ICED: IAS/CEA Evolution of Dust in Nearby Galaxies

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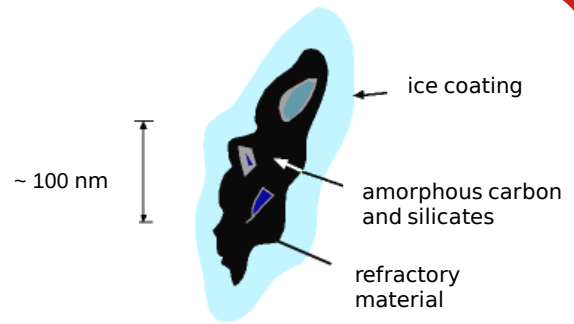
Overview

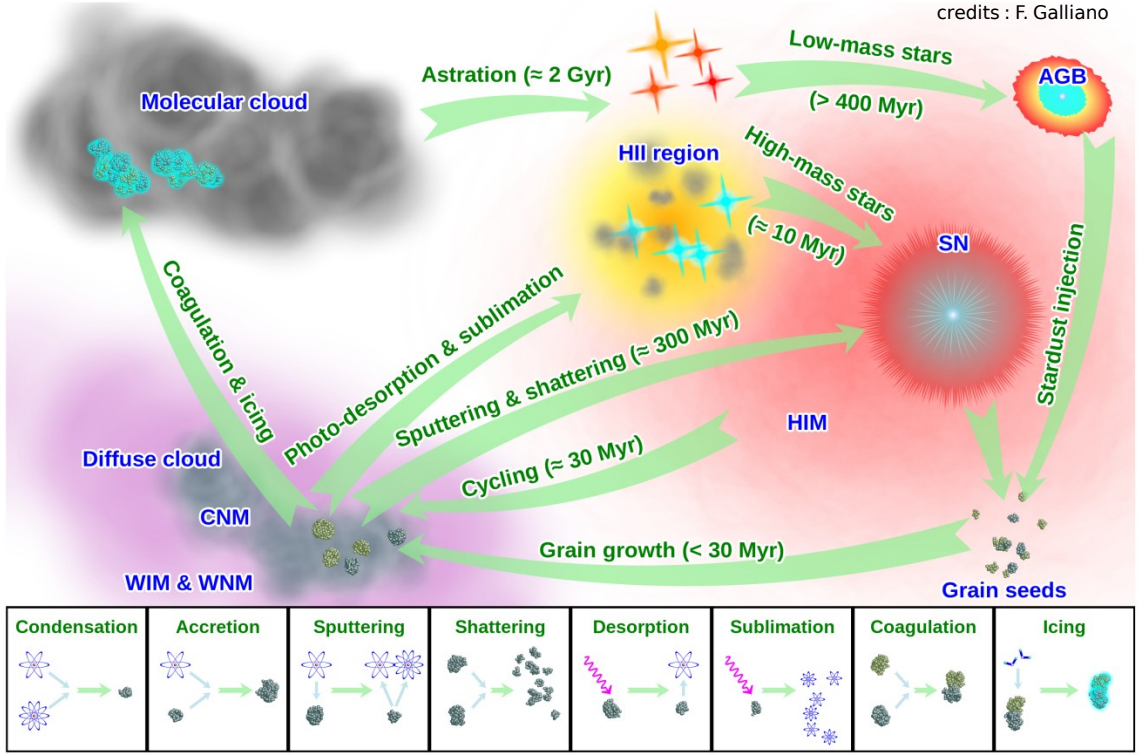
- **Interstellar Dust** (ISD) in galaxies.
- The crucial role of **Nearby Galaxies**.
- **Main objective** of the project (pilot study on **M99**).
- Available **data**: NIKA2, DustPedia, CO and HI maps.
- Preparing the maps for pixel-by-pixel SED fitting.
- **Modelling** ISD : THEMIS & HerBIE.
- Preliminary results : integrated SED.
- Preliminary results : spatially-resolved analysis.
- Summary and future perspectives.

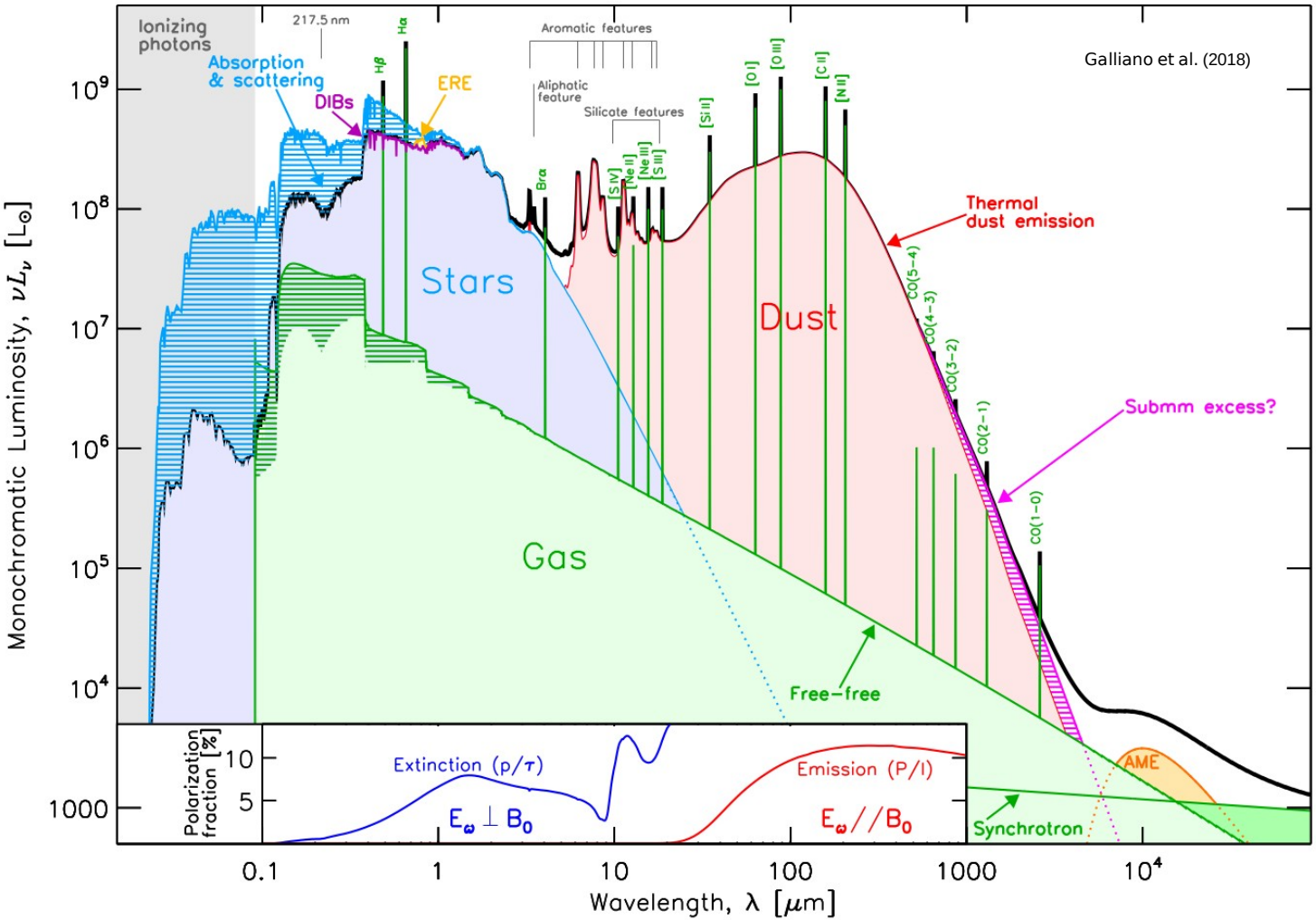
Dust grains lifecycle



ISD grains are :

- solid particles
- made of heavy elements
  (e.g., O, C, Si, Mg, Fe)
- characterized by typical size of 0.3 nm < a < 0.3 µm
- < 1 % of ISM mass.





Spectral Energy Distribution (SED) of a MW-like galaxy

- Dust grains **absorb** and **reradiate** ~30% of stellar power in the **IR** (through scattering, absorption, extinction).
- Dust mass is dominated by **large grains**, responsible for the **thermal emission in the FIR**.
- **Small grains** out of thermal equilibrium are responsible for the **MIR features** (aromatic and aliphatic carbon features and silicate features).

Most of our knowledge of ISD properties comes from studies of the **Milky Way**.
(Draine 2003a)

credits : ESO ; NASA/ESA

Small range of environmental conditions

- Confusion along the sightline.
- No extremely luminous star forming regions (like 30 Doradus in LMC).
- Narrow radial metallicity gradient.
- Passive SMBH.

Nearby galaxies (< 100 Mpc) provides unique constraints on ISD properties.

- Faced-on galaxies ➞ ***clearer sightlines*** .
- SSC in Blue Dwarfs ; bright AGNs ; low Z objects ➞ probe ISD in ***extreme conditions*** .
- Intermediate step towards understanding ISD and ISM in ***distant galaxies***.

ICED main objective

- The main objective of the project is to **study Interstellar Dust grains properties in different local environments** (nearby galaxies ; i.e. dwarfs, normal, AGN) **through spatially-resolved modelling of their optical/near-IR-to-cm SEDs.**
- This will be important for going beyond the limiting view that we currently have, mostly based on Milky-Way studies.
- **Pilot study on M99**..

Tools :

- The data used are part of the European consortium of the ***NIKA2 Guaranteed Time program, IMEGIN*** (P.I. Madden), currently acquiring 1- 2 mm continuum maps of nearby galaxies at the IRAM-30m telescope.
- NIKA2 data complemented by the multi-wavelength images of the ***DustPedia*** sample.
- SED modelling performed with the ***THEMIS*** dust evolution model (Jones et al., 2017) within the hierarchical Bayesian SED fitting code ***HerBIE*** (Galliano, 2018).

IMEGIN, NIKA2 Guaranteed Time program

Interpreting the Millimetre Emission of Galaxies wIth NIKA2 (PI : Madden)

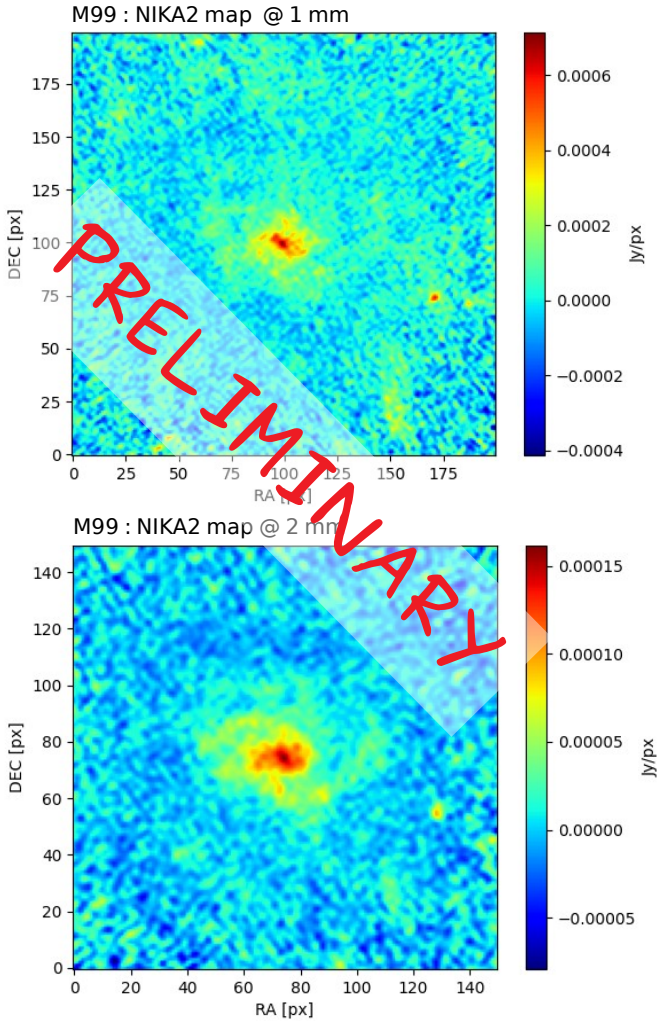
Main objectives :

- ISD, free-free and synchrotron emission in spatially-resolved galaxy SEDs.
- Dust-to-gas mass ratio within galaxies.
- Dust millimeter opacity.
- Sub-millimeter excess in galaxies.

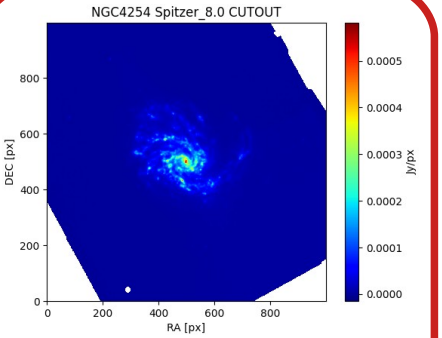
NIKA2 (IRAM 30m) observes @ **1** and **2 mm**, with unprecedent angular resolution at these λ (**12”** and **18”**).

It allows us to :

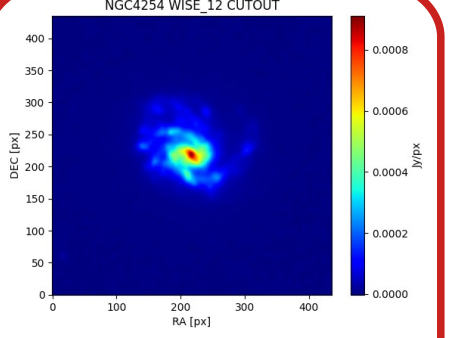
- sample galaxy SED in the mm range (between SPIRE 500 and radio VLA);
- study the spatially-resolved properties of galaxy mm emission.



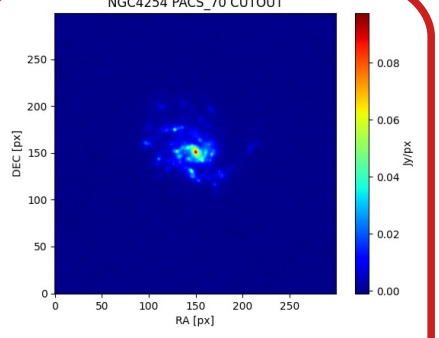
DustPedia archive provides access to multi-λ imagery and photometry for 875 nearby galaxies.
We take advantage of this archive for collecting all **M99 available maps**, from the near to the far IR.



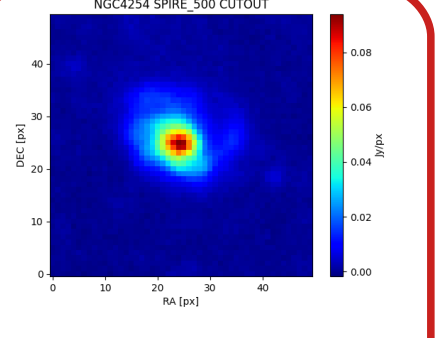
- **Spitzer IRAC 3.6, 4.5, 5.8, 8** (μm)
  θ_{res} [arcsec] ~ 1.66, 1.72, 1.88, 1.98
- **Spitzer MIPS 24** (μm)
  θ_{res} [arcsec] ~ 6



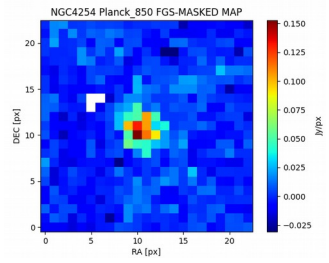
- **WISE 3.4, 4.6, 12, 22** (μm)
  θ_{res} [arcsec] ~ 6.1, 6.4, 6.5, 12



- **Herschel PACS 70, 100, 160** (μm)
  θ_{res} [arcsec] ~ 5.5, 6.5, 11



- **Herschel SPIRE 250, 350, 500** (μm)
  θ_{res} [arcsec] ~ 18, 24.5, 36



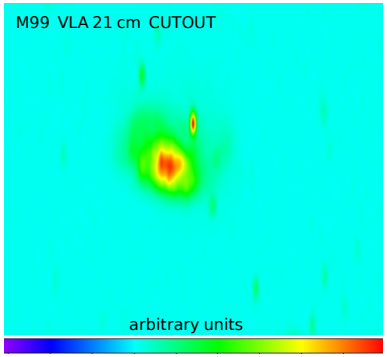
- **Planck 350, 550, 850, 1380** (μm)
  θ_{res} [arcsec] ~ 5, 5, 5, 5.5

Due to the scarce angular resolution, we use Planck maps only for the integrated SED modelling and inter-calibration (SPIRE, NIKA2).

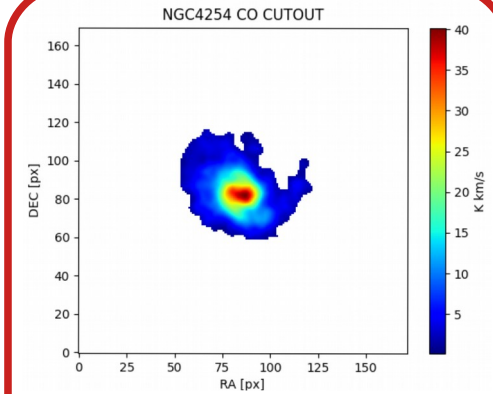
DustPedia
http://dustpedia.astro.noa.gr/

Some ancillary maps of M99 are publicly available.

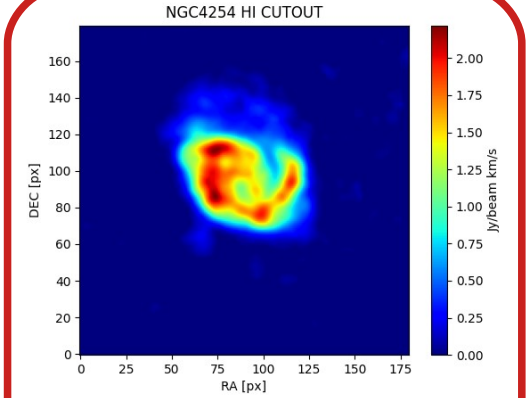
- Radio maps at 3, 6, 18, 21 cm (VLA) for extending the SED modelling to the radio regime (free-free and synchrotron).
- CO(1-0) and HI maps for complementing the characterization of the galaxy that we obtain through the spatially-resolved SED fit (i.e., with molecular and neutral hydrogen maps).



- **VLA 3, 6, 18, 21** (cm)
  θ_{res} [arcsec] ~ 68, 153, 40x10, 50x12
  (courtesy of F. Tabatabaei)



- **CO(1-0) EMPIRE**
  IRAM 30m
  θ_{res} [arcsec] ~ 27
  (Jiménez-Donaire+19)



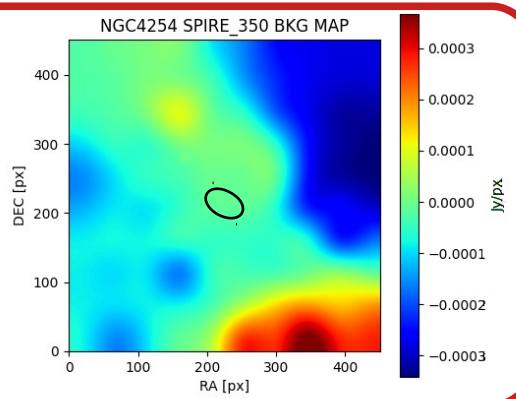
- **HI VIVA**
  VLA
  θ_{res} [arcsec] ~ 30
  (Chung+09)

M99 multi-λ maps have different size, spatial resolution, pixel size, orientation, units.
In order to perform the pixel-by-pixel SED fitting, we need to homogenize these quanties.

We reprocessed the original maps following these steps :

- **Backgroung and foreground subtraction.**
  - Foreground large scale emission (e.g. Galactic cirrus in the MIR-submm, sky brightness in the NIR).
  - Unresolved background sources.
  - Any instrumental gradient.

Python photoultils
Background2D
5σ (sigma clip)

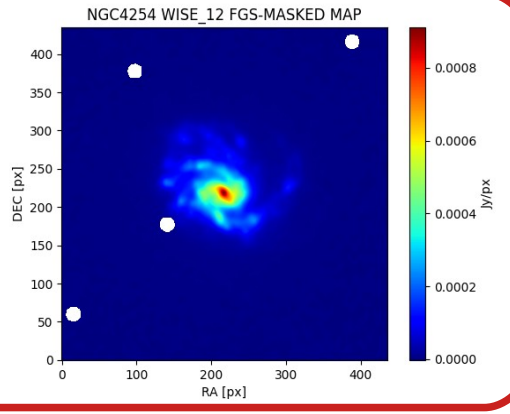


- **Mask bright foreground stars.**
  $mag_{AB}(J) < 12.5$
  (point source catalog by Cutri et al. 2003)

  Important only for λ < 25 μm.

Soon available an updated version **subtracting the foreground stellar flux**

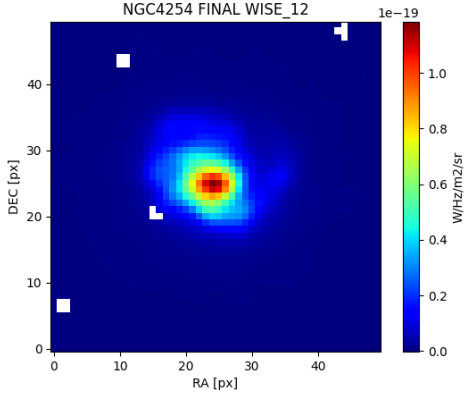
(important if we have bright/saturated stars in front of the galaxy)



- **Convolve the images to SPIRE 500 resolution.** (same resolution)

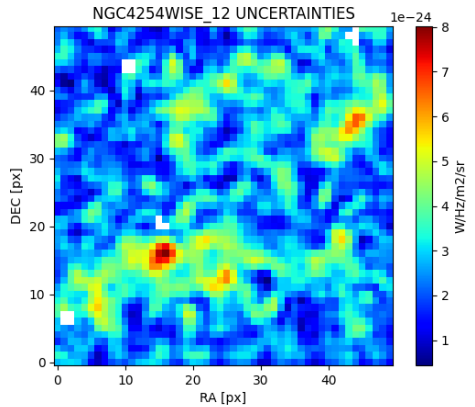
  Astronomical Convolution-kernel repository
  https://www.astro.princeton.edu/~draine/Kernels.html
  (Aniano et al. 2011)

- **Regrid and reproject the maps to the same frame** (same pixel size and orientation)



- **MC for estimating the uncertainty maps .** (see uncertainty workshop on Wednesday)

  Uniform noise is assumed when error maps are not available.



In the process, the maps are also cut to the same size and converted to the same units (W/m^2/Hz/sr).

HerBIE

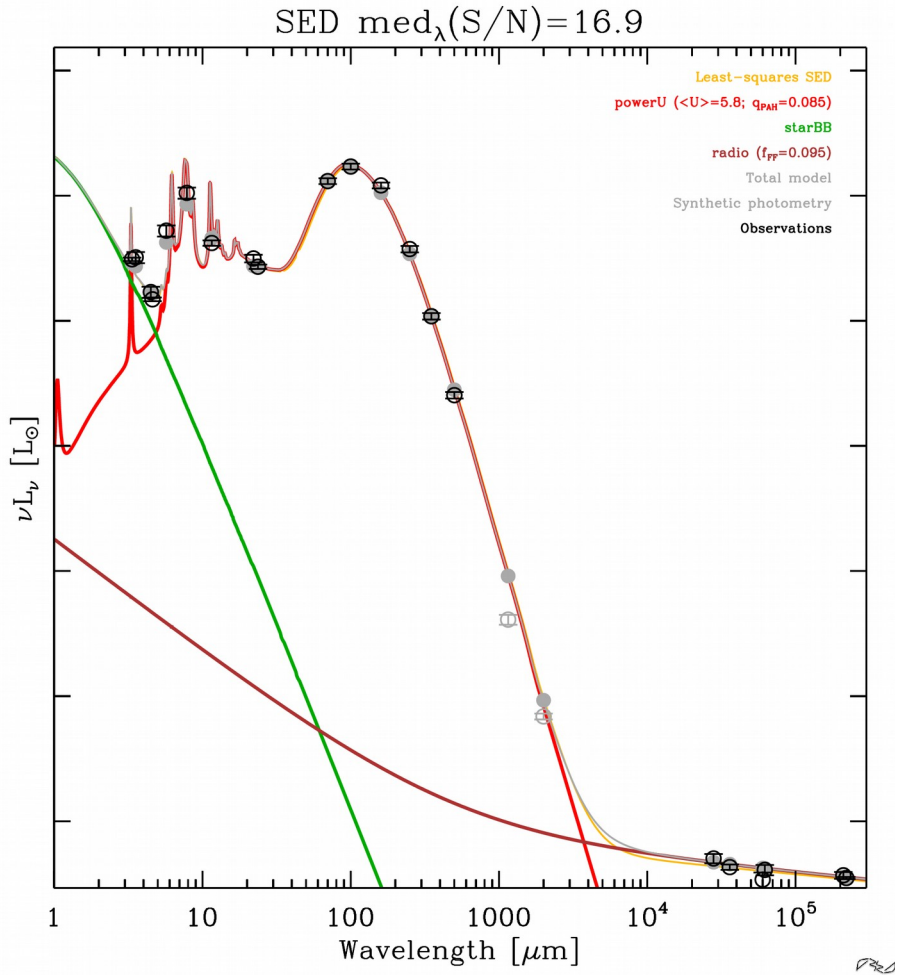
Hierarchical Bayesian Inference for dust Emission (Galliano 2018)

- We use **HerBIE to fit dust SED**.
- It has a multi-level approach : the distribution of dust parameters are controlled by a set of hyperparameters.
- It includes the stochastic heating of ISD grains and accounts for the mixing of physical conditions in the observed regions.
- Initial conditions given by chi^2 analysis.
- HerBIE returns the **pdf and the map of dust parameters along with their uncertainties** (noise and calibration).

THEMIS

The Heterogeneous dust Evolution Model for Interstellar Solids (Jones et al. 2017)

- THEMIS is a dust evolution model anchored to the laboratory-measured properties of ISD analogues (i.e. amorphous hydrocarbons and silicates).
- It provides HerBIE with **realistic ISD grains optical properties**.



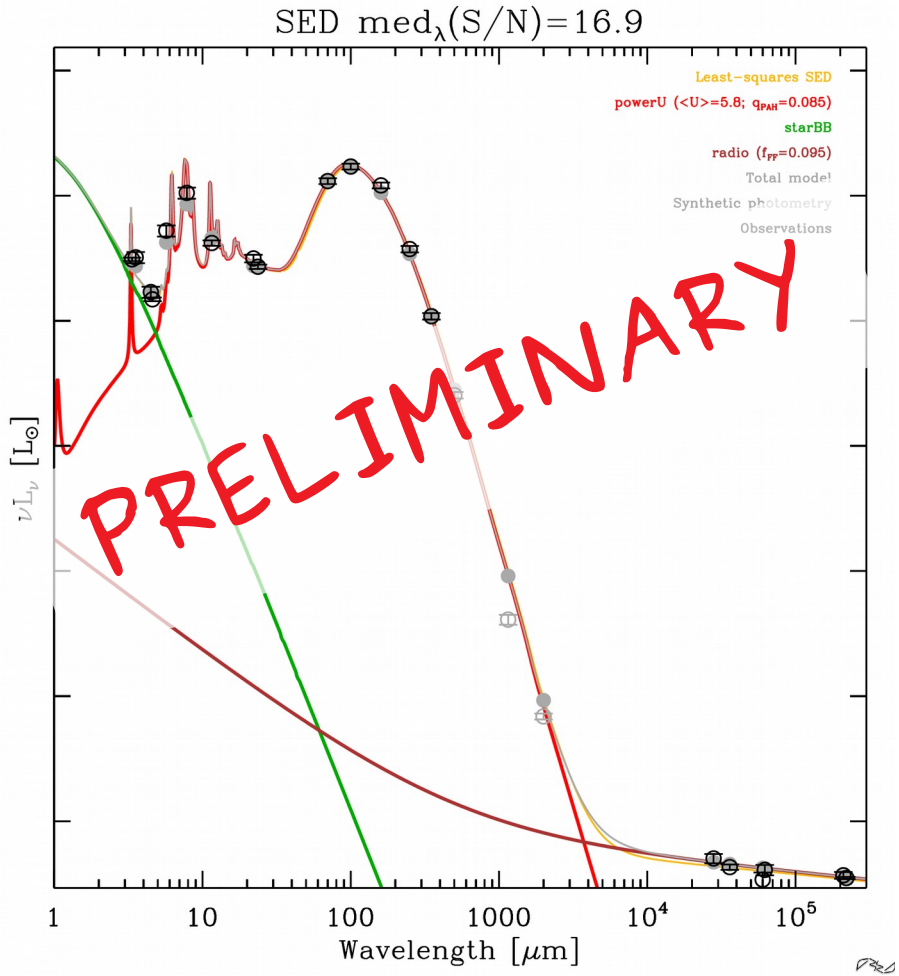
M99 integrated SED (HerBIE)

We integrate the fluxes over a **semi-major axis of 210"** (~ 3.5 arcmin ; axial ratio ~ 1.35 ; Clarck et al. 2018), on the bkg-subtracted maps.

- Photometry checked against DustPedia values.
- Inter-calibration between different filters at the same λ (e.g., IRAC – WISE).

We do not include in the fit **NIKA2 photometry** (**grey empty circles**).

NIKA2 filters out scales larger than ~ 5 arcmin. IMEGIN team is working for recovering the missing flux.



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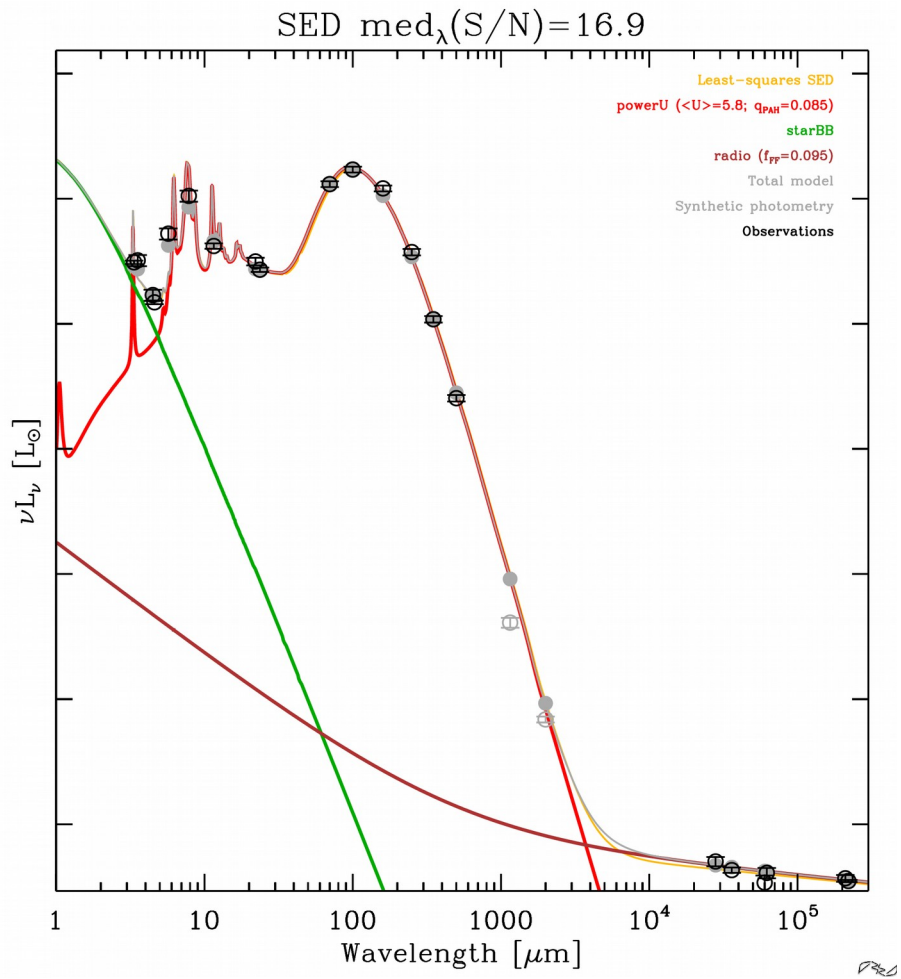
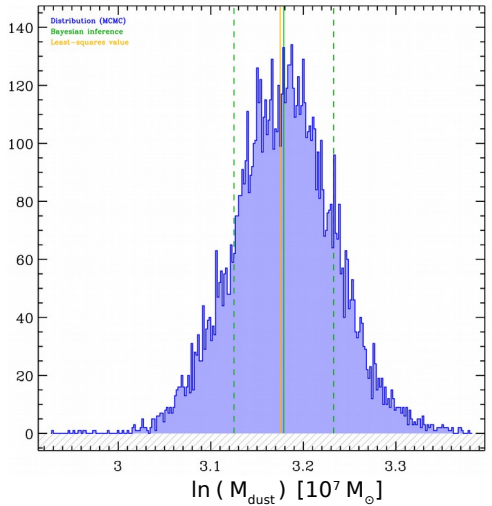


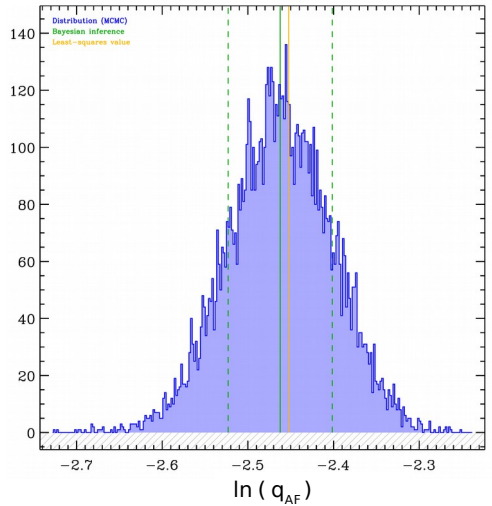
M99 integrated SED (HerBIE)

10 000 MCMC runs.

Probability distribution function of free parameters, e.g. :



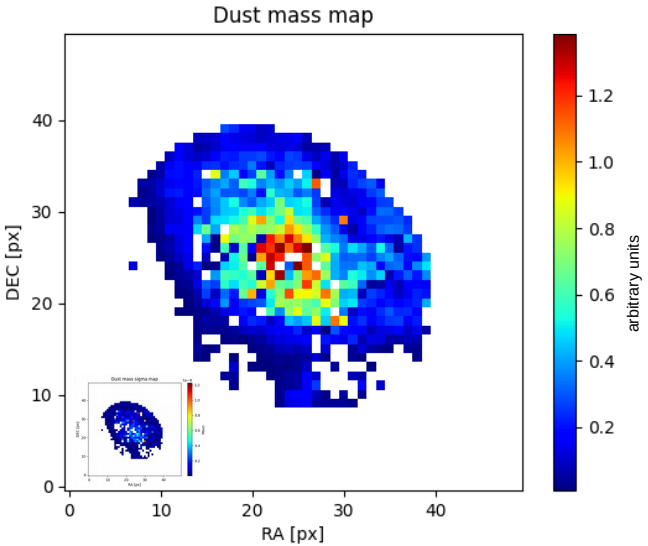
$M_{dust} \sim 10^8\ M_\odot$



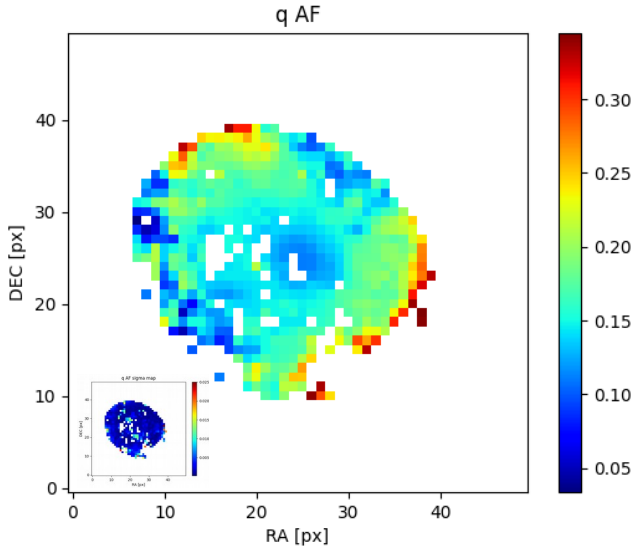
$q_{AF} \sim 0.09$

M99 spatially-resolved maps

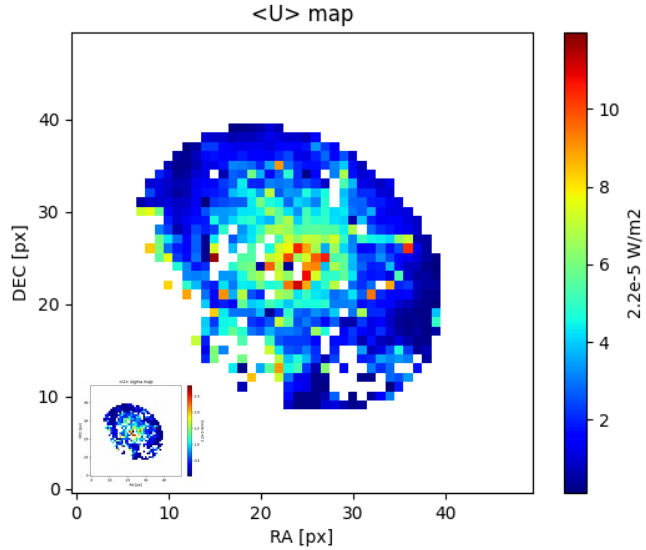
Pixel-by-pixel SED fit of M99 (performed with HerBIE) allows us to investigate the spatial distribution of the main parameters characterizing ISD emission in the galaxy.



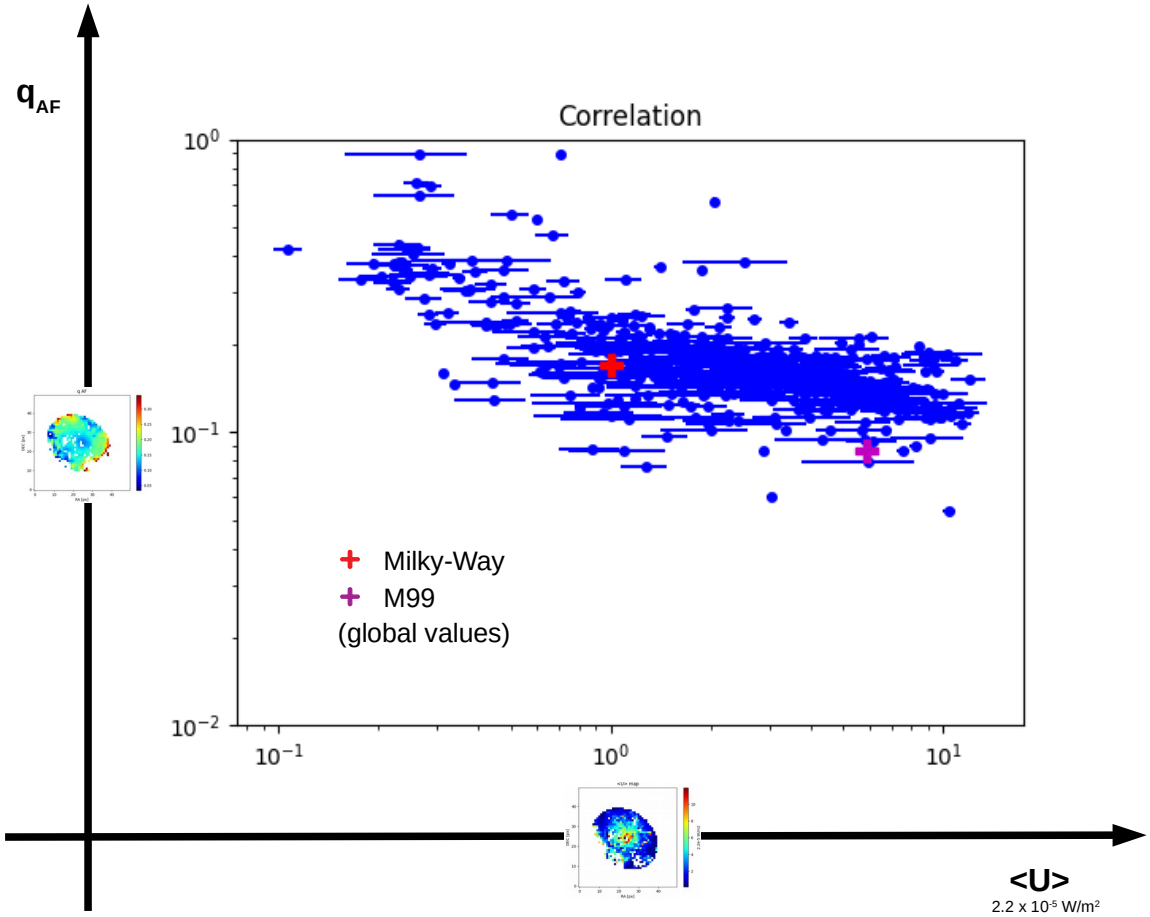
- Dust mass (dominated by large grains) is mostly located in the central part of the M99.



- Small grains carrying aromatic features (i.e., the fraction of is q_{AF}) are located preferentially in the periphery of M99.



- The averaged interstellar radiation field (ISRF), i.e. <U>, peaks in the center of M99 and progressively decreases towards the periphery.



- It results in an **anti-correlation** between aromatic features carriers and the strength of the interstellar radiation field.
- In hard radiation field conditions, **small dust grains are very efficiently depleted**.
- The anti-correlation is also observed in other nearby galaxies / SF regions (e.g., M83, M82, M51, M17, 30 Dor, Orion bar).

Summary

- I have presented some **preliminary results** of an ongoing project aimed at studying the global and local properties of ISD in nearby galaxies, by fitting their SED with the hierarchical bayesian code **HerBIE** (Galliano 2018), where we included the prescriptions of **THEMIS** (Jones et al. 2017), a dust evolution model anchored to the laboratory-measured properties of ISD analogues .
- Focusing on **M99**, I have shown that this approch allows us to get the most important **ISD parameter maps** (e.g., dust mass, mean ISRF, fraction of small grains) and it is effective in retriving the typical pysically-motivated **correlations** between the parameters.

What's next ?

We plan to :

- **include NIKA2 maps** in our analysis (IMEGIN ; PI Madden) ;
- extend the analysis to **other galaxy types**, e.g. dwarf galaxies (*Submillimeter Excess In Nearby Fairly-Extended Low-metallicity Dwarfs*; IRAM 30m proposal, PI Galliano).

- **NIKA2 pool observations**: now until february 2023.
- Other **NIKA2 publications** (in prep): NGC891 (Katsioli et al.) & NGC6946 (Ejlali et al.).
- First full *IMEGIN consortium meeting*, spring 2023: (funded by: OSUPS + possibly PCMI).