



Galaxy formation and evolution

PAP318, 5 op, autumn 2022

BK106, Exactum

**Lecture 2: Observations of galaxies,
14/09/2022**

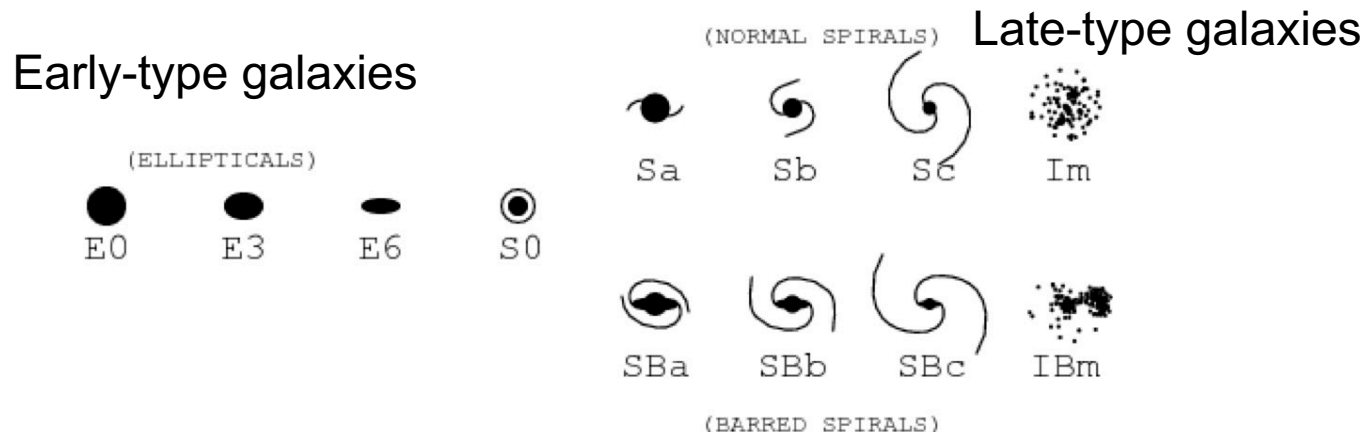


On this lecture we will discuss

1. Galaxy classification. What are the criteria for the morphological classification of galaxies?
2. The photometric, kinematic and physical properties of elliptical galaxies, disk galaxies, dwarf galaxies, nuclear stellar clusters, starbursts and active galactic nuclei.
3. The statistical properties of the galaxy population, including the luminosity function, the size distribution, the colour distribution, the mass-metallicity relation and their environmental dependence.
4. Properties of galaxies at high redshifts, galaxy counts and photometric redshifts. Methods for observing the high-redshift galaxy population. First results from JWST.
5. The lecture notes correspond to: **MBW: p. 37-66, 72-81 (§2.3-2.4, §2.6)**
L: p. 49-94 (§3.1-3.10)



2.1 The classification of galaxies I



- The classic Hubble tuning-fork diagram still forms the basis for modern morphological galaxy classification. Works best for bright galaxies.
- 1. Elliptical galaxies, have smooth, almost elliptical isophotes and are divided into subtypes E0, E1, ... E7, where the integer (0-7) is the number closest to $10(1-b/a)$, where a is the major and b the minor axis of the isophote.
- 2. Spirals have thin disks with spiral arm structures and they are divided into two branches, barred and normal spirals.



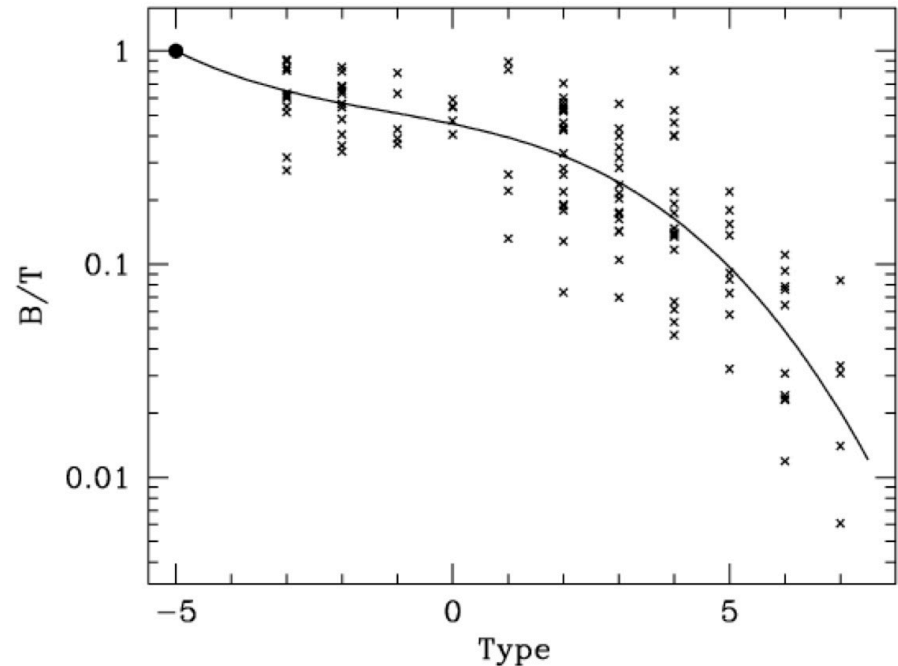
The classification of galaxies II

- Spirals are further subdivided into three classes of a, b and c according to the following criteria: 1) the fraction of light in the central bulge, 2) the tightness at which the spiral arms are wound and 3) the degree to which the spiral arms are resolved into stars, HII regions and ordered dust lanes.
- 3. Lenticular or S0 galaxies are intermediate between ellipticals and spirals. Similar to elliptical galaxies they have a smooth light distribution with no spiral arms, gas and HII regions and similar to spirals they have a relatively thin stellar disk and a bulge.
- 4. Irregular galaxies have neither a dominating bulge nor a rotationally symmetric disk and lack obvious symmetry. The appearance is patchy with numerous HII regions. Nowadays gas-rich irregular galaxies are often considered to be an extension of the spiral galaxy class.



de Vaucouleurs' classification

- Another commonly used galaxy classification is the one due to de Vaucouleurs, who used a finer gradation by adding new intermediate types, such as S0a, Sab, Sbc, etc. He also extended the spiral sequence to irregulars, Sd, Sdm, Sm, Im (m=magellanic).
- Furthermore he used numbers between [-6,10] corresponding to [E...Sp...Ir] to represent all morphological types (de Vaucouleurs' T-types)

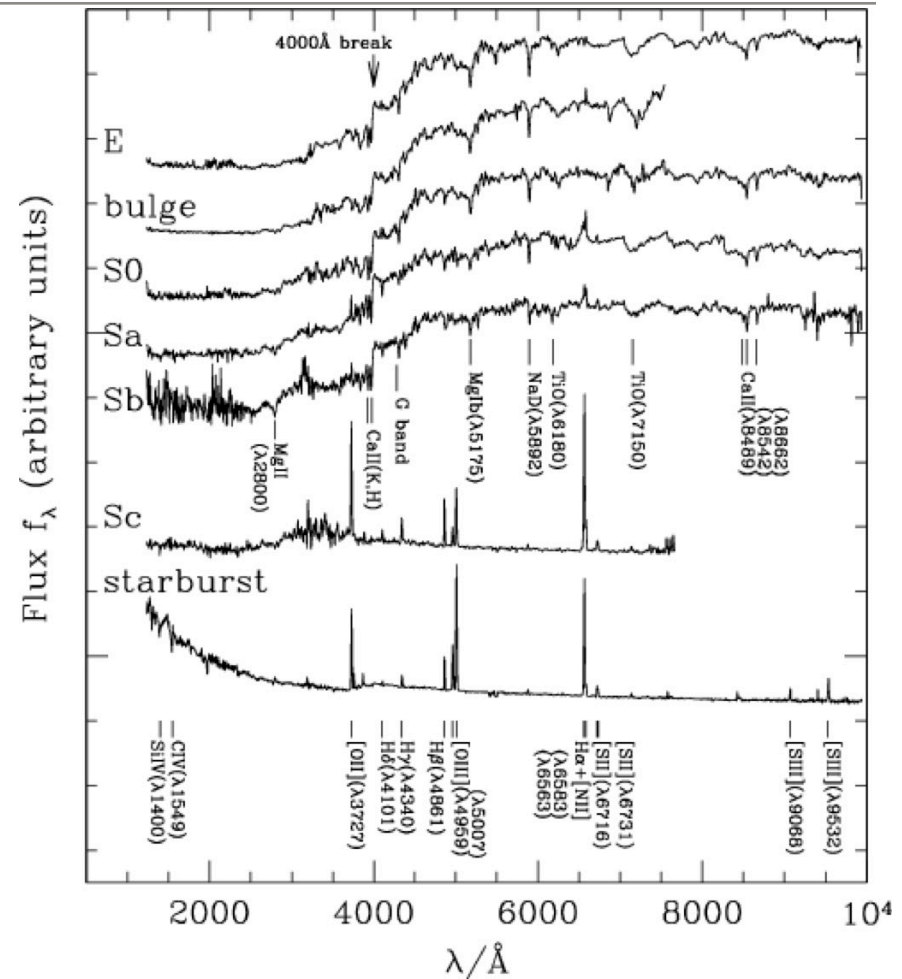


The classification is primarily a sequence of the importance of the bulge. The numerical T types do not distinguish between barred and unbarred galaxies.



Galaxy spectra

- Galaxy spectra consist of the combined light output of all the stars in the galaxy.
- Early-type galaxies have prominent absorption lines, with a strong 4000Å break and little blue light -> primarily old low-mass stars.
- In contrast, late-type galaxies have rising blue continuums and emission lines. -> hot young stars that are able to ionise the interstellar medium.





2.2 Elliptical galaxies: Surface brightness

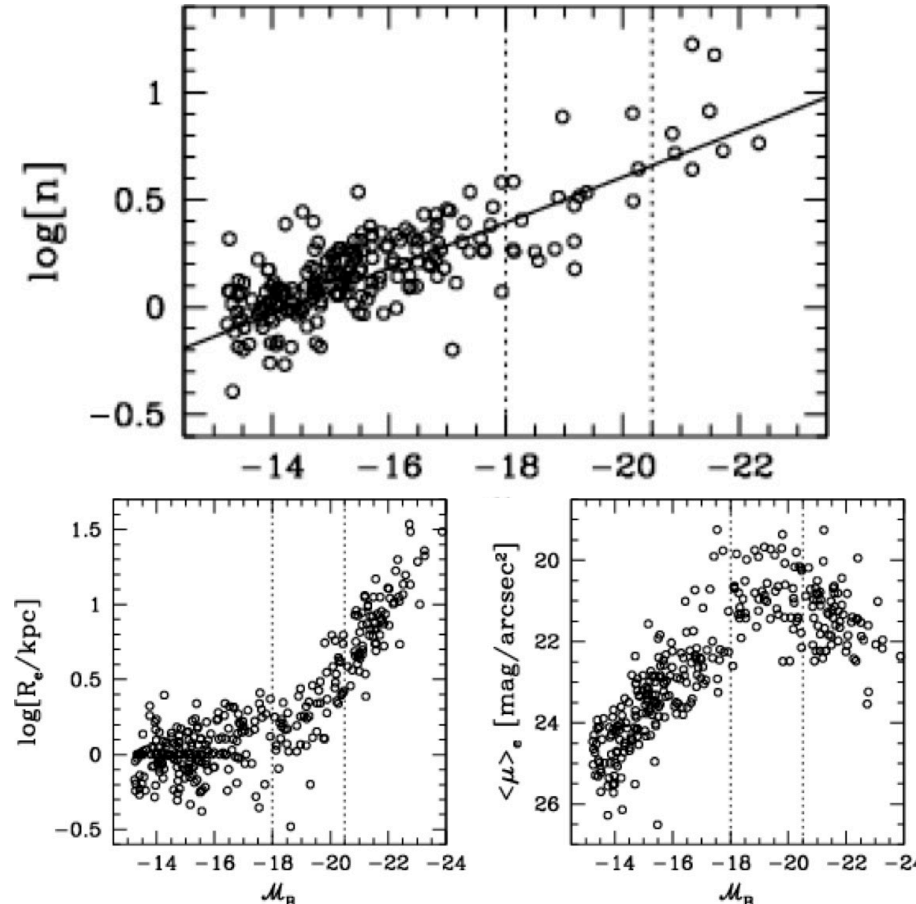
- The surface brightness profiles of ellipticals can be well fitted by the general Sérsic profile:

$$I(R) = I_0 e^{-\beta_n [(R/R_e)^{1/n}]}$$

- R_e is the half-light radius, I_0 is the central surface brightness, n is the Sérsic index ($n=4$ de Vaucouleurs' profile) and β_n follows from the definition of R_e .

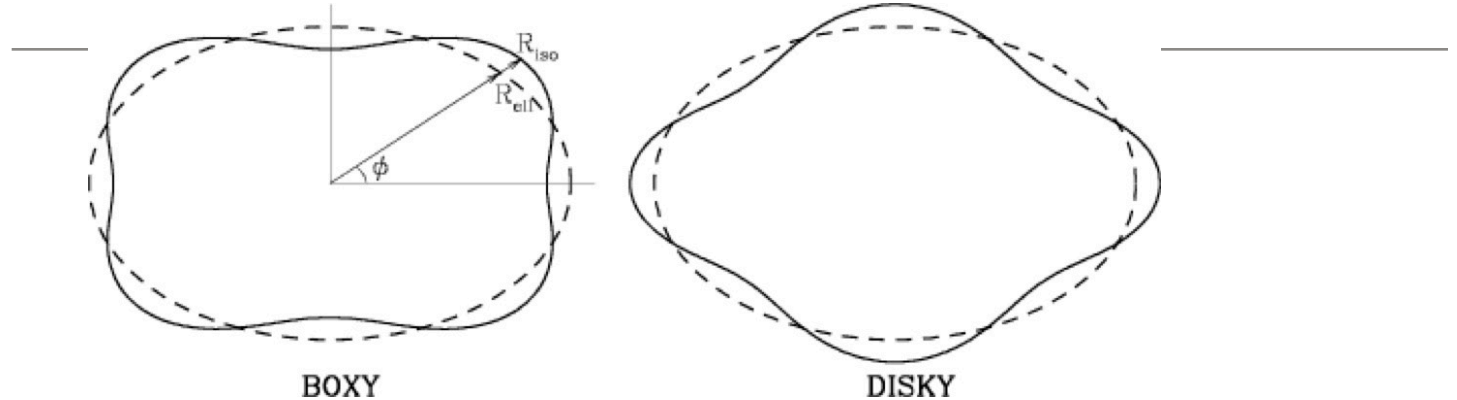
- Total luminosity: (Problem set 1)

$$L = 2\pi \int_0^\infty I(R) R dR = \frac{2\pi n \Gamma(2n)}{(\beta_n)^{2n}} I_0 R_e^2$$





Isophotal shape



- The isophotal shape of ellipticals can be quantified by how the intensity fluctuates along the best fit ellipse:

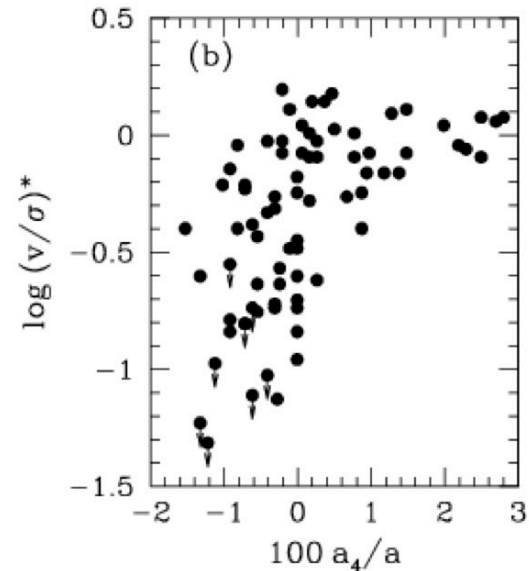
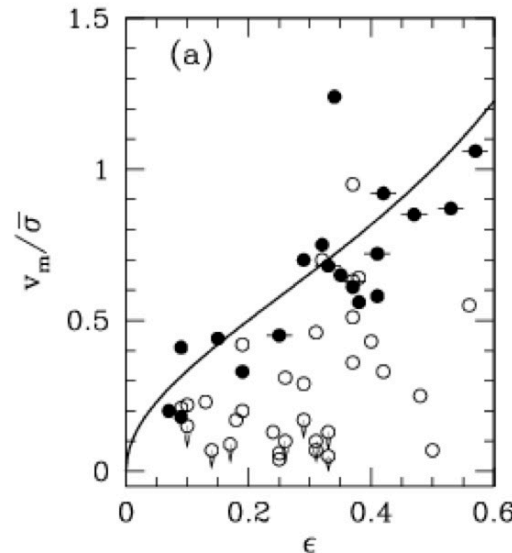
$$I(\phi) = I_0 + \sum_{n=1}^{\infty} (A_n \cos n\phi + B_n \sin n\phi)$$

- Ellipticals with $a_4 < 0$ are called boxy and they are usually very bright, rotate slowly and show strong radio and X-ray emission.
- Ellipticals with $a_4 > 0$ are called disky and they are usually fainter, show more significant rotation and have little or no radio and x-ray activity.



Kinematic properties

- Giant ellipticals typically rotate very slowly and their very low v_{rot}/σ values cannot explain the observed flattening. Thus, their shapes must be due to velocity anisotropy, rather than rotation.
- In contrast ellipticals with intermediate L show v_{rot}/σ values that are consistent with rotational flattening.
- Kinematic and photometric properties are linked!



The solid line gives the expected flattening (ϵ) as a function of the rotation measure v_{rot}/σ . Note that although low-L ellipticals have $v_{\text{rot}}/\sigma \sim 1$, disk galaxies have significantly higher values of $v_{\text{rot}}/\sigma \sim 20$.

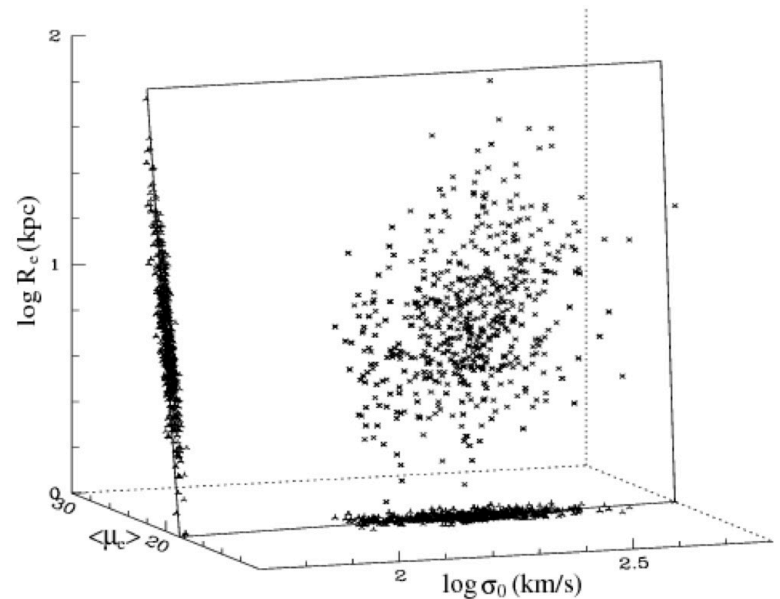


Scaling relations

- Elliptical galaxies follow quite tight scaling relations, of which the most famous is the fundamental plane:

$$\log R_e = a \log \sigma_0 + b \log \langle I \rangle_e + C$$

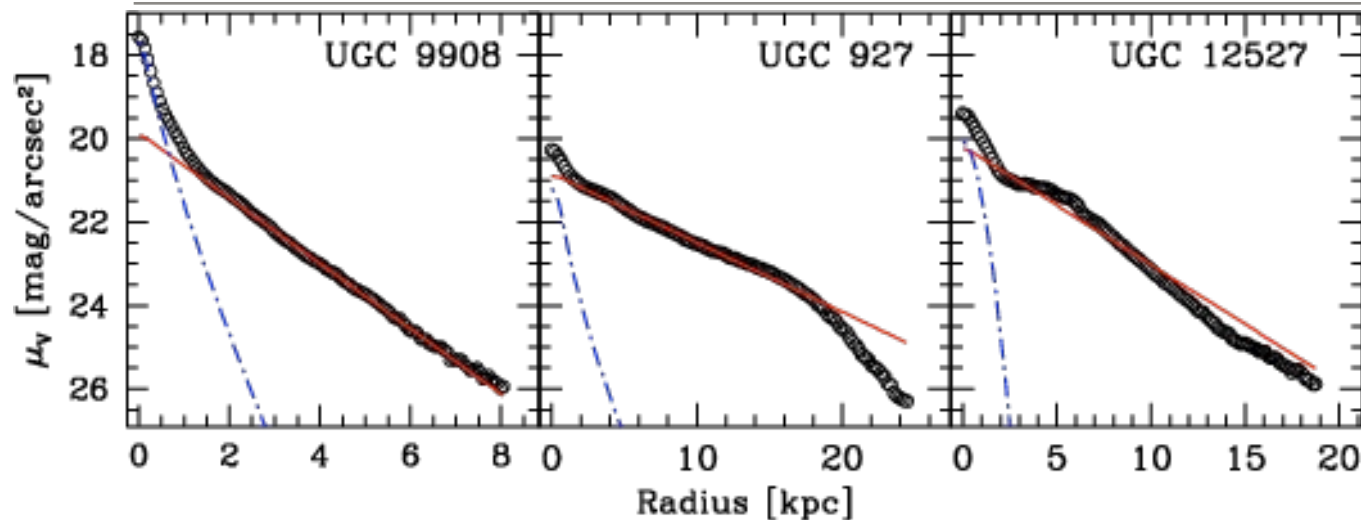
- This means that if we measure two out of three (R_e , σ_0 , $\langle I \rangle_e$) we can predict the third quantity.
- Elliptical galaxies also contain substantial amounts of gas, but almost all of its hot ($T \sim 10^7$ K) and thus non-starforming, unlike disk galaxies, which have cold gas.



The fundamental plane of elliptical galaxies.



2.3 Disk galaxies: Surface brightness



- The surface brightness profiles can be fitted by exponential profiles:

$$I(R) = I_0 e^{-R/R_d}, \quad I_0 = \frac{L}{2\pi R_d^2}$$

- The inner parts of typical disk galaxies can be fitted by a Sérsic function and this describes the bulge-component, which can to first approximation be seen as a ‘mini-elliptical’.



Colours and gas content

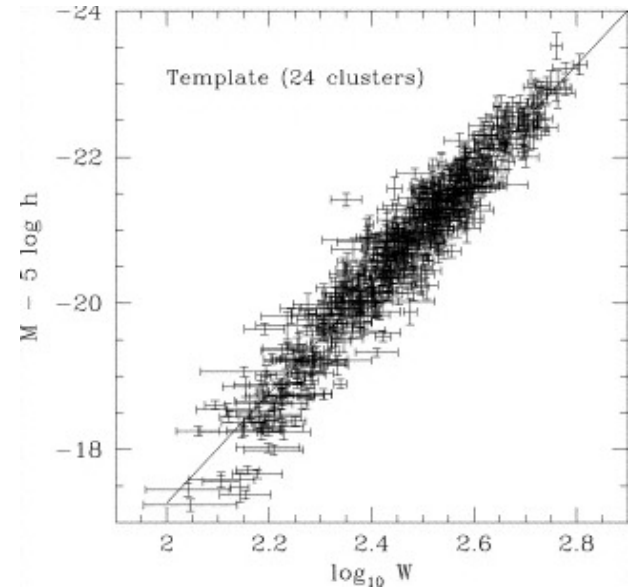
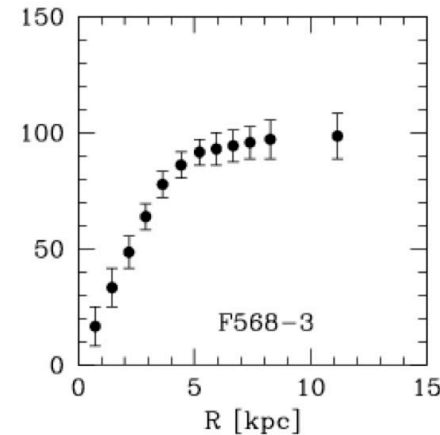
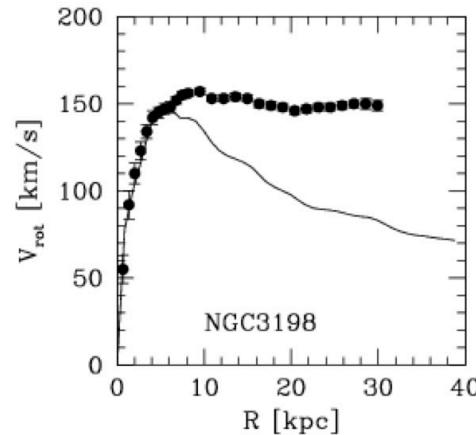
- In general disk galaxies are bluer than elliptical galaxies of the same luminosity. Similar to ellipticals, more luminous disk galaxies are redder than lower luminosity disks, although the scatter is quite large.
- Disk galaxies also reveal colour gradients with the outer parts being typically bluer than the inner regions, which are redder.
- Unlike ellipticals, the gas content in disk galaxies is mainly neutral (HI) and molecular hydrogen (H_2). The gas mass fraction increases from $\sim 5\%$ for early-type spirals up to $\sim 80\%$ for very late-type low surface brightness disk galaxies.
- The metallicity is found to decrease with increasing radius and as a rule of thumb the metallicity decreases by one order of magnitude for a hundred-fold decrease in surface density.



Kinematics and the Tully-Fisher relation

$$V(R) = \sqrt{\frac{GM(R)}{R}}$$

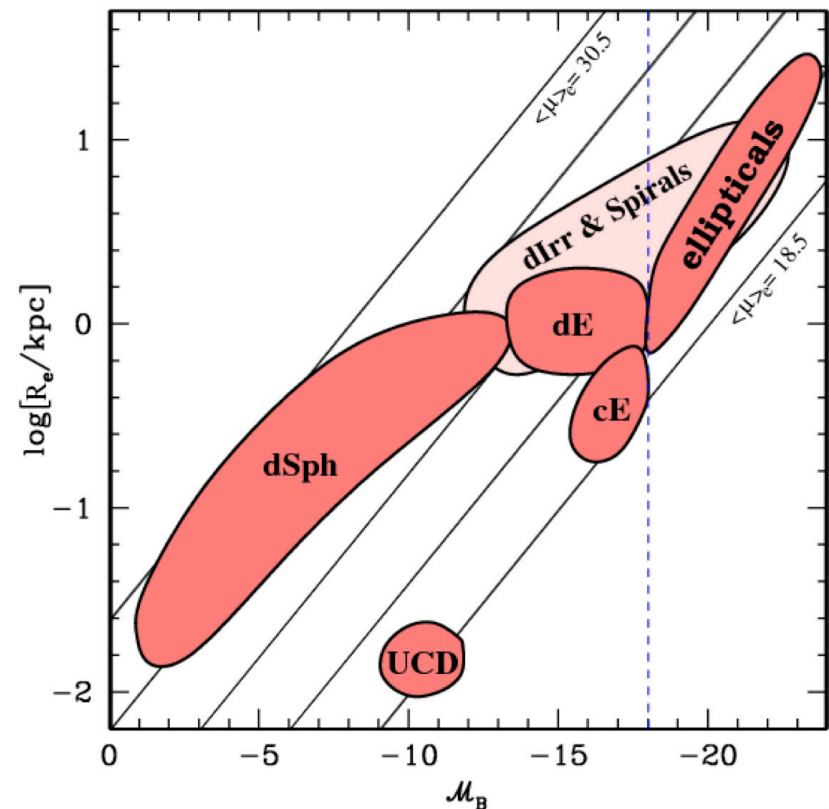
- The stars and cold gas in galaxy disks move on roughly circular orbits, therefore the kinematics is largely defined by the rotation curve, which can also be used to probe the dark matter content of the galaxy: $M(R) \propto R$.
- Disk galaxies obey a well-defined scaling relation. Brighter galaxies rotate faster. This is the Tully-Fisher relation: α varies with the observed waveband.





2.4 Dwarf galaxies

- For historical reasons, galaxies with $M_B \geq -18$ are often called dwarf galaxies. Currently the faintest known galaxy, Willman I is a dwarf spheroidal galaxy in the local group with $M_V \sim -2.6$.
- By number, dwarfs are the most abundant galaxies in the Universe, but they contain a relatively small fraction of all the stars.
- Dwarfs can be divided into systems with gas and ongoing star formation (dwarf irregulars, dIrr) and gas-poor systems with no young stars – the dwarf ellipticals (dE) and dwarf spheroidals (dSph).





Nuclear star clusters

- Up to ~80% of fainter ellipticals ($M_B \leq -15$) contain nuclear star clusters in their centers. Also 50-70% of late-type galaxies have nuclear star clusters.
- Thus, a large fraction of all galaxies, independent of their morphology contain nuclear star clusters, the only exception are the bright elliptical galaxies ($M_B \leq -20.5$) that are 'cored' and do not have nuclear clusters.
- The nuclear clusters have stellar masses of 10^6 - $10^8 M_\odot$ and typical radii of only ~5 pc. They are brighter and denser than even globular clusters.



The nuclear stellar cluster of the Milky Way. There is also indications for a correlation $M_{\text{CMO}}/M_{\text{gal}} \sim 0.018$, equally valid for nuclear clusters and black holes (CMO=central massive object).



Starbursts

- In normal galaxies the specific star formation rate, defined as: $sSFR = SFR/M_*$ is typically of the order of 0.1 Gyr^{-1} , implying star formation timescales of $\sim 10 \text{ Gyr}$.
- Some galaxies have extremely elevated SFRs and implied star formation timescales of only 100 Myr.
- The reason for the elevated star formation rate is almost always the interaction or merger of two gas-rich galaxies and most of the stellar light is typically absorbed by dust and re-radiated in the infrared region.

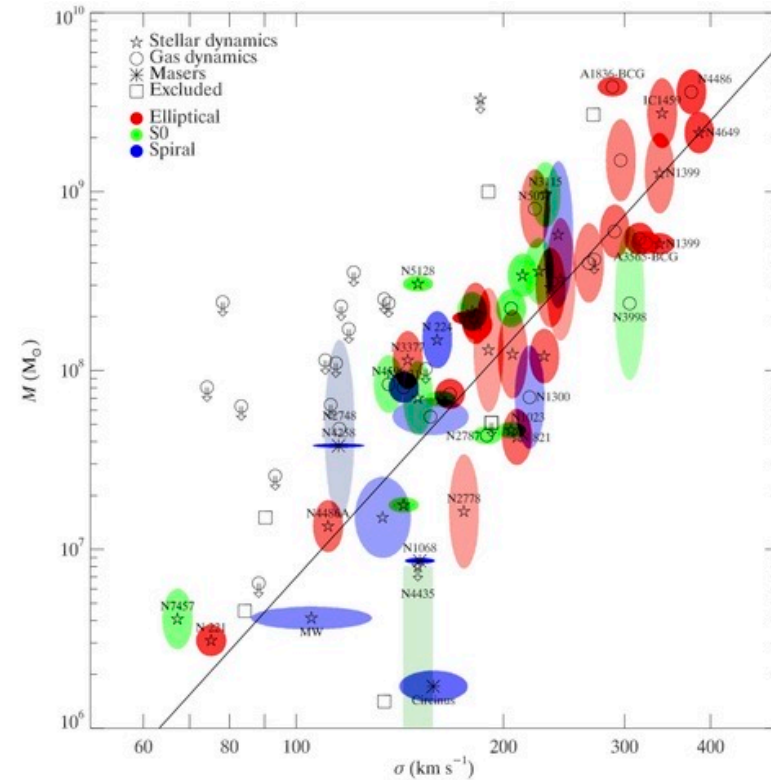


Starburst galaxy M82, the elevated SFR is often accompanied by galaxy scale outflows, with the mass outflow rate typically being roughly equal to the SFR.



Active galactic nuclei (AGNs)

- The centres of many galaxies contain supermassive black holes that can outshine their entire host galaxies.
- While, normal stars emit in a relatively narrow spectral window, AGNs are powerful emitters of non-thermal emission from radio to the gamma-ray wavelengths.
- The mass of the supermassive black holes is tightly correlated with the host galaxy masses. The enormous energy output of AGNs have an important effect on galaxy formation and may even establish the upper mass limit of galaxies.





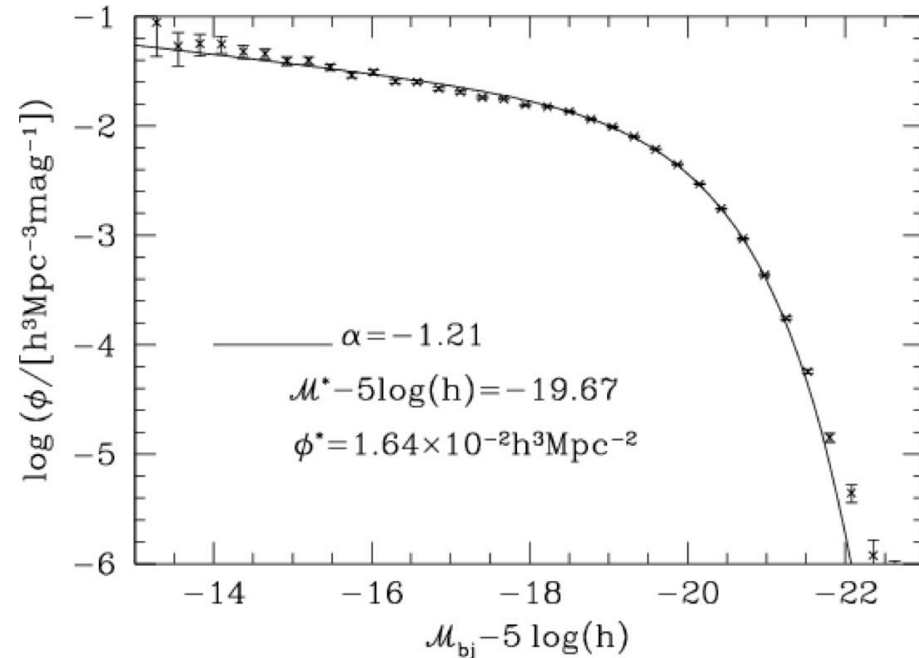
2.5 Statistical properties: Luminosity function

- The luminosity function $\phi(L)dL$ describes the number density of galaxies with luminosities in the range $L \pm dL/2$ and can be fitted by the empirical Schechter function:
- L^* is the characteristic luminosity, α is the faint-end slope, and ϕ^* is an overall normalization.
- The mean number density, n_g , and mean luminosity density L_g can be derived by integration (P.S. 1):

$$\phi(L)dL = \phi^* \left(\frac{L}{L^*} \right)^\alpha e^{-(L/L^*)} \frac{dL}{L^*}$$

$$n_g = \int_0^\infty \phi(L)dL = \phi^* \Gamma(\alpha + 1)$$

$$L_g = \int_0^\infty \phi(L)LdL = \phi^* L^* \Gamma(\alpha + 2)$$



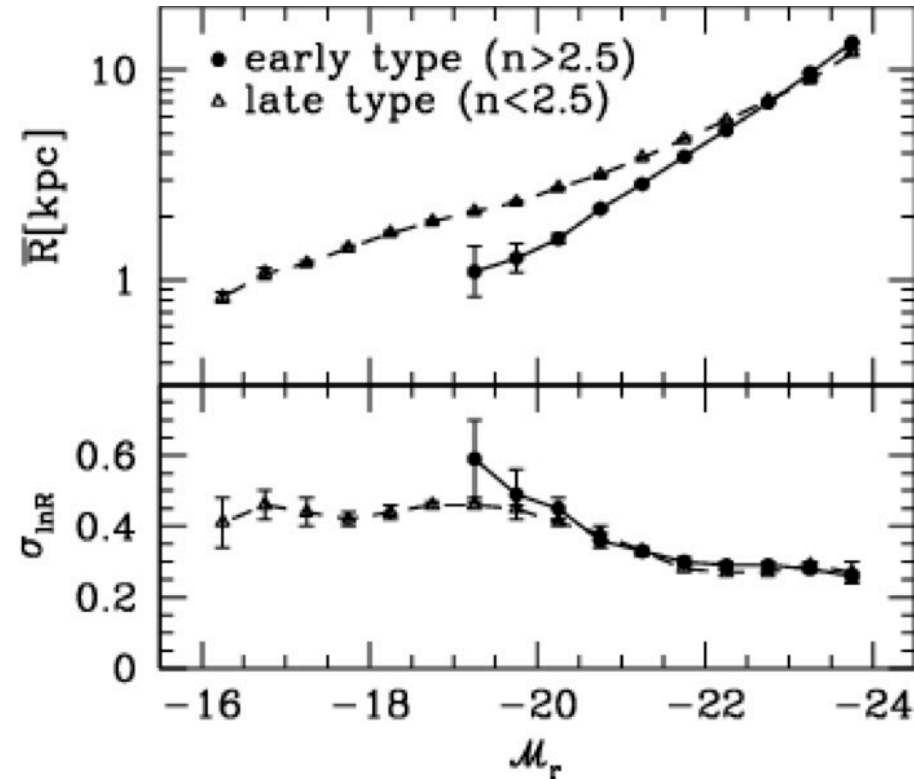


Size distribution

- Galaxies of a given luminosity may have very different sizes and therefore surface brightnesses.
- The size distribution for galaxies for a given L can be described by a log-normal function:

$$P(R|L)dR = \frac{1}{\sqrt{2\pi}\sigma_{\ln R}} e^{-\frac{\ln^2(R/\bar{R})}{2\sigma_{\ln R}^2}} \frac{dR}{R}$$

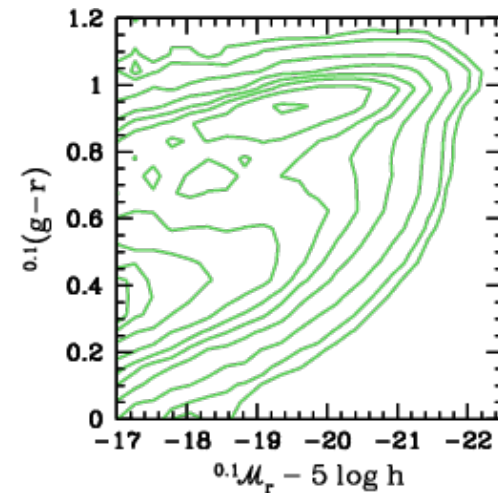
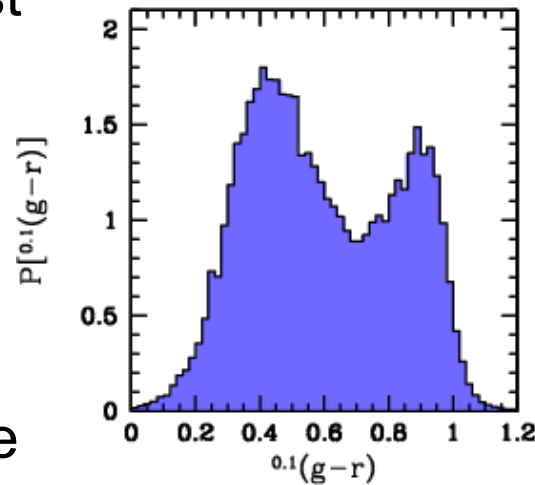
- The mean radius increases with galaxy luminosity roughly as a power law for both early- and late-type galaxies.





Colour distribution

- The colour of galaxy depends on its age, metallicity and dust content, with larger values resulting in redder colours.
- The local galaxy distribution is clearly bimodal with late-type galaxies in a blue cloud and early-type galaxies on the red sequence. A few galaxies are found in the 'green valley' between the two general populations.

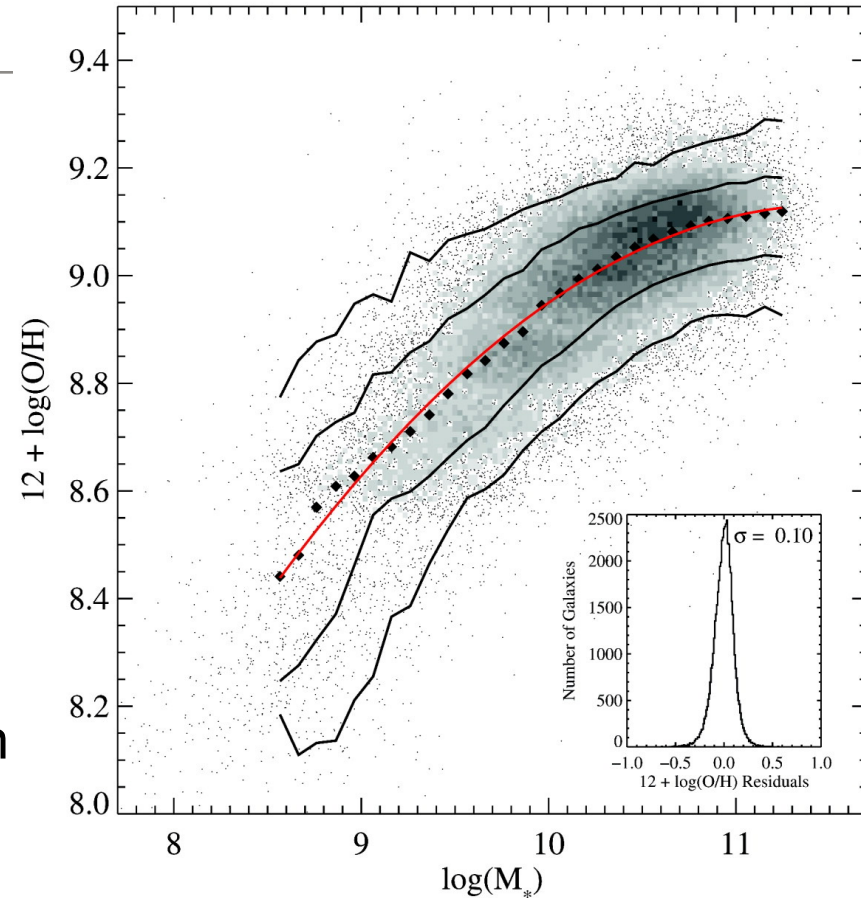


Fainter galaxies are on average bluer disk galaxies and brighter galaxies are on average redder ellipticals, but the dispersion for both galaxy types is relatively large.



Mass-metallicity relation

- The average galaxy metallicity is an important parameter, and it can be different for the stars and the gas in the galaxy depending on the galaxy's inflow/outflow history.
- The Figure shows the average gas oxygen content relative to hydrogen in units of $12 + \log[(O/H)]$. For the Sun $12 + \log[(O/H)] \sim 8.9$
- The correlation is remarkably tight with more massive galaxies having higher metallicities with a clear flattening above a few times $10^{10} M_{\odot}$.

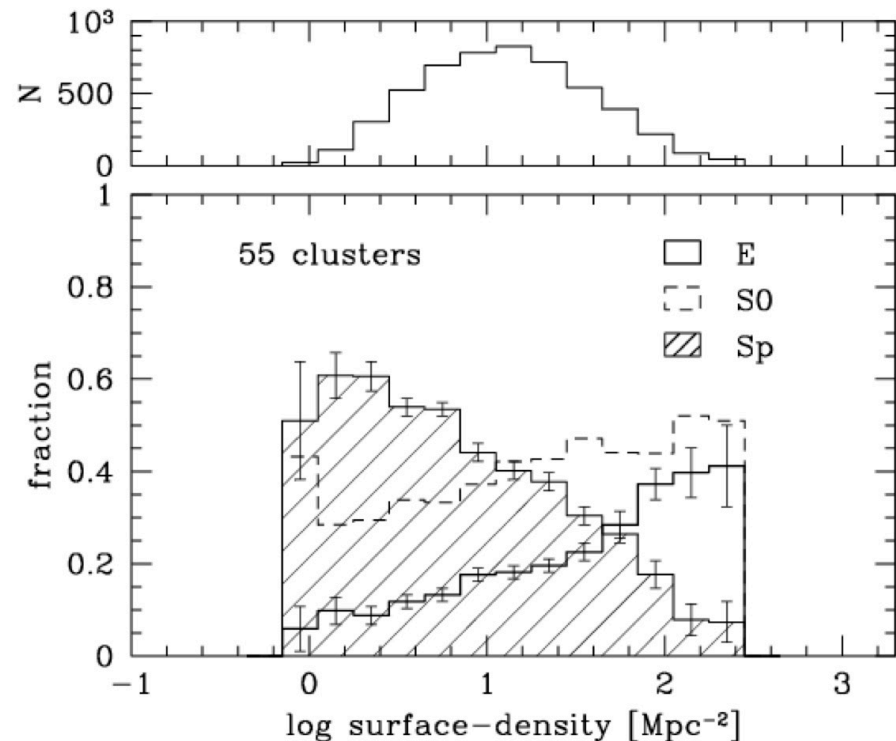


$$[O/H] = \log \left(\frac{N_O}{N_H} \right)_* - \log \left(\frac{N_O}{N_H} \right)_{\odot}$$



Environmental dependence

- The morphological mix of galaxies depends on the environment. Galaxy clusters host larger fractions of early-type galaxies than the general field.
- The fraction of spiral galaxies decreases from ~60% in the lowest density regions to less than 10% in the highest density regions.
- The S0 fraction is also higher in clusters, although the trend with environmental density is weaker than for spirals.

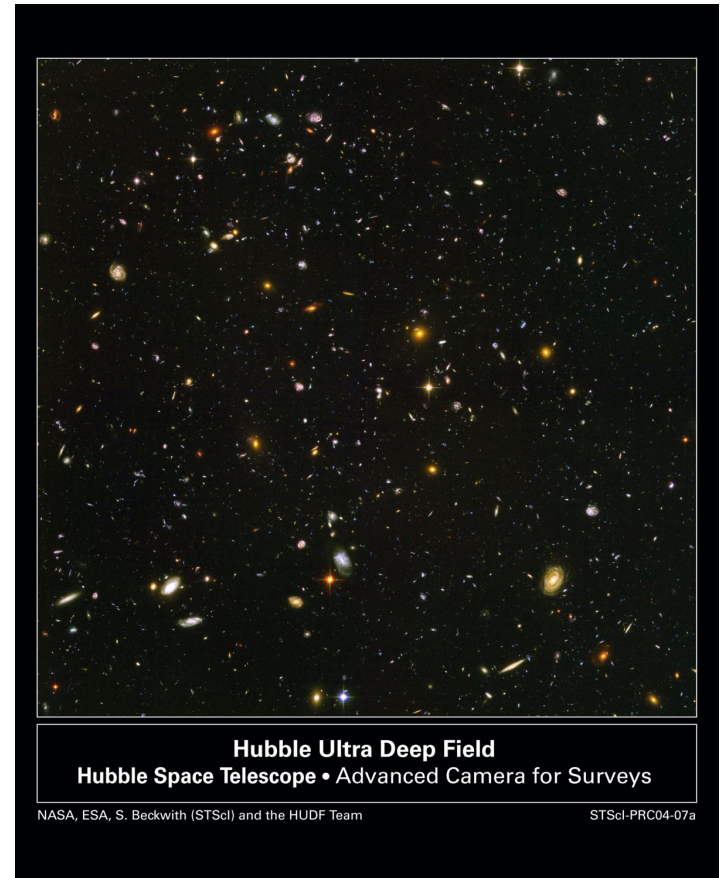


The morphology-density relation



2.6 Galaxies at high redshifts

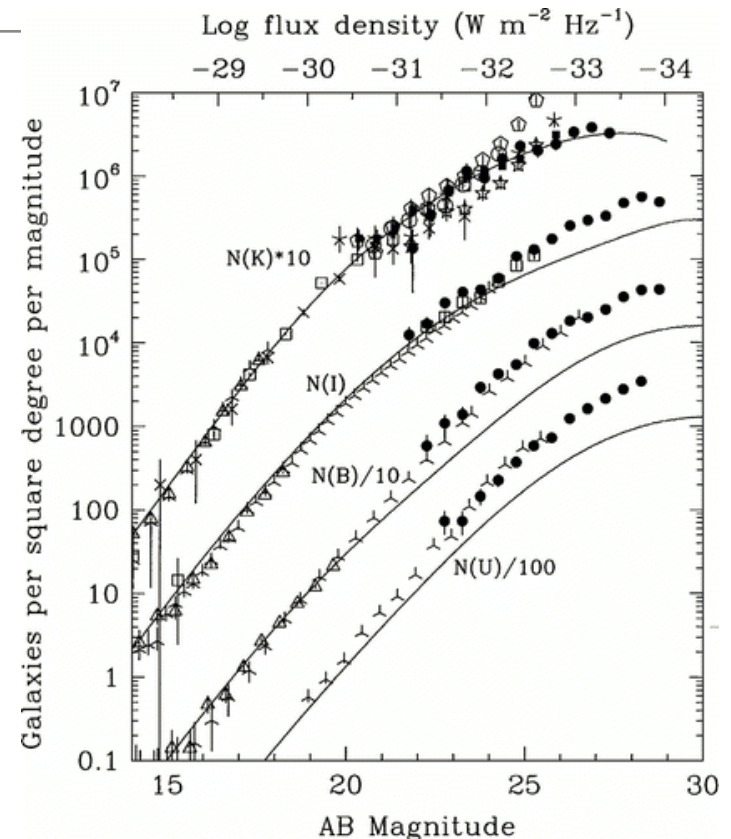
- Since the speed of light is finite, observed galaxies at high redshifts are younger. Observing galaxies at different redshifts provides a direct window on their formation and evolution.
- If high redshift galaxies would have similar luminosities and sizes as present-day galaxies, they would be extremely faint and have very low surface brightnesses.
- Currently galaxies are known up to $z \sim 9$, with several candidates at slightly above $z \sim 10$ and one confirmed galaxy at $z \sim 11$ (GN-z11 in the GOODS north field). JWST has just observed a few candidate galaxies up to $z \sim 15$ (yet to be confirmed).





Galaxy number counts

- In the absence of redshifts, some information about the evolution of the galaxy population can be obtained from simple galaxy counts:
- $$d^2 N(m) = \mathcal{N}(m) dm d\omega$$
- The measurement is straightforward, but the interpretation is complicated by the fact that the observations probe galaxies at different redshifts, different absolute L and different rest-frame wavelengths.
 - Despite these problems, a clear detection of galaxy evolution can be made.

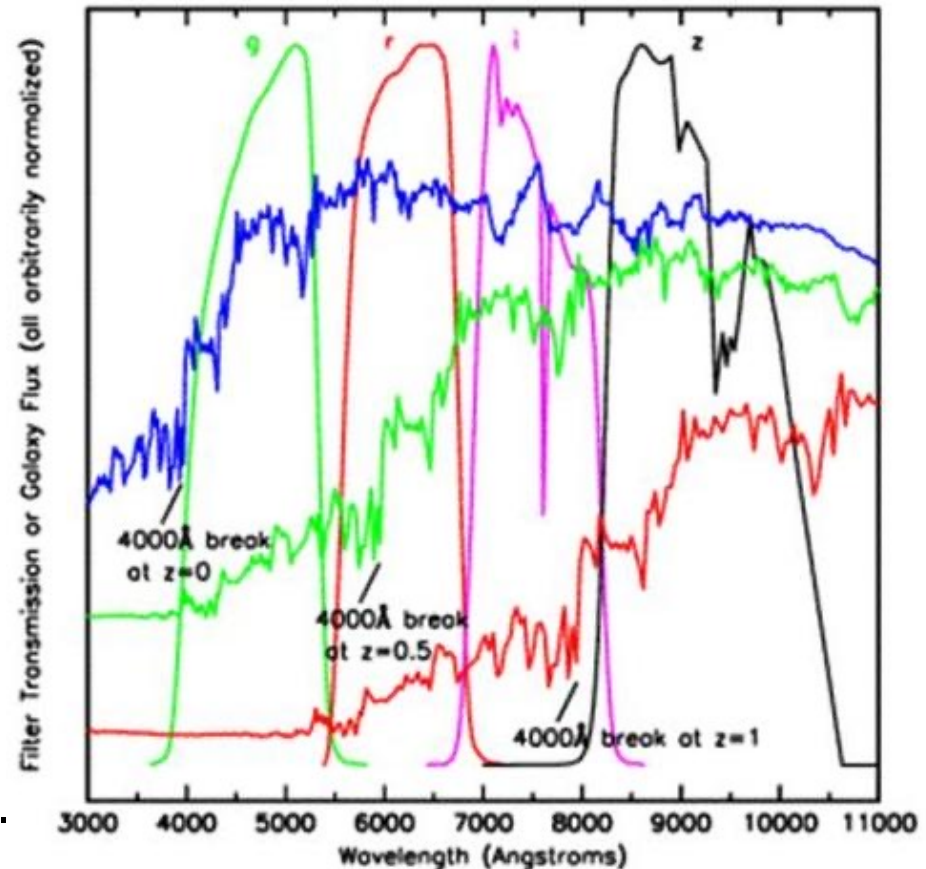


The solid lines show a no-evolution model which strongly underpredicts the number of faint galaxies.



Photometric redshifts

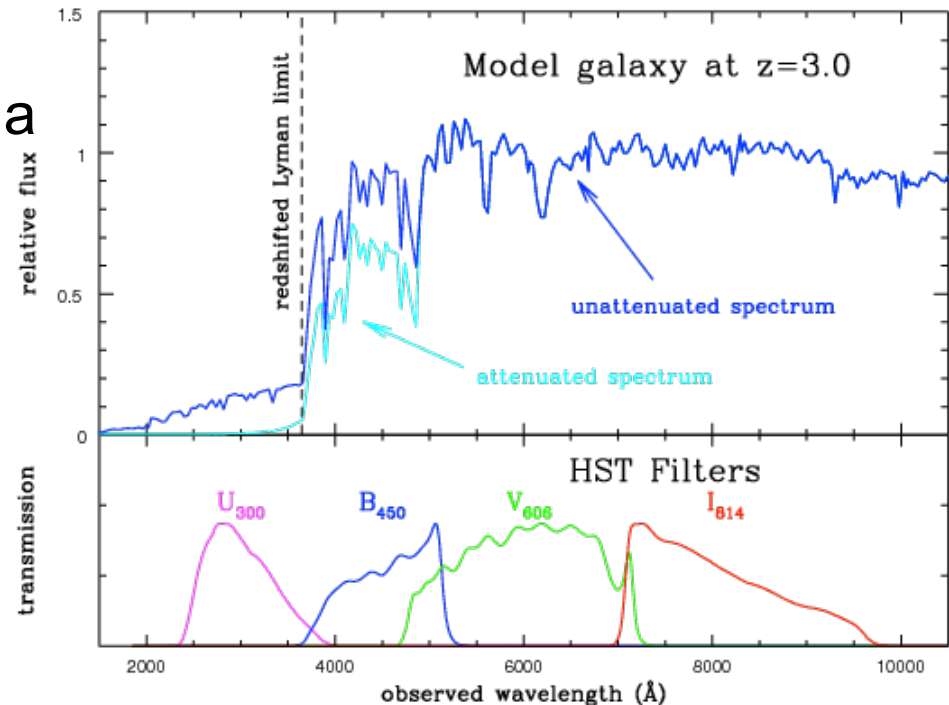
- Measuring accurate redshifts requires spectroscopy, which is very expensive for faint objects.
- Instead, galaxies can be observed in a number of broad band filters, which gives a very low resolution 'spectrum' that can be used to estimate the redshift of the galaxy.
- The method requires SED modelling and clear spectral features. An example is the 4000Å break from low mass stars.





Lyman break galaxies (LBGs)

- A star-forming galaxy has a roughly flat SED until the Lyman break ($\lambda \sim 912 \text{ \AA}$), where there is a prominent break in the spectra due to strong absorption from neutral hydrogen.
- LBGs can be observed at $z \sim 3$ using the U- (blueward) and B- bands (redward of the break).
- The same technique can be applied at higher redshifts using bands at longer wavelengths.

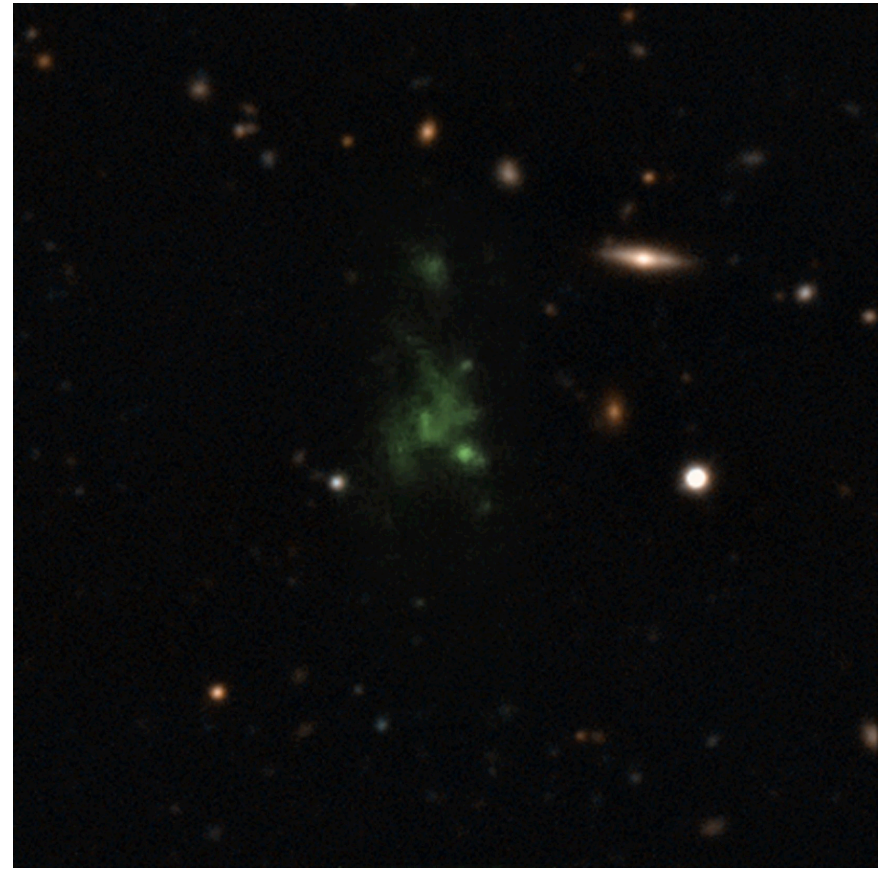


Need follow-up spectroscopy to confirm the true nature of these objects.



Lyman α emitters (LAEs)

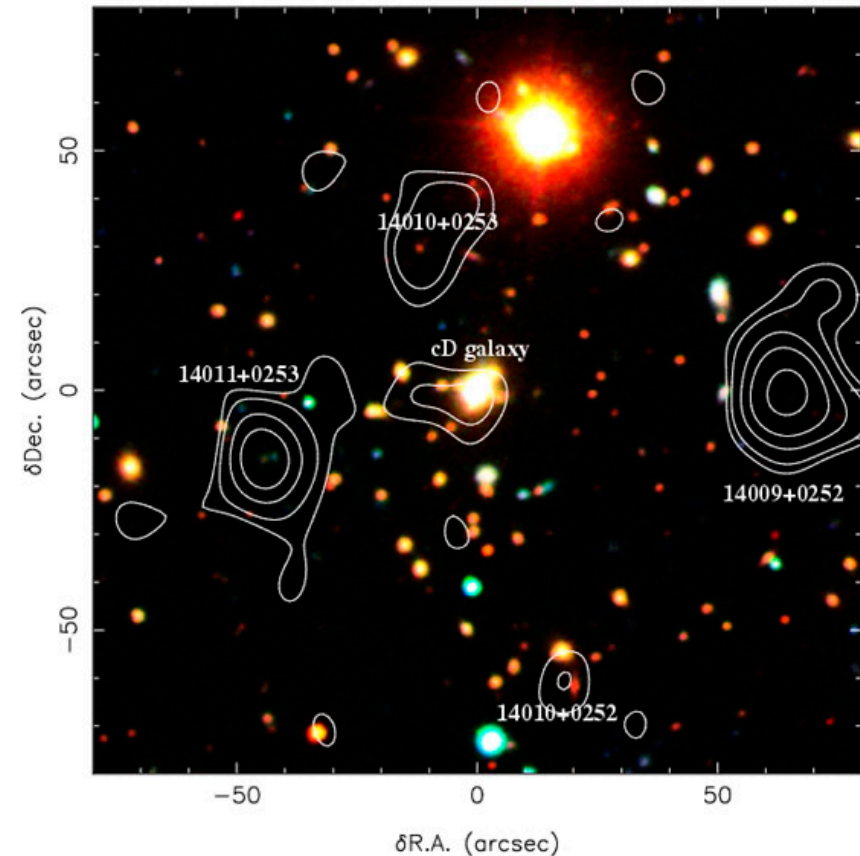
- In addition to broad-band selections, galaxies can also be searched in very narrow-band photometry by centering the filter at the expected redshift of a strong emission line, in practise the Ly α -line ($\lambda \sim 1216 \text{ \AA}$).
- Objects with strong Ly α are either quasars or starbursts, however the line is easily quenched by dust extinction in most galaxies.
- Possible contamination also arises from other lines at lower redshifts, e.g. OII lines at $\lambda \sim 3727 \text{ \AA}$.





Submillimetre galaxies

- The Lyman techniques select galaxies according to their rest-frame UV light.
- The high-redshift counterparts of local starbursts would have most of their UV photons observed and re-radiated in the far-infrared.
- Such galaxies can therefore be detected in the submillimetre waveband.
- The optical counterpart is usually very weak and the implied SFR of submillimetre galaxies can be extremely high up and beyond of $\text{SFR} \sim 1000 M_{\odot}/\text{yr}$.





Extremely red objects

- Observations of objects with extremely red colours ($R-K > 5$) probe massive old early-type galaxies at $z \sim 0.7-1.5$.
- Some fraction of the extremely red objects can also be dusty starbursts with red colours.
- Deep imaging in the near-IR is also important for probing 'normal' galaxies at $z \sim 1$, as opposed to a biased star-forming population such as the LBGs.





First results from James Webb Space Telescope (JWST)

- The first observations (summer 2022) by the JWST seems to indicate an overabundance of bright star-forming galaxies in the very early Universe ($t < 500$ Myr).
- Results based mainly on photometric redshifts and cover only one observational field, thus some caution is warranted.
- Indications are that star formation was more effective and supernova feedback weaker than expected. Why this was the case still remains to be understood.



The SMACS 0723 galaxy cluster observed by JWST (first light image).



What have we learned?

1. The classical morphological galaxy classifications are still useful today and they work best for bright regular objects in the local Universe, the Hubble sequence at high- z would be very different.
2. The vast majority of the bright galaxy population can be divided into elliptical galaxies and disk galaxies with distinct photometric, kinematic and physical properties.
3. Statistically, we can predict the sizes, the colours, the metallicities and the likely environment of a galaxy based on its absolute luminosity.
4. Spectroscopy of galaxies at high redshifts is time consuming, therefore it is better to use broad and narrow-band photometric techniques for selecting interesting galaxy candidates as a function of redshift for further study. JWST is in the process of revolutionising the field.