NIKA2 observations of starless cores in Taurus and Perseus

(Dust and gas of pre-stellar cores)

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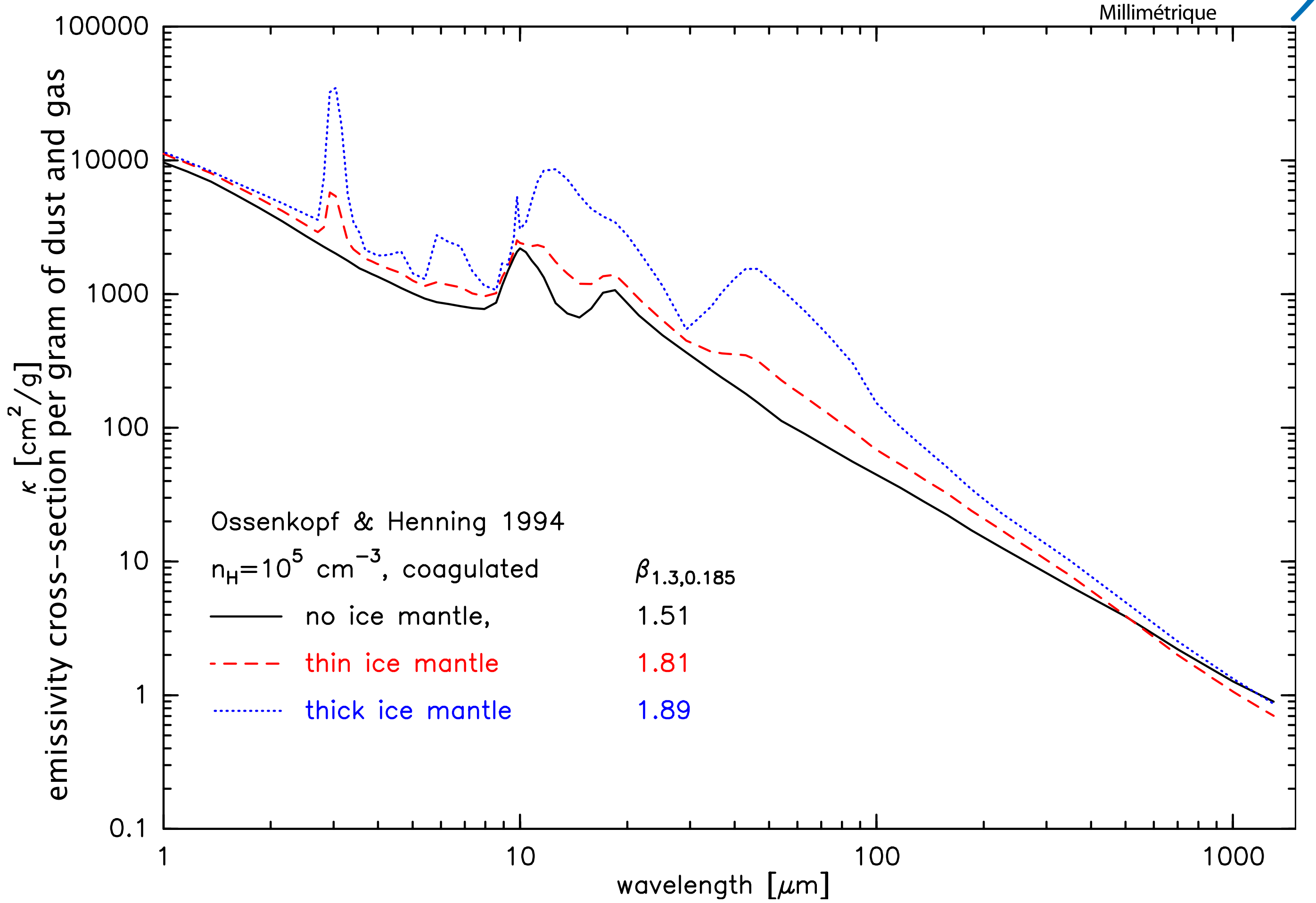
on behalf of the GEMS 30m Large Program team
and the NIKA2 collaboration

Prestellar cores

- Starless cores allow to study the **initial phases of star formation**: no shocks or outflows, no internal heating source, shielding from FUV ($A_V > 10$mag), low temperatures ($T_d <$ 20K), dense n>10^4cm^{-3}, self-gravitating.

- Topics:
  - influence of environment
  - turbulence, ionization fraction
  - gas elemental abundances, depletions
  - **grain coagulation and formation of ice mantles from gas depletion**
  - dust grain chemistry
  - magnetic fields



Models of dust opacity spectra (Ossenkopf & Henning 1994) for coagulated grains and a gas density of 10^5 cm^{-3} in proto-stellar cores, **varying the ice thickness** (cf. e.g.Ormel et al. 2011). **Beta increasing with ice thickness.**

Most molecules freeze-out onto dust grains in the central part of dense cores with A_V>10mag (CO-depletion: Kramer et al. 1999; Caselli et al. 1999).

Sample of cores observed with NIKA2

- **GEMS** - Gas phase molecular abundances in 29 starless cores of nearby clouds
  A Large Program with EMIR/30m: **chemical study** along cuts through starless cores.

  Fuente et al. 2009, 2023, Spezzano et al. 2022, Navarro-Almaida et al. 2020, 2023, …

- Follow-up with **NIKA2/30m and its field-of-view of 6.5'** (Perotto, Ponthieu, Macias-Perez et al. 2020) to simultaneously map the dust emission at 1 and 2mm in a subset of GEMS cores:

  - **Taurus** region, isolated formation of low mass stars, D=135pc (12", **1620au**, 0.008pc),
  - **Perseus** region, formation of stellar clusters, D=293pc

  - Observations:
    - 67.3 hours telescope time in 2019 - 2022
    - **Six regions covered: 1000 arcmin^2 with more than a dozen cores.**
    - rms @ 2mm: 0.3 mJy/beam, rms @ 1mm: 0.9 mJy/beam.
    - Average flux uncertainties: 6% at 2mm, 8% at 1mm, **<10% for ratios**

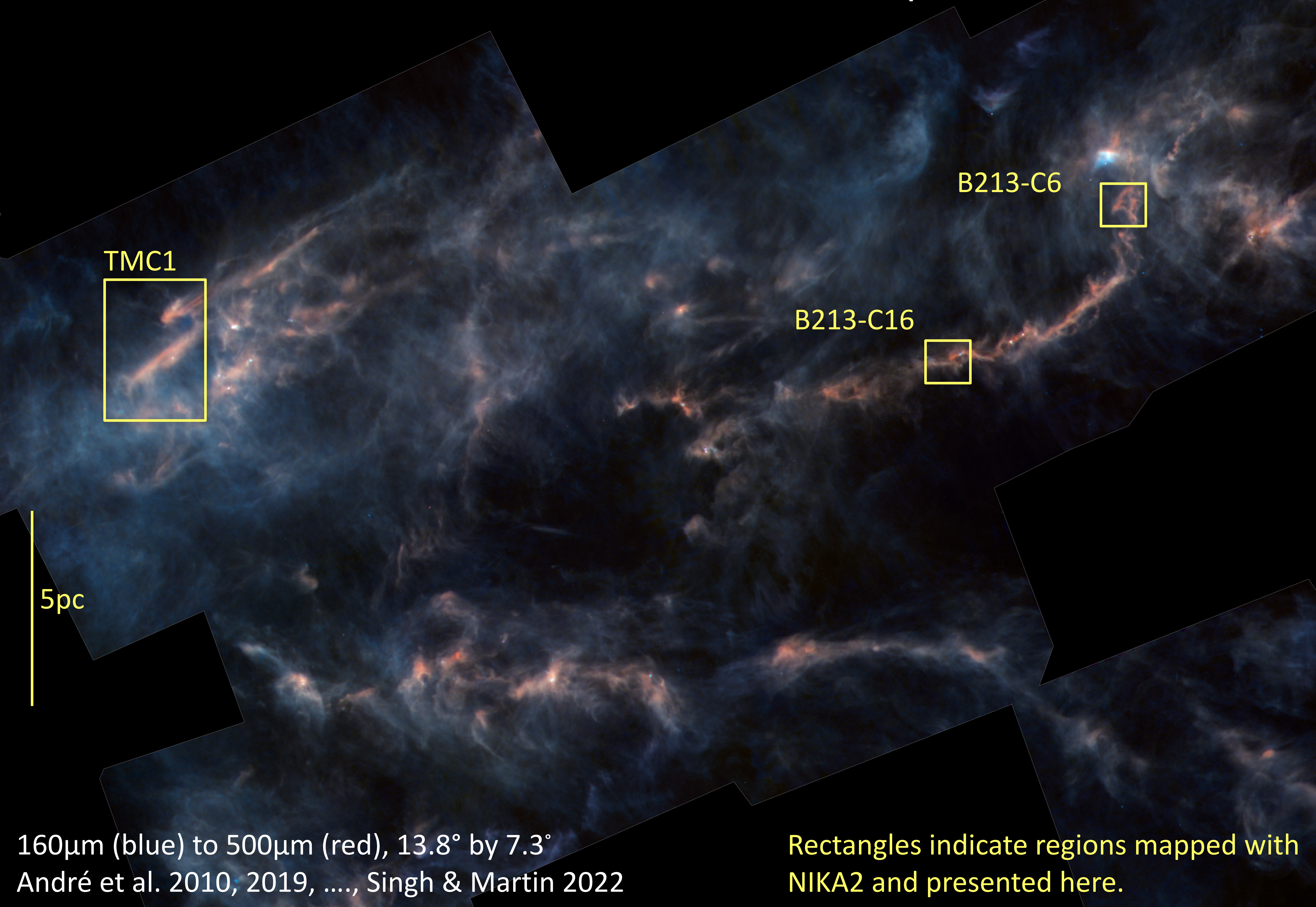
Sample of cores observed with NIKA2

- Present work:
  - GEMS - Gas phase molecular abundances in 29 starless cores of nearby clouds
    A Large Program with EMIR/30m: chemical study along cuts through cores, selected to avoid recently formed stars and outflows.
    Fuente et al. 2009, 2023, Spezzano et al. 2022, Navarro-Almaida et al. 2020, 2023, …

  - Follow-up with NIKA2/30m and its field-of-view of 6.5’ to simultaneously map the dust emission at 1 and 2mm in a subset of GEMS cores:
    - Taurus region, isolated formation of low mass stars, D=135pc (12”, 1620au, 0.008pc),
    - Perseus region, formation of stellar clusters, D=293pc

	RA (J2000)	Dec (J2000)	A_V (mag)	T_d (K)	$n(H_2)$ ($\times 10^4$ cm^{-3})	SF activity	Location
TMC1-C	04:41:38.80	+25:59:42.0	19.8	11.3	4.6	Low	Taurus
TMC1-CP	04:41:41.90	+25:41:27.1	18.2	11.9	1.5	Low	Taurus
B213-C6	04:18:08.40	+28:05:12.0	22.2	10.9	5.4	Low	Taurus
B213-C16	04:21:21.00	+27:00:09.0	24.8	10.3	5.6	Low	Taurus
NGC1333-C2	03:28:41.60	+31:06:02.0	17.4	14.8	8.3	Intermediate	Perseus
NGC1333-C7	03:29:25.50	+31:28:18.1	17.6	17.3	11.0	Intermediate	Perseus
IC348-1	03:44:01.00	+32:01:54.8	21.8	21.7	4.5	High	Perseus
IC348-10	03:44:05.74	+32:01:53.5	20.1	17.5	8.7	High	Perseus

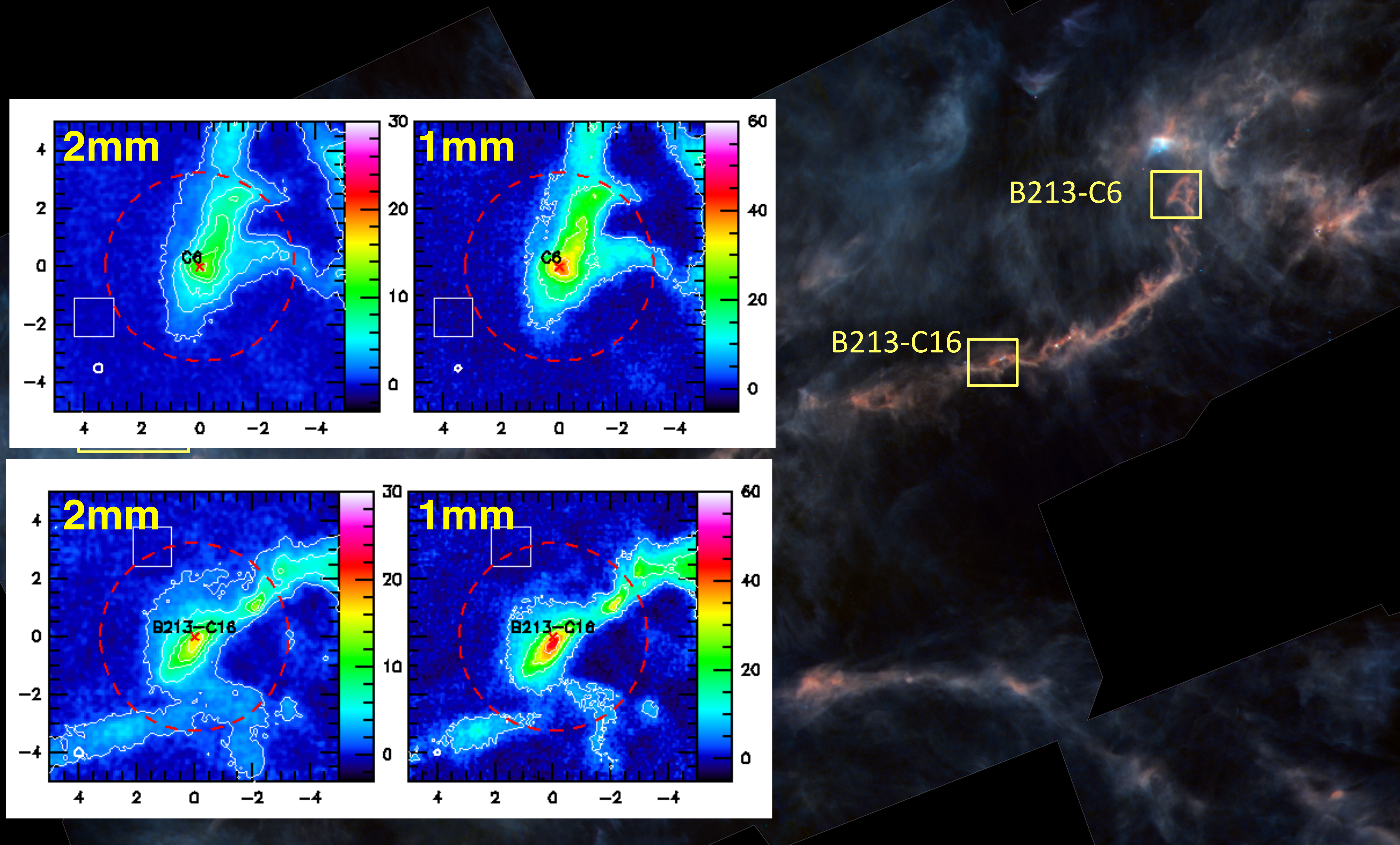
From filaments to cores: Herschel maps of Taurus



160µm (blue) to 500µm (red), 13.8° by 7.3°
André et al. 2010, 2019, …., Singh & Martin 2022

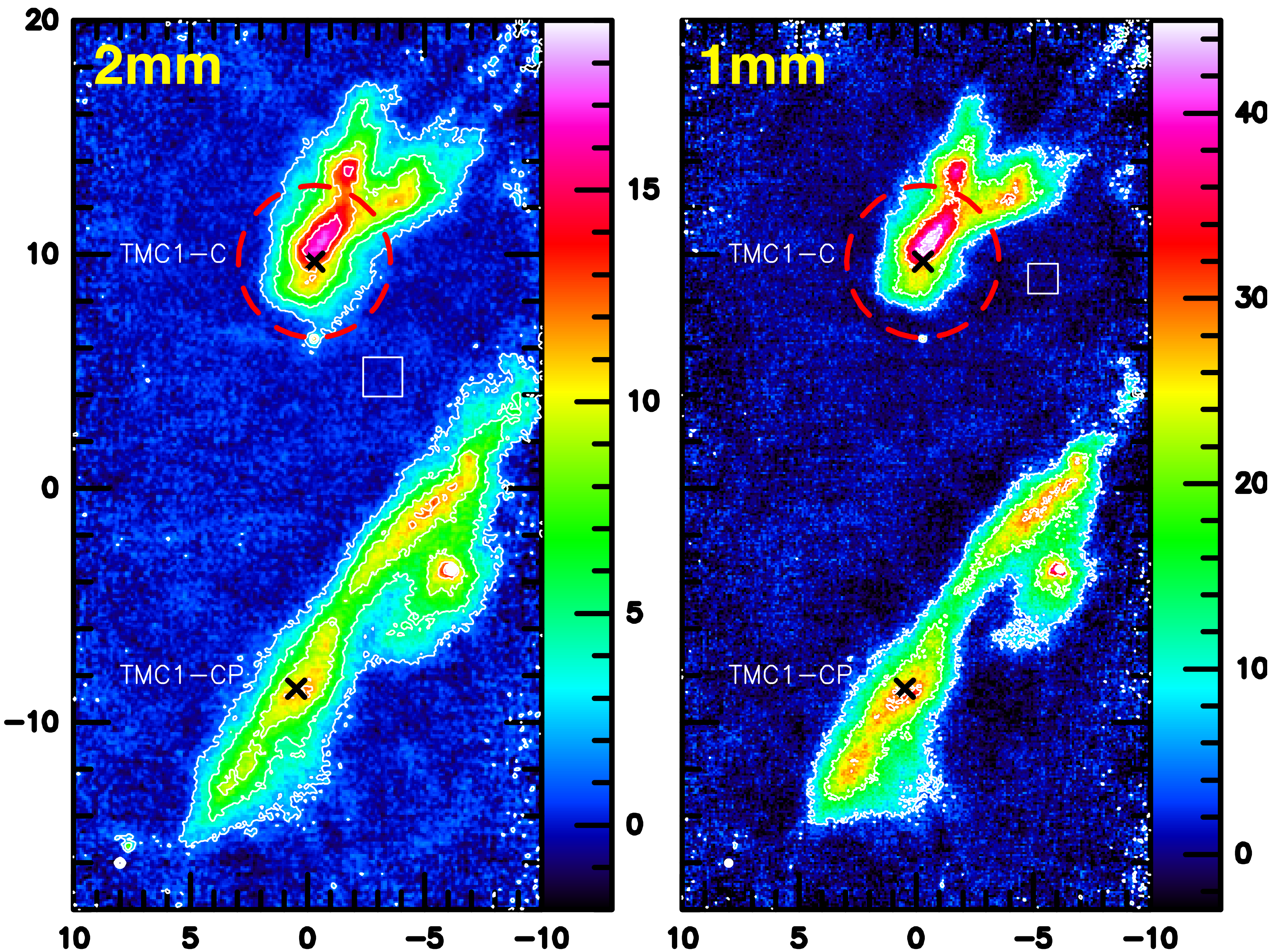
Rectangles indicate regions mapped with NIKA2 and presented here.

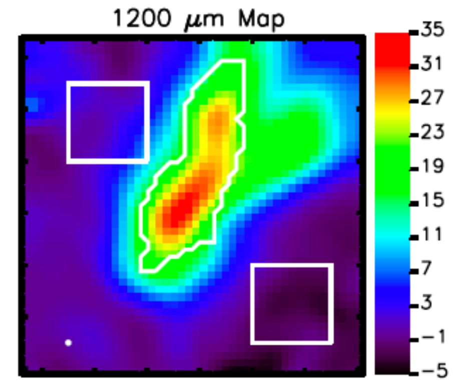
Cores in Taurus - Herschel map



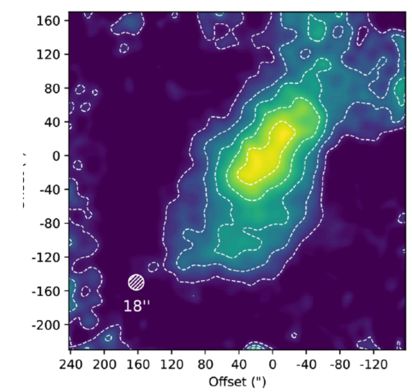
NIKA2 2mm and 1mm maps 18” and 11” resolution, respectively. Flux contours start at 6σ and rise in steps of 12σ with 1σ(2mm)=0.28mJy/beam, 1σ(1mm)=1.0mJy/beam. The red dashed circle marks the NIKA2 field-of-view of 6.5’ (0.26pc). The white rectangle marks the areas used by the reduction software piic to measure the rms level.

Cores in TMC1 - NIKA2 maps





TMC1-C by Schnee et al. 2010
1mm MAMBO/30m map
1σ=3.0mJy/b (white contour)



TMC1-C by Navarro-Almaida et al. (2023). 3mm MUSTANG-2/GBT
Contours start at 5σ

- Left: 2mm NIKA2 maps at 18”. Right: 1mm NIKA2 map at 11” resolution, both in mJy/beam.
- Flux contours start at 6σ and rise in steps of 12σ. 1σ(1mm)=1.0mJy/beam, 1σ(2mm)=0.28mJy/beam.
- The red dashed circle marks the NIKA2 field-of-view. Crosses mark the positions of GEMS cores.
- The white rectangle marks the areas in which piic measured the rms level.

1mm/2mm ratio and β

$$I_\nu = \tau_\nu B_\nu(T_\mathrm{d}) = \kappa_\nu \Sigma B_\nu(T_\mathrm{d}) \qquad \kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta$$

- T_d, β are weighted averages along the line of sight.

- Convolve 1mm map to 18" resolution using Gaussian kernel. Create maps of $R_{1,2}$ at 18" resolution. To first order, in the Rayleigh-Jeans limit, hν<<kT, the NIKA-2 1mm/2mm flux ratio $R_{1,2}$ is solely a function of β, the dust emissivity index.

$$\beta_\mathrm{RJ} = \frac{\log R_{1,2}}{\log\left(\nu_{1\ \mathrm{mm}}/\nu_{2\ \mathrm{mm}}\right)} - 2$$

Here, the 1mm/2mm ratio is a rather robust quantity, as observations are done simultaneously under the same conditions with the same instrument and through the same atmosphere.

- At the low temperatures of pre-stellar cores of ~10K, the RJ limit doesn't hold and the flux ratio is a **function of β and also of the dust temperature T_d** :

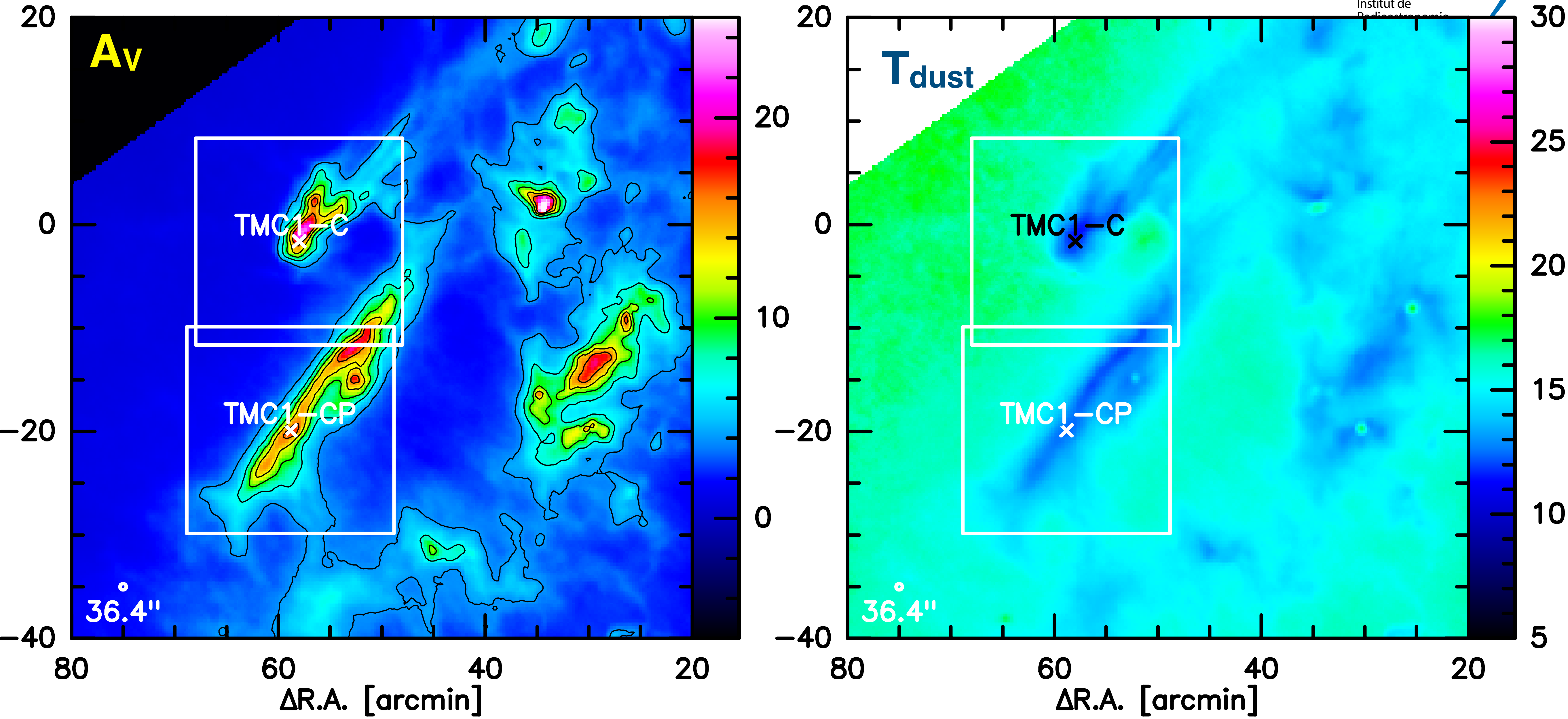
$$R_{1,2} = \frac{B_{\nu_{1.2mm}}[T_d]}{B_{\nu_{2.0mm}}[T_d]} \left(\frac{\nu_{1.2mm}}{\nu_{2.0mm}}\right)^\beta$$

- Here, the dust temperature was estimated from fits of a modified black-body to PACS/SPIRE Herschel 160, 250, 350, 500μm data from the Herschel Gould Belt Survey (HGBS, André et al. 2010) **reprocessed by Singh & Martin (2022) at 36.4" resolution (HOTT data)**.

  Maps of $\beta_{1,2}$ at 18" resolution.

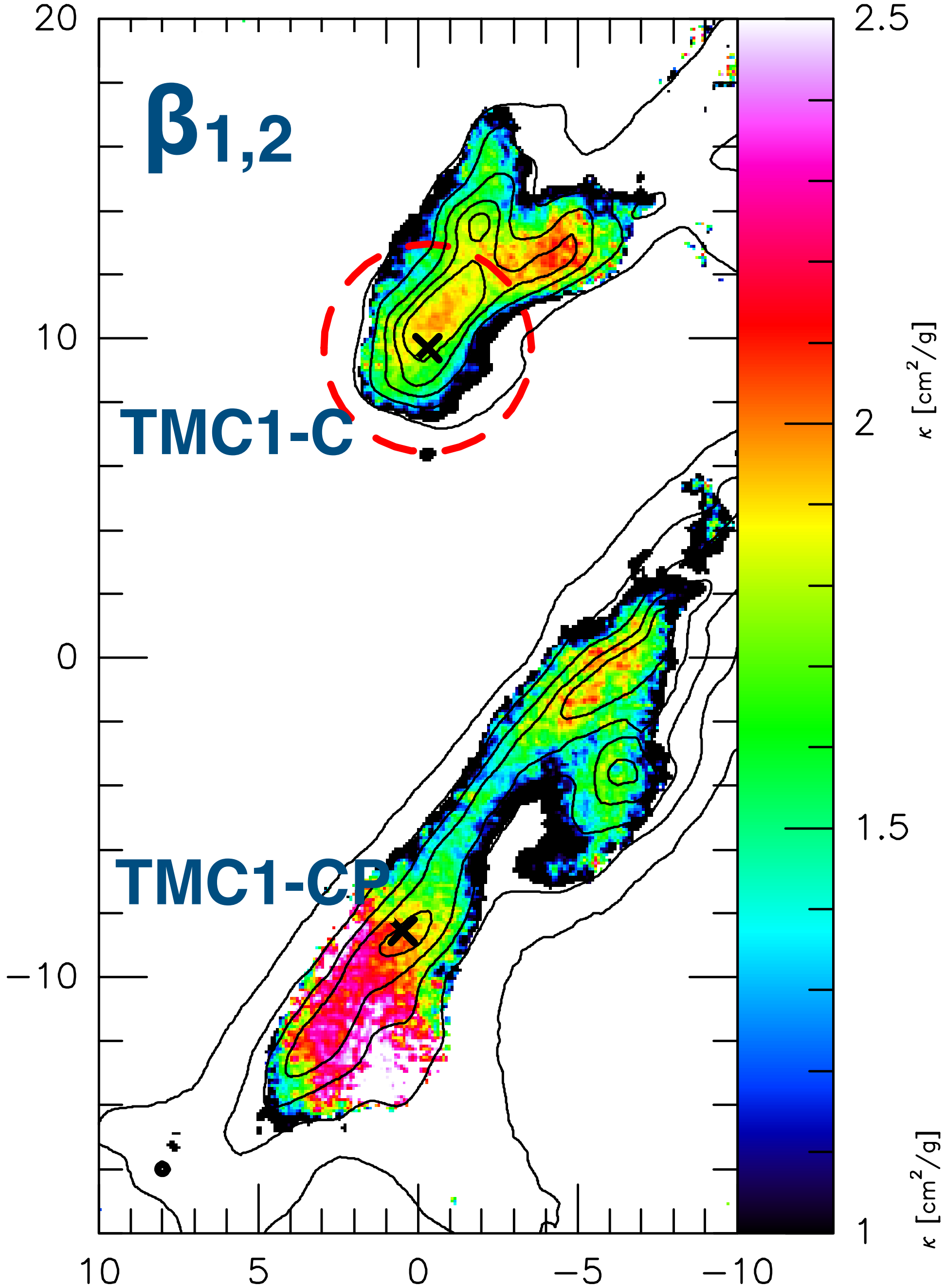
Cores in TMC1 - A_V and T_{dust} maps from Herschel

HOTT work by Singh & Martin 2022

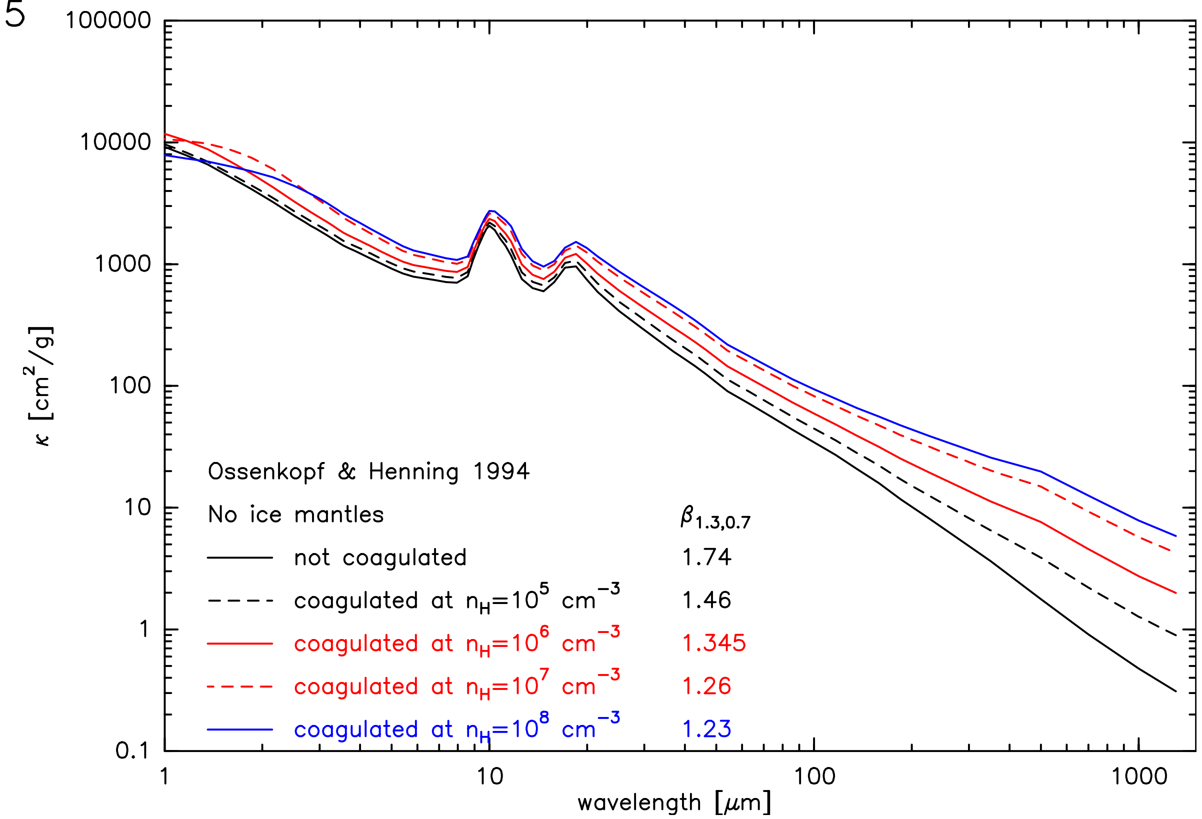


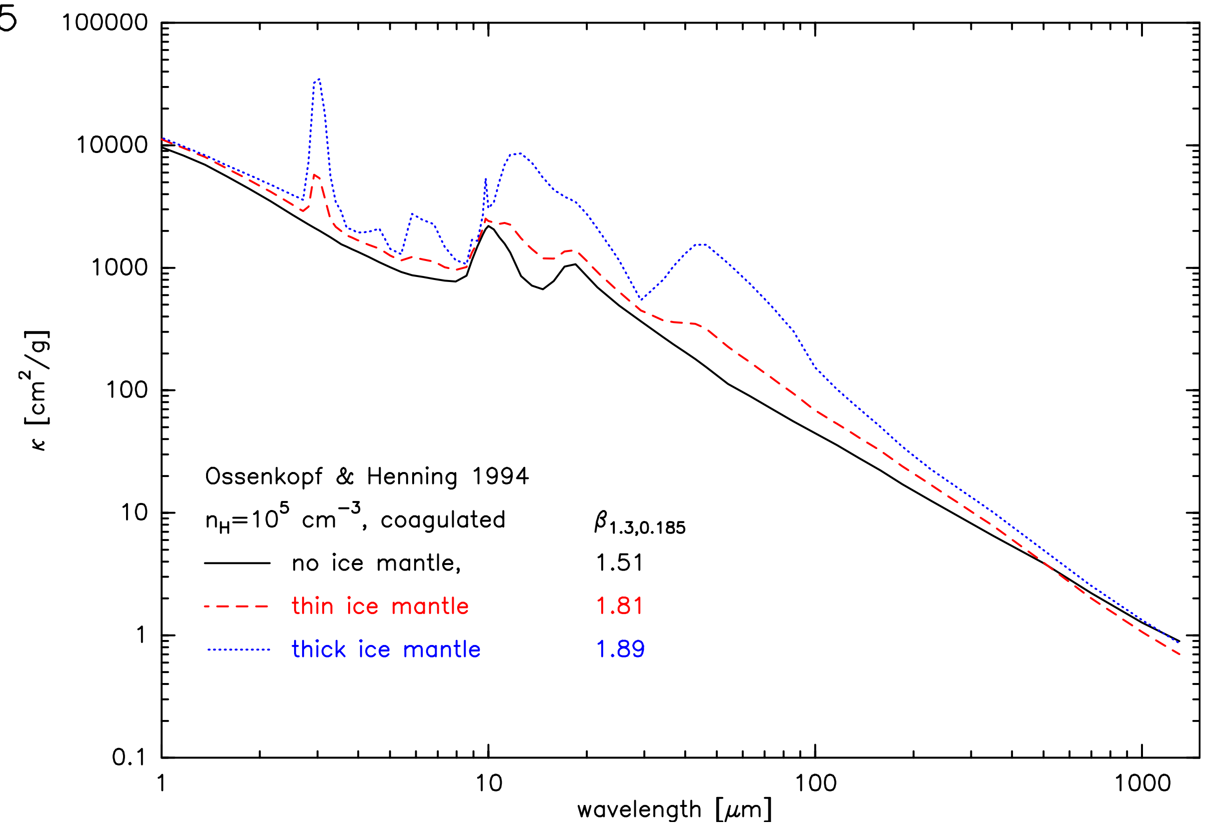
- Av contours at 4, 7, 10, 13, 16mag.
- White rectangles indicate the regions mapped with NIKA2.

Map of dust emissivity in TMC1



In some cores like in TMC1-C, β is high in the core centers, increasing from β~1.5 in the outskirts at Av~7mag to β~1.8 at Av=18mag.





OH94 models:

No ice mantles:

long wavelength slope flattens with density (and grain size).

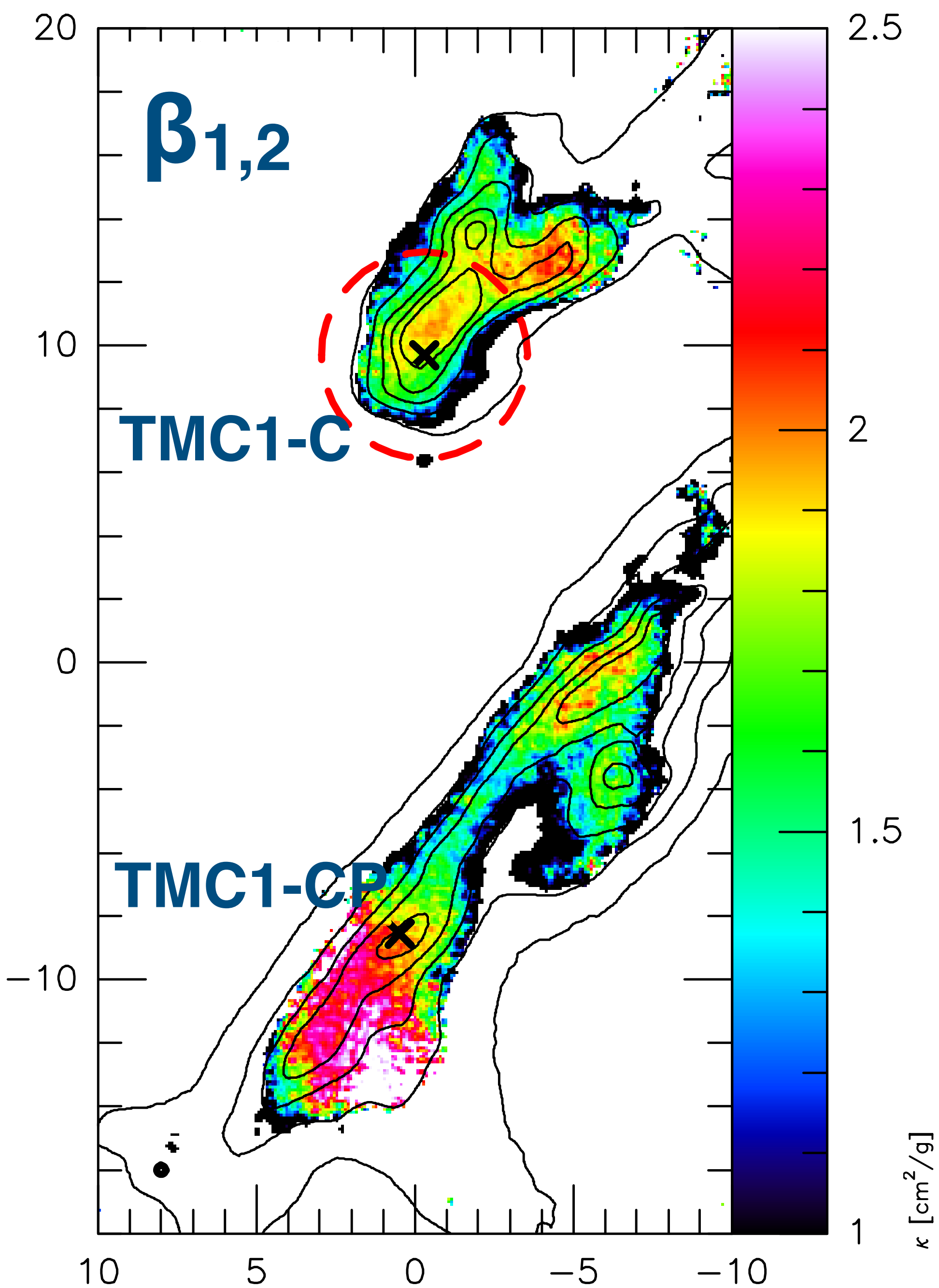
However, we observe the slope to steepen, β to rise with Av (and density).

OH94 models with ice mantles:

β increases with thickness of ice layer.

This interpretation is consistent with observations in TMC1-C.

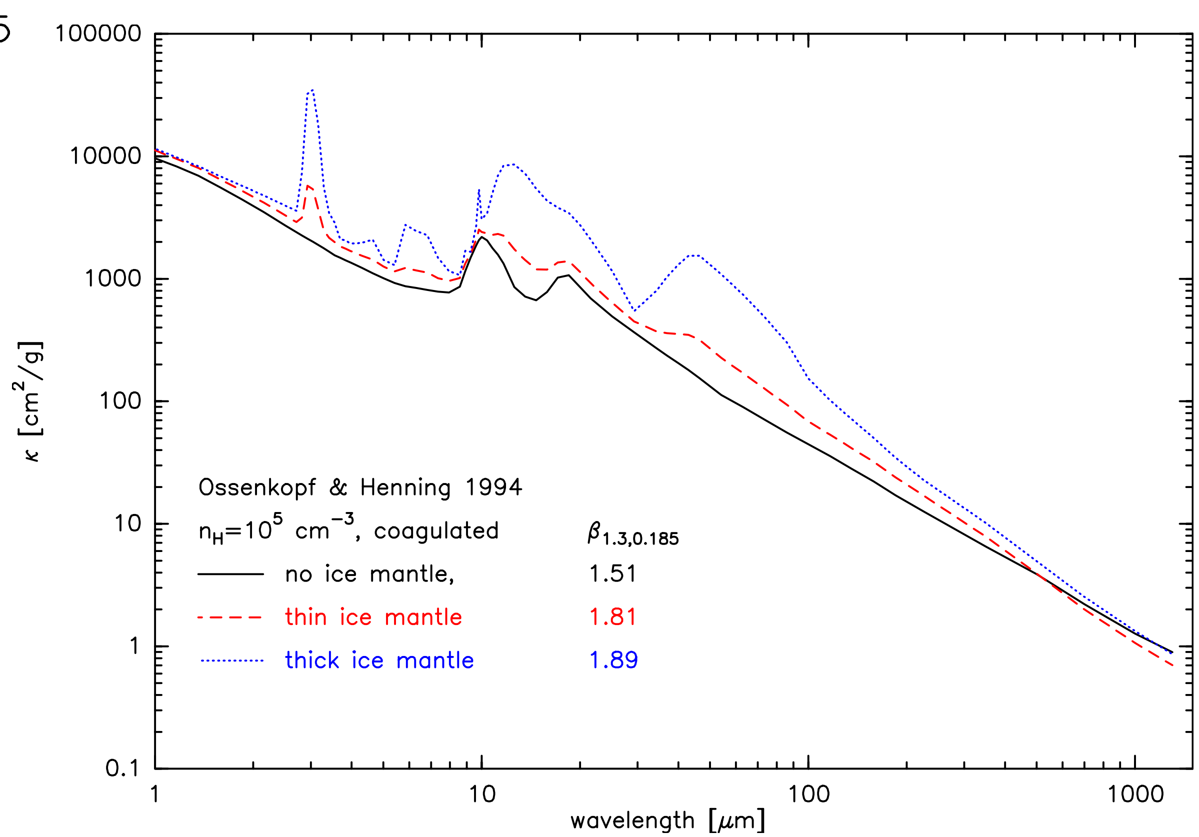
Map of dust emissivity in TMC1



In some cores like in TMC1-C, β is high in the core centers, increasing from β~1.5 in the outskirts at Av~7mag to β~1.8 at Av=18mag.

Mol	TMC 1-CP	TMC 1-NH3	TMC 1-C
R_{TD}(CO)	1.7	2.6	1.2

Ratio of CO abundances in the translucent phase at Av~5mag and at the peak of the cores, indicating CO depletion due to freeze-out onto grains in the inner cores. (Table 6 in Fuente et al. 2019)

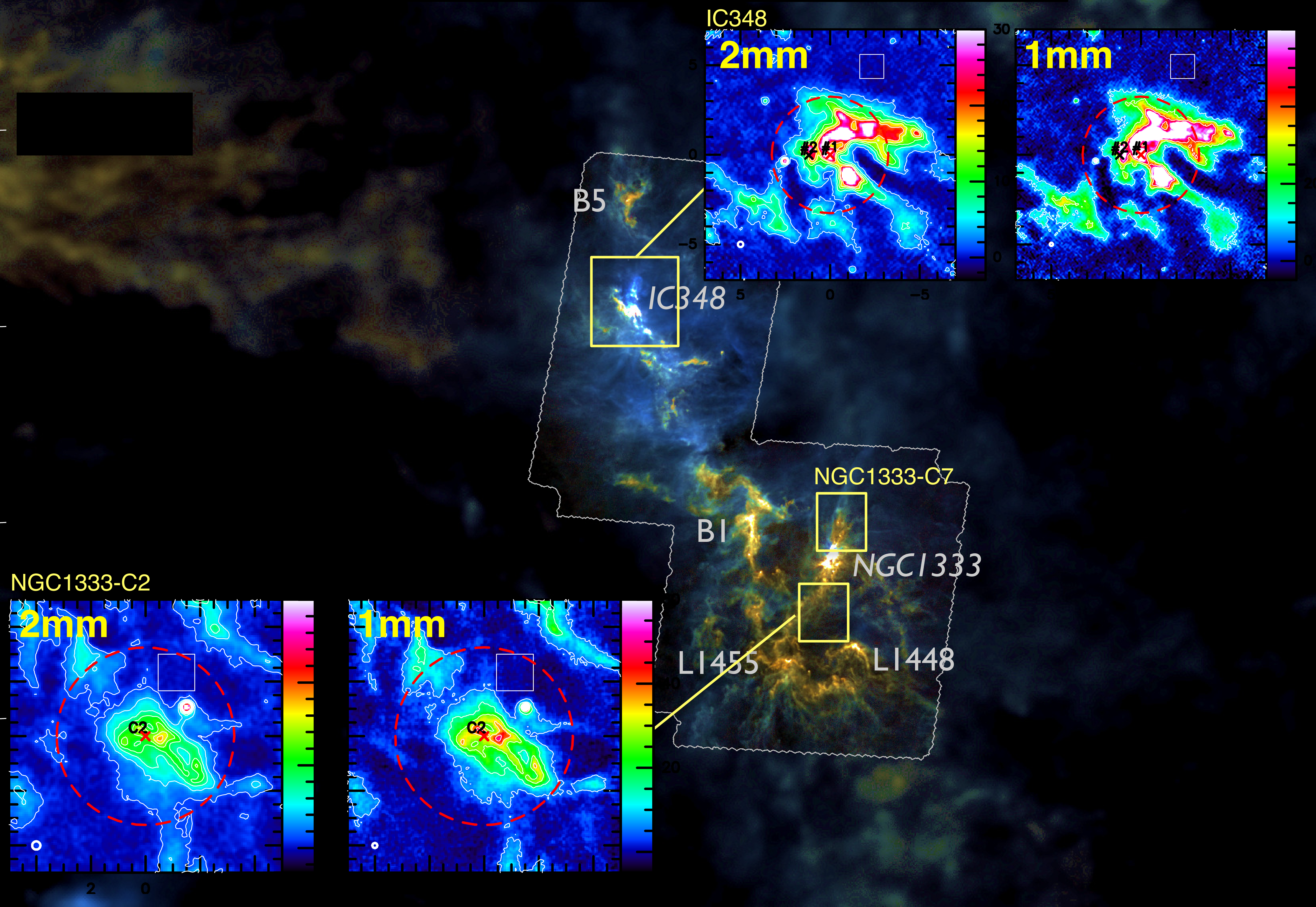


OH94 models with ice mantles:

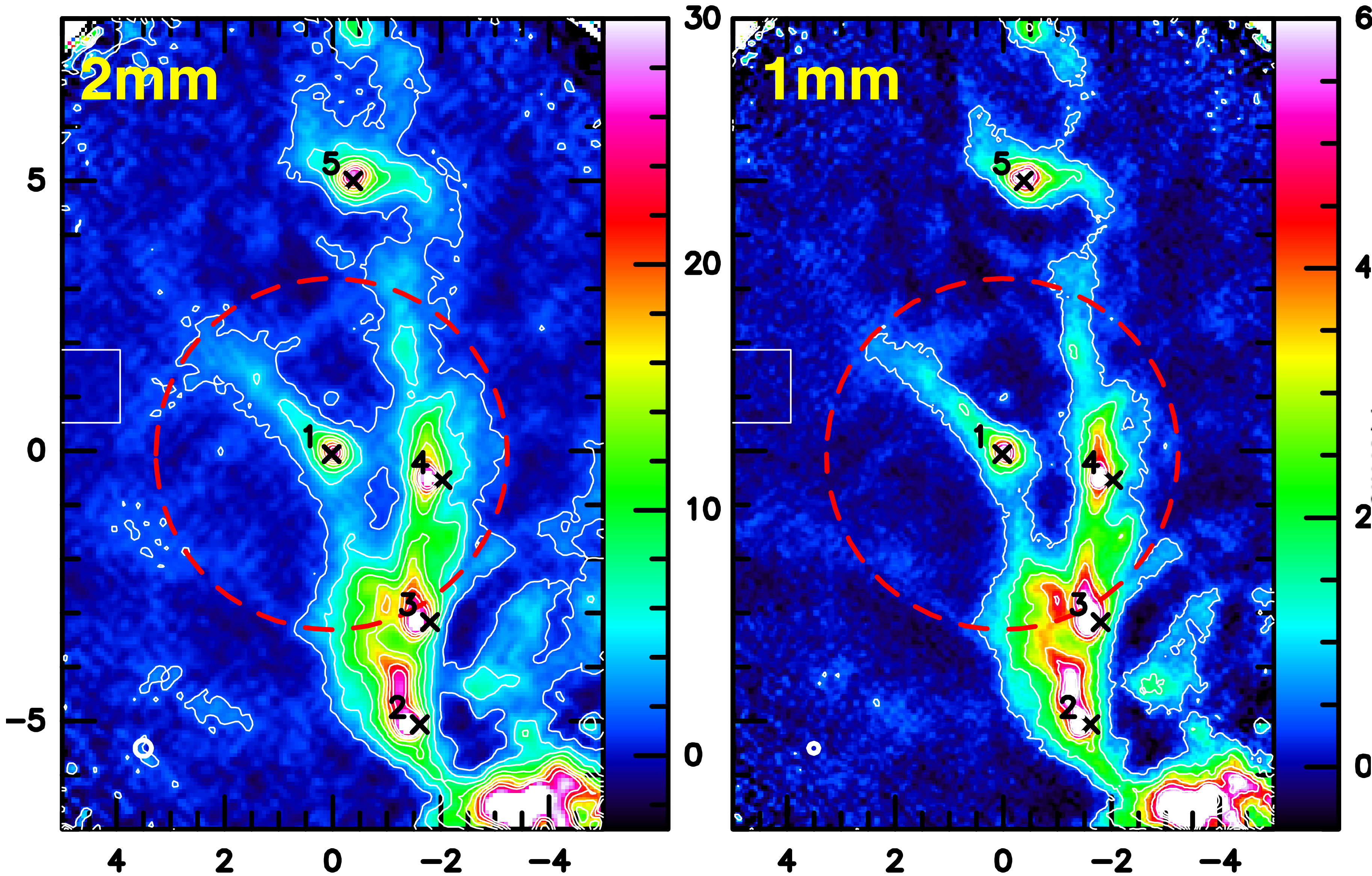
β increases with thickness of ice layer.

This interpretation is consistent with observations in TMC1-C.

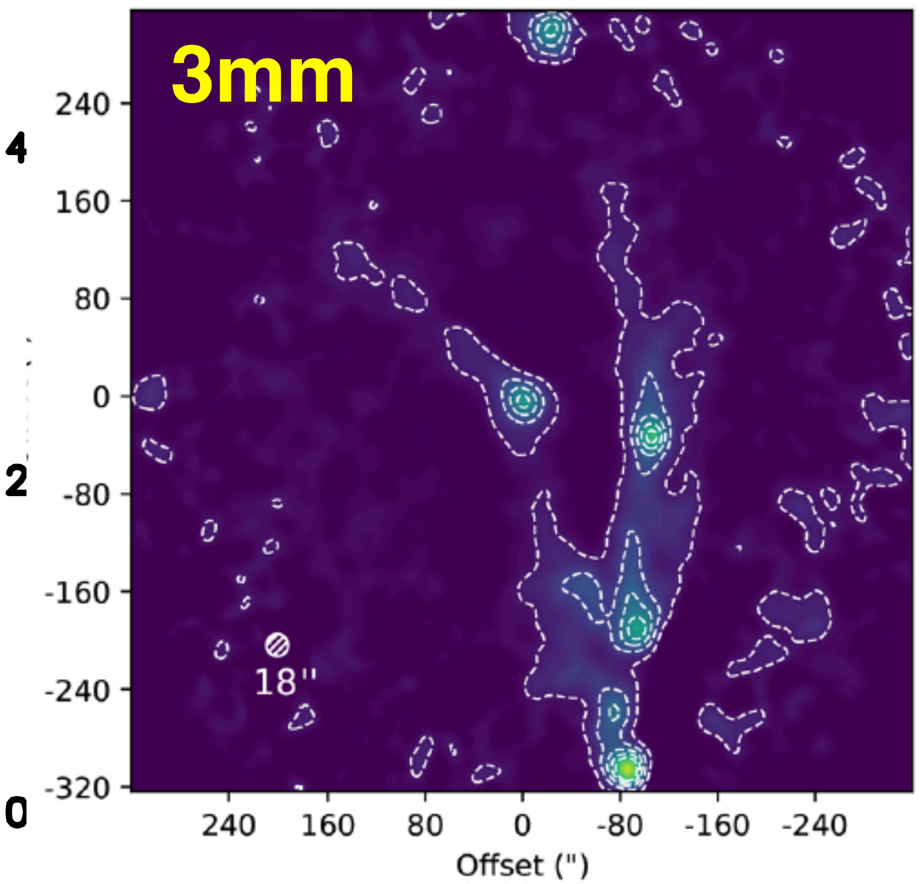
2mm & 1mm NIKA2 maps in Perseus



Cores in NGC1333-C7 Perseus



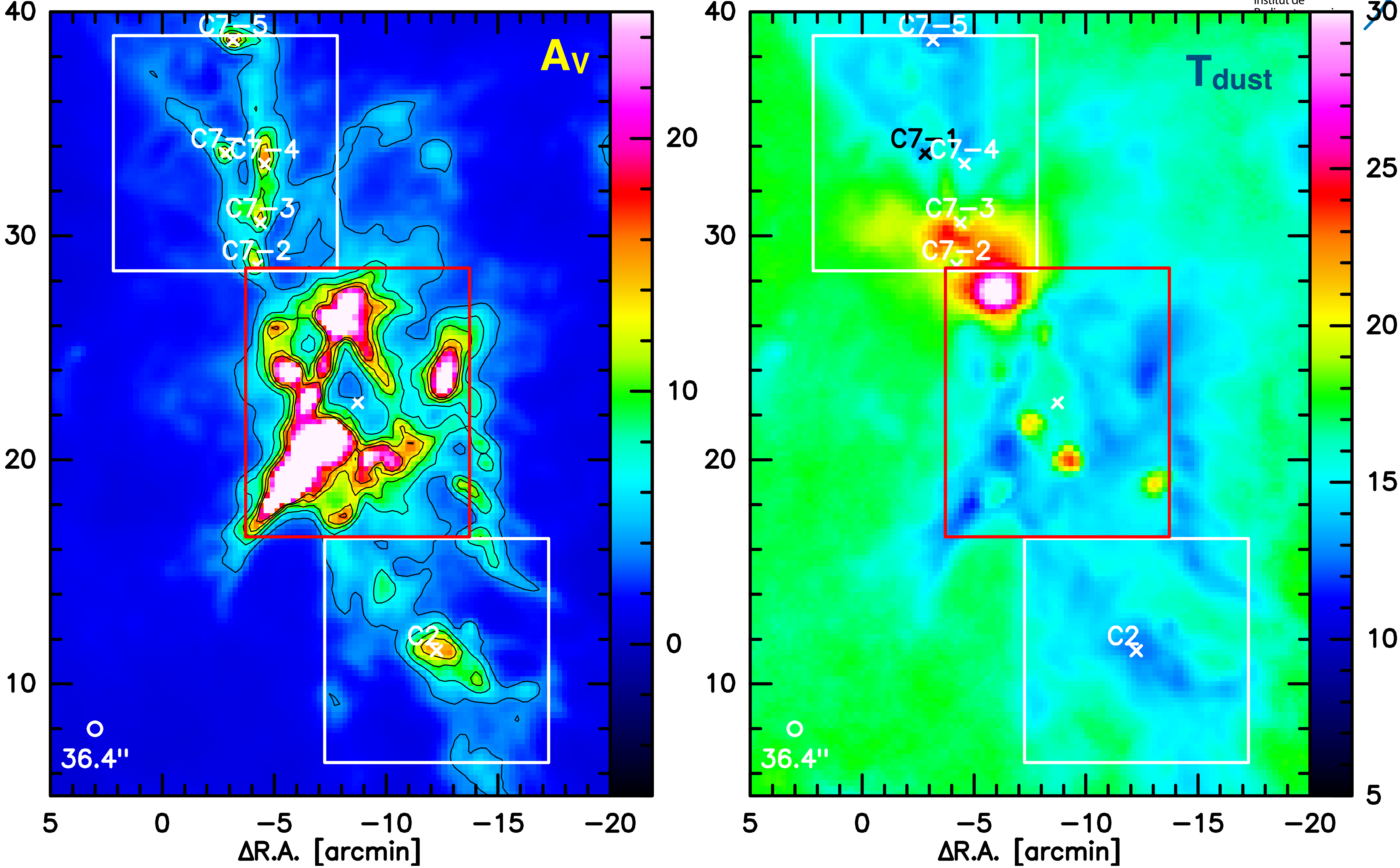
Left: 2mm NIKA2maps at 18”. Right: 1mm NIKA2 map at 11” resolution, both in mJy/beam. Flux contours start at 6σ and rise in steps of 12σ. FoV=6.5’ (0.56pc). 1σ(1mm)=0.87mJy/b, 1σ(2mm)=0.26mJy/b



3mm MUSTANG-2/GBT map by Navarro-Almaida et al. 2023. Contours start at 5sigma.

Cores in NGC1333 / Perseus - A_V and T_{dust} maps from Herschel

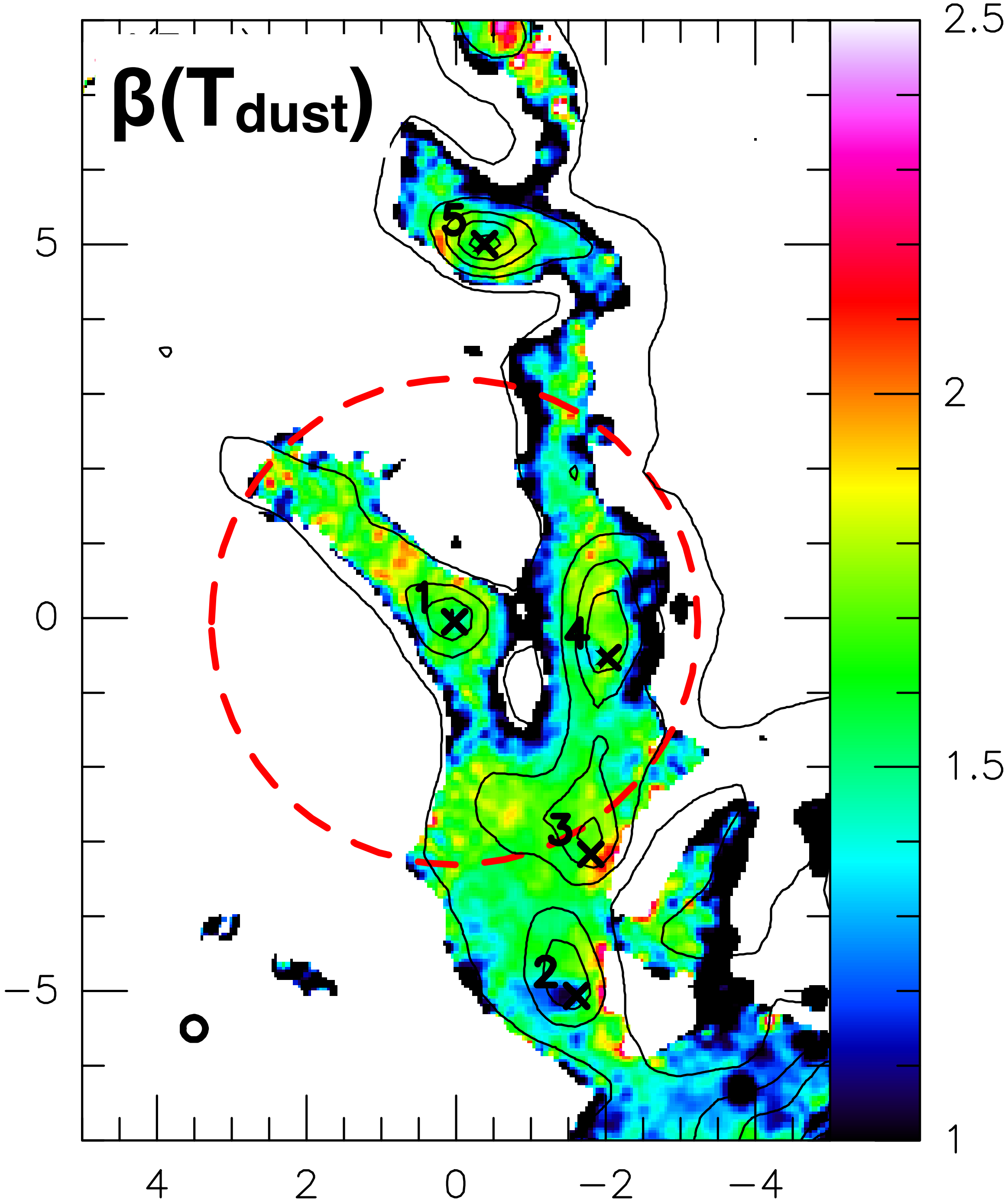
HOTT work by Singh & Martin 2022



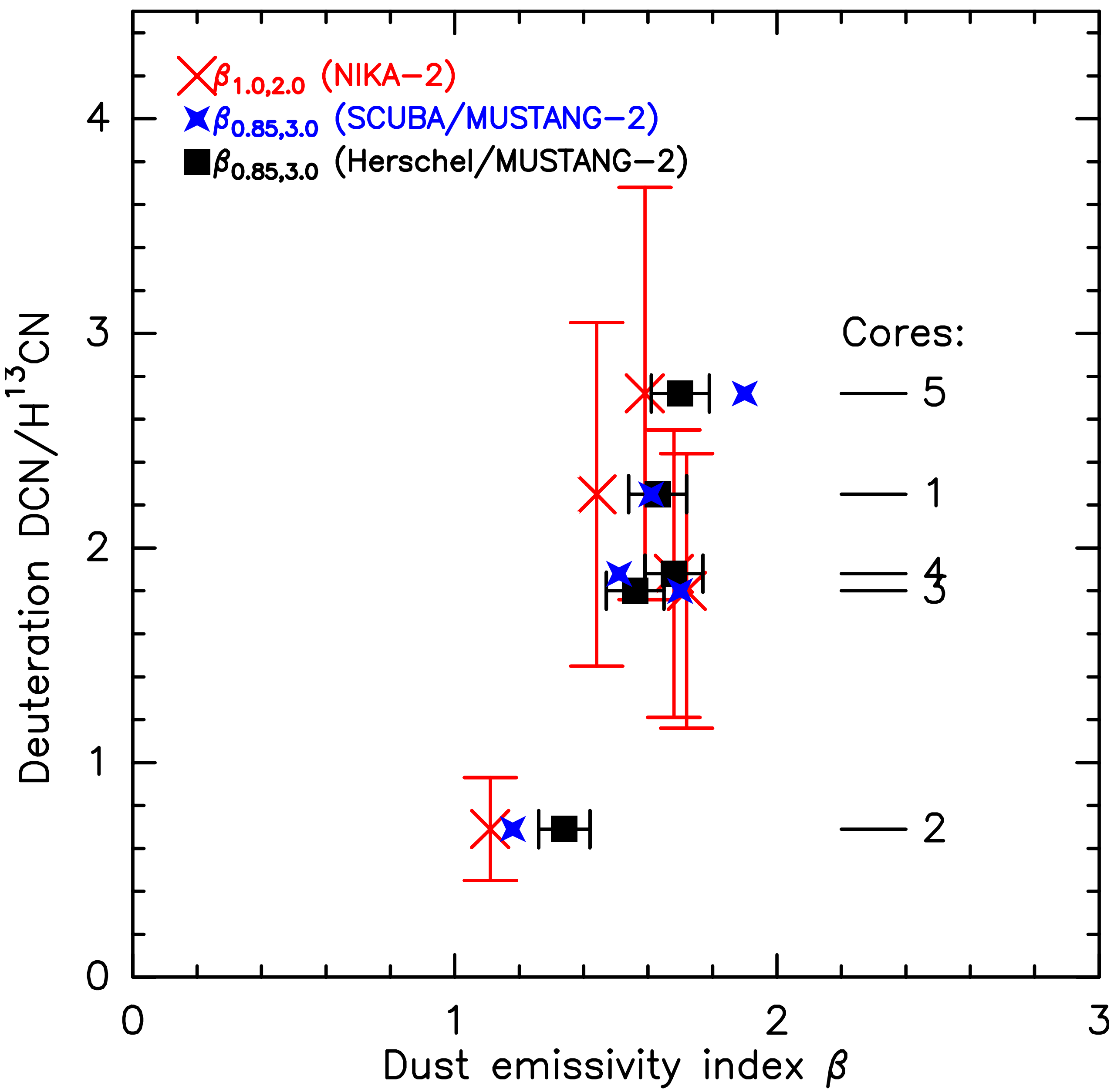
Note the temperature gradient from C7-2 to C7-5.

Cores of NGC1333-C7: β and Deuterium fraction

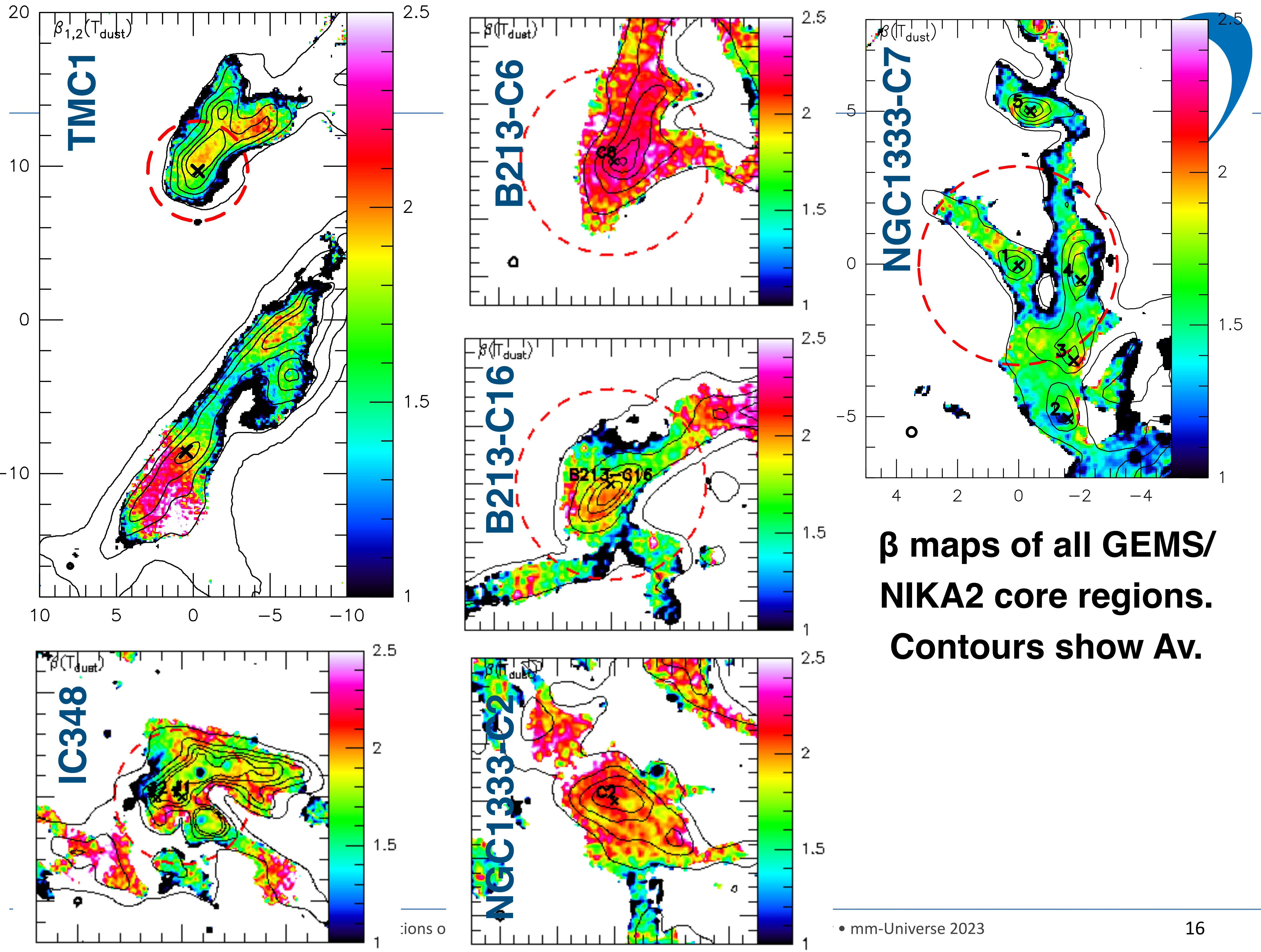
Deuterium fractionation traces evolution during starless phase and provides the only gas phase probes available for the central most regions of n~$10^6 cm^{-3}$. Deuteration fractionation is driven by low temperatures of ~10K by the lower zero-point vibrational energy compared to non-deuterated species. In addition, freeze-out of CO, a molecule that destroys H_2D^+ in the gas phase, further enhances the H_2D^+ abundance.



Map of $\beta_{1,2}(T_{dust})$ at 18” resolution. NIKA2 flux threshold of 6σ. Contours are A_v from 4 to 18mag by 3mag.

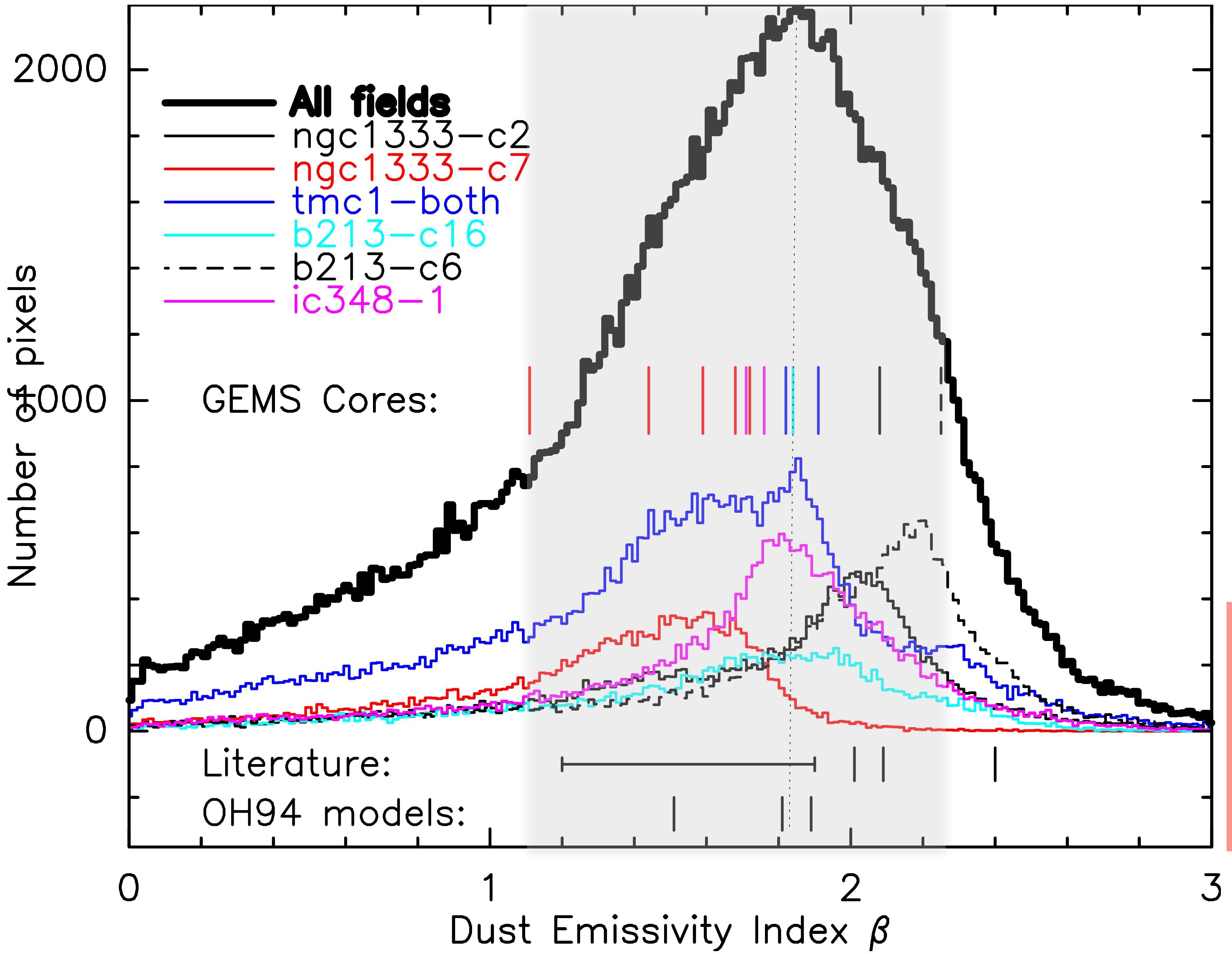


Dust emissivity β vs. the deuterium fraction $DCN/H^{13}CN$. $\beta_{0.85,3.0}$ and the deuterium fraction are taken from Navarro-Almaida et al. (2023). Core #2 is a Class-I proto-stellar object while all other cores are Class-0 or pre-stellar objects. (cf. Hacar et al. 2017)



β maps of all GEMS/ NIKA2 core regions. Contours show Av.

Dust emissivity index β in Taurus and Perseus



OH94: Ossenkopf & Henning 1994 Models with $n_H=10^5$ cm^{-3}, coagulated

- β=1.51 no ice
- β=1.81 thin ice mantle
- β=1.89 thick ice mantle

Literature for Taurus & Perseus:

- β=1.2-1.9±0.1 NGC1333-C7 by Navarro-Almaida et al. 2022 (MUSTANG-2, SCUBA, SPIRE/PACS)
- β=2.1±0.1 TMC1-C also by Navarro-Almaida et al. 2022
- β=2.0±0.5 B10 covering B213-C6 by Scibelli et al. 2023 (NIKA2)
- β=2.4±0.3 B213 by Bracco et al. 2017 (NIKA)
- β=1.6-2.0±0.4 L1544 by Chacon-Tanarro et al. 2019 (MUSTANG-2, AzTEC) [cf. 2017 paper with NIKA]

Cores in Taurus and Perseus

- Preliminary results:
  - For the cores at peak Av: **1.1 < $\beta_{1,2}$ < 2.3**
  - Grain models show that β is a strong function of grain properties e.g. coagulation and/or ice mantles.
  - Possible interpretation of the observed β variation:

    β increases with ice layer thickness (Ossenkopf & Henning 1994), i.e. with evolutionary stage. This has implications for e.g. the efficiency of chemical desorption.
  - OH94 models have difficulties to explain high indices.
  - For ngc1333-c7: **$\beta_{1,2}$ increases with deuteration**, another signature of the evolutionary stage.

Motivation: grain emissivity β at high z

Ismail, Cox et al. 2023, submitted
z-GAL: A NOEMA Large Program