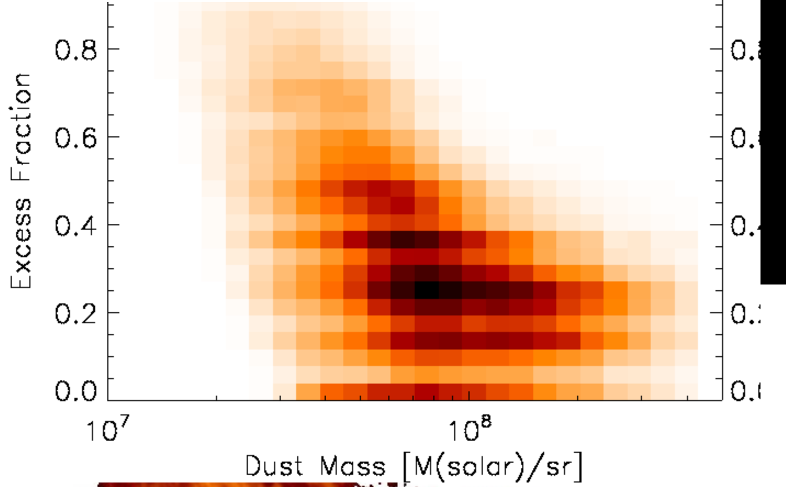
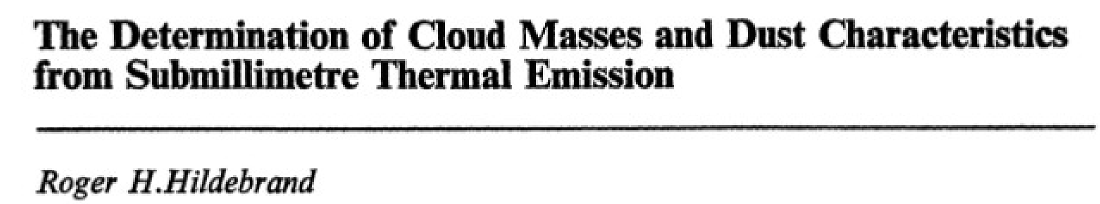
Dust Temperatures and Masses in Galaxies

Karl D. Gordon
“Dust to Galaxies”
Paris, France
30 June 2011

“Have Dust – Will Study”

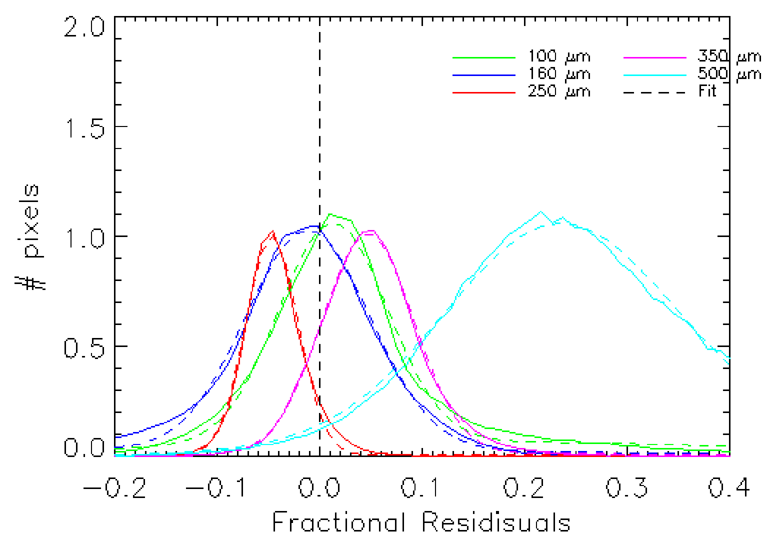
$$M_{dust} = \frac{4}{3}\frac{a\rho d^2}{Q_{em}(160)}\frac{F_{160}}{B_\nu(T_{dust})}$$

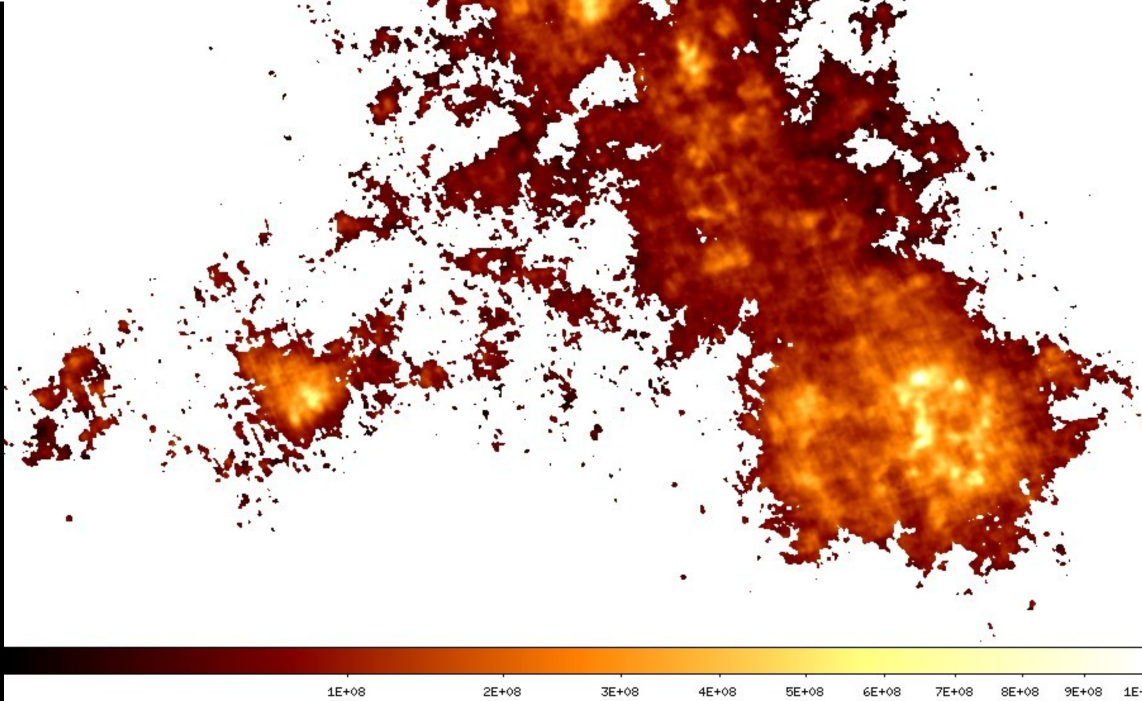




The Determination of Cloud Masses and Dust Characteristics from Submillimetre Thermal Emission

Roger H.Hildebrand





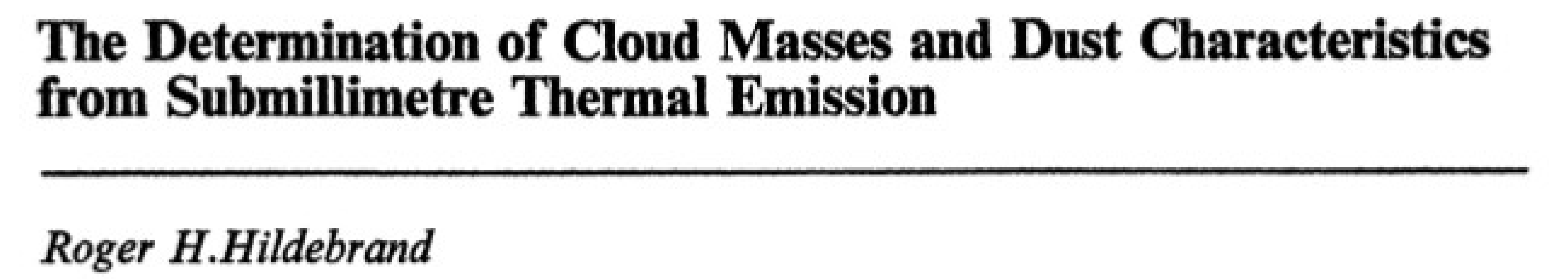
Outline

- Dust Temperatures and Masses
- Literature (IRAS/ISO/SCUBA/Spitzer/Herschel)
- Recent Laboratory work on silicates
- HERITAGE LMC/SMC effort on submm excess
- SED fitting of stars: another way to get dust masses
- Dust mass SED fitting benchmark

- Comments, questions, discussion, random thoughts, and heckling encouraged during talk

Dust Temperatures/Masses

- What they tell us
    - Dust Temp → radiation field intensity
    - Dust Mass → phase independent tracer of ISM
    - Emissivity variations → diagnostics of dust grain composition
- Single temperature modified blackbody
    - Provides a simple interpretation of the observations
    - Modified BB fits remarkably well(!) and widely used
    - But may have systematic biases
- More complicated models are possible, but the number of parameters increases (and assumptions)
    - These models still use modified BBs, just more of them
    - Dust temperature changes to <U>



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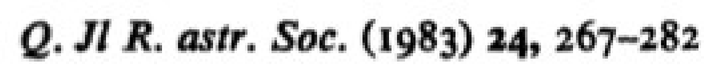
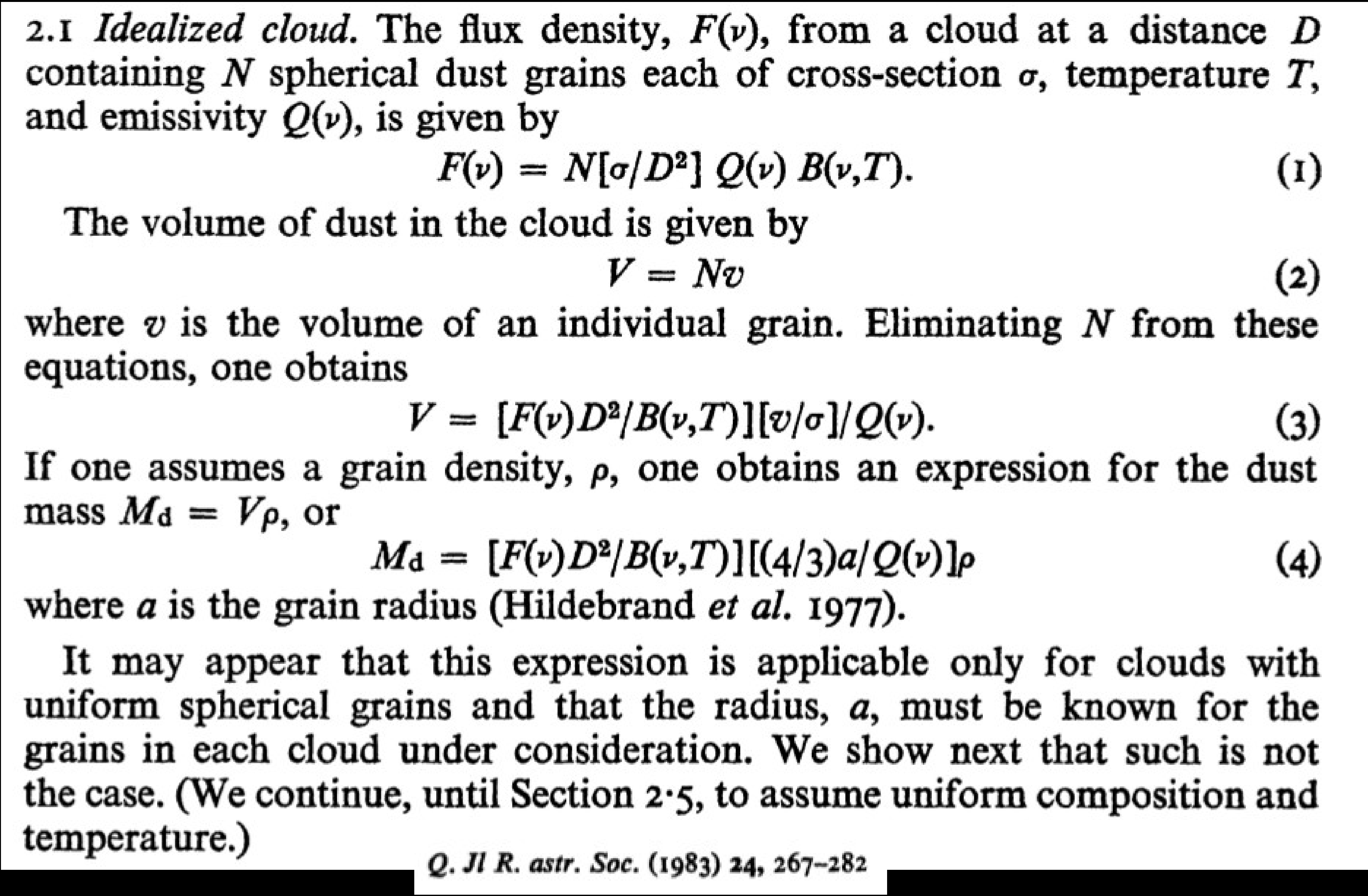


Q. Jl R. astr. Soc. (1983) **24,** 267–282

- Review
- Far-IR/submm emission measures the total grain volume
- Dust mass mainly independent of the grain radius
- Dependent on grain density
- a = 0.1 µm is the average for a MRN (1977) grain size distribution
- 1983 Chicago values for constants
- $\beta = 1$ for 50-250 µm, $\beta = 2$ for > 250 µm

Why volume?



2.1 *Idealized cloud.* The flux density, $F(\nu)$, from a cloud at a distance D containing N spherical dust grains each of cross-section σ, temperature T, and emissivity $Q(\nu)$, is given by

$$F(\nu) = N[\sigma/D^2]\,Q(\nu)\,B(\nu,T). \tag{1}$$

The volume of dust in the cloud is given by

$$V = Nv \tag{2}$$

where v is the volume of an individual grain. Eliminating N from these equations, one obtains

$$V = [F(\nu)D^2/B(\nu,T)][v/\sigma]/Q(\nu). \tag{3}$$

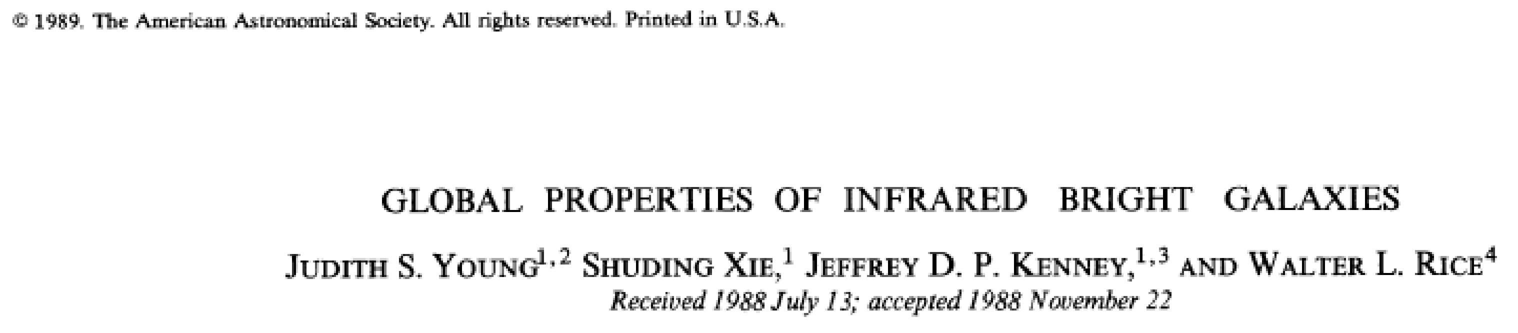
If one assumes a grain density, ρ, one obtains an expression for the dust mass $M_d = V\rho$, or

$$M_d = [F(\nu)D^2/B(\nu,T)][(4/3)a/Q(\nu)]\rho \tag{4}$$

where a is the grain radius (Hildebrand *et al.* 1977).

It may appear that this expression is applicable only for clouds with uniform spherical grains and that the radius, a, must be known for the grains in each cloud under consideration. We show next that such is not the case. (We continue, until Section 2·5, to assume uniform composition and temperature.)

Q. Jl R. astr. Soc. (1983) **24**, 267–282



THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 70:699–722, 1989 August

GLOBAL PROPERTIES OF INFRARED BRIGHT GALAXIES

JUDITH S. YOUNG[1,2] SHUDING XIE,[1] JEFFREY D. P. KENNEY,[1,3] AND WALTER L. RICE[4]

Received 1988 July 13; accepted 1988 November 22

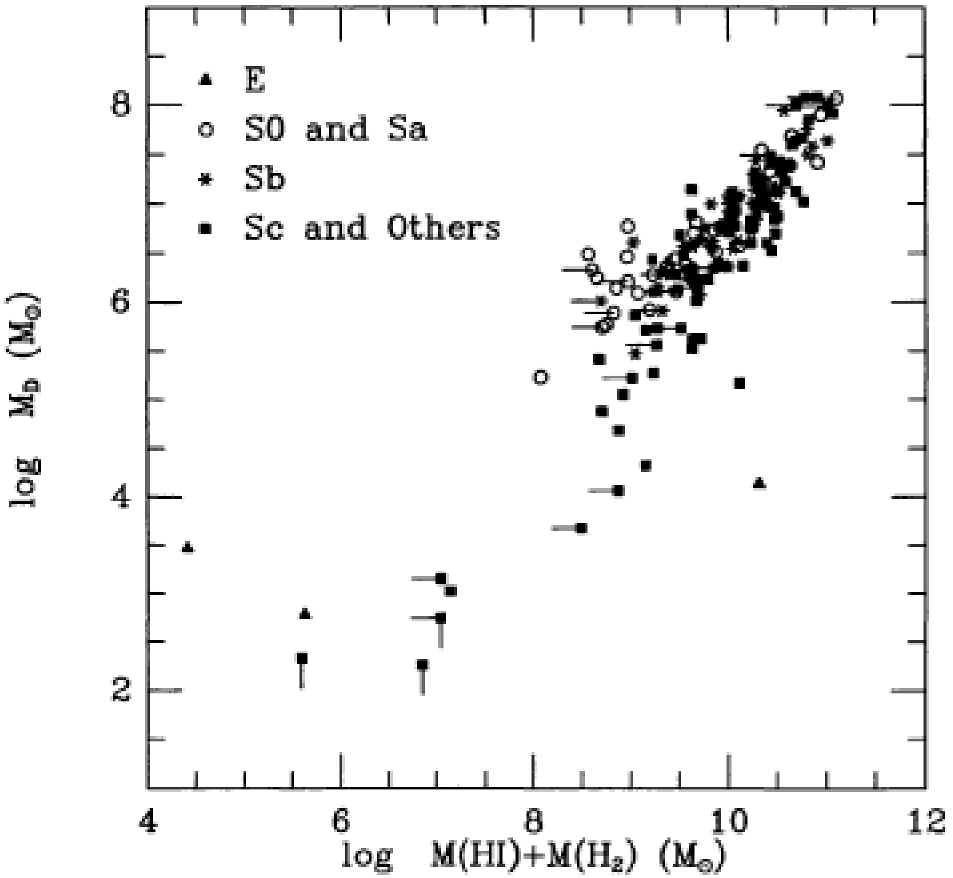


FIG. 3c

Used IRAS (12-100 μm)

182 galaxies

“Warm” dust mass (T > 25 K)

Dust mass correlates better with H_2 than HI

$M(H_2)/M(\text{dust}) \sim 570$

THE ASTRONOMICAL JOURNAL, 125:2361–2372, 2003 May

DUST TEMPERATURES IN THE *INFRARED SPACE OBSERVATORY* ATLAS OF BRIGHT SPIRAL GALAXIES[1]

GEORGE J. BENDO,[2,3,4] ROBERT D. JOSEPH,[3] MARTYN WELLS,[5] PASCAL GALLAIS,[6] MARTIN HAAS,[7] ANA M. HERAS,[8,9]
ULRICH KLAAS,[7] RENÉ J. LAUREIJS,[8,9] KIERON LEECH,[9,10] DIETRICH LEMKE,[7] LEO METCALFE,[8]
MICHAEL ROWAN-ROBINSON,[11] BERNHARD SCHULZ,[9,12] AND CHARLES TELESCO[13]

Received 2002 May 23; accepted 2003 January 24

71 galaxies with far-IR ISO 80-180 μm

No dependence of dust temperature on galaxy type

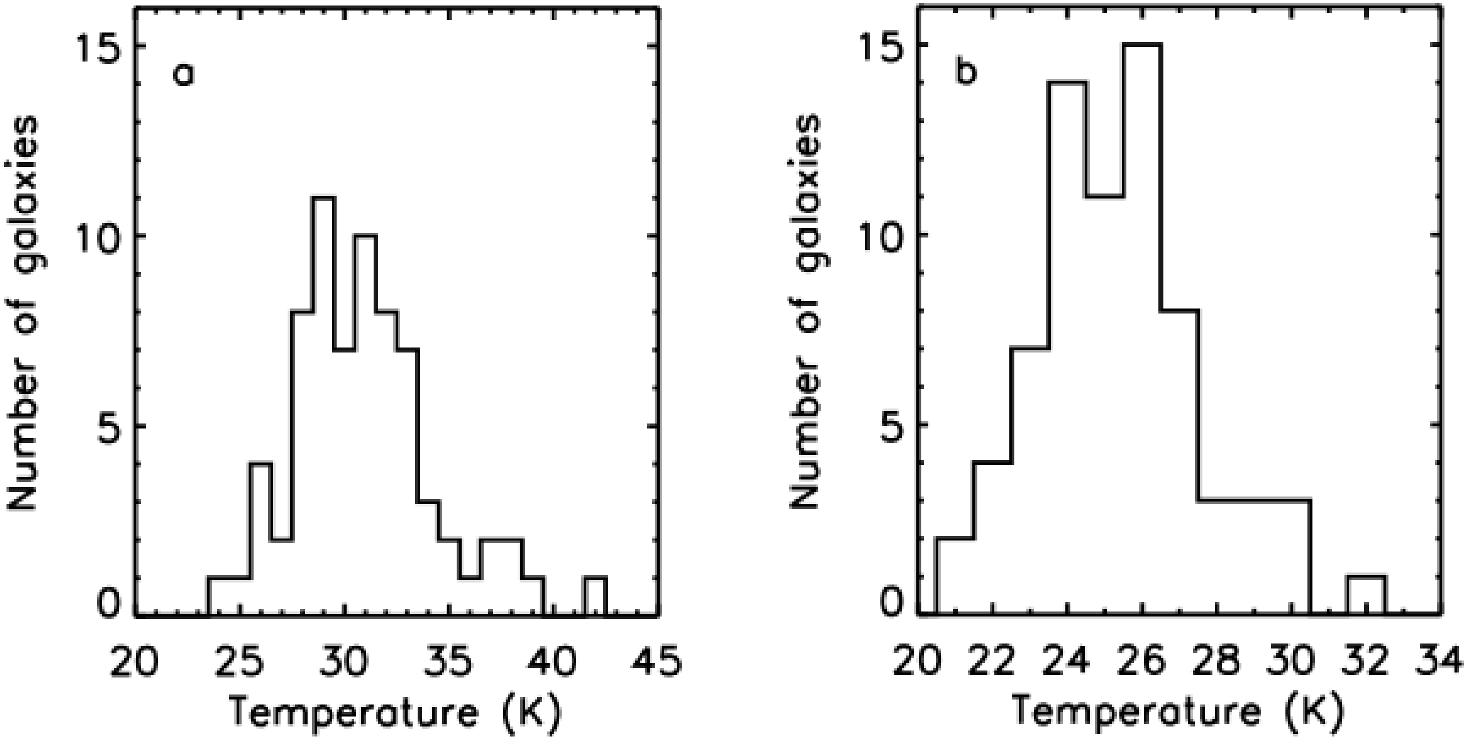


FIG. 1.—Histograms of the temperatures with (*a*) λ^{-1} and (*b*) λ^{-2} emissivities, as determined from the 60–180 μm data

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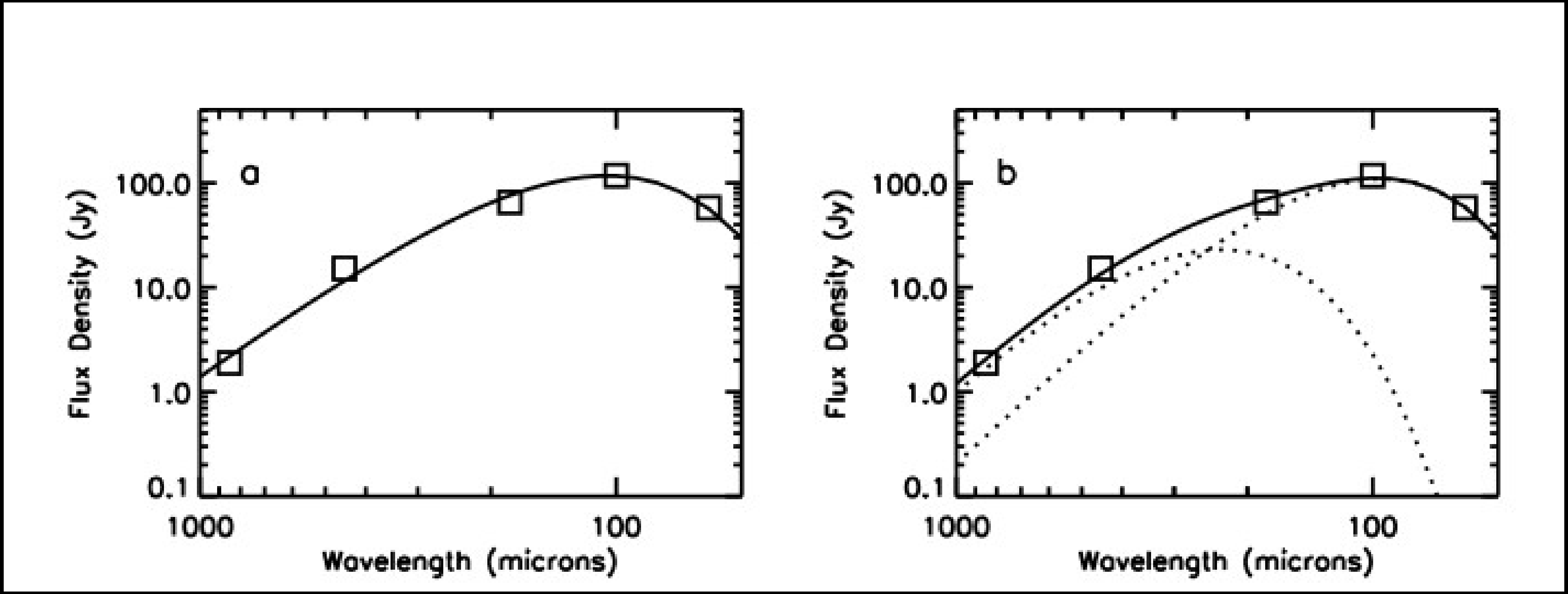
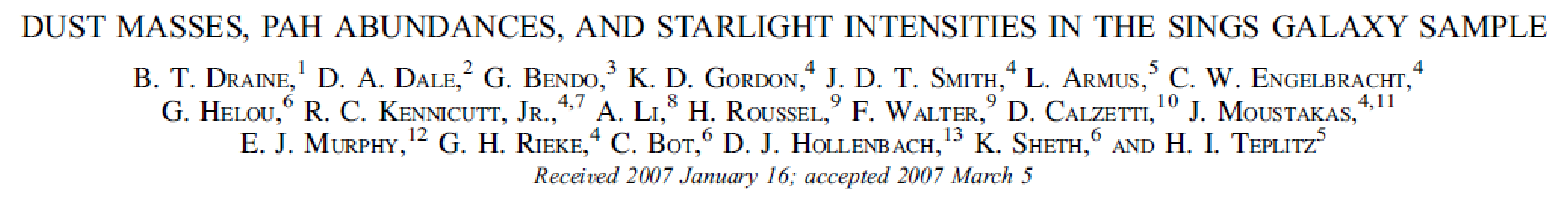
8 galaxies with SCUBA 450 & 850 μm data

$Q(\lambda) = A\lambda^{-\beta}$ best (compared to λ^{-1} and λ^{-2}) with β values from 0.9-1.9





DUST MASSES, PAH ABUNDANCES, AND STARLIGHT INTENSITIES IN THE SINGS GALAXY SAMPLE

B. T. Draine,[1] D. A. Dale,[2] G. Bendo,[3] K. D. Gordon,[4] J. D. T. Smith,[4] L. Armus,[5] C. W. Engelbracht,[4]
G. Helou,[6] R. C. Kennicutt, Jr.,[4,7] A. Li,[8] H. Roussel,[9] F. Walter,[9] D. Calzetti,[10] J. Moustakas,[4,11]
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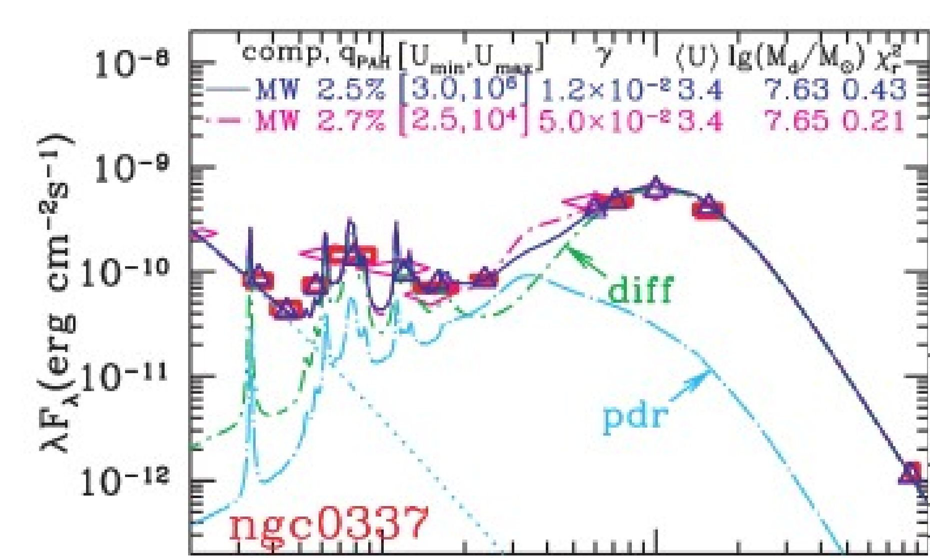
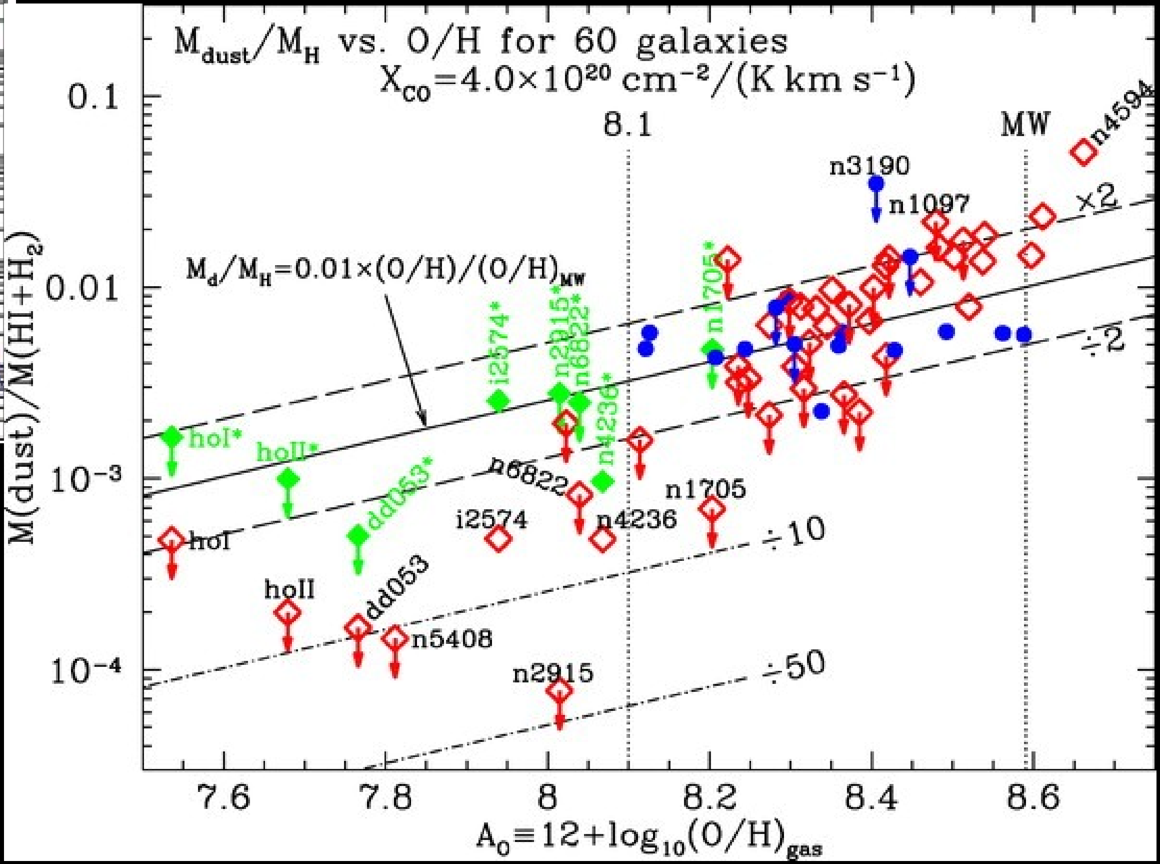
Received 2007 January 16; accepted 2007 March 5

2007, ApJ, 663, 866

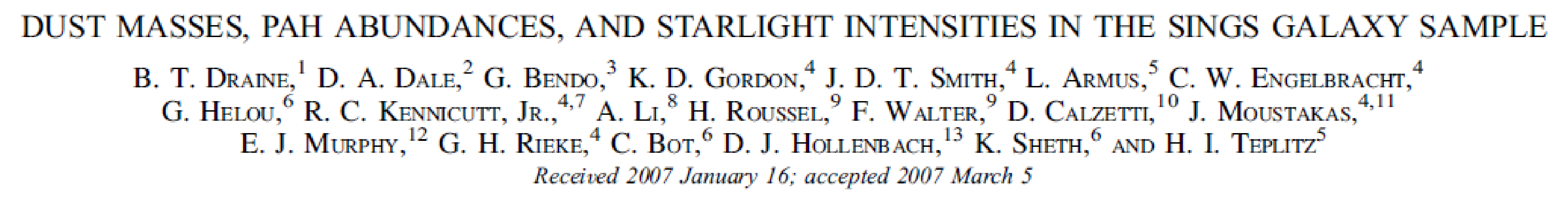




Fit the SINGS sample with a dust grain model consistent with MW dust

Grains heated by power law + delta function U
Dust-to-gas ratios reasonable

Red = whole galaxy
Blue = galaxies with SCUBA data
Green = IR emitting region only



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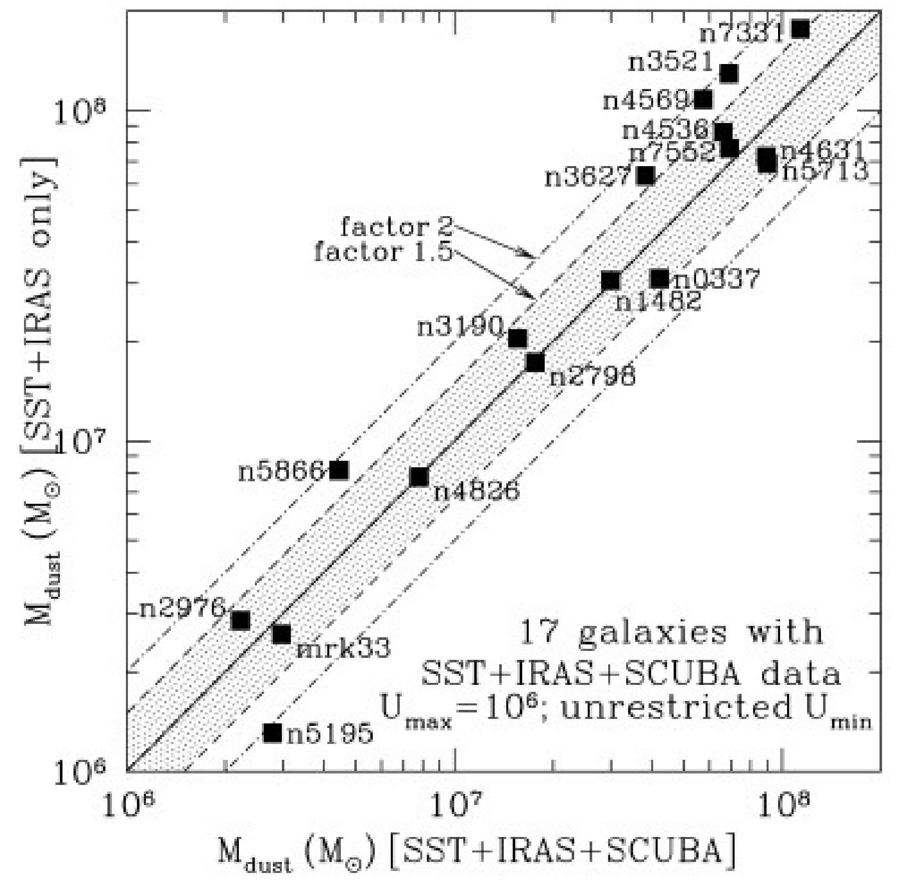
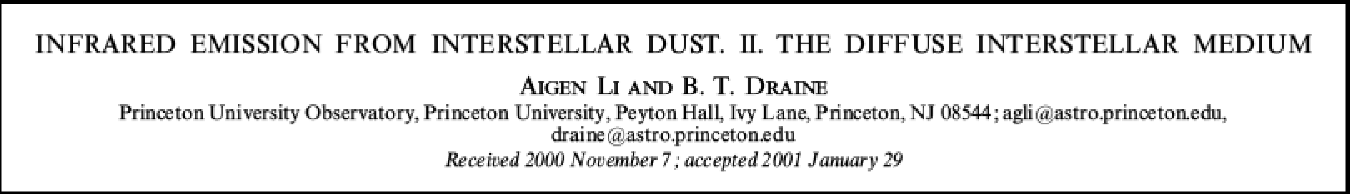


Fig. 12.—Dust mass M_{dust} determined for 17 galaxies using *IRAS* and *Spitzer* data only, vs. the masses derived using *IRAS*, *Spitzer*, and SCUBA data combined. Data are fitted by MW dust models with $U_{max} = 10^6$ but no restriction on U_{min}. Without SCUBA data, cool dust is not strongly constrained. Nevertheless, 11/17 of the galaxies fall within a factor of 1.5 of the value obtained when SCUBA data are employed, and all 17 galaxies are within a factor of 2.2. [*See the electronic edition of the Journal for a color version of this figure.*]

Dust masses w/o and w/ SCUBA data give masses within a factor of 2.2

“astronomical” silicate emissivity break



INFRARED EMISSION FROM INTERSTELLAR DUST. II. THE DIFFUSE INTERSTELLAR MEDIUM

AIGEN LI AND B. T. DRAINE

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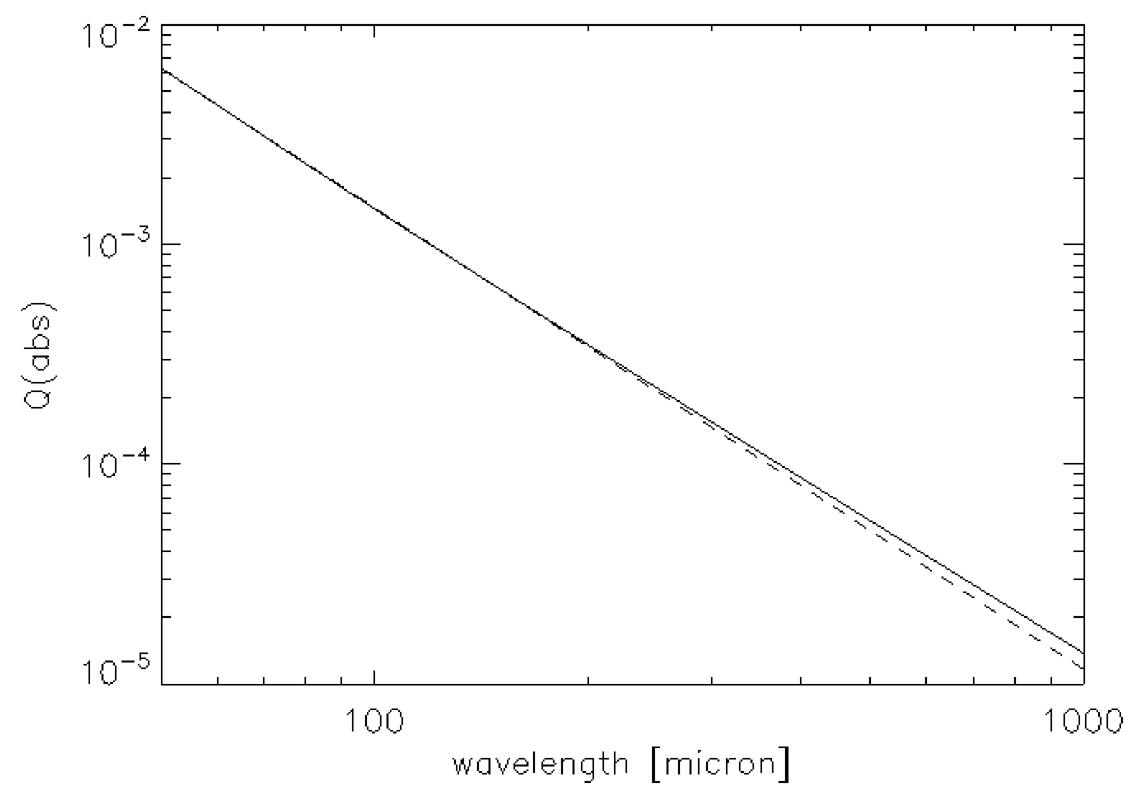
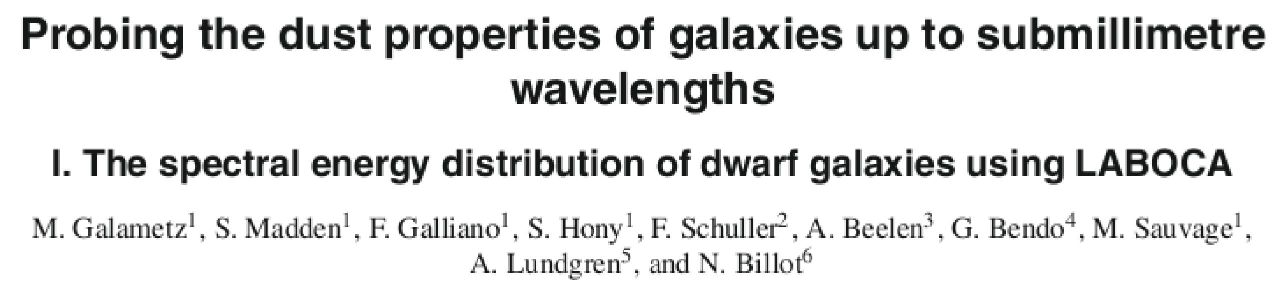
Received 2000 November 7; accepted 2001 January 29

2001, ApJ, 554, 778

"Astronomical" Silicates

- Break at 200 μm; β ~ 2 shortward
- Excess emissivity @ 500 μm = 0.11 (MW has submm excess!)
    - a = 0.1
- Driven by MW FIRAS observations



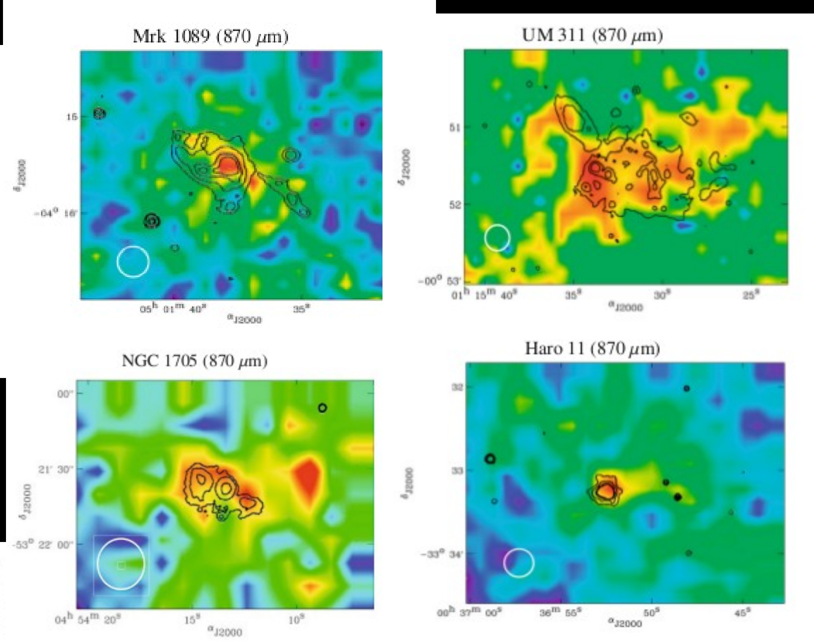


Probing the dust properties of galaxies up to submillimetre wavelengths

I. The spectral energy distribution of dwarf galaxies using LABOCA

M. Galametz[1], S. Madden[1], F. Galliano[1], S. Hony[1], F. Schuller[2], A. Beelen[3], G. Bendo[4], M. Sauvage[1],
A. Lundgren[5], and N. Billot[6]

2009, A&A, 508, 645



2 out of 4 galaxies do not show strong submm excess

Dust grain model
VCG component:
Haro 11/NGC 1705
β = 1; T = 10 K
>70% of dust mass

Unreasonable gas-to-dust ratios for Haro 11 (5)

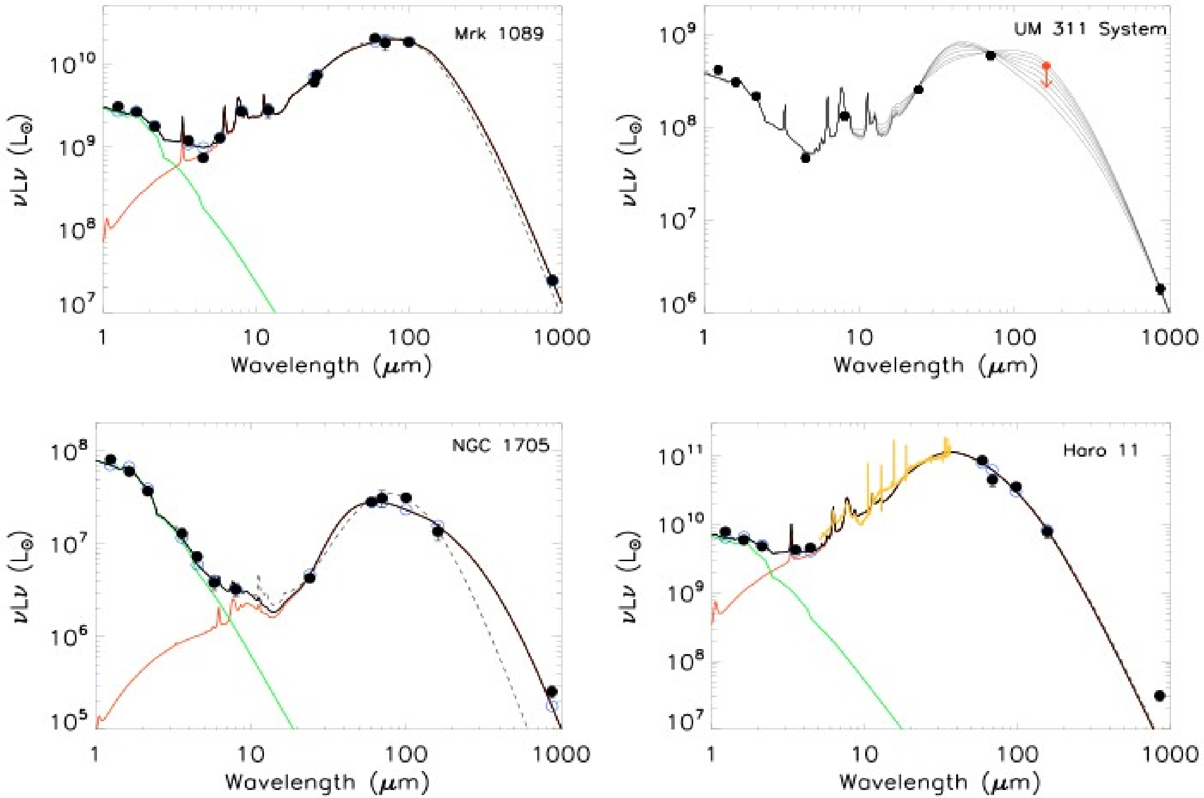


Fig. 4. SED models of Mrk 1089, the UM 311 system, NGC 1705 and Haro 11 using the fiducial model. The SEDs are plotted in black. Observational constraints (listed in Table 3) are superimposed (filled circles). The green and red lines respectively distinguish the stellar and the dust contributions. The dashed black lines present the SED models of our galaxies obtained when the LABOCA constraint is not used in the modelling. The open circles represent the expected modeled fluxes integrated over the instrumental bands. When the error bars are not shown, the errors are smaller than symbols. Note that the IRS MIR spectrum used in the modelling is overlaid in orange for Haro 11. For the UM 311 system of 3 compact sources, the 160 μm flux is an upper limit since it was calculated with a 40″ aperture. The different SEDs represent the possible SED models that fit the observational constraints with good accuracy.

What is the Submm Excess?

(What Herschel will most uniquely contribute to dust temperature & mass studies)

- Excess emission above that expected from fits to $\lambda < 200$ μm data
  - First done with IRAS/ISO versus ground-based 450/850/1200 μm
  - Expanded with Spitzer to include Spitzer MIPS 160 μm
  - With Herschel, now possible to explore the shape of the submm excess
- Either emissivity variations or colder dust ($T < 10$ K)
- In extragalactic observations, seen to increase in strength with decreasing metallicity of a galaxy
- Potential barrier to dust mass/temperature/<U> calculations
- Clue to grain properties

- Dust masses don't seem to change much with the addition of Herschel data (Draine and other talks and Herschel special issue papers)

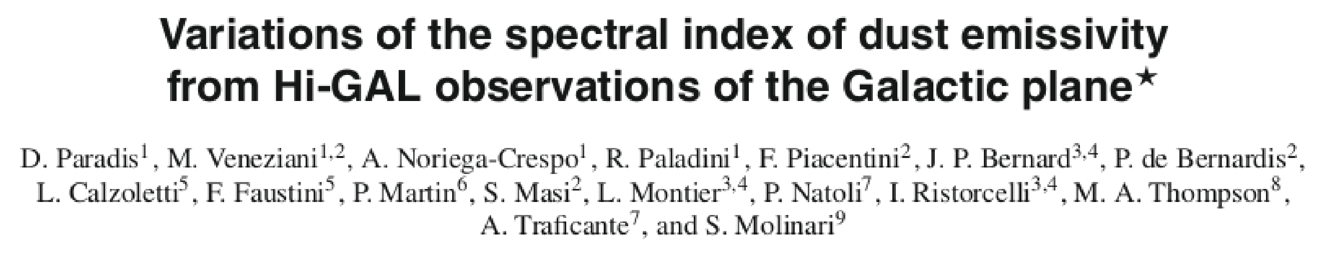
Herschel Space Observatory

- Ground-based limited to only 2 submm (often only 1)
    - Hard to define the behavior of the submm excess
- Herschel SPIRE bands at 250, 350, & 500 μm ideal
- PACS 100 (& 70/160) μm also useful constraints
- Lots of galaxies observed
- Both big and small
- All calibrated the same
    - Relative calibration errors quite small

Herschel Special Issue

(2010, A&A, 518)

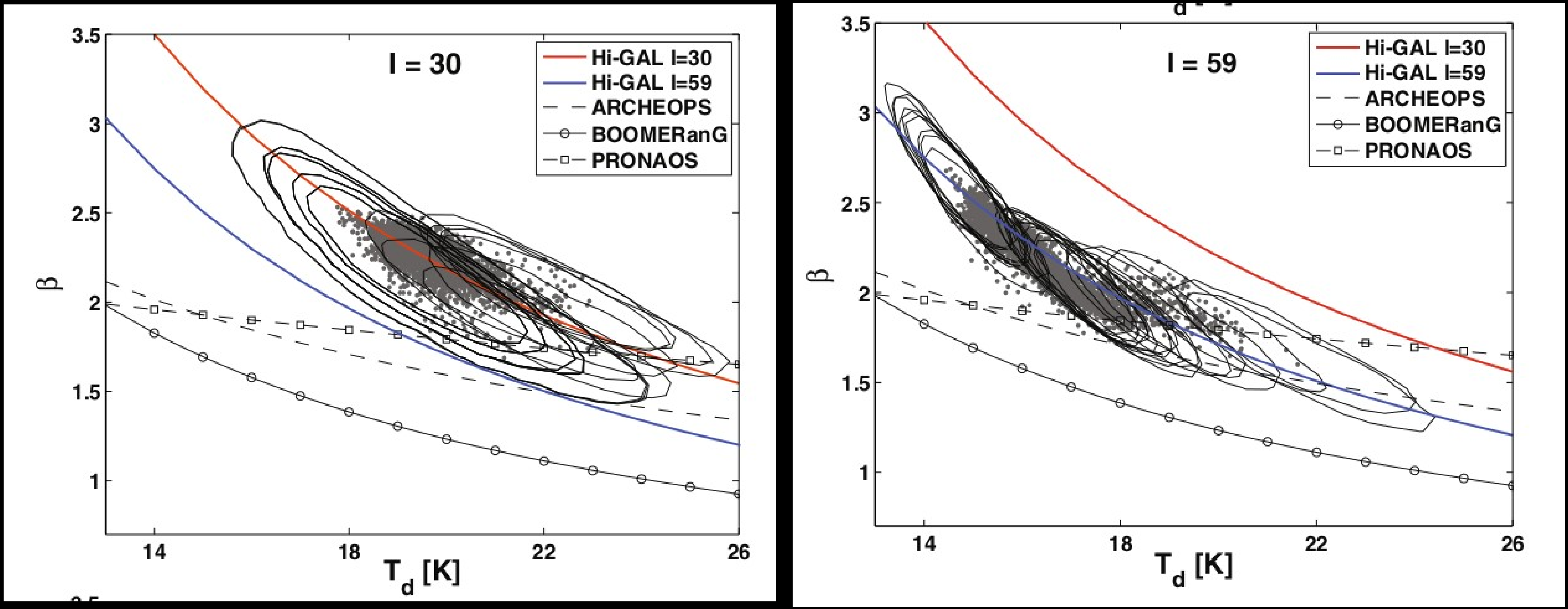
- Braine et al.; M33, dust to map total gas
- Galamtez et al; NGC 6822, ½ solar
    - amorphous carbon instead of graphite; gas-to-dust = 186
- Gordon et al.; LMC, ½ solar
    - β = 1.5; 10% excess @ 500 μm (details in following slides)
- Grossi et al.; Virgo low-met galaxies (log(O/H)+12 = 7.8-8.3)
    - Two dwarfs with 500 μm excess
- Kramer et al.; M33, ½ solar
    - β =1.5, gas-to-dust ratios of 120 to 200 a different radii
- Meixner et al.; LMC, ½ solar
    - Submm excess of 6-17% @ 500 μm
    - Amorphous carbon instead of graphite; gas-to-dust = 287
- O'Halloran et al.; NGC 1705, 1/3 solar
    - 2nd component; T = 5.8 K, β = 1; gas-to-dust ratio = 100



Variations of the spectral index of dust emissivity from Hi-GAL observations of the Galactic plane★

D. Paradis[1], M. Veneziani[1,2], A. Noriega-Crespo[1], R. Paladini[1], F. Piacentini[2], J. P. Bernard[3,4], P. de Bernardis[2], L. Calzoletti[5], F. Faustini[5], P. Martin[6], S. Masi[2], L. Montier[3,4], P. Natoli[7], I. Ristorcelli[3,4], M. A. Thompson[8], A. Traficante[7], and S. Molinari[9]

2010, A&A, 520, L8



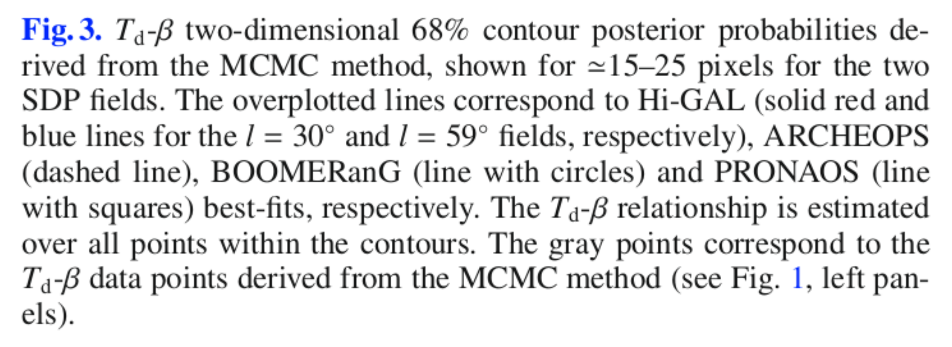
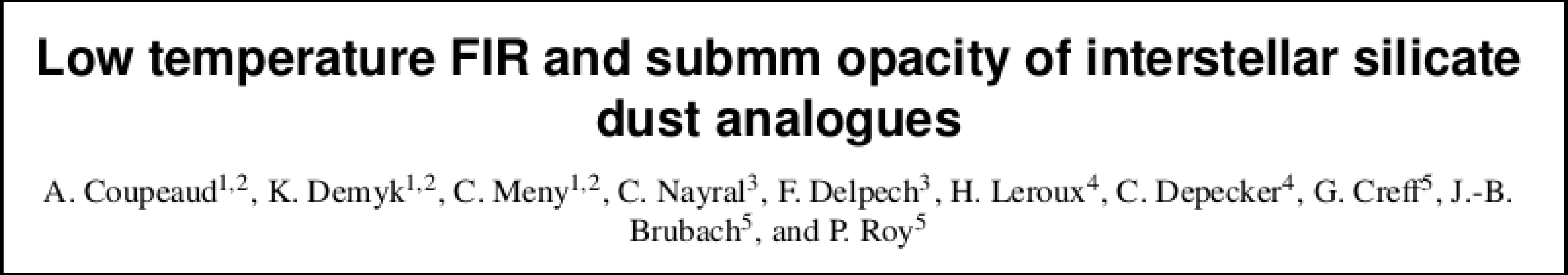


Fig. 3. T_d-β two-dimensional 68% contour posterior probabilities derived from the MCMC method, shown for ≃15–25 pixels for the two SDP fields. The overplotted lines correspond to Hi-GAL (solid red and blue lines for the $l = 30°$ and $l = 59°$ fields, respectively), ARCHEOPS (dashed line), BOOMERanG (line with circles) and PRONAOS (line with squares) best-fits, respectively. The T_d-β relationship is estimated over all points within the contours. The gray points correspond to the T_d-β data points derived from the MCMC method (see Fig. 1, left panels).

Confirms earlier T-β results
See also Planck results (Bernard talk)
already heard that T-β not explained
by fitting errors (Bernard talk)



Low temperature FIR and submm opacity of interstellar silicate dust analogues

A. Coupeaud[1,2], K. Demyk[1,2], C. Meny[1,2], C. Nayral[3], F. Delpech[3], H. Leroux[4], C. Depecker[4], G. Creff[5], J.-B. Brubach[5], and P. Roy[5]

Talk at “Herschel and the Characteristics of Dust in Galaxies” meeting and paper submitted to A&A

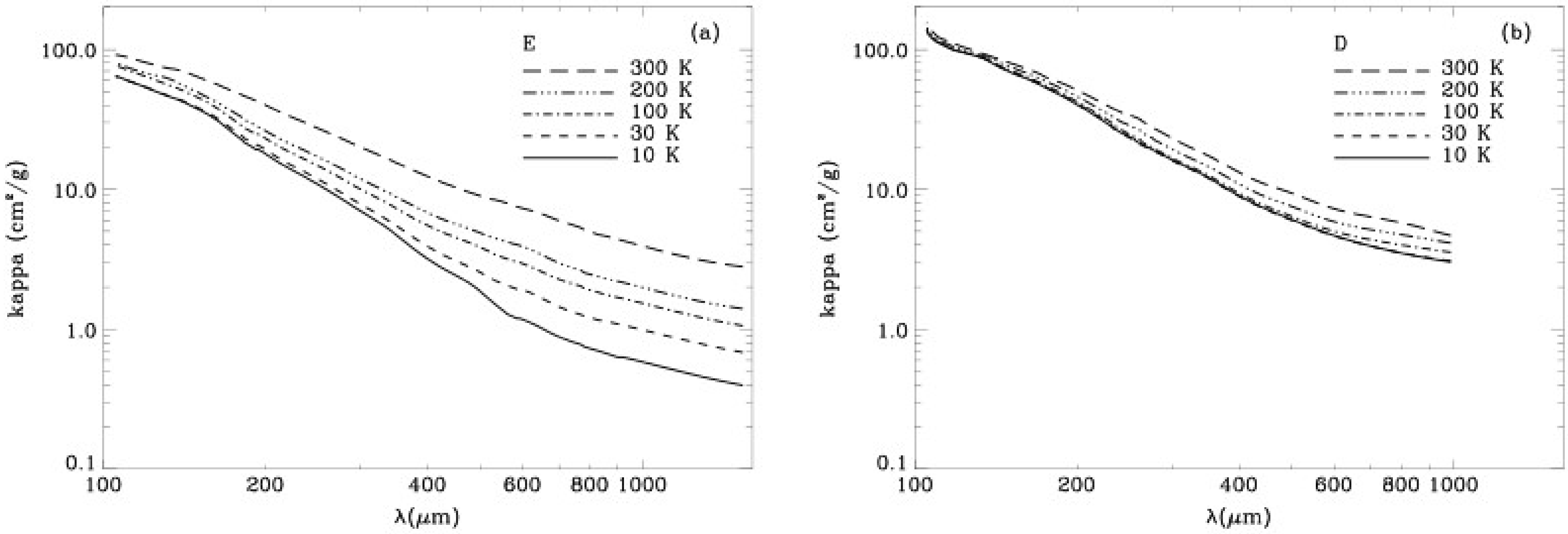
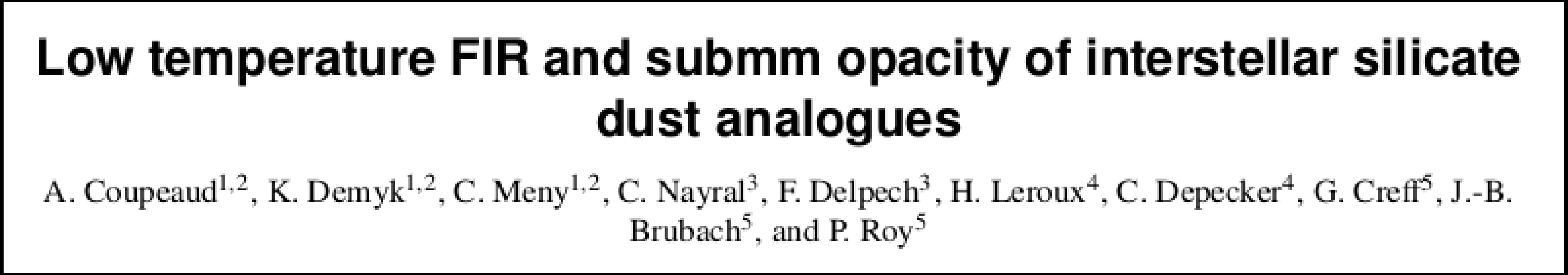


Fig. 4. Opacity of amorphous pyroxene-like samples at different temperatures in the 100-1000(1500) μm range. Panel (a): E sample, $Mg_{0.95}SiO_3$, panel (b): D sample, $Ca_{0.98}Mg_{0.9}Si_2O_6$.

Amorphous silicates have emissivities that vary with temperature with shape and strength

See also Mennella et al. 1998; Boudet et al. 2005)



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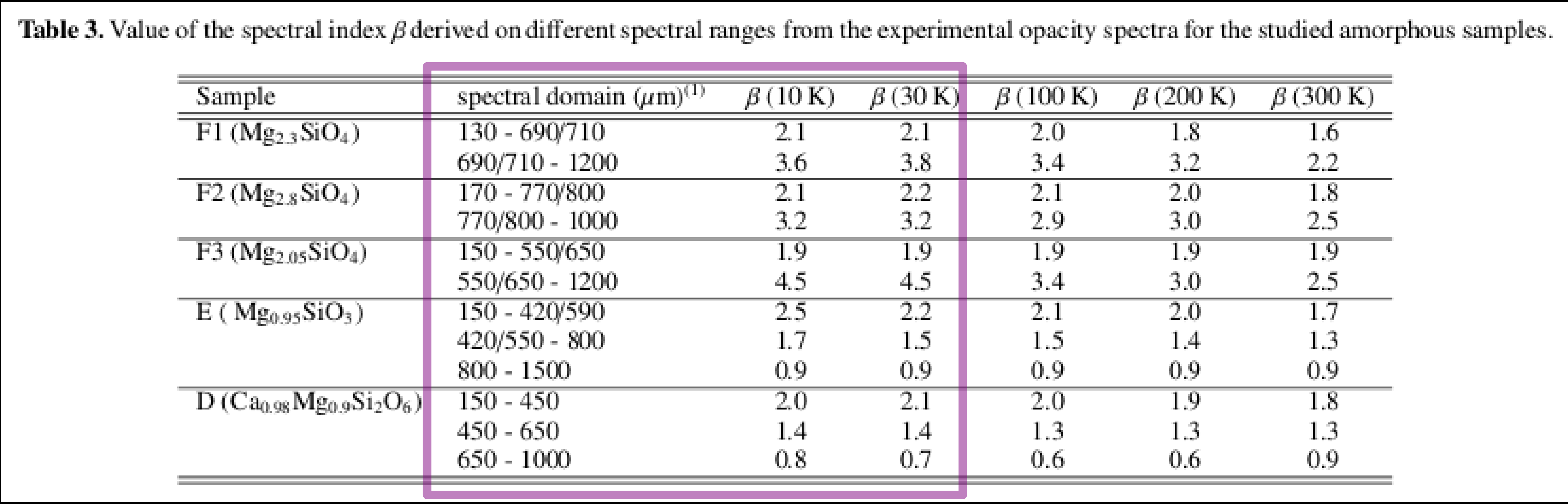


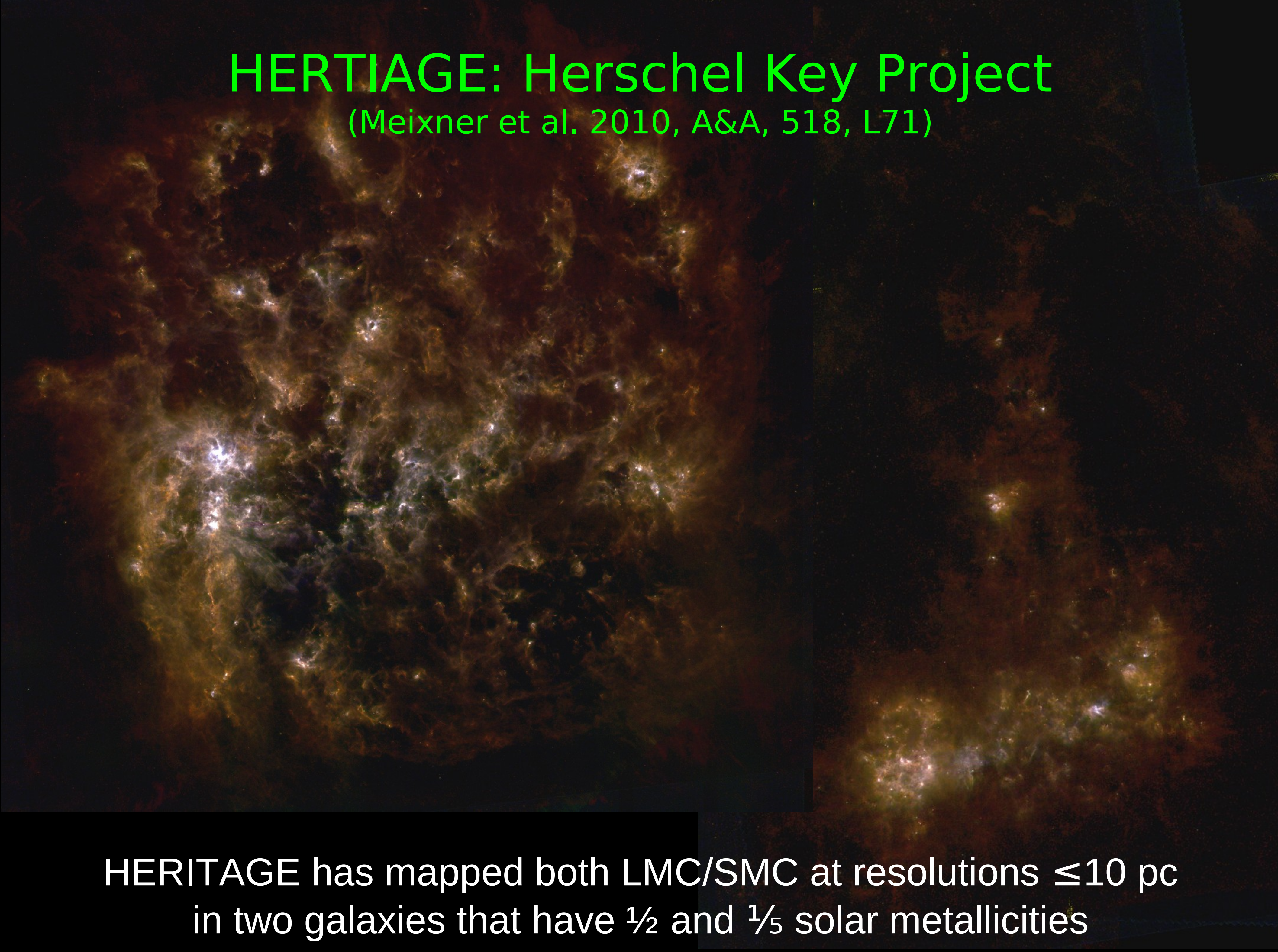
Table 3. Value of the spectral index β derived on different spectral ranges from the experimental opacity spectra for the studied amorphous samples.

Sample	spectral domain (μm)$^{(1)}$	β (10 K)	β (30 K)	β (100 K)	β (200 K)	β (300 K)
F1 ($Mg_{2.3}SiO_4$)	130 - 690/710	2.1	2.1	2.0	1.8	1.6
	690/710 - 1200	3.6	3.8	3.4	3.2	2.2
F2 ($Mg_{2.8}SiO_4$)	170 - 770/800	2.1	2.2	2.1	2.0	1.8
	770/800 - 1000	3.2	3.2	2.9	3.0	2.5
F3 ($Mg_{2.05}SiO_4$)	150 - 550/650	1.9	1.9	1.9	1.9	1.9
	550/650 - 1200	4.5	4.5	3.4	3.0	2.5
E ($Mg_{0.95}SiO_3$)	150 - 420/590	2.5	2.2	2.1	2.0	1.7
	420/550 - 800	1.7	1.5	1.5	1.4	1.3
	800 - 1500	0.9	0.9	0.9	0.9	0.9
D ($Ca_{0.98}Mg_{0.9}Si_2O_6$)	150 - 450	2.0	2.1	2.0	1.9	1.8
	450 - 650	1.4	1.4	1.3	1.3	1.3
	650 - 1000	0.8	0.7	0.6	0.6	0.9

Amorphous silicates have emissivities that vary with temperature with shape and strength

HERTIAGE: Herschel Key Project

(Meixner et al. 2010, A&A, 518, L71)



HERITAGE has mapped both LMC/SMC at resolutions ≤10 pc in two galaxies that have ½ and ⅕ solar metallicities

Fits to Full LMC/SMC HERITAGE Data

- PACS 100, 160 & SPIRE 250, 350, 500
  - Reduced by the HERITAGE team
  - PACS data “corrected” to the IRAS100/MIPS160 calibrations
- Convolve all data to SPIRE 500 resolution (40” ~ 10 pc)
- Fit the SED of each pixel (14”x14”) with good data
  - Surface brightnesses at all $\lambda > 3\sigma$ above background
- Look at the ensemble behavior of the fractional residuals
  - Should only by sensitive to relative calibration uncertainties
  - Can the fit residuals tell us the origin of the submm excess?
- Try different $\lambda^{-\beta}$ emissivity laws
- Try a broken emissivity law
- Try a second population of colder dust

Fit Details

- $F_\nu = AQ(\lambda,\beta)B_\nu(T_{dust})$
- 1: $Q_1(\lambda,\beta) = Q_o(\lambda/160)^{-\beta}$
  - β varies from 1 to 2
- 2: $Q_2(\lambda,\beta) = Q_o(\lambda/160)^{-\beta 1}$ for $\lambda < \lambda_o$

  $Q_o(\lambda/160)^{-\beta 2}$ for $\lambda > \lambda_o$
  - λ_o varied from 200 to 300 μm (held fixed)
  - $\beta 2 = \log(1+g)(\lambda_o/500)^{\beta}/\log(\lambda_o/500)$
  - g = emissivity excess @ 500 μm
- 3: $F_\nu = AQ_1(\lambda,\beta)[B_\nu(T_1) + gB_\nu(T_2)]$
  - $T_2 \leq 10$ K (held fixed)
  - $g = B_{500}(T_2)/B_{500}(T_1)$ = excess emission @ 500 μm

$$M_{dust} = \frac{4}{3}\frac{a\rho d^2}{Q_{em}(160)}\frac{F_{160}}{B_\nu(T_{dust})}$$

Where:

$a = 0.1$ μm

$\rho = 3$ g cm^{-3}

$d = 50$ kpc or 60 kpc

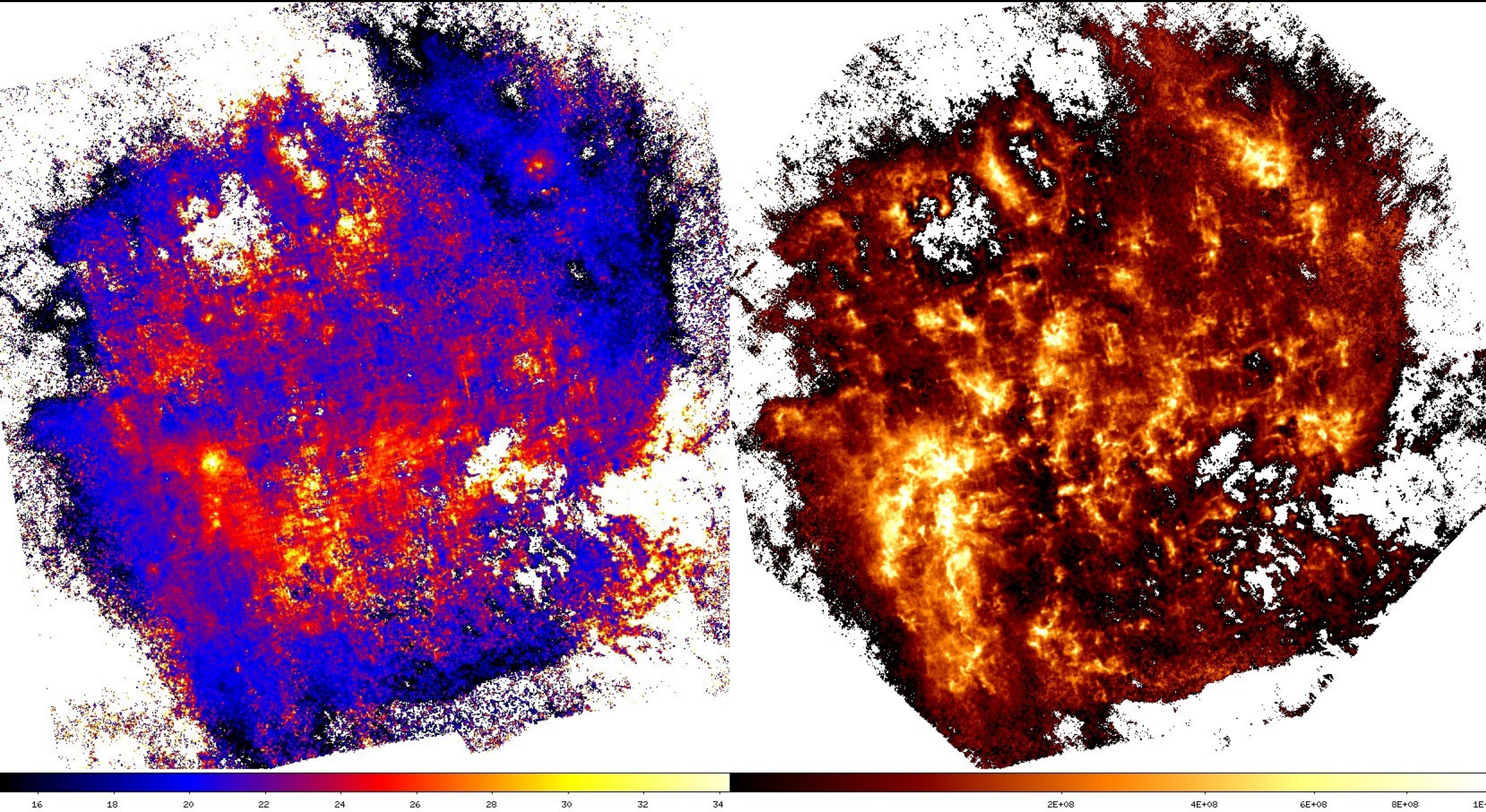
$Q_{em}(160) = 5.5\times10^{-4}$

(Loar & Draine 1993)

(Gordon et al. 2010, A&A, 518, L89; Gordon et al. 2011, in prep,)

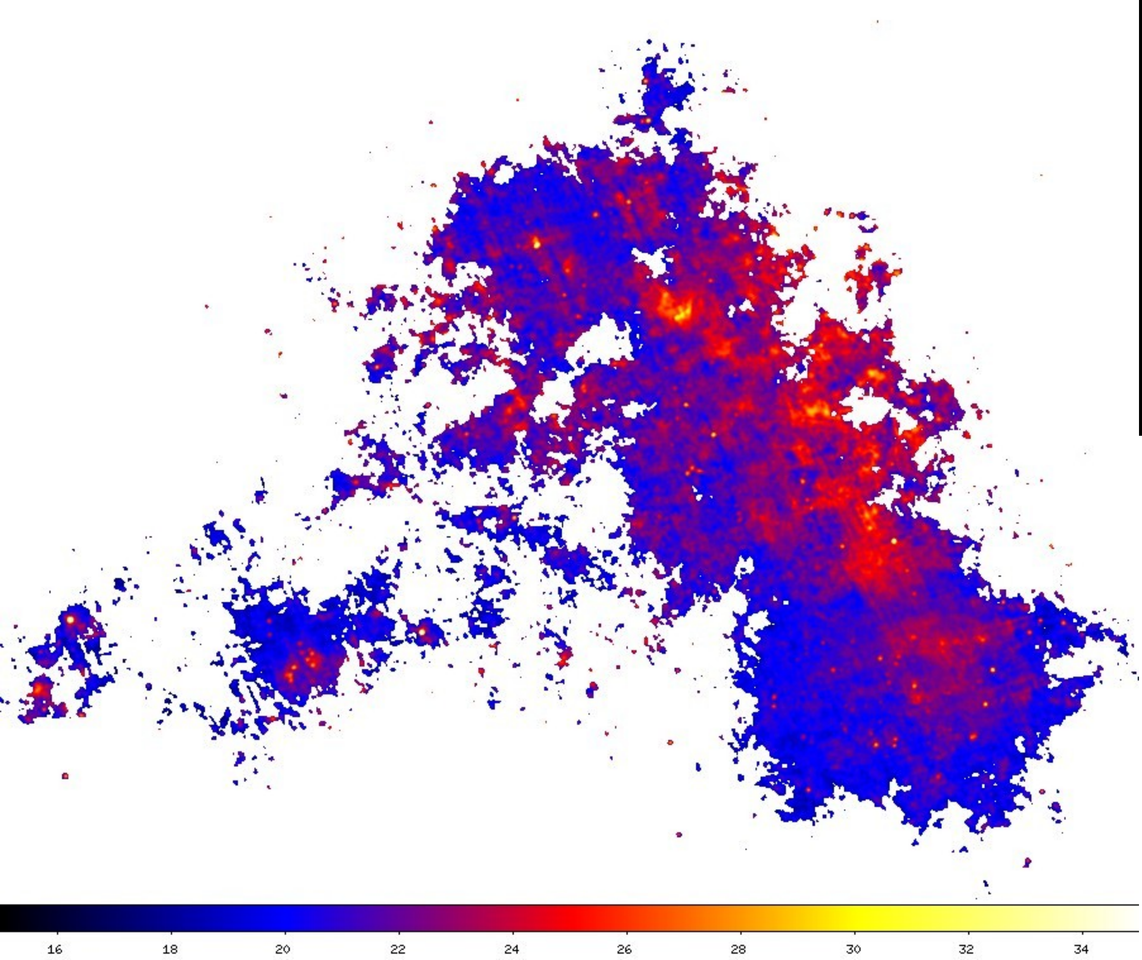
LMC Dust Temp/Mass Image

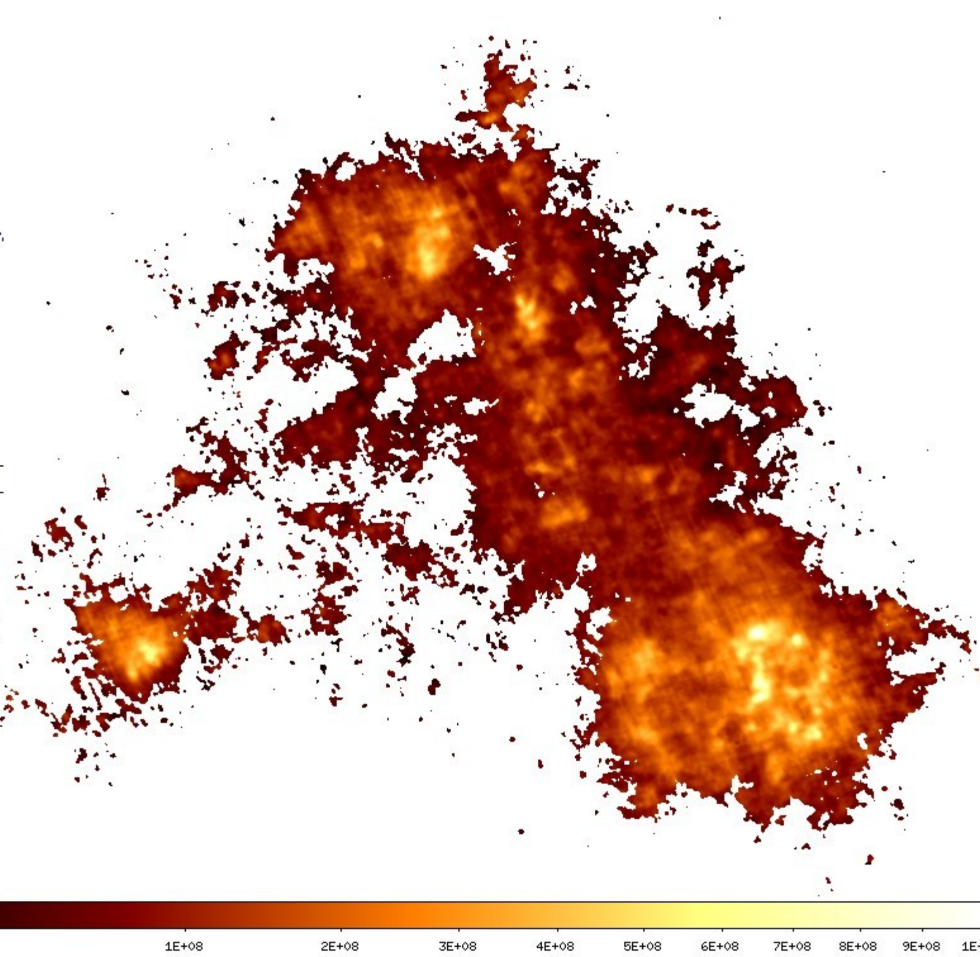
$\beta = 1.5$ (w/o 500 μm)



SMC Dust Temp/Mass Image

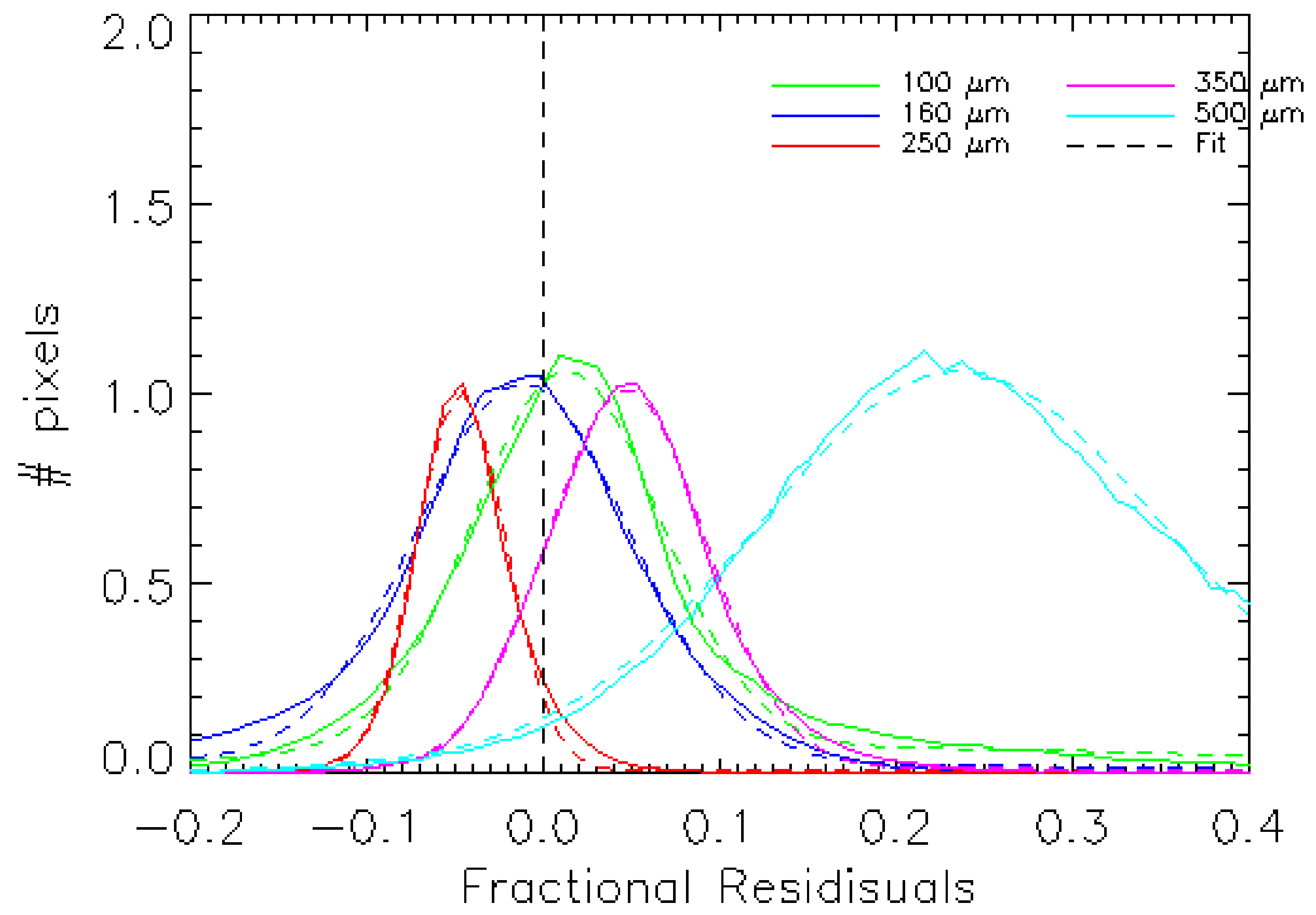
$\beta = 1.5$ (w/o 500 μm)





Fit Fractional Residuals

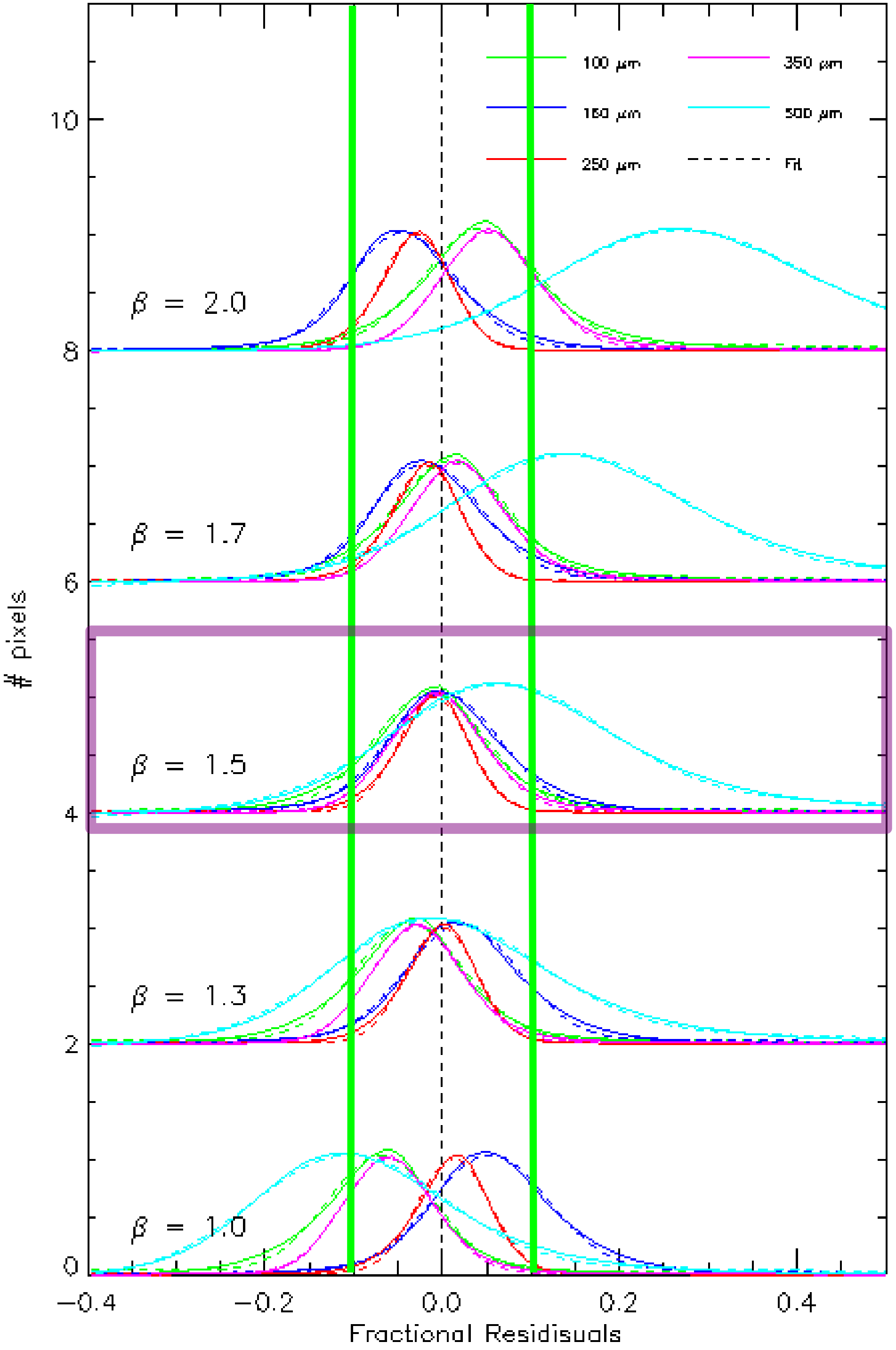
SMC β = 1.5, w/o 500 μm



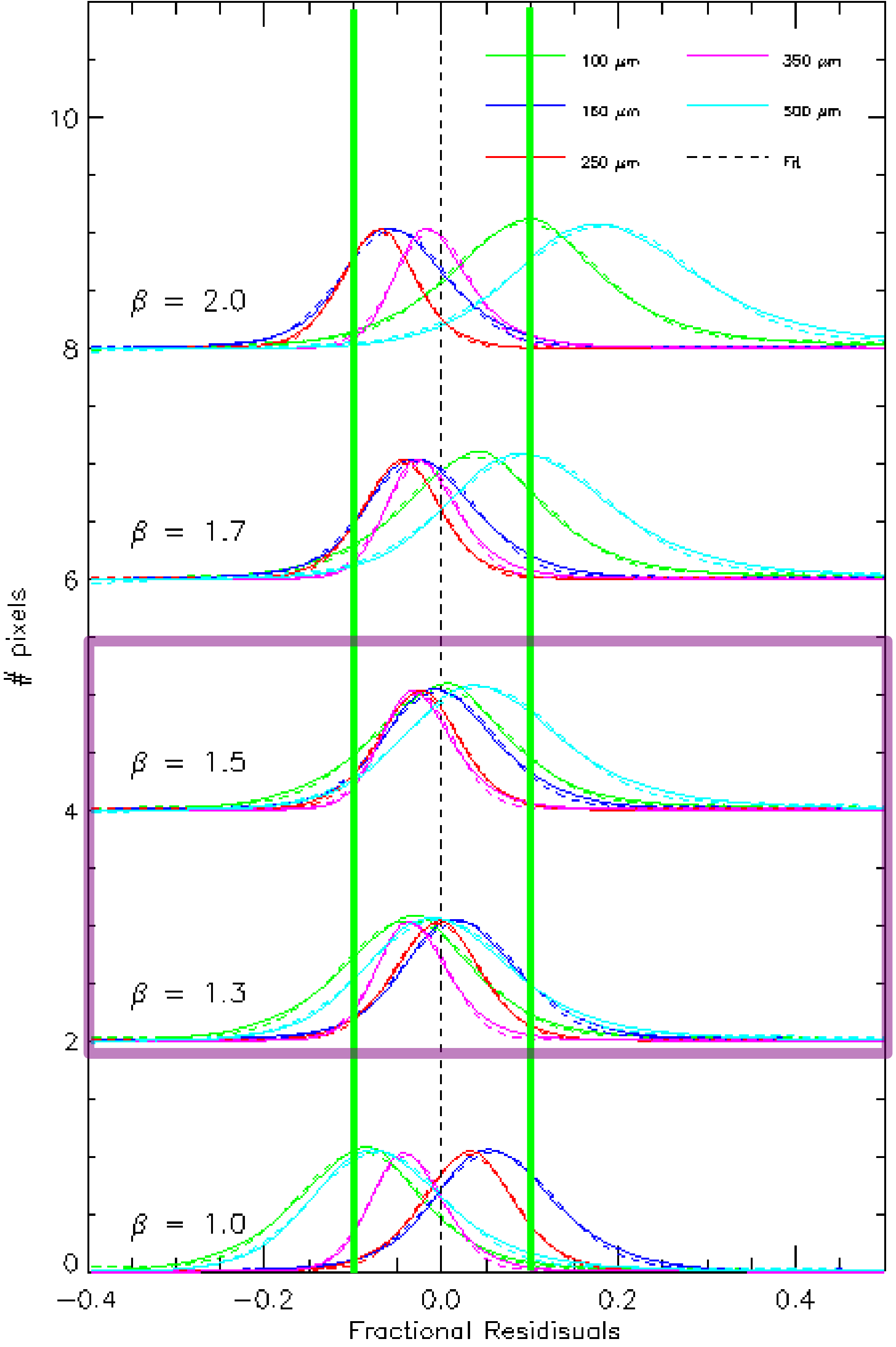
Fractional residuals should only be dependent on the relative calibration

within SPIRE or PACS 1-2%

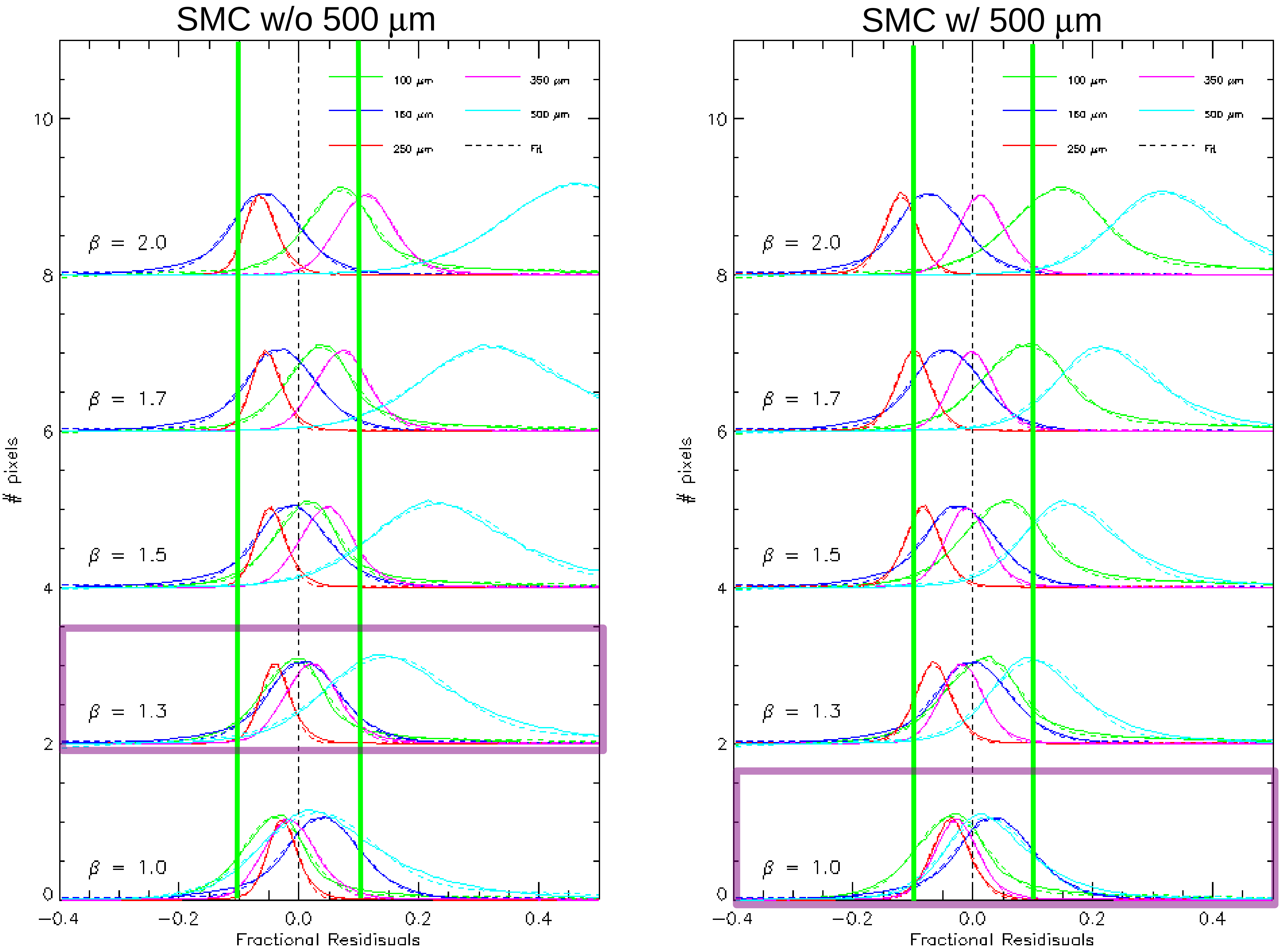
between PACS/SPIRE < 5%



LMC w/o 500 µm



LMC w/ 500 µm

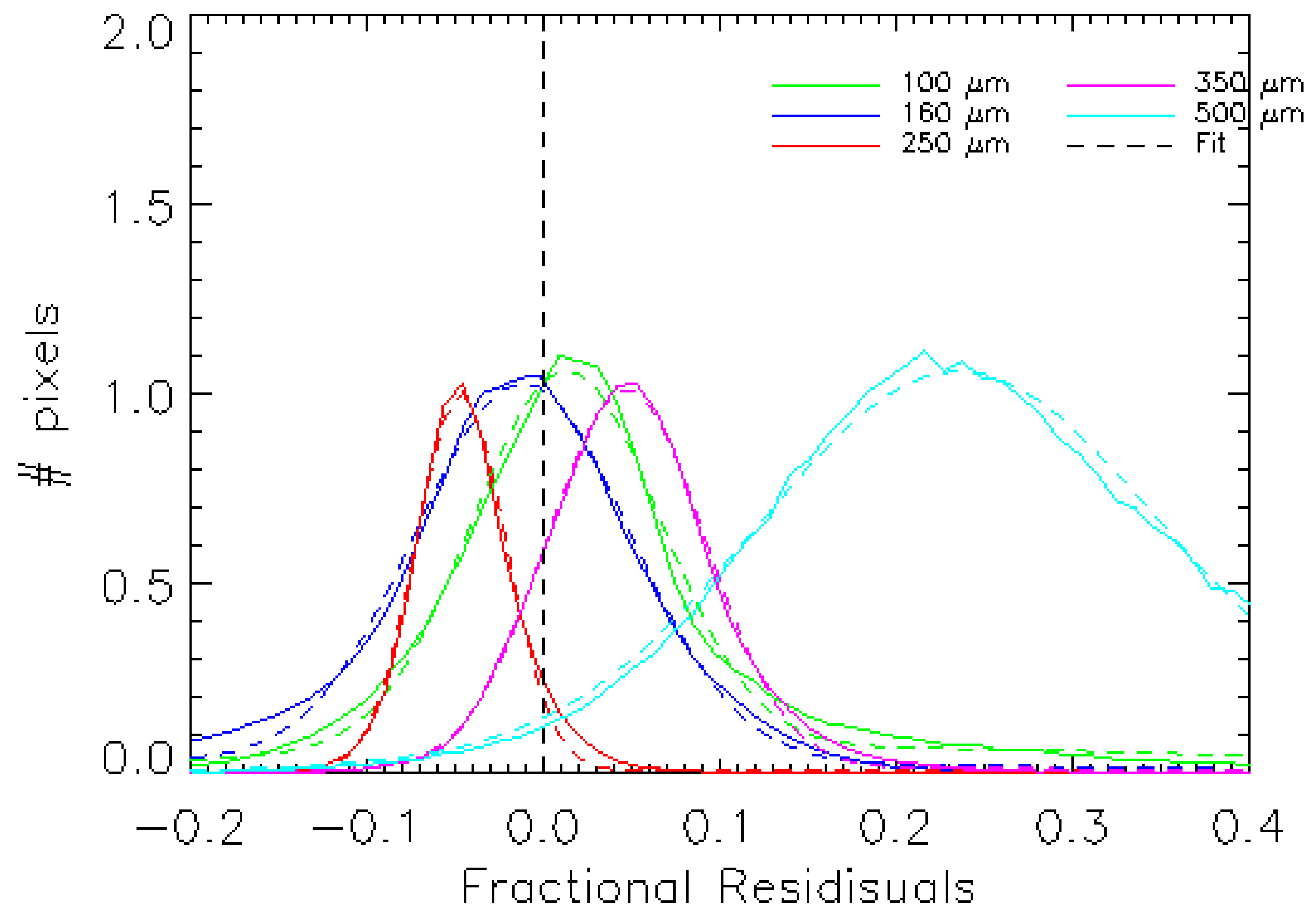


SMC w/o 500 µm

SMC w/ 500 µm

Fit Fractional Residuals

SMC β = 1.5, w/o 500 μm



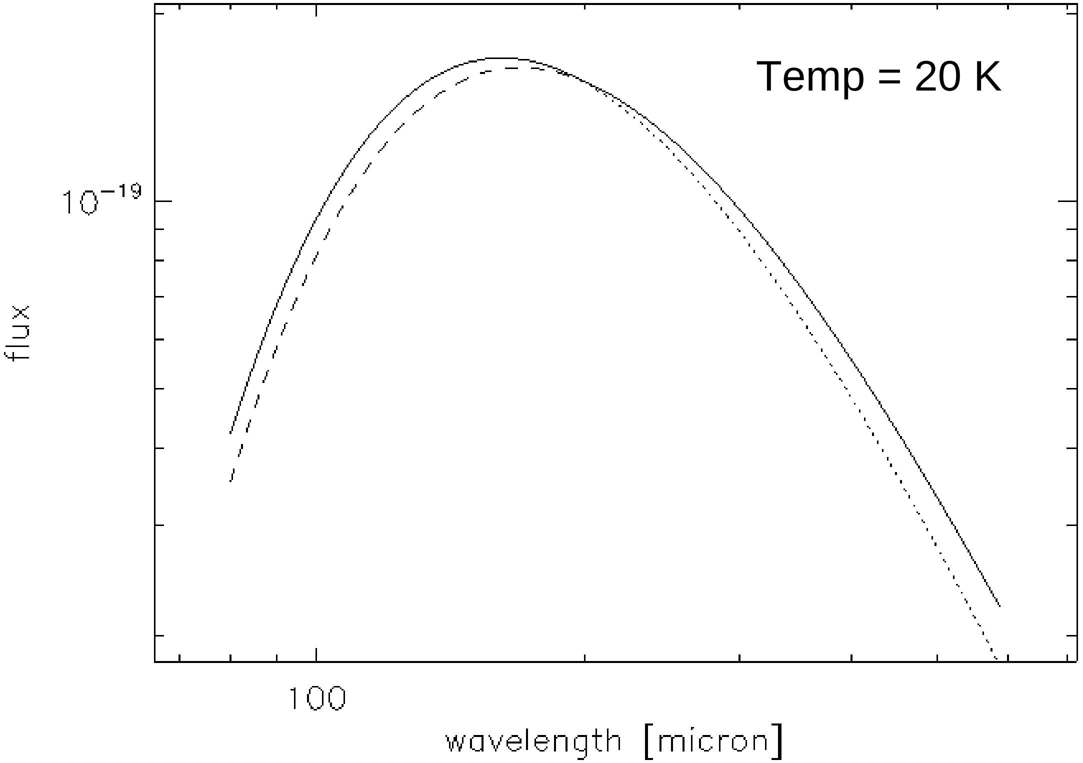
Pattern of fractional residuals

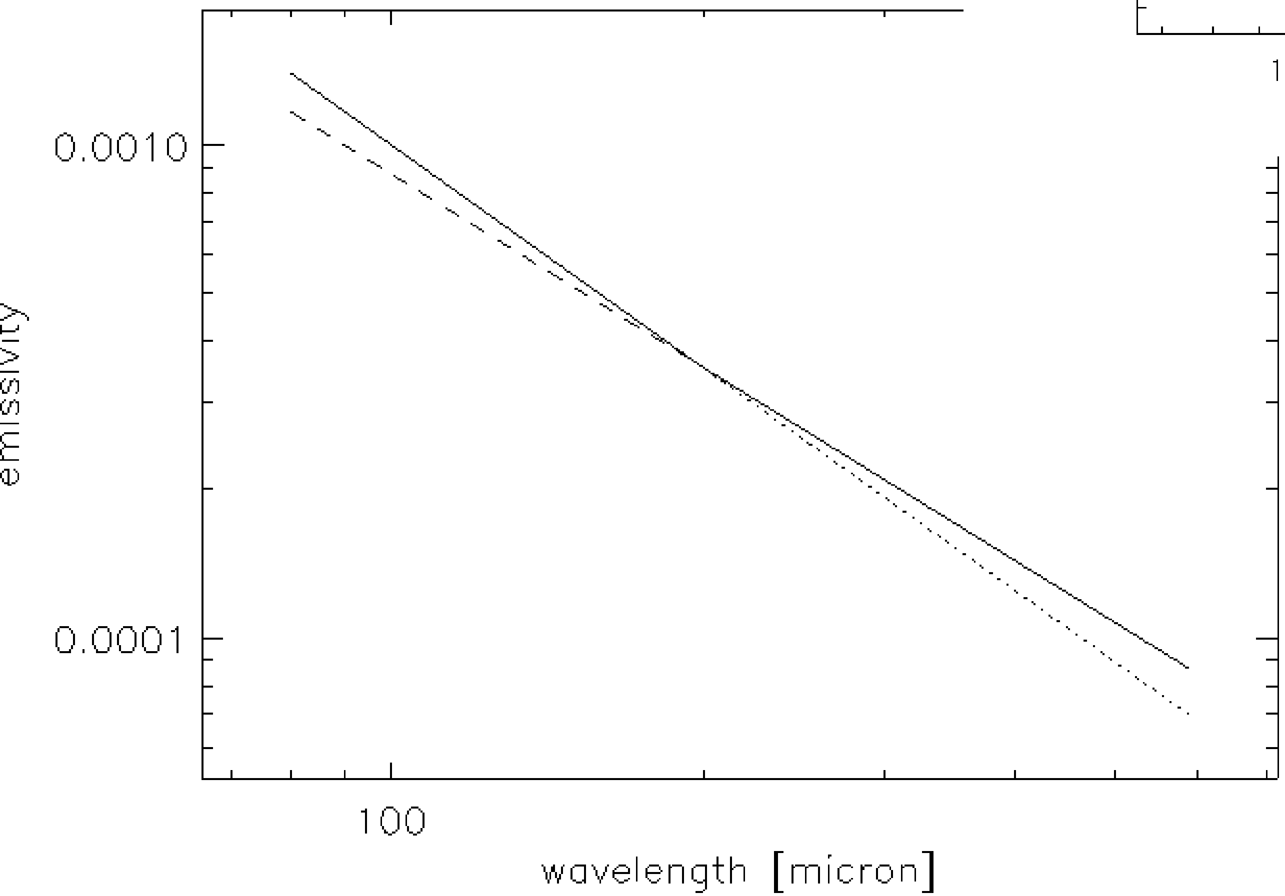
Broken Emissivity Law Example

$\beta_1 = 1.5$

Emissivity excess @ 500 µm = 0.2

$\beta_2 = 1.3$



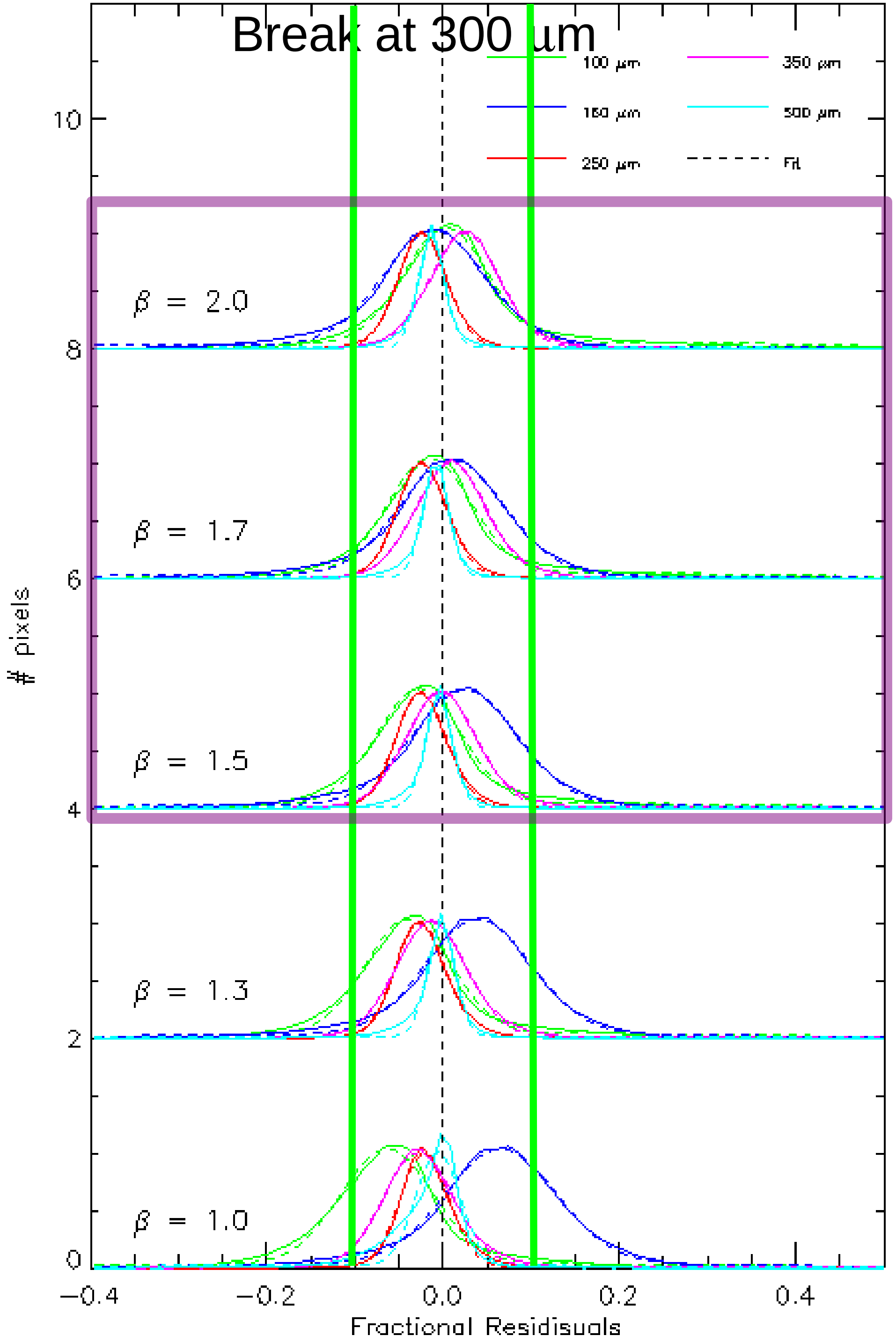


Emissivity excess @ 250 µm = 0.05

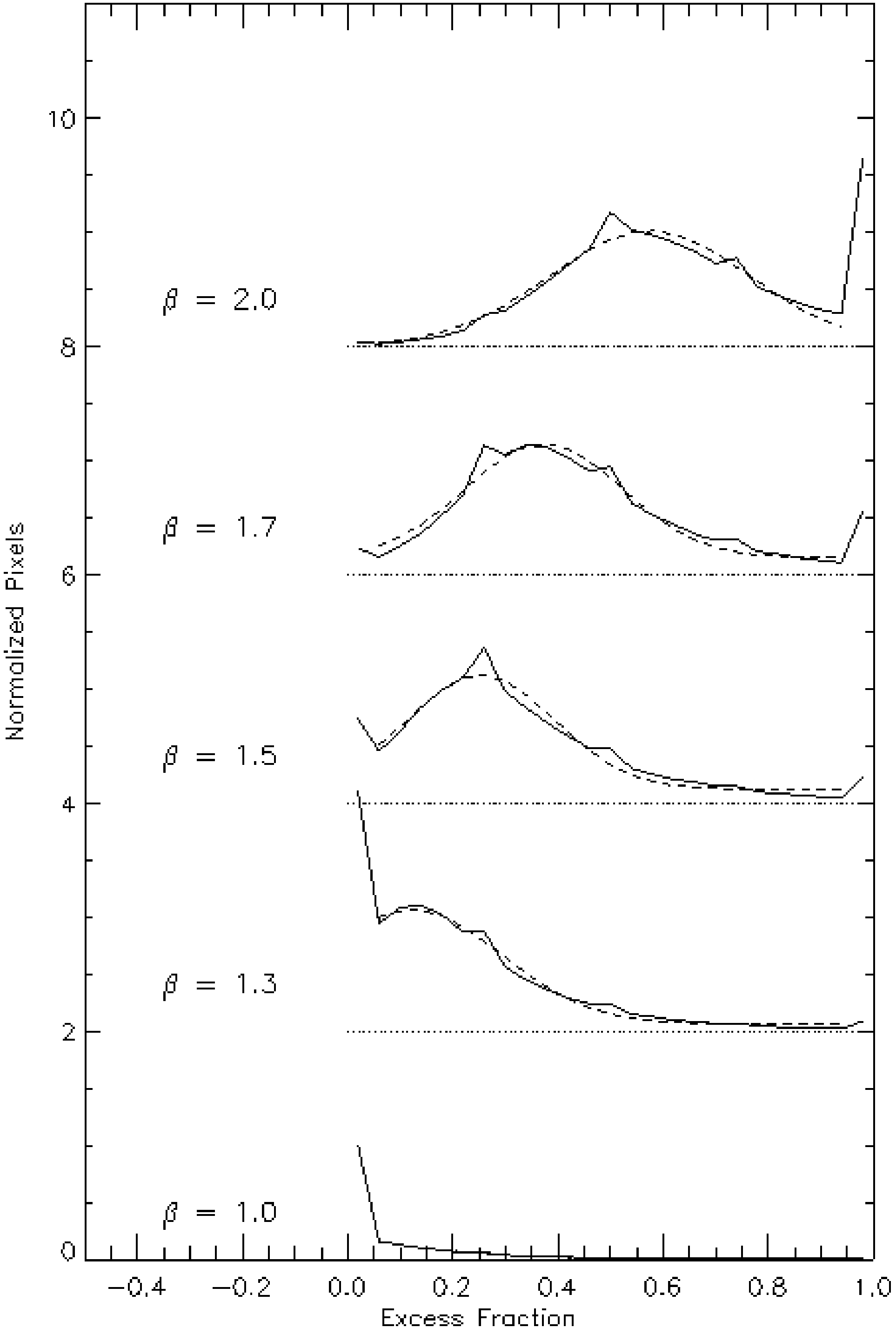
Emissivity excess @ 350 µm = 0.11

SMC w/ broken emissivity law

Break at 300 um



SMC fitted excess fractions



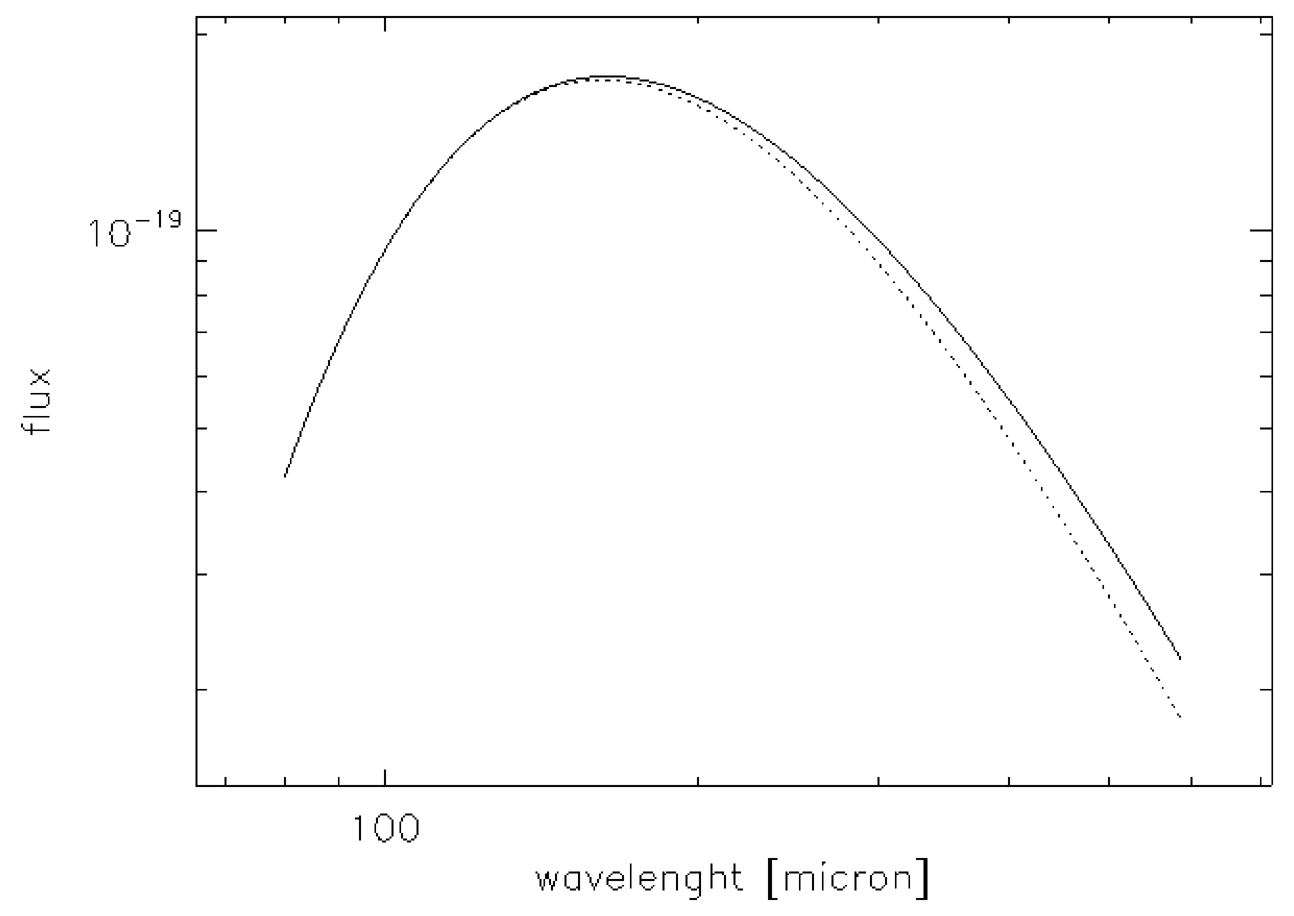
2^{nd} Colder Dust Component Example

T_1 = 20 K

Emission excess @ 500 µm = 0.2

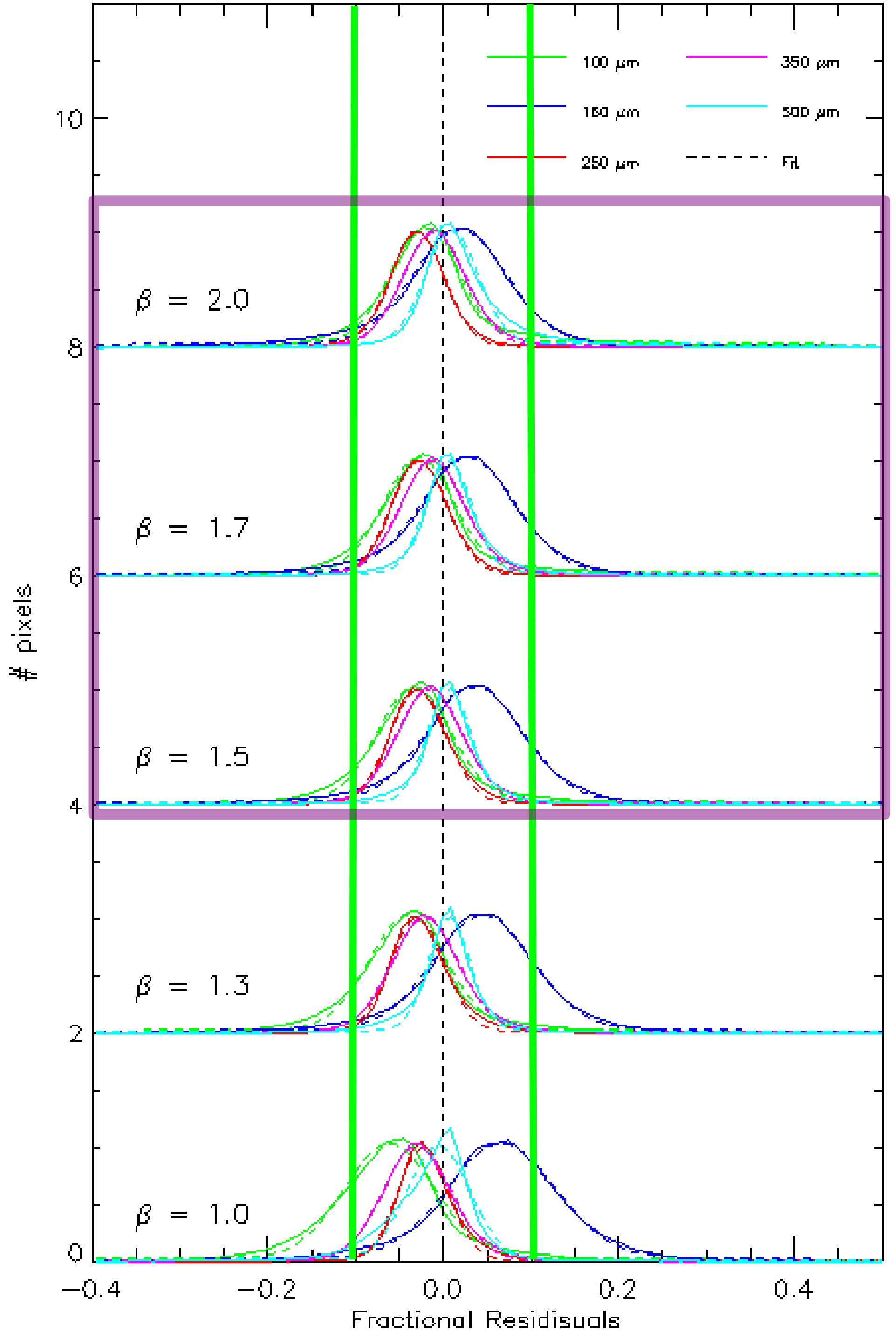
T_2 = 10 K

Mass in 2^{nd} component 19X 1^{st} component

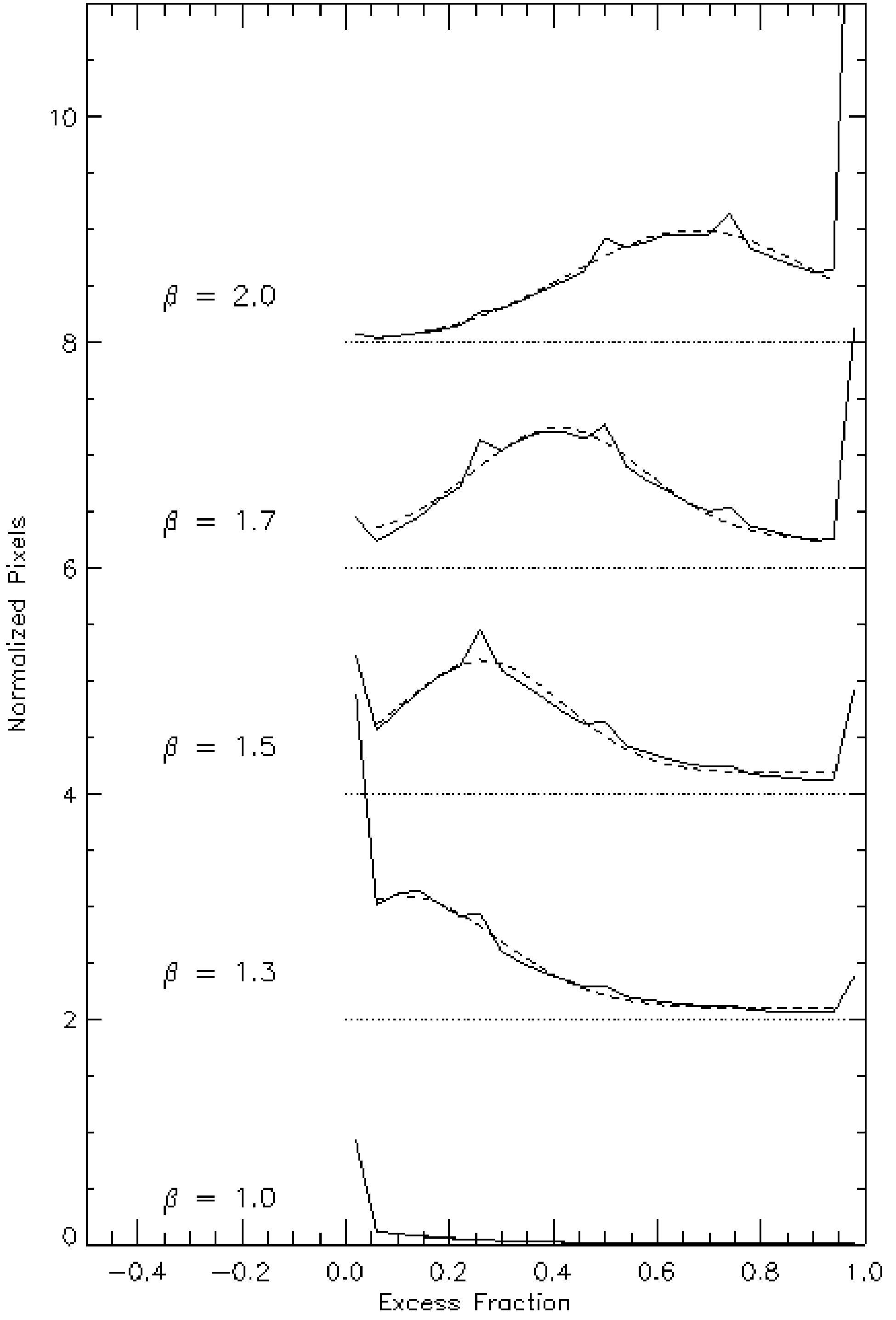


Emission excess @ 100 µm = 0.001
Emission excess @ 160 µm = 0.01
Emission excess @ 250 µm = 0.06
Emission excess @ 350 µm = 0.12

SMC w/ 2^{nd} component (T=7.5K)



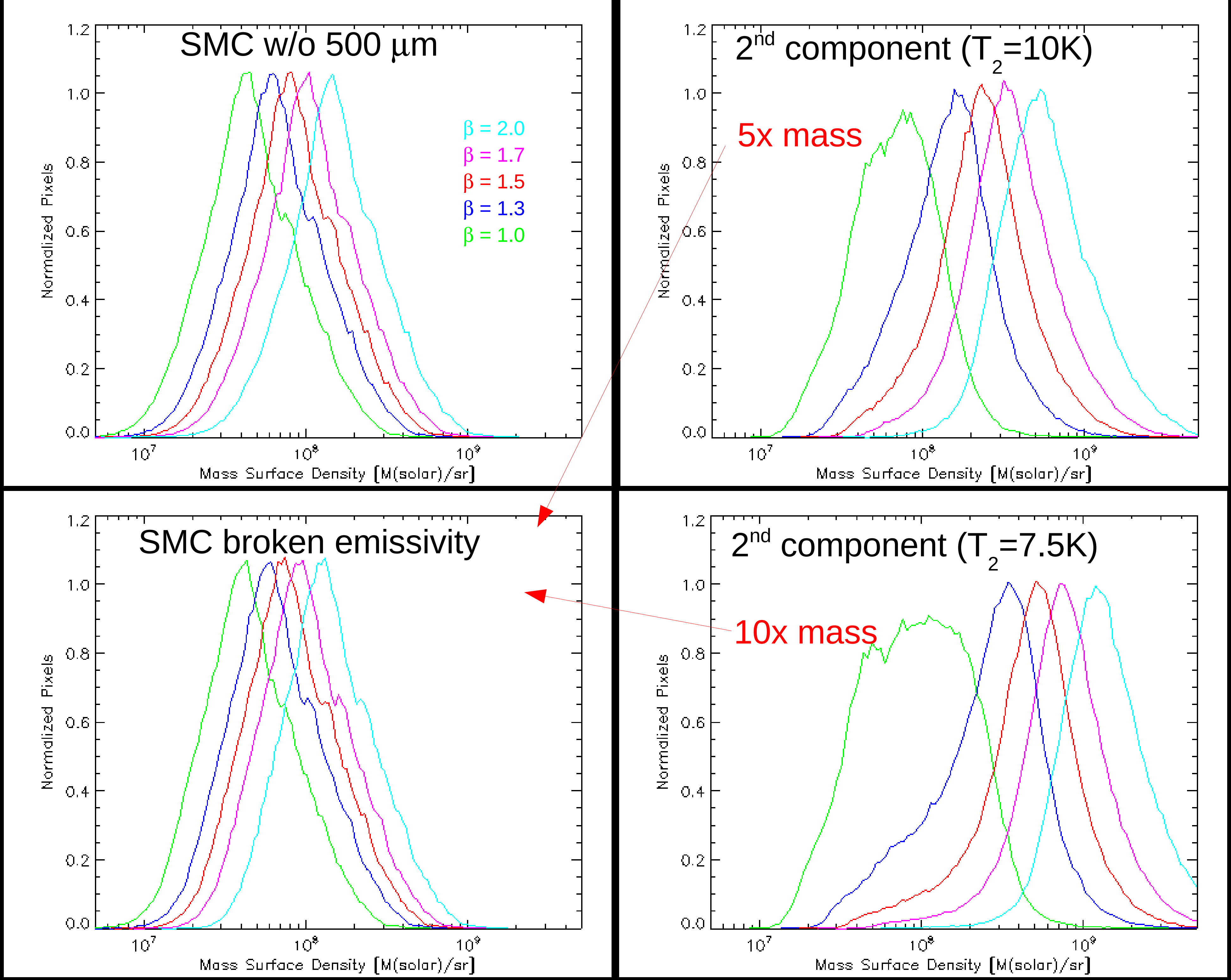
SMC fitted excess fractions



Fit Residuals Results

- Good fit residuals possible
  - (ok fits) Simple modified black body w/ low β
    - $\beta = 1.5$ (LMC) and 1.3 (SMC) consistent with previous work
  - Broken emissivity law, $\beta = 1.5\text{-}2$
  - 2nd dust component, $\beta = 1.5\text{-}2$
- All at ~10 pc resolution in both LMC and SMC
  - Best fits do vary between the two Clouds
  - Submm excess varies between the two clouds (SMC higher)
- Future: compare these results with the full grain model and TLS model
- Need additional information to determine the origin of the submm excess in the Magellanic Clouds

SMC Dust Masses



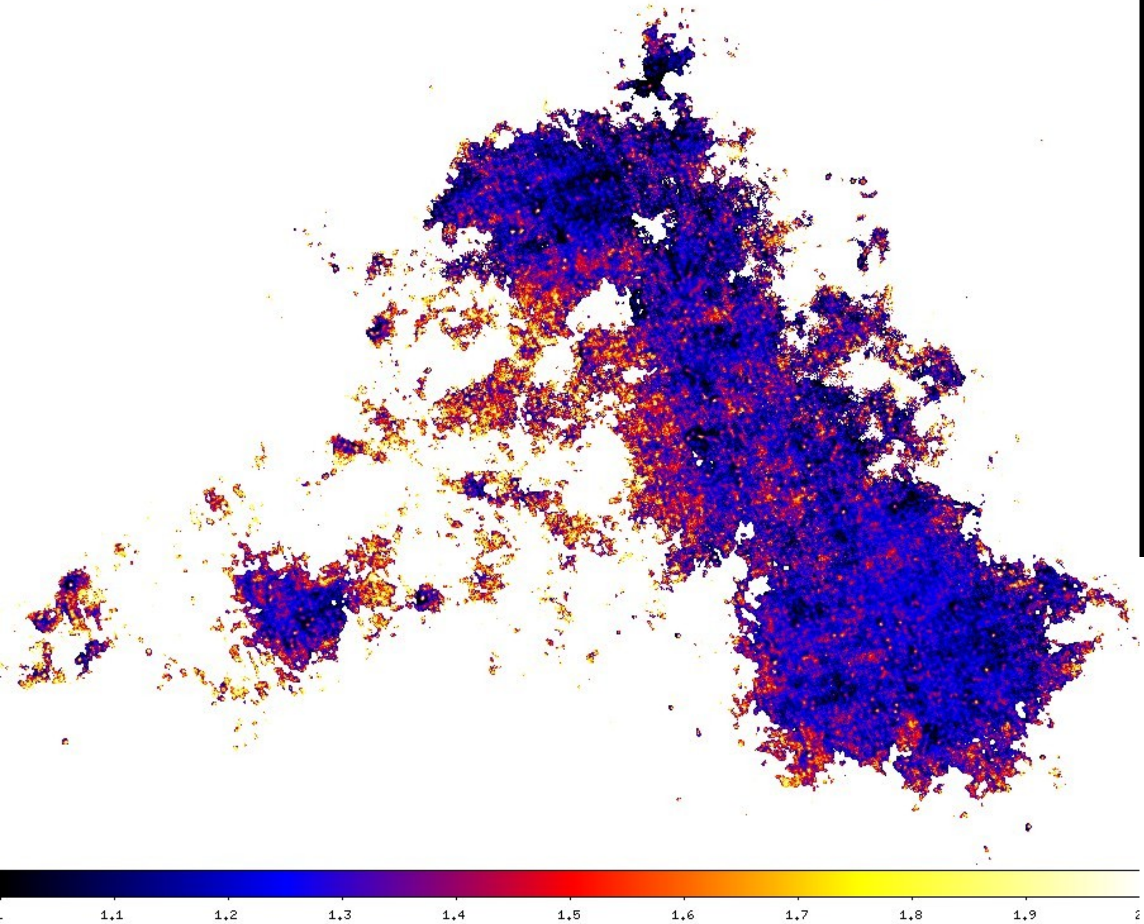
SMC Excess Fraction @ 500 μm

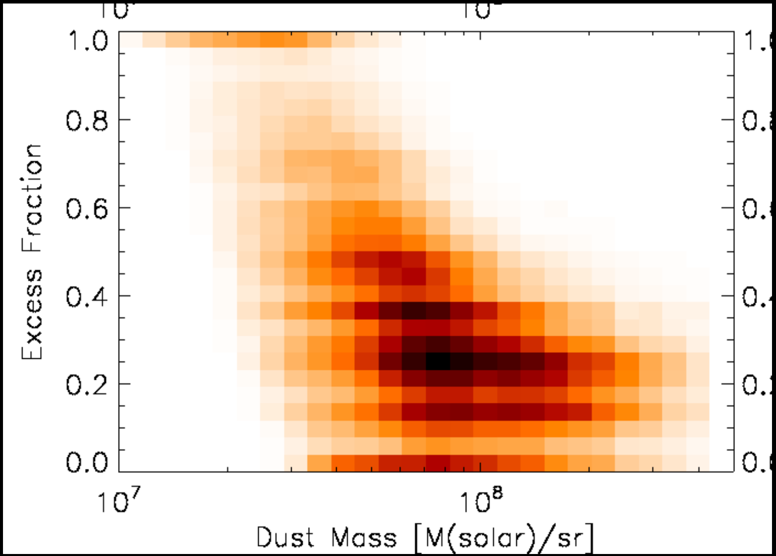
β = 1.5, bw = 300 μm

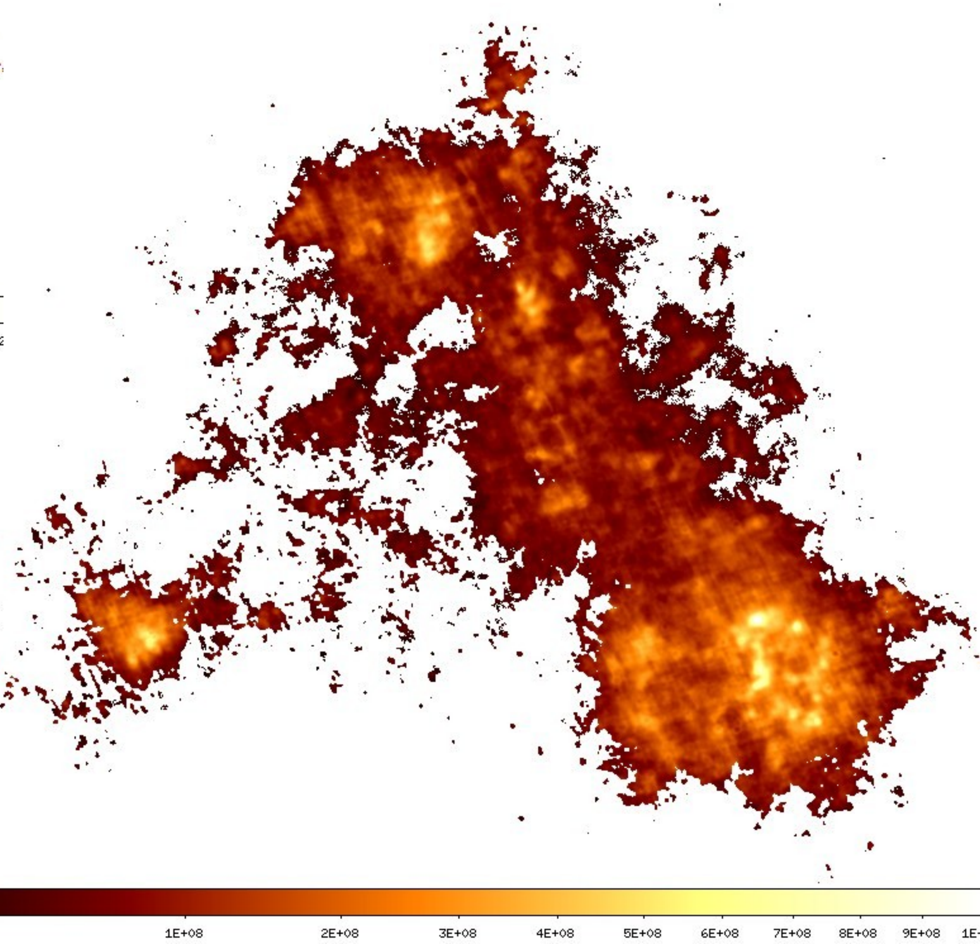
Anti-correlated with dust mass

Same results Galliano presented on LMC

Excess not constant at same metallicity

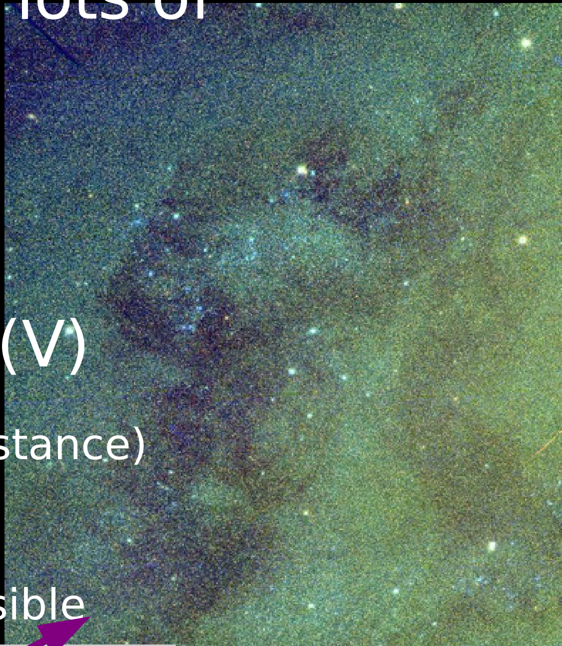


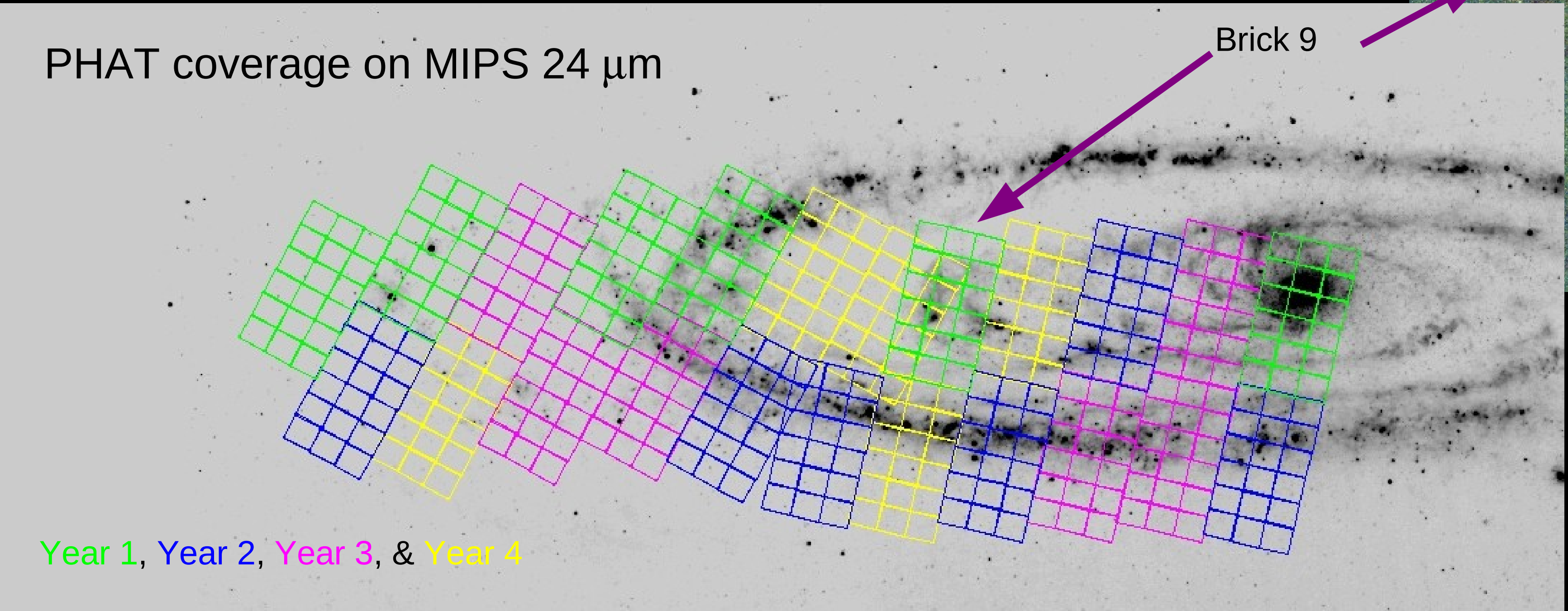




Panchromatic Hubble Andromeda Treasury

- Multi-Cycle Treasury Program (PI: Dalcanton, lots of co-Is)
  - 1/3 of M31 area, 828 orbits
  - F275W, F336W, F475W, F814W, F110W, & F160W
- Individual star SED fitting to extract A(V) & R(V)
  - Use stellar atmospheres + evolutionary tracks (known distance)
  - Also get stellar parameters at the same time
  - Probabilistic/Bayesian fitting using as much info was possible

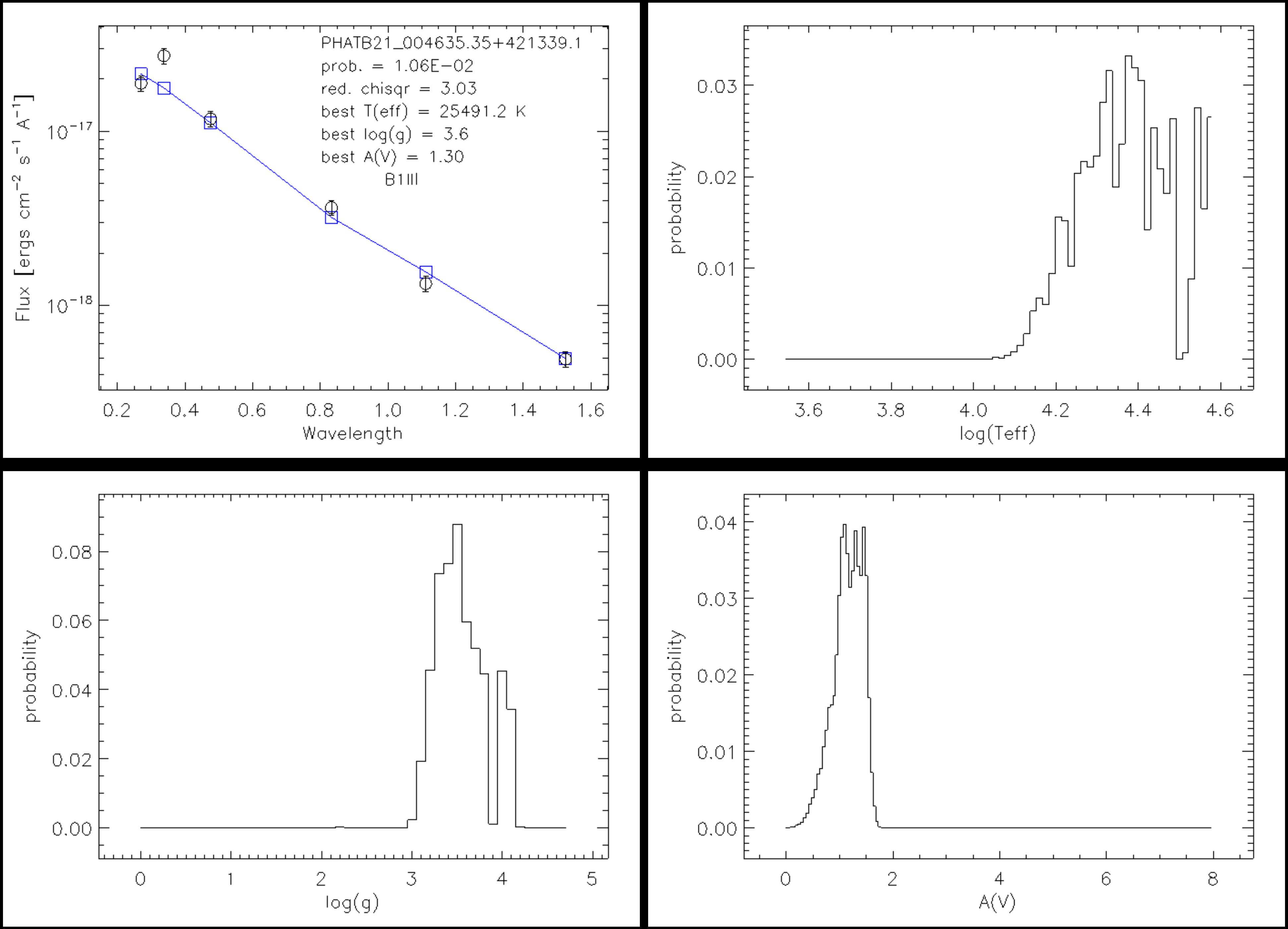




PHAT coverage on MIPS 24 μm

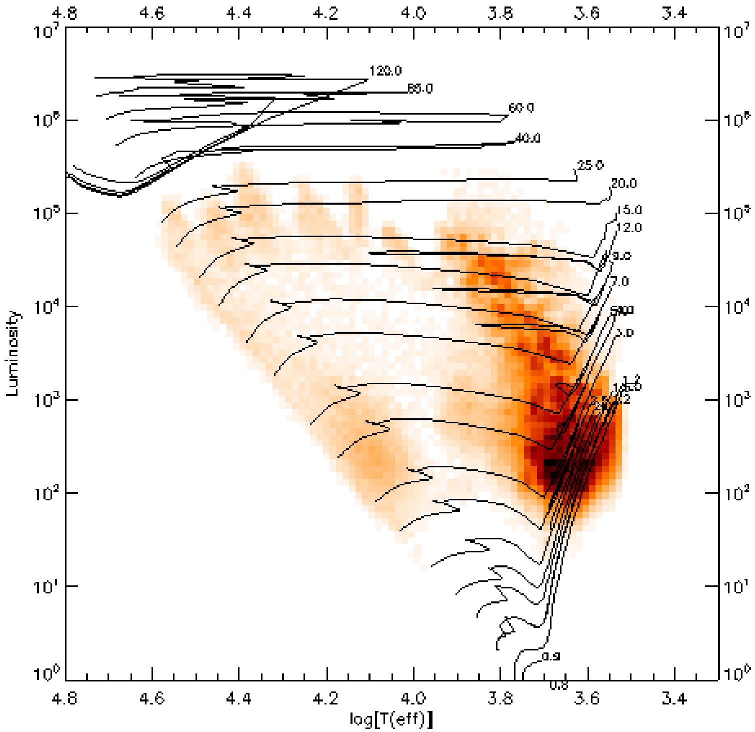
Year 1, Year 2, Year 3, & Year 4

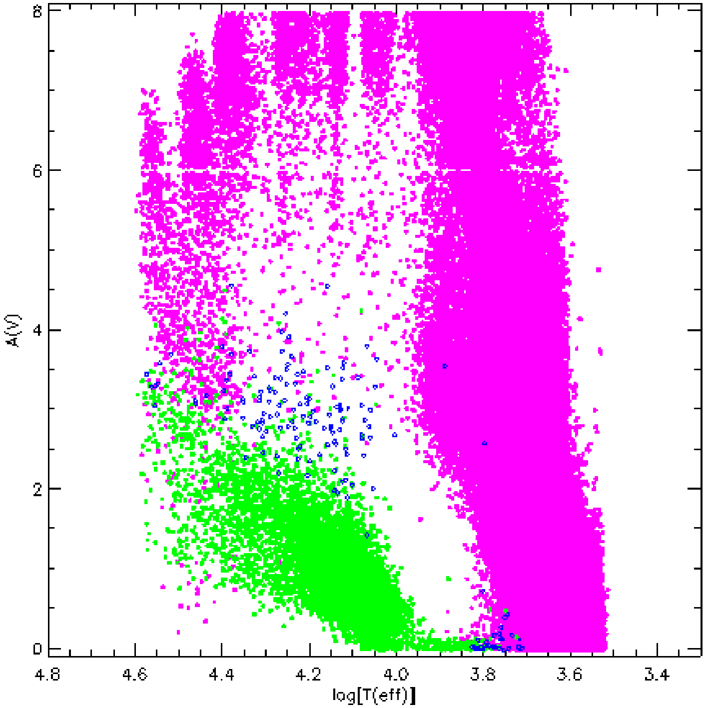
PHAT: SED fitting of Stars (Preliminary)

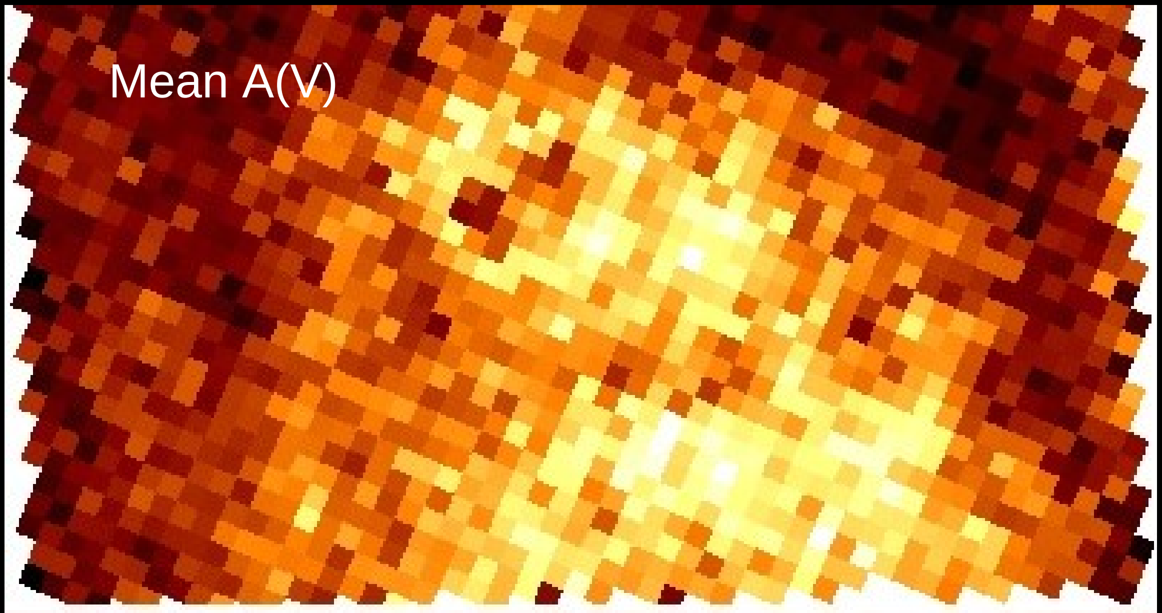


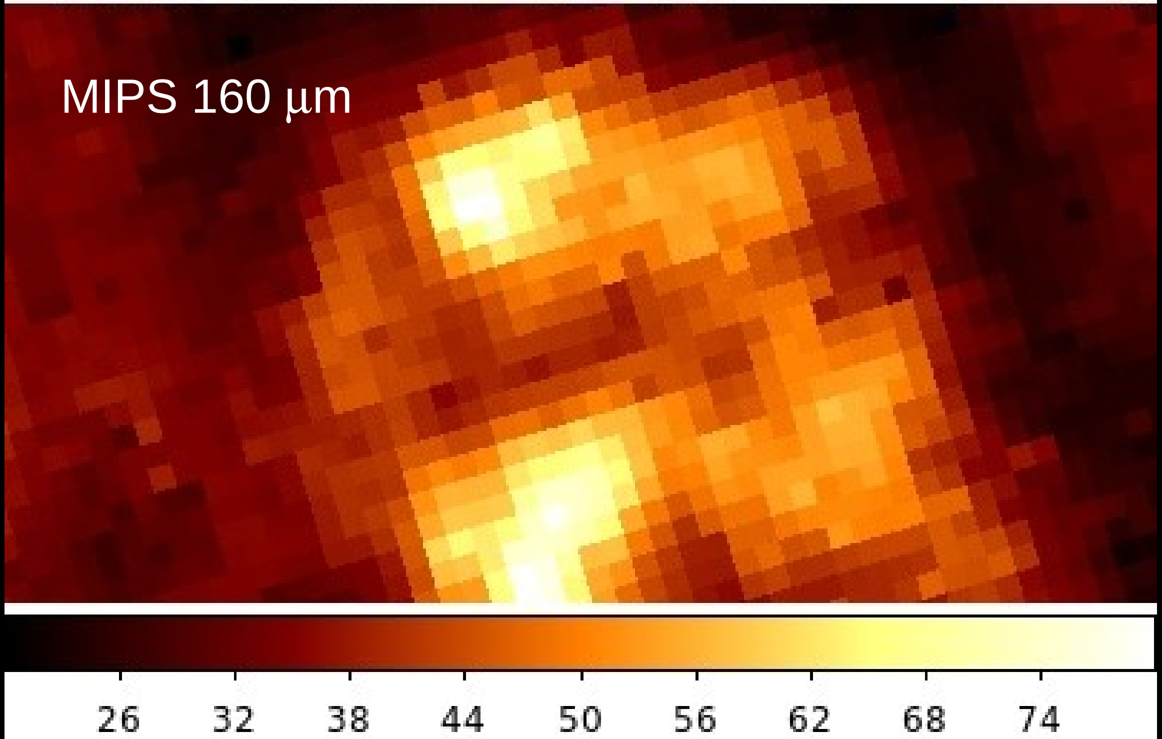
Brick 9

359,549 stars with at least 4 bands
337,562 “good” fits (prob > 0.1) used



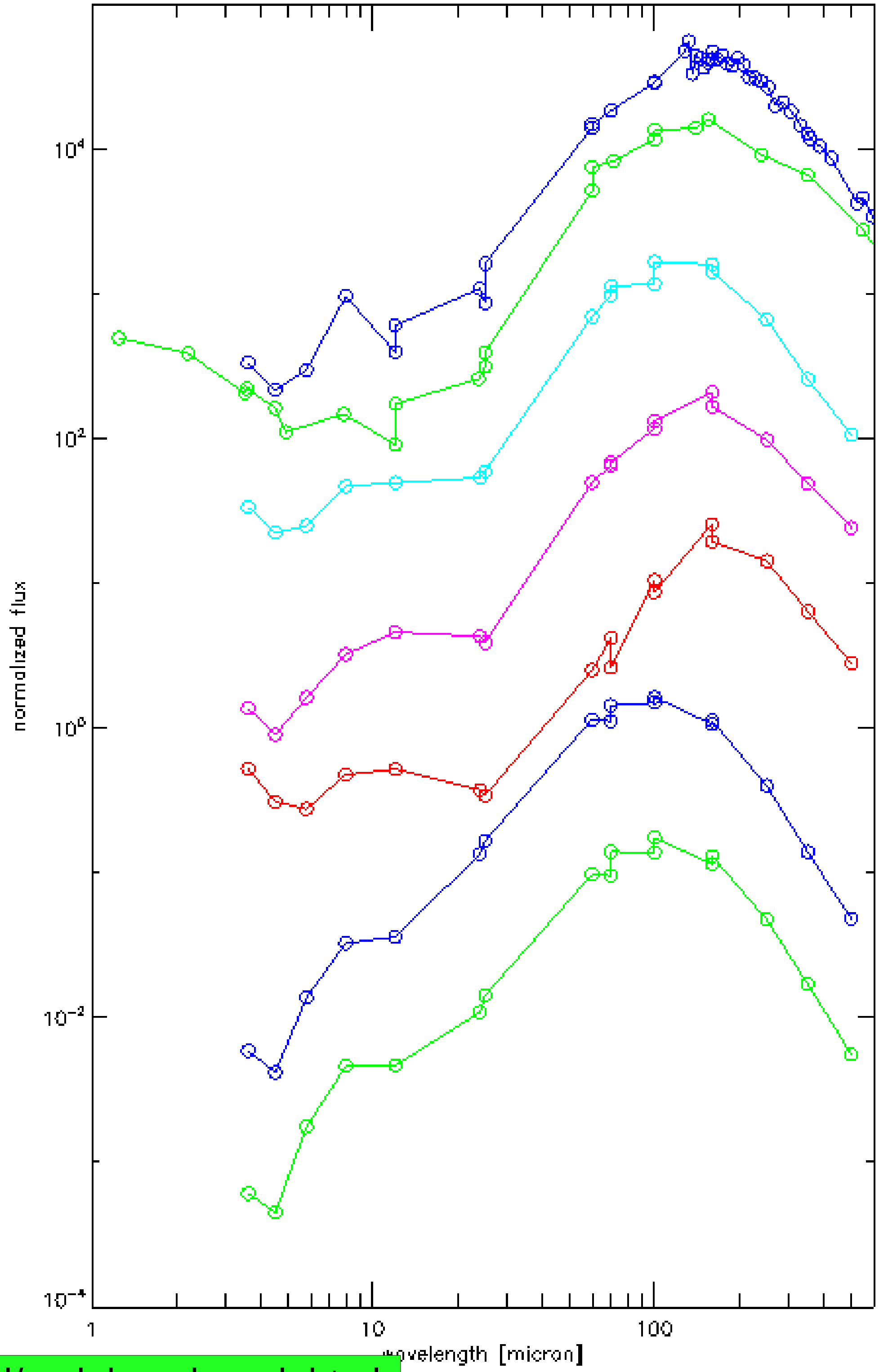






Dust Mass SED Fitting Benchmark Project

- Project idea genesis – Leiden Herschel & Dust in Galaxies meeting (Feb 2011)
- Set of ~ 10 observed IR (+UV/Opt) SEDs
    - Include MW high-lat SED
    - Normalized and w/o names
- Fit same data with different models
    - By the modelers themselves
- Probe the systematics between dust mass models
- Goal to write a short paper



http://dirty.as.arizona.edu/~kgordon/bsed/sed_benchmark.html

Summary/Thoughts

- Dust mass, temperature/<U>, and emissivity values provide valuable diagnostics of ISM and environment
  - Phase independent ISM tracer
  - Tracer of mean radiation field
  - Probe of dust grain properties (correlate with aromatics/UV bump?)
- Single temperature modified blackbody fits still useful
  - Just as accurate for dust masses as complicated fits (?)
  - May be dependent on physical resolution probed
  - Fractional residual analysis of full dust grain models?
- Submm Excesses in Magellanic Clouds
  - LMC/SMC best fit with $\beta = 1.5$ with broken emissivity law
    - Julia Roman-Duval's analysis of gas-to-dust ratios
  - LMC, 500 μm: ~10%
  - SMC, 500 μm: ~20%
  - Excess due to emissivity variations – not very cold ($T < 10$ K) dust
- Systematics between dust mass measurements in the ISM and circumstellar (AGB/SN) shells (dust reservoir versus production)

Thanks