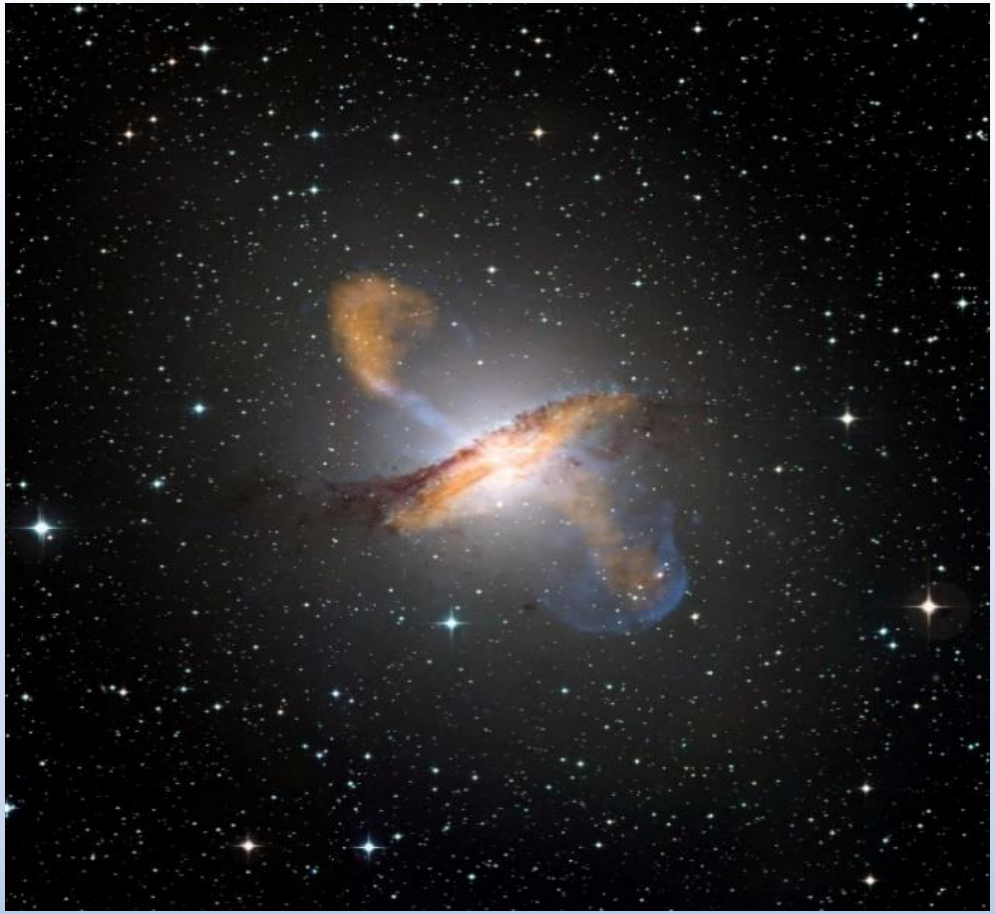
European University Cyprus

ARC Aristarchus Research Center

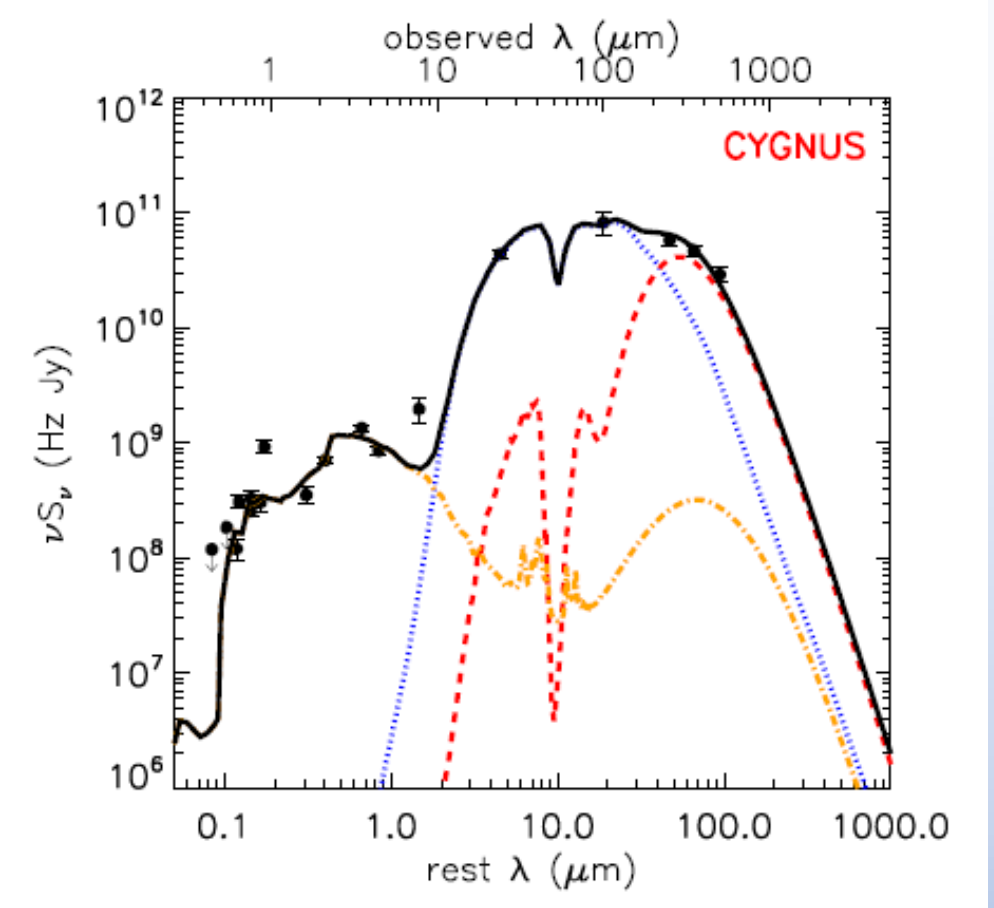
Charalambia Varnava

Two complementary ways of looking at galaxies: Images (left) and Spectral Energy Distributions or SEDs (right)

Nearby radio galaxy Centaurus A



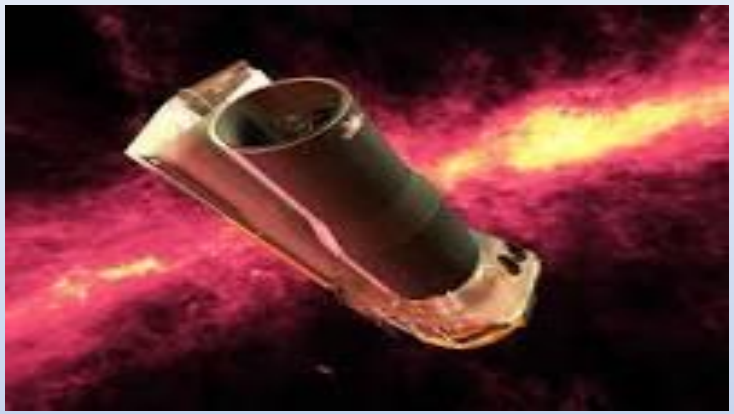
SED of an obscured hyperluminous quasar at z~4.3 (Efstathiou et al. 2021)



varnava.haris@gmail.com

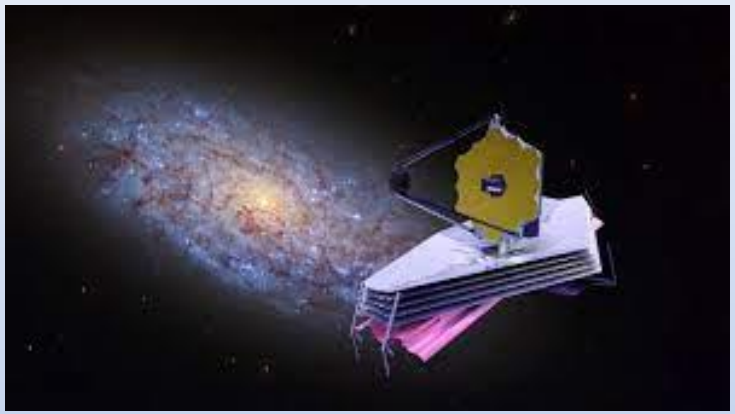
SMART: **S**pectral energy distributions **M**arkov chain **A**nalysis with **R**adiative **T**ransfer models

- Developed a new (Markov chain Monte Carlo (MCMC) SED fitting code, **SMART**, which fits SEDs *exclusively* with radiative transfer models. Available at: **https://github.com/ch-var/SMART**
- Takes comparable time to popular SED fitting methods based on energy balance (e.g. CIGALE, Noll et al. 2009; Boquien et al. 2019)
- Can be used to fit the SED of a galaxy at any redshift
- Promises to be very useful for analysing multi-wavelength SEDs of galaxies and obscured active galactic nucleus (AGN) from a number of ground-based and spaceborn facilities, such as:



SPITZER
(IR)

HERSCHEL
(FIR to submillimetre)



JWST
(optical to MIR)

Novel Features of SMART

1. More physically motivated and versatile compared to popular energy balance methods, such as CIGALE (Noll et al. 2009; Boquien et al. 2019) and MAGPHYS (da Cunha et al. 2008), that do not take properly into account the effects of dust in a realistic geometry

2. The code is parallelized and considerably faster than other MCMC codes, such as SATMC

3. Makes use of four different types of pre-computed AGN torus libraries, as in Efstathiou et al. (2022)

4. As in Efstathiou et al. (2022), can optionally add a component of polar dust in the fitting

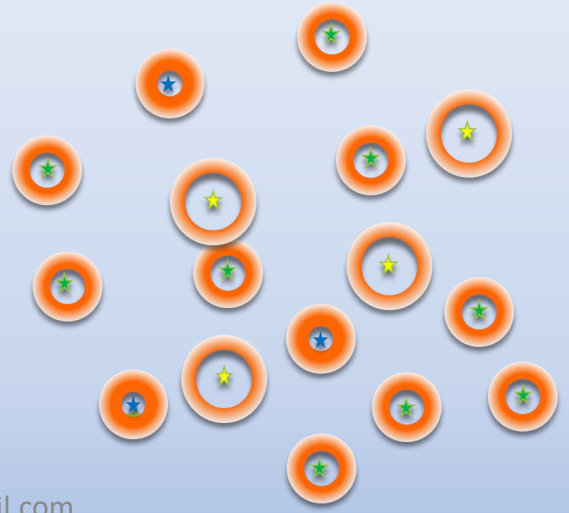
5. Designed to fit an SED in comparable time with a spheroidal or disc host galaxy model

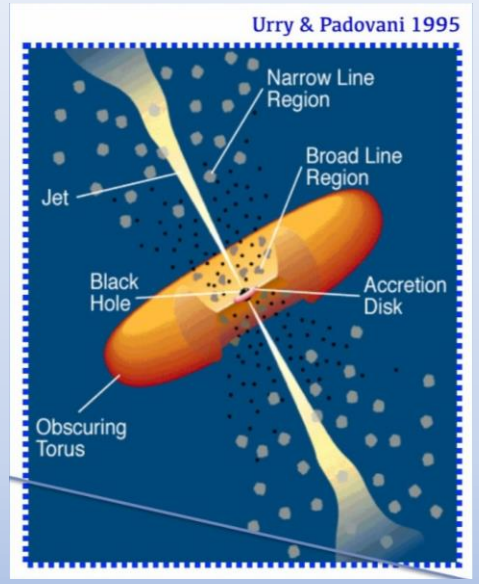
6. Can fit part of a galaxy and, if necessary, switch off any of the four components (AGN torus, starburst, spheroidal/disc, polar dust)

7. Can fix any of the model parameters

Description of SMART

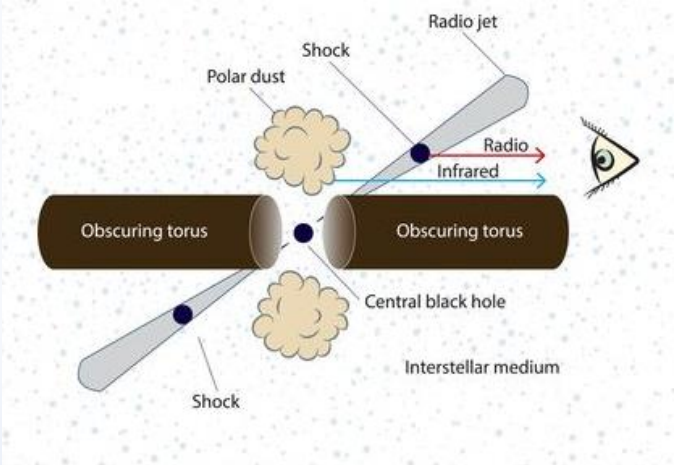
- Developed a new method for fitting radiative transfer models to data, using an MCMC code
- As an MCMC sampler it utilizes the publicly available *emcee* code (Foreman-Mackey et al. 2013)
- Fits the ultraviolet to submillimetre SEDs *exclusively* with radiative transfer models that currently constitute four types of pre-computed libraries:
  - Starburst (Efstathiou et al. 2000, Efstathiou & Siebenmorgen 2009) – independent of redshift
  - AGN torus – independent of redshift



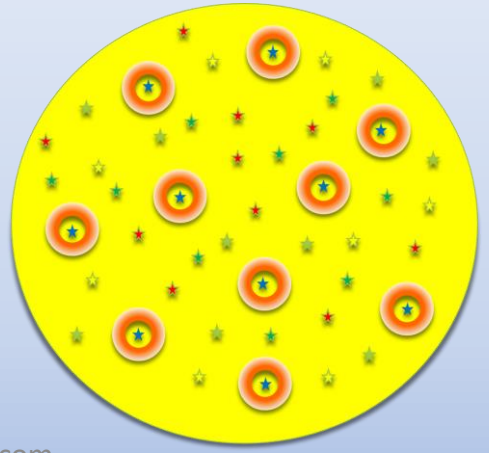


Description of SMART

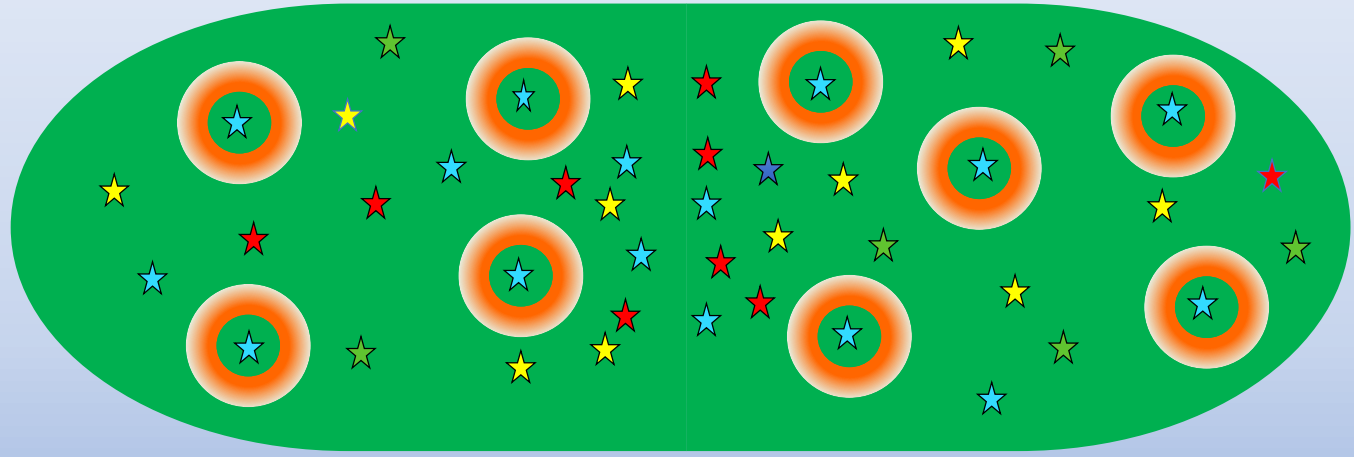
- AGN polar dust (Efstathiou et al. 1995)
  - – independent of redshift
  - – optionally incorporated in **SMART**



- Spheroidal (Efstathiou et al. 2021)
  - – dependent on redshift



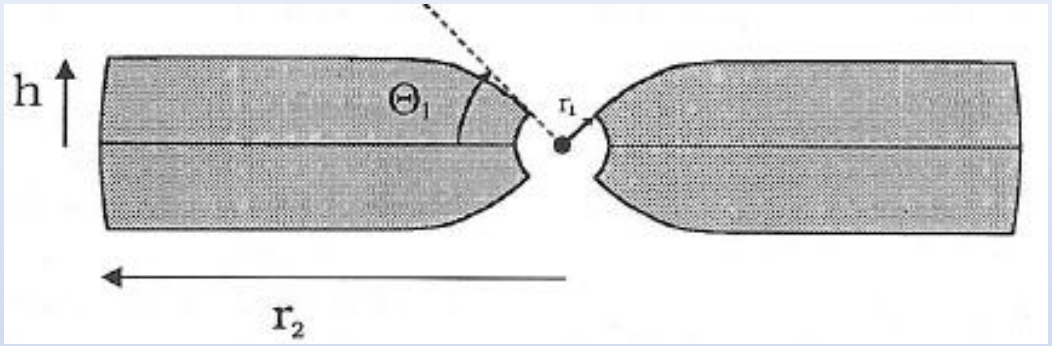
- Disc (Efstathiou et al., in preparation)
  - – dependent on redshift



Description of SMART

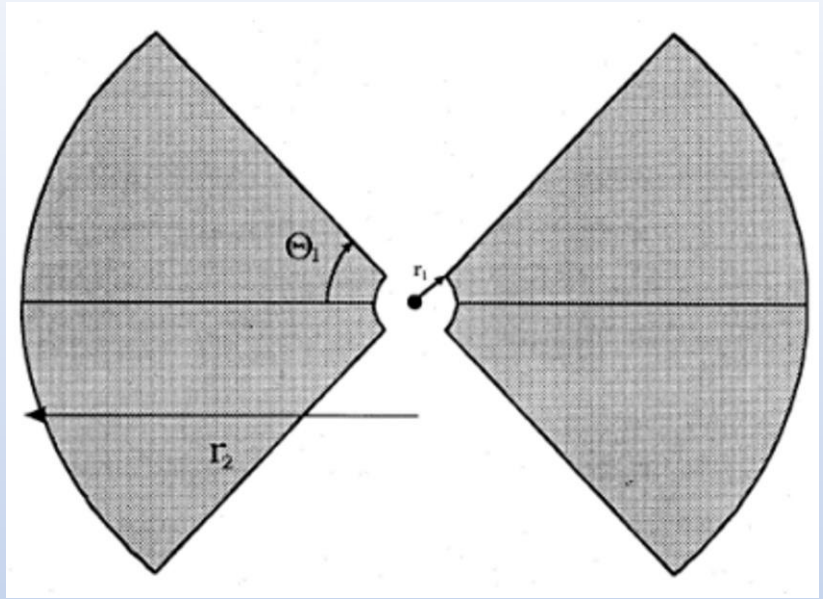
- Allows us to explore the impact of four different AGN torus models and therefore constrain the properties of the obscuring torus:

1. The CYprus models for Galaxies and their NUclear Spectra (CYGNUS) smooth AGN torus model (Efstathiou & Rowan-Robinson, 1995)



Tapered disc geometry

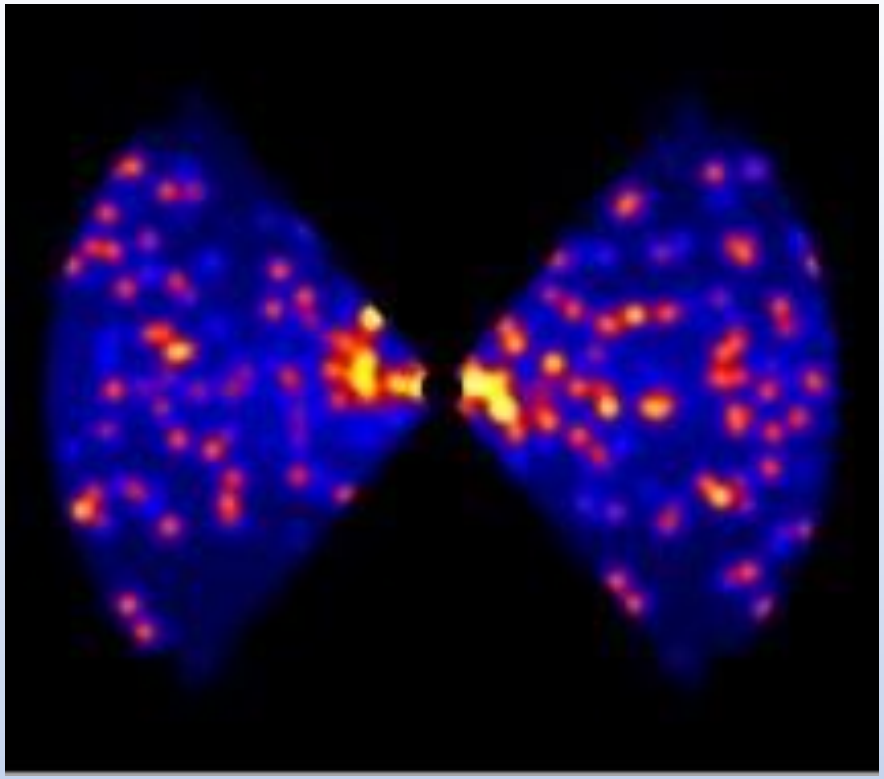
2. The smooth AGN torus model of Fritz et al. (2006)



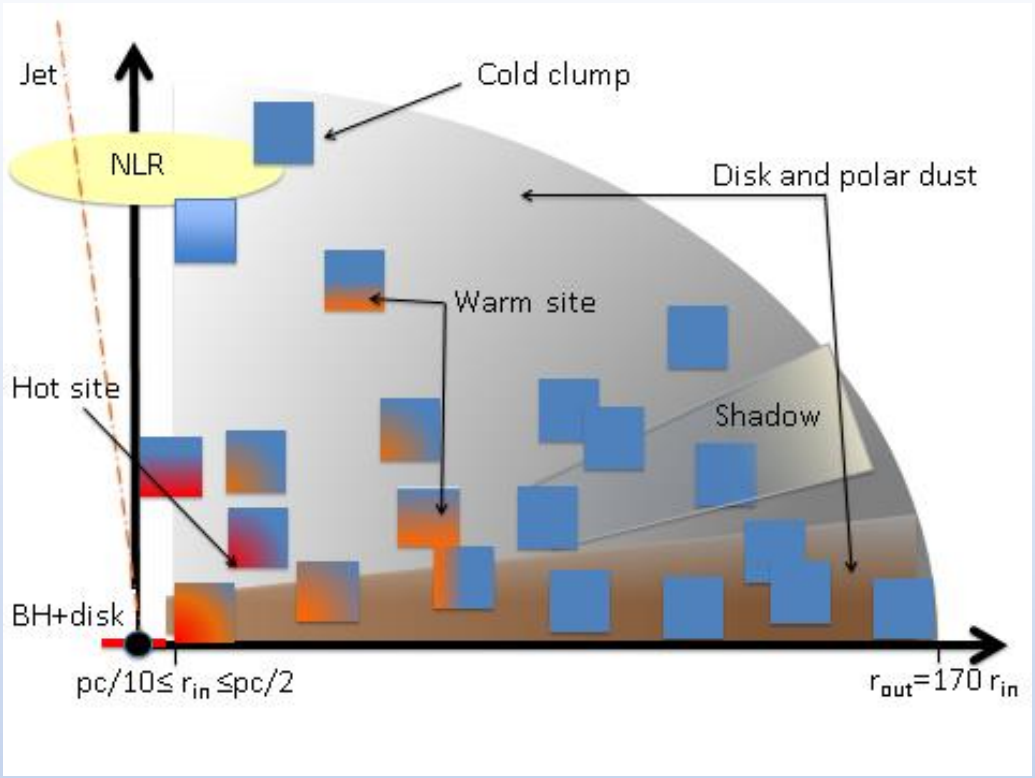
Flared disc geometry

Description of SMART

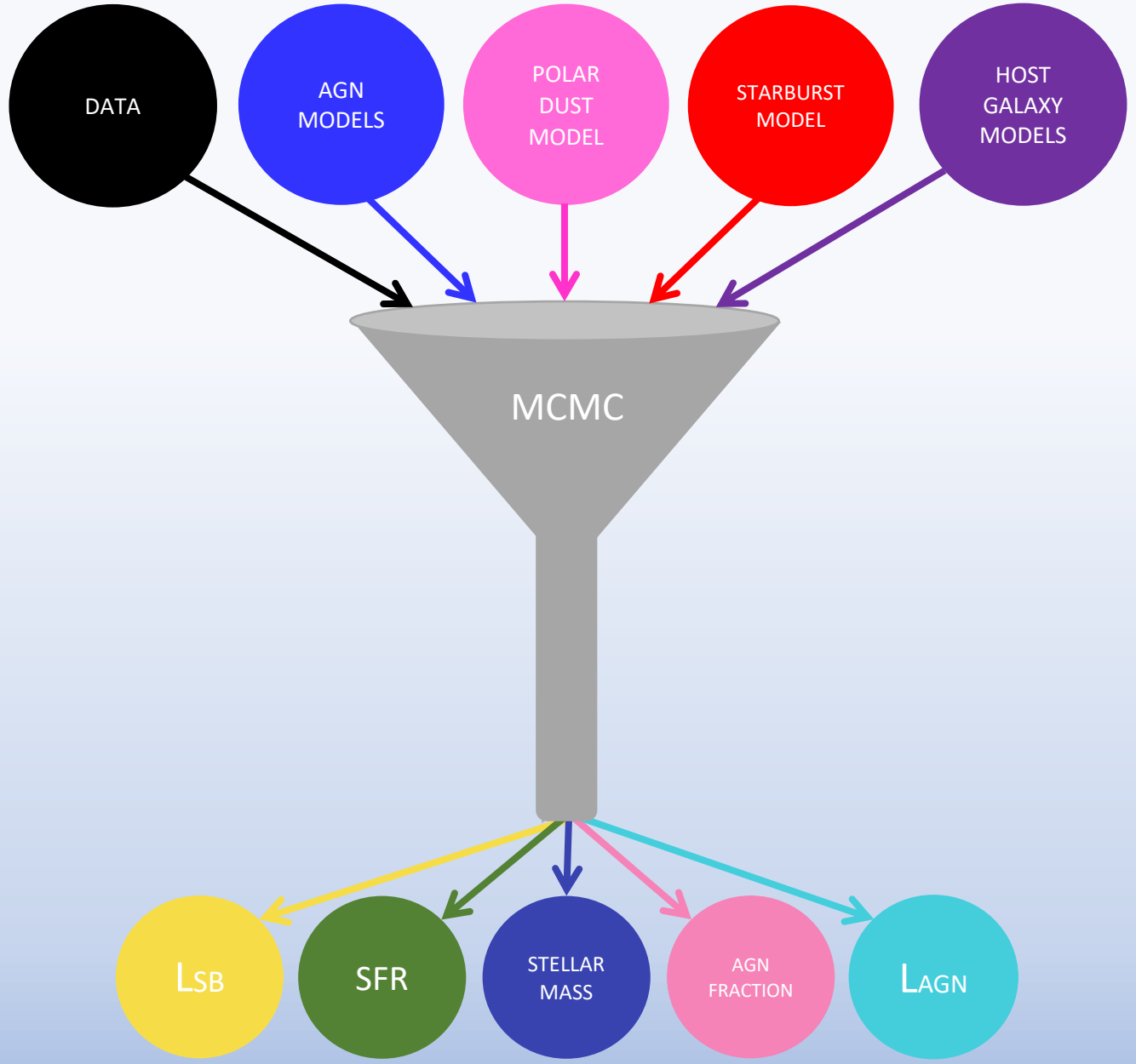
3. The two-phase AGN torus model SKIRTOR of Stalevski et al. (2016)



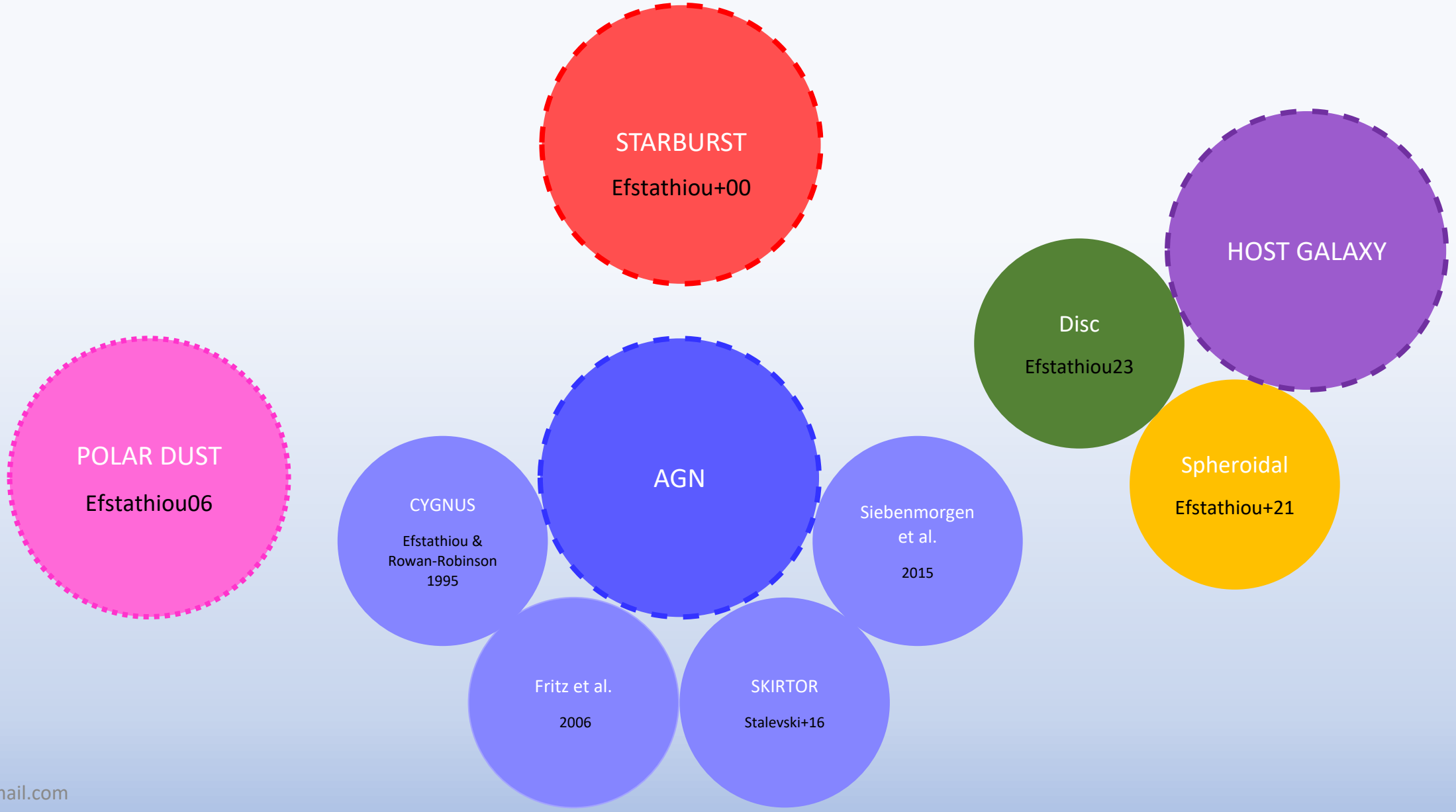
4. The two-phase AGN torus model of Siebenmorgen et al. (2015)



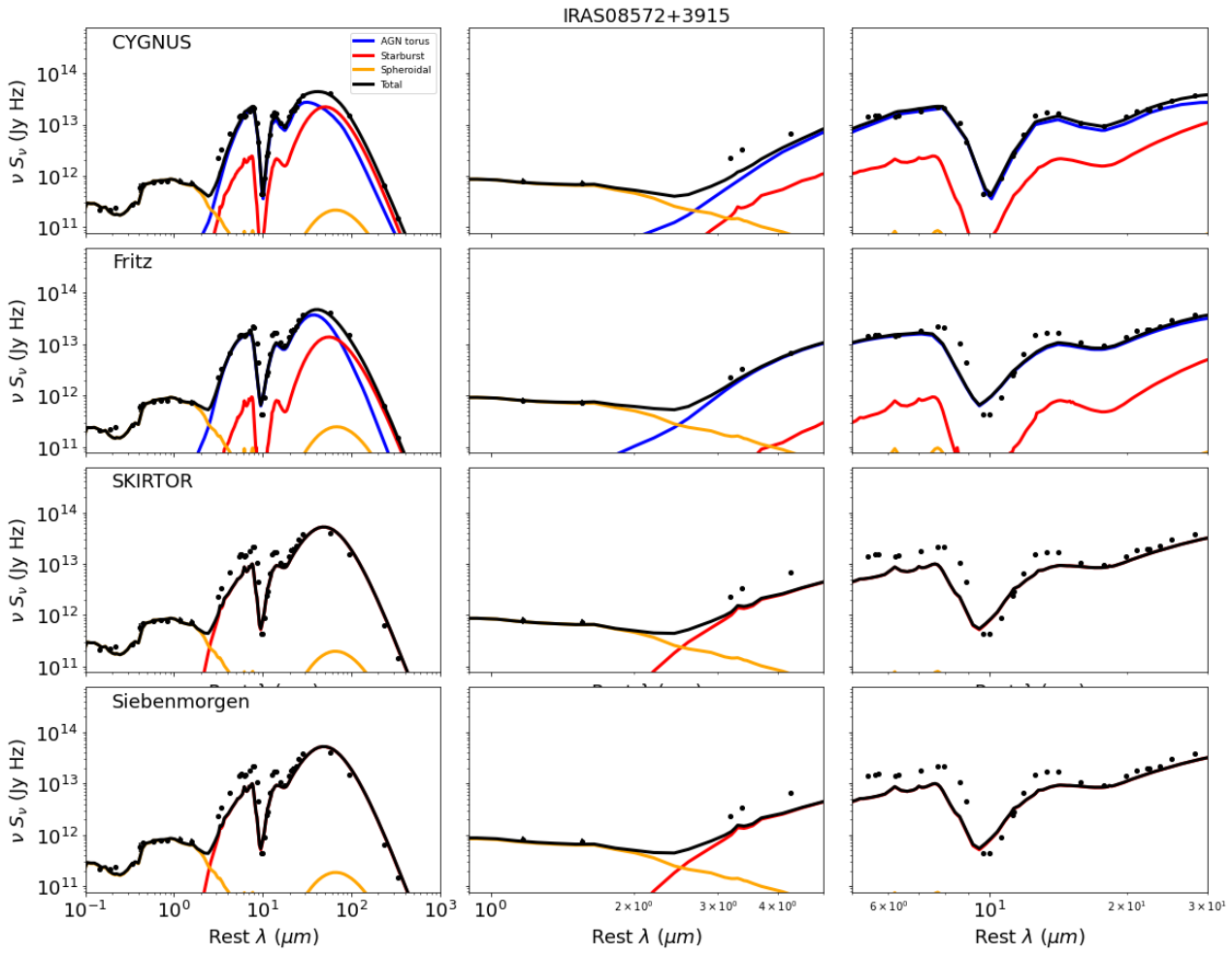
The SMART Method



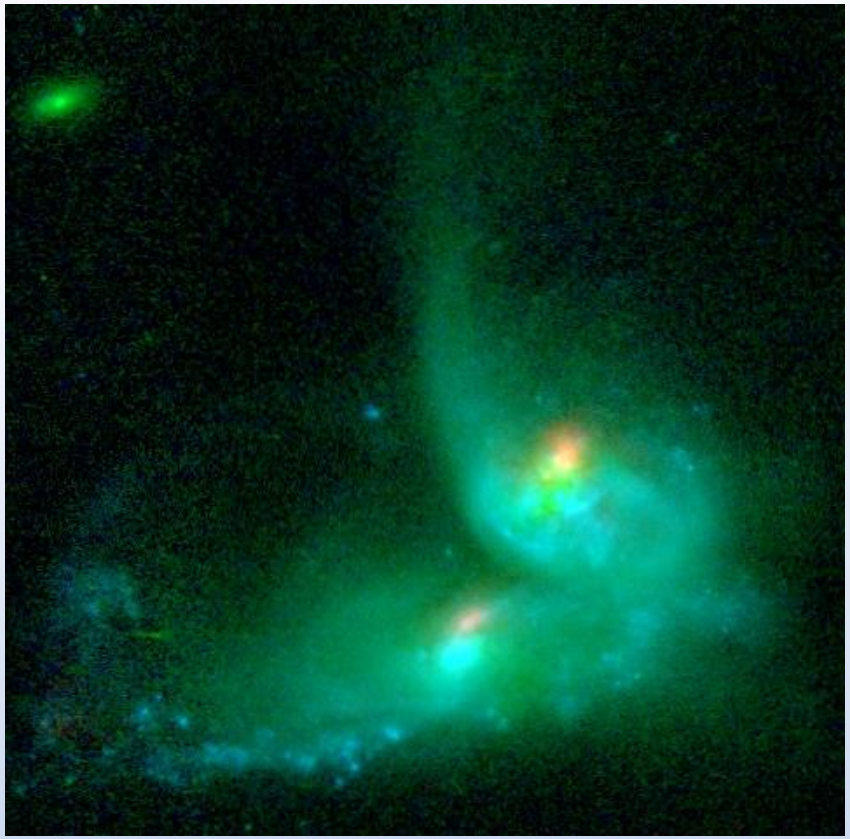
Models used by SMART



Comparison SED fit plots of the deeply obscured ultraluminous infrared galaxy (ULIRG) IRAS 08572+3915 (Efstathiou et al. 2014)

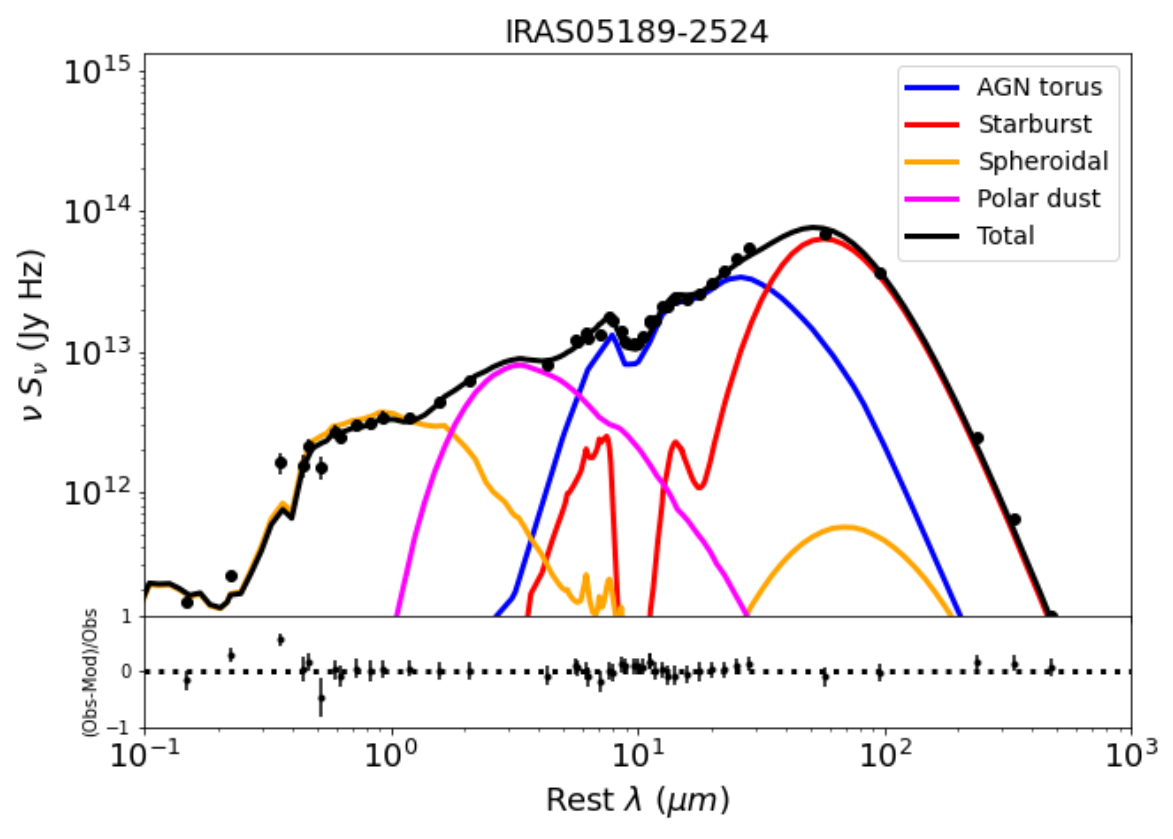


Comparison SED fit plots of IRAS 08572+3915: AGN torus (blue), starburst (red), spheroidal host (orange), total (black)

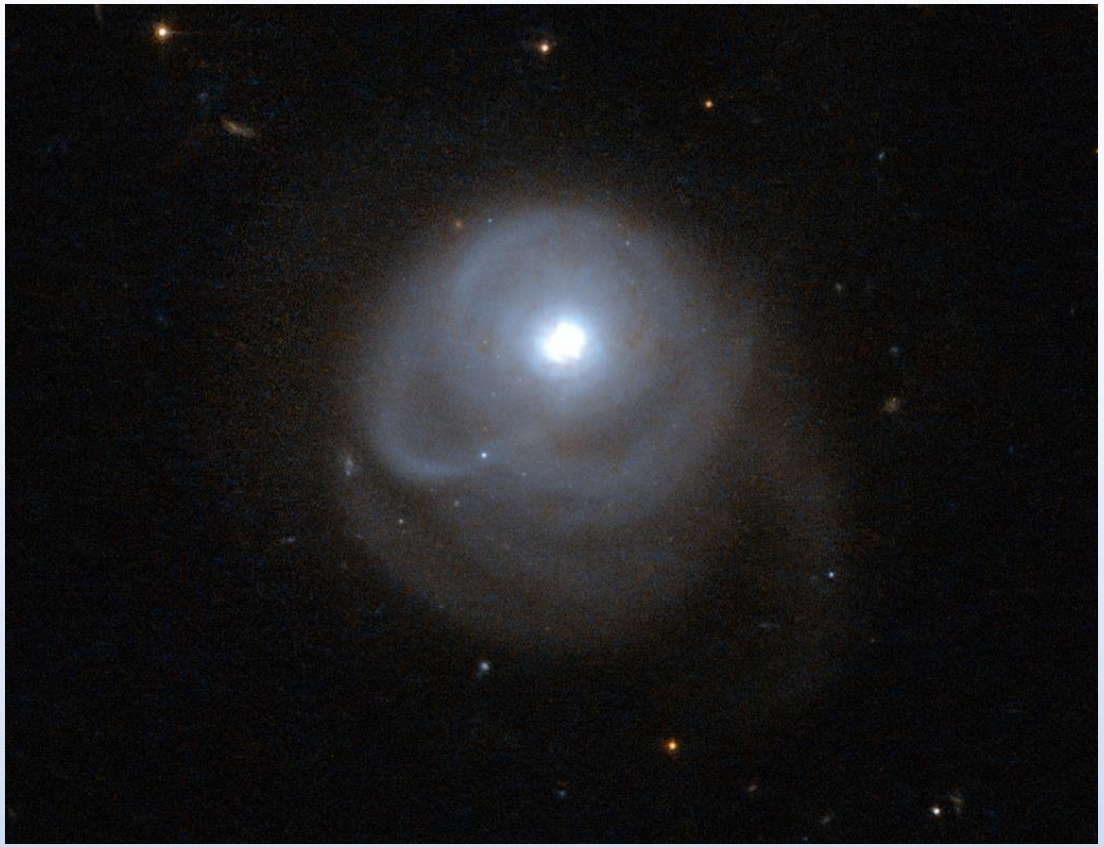


Optical Hubble Space Telescope image of IRAS 08572+3915

SED fit plot of a ULIRG associated with polar dust, IRAS 05189-2524

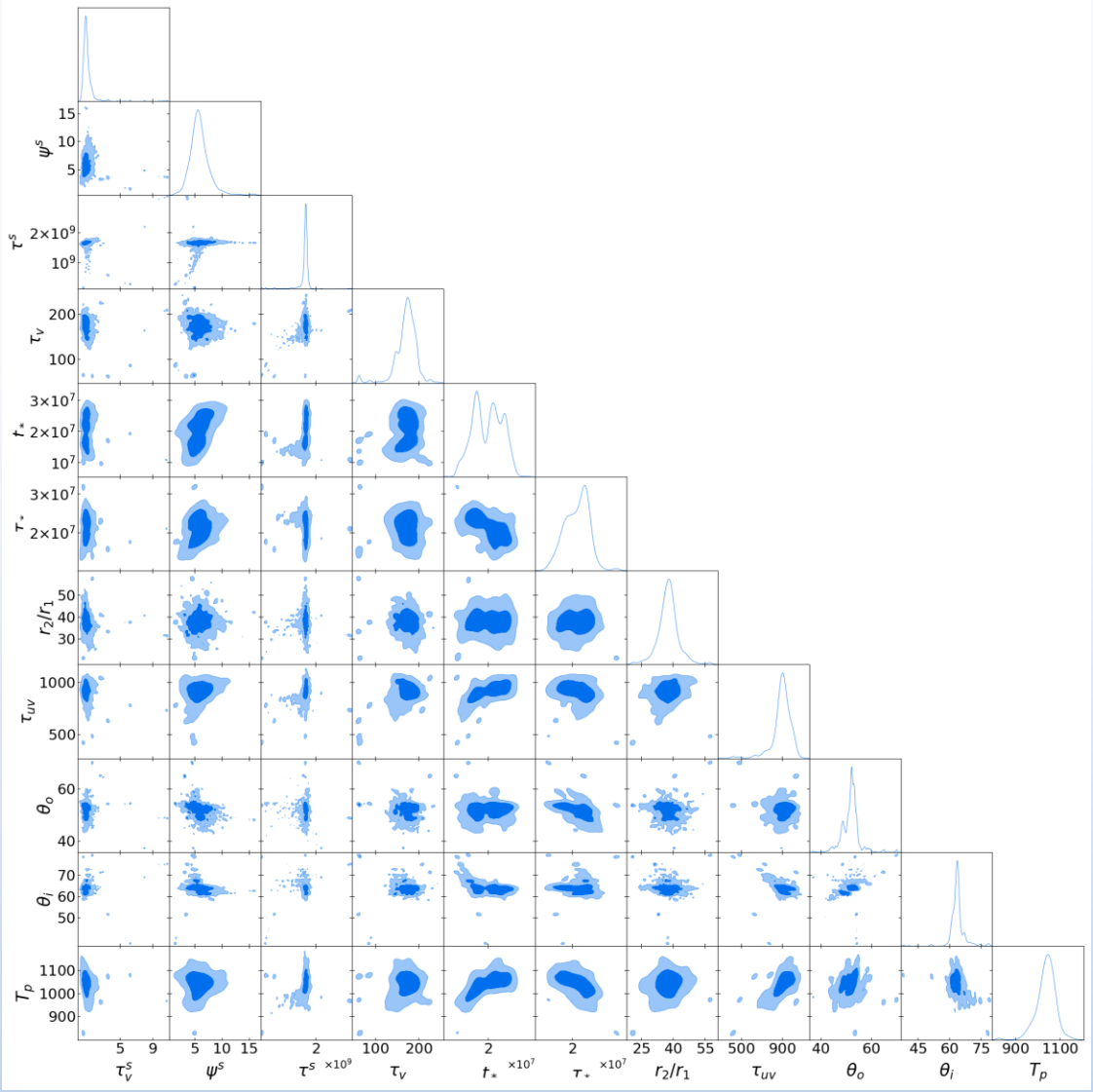


SED fit plot of IRAS 05189-2524: AGN torus (blue), starburst (red), spheroidal host (orange), polar dust (magenta), total (black)



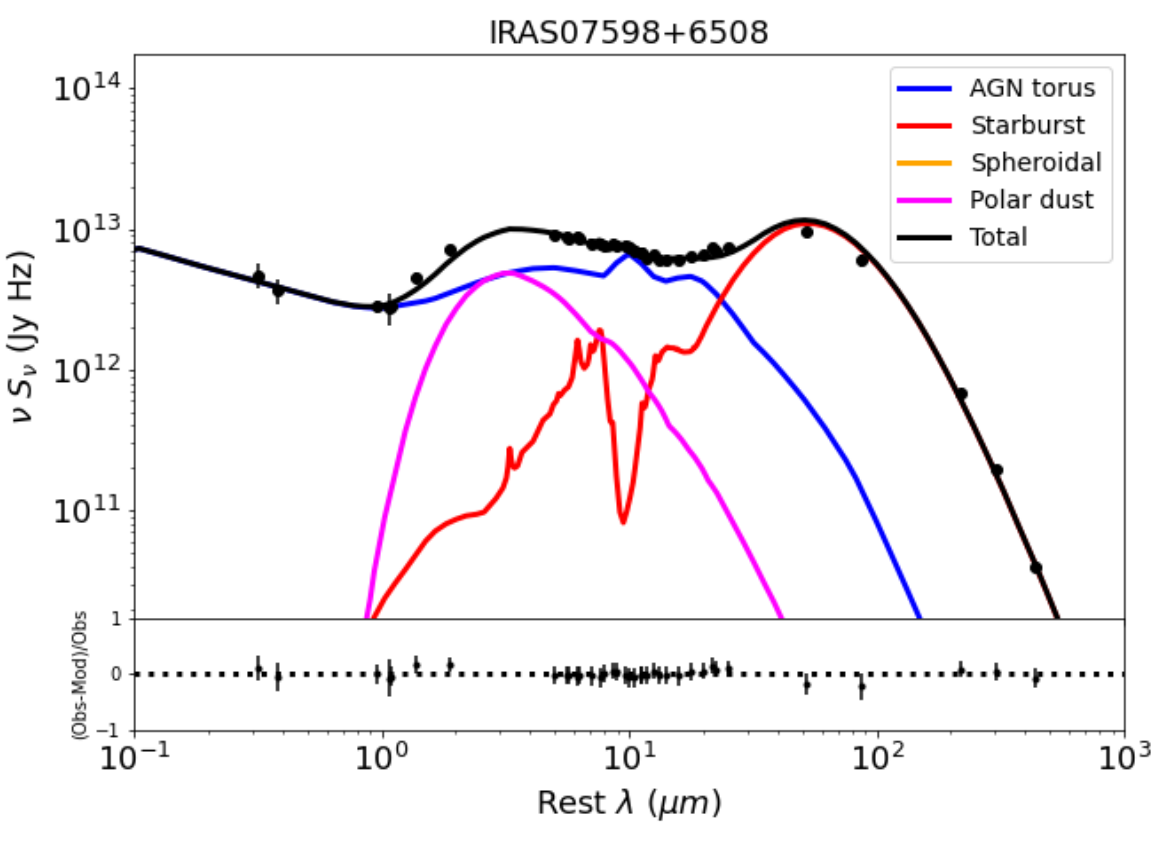
Optical Hubble Space Telescope image of IRAS 05189-2524

Corner plot of the galaxy IRAS 05189-2524

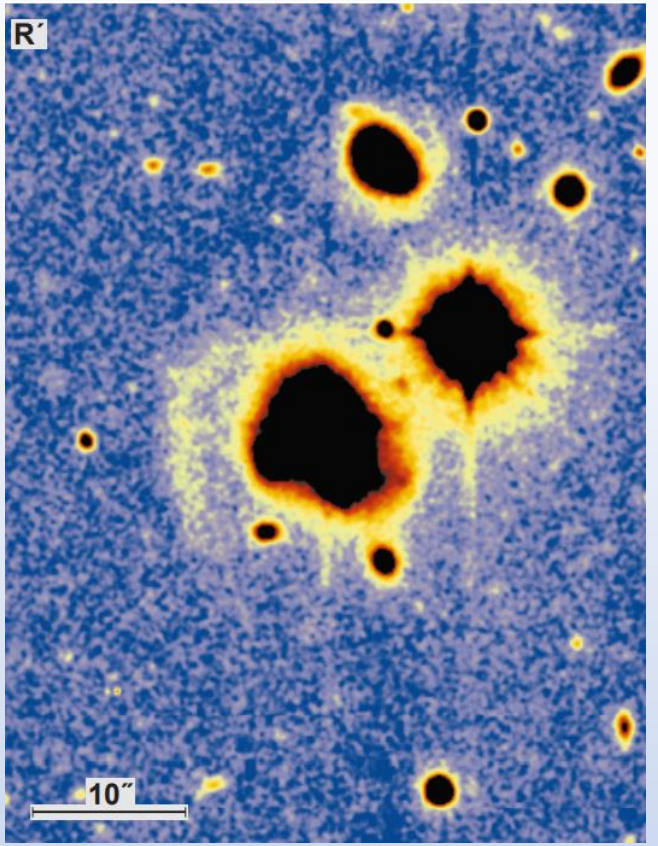


Corner plot of IRAS 05189-2524

SED fit plot of a ULIRG with an unobscured quasar and also associated with polar dust, IRAS 07598+6508

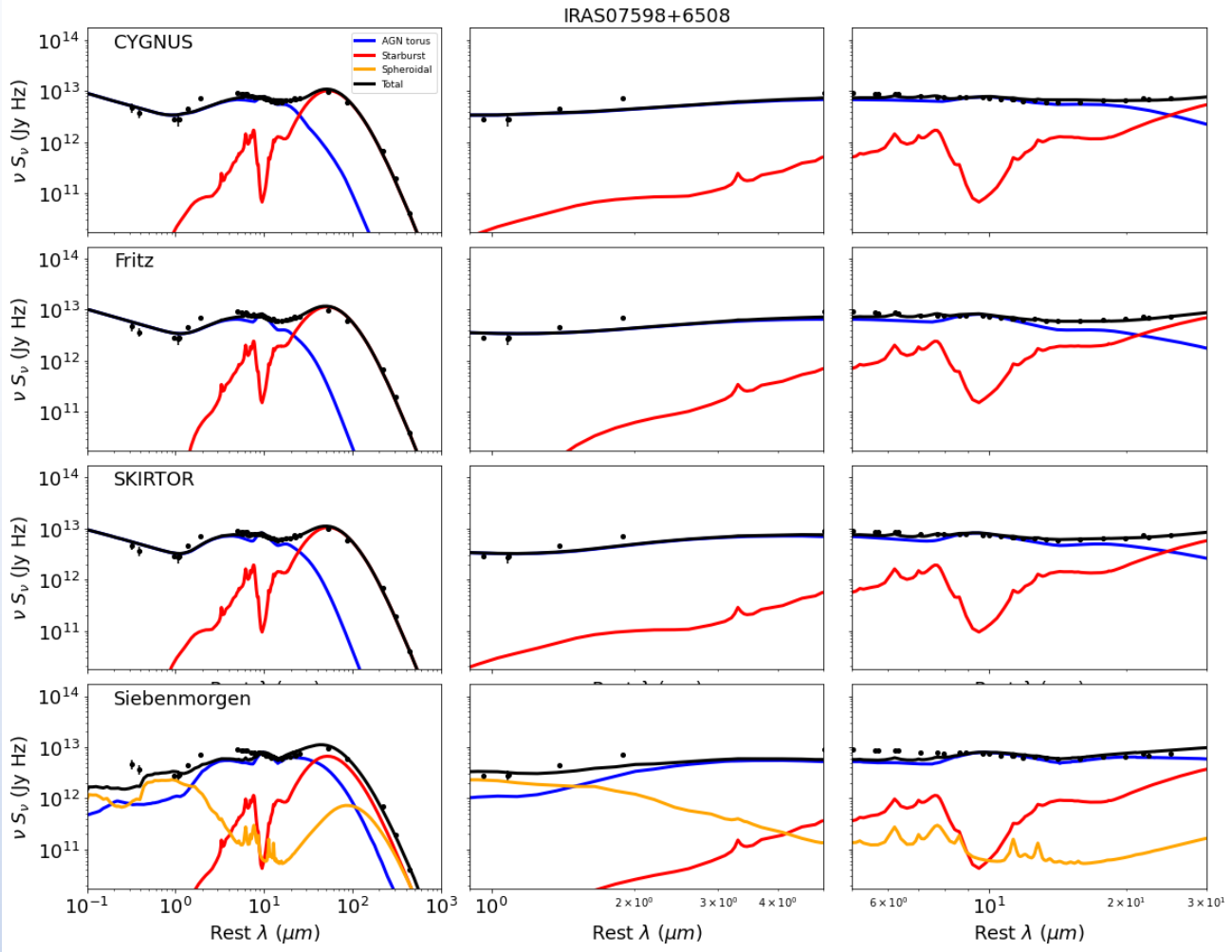


SED fit plot of IRAS 07598+6508: AGN torus (blue), starburst (red), spheroidal host (orange), polar dust (magenta), total (black)



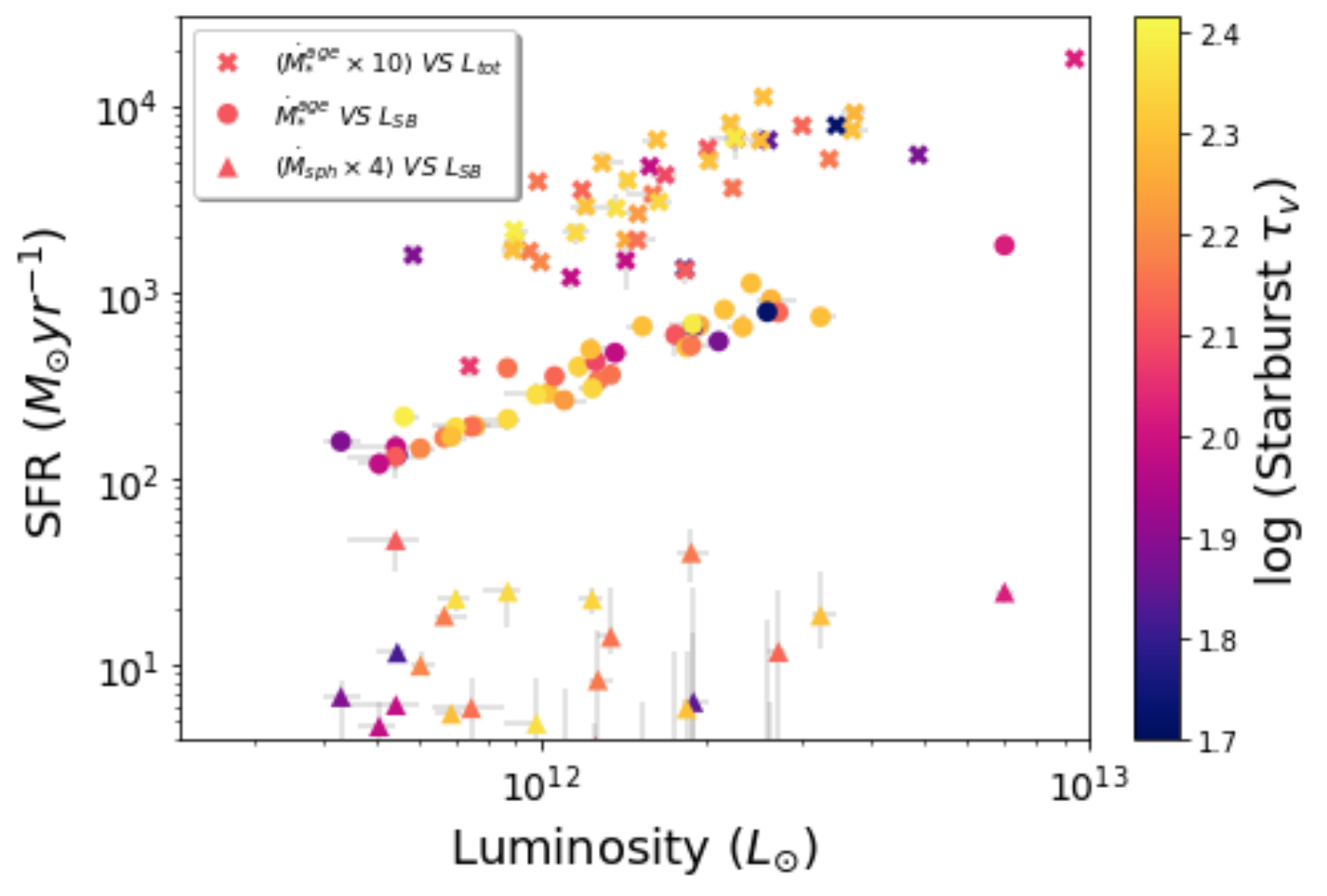
R' image of IRAS 07598+6508 (Canalizo & Stockton 2000)

Comparison SED fit plots of the galaxy IRAS 07598+6508 without using the polar dust component



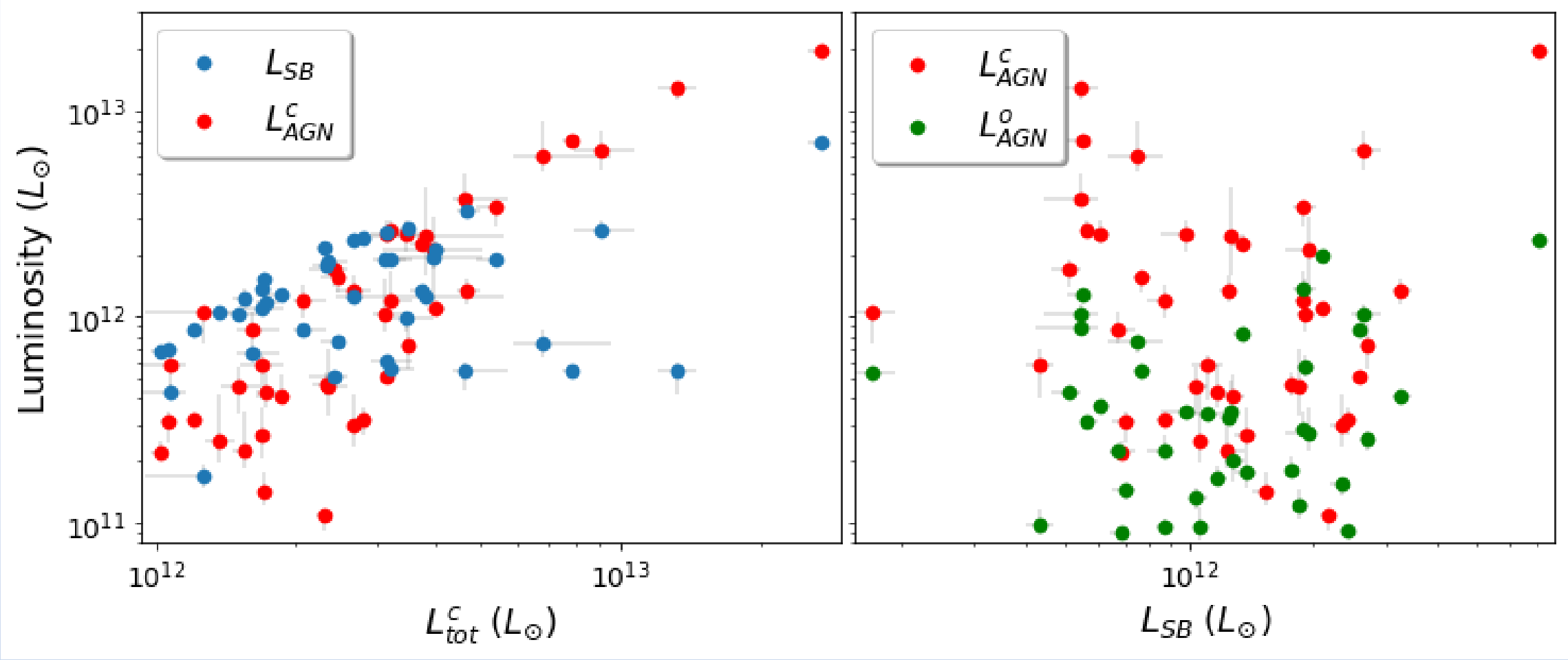
Comparison SED fit plots of IRAS 07598+6508 without using the polar dust component: AGN torus (blue), starburst (red), spheroidal host (orange), total (black)

Examples of selected extracted physical quantities for the HERschel Ultraluminous Infrared Galaxy Survey (HERUS) sample, using the CYGNUS combination of models



Star formation rate (SFR) against infrared (IR) luminosities (starburst or total)

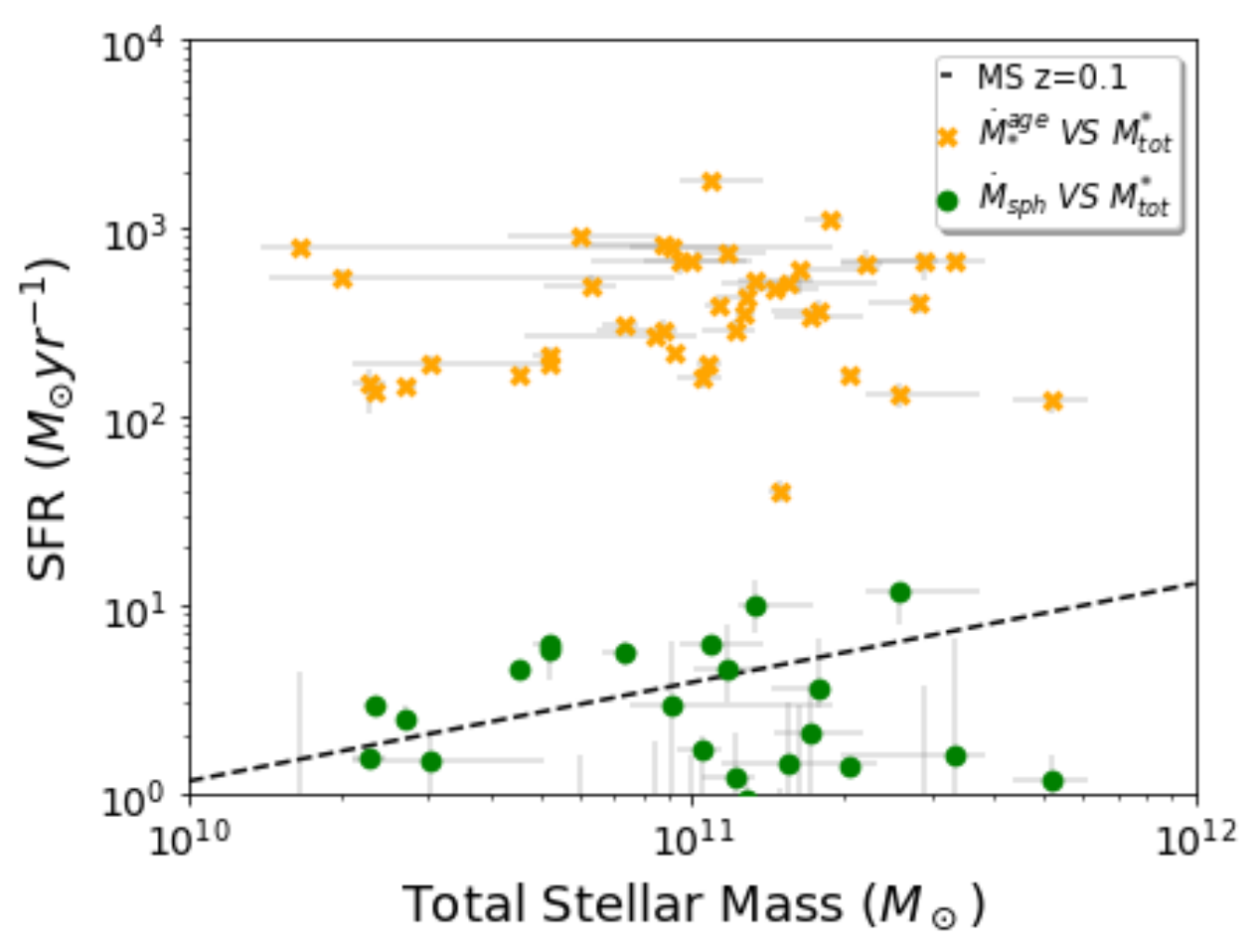
Examples of selected extracted physical quantities for the HERUS sample, using the CYGNUS combination of models



Left: Starburst and anisotropy-corrected AGN luminosity against total corrected IR luminosity

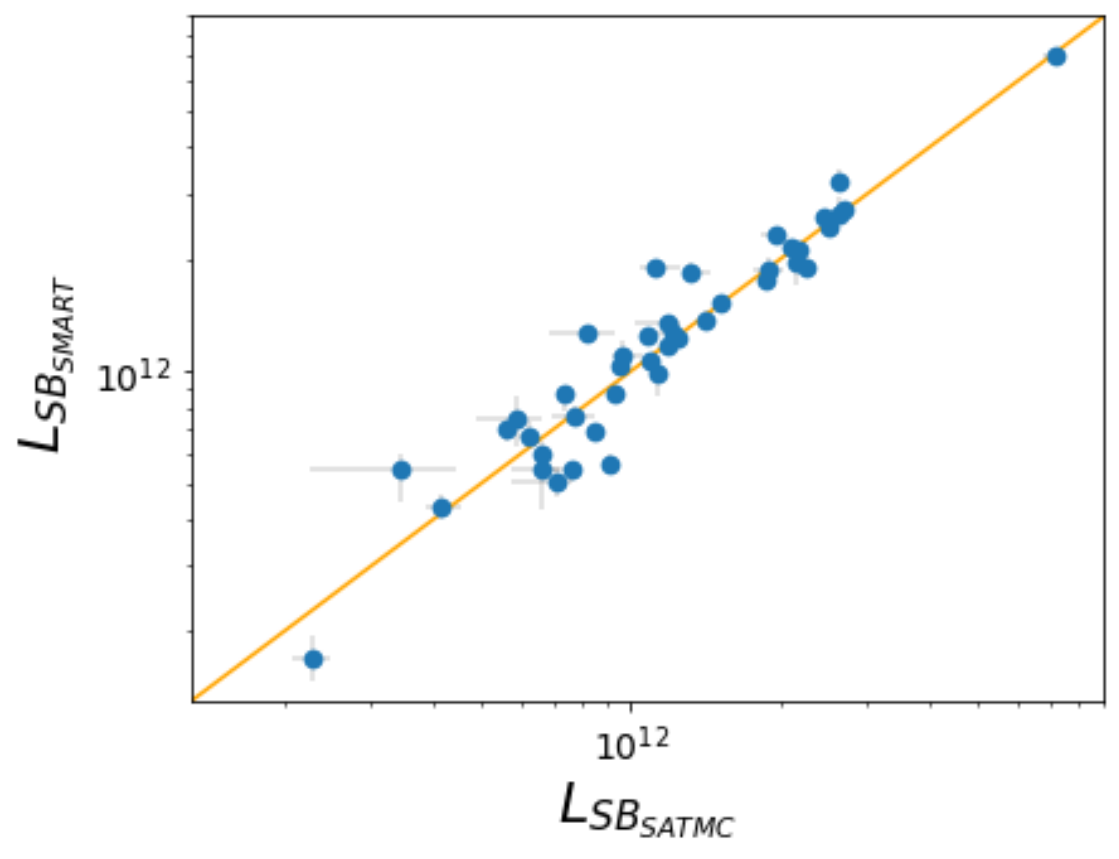
Right: Observed and anisotropy-corrected AGN luminosity against starburst luminosity

Examples of selected extracted physical quantities for the HERUS sample, using the CYGNUS combination of models

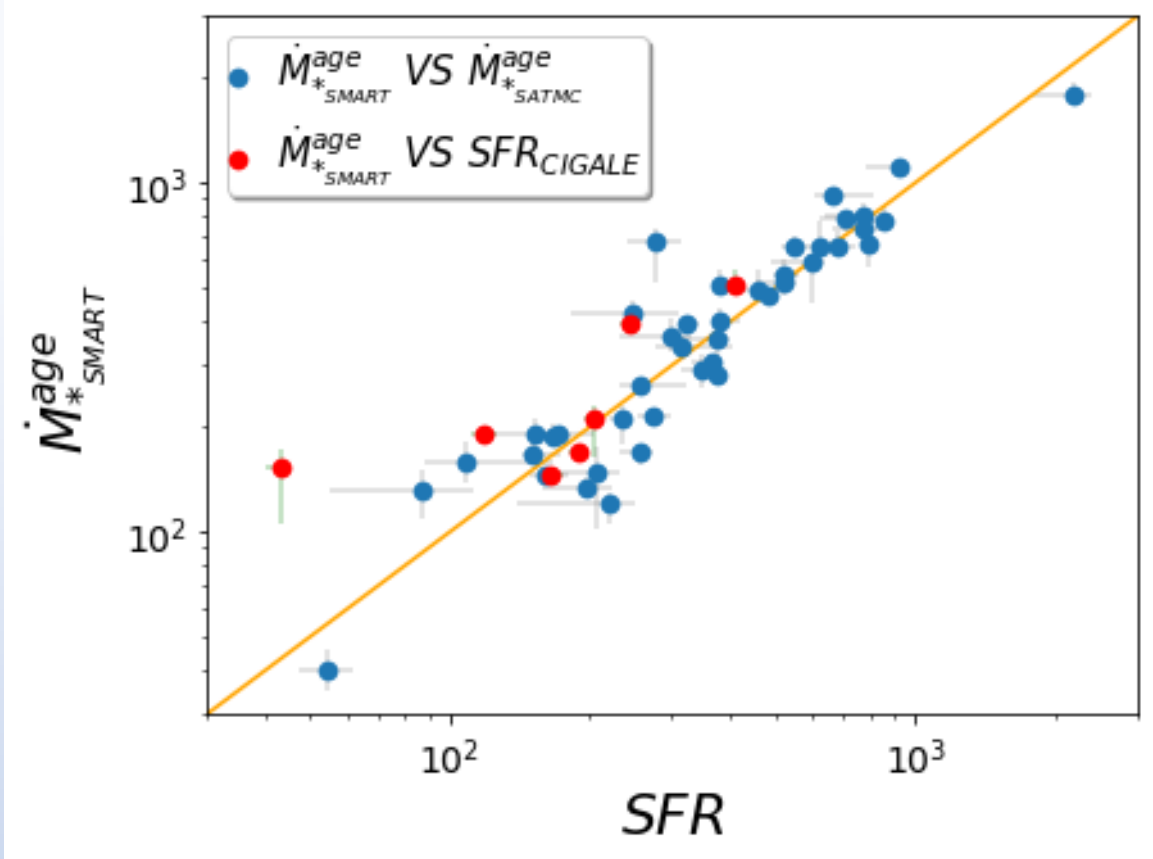


Starburst or host SFR against total stellar mass

Comparison with results from other approaches for the HERUS sample

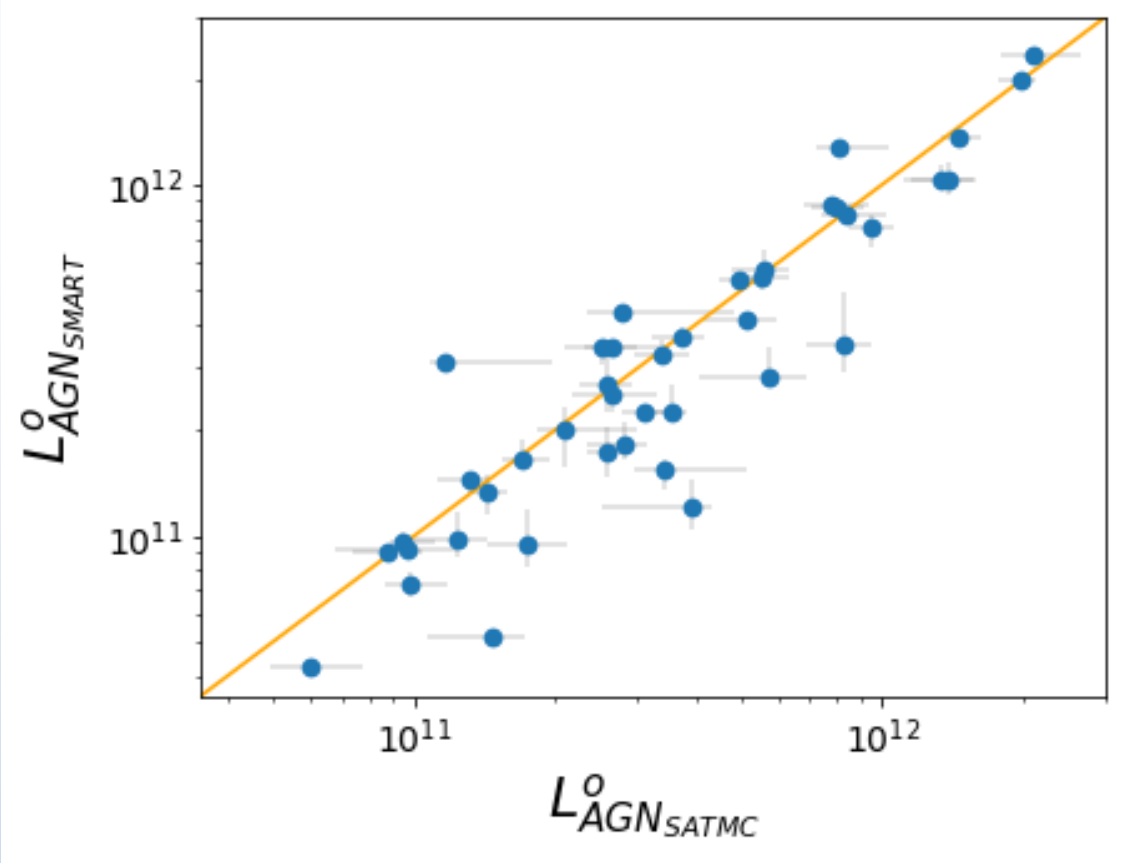


Plot of the starburst luminosity extracted by SMART against the same quantity extracted by SATMC

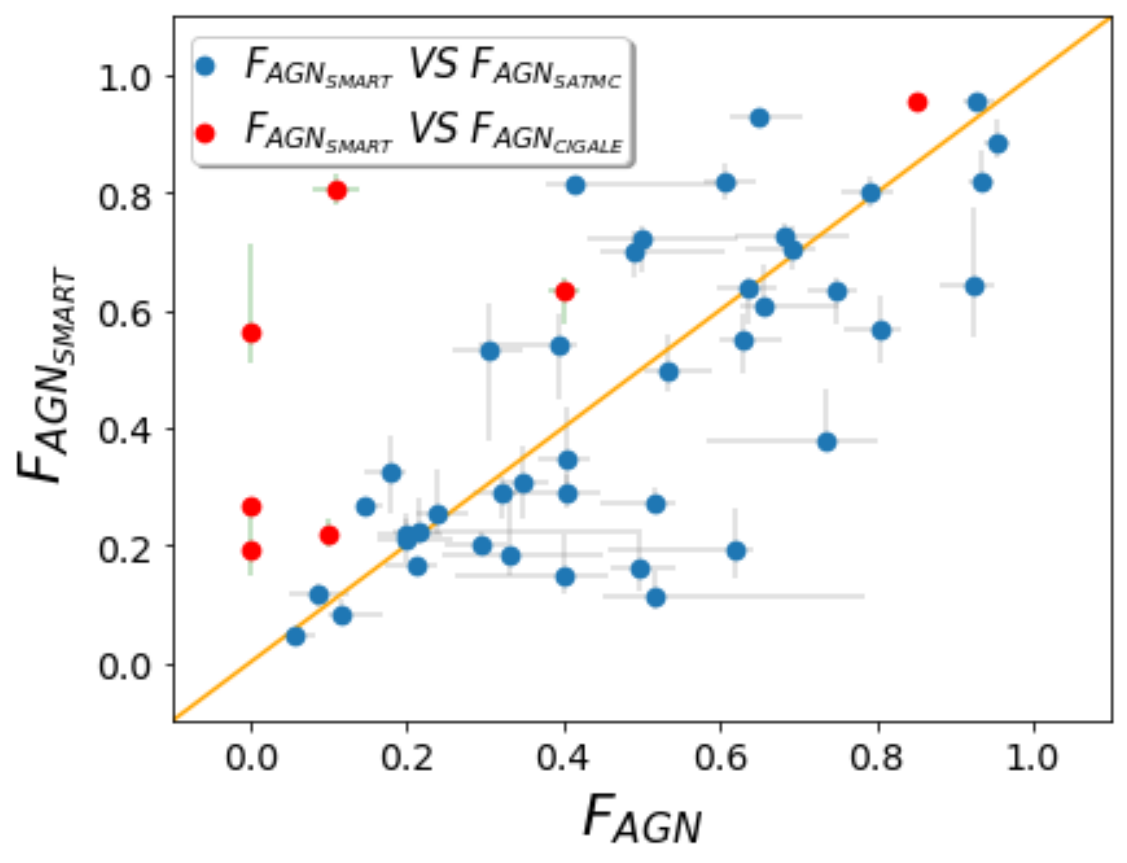


Plot of the starburst SFR extracted by SMART against the same quantity extracted by SATMC and CIGALE

Comparison with results from other approaches for the HERUS sample

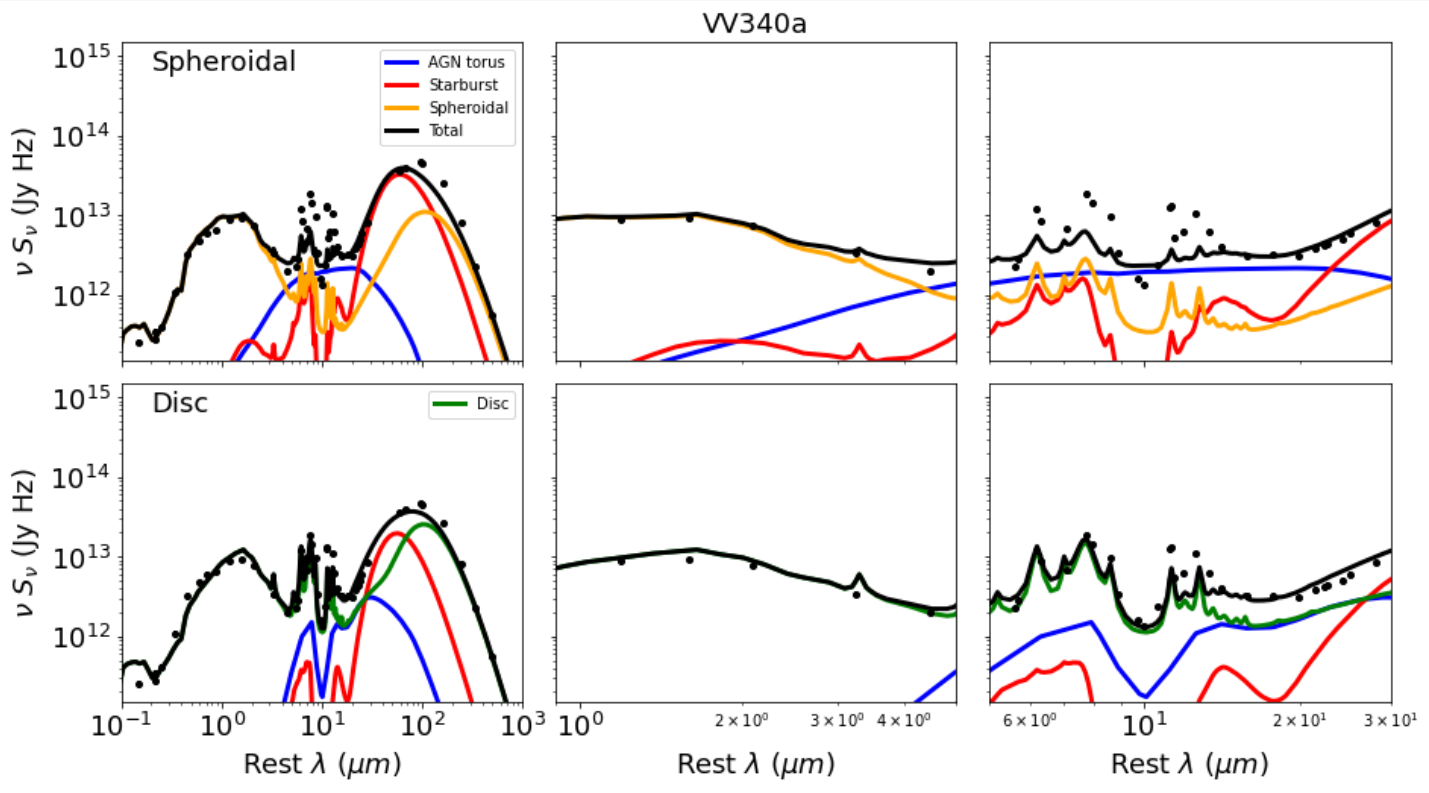


Plot of the observed AGN torus luminosity extracted by SMART against the same quantity extracted by SATMC

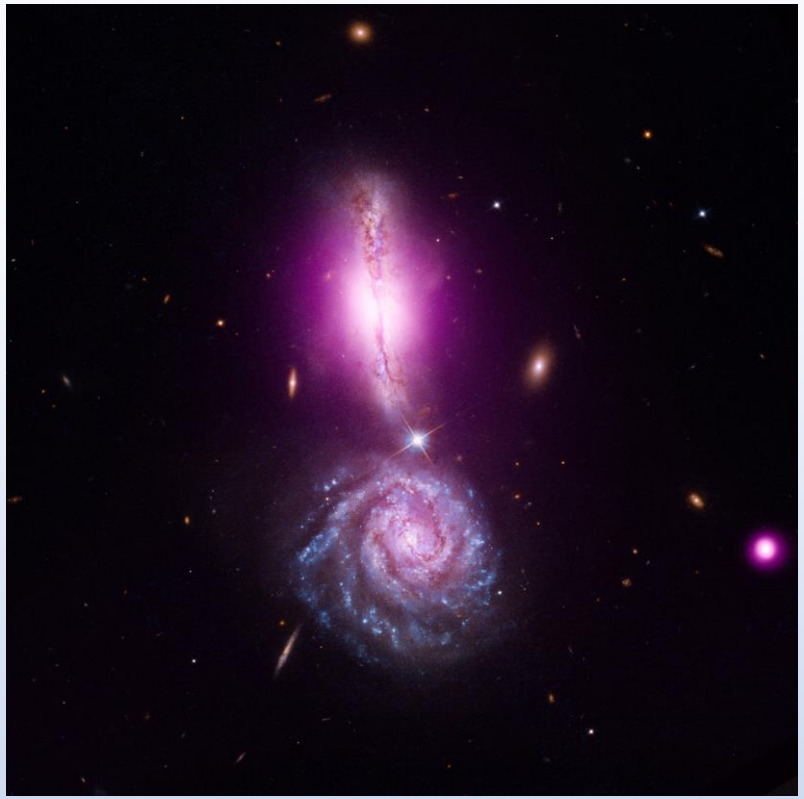


Plot of the AGN fraction extracted by SMART against the same quantity extracted by SATMC and CIGALE

Comparison of the two different host galaxy models used by SMART for a luminous infrared galaxy associated with a spiral galaxy

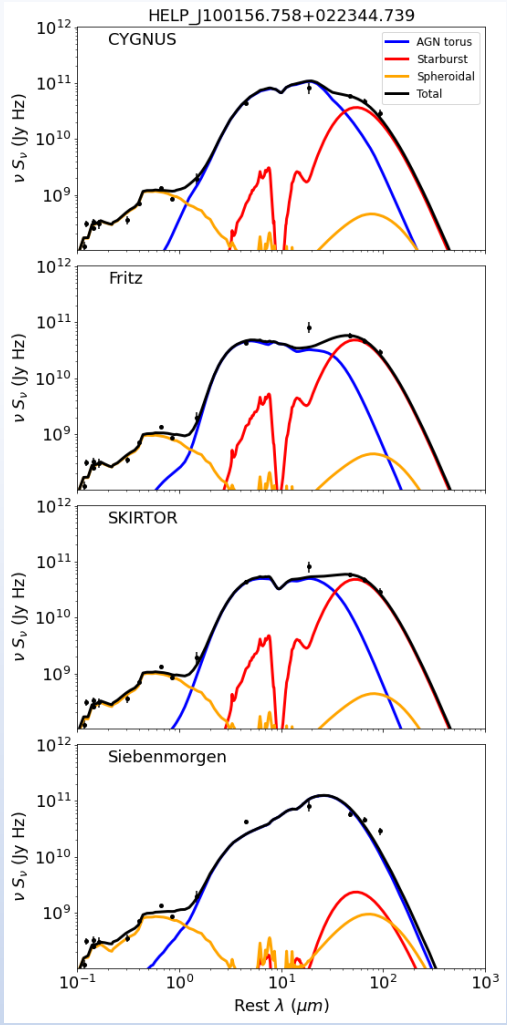


*Comparison SED fit plots of the galaxy VV 340a that **SMART** predicts it has a spiral morphology: AGN torus (blue), starburst (red), spheroidal host (orange), disc host (green), total (black)*

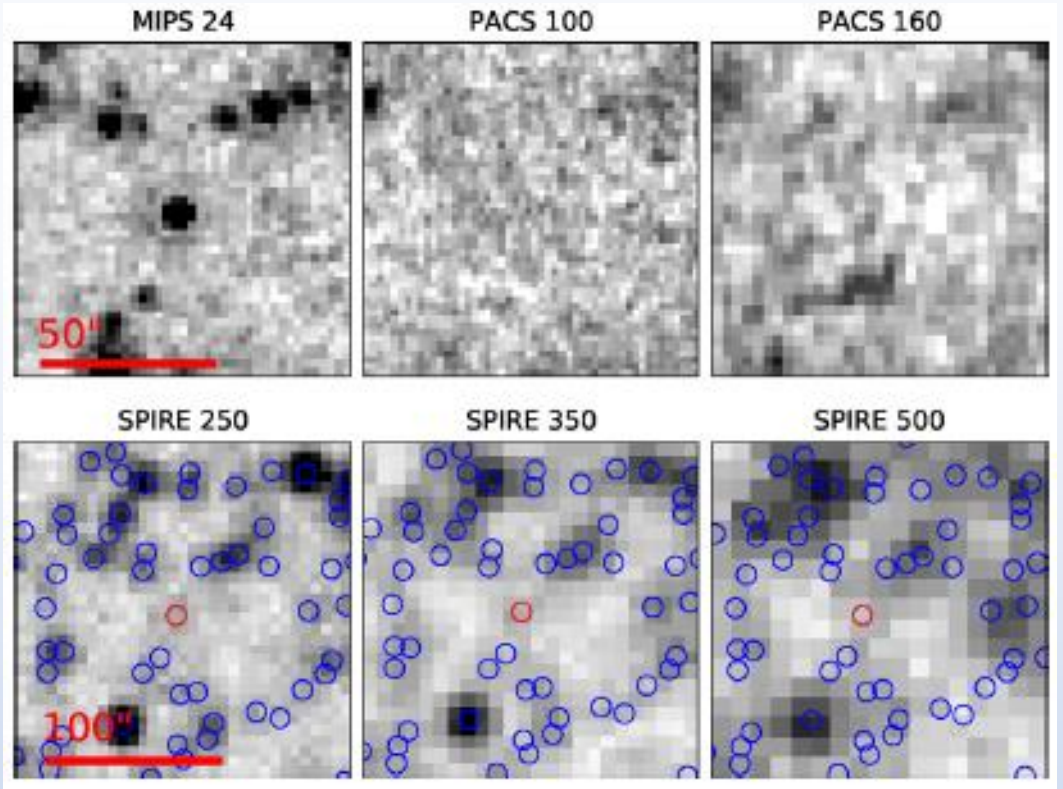


Composite image of X-ray data from Chandra (purple) and optical data from Hubble Space Telescope (red, green, blue) of VV 340

Comparison SED fit plots of the hyperluminous obscured quasar HELP_J100156.75+022344.7 at z~4.3 (Efstathiou et al. 2021)



Comparison SED fit plots of HELP_J100156.75+022344.7: AGN torus (blue), starburst (red), spheroidal host (orange), total (black)



Postage stamps in various filters (Efstathiou et al. 2021)

Conclusions

- Developed a new fast MCMC SED fitting code, which uses *exclusively* radiative transfer models
- Takes comparable time to energy balance codes like CIGALE and MAGPHYS
- Tested with a range of obscured AGN in the redshift range ~0-7
- As **SMART** can fit with four different AGN torus models, it allows us to constrain the properties of the obscuring torus in AGN and quantify the uncertainties in AGN fraction and SFR
- Promises to be very useful for understanding galaxies and AGN at any redshift in the *JWST* era, as well as galaxy formation and evolution in general

List of Publications

- Varnava C. & Efstathiou A., 2024. SMART: Spectral energy distributions Markov chain Analysis with Radiative Transfer models, MNRAS, stae1141

- Varnava C. & Efstathiou A., 2024. Exploring the properties of the obscured quasar COS-87259 at z=6.853, MNRAS: Letters, in preparation

- Varnava C. & Efstathiou A., 2024. SED fitting of ultraluminous infrared galaxies with SMART: Constraints on their star formation rate and active galactic nucleus fraction from a broad range of dusty torus models, MNRAS, in preparation

- Efstathiou A., Lonsdale C. J. and Varnava C., 2024. Constraints on the starburst and active galactic nucleus activity of heavily obscured quasars at redshifts z~0.3–3. MNRAS, in preparation

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ch-var / SMART

SMART

can be found at:

https://doi.org/10.1093/mnras/stae1141

The code is available at:

https://github.com/ch-var/SMART

Thank you!

Charalambia Varnava
varnava.haris@gmail.com