Galaxies: Structure, formation and evolution

Lecture 18

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Extremely red objects - $R - K > 5$

Consist of almost equal numbers of

1. elliptical galaxies that already have, at $z \sim 1$, a luminosity similar to that of today's ellipticals, and are at that epoch already dominated by an old stellar population
2. Galaxies with active star formation which do not show a 4000Å break but which feature the emission line of [OII] at $\lambda = 3727$Å, a clear sign of star formation. These are red because they are heavily dust obscured. Radio-FIR observations show that these are ULIRGS.

Photometric redshifts - by product of stellar population synthesis

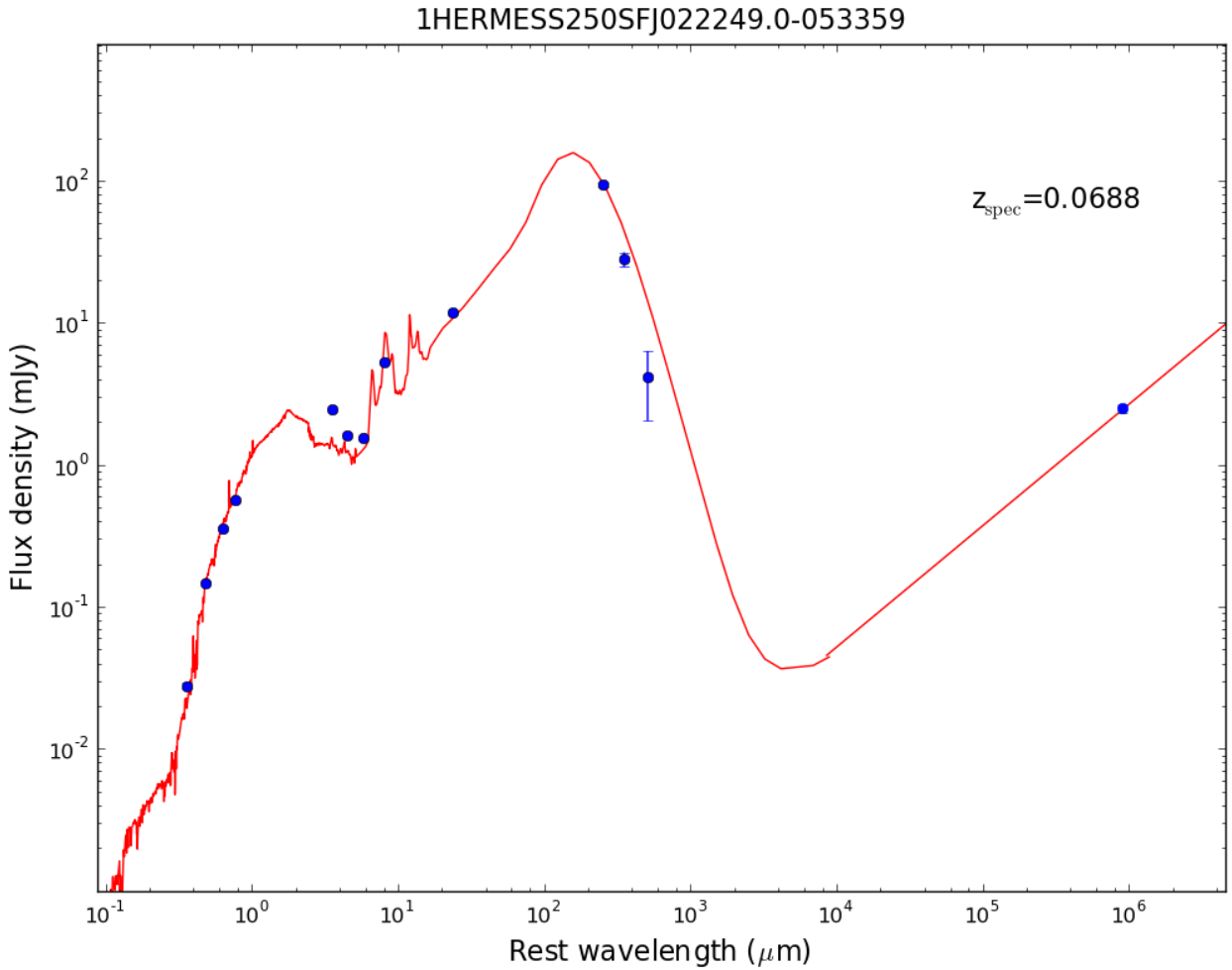
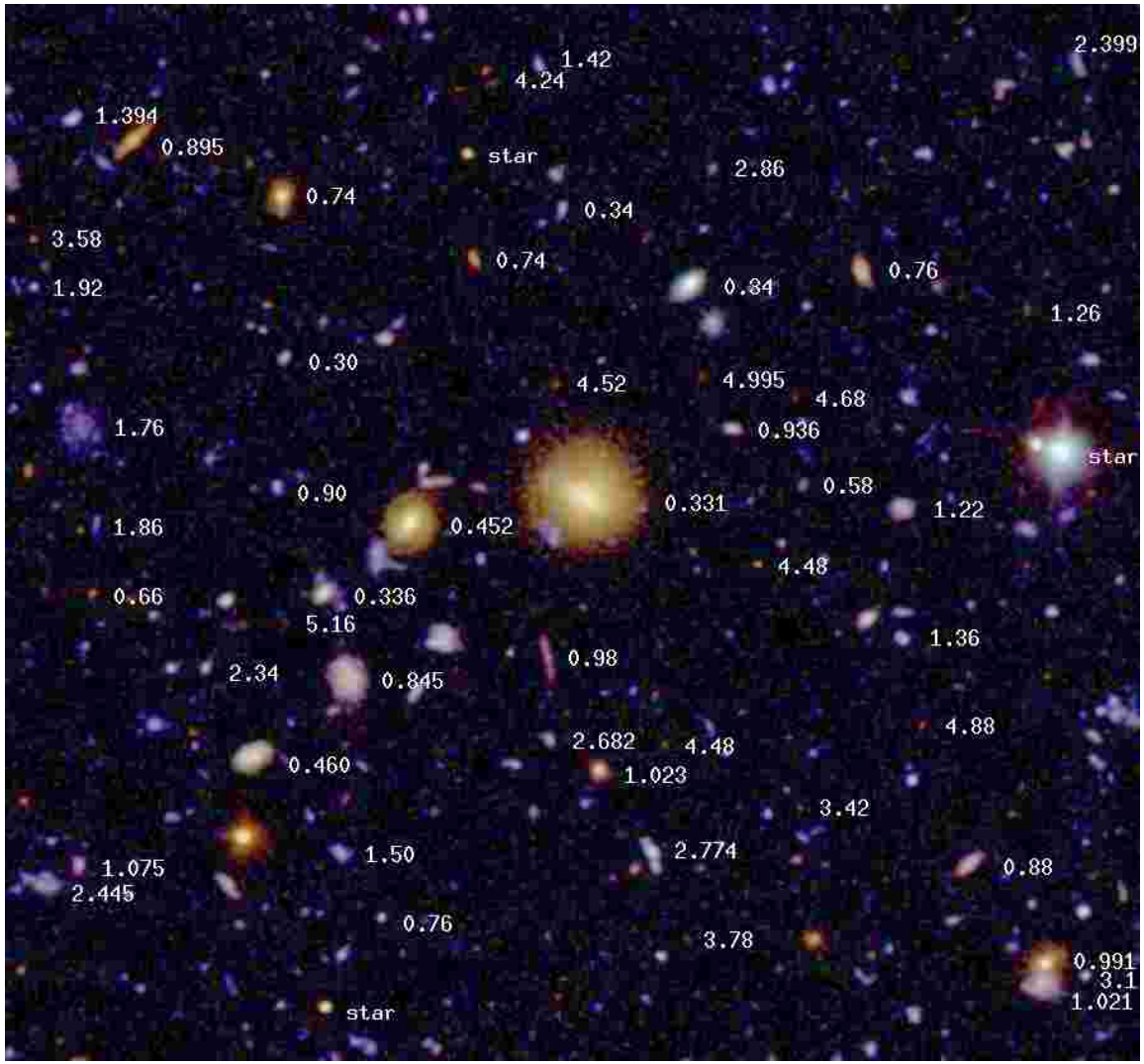
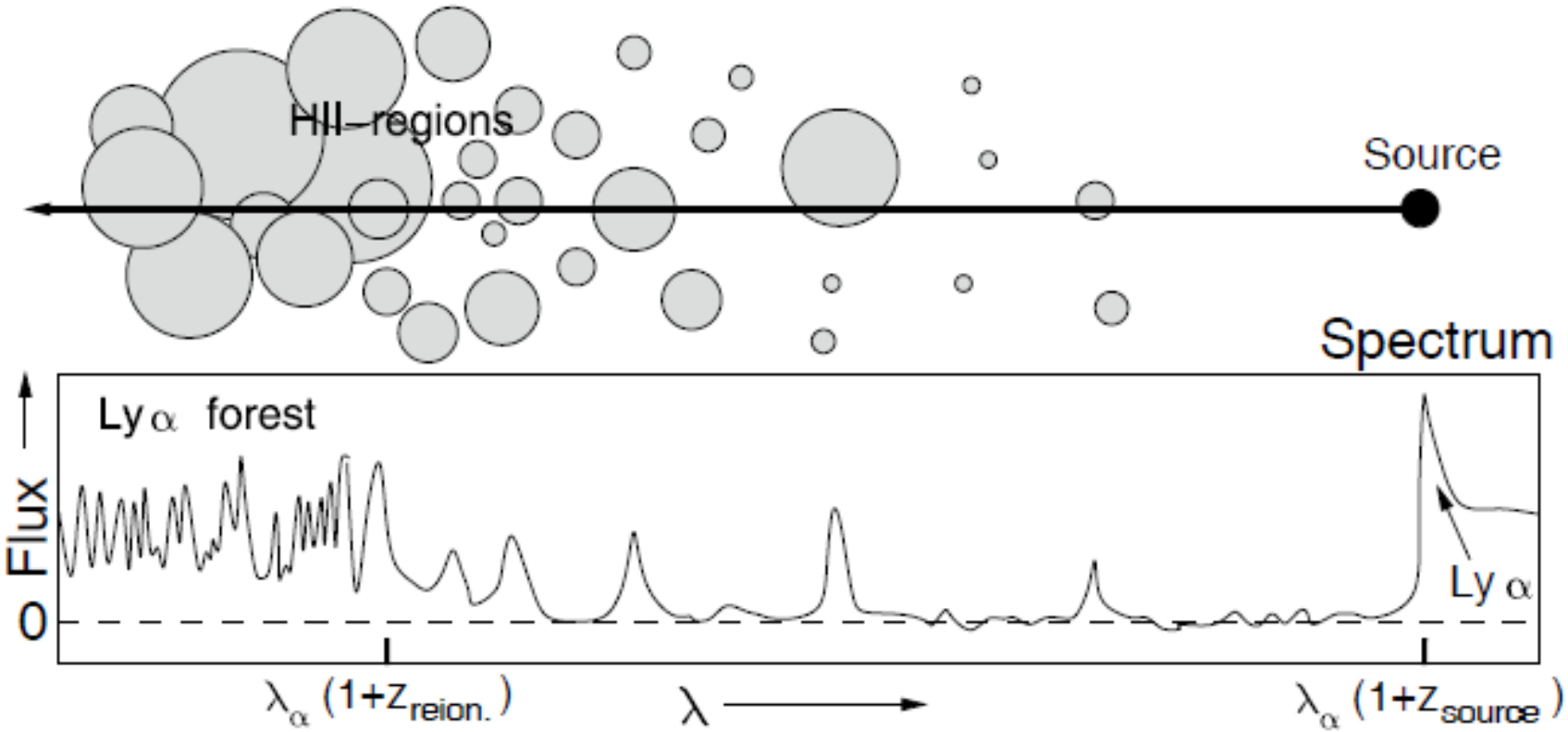


Photo z for thousands of objects



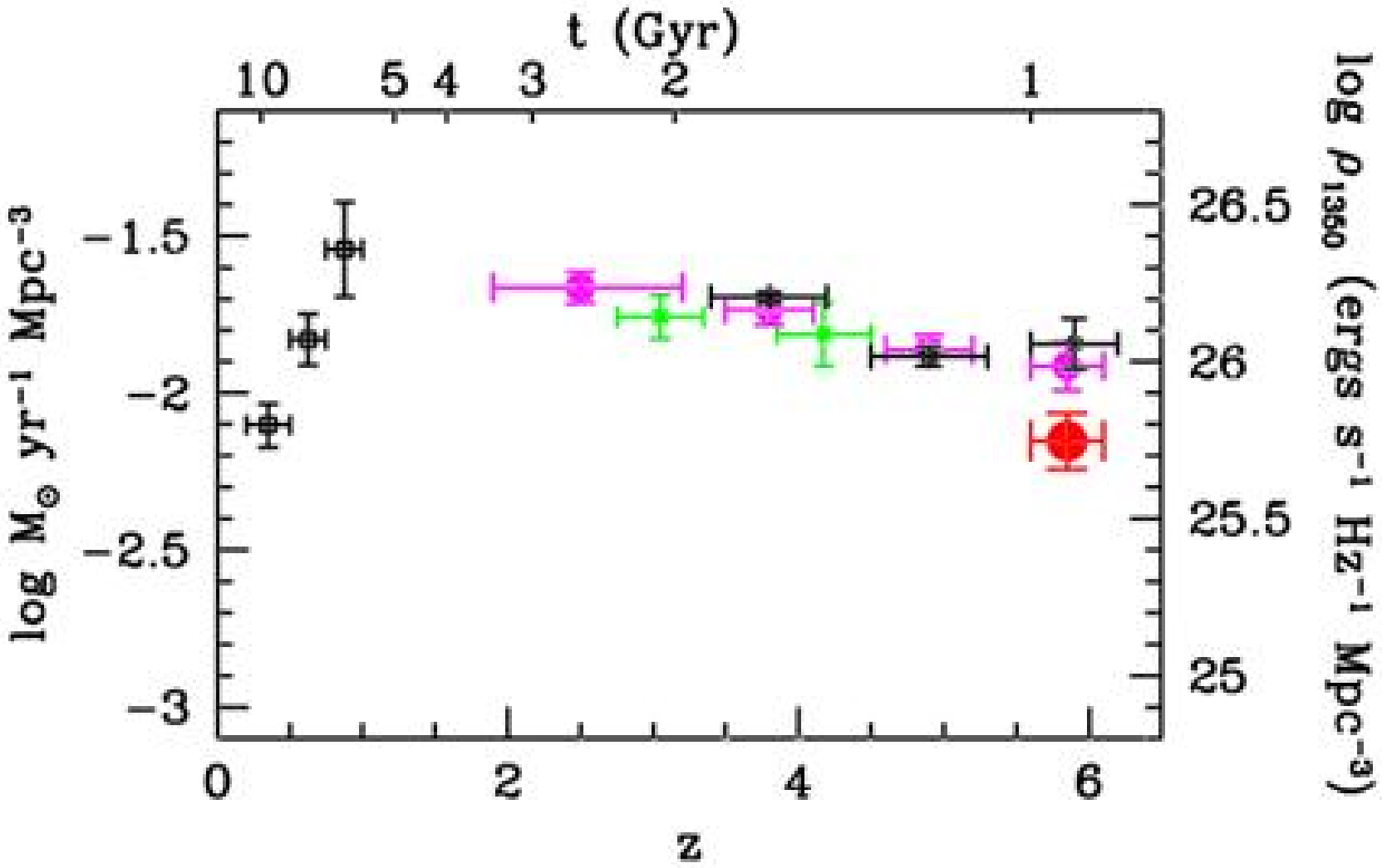
Reionisation spectrum



SFR over cosmic time

The density of star formation, $\rho_{\rm SFR}$, is defined as the mass of newly formed stars per year per unit (comoving) volume, typically measured in $M_\odot {\rm yr}^{-1}$ Mpc^{-3}. Therefore, $\rho_{\rm SFR}$ as a function of redshift specifies how many stars have formed at any time.

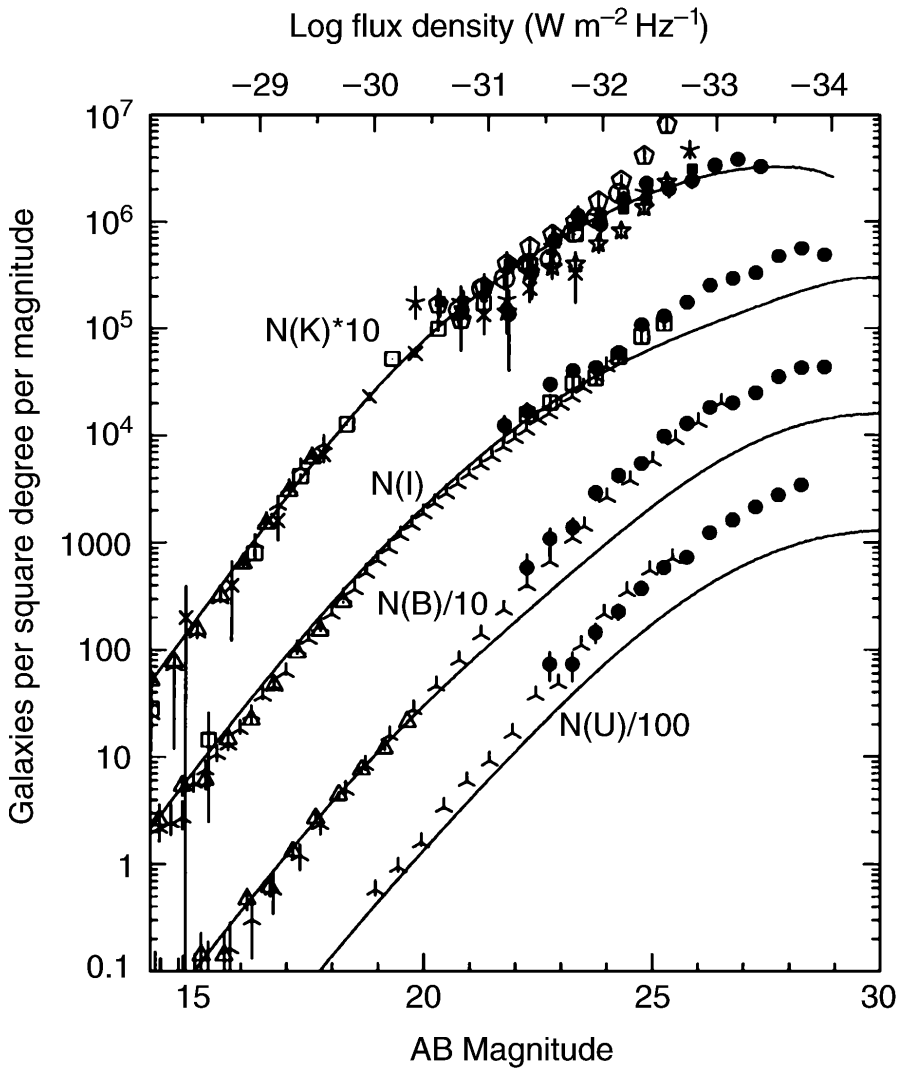
Lilly-Madau diagram



Hierarchical galaxy formation

(i) encounters and mergers of galaxies play a central role in their evolution, and in fact galaxies are formed by the mergers of smaller galaxies (ii) even apparently isolated galaxies are surrounded by much larger dark halos whose outermost tendrils are linked to the halos of neighboring galaxies and (iii) gas, stars, and dark matter are being accreted onto galaxies continuously up to the present time.

HDF number counts - evidence of evolution



Luminosity evolution versus density evolution

Luminosity evolution measured in terms of luminosity per comoving unit volume. Density evolution in terms of number of galaxies per comoving unit volume. Extremely difficult to disentangle at high redshift due to selection biases.
But luminosity functions can be compared at two redshifts to see which of these is dominant.

Topics not covered in the high redshift universe

- Lyman alpha absorber, damped DLAs and Lyman limit systems
- backgrounds: CMB, CIB, CXB

High supernova rates in starburst galaxies

Measuring star formation - IR

Emission in the far infrared (FIR). This is radiation emitted by warm dust which is heated by hot young stars. For the relation of FIR luminosity to the SFR, observation yields the approximate relation

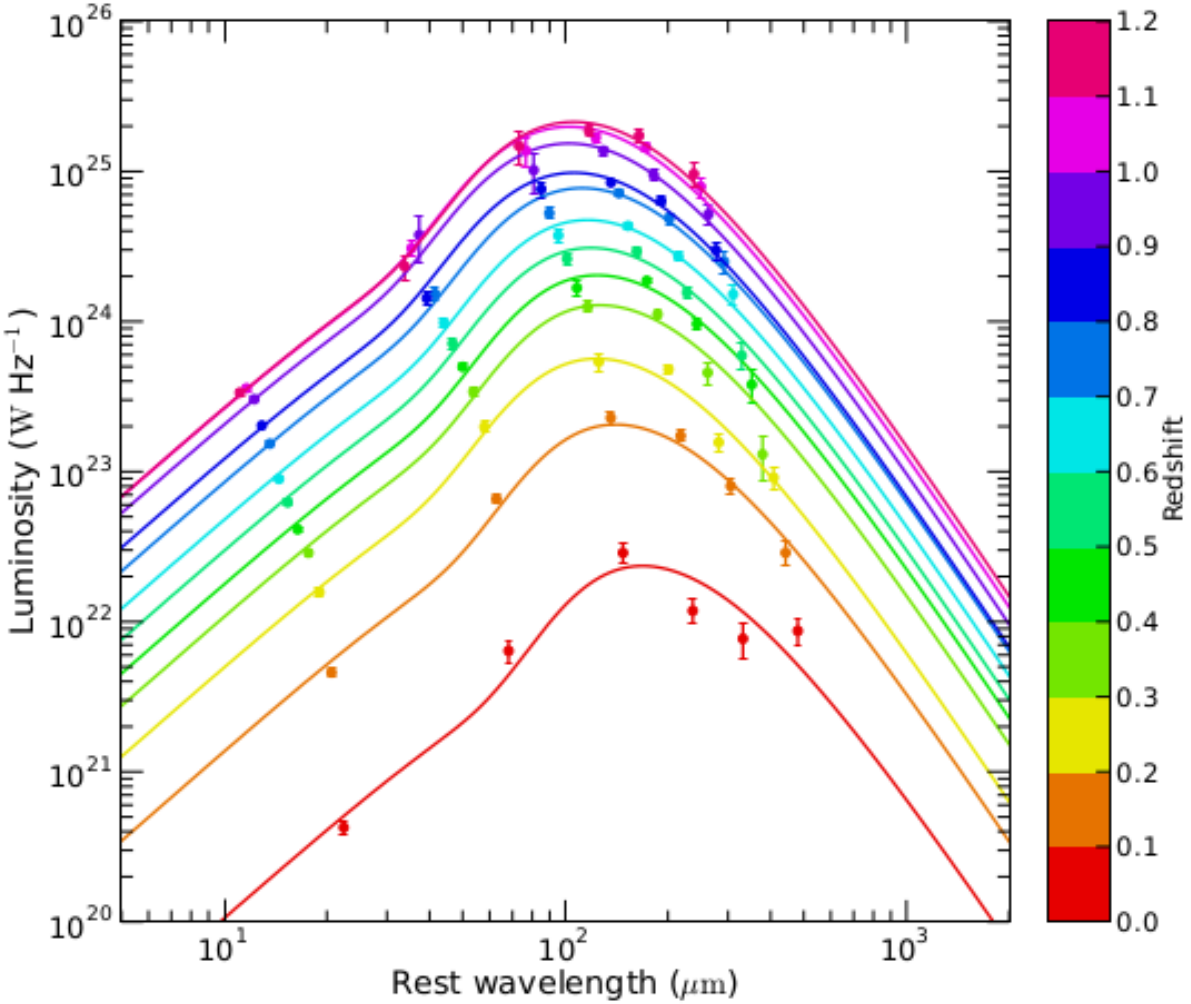
$$\frac{\mathrm{SFR}_{\mathrm{FIR}}}{M_\odot/\mathrm{yr}} \sim \frac{L_{\mathrm{FIR}}}{5.8 \times 10^9 L_\odot}$$

Measuring the SFR - Radio

A very tight correlation exists between the radio luminosity of galaxies and their luminosity in the FIR, over many orders of magnitude of the corresponding luminosities. Since $L_{\rm FIR}$ is a good indicator of the star-formation rate, this should apply for radiation in the radio as well.

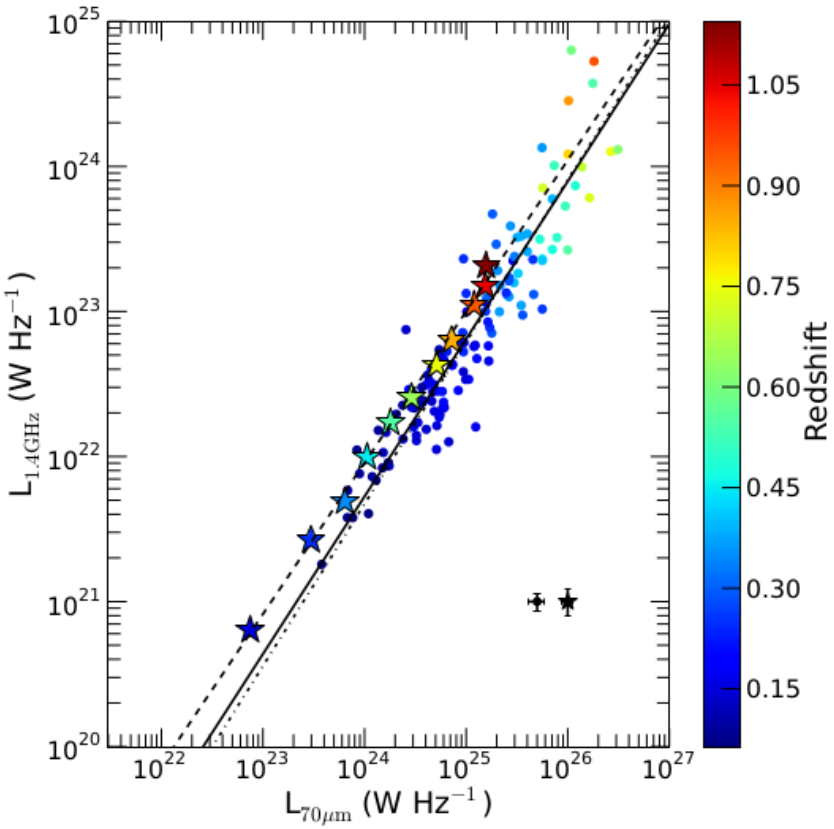
$$\frac{\mathrm{SFR}_{1.4\mathrm{GHz}}}{M_\odot/\mathrm{yr}} \sim \frac{L_{1.4\mathrm{GHz}}}{8.4 \times 10^{27} \mathrm{erg\ s^{-1} Hz^{-1}}}$$

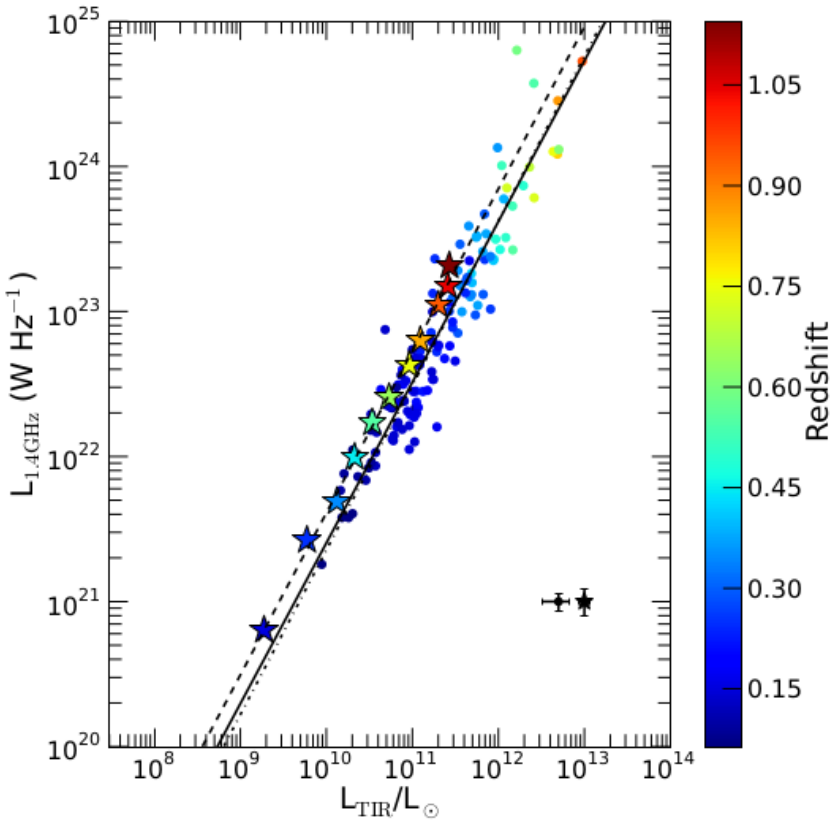
FIR SED of stacked sources at different redshifts



Basu, Wadadekar et al. (2015)

The Radio FIR correlation





Basu, Wadadekar et al. (2015)

Measuring the SFR - H_α

This line emission comes mainly from the HII regions that form around young hot stars.

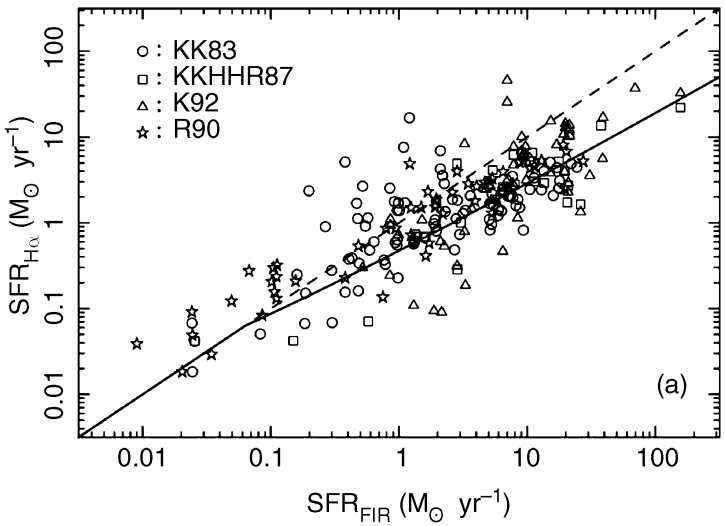
$$\frac{\mathrm{SFR}_{\mathrm{H}\alpha}}{M_\odot/\mathrm{yr}} \sim \frac{L_{\mathrm{H}\alpha}}{1.3 \times 10^{41} \mathrm{erg\ s^{-1}}}$$

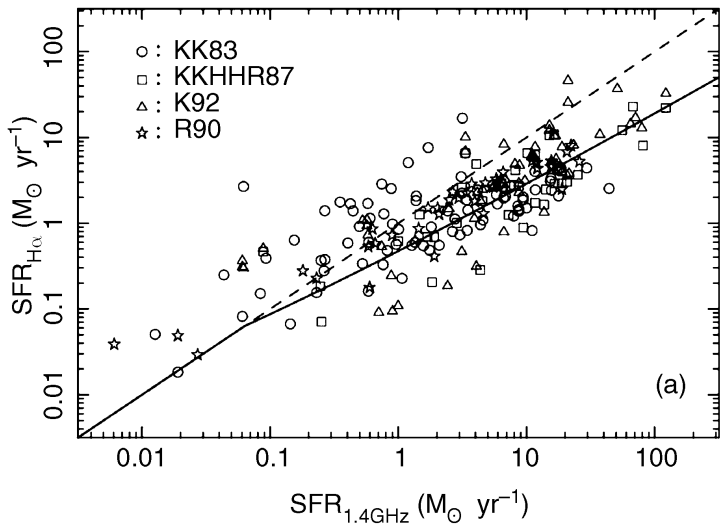
Measuring the SFR - UV

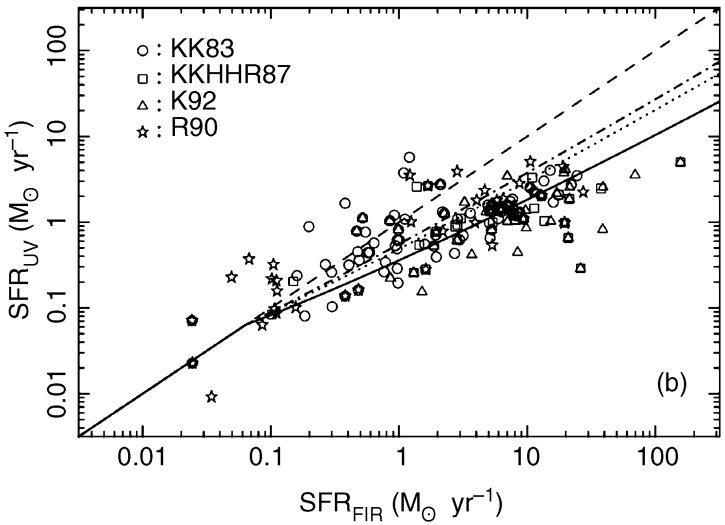
This is only emitted by hot young stars, thus indicating the SFR in the most recent past - an *instantaneous* SFR

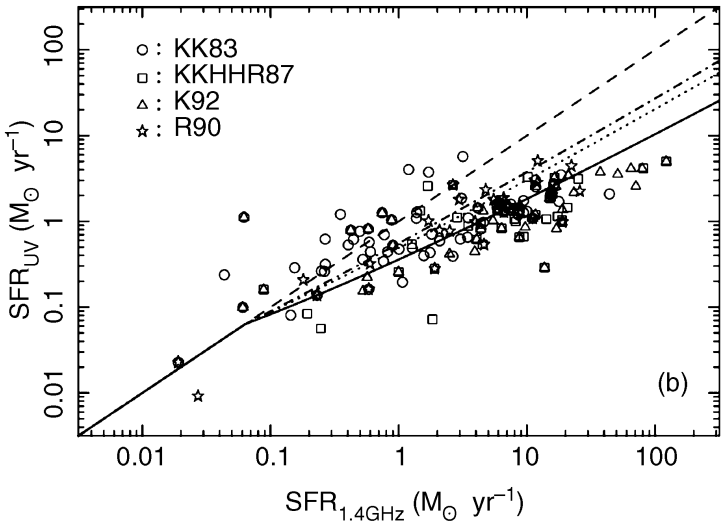
$$\frac{\mathrm{SFR_{UV}}}{M_\odot/\mathrm{yr}} \sim \frac{L_{\mathrm{UV}}}{7.2 \times 10^{27} \mathrm{erg\ s^{-1} Hz^{-1}}}$$

SFR estimators compared









Other star formation indicators

The fine-structure line of singly ionized carbon at $\lambda = 157.7\mu$m is of particular importance as it is one of the brightest emission lines in galaxies, which can account for a fraction of a percent of their total luminosity. The emission is produced in regions which are subject to UV radiation from hot stars, and thus associated with star-formation activity. Due to its wavelength, this line is difficult to observe and has, until recently, been detected only in star-forming regions in our Galaxy and in other local galaxies. All this has changed with ALMA.