwarf
And VI
Fornax Dwarf
1 Mly
Pegasus Dwarf
NGC 6822
2 Mly
IC 1613
Phoenix Dwarf
3 Mly
Cetus Dwarf
Aquarius Dwarf
4 Mly
WLM
SagDIG
Tucana Dwarf
20h
21h
22h
23h
0h

Dynamical friction

How large galaxies eat dense cores of victims!



Represent core as point mass m. In its frame, stars are streaming by:



How it works:

- As a massive galaxy moves through a sea of stars, gas, (and the dark halo), it causes a wake behind, increasing the mass density in this region

- This increase in density causes the galaxy to slow down and lose kinetic energy

- The galaxy will eventually fall in and merge with the companion

Journal Class

- **No certainty of a Milky Way–Andromeda collision**
- Sawala et al. 2025

Discussion leader: **Shane Li**

Note: To encourage discussion everybody must pose at least one question during the group discussion

Dwarf Galaxies

Table 4.2 Dwarf galaxies, compared with the nuclear star cluster of M33, and three Milky Way globular clusters

System	L_V ($10^7 L_\odot$)	σ_r (km s^{-1})	r_c (pc)	r_t (pc)	t_{sf} (Gyr)	$\mathcal{M}/L_V$ ($\mathcal{M}_\odot/L_\odot$)	$\log_{10}(Z/Z_\odot)$ range
NGC 147 dE	12	20–30	260	1000	3–5	7 ± 3	−1.5 to −0.7
NGC 185 dE	13	20	170	2000	< 0.5	5 ± 2	−1.2 to −0.8
Pegasus dIrr	1	9(HI)		500(HI)	< 0.1	2–4	−2.3 to −1.7
Fornax dSph	1.5	13	400	5000	< 2	~15	−2 to −0.4
M33 nucleus	0.25	24	< 0.4		< 1:	~1	−1.9 to −0.7
Sculptor dSph	0.2	9	200	2000	> 10	~10	−2.6 to −0.8
ω Cen gc	0.1	20	4	70	> 10	2.5	−1.6 to −1.2
M15 gc	0.04	12	< 0.01	85	> 10	2	−2.15
Carina dSph	0.04	7	200	900	2–10	~40	−2.7 to −0.3
M92 gc	0.02	5	0.5	50	> 10	1.5	−2.15

Worksheet: Use the virial theorem to determine the masses for the Carina dwarf spheroidal and for the ω Cen globular cluster. Comment on their M/L ratios using the table provided below.

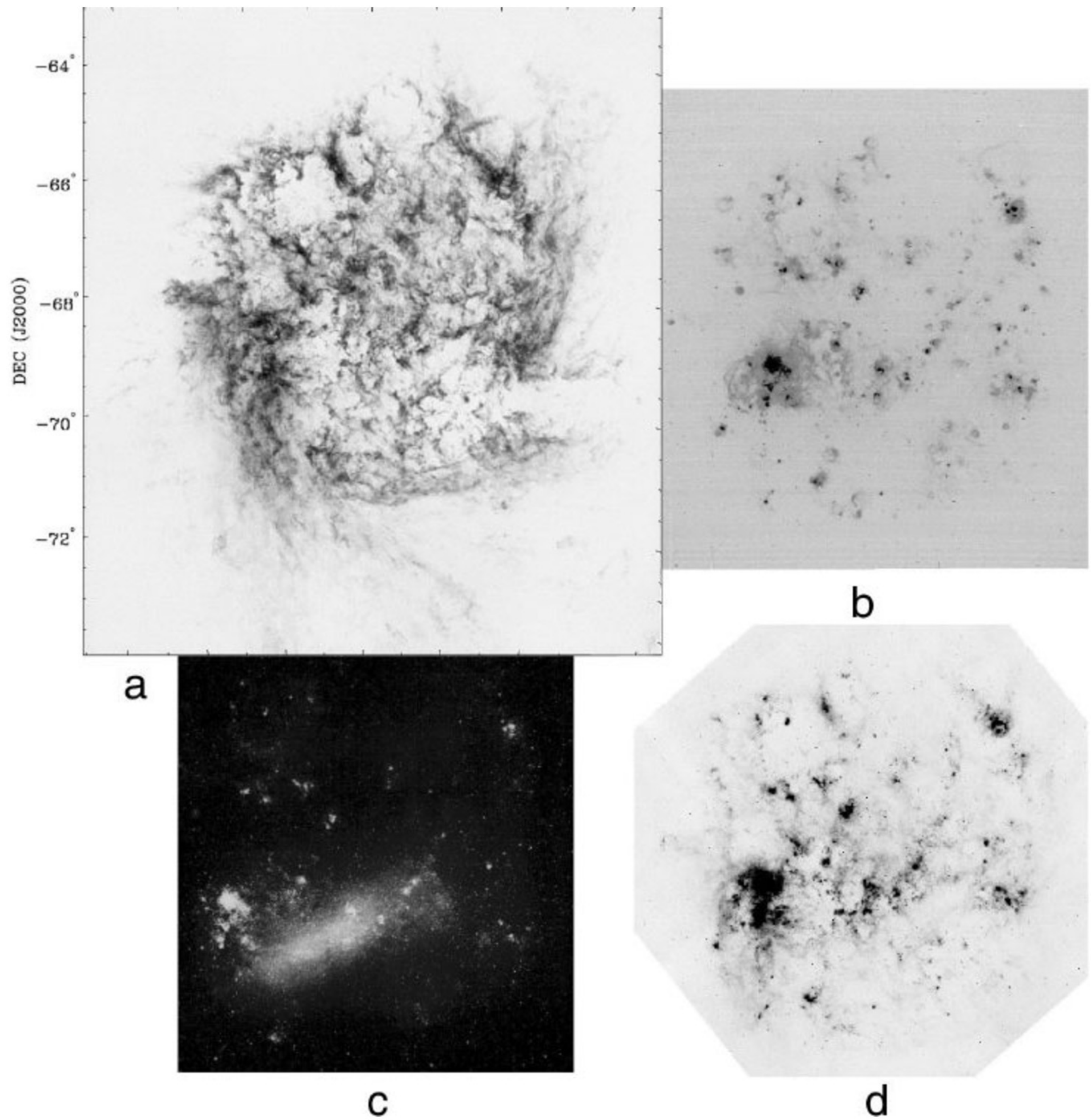
Table 4.2 Dwarf galaxies, compared with the nuclear star cluster of M33, and three Milky Way globular clusters

System	L_V ($10^7 L_\odot$)	σ_r (km s^{-1})	r_c (pc)	r_t (pc)	t_{sf} (Gyr)	$\mathcal{M}/L_V$ ($\mathcal{M}_\odot/L_\odot$)	$\log_{10}(Z/Z_\odot)$ range
NGC 147 dE	12	20–30	260	1000	3–5	7 ± 3	−1.5 to −0.7
NGC 185 dE	13	20	170	2000	< 0.5	5 ± 2	−1.2 to −0.8
Pegasus dIrr	1	9(HI)		500(HI)	< 0.1	2–4	−2.3 to −1.7
Fornax dSph	1.5	13	400	5000	< 2	~15	−2 to −0.4
M33 nucleus	0.25	24	< 0.4		< 1:	~1	−1.9 to −0.7
Sculptor dSph	0.2	9	200	2000	> 10	~10	−2.6 to −0.8
ω Cen gc	0.1	20	4	70	> 10	2.5	−1.6 to −1.2
M15 gc	0.04	12	< 0.01	85	> 10	2	−2.15
Carina dSph	0.04	7	200	900	2–10	~40	−2.7 to −0.3
M92 gc	0.02	5	0.5	50	> 10	1.5	−2.15

The Large Magellenic Cloud

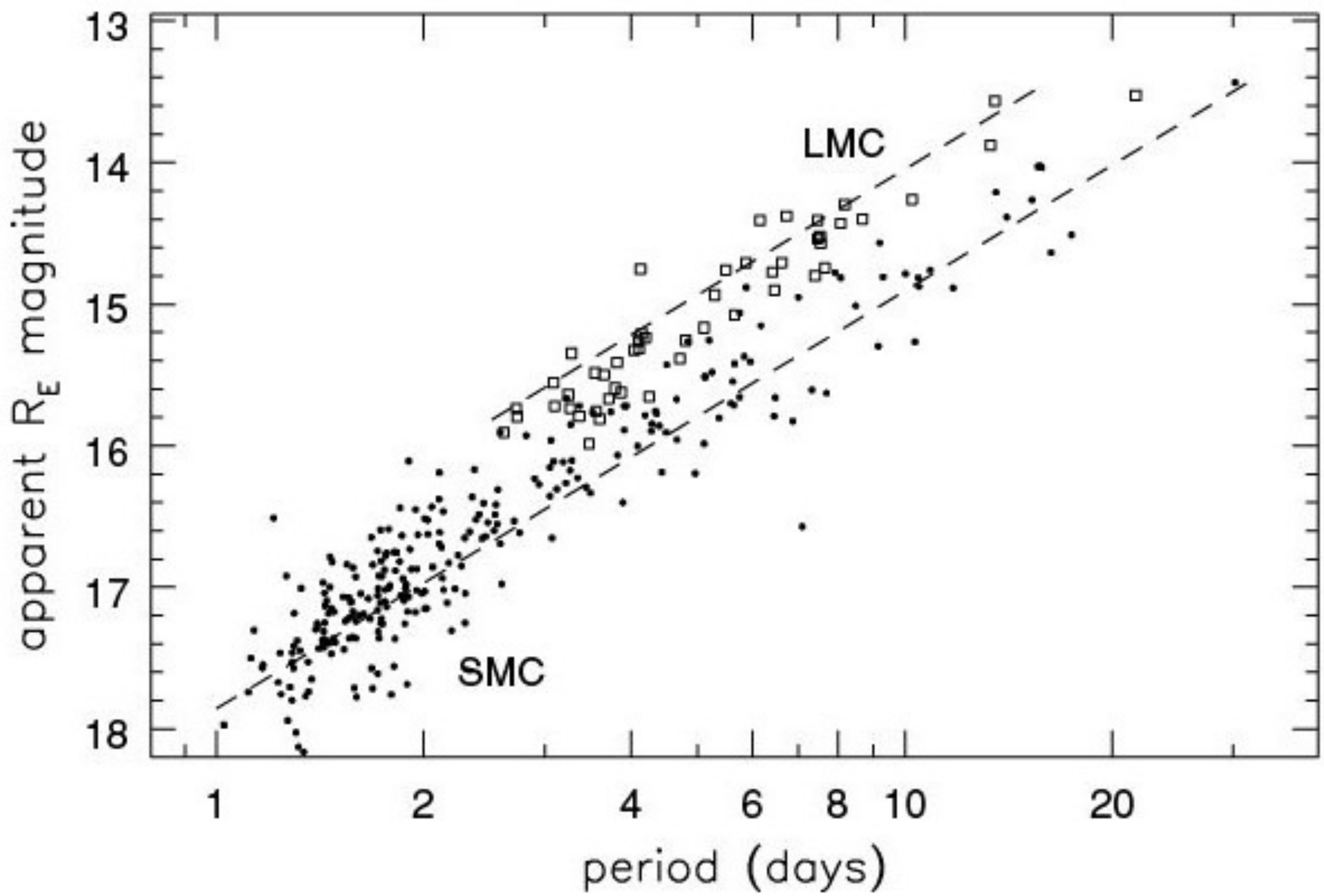
a) HI
b) Halpha
c) Optical
d) IR 24 microns

Distance ~ 50 kpc
LMC orbital period Is ~ 2 Gyr



Cepheid distances to LMC and SMC

Cepheids
Squares = LMC
Dots = SMC

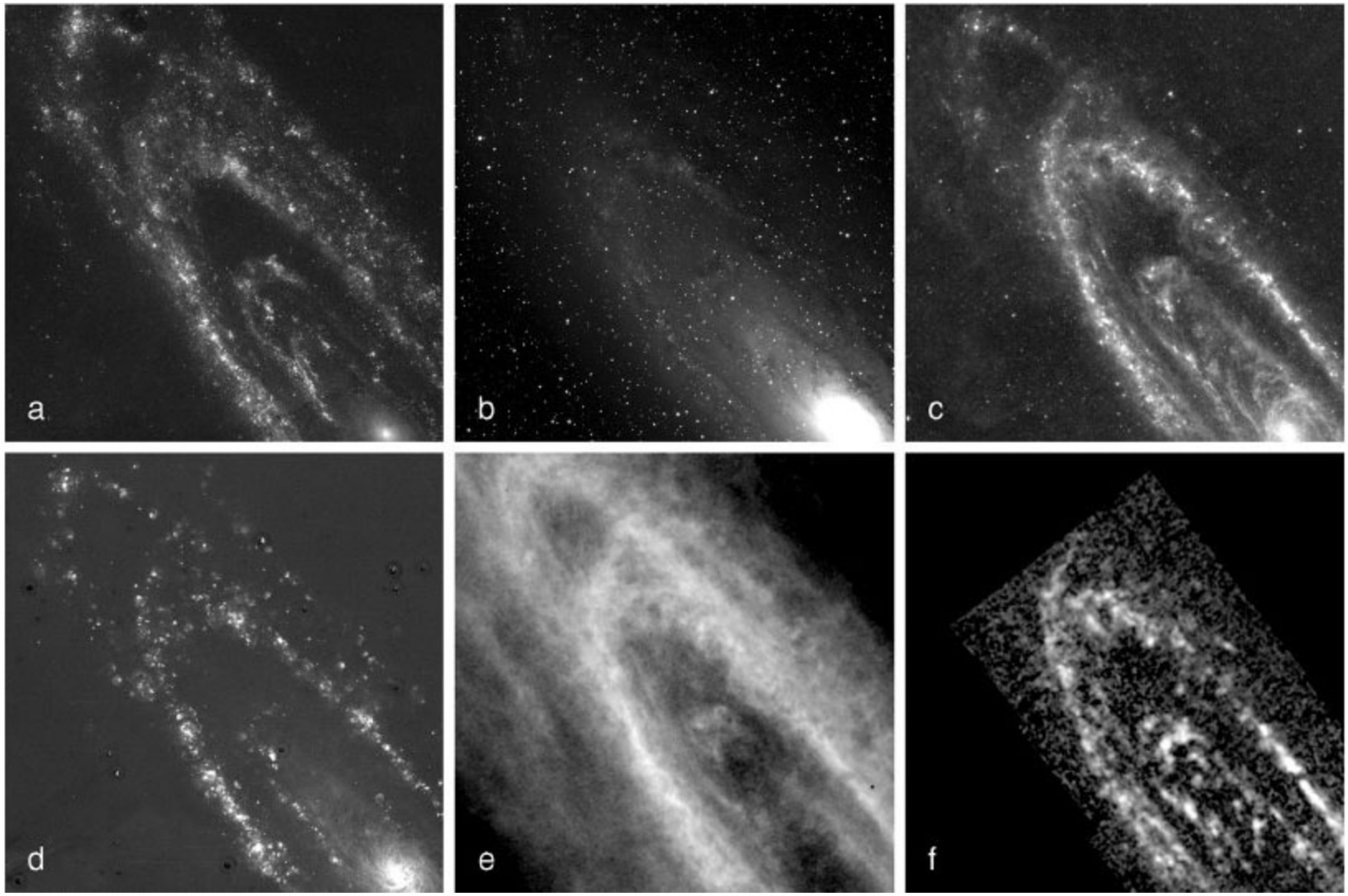


Distance ~ 50 kpc
LMC orbital period
Is ~ 2 Gyr

Which is further
away from us?

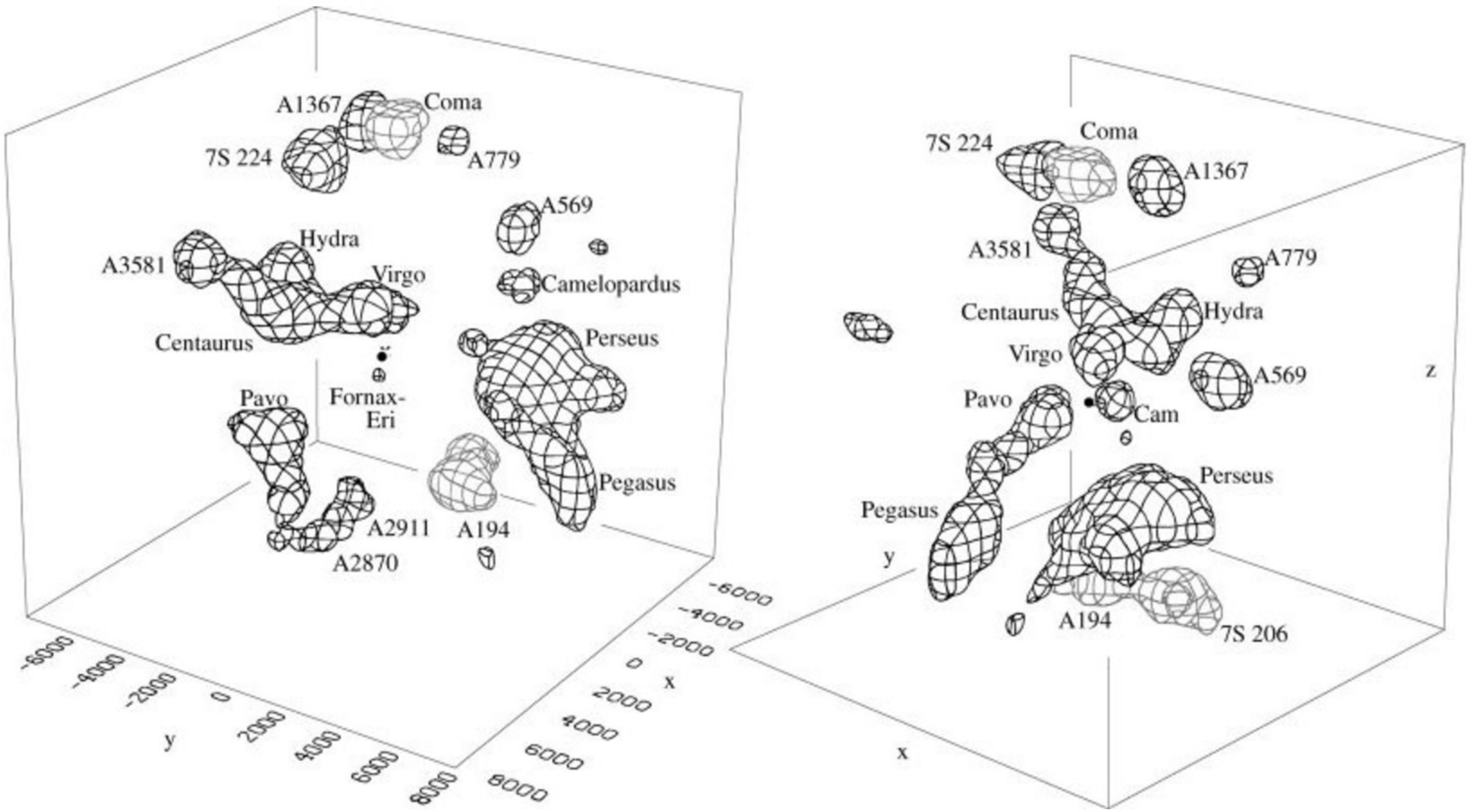
The Andromeda Galaxy, M31

a) UV
b) B band
c) IR
d) Halpha
e) HI
f) CO



Note the “Ring of Fire”, especially in IR and Halpha

Beyond the Local Group



How did the Local Group form?

- What clues do we have?

How did the Local Group form?

- Age of stars ~ 0-12 Gyr
- Most dSph no longer forming stars and in orbits around MW or M31
- Most dIrr are forming stars and are “free fliers”
- Metallicity very low in oldest globular clusters

- Look at virial temperature
- Look at Jean’s mass
- Look at timescale for collapse
- Top-down or bottom-up?