# Probing spatially-resolved dust properties in M99 with IRAM-NIKA2

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# Overview

## Introduction

- Interstellar dust in galaxies
- the role of Nearby Galaxies
- IMEGIN Large Program

## Data

NIKA2 maps + ancillary data

## Method

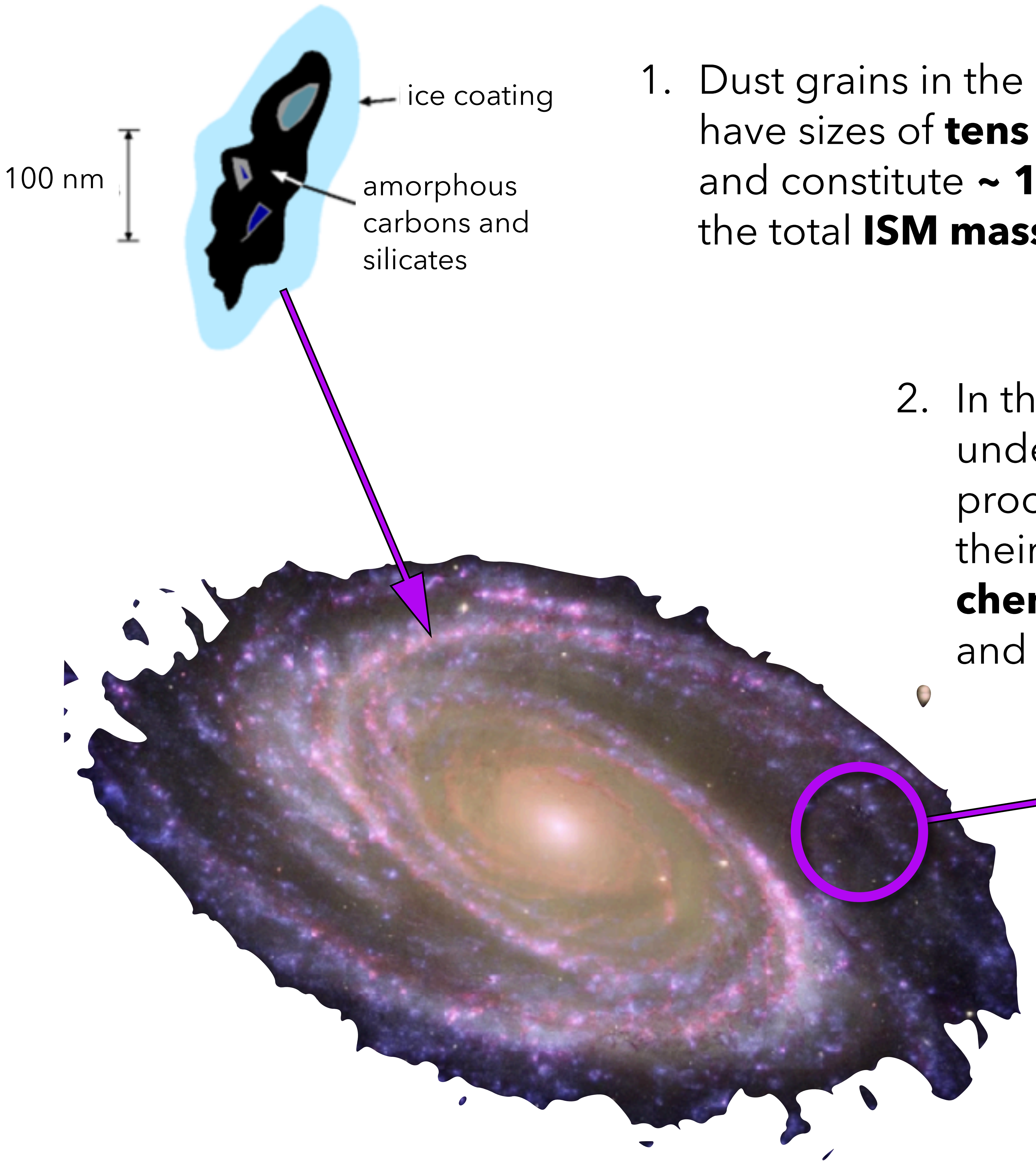
SED fitting + dust models

## Results

- Disk, arms, centre of M99
- ~ kpc scale

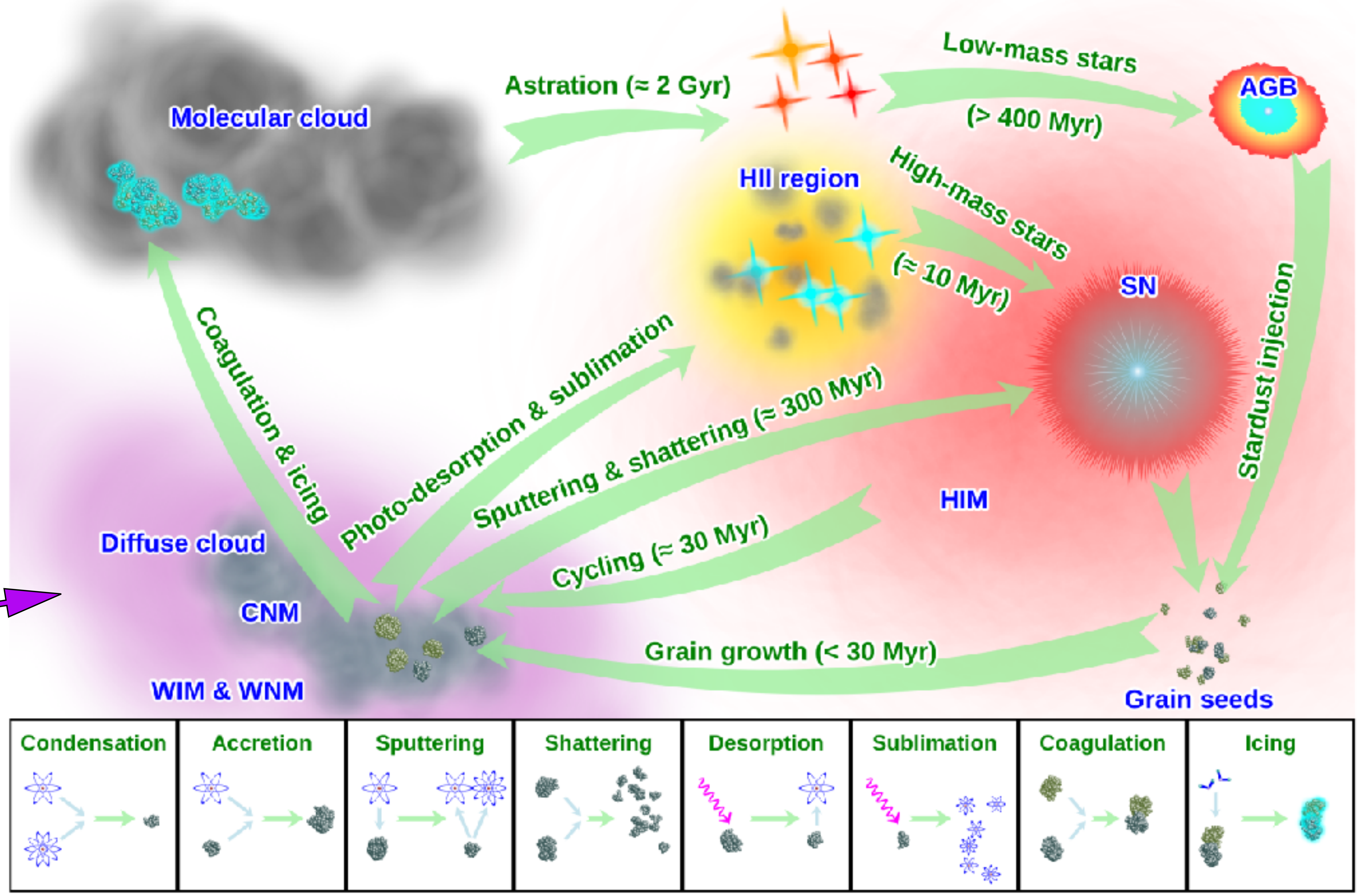
## Summary

# Interstellar dust in galaxies




1. Dust grains in the ISM have sizes of **tens of nm** and constitute **~ 1%** of the total **ISM mass**.

2. In the ISM, dust grains undergo a variety of processes which **alter** their **size** distribution, **chemical composition** and **abundance**.

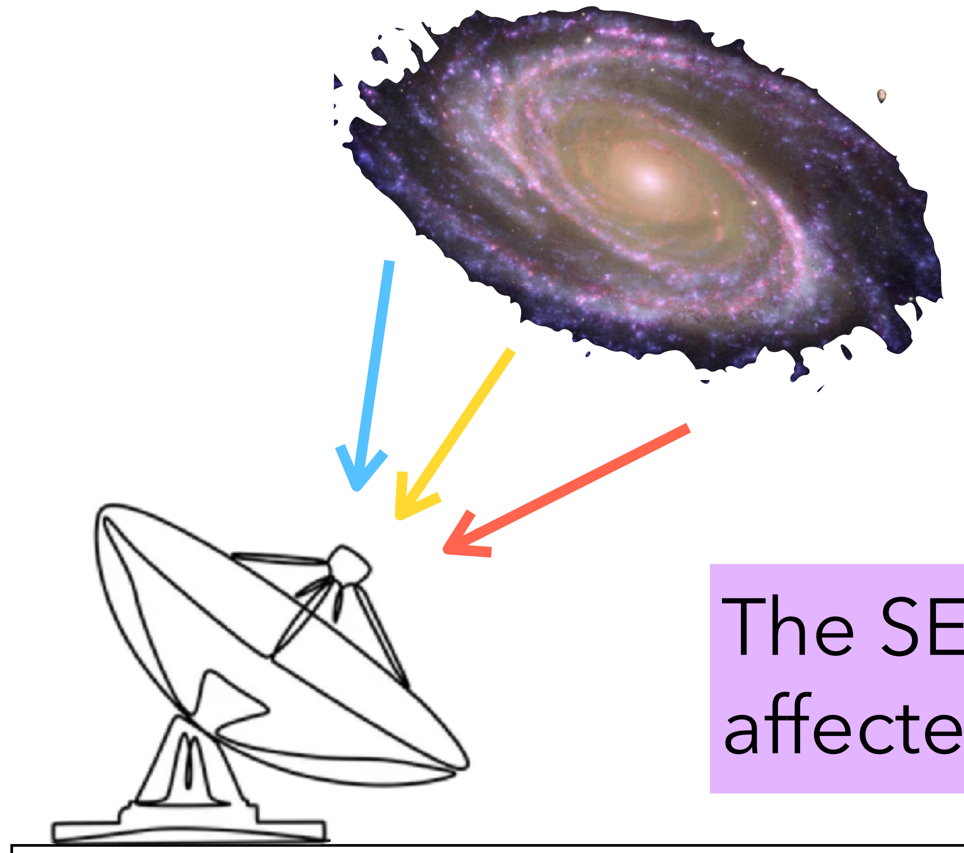



**CHANGES IN THE DUST GRAIN SIZE AND CHEMICAL COMPOSITION**

References: Mathis et al. 1977; Galliano et al. 2018; Draine & Hensley 2022

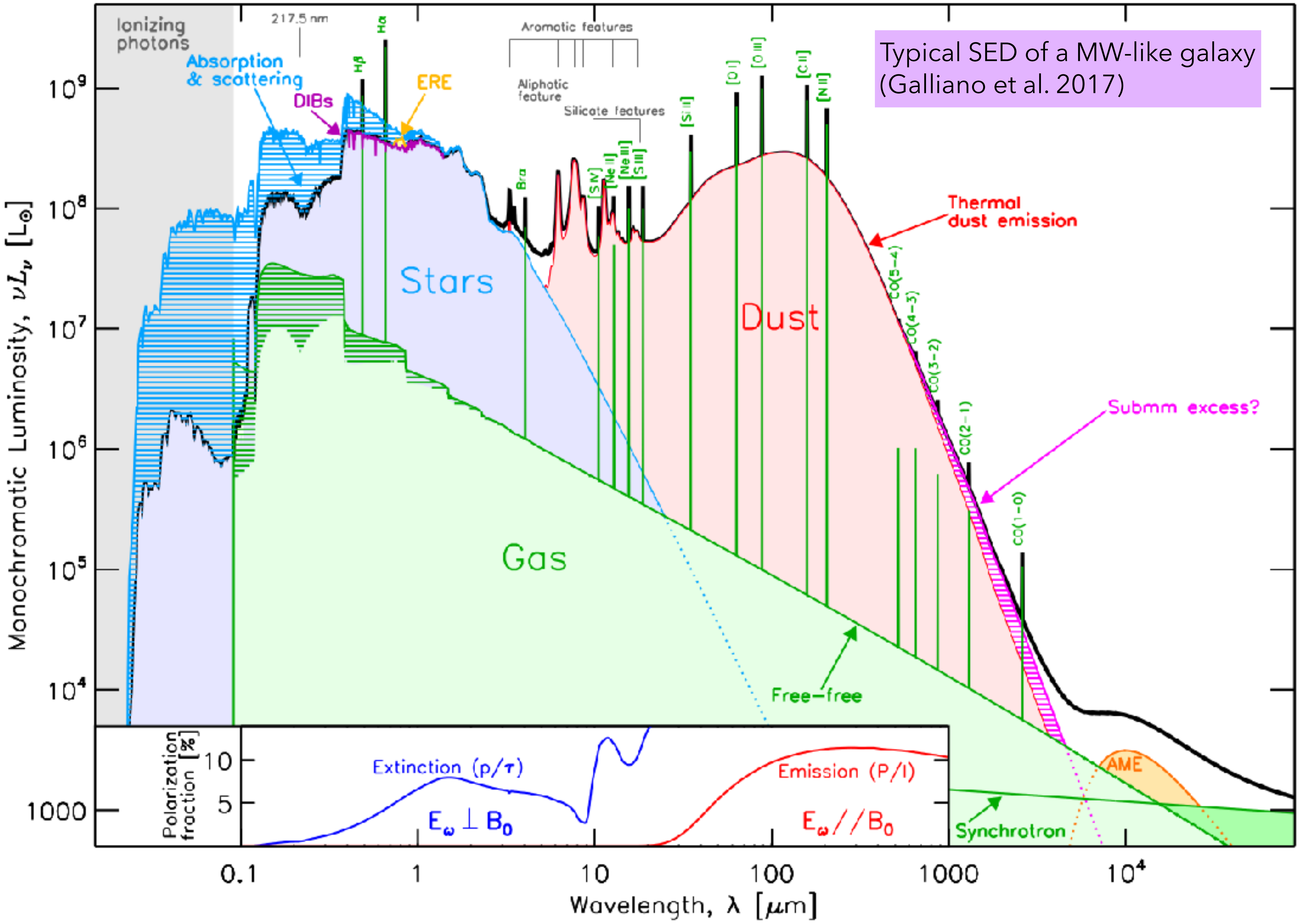
Credits: www.astronomynotes.com; NASA/JPL-CALTECH/ESA/HARVARD-SMITHSONIAN CFA; F. Galliano

# Interstellar dust in galaxies



The SED of galaxies is strongly affected by the presence of dust.

1. Dust grains **absorb** and **re-radiate** ~30% of **stellar power in the IR** (through scattering, absorption, extinction).
2. **Large grains**, which dominate the dust mass budget, are responsible for the **thermal emission** in the **FIR**.
3. **Small grains**, out of thermal equilibrium, are responsible for the **MIR features**.
4. In the mm regime, the **sub-mm excess** and the **AME** are linked to the presence of very cold dust and spinning grains (Galliano+18; Ysard+22).




Typical SED of a MW-like galaxy (Galliano et al. 2017)

Credits: NASA/JPL-CALTECH/ESA/HARVARD-SMITHSONIAN CFA

# Why Nearby Galaxies?

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

However these studies are affected by, e.g.

- MW hosting limited range of environmental conditions
(e.g. no AGN, limited Z, … ).

Instead, **Nearby Galaxies** (< 100 Mpc) can provide **unique constraints** on interstellar dust properties:
(Galliano, Galametz & Jones 2018)





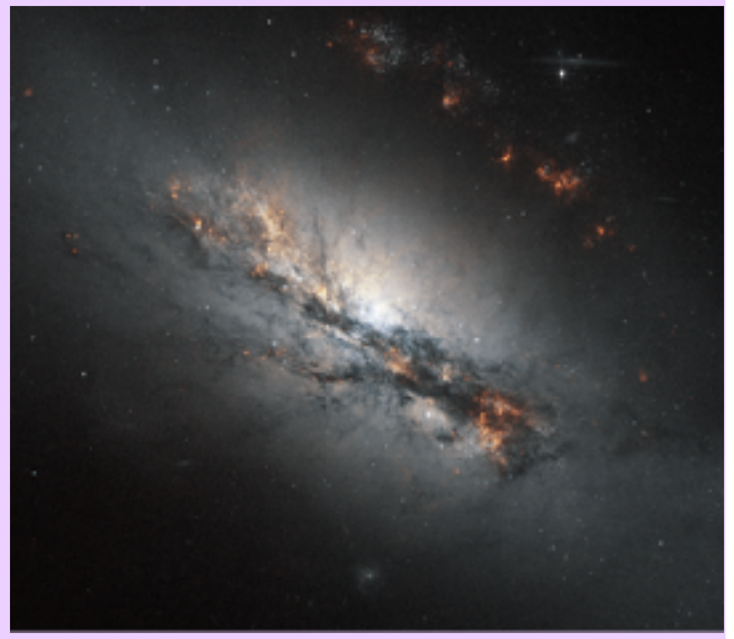
Credits : NASA/ESA Hubble Space Telescope

- face-on galaxies ⟶ clearer sightline.
- edge-on galaxies ⟶ high vertical distances.
- blue dwarfs, bright AGNs, low Z objects ⟶ probe interstellar dust in extreme conditions.
- intermediate step towards understanding interstellar dust and interstellar medium in distant galaxies.

# IMEGIN Large Program

**IMEGIN** (Interpreting the Millimeter Emission of Galaxies with IRAM-30m/NIKA2) is a **NIKA2 Guaranteed Time Large Program** (**~ 200 hours** of observing time) targeting **22 nearby galaxy** (priority A).


Katsioli et al. 2023 (A&A)

Ejlali et al. 2025 (A&A)

Katsioli et al. 2025 submitted


Pantoni et al. 2025 submitted

+ MORE TO COME!

stay tuned

**NIKA2** (IRAM 30m) observes the **1.15** and **2 mm continuum**, with angular resolution of **12''** and **18''** (~ kpc).

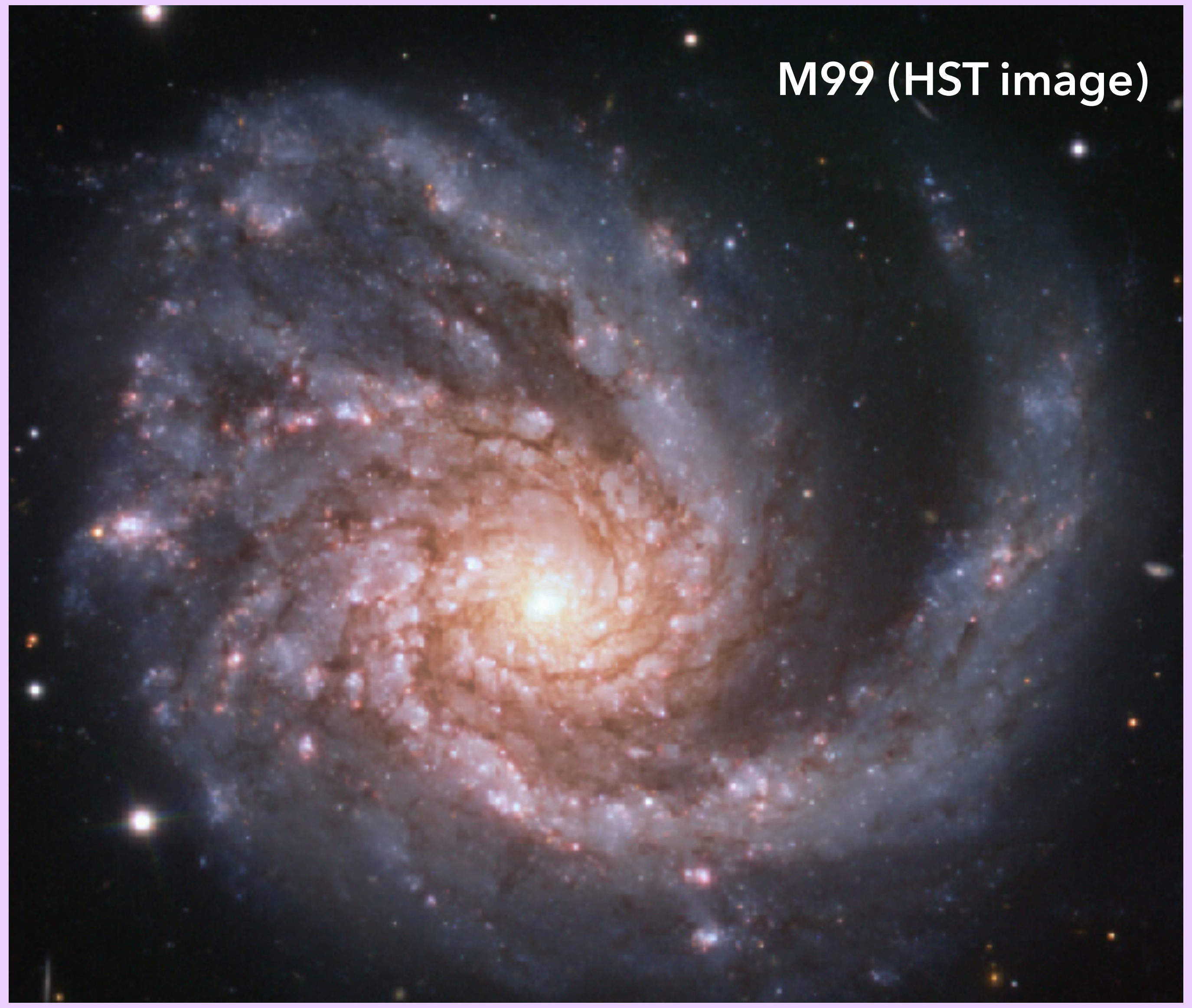
It allows us to:

- sample galaxy SED in the <u>mm range</u>;
- study the <u>spatially-resolved</u> mm <u>properties</u> of galaxies.

## Main objectives

- Decomposing the mm emission in galaxies in **dust**, **free-free** and **synchrotron** through spatially-resolved SED fitting.
- Constraining the evolution of **dust-to-gas** and **dust-to-stellar mass ratios**.
- Investigating the variations of the microscopic properties of dust (**FIR/mm spectral index, β**).
- Studying the **sub-mm excess** in galaxies.

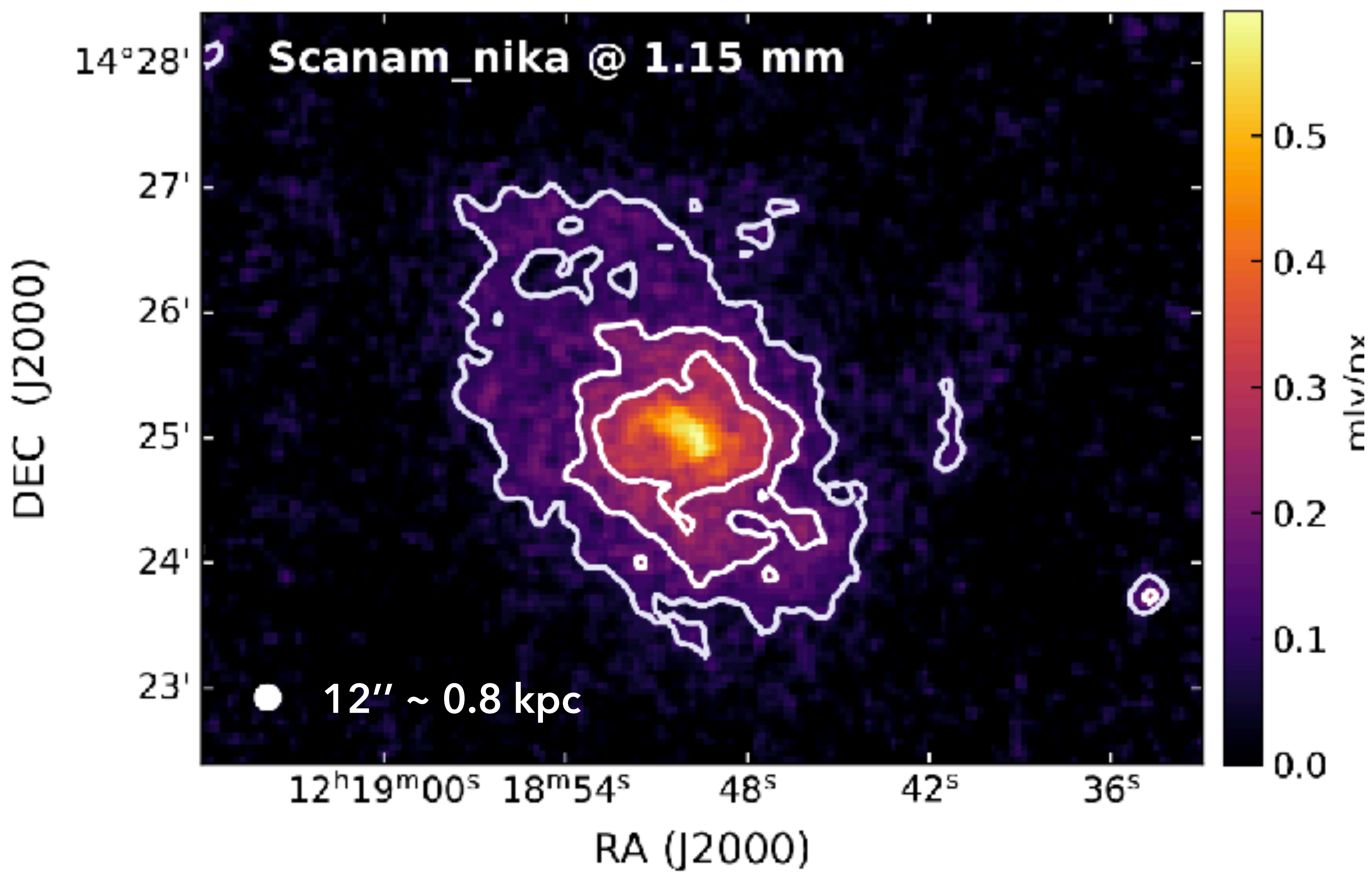
# M99 (NGC 4254) at mm wavelength

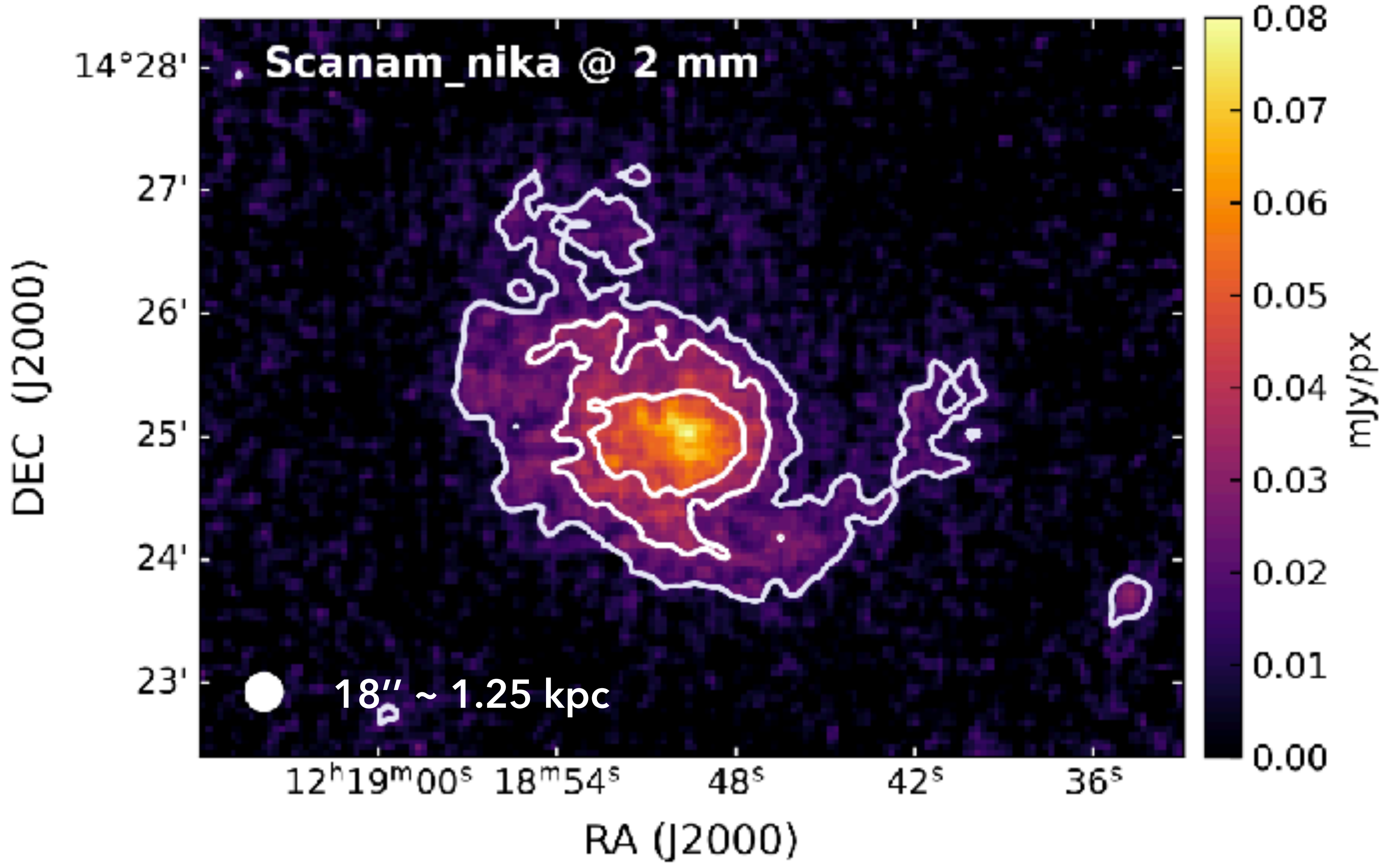



- Face-on galaxy
- Milky-Way like
- No AGN
- D(L) = 14.4 Mpc
- 25″ = 1.75 kpc

**Pantoni et al. 2025 submitted**

- **NIKA2** angular resolution allows for detailed modeling of the mm properties of dust through spatially-resolved SED fitting, although **spatial scales of 12″ (~0.8 kpc)** may still encompass both dense molecular clouds and HII regions.

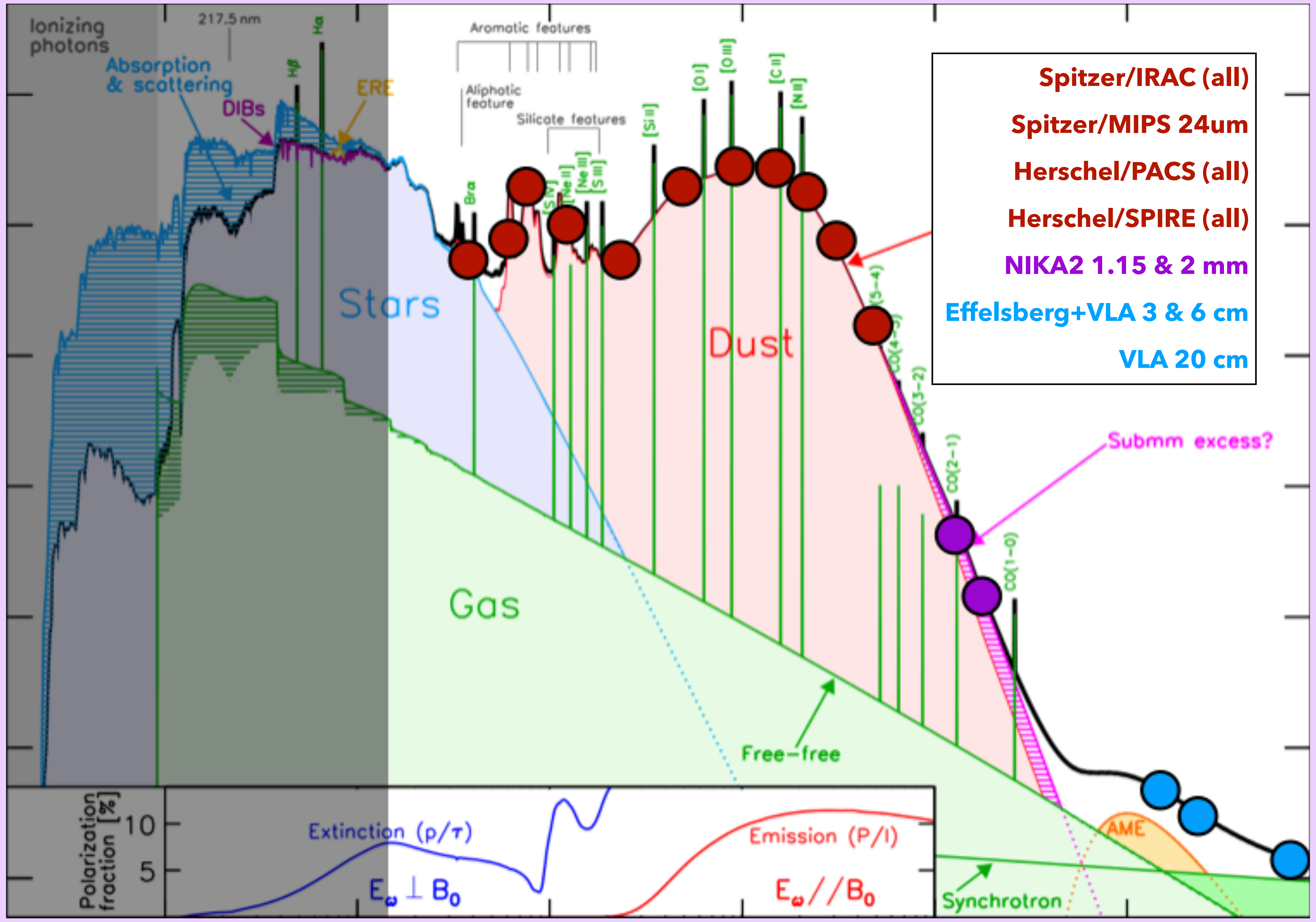


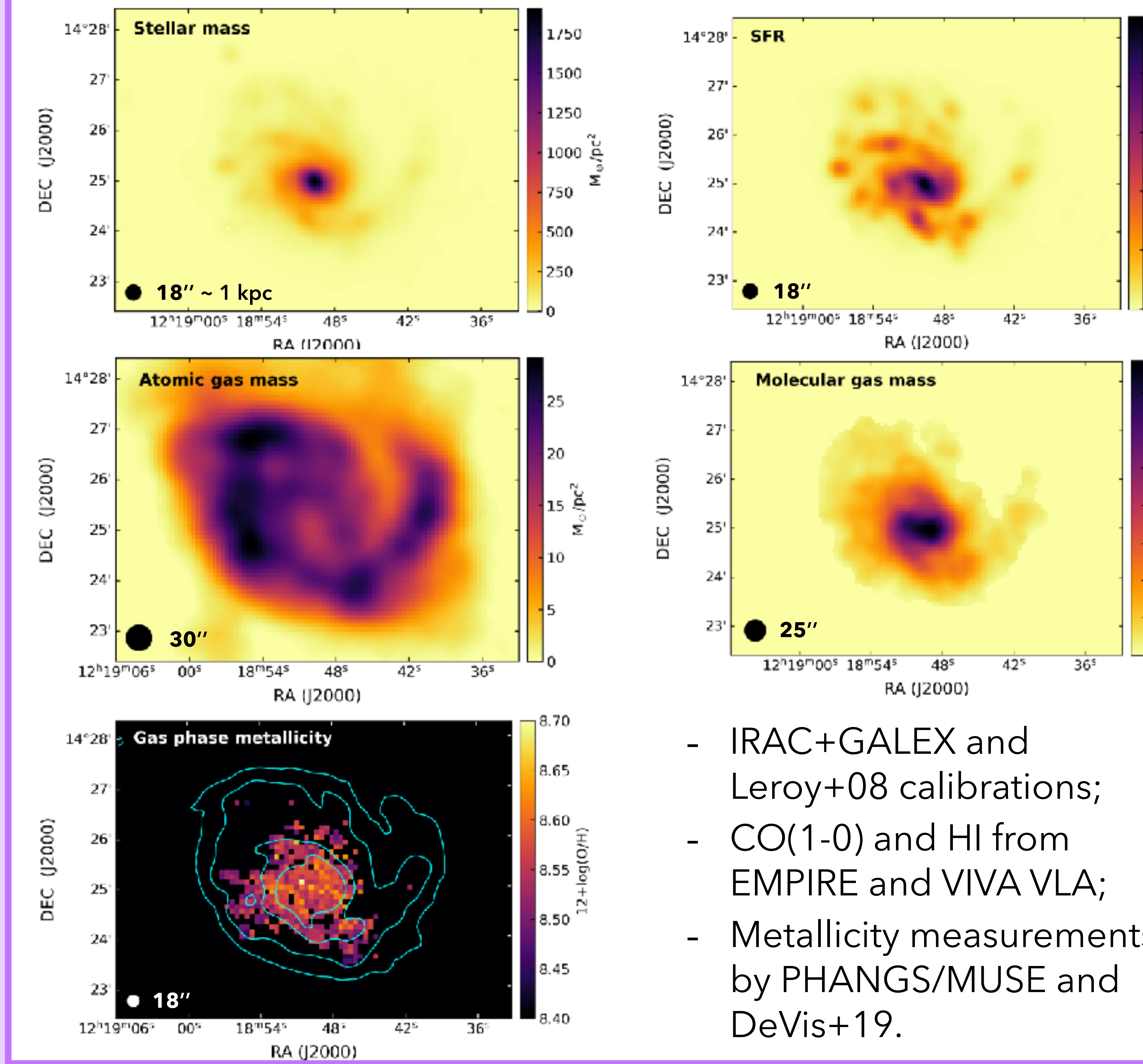




- The NIKA2 maps suffer from large scale filtering. We have quantified and included this effect (**up to 2%** in the **bulge**, **10%** in the **arms**, **20%** in the **inter-arms**) in the uncertainty budget

# SED: ancillary data

- The NIR to FIR images of M99 are taken from the **DustPedia archive**, for a total of **11 maps** with angular resolution comparable with NIKA2 (**from 0.6″ to 36″**).
- The radio maps at 3 cm and 6 cm are **VLA+Effelsberg** (15″) from Chemin+16; **VLA only** at 20 cm (5″; PHANGS, private).



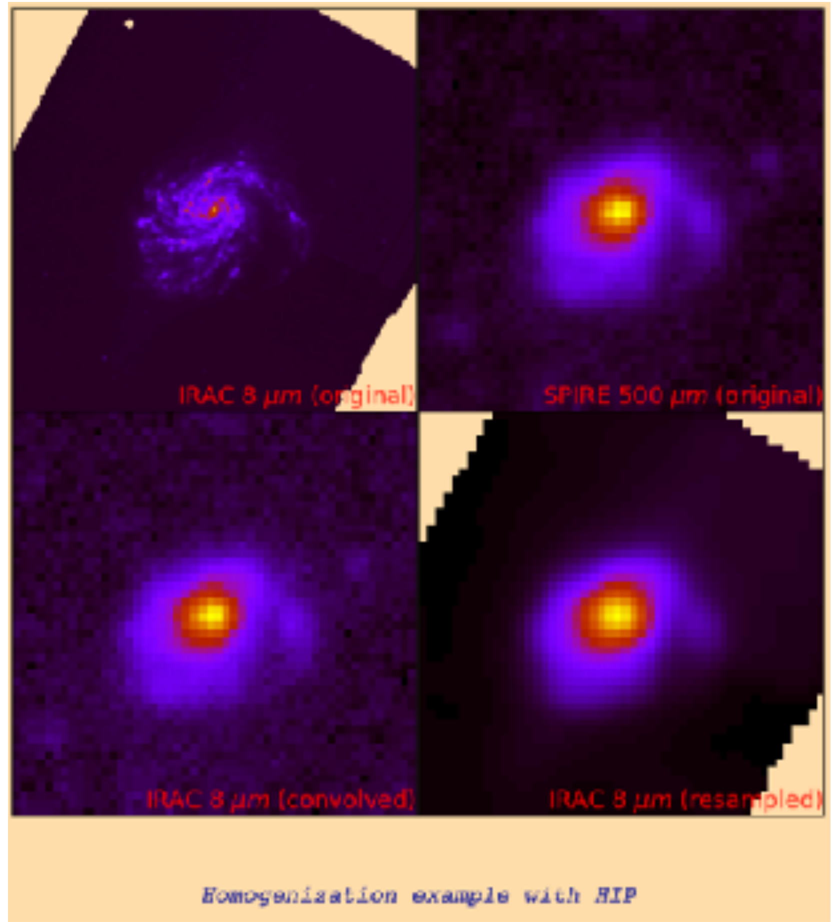

- IRAC+GALEX and Leroy+08 calibrations;
- CO(1-0) and HI from EMPIRE and VIVA VLA;
- Metallicity measurements by PHANGS/MUSE and DeVis+19.

# SED fitting with HerBIE

Homogenized data

**HerBIE** (Galliano 2018)
A hierarchical bayesian SED fitting code

Maps of the parameters and uncertainties.




Homogenization for IMEGIN photometry (HIP, Pantoni et al., GitLab - J. Tedros)

Stellar NIR emission (R-J regime)

Radio (free-free + synchrotron): $\alpha_{sync}$, $f_{ff}$

Dust model

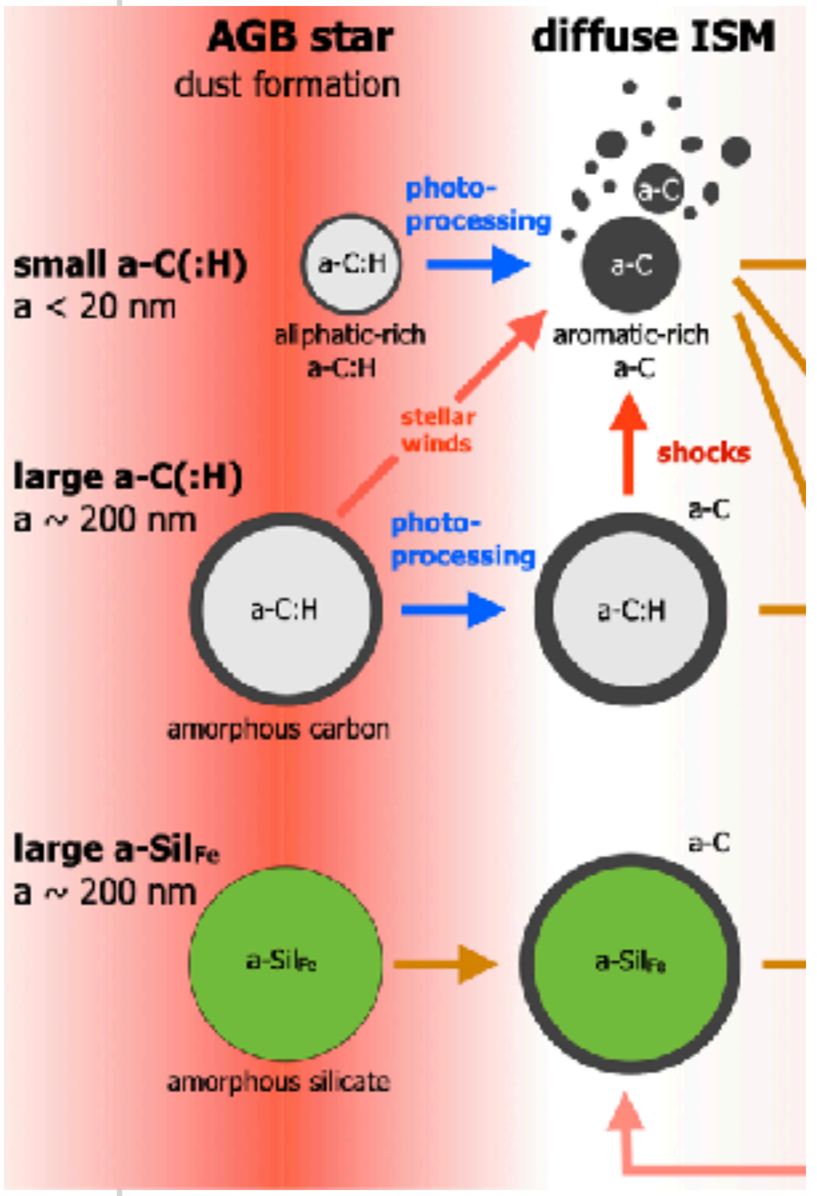
- **THEMIS** dust model (Jones et al. 2017).

  Based on laboratory-measured properties of dust grains analogs.
  Mixture of carbonaceous (a<1.5 nm) and silicate (a>1.5 nm) grains.

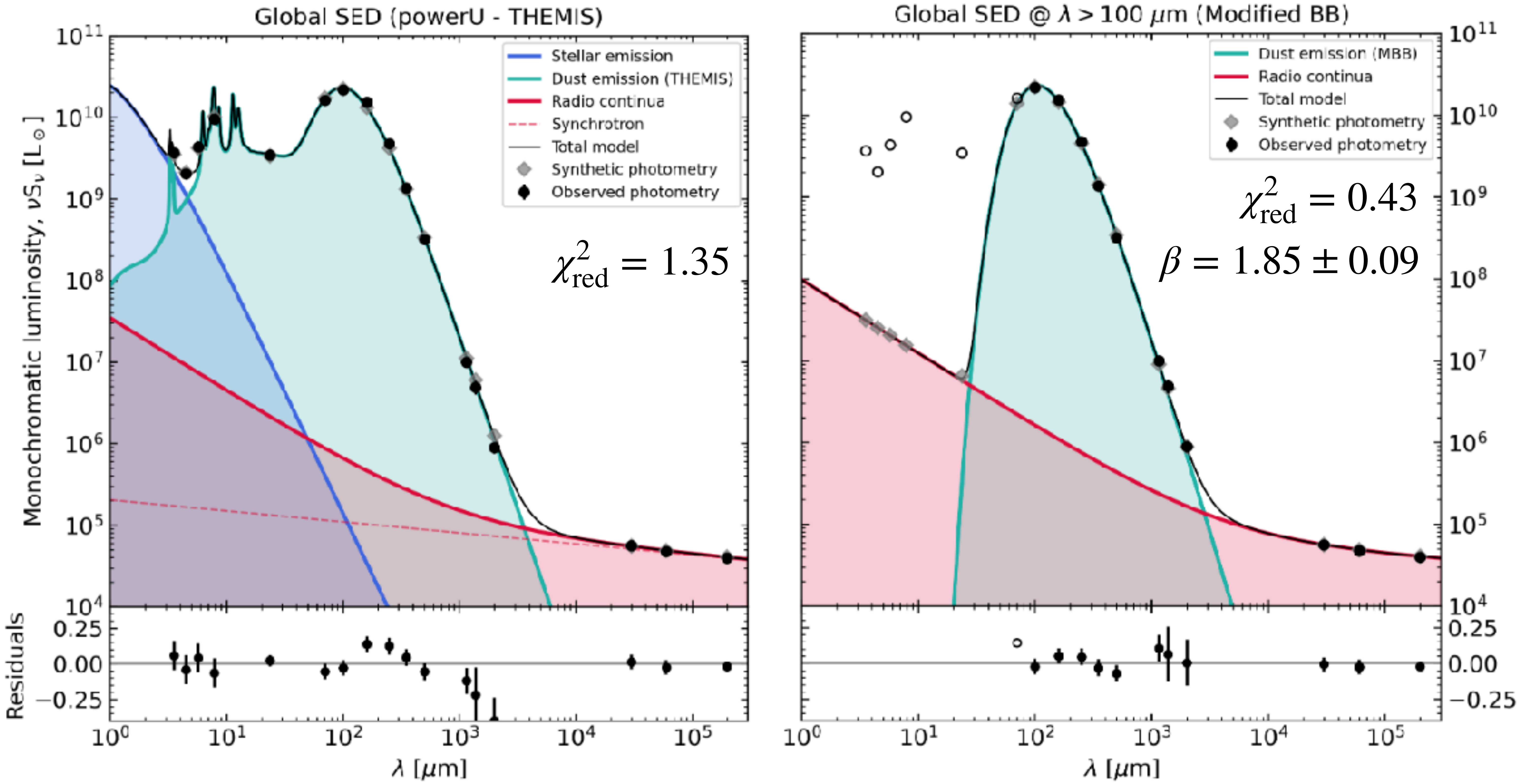
  $M_{dust}$ , $\langle U \rangle$, $q_{AF}$ ($\beta_{dust} = 1.79$)

- **Modified Black-Body** model (empirical)
  $\beta_{dust}$, $T_{dust}$ , $M_{dust}$

References: Jones et al. 2013



# A global view of the dust in M99

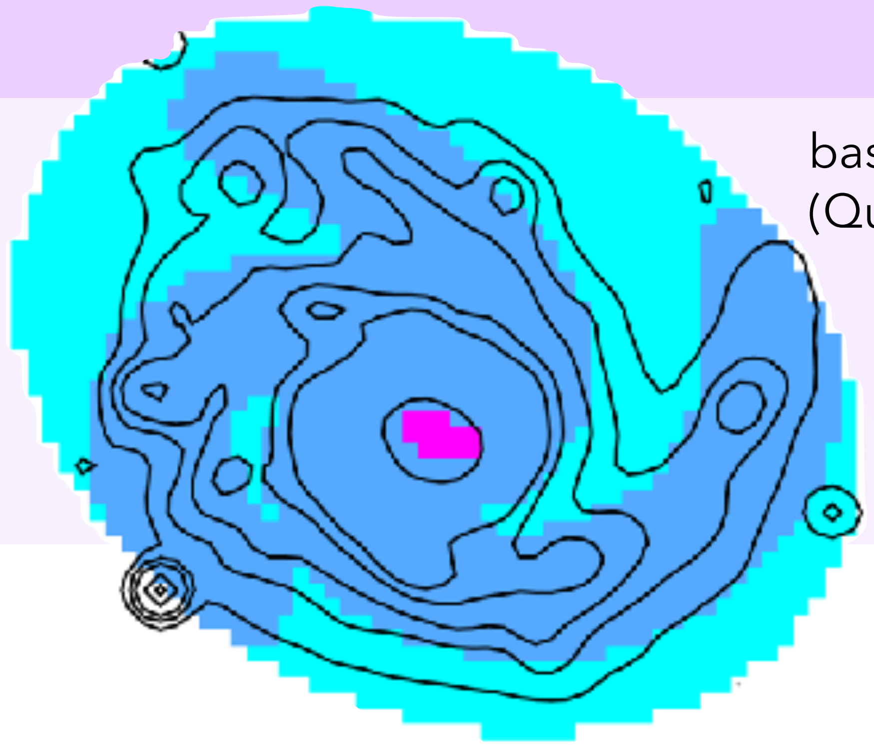



| Parameter | HerBIE value (powerU - THEMIS) | Units |
|---|---|---|
| $M_{dust}$ | $(3.2 \pm 0.2) \times 10^7$ | $M_\odot$ |
| $q_{AF}$ | $15 \pm 1$ | % |
| $L_\star$ | $(3.8 \pm 0.7) \times 10^{10}$ | $L_\odot$ |
| $\langle U \rangle$ | $5.6 \pm 0.6$ | $\langle U \rangle_\odot$ |
| $L_{radio}$ | $(7.0 \pm 0.6) \times 10^4$ | $L_\odot$ |
| $\alpha_{sync}$ | $0.87 \pm 0.04$ | |
| $f_{FF}$ | $15 \pm 12$ | % |

| | 1.15 mm | 2 mm | 5 mm | 1 cm |
|---|---|---|---|---|
| DUST | 99% | 91% | 20% | 2% |
| RADIO | 1% | 10% | 80% | 98% |
| ff | 52% | 40% | 23% | 15% |
| sync | 48% | 60% | 77% | 85% |

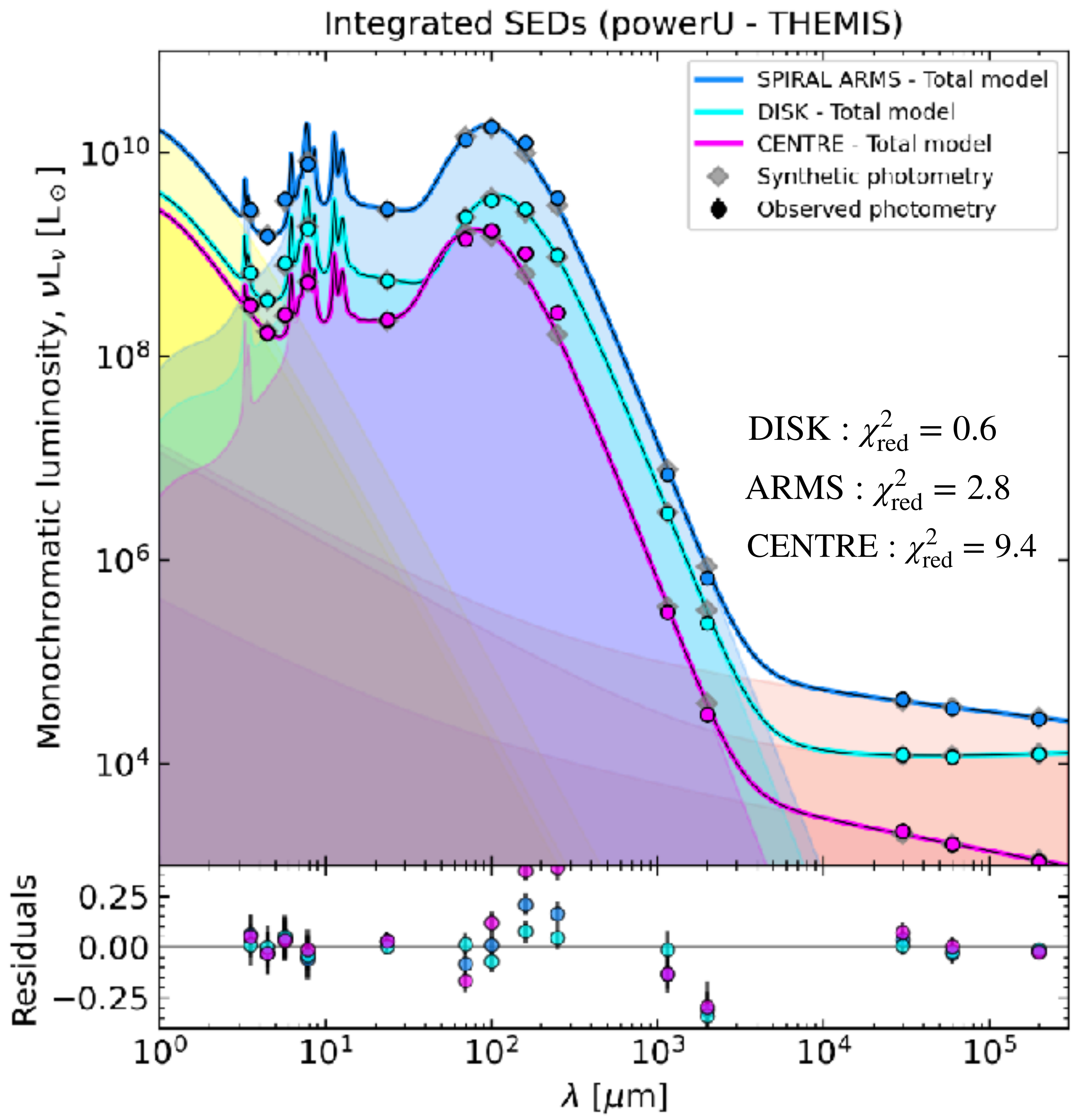
The steeper FIR slope we find for the integrated SED of M99 may result from the contribution to the total dust emission of **colder and denser regions** than the typical conditions observed in diffuse ISM of the MW (which sets the THEMIS value).

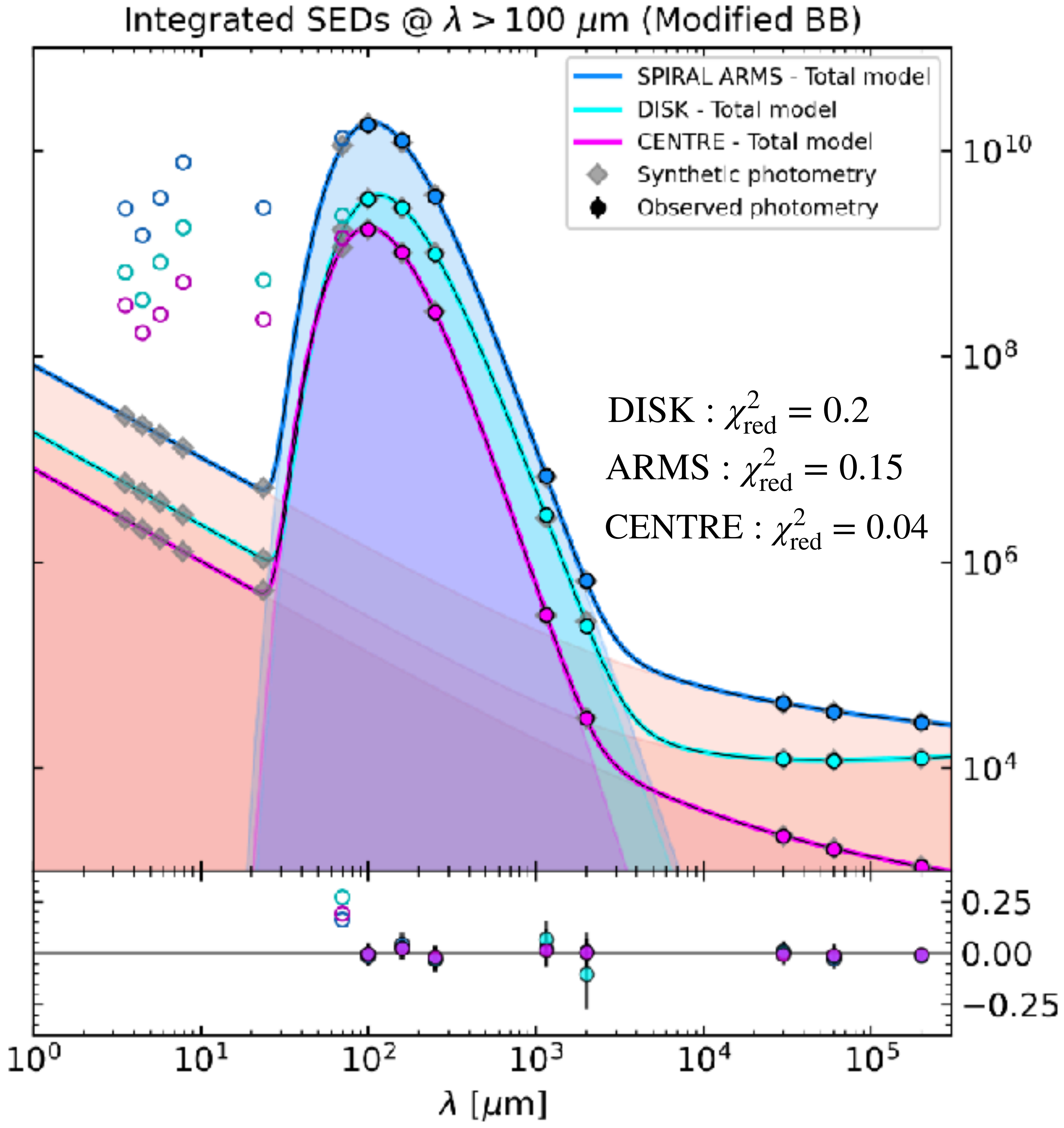
# $\beta_{dust}$ in M99 disk, arms, centre



based on PHANGS env masks (Querejeta et al. 2021)

**Ang. res. 18″ ~ 1.25 kpc**
**px size 6″ ~ 0.42 kpc**




$$\beta^{MBB}_{DISK} = 1.72 \pm 0.09$$

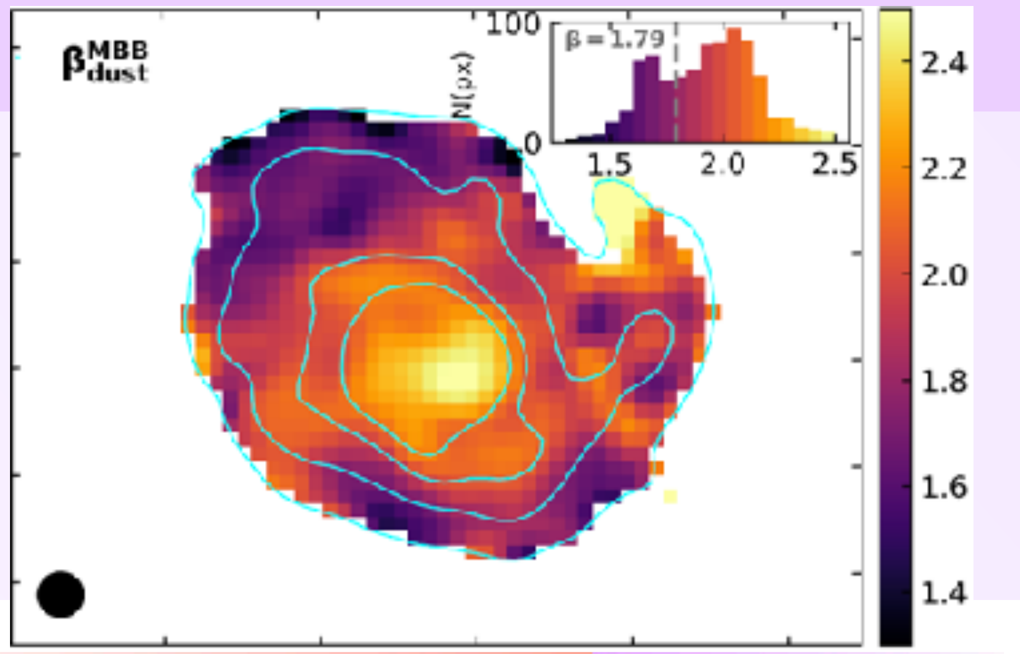
**Consistent with THEMIS** value (i.e. 1.79), which is the typical value for diffuse ISM in the MW.

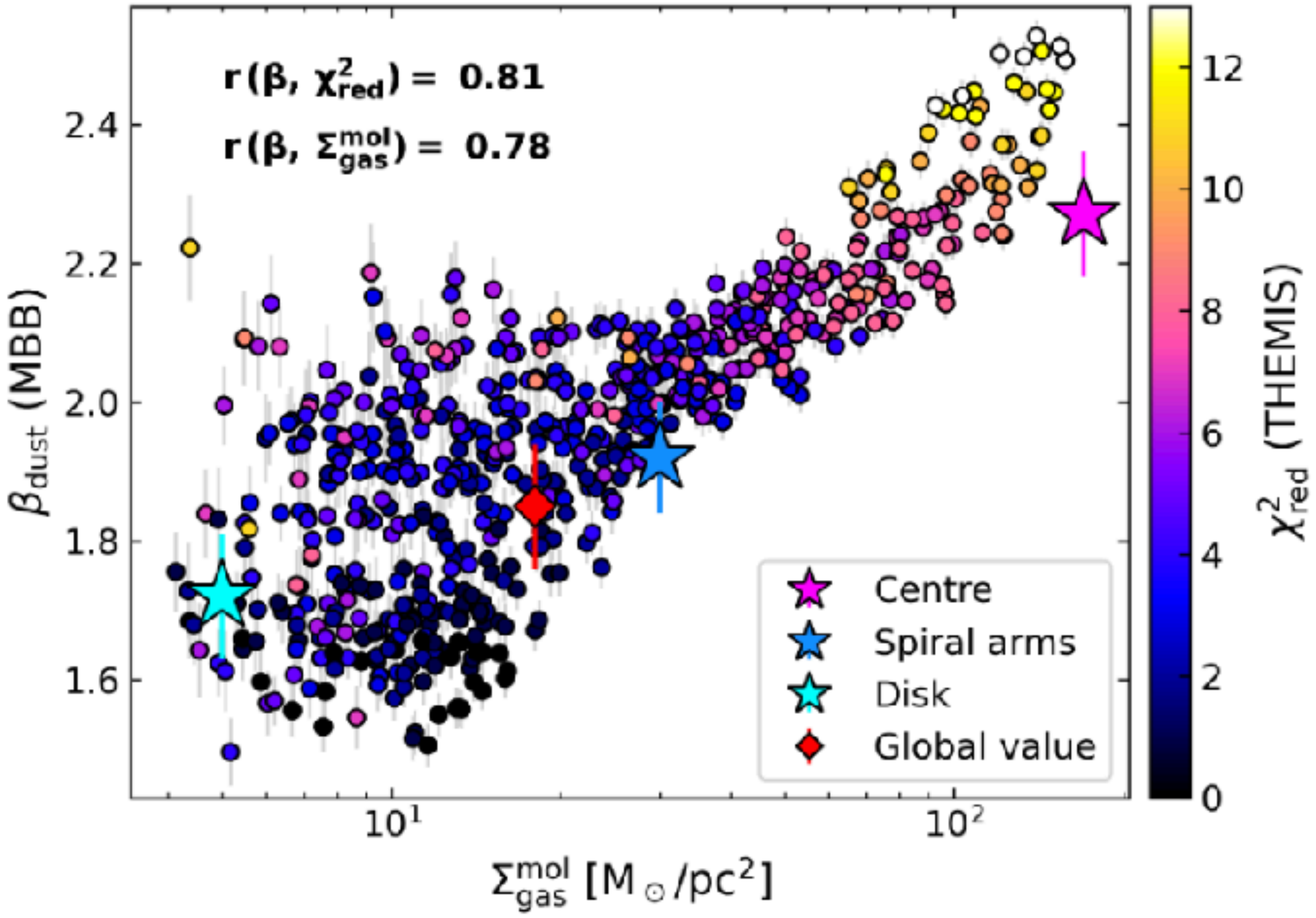
$$\beta^{MBB}_{ARMS} = 1.92 \pm 0.08$$

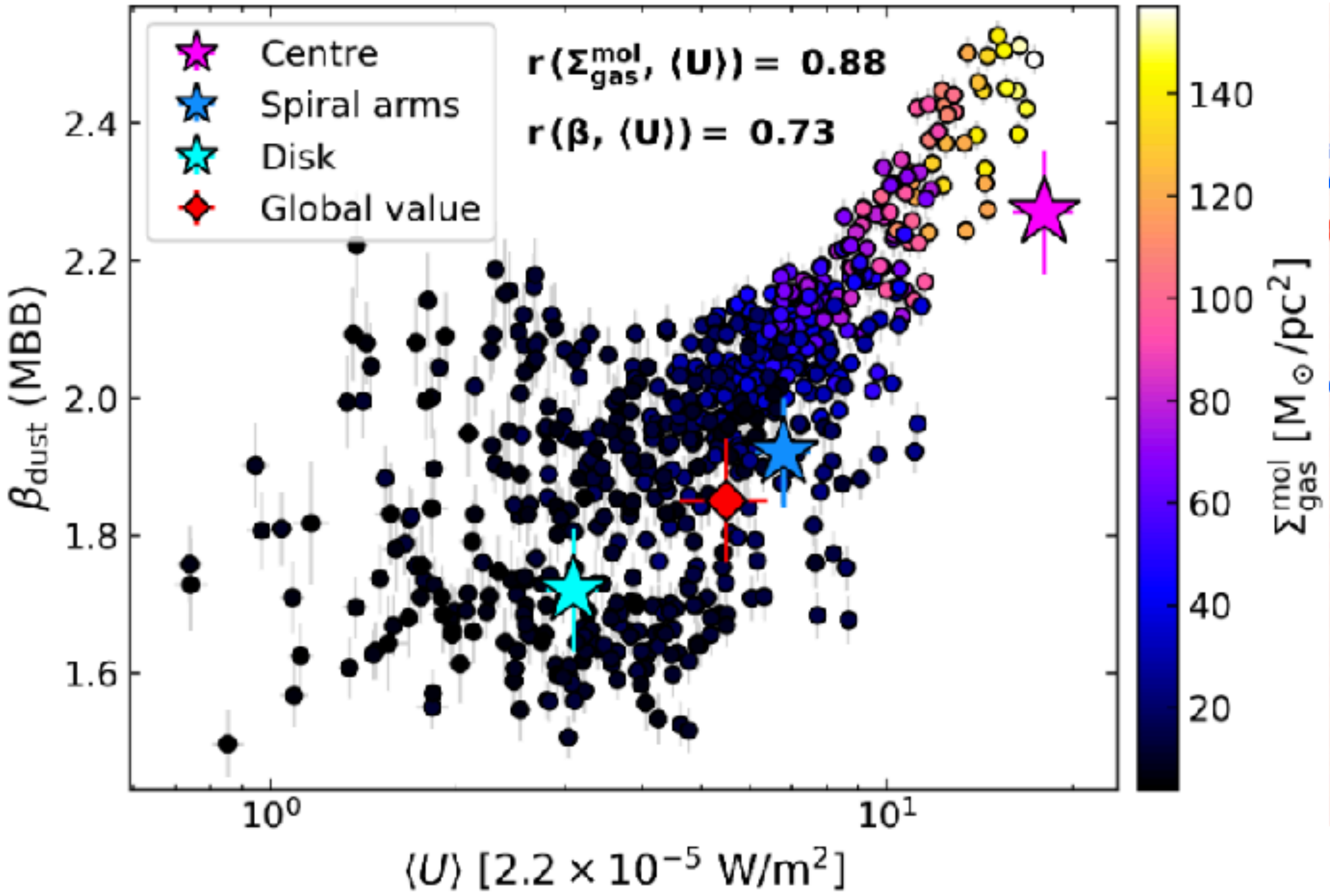
$$\beta^{MBB}_{CENTRE} = 2.27 \pm 0.09$$

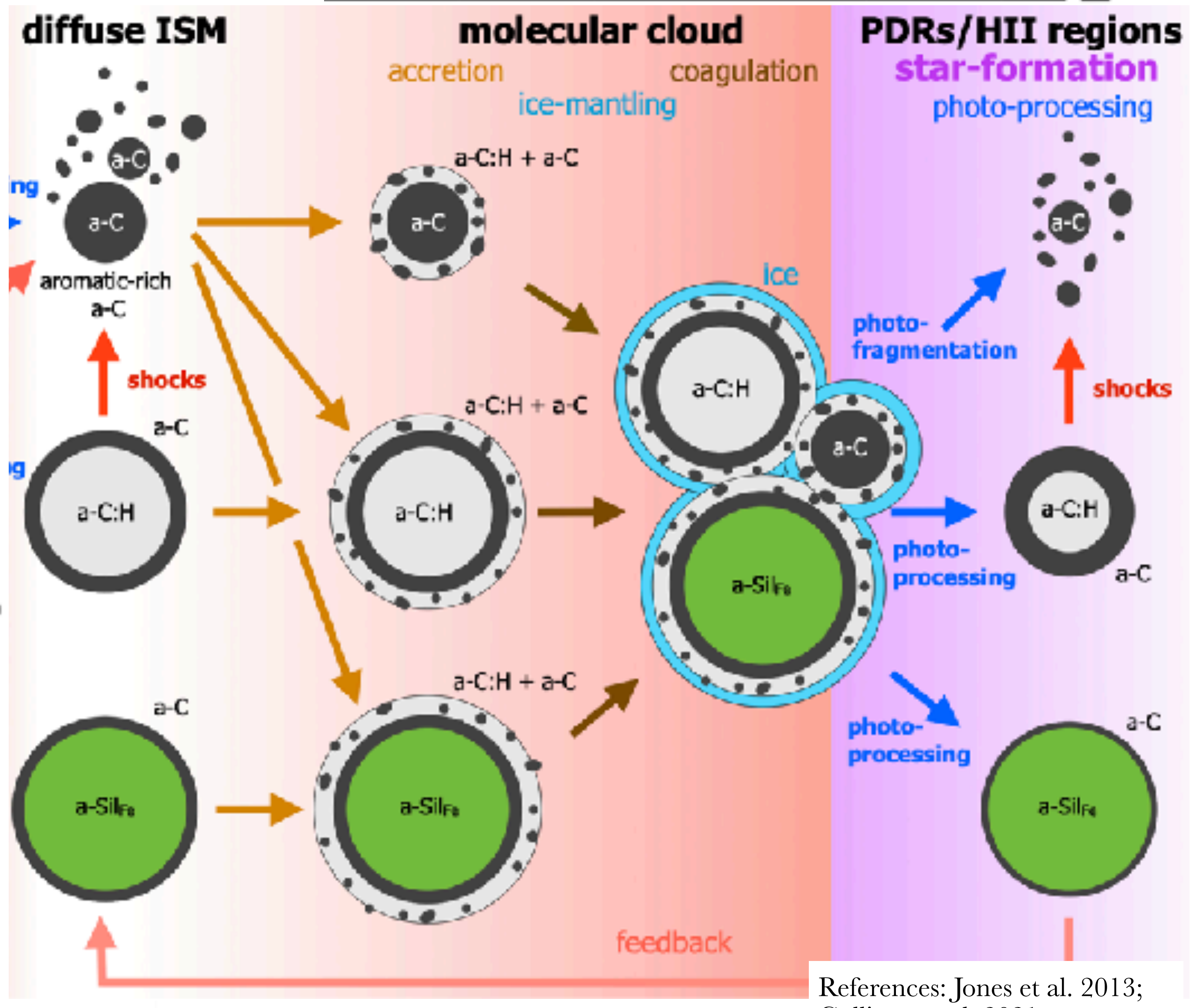
**Steeper FIR slopes:**
dust grains are highly reprocessed in spiral arms and bulge: drastic change in their <u>size distribution</u> and <u>chemical composition</u>.

# $\beta_{dust}$ variations on scales ~1.75 kpc

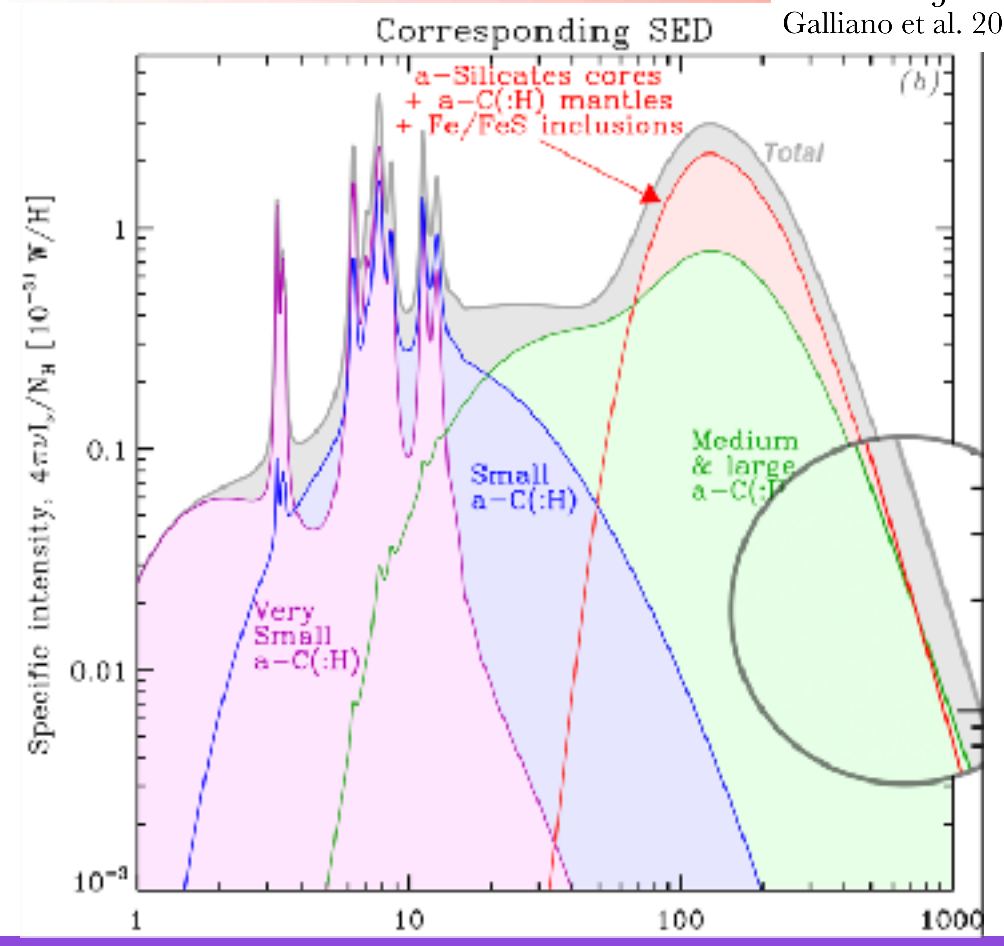


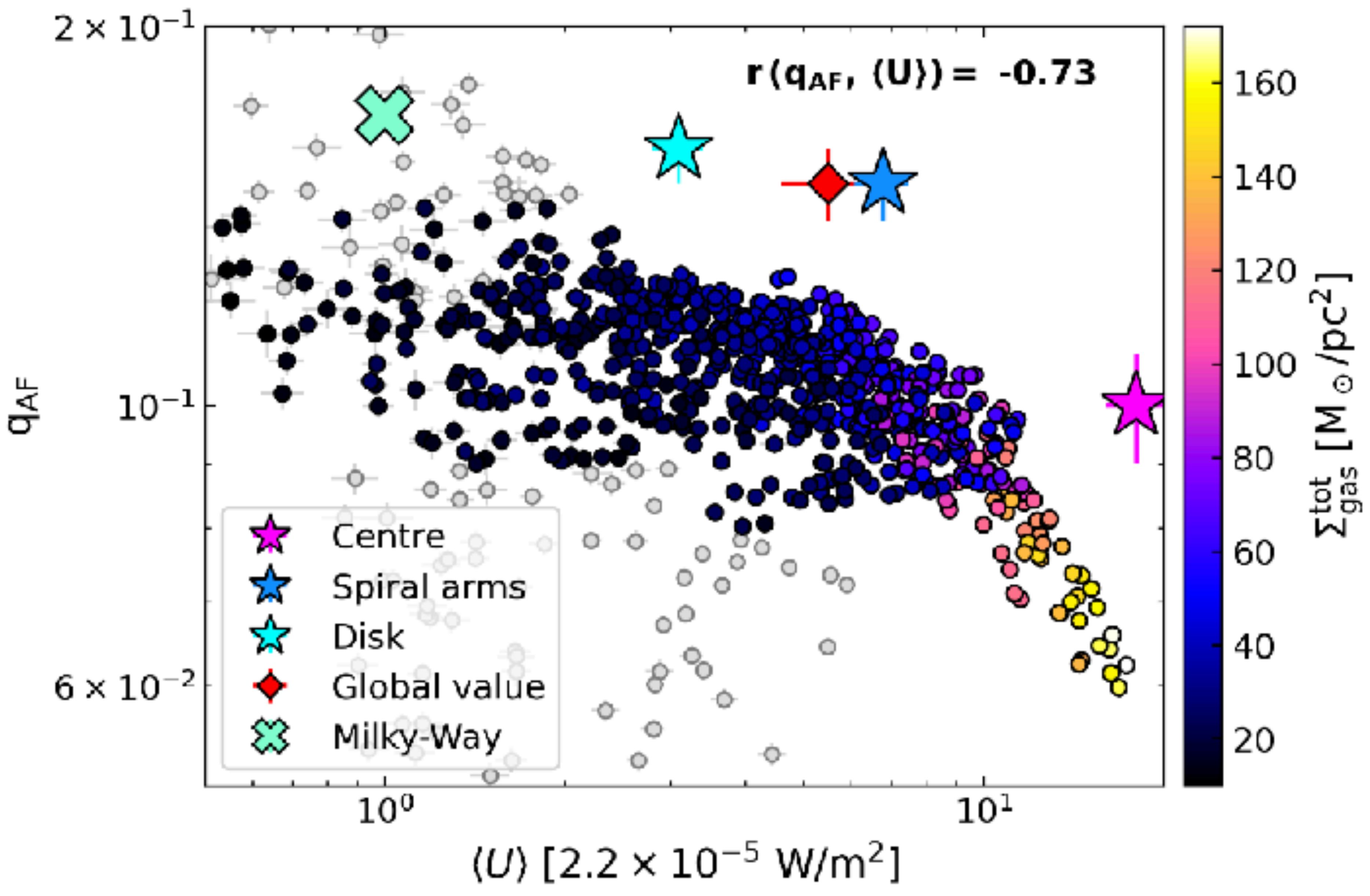



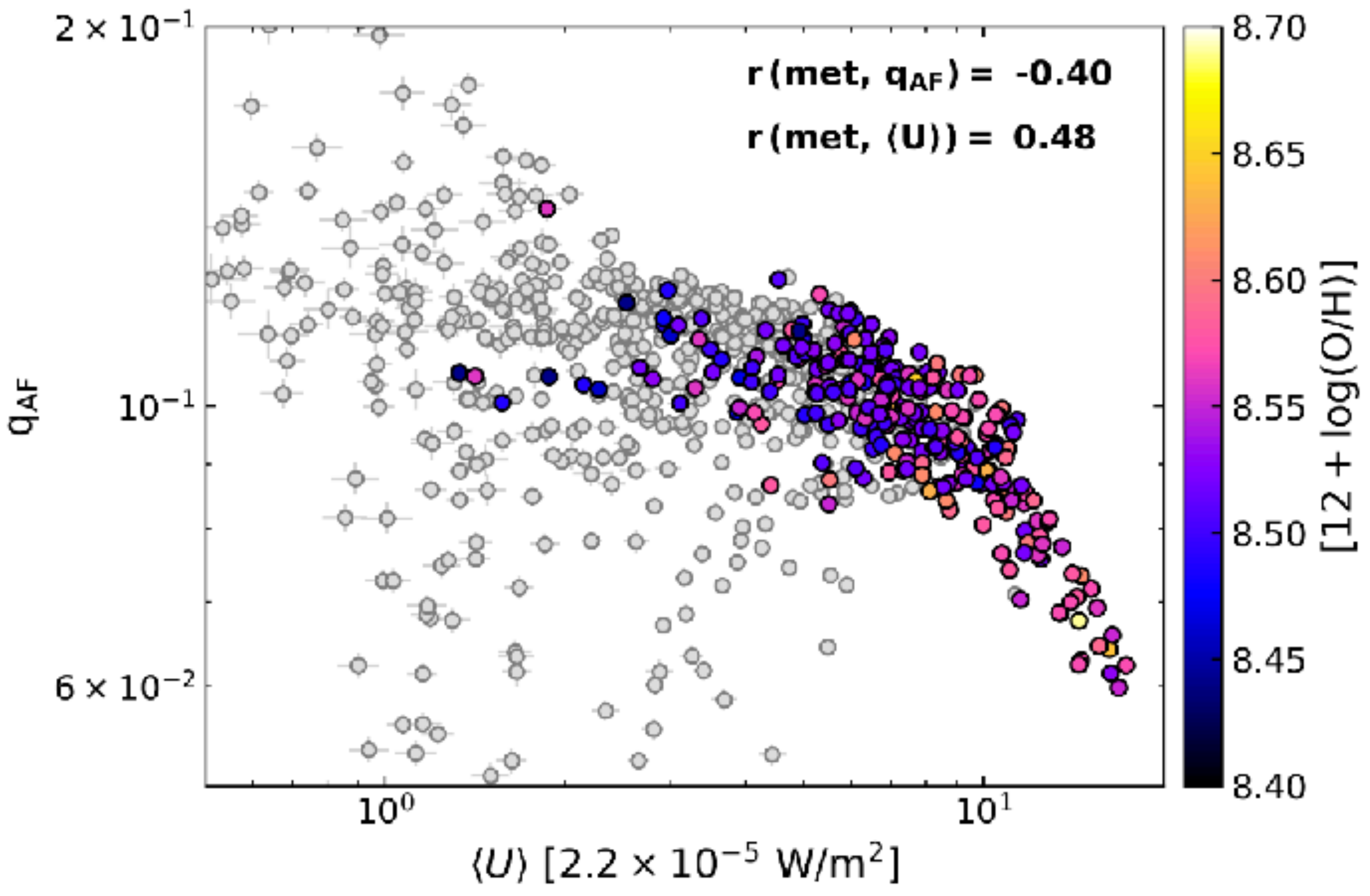

References: Jones et al. 2013; Galliano et al. 2021



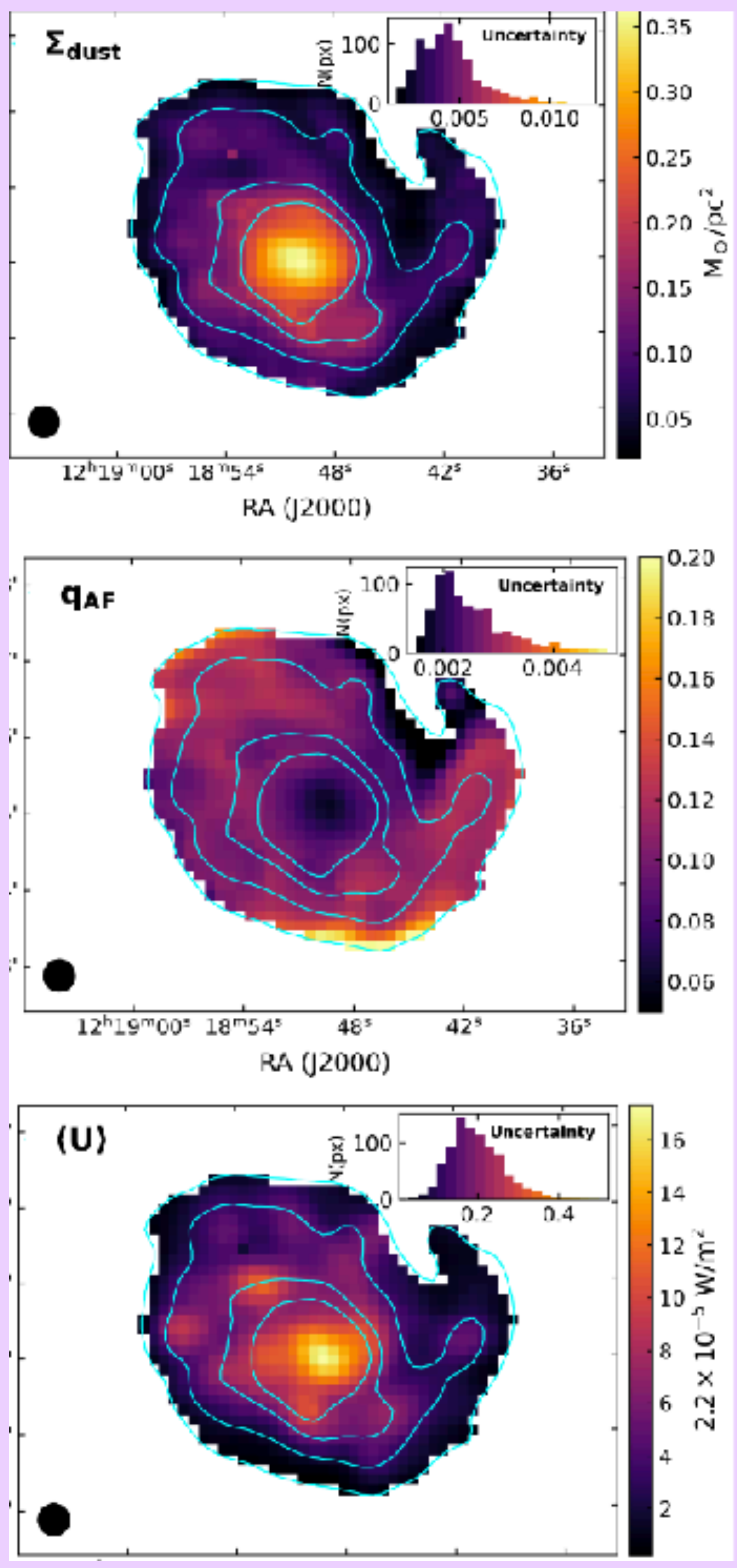

- **dense regions (MCs):** coagulation into aggregates; accretion of aliphatic-rich amorphous carbon mantles (Köhler+15; Ysard+16)
- **highly irradiated regions (HII regs):** loosing (or reducing the thickness) of the dehydrogenated carbonaceous mantles of large grains (e.g. through photo-processing; Köhler+14; Ysard+15).
- changing in the relative abundance of carbonaceous and silicate grains (with silicate showing steeper β) .

# Small dust grains at 1.75 kpc scales



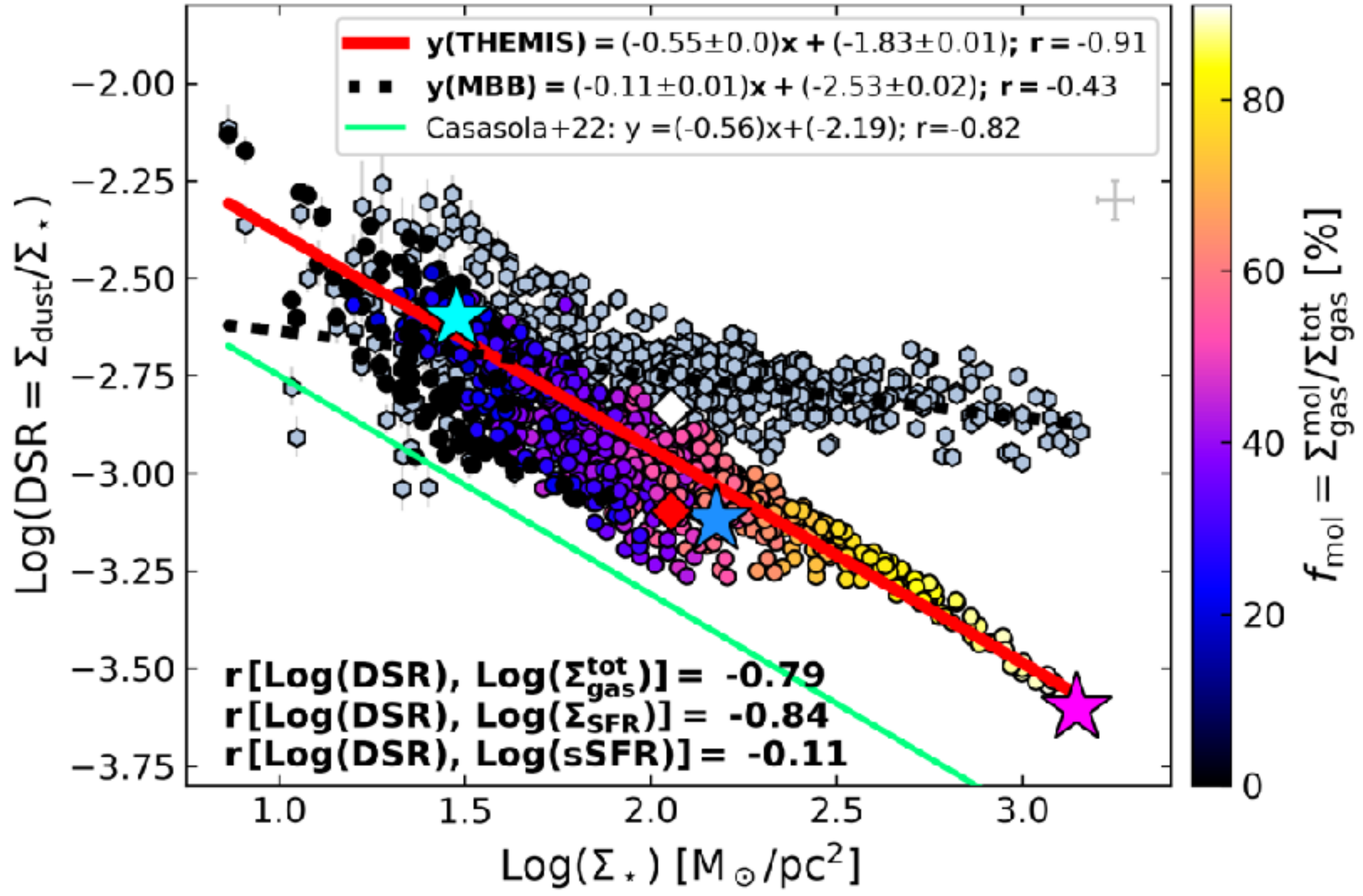



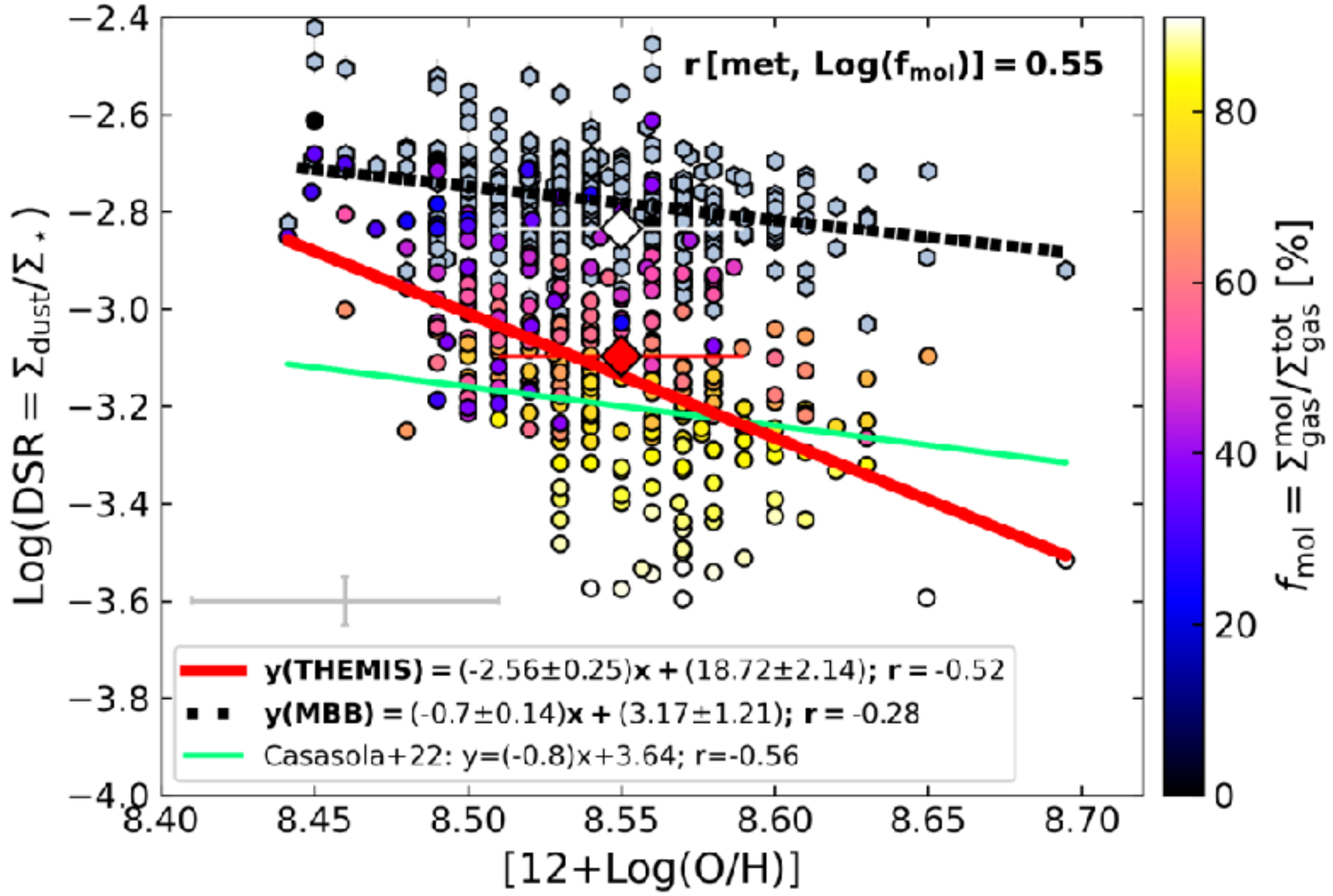

HerBIE maps




- The small grain fraction **qAF** shows an **inverse trend** with **⟨U⟩**: small grains are efficiently destroyed if exposed to hard interstellar radiation fields (see also, Boulanger et al. 1988;Puget & Leger 1989; Contursi et al. 2000).
- Metallicity (central 8 kpc) plays only a marginal role.

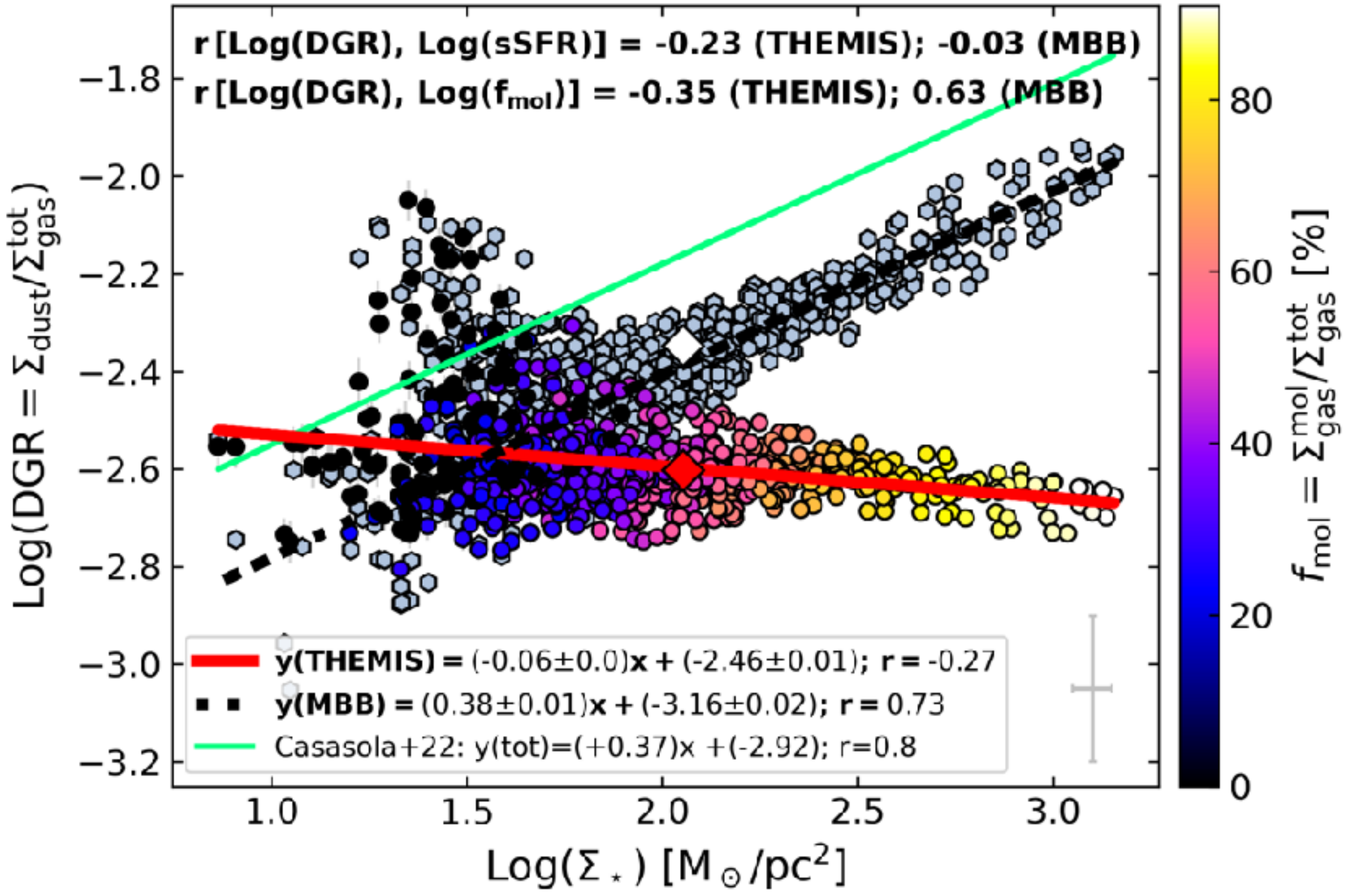
# Dust scaling relations: Dust-to-Stellar Ratio

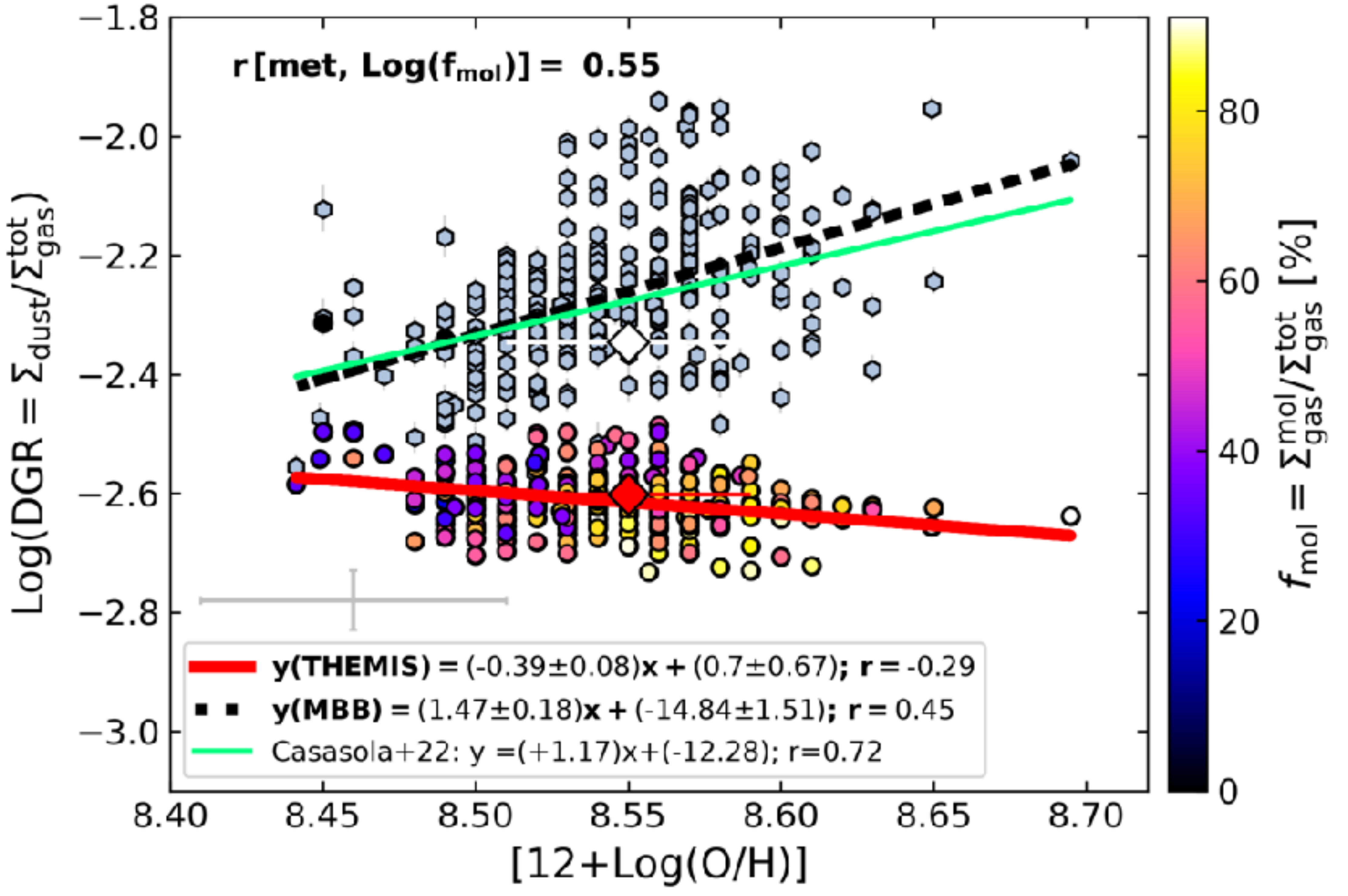



- Clear **anti-correlation** between DSR and Σ$_{star}$: in star-forming galaxies, stellar mass accumulates continuously over time, but dust may be destroyed by shocks, radiation, and astration.
- **Moderate** anti-correlation between the DSR and gas-phase metallicity.
- Caution: THEMIS dust masses may be underestimated (because of fixed β).

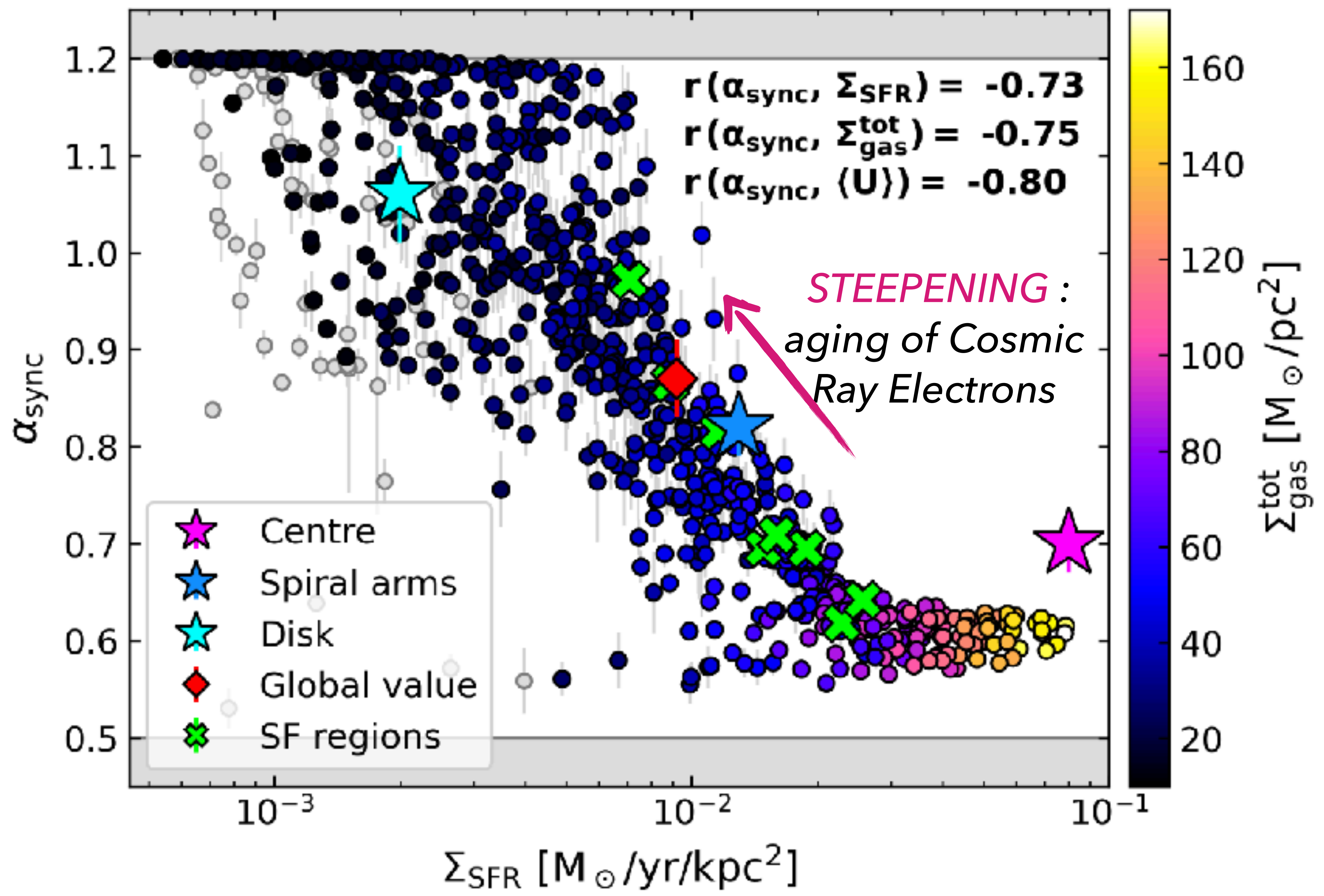
# Dust scaling relations: Dust-to-Gas Ratio

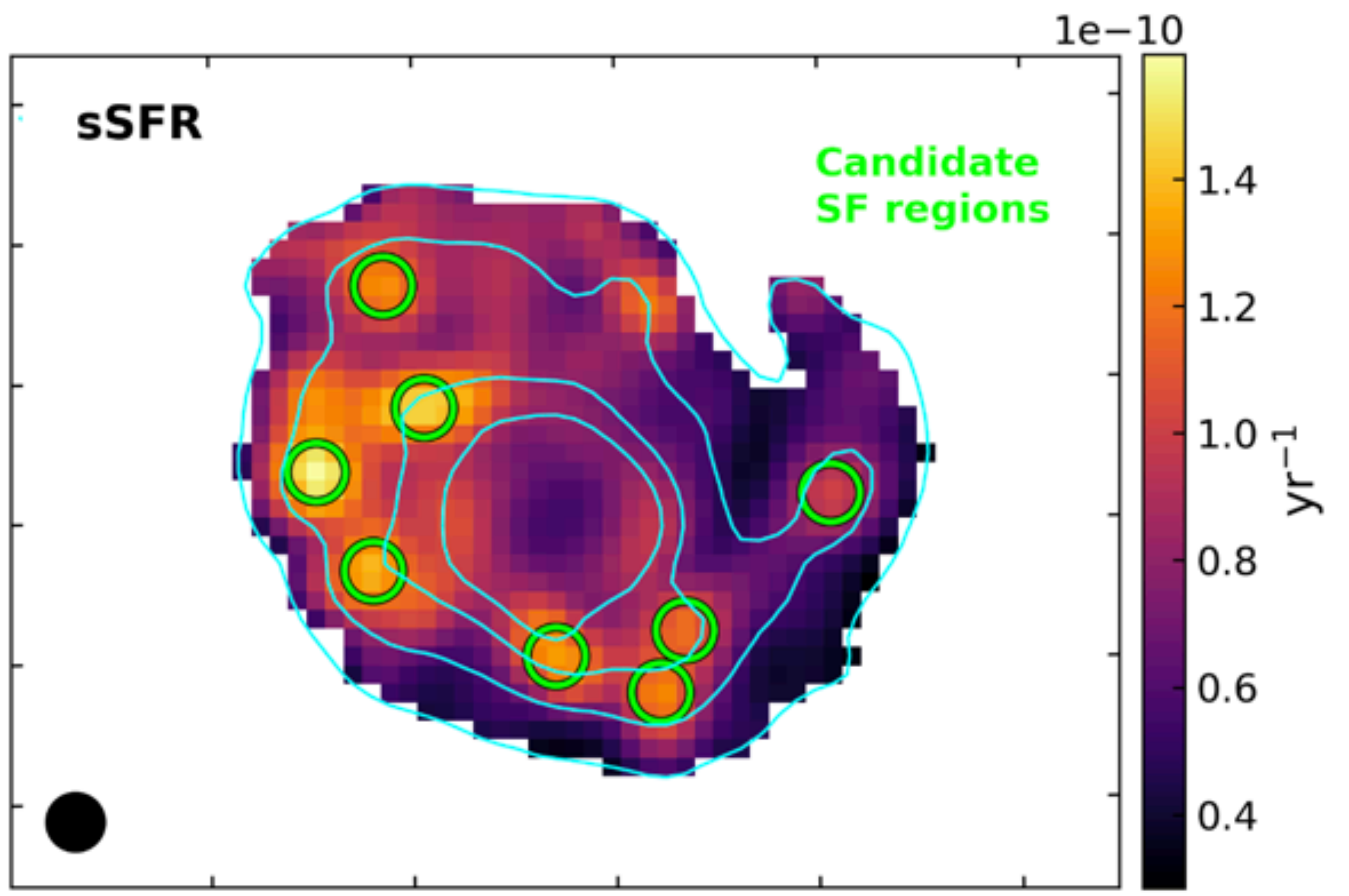



- **Direct correlation** is usually measured between $\Sigma_{star}$ and DGRs, consistent with a **more metal-rich ISM** resulting from prolonged, steady SFHs (e.g., De Looze et al. 2020; Galliano et al. 2021); similarly, between DGRs and the gas-metallicity in **dense environments** (grain growth, Casasola et al. 2022).
- Caution: THEMIS dust masses may be underestimated (because of fixed β).

# Synchrotron spectral index at ~1.75 kpc




Systematic variation of the **synchrotron spectral index** (consistent with Gajovi´c+24; Fletcher +11).

Disk: older, lower-energy electrons, tracing **older stellar populations**.

Arms + bulge: the flatter indices are consistent with **younger stellar population**.

# Summary and Conclusions

Focusing on M99, I have shown that our method

- allows us to get the most important **dust parameter** maps (e.g., dust mass, beta, mean ISRF, fraction of small grains) and the **resolved scaling relations** with the other **ISM components**;
- is **effective** in retrieving the typical correlations between free parameters;
- allows us to **put constraints on dust evolution** in the diverse local environments within a galaxy (i.e., HII regions, arms, bulge, disk).

NIKA2 maps were essential for modeling the dust millimeter emission at kpc scale.

## Main results:

- Significant **steepening of the FIR dust spectral** index in **denser star-forming regions** ($\beta>2$) where dust grains are highly reprocessed (coagulation + loss of carbonaceous mantle);
- **Small grains**, sensitive to energetic UV photons, are destroyed in **intense radiation fields** (sublimation + desorption).
- Correlations of **DSR** and **DGR** with stellar mass surface density, molecular gas fraction, and gas-phase metallicity are **well reproduced** only when allowing $\beta$ to vary.
- Steepening of **radio spectral index** reflects the ageing of CREs as they propagate far from the sites of star formation.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