Dust studies in Herschel Cold Cores fields

- *Dust Opacity*
- *Dust Spectral Index*
- *Modelling Clump Structure*
- *Estimating Extinction*

M. Juvela
Toulouse 2015

Paper V: Dust Opacity

- to determine the value of dust opacity
  - in reality, the submillimetre opacity in relation to near-infrared extinction
- to compare the values in the different regions
- to examine variations within the fields, as function of column density

Galactic cold cores V. Dust opacity ⋆ ⋆⋆

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$$\tau(250\mu\mathrm{m}) = \frac{I_\nu(250\mu\mathrm{m})}{B_\nu(T)}$$

Dust optical depth τ(250µm)

- mod. black body fits 100-500µm, 250-500µm
  - SPIRE provides significantly larger area
  - shorter wavelengths give better constraints of temperature
  - spectral index fixed to a value of β=2.0
    - higher than values ~1.8 found in diffuse medium, ~30% effect on κ

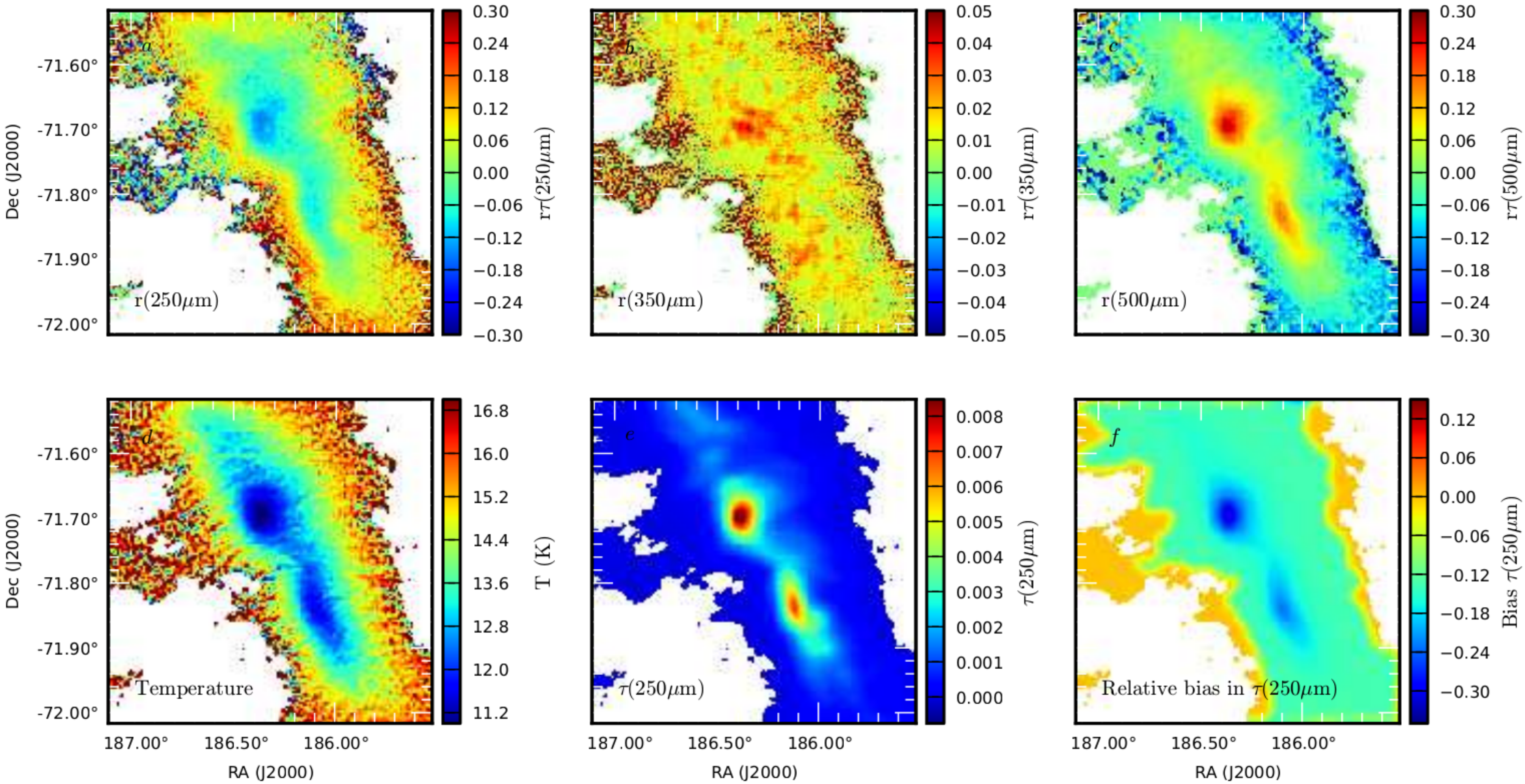
Near-infrared optical depth τ_J

- using the reddening of the background stars
  - NICER: combining J-H and H-K data, comparing with the average colours in a reference area
    - 2MASS survey data, J, H and K bands (1.25-2.2µm)
    - number of stars → 2'-3' resolution for nearby fields, nothing for the most distant ones
  - extinction curve is relatively robust

Bias in τ(250µm)

- line-of-sight temperature variations
  → colour temperature > mass-averaged T
  → τ underestimated
- correct using modelling
  - 3D cloud model matched with the maps
  - analyse the synthetic surface brightness, compare with the known column density of the model
- uncertainties
  - radiation field anisotropy
  - line-of-sight density structure
  - ratio between submm and NIR dust opacity

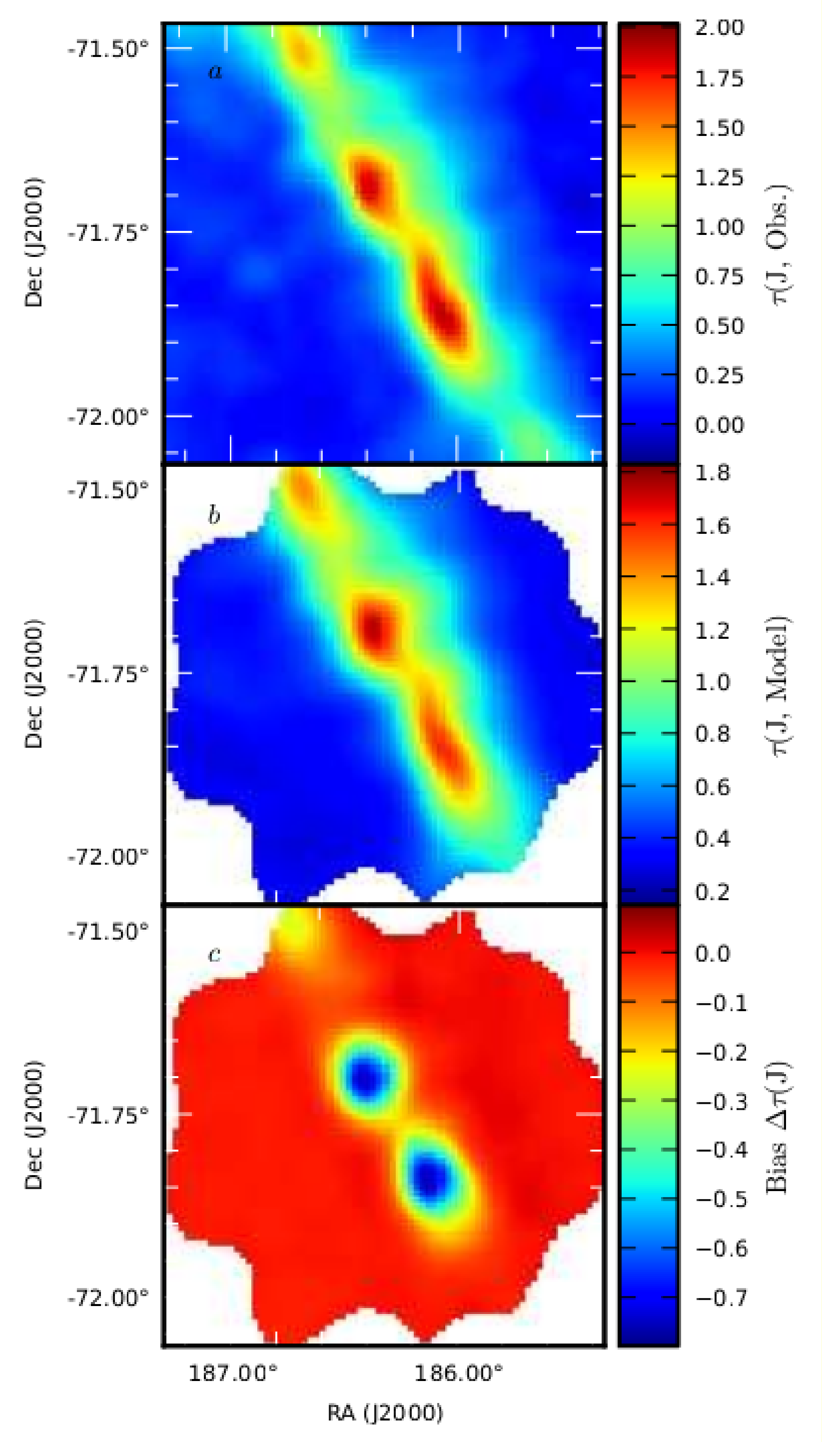
Musca filament



Upper row: residual maps for the fits to three SPIRE bands
Lower row: synthetic T_C and maps and the relative bias

Bias in $\tau(J)$

- two problems
  - stellar density decreases with column density
    - extinction underestimated, depends on gradients
  - for distant fields foreground stars can be a problem
- correct using simulations
  - τ maps from Herschel (18''), simulate different realisations of background stars
  - foreground stars deduced based on Besancon model
  - other statistics derived from a reference region



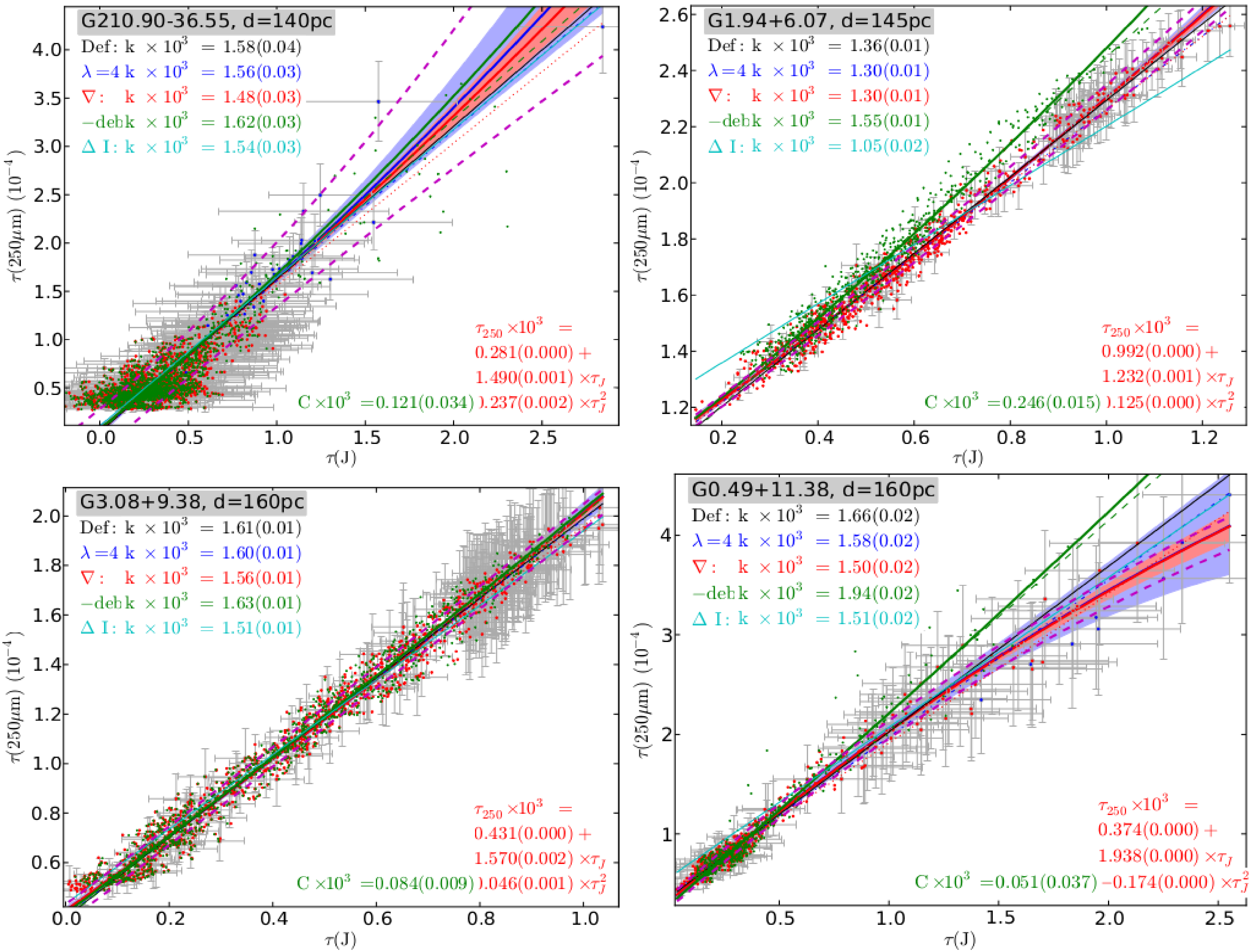
Input map of NIR opacity, based on Herschel data

The simulated NICER map, average of 100 realisations

The absolute bias: <simulations> - input τ

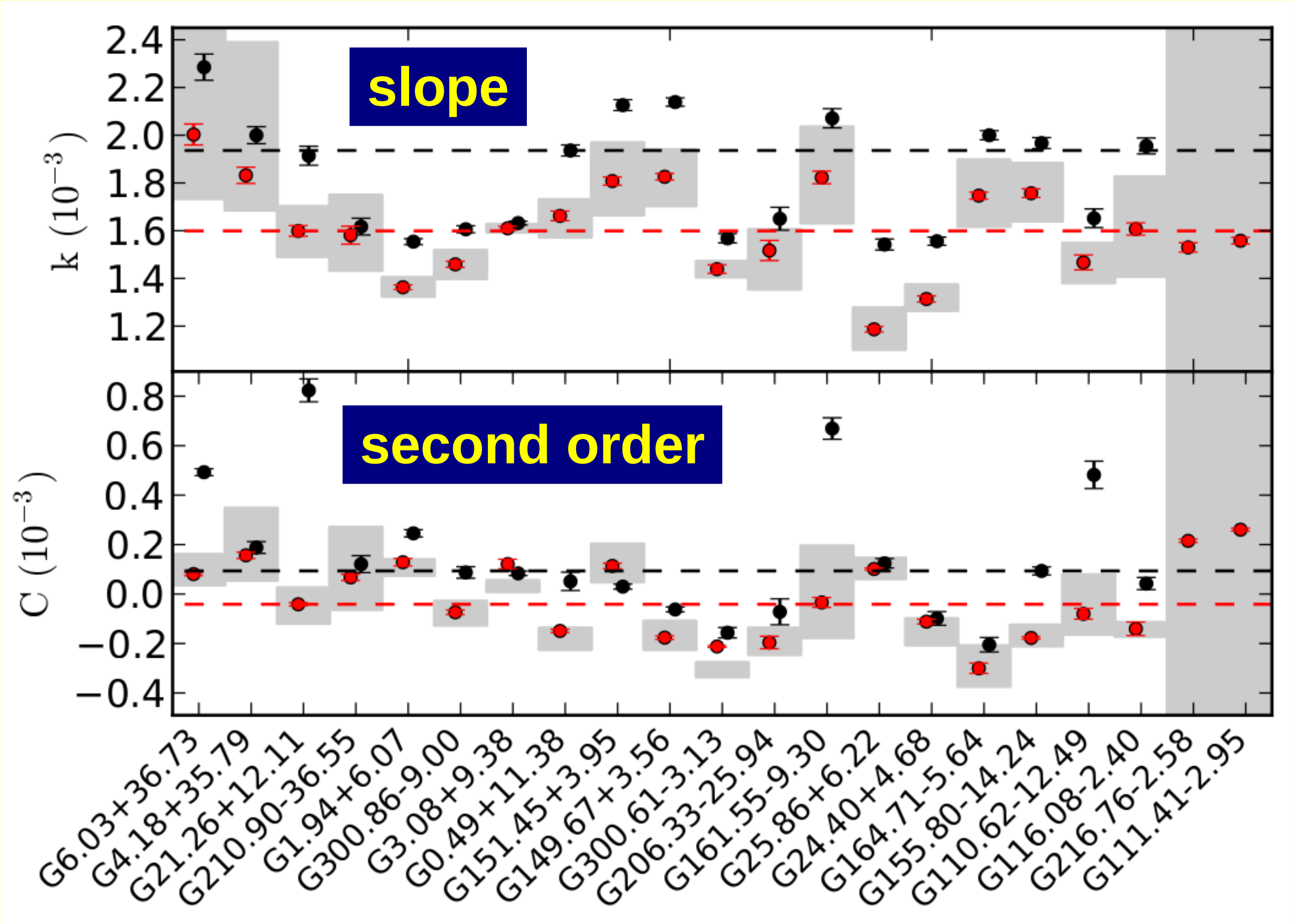
The **correlations**

- τ(250µm) data are bias-corrected and colvolved to the resolution of τ(J) data
- fits τ(250µm) vs. τ(J)
  - possibly different τ(J) intervals
  - linear models with slop *k* and models including a second order term $\tau(J)^2$ with multiplier *C*



G210.90-36.55, d=140pc
Def: k × 10^3 = 1.58(0.04)
λ=4 k × 10^3 = 1.56(0.03)
∇: k × 10^3 = 1.48(0.03)
−debk × 10^3 = 1.62(0.03)
Δ I: k × 10^3 = 1.54(0.03)
τ250 ×10^3 =
0.281(0.000) +
1.490(0.001) ×τJ
C ×10^3 =0.121(0.034)).237(0.002) ×τJ^2
τ(250μm) (10^-4)
τ(J)
G1.94+6.07, d=145pc
Def: k × 10^3 = 1.36(0.01)
λ=4 k × 10^3 = 1.30(0.01)
∇: k × 10^3 = 1.30(0.01)
−debk × 10^3 = 1.55(0.01)
Δ I: k × 10^3 = 1.05(0.02)
τ250 ×10^3 =
0.992(0.000) +
1.232(0.001) ×τJ
C ×10^3 =0.246(0.015)).125(0.000) ×τJ^2
τ(250μm) (10^-4)
τ(J)
G3.08+9.38, d=160pc
Def: k × 10^3 = 1.61(0.01)
λ=4 k × 10^3 = 1.60(0.01)
∇: k × 10^3 = 1.56(0.01)
−debk × 10^3 = 1.63(0.01)
Δ I: k × 10^3 = 1.51(0.01)
τ250 ×10^3 =
0.431(0.000) +
1.570(0.002) ×τJ
C ×10^3 =0.084(0.009)).046(0.001) ×τJ^2
τ(250μm) (10^-4)
τ(J)
G0.49+11.38, d=160pc
Def: k × 10^3 = 1.66(0.02)
λ=4 k × 10^3 = 1.58(0.02)
∇: k × 10^3 = 1.50(0.02)
−debk × 10^3 = 1.94(0.02)
Δ I: k × 10^3 = 1.51(0.02)
τ250 ×10^3 =
0.374(0.000) +
1.938(0.000) ×τJ
C ×10^3 =0.051(0.037) −0.174(0.000) ×τJ^2
τ(250μm) (10^-4)
τ(J)

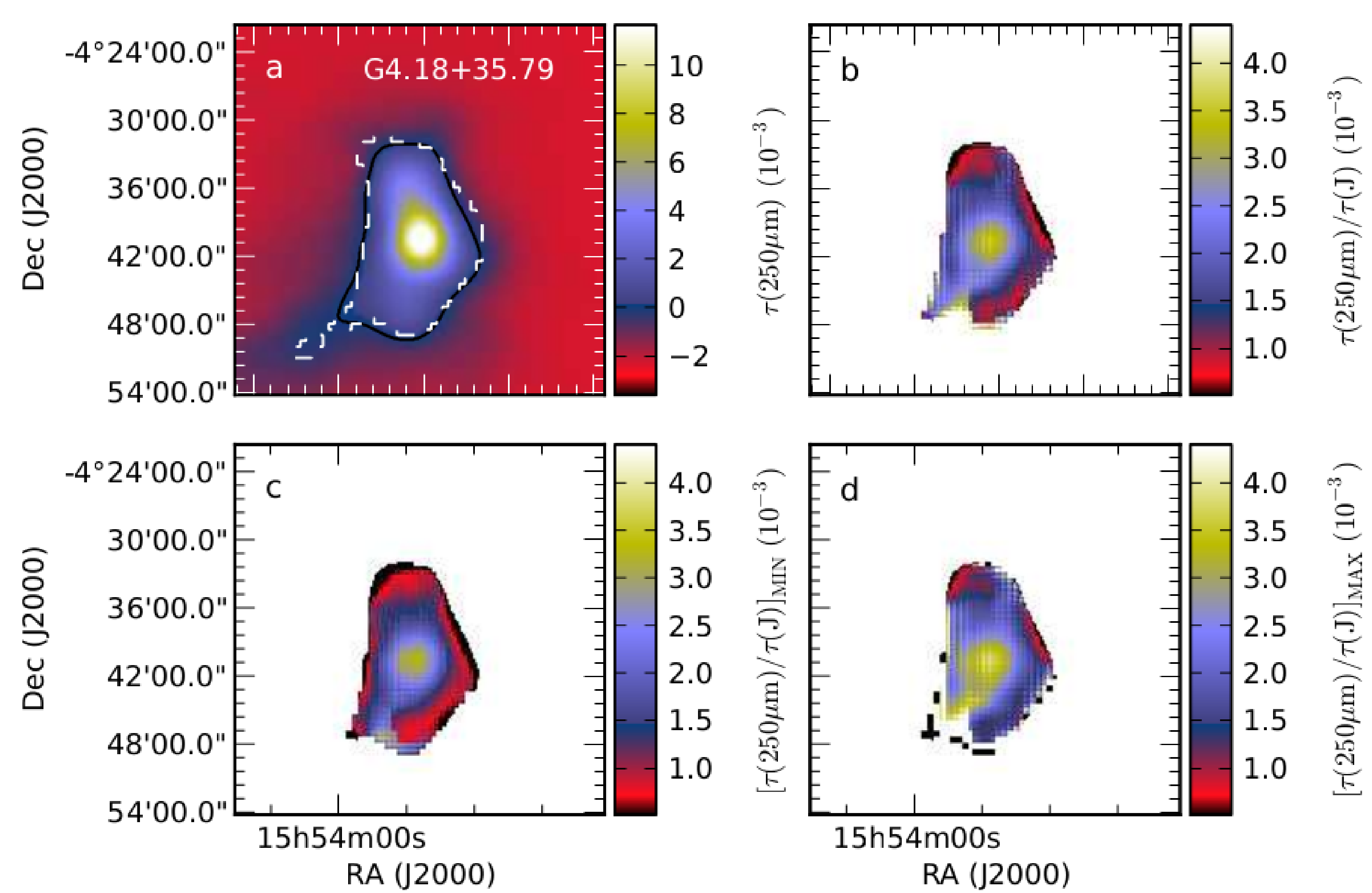
Based on the uncertainty of *k*, only the 21 most reliable **selected** out of the original sample of 116 fields



Gray bands = uncertainty of the distance !

τ(250μm)/τ(J) in **ratio maps**

τ(250μm) | τ(250μm)/τ(J)



Minimum τ(250μm)/τ(J) | Maximum τ(250μm)/τ(J)

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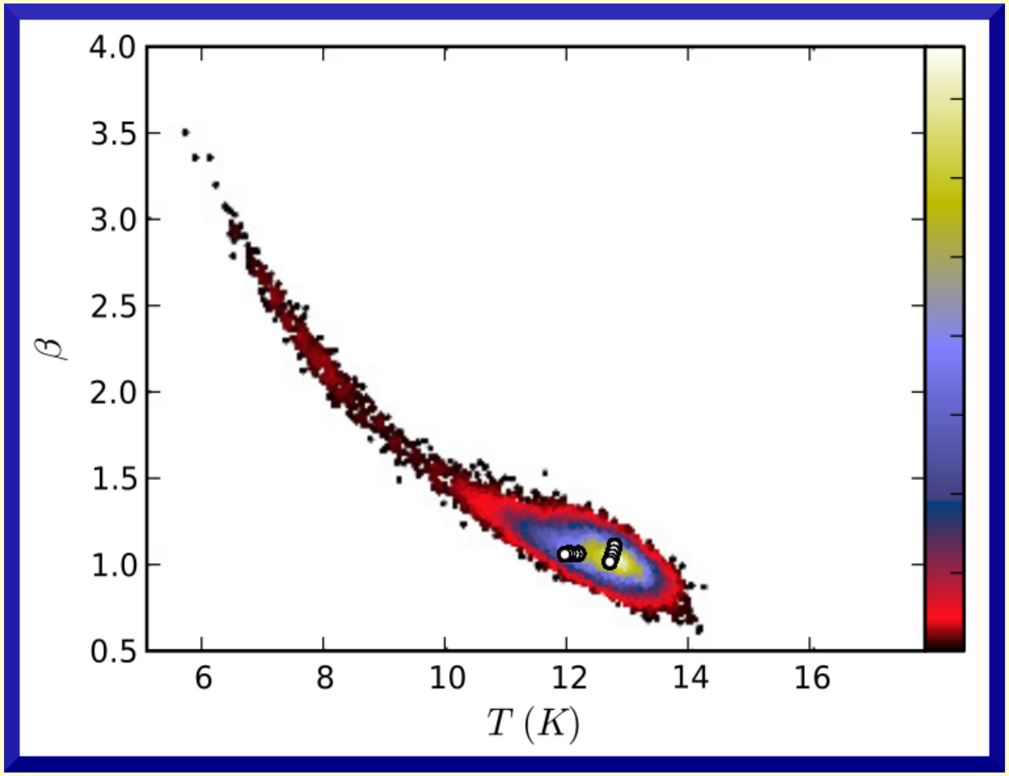
29/01/2015	preprint version available online
06/03/2015	proofs sent to author
09/03/2015	corrected proofs received from author

Estimation of dust spectral index



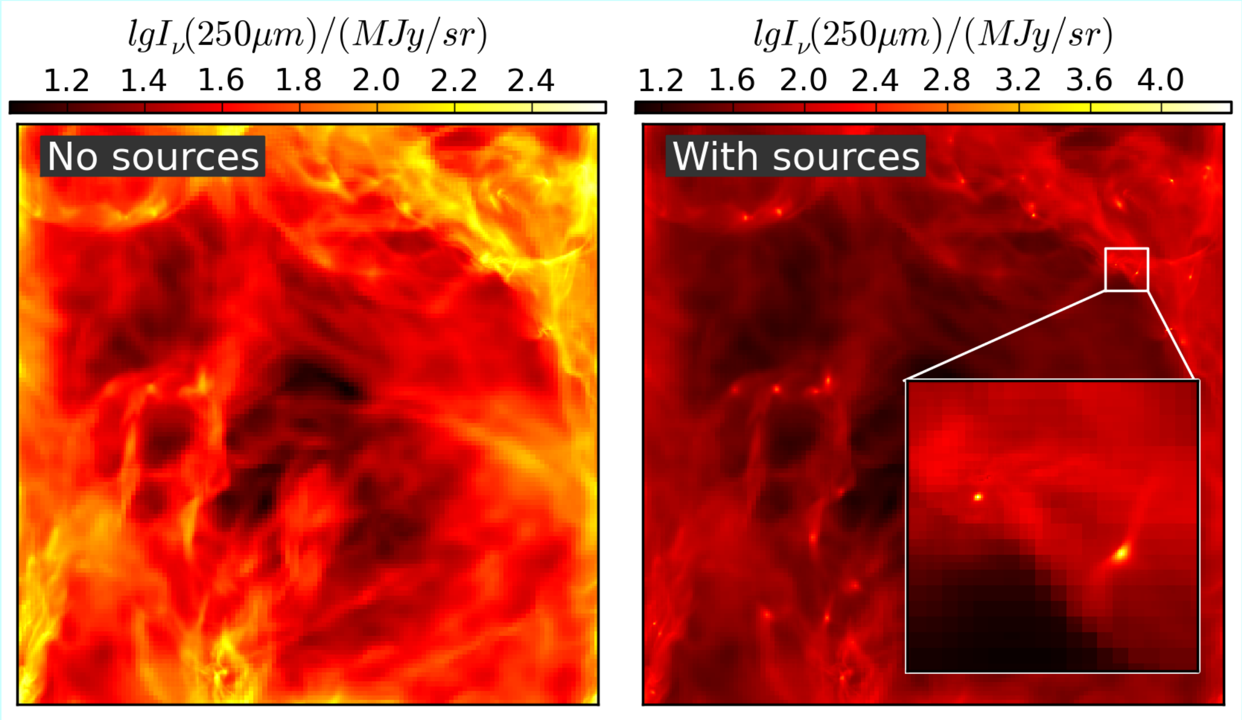
The problem

- apparent *T* and β values become correlated whenever
  - the observations contain **noise**
  - there are **temperature variations** either along the line-of-sight or otherwise within the beam
- **both** factors are **always** present
  - it is difficult to separate intrinsic dust properties from *T* and noise effects

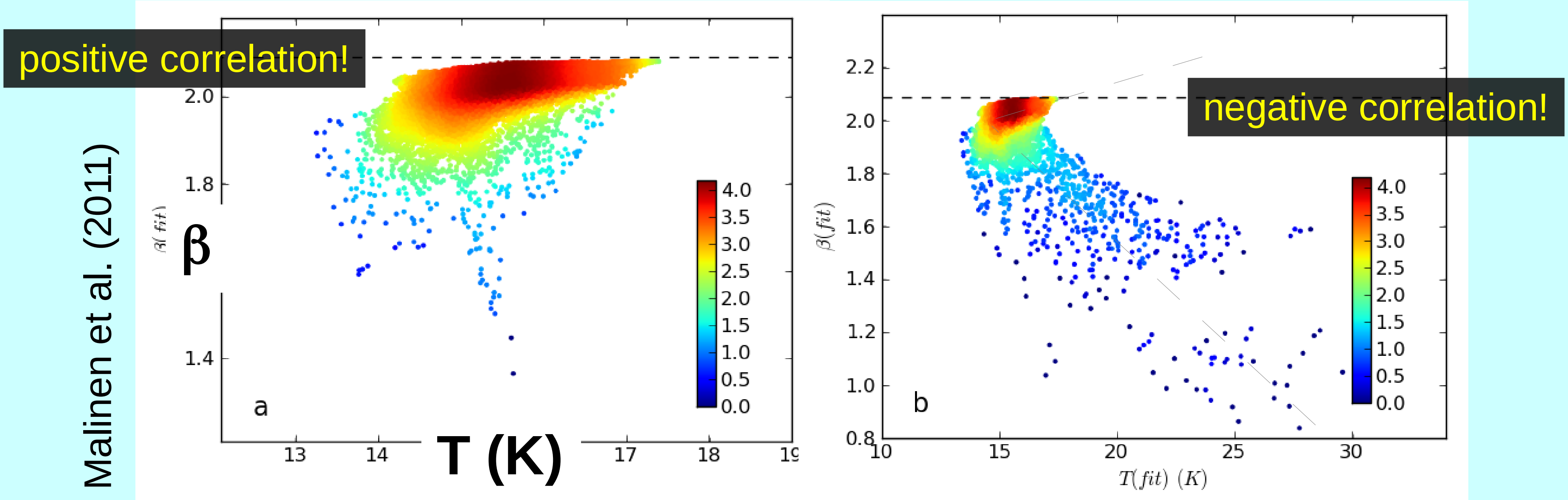
The difference between cores that are heated
externally by ISRF or **by protostars**?

2012

High resolution AMR MHD +
radiative transfer modelling
(see Luntila et al. 2012)



Malinen et al. (2011)



Hierarchical models

- adds to the model a statistical description of the distribution of (T, β) values

$$p(I,T,\beta,\delta|S) \propto p(\theta) \prod_{i=1}^{N_S} \left[\underline{p(I_i,T_i,\beta_i,\delta_j|\theta)} \prod_{j=1}^{N_f} p(S_{i,j}|I_i,T_i,\beta_i,\delta_j) \right]$$

priors

product over sources

hierarchical part

product over bands

likelihood function

calibration factors

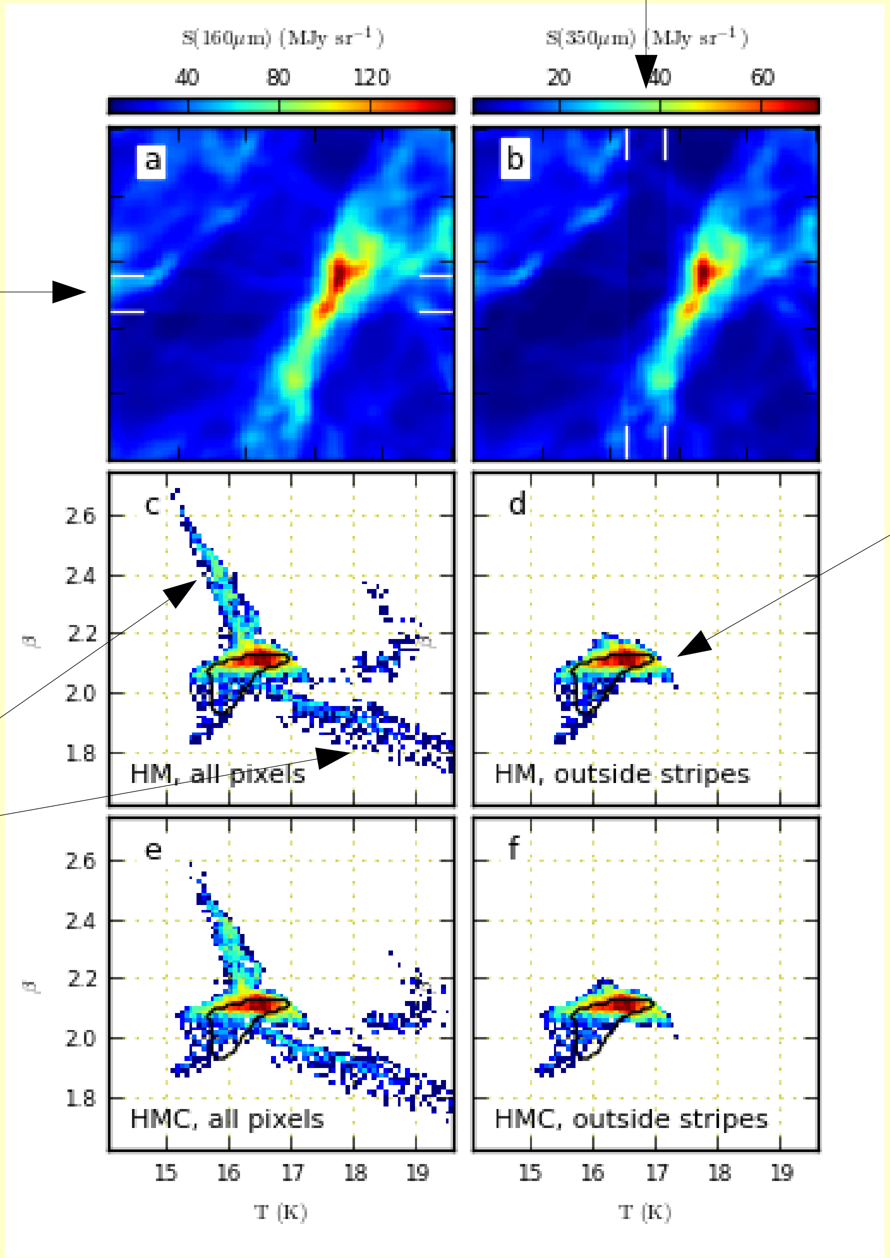
probability from normal or Student distribution

(Kelly et al. 2011;
Juvela, Montillaud, Ysard, Lunttila 2013)

Mapping artefacts

-2MJy/sr

+3MJy/sr



Small effect reflected outside stripes?

Affected, mainly low SN pixels.

GCC: opacity spectral index

Spectral index as function of temperature, column density, and wavelength

Galactic cold cores VII. Dust opacity spectral index ⋆ ⋆⋆

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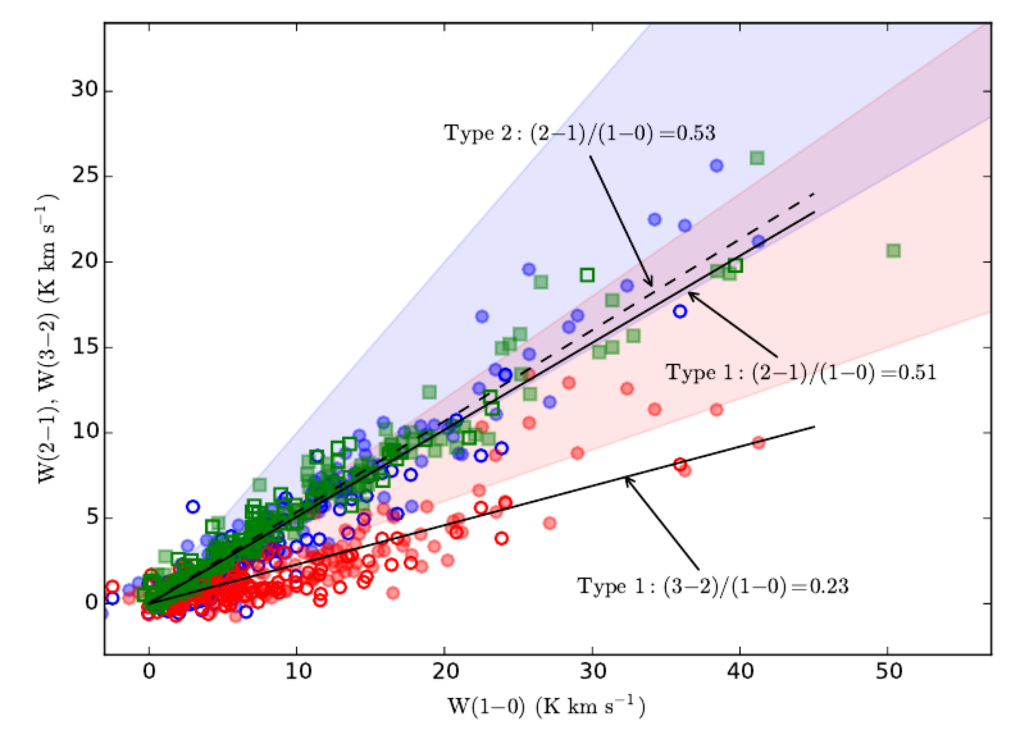
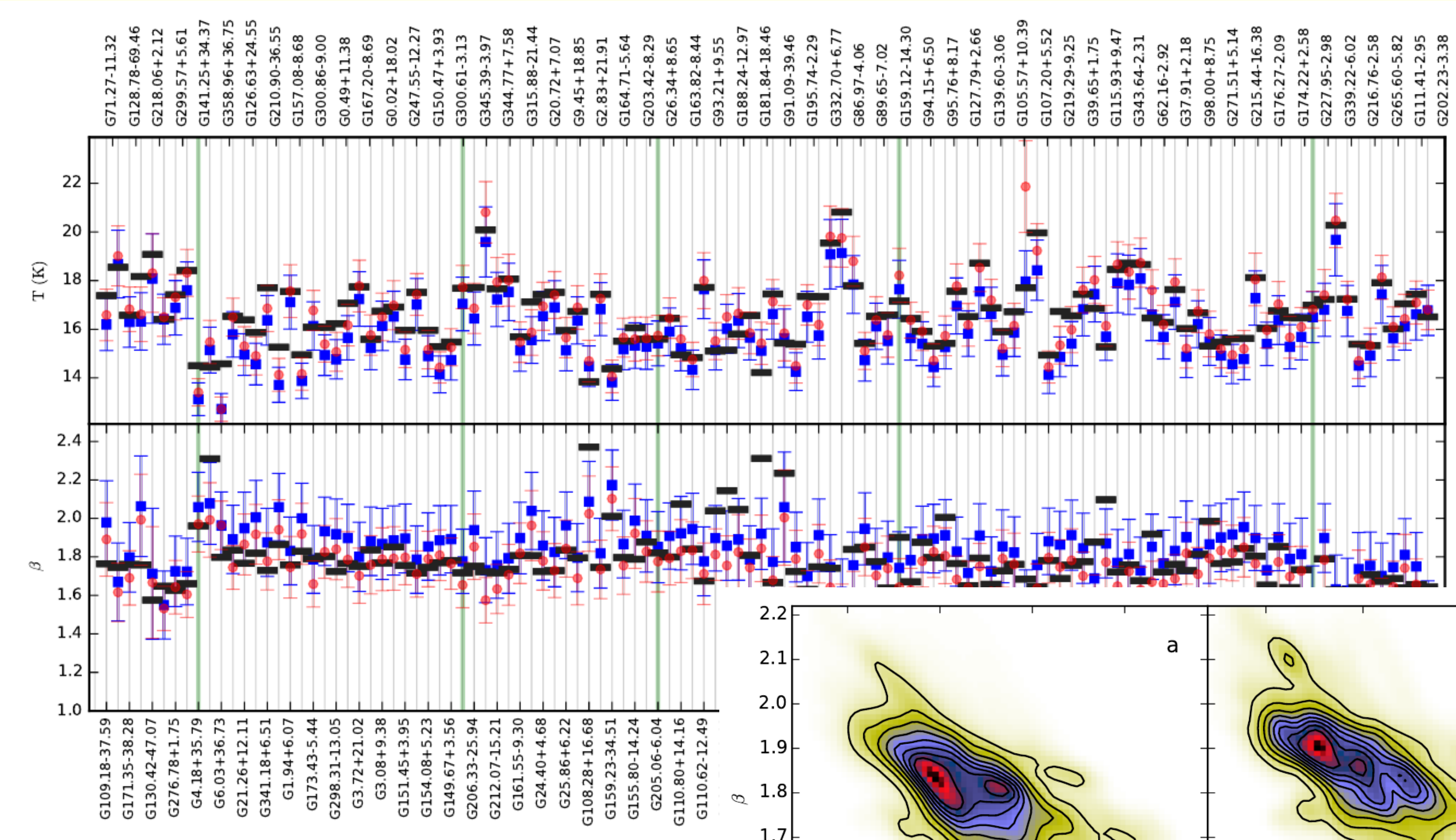
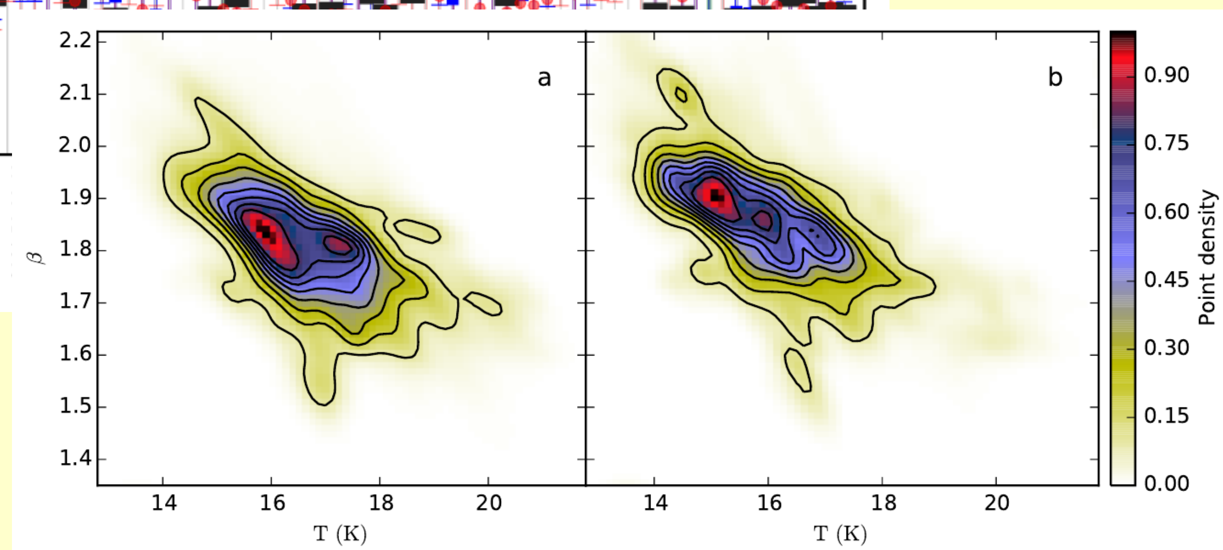
- Herschel maps 160-500μm
  - zero points from Planck or AKARI
- Planck data 857-217GHz
  - significant CO corrections in the 217GHz band, less in 353GHz
  - CO(1-0) intensity from Planck Type 3 CO maps ... needs assumption of line ratios



CO line ratios based on Planck Type 1 and 2 CO maps of the examined fields.





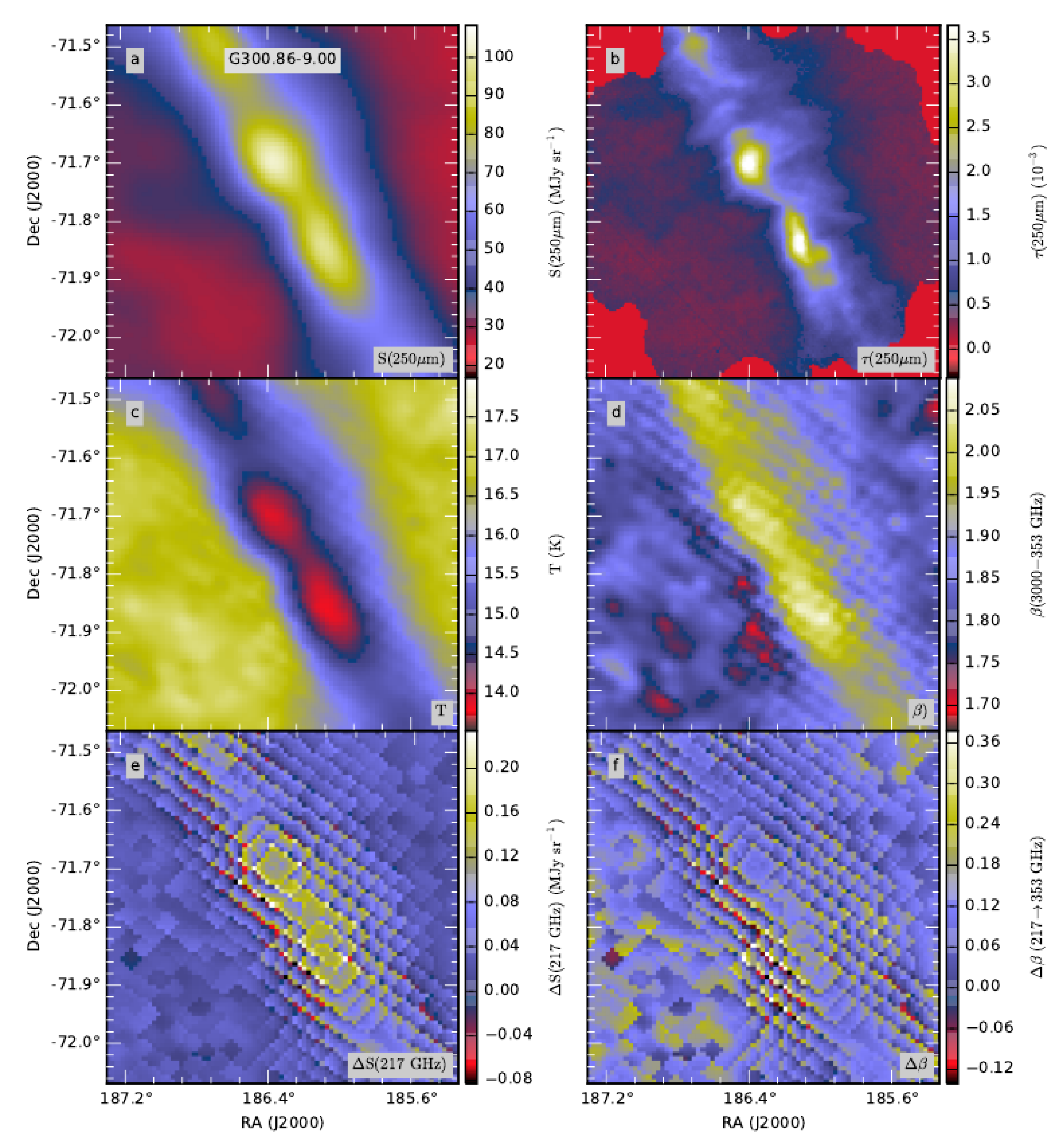
General results based on IRAS and Planck

- expected range of temperatures and spectral indices
- relatively weak T – β anticorrelation

More clear (?) **anticorrelation** seen in higher resolution Herschel observations.
Some evidence of **217GHz excess**.

S(250μm)

τ(250μm)

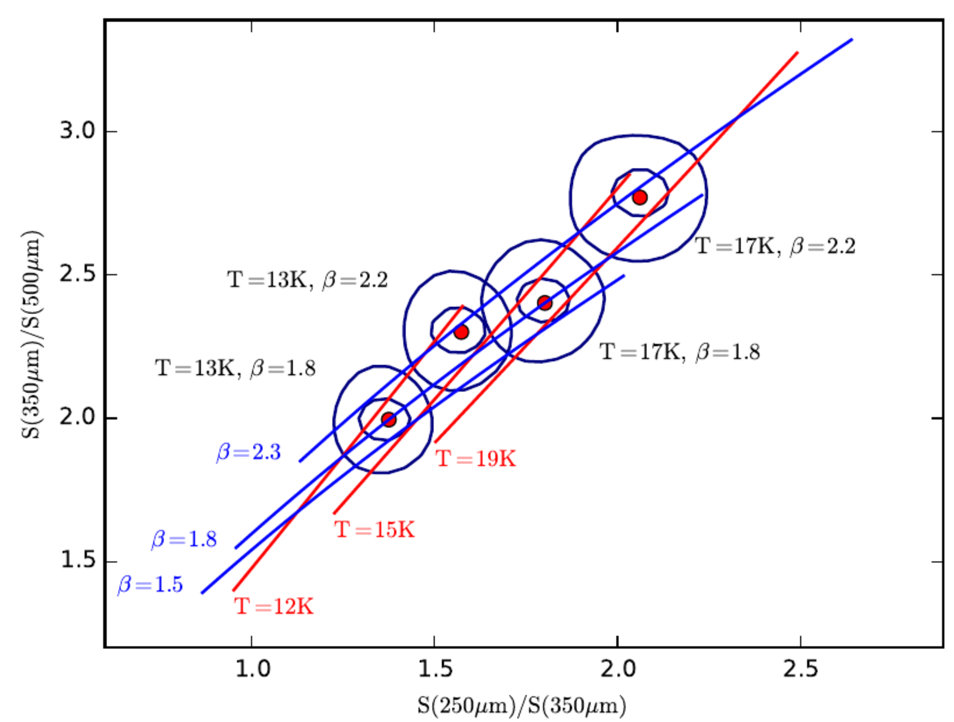


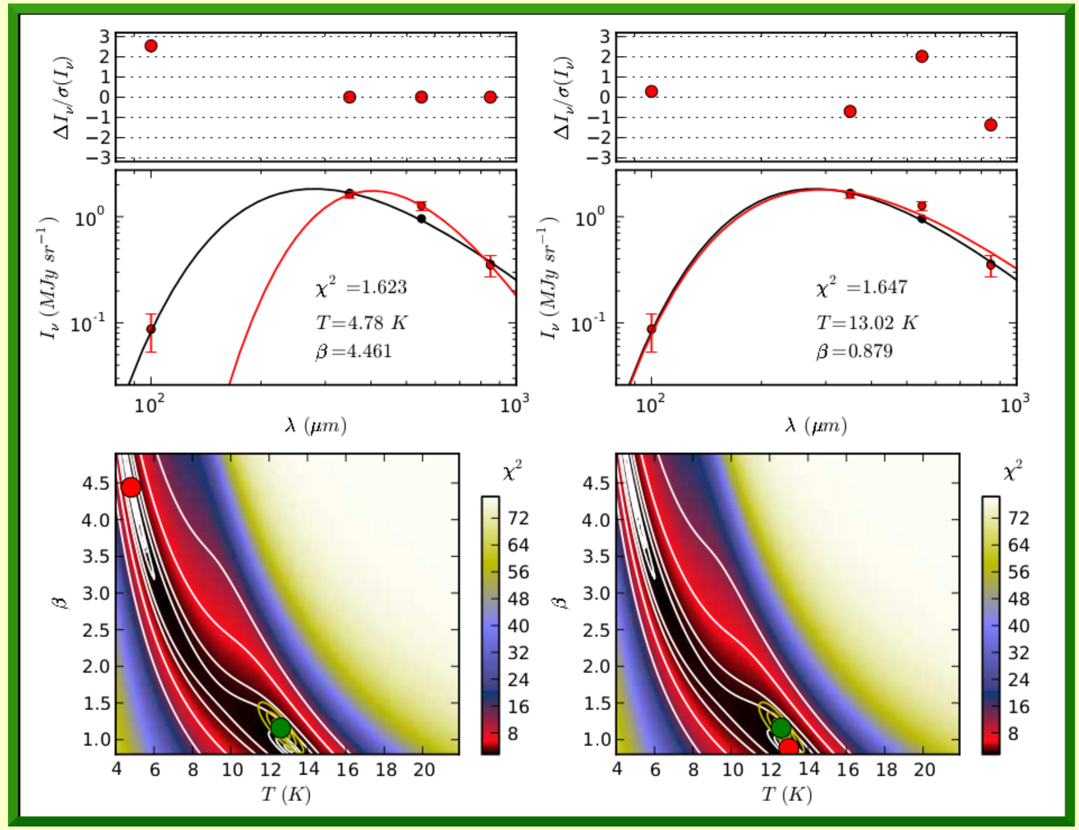
T

β

217GHz
minus fit

fit up to
217GHz
vs. fit up to
345GHz





Juvela & Ysard (2012b)

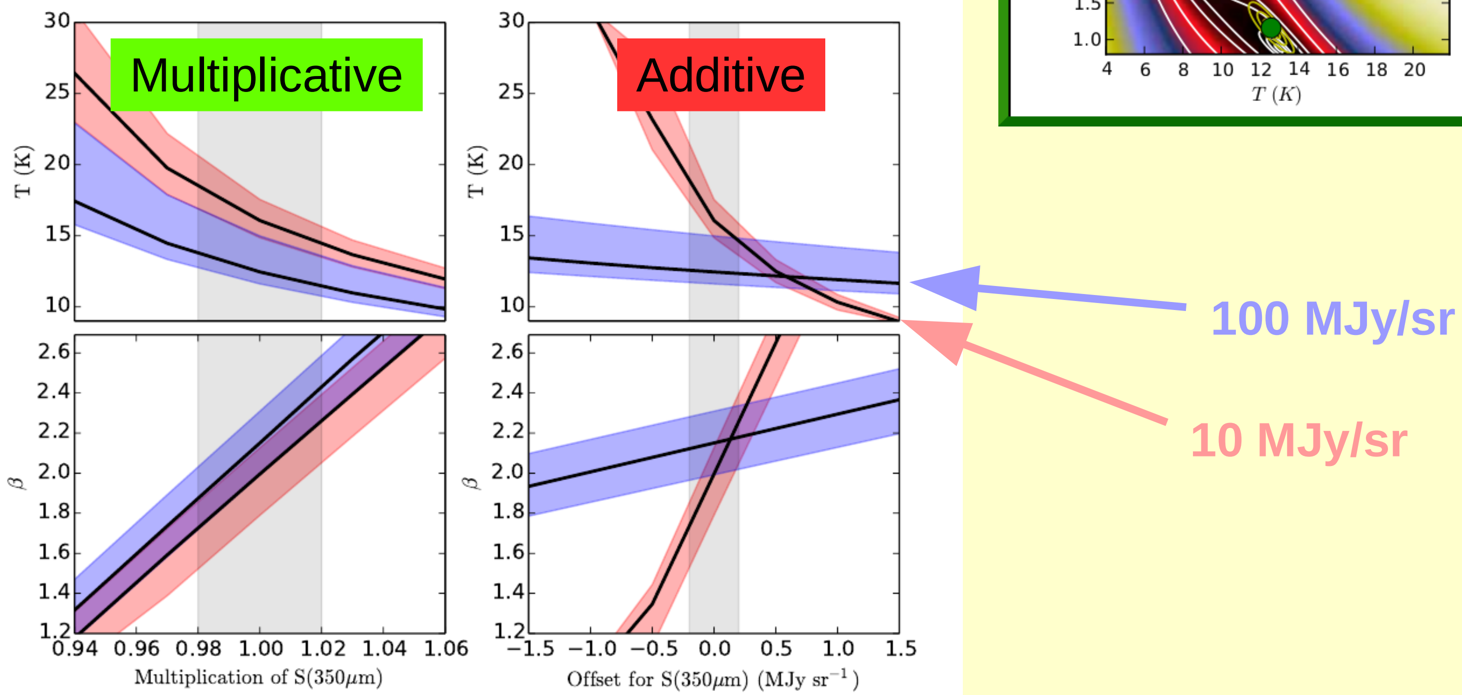
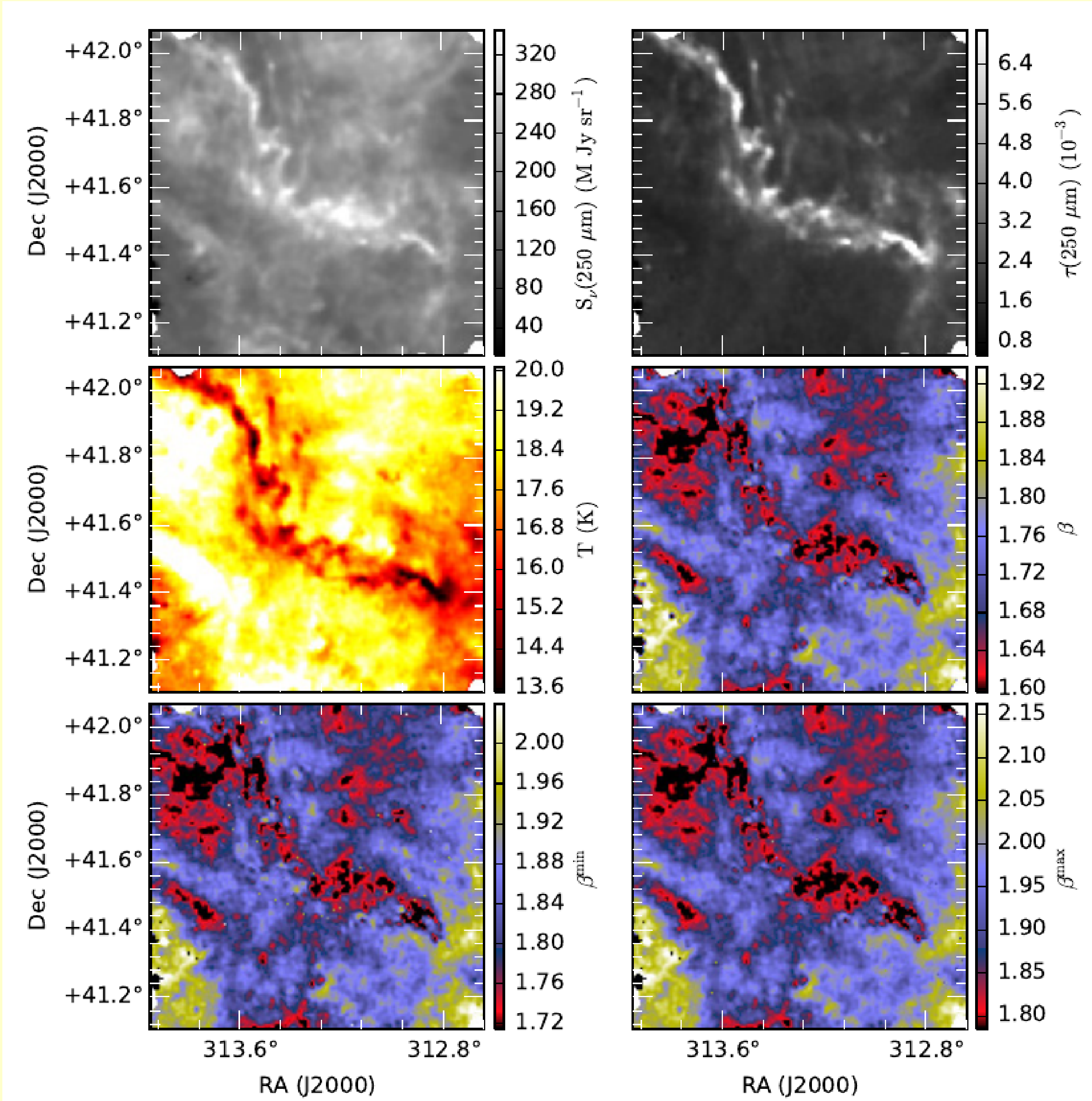


Fig. 10. The same as Fig. 9 but for hypothetical errors in the 350 μm surface brightness.

T



+42.0°
+41.8°
+41.6°
+41.4°
+41.2°
Dec (J2000)
313.6°
312.8°
RA (J2000)
320 280 240 200 160 120 80 40
$S_\nu(250\ \mu m)$ (M Jy sr^{-1})
6.4 5.6 4.8 4.0 3.2 2.4 1.6 0.8
$\tau(250\ \mu m)$ (10^{-3})
20.0 19.2 18.4 17.6 16.8 16.0 15.2 14.4 13.6
T (K)
1.92 1.88 1.84 1.80 1.76 1.72 1.68 1.64 1.60
β
2.00 1.96 1.92 1.88 1.84 1.80 1.76 1.72
$\beta^{\min}$
2.15 2.10 2.05 2.00 1.95 1.90 1.85 1.80
$\beta^{\max}$

β

IRAS & Planck

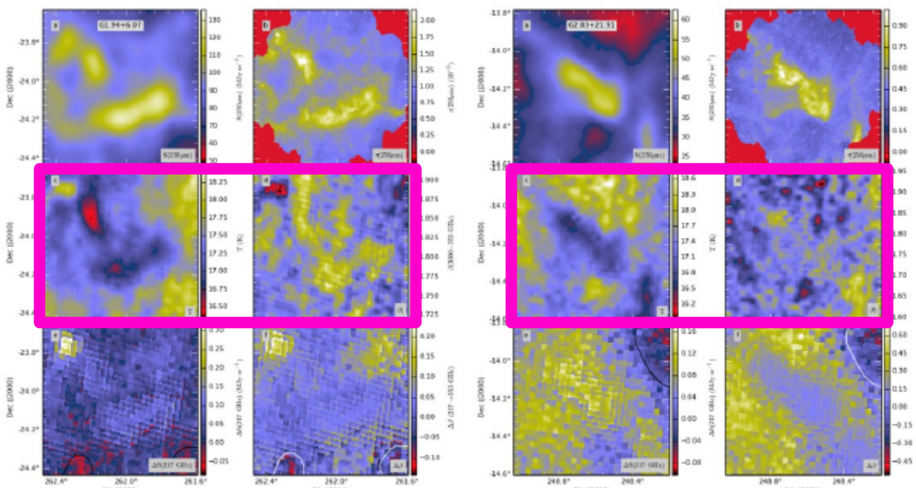
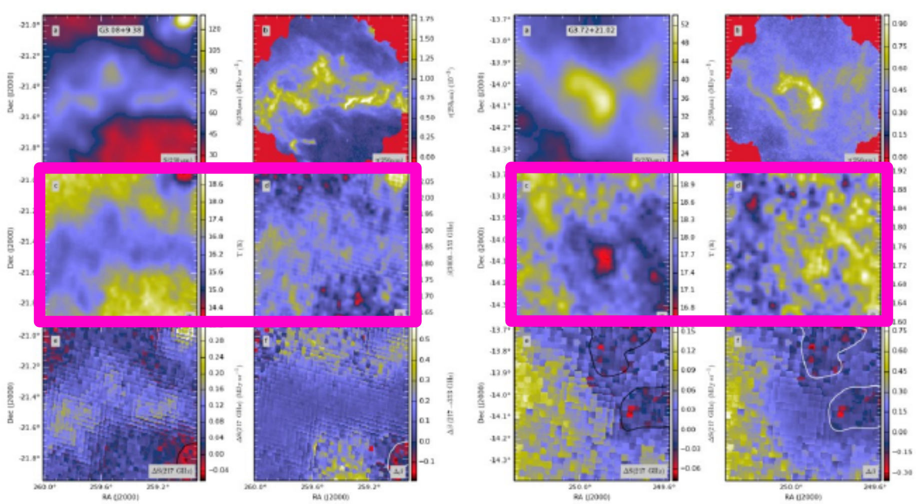


Fig. B.3. Continued… Fields G1.94+6.07 and G2.83+21.91



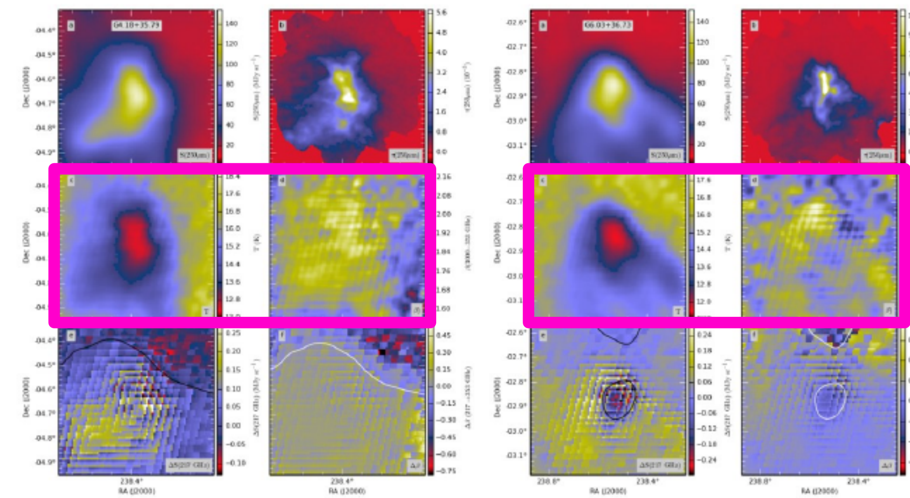
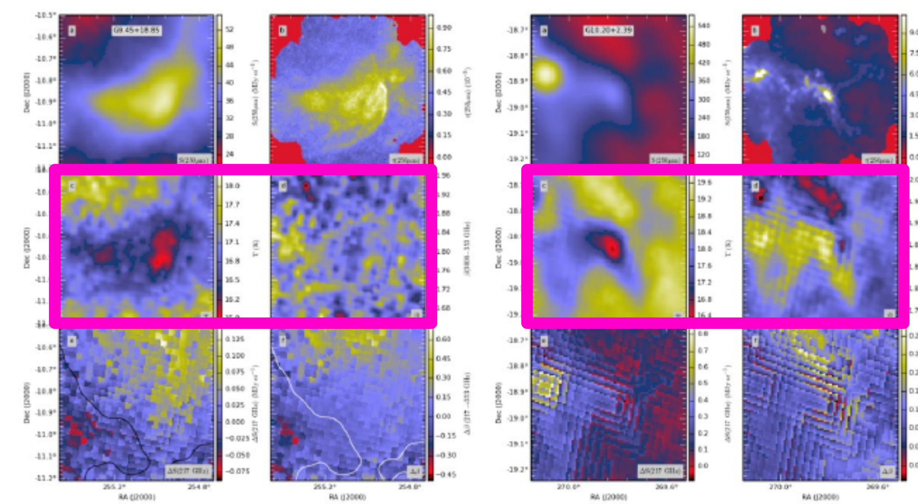
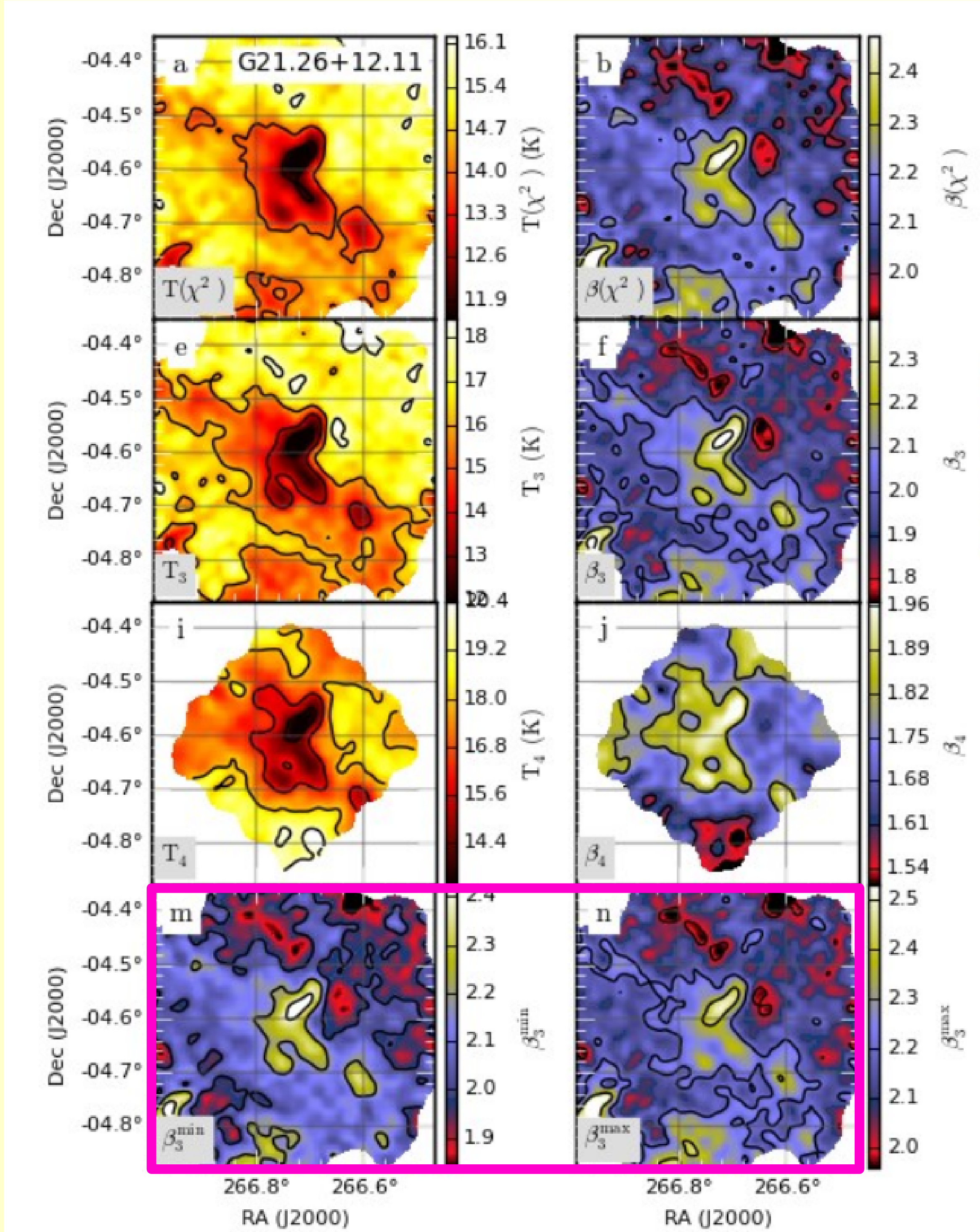


Fig. B.5. Continued… Fields G4.18+35.79 and G6.03+36.73

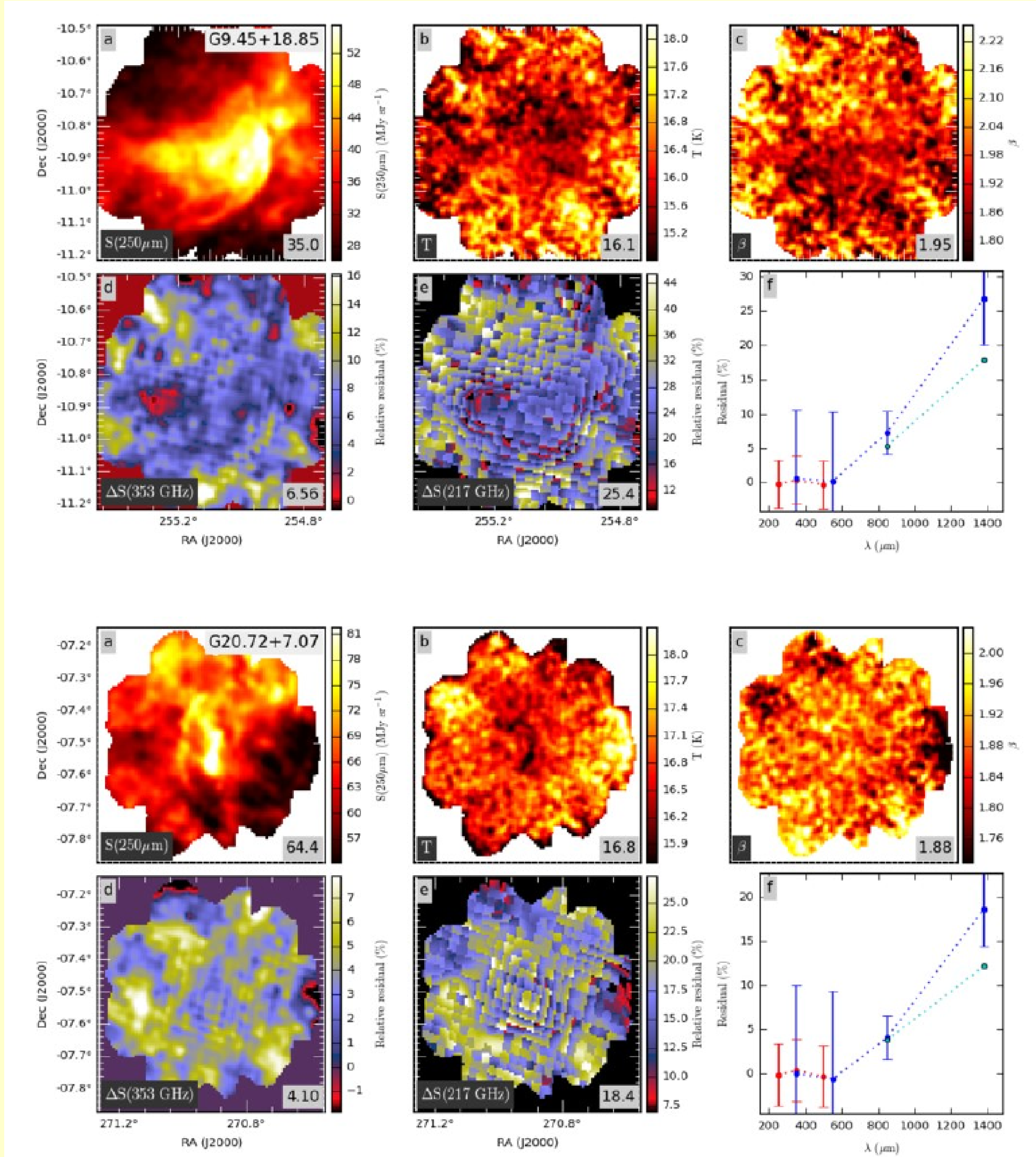


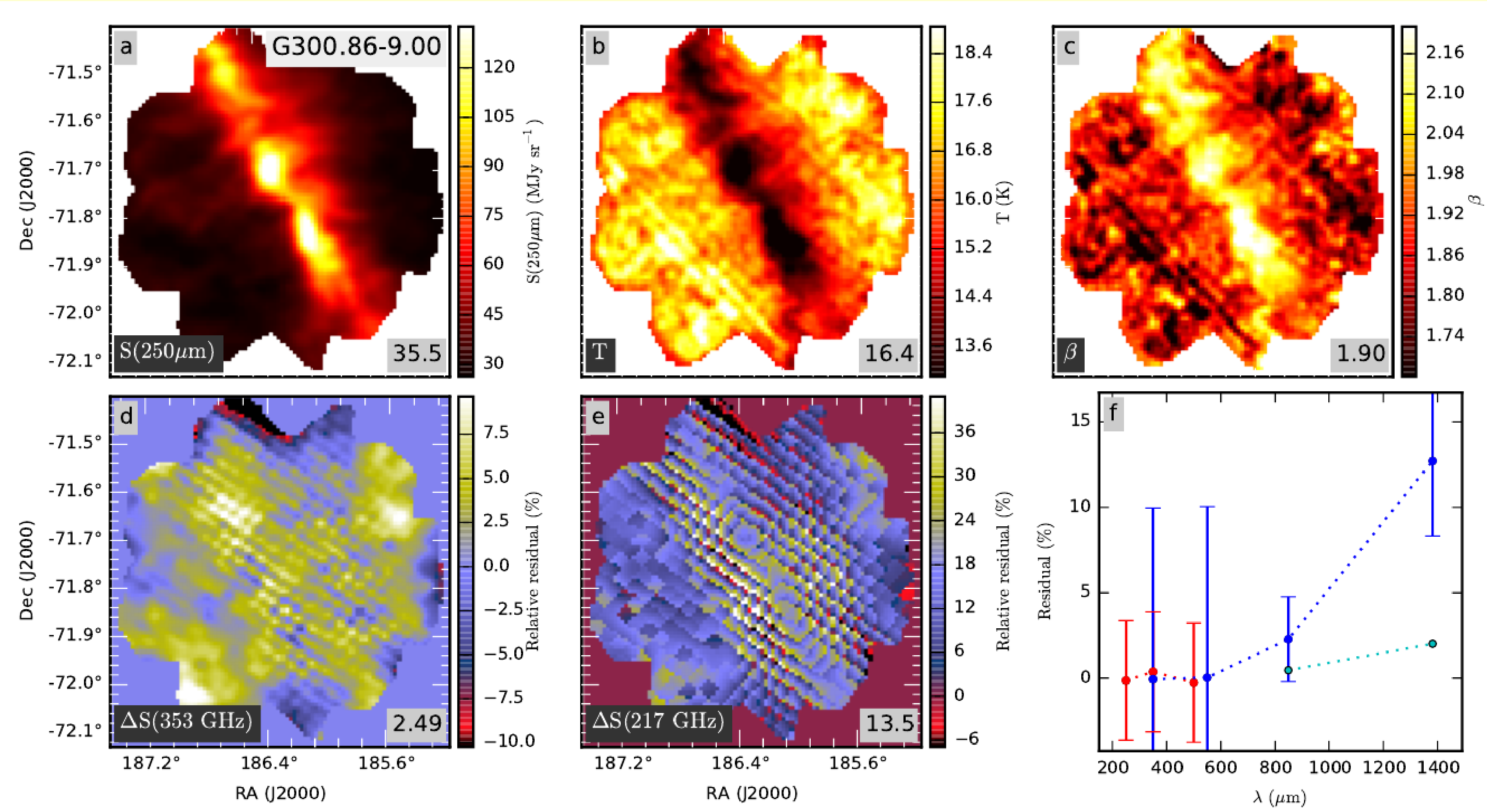
Herschel



G21.26+12.11
a
b
e
f
i
j
m
n
T(χ²)
β(χ²)
T₃
β₃
T₄
β₄
β₃^min
β₃^max
T(χ²) (K)
T₃ (K)
T₄ (K)
Dec (J2000)
RA (J2000)
-04.4°
-04.5°
-04.6°
-04.7°
-04.8°
266.8°
266.6°

Herschel + Planck





a
G300.86-9.00
S(250μm)
35.5
b
T
16.4
c
β
1.90
d
ΔS(353 GHz)
2.49
e
ΔS(217 GHz)
13.5
f
Dec (J2000)
RA (J2000)
S(250μm) (MJy sr−1)
T (K)
Relative residual (%)
Residual (%)
λ (μm)

Conclusions

- Dust opacity spectral index shows clear spatial variations, anti-correlated with temperature, correlated with column density
- Based on IRAS and Planck, the median values are $T = 16.1$ K and $\beta_{FIR} = 1.84$
- With Herschel data, we find in many clumps with values up to $\beta \sim 2.2$ ($\nu \leq 353$ GHz)
- Millimetre emission shows excess relative to the fits to submillimetre data
- Two component fits give average values of $\beta_{FIR} = 1.91$ and $\beta_{mm} = 1.66$.
- β_{FIR} is significantly higher than values reported for diffuse medium, β_{mm} is close to the values Planck studies have found for diffuse regions at high Galactic latitudes

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09/02/2015	Revision 1 received by Ed.
10/02/2015	Revised version to referee 1
27/03/2015	Referee comments sent to author
20/04/2015	Revision 2 received by Ed.
24/04/2015	Revised version to referee 1

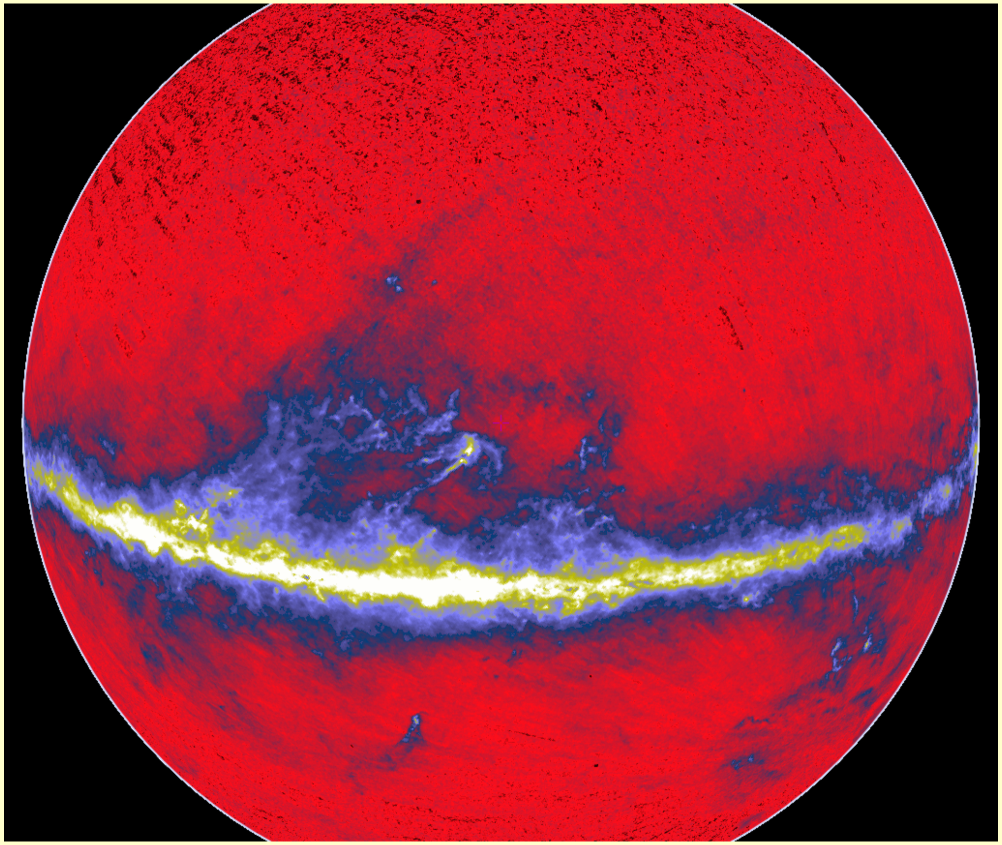
Modelling

3D radiative transfer modelling was already used examine τ(submm) bias

The Plan

- even higher resolution modelling $\rightarrow$ evaluate better the structure of the cores/clumps
  - better estimates of radial profiles
  - better estimates of gravitational energy, read **directly from the 3D model**
- successful modelling may cause some re-evaluation of the behaviour of κ and β
- extinction (and potentially even scattering) may be used for additional constraints

Juvela & Montillaud (2015a): Allsky NICER and NICEST extinction maps based on the 2MASS near-infrared survey



`www.interstellarmedium.org/Extinction`

NICER and NICEST maps at 3.0´, 4.5´, and 12' resolution, as Healpix files (NSIDE=2048).

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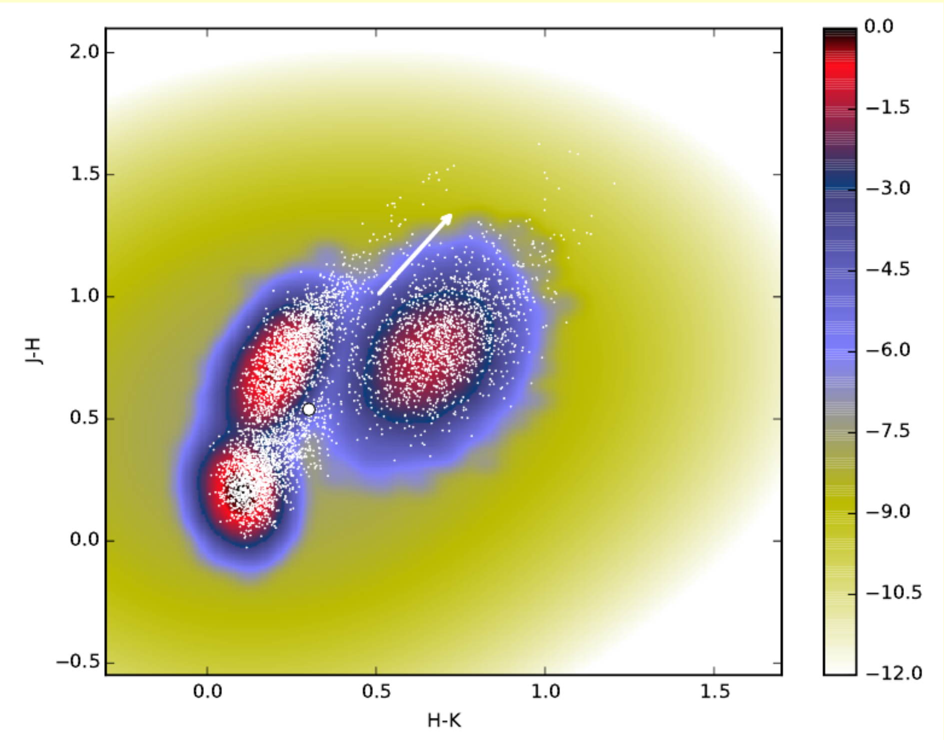
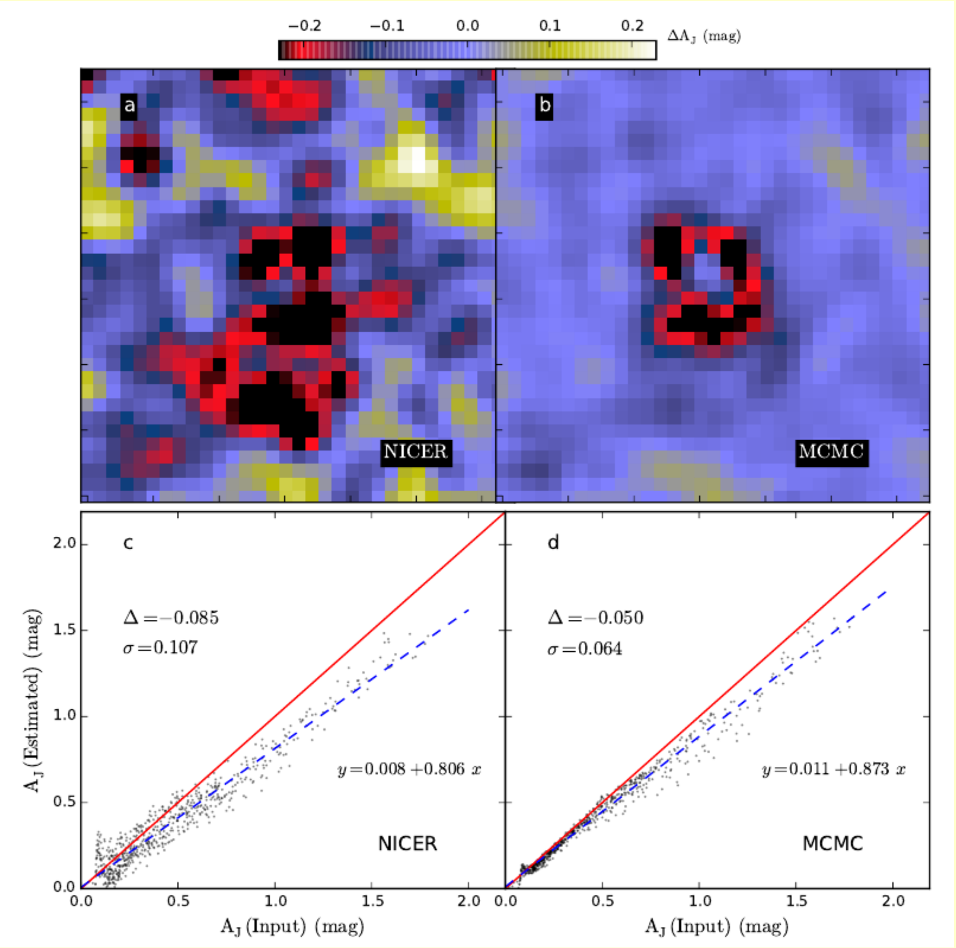
19/05/2015	Revised version to referee 1

Juvela & Montillaud (2015b): Near-infrared extinction with discretised stellar colours





Intrinsic colours: deviations from gaussian approximation → not very important in practice

A priori information of small-scale column density structure → potentially significant improvements as reduced bias and reduced rms noise.

Juvela (in prep?): New **radiative transfer programs** for dust continuum calculations

- SOC – **S**cattering calculations with **O**pen**C**L
  - improvement in run times of a factor of a few
    - compared to CRT with OpenMP parallelisation
    - potentially higher gains for GPUs, a factor of >10 compared to CRT on a single core (small models?)
- SOCAM, SOCAMP, SOCAMI
  - calculations of thermal dust emission
  - SOCAM slightly faster than CRT, SOCAMP even faster for models >> 200^3 cells
  - SOCAMI uses arbitrary (but common) values for x, y, and z cell boundaries