THE *CYGNUS* MODELS FOR THE SPECTRAL ENERGY DISTRIBUTIONS OF GALAXIES AND THEIR SUPERMASSIVE BLACK HOLES

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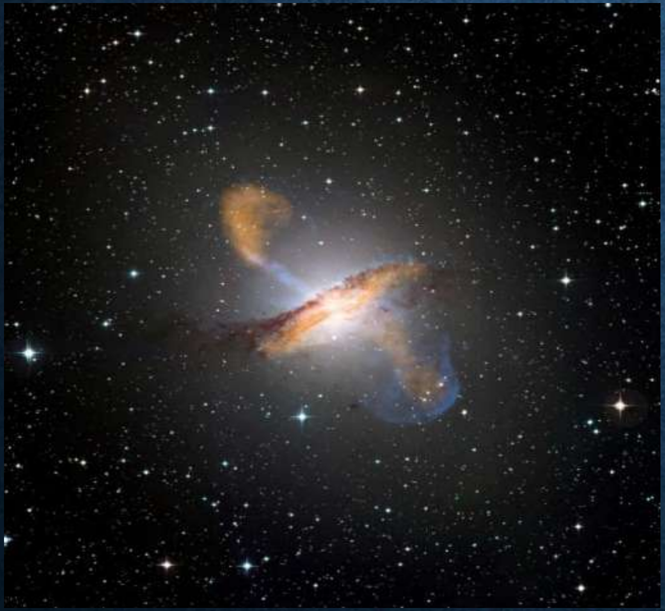
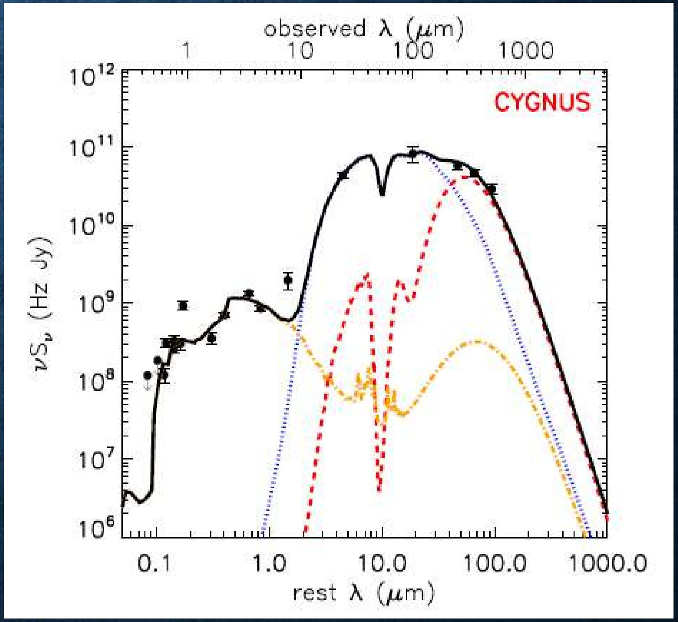
TWO COMPLEMENTARY WAYS OF LOOKING AT GALAXIES: IMAGES (LEFT) & SPECTRAL ENERGY DISTRIBUTIONS (RIGHT)

Nearby radio galaxy Centaurus A



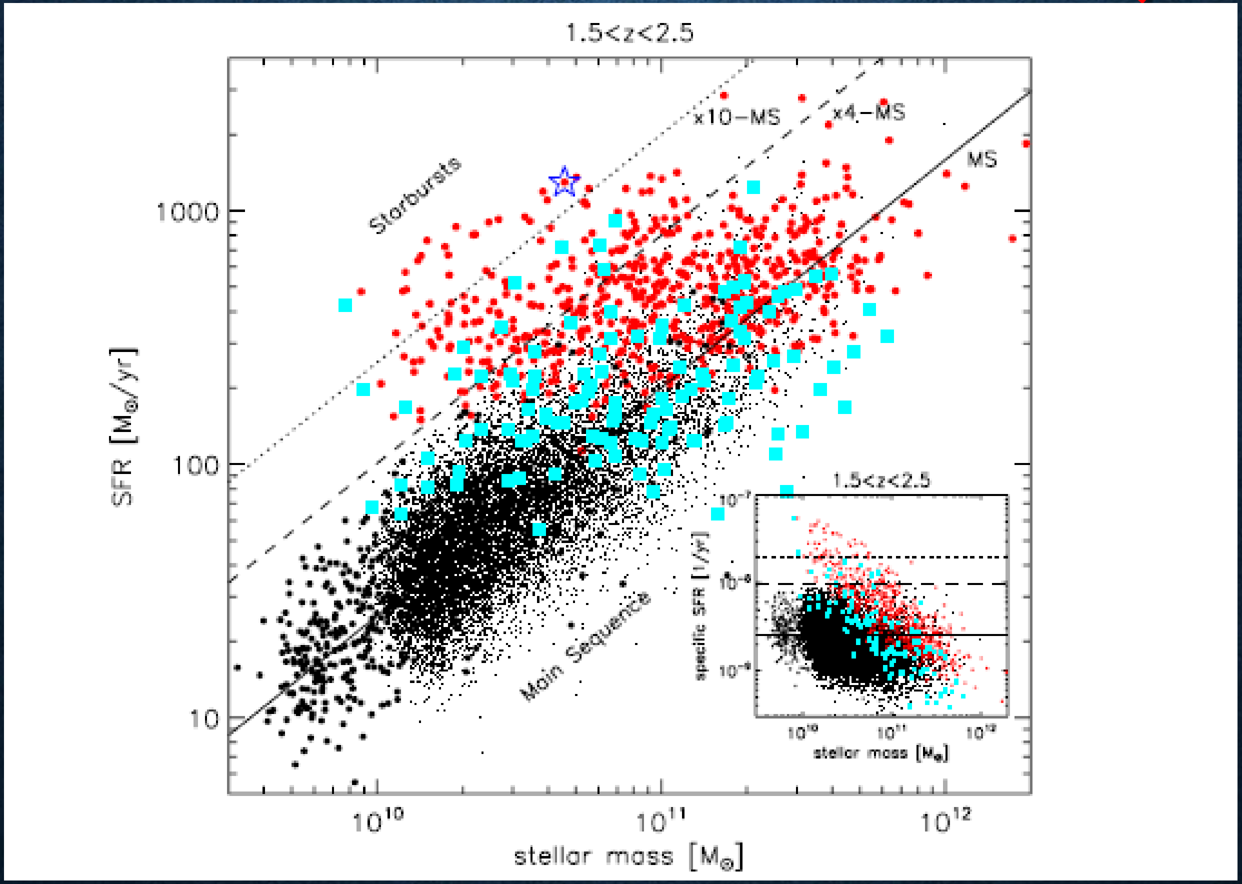
SED of an obscured hyperluminous quasar at z~4.3 (Efstathiou et al 2021)



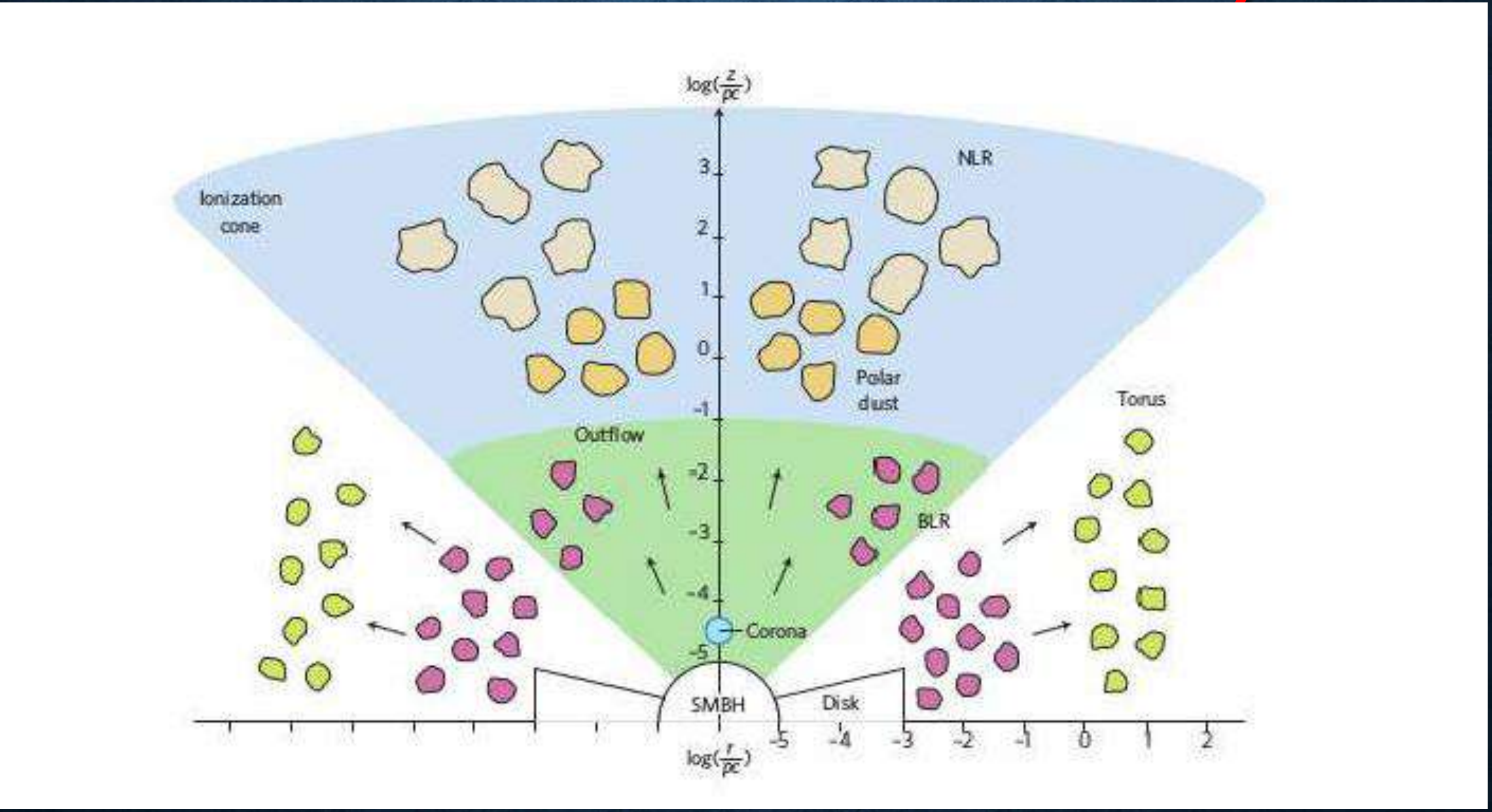
WHAT CAN WE LEARN BY ANALYZING THE SPECTRAL ENERGY DISTRIBUTIONS OF GALAXIES ?

- Physics of star-forming galaxies
- Physics of active galactic nuclei (AGN)
- Effect of AGN feedback in shaping galaxies
- The star formation and accretion history of the universe
- Can incorporate SED models in simulations of galaxy formation and evolution and ensure everything is self-consistent

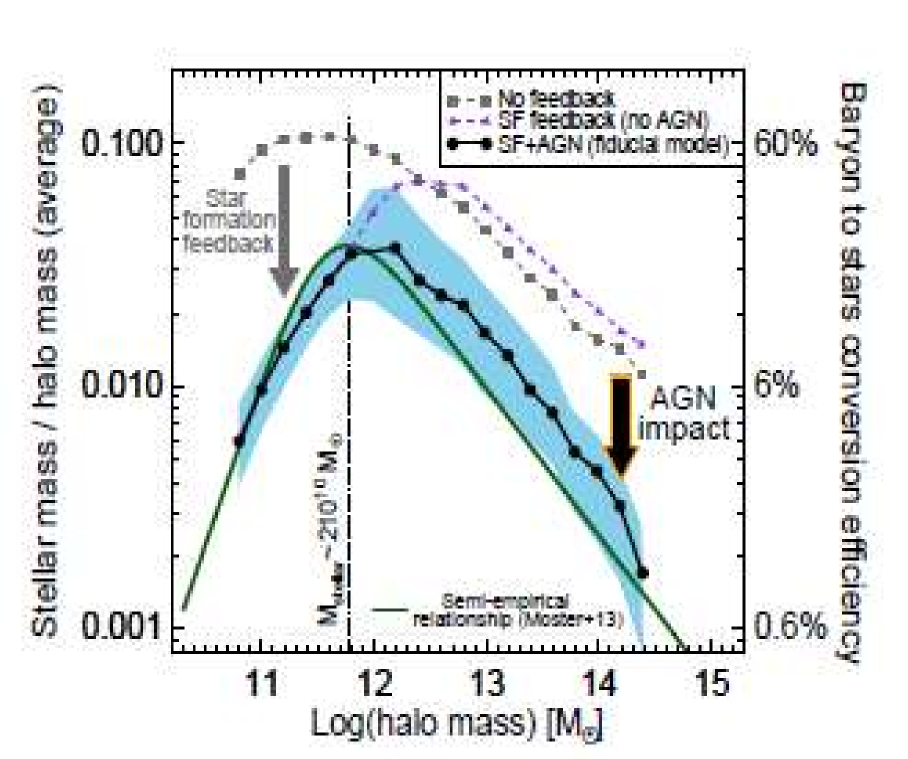
PHYSICS OF STAR-FORMING GALAXIES (MAIN-SEQUENCE AND STARBURST GALAXIES; FROM RODIGHIERO ET AL 2011)

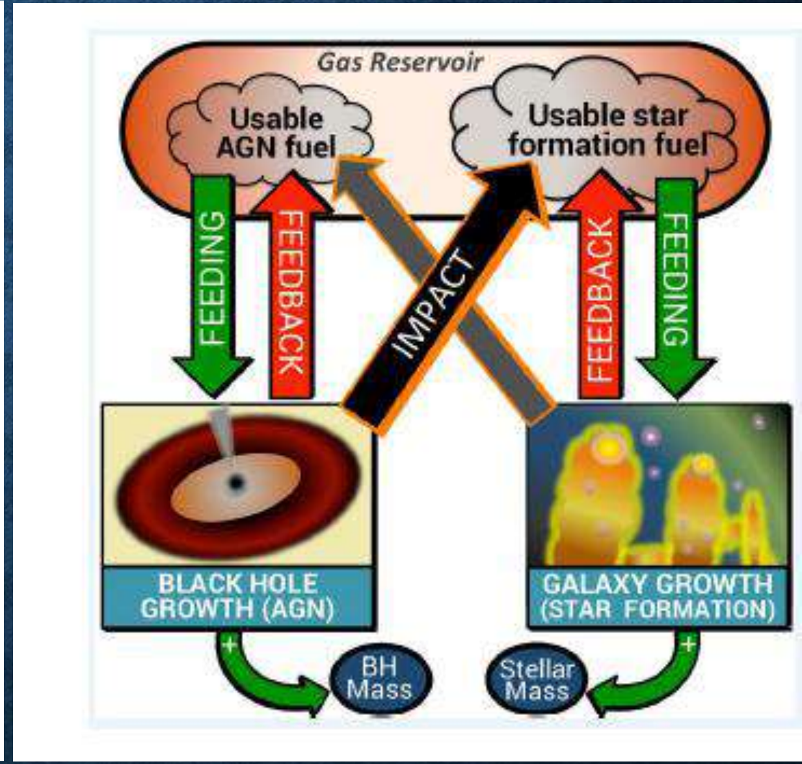


PHYSICS OF ACTIVE GALACTIC NUCLEI (AGN; FROM RAMOS ALMEIDA & RICCI 2017)

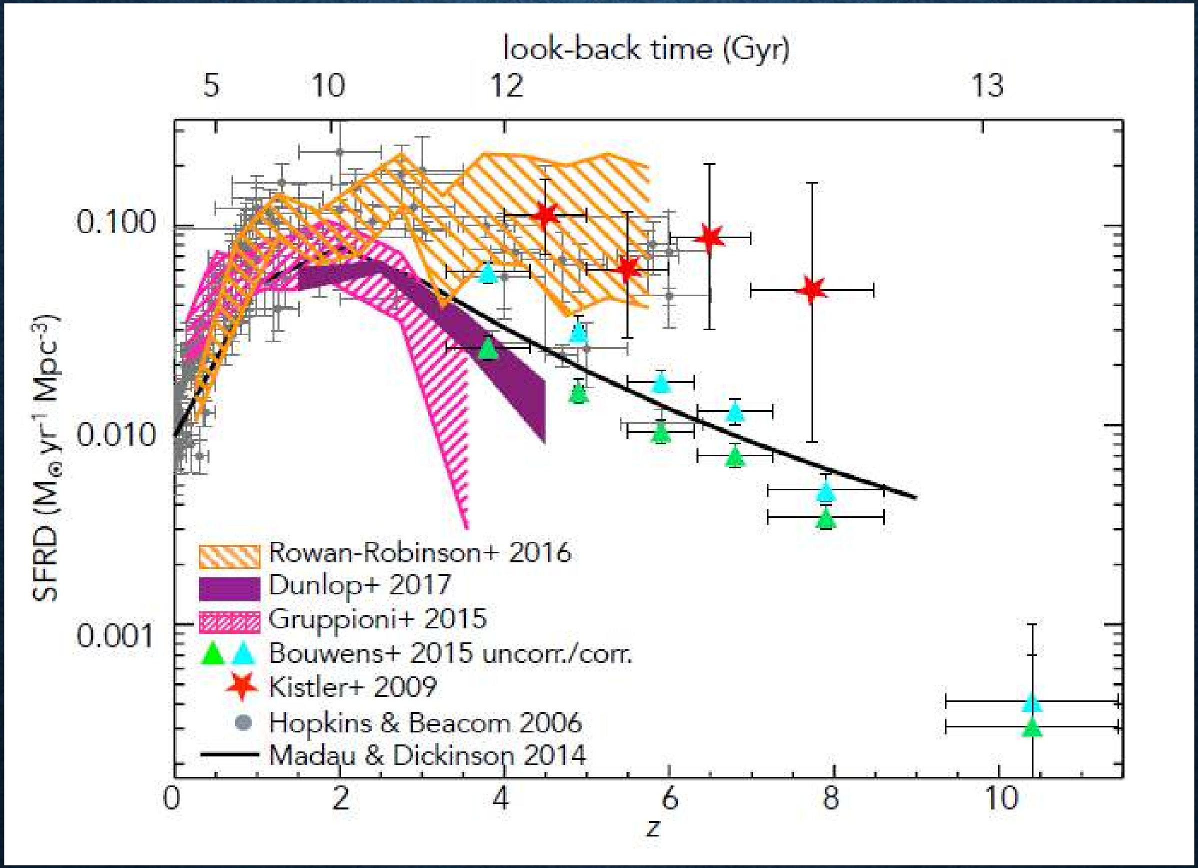


EFFECT OF AGN FEEDBACK IN SHAPING GALAXIES (FROM HARRISON 2017)





STAR FORMATION HISTORY OF THE UNIVERSE (FROM GRUPPIONI ET AL 2017)



SIMULATIONS OF GALAXY FORMATION (e.g. EAGLE)

- Models that take into account most of the physics of galaxy formation we know about.
- In order to compare the models with observations we need to take into account the effects of dust
- Most successful attempt to do this is the collaboration of the Durham and Padova groups.

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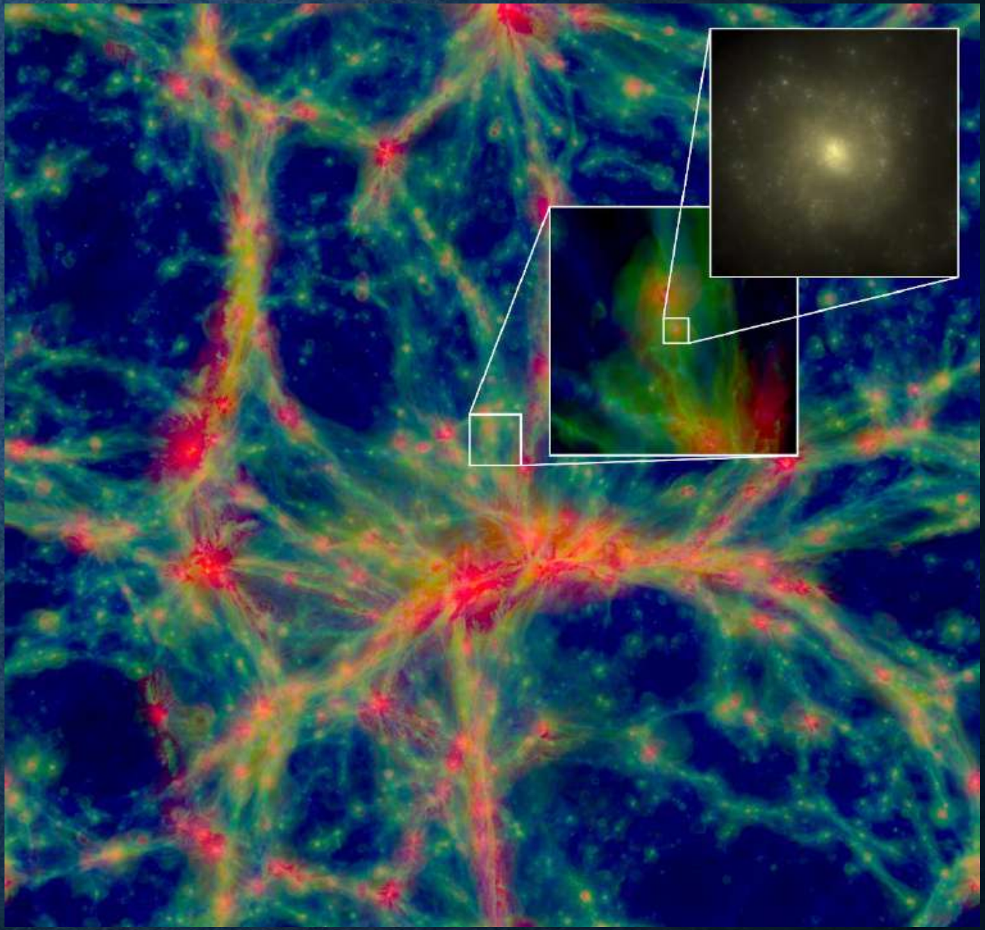
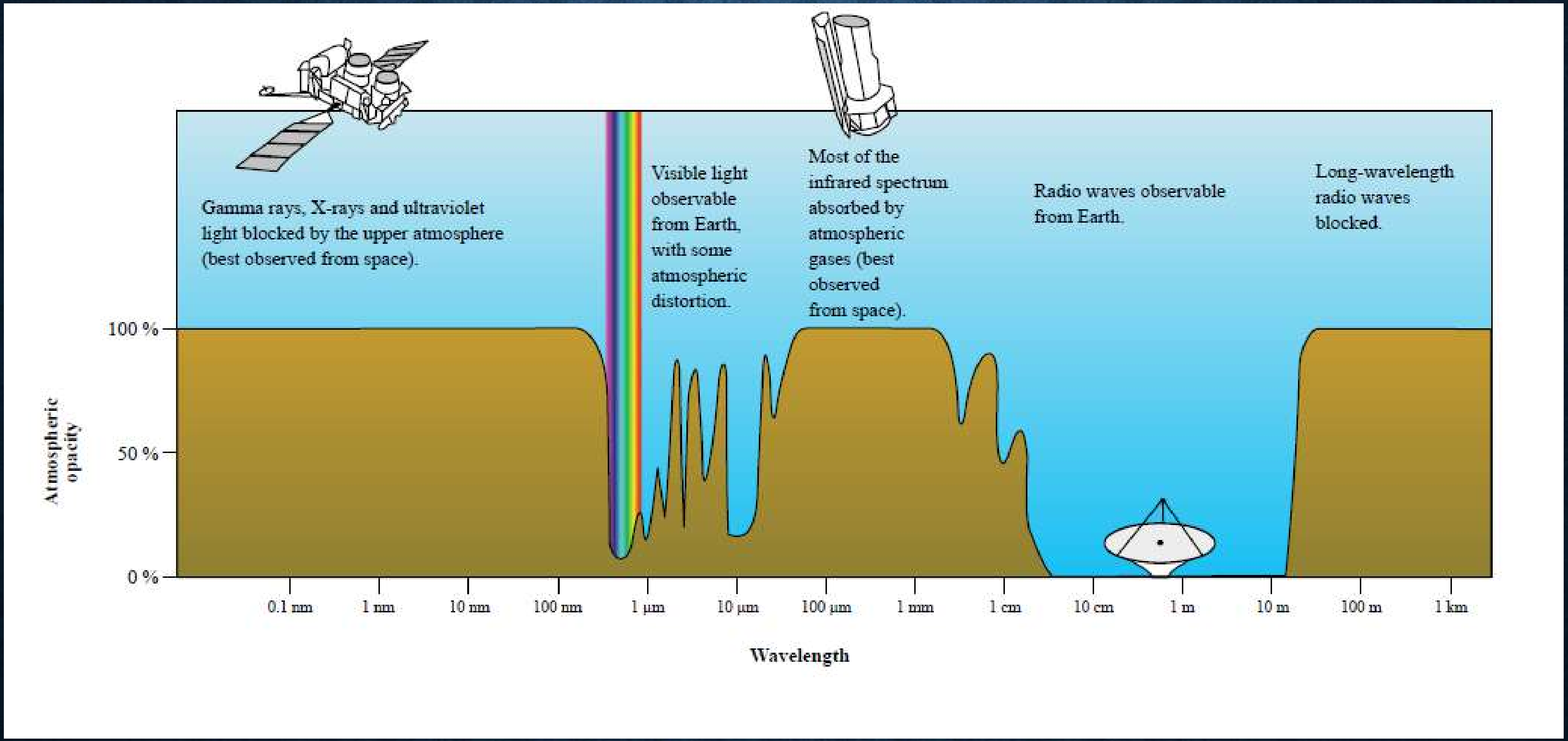


WE NEED A MULTI-WAVELENGTH VIEW OF GALAXIES

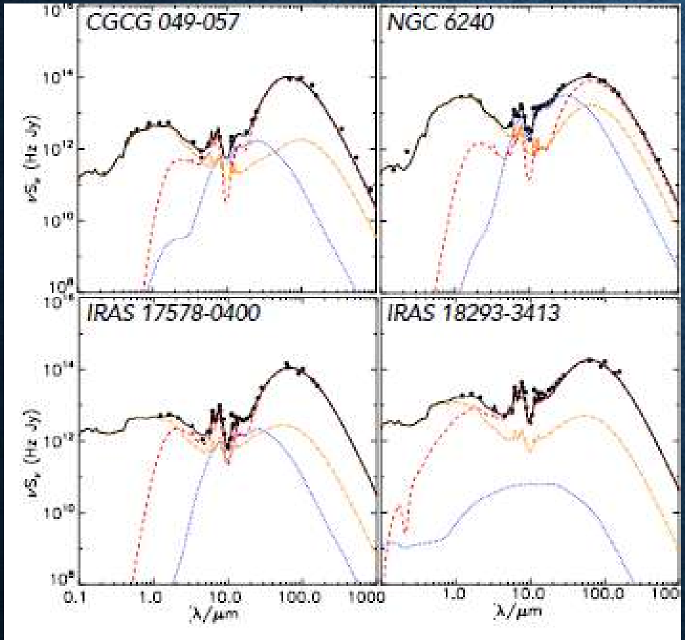
- Three main types of activity in galaxies: star formation in quiescent disk galaxies, bursts of star formation in starbursts and accretion of matter onto a supermassive black hole (active galactic nuclei or AGN).
- All three processes associated with a lot of gas.
- Gas is associated with a small amount 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.

THE ELECTROMAGNETIC SPECTRUM AND ATMOSPHERIC OPACITY (OBSERVATIONS AT WAVELENGTHS WHERE OPACITY APPROACHES 100% CAN ONLY BE DONE FROM SPACE)



SPECTRAL ENERGY DISTRIBUTION DE-COMPOSITION WITH RADIATIVE TRANSFER MODELS

Models for Luminous Infrared Galaxies by Herrero-Illana et al (2017)



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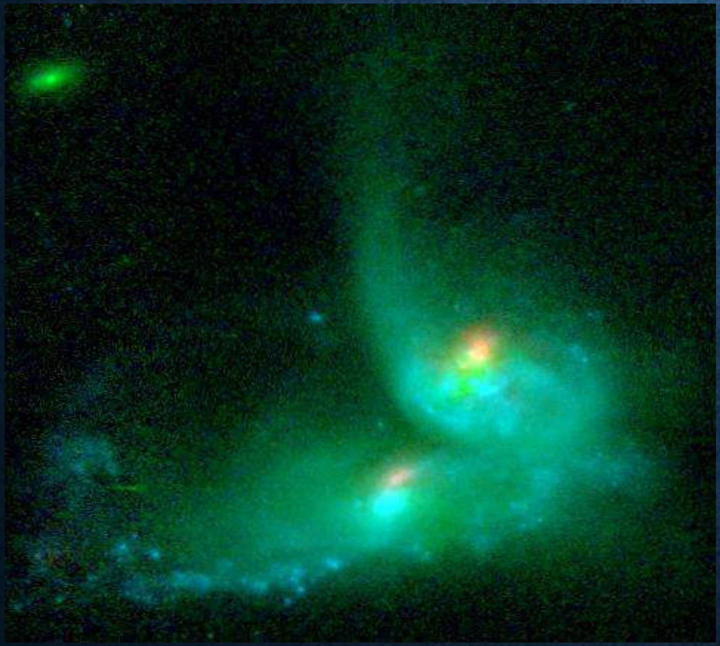
Physical Quantities we can extract

- Luminosities of different galaxy components (host, starburst, AGN)
- Star formation rate (SFR)
- Stellar mass (SM)
- AGN fraction
- Black hole mass
- Dust mass
- Supernova rate

LOCAL ULTRALUMINOUS INFRARED GALAXIES (ULIRGS)

IRAS 08572+3915: an example of an interacting ULIRG



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- 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 SUBMILLIMETER GALAXIES

James Clerk Maxwell Telescope

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

Discovery of submillimeter 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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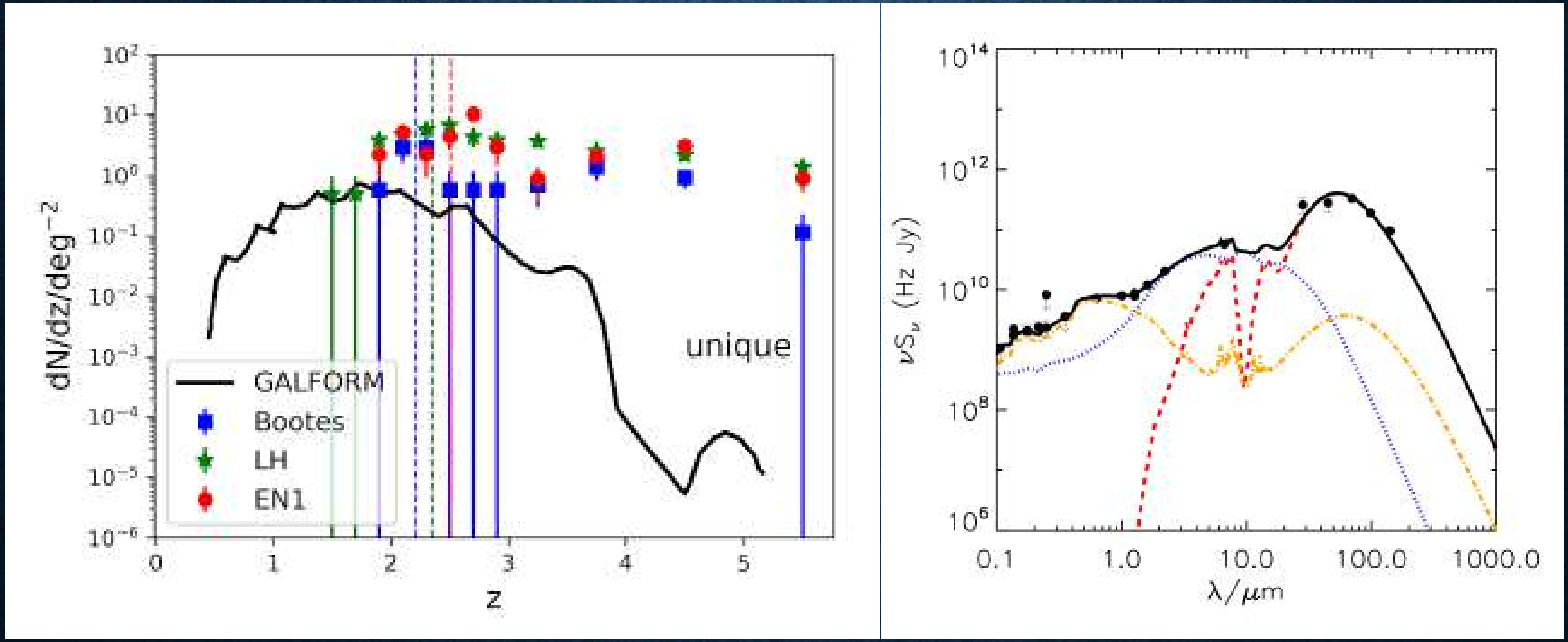
In the local Universe, most galaxies are dominated by stars, with less than ten per cent of their visible mass in the form of gas. Determining when most of these stars formed is one of the central issues of observational cosmology. Optical and ultraviolet observations of high-redshift galaxies (particularly 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.

THERE ARE FAR MORE LUMINOUS MERGERS AT HIGH REDSHIFT THAN PREDICTED BY THE COSMOLOGICAL MODEL (WANG ET AL 2021)



The radiative transfer problem

The radiative transfer problem describes the interaction between radiation and matter. It is a very general problem with applications in all sciences...

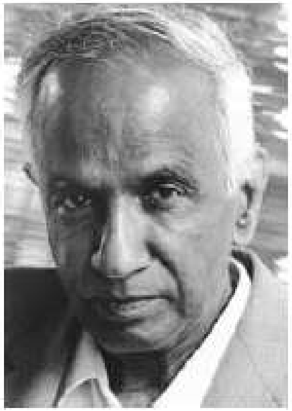
Generally described by the following equation (RTE)

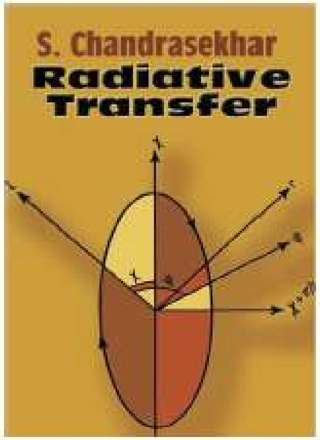
$$\boxed{\frac{\mathrm{d}I}{\mathrm{d}s}(\boldsymbol{x}, \boldsymbol{n}, \lambda) = -\kappa(\boldsymbol{x}, \lambda)\rho(\boldsymbol{x})I(\boldsymbol{x}, \boldsymbol{n}, \lambda) + j(\boldsymbol{x}, \boldsymbol{n}, \lambda)}$$

Rate of change of the intensity of the radiation field

Sinks: removal of radiation due to interaction with matter

Source terms: creation of radiation





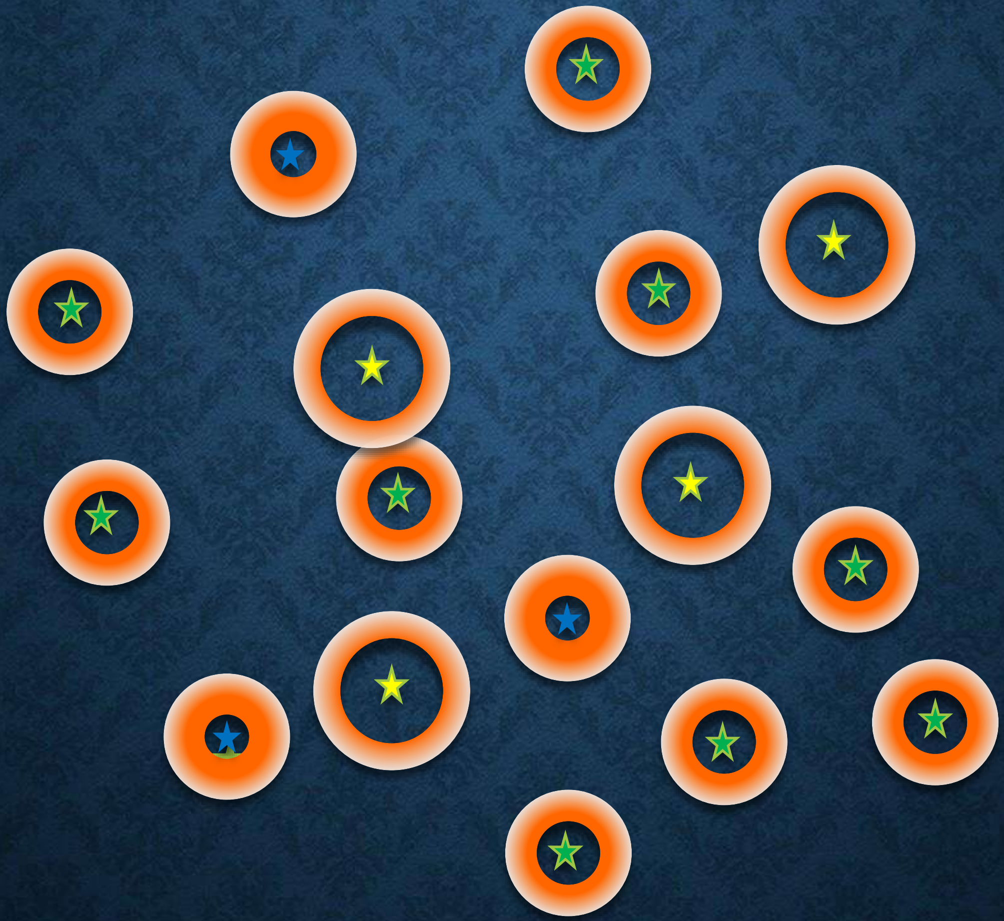
RADIATIVE TRANSFER MODELS

- 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

CYGNUS (CYPRUS MODELS FOR GALAXIES AND THEIR NUCLEAR SPECTRA)

- Collection of radiative transfer models for AGN tori, starbursts and host galaxies
- Starburst (Efstathiou et al 2000, Efstathiou & Siebenmorgen 2009)
- AGN torus (Efstathiou & Rowan-Robinson 1995, Efstathiou et al 2013)
- Spheroidal host (Efstathiou & Rowan-Robinson 2003, Efstathiou et al 2021)
- Disc host (Efstathiou & Siebenmorgen, in preparation)

Schematic diagram of the giant molecular cloud (GMC) distribution in an Efstathiou et al. starburst



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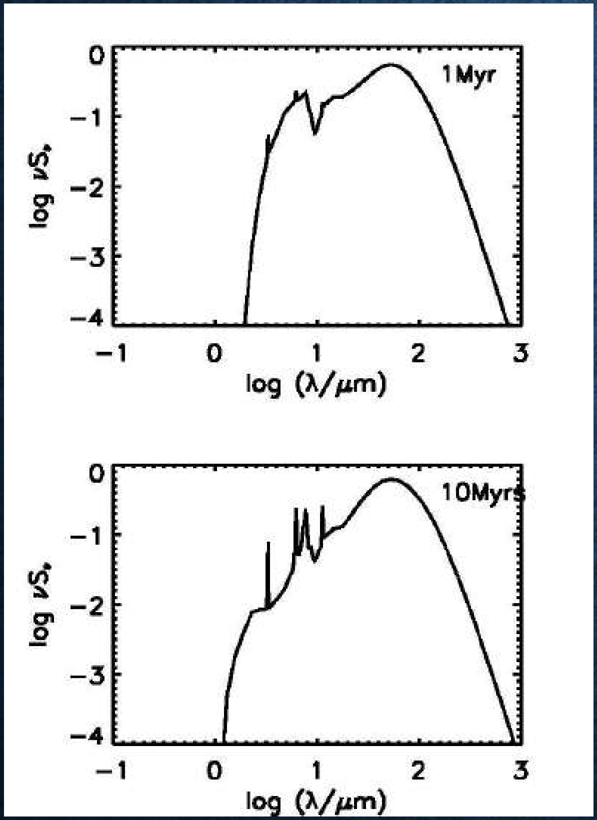
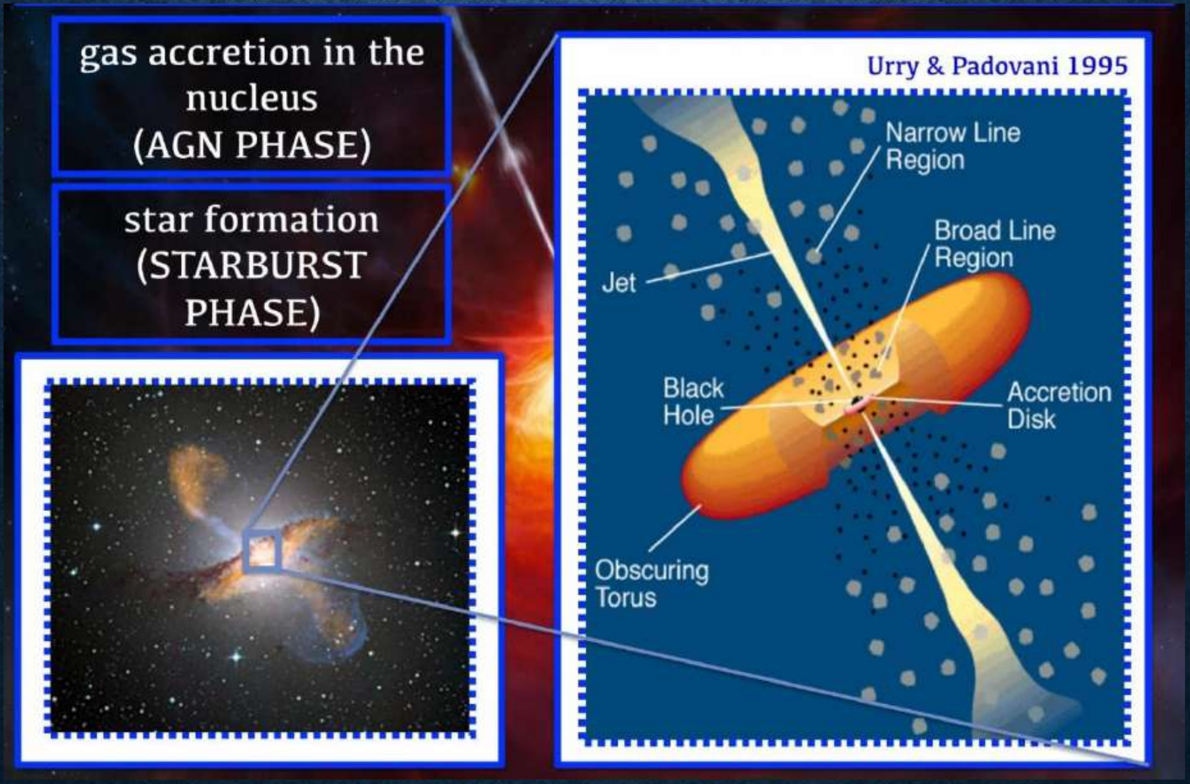
EVOLUTION OF THE SPECTRUM OF A GIANT MOLECULAR CLOUD (EFSTATHIOU ET AL. 2000)



- Model predicts that there is a strong evolution in the spectrum of a star-forming region GMC in the first ~10-20Myr after star formation as it is transformed from an HII region to a PDR.
- PAH features get progressively stronger with age.
- This property can be used to age the starburst episode and get a better estimate of the SFR.

UNIFIED MODEL FOR ACTIVE GALACTIC NUCLEI (AGN) AND QUASARS: THE AGN TORUS



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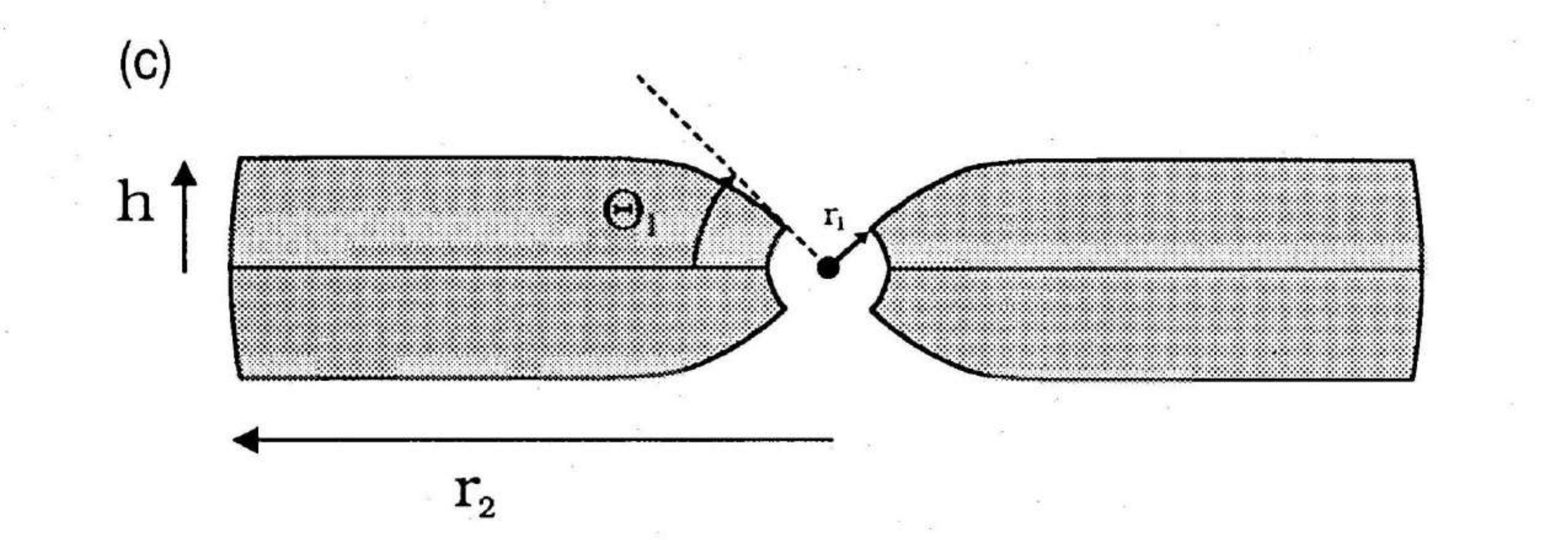
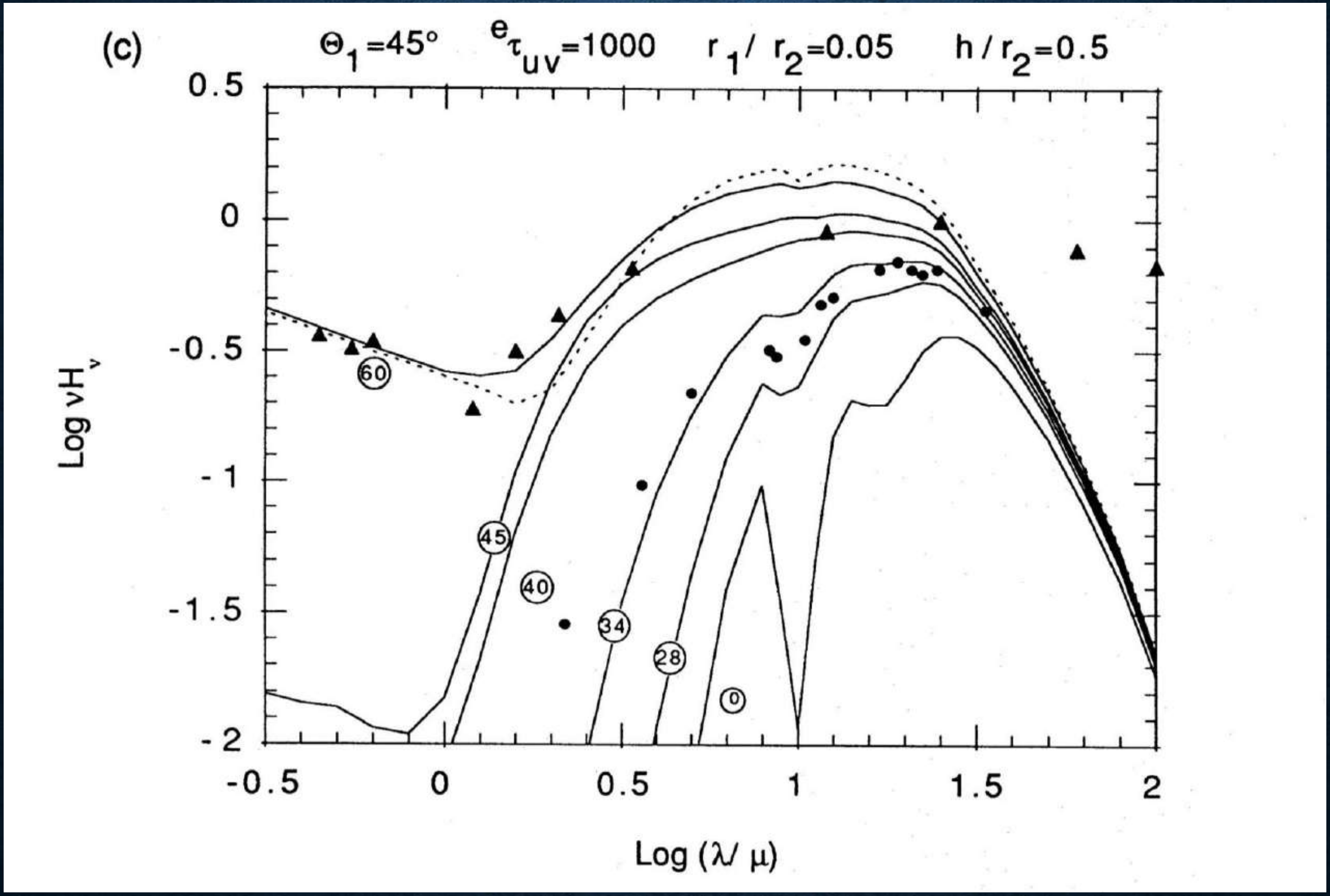
AGN TORUS MODEL OF EFSTATHIOU & ROWAN-ROBINSON (1995)

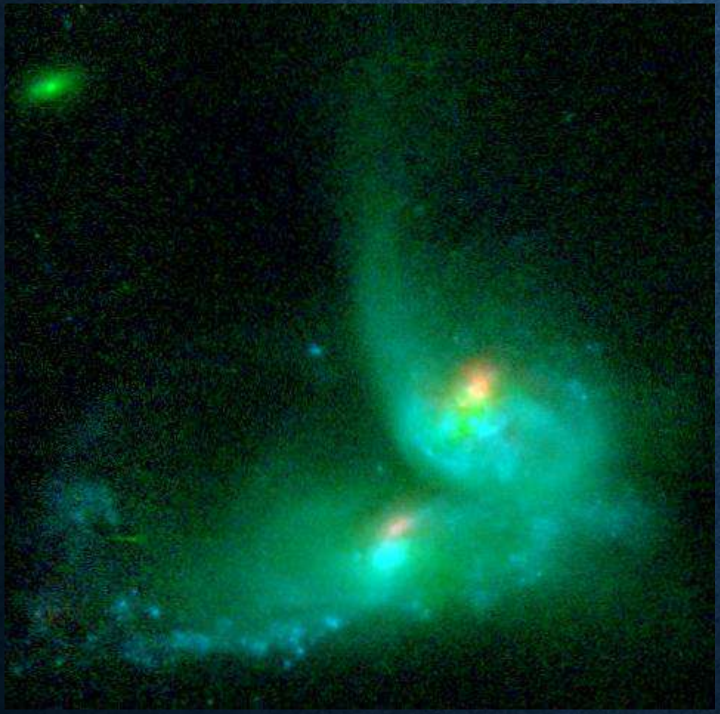


VARIATION OF THE SPECTRUM OF A TAPERED DISC WITH INCLINATION (EFSTATHIOU & ROWAN-ROBINSON 1995)



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

Optical image (Hubble Space Telescope) of IRAS 08572+3915



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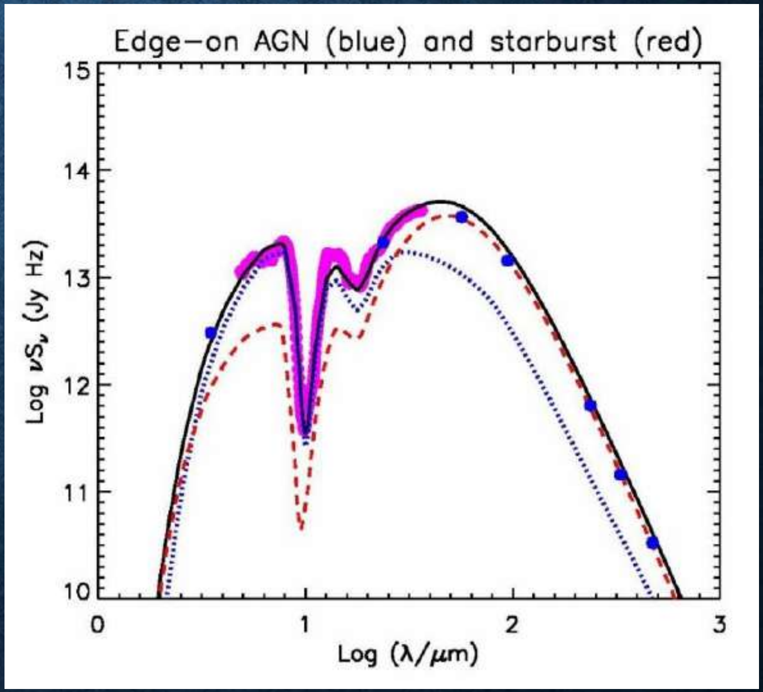
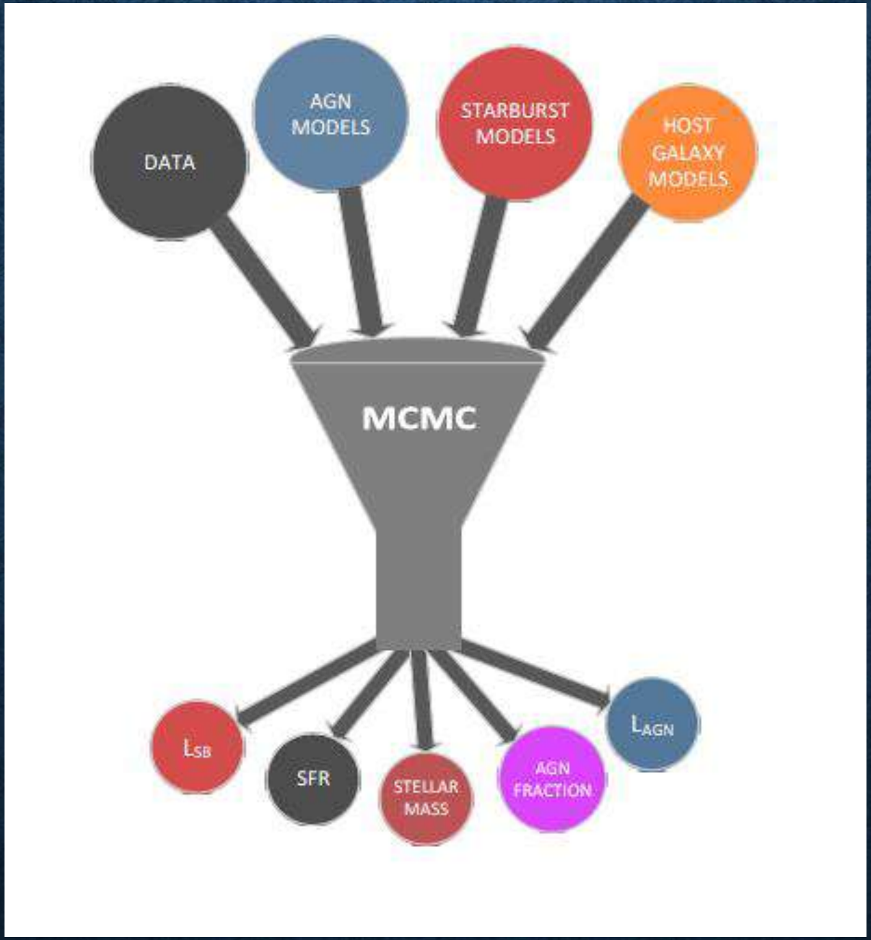
A model for the 1-1000μm spectrum



MODELS FOR SPHEROIDAL AND DISC GALAXIES (EFSTATHIOU & ROWAN-ROBINSON 2003, EFSTATHIOU ET AL 2021, EFSTATHIOU & SIEBENMORGEN, IN PREPARATION)

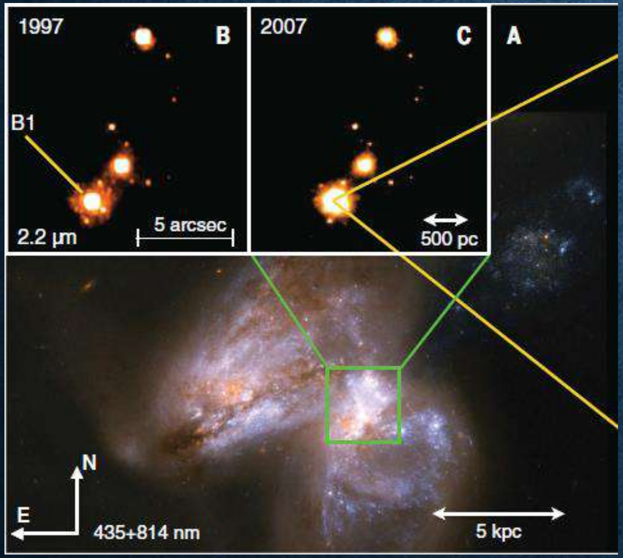
- Codes that calculate the ultraviolet to millimetre emission of spheroidal or disc galaxies
- Incorporates the stellar population synthesis model of Bruzual & Charlot and the starburst model of Efstathiou, Rowan-Robinson & Siebenmorgen, as revised by Efstathiou & Siebenmorgen (2009)
- Self-consistently calculates the radiative transfer problem in a spheroidal or disc galaxy with multiple scattering

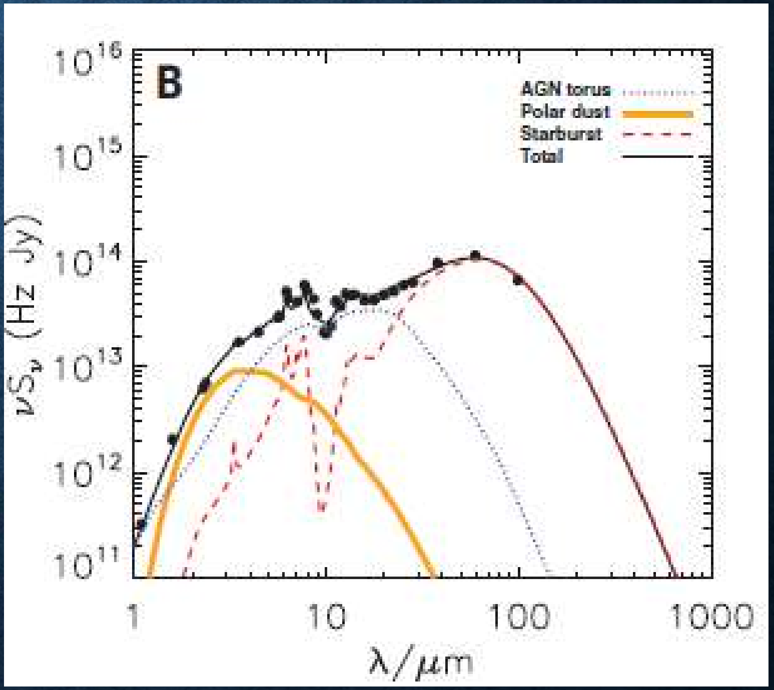
METHOD OF FITTING AN SED WITH LIBRARIES OF MODELS AND MCMC (SATMC OR EMCEE)



DISCOVERY OF A DUST-ENSHROUDED TIDAL DISRUPTION EVENT IN THE GALAXY MERGER ARP299

PUBLISHED IN 'SCIENCE' (MATTILA, PEREZ-TORRES, EFSTATHIOU ET AL 2018)





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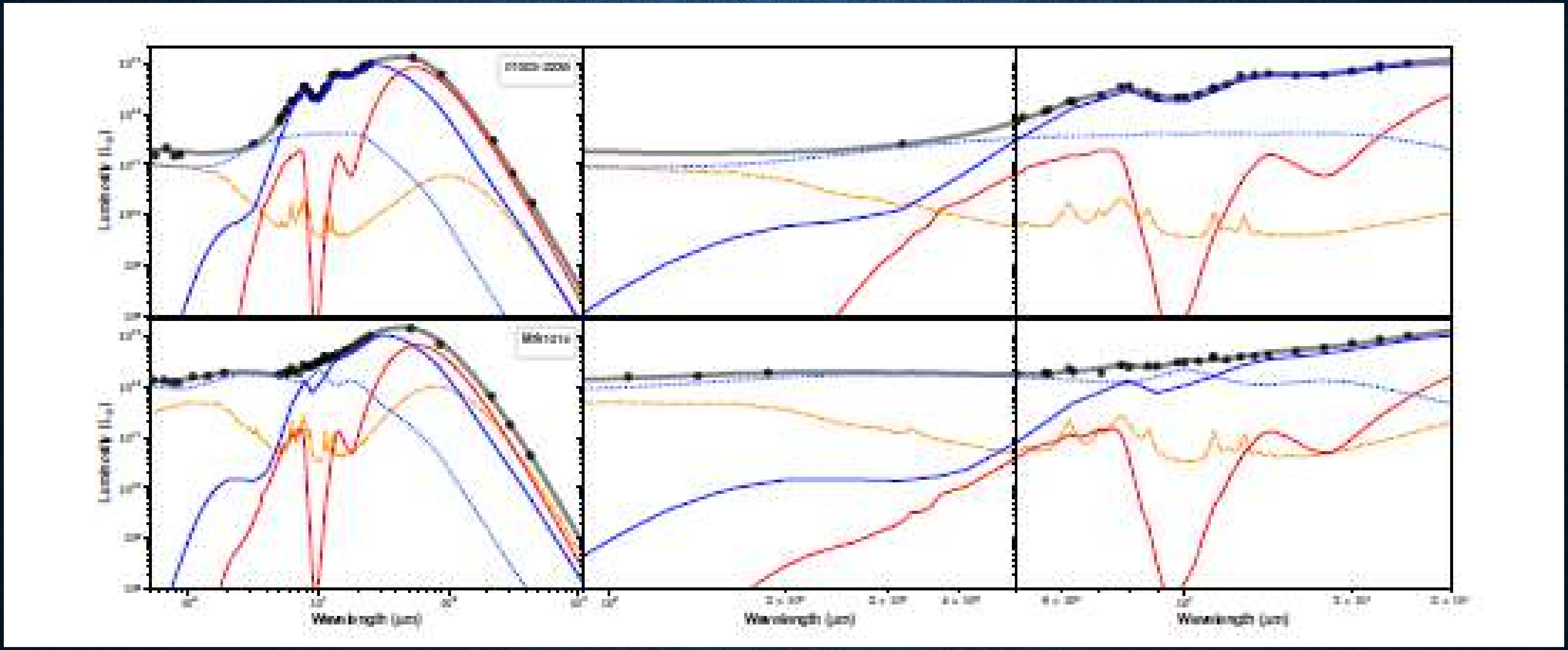
SED FITTING OF HERUS GALAXIES WITH CYGNUS (EFSTATHIOU ET AL 2021): EVIDENCE FOR DUAL AGN

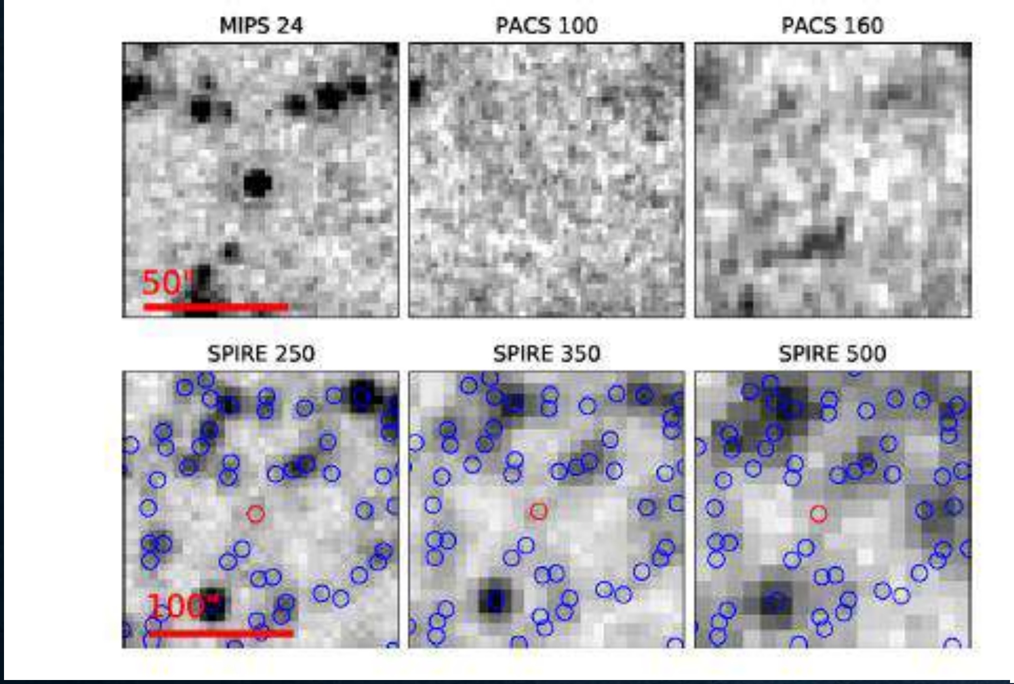


HERSCHEL EXTRAGALACTIC LEGACY PROJECT (HELP)

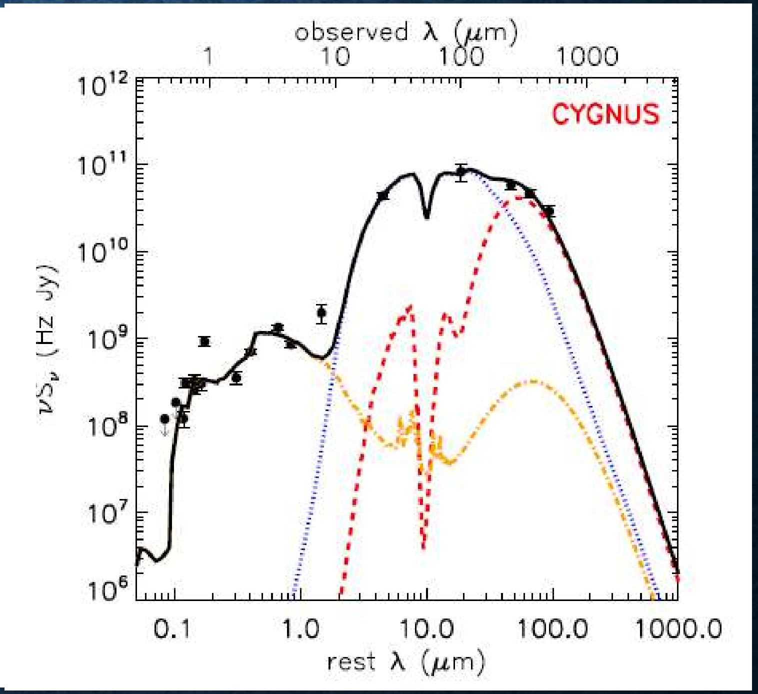
- 3.5million euro FP7 project (1/1/2014-30/6/2018) which provided multi-wavelength spectral energy distributions of ~170 million galaxies out to redshift ~4-6 (~whole history of the Universe).
- (Lead Inst.: Sussex, Participating Inst.: Cambridge, Marseille, Cardiff, Leiden, EUC, etc.)
- Combined data from ground-based telescopes and Herschel/Spitzer.
- Multi-wavelength data will give accurate photometric redshifts, stellar masses, star formation rates, AGN fractions etc.
- Project will revolutionize studies of galaxy formation and evolution

DISCOVERY OF AN OBSCURED HYPERLUMINOUS QUASAR AT Z~4.3 (EFSTATHIOU ET AL 2021)

Postage stamps in various filters



Model of the spectrum of emission



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ALMA AND JWST

ALMA completed in 2013

JWST to be launched in 2021

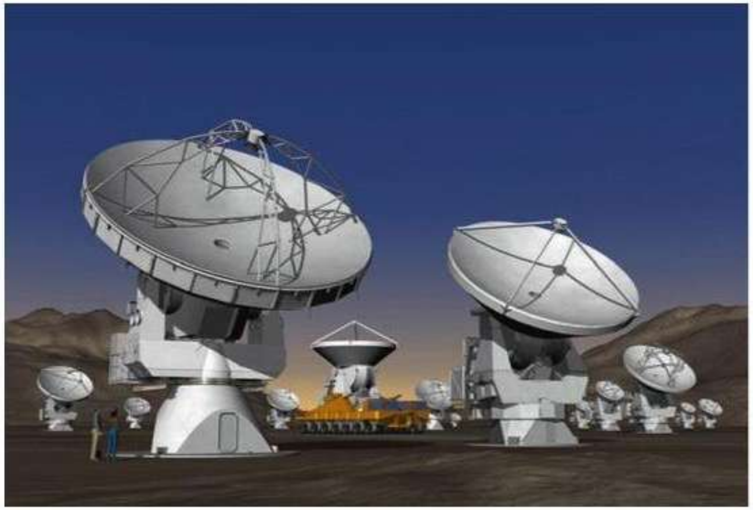
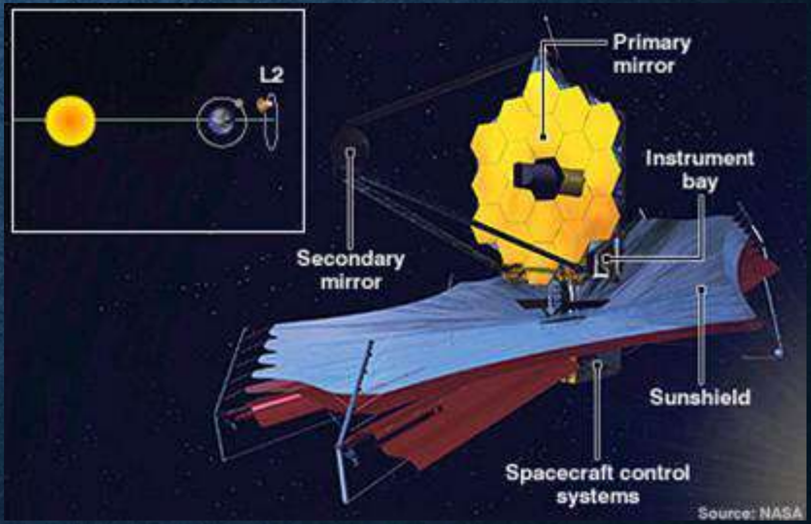


Figure 5.27 Artist's impression of the Atacama Large Millimetre Array. Image: European Southern Observatory.



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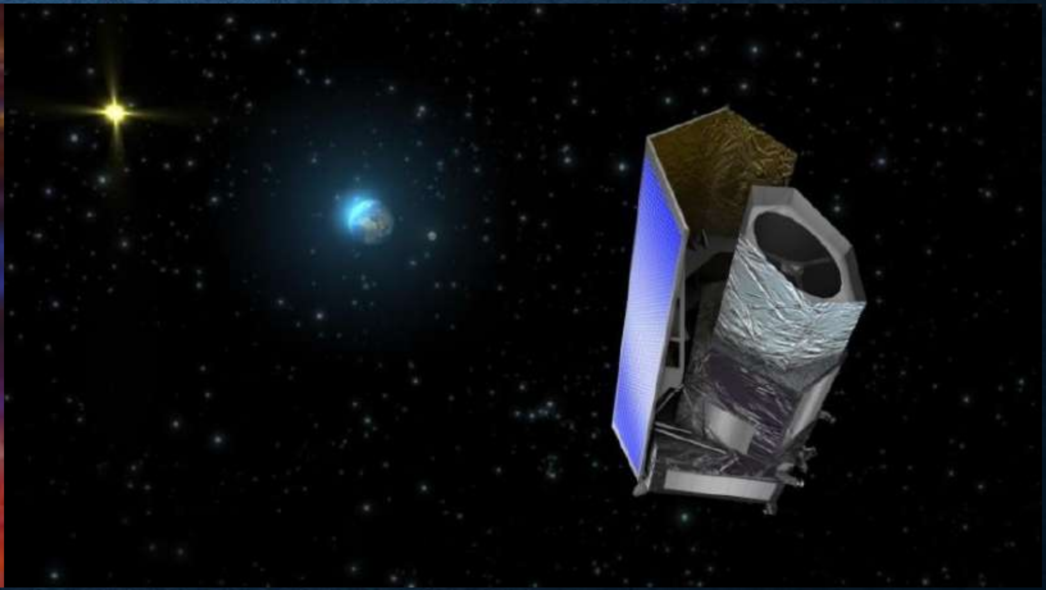
HERSCHEL AND EUCLID

Herschel that operated between 2009-2013

Euclid to be launched in about 2022



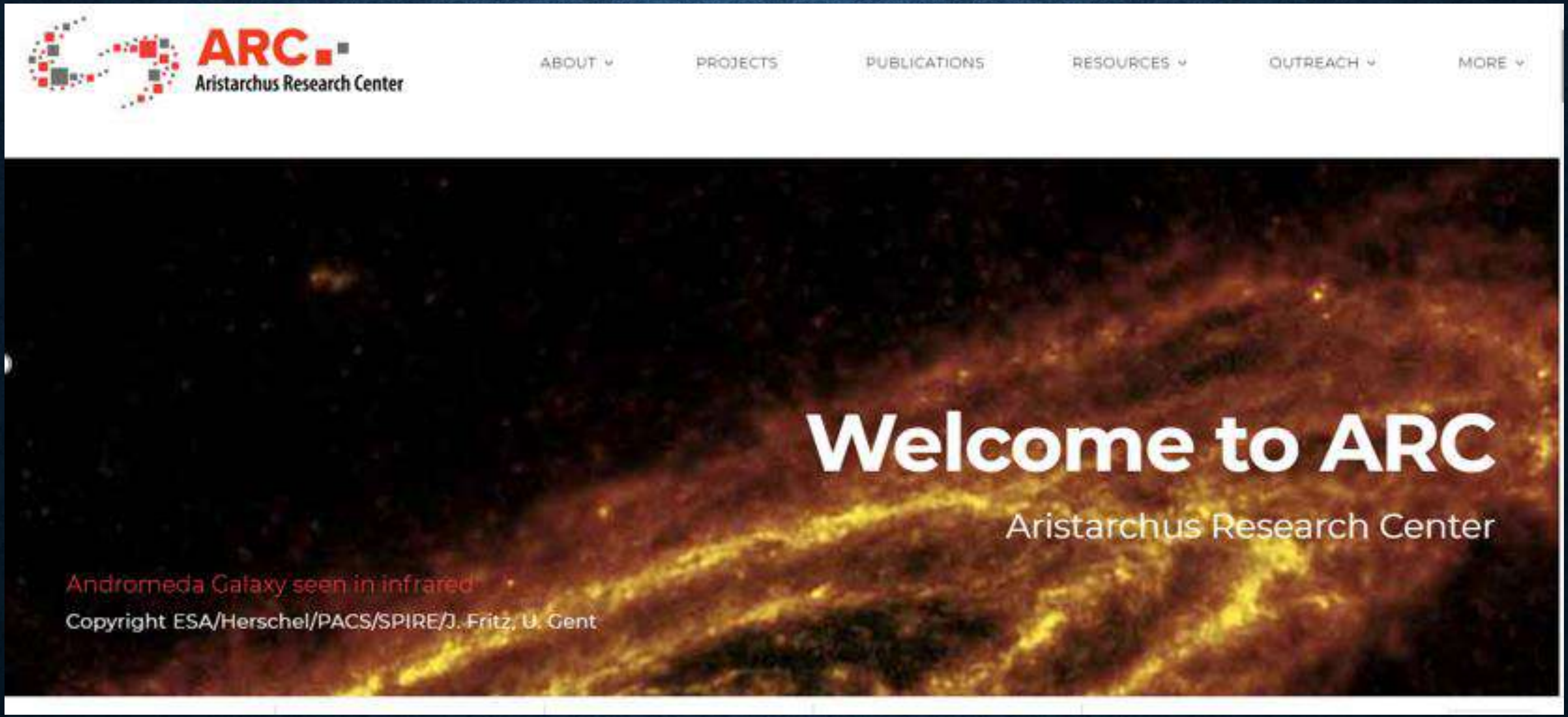
IMPORTANT TELESCOPE FACILITIES WHICH ARE RELEVANT FOR CYGNUS

- SPITZER - infrared
- HERSCHEL - far-infrared to submillimeter
- EUCLID - optical to near-infrared
- JWST - optical to mid-infrared
- SKA - radio
- LSST - optical

CONCLUSIONS AND IDEAS FOR FUTURE WORK

- We have fairly good models for the emission of starbursts, AGN dust tori and quiescently star-forming galaxies
- These models can be used to de-compose the SEDs of large samples of galaxies preferably including rest frame mid-IR spectroscopy (Spitzer, JWST, SPICA) – involved in a number of projects (including HERUS and HELP) that aim to do this
- Incorporate RT models in simulations of star-forming regions, AGN tori and simulations of galaxy formation and evolution (e.g. semi-analytic models and simulations of mergers)
- The models are available on request (a.efstathiou@euc.ac.cy) and from our group webpage (https://ahpc.space/cygnus/)

ARISTARCHUS RESEARCH CENTER (ARC) AT EUC



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