MODELS FOR LUMINOUS INFRARED GALAXIES IN THE NEAR AND FAR UNIVERSE

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SEES Workshop - Cambridge 25th September 2015

A PANCHROMATIC VIEW OF GALAXIES

- Three main types of activity in galaxies: star formation in quiescent disk galaxies, bursts of star formation in starbursts and accretion of matter onto a supermassive black hole (active galactic nuclei or AGN).
- All three processes associated with a lot of gas.
- Gas is associated with a small amount of material (~1%) in solid form (dust) which is much more opaque than gas.
- Dust absorbs the optical and ultraviolet radiation and re-emits in the infrared (1-1000μm)
- We therefore need observations of galaxies from 0.1-1000μm and radiative transfer models for their emission in order to interpret the observations
- We also need methods for comparing efficiently the models with the data and estimating physical parameters such as stellar mass, star formation rate, supernova rate etc.

ULTRALUMINOUS INFRARED GALAXIES (ULIRGS)

Antennae: an example of an interacting ULIRG

- Discovered by the Infrared Astronomical Satellite (IRAS) in 1983
- ULIRGs emit most of their energy in the infrared (1-1000μm)
- Result of the interaction of two large spiral galaxies
- Burst of star formation and accreting supermassive black hole

SCUBA AND DISCOVERY OF SUBMM GALAXIES

James Clerk Maxwell Telescope

Figure 5.30 The James Clark Maxwell Telescope. Image: Science and Technology Facilities Council.

Discovery of submillimetre galaxies (Hughes et al. 1998)

articles

High-redshift star formation in the Hubble Deep Field revealed by a submillimetre-wavelength survey

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In the local Universe, most galaxies are dominated by stars, with less than ten per cent of their visible mass in the form of gas. Determining when most of these stars formed is one of the central issues of observational cosmology. Optical and ultraviolet observations of high-redshift galaxies (particularly those in the Hubble Deep Field) have been interpreted as indicating that the peak of star formation occurred between redshifts of 1 and 1.5. But it is known that star formation takes place in dense clouds, and is often hidden at optical wavelengths because of extinction by dust in the clouds. Here we report a deep submillimetre-wavelength survey of the Hubble Deep Field; these wavelengths trace directly the emission from dust that has been warmed by massive star-formation activity. The combined radiation of the five most significant detections accounts for 30–50 per cent of the previously unresolved background emission in this area. Four of these sources appear to be galaxies in the redshift range $2 < z < 4$, which, assuming these objects have properties comparable to local dust-enshrouded starburst galaxies, implies a star-formation rate during that period about a factor of five higher than that inferred from the optical and ultraviolet observations.

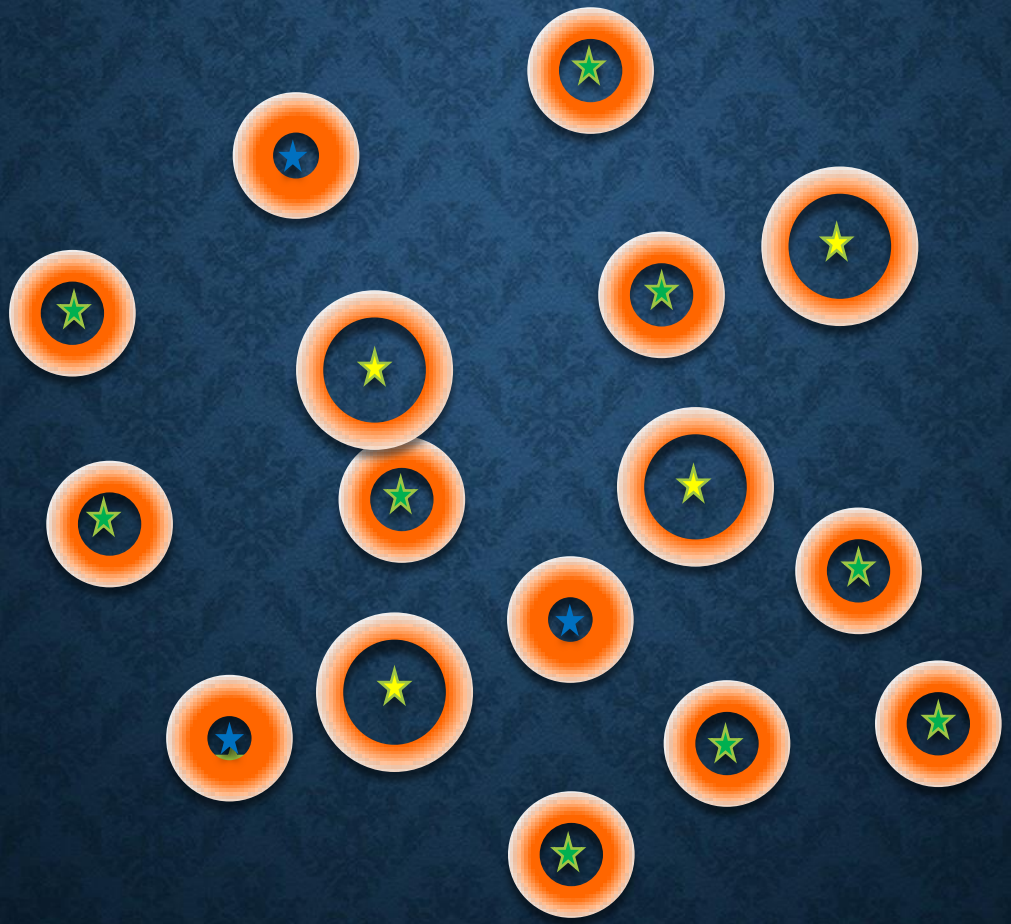
RADIATIVE TRANSFER MODELS

- Radiative transfer in a dusty medium is described by an integro-differential equation
- Solution must take into account absorption, scattering and re-emission by dust grains
- Two different methods of solution have been applied: Ray-tracing and Monte Carlo
- First spherically symmetric radiative transfer models were developed in the mid-70s
- First axisymmetric (2D) radiative transfer models in the early 90s
- We now have fully 3-D models – mainly Monte Carlo

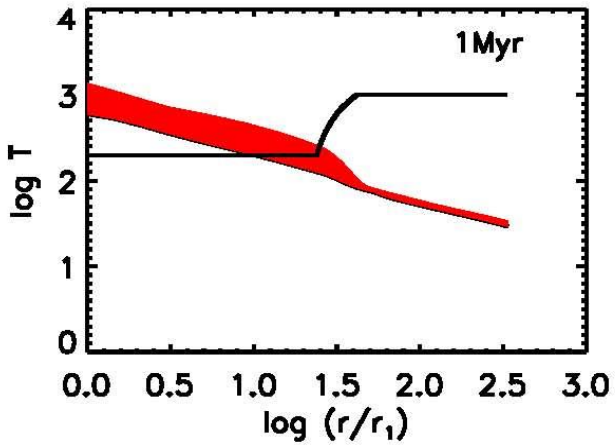
STARBURST MODEL OF EFSTATHIOU, ROWAN-ROBINSON & SIEBENMORGEN (2000), REVISED BY EFSTATHIOU & SIEBENMORGEN (2009)

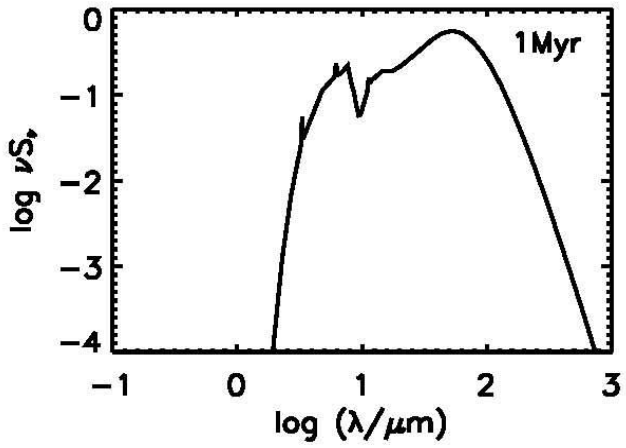
- Incorporates the stellar population synthesis model of Bruzual & Charlot that gives the spectrum of the stars as a function of their age
- Radiative transfer that includes the effect of small grains/PAHs (Siebenmorgen & Krugel)
- Simple model for the evolution of giant molecular clouds that constitute the starburst

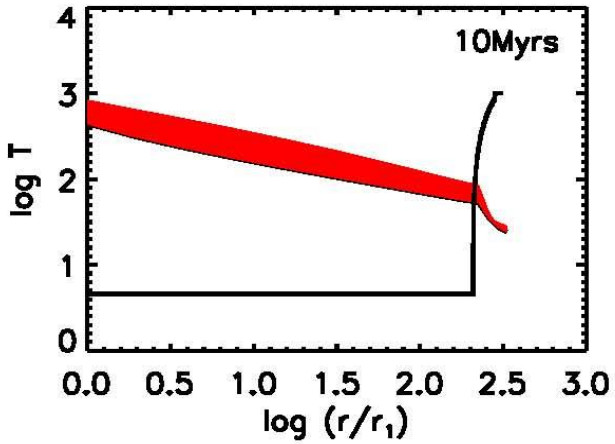
Schematic diagram of the GMC distribution in an Efstathiou et al. starburst

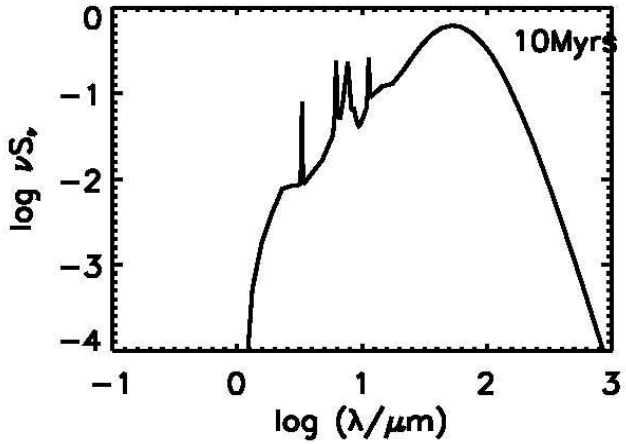


EVOLUTION OF THE SPECTRUM OF A GIANT MOLECULAR CLOUD (EFSTATHIOU ET AL. 2000)



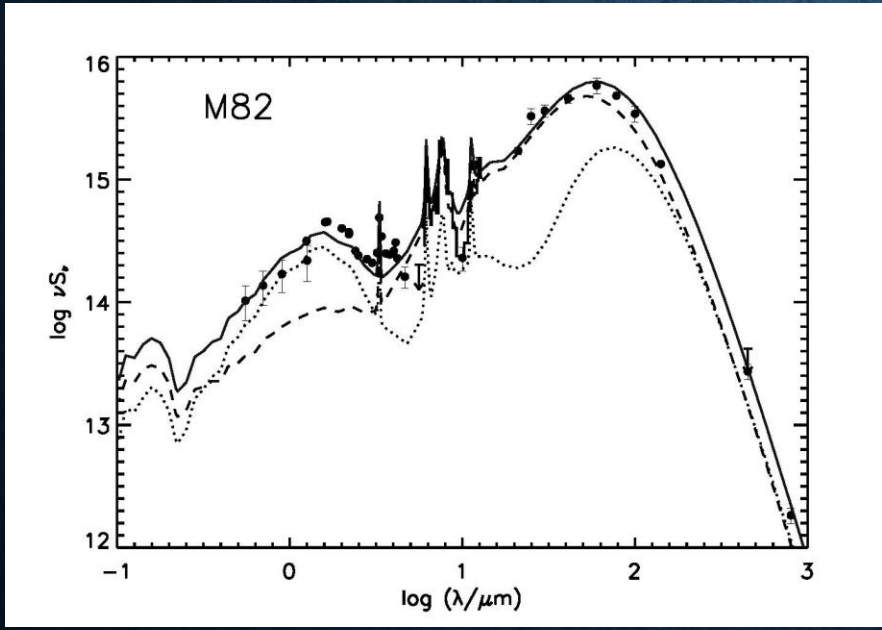




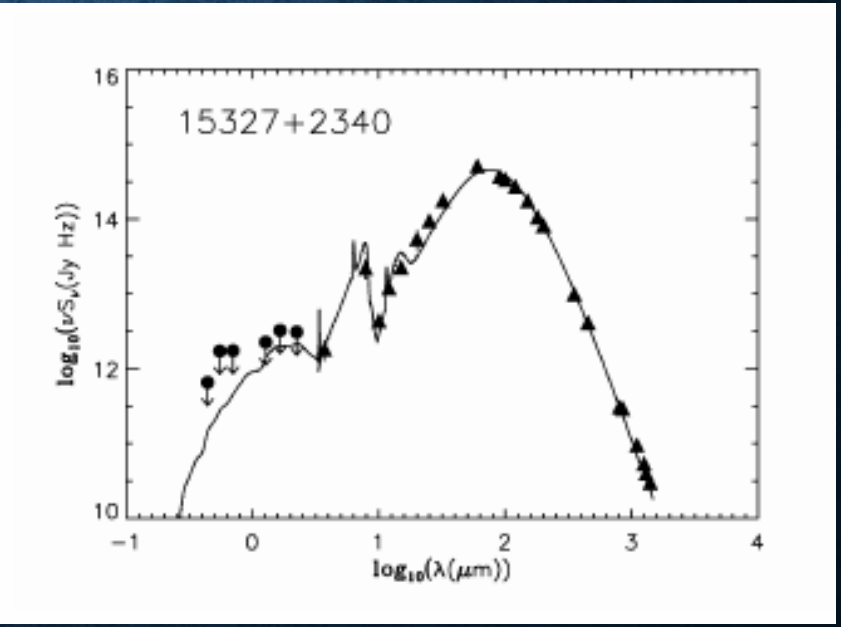


MODELS FOR LOCAL STARBURST GALAXIES

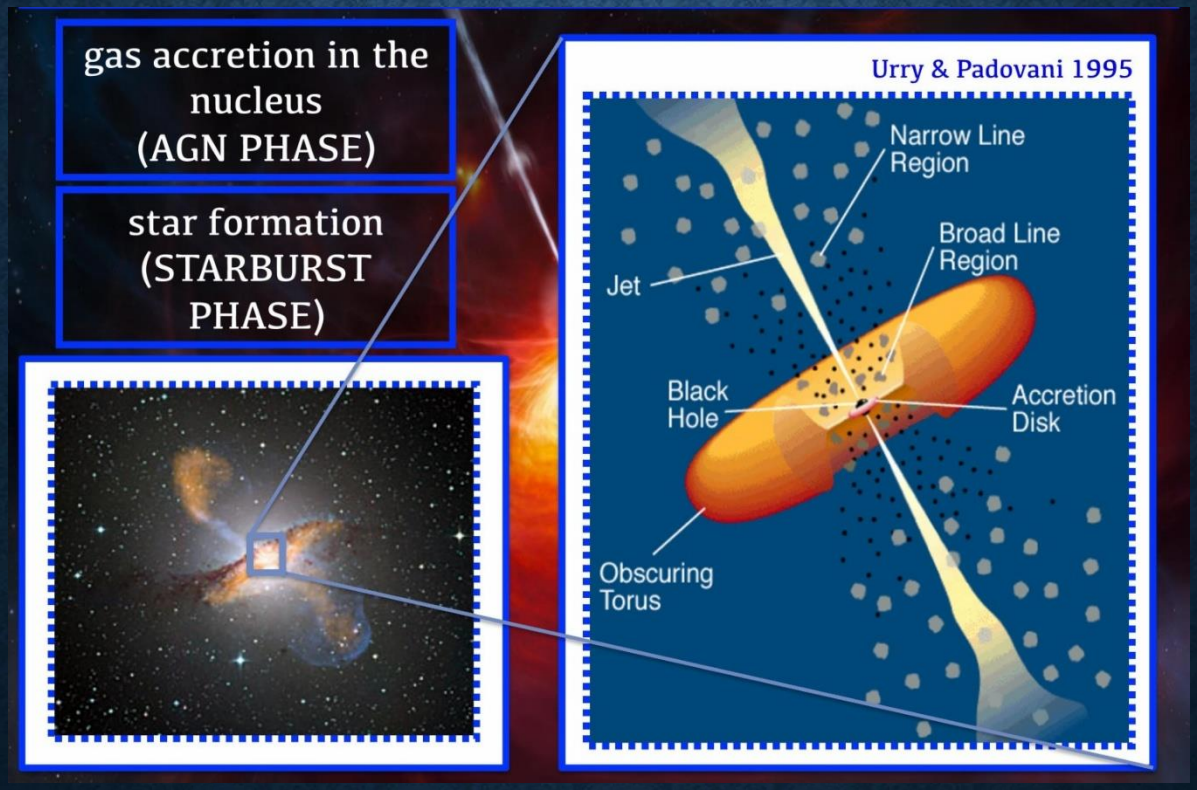
M82: the nearest starburst galaxy (Efstathiou et al. 2000)



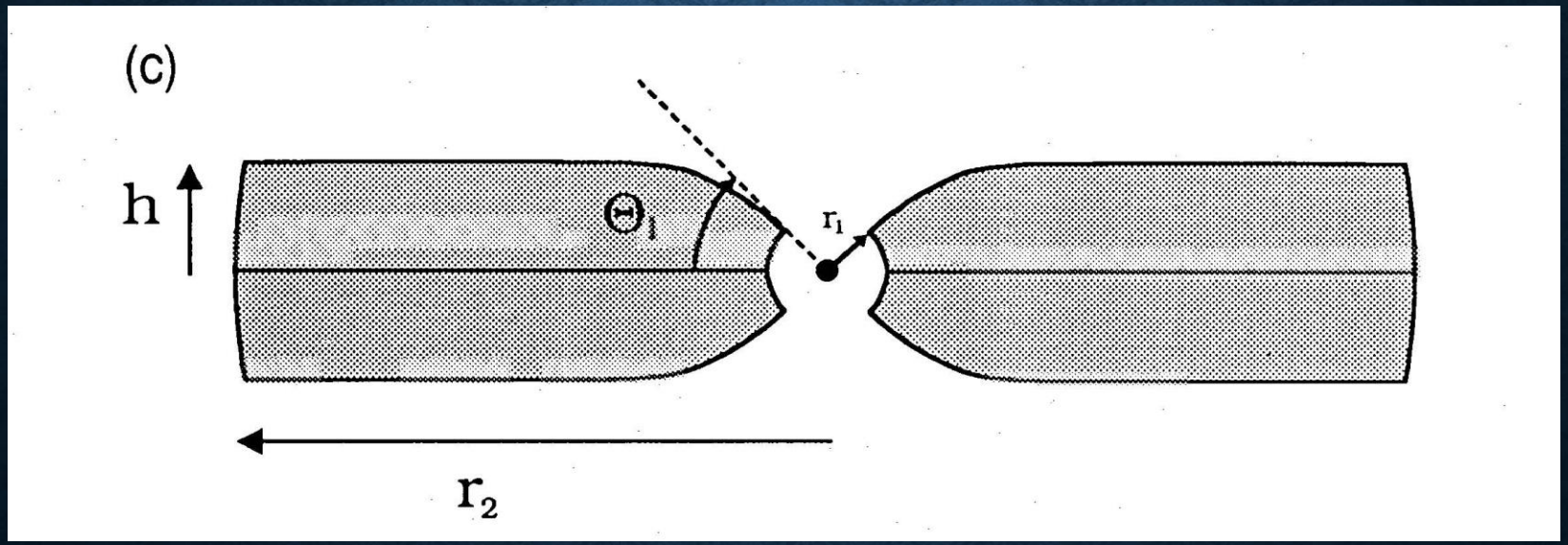
Arp220: the prototypical local ULIRG (Farrah et al 2003)



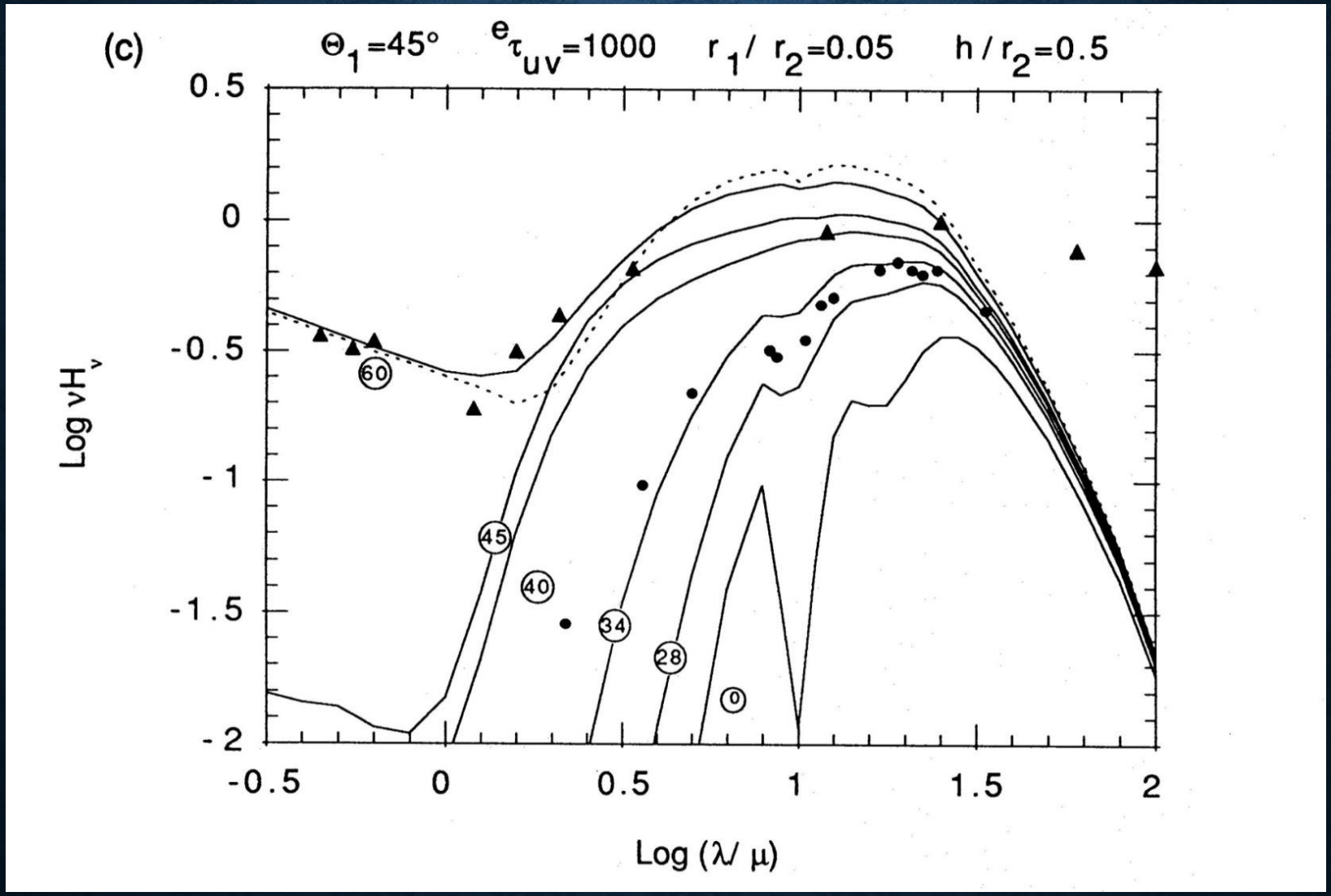
UNIFIED MODEL FOR ACTIVE GALACTIC NUCLEI (AGN) AND QUASARS



TAPERED DISC OF EFSTATHIOU & ROWAN-ROBINSON (1995)

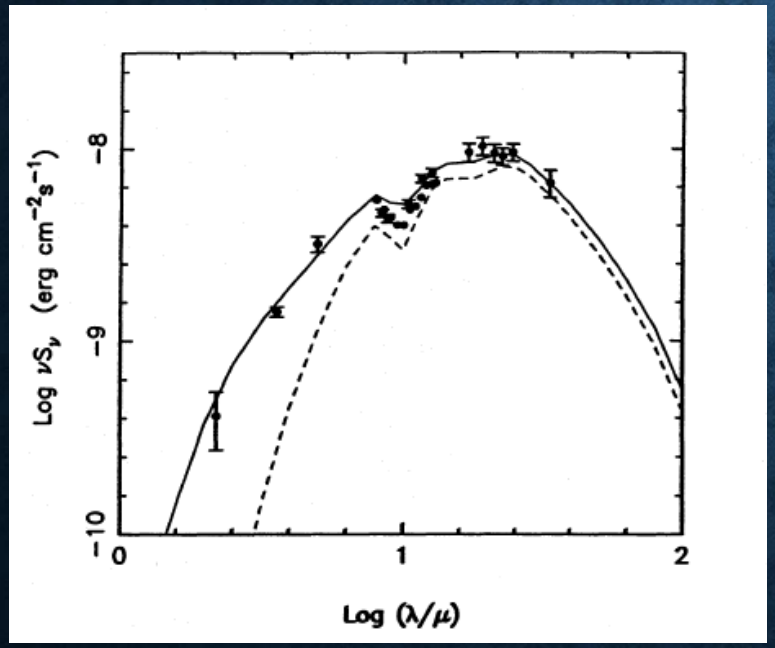


VARIATION OF THE SPECTRUM OF A TAPERED DISC WITH INCLINATION (ERR95)

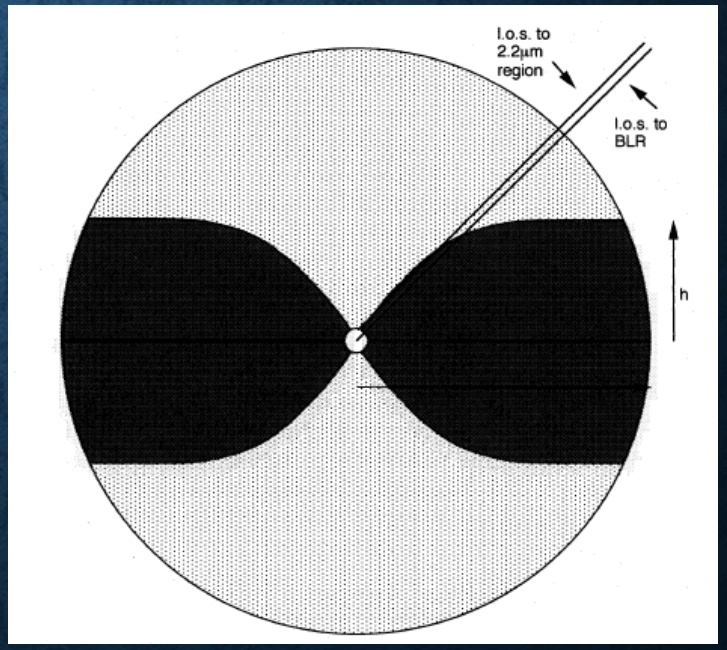


AGN TORUS AND CONICAL DUST MODEL FOR NGC 1068

Tapered disc + conical dust model of the nucleus of NGC1068 (Efstathiou et al. 1995)

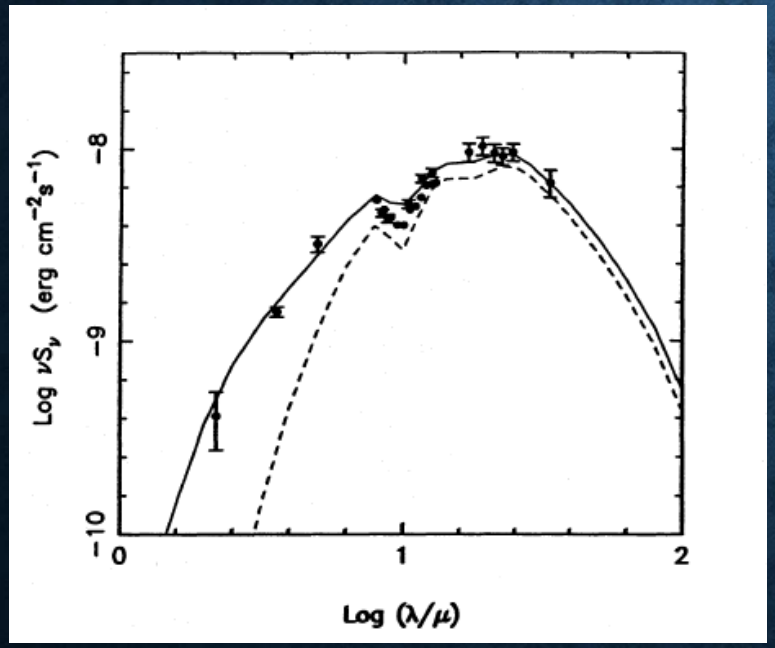


Tapered disc + conical dust geometry (Efstathiou et al. 1995)

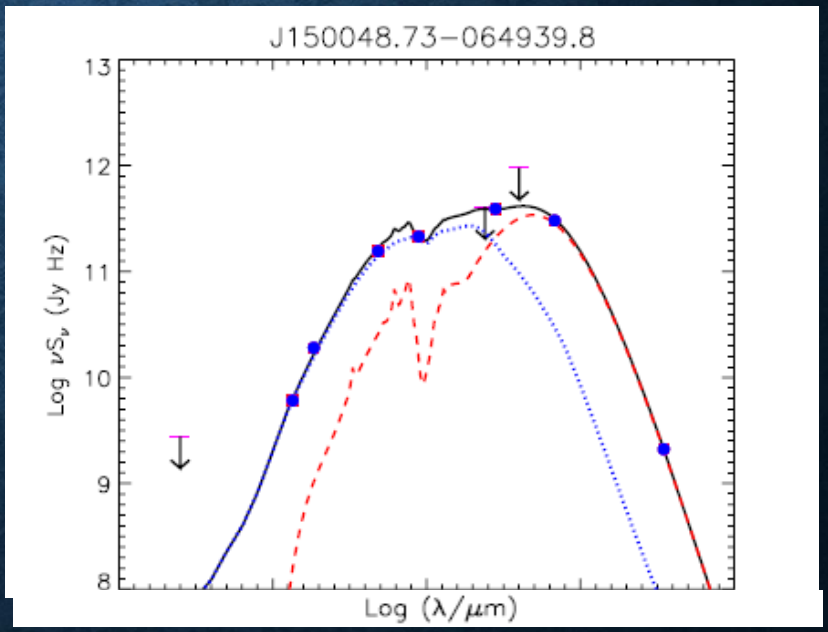


AGN TORUS MODELS FOR NGC 1068 AND A Z=1.5 WISE/ALMA OBSCURED QUASAR

Tapered disc + conical dust model of the nucleus of NGC1068 (Efstathiou et al. 1995)



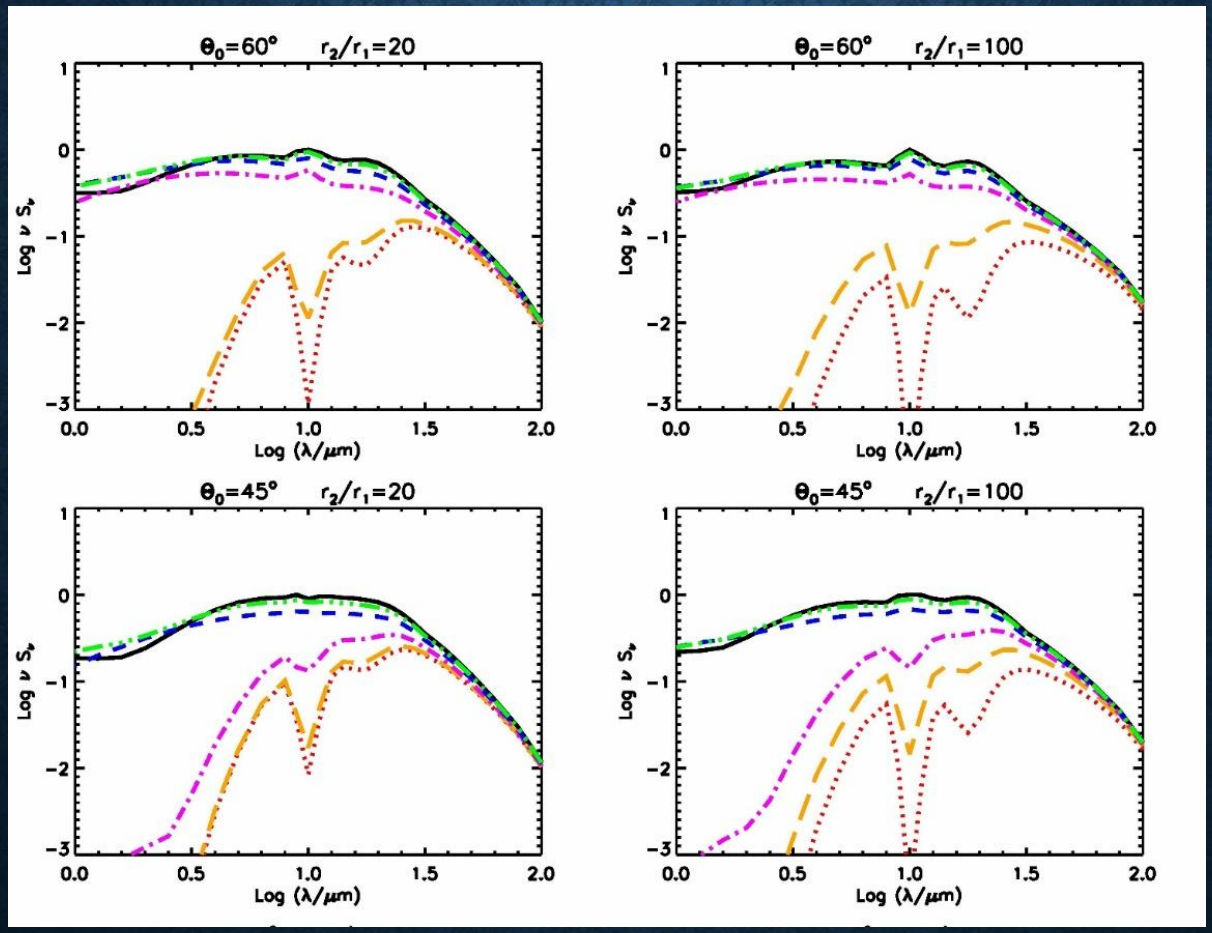
Tapered disc/starburst model for a z=1.5 WISE/ALMA quasar (Lonsdale et al. 2015)



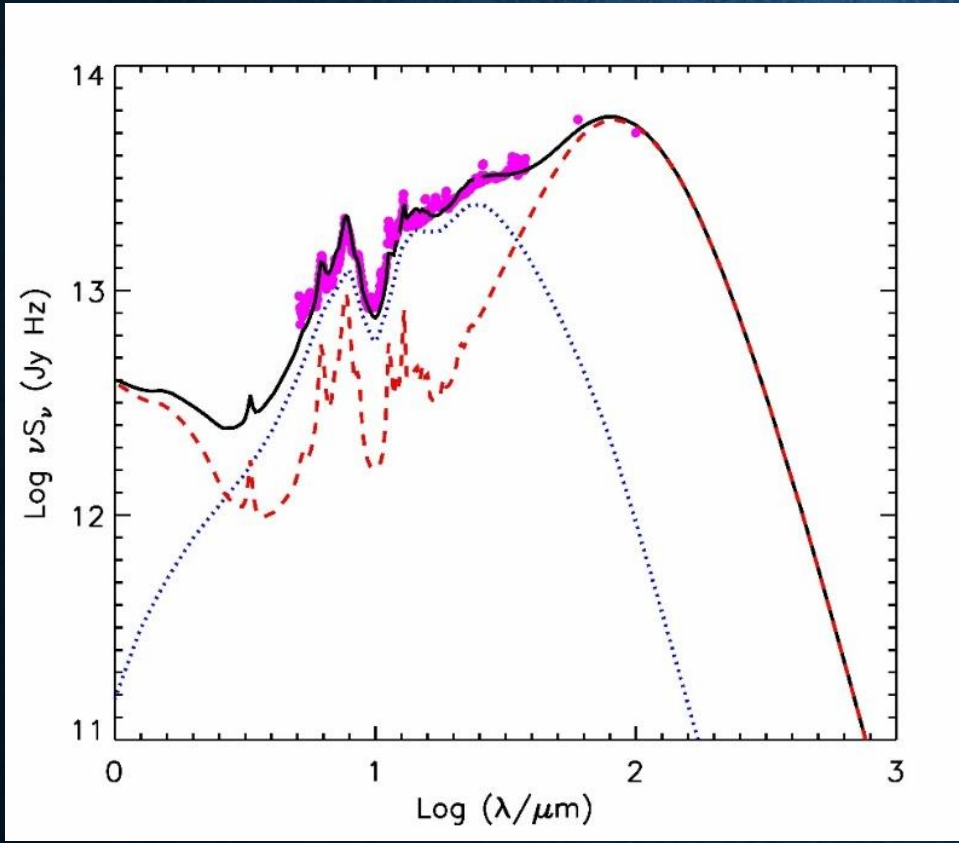
LARGE GRID OF TAPERED DISC MODELS (EFSTATHIOU ET AL. 2013)

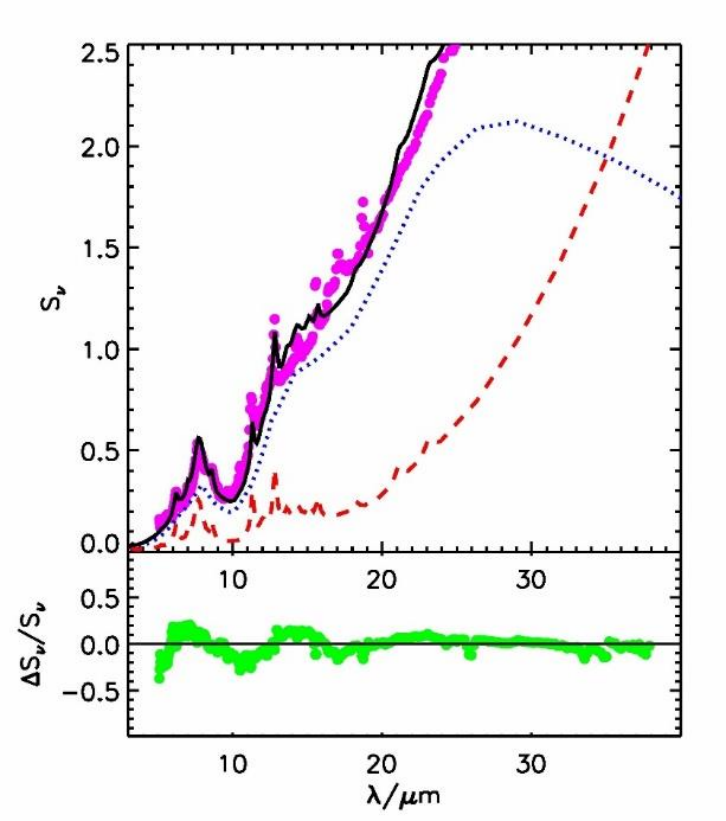
- Computed a large grid of tapered disc models (~10,000 model spectra) with the method of Efstathiou & Rowan-Robinson
- Vary outer to inner disc radius in the range 20 to 100
- Vary equatorial 1000Angstrom optical depth in the range 250 to 1250 (Av ~50-250)
- Vary torus opening angle in the range 30-75degrees
- Compute model spectra for 74 inclinations

PREDICTED SPECTRA FROM GRID OF TAPERED DISC MODELS (EFSTATHIOU & ROWAN-ROBINSON 1995, EFSTATHIOU ET AL. 2013)



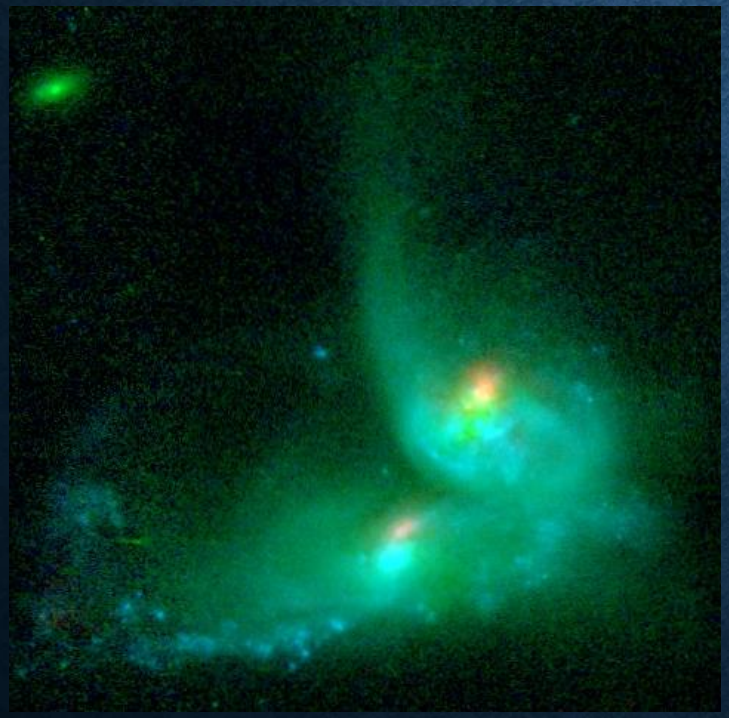
FIT TO THE AVERAGE SPECTRUM OF SEYFERT 2s WITH A COMBINATION OF STARBURST AND TAPERED DISC MODELS (EFSTATHIOU ET AL. 2013)



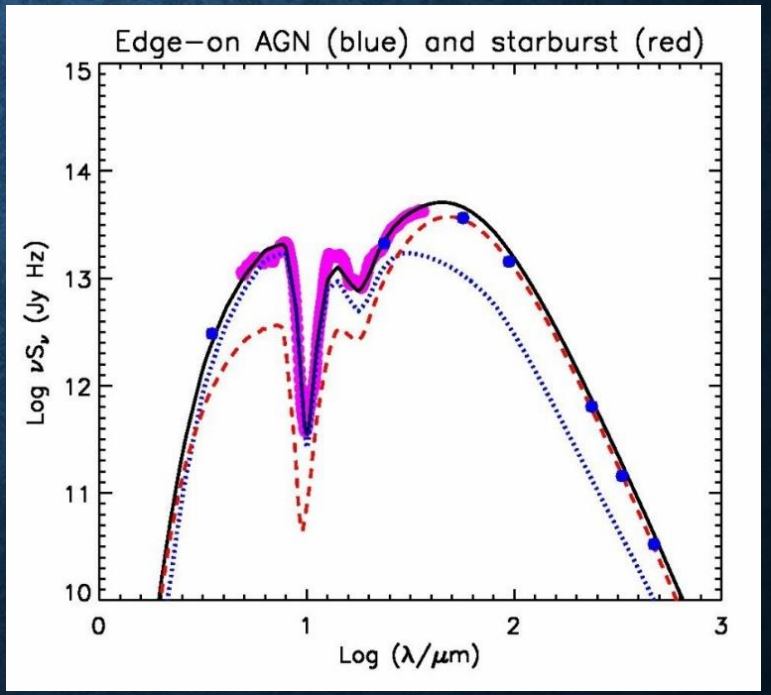


IRAS 08572+3915: DISCOVERY OF THE MOST LUMINOUS INFRARED GALAXY IN THE LOCAL (Z < 0.2) UNIVERSE (EFSTATHIOU ET AL. 2014)

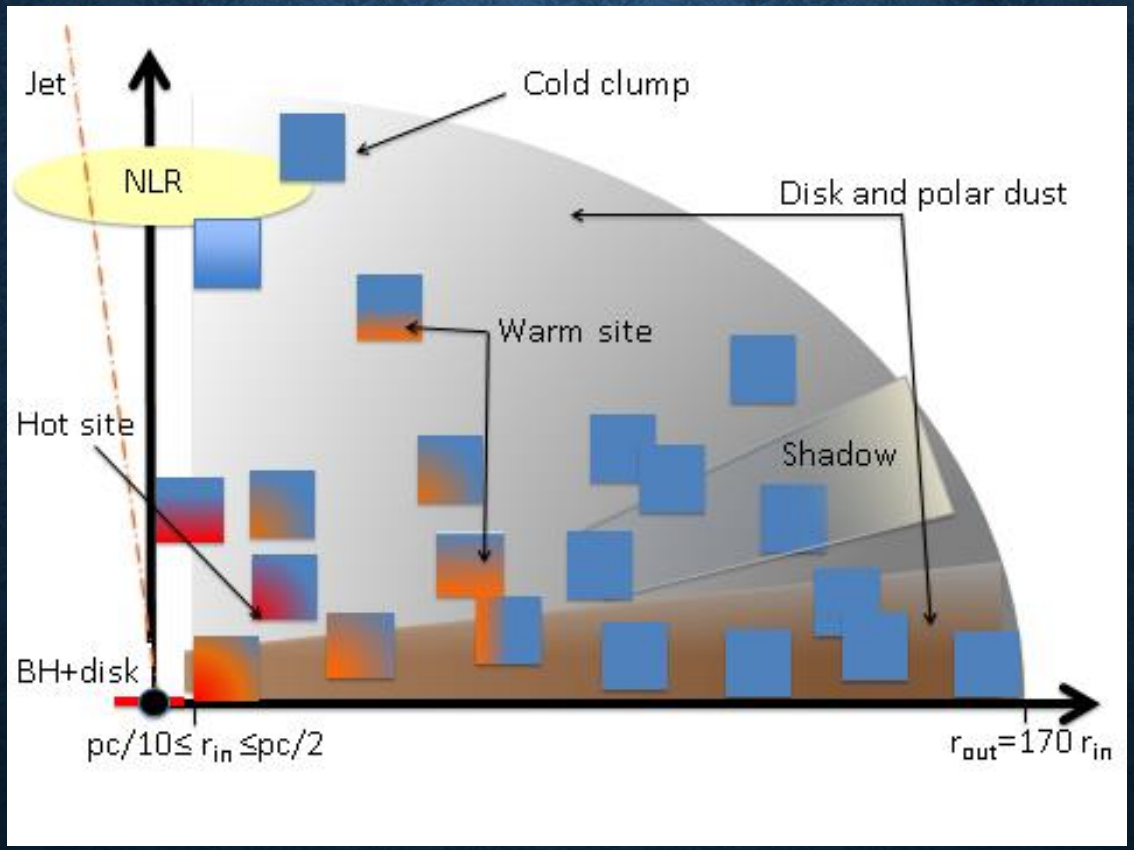
Optical image (Hubble Space Telescope)



A model for the 1-1000micron spectrum



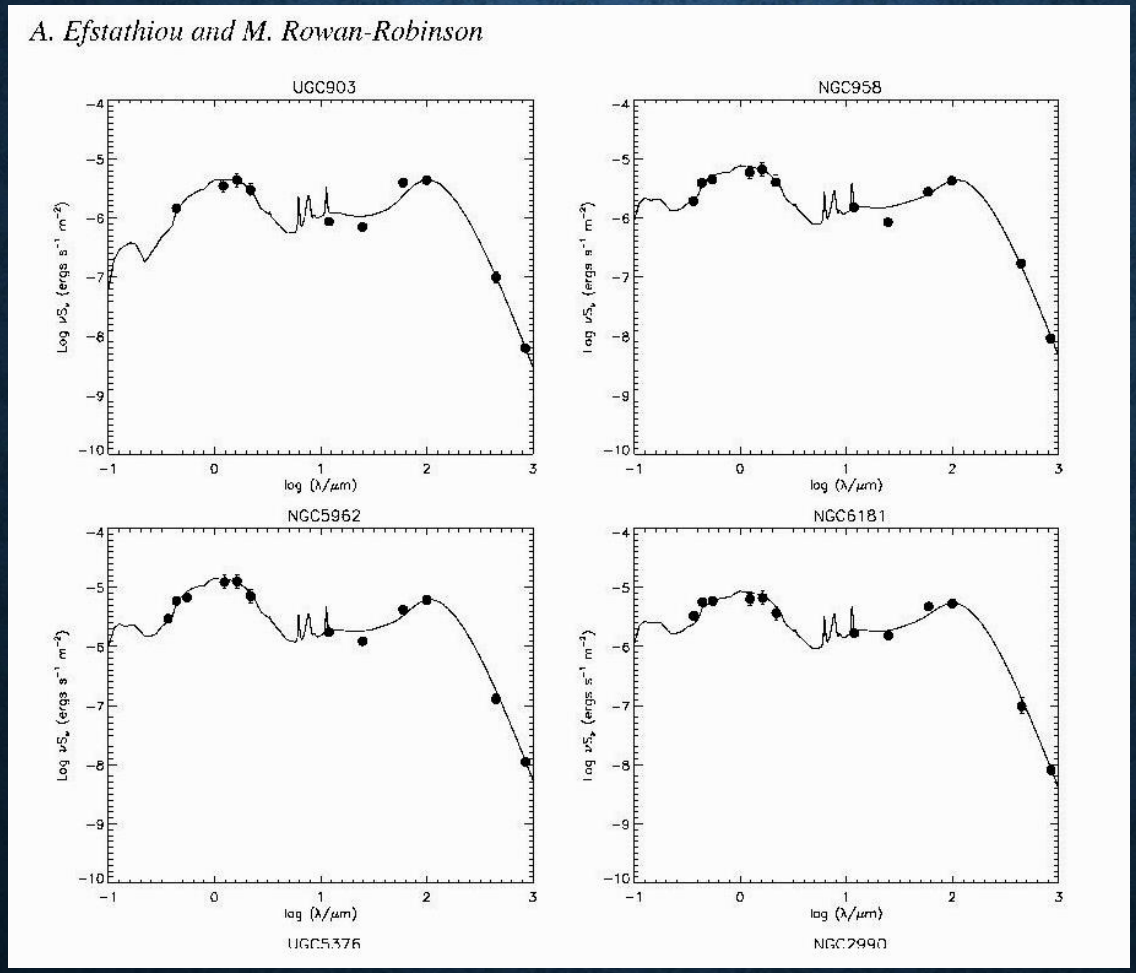
NEW 2-PHASE AGN TORUS MODEL SIEBENMORGEN, HEYMANN & EFSTATHIOU (2015)



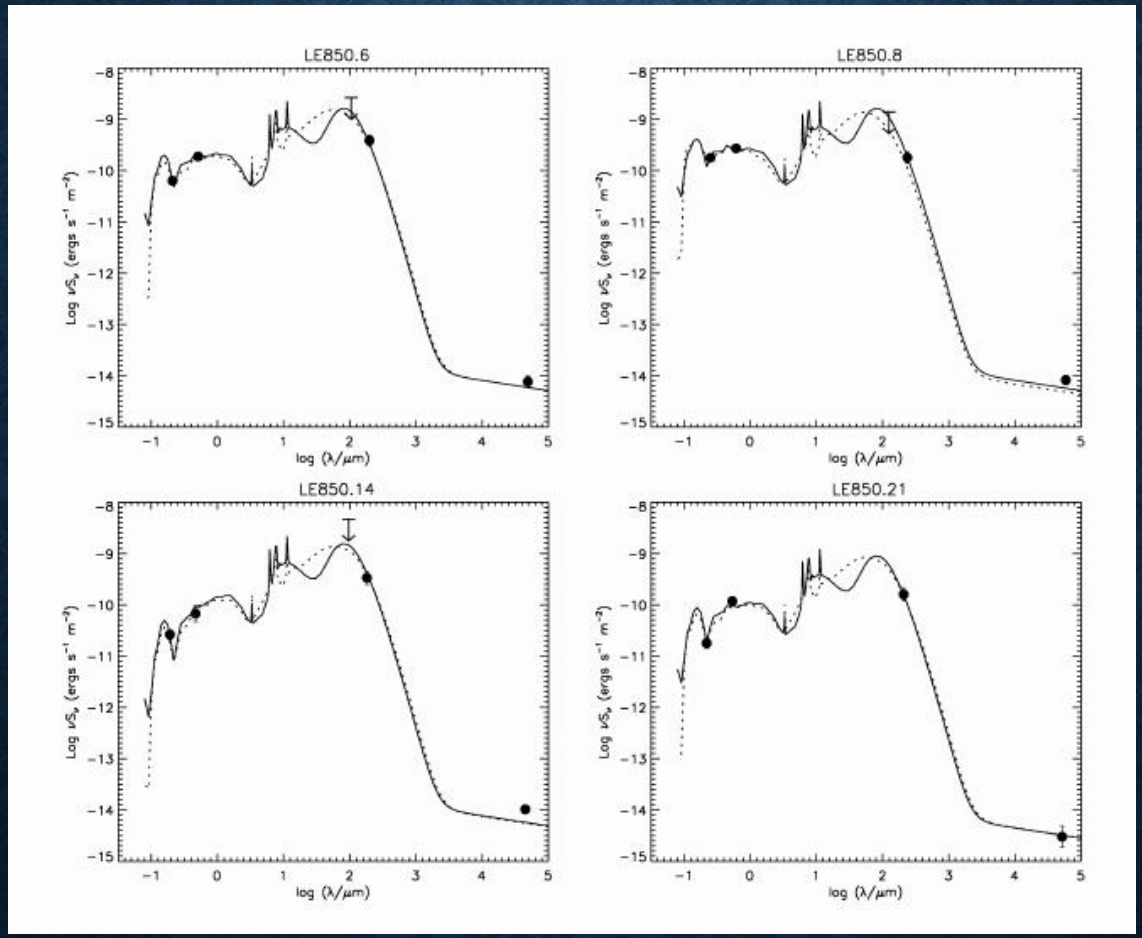
MODEL FOR QUIESCENT GALAXIES (CIRRUS) EFSTATHIOU & ROWAN-ROBINSON (2003) FIRST ENERGY BALANCE MODEL

- Uses the model of Bruzual & Charlot to synthesize the optical/UV spectrum assuming a star formation history
- Self-consistently takes into account absorption and emission by dust (assuming a screen geometry)
- Can combine cirrus and starburst emission
- Extremely fast (less than 1s per model)

MODELS OF NORMAL SPIRAL GALAXIES
EFSTATHIOU & ROWAN-ROBINSON (2003)



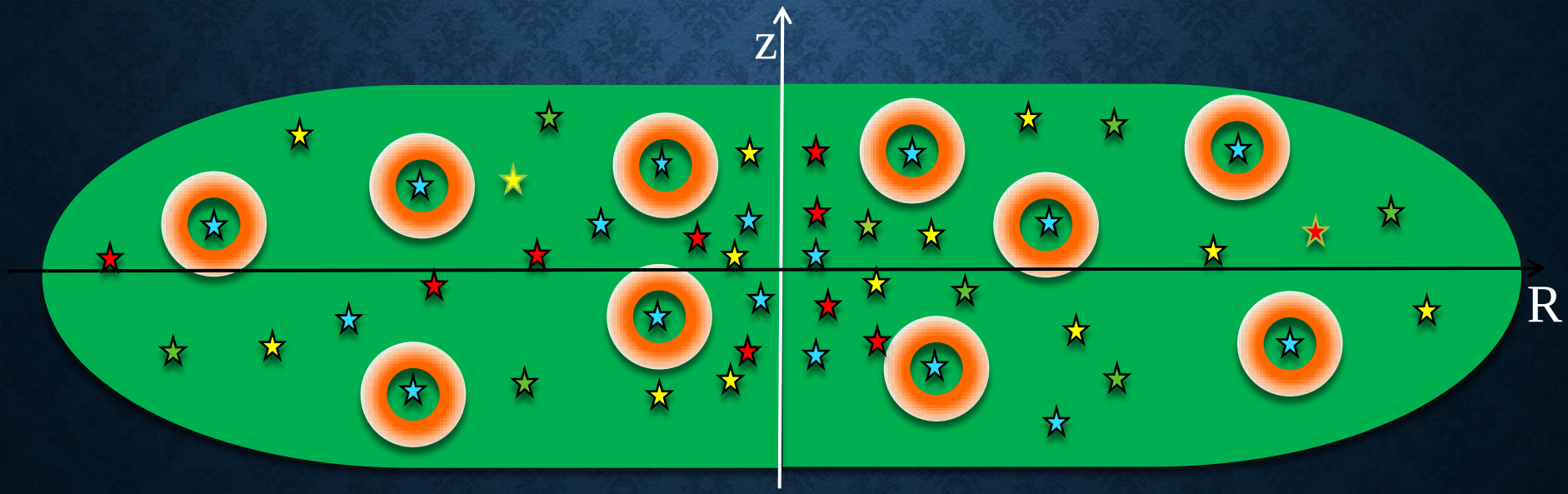
CIRRUS & STARBURST MODELS FOR SUBMM GALAXIES (ERR03)



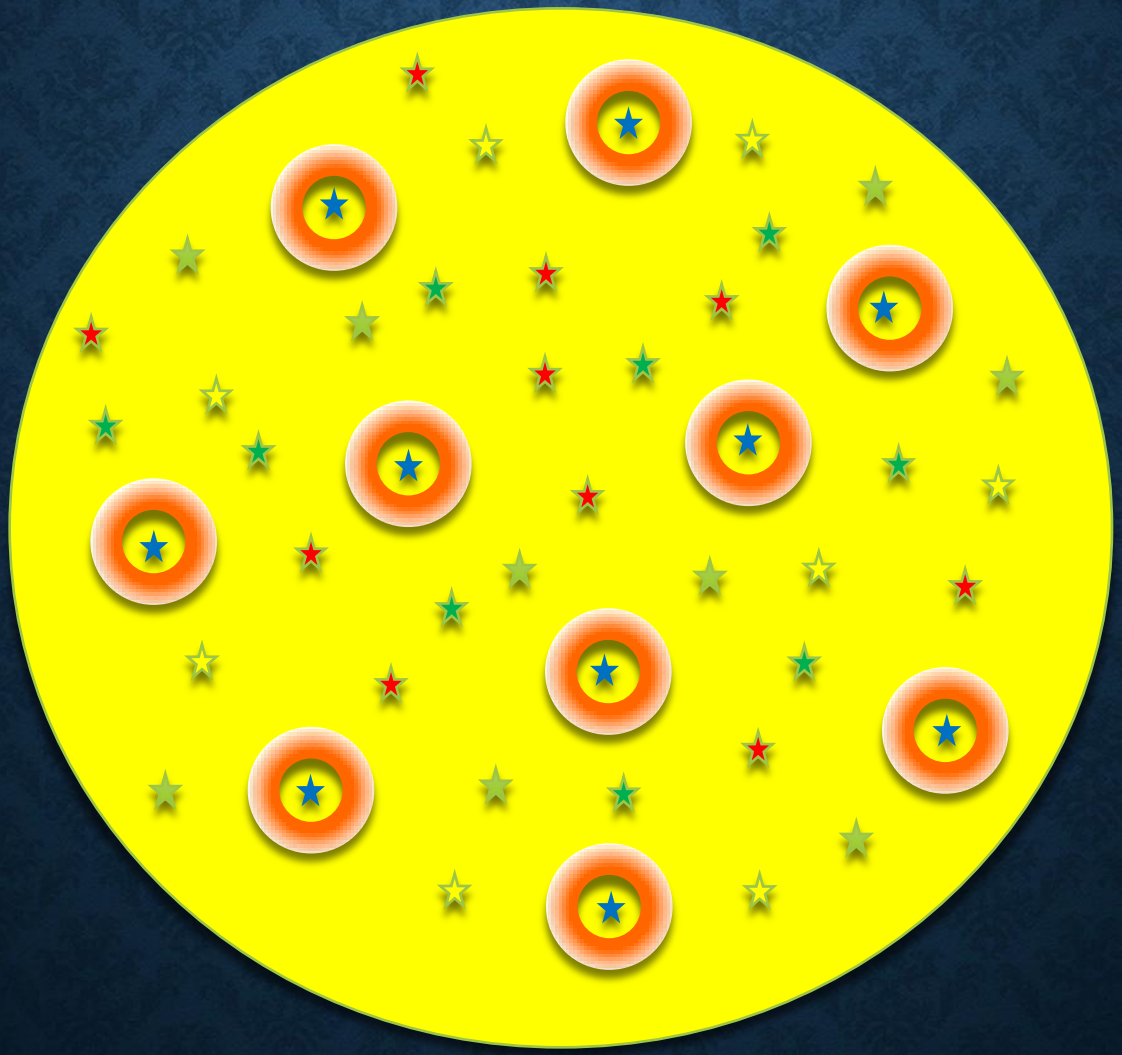
A MORE REALISTIC MODEL FOR DISC GALAXIES (EFSTATHIOU & SIEBENMORGEN 2015, IN PREPARATION)

- A code that calculates the ultraviolet to millimetre emission of disc galaxies
- Incorporates the stellar population synthesis model of Bruzual & Charlot and the starburst model of Efstathiou, Rowan-Robinson & Siebenmorgen, as revised by Efstathiou & Siebenmorgen (2009)
- Self-consistently calculates the radiative transfer problem in a disc galaxy with multiple scattering
- Code runs in about 1 minute

Schematic diagram of a disk galaxy in the Efstathiou & Siebenmorgen (2015) model



Schematic diagram of a spheroidal galaxy

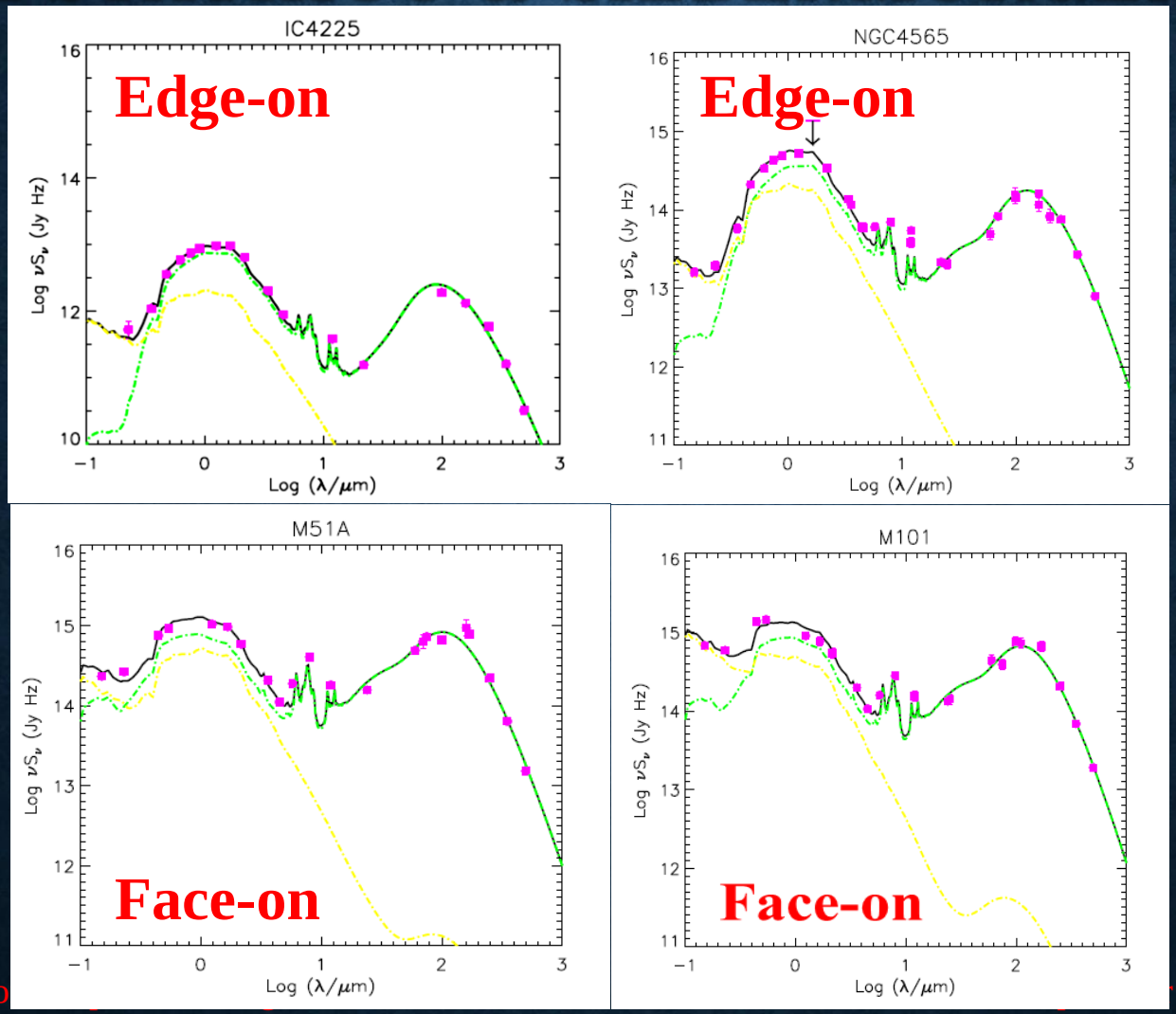


MODEL FITTING

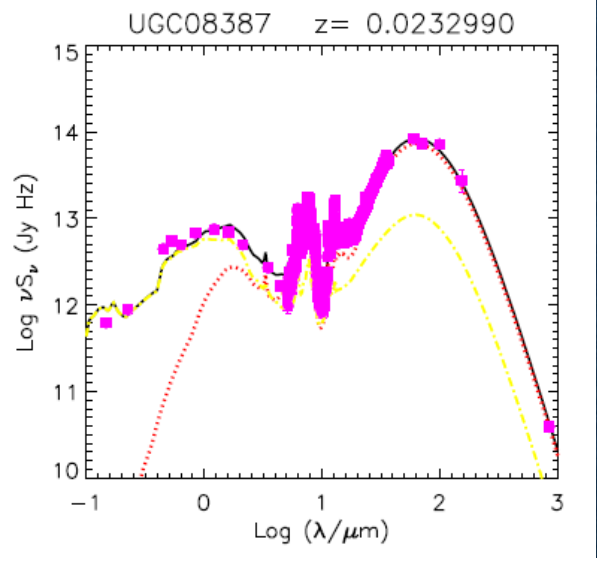
- We are exploring three different methods for fitting a UV-mm spectrum of a galaxy with multi-component radiative transfer models:

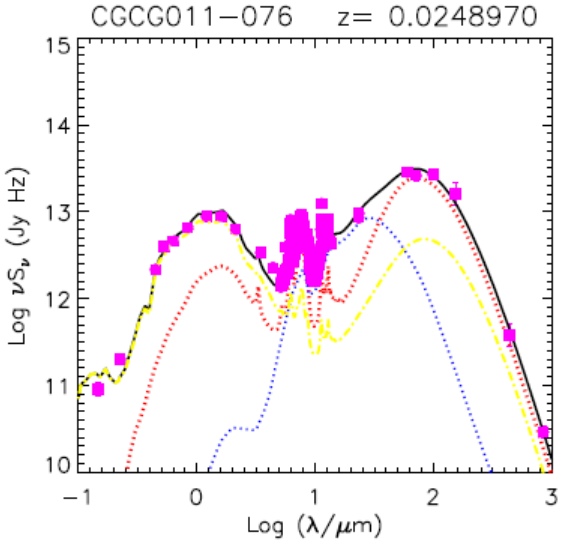
1. Brute force $\chi 2$ minimization method
2. Gradient or Levenberg-Marquardt method
3. SATMC code – Markov Chain Monte Carlo code

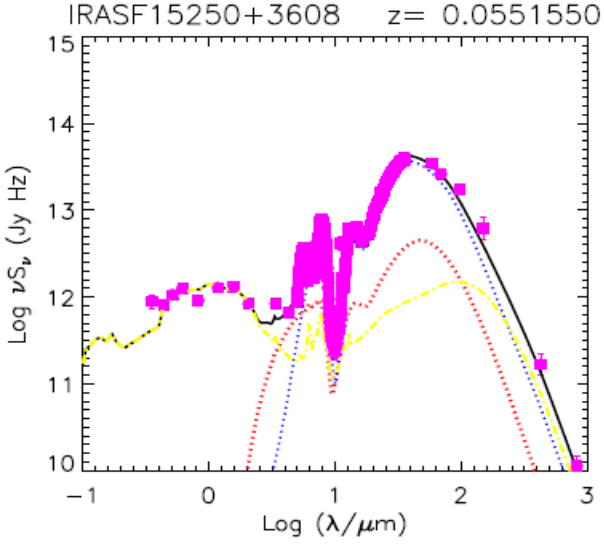
MODELS OF LOCAL SPIRAL GALAXIES (EFSTATHIOU & SIEBENMORGEN 15)

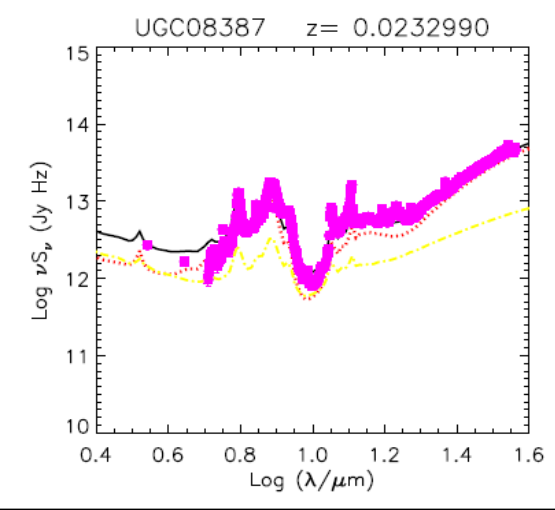


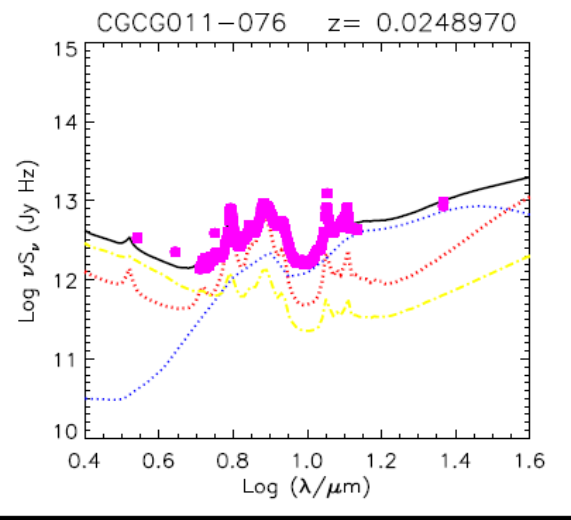
MODELS OF LOCAL LIRGS AND ULIRGS

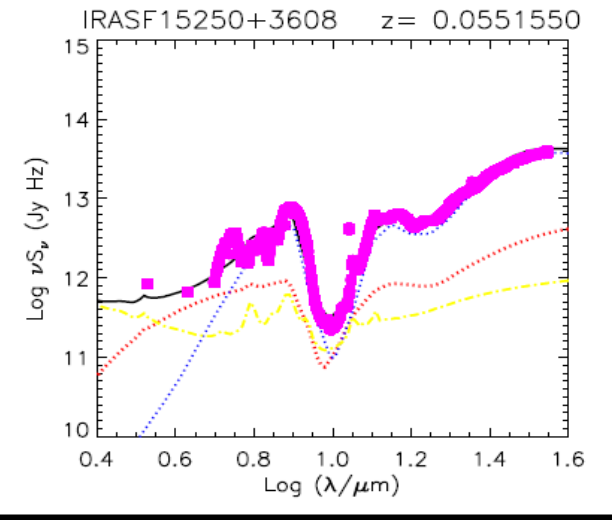




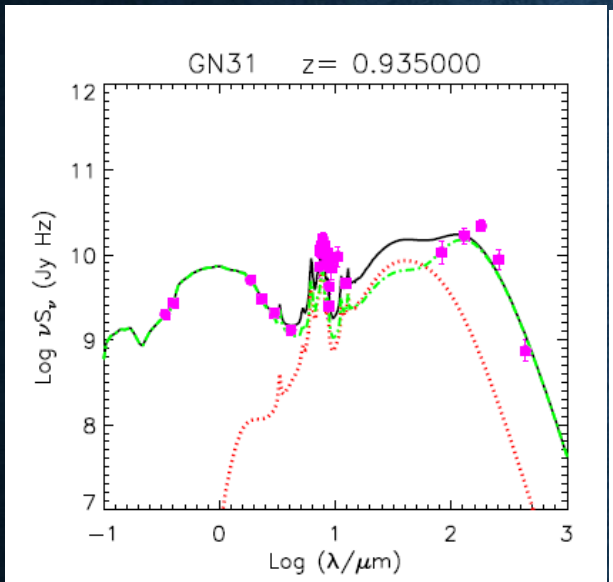


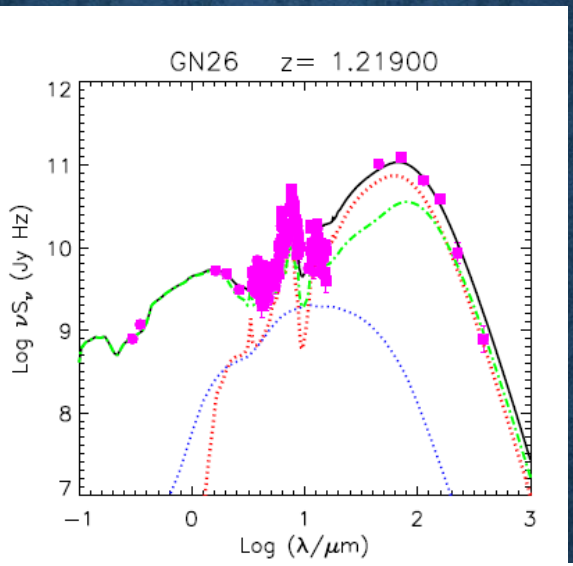


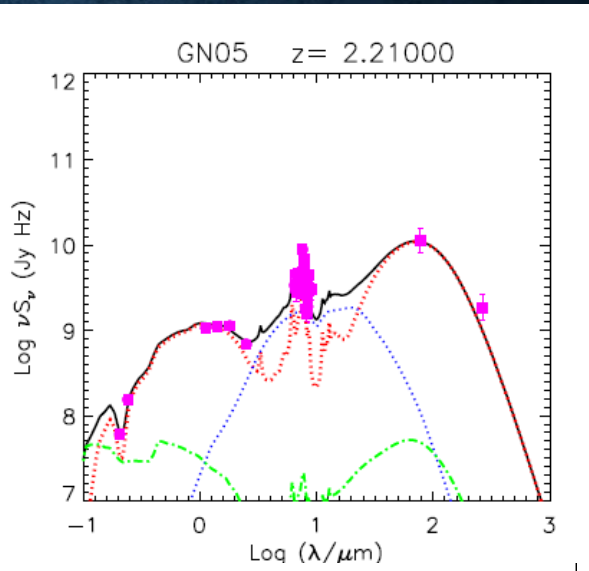


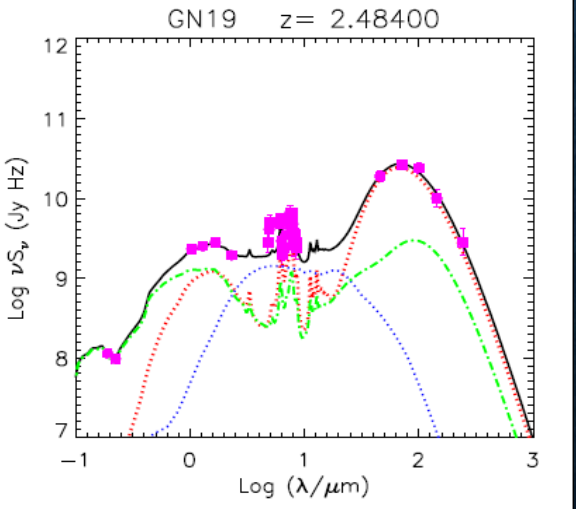


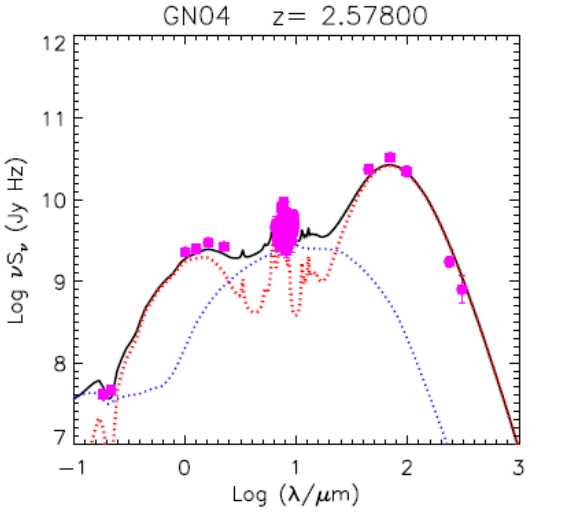
MODELS OF HIGH-Z LIRGS AND ULIRGS

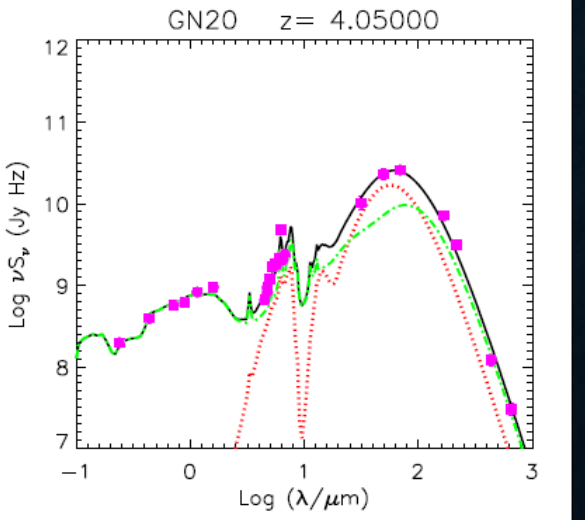












HERSCHEL EXTRAGALACTIC LEGACY PROJECT (HELP)

- New 3.5million euro FP7 project (started 1/1/2014) which will provide spectral energy distributions of ~1 million galaxies out to redshift ~4 (~whole history of the Universe).
- (Lead Inst.: Sussex, Participating Inst.: Cambridge, Marseille, Cardiff, Leiden, EUC, etc.)
- Will combine data from ground-based telescopes and Herschel/Spitzer.
- Multi-wavelength data will give accurate photometric redshifts, stellar masses, star formation rates, AGN lum. etc.
- Project will revolutionize studies of galaxy formation and evolution.

CONCLUSIONS

- We have fairly good models for the emission of starbursts, AGN dust tori and quiescently star-forming galaxies
- Need to test these models with large samples of galaxies preferably including Spitzer mid-IR spectroscopy – I am involved in a number of projects (including HERUS and HELP) that aim to do this
- Need to incorporate these models in models of galaxy formation and evolution – semi-analytic models and simulations of mergers etc.
- The models are available on request (a.efstathiou@euc.ac.cy) and soon from our group webpage (http://ahpc.euc.ac.cy)