ICED: IAS/CEA Evolution of Dust in Nearby Galaxies

A talk by **Lara Pantoni** (Postdoc at CEA, Paris-Saclay, France)
on behalf of the NIKA2 collaboration

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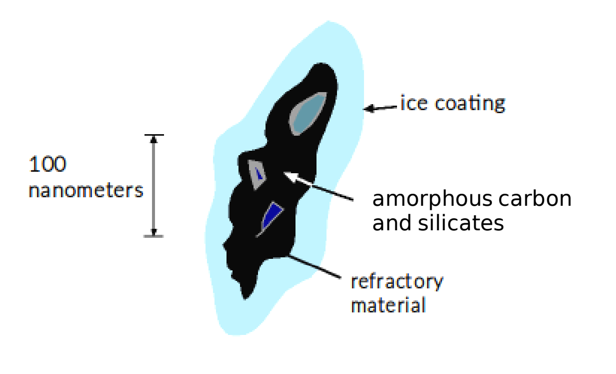
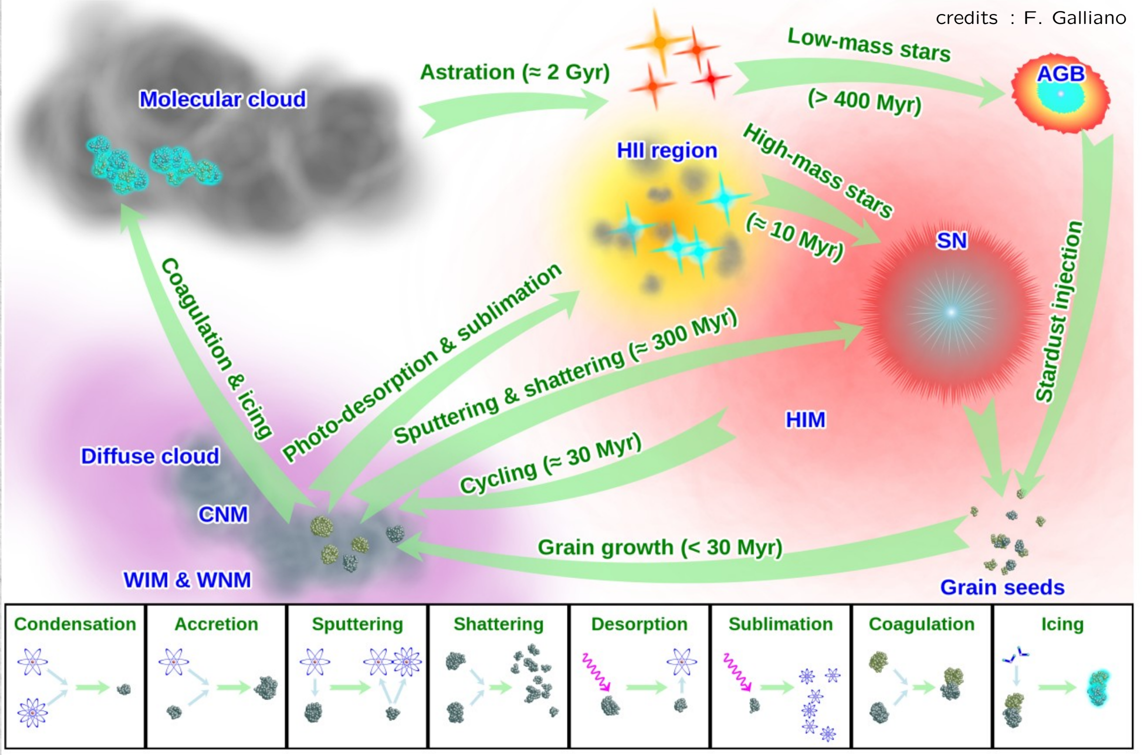
Introduction: Interstellar Dust grains

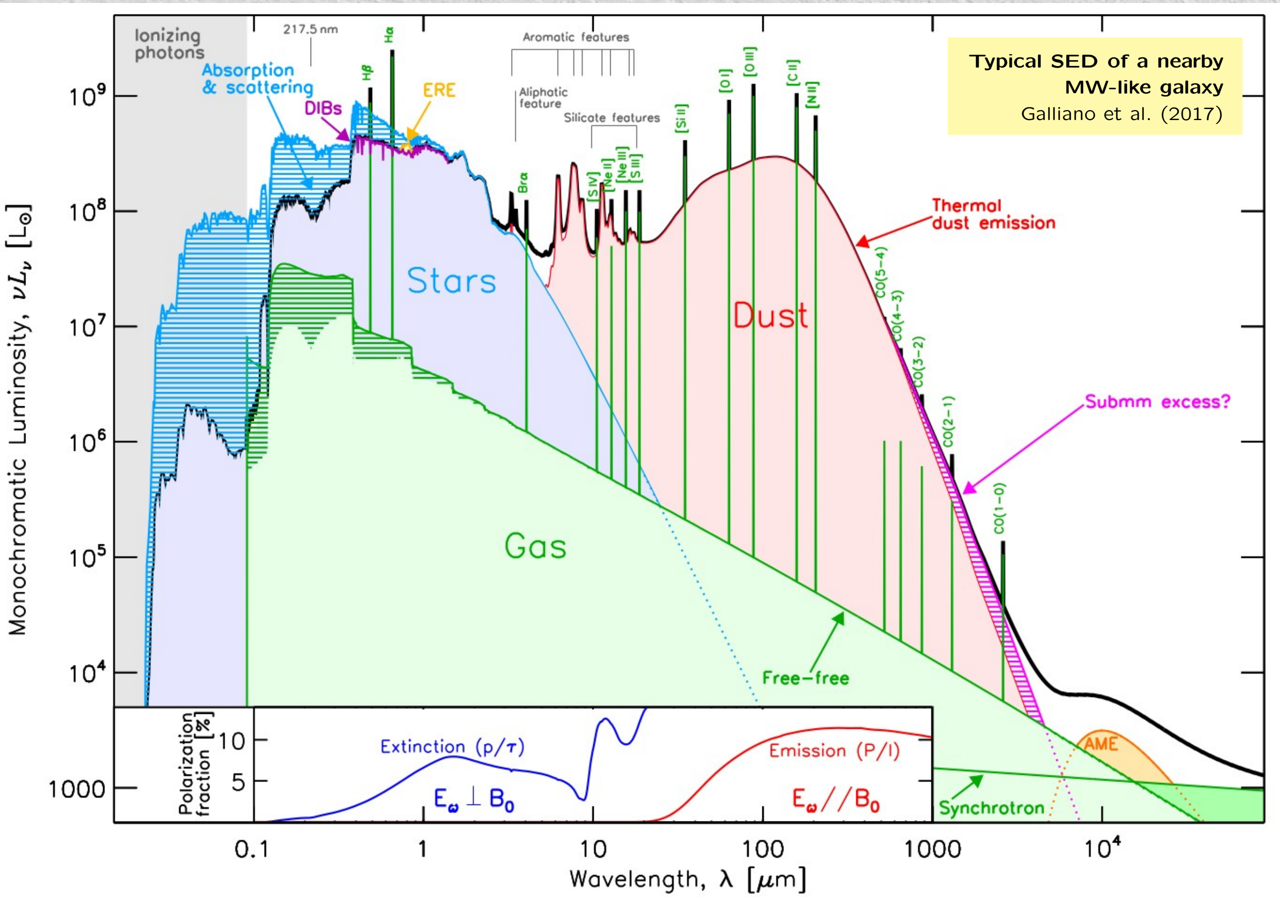


ISD grains are :

- 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.



Introduction: Interstellar Dust in galaxies



- 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).
- In the mm regime, the **submm excess** and the **AME** are thought to be linked with the presence of **very cold dust** and **spinning dust grains** (respectively; Galliano+18, Ysard+22).

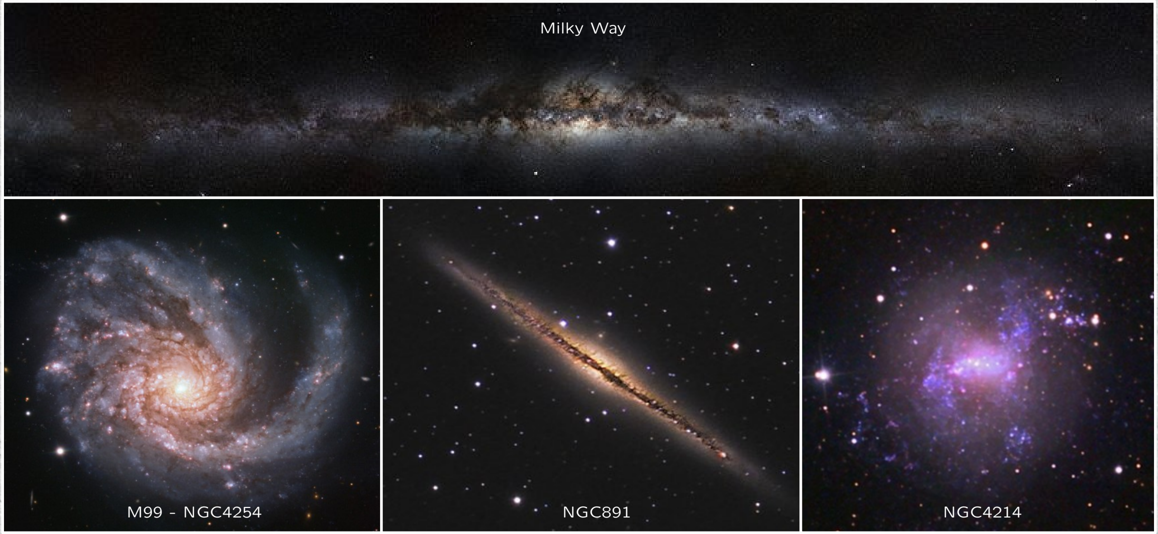
Introduction: why Nearby Galaxies?

Most of our knowledge of ISD properties comes from studies of the **Milky Way**.
(Draine 2003[a], Galliano, Galametz & Jones 2018)

MW hosts a **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.

credits : ESO; NASA/ESA



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

- Faced-on galaxies $\rightarrow$ **clearer sightlines**.
- Edge-on galaxies $\rightarrow$ **high vertical distances**.
- Blue Dwarfs ; bright AGNs ; low Z objects
  $\rightarrow$ probe ISD in **extreme conditions**.
- Intermediate step towards understanding ISD and ISM in **distant galaxies**.

ICED: main objectives

- 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 **NGC4254** (Pantoni et al. in prep.).

Tools :

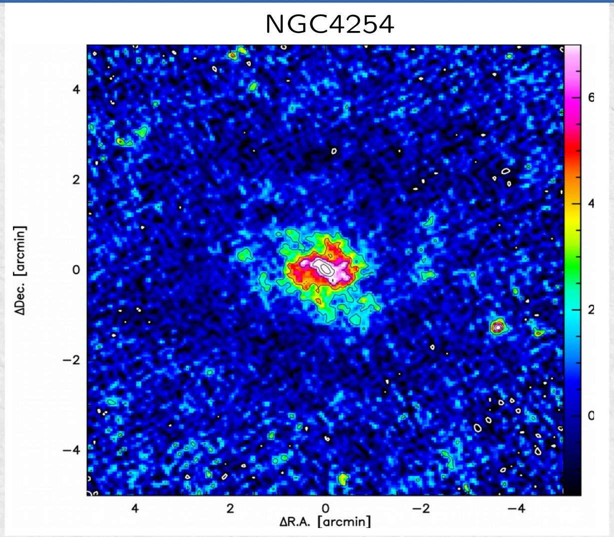
- **1.15 - 2 mm continuum maps** acquired at the IRAM-30m telescope with **NIKA2** (***IMEGIN*** *Guaranteed Time Large Program* - P.I. Madden; see also Perotto+20, Adam+18, Calvo+16, Bourrion+16).
- NIKA2 data complemented by the multi-wavelength images of the ***DustPedia*** sample.
- SED modelling performed with the ***THEMIS*** dust evolution model (Jones et al., 2017) within the hierarchical Bayesian SED fitting code ***HerBIE*** (Galliano, 2018).

IMEGIN LP: NGC4254 NIKA2 maps

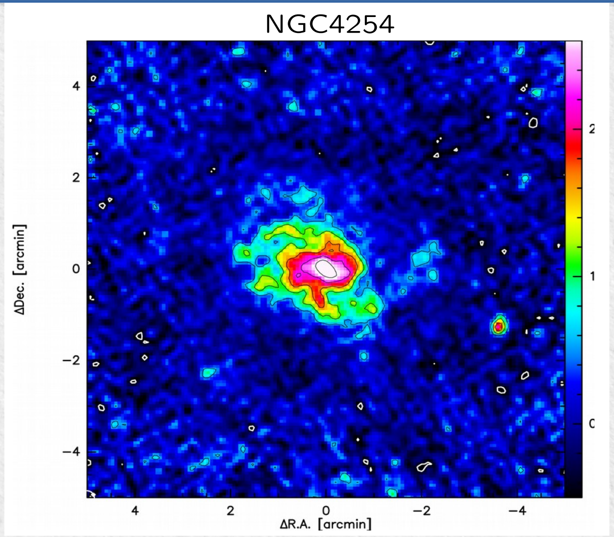
NIKA2 Guaranteed Time Large Program for Interpreting the Millimetre Emission of Galaxies (PI: Madden)

NIKA2 (IRAM 30m) observes @ **1.15** and **2 mm**, with angular resolution of **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 (e.g., opacity, dust-to-gas ratio, submm excess).



NIKA2 1.15mm (IRAM 30m)
θ_{res} [arcsec] ~ 12
rms ~ 0.8 mJy/beam



NIKA2 2mm (IRAM 30m)
θ_{res} [arcsec] ~ 18
rms ~ 0.24 mJy/beam

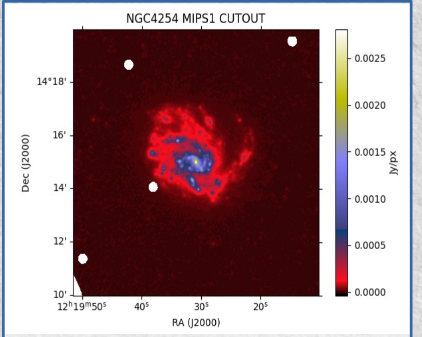
Preliminary NIKA2 maps of NGC4254.

See Perotto+20, Adam+18, Calvo+16, Bourrion+16.

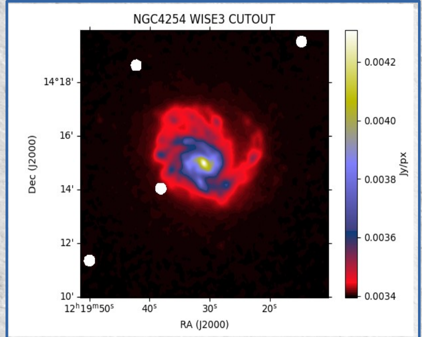
NIKA2 data were reduced with **PIIC** (Zylka 2013) by C. Kramer.

Ancillary data (NGC4254)

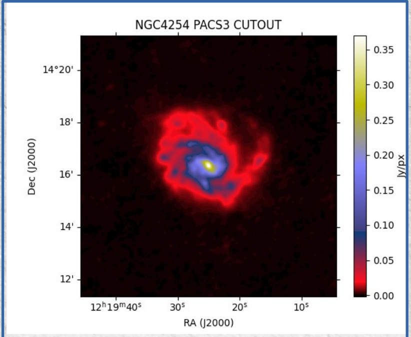
DustPedia archive provides access to multi-λ imagery and photometry for 875 nearby galaxies.
We take advantage of this archive for collecting **NGC4254's IR maps** (for ISD SED fitting).



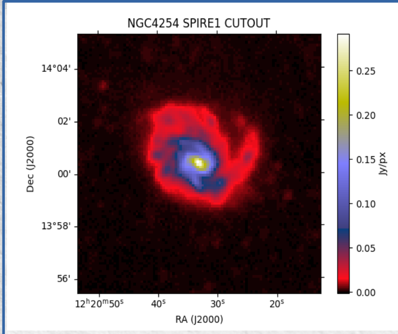
- **Spitzer IRAC 3.6, 4.5, 5.8, 8** (µm)
  θ_{res} [arcsec] ~ 1.66, 1.72, 1.88, 1.98
- **Spitzer MIPS 24** (µm)
  θ_{res} [arcsec] ~ 6



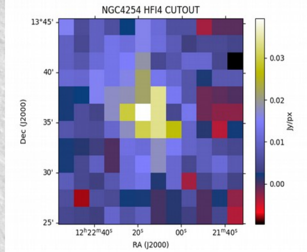
- **WISE 3.4, 4.6, 12, 22** (µm)
  θ_{res} [arcsec] ~ 6.1, 6.4, 6.5, 12



- **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



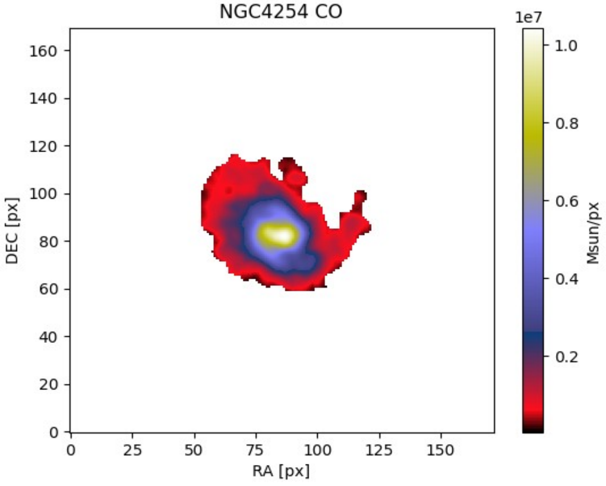
- **Planck 350, 550, 850, 1380** (µm)
  θ_{res} [arcmin] ~ 5
  Due to the scarce angular resolution, we use Planck maps only for the global SED modelling and for inter-calibration (SPIRE, NIKA2).

DustPedia

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

Ancillary data (NGC4254)

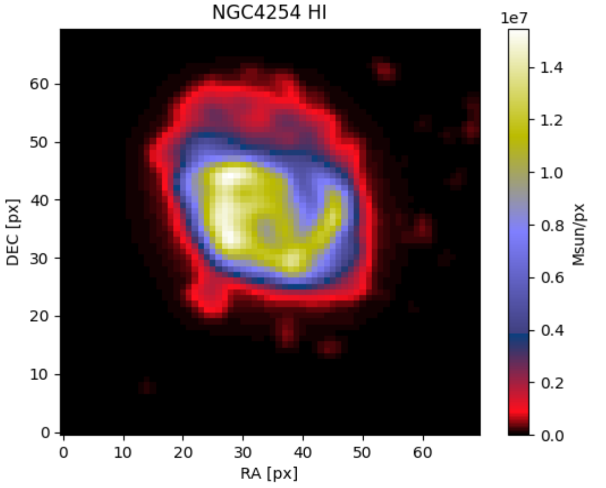
- **Radio** maps at 3 and 6 cm (VLA + Effelsberg; Chyzy et al. 2007) for free-free and synchrotron fitting;
- **CO**(1-0), (2-1), (3-2) and **HI** maps → molecular and neutral hydrogen maps;
- GALEX + IRAC1 and MIPS1 maps → **stellar mass** and **SFR** maps (calibrations by Leroy et al. 2008).



CO(1-0) EMPIRE-IRAM 30m

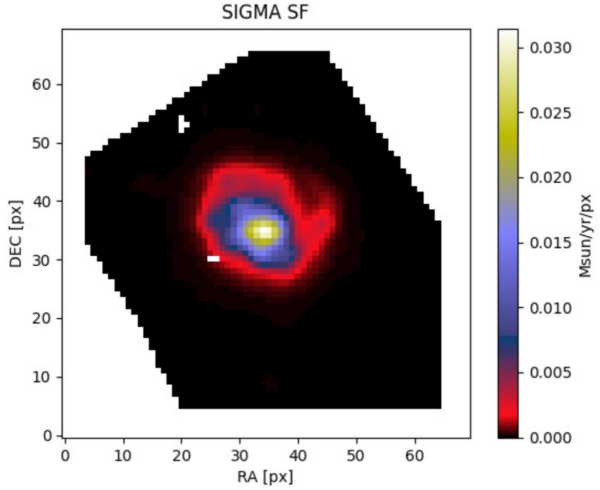
θ_{res} [arcsec] ~ 27

(Jiménez-Donaire+19)



HI VIVA-VLA θ_{res} [arcsec] ~ 30

(Chung+09)



SFR density

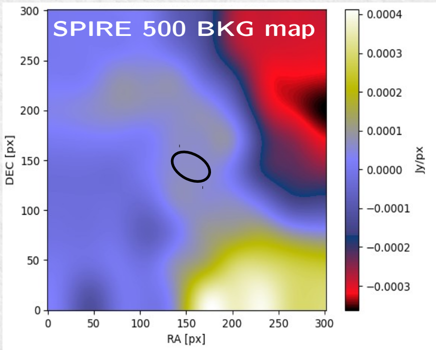
GALEX FUV + MIPS 24

(Dustpedia + calibration by Leroy+08)

Homogenization of IMEGIN Photometry (HIP)

The 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 quantities.

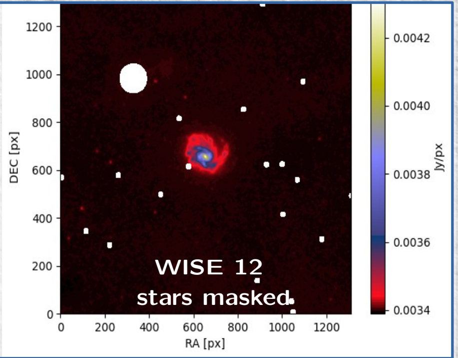
- **Background and foreground subtraction.**
  - Foreground large scale emission (e.g. Galactic cirrus in the MIR-submm, sky brightness in the NIR).
  - Unresolved background sources.
  - Any instrumental gradient.



Pantoni et al. in prep.

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

  Important only for $\lambda < 25$ µm.



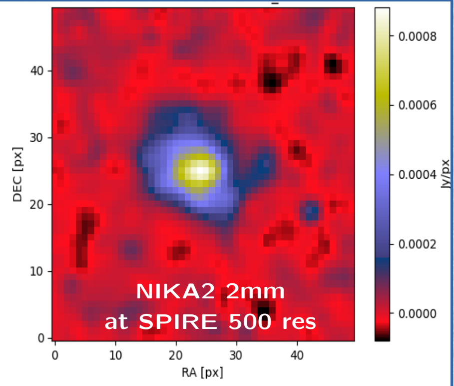
Homogenization of IMEGIN Photometry (HIP)

Pantoni et al. in prep.

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

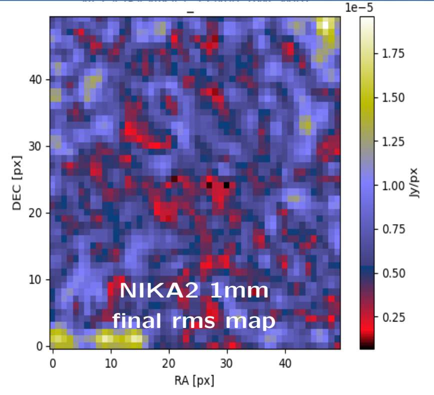
  Astronomical Convolution-kernel repository
  (Aniano et al. 2011)

- **Regridding and reprojecting the maps to the same frame**
  (same pixel size and orientation)



- **Subtracting CO(2-1) emission in the 1.15 mm continuum (NIKA2)** using the approach presented in Drabek et al. (2012).

- **Monte Carlo method for propagating uncertainties** through map homogenisation and estimating the final uncertainty maps.



Methods: dust SED fitting and modelling

We use **HerBIE** **(Galliano 2018)** to fit the dust SED of NGC4254.

HerBIE is a hierarchical bayesian SED fitting code which:

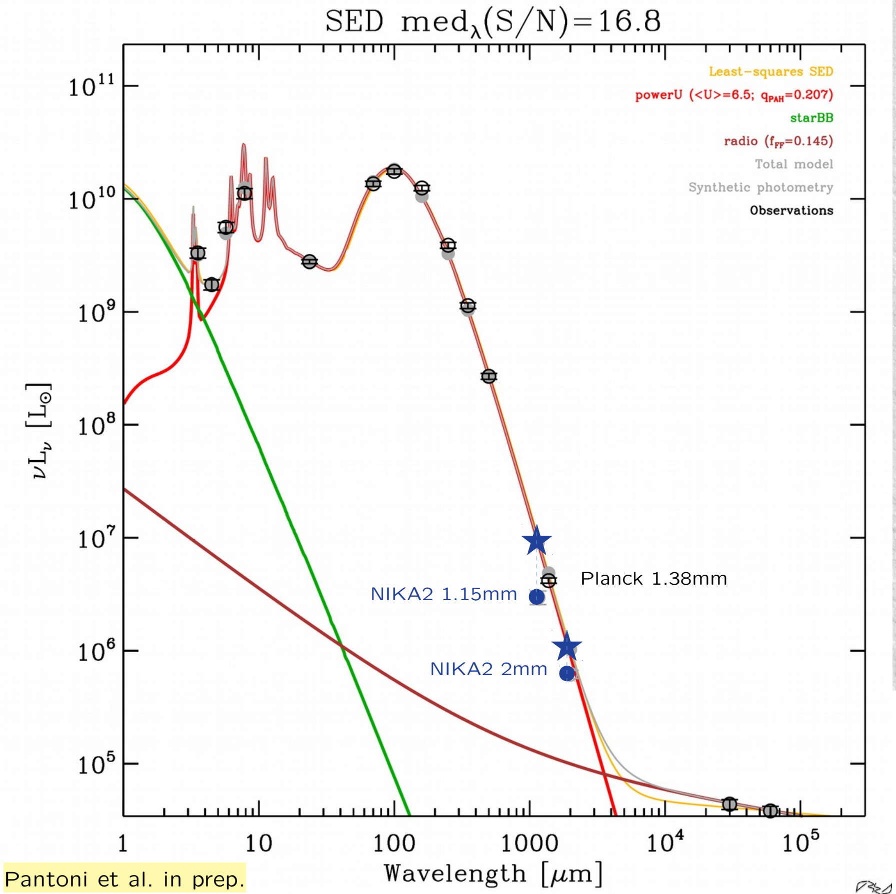
- allows for the use of a **non-uniformly illuminated dust mixture** (free parameters : $\mathbf{M_{dust}}$, $\langle \mathbf{U} \rangle$, $\mathbf{q_{AF}}$) ;
- includes **Near-IR** emission by **stellar populations** (BB of given T) ;
- includes **free–free** and **synchrotron** continua (radio).

HerBIE returns the **pdf,** the **map of dust parameters** and **their uncertainties** (noise and calibration).

HerBIE incorporates the state-of-the-art dust model **THEMIS** **(Jones et al. 2017)**.

- THEMIS dust mixture consists of core-mantle carbon and silicate grains.
- The model is anchored **to the laboratory-measured optical properties** (e.g., Q_{ex}, n) of ISD analogues (i.e. amorphous hydrocarbons and amorphous silicates).

NGC4254: large-scale emission filtering



Pantoni et al. in prep.

Large-scale filtering may occur when observing extended sources with ground-based observatories, as a side consequence of removing the atmospheric noise on large angular scales (e.g., Sadavoy+13; Smith+21; Pattle+23).

By comparing NGC4254 **NIKA2 1.15mm** global flux and Planck 1.38 mm (corrected for filter shape and central wavelength), we find that **more than 60% of the flux is filtered-out**:

→ in accordance with NGC6946's transfer function (IMEGIN; Ejiali et al. in prep.);
→ we find consistent values of filtered-out flux when we compare with the flux predicted by the model.

NIKA2 2mm loss is ~ **40%**.

Global SED fit with HerBIE

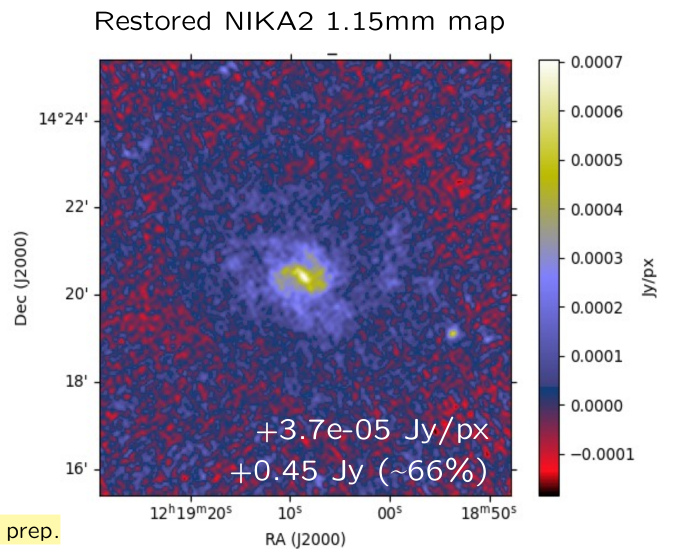
- HFI4 included;
- NIKA2 measured (circles), expected (stars).

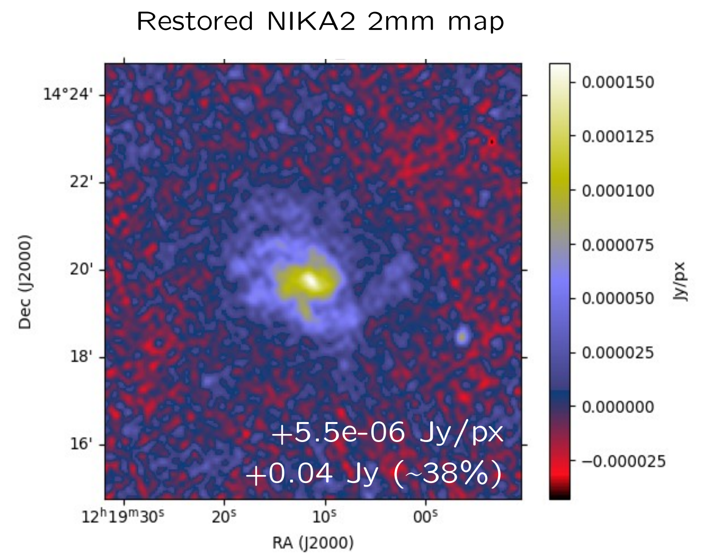
NGC4254: large-scale emission filtering

A possible approach consists in developing some **techniques for restoring the filtered-out flux** taking advantage of **space observatories (e.g. Planck)** observing in the same wavelength range.

I. UNIFORM FLUX REDISTRIBUTION

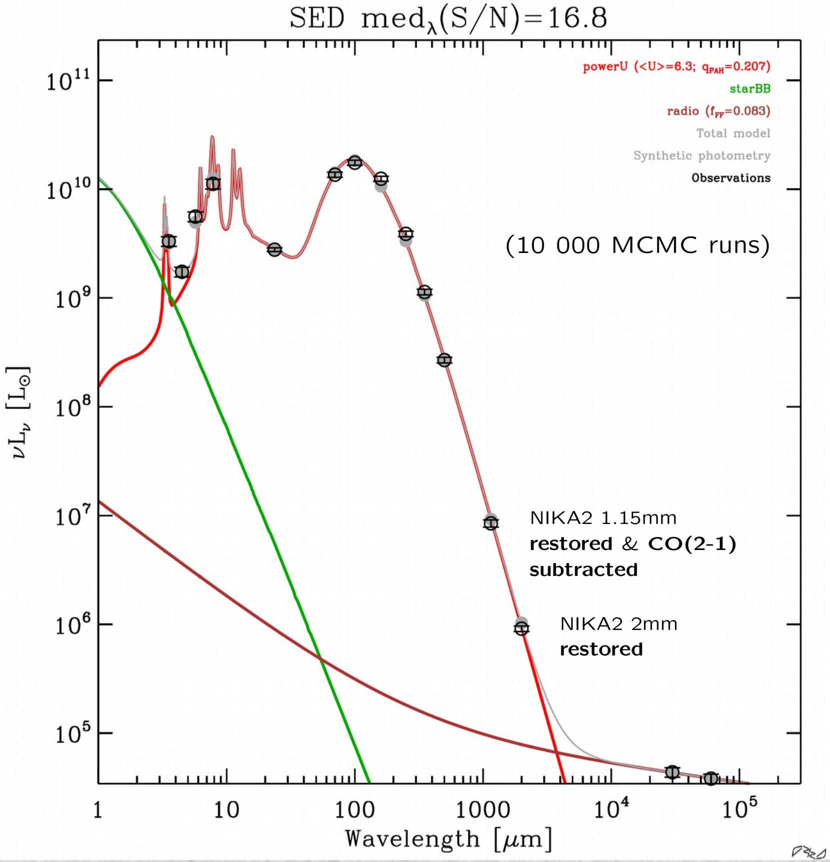
The basic idea is redistributing uniformly the amount of flux that is filtered out on a global scale, by comparing with Planck HFI4 (1.38 mm).





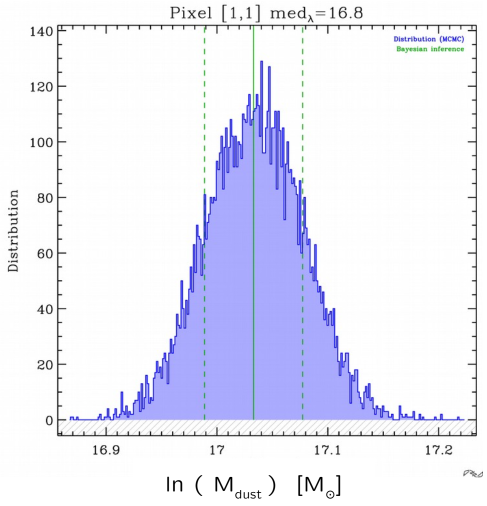
Pantoni et al. in prep.

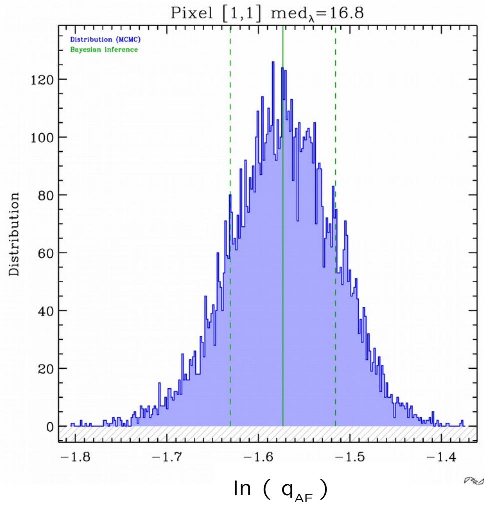
Preliminary results: integrated SED



Global photometry is computed on the same DustPedia ellipse; values were checked against literature.

The **SED fitting with Herbie** (Galliano+18) gives the probability distribution function of free parameters, e.g. :





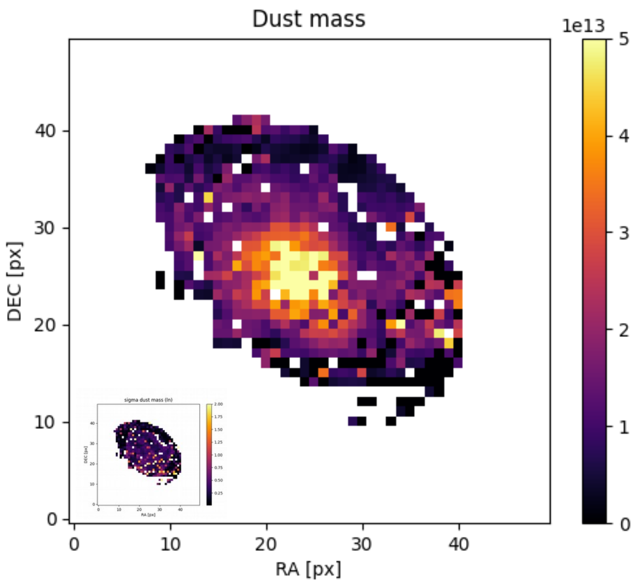
$M_{dust} = (2.5\pm0.1)\times10^7\ M_\odot$

$q_{AF} = 0.2\pm0.01$

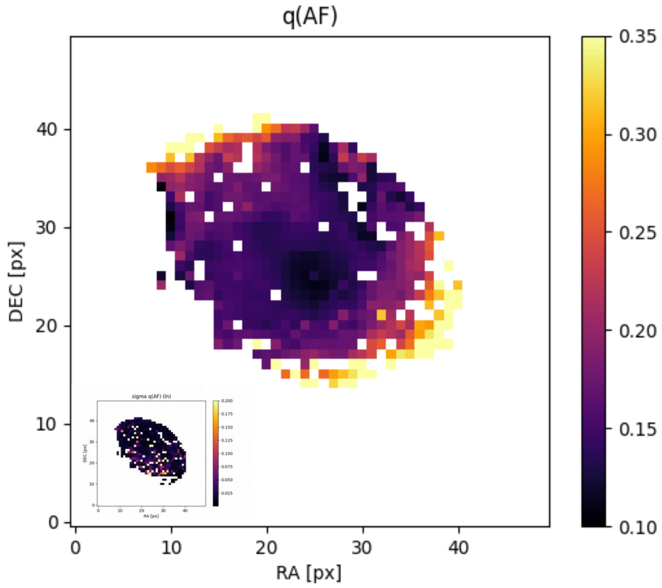
Pantoni et al. in prep.

Preliminary results: spatially resolved analysis

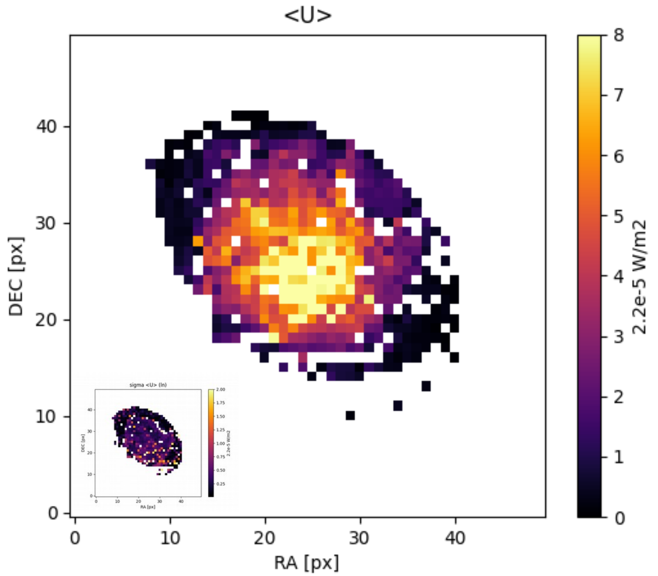
Pixel-by-pixel SED fit of **NGC4254** (performed **with HerBIE**, 7.4e7 runs) allows us to study the spatial distribution of the main parameters characterizing ISD emission in the galaxy.



- Dust mass (dominated by large grains) is mostly located in the central part of the NGC4254.



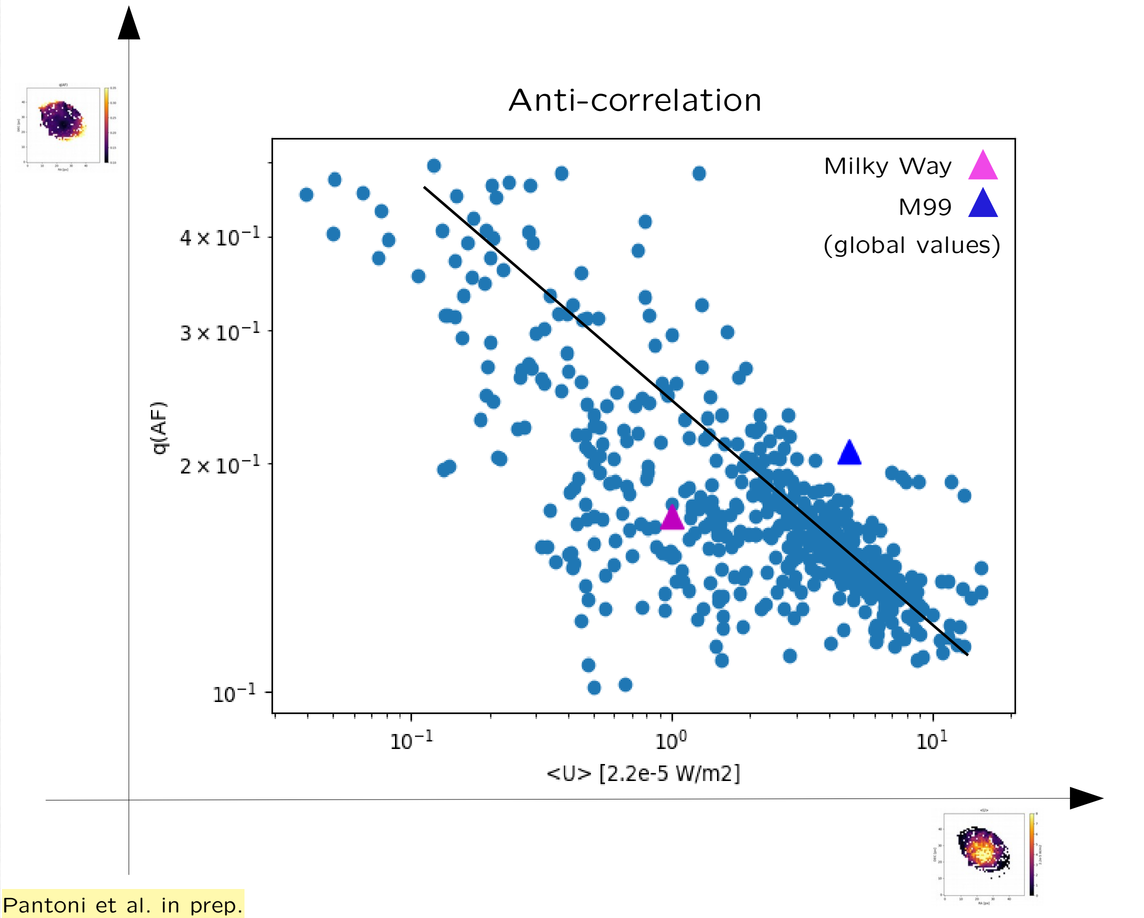
- Small grains carrying aromatic features (i.e., the fraction of is q_{AF}) are located preferentially in the periphery of NGC4254.



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

Pantoni et al. in prep.

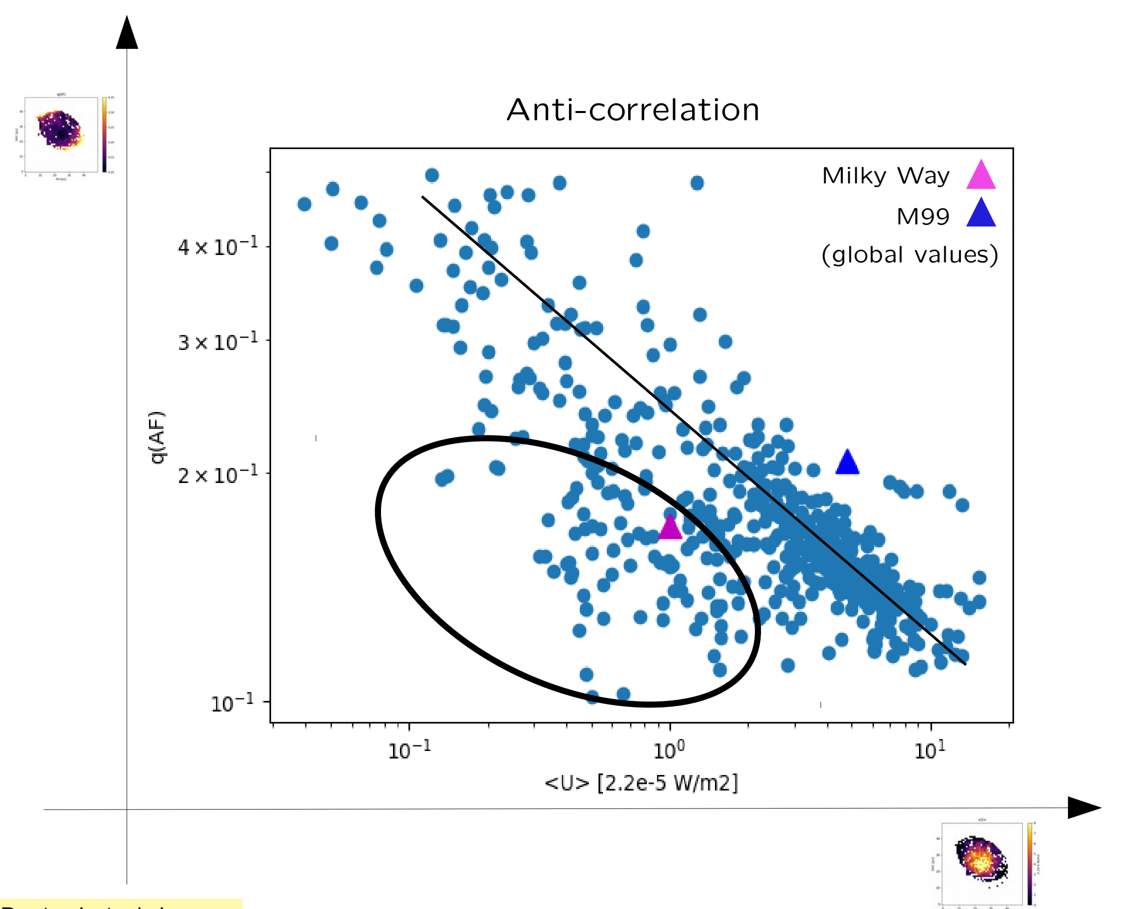
Preliminary results: spatially resolved analysis



Pantoni et al. in prep.

- 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).

Preliminary results: spatially resolved analysis

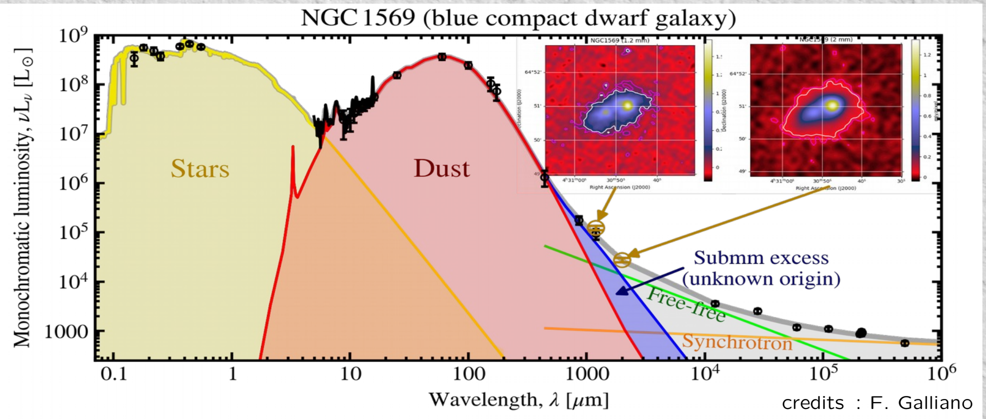


Pantoni et al. in prep.

- At **lower radiation field** intensities, small grains are not efficiently destroyed.
- In low radiation field conditions, observing a small fraction of AF carriers may indicate that **small grains** are depleted because of **coagulation onto larger grains**.
- This implies some changes in **FIR dust grain SED** (e.g., emissivity, shifting of the peak, shape of the bump).

Ongoing projects and perspectives

- **HIP** (the **Homogenization of IMEGIN Photometry** post-processing pipeline) is available on GitLab for the IMEGIN team. We are currently working for including NIKA2 flux restoration and CO(2-1) subtraction for correcting NIKA2 1.15mm maps. We are going to **make it publicly available**.
- A. Nersesian et al. (in prep., earlier today): **multi-wavelength morphology of IMEGIN galaxies**.
- G. Ejlali et al. in prep., Friday 30/6/23, 11:10 AM : **NGC2146**, **NGC2976** and **NGC6946**.
- S. Katsioli et al. submitted to A&A, Friday 30/6/23, 11:35 AM : Stratification of ISM properties in **NGC891**.
- Further in-depth with NIKA2 on **dwarf galaxies** (**NGC1569**, **NGC4214**, **NGC4449**) thanks to the ongoing project **SEINFELD** (*Sub-millimeter Excess In Nearby Fairly-Extended Low-metallicity Dwarfs*; PI: Galliano) for constraining the millimeter emission of low metallicity objects.



Summary

- I have presented some **preliminary results** of the ICED project on **NGC4254** (Pantoni et al. in prep.), **part of the IMEGIN NIKA2 LP** (PI: S. Madden), aimed at studying the global and local properties of ISD in nearby galaxies with NIKA2 (IRAM 30m), by **fitting dust SED** with the hierarchical bayesian code **HerBIE** (Galliano 2018) with the prescriptions of the **dust evolution model THEMIS** (Jones et al. 2017), that is anchored to the laboratory-measured properties of ISD analogues.

- Focusing on **NGC4254**, I have described our method for **data homogenization (HIP) and analysis**, along with one approach for dealing with **large scale filtering in NIKA2 maps** (Pantoni et al. in prep.).
- Our method: **1)** allows us to get the most important **ISD parameter maps** (e.g., dust mass, mean ISRF, fraction of small grains);
  2) is effective in retriving the typical **correlations** between free parameters;
  3) allows us to **put constraints on dust evolution** in the diverse local environments within a galaxy (i.e., HII regions, arms, nucleus, halo, disk).
- NIKA2 maps were essential for modelling the dust millimeter emission.

ACKNOWLEDGEMENTS

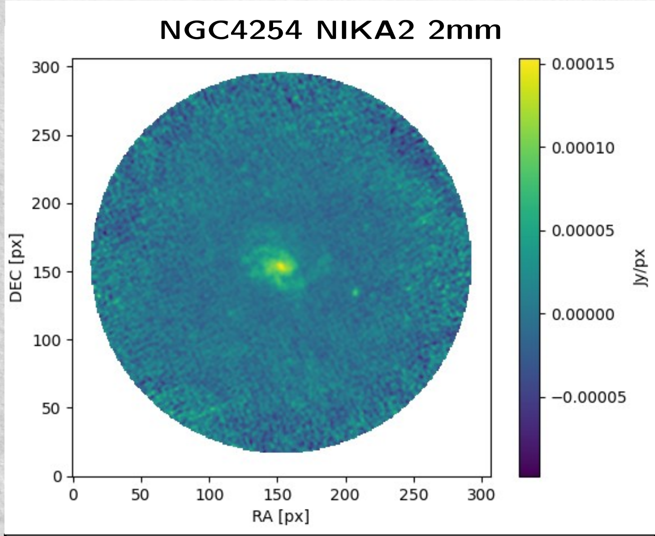
S. Madden, F. Galliano, J. Tedros, A. Nersesian, H. Roussel, C. Kramer, G. Ejlali, S. Katsioli, X. Desert, A. Jones, N. Ysard, M. Smith, M. Xilouris, A. Hughes and NIKA2 collaboration.

Backup slides

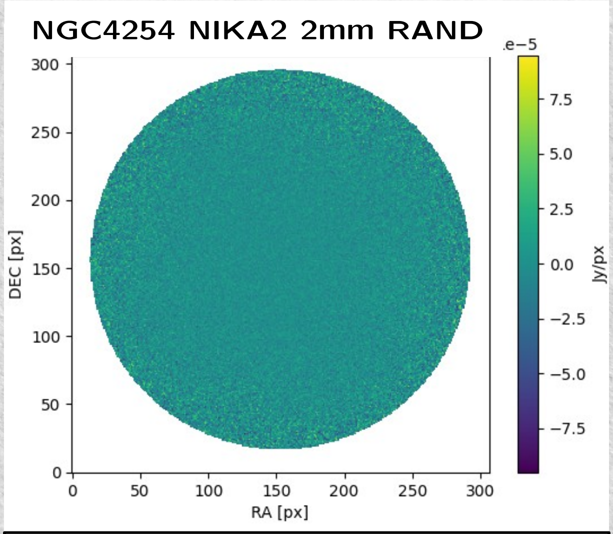
HIP: Monte Carlo for uncertainty propagation

Monte Carlo method (frequentist approach) relies on **random perturbations** that are **added to the data** map for a **number N of iterations**. It accounts for e.g. correlations between pixels.

1) The random perturbation is a random normal distribution centered on zero with standard deviation equal to the original uncertainty (PIIC pipeline) on the data map.



DATA



RANDOM PERTURBATION

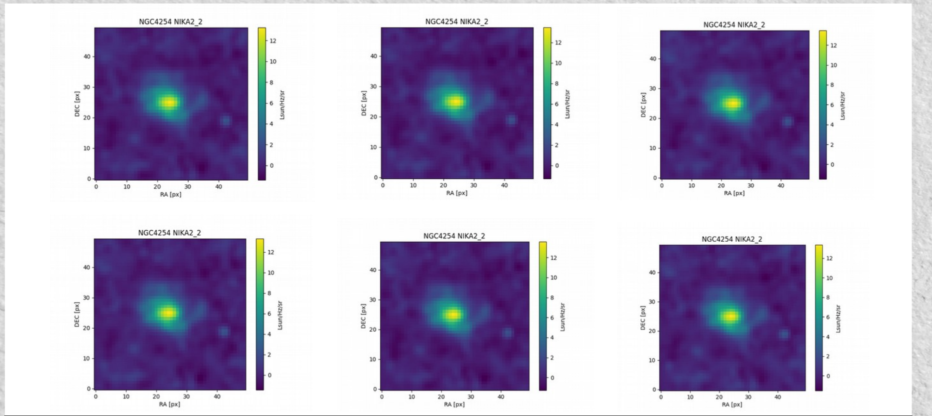
Do it **N times** and **iterate through data processing...**

Pantoni et al. in prep.

HIP: Monte Carlo for uncertainty propagation

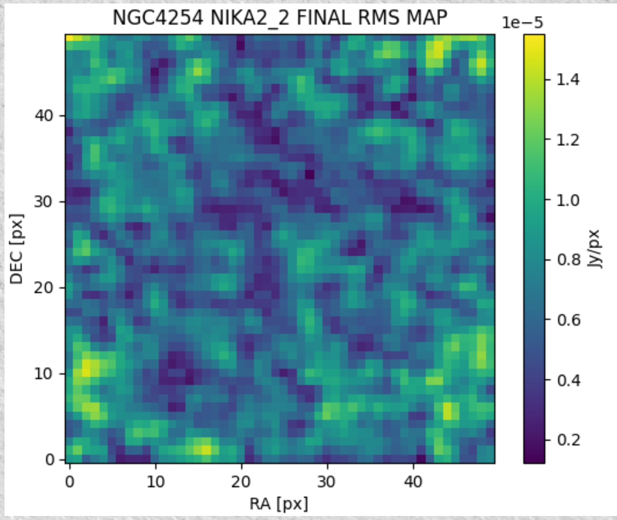
2) After N iterations, we have N perturbed data map that have been processed in the same way.

3) The px-by-px standard deviation of the N data maps gives the **final statistical uncertainty map**.



N random realization of the processed data map

STD



Pantoni et al. in prep.

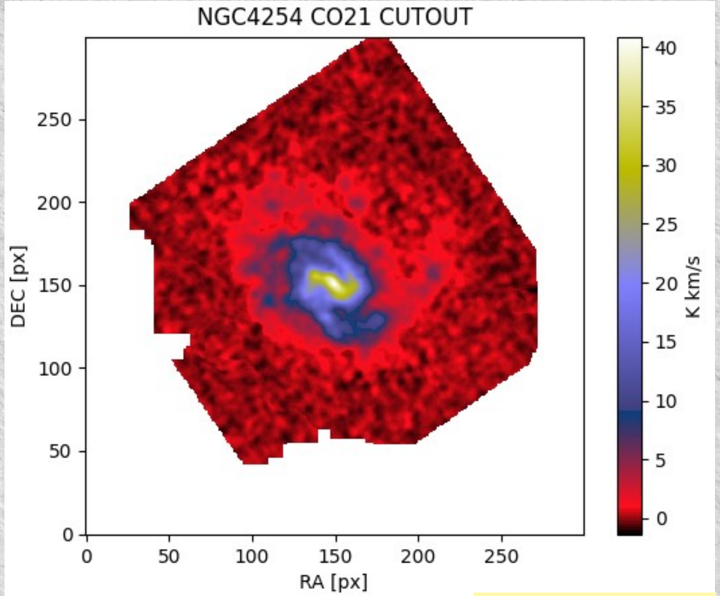
HIP: CO(2-1) subtraction

This step allows us to correct for the CO(2-1) continuum contamination at 1.15 mm (NIKA2). In case of large-scale emission filtering, it is applied on the *restored* NIKA2 map (where the lost flux is added back). Uncertainties are propagated through MC method.

For NGC4254, we use the CO(2-1) map from HERACLES (Leroy+09), and equation (8) in Drabek+12:

$$\frac{C}{\mathrm{mJy\ beam^{-1}\ per\ K\ km\ s^{-1}}} = \frac{F_\nu}{\int T_{\mathrm{MB}}\,\mathrm{d}v} = \frac{2k\nu^3}{c^3}\frac{g_\nu(\mathrm{line})}{\int g_\nu\,\mathrm{d}\nu}\Omega_{\mathrm{B}}, \quad (8)$$

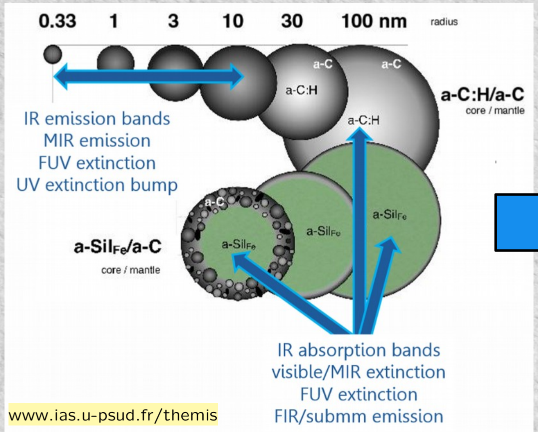
where frequencies are measured in GHz and $1\,\mathrm{Jy} = 10^{26}\,\mathrm{W\,m^2\,Hz^{-1}} = 10^{23}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$.



Pantoni et al. in prep.

The global flux at 1.15mm (NIKA2) corrected for CO(2-1) contamination is ~ 0.63 Jy, against the original ~ 0.69 Jy (restored). CO(2-1) contribution to NIKA2 1mm is ~ **9%**.

Methods: dust SED fitting and modelling



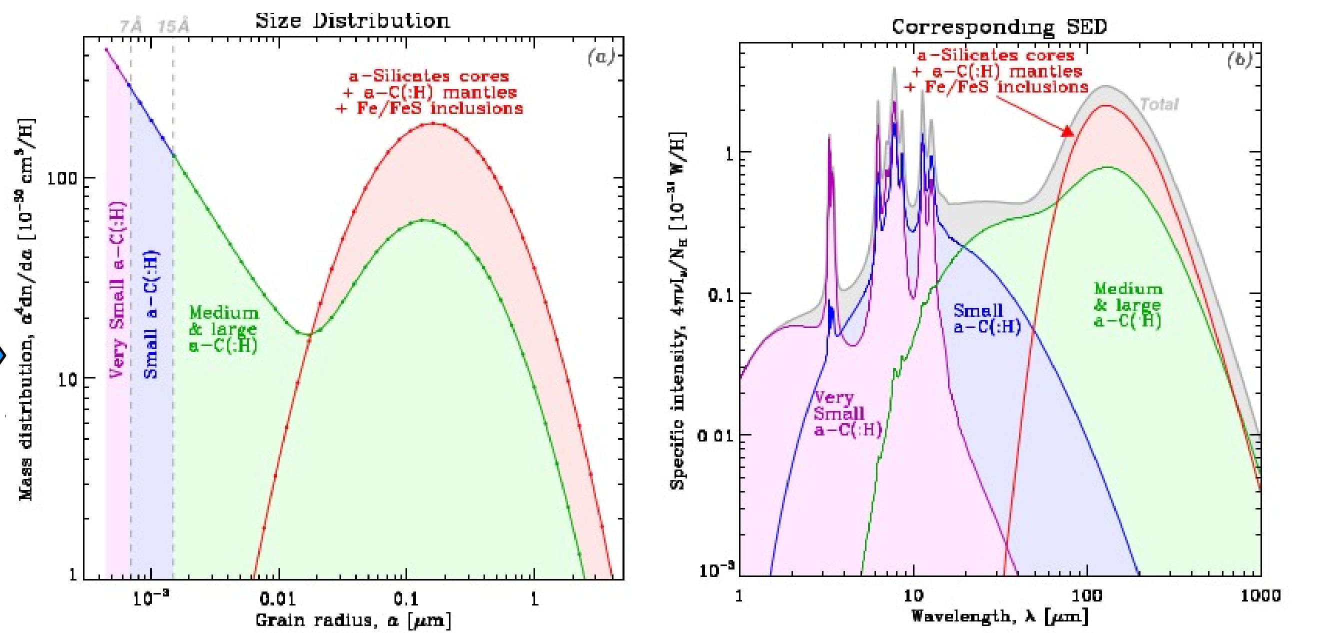
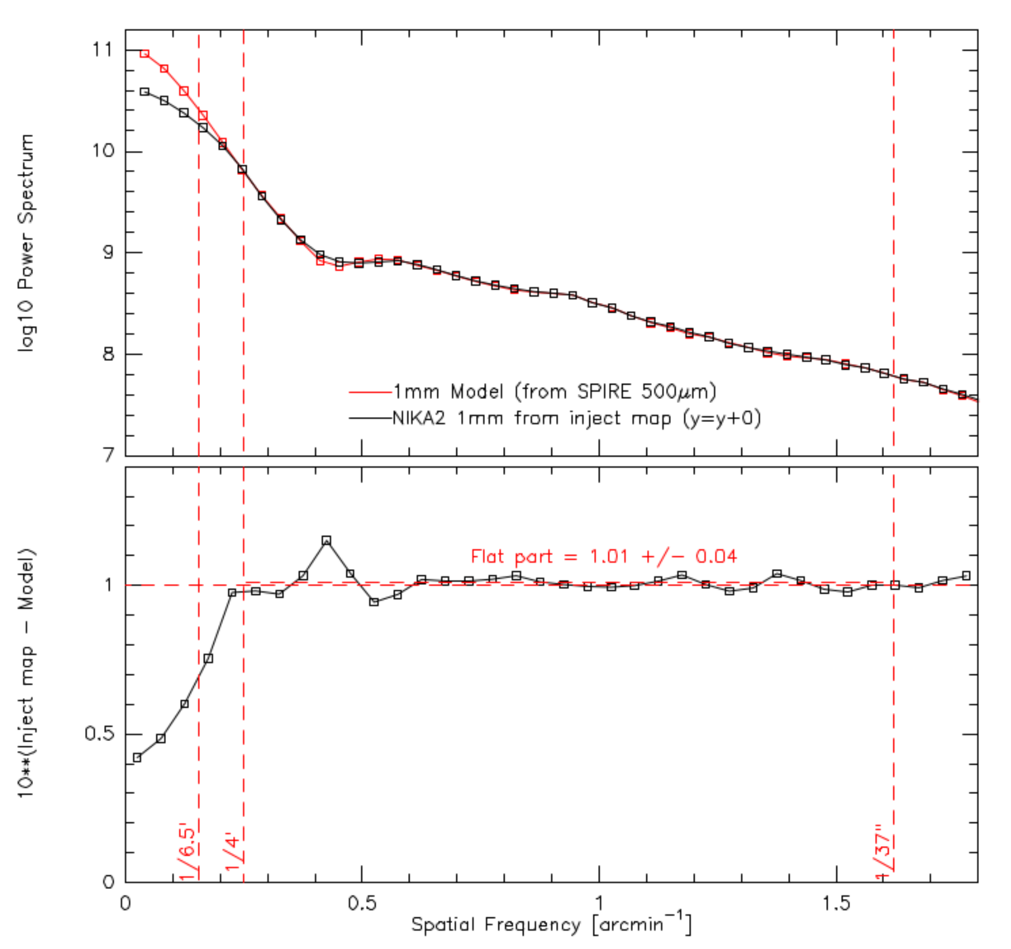


Fig. 1. *Parametrization of the THEMIS model.* Panel *(a)* shows the size distribution of the two main components of THEMIS: amorphous carbons and silicates. We show how we divide the a-C(:H) size distribution into three independent components. Panel *(b)* shows the SED corresponding to each component (same color code as panel *a*). The SED is shown for the ISRF of the solar neighborhood (Mathis et al. 1983).

Galliano et al. 2021

Large-scale emission filtering: NGC6946

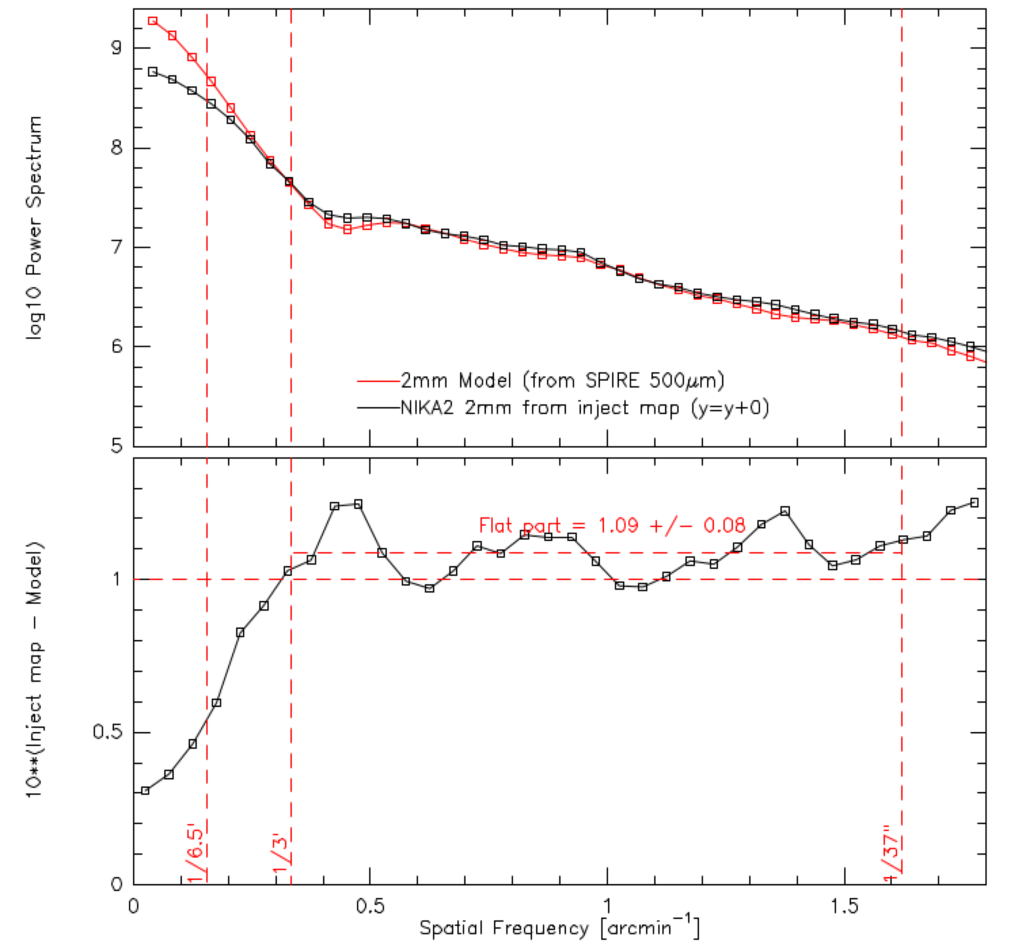


NIKA2 1.15mm radial POWER SPECTRUM (NGC6946 - IMEGIN; by C. Kramer)

NIKA2 1.15mm TRANSFER FUNCTION (NGC6946 - IMEGIN; by C. Kramer)

- At 1.15 mm, the flat part extends till 4.5'.
- At the scale of the NIKA2 field-of-view, the transfer function is reduced to 70%.
- The flat part stays at 1.01 ± 0.04.

Large-scale emission filtering: NGC6946



NIKA2 2mm radial POWER SPECTRUM (NGC6946 - IMEGIN; by C. Kramer)

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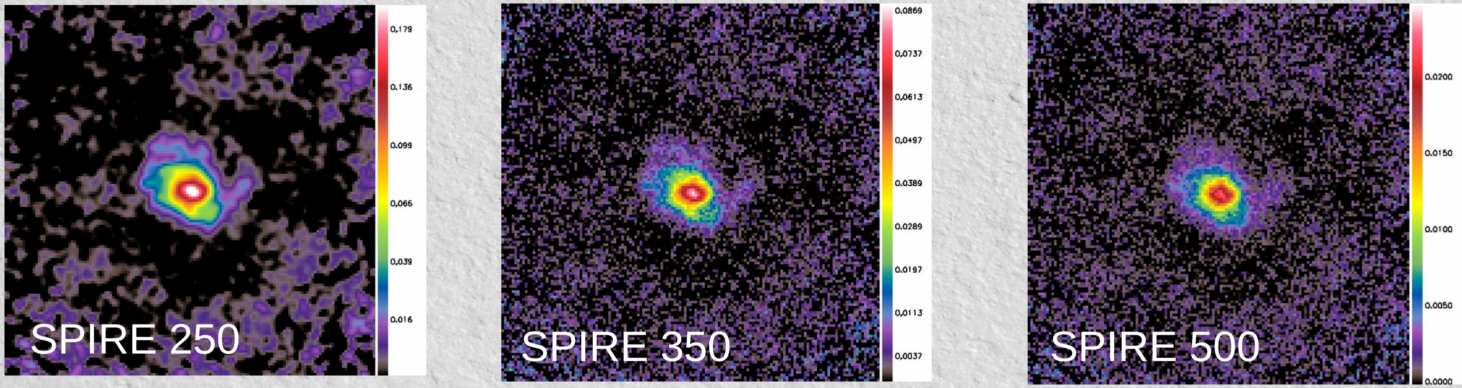
NIKA2 2mm TRANSFER FUNCTION (NGC6946 - IMEGIN; by C. Kramer)

- At 2 mm, the flat part extends till 3'.
- At the scale of the NIKA2 field-of-view, the transfer function is reduced to ~ 50%.
- The flat part stays at 1.09 ± 0.08

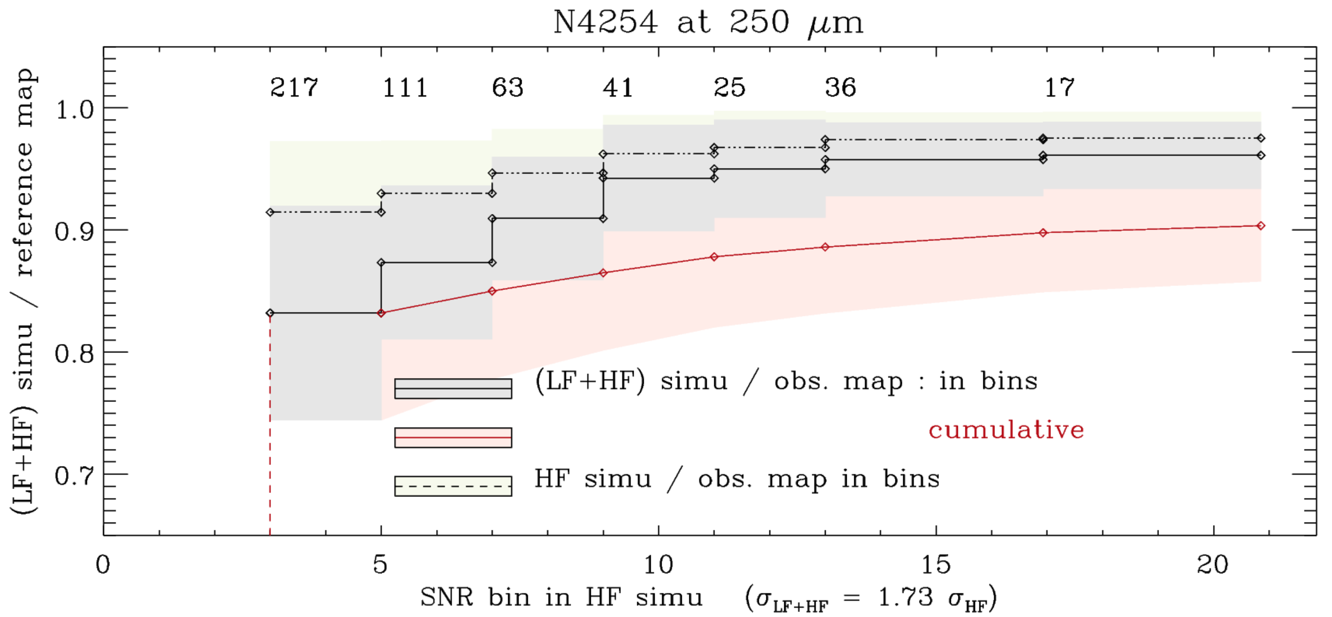
NGC4254: large-scale emission filtering

One possible approach consists in **filtering-out the multi-wavelength ancillary maps as the NIKA2 maps** were filtered-out, adding the ancillary maps to the timeline series (see e.g. Pattle et al. 2023; Sadavoy et al. 2013).

Simulation for Herschel-SPIRE bands (by H. Roussel, to be used in Pantoni et al. in prep):

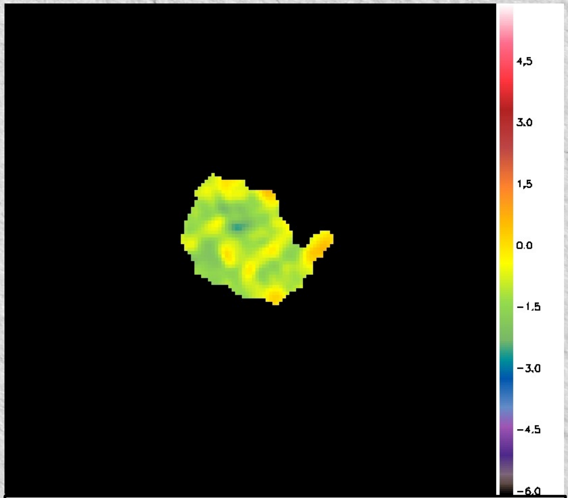


NGC4254: large-scale emission filtering



SPIRE 250 TRANSFER FUNCTION

Courtesy of H. Roussel



SPIRE 250 SIGMA TOT

NGC4254: large-scale emission filtering

An alternative/complementary approach consists in developing some **techniques for restoring the filtered-out flux** taking advantage of **space observatories (e.g. Planck)** observing in the same wavelength range.

I. **FEATHERING** (e.g. Smith et al. 2021)
   is a method originally used in radio astronomy for combining interferometric data with single dish.
   The method is **suitable for NGC6946** (d ~ 11.5 arcmin; Ejilali et al. in prep.).
   Its applicability to the case of NGC4254 (d ~ 5 arcmin; Pantoni et al. in prep.) is still under discussion.

II. **UNIFORM FLUX REDISTRIBUTION**
   The basic idea is redistributing uniformly the amount of flux that is filtered out on a global scale, by comparing with Planck HFI4 (1.38 mm).

NGC4254: large-scale emission filtering

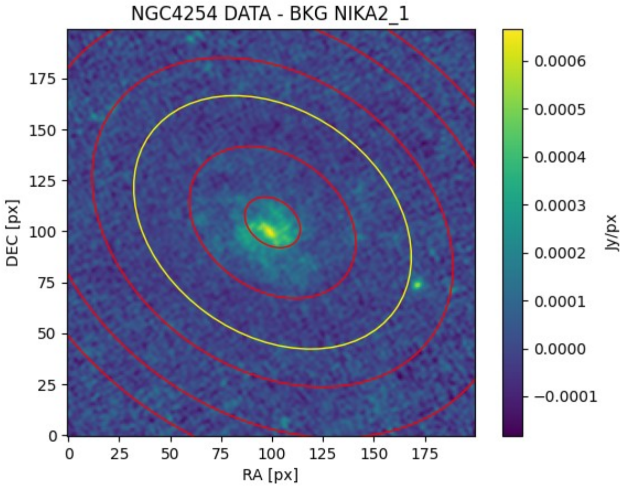
UNIFORM FLUX REDISTRIBUTION

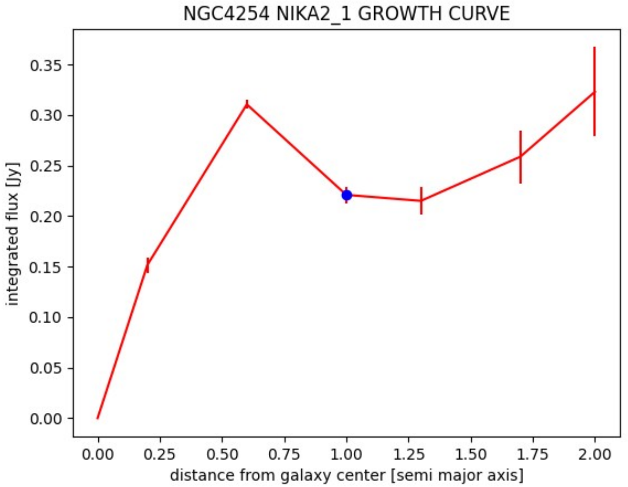
The basic idea is redistributing uniformely the amount of flux that is filtered out <u>on a global scale</u>, by comparing with Planck HFI4 (1.38 mm).

- Planck 1.38mm integrated flux (bkg-subtracted) is extrapolated to 1.15mm and 2mm as $\boldsymbol{\nu}^{2+\beta}$, where β **is randomly chosen** from a uniform distribution defined in the range $\mathbf{1} < \beta < \mathbf{2}$. This is done N times: the mean values give the extrapolated fluxes at NIKA2 wavelengths.
- This allows us to get the integrated flux at 1.15mm and 2mm (NGC4254 is not detected by HFI5, 2mm) as it was observed from space.
- A color-correction which takes into account the different filter's shapes and central wavelengths is also used for comparison (at 1.15mm): the two global fluxes match perfectly ($\sim$ 0.7 Jy).
- We assume a **uniform flux filtering across the galaxy**, so that the amount of *flux lost* (i.e. flux extrapolated from HFI4 *minus* NIKA2 flux) is **equally redistributed within the pixels** where we see the galaxy emission and added back.
- **Uncertainties** are propagated through **MC method**.

Pantoni et al. in prep.

ORIGINAL





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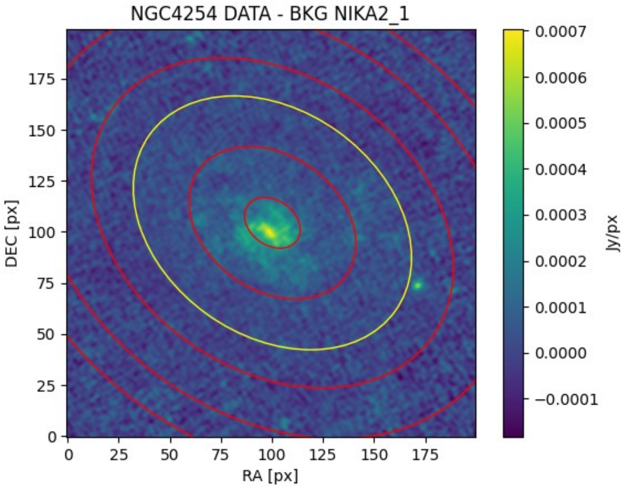
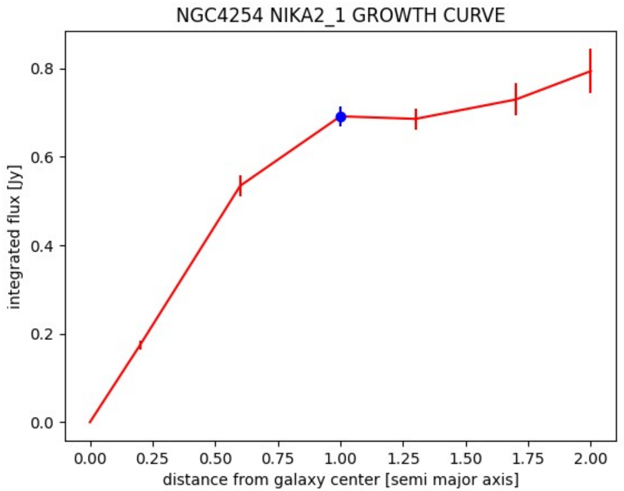
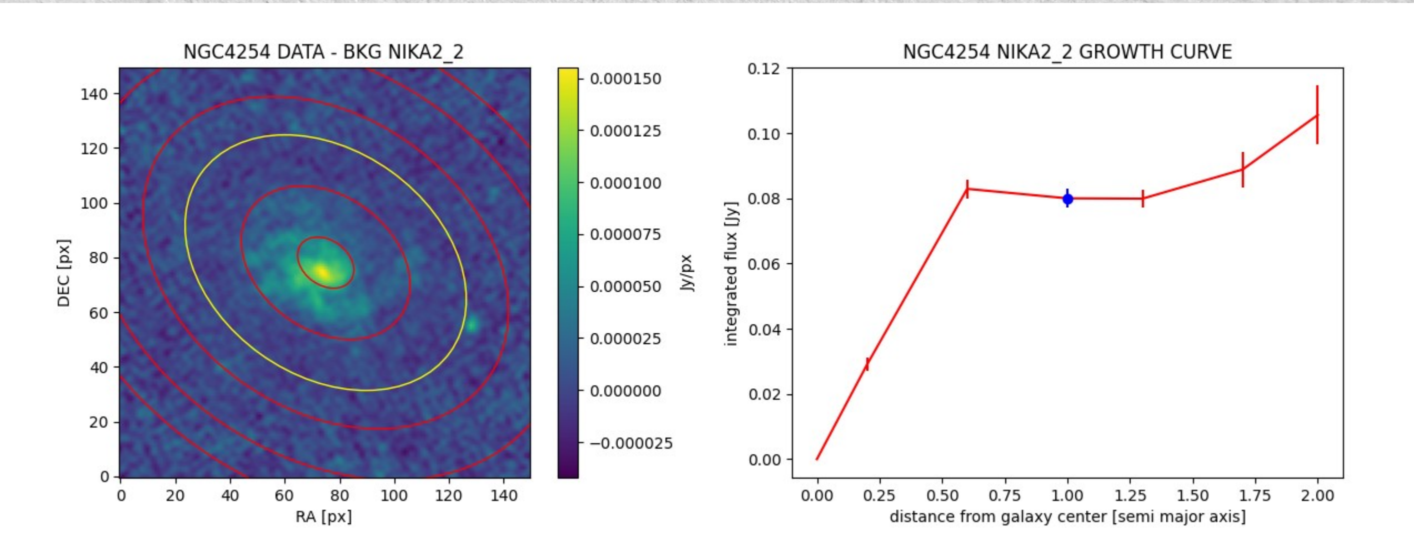




Pantoni et al. in prep.

ORIGINAL



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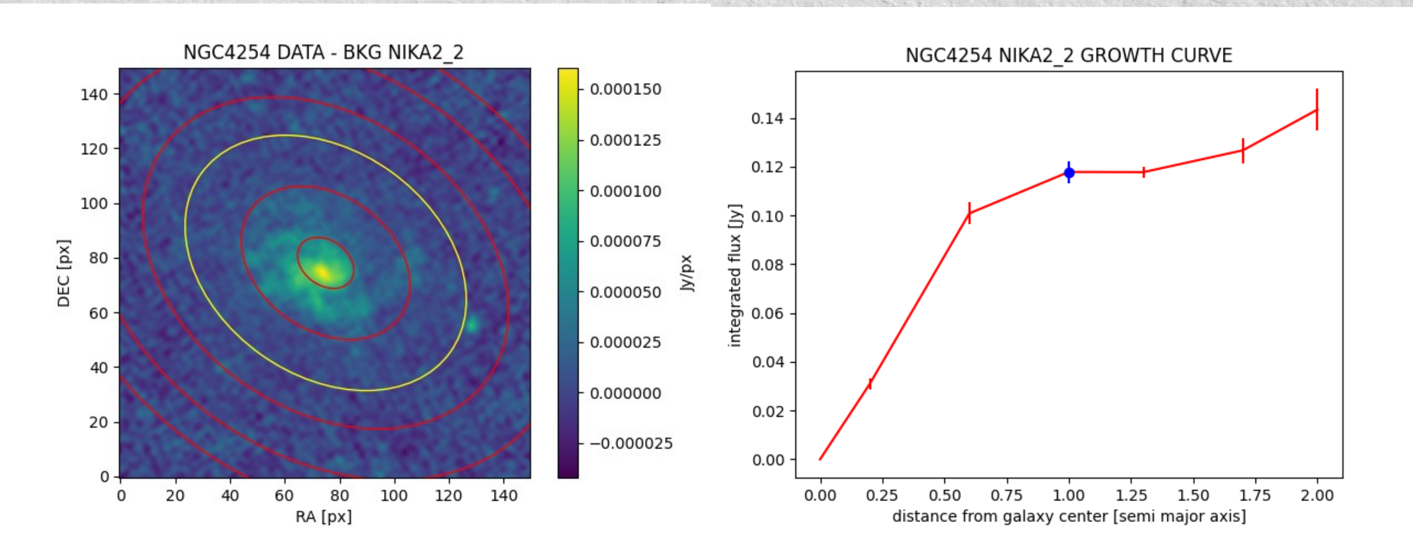

Pantoni et al. in prep.