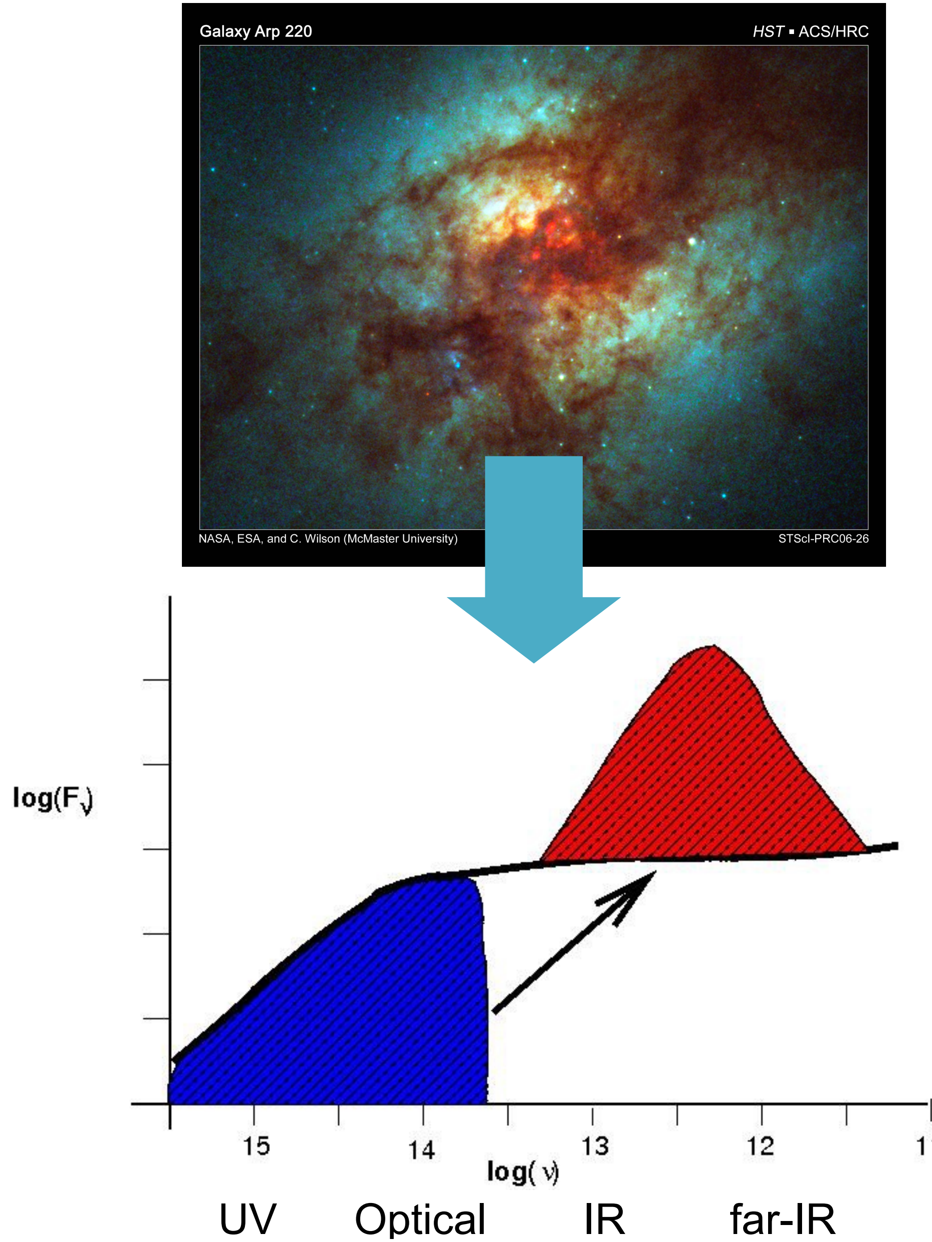
Galaxy Formation and Evolution

Lecture 08:
Studying galaxy evolution in the IR/sub-mm

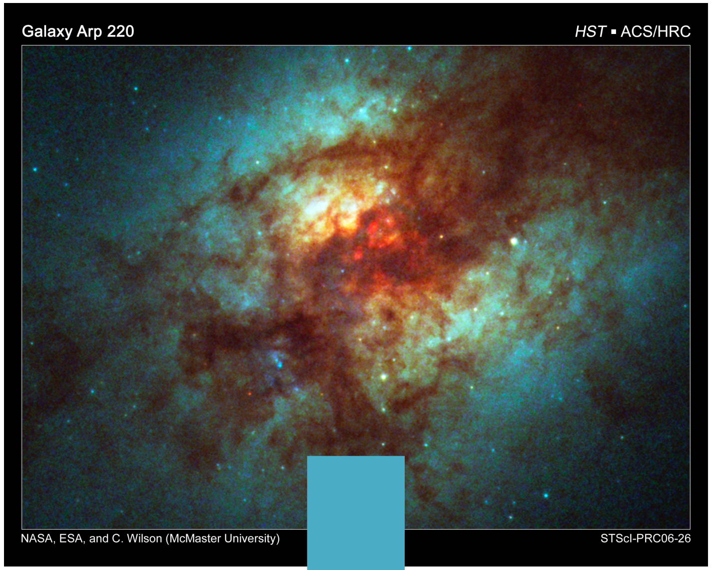
Course contents

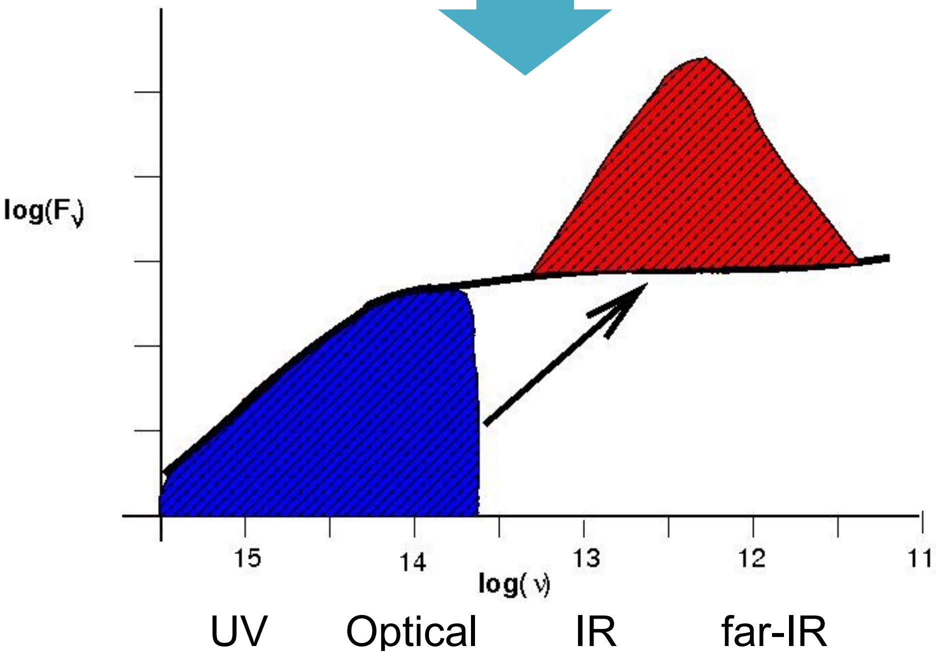
Dust reprocessing of light from a starburst



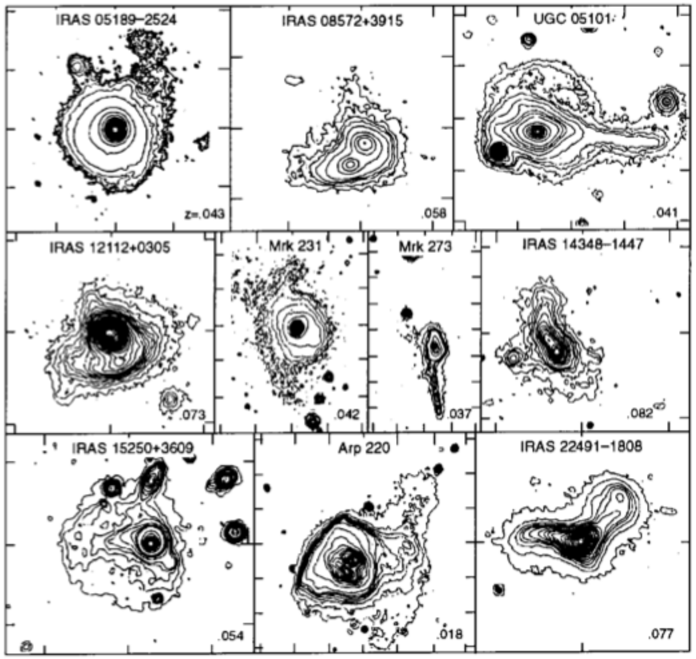
Dust reprocessing of light from a starburst

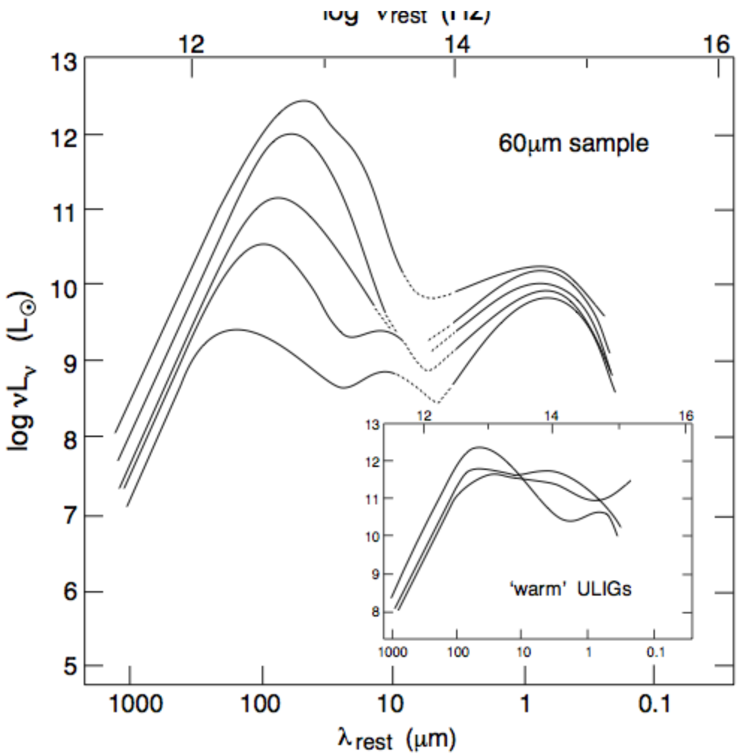
The Optical/UV light emitted by stars in circum-nuclear starbursts is absorbed by dust, heating it to T_{dust}~20-100K. The energy is re-radiated at far-IR and sub-mm wavelengths (>10μm) as thermal (~black body) radiation. Thus, the far-IR luminosity can be used to measure the star formation rate.





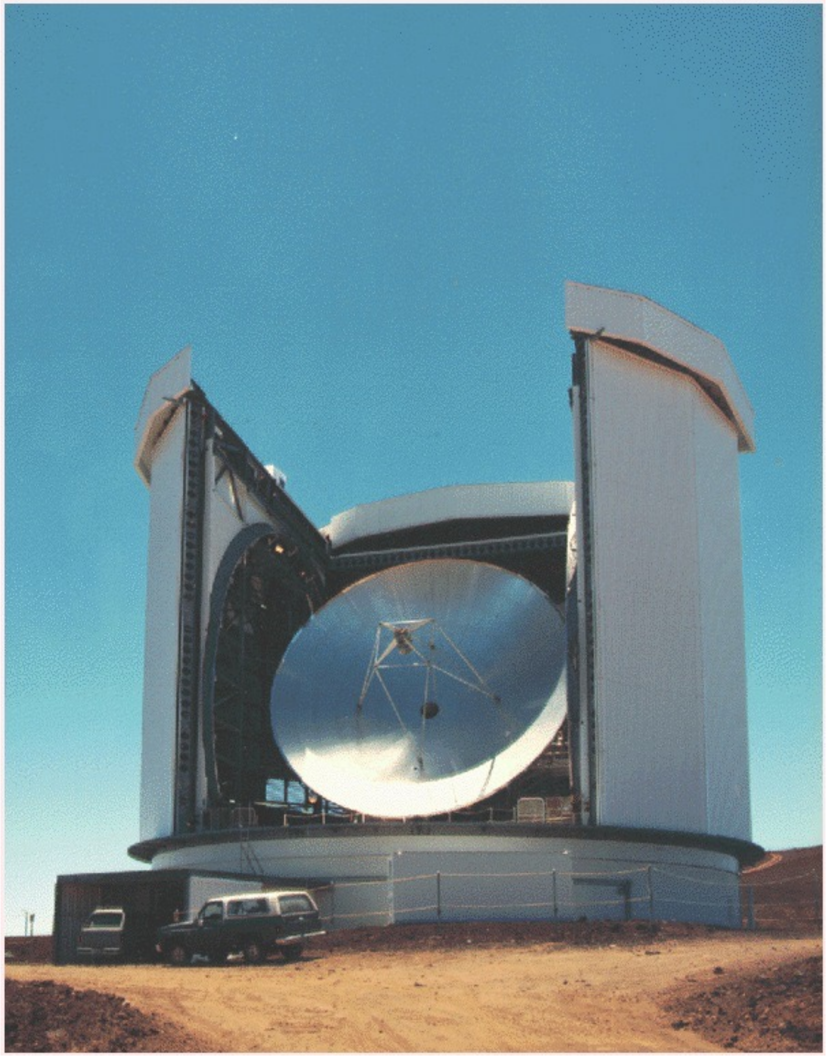
Ultra-Luminous Infrared Galaxies (ULIRG)



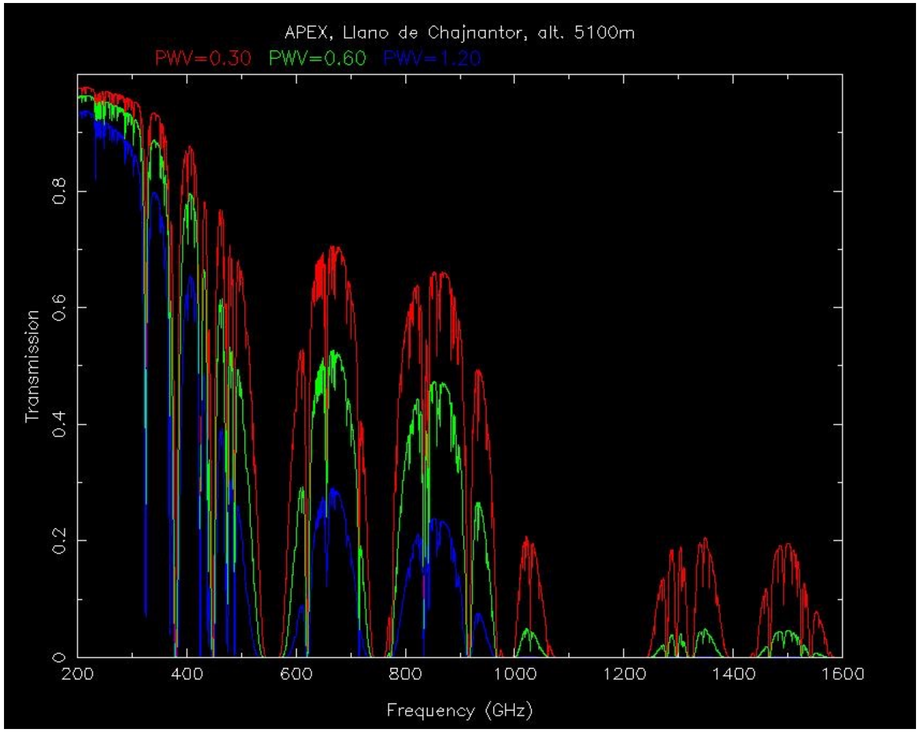


Much of the far-IR emission in ULIRGs is produced by starburst heating of the cool dust in the central regions of the systems.

Sub-mm astronomy



The James Clerk Maxwell Telescope (JCMT) at 4100m on Hawaii.

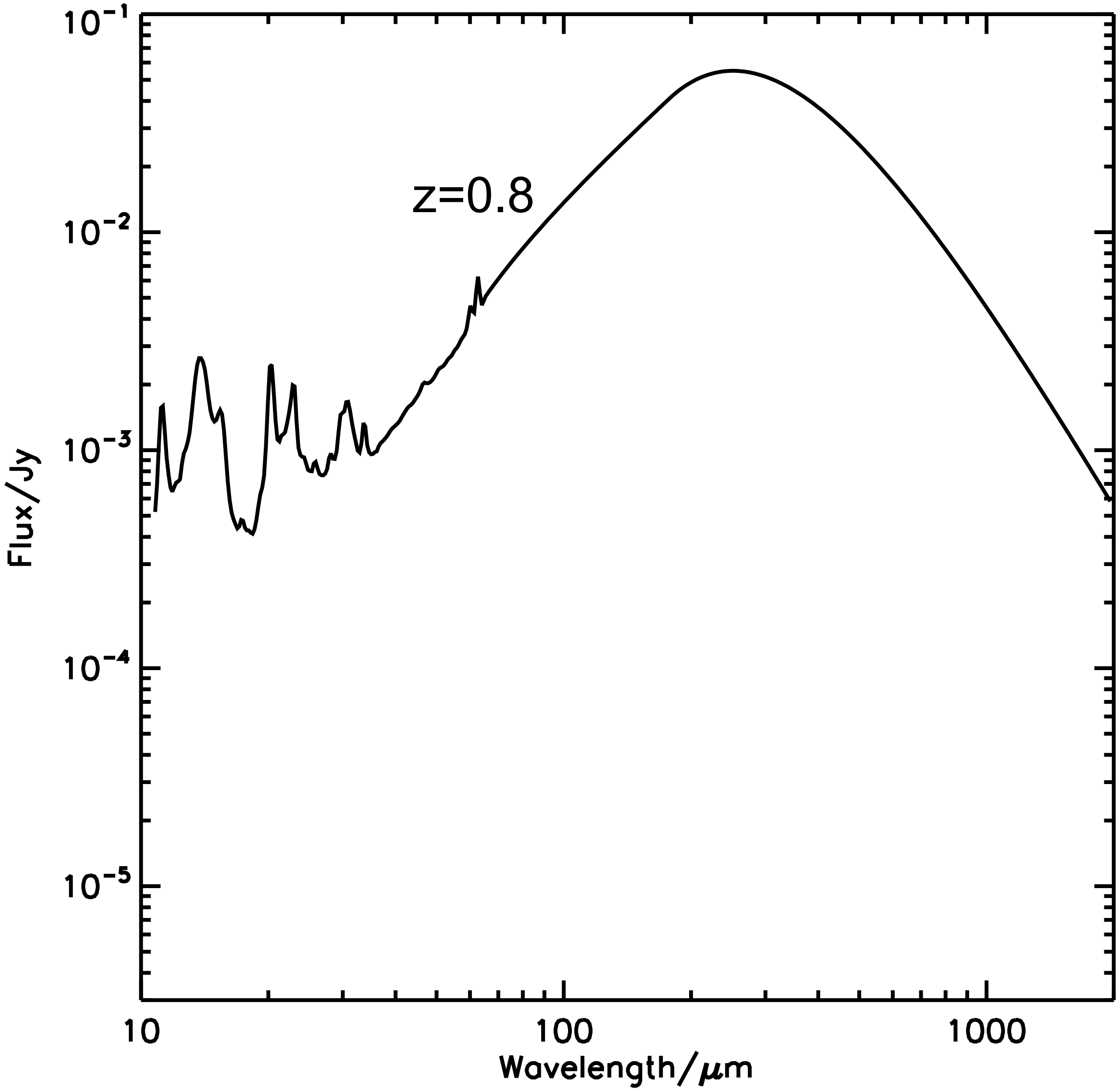


High altitude sites such as Mauna Kea on Hawaii can exploit atmospheric windows at 1.2, 0.85, 0.45, 0.35 mm (between radio and far-IR). But the atmospheric transmission depends strongly on the water vapour content of the atmosphere at the time of the observations.

Positive K-correction at sub-mm wavelengths I

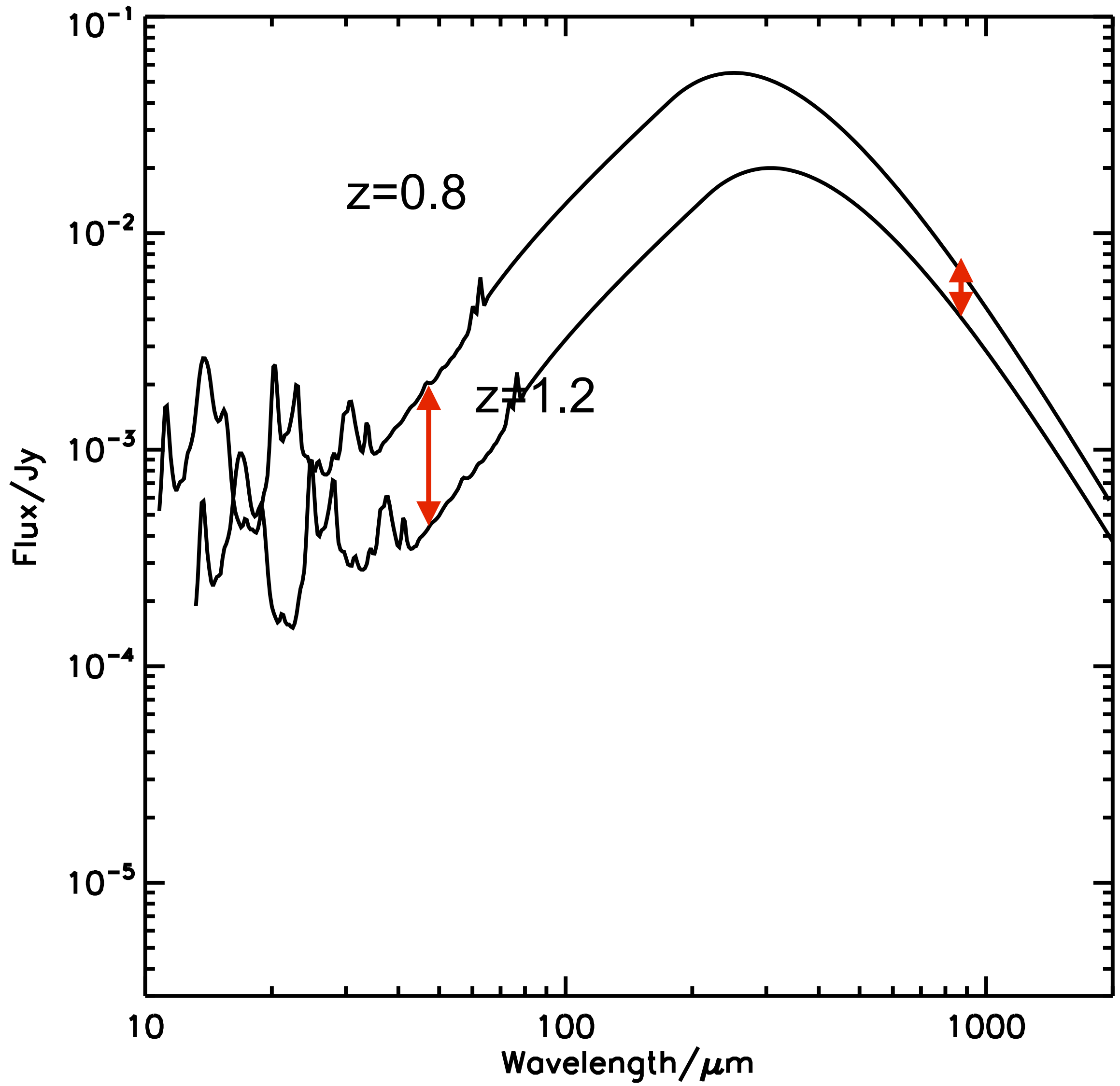
Galaxy of luminosity:

$10^{12}\,L_{Sun}$



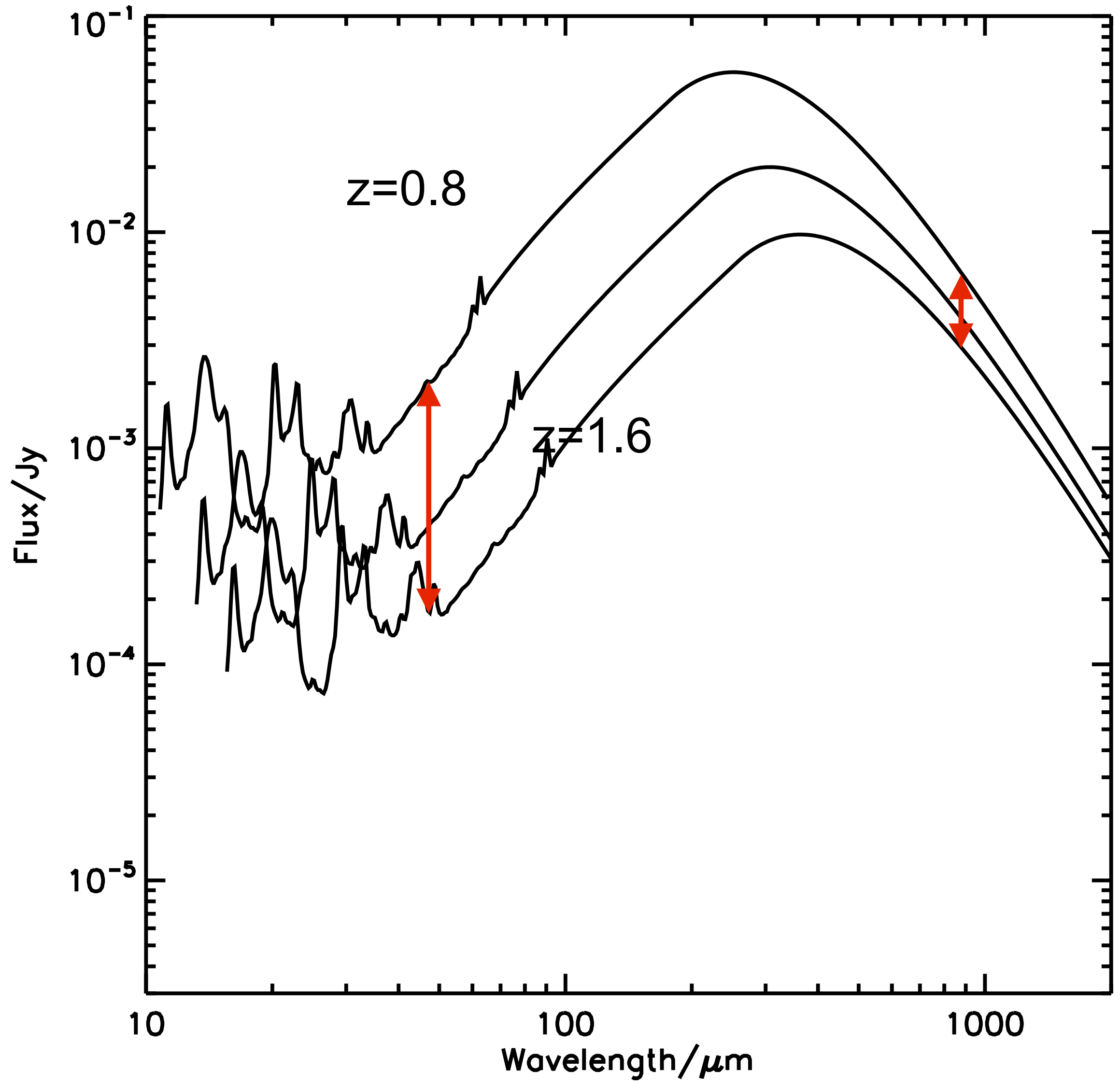
Positive K-correction at sub-mm wavelengths I

Galaxy of luminosity:
$10^{12}\ L_{Sun}$



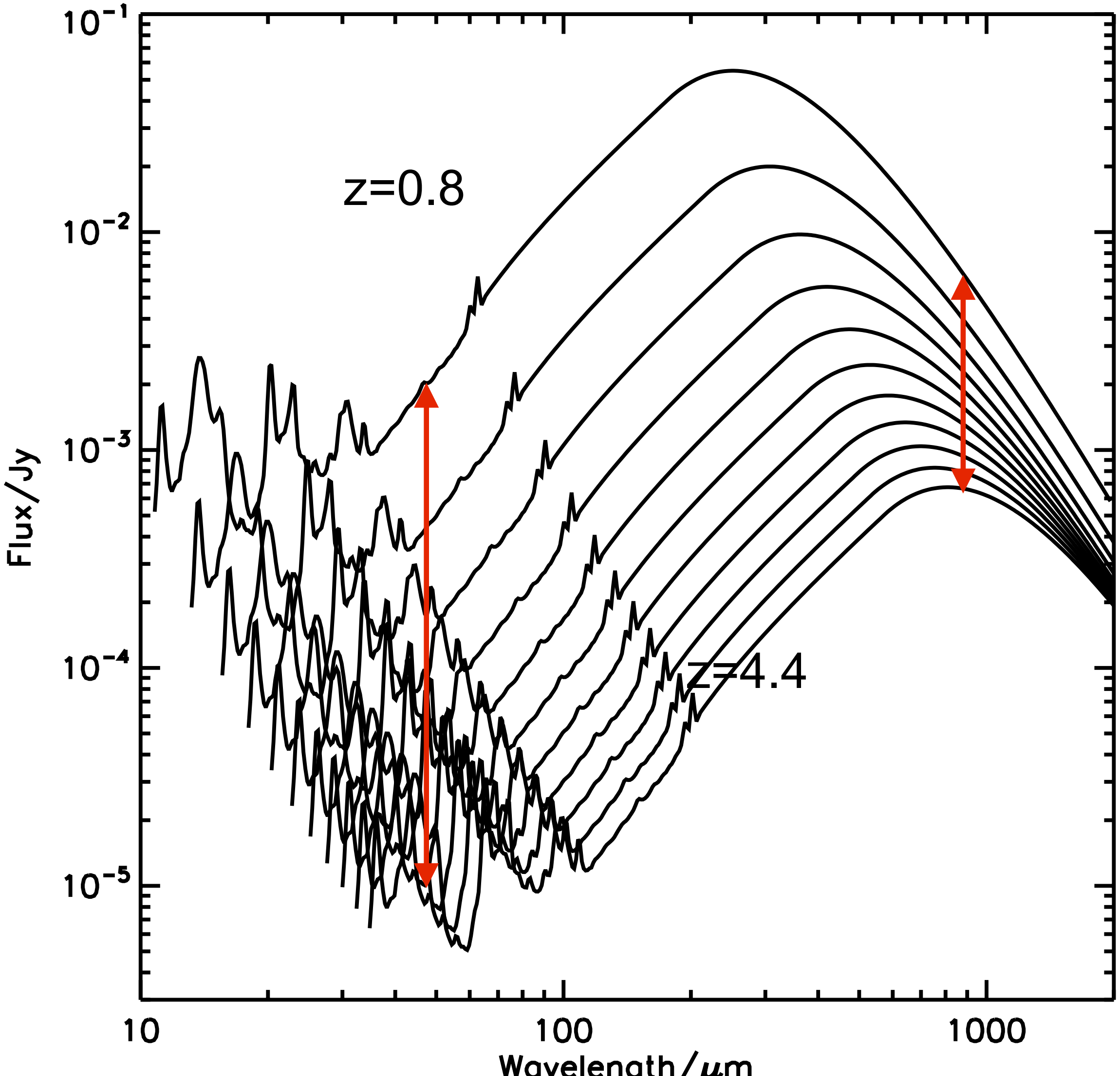
Positive K-correction at sub-mm wavelengths I

Galaxy of luminosity: $10^{12}\ L_{Sun}$

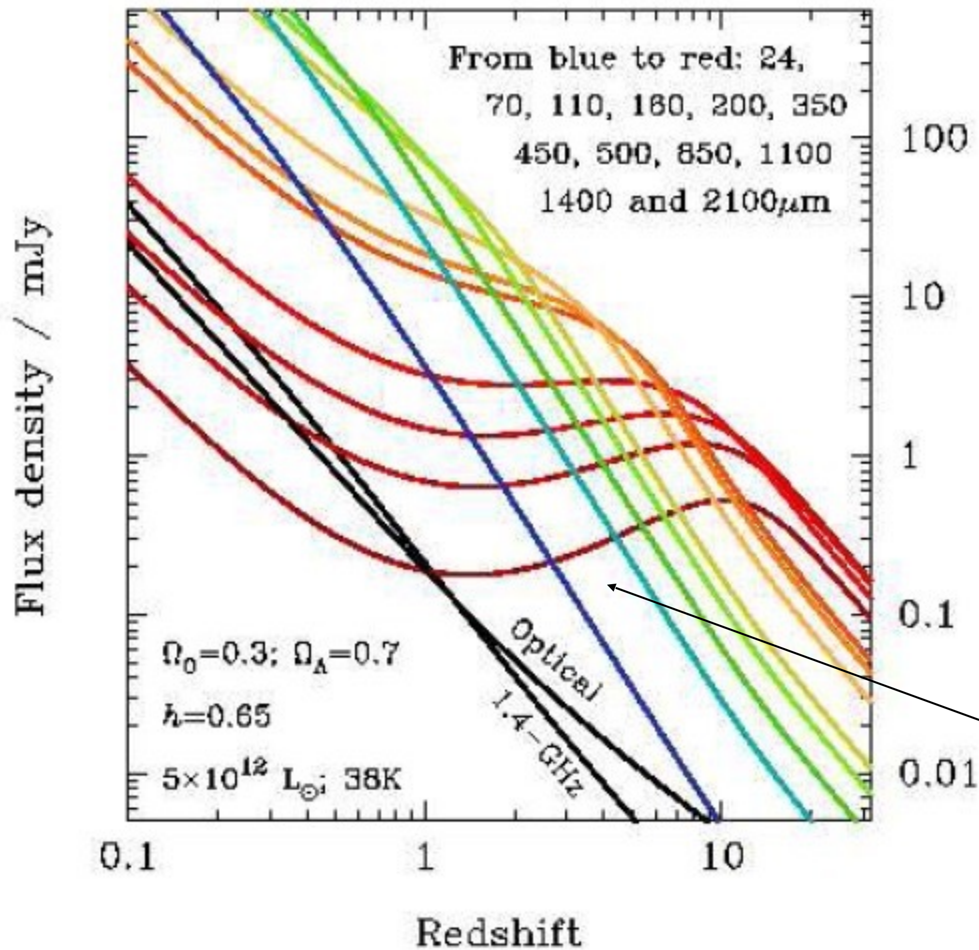


Positive K-correction at sub-mm wavelengths I

Galaxy of luminosity:
$10^{12}\,L_{Sun}$



Positive K-correction at sub-mm wavelengths II



Flux as a function of redshift predicted for various far-IR and sub-mm wavelengths, assuming a ULIRG-like SED with a dust temperature of 36K.

As the far-IR thermal emission bump of the ULIRG becomes successively redshifted into the sub-mm, the positive K-correction compensates for the usual geometrical and cosmological dimming of a source with redshift.

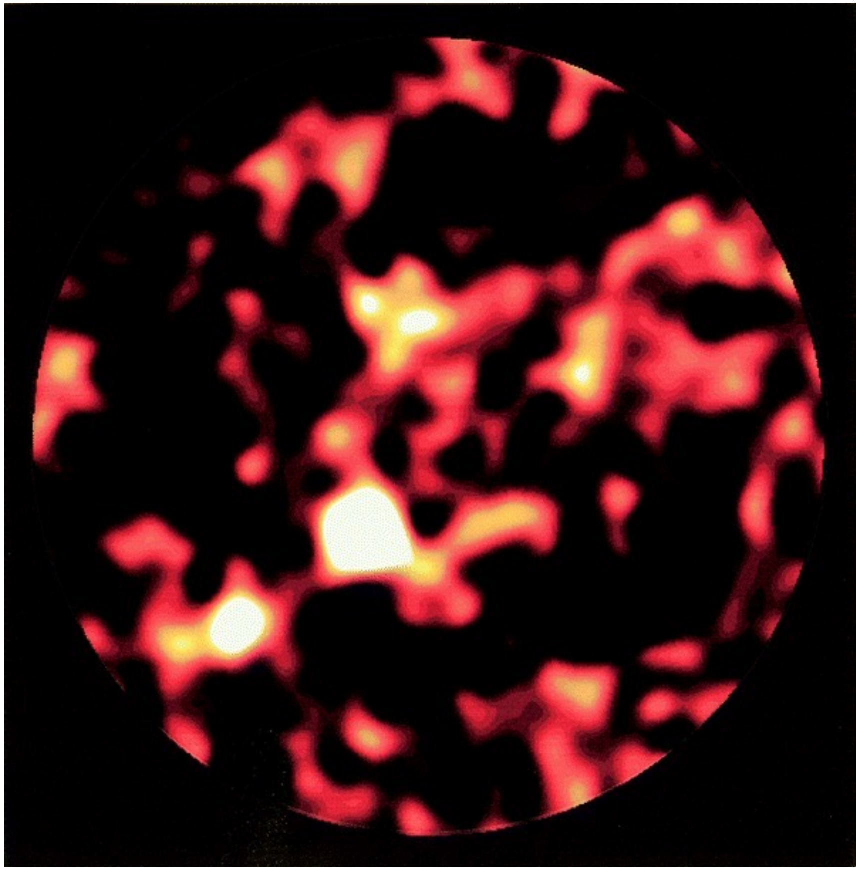
In theory, because of the positive K-correction, sources at z~10 should be as bright as those at z~1 (for observations around 1mm)

Detecting high redshift galaxies at sub-mm wavelengths

- The sub-mm wavelength region has the great advantage that the far-IR thermal bump (sampling the re-processed optical/UV light of a starburst) is redshifted into the sub-mm for high redshift objects.
- However, it requires high, dry sites in order for the atmosphere to be sufficiently transparent.
- Also, with typical dish sizes of ~25m, the spatial resolution is limited (~15” at 850μm), making it difficult to pinpoint sub-mm sources at optical/IR wavelengths.
- In the near-future the resolution problem should be solved with the development of large sub-mm interferometers (e.g. ALMA).

Detection of the first SMGs I

HDF-N map

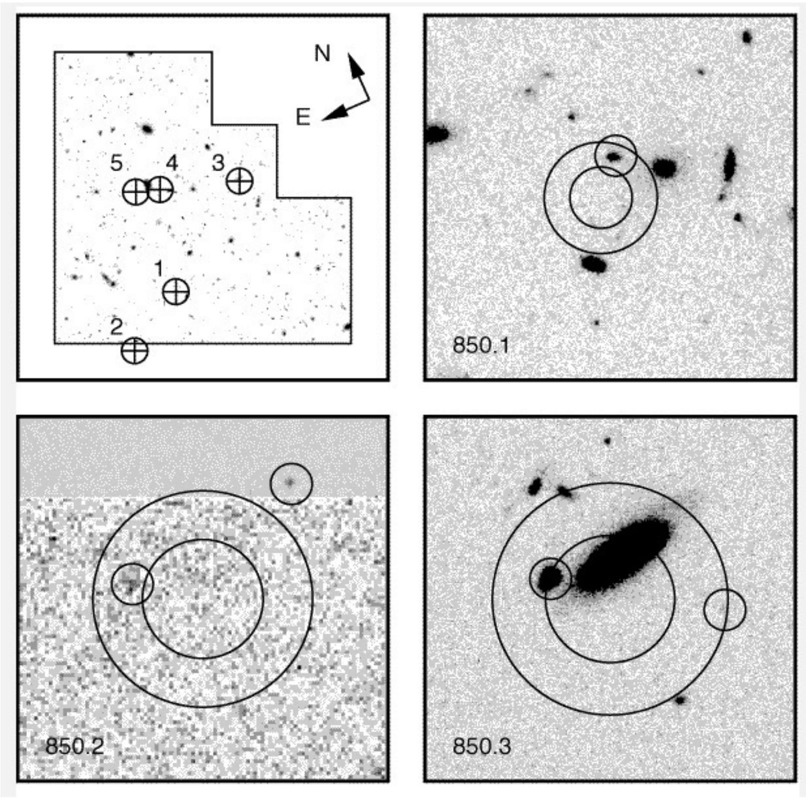


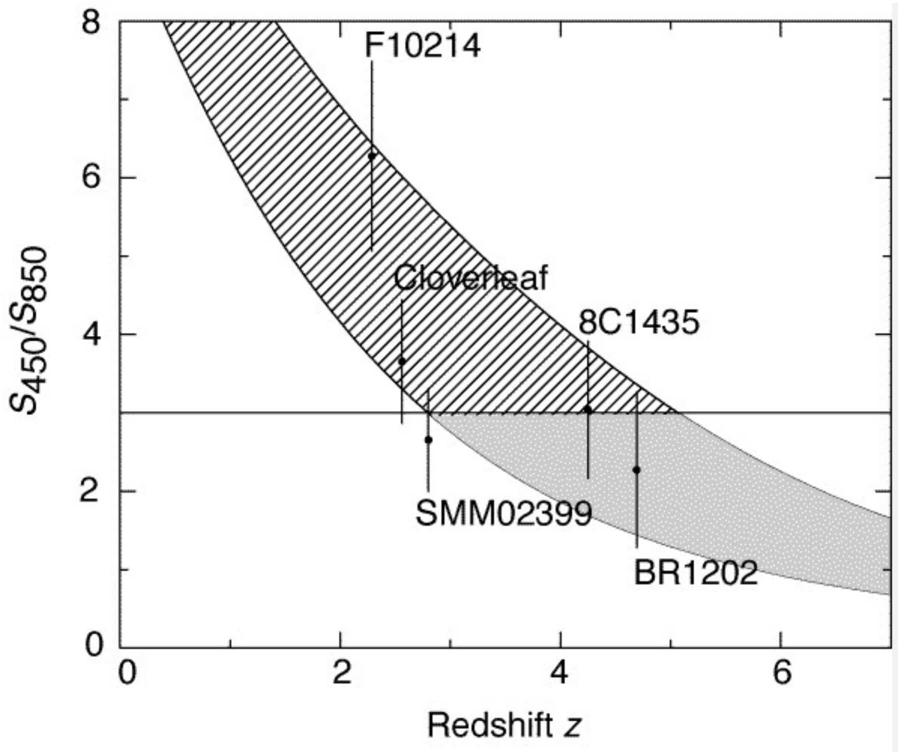
Hughes et al. (1997)

850μm map of the Hubble Deep Field North, made with the sensitive SCUBA bolometer array on the JCMT, Hawaii.

Detection of the first SMGs II

Positions and redshifts





It can be difficult to pinpoint faint sources at sub-mm wavelengths because of the large positional uncertainty/poor resolution.

Crude photometric redshifts for sub-mm sources can be estimated using sub-mm flux ratios (colours), assuming a plausible range of dust temperatures.

Star formation rate densities

Using sub-mm and radio observations

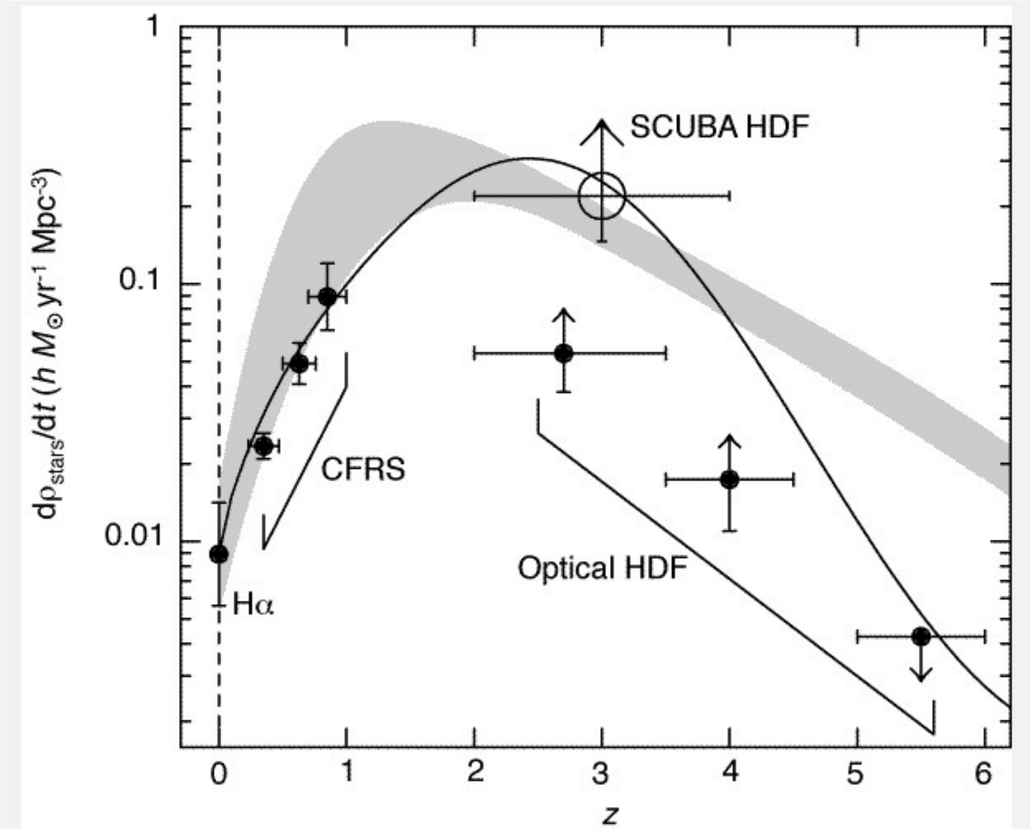
1. Assume spectral energy distribution (depending on temperature) to determine the bolometric far-IR luminosity for each source from the sub-mm and radio monochromatic luminosities.
2. Convert between bolometric far-IR luminosity and star formation rate for each source assuming scaling relationship determined in the local Universe.

$$SFR(M_{sun}\,yr^{-1}) = 4.5 \times 10^{-44} L_{FIR}(erg\,s^{-1})$$ (Kennicutt 1998)

3. Sum star formation rates of all sources in redshift range (integrating down luminosity function to account for fainter sources).
4. Divide by the co-moving volume (the volume that the solid angle and redshift range of survey would encompass at z=0).

Detection of the first SMGs III

Star formation rates



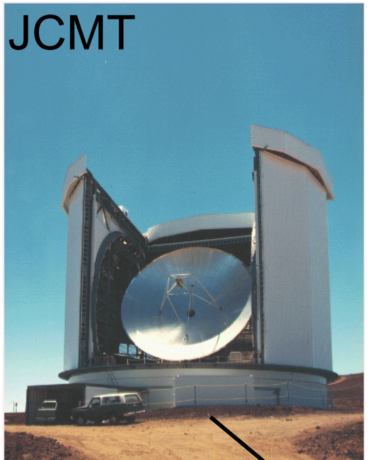
Hughes et al. (1997)

Initial sub-mm results from JCMT/SCUBA suggested star formation rates at z~2-4 in HDF significantly larger than those estimated from optical (rest frame UV) measurements (but based on only 4 firm sub-mm detections!).

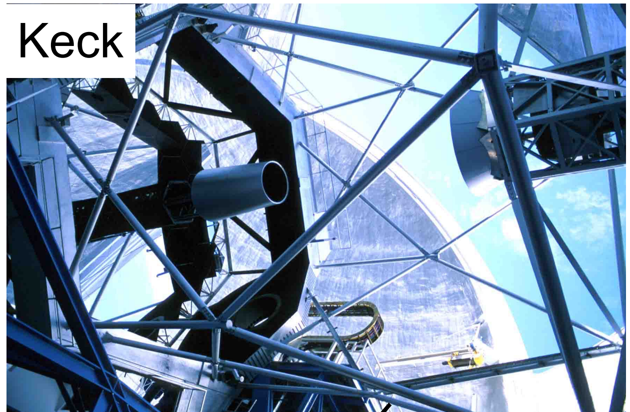
Summary of early sub-mm results

- The first deep sub-mm surveys provided evidence for a population of luminous star-forming galaxies that is not picked up in optical/UV surveys using the Lyman break technique.
- They also suggested that the star formation density associated with the sub-mm detected objects is comparable with that of LBG galaxies at similar redshifts (the latter corrected for extinction).
- However, due to the difficulty of pin-pointing the positions of the optical counterparts of the sub-mm sources, the early surveys were highly incomplete, and the redshift estimates (based on sub-mm colours) were very crude.

Pin-pointing the positions and redshifts of SMGs



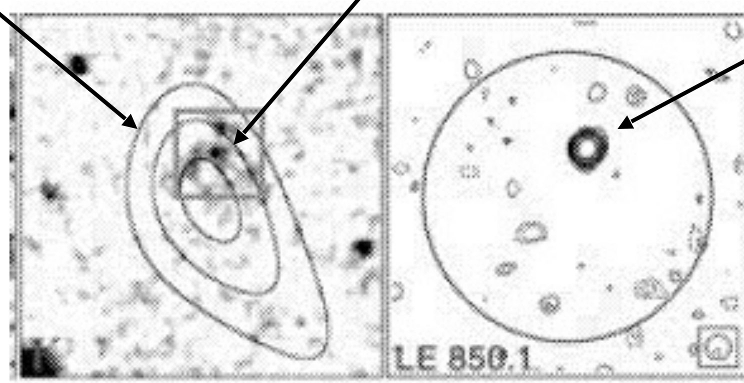
850μm



Optical

1.4GHz

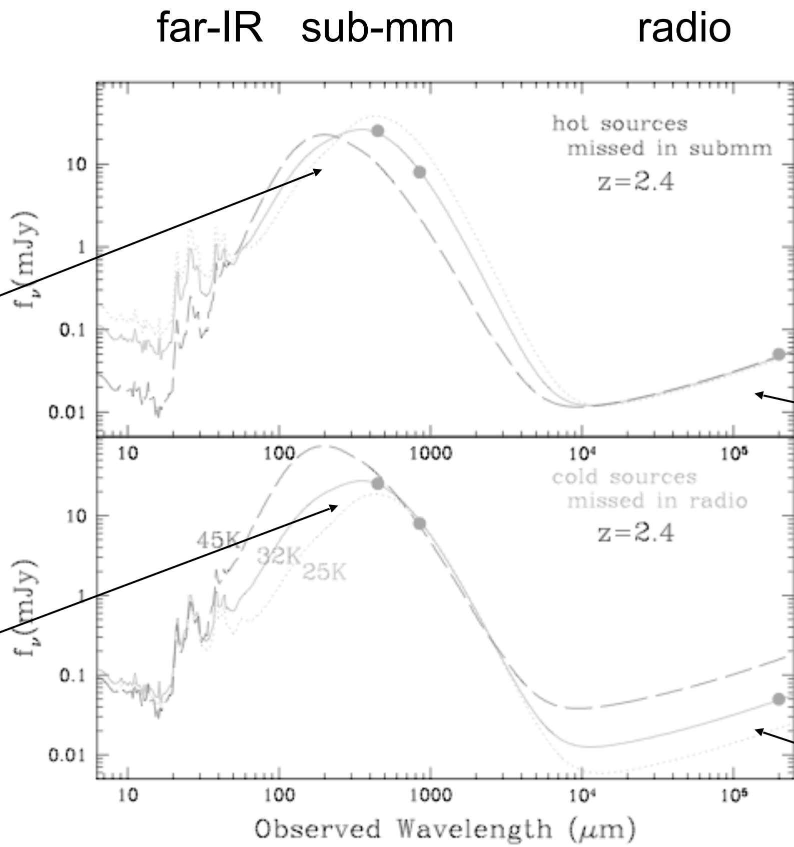
10”



Observations with radio interferometers (e.g. VLA) allow the positions of the SMG to be pinpointed to 1.5” accuracy. Then deep optical spectroscopic observations with 8-10m telescopes (e.g. Keck telescope) can be used to determine the redshifts of the selected objects.

Radio+sub-mm selection of SMG

The far-IR and sub-mm radiation of starbursts represents the *thermal re-radiation* of the optical/UV light of starbursts absorbed by dust.



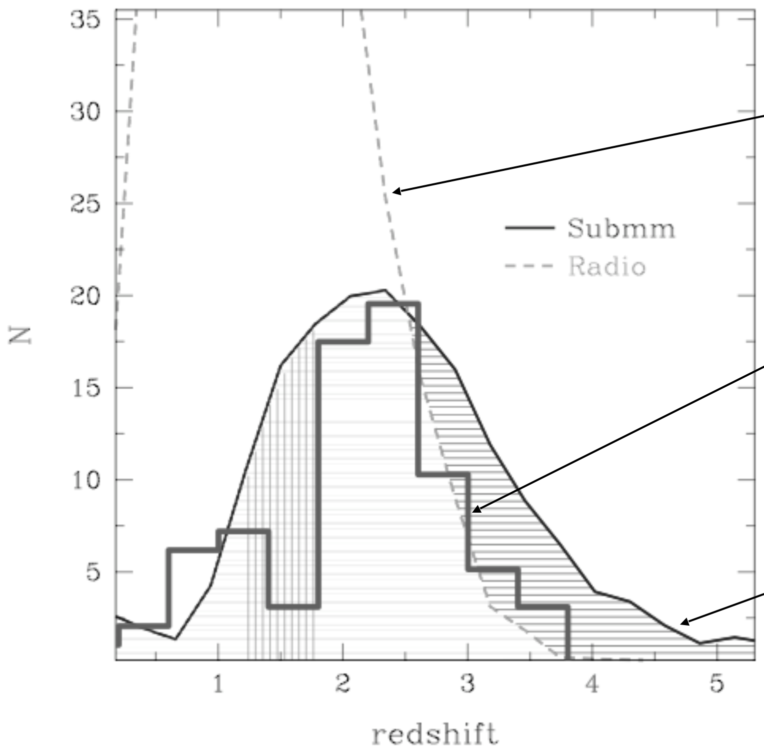
The radio emission from starbursts represents the synchrotron emission of supernova remnants associated with the explosion of massive stars in the starbursts.

Objects detected at sub-mm wavelengths may be too faint to detect at radio wavelengths if the dust is too cold. On the other hand, objects detected at radio wavelengths may be missed at sub-mm wavelengths if the dust is too warm. *Of the 150 brightest SMG detected in deep field observations by 2005, only ~50% had secure spectroscopic redshifts* (Chapman et al. 2005).

Results for radio-selected SMG I:

Redshift distribution

Chapman et al. (2005)



Impact of radio flux limit.

Actual distribution of SMG with measured redshifts.

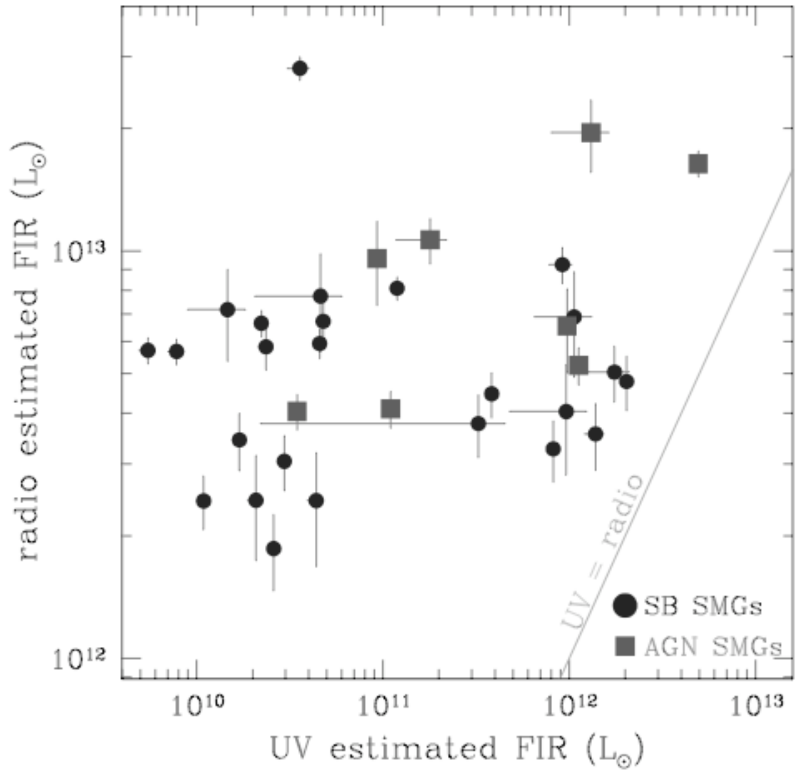
Predicted distribution based on model for the evolution of SMG.

The median redshift of SMG with spectroscopic redshifts is z~2.4. However, there is substantial incompleteness (shaded region) especially at z>2.5 and z~1.5 (the redshift desert)

Results for radio-selected SMG II

Comparison of UV and far-IR luminosities

The typical far-IR luminosity of an SMG is ~5×10^{12} L_{sun}, as determined from radio and sub-mm obs. (similar to ULIRGs in the local Universe).

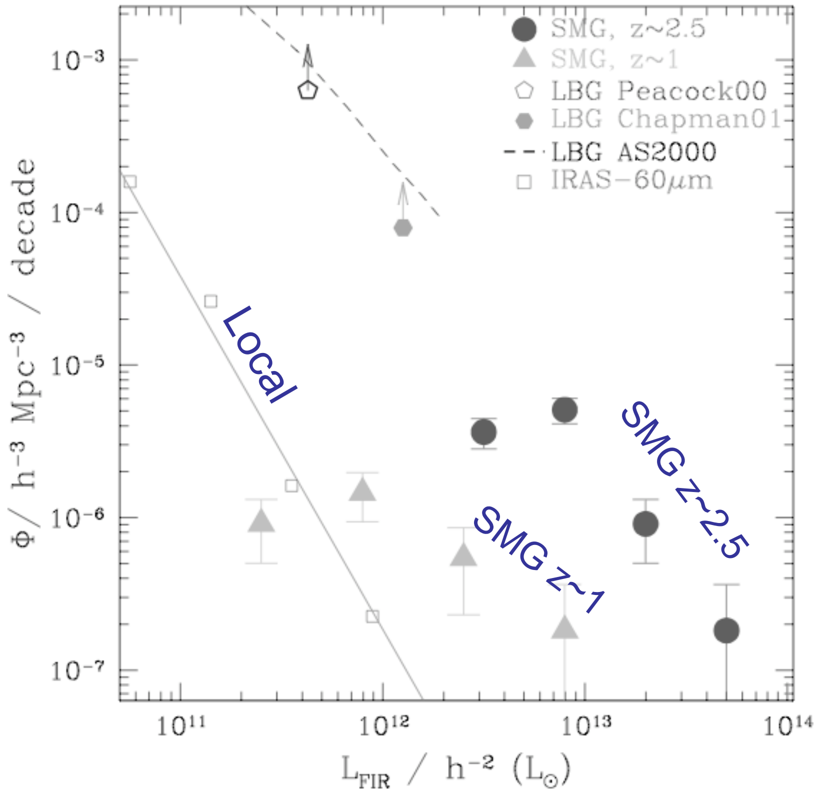


Chapman et al. (2005)

The far-IR luminosities estimated for the starbursts in SMG using the radio and sub-mm observations are typically a factor >100x larger than predicted by rest-frame UV observations of the same sources. Most of the starburst activity in these sources is hidden by dust in the UV.

Results for radio-selected SMG III

Luminosity function



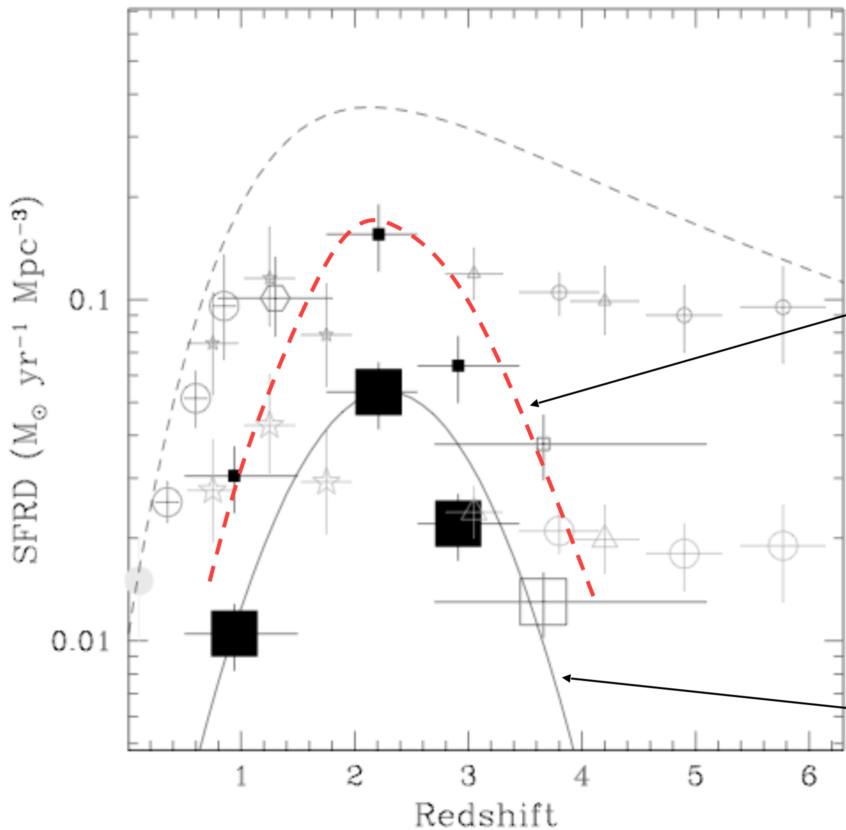
Chapman et al. (2005)

For luminosities $5x10^{12}$ -- 10^{13} L_{sun} the space density of SMG at z~2.5 is >1000x that of ULIRGs in the local Universe, and ~10x that of SMG at z~1.

Results for radio-selected SMG IV

Star formation history

Chapman et al. (2005)



Star formation history including the fainter sub-mm sources down to 1mJy (assuming that the fainter sources have the same z distribution).

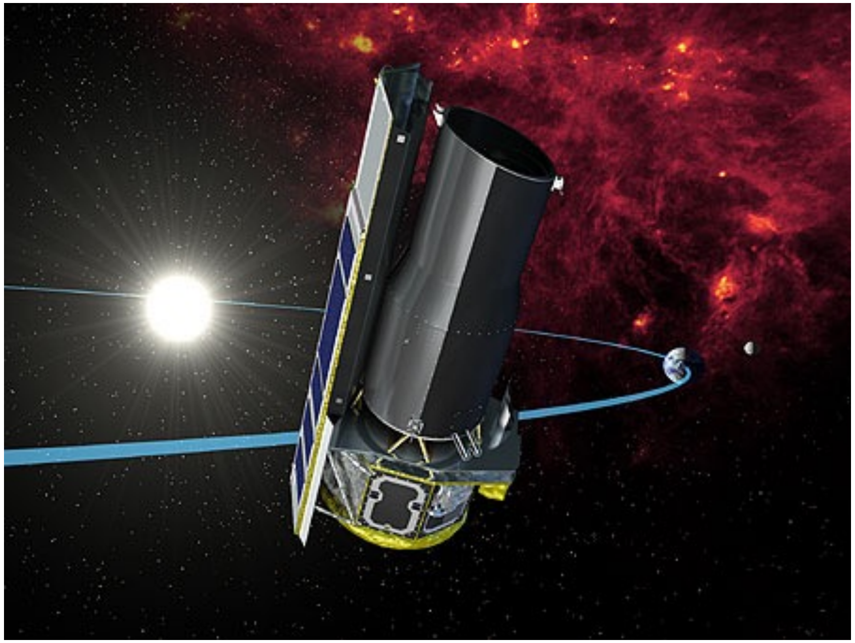
Star formation history of the brighter SMG (S > 5 mJy)

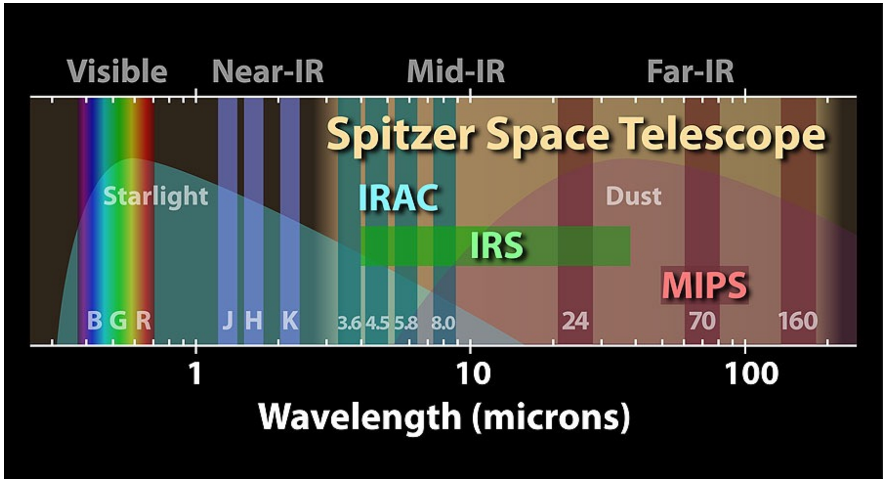
Including the fainter sources, the SMG have a similar star formation rate density to the LBG (latter corrected for extinction). But, unlike the LBG, the SMG appear to show a decline in SFR towards higher redshifts.

Summary of results for radio-selected SMG

- SMG appear to be the high redshift counterparts of ULIRGs, but >1000x more numerous.
- At a median redshift of z~2.4, SMG contribute as much of the star formation density as LBG at similar redshifts. However, unlike LBG, their contribution to global star formation appear to decline to higher redshifts.
- It is unlikely that the SMG detected at z~2.4 represent massive (>10^{11} M_{sun}) elliptical galaxies in formation.
- The detected SMG are not the same population as the LBG, which are more numerous, and have far-IR luminosities that are a factor ~10-100x lower.
- But all these results are affected by the redshift incompleteness of the current SMG samples.

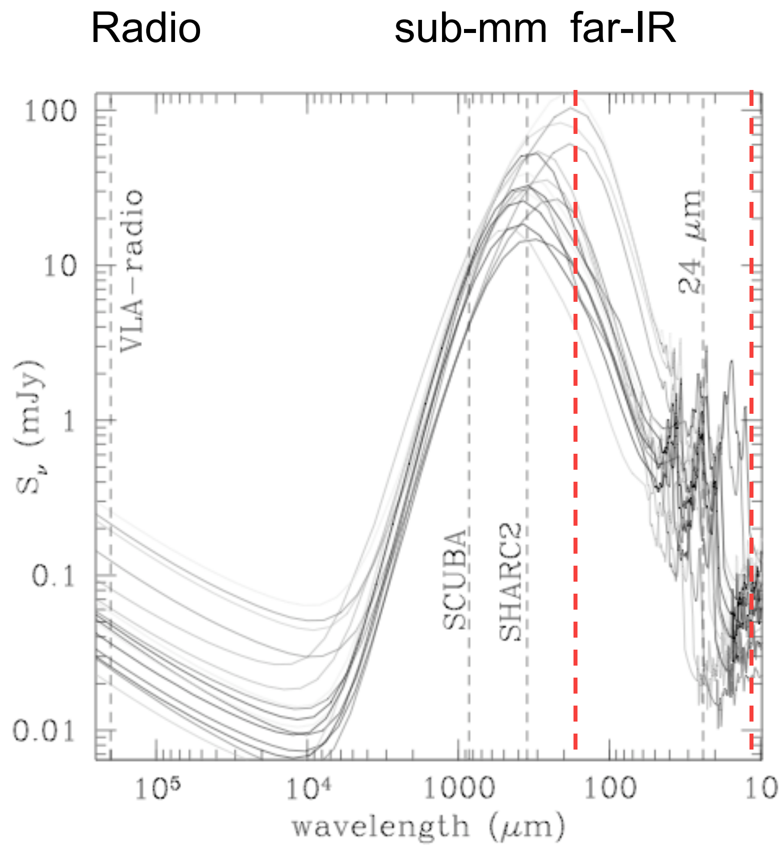
Using Spitzer to detect galaxies at high redshifts





The Spitzer Space Telescope -- launched in 2003 on an Earth-trailing orbit -- is factors ~10 - 1000x more sensitive that previous far-IR satellites (e.g. IRAS, ISO). Its sensitivity allows us to detect the thermal dust emission of starbursts at high redshifts at mid- to far-IR wavelengths.

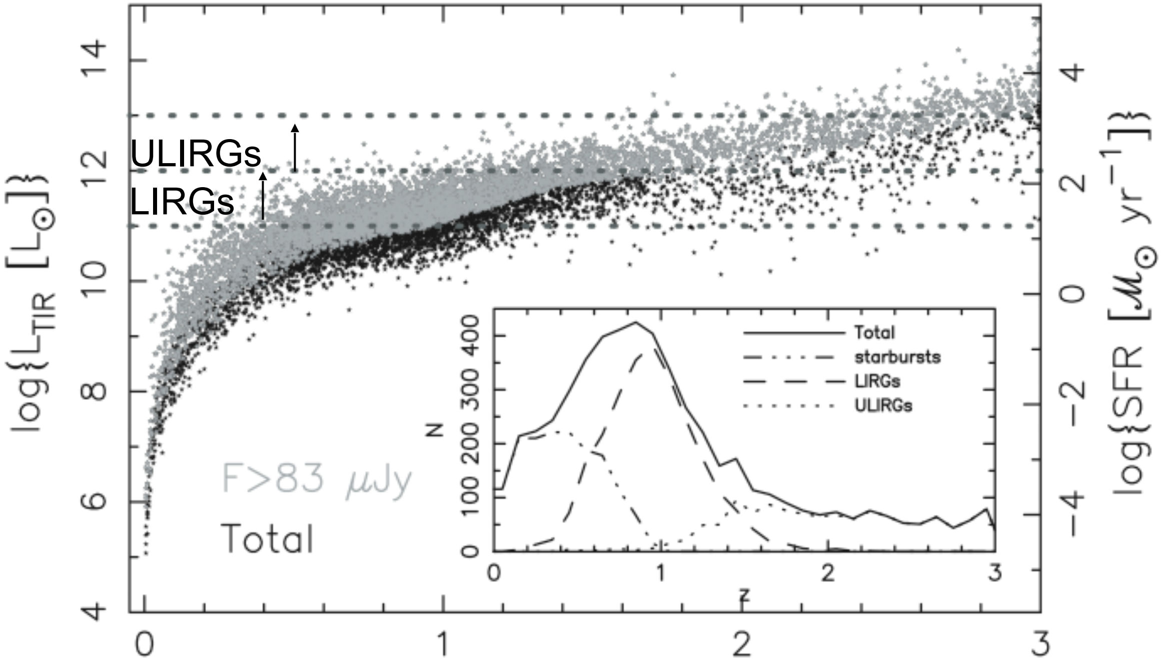
Far-IR/sub-mm SEDs of star forming galaxies



Spitzer observes on the short wavelength side of the thermal infrared bump (~3 - 160μm). Its sensitivity is sufficient to detect populations of high redshift star forming galaxies, despite the negative K-correction.

Spitzer results on high-z star forming galaxies I

Far-IR luminosities



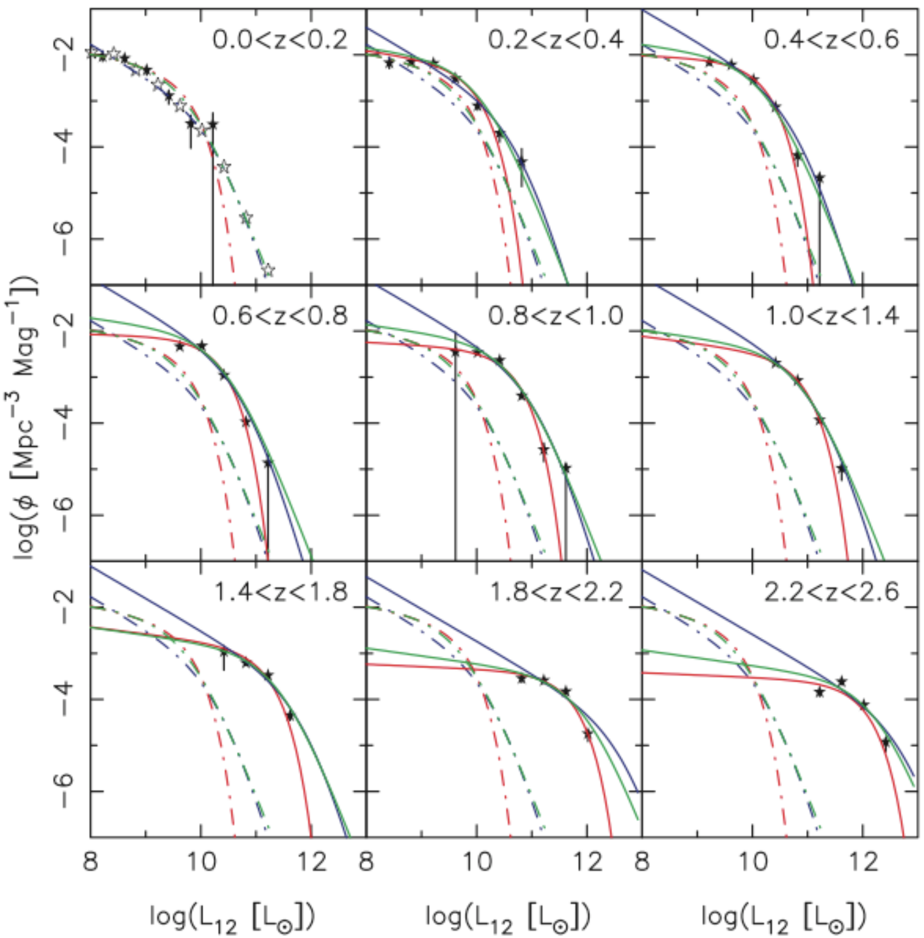
z

Perez Gonzalez et al. (2005)

Using at sample selected at 24μm from Spitzer observations, and complementary deep-field optical/IR observations (for photometric redshifts), large populations of starburst galaxies have been detected at high redshifts. At $0.8 < z < 1.5$ the 24μm source population is dominated by luminous IR galaxies (LIRGs: $L_{fir} > 10^{11}$ L_{sun}), whereas at $z > 1.5$ it is dominated ULIRGs.

Spitzer results for high-z star forming galaxies II

Far-IR luminosity functions



Perez Gonzalez et al. (2005)

Mirroring the results for SMG, the 24μm-selected galaxies show substantial evolution in their luminosity function over the redshift
the redshift
range 0 < z < 2.6 -- there are orders of magnitude more LIRG/ULIRG-type objects at high redshifts (but the shape of the high redshift lumnosity function is highly uncertain).

Star formation rate density

Using 24μm observations

1. Assume spectral energy distribution (depending on temperature) to determine the bolometric far-IR luminosity for each source from the 24μm monochromatic luminosities.
2. Convert between bolometric far-IR luminosity and star formation rate for each source assuming scaling relationship determined in the local Universe:

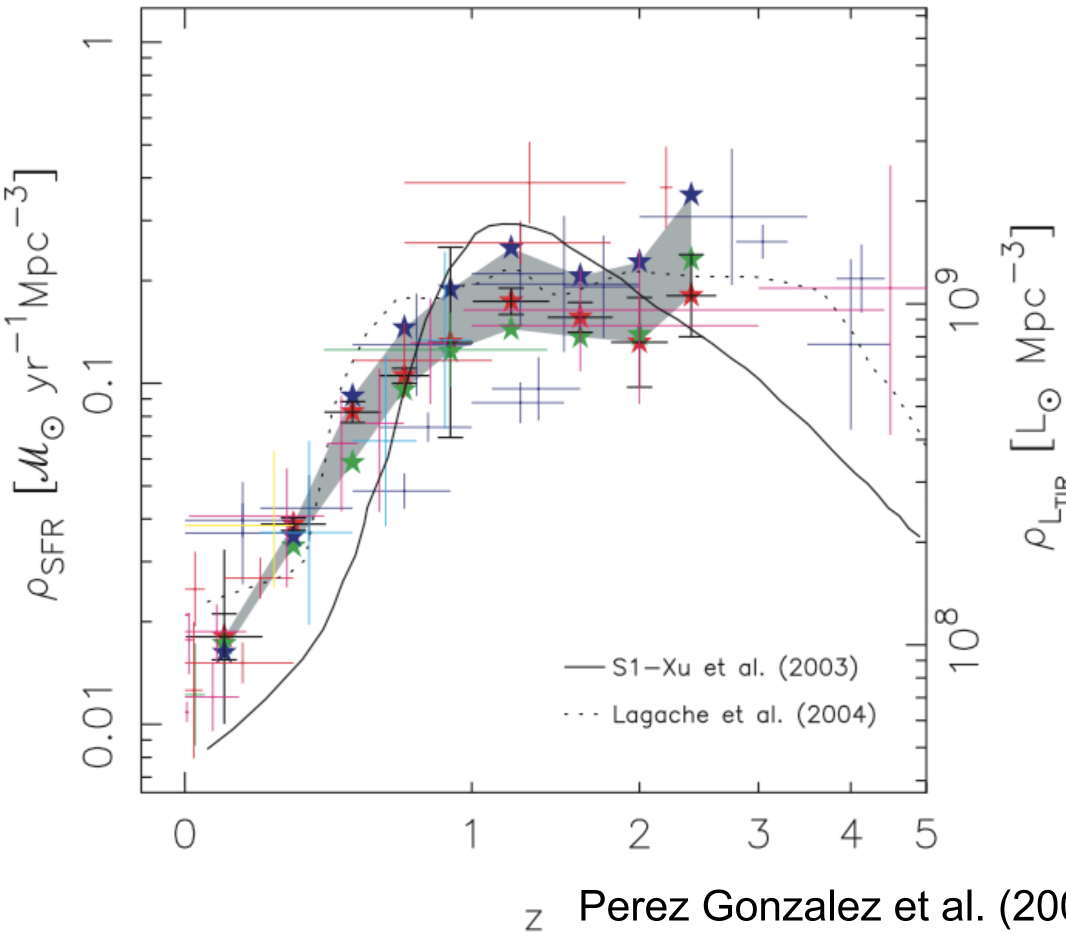
$$SFR(M_{sun}\, yr^{-1}) = 4.5 \times 10^{-44}\, L_{FIR}(erg\, s^{-1})$$ (Kennicutt 1998)

3. Sum star formation rates of all sources in redshift range (integrating down luminosity function to account for fainter sources).
4. Divide by the co-moving volume (the volume that the solid angle and redshift range of survey would encompass at z=0).

Spitzer results for high-z star forming galaxies III

Star formation history

The shaded area shows the star formation density calculated using the results from the 24μm-selected sample. The vertical spread reflects the different results obtained by assuming different shapes for the far-IR luminosity function.



Perez Gonzalez et al. (2005)

The star formation density of the 24mm selected sample is similar to that of the UV (LBG) and sub-mm (SMG) selected objects at similar redshifts (other symbols).

Summary of Spitzer 24μm results

- At 24μm Spitzer has detected a population of star forming galaxies at high redshifts that have luminosities comparable with luminous- and ultra-luminous infrared galaxies in the local Universe.
- The 24μm-selected galaxies make up a substantial fraction of the star formation density of the Universe over the redshift range $1 < z < 3.5$ (comparable with the LBG).
- At the higher redshifts the 24μm-selected galaxies overlap in far-IR luminosity and SFR rate with the SMG, but the relationship between the two populations is not yet clear.

Uncertainties from sub-mm/far-IR observations

- For the SMG there is substantial incompleteness in the samples at the high redshift end; the apparent fall-off in star formation density of SMG at $z>2.5$ is surprising.
- A major uncertainty for the 24μm-selected galaxies and SMG is that we only have photometric redshifts for most of the sources.
- For both the SMG and the 24μm-selected samples we have to rely on assumed SED shapes to determine the total far-IR luminosities (to convert between monochromatic and bolometric luminosities).
- A further uncertainty is that the conversion between far-IR luminosity and star formation rate is based on empirical relationships derived for galaxies in the local Universe, which may not hold at high redshifts.

Summary: dust-obscured star formation at high redshifts

- LBG, SMG and 24μm-selected galaxies each contribute similar amounts of the global star formation density at z~2.
- Based on the slopes of their UV spectra, only ~20% of the star formation in LBG galaxies is directly visible at UV wavelengths; the rest is obscured by dust.
- For SMG and 24μm-selected galaxies <10% of the star formation is directly visible at UV wavelengths.
- The SMG and 24μm-selected galaxies together contribute >50% of the star formation density at high redshifts (based on the far-IR luminosities).

➔ *At least 80-90% of the total (LBG+SMG+24μm) star formation density of the Universe is hidden by dust at high redshifts.*

Lecture 7: learning objectives

- An appreciation of the importance of correcting for dust extinction in determining the star formation history of the Universe
- A knowledge of the advantages and disadvantages of using sub-mm observations
- A knowledge of the contribution of Spitzer to our understanding of star formation in the distant Universe
- A knowledge and understanding of the main results derived from sub-mm and Spitzer observations, especially concerning the amount of obscured star formation in the Universe.