Accelerating SED fitting
With Radiative Transfer Models

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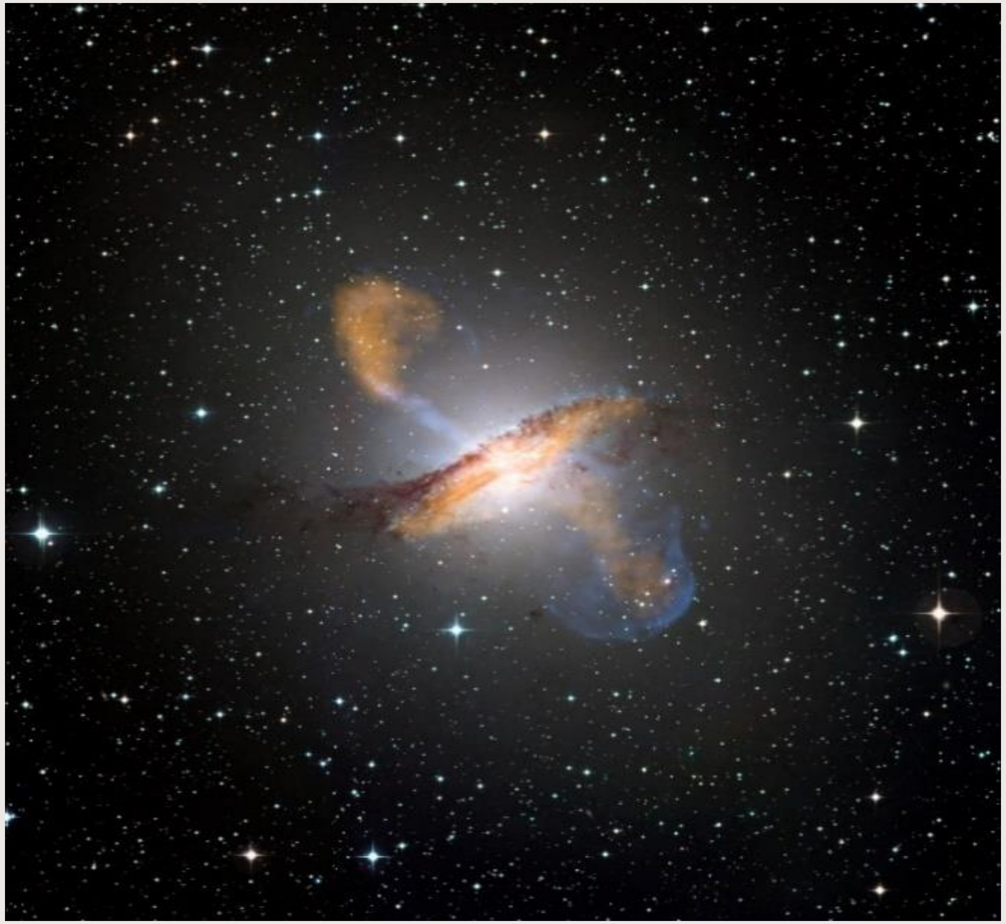
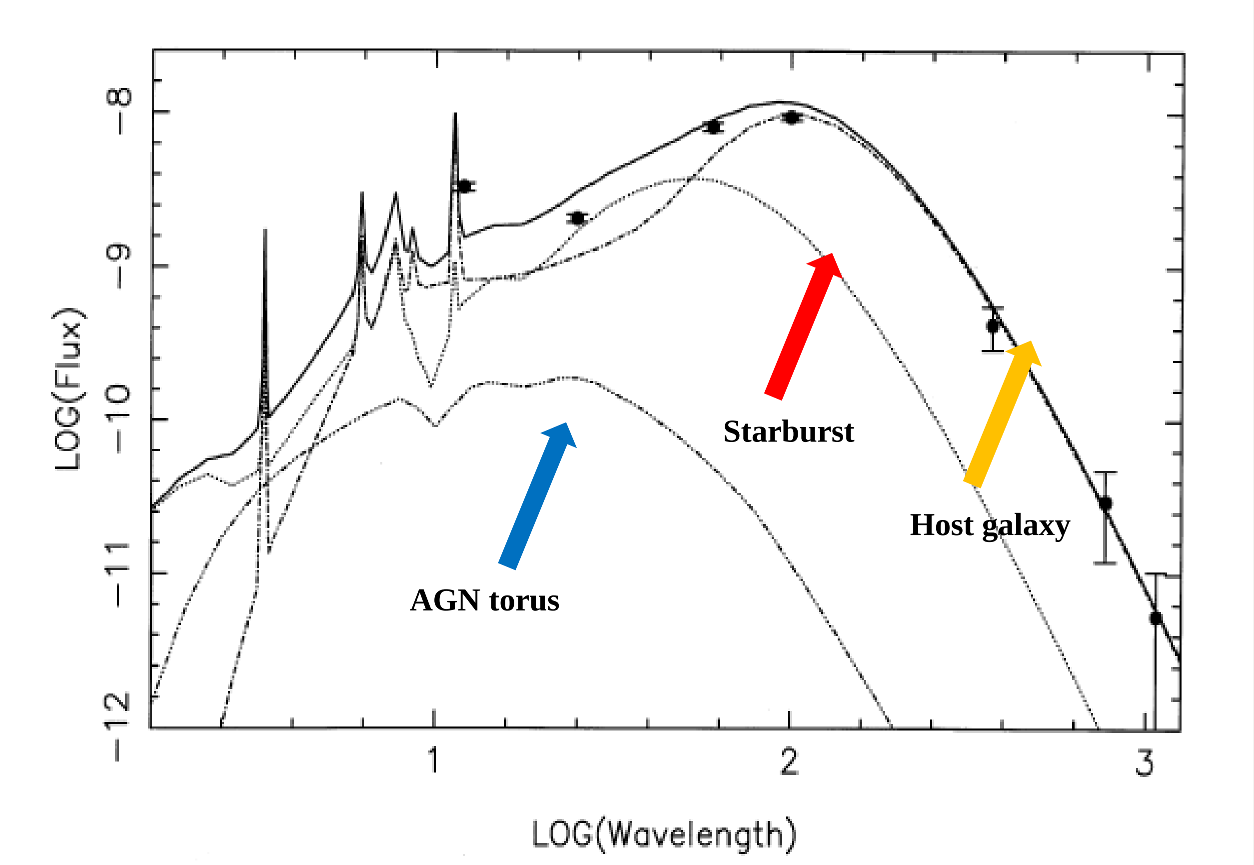
Setting up the Scene

Local Galaxies: Two complementary ways of looking at galaxies: Images and Spectral Energy Distributions (SEDs)

Nearby radio galaxy Centaurus A

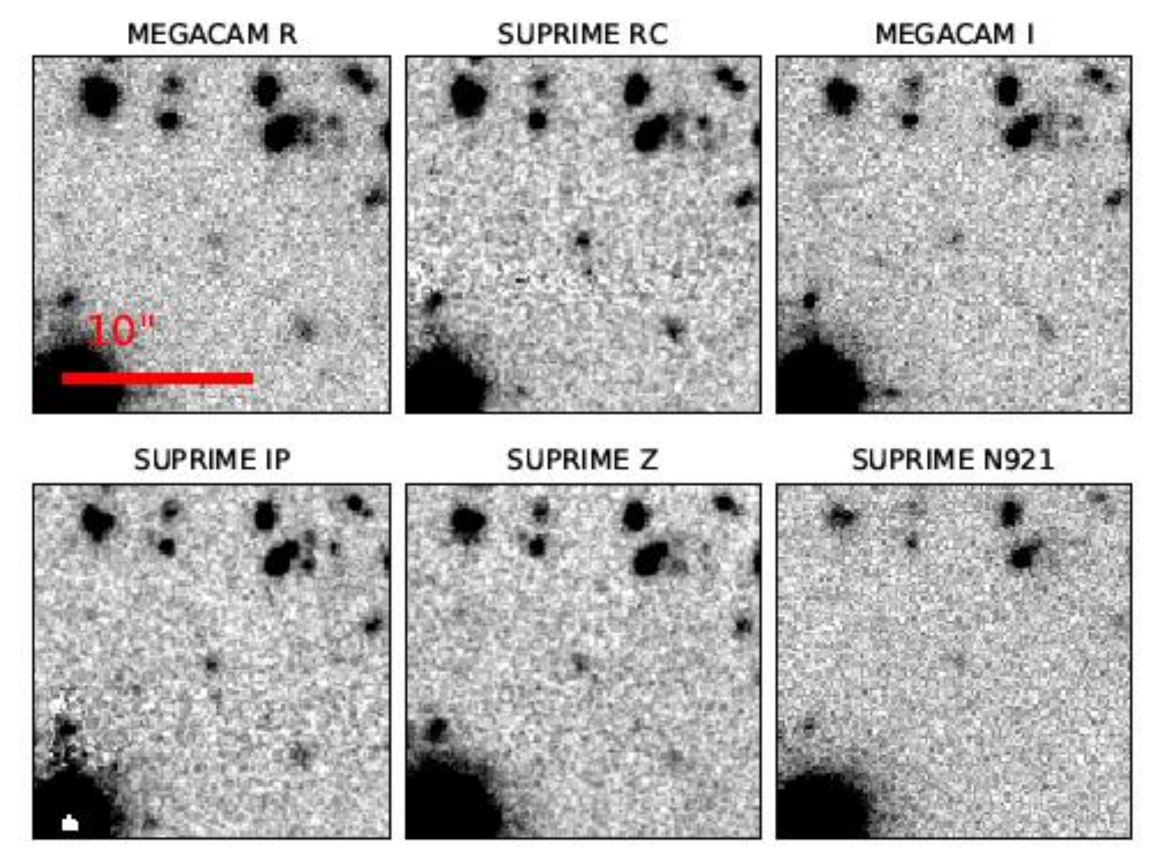


SED fit of Centaurus A with radiative transfer models (Alexander et al. 1999)

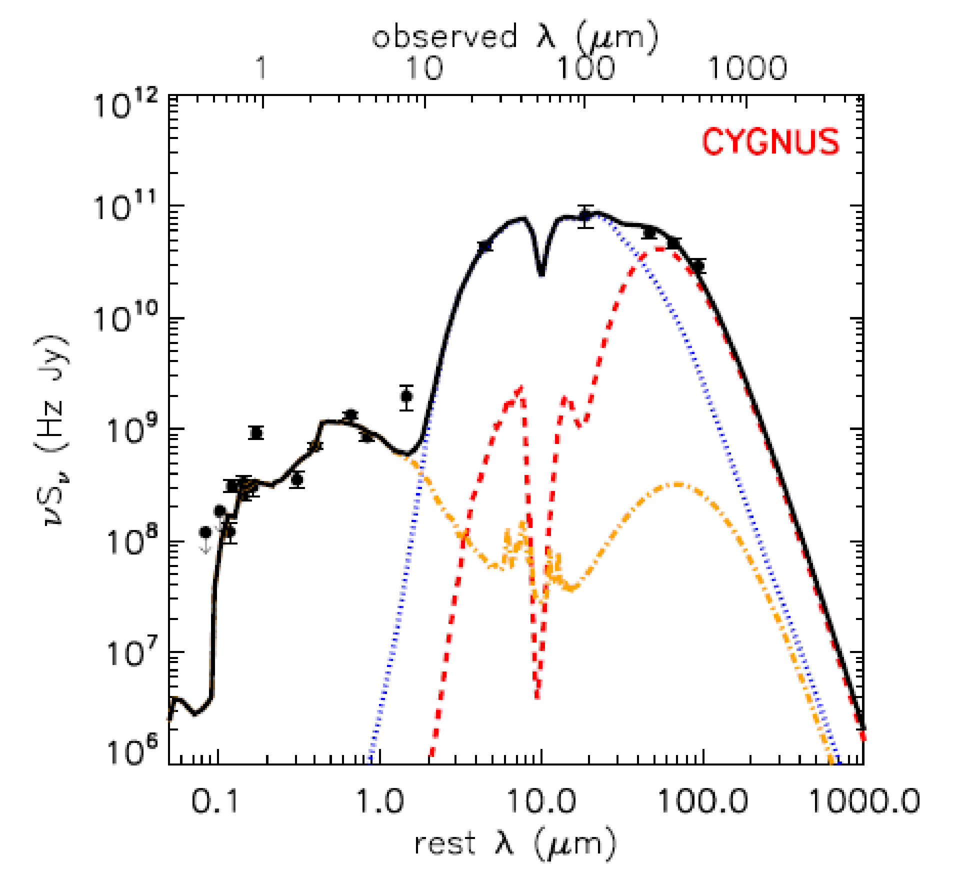


However, far and away z~4.3 :

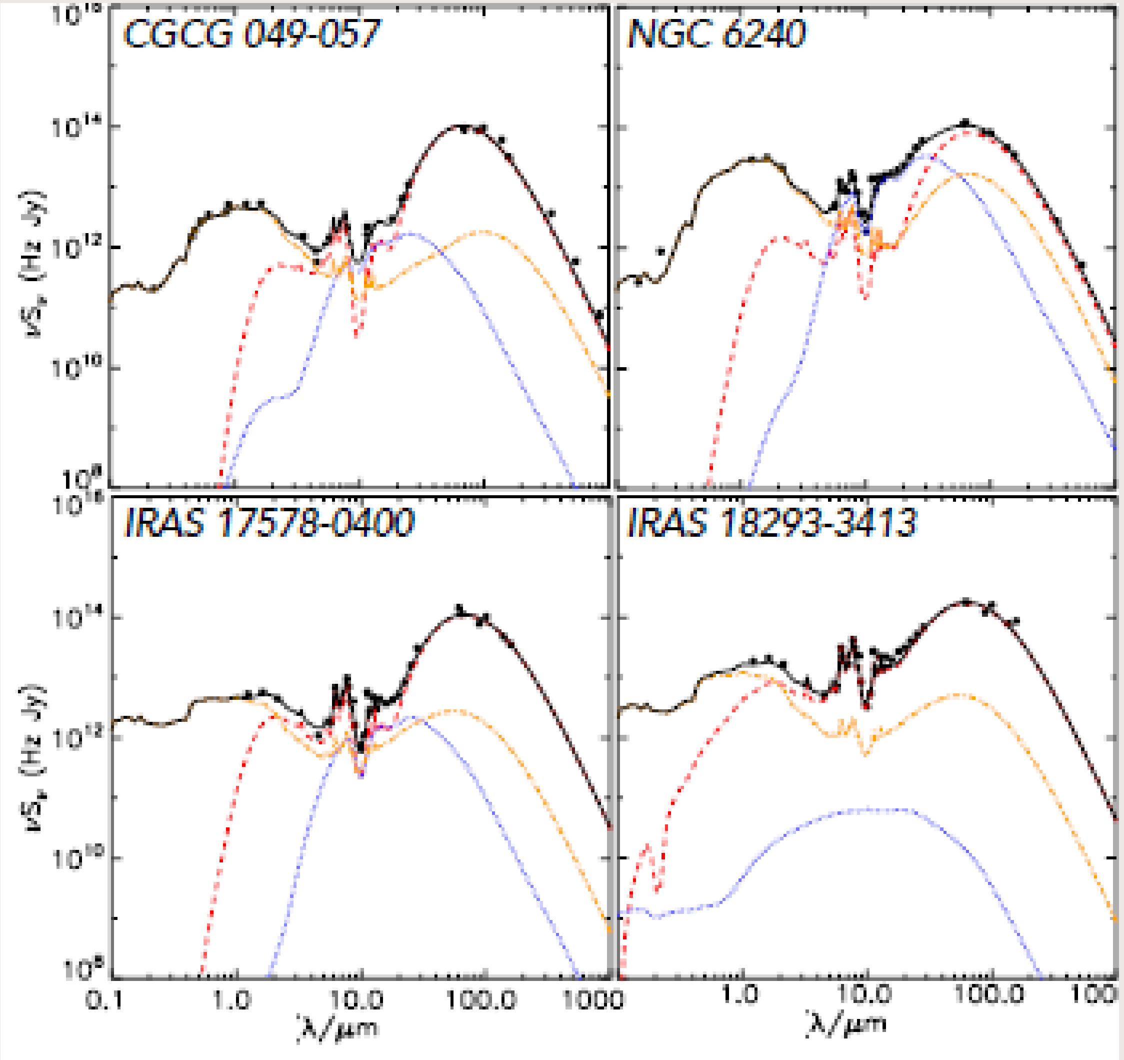
Postage stamps of the galaxy HELP_J100156.75+022344.7 in the COSMOS field (Efstathiou et al. 2021)



SED fit of HELP_J100156.75+022344.7 at z~4.3 with radiative transfer models (Efstathiou et al. 2021)



SED de-composition with Radiative Transfer Models



SED fits for Luminous Infrared Galaxies (LIRGs) by Herrero-Illana et al. (2017) using SATMC+; Starburst (Red), CYGNUS AGN (blue), spheroidal (orange)

Physical Quantities we can extract:

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

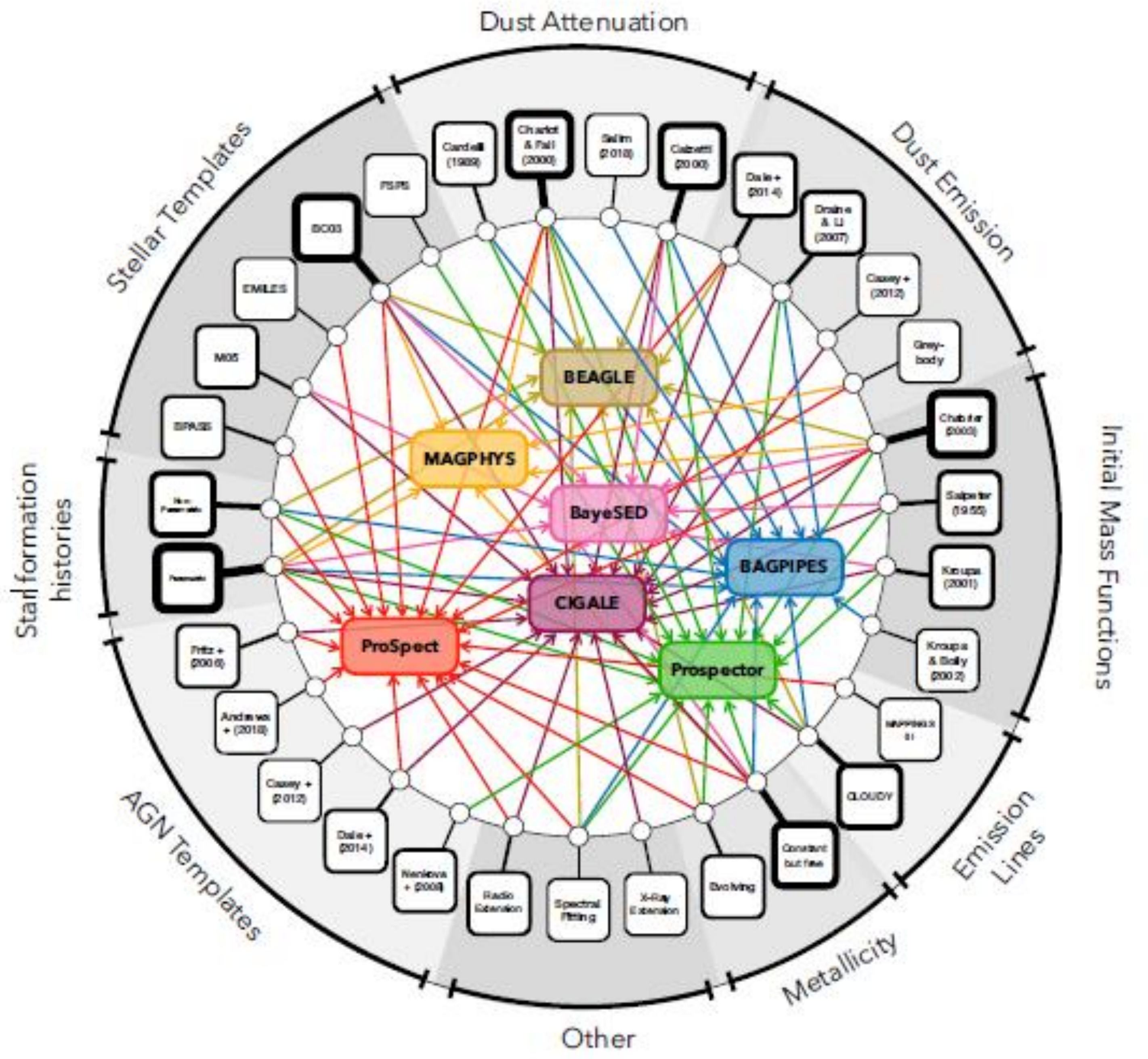
SED FITTING

Important to fit SEDs:

<u>Star Formation Rate (SFR), Stellar Mass, AGN fraction etc</u>

Many SED fitting tools:

<u>BAGPIPES, BayeSED, BEAGLE, CIGALE, MAGPHYS, Prospector etc</u>



SED FITTING

...with Radiative Transfer Models

- ✓ Starburst
- ✓ AGN
- ✓ Host
  - ➢ Disk
  - ➢ Spheroids

Efstathiou+Rowan-Robinson Starburst SEDs

The Starburst SEDs of Efstathiou, Rowan-Robinson, & Siebenmorgen (2000) based on radiative transfer.

Gr[illegible]il

Radiative tr[illegible] model that takes into acc[illegible]tellar population synthesis as well as the effects of dust in a galaxy, Silva et al.

MappingsIII Starburst SED

Starburst UV-IR SEDs described in Groves et al. (2008)

MappingsIII (also available here) code

"Modelling And Prediction in Photo-Ionized Nebulae and Gasdynamical Shocks" photoionization radiative transfer code that includes both line processes and dust emission.

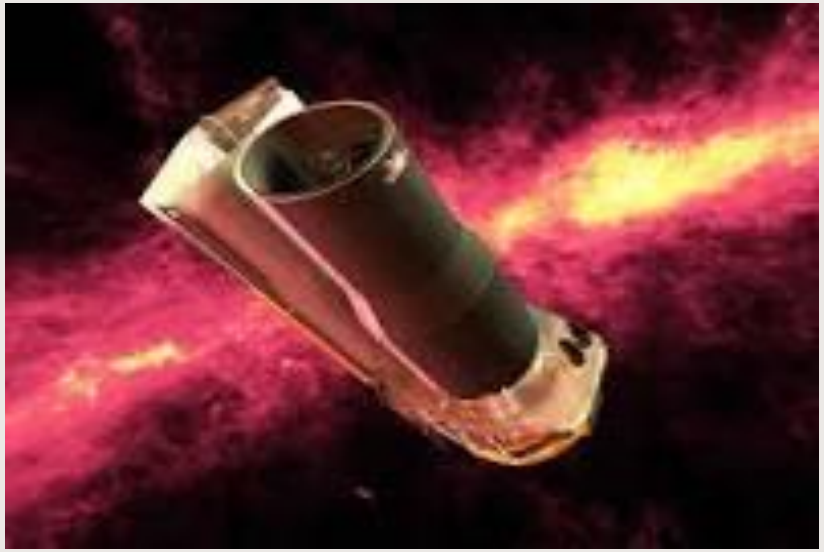
Siebenmorgen+Kruegel Starburst SEDs

Starburst SEDs from the Siebenmorgen & Krügel (2007) model based on radiative transfer.

The CYprus models for Galaxies and their NUclear Spectra (CYGNUS) project

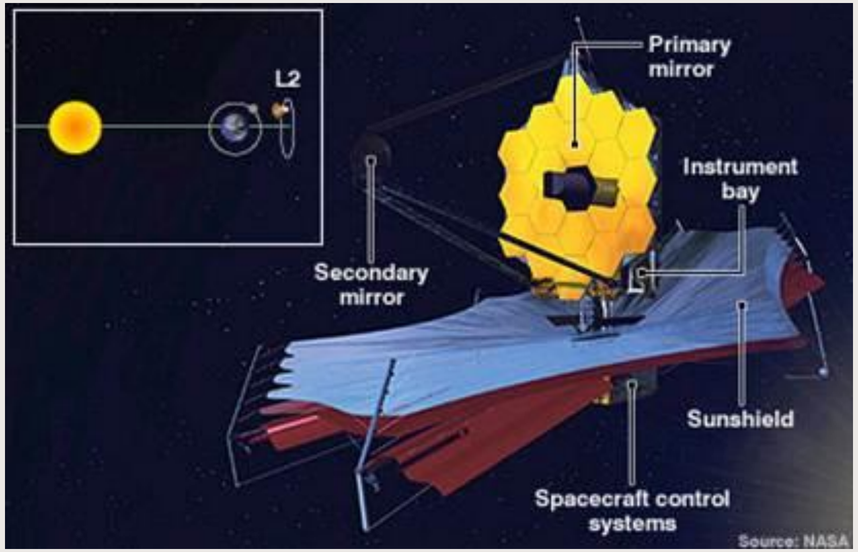
- A holistic approach in the study of the SEDs of galaxies
- We develop our own libraries of radiative transfer models for AGN tori, starbursts and host galaxies (spheroids and discs)
- Use other model libraries which are publicly available
- Develop methods for fitting the models to multi-wavelength data
- Our methods promise to be very useful for analysing multi-wavelength SEDs of galaxies from a number of ground-based and space-born facilities, such as:

SPITZER
(IR)

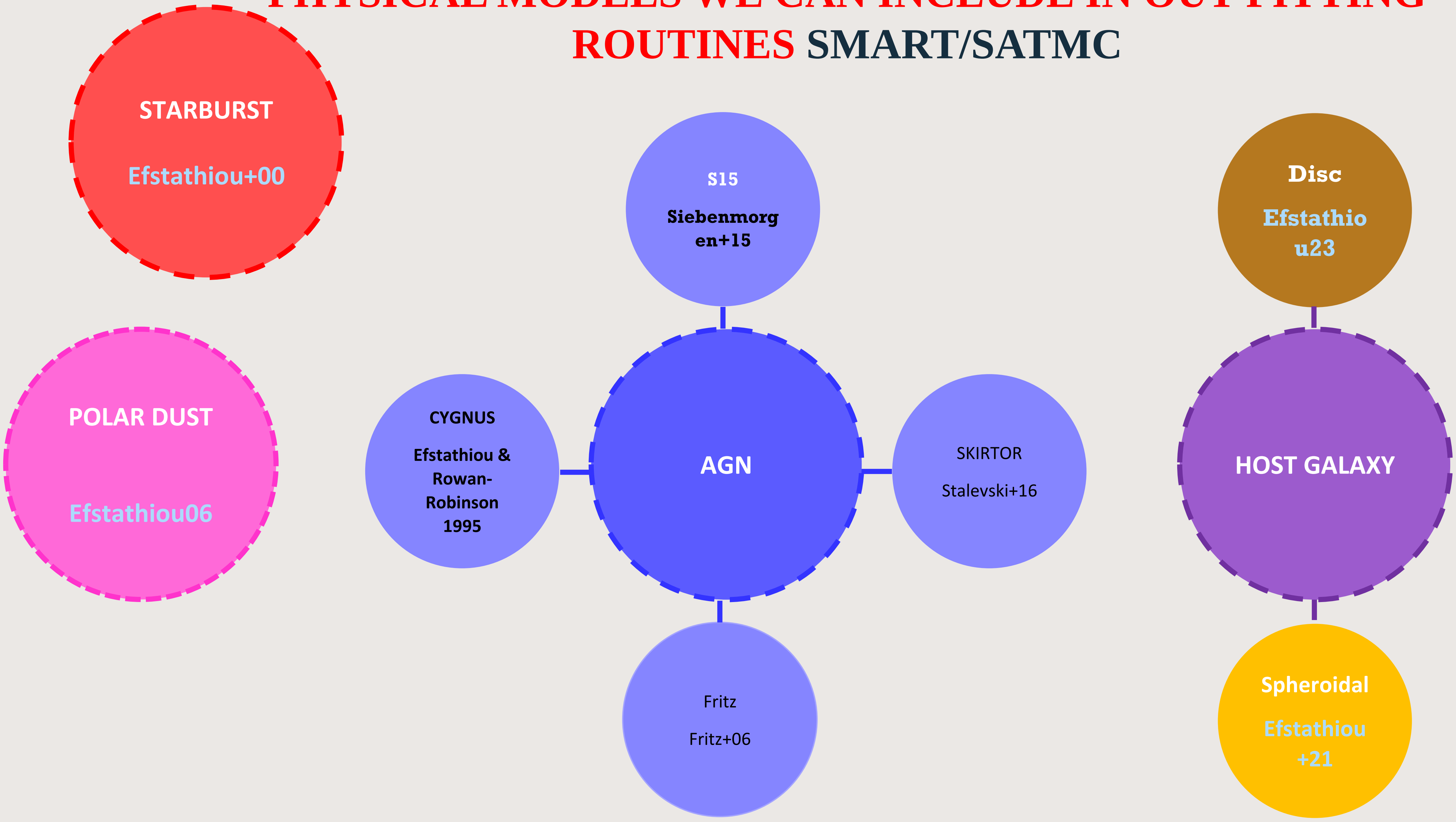


HERSCHEL
(far-IR to submillimetre)

James Webb Space Telescope (JWST)
(optical to mid-IR)

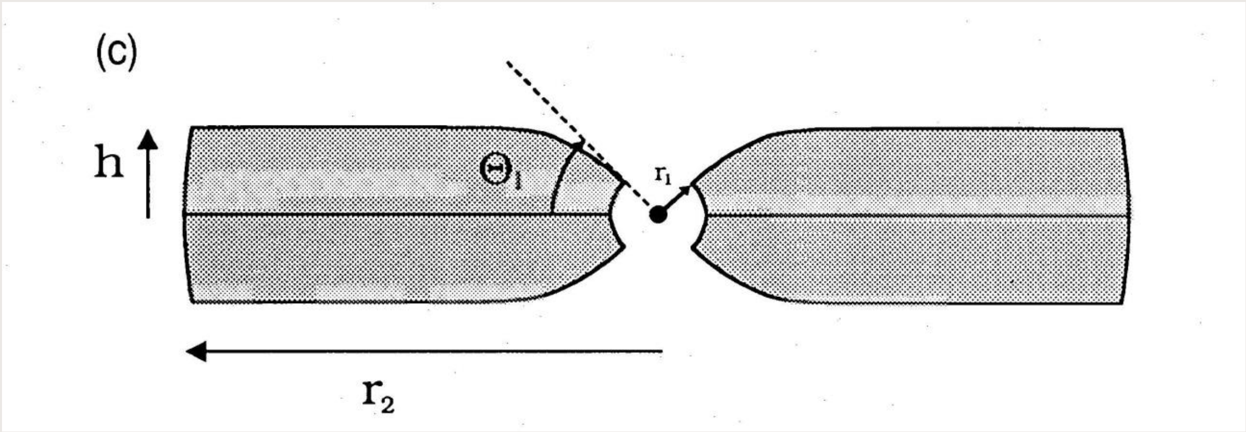


PHYSICAL MODELS WE CAN INCLUDE IN OUT FITTING ROUTINES SMART/SATMC

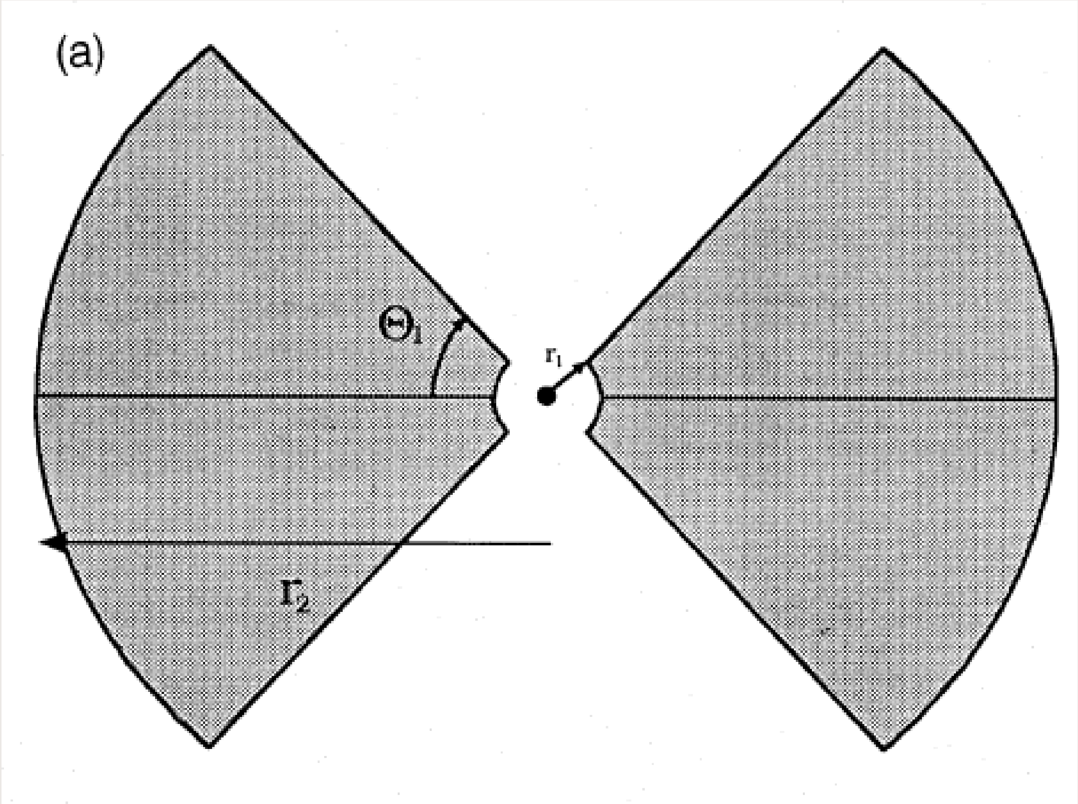


INCLUDED IN -SMART/SATMC
Smooth AGN torus models

Tapered disc (Efstathiou & Rowan-Robinson 1995)

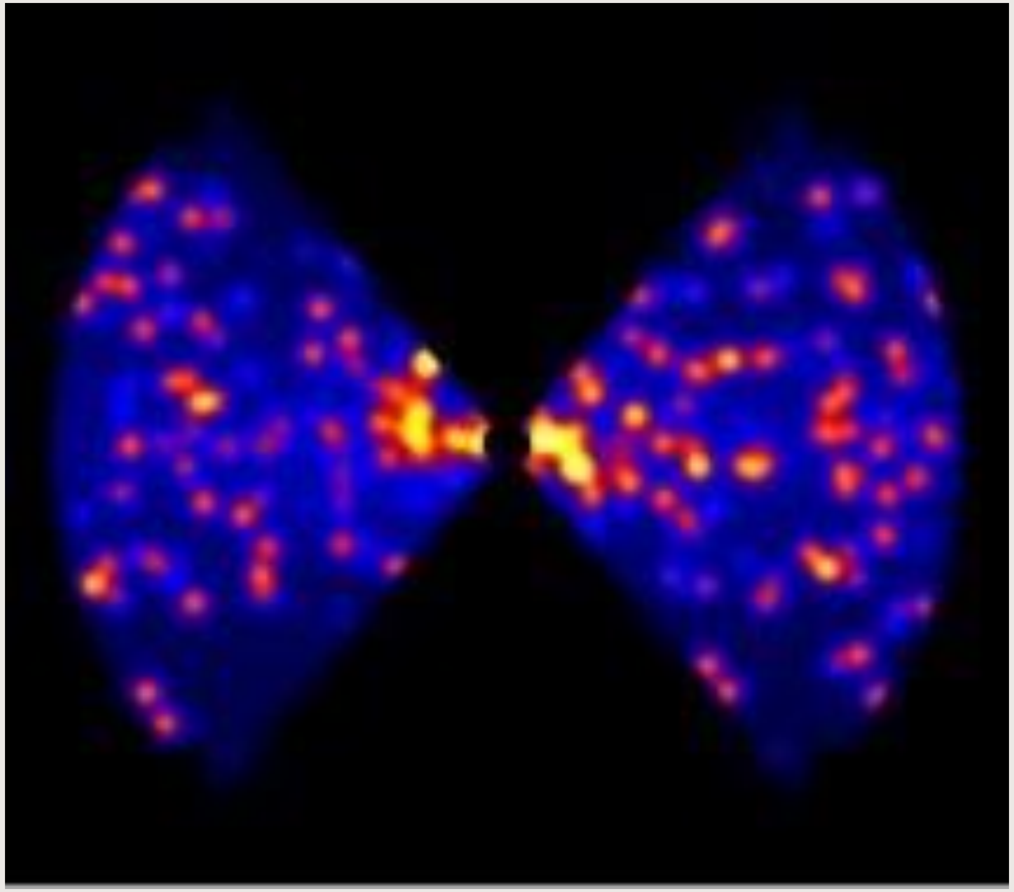


Flared disc (Fritz+06; see also Efstathiou & Rowan-Robinson 1995)

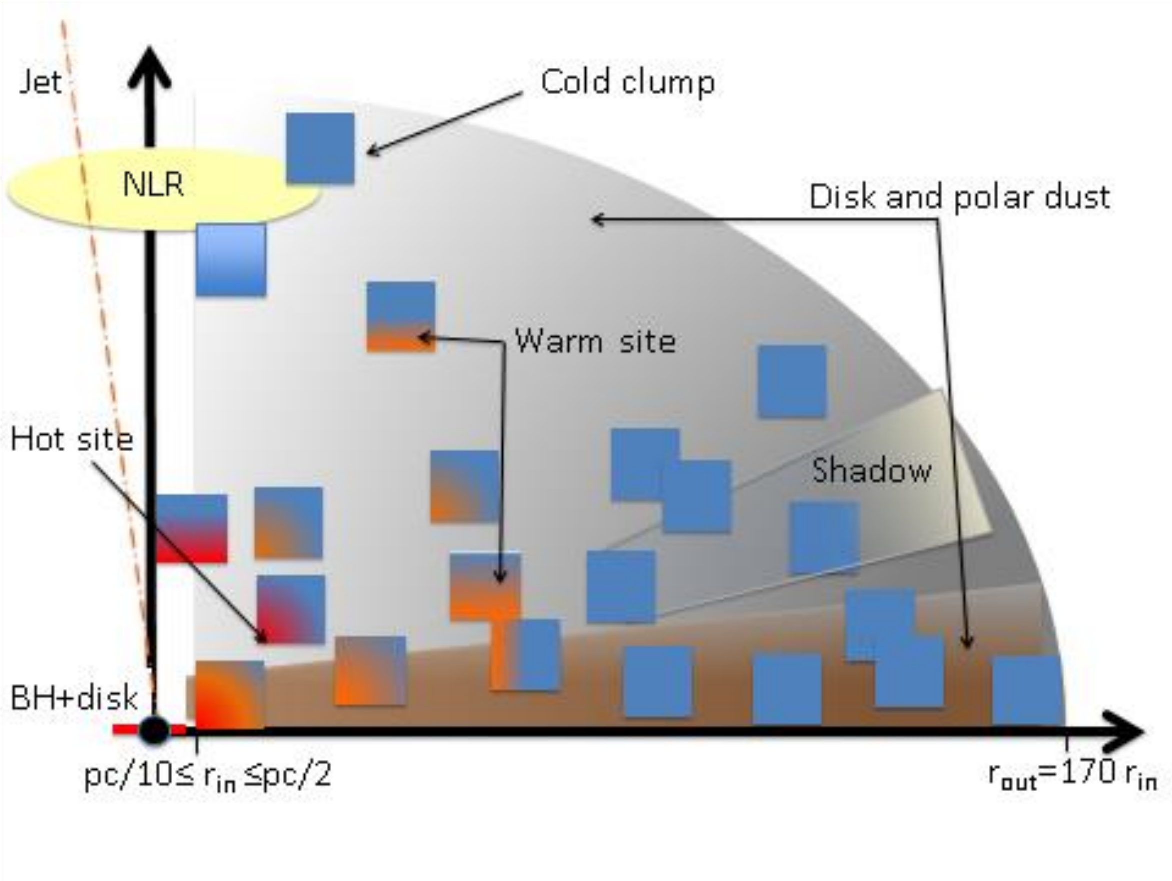


INCLUDED IN -SMART/SATMC Two-phase AGN torus models

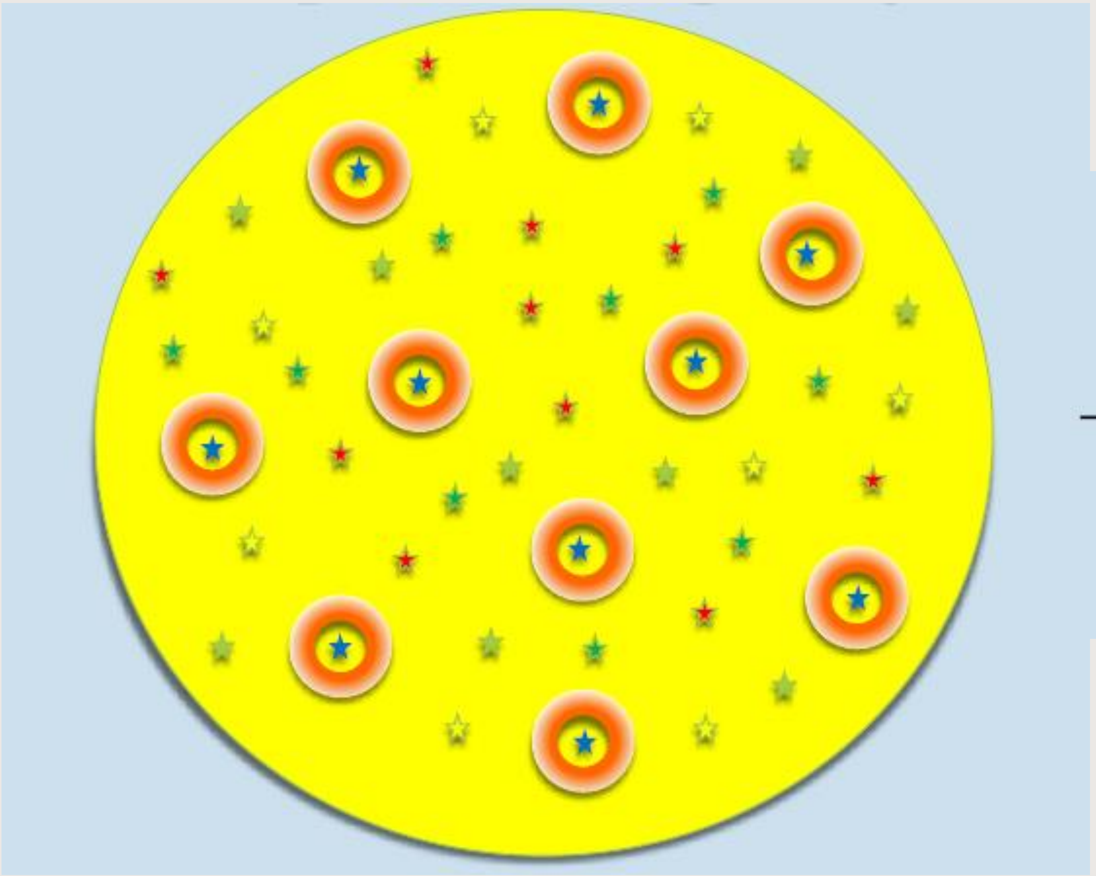
SKIRTOR (Stalevski+12, 16)

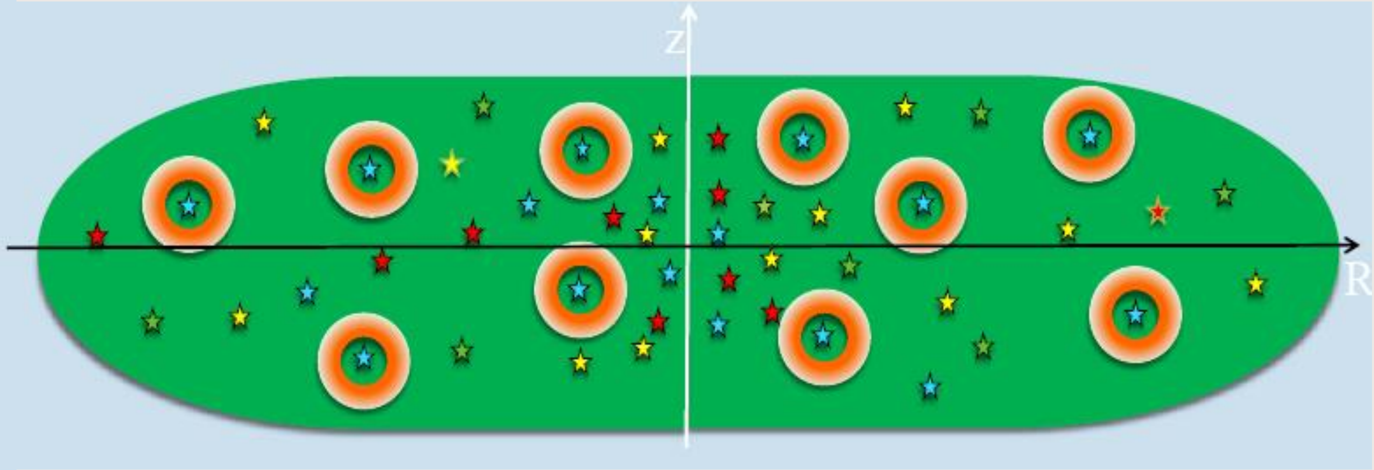


Siebenmorgen+15



Schematic diagrams of the CYGNUS spheroidal and disk galaxy models



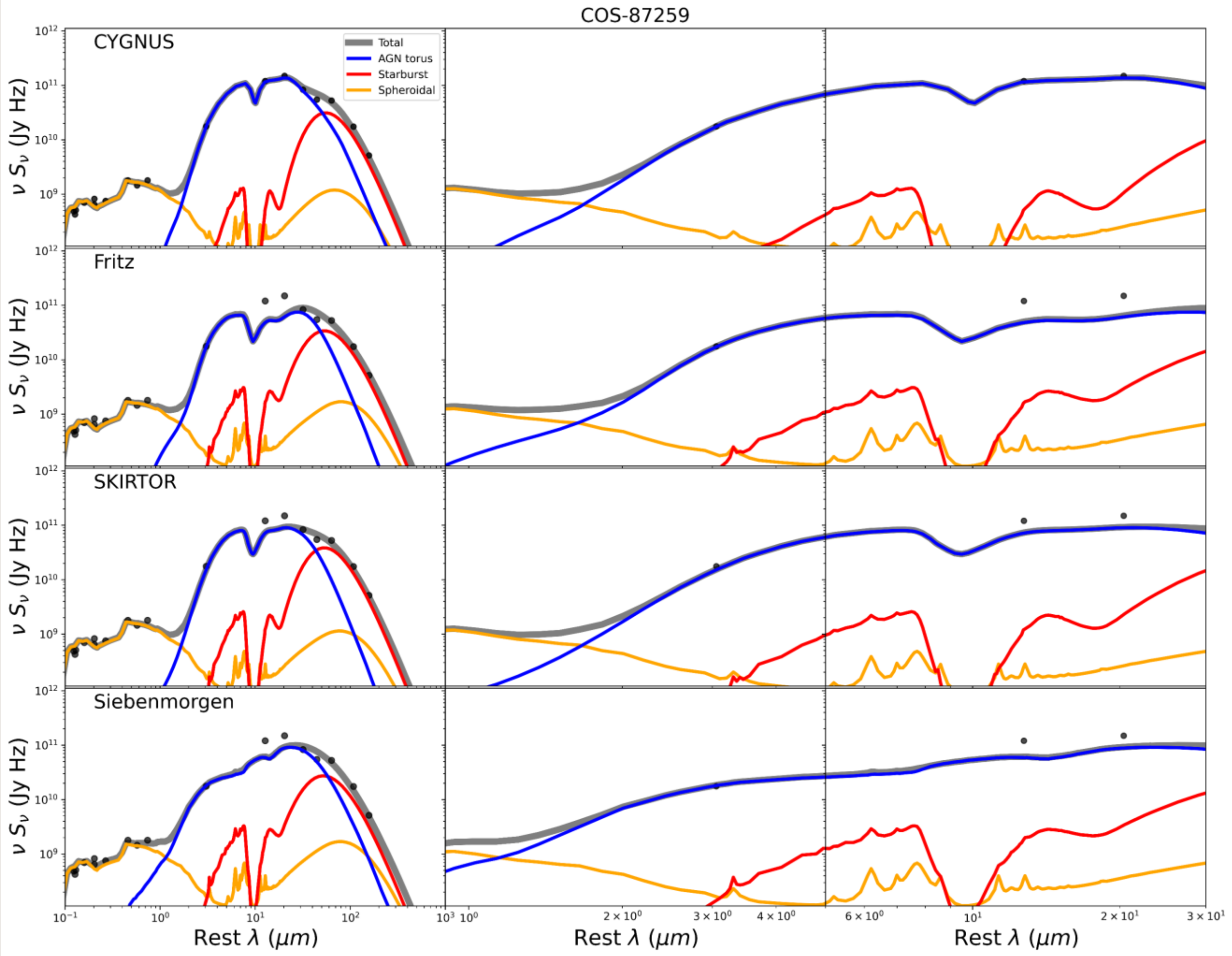


Models for spheroidal and disc galaxies

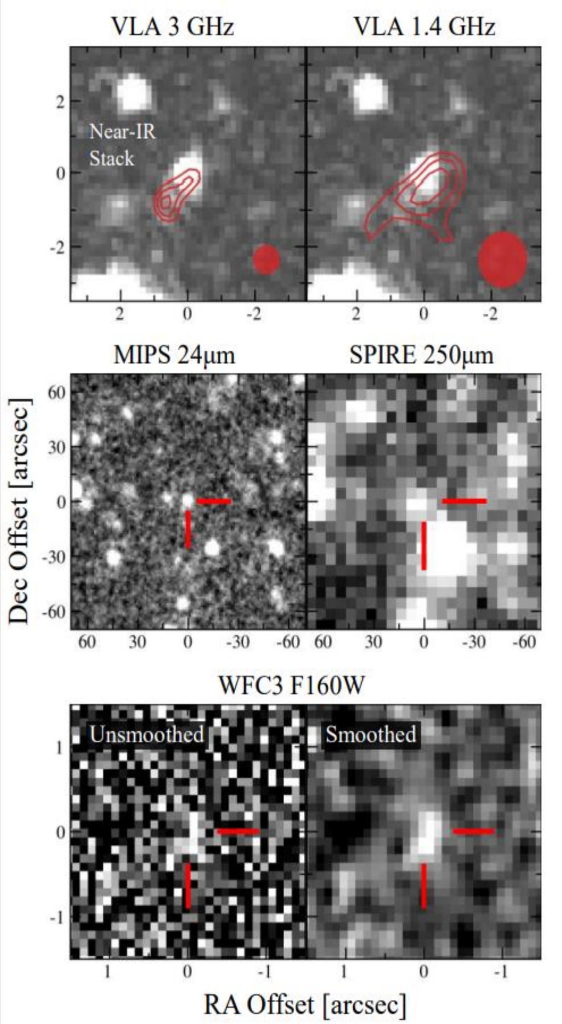
(Efstathiou et al. 2021, Efstathiou, in preparation)

- A code that calculates 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
- The spheroidal models take ~10s to run and the disc models ~20minutes

SED fits of the hyperluminous infrared galaxy (HLIRG) COS-87529 at z=6.853 in the COSMOS field (using SMART: Varnava et al. 2024)



Comparison SED fit plots of the HLIRG COS-87529 at z=6.853 in the COSMOS field: AGN torus (blue), starburst (red), spheroidal host (orange), total (black)



Postage stamps in various filters (Endsley et al. 2022)

ML aims to improve CYGNUS models

CYprus models for **G**alaxies and their **NU**clear Spectra

SED fitting – with Radiative Transfer models

- AGN
- Starburst
- Host
  - ✓ Disk
  - ✓ Spheroidal

  HOW : Use precomputed libraries

  & with ML

  - ***Accelerate computations***
  - ***Include more parameters***

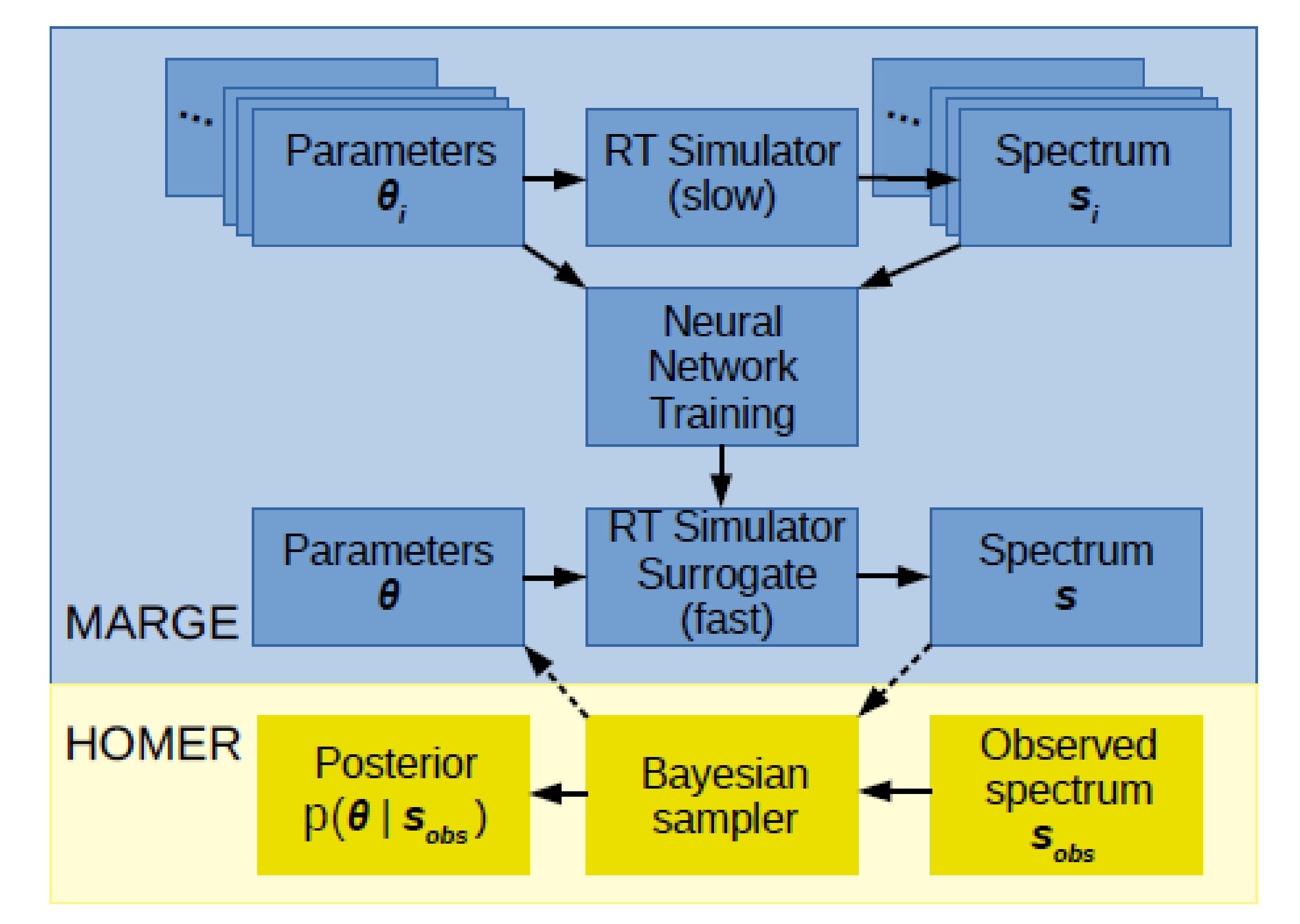
  *...up to **18 parameters** with a non-parametric star formation and metallicity history*

Stand on the shoulders …of the community

Machine learning **A**lgorithm for **R**adiative transfer of **G**enerated **E**xoplanets **MARGE** *(Himes et al. 2021)*

Characterizing the Atmospheres of Exoplanets.

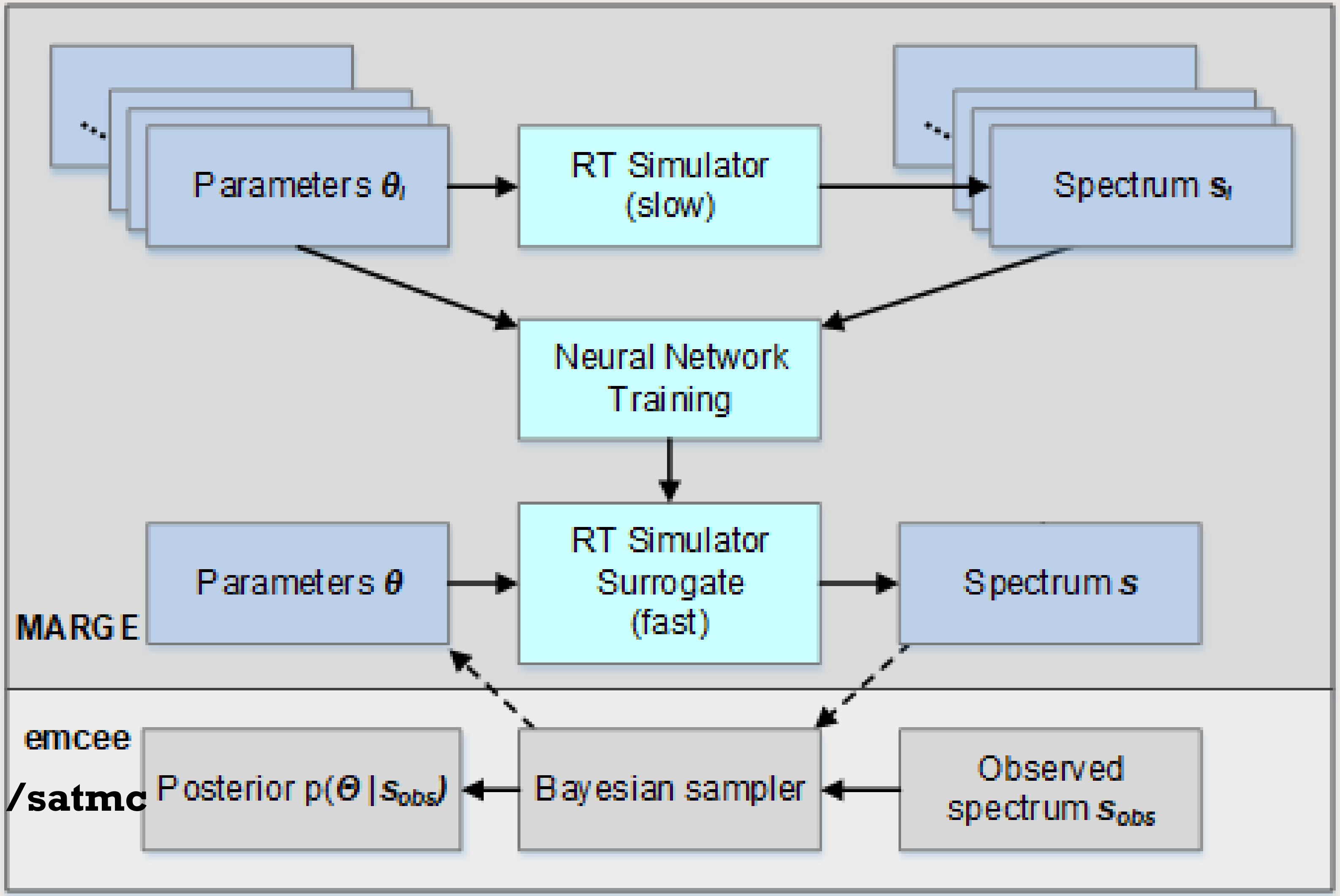
BART […]



Accelerating CYGNUS SED fitting methods

Integrate MARGE framework into CYGNUS methods

Efstathiou Models for AGN/sturburst/HostGalaxy



Increasing parameter (space)

CYGNUS Starburst			
Initial optical depth of GMCs	τ_v	50–250	Efstathiou et al. (2000), Efstathiou & Siebenmorgen (2009)
Starburst SFR e-folding time	τ_*		
Starburst age	t_*		
CYGNUS Spheroidal Host			
Spheroidal SFR e-folding time	τ^s		
Starlight intensity	ψ^s		
Optical depth	τ_v^s		
CYGNUS Disc Host			
Disc SFR e-folding time	τ^d	0.5–8 Gyr	Efstathiou & Rowan-Robinson (2003), Efstathiou et al. (in prep.)
Starlight intensity	ψ^d	1–9	Incorporates Bruzual & Charlot (1993, 2003)
Optical depth	τ_v^d	0.1–29	Range of metallicities, Salpeter IMF
Inclination	θ_d	0°–90°	Standard galactic dust mixture with PAHs

arbitrary start formation & metallicity history

&

Metallicity – 5 bins
Star formation – 10 bins

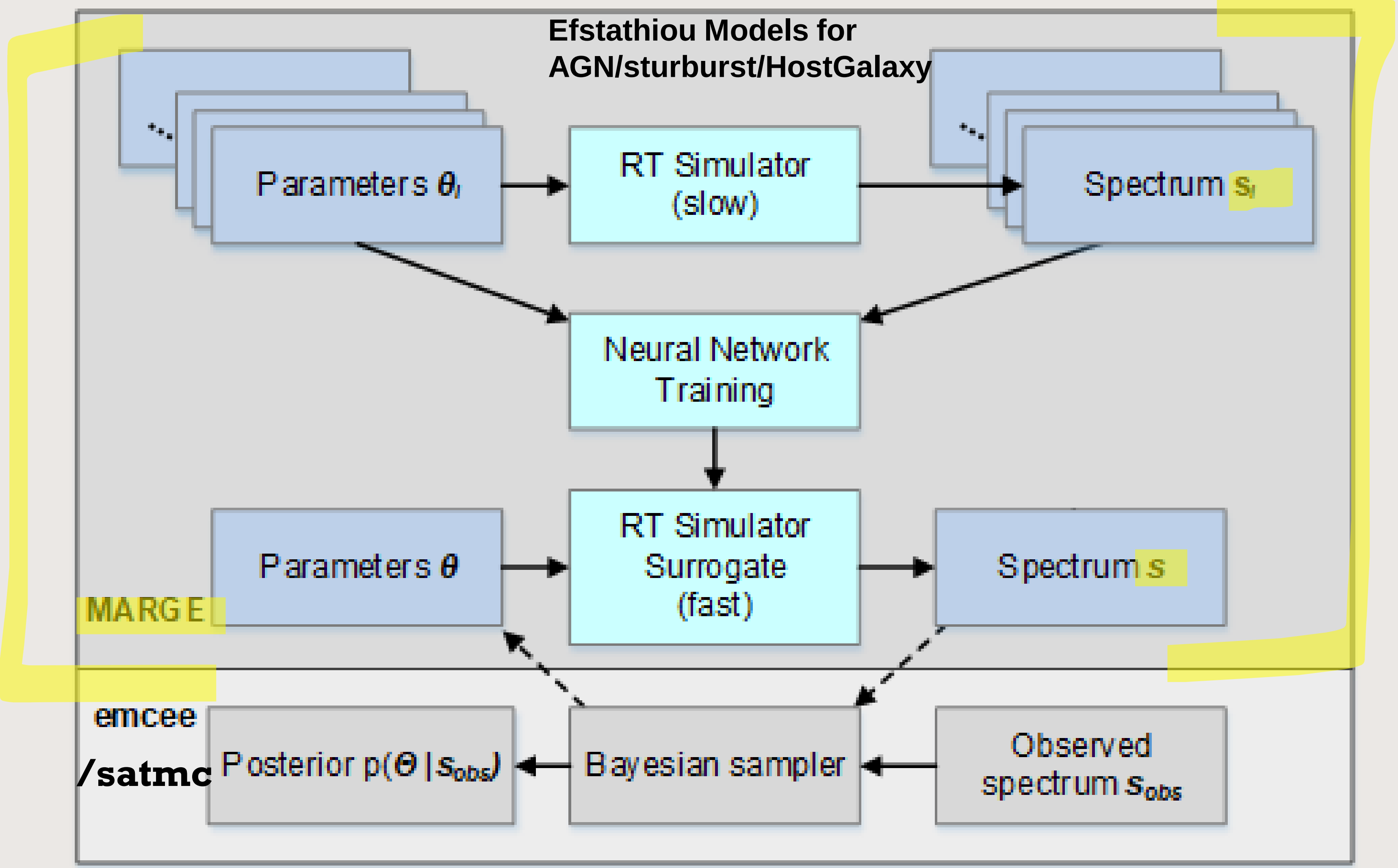
..SO CURRENT PARAMETERS

- **Redhift or equivalently the age** of the galaxy
- **Optical Depth** of the spheroidal galaxy
- **Intensity of Starlight**
- 10 parameters for each of the bins we use for the **star formation rate** of the galaxy
- 5 parameters for each of the bins we use for the **metallicity** of the galaxy

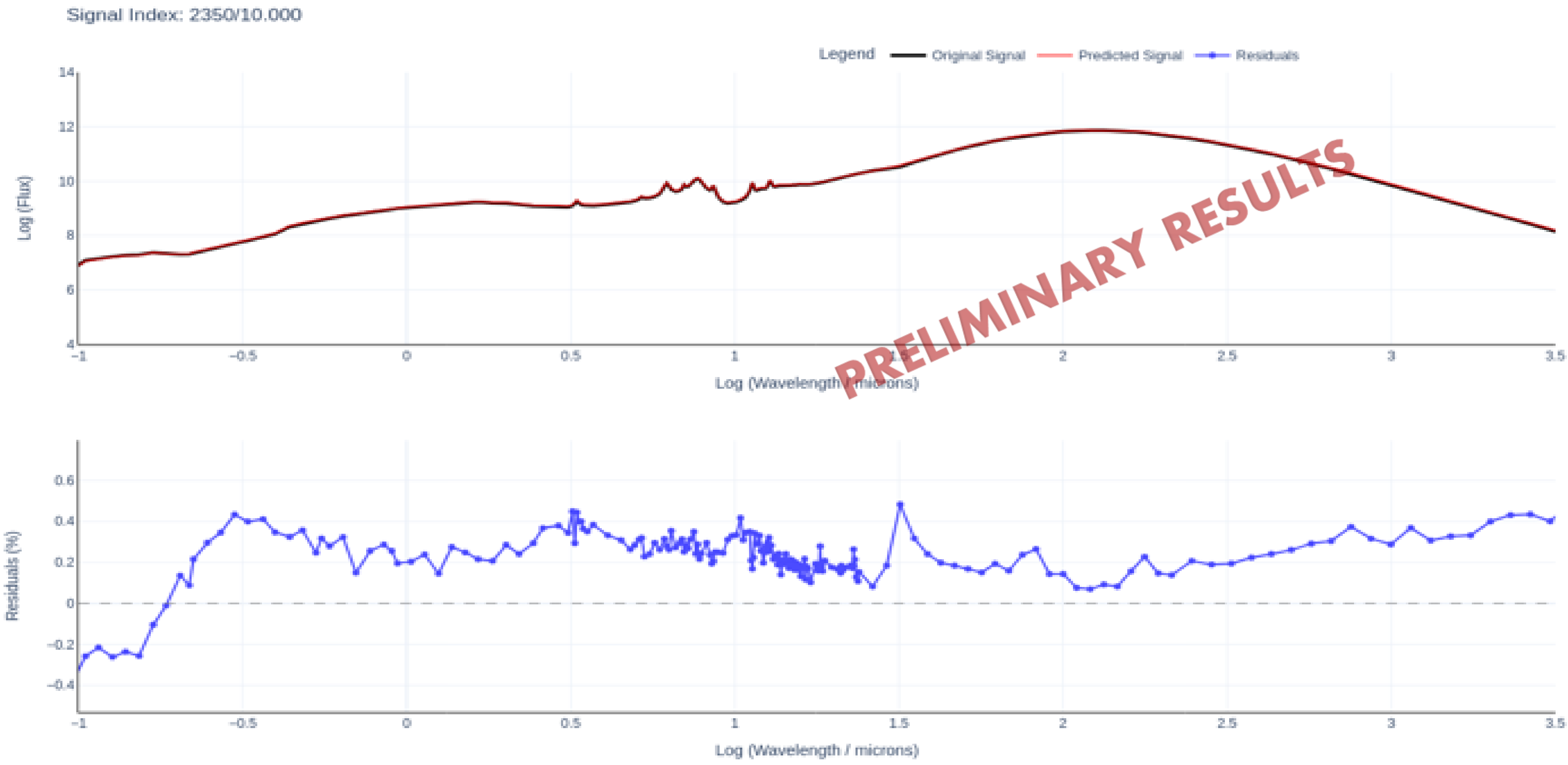
To run the spheroidal model for a particular combination of parameters need ~10s

Accelerating CYGNUS SED fitting methods

Integrate MARGE framework into CYGNUS methods

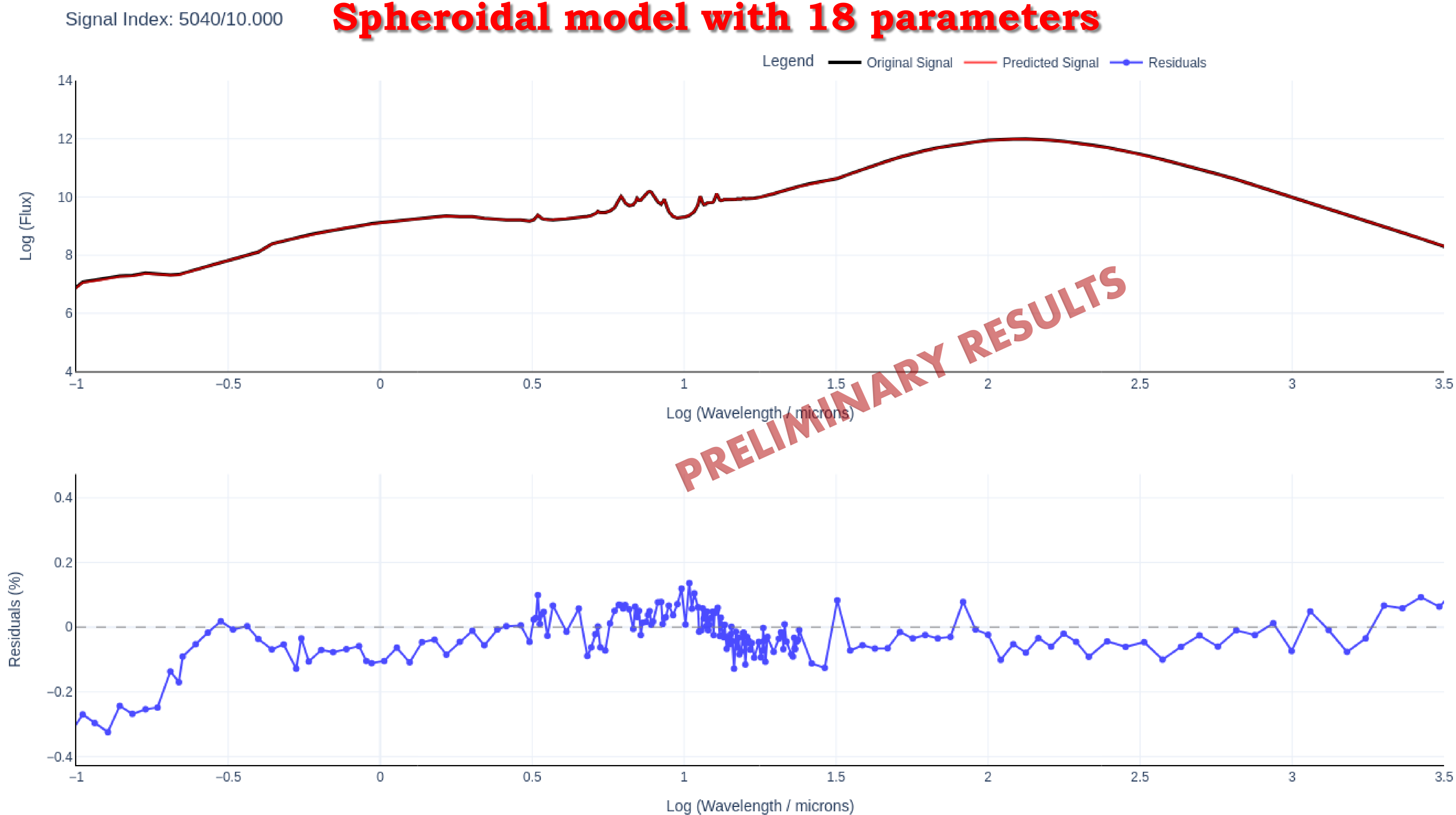


Spheroidal model with 18 parameters



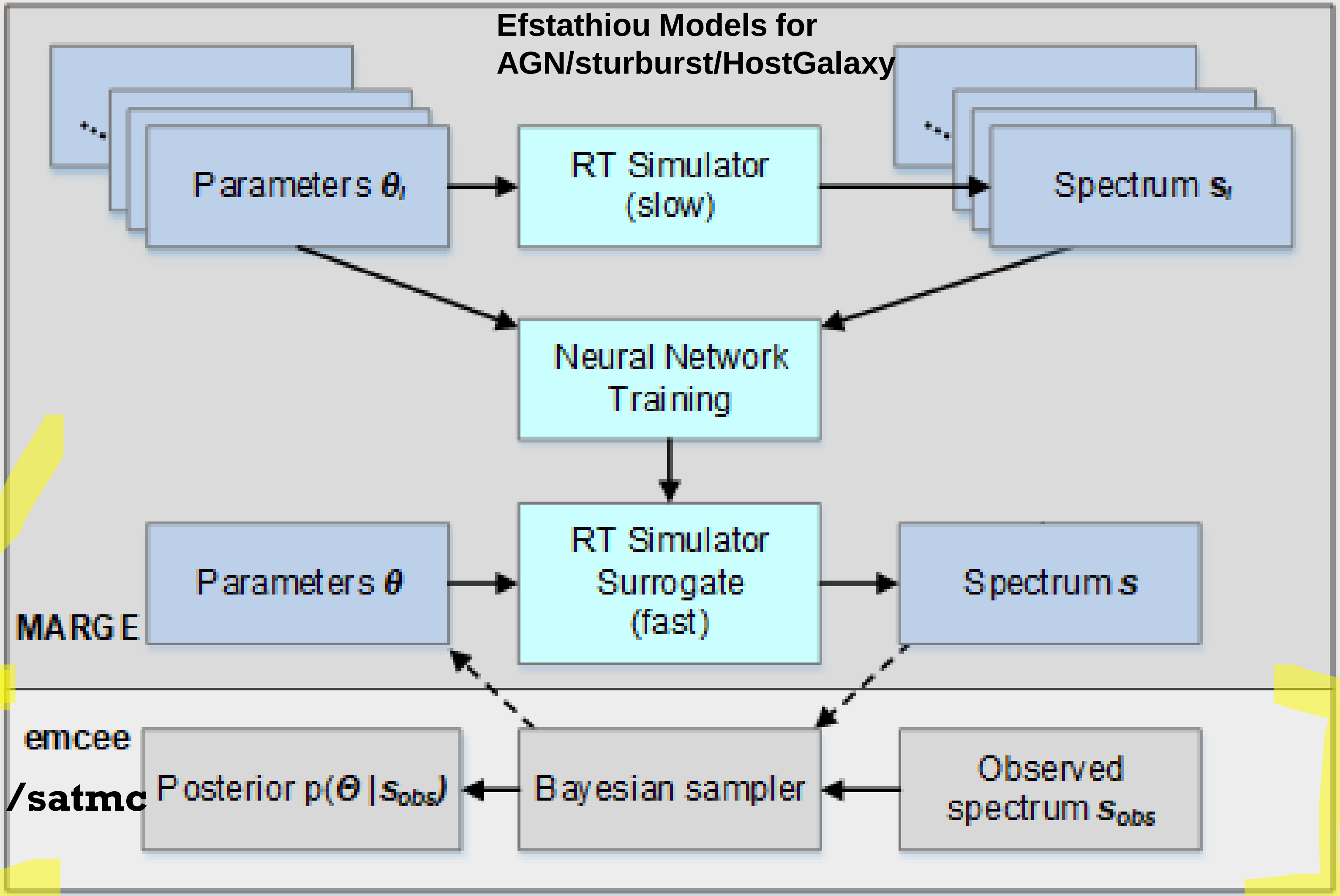
Spheroidal model with 18 parameters

Spheroidal model with 18 parameters



Accelerating CYGNUS SED fitting methods

Integrate MARGE framework into CYGNUS methods



FURTHER DEVELOPMENT OF CYPRUS MODELS FOR GALAXIES AND THEIR NUCLEAR SPECTRA

CYGNUS+

WP: Using JWST data with CYGNUS+ and Compare with other SED methods

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THANK YOU