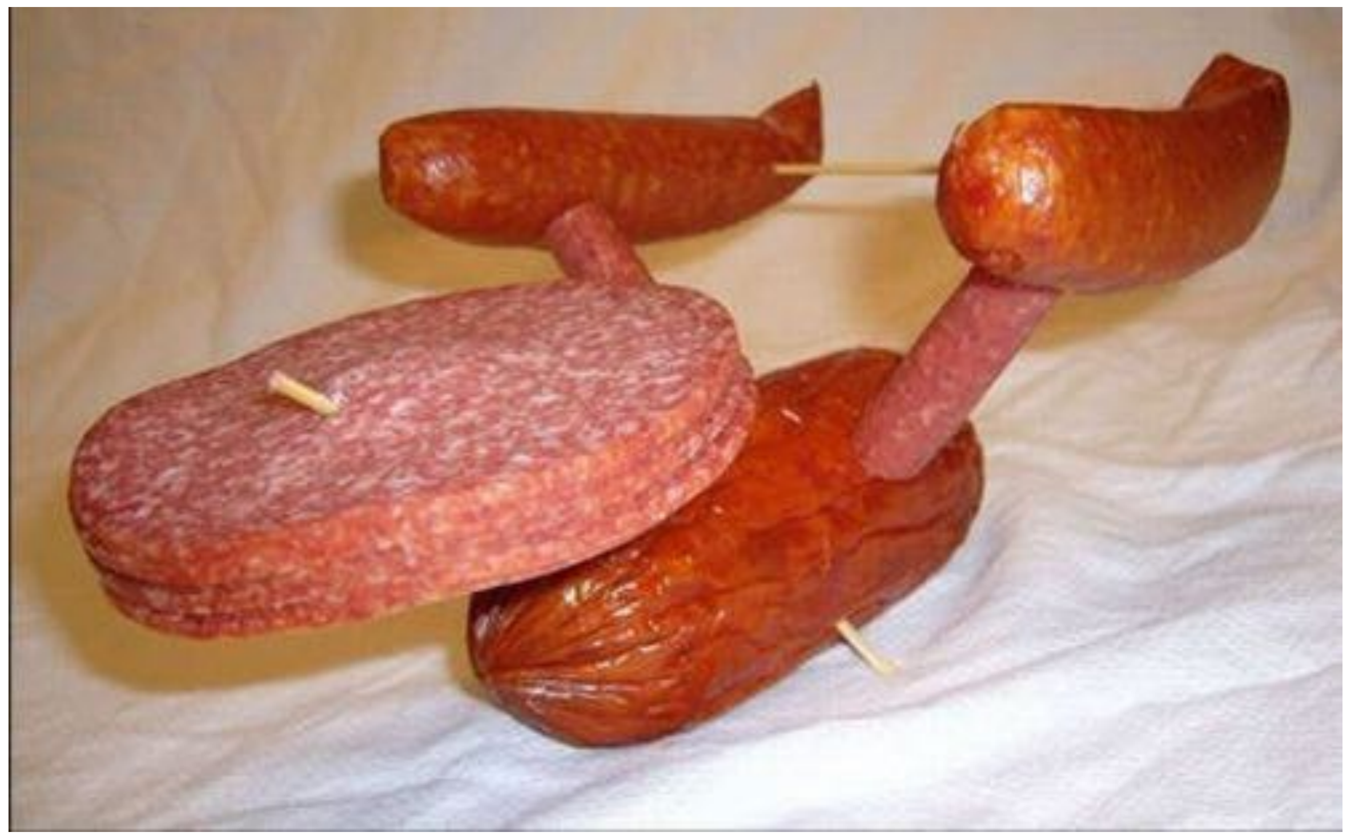
Phenomenology of Galaxies
PHYS 4230



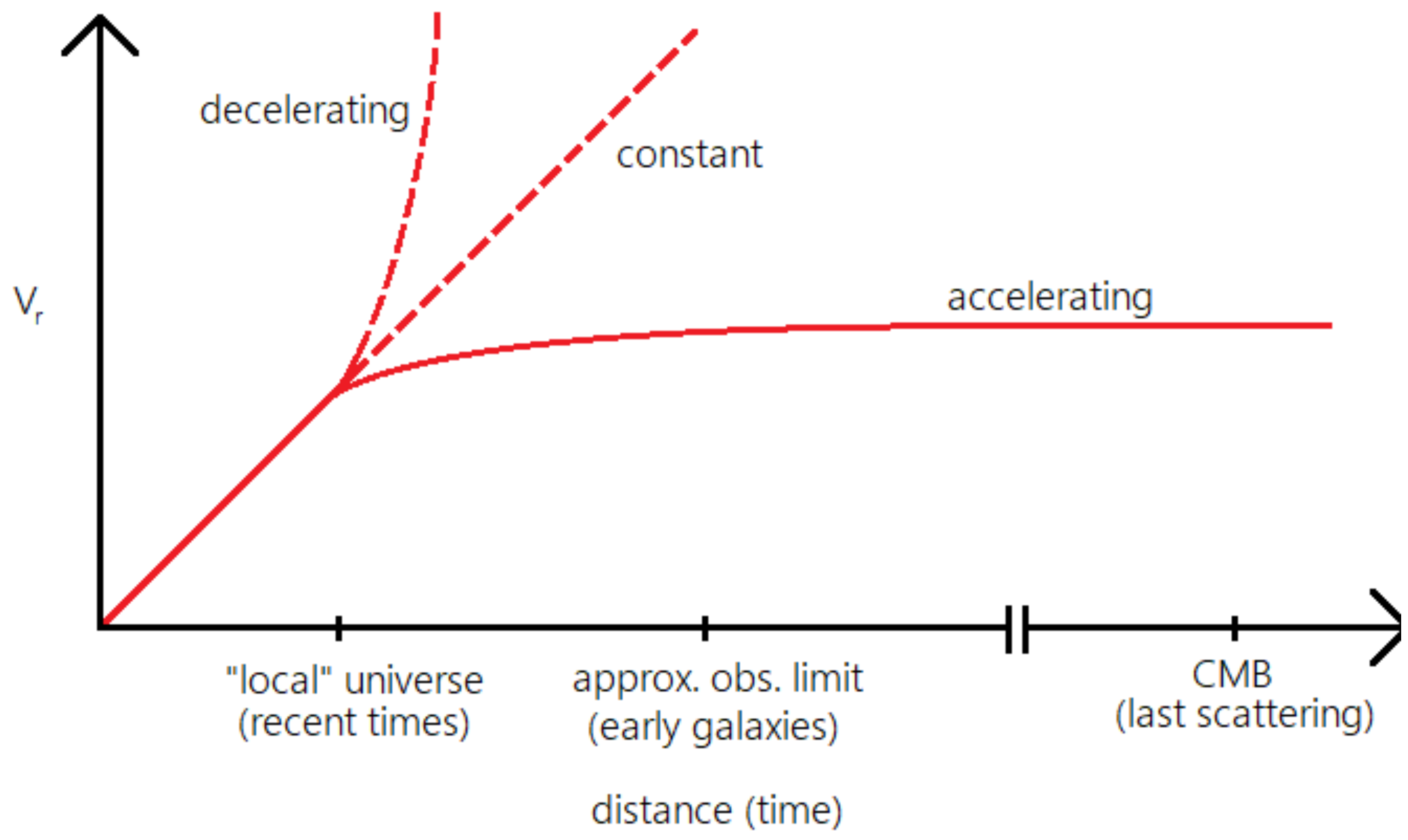
… To Explore Strange New Worlds

Big Questions: How universe formed;
How it will die; All this dark energy and dark matter…
Need to know about galaxies and their evolution to get reasonable ideas.

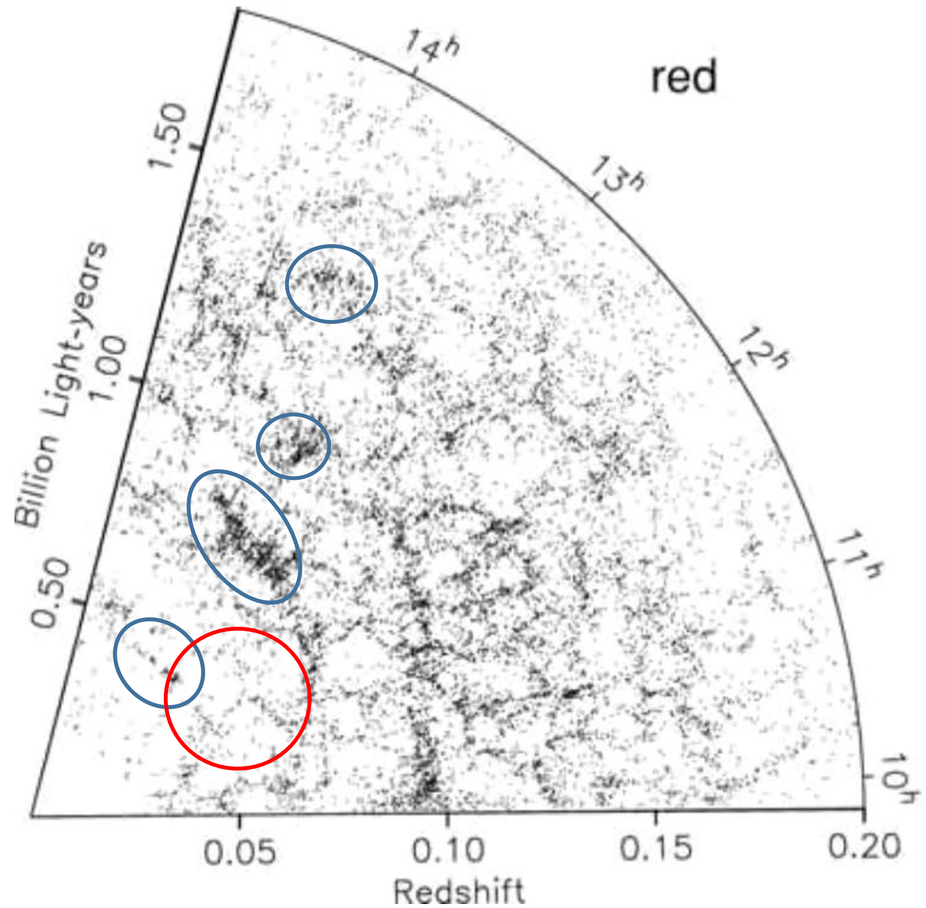
Ben:

Large Scale Structure and Cosmology

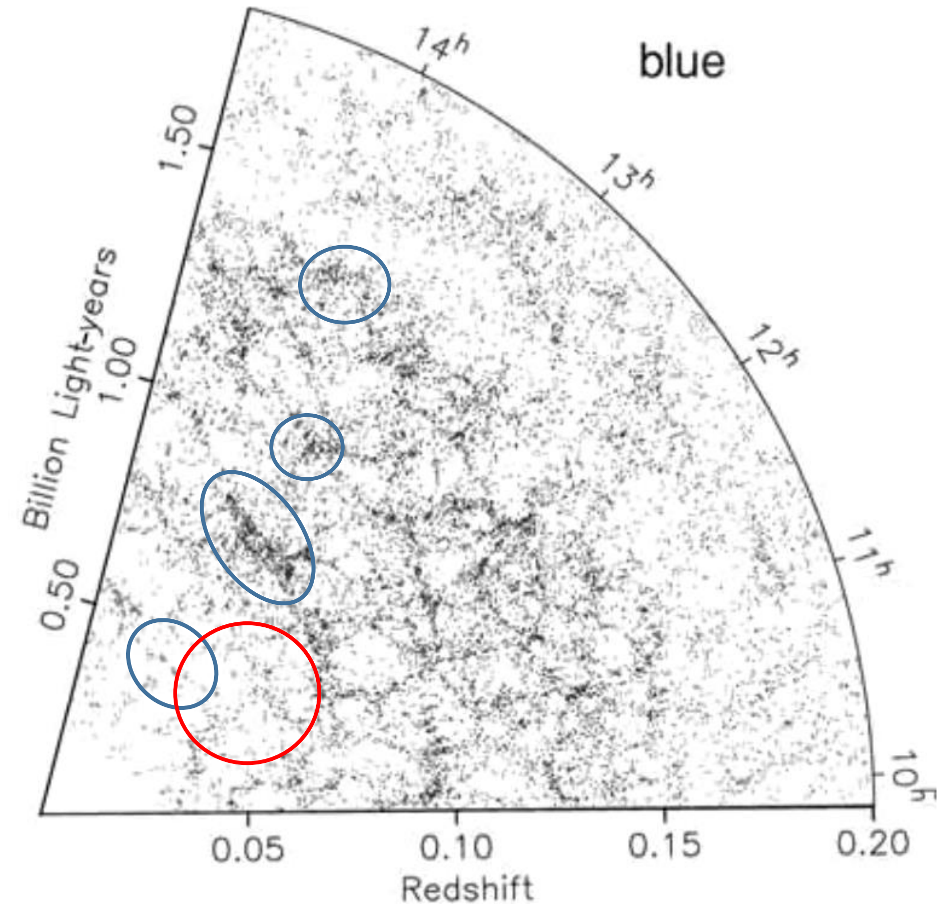
$$V_r = H_0 d + V_P$$



MORPHOLOGY DISTRIBUTION



Elliptical, S0



Spirals, Irregulars

Clustering of different morphological types.
S+G, Fig. 8.5, p. 321

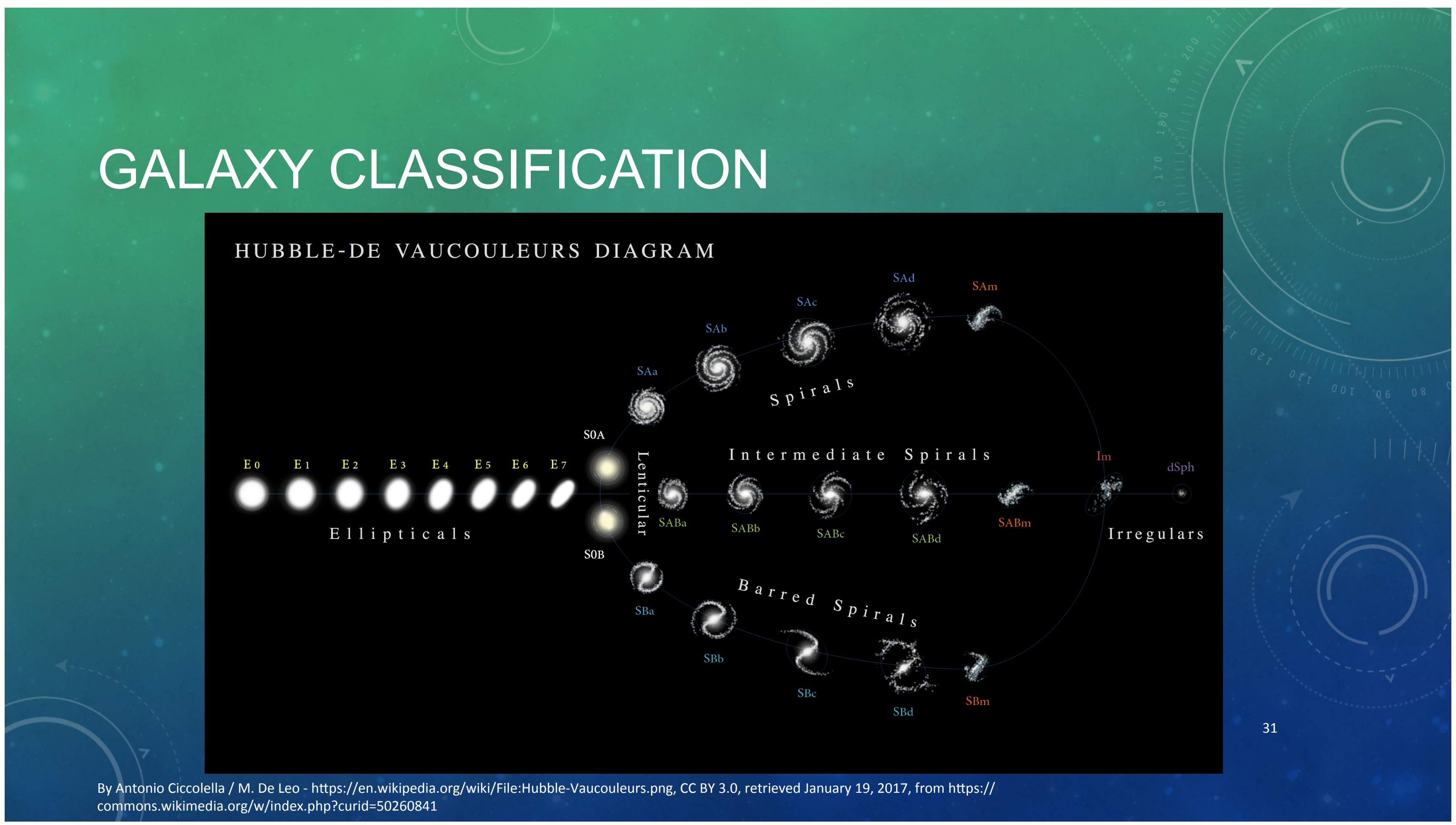
Large Scale Structure intertwined with cosmology and galaxy evolution.

Including gas flowing in along the cosmic web into galaxies.

Keagan:

Review

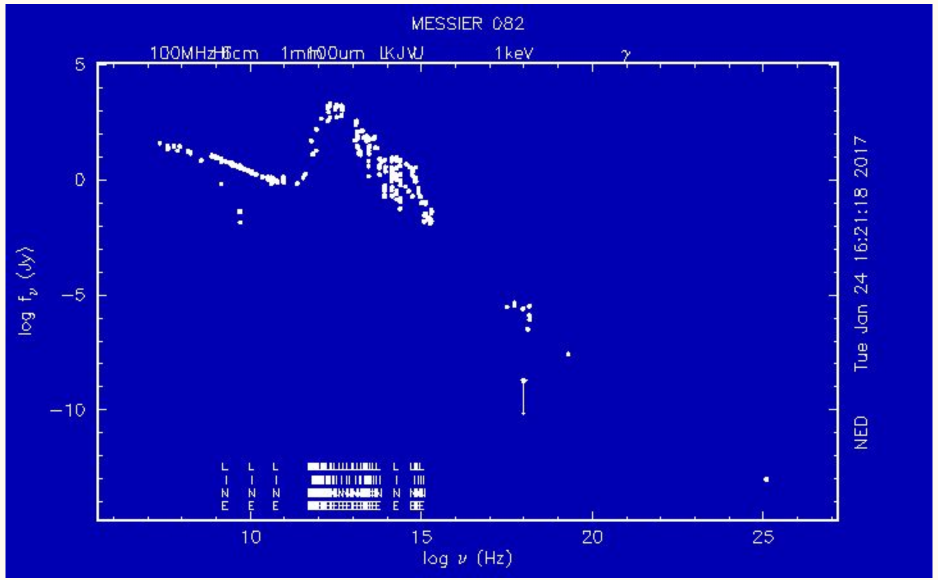
- stars (blackbody; spectra; photometry)
- Magnitudes; colour indices; filters
- less historic galaxy classification

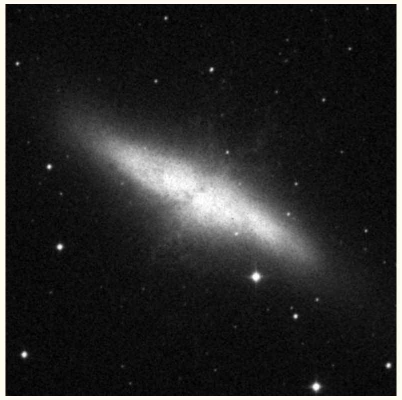


Christie:

- Continuum and Line emission
- Not Blackbody

Spectral Energy Distribution M82

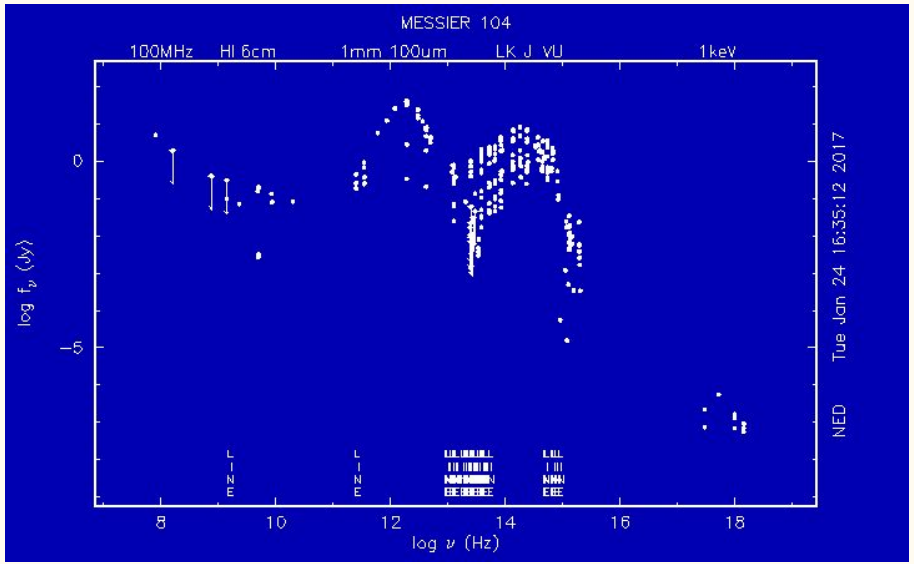


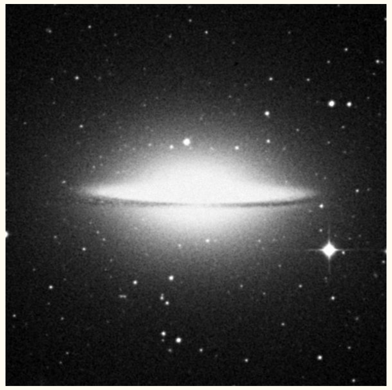


NASA/IPAC Extragalactic Database
The STScI Digitized Sky Survey

Bulge!

Spectral Energy Distribution M104





NASA/IPAC Extragalactic Database
The STScI Digitized Sky Survey

Stellar Mass-to-Light Ratio

Surface Brightness

- The surface brightness (I(x)) of a galaxy is the amount of light per square arcsecond on the sky at a particular point.
  - $I(x) = F/\boldsymbol{\alpha} = (L/4\pi d^2)/(D^2/d^2) = L/(4\pi D^2)$ (1.23)
- Units: mag arcsec^{-2} (the apparent magnitude of a star that appears as bright as one square arcsecond of the galaxy's image) or $L_\odot$ pc^{-2}
- The surface brightness at any point does not depend on distance d unless a galaxy is so far away that the expansion of the Universe reduces I(x).

Sparke & Gallagher (2007, p. 42)

Luminosity Function: L* and M* galaxies

The Schechter Function

- ❑ The Schechter function overestimates the density of very faint galaxies, however most of the light comes from galaxies close to L*.

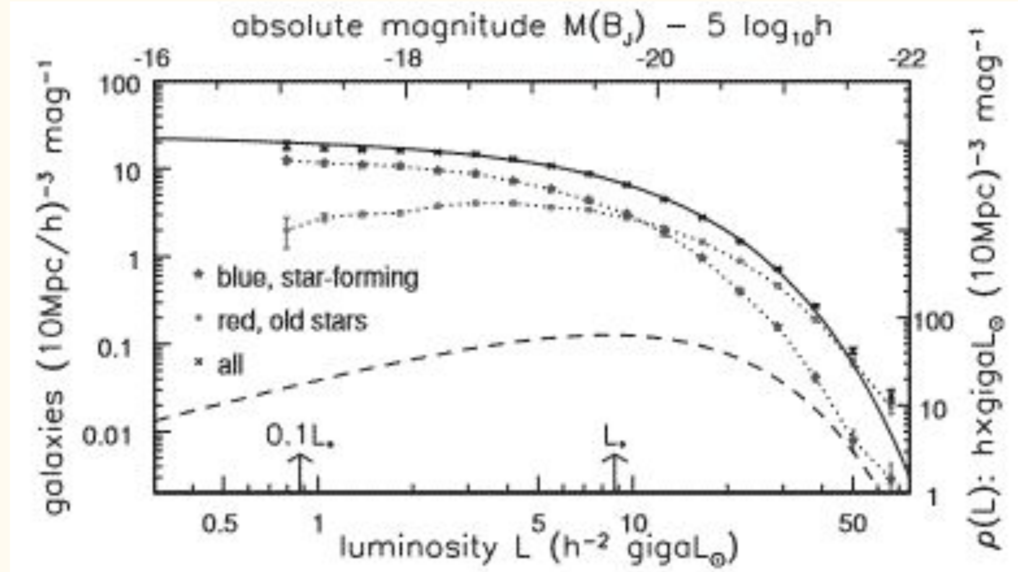


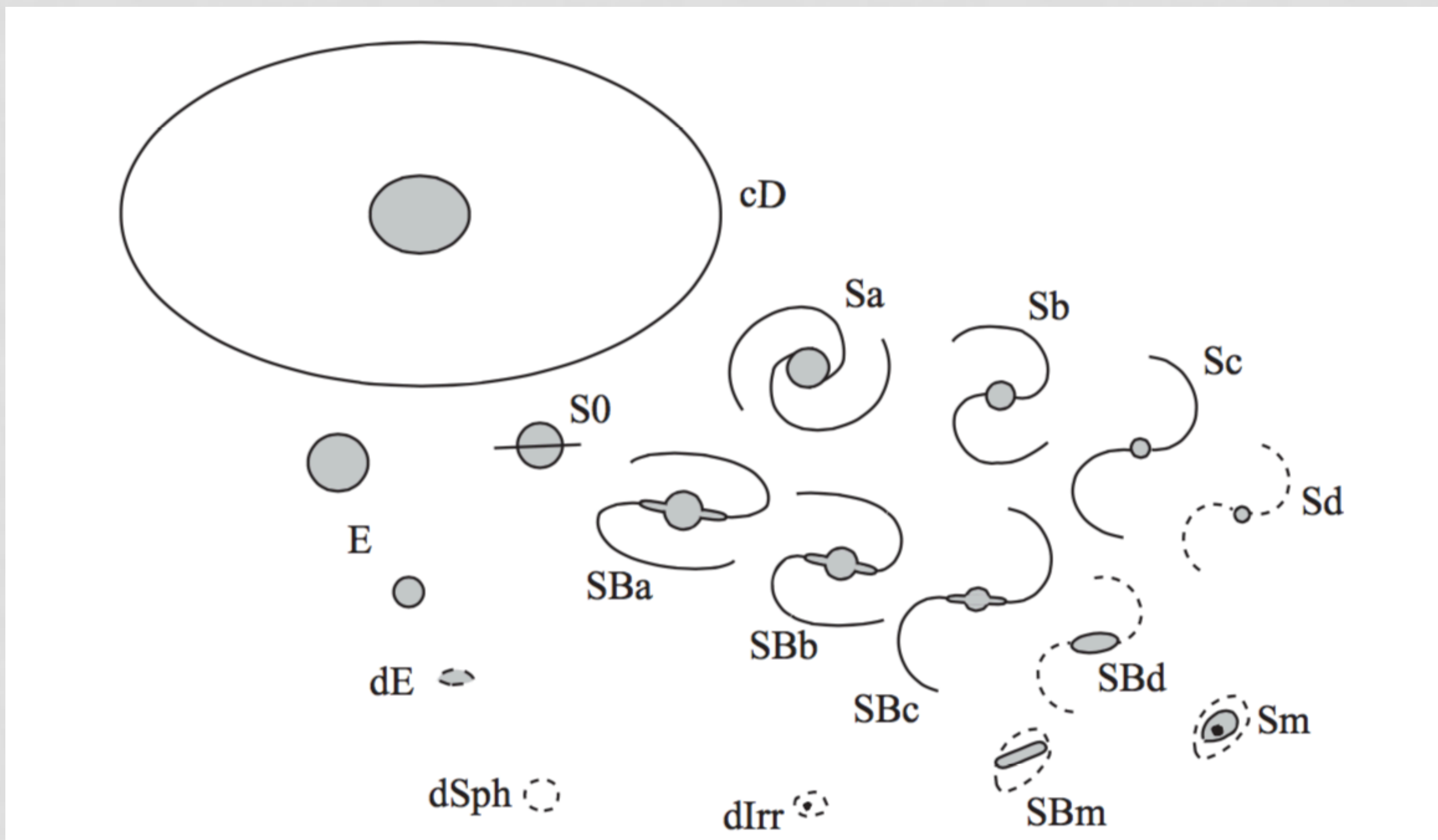
Fig. 1.16. Number of galaxies per 10 Mpc cube between absolute magnitude $M(B_J)$ and $M(B_J) + 1$ (crosses). Dotted lines show numbers of blue (stars) and red (filled dots) galaxies making up this total; vertical bars indicate errors. The solid line shows the luminosity function of Equation 1.24; the dashed line gives $\Phi(M) \times L/L_\star$, the light from galaxies in each interval of absolute magnitude. The blue bandpass B_J is matched to the photographic plates used to select the galaxies – 2dF survey, D. Croton.

Sparke & Gallagher (2007, p. 45)

- Malmquist Bias (Kate; Assignment) error

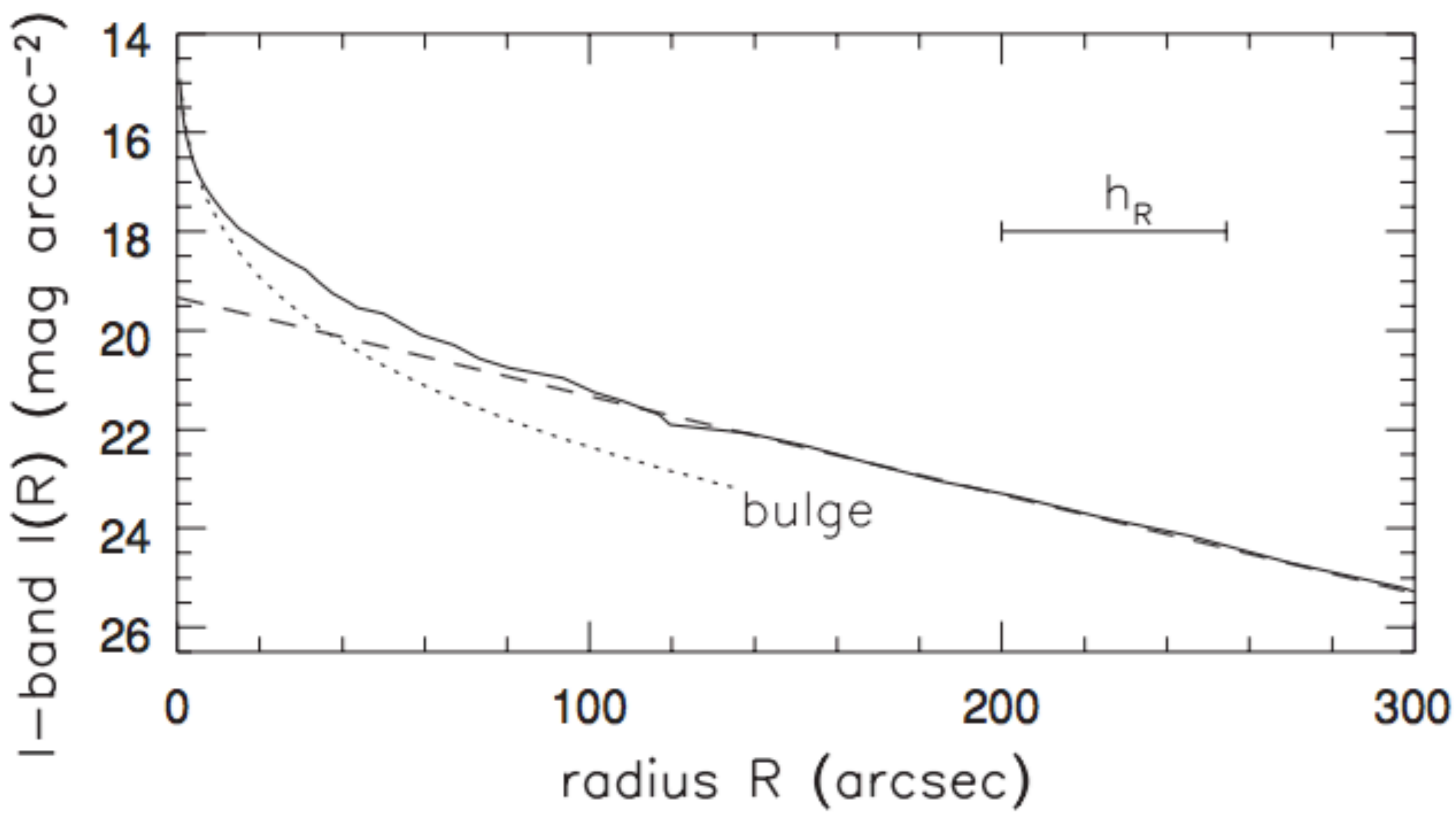
Kate: Photometry of Spirals

AN ALTERNATE HUBBLE DIAGRAM



Retrieved from Sparke & Gallagher
"Galaxies in the Universe" 2nd ed. p. 38

Mug:



$$I(R,z) = I(R)\exp\left(-\frac{|z|}{h_z}\right)$$

SPIRAL STRUCTURE (CONT.)

- Barred
  - The bars are elliptically shaped
  - Often contain rings or lenses
  - Often lopsided – the bar and bulge not necessarily at the center of the galaxy's light distribution

Barred spiral galaxy example NGC 1300

Image retrieved from APOD Feb 1 2017: https://apod.nasa.gov/apod/ap160109.html

Information taken from Binney and Merrifield "Galactic Astronomy" 1998

Bars and Rings?

Ben: Photometry of Ellipticals

LUMINOSITY PROFILE

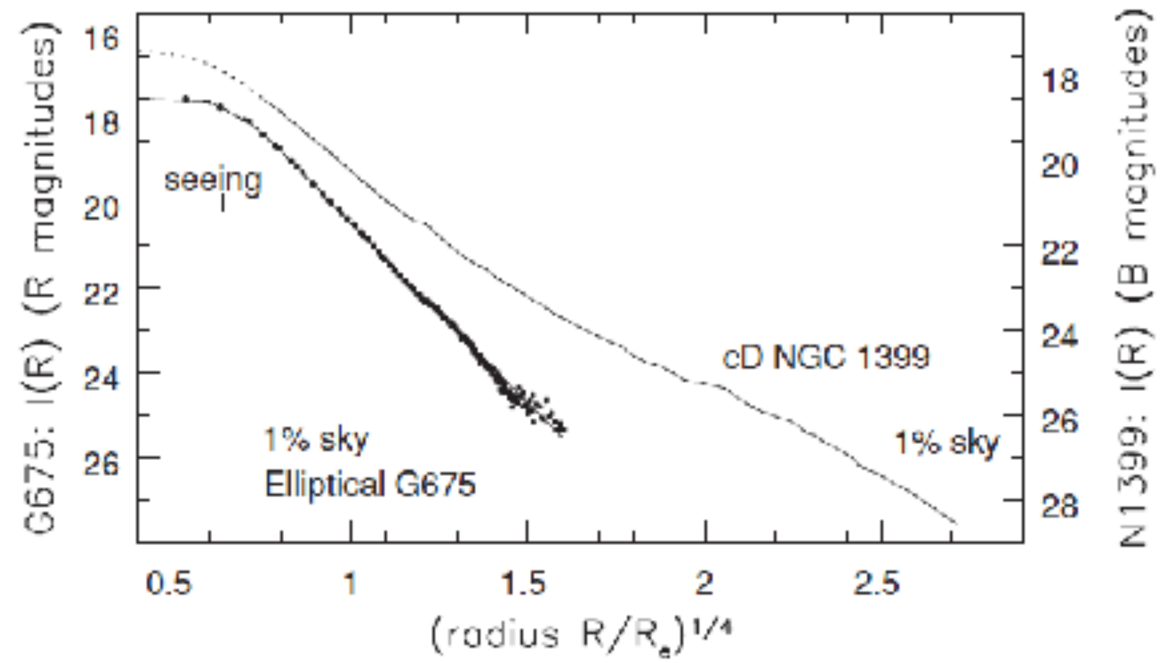
- Very little absorption by dust
- SB of ellipticals highly concentrated in centre
- Can use Sersic's formula to model SB, with modifications:

$$I(R) = I(R_e)e^{-b\left(\frac{R}{R_e}\right)^{\frac{1}{n}}-1}$$

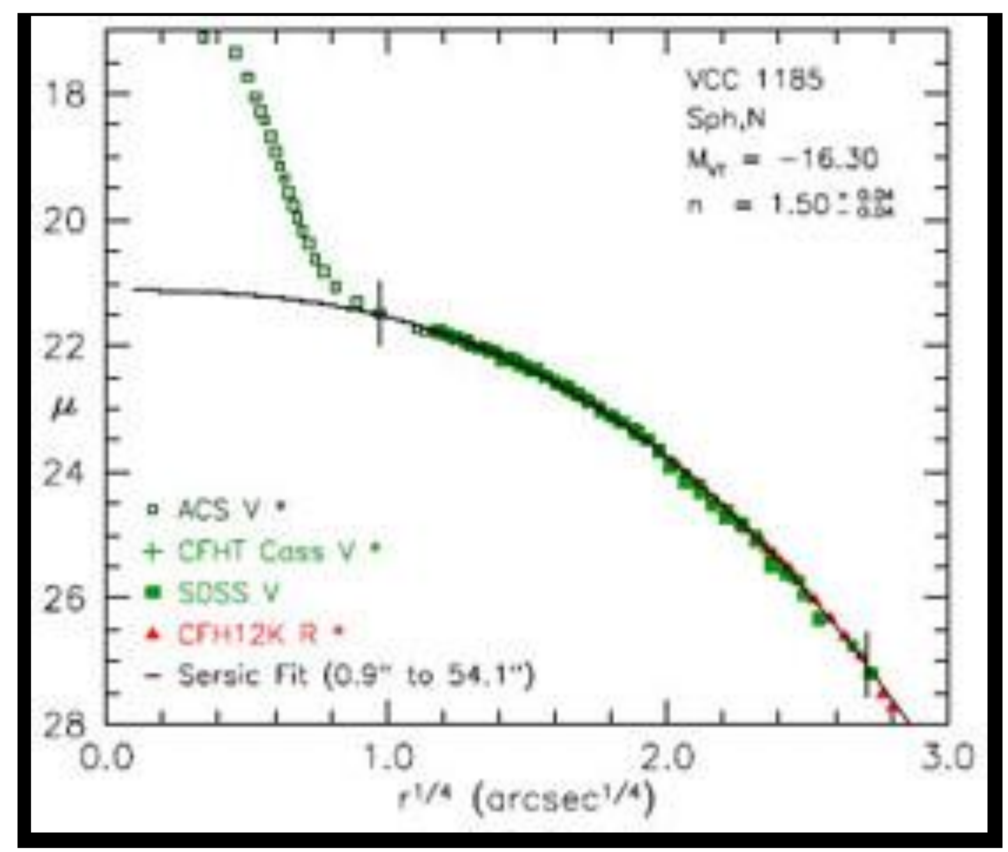
- R_e is the radius of circle enclosing half the light
- For large galaxies, we take $n = 4$, $b \cong 1.999n - 0.327$
- For small ones, we just use the exponential:

$$I(R) = I(R_e)e^{\frac{-R}{R_e}}$$

(S+G, pp. 242-4, 2007)



- Cusp
- Core



Globular Cluster M15

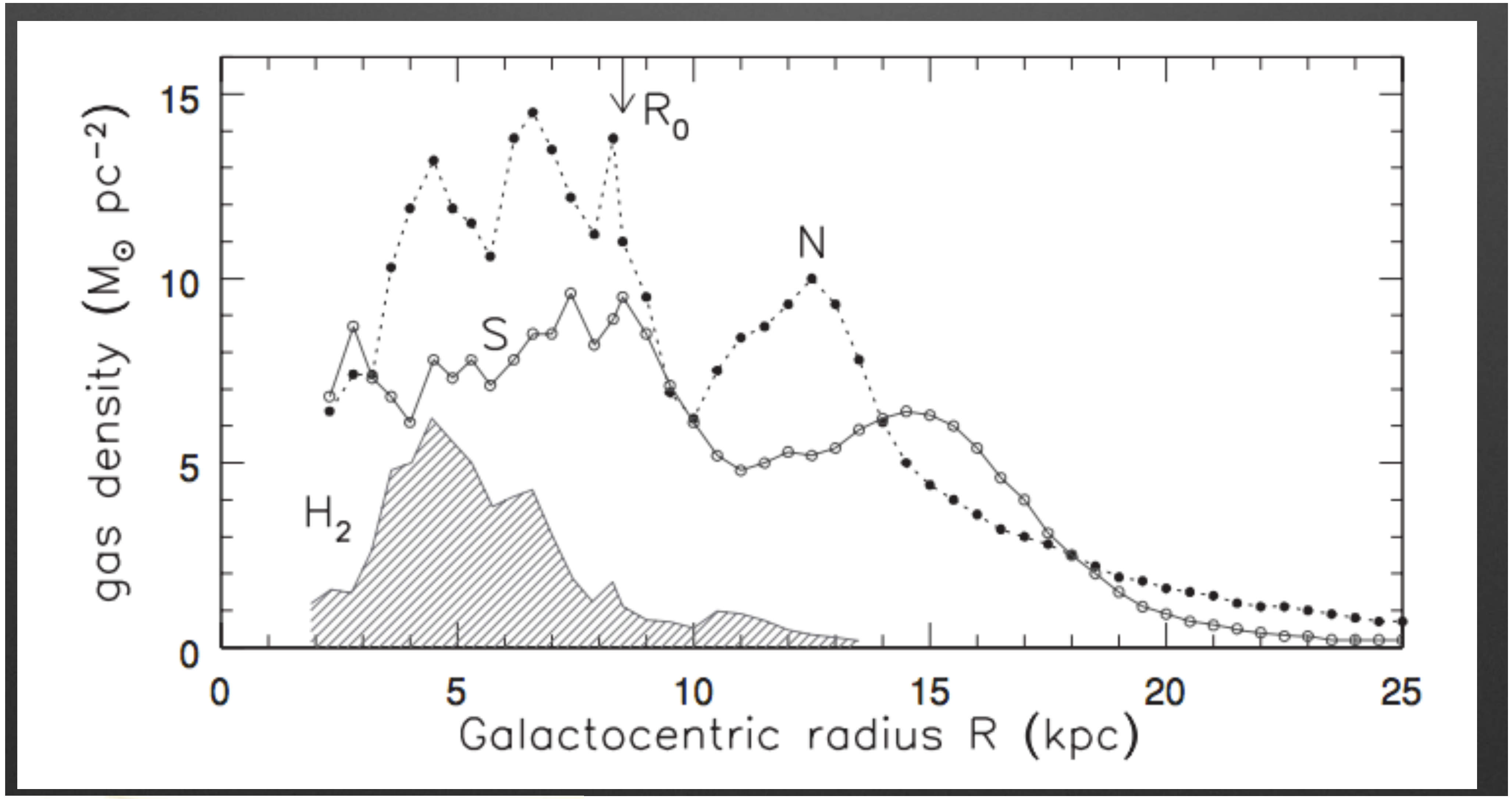
NASA and the Hubble Heritage Team (STScI/AURA - Hubble Space Telescope WFPC2 - STScI-PRC00-25


NEVER
TRUST
AN ATOM
They Make Up
Everything

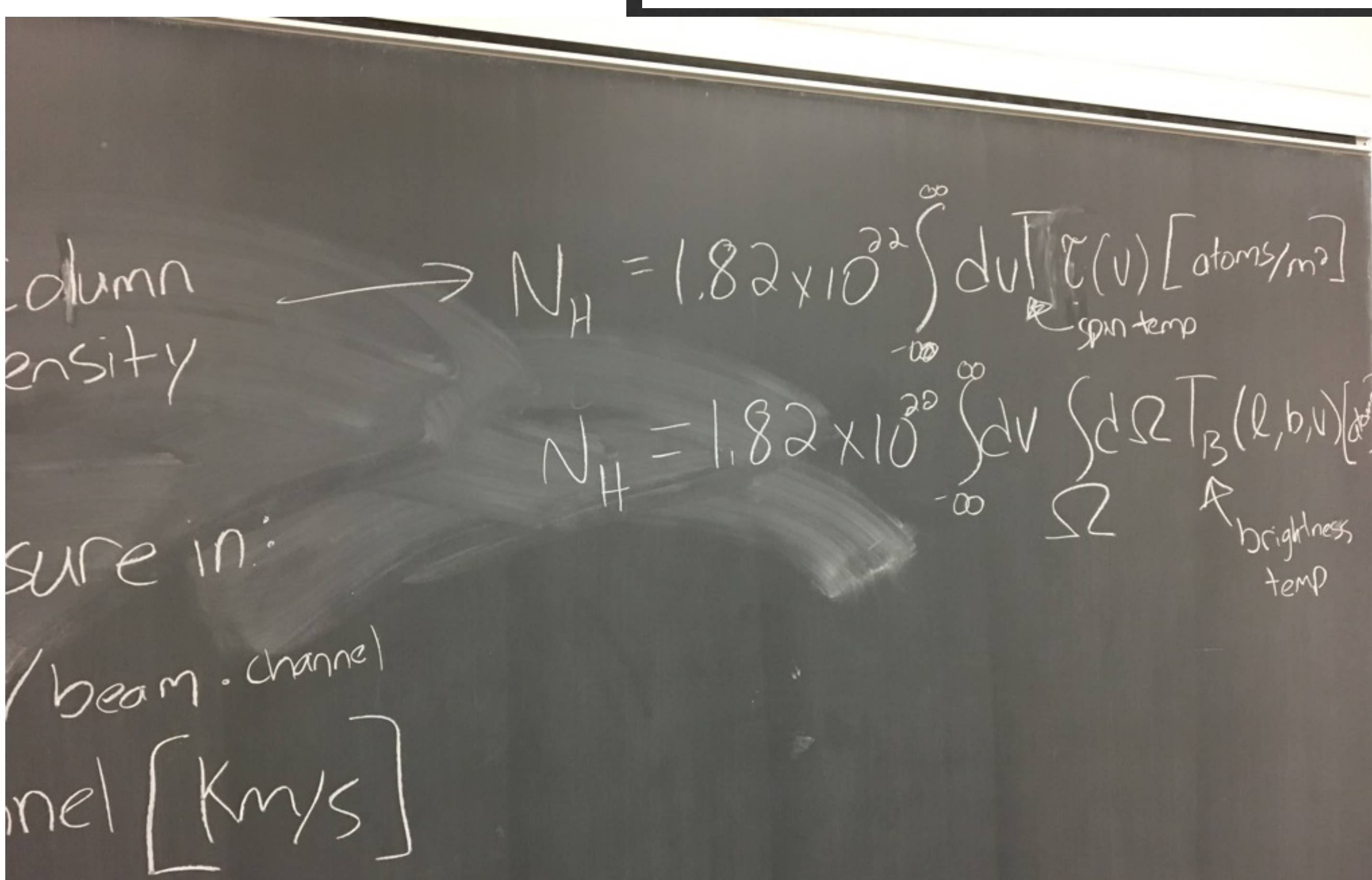
Jordan:

Milky Way Composition

Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Dust grains						10^7–10^8	Tiny
large $\lesssim 1\ \mu m$	Silicates, soot		~20		150 pc		
small ~ 100 Å	Graphitic C		30–100				
PAH < 100 atoms	Big molecules				80 pc		
Cold clumpy gas	Molecular: H_2	> 200	< 100	Big	80 pc	(2) × 10^9	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3 × 10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2 × 10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	1–10^4	~10 000	Big	80 pc	5 × 10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	~10^6	2 500	~5 kpc	(10^8)	45%
Gas motions	$\frac{3}{2}\langle\rho_{HI}\rangle\sigma_r^2$	$\langle n_H \rangle \sim 0.5$	10 km s^{-1}	8 000			
Cosmic rays	Relativistic	1 eV cm^{-3}		8 000	~3 kpc	Tiny	
Magnetic field	$B \sim 5\ \mu G$	1 eV cm^{-3}		8 000	~3 kpc		
Starlight	$\langle \nu h_P \rangle \sim 1$ eV	1 eV cm^{-3}			~500 pc		
UV starlight	11–13.6 eV	0.01 eV cm^{-3}					



gas density (M⊙ pc⁻²)
Galactocentric radius R (kpc)
R0
N
S
H2
0
5
10
15
20
25



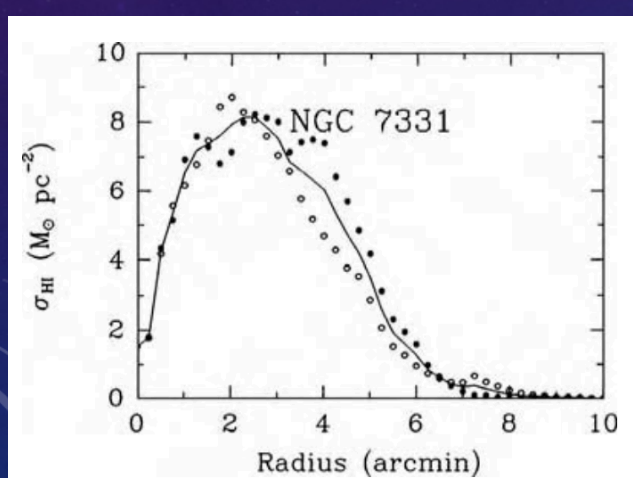
olumn
ensity
N_H = 1.82x10^22 ∫ dv T τ(v) [atoms/m2]
spin temp
N_H = 1.82x10^20 ∫ dv ∫ dΩ T_B(l,b,v)
brightness temp
sure in:
/beam · channel
nel [Km/s]

Using the gas…

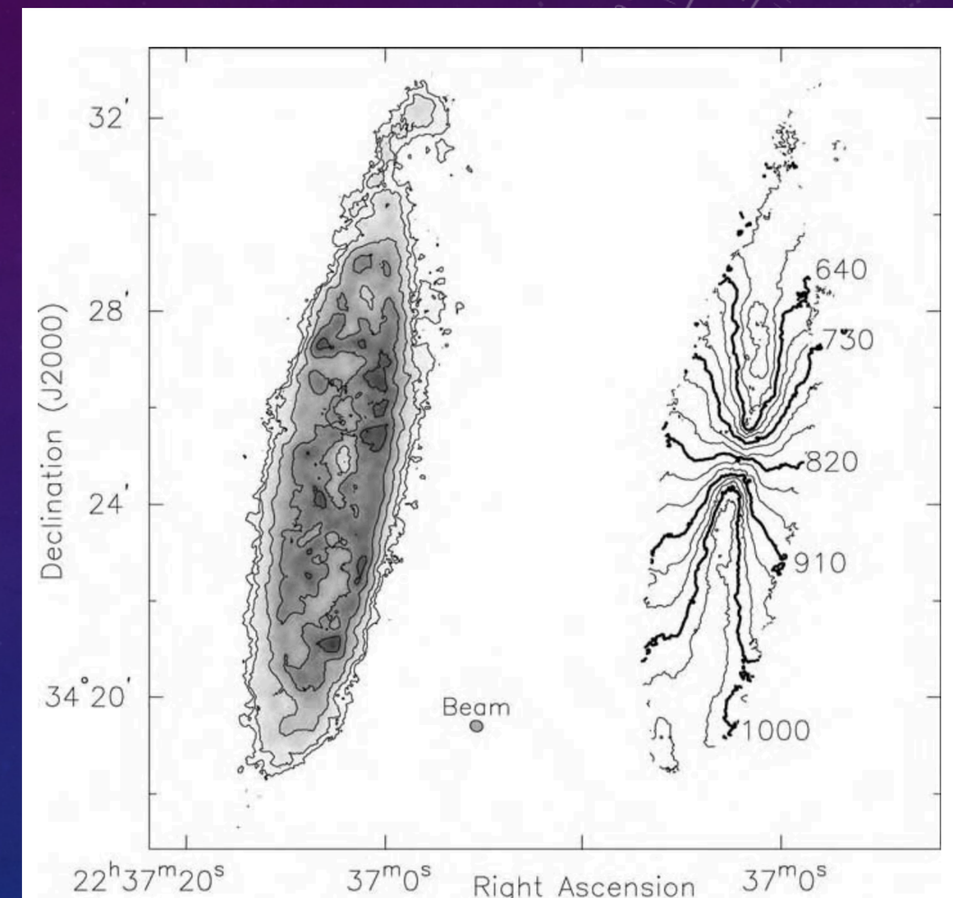
Dan: Cold gas; Telescopes; analysis (moment maps, channel maps)

Data – Moment Maps

- ’Moment Zero’ Map gives N_{HI} (column density)
- Summing globally gives gas mass
- We also get density vs. radius



Density vs. radius
[S&G pg. 211



NGC 7331 Moment zero map (left) and velocity field map (right) – Data from VLA [S&G pg. 210]

Craft Time!

Congratulations to Wolfgang who actually finished his! The extra decorations are in OPUS if anyone would like to bedazzle their antenna.

Wolfgang:

TULLEY-FISHER RELATION

- The width of the HI distribution, ΔV, can be seen to correlate well with absolute magnitude
- This works even though the rotation velocity is dictated largely by non-visible mass
- This can be used to measure the distance to galaxies, by calculating a distance modulus

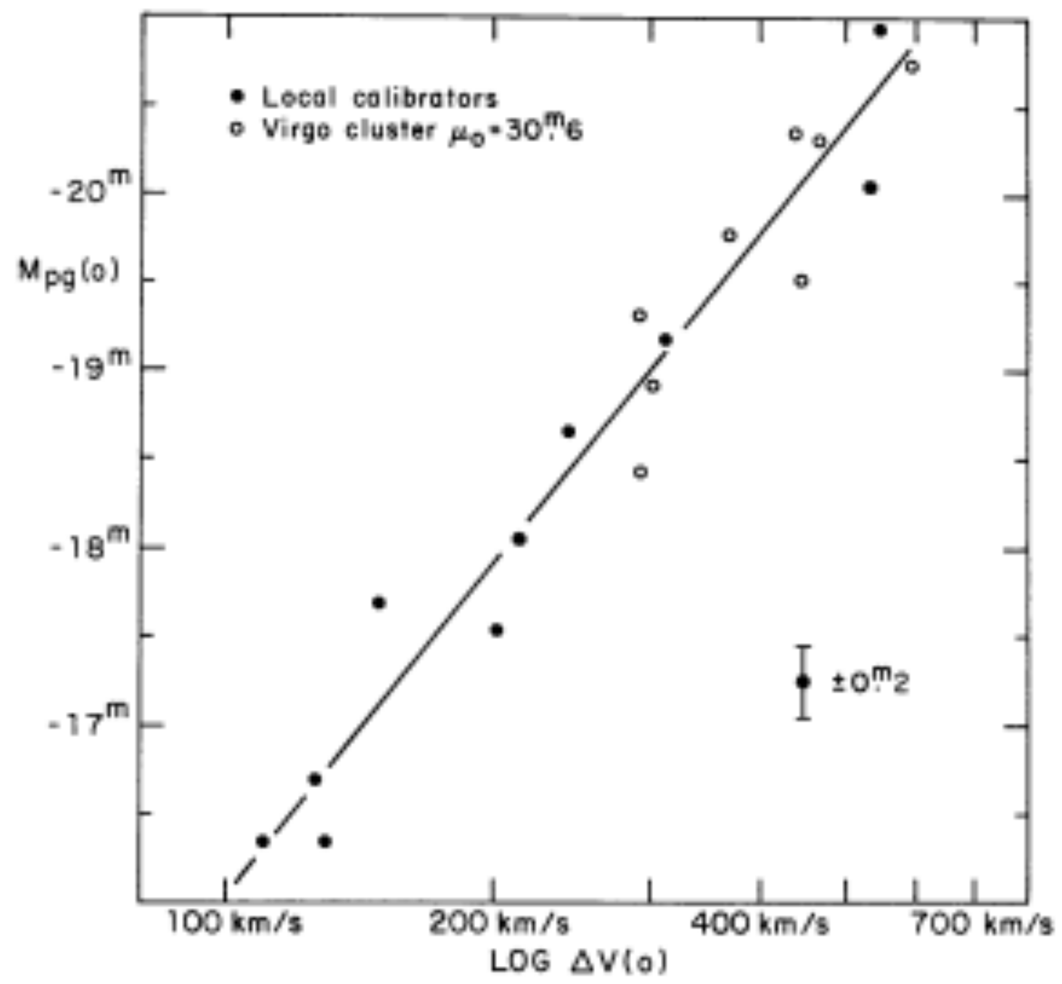
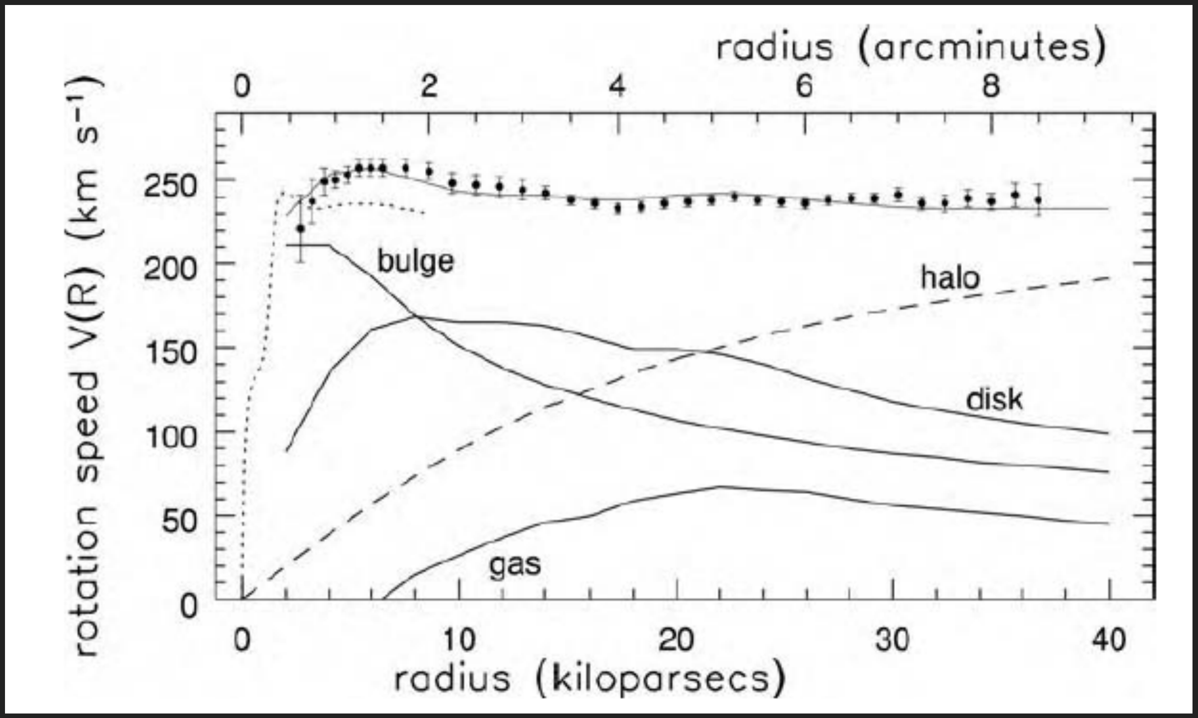


Fig. 5 (a) Absolute magnitude — global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30^m.6 \pm 0^m.2$

Tully, R. B. and Fisher, J. R., "A new method of determining distances to galaxies". Astronomy and Astrophysics, vol. 54, no. 3, Feb. 1977, pp. 661–673

Galaxy Mass-to-light Ratio; Mass Modelling —-> Dark Matter

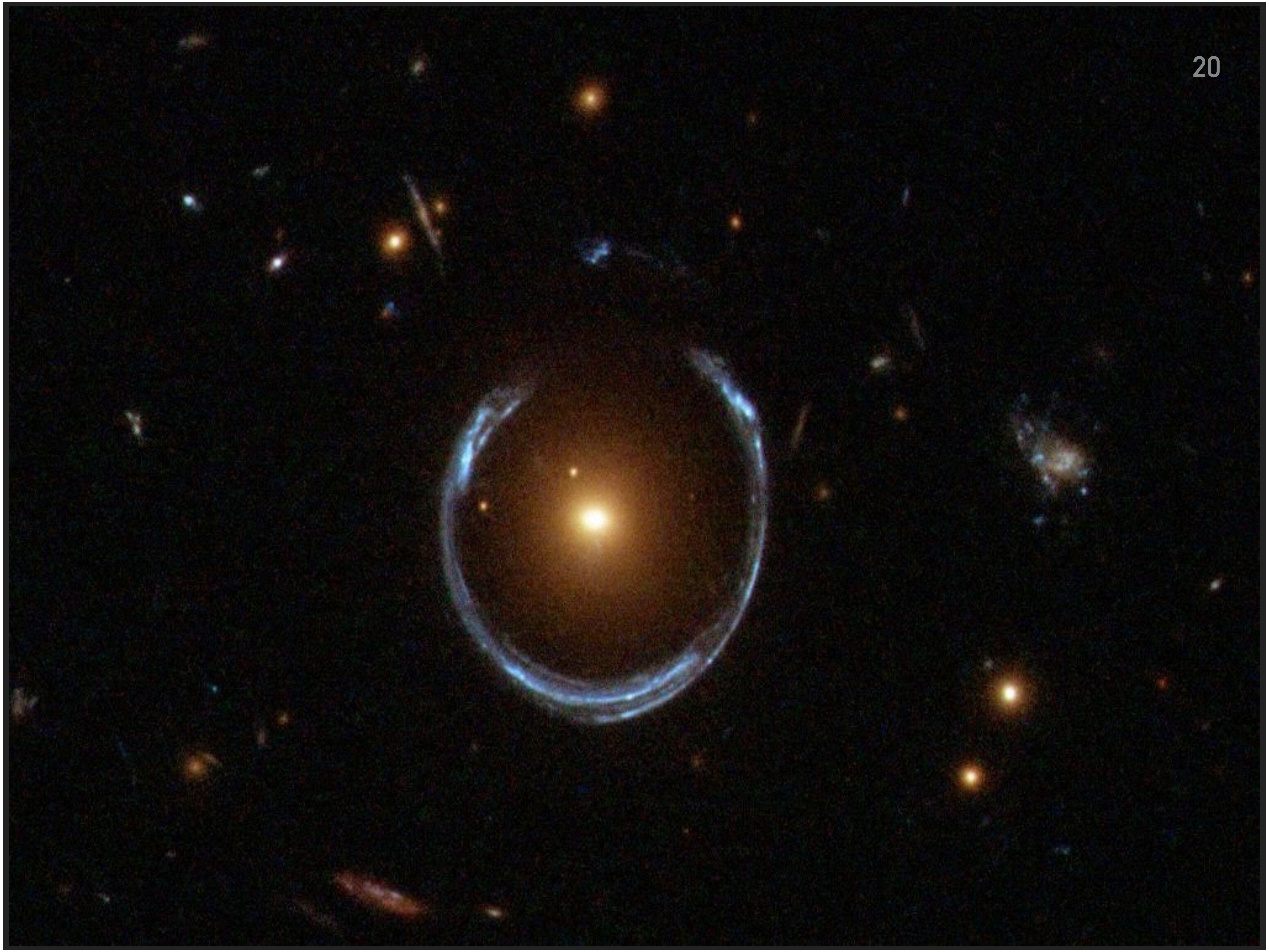
RADIO HI



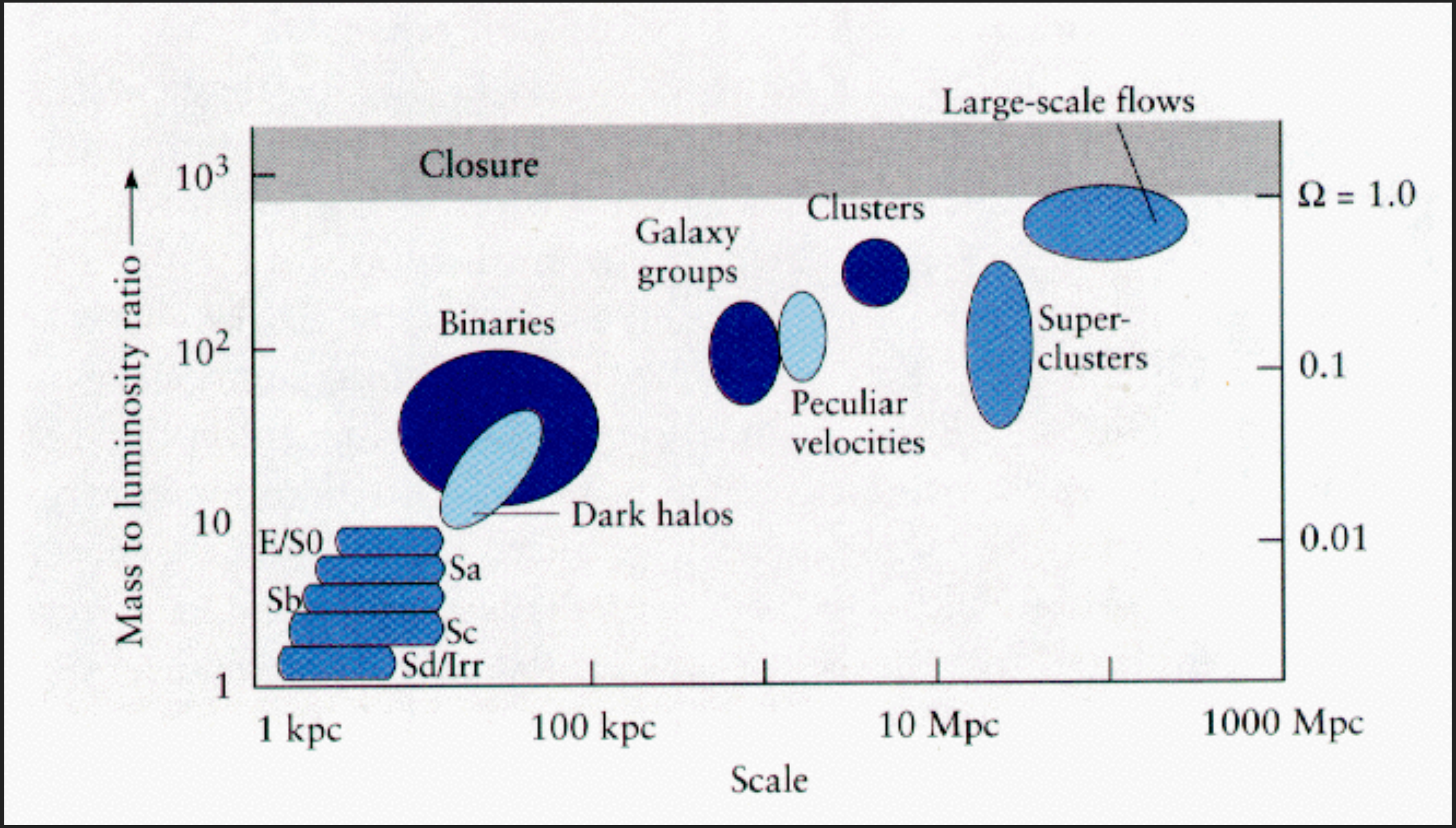
- Dynamical mass is the mass calculated from the observed dynamics of the system, the line at the top
- The predicted rotation curve due to luminous mass is shown below, and is insufficient to account for the total mass. The dashed line must be added

Sparke & Gallagher, p.217

Don’t need Newton’s Laws — still get DM with Gravitational Lensing

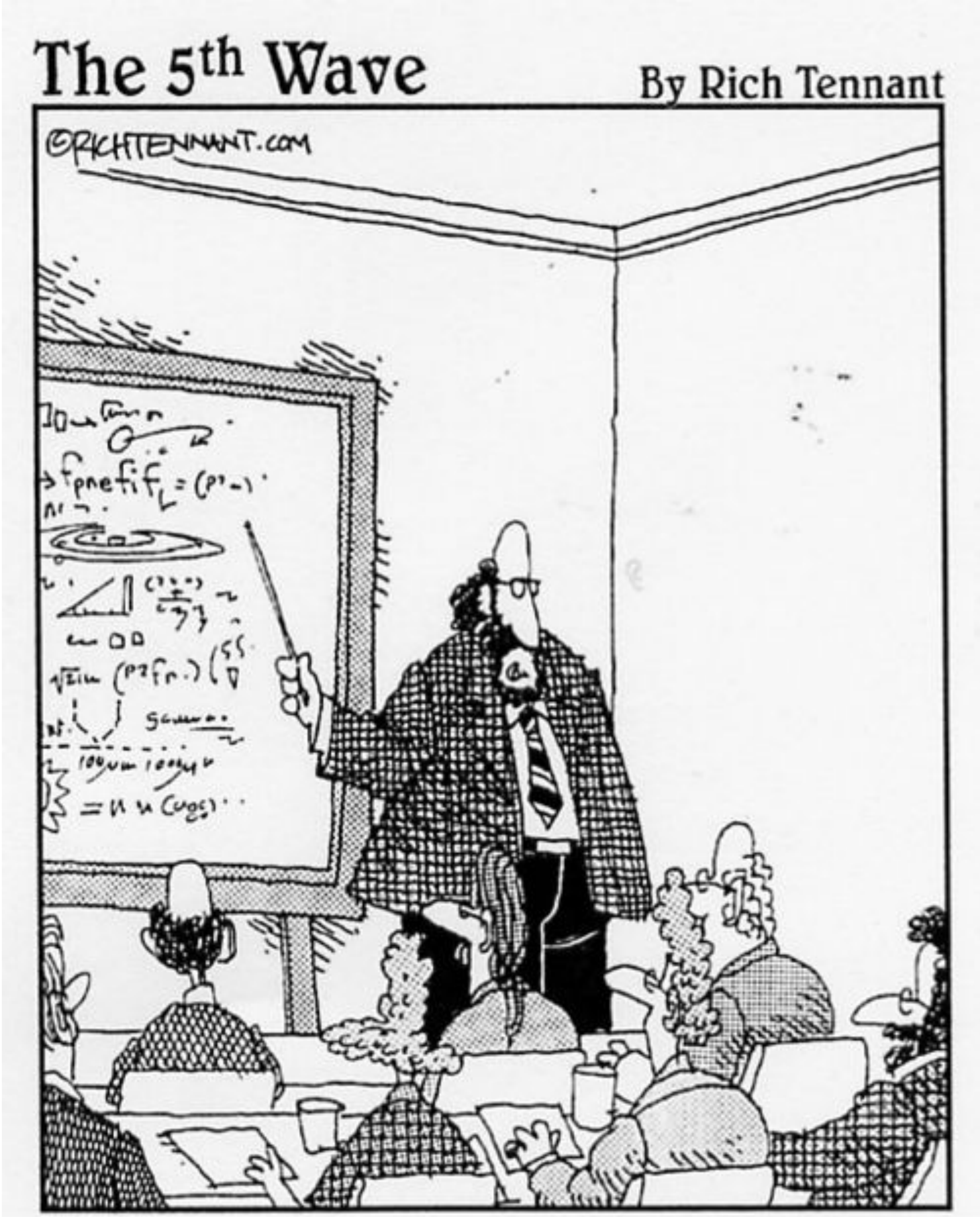


MASS-TO-LIGHT RATIOS IN THE UNIVERSE



- The larger scale we look at, the more M/L begins to look like the number derived by cosmological models

Image: lecture given by James Schombert



"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

Cole:

Molecular Gas

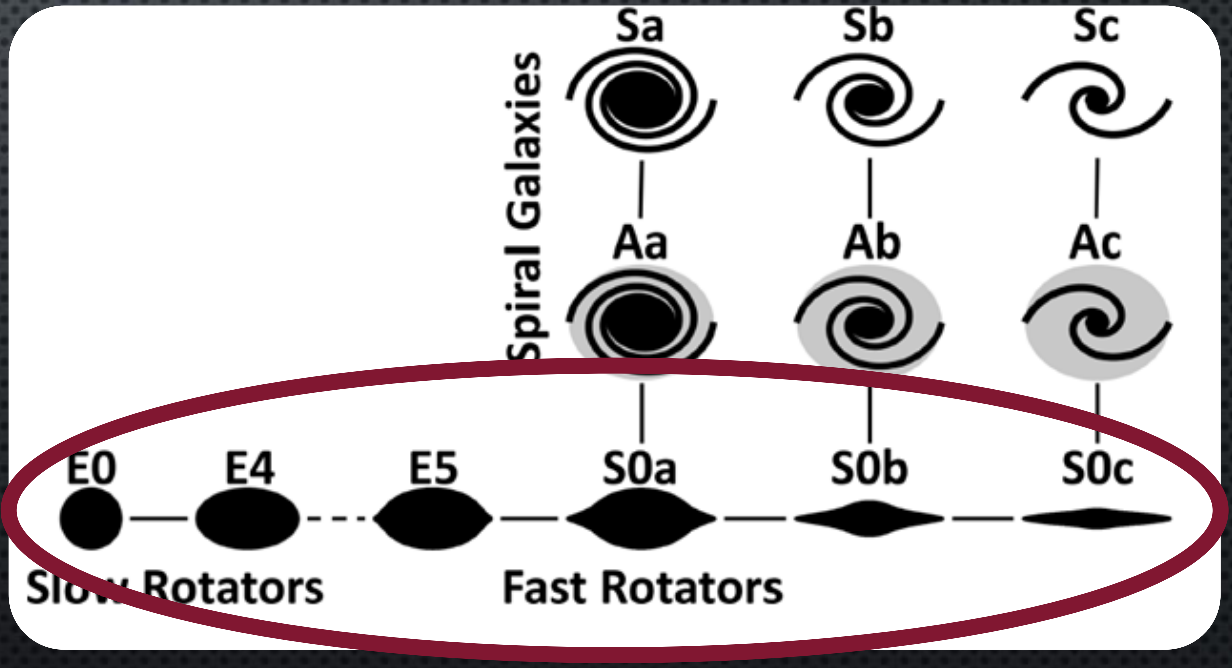
CONVERSION FROM CO TO H_2

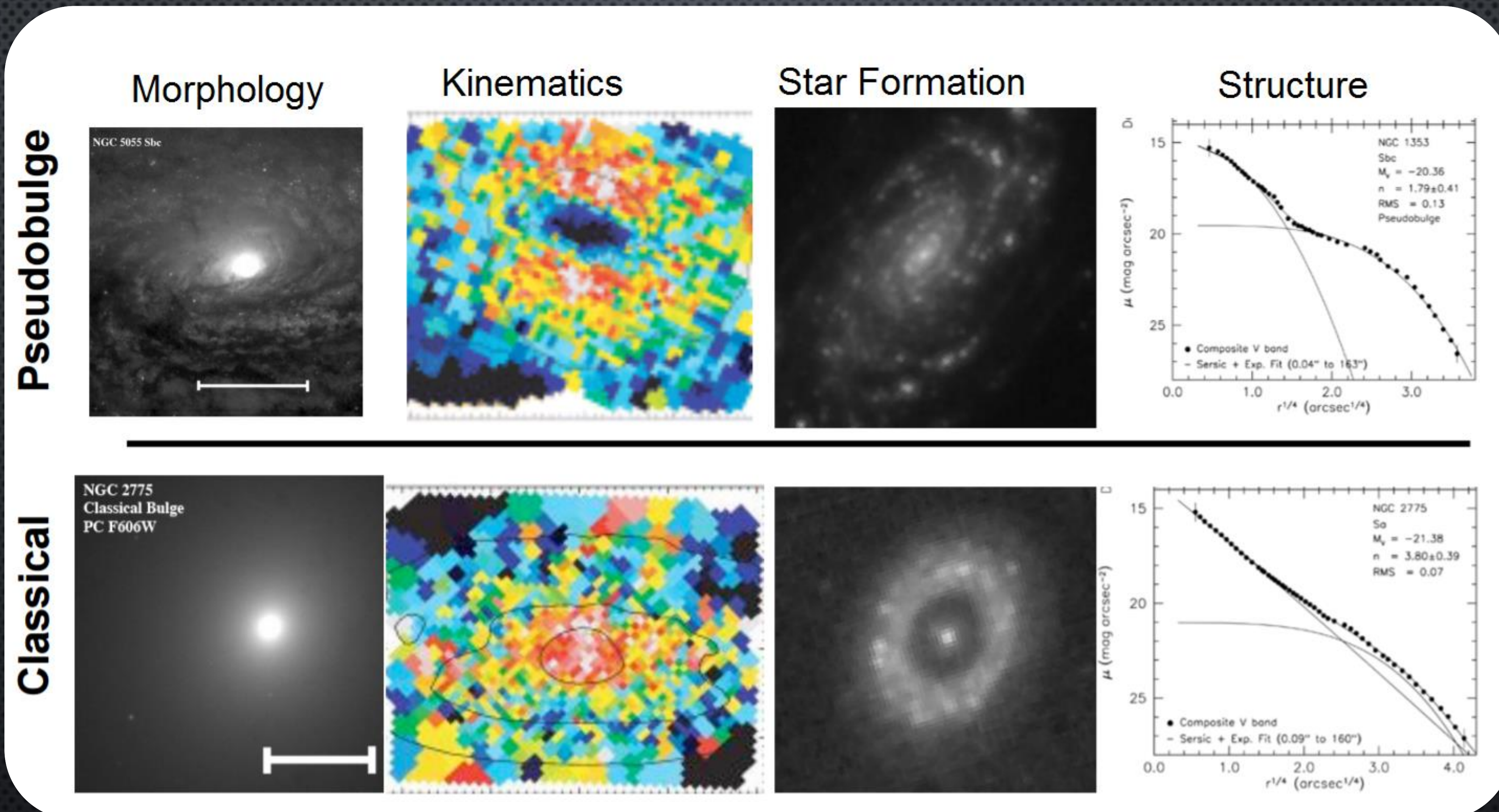
- RELATIONSHIP BETWEEN CO LINE STRENGTH AND H_2 DENSITY FOR THE $J = 1 \rightarrow 0$ TRANSITION
- *X* IS THE CONVERSION FACTOR
- STANDARD *X* FOR THE MILKY WAY IS
  $X = (2.3 \rightarrow 2.8) \times 10^{20}\ \mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}$
- *X* VARIES BASED ON METALLICITY AND GALACTIC MORPHOLOGY
  $X = (0.6 \rightarrow 10) \times 10^{20}\ \mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}$

$$\left[\frac{\mathcal{N}_{\mathrm{H}_2}}{\mathrm{cm}^{-2}}\right] = X \int_v \left[\frac{\mathrm{T_B}[\mathrm{CO}(J = 1 \rightarrow 0)]}{\mathrm{K}}\right] \left[\frac{dv}{\mathrm{km\,s}^{-1}}\right]$$

ACTUAL PROPERTIES OF EARLY-TYPE GALAXIES

- STILL DO NOT EXHIBIT MUCH ACTIVE STAR FORMATION
  - DO CONTAIN GAS AND DUST: CO IS QUITE PROMINENT
- STARS CAN FOLLOW AN ORDERLY ORBIT





Morphology
Kinematics
Star Formation
Structure
Pseudobulge
Classical
NGC 5055 Sbc
NGC 1353
Sbc
M_V = −20.36
n = 1.79±0.41
RMS = 0.13
Pseudobulge
Composite V band
Sersic + Exp. Fit (0.04" to 163")
μ (mag arcsec⁻²)
r^1/4 (arcsec^1/4)
NGC 2775
Classical Bulge
PC F606W
NGC 2775
Sa
M_V = −21.38
n = 3.80±0.39
RMS = 0.07
Composite V band
Sersic + Exp. Fit (0.09" to 160")
μ (mag arcsec⁻²)
r^1/4 (arcsec^1/4)

Robert: Interactions, Mergers, Starburst, AGN

Galaxy Interactions – Major and Minor

- Major interactions are interactions in which the interacting galaxies have similar (i.e. within an order of magnitude) masses
  - Causes significant tidal disruption of both galaxies
- Minor interactions involve galaxies with significantly different masses
  - Parent (larger galaxy) not significantly affected
  - Includes satellite interactions

Toomre Sequence

- Peculiar galaxies are transient phenomena
- Colliding spirals generally produce an elliptical galaxy
  - Note that this is the opposite of the Hubble tuning fork
- Will deal more with this on the assignment

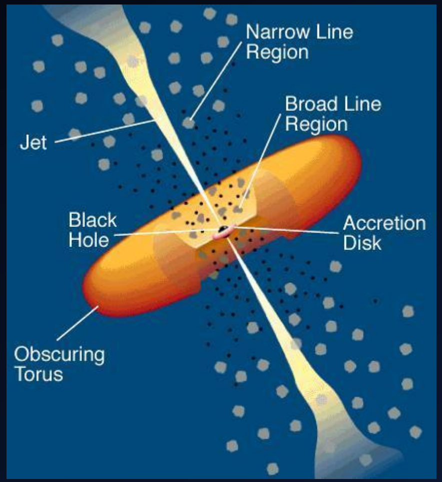
Starburst Galaxies

- Starbursts are typically quite blue in optical because of a burst of star formation within the last few Gyr
- Typically produce the majority of their luminosity in IR

Antennae galaxies, Hubble Heritage

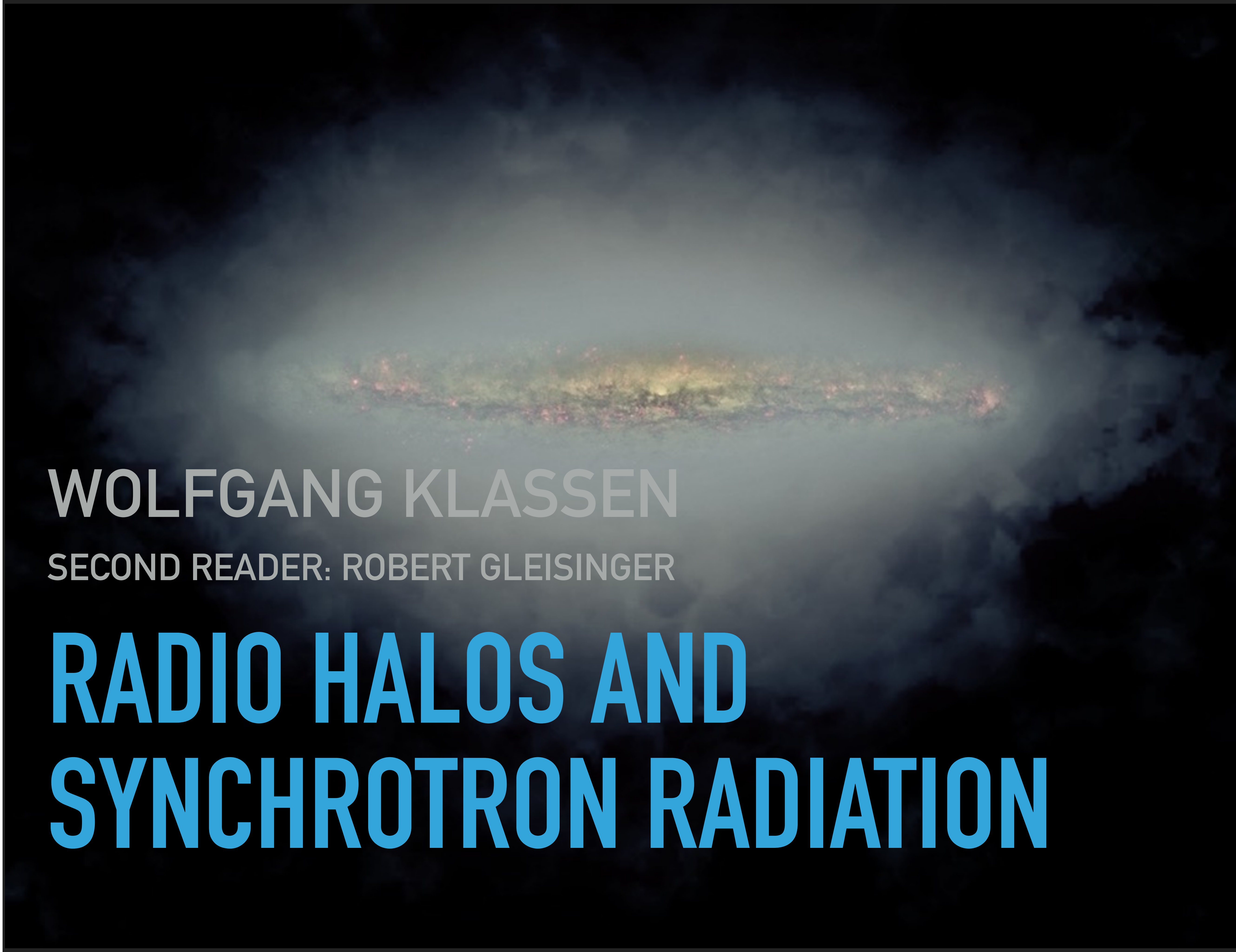
AGN Unification

- A family of models that is intended to explain the vast diversity of AGN classes with a similar set of structures
- Includes:
  - Supermassive black hole
  - Accretion disk
  - Obscuring clouds
  - Outflows/Jets



AGN Unification Model Urry & Padovani 1995

As galaxies interact/merge gas also flows along cosmic web so that, while some mergers become Es, others form bulges and disks (from web) forming S and SBs.

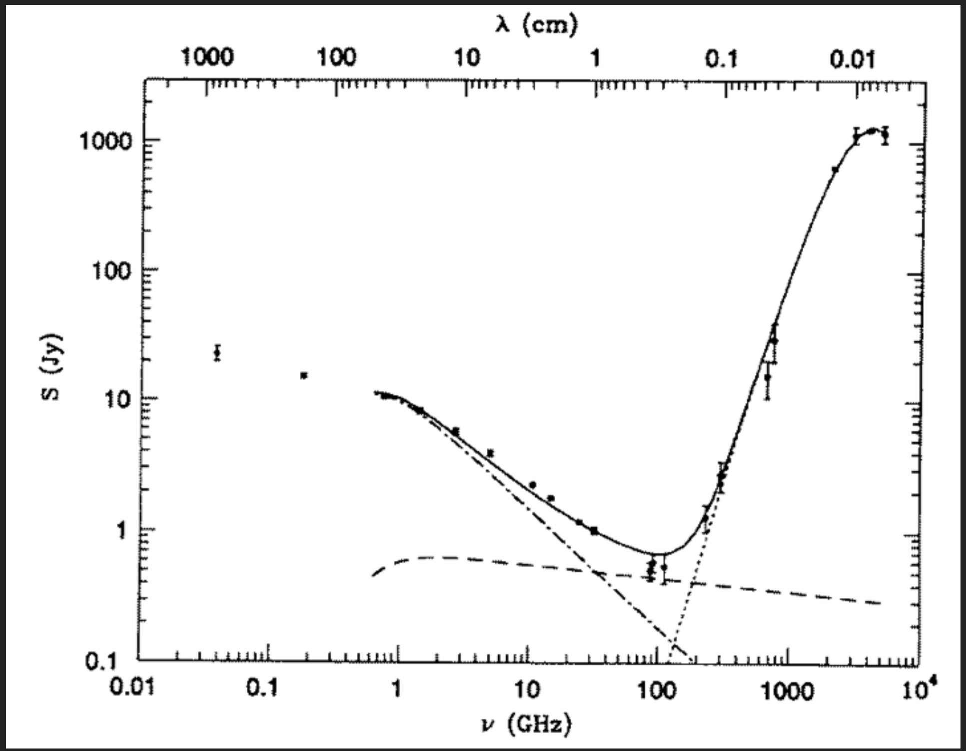


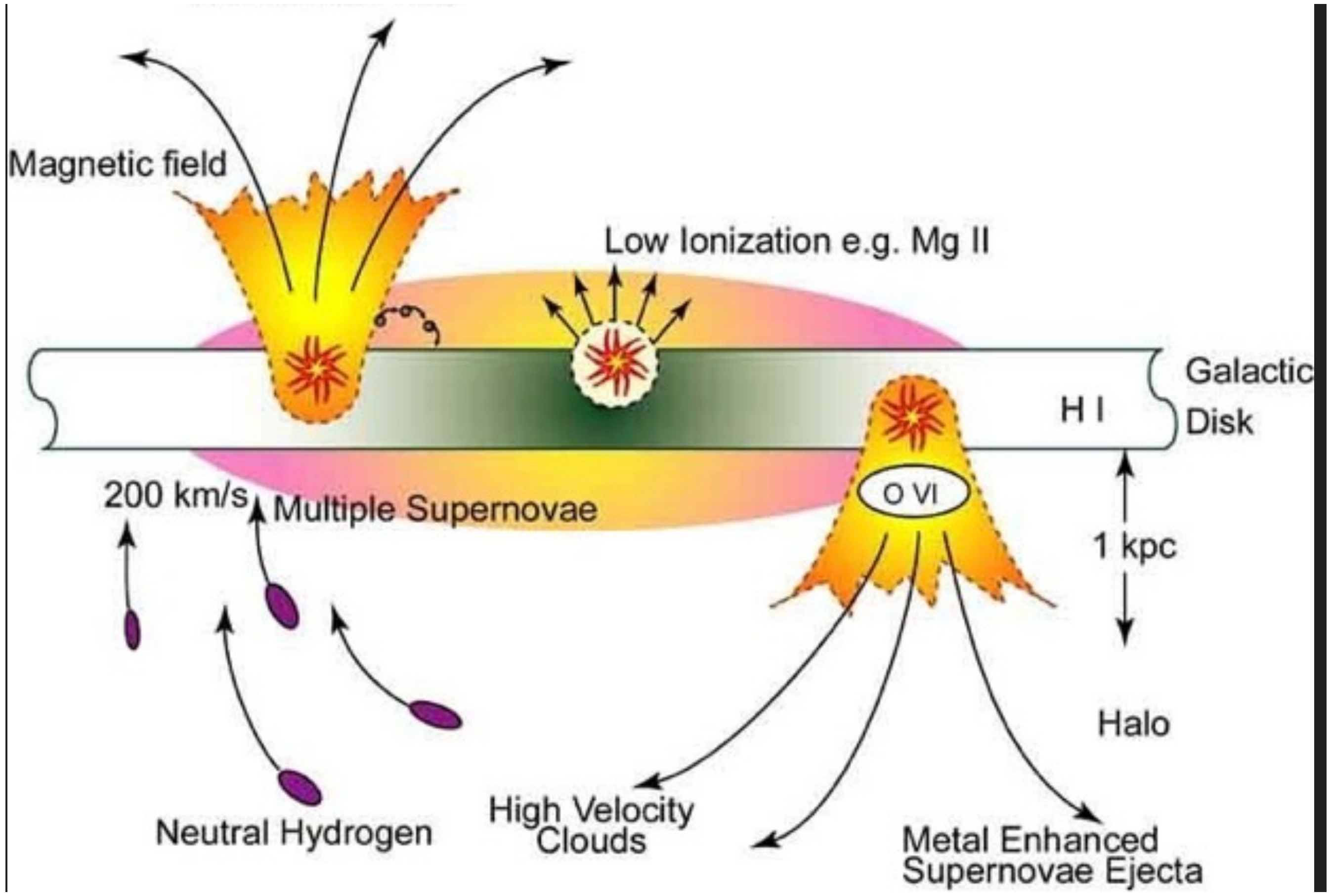
WOLFGANG KLASSEN

SECOND READER: ROBERT GLEISINGER

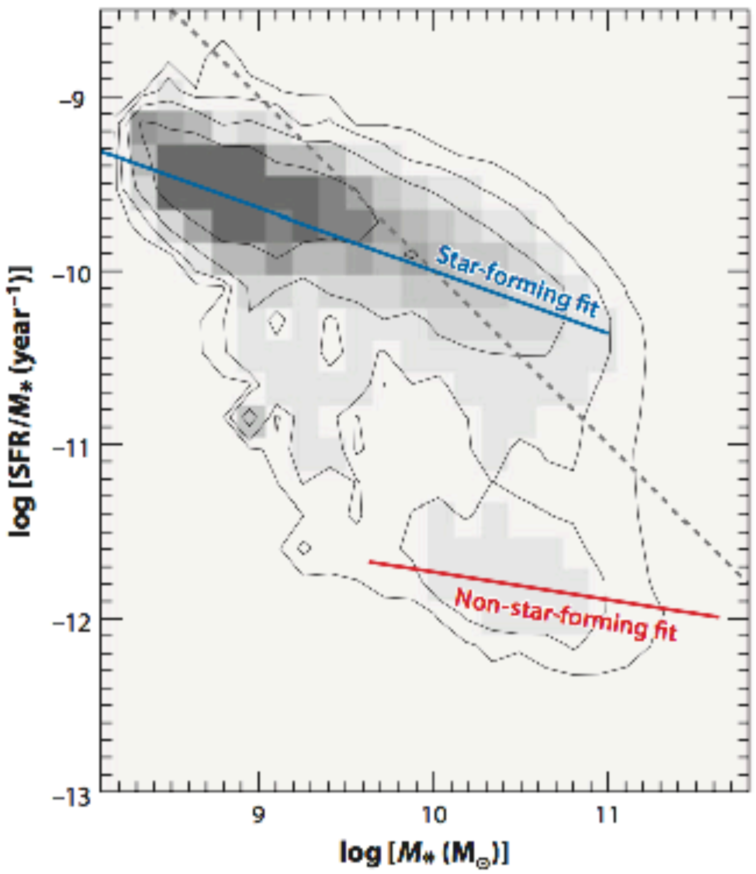
RADIO HALOS AND SYNCHROTRON RADIATION

SPECTRAL INDEX





Scott: Galaxy Evolution; Star Formation Rate; Galaxy Main Sequence
SFR*



Galaxy Main Sequence

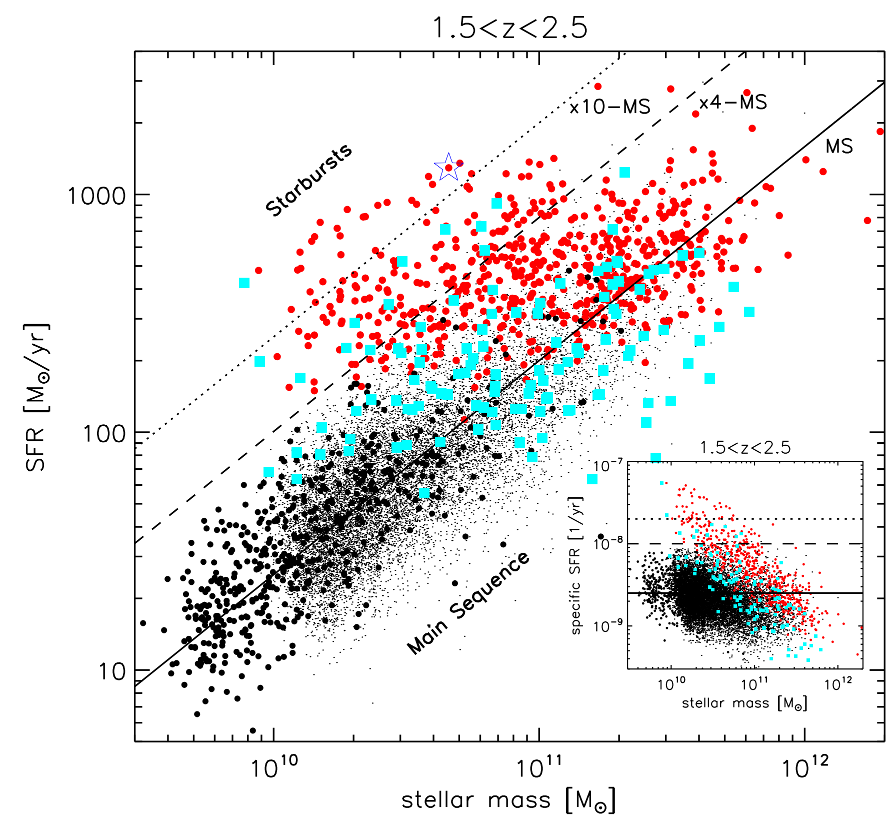


Fig. 28. – Star formation rate vs stellar mass relation at $1.5 < z < 2.5$, for different samples of galaxies (various symbols). The solid black line indicates the Main Sequence of star forming galaxies, and a population of starbursts is evident in the top left panel. In the inset, the same relation is shown but as a function of specific SFR. Figure from [132].

Secular Evolution

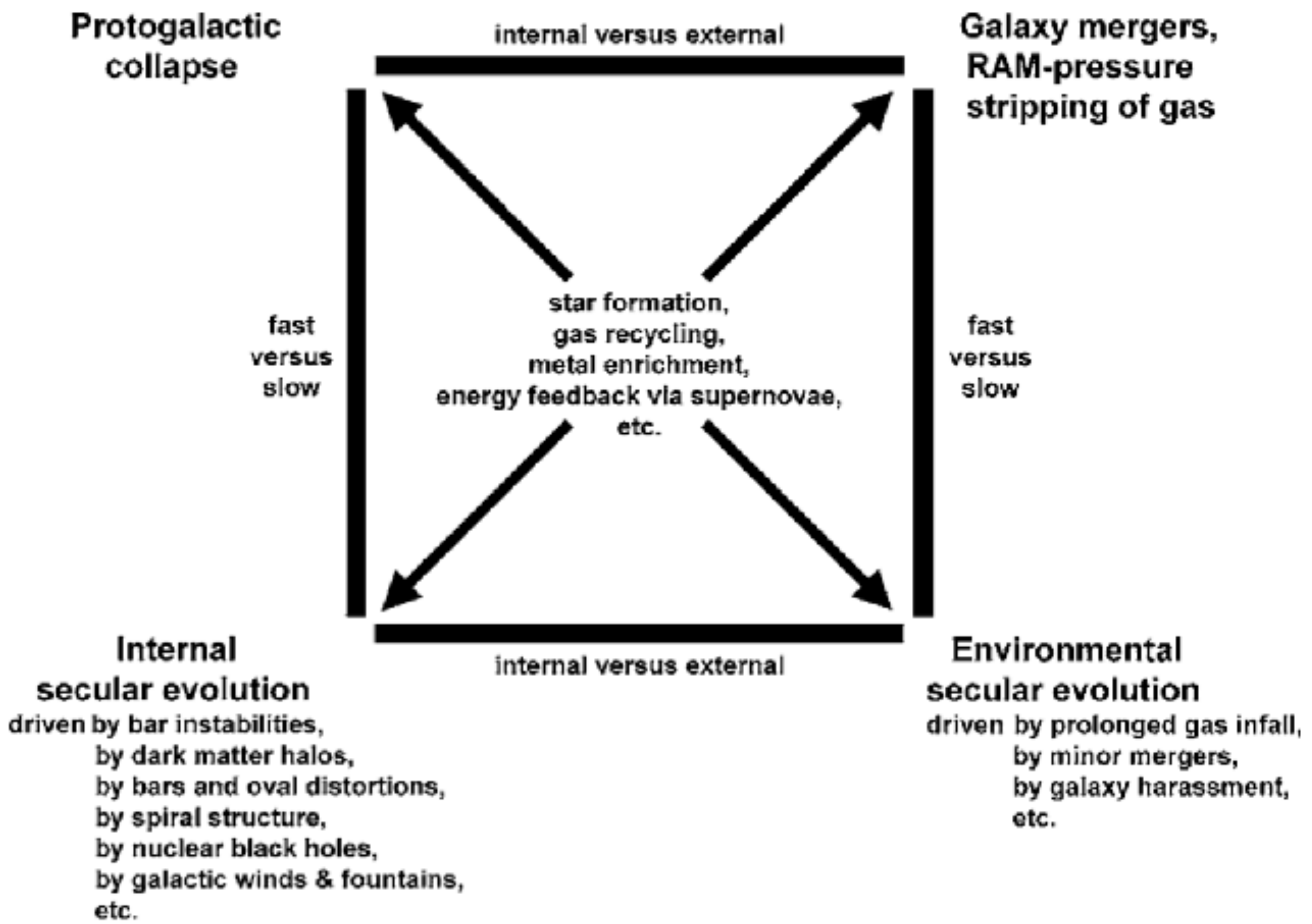


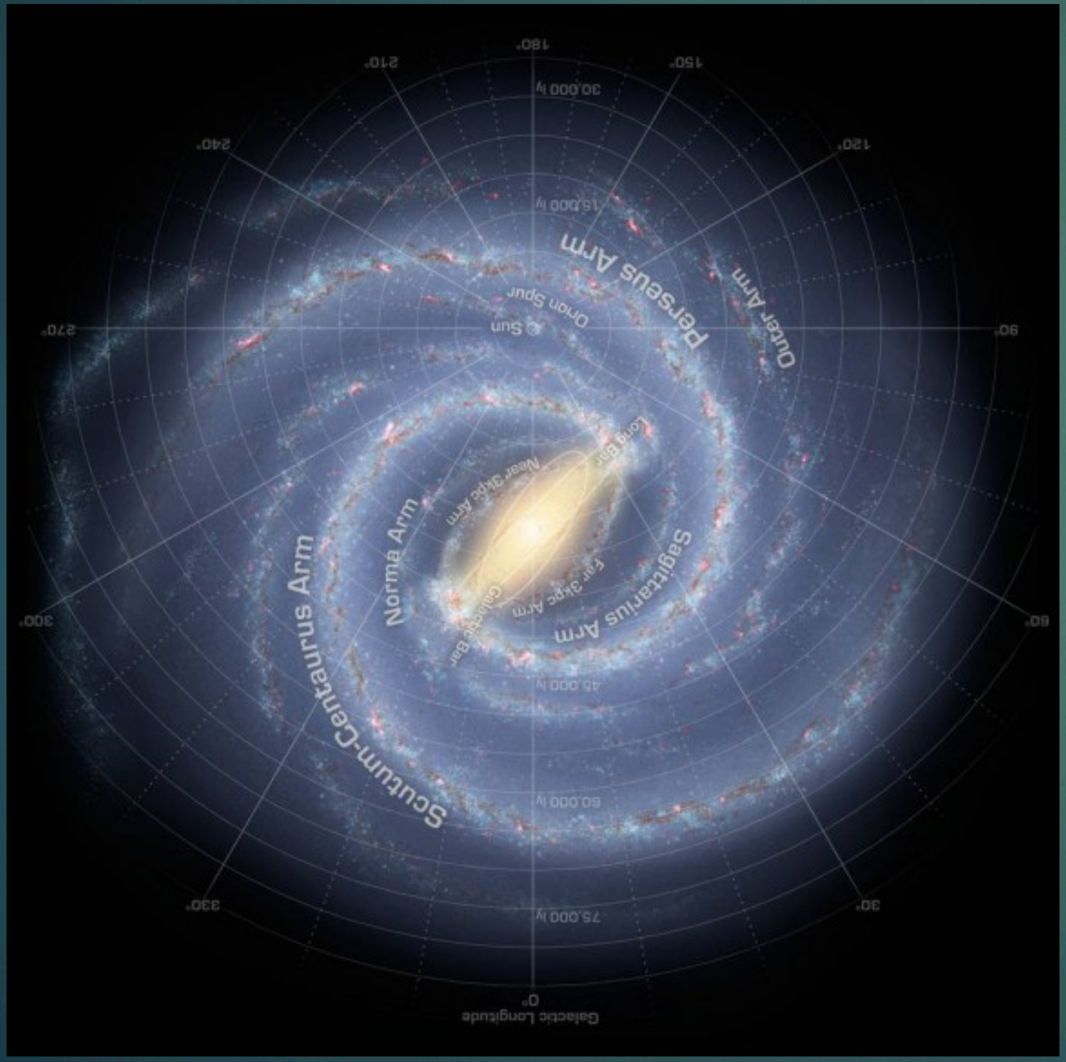
Figure 1 Morphological box (Zwicky 1957) of processes of galactic evolution updated from Kormendy (1982a). Processes are divided vertically into fast (*top*) and slow (*bottom*). Fast evolution happens on a free-fall ("dynamical") timescale, $t_{\rm dyn} \sim (G\rho)^{-1/2}$, where ρ is the density of the object produced and G is the gravitational constant. Slow means many galaxy rotation periods. Processes are divided horizontally into ones that happen purely internally in one galaxy (*left*) and ones that are driven by environmental effects such as galaxy interactions (*right*). The processes at center are aspects of all types of galaxy evolution. This paper is about the internal and slow processes at lower left.

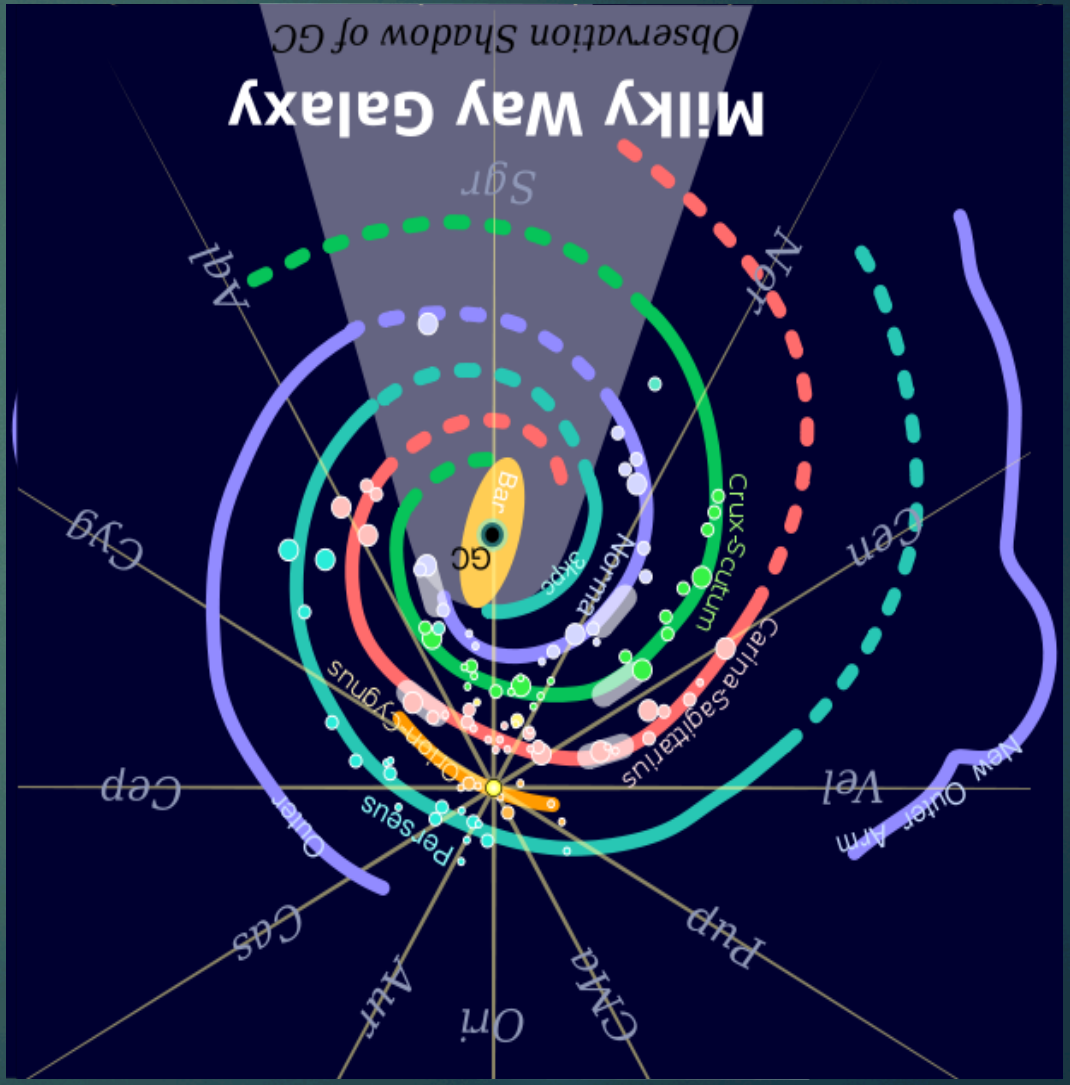

MilkyWay
THE MILKY WAY AS SEEN FROM MARS
Mars

John:

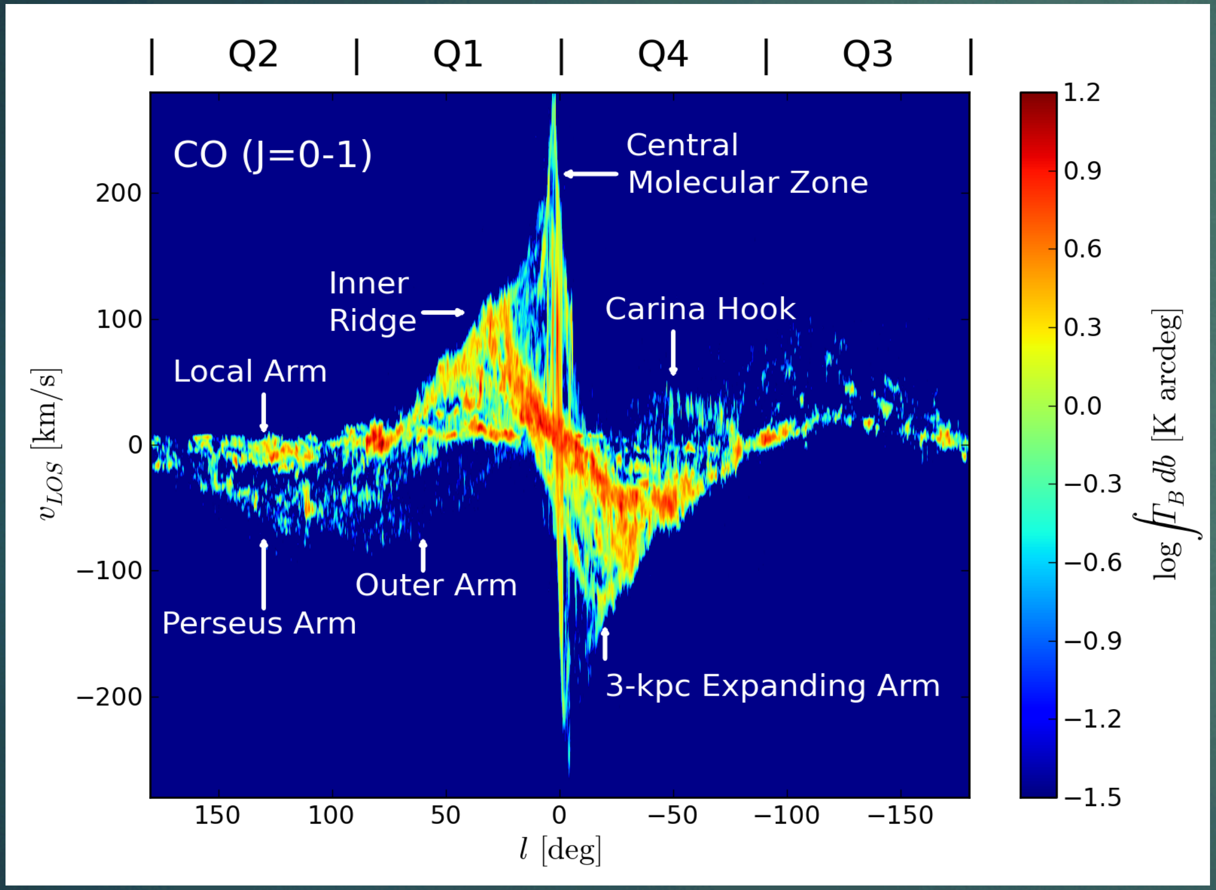
Milky Way

Spiral Arms





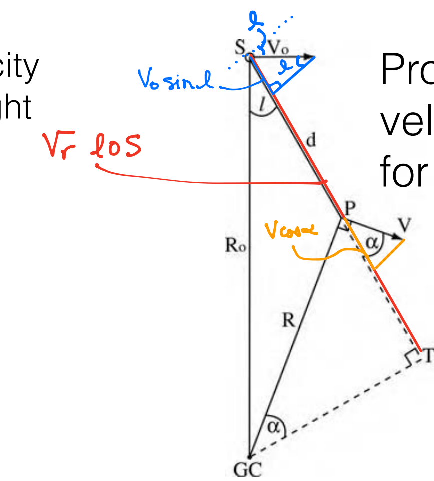
Milky Way Rotation



PV diagram

The morphology of the Milky Way

Observed velocity along line of sight



Project circular velocities onto the LOS for radial velocities.

We can calculate the radial velocity V_r of a star or gas clou
follows an exactly circular orbit; see Figure 2.19. At radius R
precisely, the local standard of rest) orbits with speed V_0, while a star P at radius R has orbital speed $V(R)$. The star moves away from us at speed

$$V_r = V\cos\alpha - V_0 \sin l. \tag{2.10}$$

Using the sine rule, we have $\sin l / R = \sin(90^\circ + \alpha)/R_0$, and so

$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0}\right). \tag{2.11}$$

Problem 2.15 For a simple model of the Galaxy with $R_0 = 8$ kpc and $V(R) = 220\,\mathrm{km\,s^{-1}}$ everywhere, find $V_r(l)$ for gas in circular orbit at $R = 4, 6, 10,$ and 12 kpc. Do this by varying the Galactocentric azimuth ϕ around each ring; find d for each (ϕ, R), and hence the longitude l and V_r. Make a plot similar to Figure 2.20 showing the gas on these rings. In Figure 2.20 itself, explain

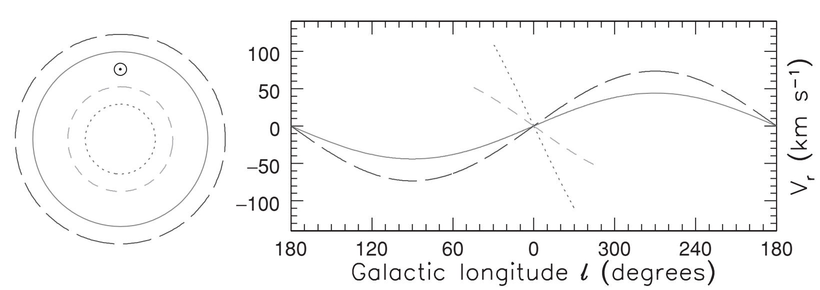
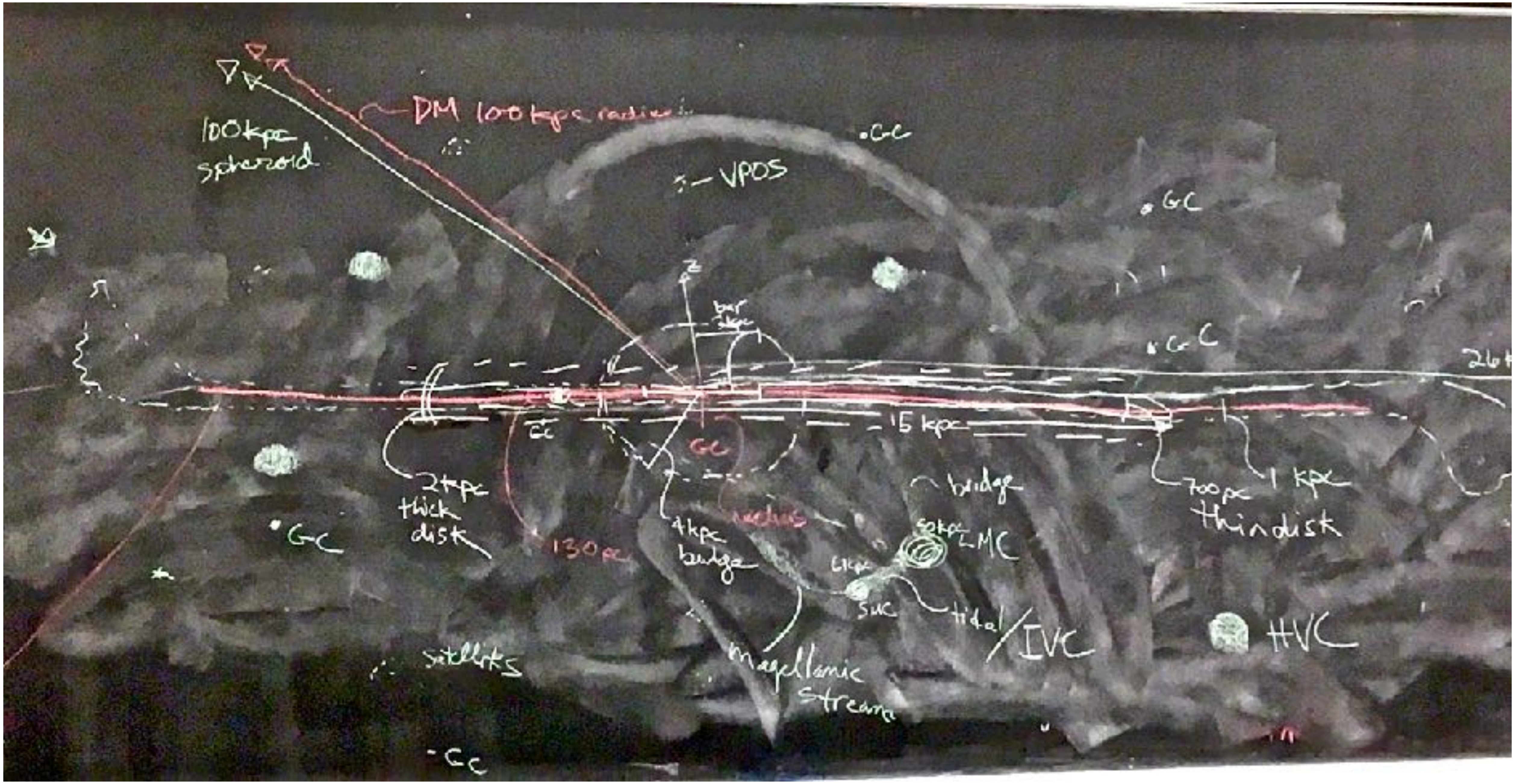


Fig. C.1. Radial velocity V_r of gas on four rings, at radii $R = 4, 6, 10,$ and 12 kpc, with circular speed $V(R) = 220\,\mathrm{km\,s^{-1}}$. The Sun ⊙ is at $R_0 = 8$ kpc.

MW Structure Diagram



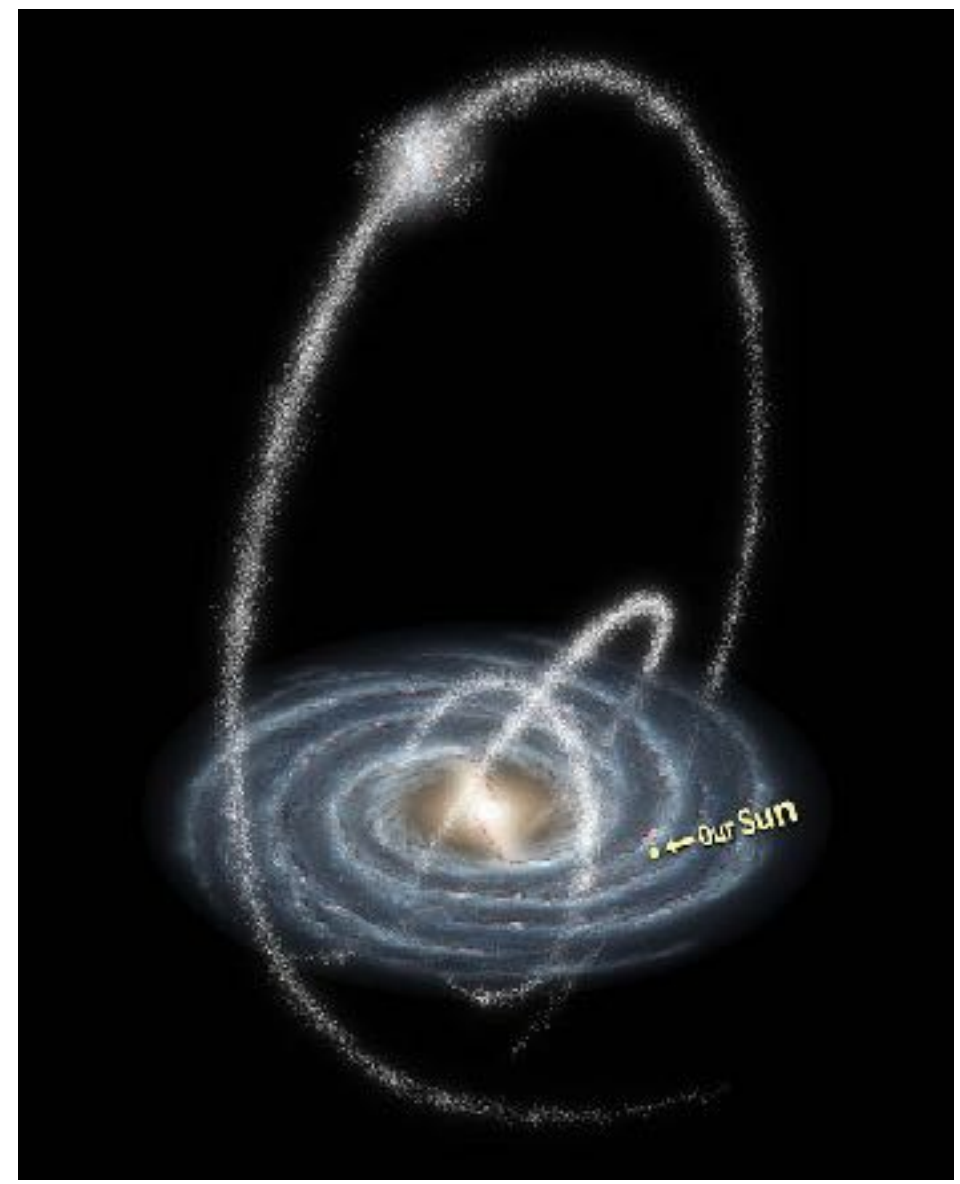
- DM == Dark Matter Halo

“Fossils”

The goals of Galactic Archaeology are to find signatures or fossils from the epoch of Galaxy assembly.

- identify observationally how important mergers and accretion events were in building up the Galactic disk, bulge and halo of the Milky Way.
- reconstruct the star-forming aggregates (clouds that formed stars; globular clusters) and accreted galaxies that built up the the Galaxy.
- recognize aggregates:
    - kinematically as stellar moving groups.
    - by their chemical signatures (chemical tagging)

https://ned.ipac.caltech.edu/level5/Sept15/Freeman/Freeman5.html



NASA

Interactions with satellites and Andromeda
—> Large Scale Structure in the Universe.

More to the Story!!!

- Galaxies not in the Hubble-deVaucoleurs Classification.

Ben — Green Pea and mergers/bulge formation
Christie — polar ring and “”
Cole — tadpoles and blazers
Kate — polar ring and lack of DM in past rotation curves (inclination and stacking)
Dan — multiple merger and SF around a black hole
Wolfgang — IC 3583 barred IRR and VPOS
Jordan — A+E and dwarf with large black hole
Keagan — NGC 7292 barred IRR and lack of DM in past rotation curves
Robert — UDG Dragonfly 44 (how measure DM?) and early uni galaxy with oxygen

- Your Presentations

Now for something serious.